ガンマ線バースト・高速電波バースト研究の現状、宇宙論との関係

Kunihito Ioka (KEK)

Theoretical Astrophysics
Tohoku University

KEK
HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION

The Graduate University for Advanced Studies
Sokendai

ガンマ線バースト・高速電波バースト研究の現状、宇宙論との関係

Kunihito Ioka (KEK)

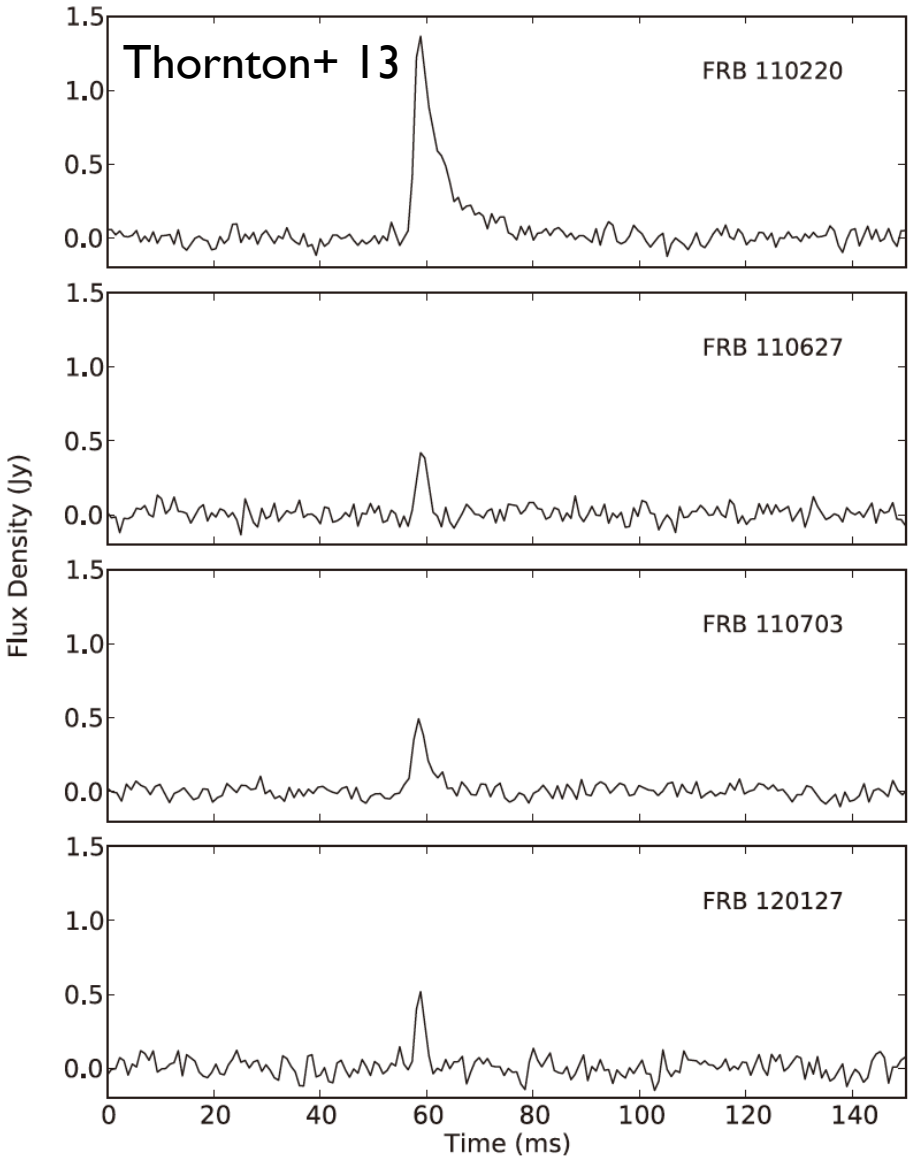
Theoretical Astrophysics
Tohoku University

KEK
HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION

The Graduate University for Advanced Studies
Sokendai

天
Cosmophysics
KEK

Fast Radio Bursts



F=0.6-8.0 Jy ms !!!

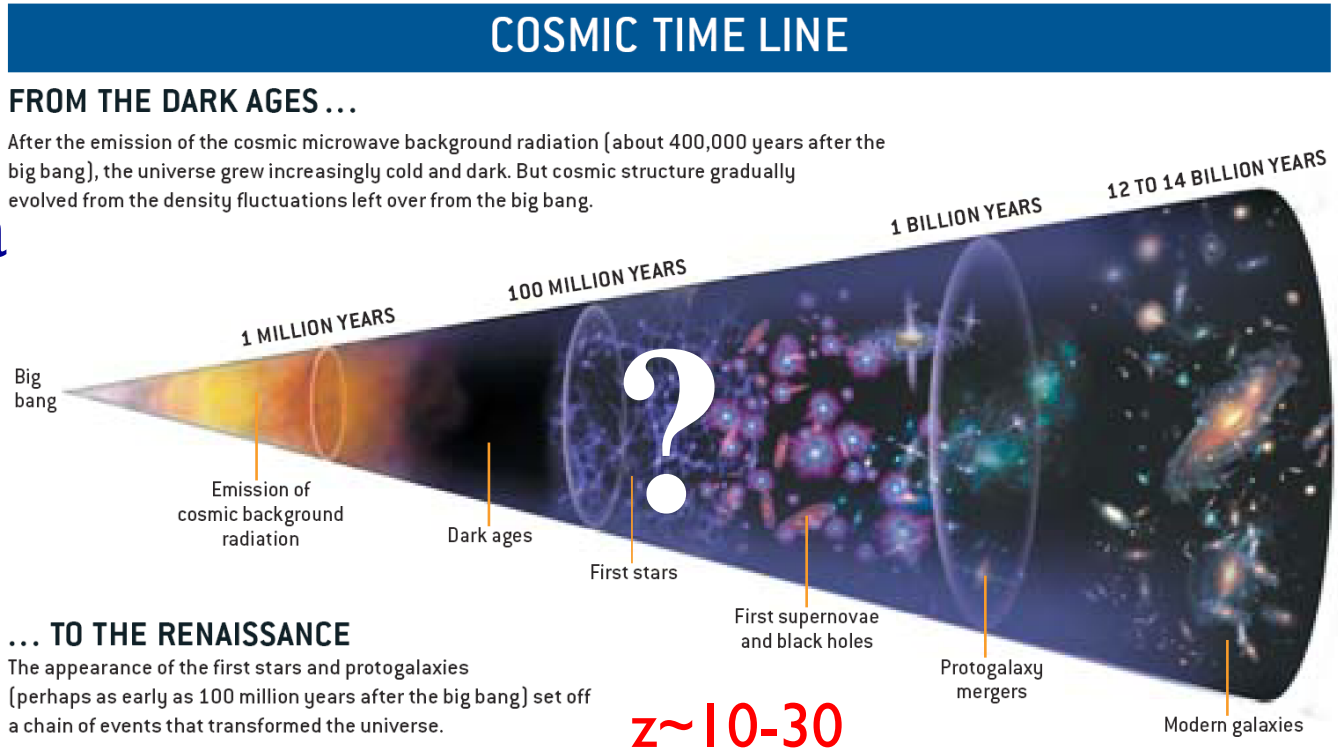
Most luminous radio transients if cosmological

~10年前

GRB Cosmology

Massive star origin ⇒ High redshift GRBs

Like QSO
Like Supernova
Star formation
Reionization
Metal, Dust
Dark energy
…



Larson & Bromm 02

z~10-30

GRB

z~8

QSO, galaxy

GRBs are useful for probing high-z

Radio Dispersion

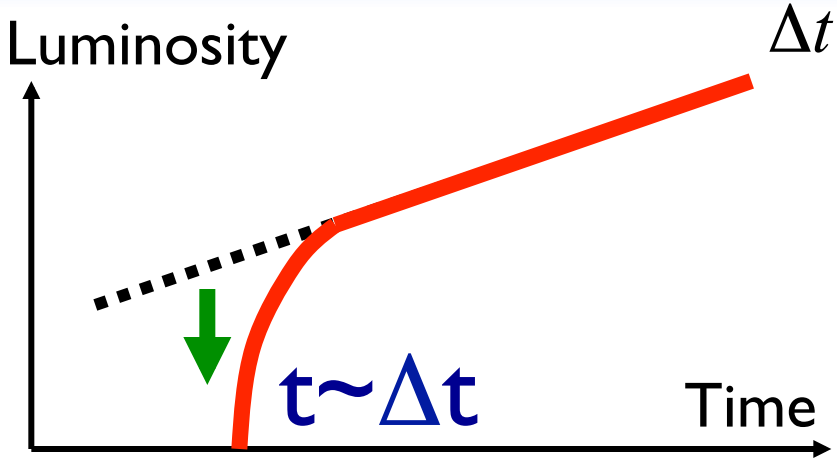
In a plasma, a light signal is delayed

$$\omega^2 = k^2c^2 + \omega_p^2$$

plasma frequency

$$\omega_p = \sqrt{\frac{4\pi ne^2}{m}} = 5.63\times10^4 n^{1/2}\ \mathrm{s}^{-1}$$

$$\Delta t = 4.15\ \mathrm{s}\left(\frac{\nu}{1\ \mathrm{GHz}}\right)^{-2}\left(\frac{\mathrm{DM}}{10^3\ \mathrm{pc\ cm}^{-3}}\right)$$



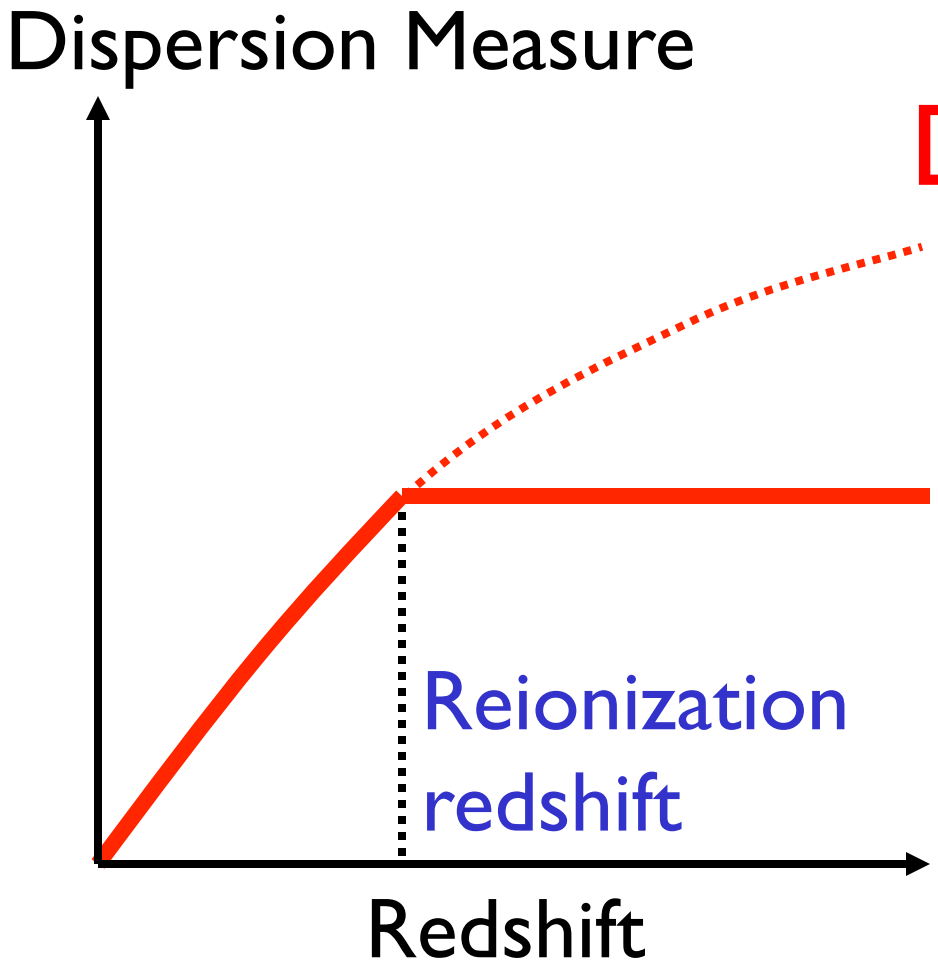
Distortion in light curve

⇒ DM

⇒ Reionization History

Dispersion Measure

is the column density of free electrons along light path



Dispersion Measure

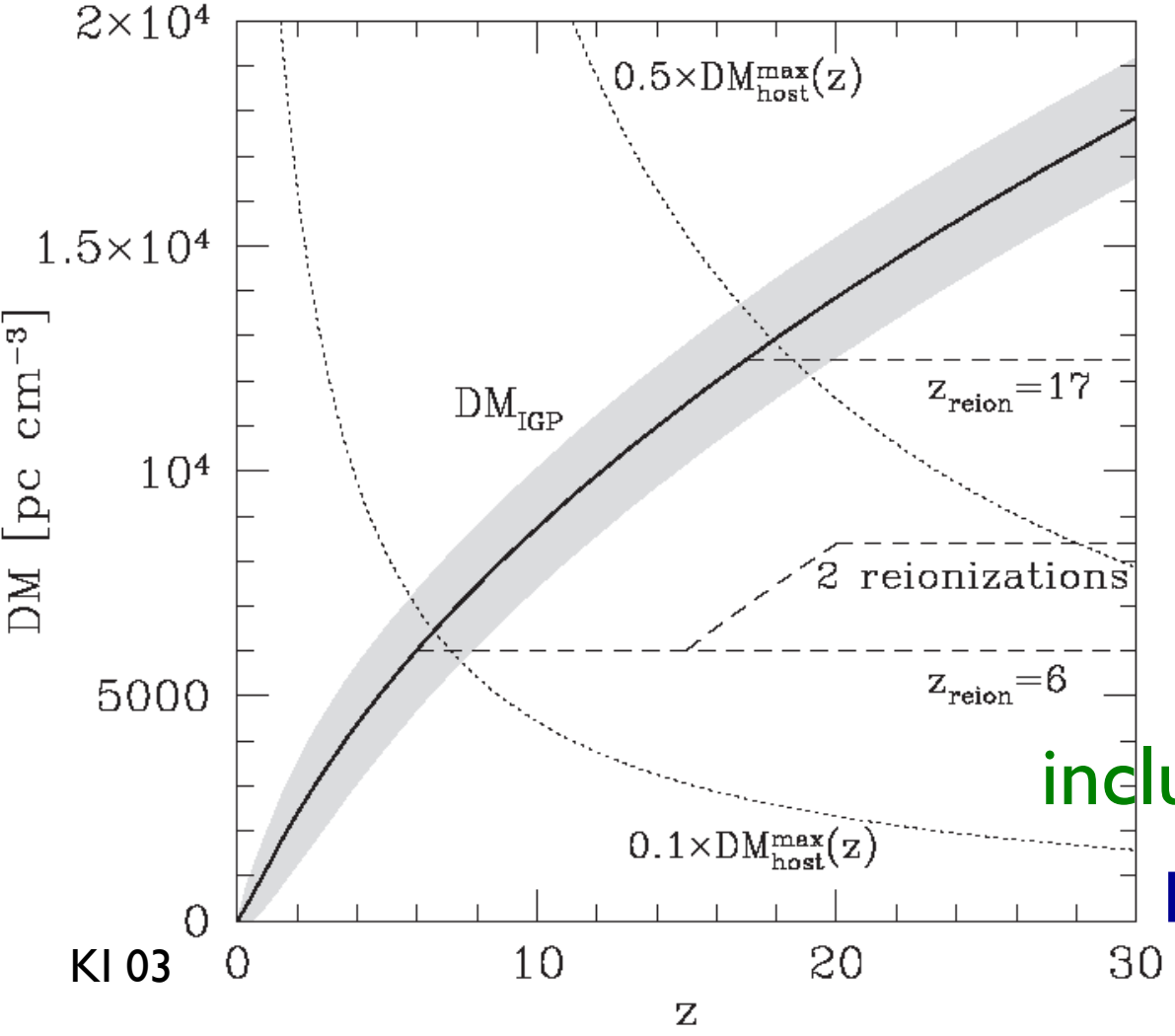
↓

Reionization History

Recombined electrons provide no DM

KI 03, Inoue 04

Intergalactic DM



KI 03

$$\Delta t = \int_0^z dz \frac{dt}{dz} \frac{1}{2} \frac{(1+z)\nu_p^2}{\left[(1+z)\nu\right]^2}$$

$$= \frac{e^2}{2\pi m_e c} \frac{1}{\nu^2} \times$$

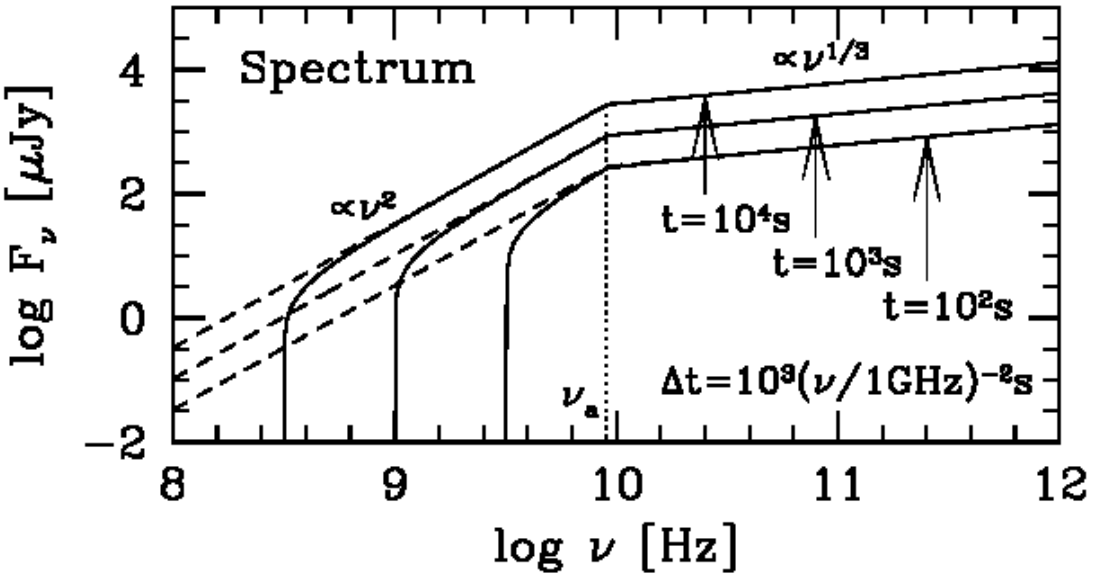
$$\frac{cn_0}{H_0} \int_0^z \frac{(1+z)\,dz}{\left[\Omega_m (1+z)^3 + \Omega_\Lambda\right]^{1/2}}$$

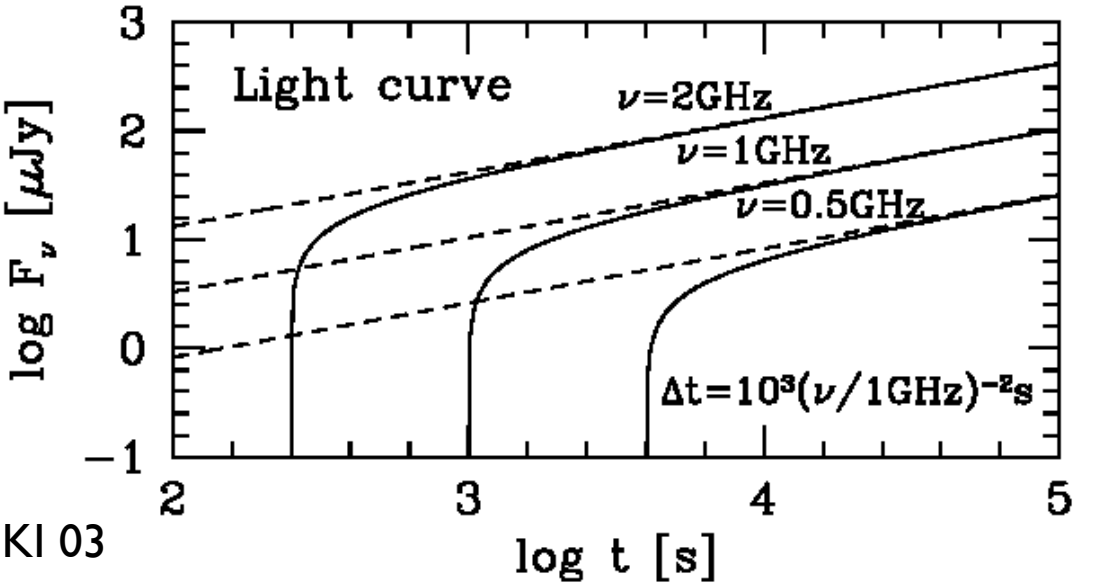
DM_{IGP}

including missing baryon

DM_{Galaxy}~30-10^3 pc cm^{-3}

DM from Afterglow





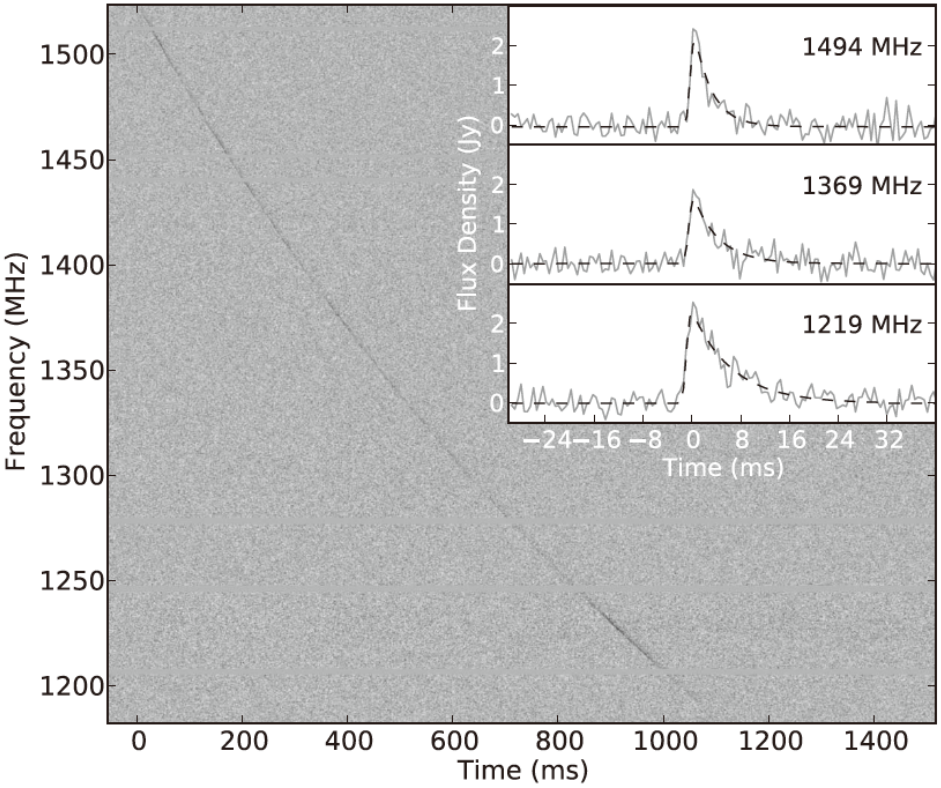
KI 03

Distortion at $t \sim \Delta t$ $\Rightarrow$ DM

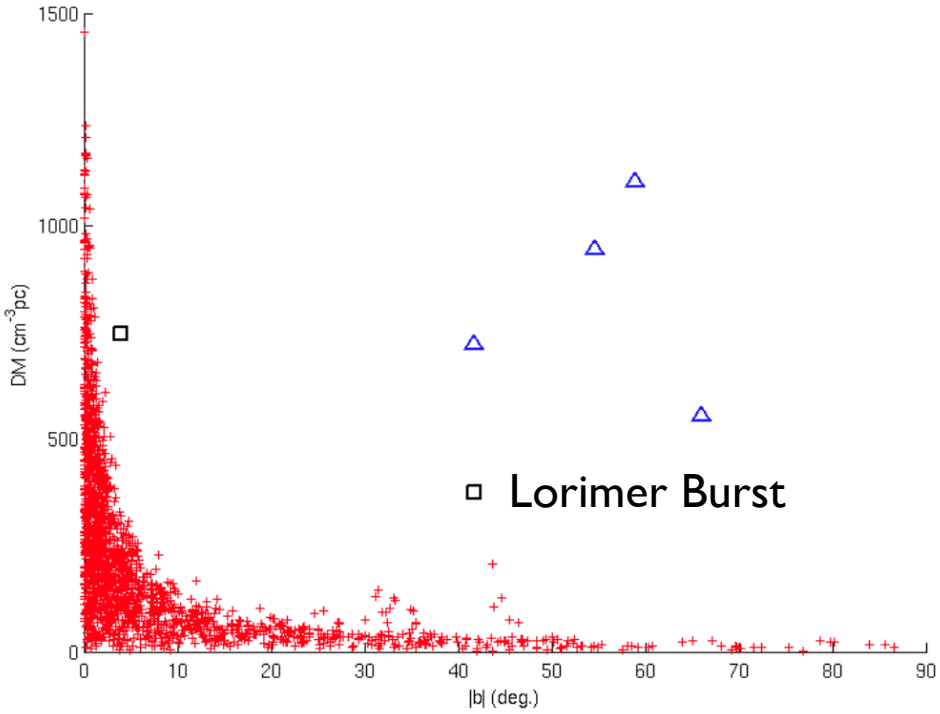
$\Delta t \propto \nu^{-2}$

Unfortunately radio afterglows are not so bright

Dispersion Measure



Thornton+ 13



Galactic latitude

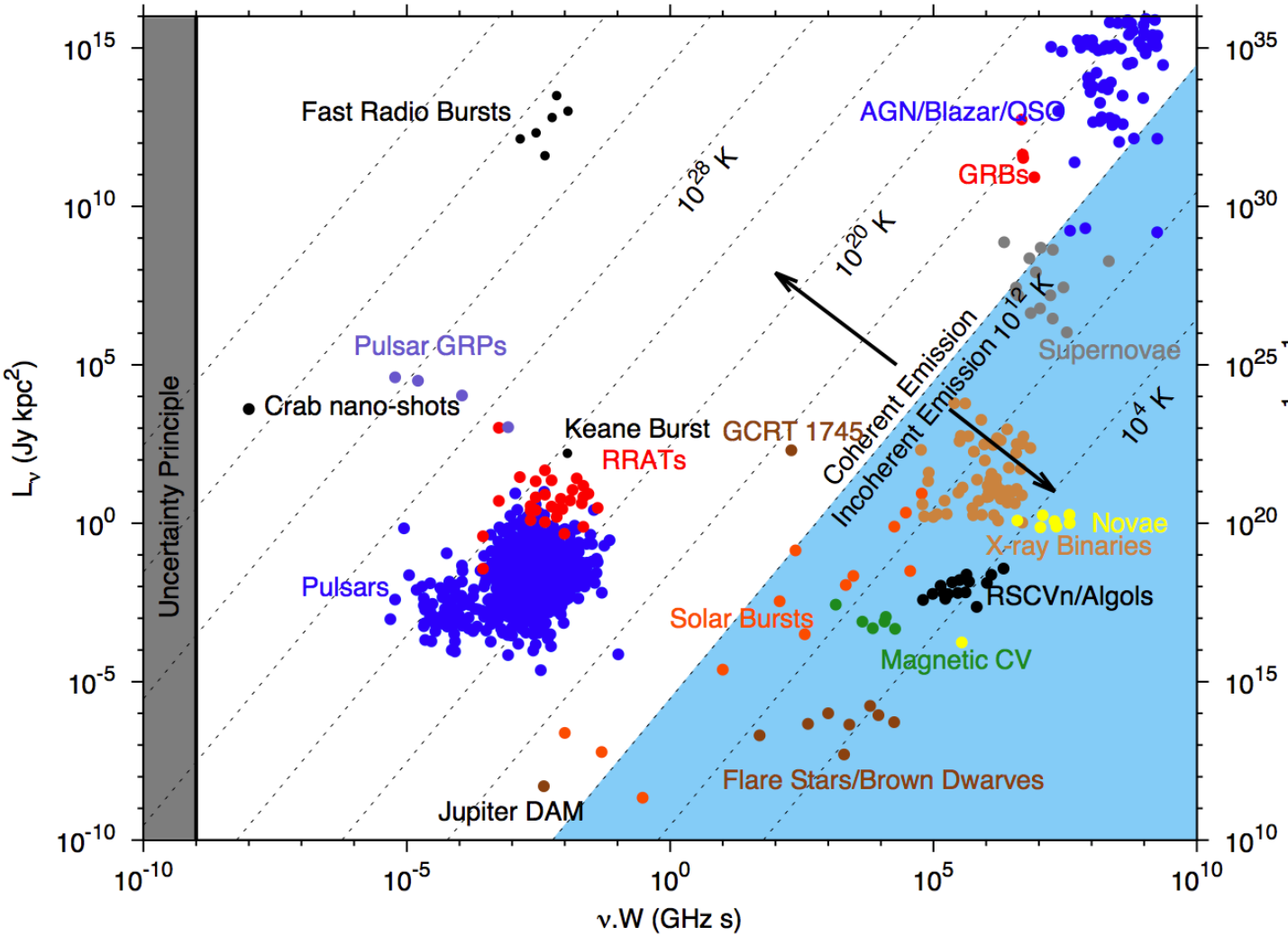
$\delta t \propto DM \cdot \nu^{-2}$

DM=500-1000 cm^{-3} pc

Brightness Temperature

$$T_{\rm B} \simeq 10^{36}{\rm K}\left(\frac{S_{\rm peak}}{\rm Jy}\right)\left(\frac{\rm GHz}{\nu}\right)^2\left(\frac{\rm ms}{\Delta t}\right)^2\left(\frac{d}{\rm Gpc}\right)^2\frac{(1+z)^4}{\gamma^2}$$

d: comoving distance



$P \sim |E|^2$
$\sim |E_1 + \ldots + E_N|^2$
$\sim N|E_1|^2$
(incoherent)
$\sim N^2|E_1|^2$
(coherent)

Pietka+ 14

Summary of FRB Obs.

- DM=500-1000 cm^{-3} pc (z=0.5-1, d_L~2-6Gpc)
- S_ν~Jy $\Rightarrow$ E_{iso}~$10^{39\text{-}41}$ erg (~10x if $\Delta\nu\sim\nu$)
- δt=5.6ms,<4.3,1.4,1.1ms
  $\Rightarrow c\delta t(1+z)^{-1} < 1500(1+z)^{-1}$ km
- Rate~$(1\pm0.5)\times10^4$/sky/day~10^{-3}/yr/galaxy
  $\Leftrightarrow$ Supernova rate 10^{-2}/yr/galaxy
- High brightness temperature > 10^{35}K
- No repeats & No counterparts so far

Expected Rate

Hassall+ 13
Lorimer+ 13
Trott+ 13

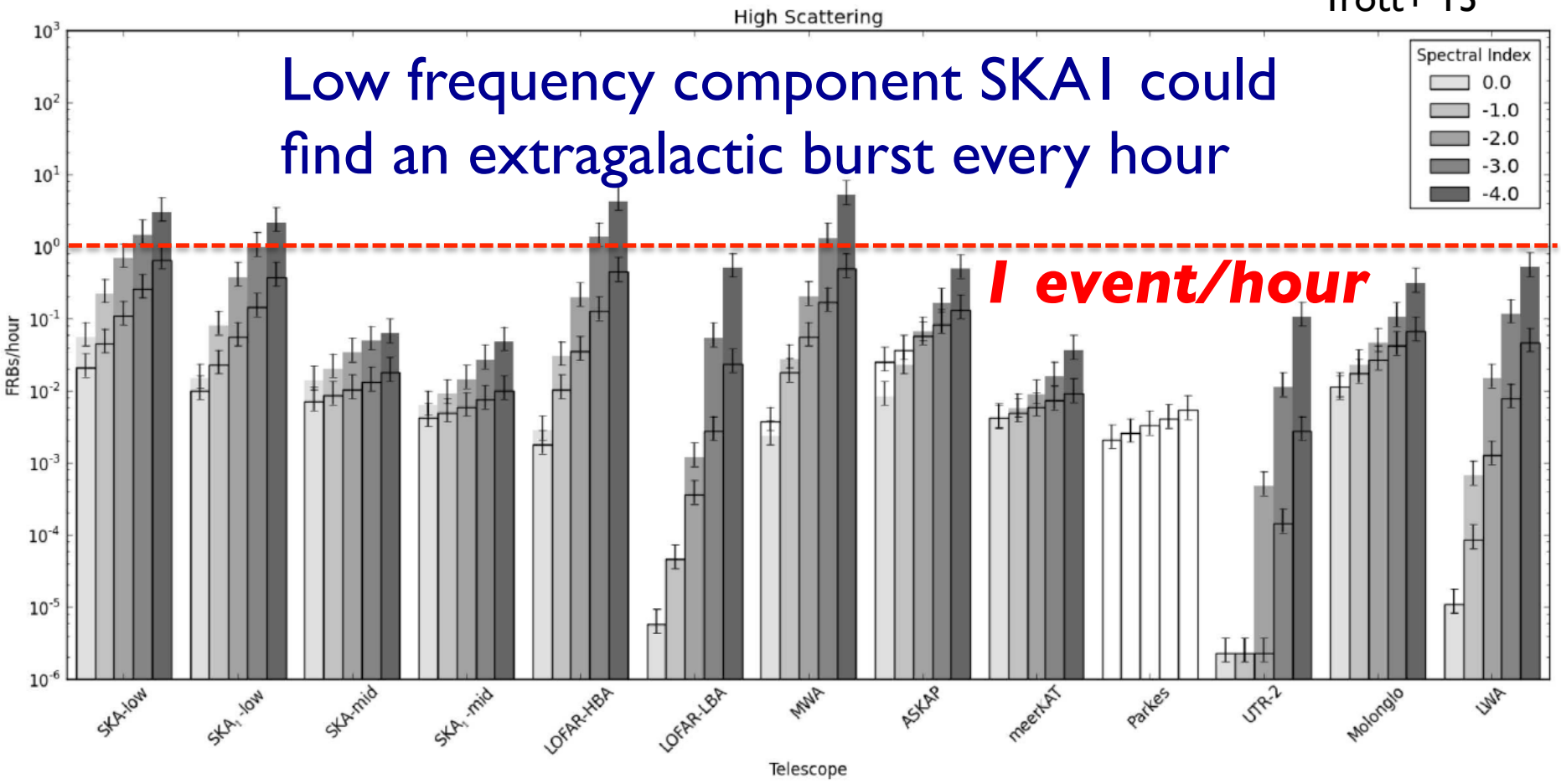


Figure 2. Expected number of FRBs per hour for various observatories in the high-scattering simulations. The solid bars show the number of FRBs detectable in imaging surveys, assuming different spectral indices of: 0.0 (white), -1.0, -2.0, -3.0 and -4.0 (darkest grey). The number of FRBs detectable in beamformed surveys are indicated by the corresponding transparent bars. The DM range used was $0 - 6000$ pc cm^{-3}.

Contents for FRB

- ***Possible origins***
- Real cosmic signal?
- Galactic?
- FRB cosmology

Possible Origins

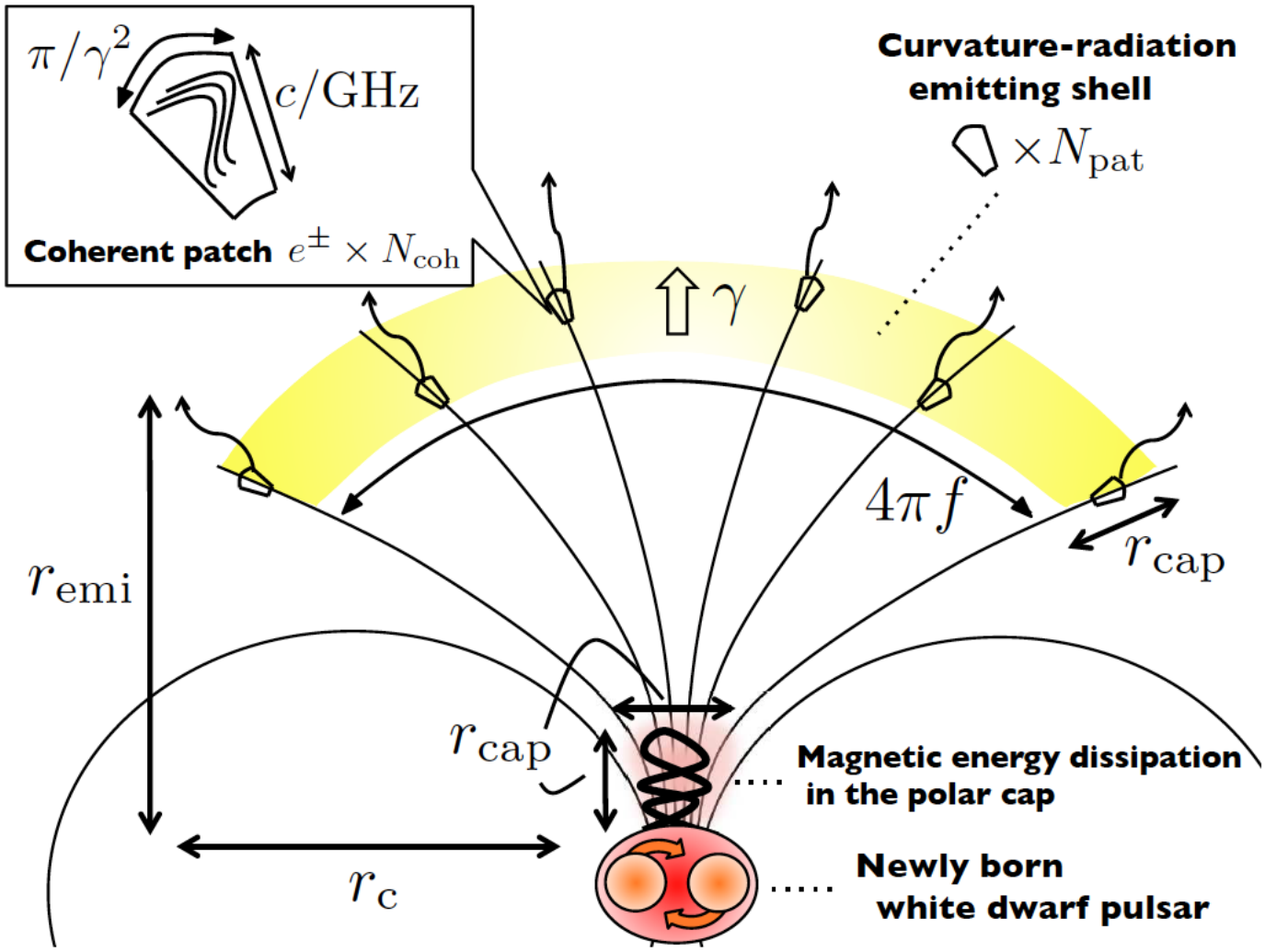
- ***Perytons*** Burke-Spolaor+ 11; Kulkarni+ 14
- ***Galactic***
  - Nearby flaring star Loeb+ 13
  - RRAT (Rotating Radio Transient; intermittent pulsar)
- ***Extragalactic***
  - Magnetar giant flare Popov & Postnov 07; Thornton+ 13; Lyubarsky 14; Penn & Conner 15
  - NS-NS merger Hansen & Lyutikov 01; Totani 13
  - WD-WD merger Kashiyama+ 13
  - Collapse of hypermassive NS Falcke & Rezzolla 13; Zhang 13
  - Supernova into a nearby star Colgate+ 71,75; Egorov & Postnov 09
  - Supergiant pulse Cordes & Wasserman 15
  - Pulsar-orbiting bodies Mottez & Zarka 14

Possible Exotics

- Evaporation of BH Rees 77; Blandford 77; Kavic+ 08; Keane+ 12
- PBH to white hole Barrau+ 14
- Superconducting cosmic strings Cai+ 12; Yu+ 14
- Axion stars Iwazaki+ 14; Tkachev+ 14
- …

Binary White Dwarf Mergers?

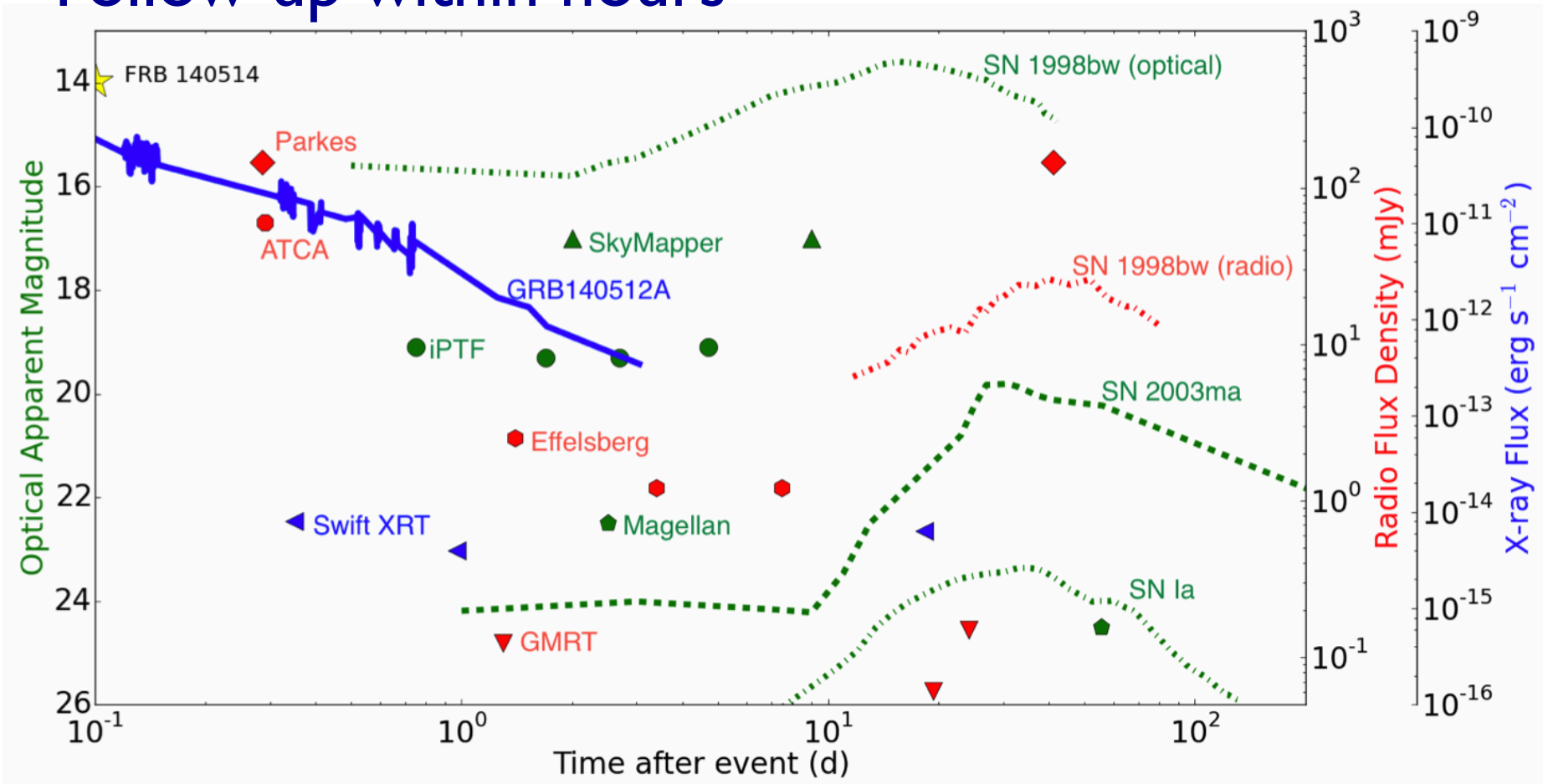
Kashiyama, KI & Meszaros 13



- Energetics $E_B \sim 10^{40}$erg
- Timescale $r_{cap}/c \sim$ms
- Event rate ~SN Ia
- SN Ia as a counterpart?

No Counterpart So Far

Follow-up within hours

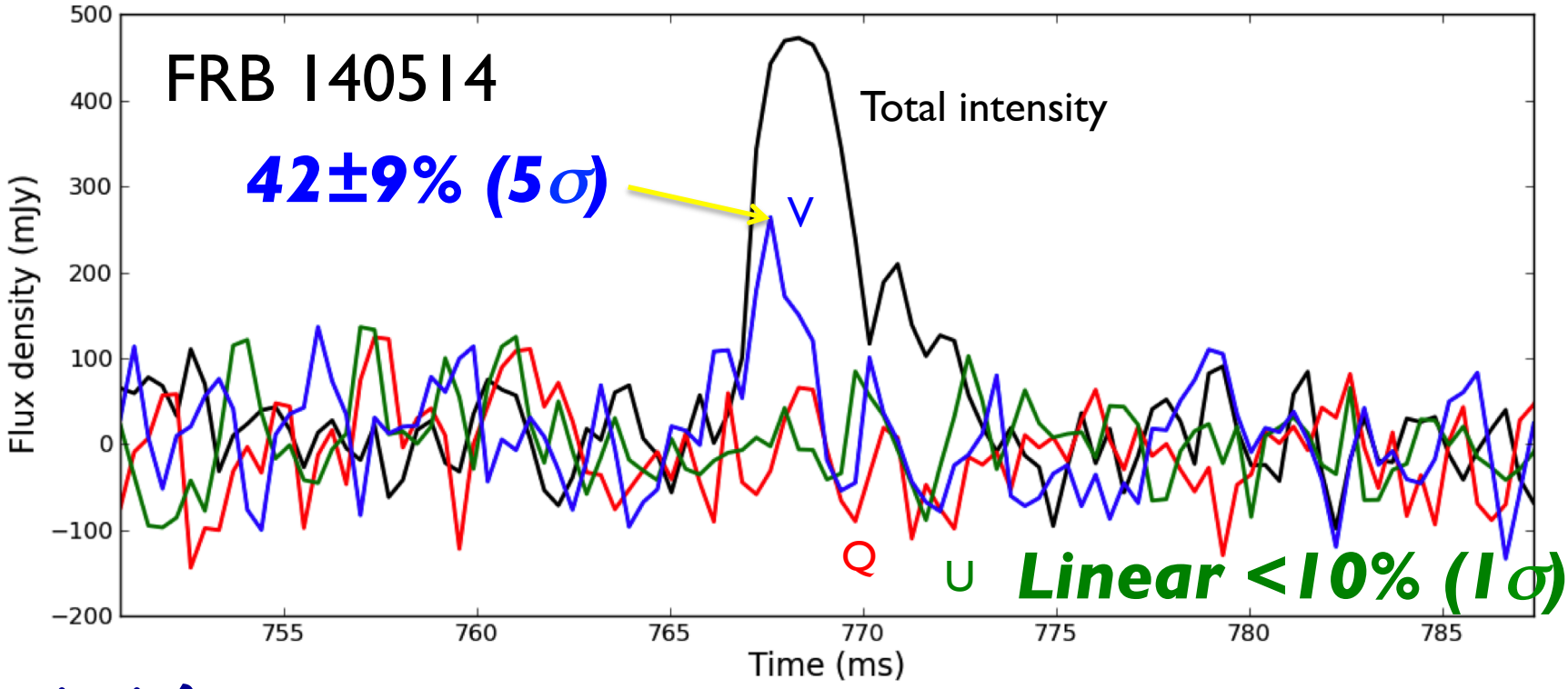


Rule out supernovae and long GRBs

Petroff+ 14

Circular Polarization

21±7% (3σ) circular polarization!!!



Intrinsic? (Cyclotron maser in flare stars 90-100%, AGN ~0.3%, Pulsar pulses)

Faraday conversion from linear to circular? (not likely)

Scintillation-induced CP?

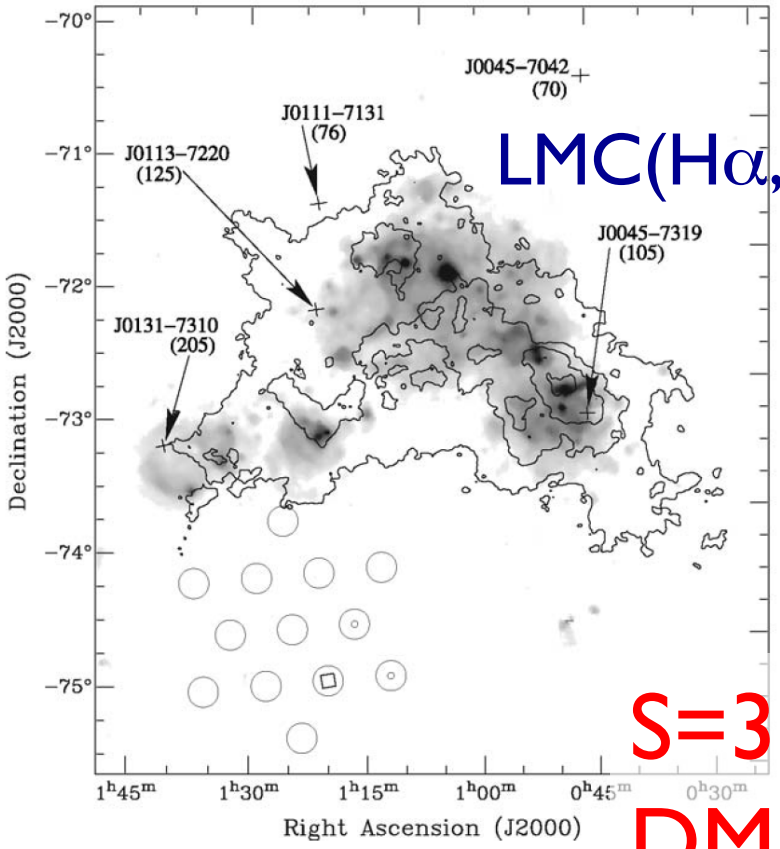
Petroff+ 14

Contents for FRB

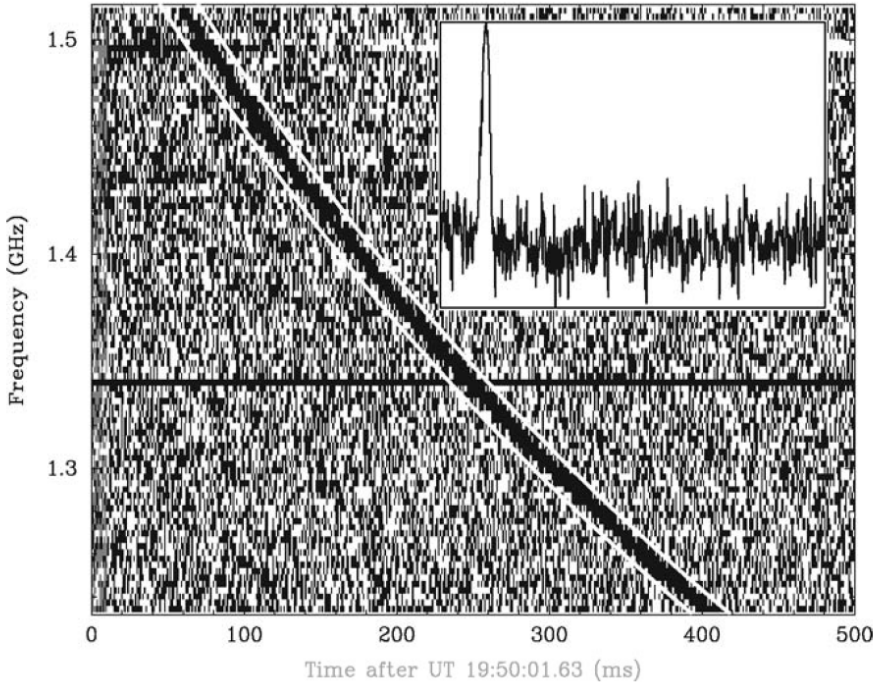
- Possible origins
- ***Real cosmic signal?***
- Galactic?
- FRB cosmology

Lorimer Burst 010724

Lorimer+ 07



LMC(Hα, HI)



S=30±10Jy, δt<5ms

DM=375 cm^3 pc ⇒ z~0.1-0.3

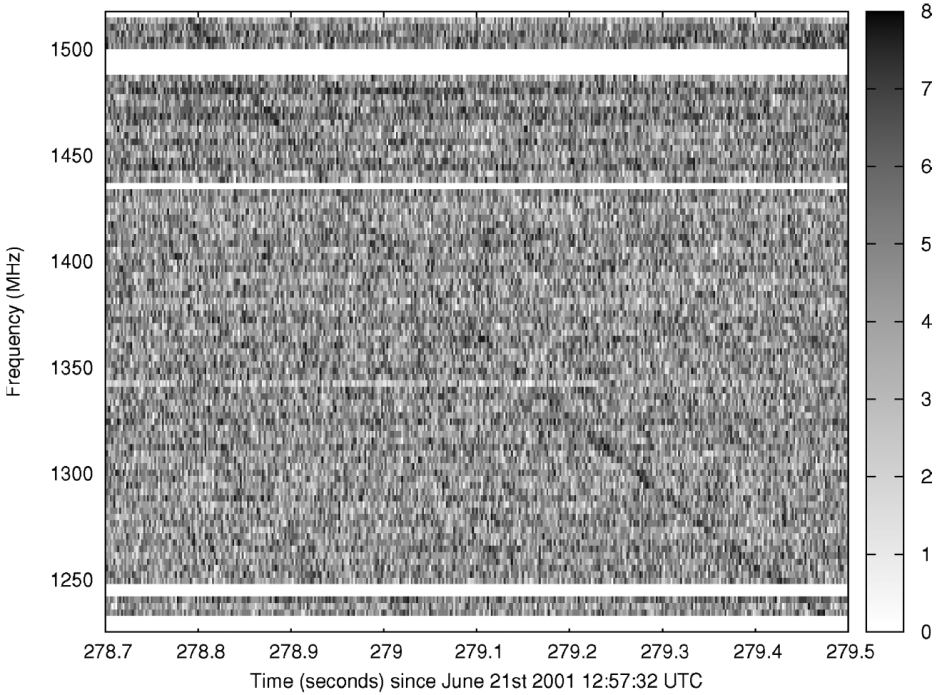
W∝f$^{-4.8±0.4}$, S∝f^{-4}

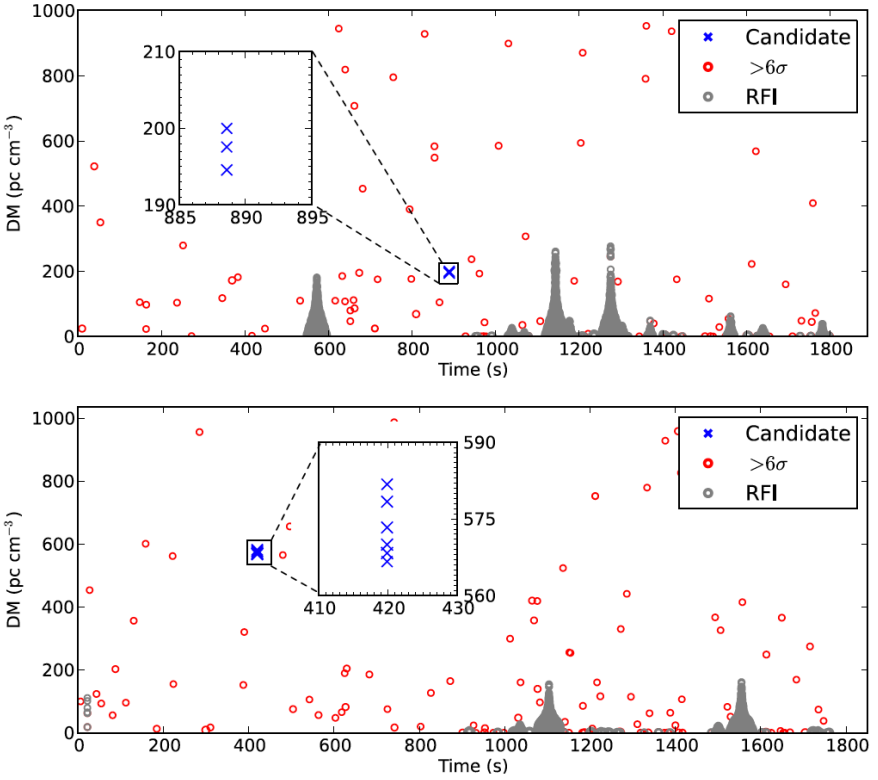
b=-41.8deg

Fig. 1. Multiwavelength image of the field surrounding the burst. The gray scale and contours respectively show Hα and H I emission associated with the SMC (*32*, *33*). Crosses mark the positions of the five known radio pulsars in the SMC and are annotated with their names and DMs in parentheses in units of cm^{-3} pc. The open circles show the positions of each of the 13 beams in the survey pointing of diameter equal to the half-power width. The strongest detection saturated the single-bit digitizers in the data acquisition system, indicating that its S/N >> 23. Its location is marked with a square at right ascension 01^h 18^m 06^s and declination −75° 12′ 19″ (J2000 coordinates). The other two detections (with S/Ns of 14 and 21) are marked with smaller circles. The saturation makes the true position difficult to localize accurately. The positional uncertainty is nominally ±7′ on the basis of the half-power width of the multibeam system. However, the true position is probably slightly (about 1 arcmin) northwest of this position, given the nondetection of the burst in the other beams.

Fig. 2. Frequency evolution and integrated pulse shape of the radio burst. The survey data, collected on 24 August 2001, are shown here as a two-dimensional "waterfall plot" of intensity as a function of radio frequency versus time. The dispersion is clearly seen as a quadratic sweep across the frequency band, with broadening toward lower frequencies. From a measurement of the pulse delay across the receiver band, we used standard pulsar timing techniques and determined the DM to be 375 ± 1 cm^{-3} pc. The two white lines separated by 25 ms trace the expected behavior for the cold-plasma dispersion law assuming a DM of 375 cm^{-3} pc. The horizontal line at ~1.34 GHz is an artifact in the data caused by a malfunctioning frequency channel. This plot is for one of the offset beams in which the digitizers were not saturated. By splitting the data into four frequency subbands, we have measured both the half-power pulse width and flux density spectrum over the observing bandwidth. Accounting for pulse broadening due to known instrumental effects, we determine a frequency scaling relationship for the observed width $W = 4.6$ ms $(f/1.4\ \mathrm{GHz})^{-4.8 \pm 0.4}$, where f is the observing frequency. A power-law fit to the mean flux density obtained in each subband yields a spectral index of −4 ± 1. The inset shows the total-power signal after a dispersive delay correction assuming a DM of 375 cm^{-3} pc and a reference frequency of 1.5 GHz. The time axis on the inner figure also spans the range 0 to 500 ms.

Similar Events?





J1852-08 (Keane FRB 010621)

DM=746 cm^{-3} pc

400mJy, 7.8ms

Keane+ 12

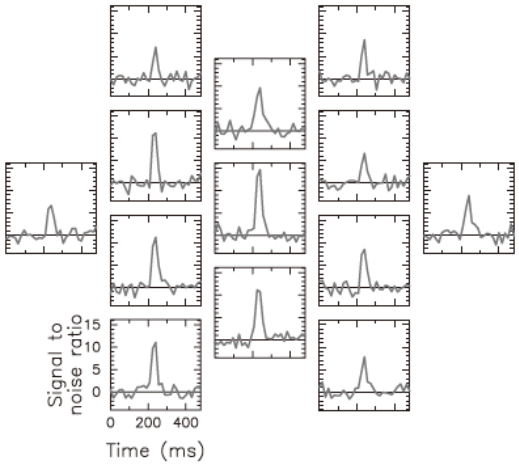
Bannister+ 12

Rubio-Herrera+ 13

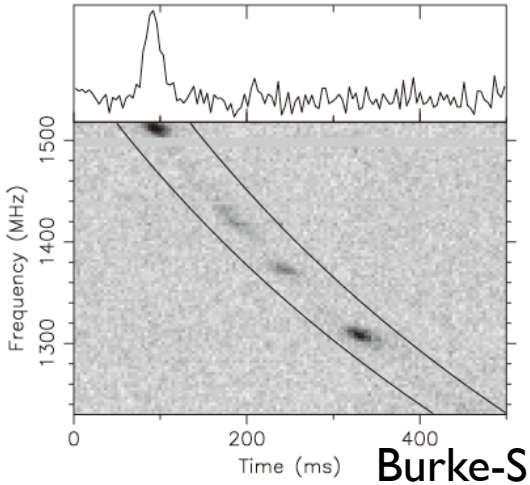
GRB100704A

GRB101011A

Terrestrial?



(a) Peryton 08 in 13 beams

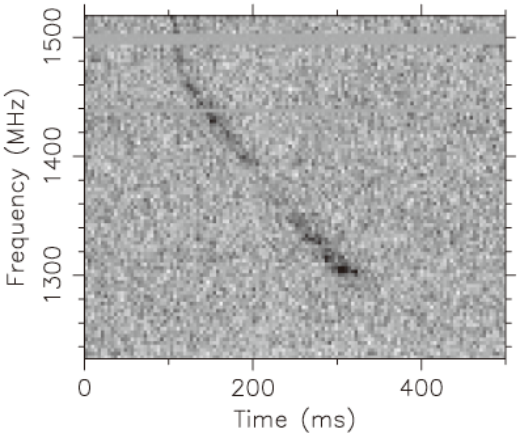


(b) Peryton 08

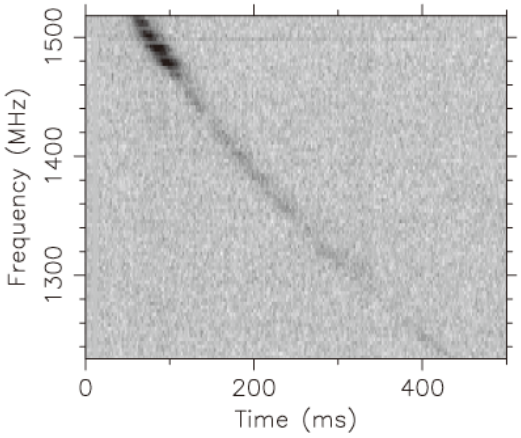
16 "Perytons" in all

13 telescope receivers

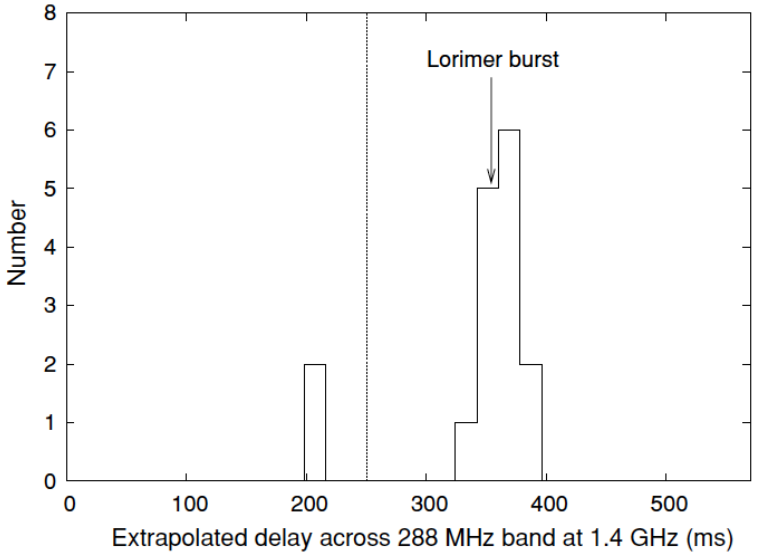
Burke-Spolaor+ 11; Kocz+ 12; Saint-Hilaire+ 12



(c) Peryton 06



(d) Peryton 15



Dispersion Measure

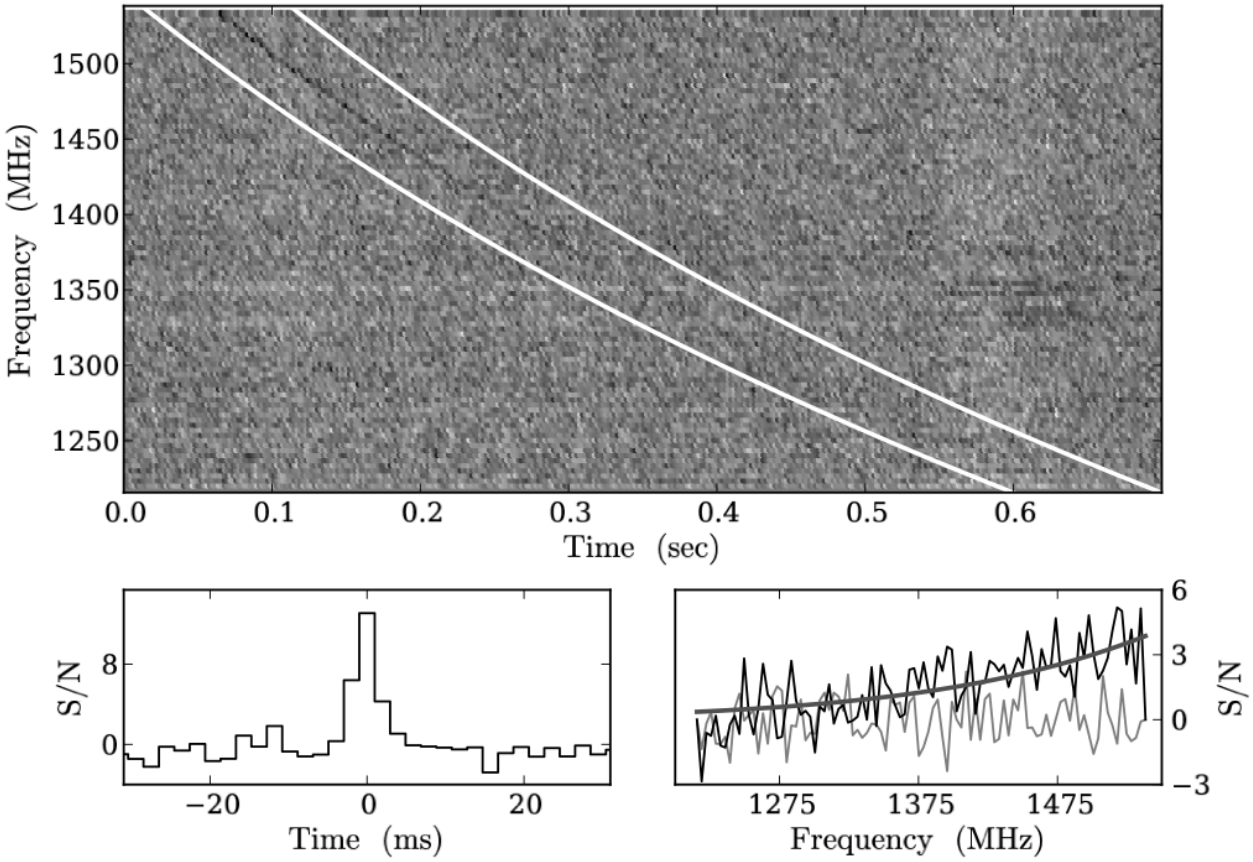
Lightening, Aircraft, Electronics, …?

Not Terrestrial?

- Perytons have symmetric W>20 msec which is larger than 4 FRBs by >3
- FRB 110220 has an exponential tail
- Perytons have DM~375 cm^{-3} pc < DM~500-1000 cm^{-3} pc for 4 FRBs
- 4 FRBs are only detected in a single beam
- Perytons prefer daytime, and recur

Arecibo FRB (not Parkes)

A different telescope also detected FRB



FRB 121102

Galactic anti-center

b=-0.2±0.2°

DM=557.4±3 pc/cm^3

delay β=-2.01±0.03

Width 3±0.5 ms

No scattering signal

Spectral α~10

(sidelobe effect?)

Rate is consistent

Still in Chaos

- No FRB at intermediate Galactic latitude (-15°<b<15°) by Parkes HTRU Petroff+ 14
  - Non-uniform sky distribution (99%CL)
  - Disfavor a Galactic origin

  Burke-Spolaor & Bannister 14
- FRB 011025 in Parkes archives (5°<|b|<30°)
  - Rate ~2×10^3/sky/day ~ (1/5)×(Thornton+ 13)
- FRB 131104 toward Carina dwarf Sph Ravi+ 14
- Keane FRB 010621 is Galactic? Bannister & Madsen 14
- VLA & LOFAR detect no FRB Law+ 14; Coenen+ 14

FRB 011025

- Parkes archival data (5°<|b|<30°)
- Rate ~ 2×10^3/sky/day ~ 5x (Thornton+ 13)

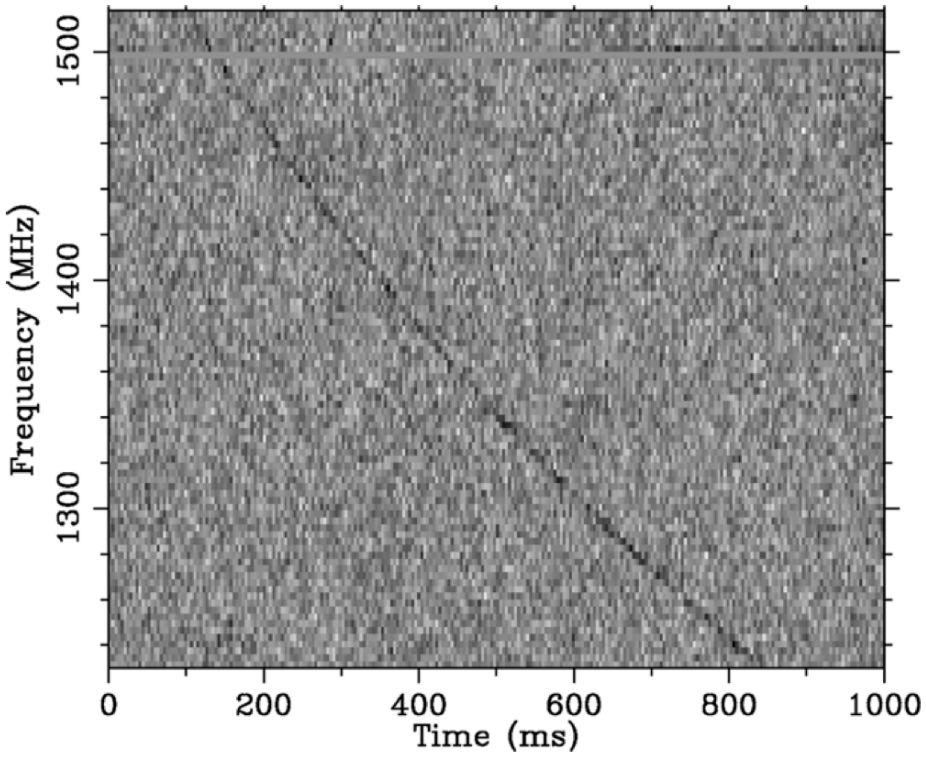


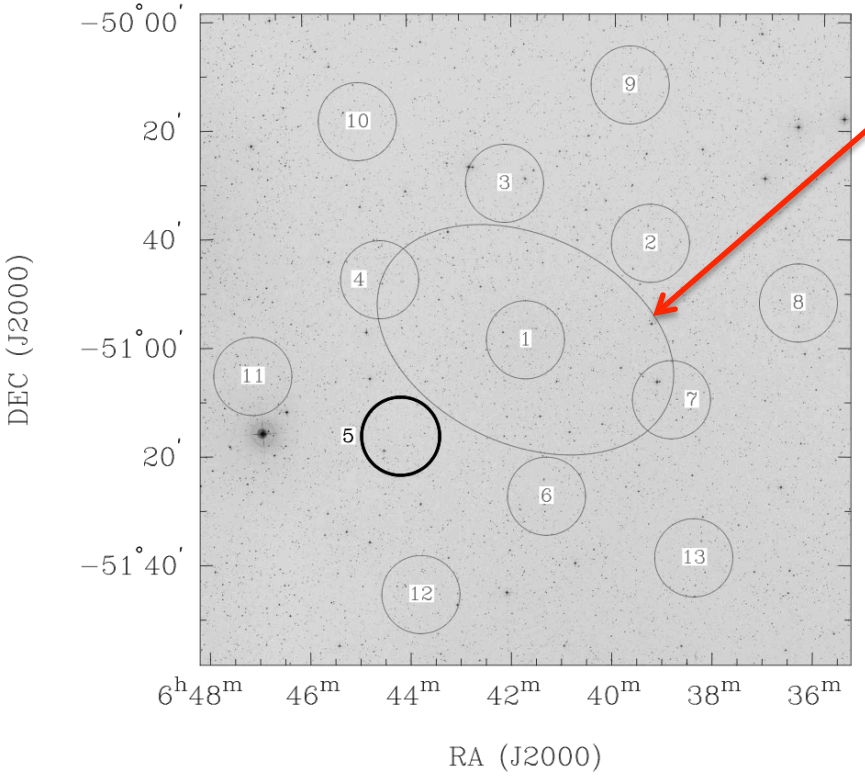
Table 1
Properties of FRB011025

Pointing R.A., decl. (J2000)	19:06:53.0, −40:37:14.4
Pointing gl, gb	356.641, −20.021
$t_{1516.5}$(UTC Y-M-D, h:m:s)	2001 Jan 25, 00:29:13.23 ± 0.02
Delay index ($dt \propto f^a$)	-2.00 ± 0.01
DM	790 ± 3 pc cm^{-3}
DM_E	680 pc cm^{-3}
w_{50}	9.4 ± 0.2 ms
Scattering index ($w_{50} \propto f^{\mu}$)	-4.2 ± 1.2
$S_{peak,min}$	300 mJy
Fluence	$<2.82 \times 10^{-3}$ Jy s

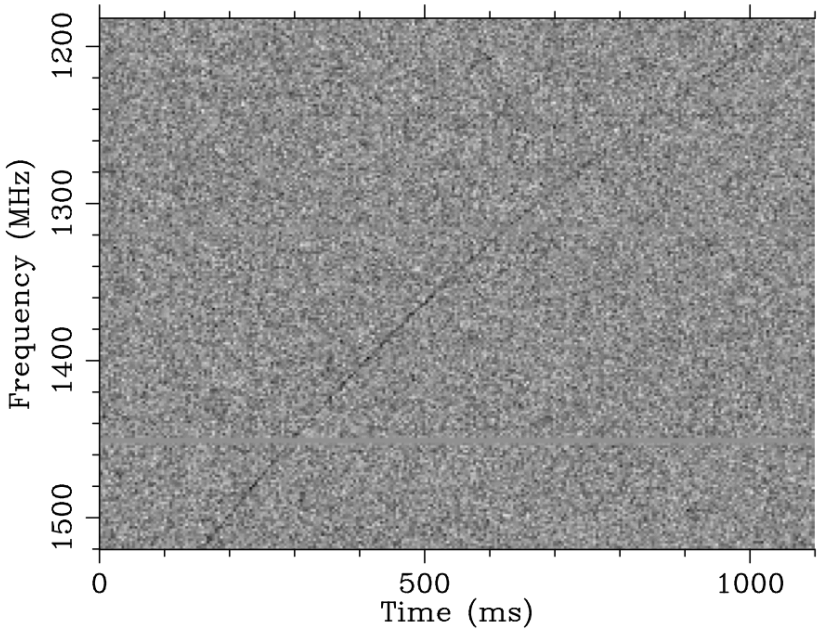
Note. Parameter $t_{1516.5}$ refers to the arrival time of the burst at 1516.5 MHz.

Burke-Spolaor & Bannister 14

FRB 131104



Carina dSph @101±5 kpc?



Parkes

Table 1
Details of time-frequency fits (all uncertainties are the 95% confidence intervals).

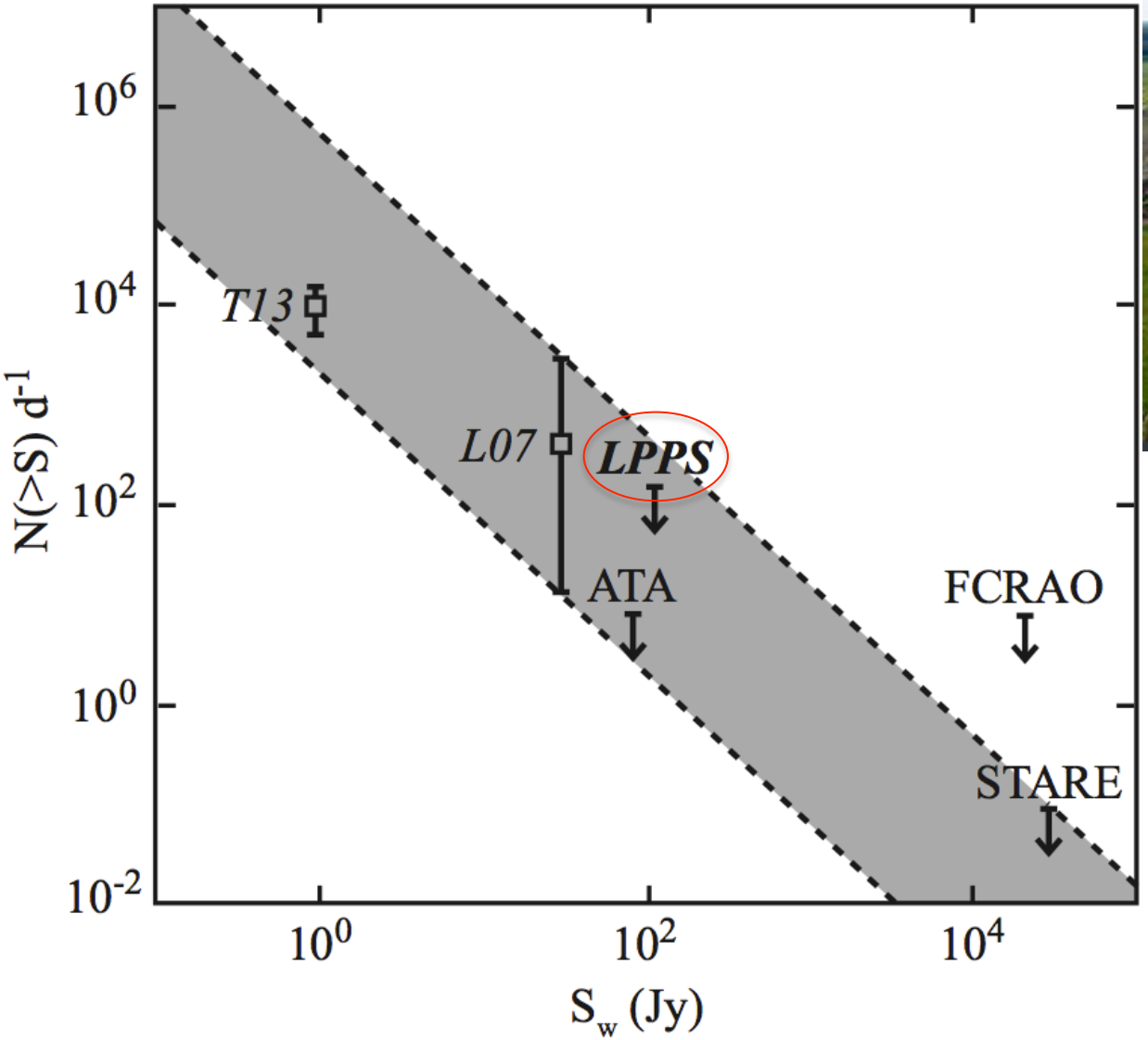
Ravi+ 14

Model	c_{1232} (Jy ms)	c_{1332} (Jy ms)	c_{1432} (Jy ms)	c_{1532} (Jy ms)	DM (cm^{-3} pc)	τ_s (ms)	α	t_0 (s)	ΔBIC
0	$0.65^{+0.07}_{-0.07}$	$0.78^{+0.04}_{-0.08}$	$1.16^{+0.09}_{-0.09}$	$1.7^{+0.1}_{-0.3}$	$779.1^{+0.1}_{-0.2}$	–	–	$1.03435^{+7\times10^{-5}}_{-8\times10^{-5}}$	0
1	$0.78^{+0.07}_{-0.07}$	$0.78^{+0.08}_{-0.04}$	$0.99^{+0.04}_{-0.09}$	$1.4^{+0.1}_{-0.1}$	$779.0^{+0.2}_{-0.2}$	$1.1^{+0.1}_{-0.1}$	–	$1.0338^{+1\times10^{-4}}_{-1\times10^{-4}}$	-299
2	$0.9^{+0.1}_{-0.1}$	$0.8^{+0.2}_{-0.2}$	$0.95^{+0.04}_{-0.09}$	$1.2^{+0.1}_{-0.1}$	$778.5^{+0.2}_{-0.3}$	$2.0^{+0.8}_{-0.5}$	$4.4^{+1.6}_{-1.8}$	$1.0340^{+1\times10^{-4}}_{-1\times10^{-4}}$	-306

2nd FRB with exponential tail (after FRB110220)

$W_{intrinsic}$<0.64 ms

LOFAR



~142MHz
R<150/day/sky
for S>107 Jy

Coenen+ 14

VLA Interferometer

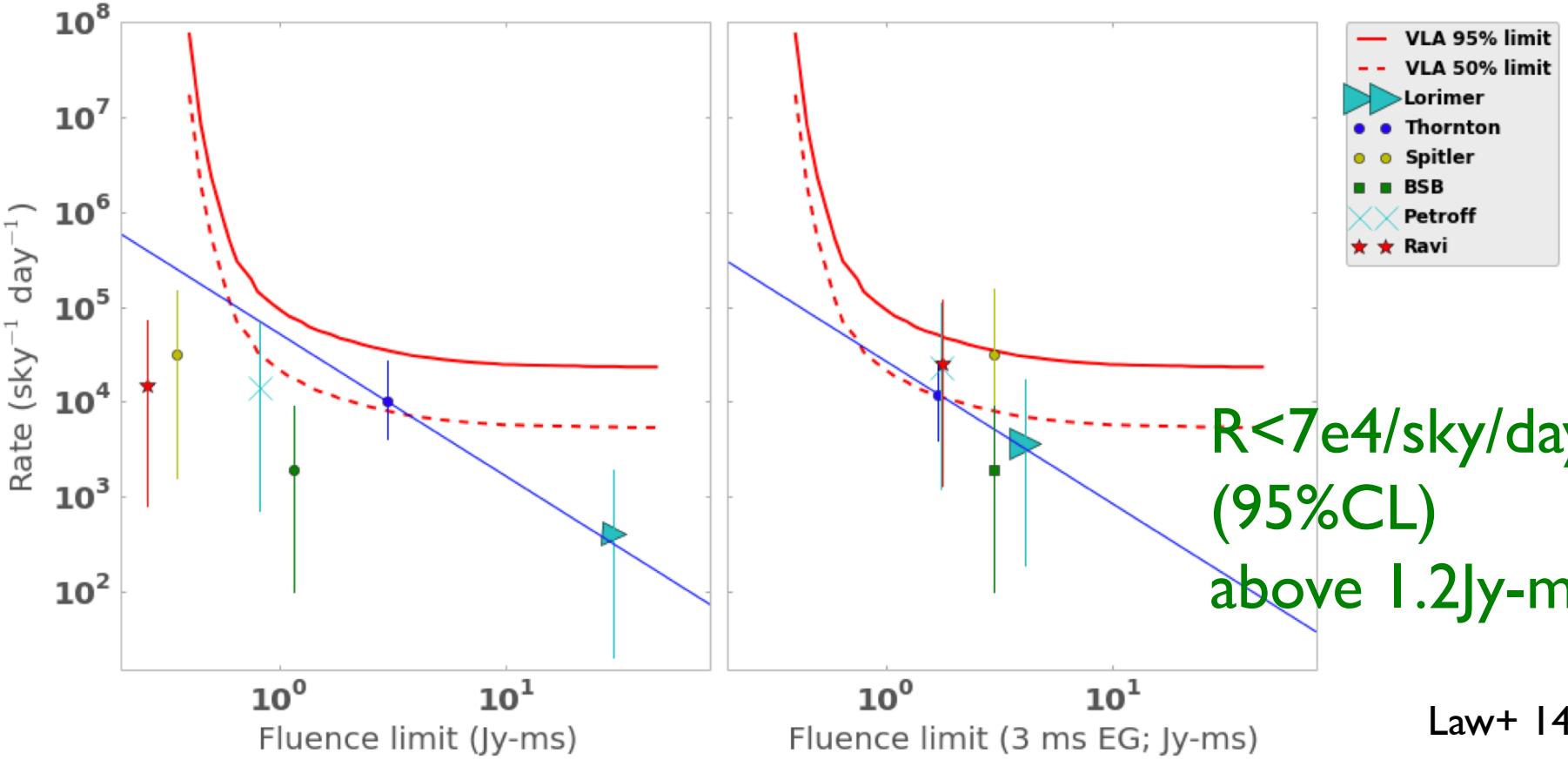
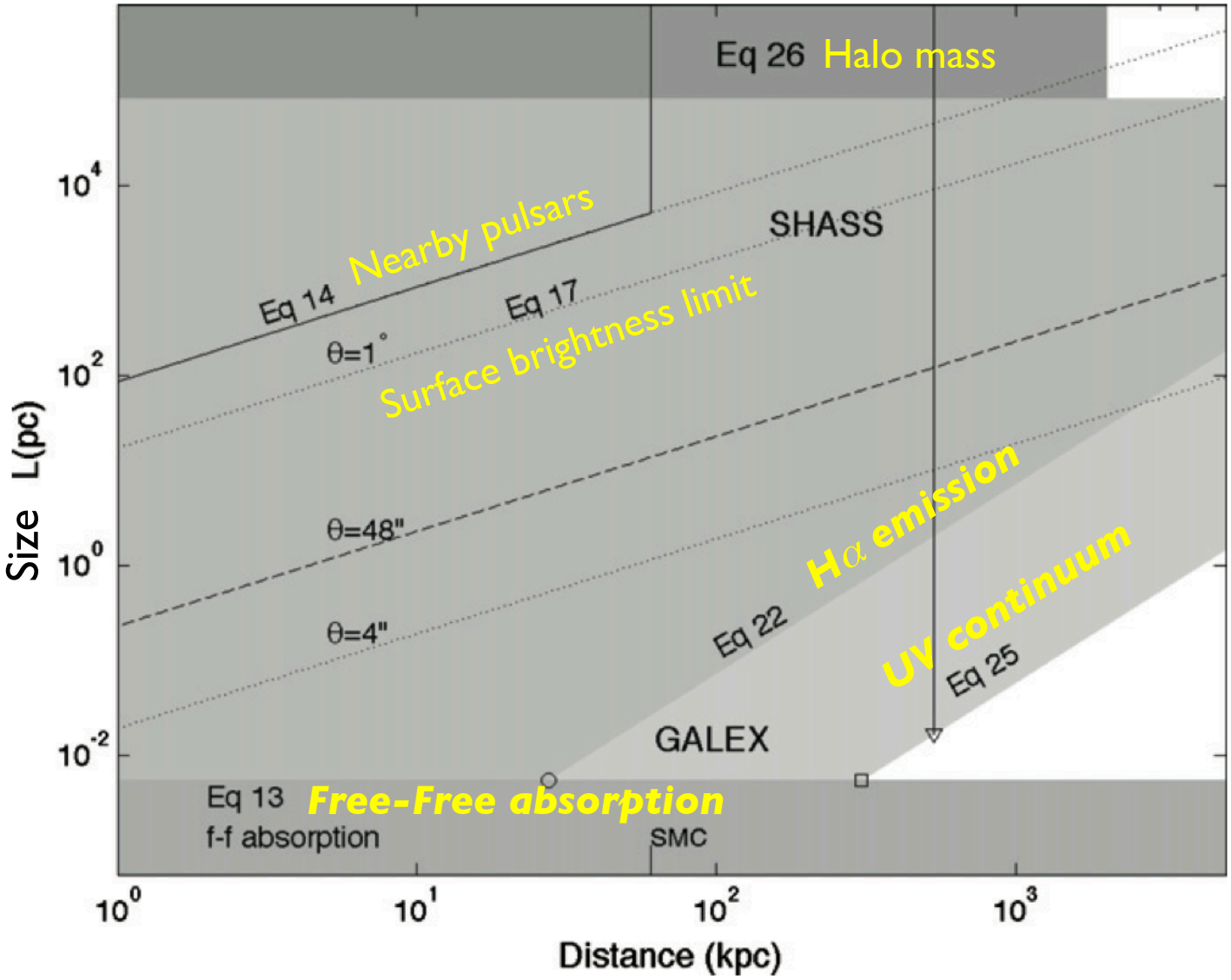


FIG. 9.— *Left:* FRB rates and VLA rate limit as a function of limiting fluence as quoted in (or inferred from) publications (Lorimer et al. 2007; Thornton et al. 2013; Spitler et al. 2014; Burke-Spolaor & Bannister 2014; Ravi et al. 2014; Petroff et al. 2014a). The blue line shows an extrapolation of the rate of Thornton et al. (2013), assuming a Euclidean distribution ($-3/2$ powerlaw slope in this space) from a fluence limit of 3 Jy-ms. The VLA 50% and 95% upper limits are shown with a dashed and solid line, respectively. The VLA rate limit is not complete at very high fluences (far right) as described in §6.4. The fluence limit of Lorimer et al. (2007) is a lower limit recently calculated in a reanalysis (Keane & Petroff 2014). *Right:* Same as the left panel, but for recalculated flux limits. All flux limits assume a 3 ms pulse width and that FRBs originate outside the Galaxy with DM of 779 pc cm^{-3}.

Contents for FRB

- Possible origins
- Real cosmic signal?
- ***Galactic?***
- FRB cosmology

Distance to DM Nebula

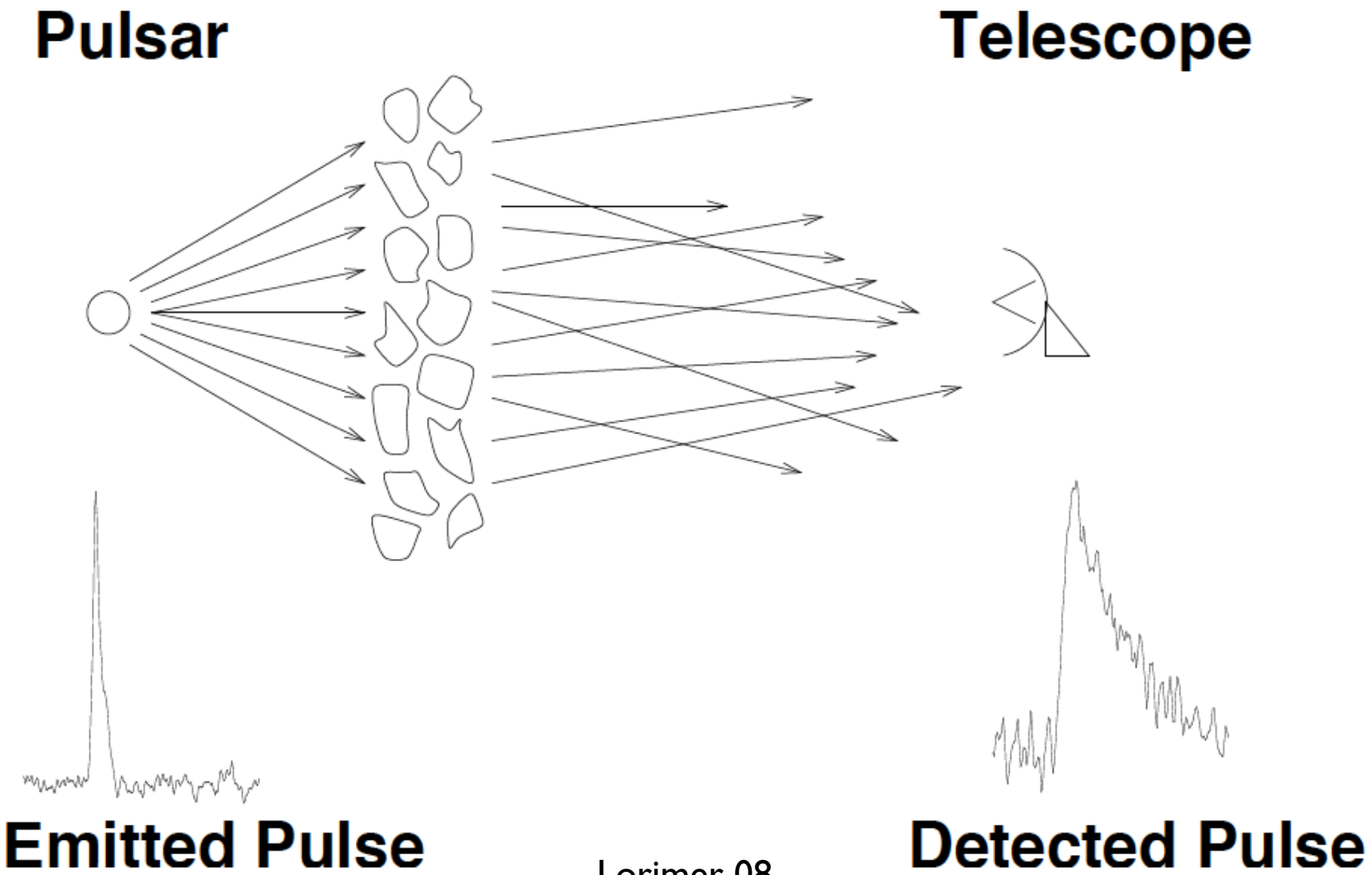


DM ⇒
Ionized gas

If localized,
Recombination
⇒ Hα emission
Ionizing source
⇒ UV conti.

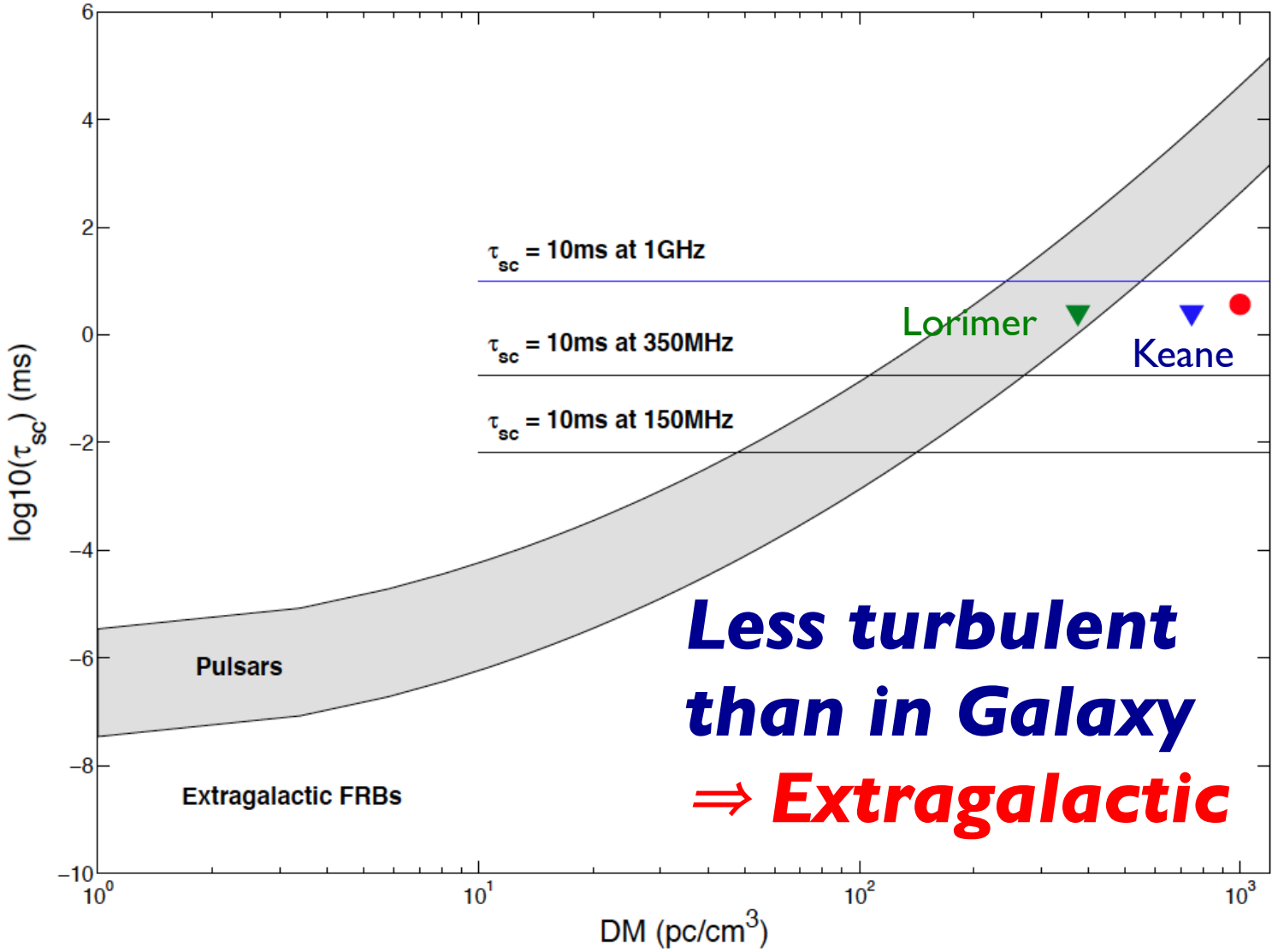
No emission
⇒ ***Outside of our Galaxy***

Pulse Scattering



Lorimer 08

Less Scattering



Lorimer+ 13
Luan & Goldreich 14

Host galaxy

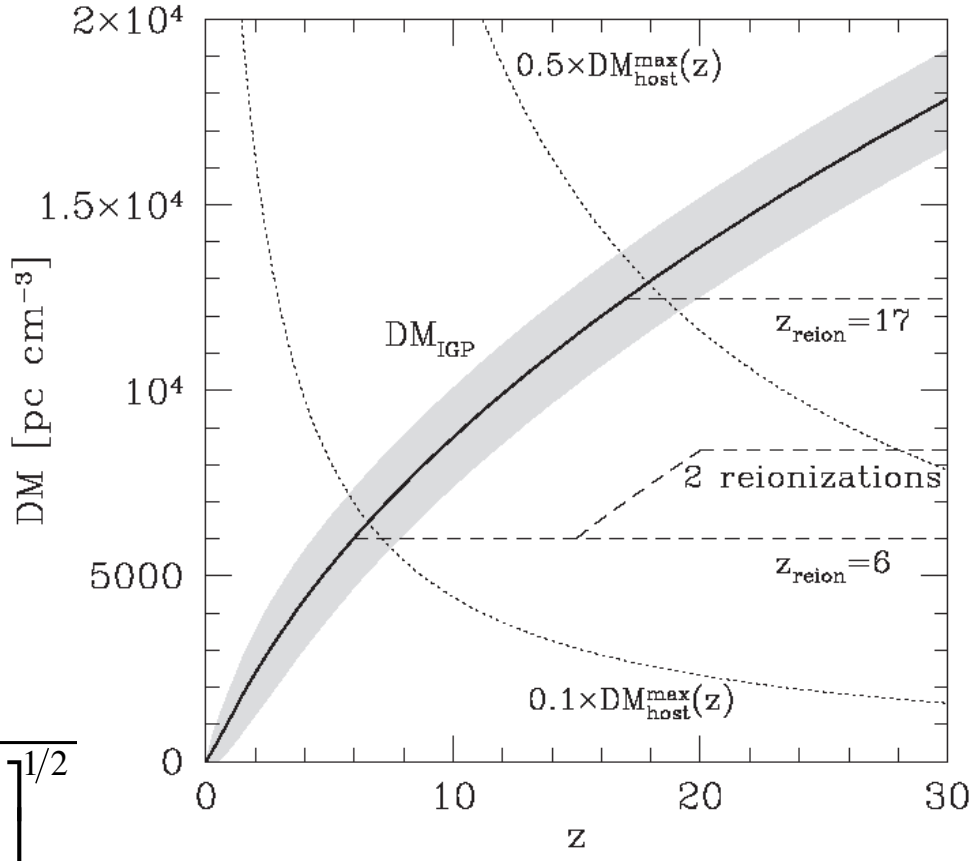
- Most likely, scattering occurs in host galaxies
- Also in the turbulent region
- Center of host galaxy? DM>700 cm^{-3} pc
  - $W \propto D_{bs}D_{os}/(D_{bs}+D_{os})^2$ Kulkarni+ 14; Luan & Goldreich 14
  - $D_{bs} << D_{os} \Rightarrow$ the pulse width is small as observed
- Elliptical host: low DM
- Spiral host: DM>700 cm^{-3} pc if i>87deg (5%)
- Intervening galaxies: P<5%

Contents for FRB

- Possible origins
- Real cosmic signal?
- Galactic?
- ***FRB cosmology***

FRB Cosmology

- Reionization
- Missing baryon
- Dark energy, cosmological parameters



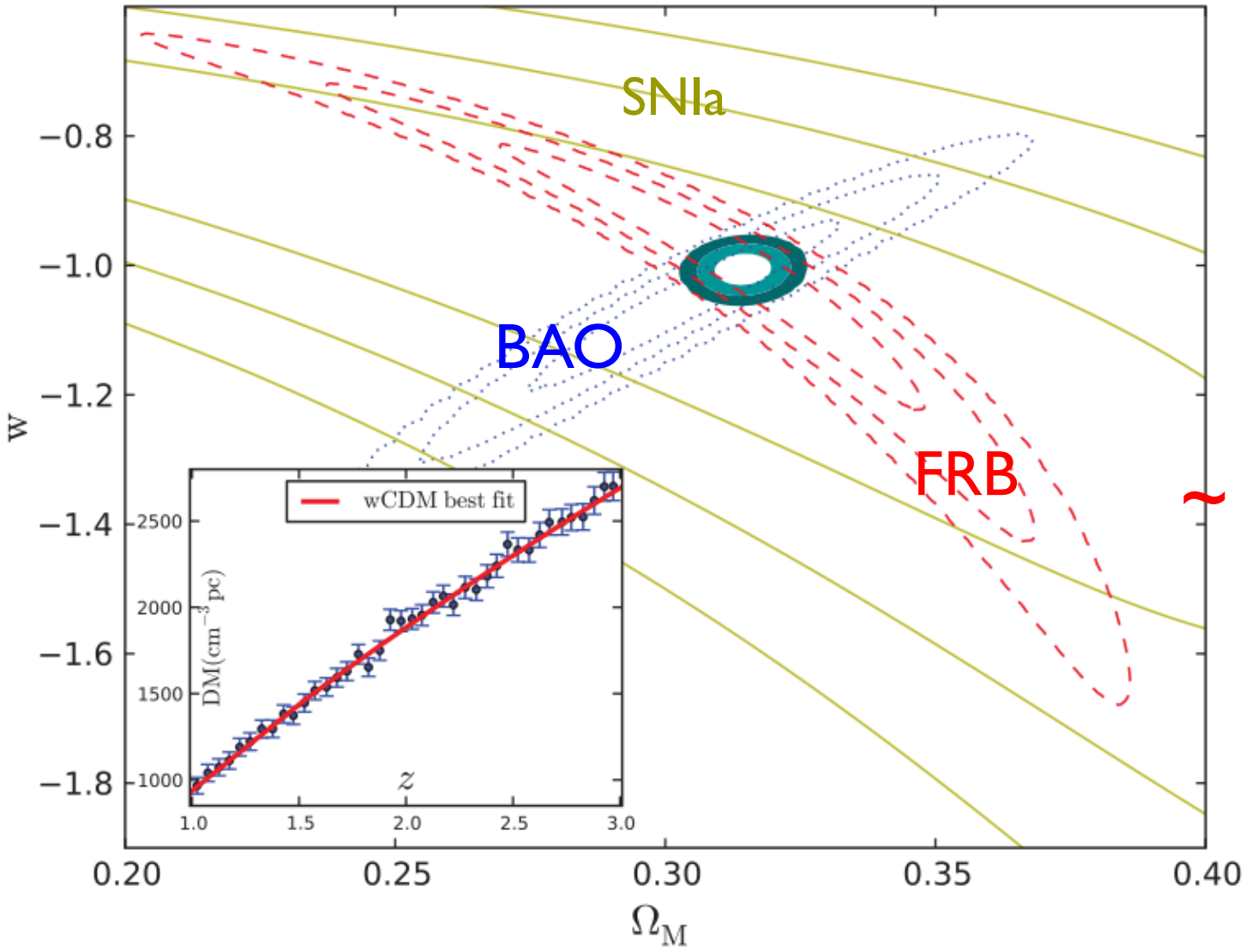
$$\mathrm{DM_{IGP}} = \frac{3cH_0\Omega_b}{8\pi G m_p}\int_0^z \frac{(1+z)\,dz}{\left[\Omega_m(1+z)^3+\Omega_\Lambda\right]^{1/2}}$$

$$d_L = \frac{c(1+z)}{H_0}\int_0^z \frac{dz}{\left[\Omega_m(1+z)^3+\Omega_\Lambda\right]^{1/2}}$$

Fast radio bursts as cosmological tools

New frontier?

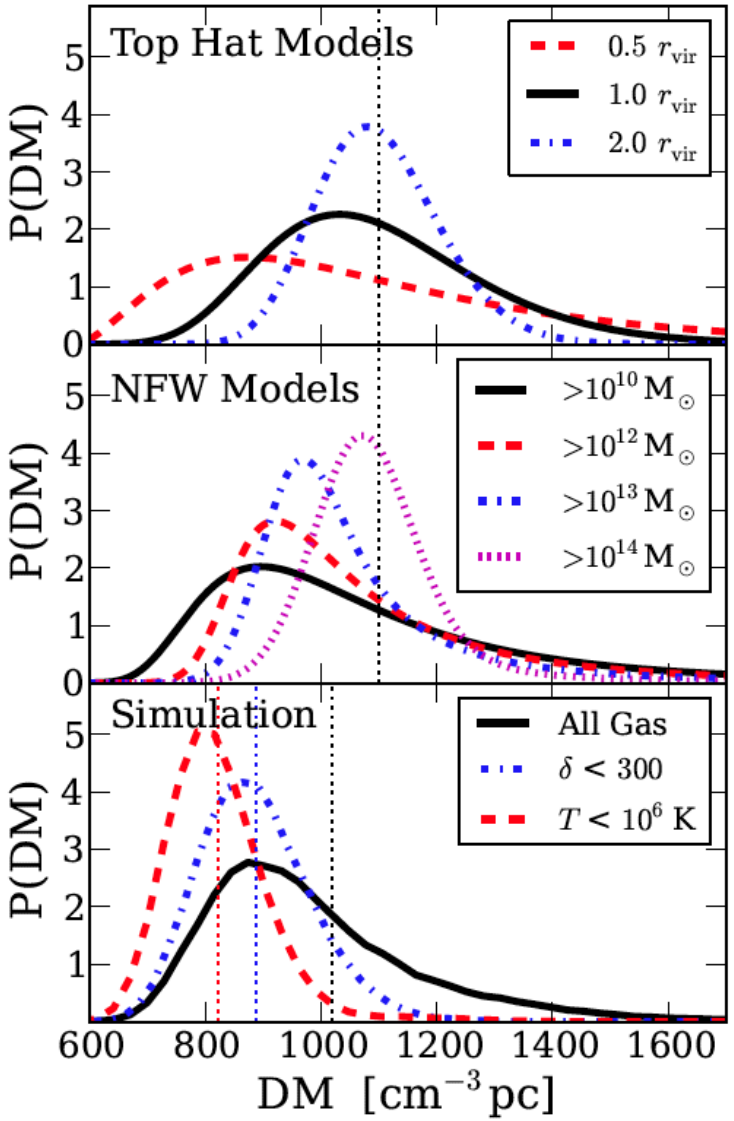
Dark Energy



~1000 FRBs

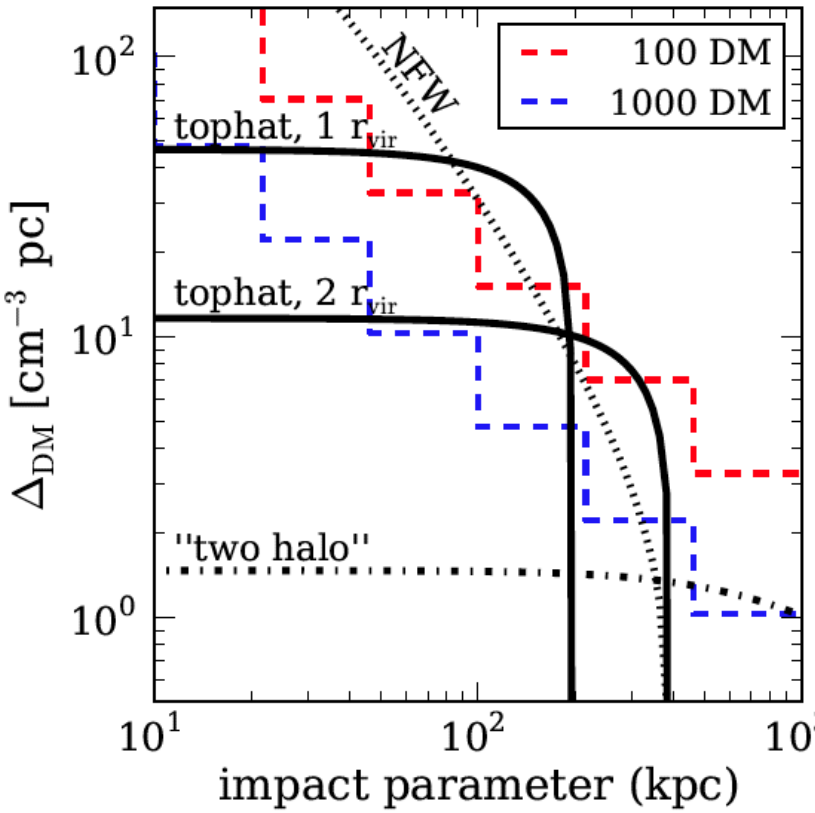
Zhou+ 14
Gao+ 14
Kashiyama+ 13

Locating Missing Baryon



Half of baryon is missing

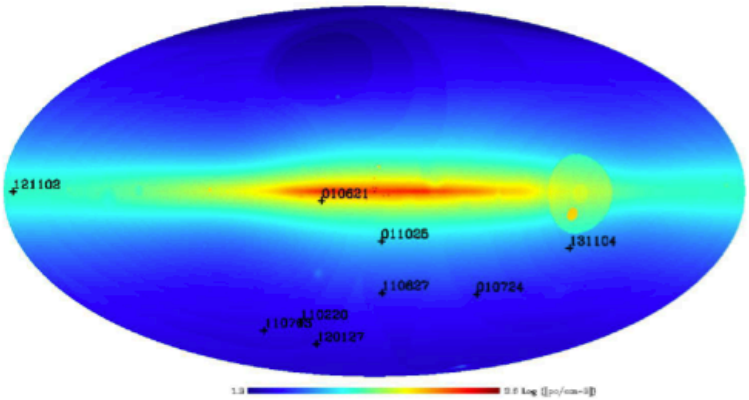
DM is sensitive its distribution

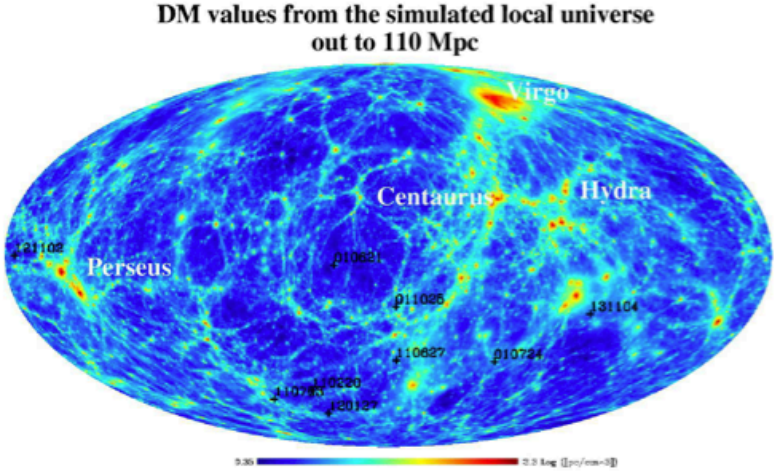


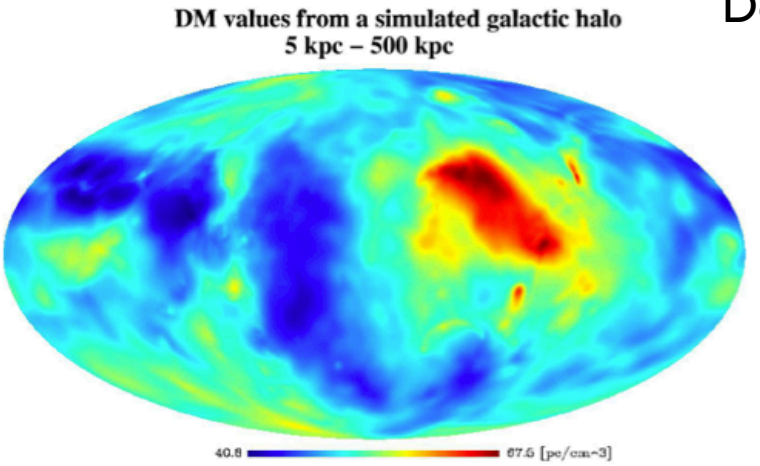
1σ error w/ stacking

McQuinn 13

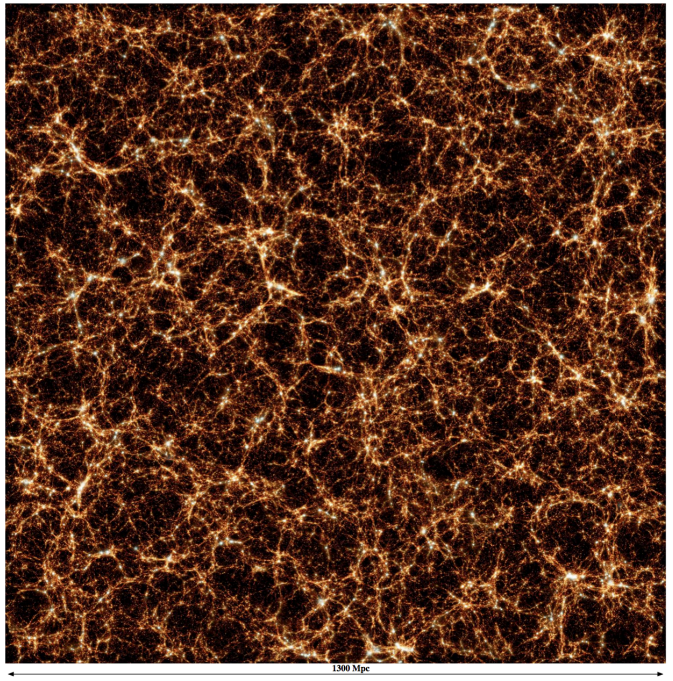
Cosmological Simulation







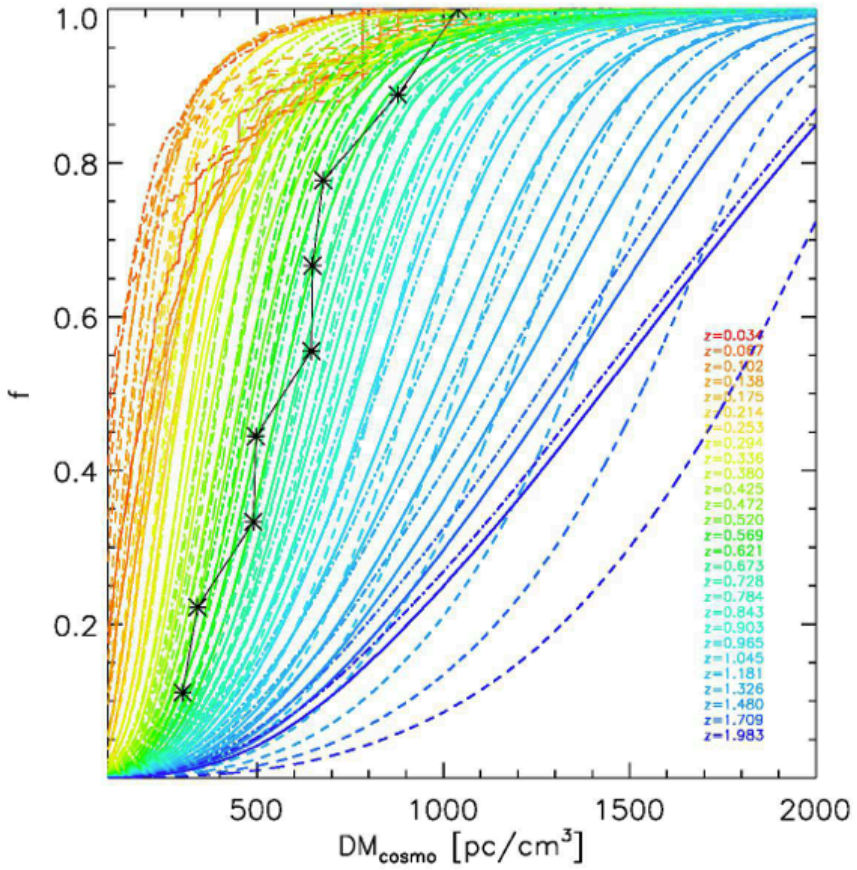
Dolag+14

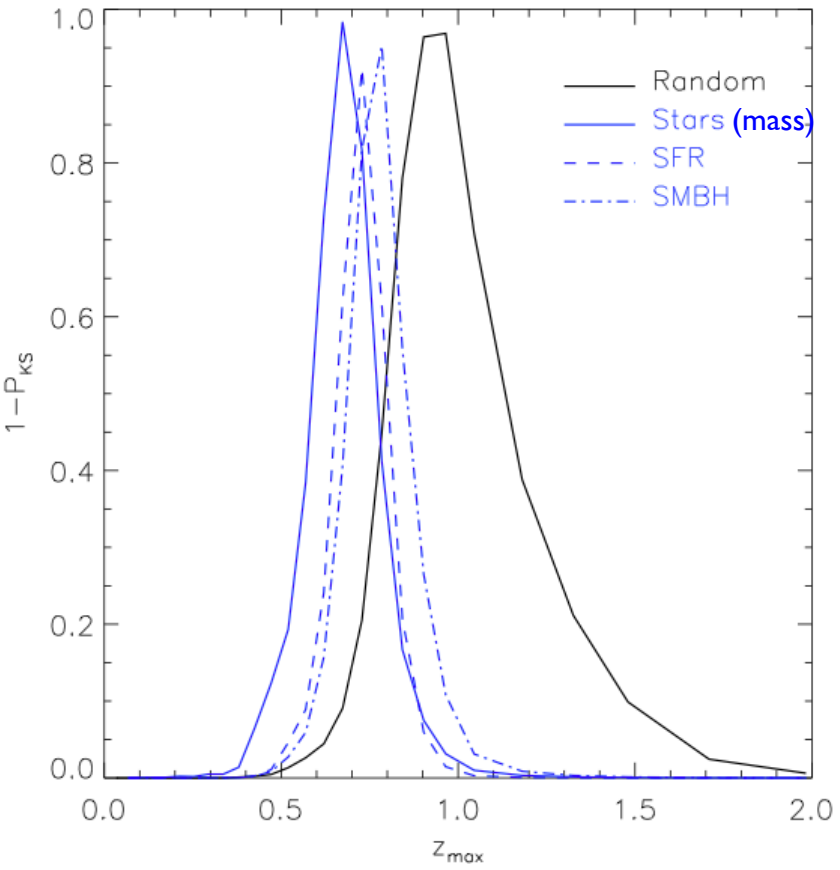


DM_{halo}~30pc/cc~DM_{Gal}

Distribution of DM_{cosmo}

DM Distribution



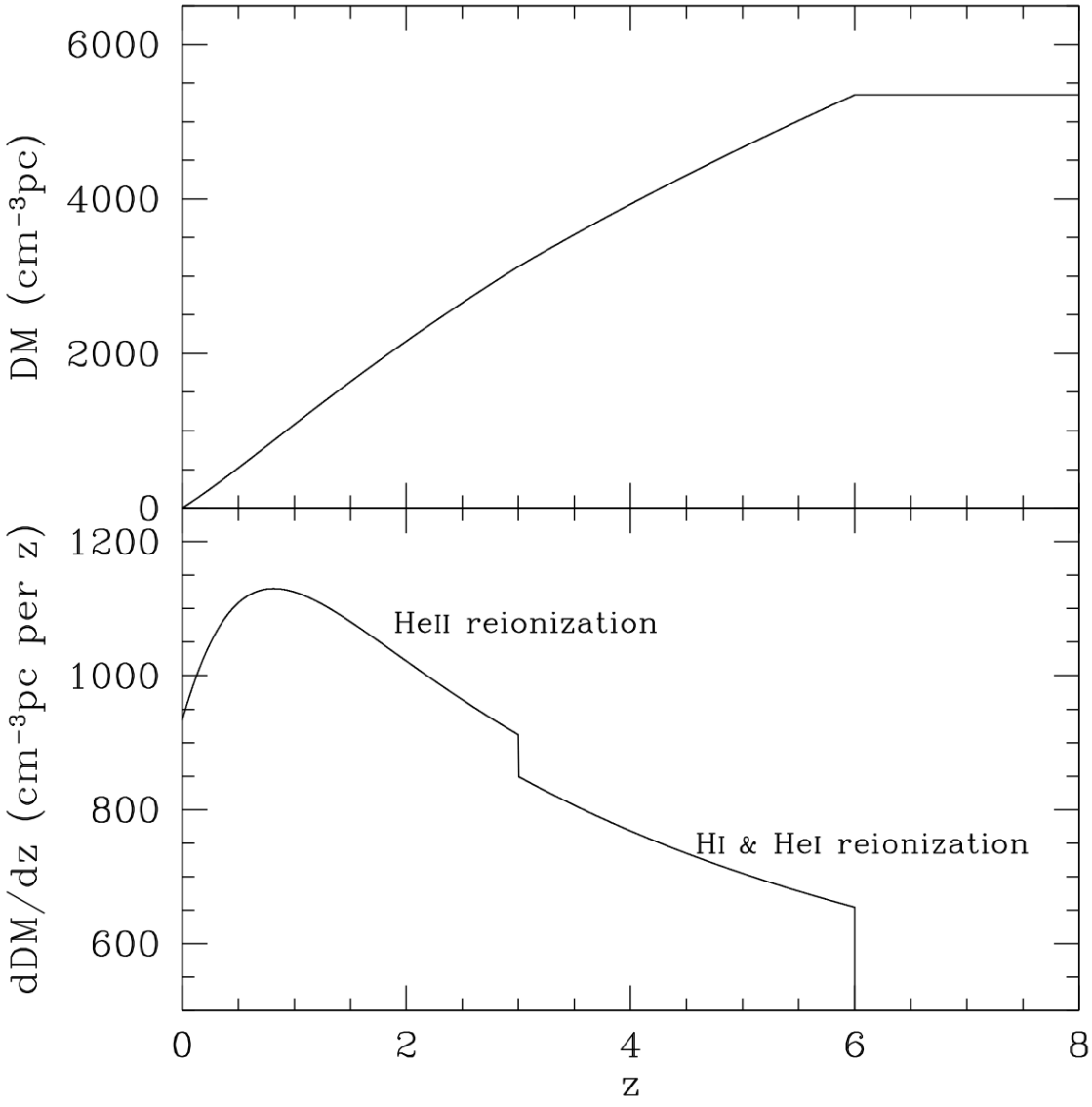


Distribution is consistent with extragalactic origin

Depend on FRB location

Dolag+14

He Reionization



H I: 13.6 eV

He I: 24.6 eV

He II:54.4 eV

HeII reioniz**e**d @z<3

Probing AGN (X-ray)

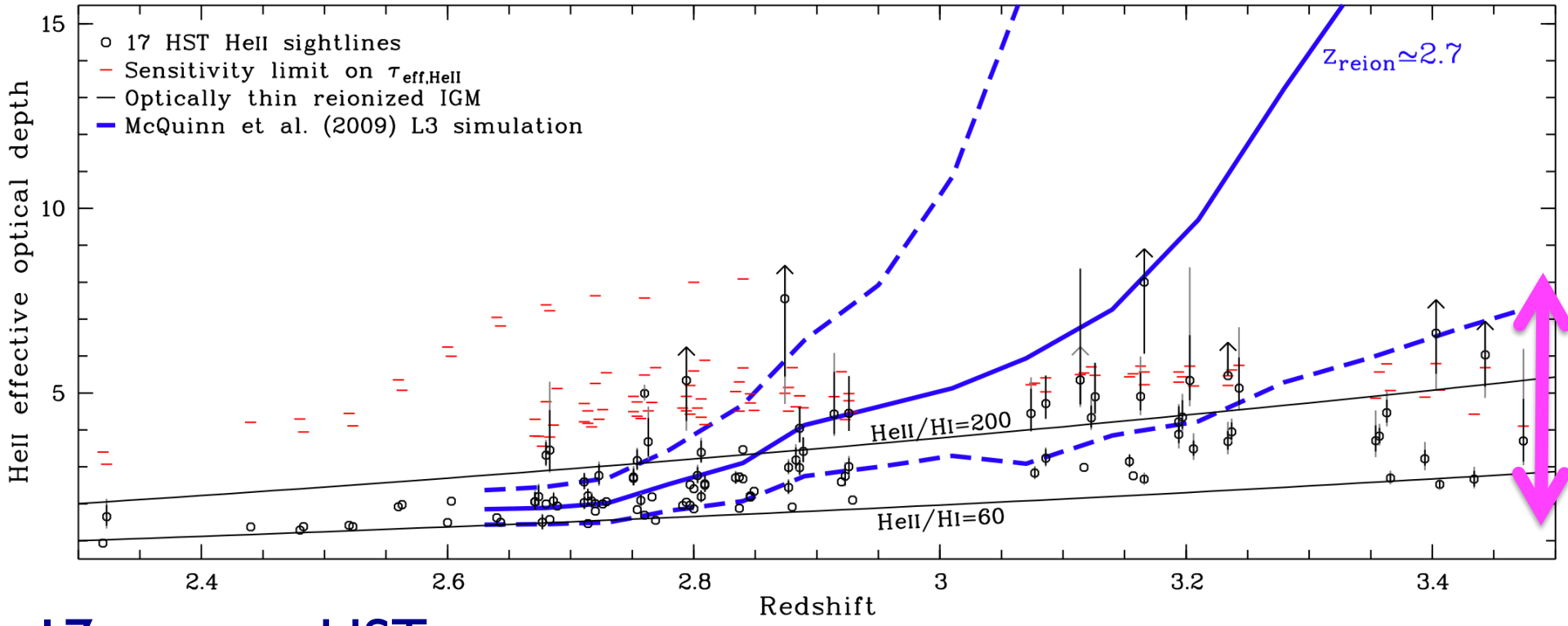
Zheng+ 14

Deng & Zhang 14

Zhou+ 14

Extended He Reionization

He II reionization is still unclear



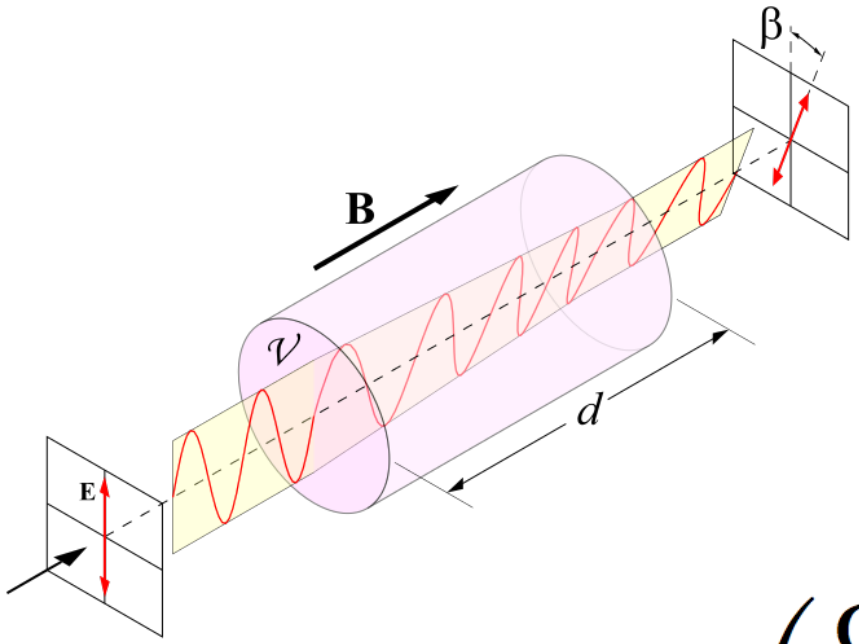
17 quasars, HST

Worseck+ 14

A strong sightline-to-sightline variance

Average x_{HeII}~0.003 @z~0.34 ⇒ ionized at early times?

Magnetic Field



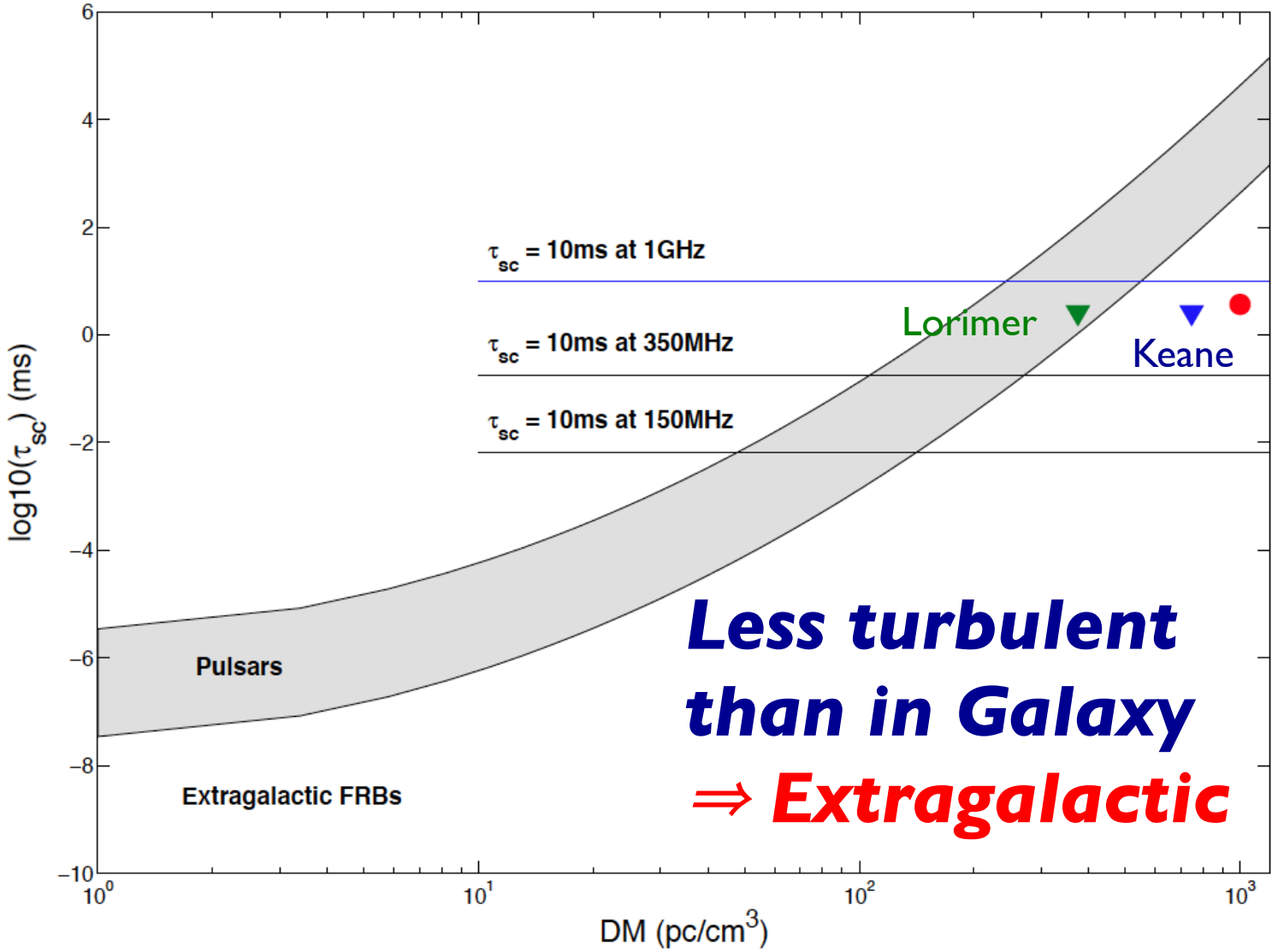
Faraday rotation ⇒
Still unknown IGM B

$$\mathrm{RM} = 8.61\,\mathrm{rad\,m^{-2}} \left(\frac{\Omega_b h^2}{0.022}\right)\left(\frac{h}{0.7}\right)^{-1}\left(\frac{B_0}{10\ \mathrm{nG}}\right)$$

$$\times \int_0^z \frac{f_e(z) b_\parallel(z) dz}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}}. \qquad b_\parallel(z) \equiv B_\parallel(z)/B_0$$

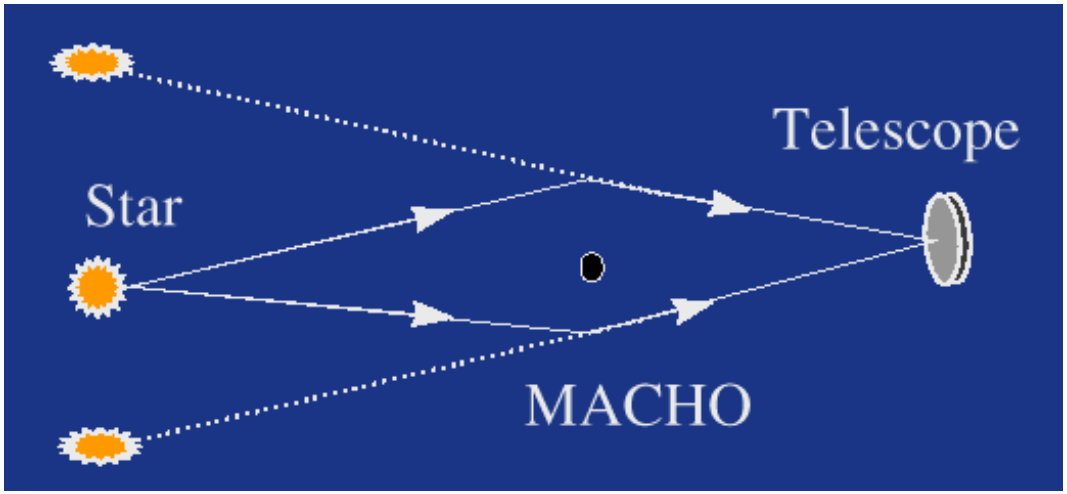
Zheng+ 14

Turbulence



Lorimer+ 13
Luan & Goldreich 14

Femto-Lensing



$$\Delta t_l \equiv 41(1+z_l)(M/1\,M_\odot)\ \mu\mathrm{s}.$$

$$A(\omega) = \frac{u^2+2}{u\sqrt{u^2+4}} + \frac{2}{u\sqrt{u^2+4}}\cos(\omega\Delta t_l),$$

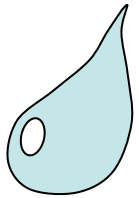
Interference fringe in spectrum

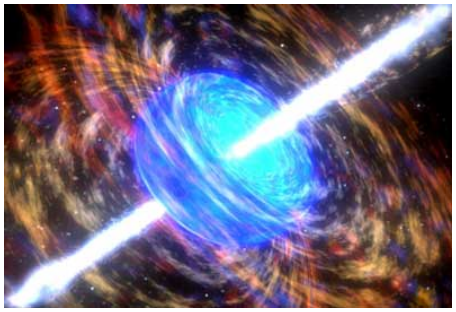
$$\nu = \omega/(2\pi)$$

Gamma-Ray Burst

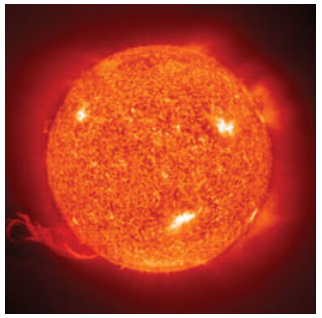
$E=mc^2$ (by Einstein)

=





=



Atomic bomb ~1kg

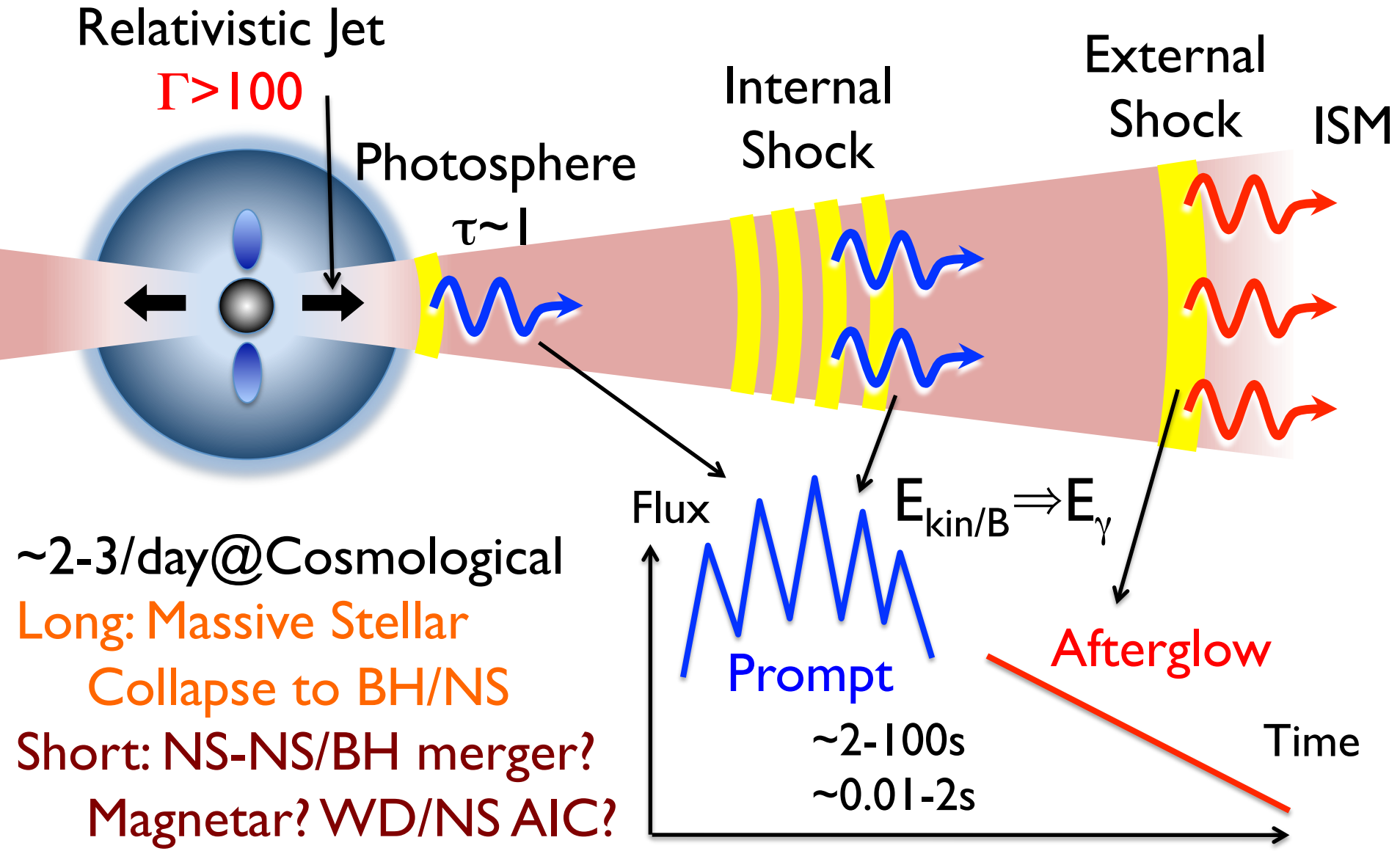
GRB
~10^{52}erg

Sun
~10^{33}g

In ~sec, GRB release energy Sun emit over lifetime

GRB is the most luminous object

GRB in a Nutshell



~2-3/day@Cosmological

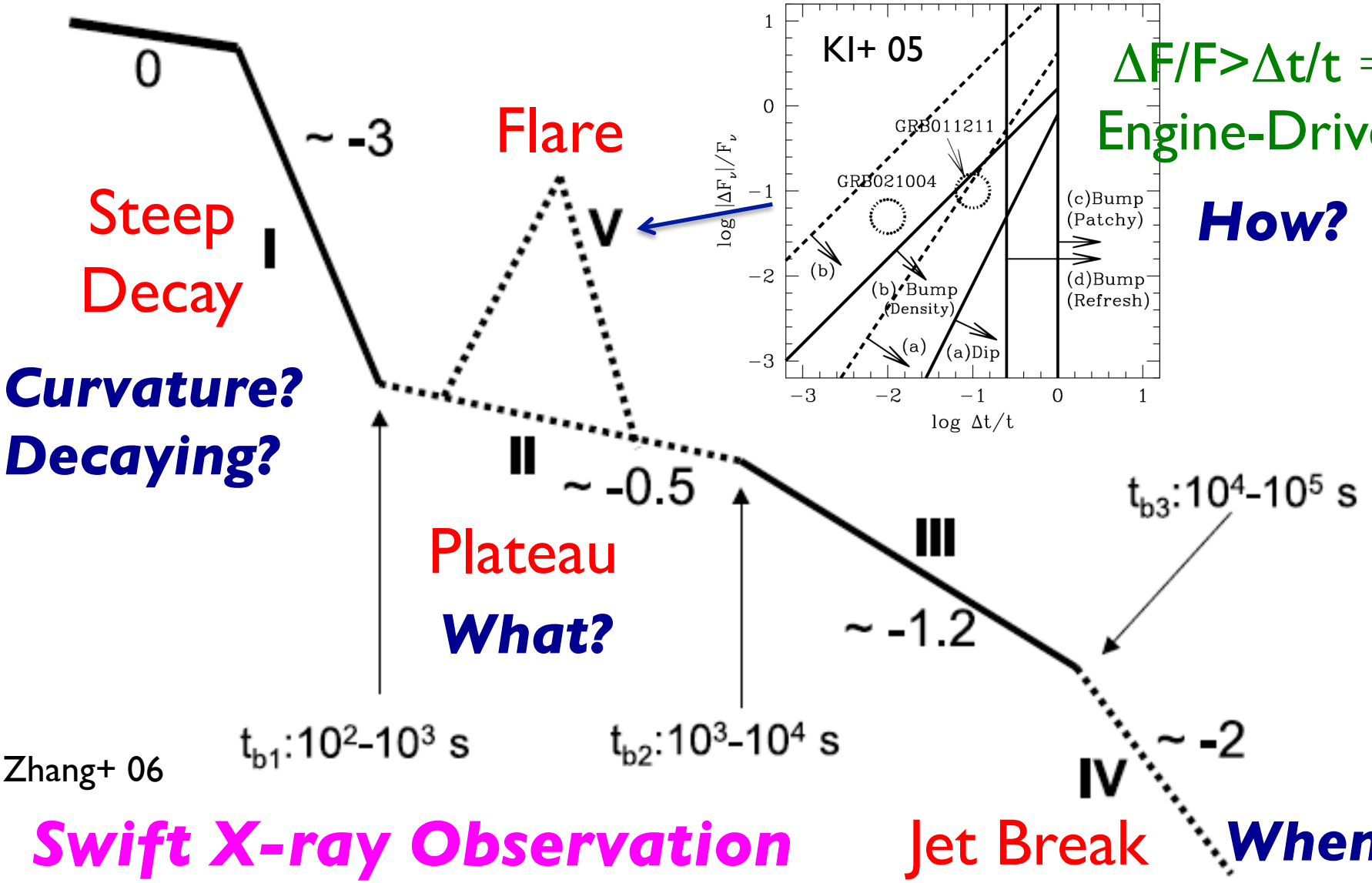
Long: Massive Stellar Collapse to BH/NS

Short: NS-NS/BH merger? Magnetar? WD/NS AIC?

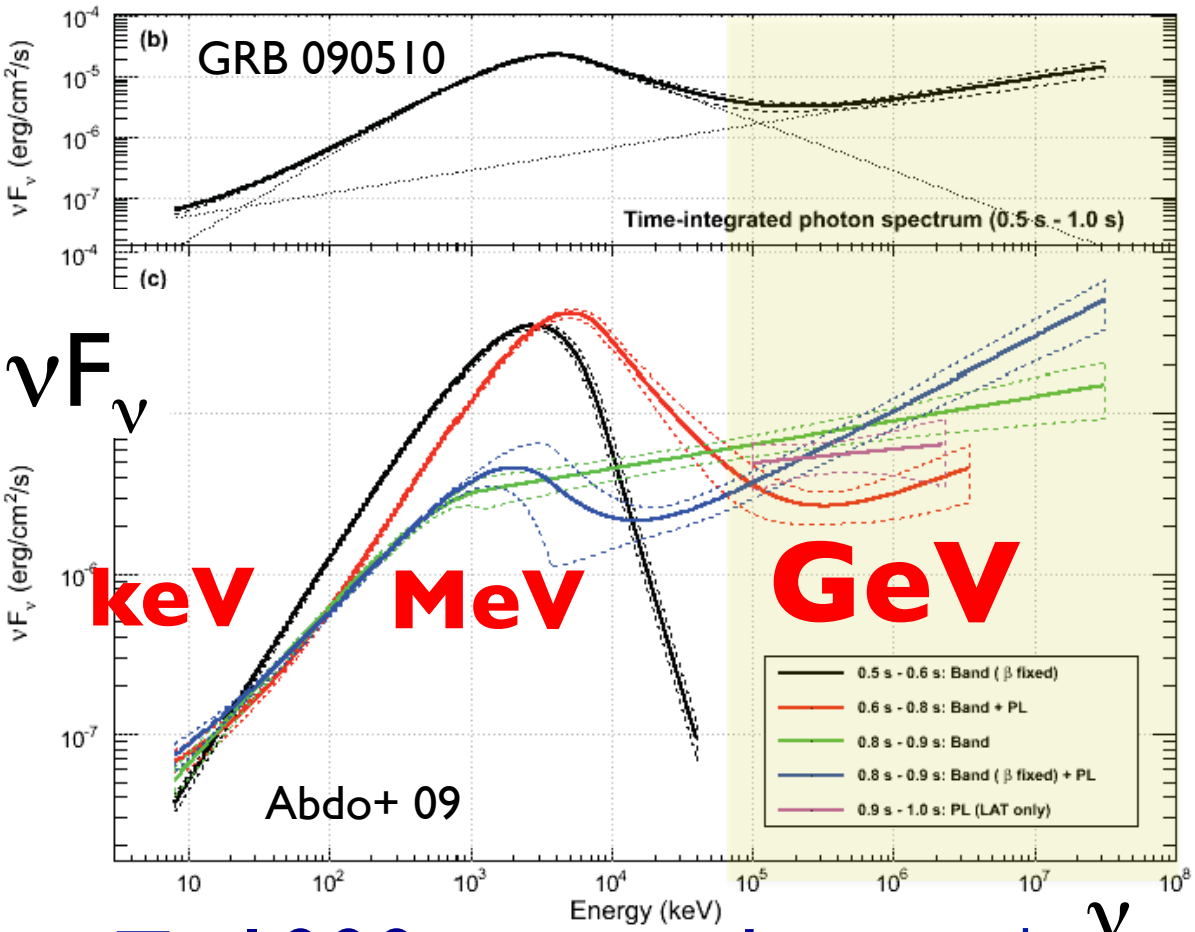
Unresolved Problems

- ***Early X-ray afterglow (First 3hr)***
  - Steep decay, Flare, Plateau, Optical flash
- ***Prompt GRB emission mechanism***
  - Photosphere or Poynting (γ jet or B jet)
  - Band spectrum (E_{peak} relation, Spectral index)
  - GeV γ-ray
- ***Central engine***
  - Black hole or Magnetar (High-B neutron star)
  - Blandford-Znajek or $\nu\nu$ annihilation

Early Afterglow Puzzles



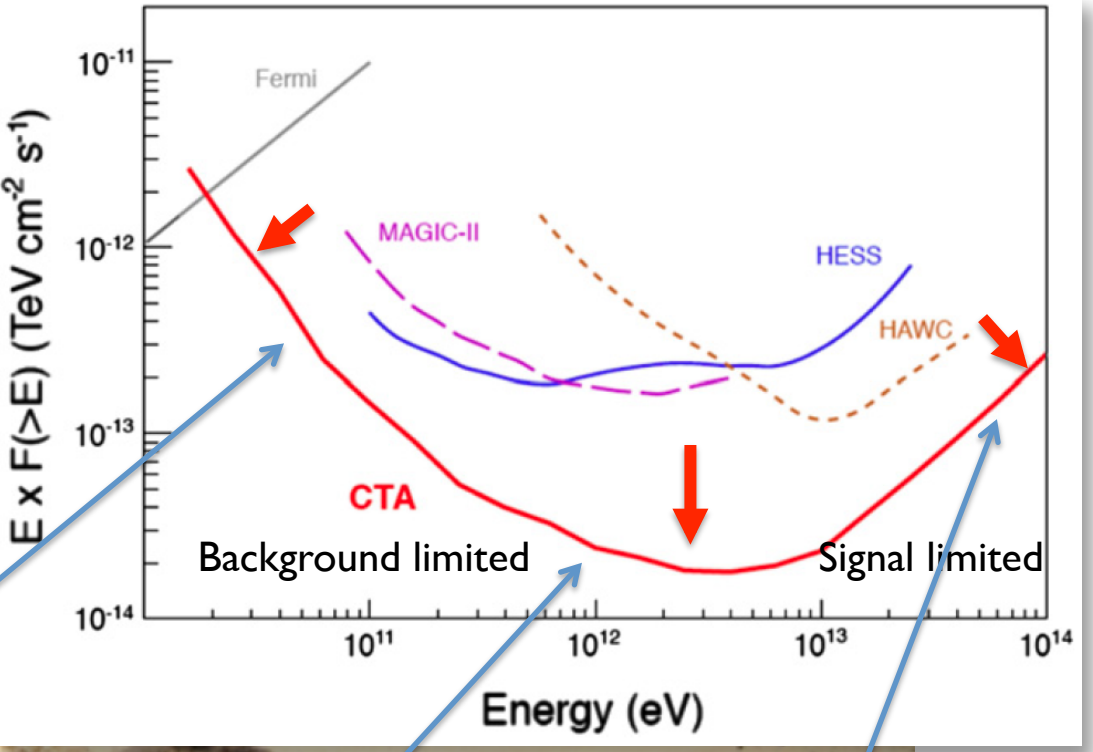
>GeV γ-ray from GRBs



- Γ>1000 to avoid $\gamma\gamma \rightarrow e^+e^-$
- ***>10^{17}eV p+$\gamma \rightarrow \pi \rightarrow \gamma$,e?*** Asano+

CTA

- ~20GeV-100TeV
- x10 Sensitivity
- $\Delta\theta$~1-2 min
- FOV~5-10 deg
- ~20 s slew (LST)
- ~2015-
- ~150€



AGN
Pulsar
GRB

LSTs

MSTs
~1 mCrab
Deep Survey

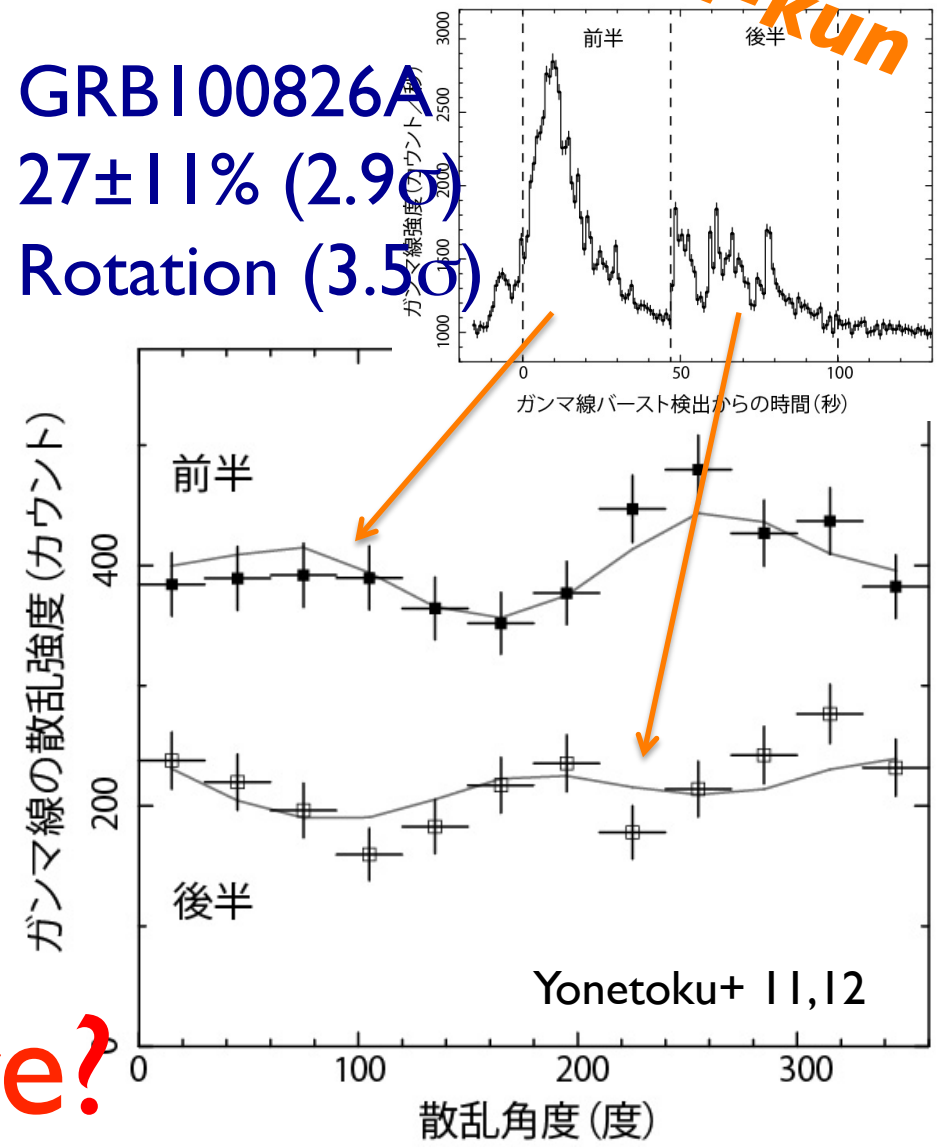
SSTs
~10km^2
Cosmic Ray
Knee

Detectability: Kakuwa+ 12; Inoue+ 13

GRB Polarization

Tsubame soon
Ask Toma-kun

GRB100826A
27±11% (2.9σ)
Rotation (3.5σ)



Patchy B? γ-shere?

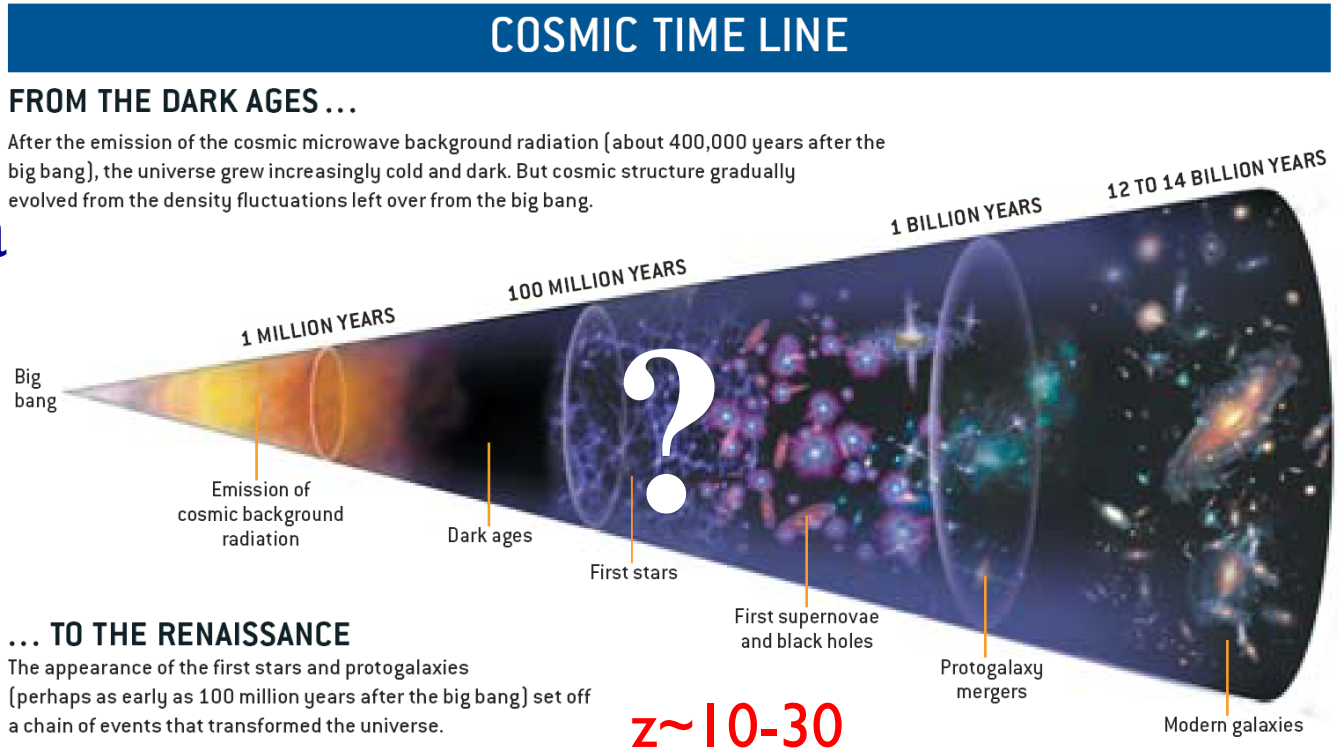
Contents for GRB

- ***GRB Cosmology***
- Pop III GRB
- Ultralong GRB
- Short GRB
- Other topics

GRB Cosmology

Massive star origin ⇒ High redshift GRBs

Like QSO
Like Supernova
Star formation
Reionization
Metal, Dust
Dark energy
…



Larson & Bromm 02

GRBs are useful for probing high-z

z~10-30

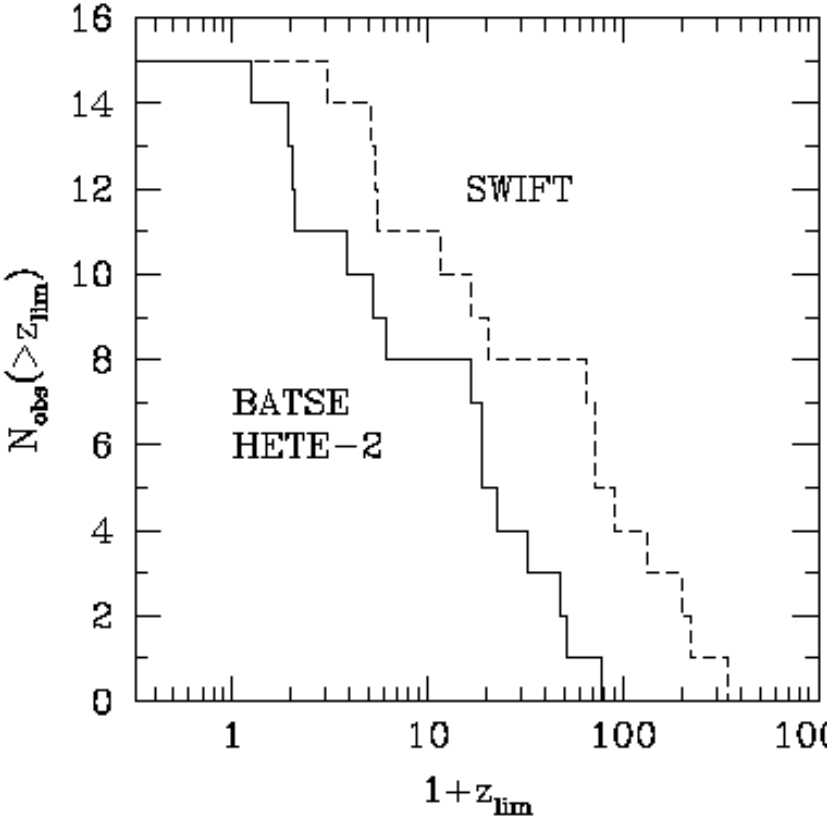
GRB ⟷

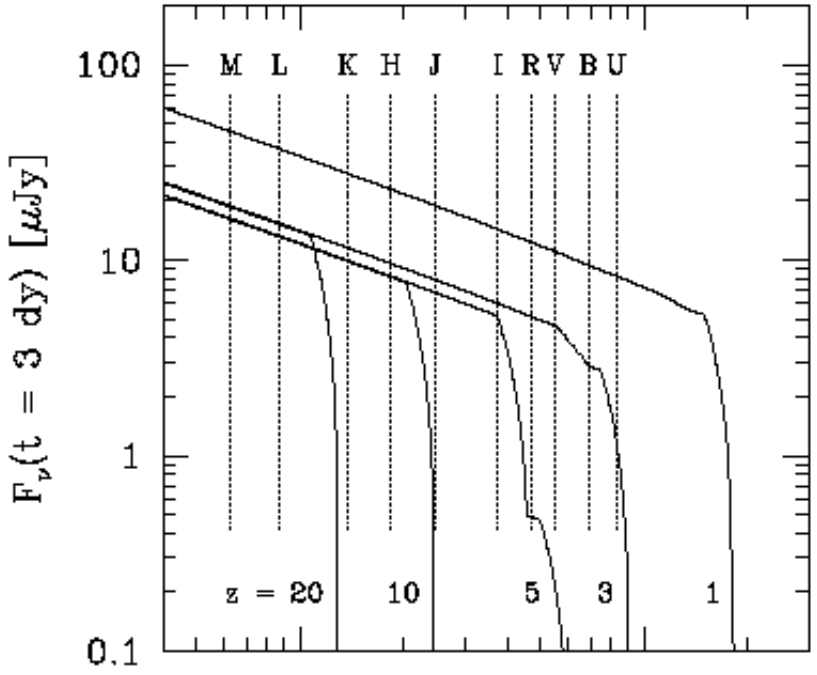
z~8

QSO, galaxy ⟷

Anticipated from ~2000

Lamb & Reichart 01, Ciardi & Loeb 00



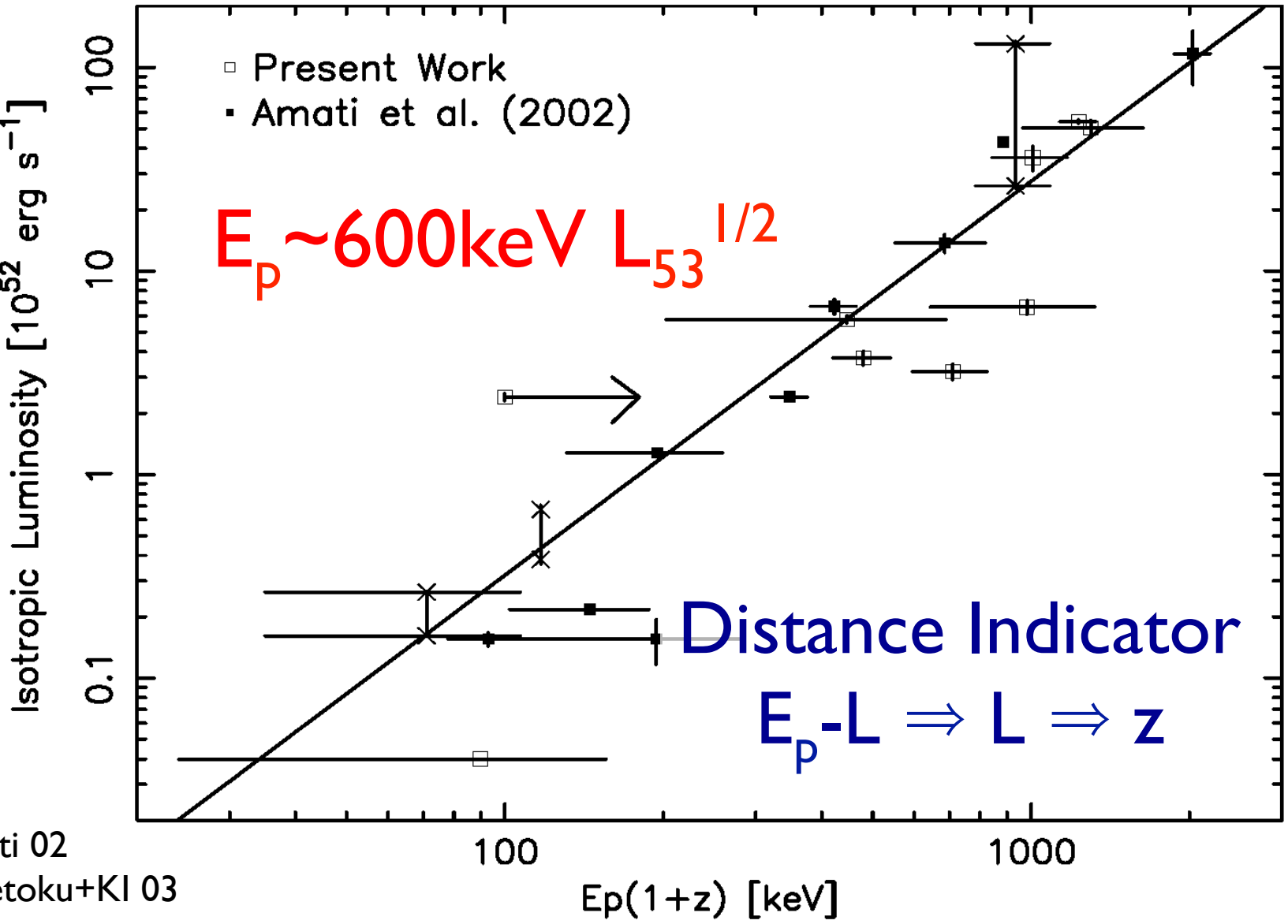


GRB is detectable up to z~100

t dilation + K-corr.⇒ AG is detectable @high-z

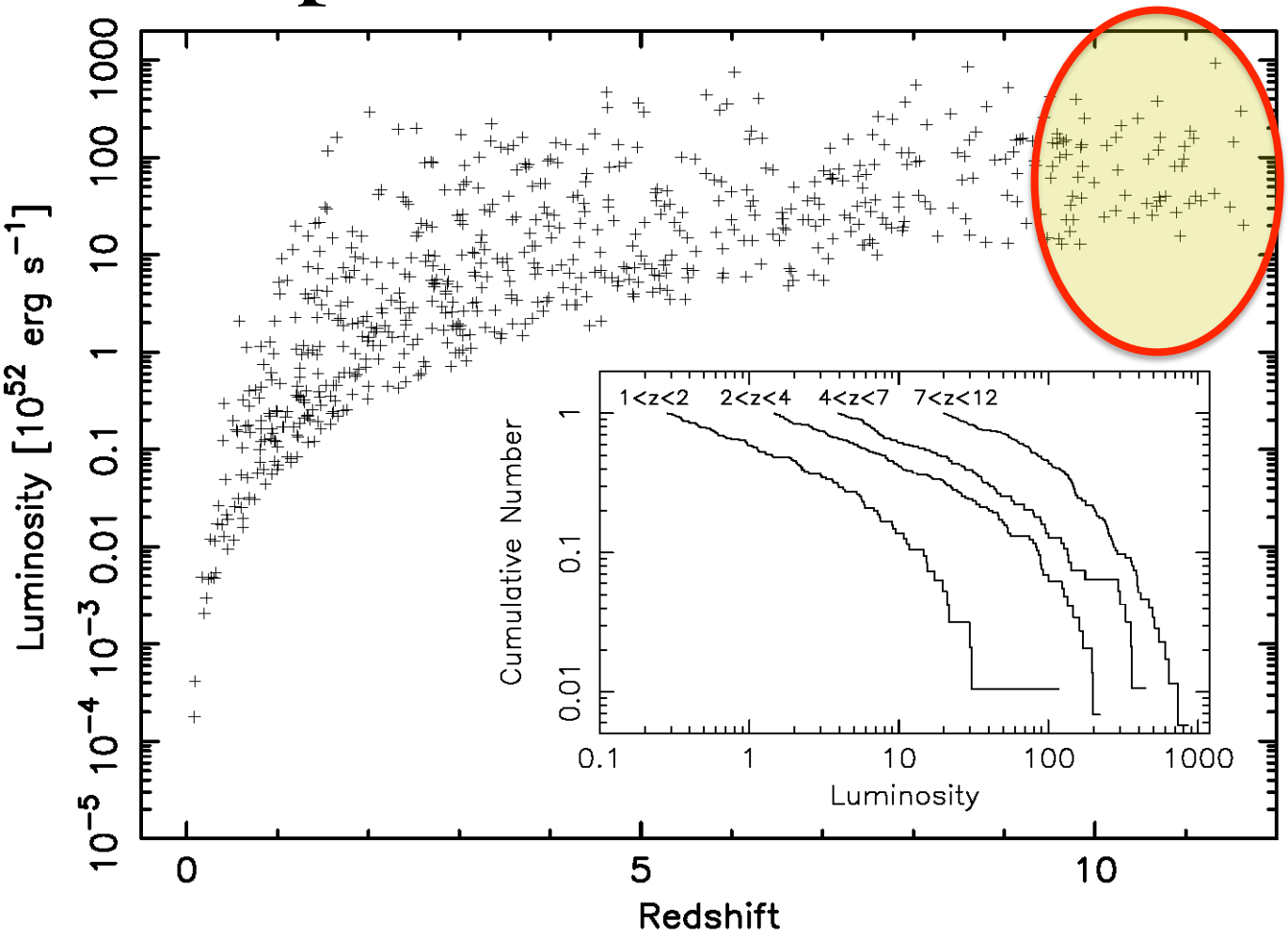
Lyα trough ⇒ redshift

Amati/Yonetoku Relation



Amati 02
Yonetoku+KI 03

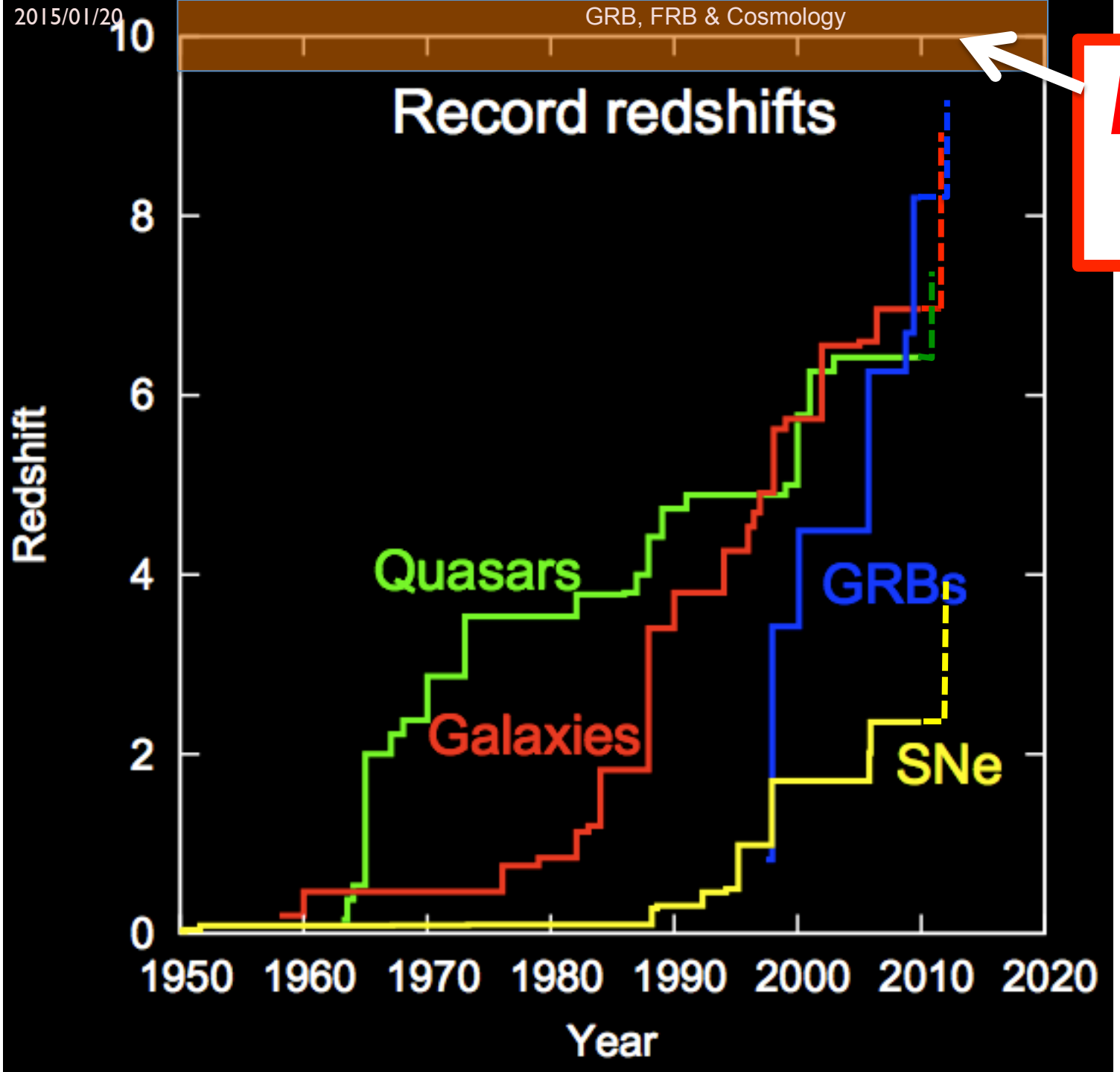
E_p-L imply z>10 GRB



We can assign redshift to GRB w/o measured redshift

Yonetoku+KI 03

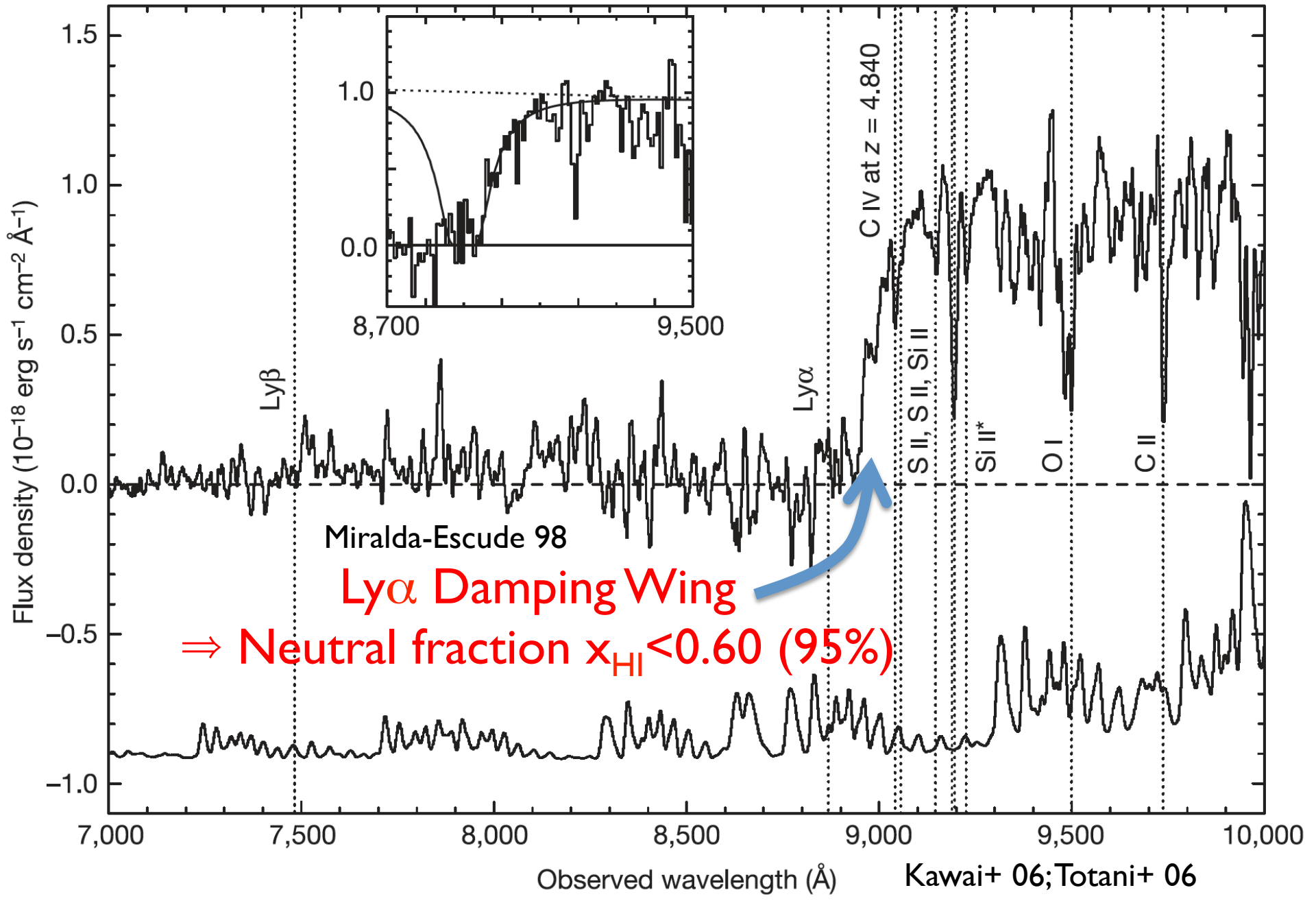
z>10 GRBs have been already detected!?



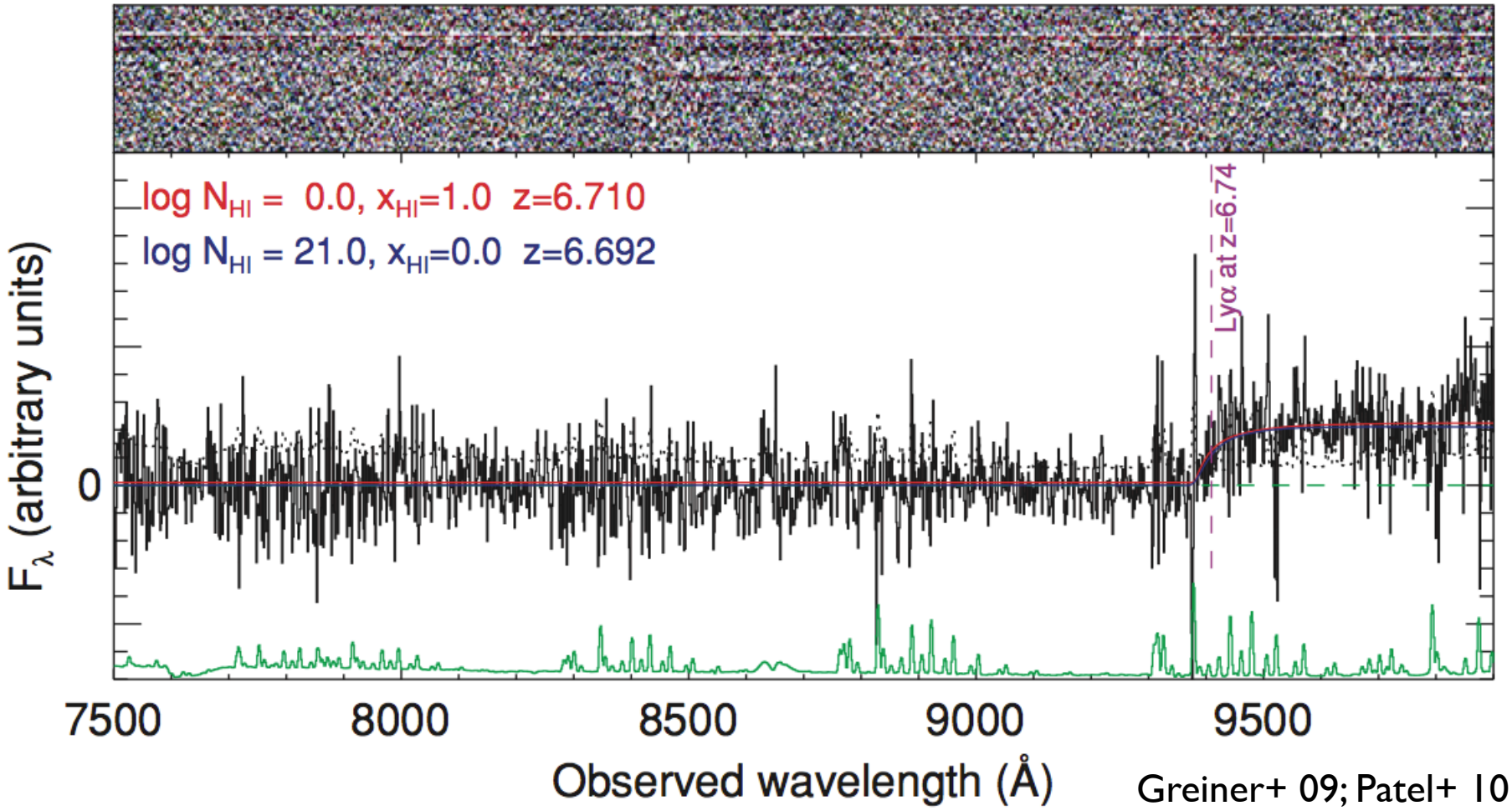
1st Star Era!!

z=5.913: GRB130606A
z=6.3: GRB050904
z=6.33: GRB140515A
z=6.41: Quasar
z=6.73: GRB080913
z=7.085: Quasar
z=8.23: GRB090423
z=8.6: Galaxy
z=9.4: GRB090429B

z=6.295, GRB050904 at t=3.4d, Subaru FOCAS 4.0 hrs



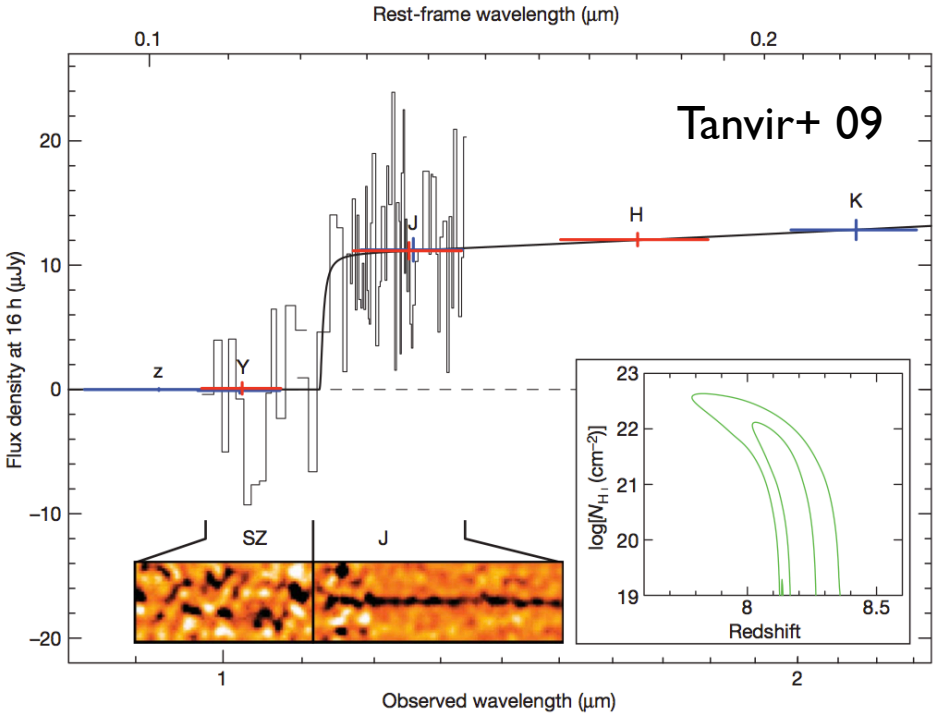
GRB 080913 @z~6.7

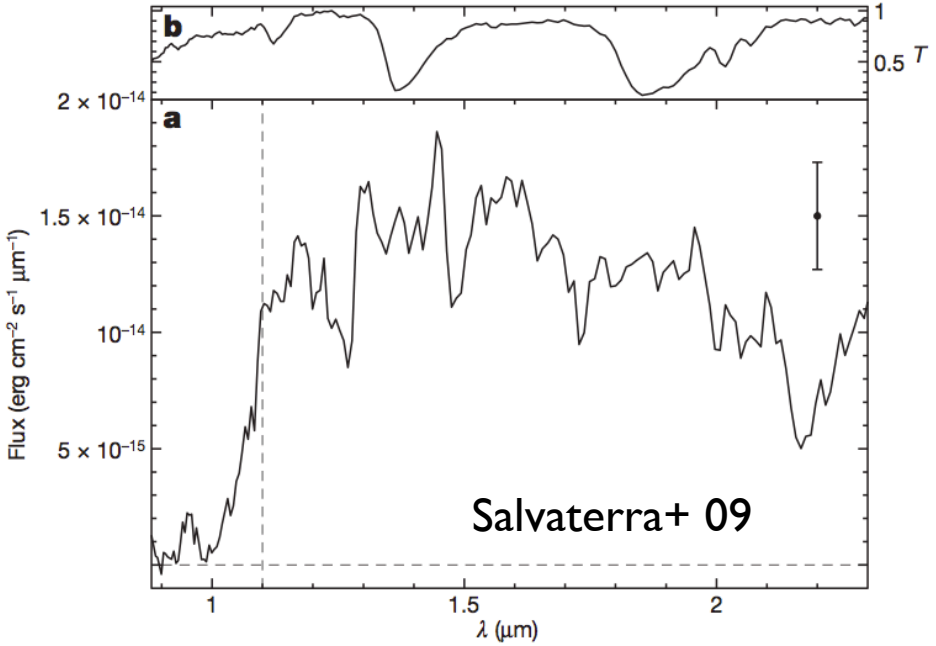


Greiner+ 09; Patel+ 10

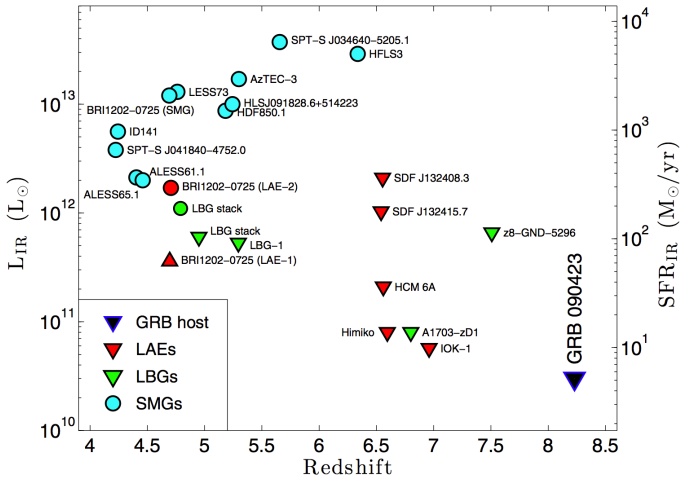
Damping wing does not discriminate DLA or IGM

GRB 090423 @z~8.2





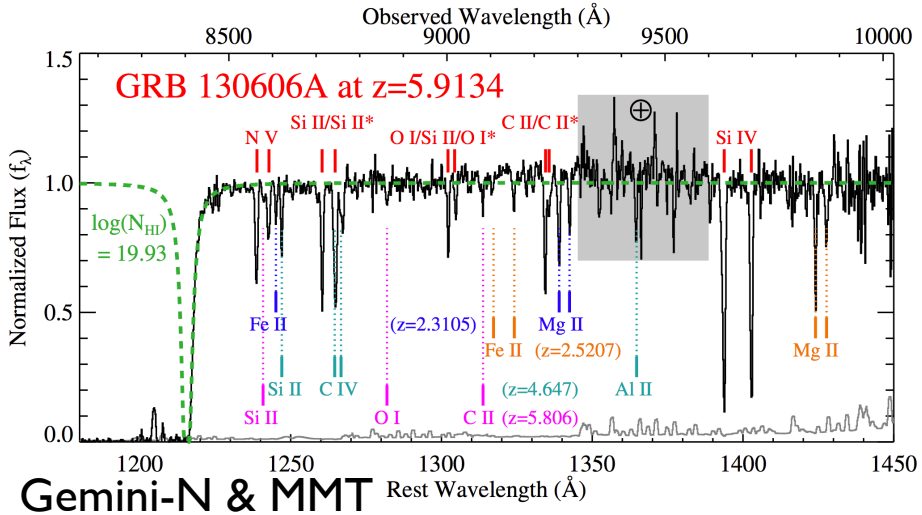
Only upper bound on N_{HI} (Unclear damping wing)

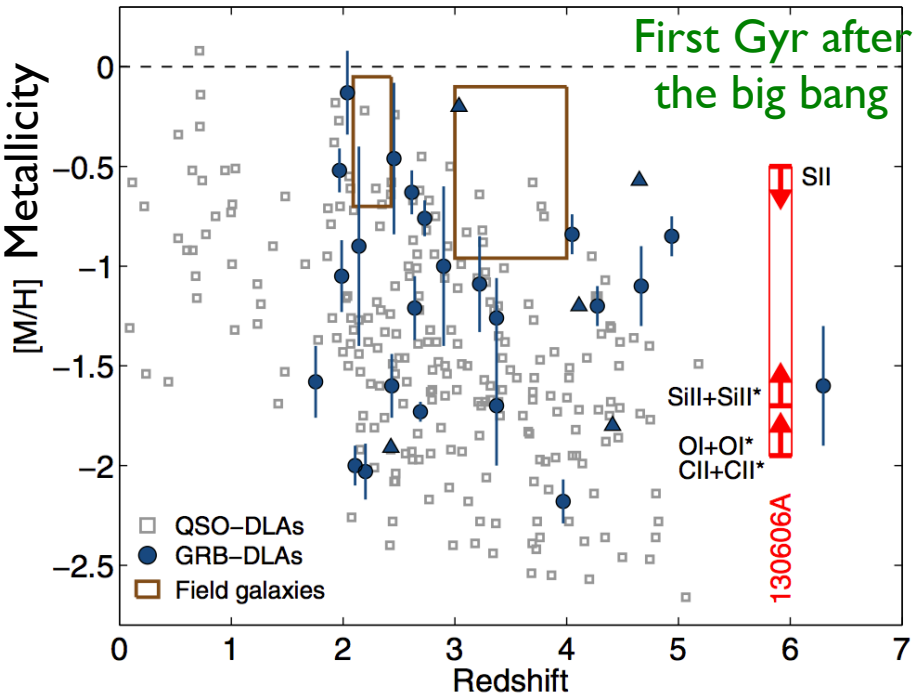


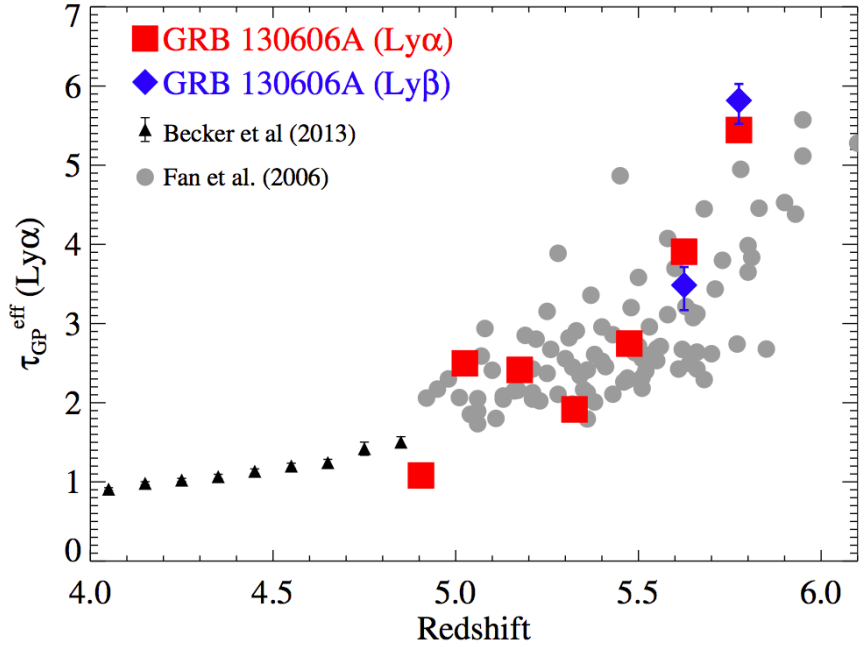
ALMA SFR_{IR}< $5M_\odot$/yr

Berger+ 14

GRB 130606A @z~5.9





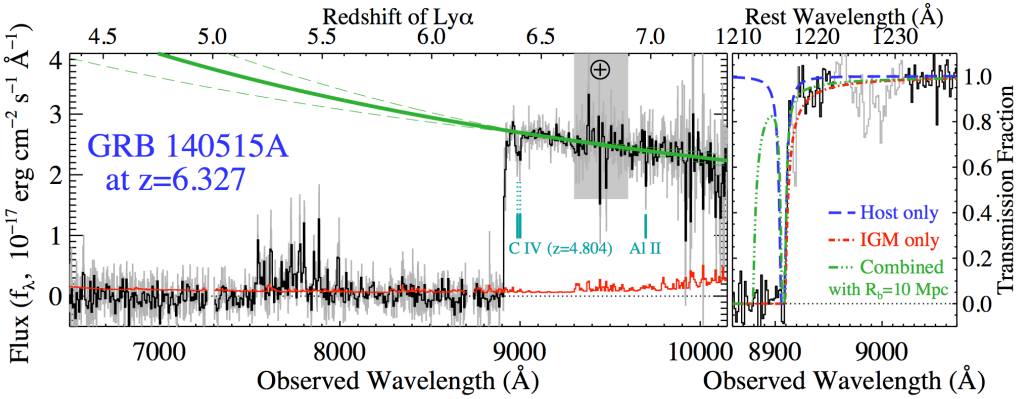


x_{HI}<0.11 (2σ) Chornock+ 13

~0.1-0.5 Totani+ 14 (Subaru)

<0.03 (3s) Hartoog+ 14 (VLT/X-shooter), Castro-Tirado+ 14 (GTC)

GRB 140515A @z~6.3

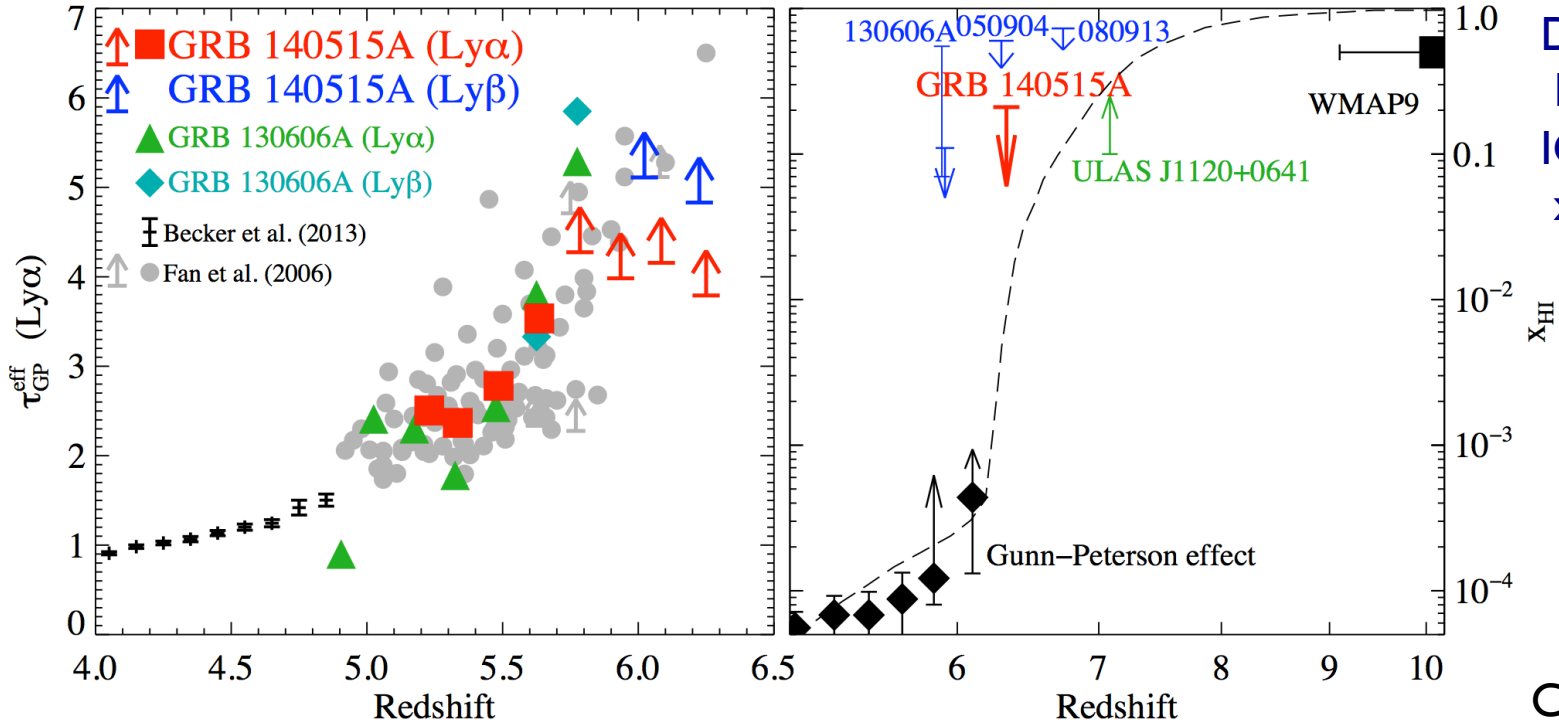


Gemini-North

High-z was serendipitous

DLA+IGM: x_{HI}~0.12±0.05

No metal line: [Z/H]<-0.8



DLA only:

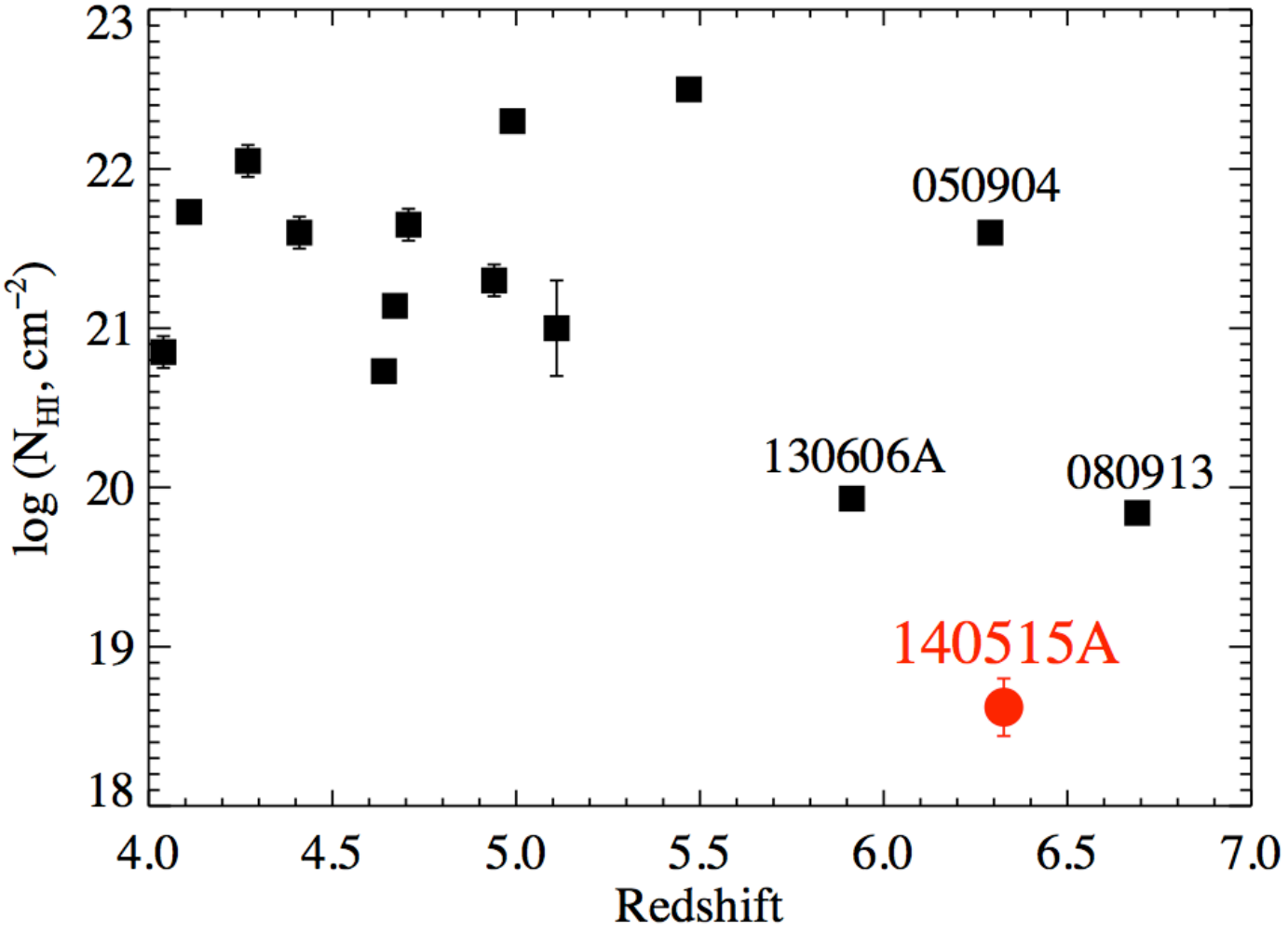
N_{HI}~18.62±0.08

IGM only:

x_{HI}~0.056 $^{+0.011}_{-0.027}$

Chornock+ 14

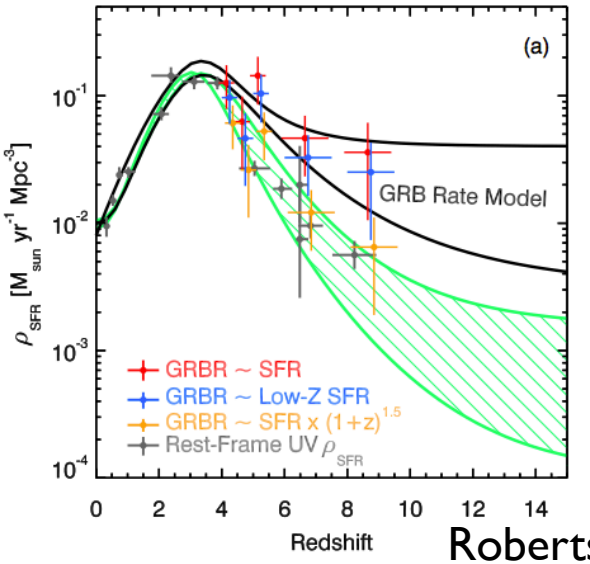
Host Absorption

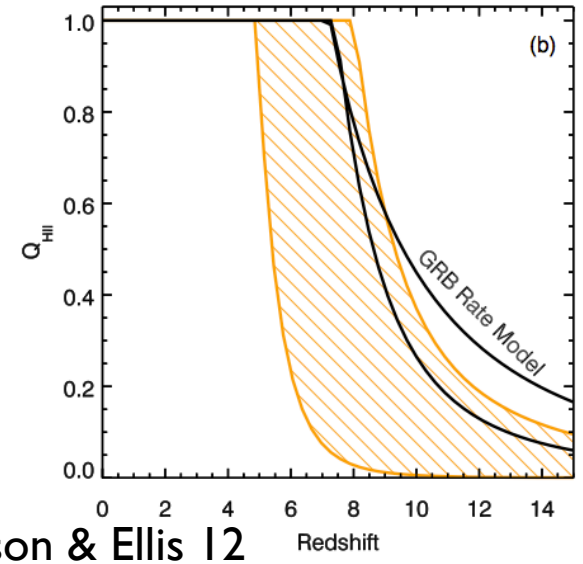


Chornock+ 14

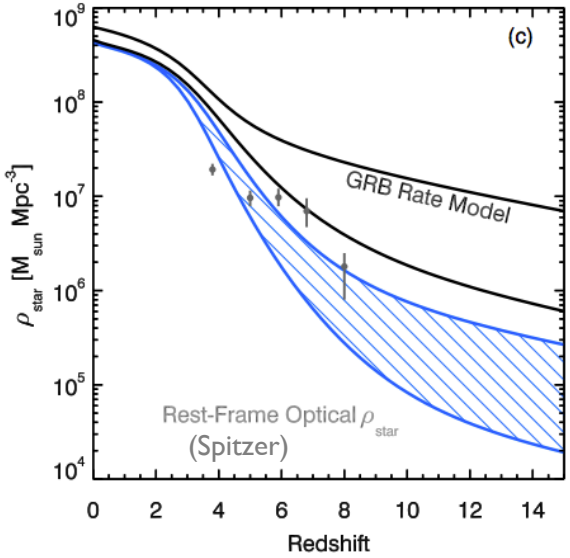
Escape fraction of ionizing photons increases at z>6?

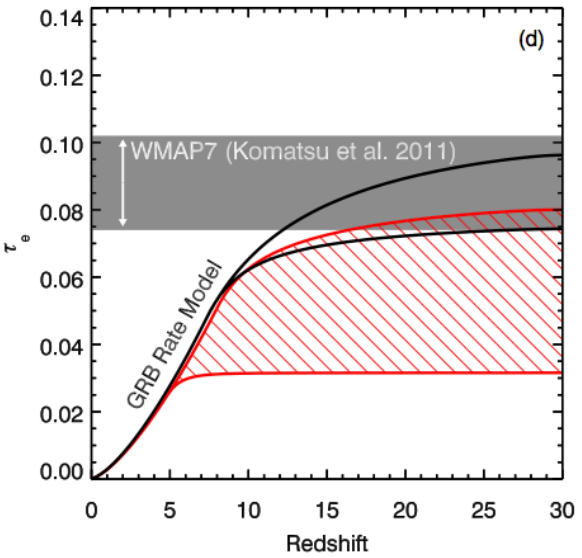
GRB & Reionization





Robertson & Ellis 12





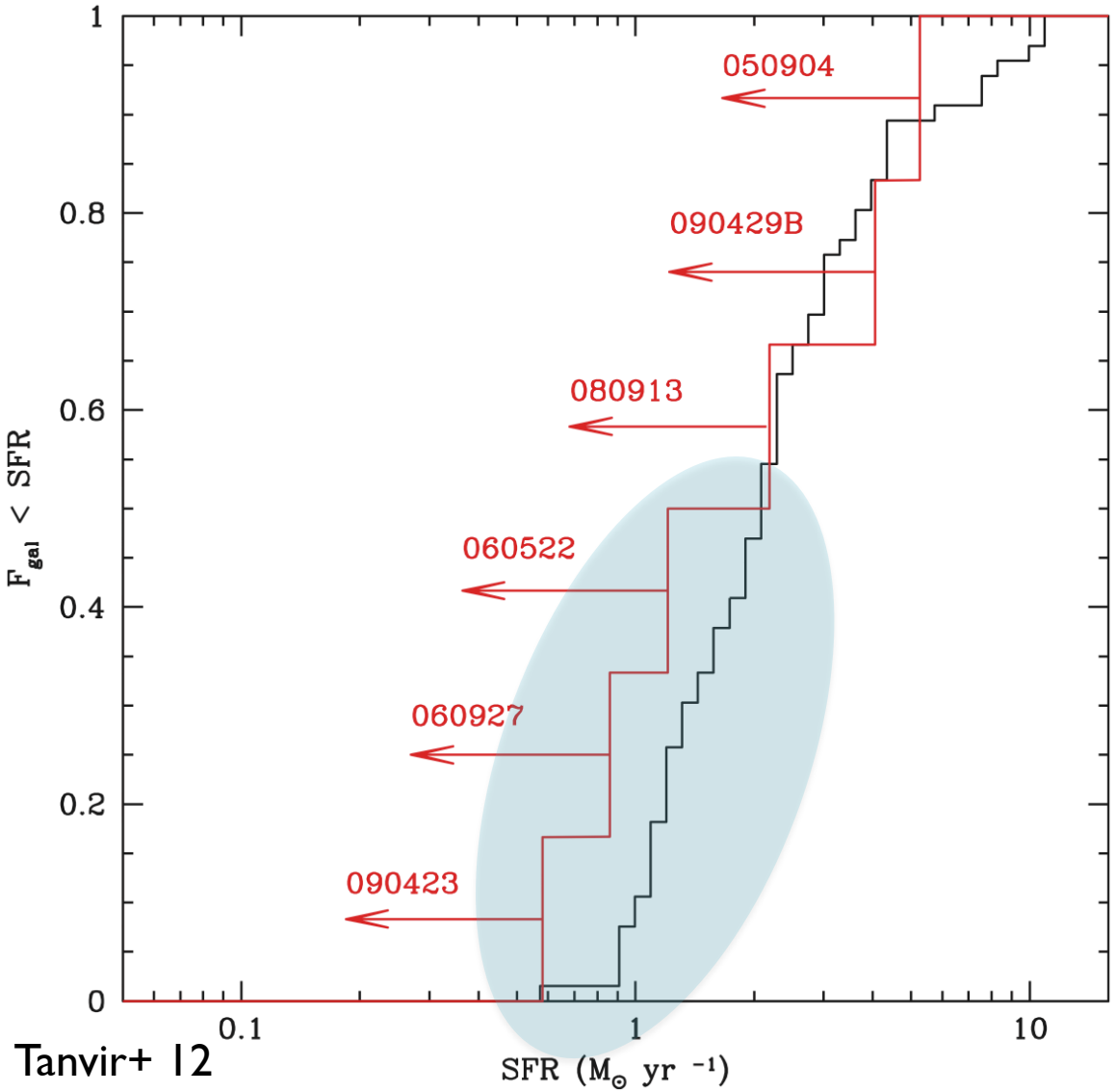
GRB $\propto$ SFR $(1+z)^{1.5}$
to match GRB & UV

GRB $\propto$ SFR $(1+z)^{0.5}$
$\Rightarrow$ Reionization implied
by CMB polarization

But, overproduce
stellar mass density?

$Z \sim 0.2 Z_{\odot}$
Clumpiness=3 (up), 2.5 (low)
f_{esc}=0.06 (up), 0.2 (low)

GRB & Star Formation



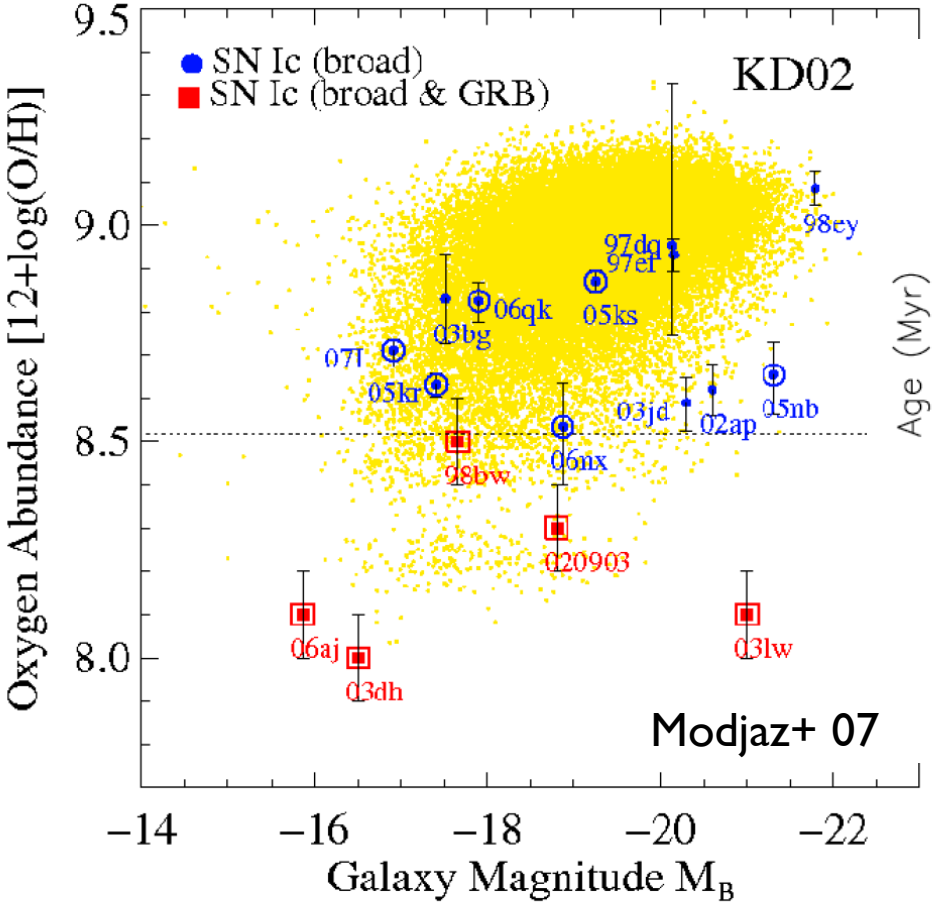
Tanvir+ 12

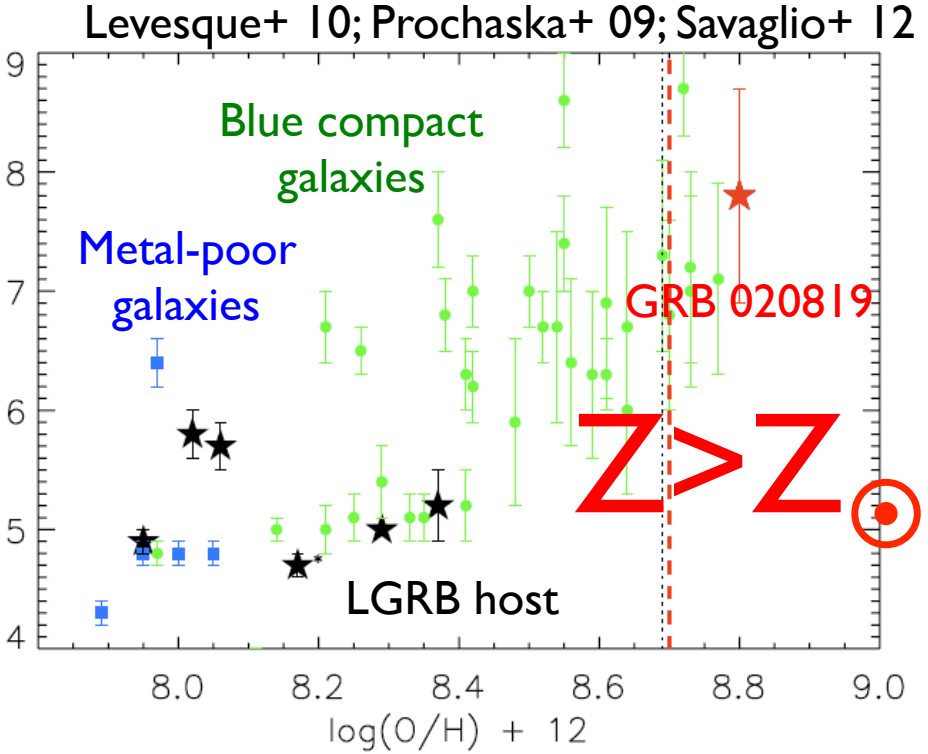
GRB @z>5 v.s.
Hubble UDF gal. @z~7

If GRB ∝ SFR (Totani+97)

⇒ ***Much star formation (UV photons) arises in faint galaxies?***

Low Metal for GRB?



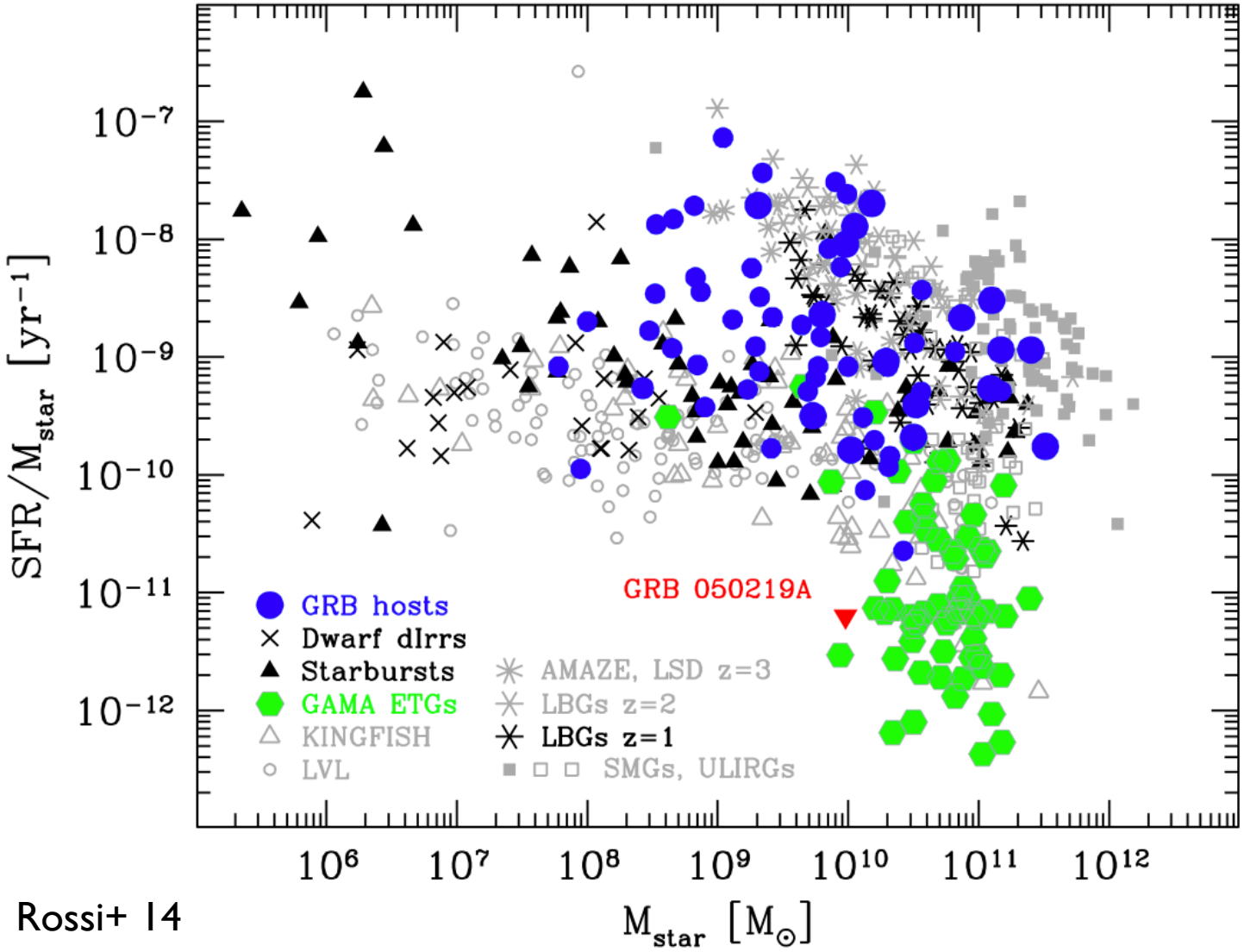


Metal ⇒ Wind ⇒
Ang. Mom. Loss ⇒ No GRB?

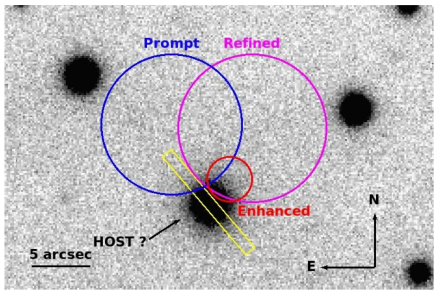
Fundamental plane
SFR-Metal-Mass
Host is typical?

Mannucci 11

LGRB in Early-Type Gal.



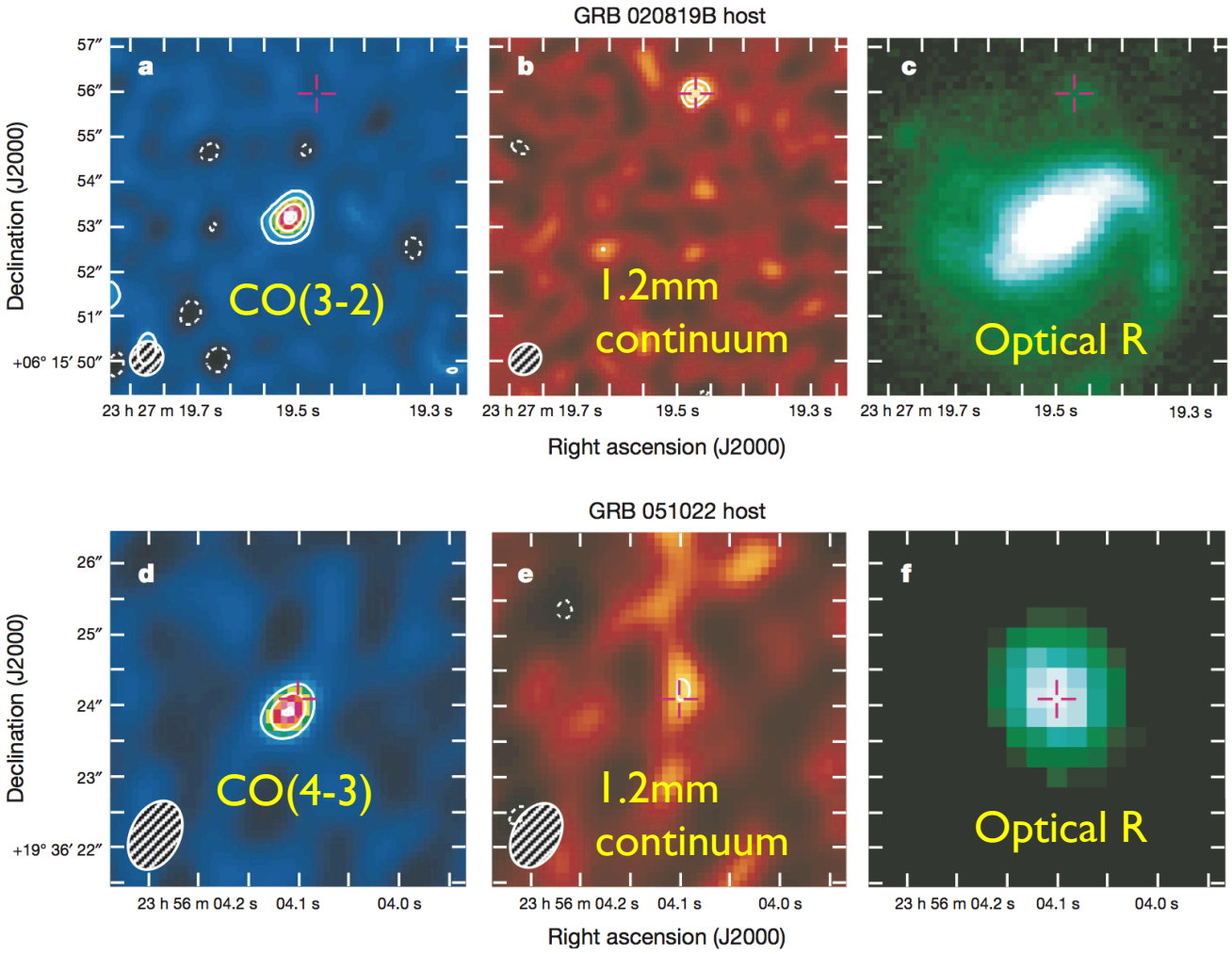
Rossi+ 14



T_{90}~24 s

z=0.211
3Gy-old ETG
Not *forming

Small Gas-to-Dust Ratio



CO line by ALMA
⇒ Molecular gas
mm continuum
⇒ Dust

M_{gas}/M_{dust}<9-14
(GRB 020819)
< Star-forming gal.
Gas into stars?

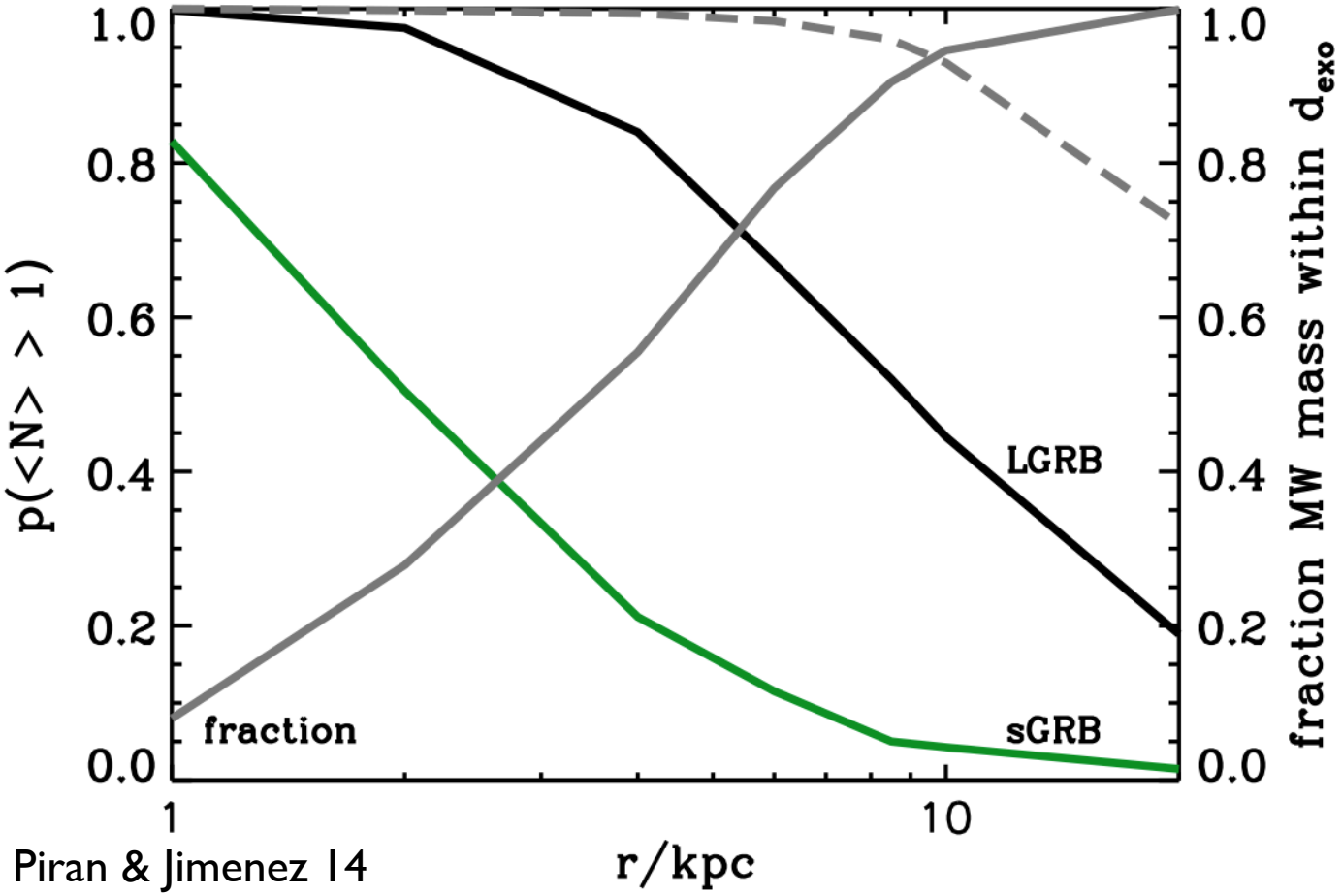
Dust extinction
⇒ Dark afterglow

Hatsukade+ 14
Stanway+ 14 for GRB 080517

Life Extinction

Lethal GRBs are abundant in the inner Galaxy

Low-density region in the outskirts of large galaxies is safe



Piran & Jimenez 14

No life @z>0.5

~100 kJ/m^2
⇒ Nitric oxide
⇒ Ozone layer

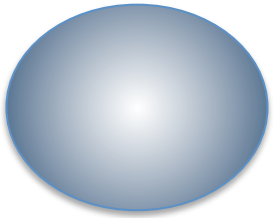
$\Lambda \Rightarrow$ Large gal.
in low-density
Fermi's paradox

Contents for GRB

- GRB Cosmology
- ***Pop III GRB***
- Ultralong GRB
- Short GRB
- Other topics

Very Massive Pop III Star?

Present Day Massive Star ~20$M_\odot$



Abel+ 02; Bromm+ 02;
Omukai+ 03; Yoshida+ 08

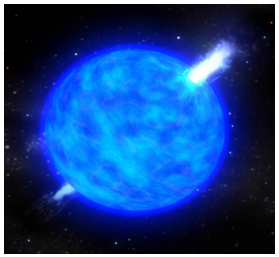
Pop III (Zero Metal) ~1000$M_\odot$ (!?)

Mini halo (first object): ~1000$M_\odot$
If all the mass is accreted to a proto-star,

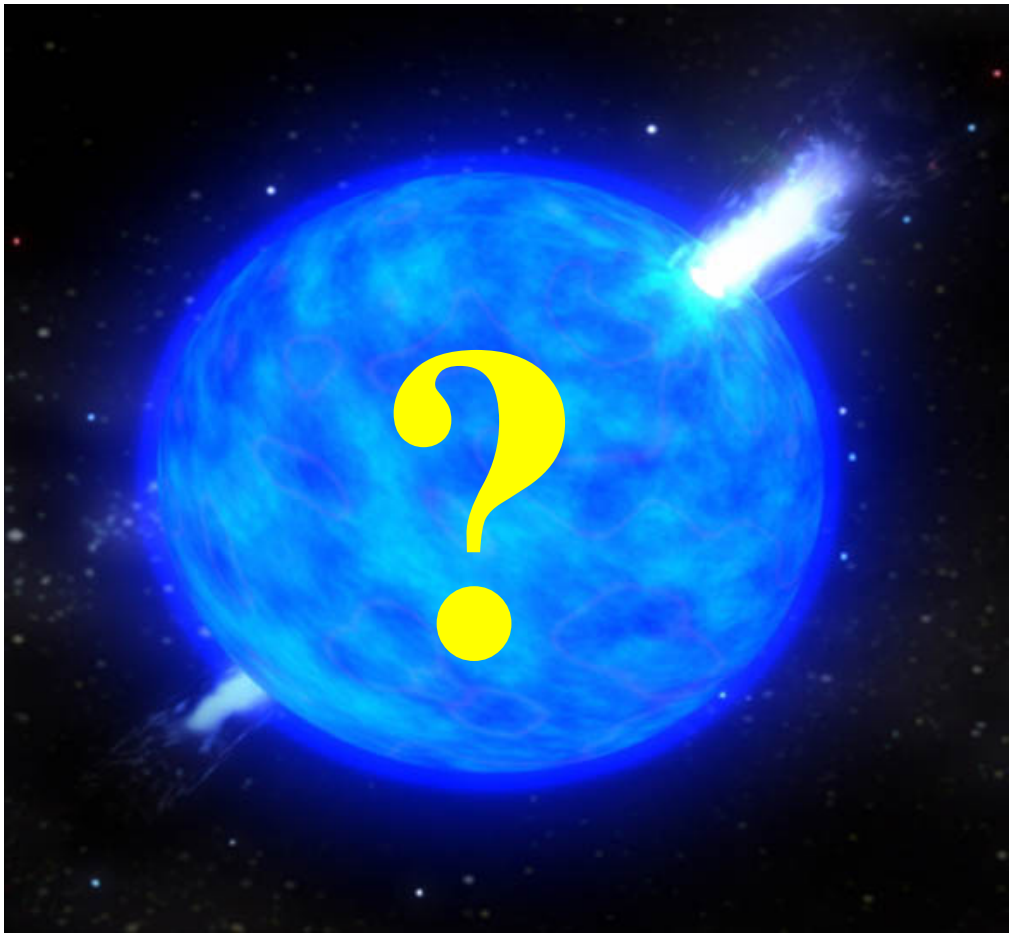
First stars are very MASSIVE?

Pop III GRB?

Present Day GRB

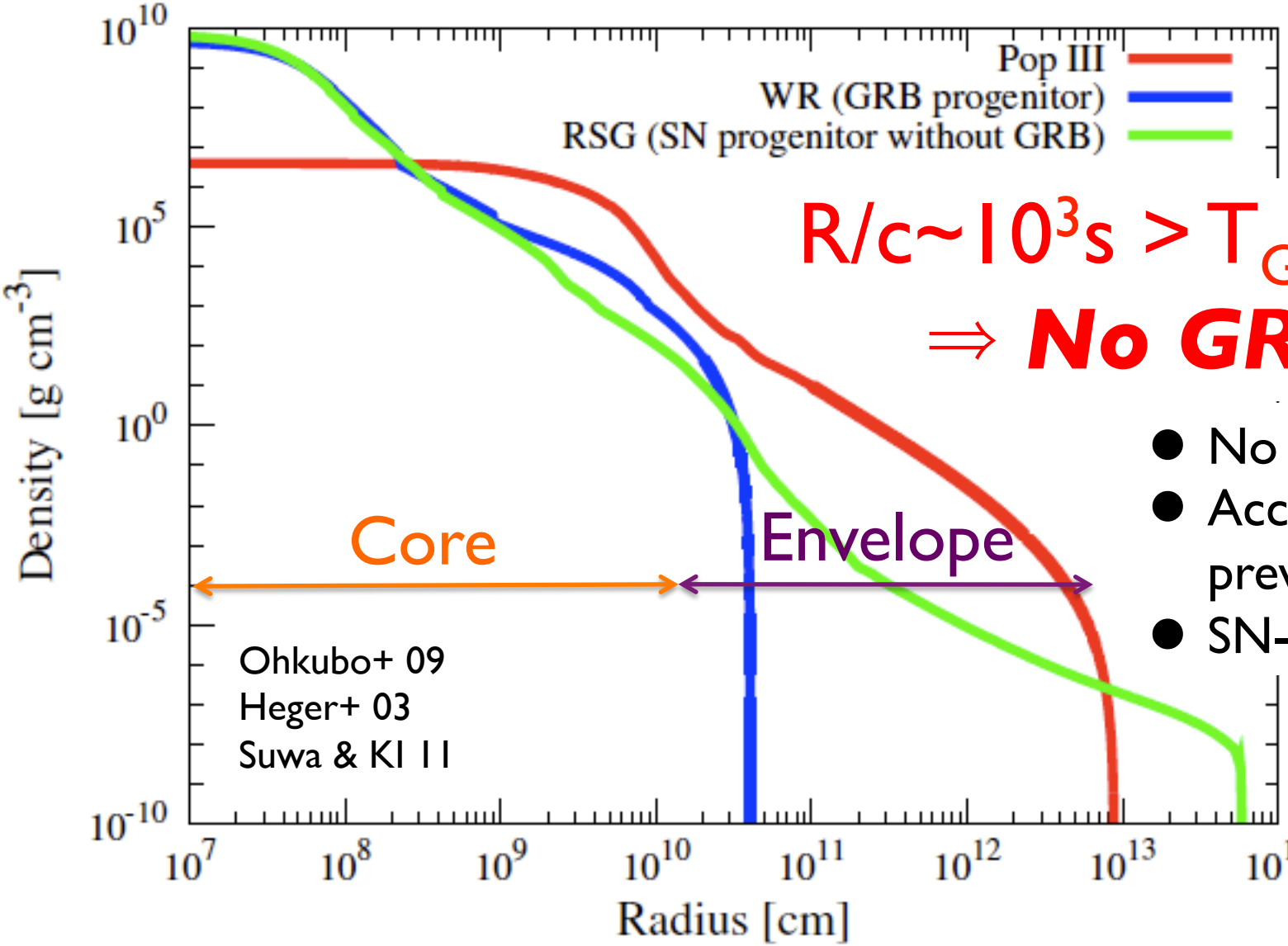


Komissarov & Barkov 10
Meszaros & Rees 10
Suwa & KI 11
Nagakura, Suwa & KI 12



Gigantic (x100) GRB @ z~10-30???

Massive Envelope



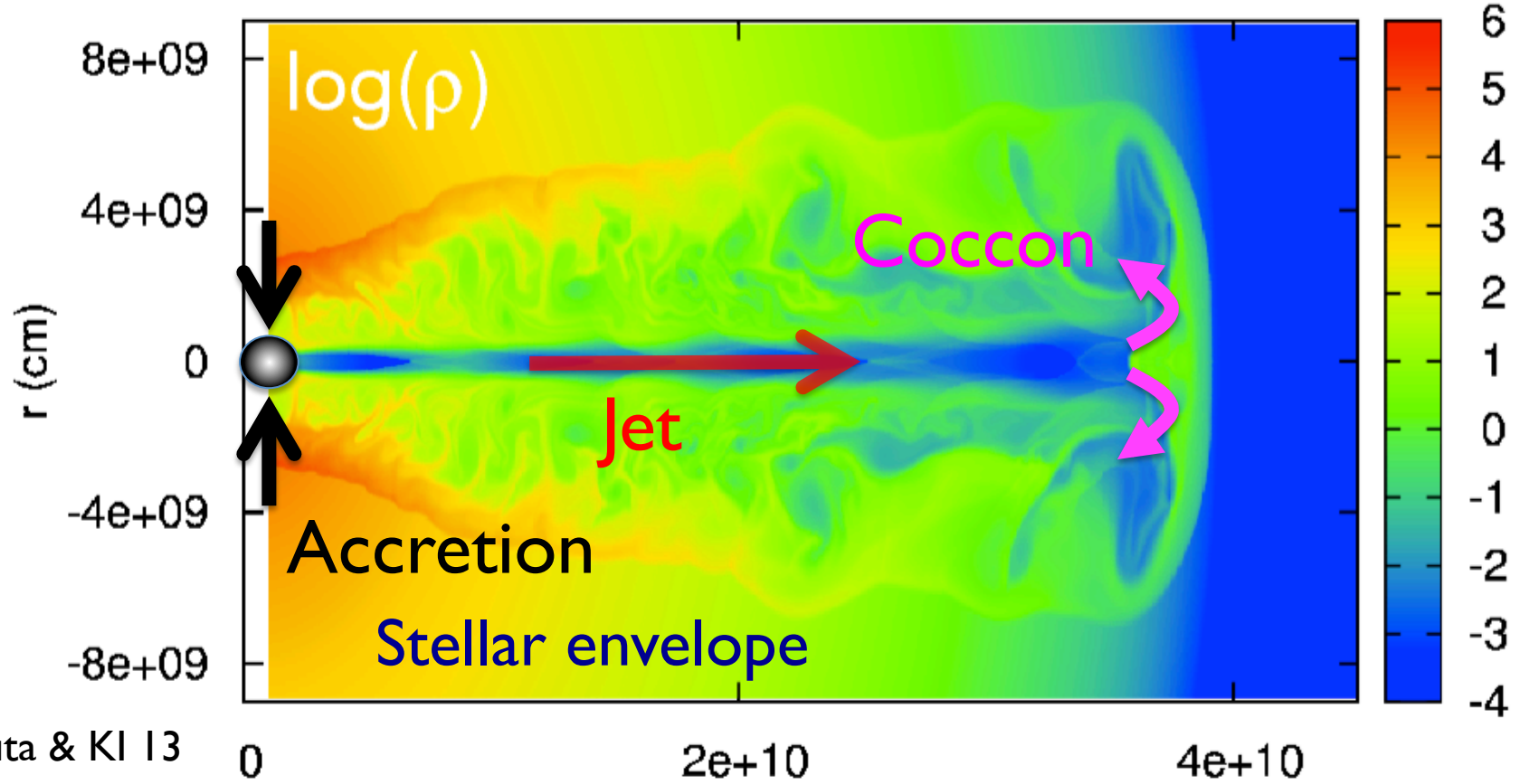
$R/c \sim 10^3 s > T_{GRB} \sim 10 s$

$\Rightarrow$ ***No GRB?***

- No mass loss
- Accretion may prevent CHE
- SN-II w/o GRB

Duration ~10 sec?

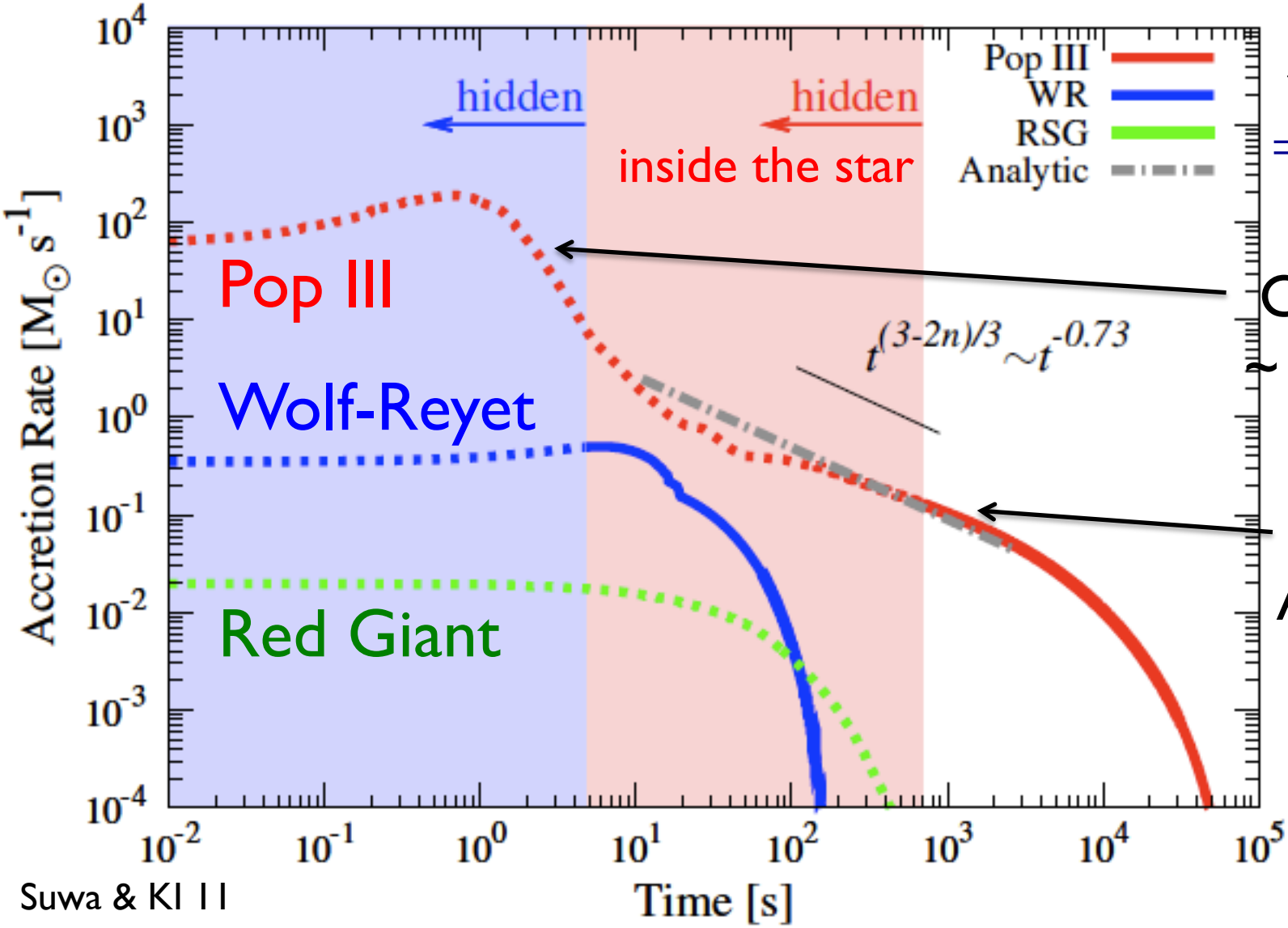
Loophole: $T_{Pop\ III\ GRB}$~10 sec?



Mizuta & KI 13

Big envelope is ○ for jet injection but × for penetration

Envelope Accretion



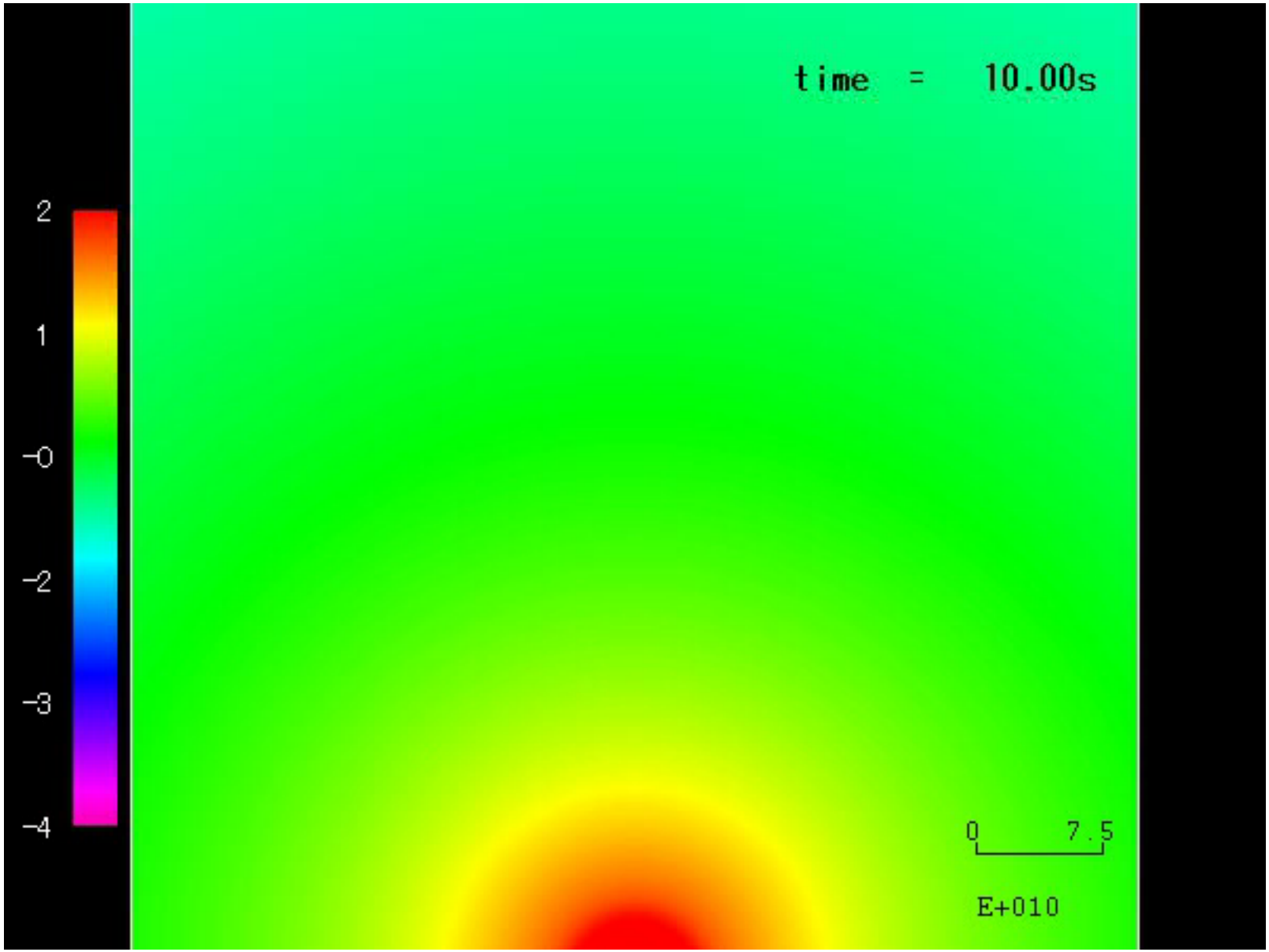
$L \propto \dot{M}$

$\Rightarrow v_{\rm Jet\ head}$

Core Acc.
~ a few sec

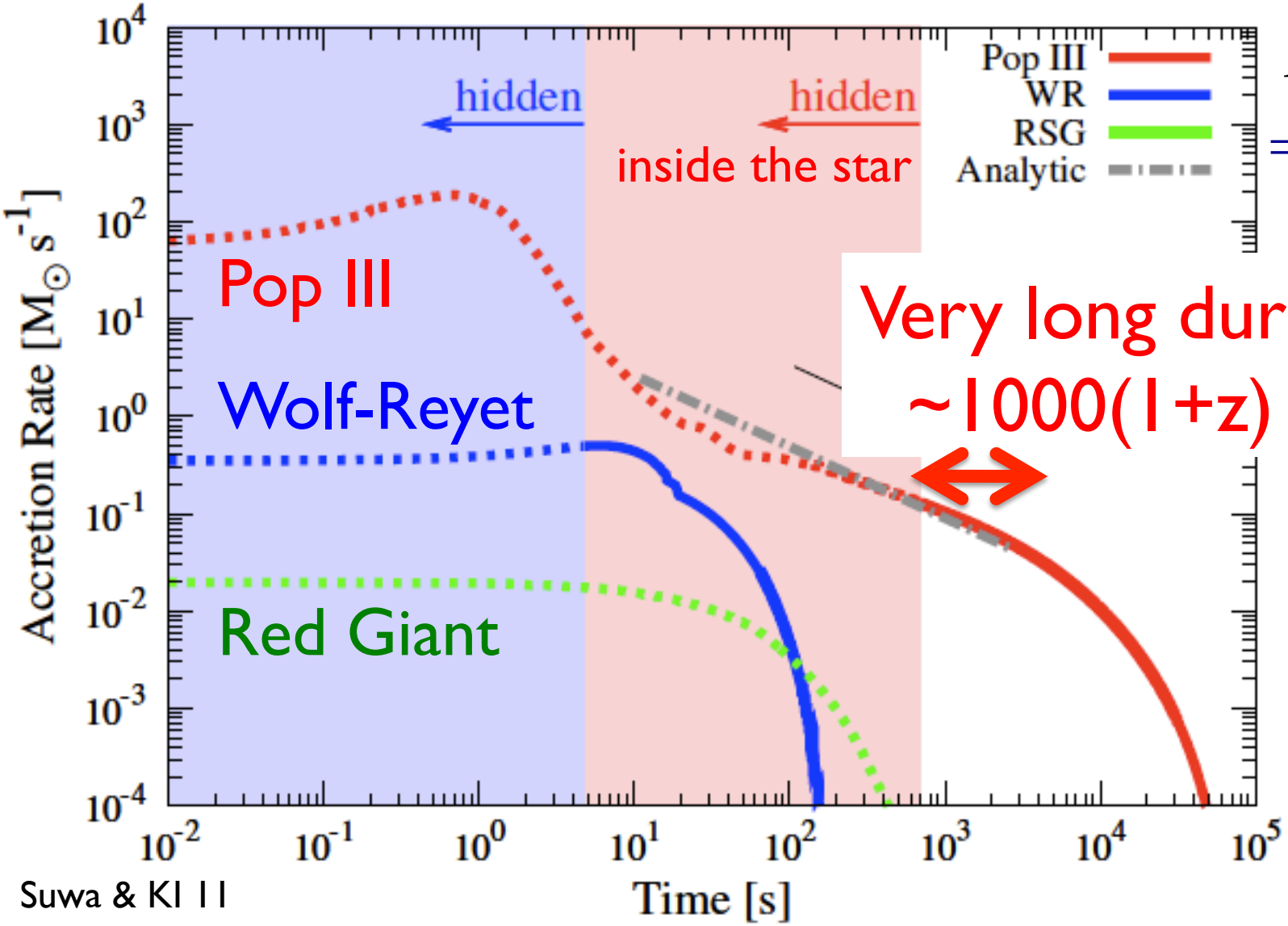
Envelope Accretion

Suwa & KI 11



Nagakura+ 12 2D, rela-hydro, Mass accretion from inner boundary ⇒ Jet

Long Duration



$L \propto \dot{M}$

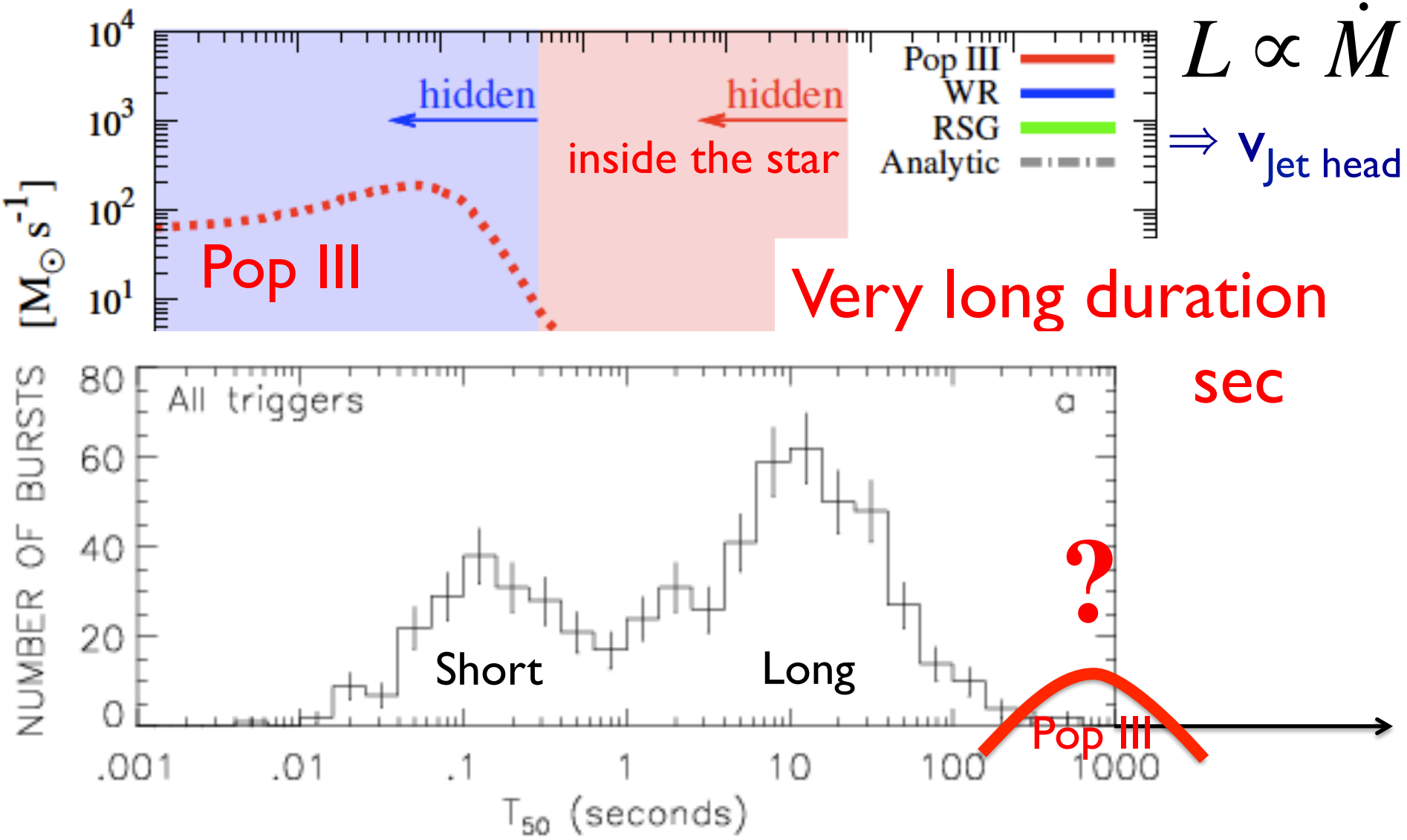
$\Rightarrow v_{\text{Jet head}}$

Very long duration

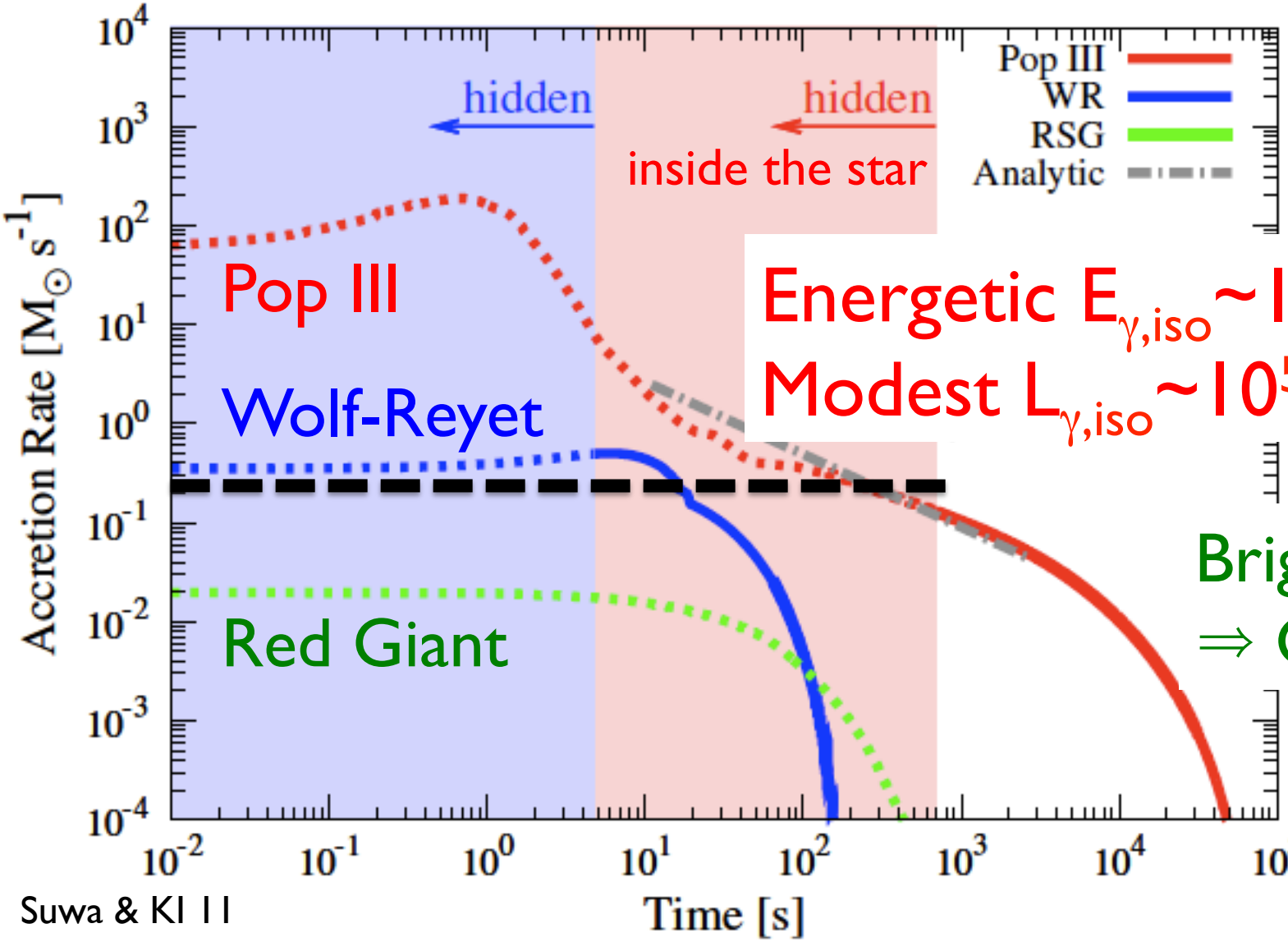
~1000(1+z) sec

Suwa & KI 11

Long Duration



Not so Bright



$L \propto \dot{M}$

$\Rightarrow v_{\text{Jet head}}$

Energetic $E_{\gamma,\text{iso}} \sim 10^{55}$erg

Modest $L_{\gamma,\text{iso}} \sim 10^{52}$erg/s

Bright phase

$\Rightarrow$ Cocoon

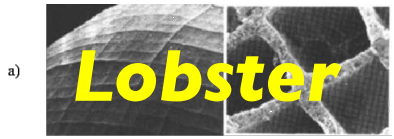
Suwa & KI 11

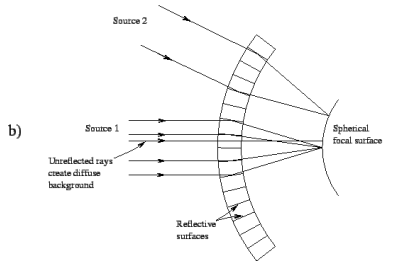
Detectability

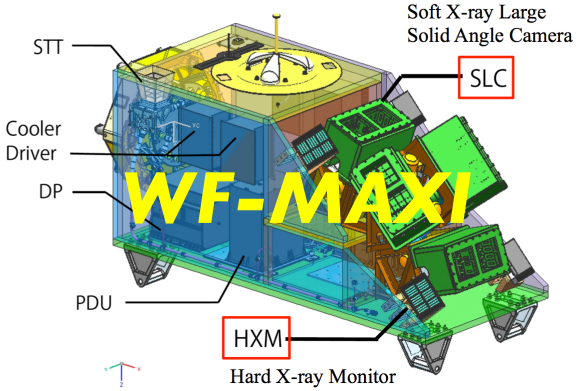
- Pop III GRB at z~20

$$F = \frac{\varepsilon_\gamma L_{\rm iso}}{4\pi r_L^2} \sim 10^{-9}\ {\rm erg\ cm^{-2}\ s^{-1}}$$

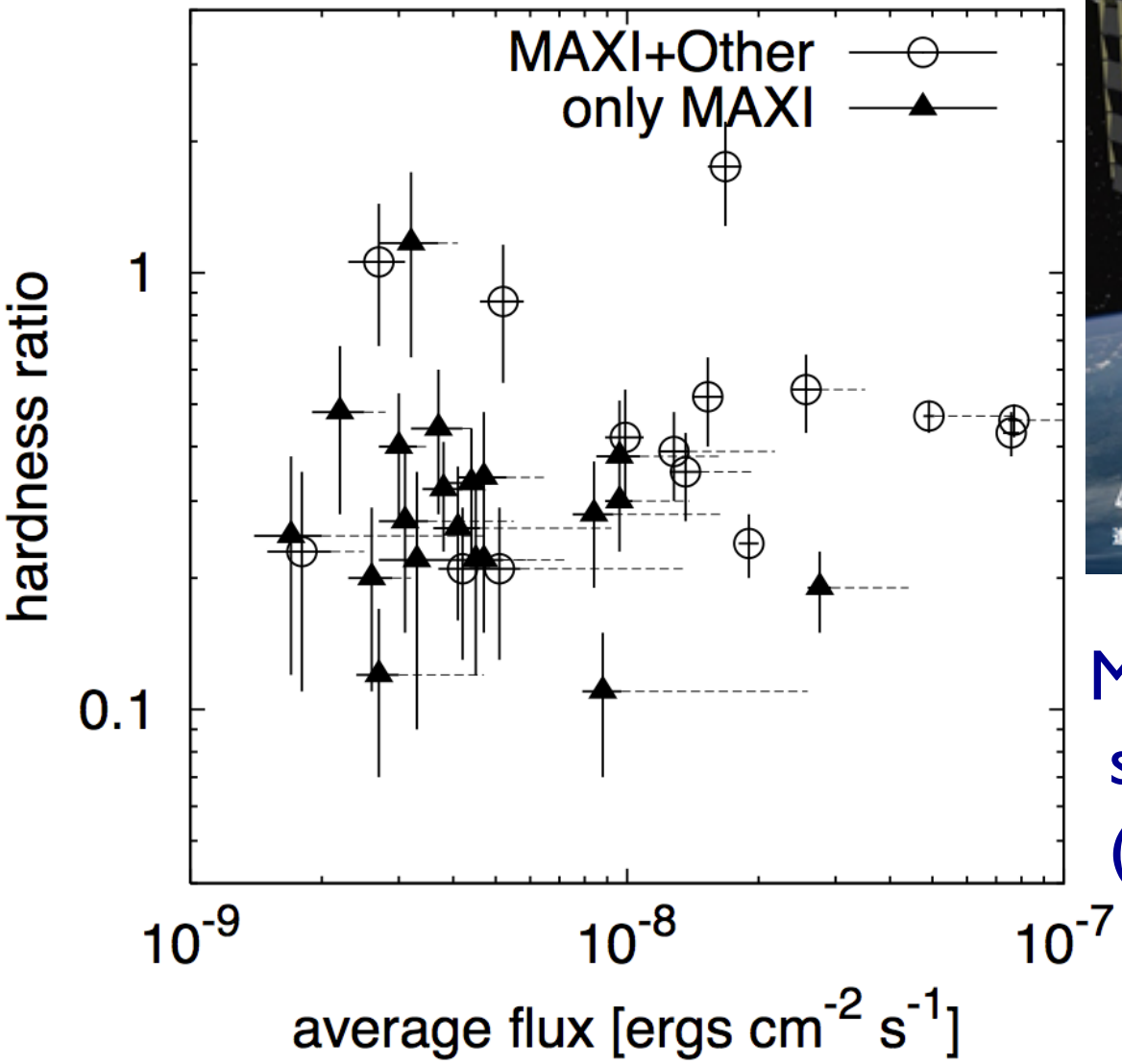
- Swift BAT sensitivity ~10^{-8} erg cm^{-2} s^{-1}
- ***Future soft X-ray surveys***

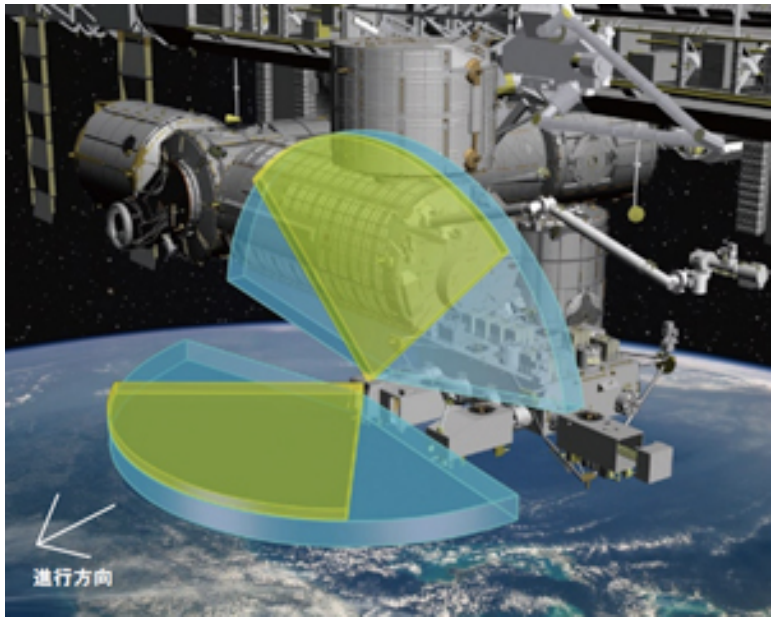






MAXI GRB

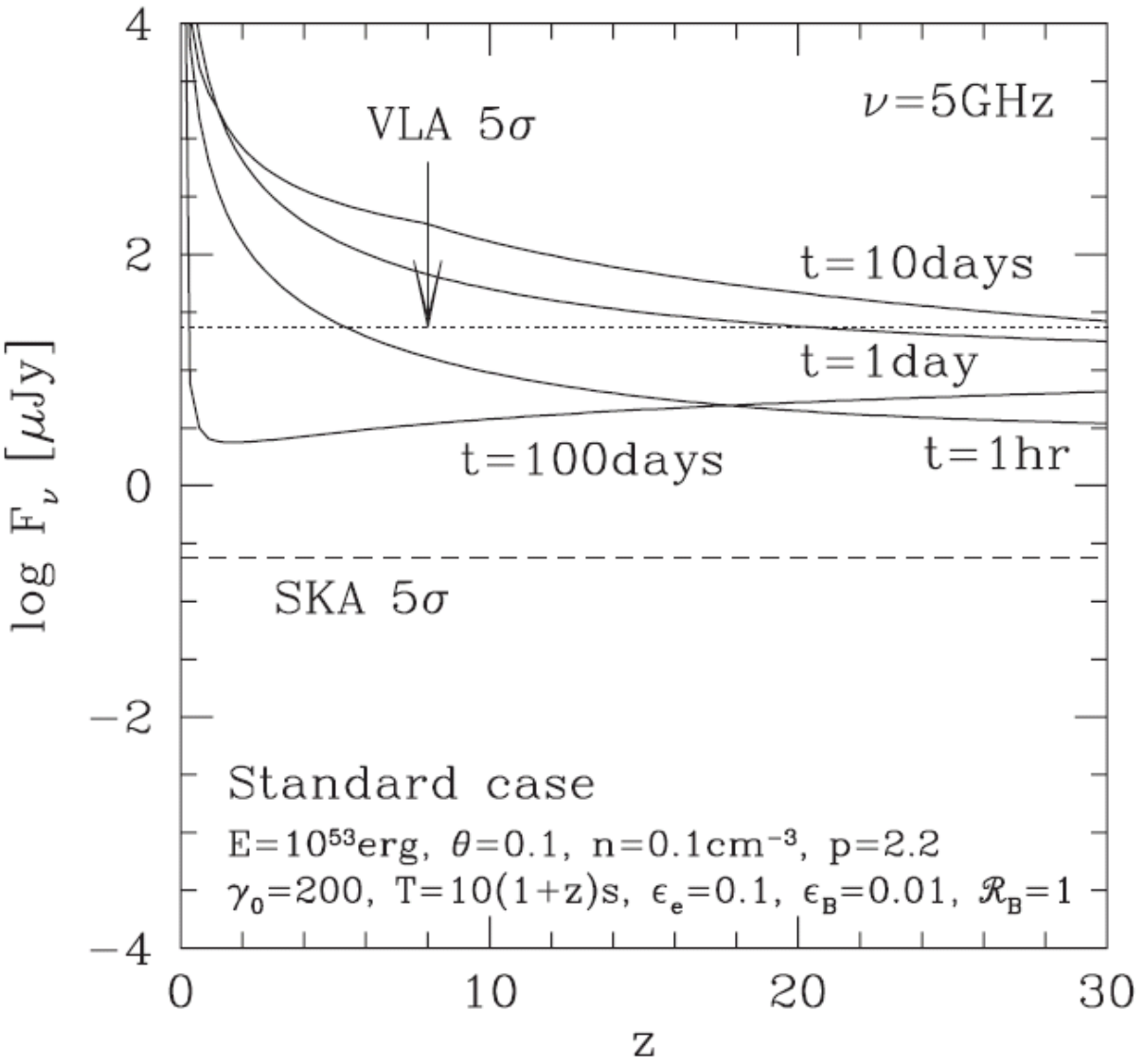


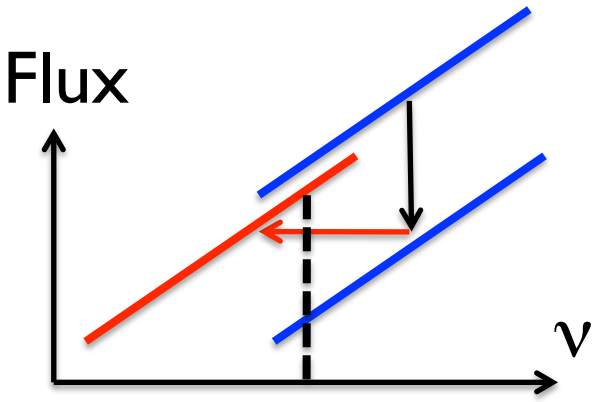


MAXI detects soft GRB, such as ***X-Ray Flashes*** (2-30 keV) (Aug 09-13)

Serino+ 14

Radio Afterglow





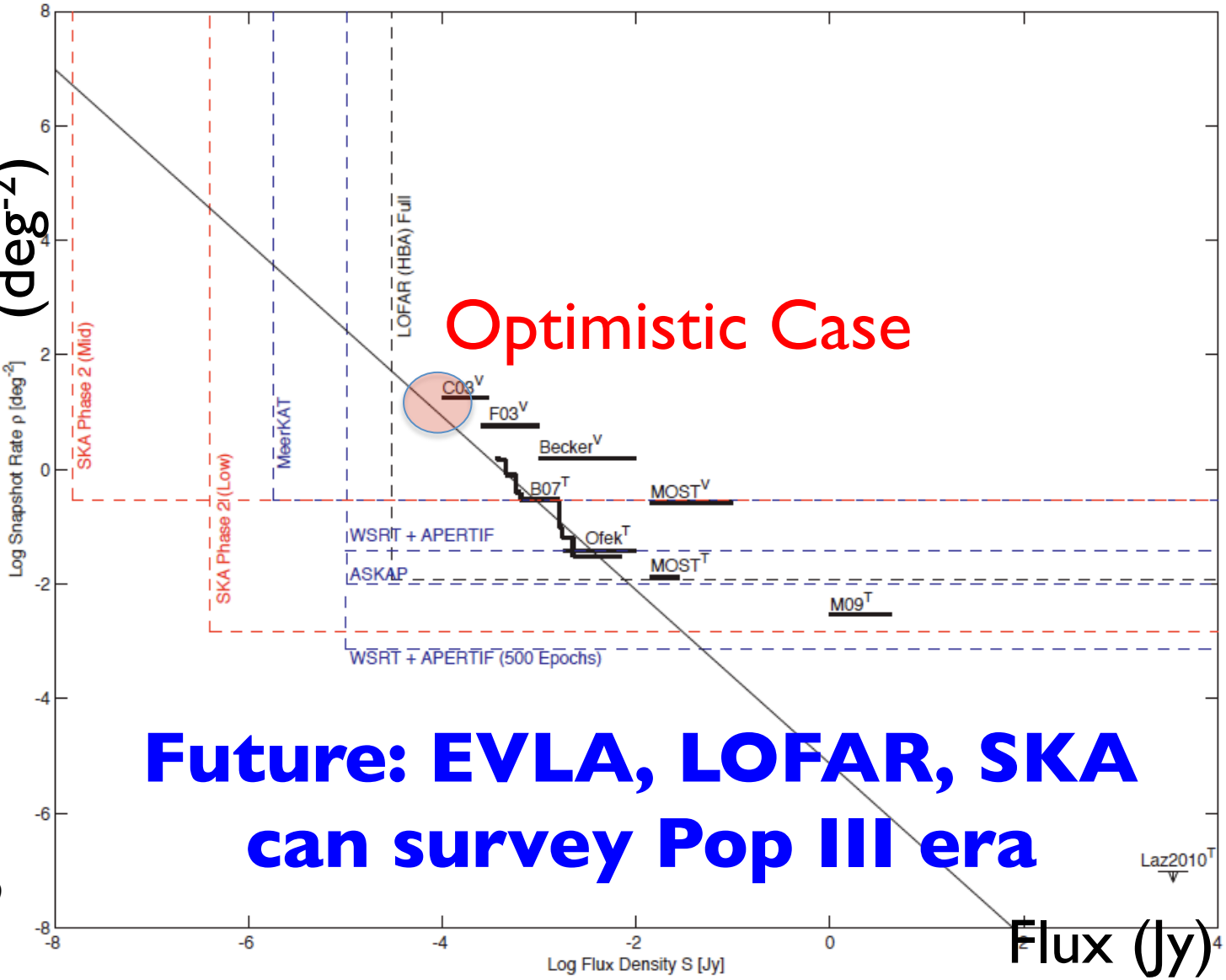
K-correction ⇒
Not dim @high-z

Spherical after jet break

KI & Meszaros 05
Inoue+ 07, Toma+ 10

Future Radio Transient

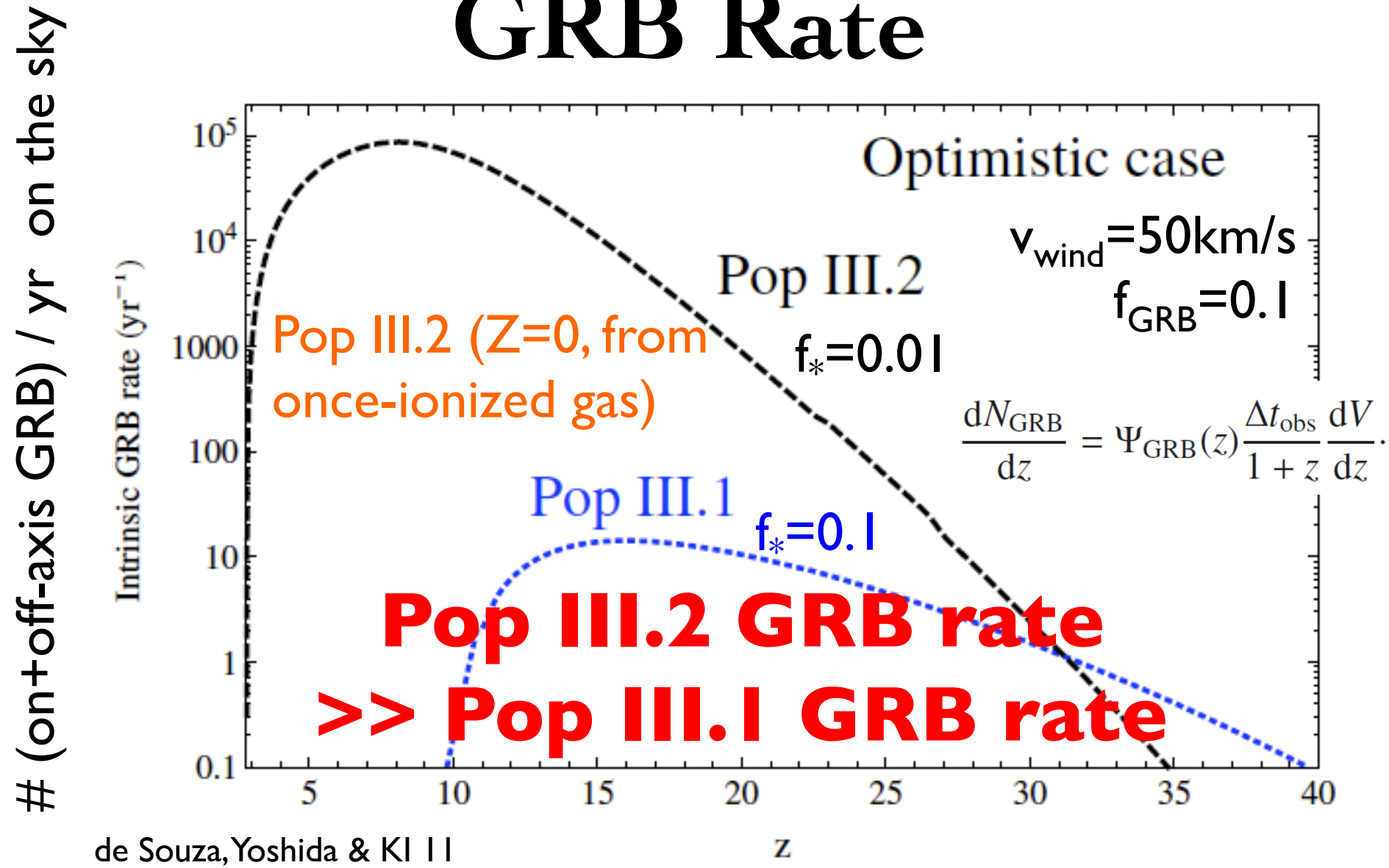
Surface density (deg^{-2})



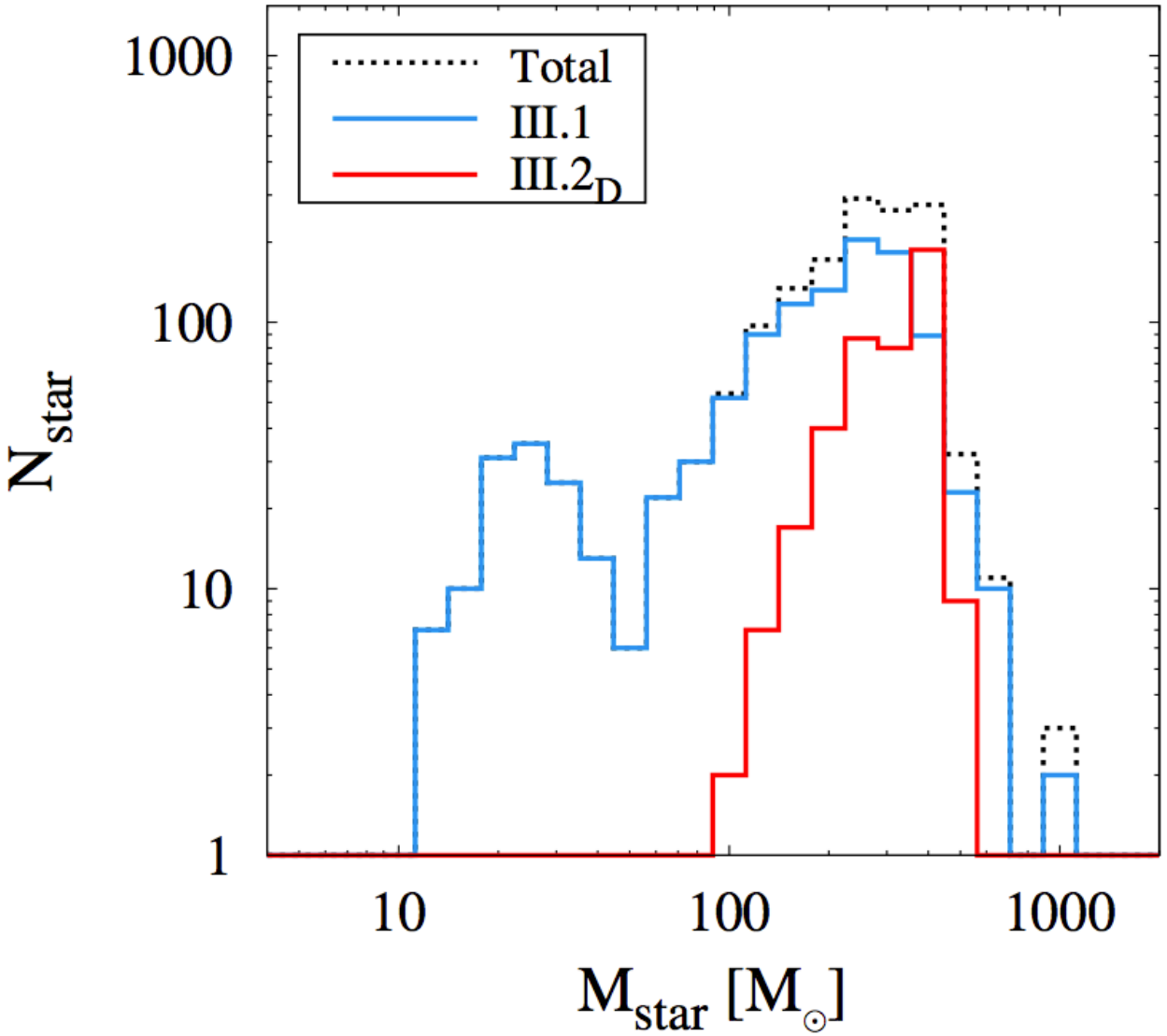
1112.2579

Flux (Jy)

Pop III.1 & III.2 GRB Rate



Pop III.2$_D$



#(Pop III.2) < #(Pop III.2$_D$)

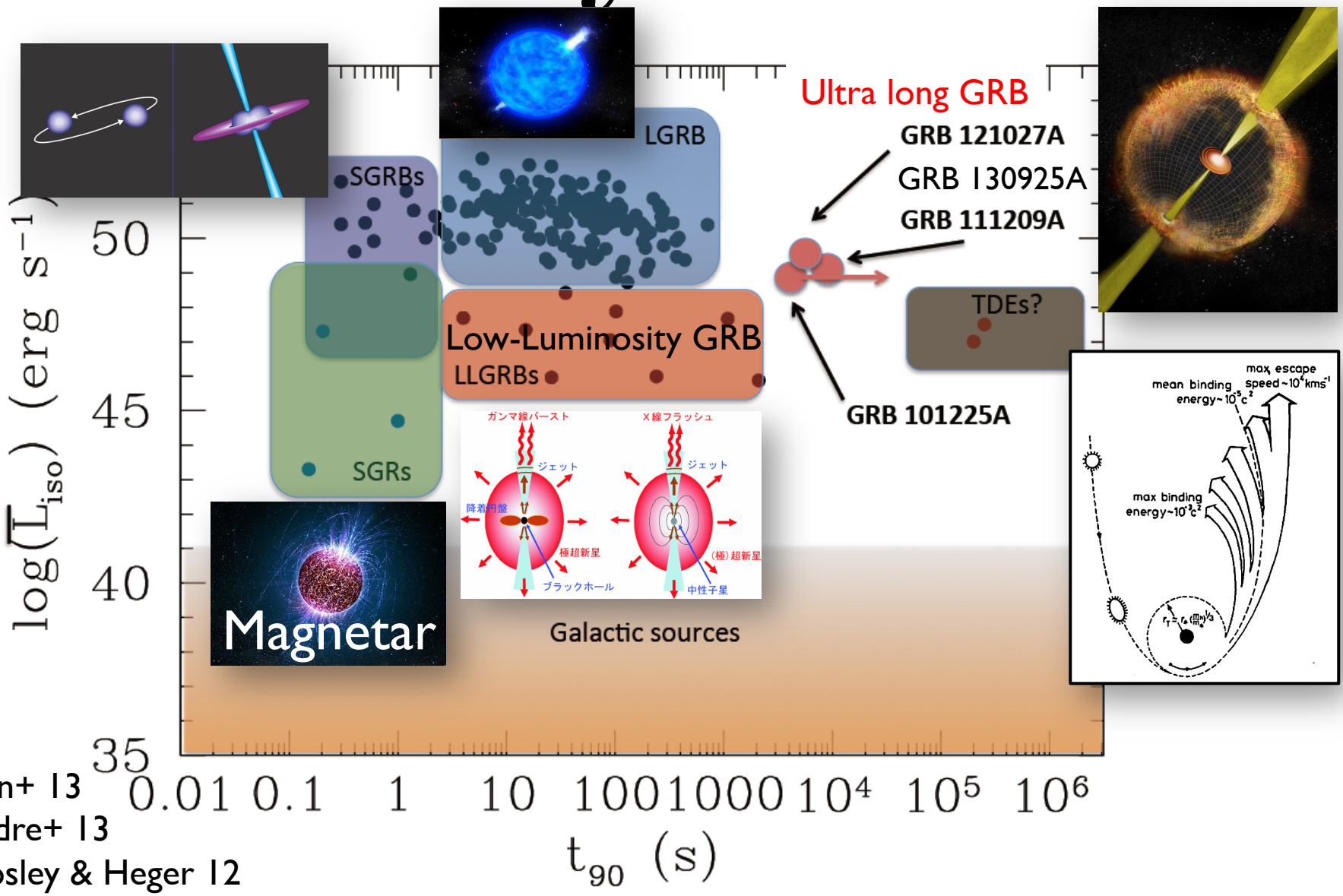
GRB III.2$_D$ is more energetic than GRB III.2 (easy to detect)

Hirano+ 14

Contents for GRB

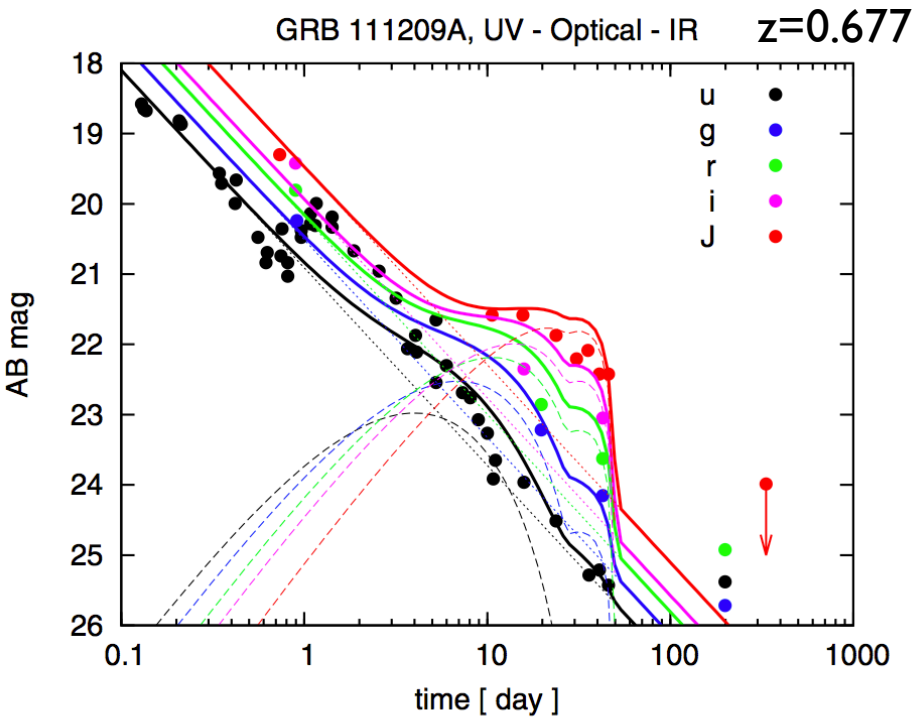
- GRB Cosmology
- Pop III GRB
- ***Ultralong GRB***
- Short GRB
- Other topics

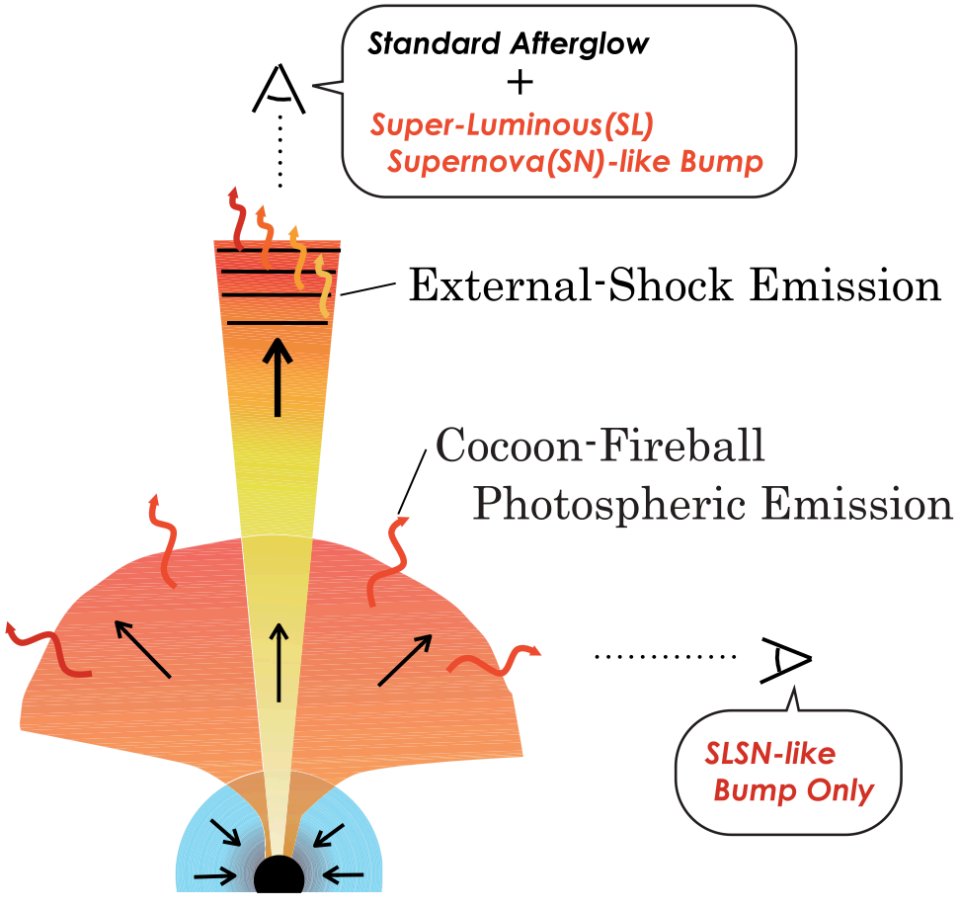
Diversity of GRB



Levan+ 13
Gendre+ 13
Woosley & Heger 12

Cocoon Emission





Blue supergiant (BSG)

$M=75M_\odot$, $Z=1e\text{-}4Z_\odot$, $R=8.6e12$cm

$E_c=1e53$ erg, $M_c=5.8M_\odot$

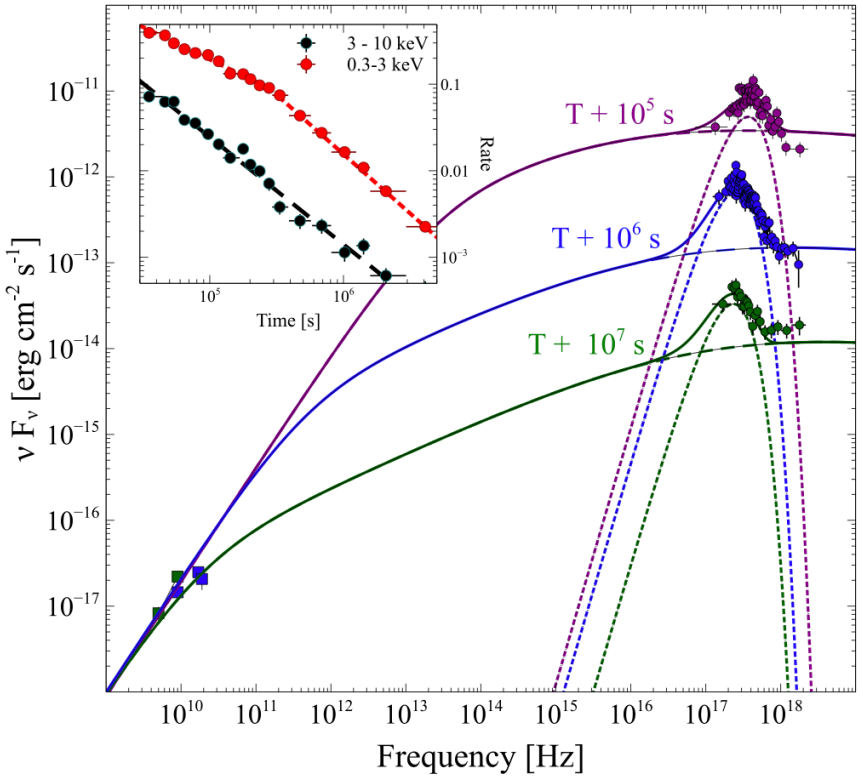
Nakauchi+ 13, 12; Kashiyama+ 13

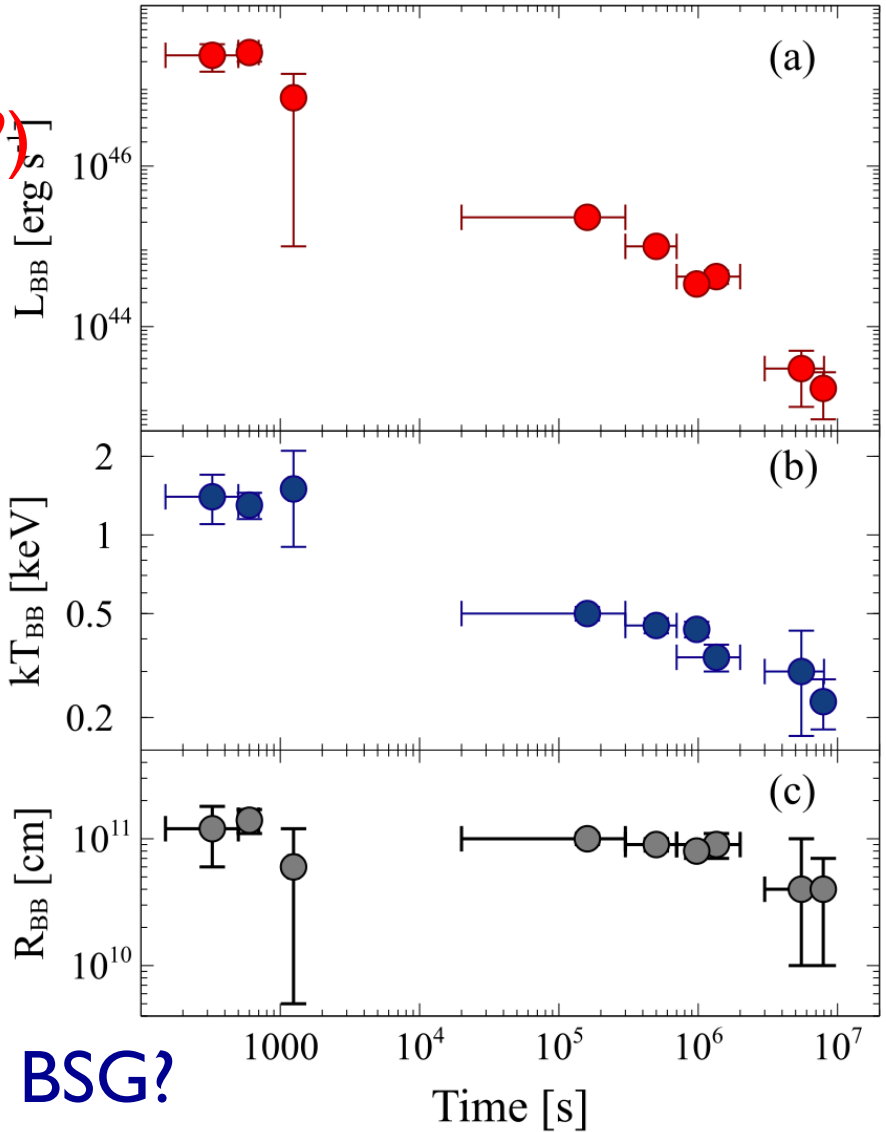
Cocoon thermal emission

≈ Superluminous supernova

Ultralong GRB 130925A

Afterglow in low density wind
+ Thermal component (Cocoon?)

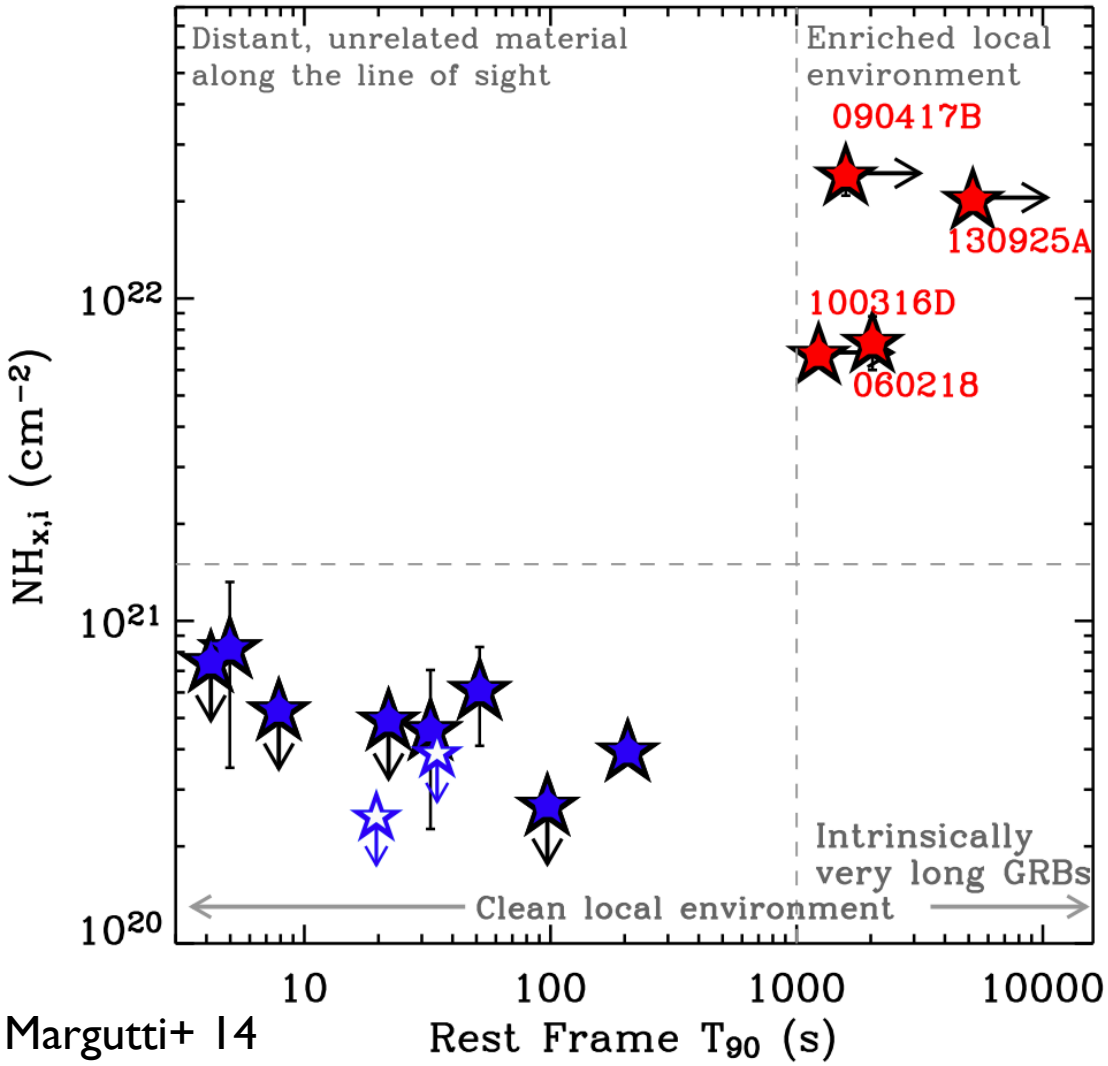




Piro+ 14; Zhao & Shao 14; Evans+ 14

~3e-8$M_\odot$/yr, ~10^3km/s ⇒ Low-Z BSG?

Mass Loss or Large Envelope?



Margutti+ 14

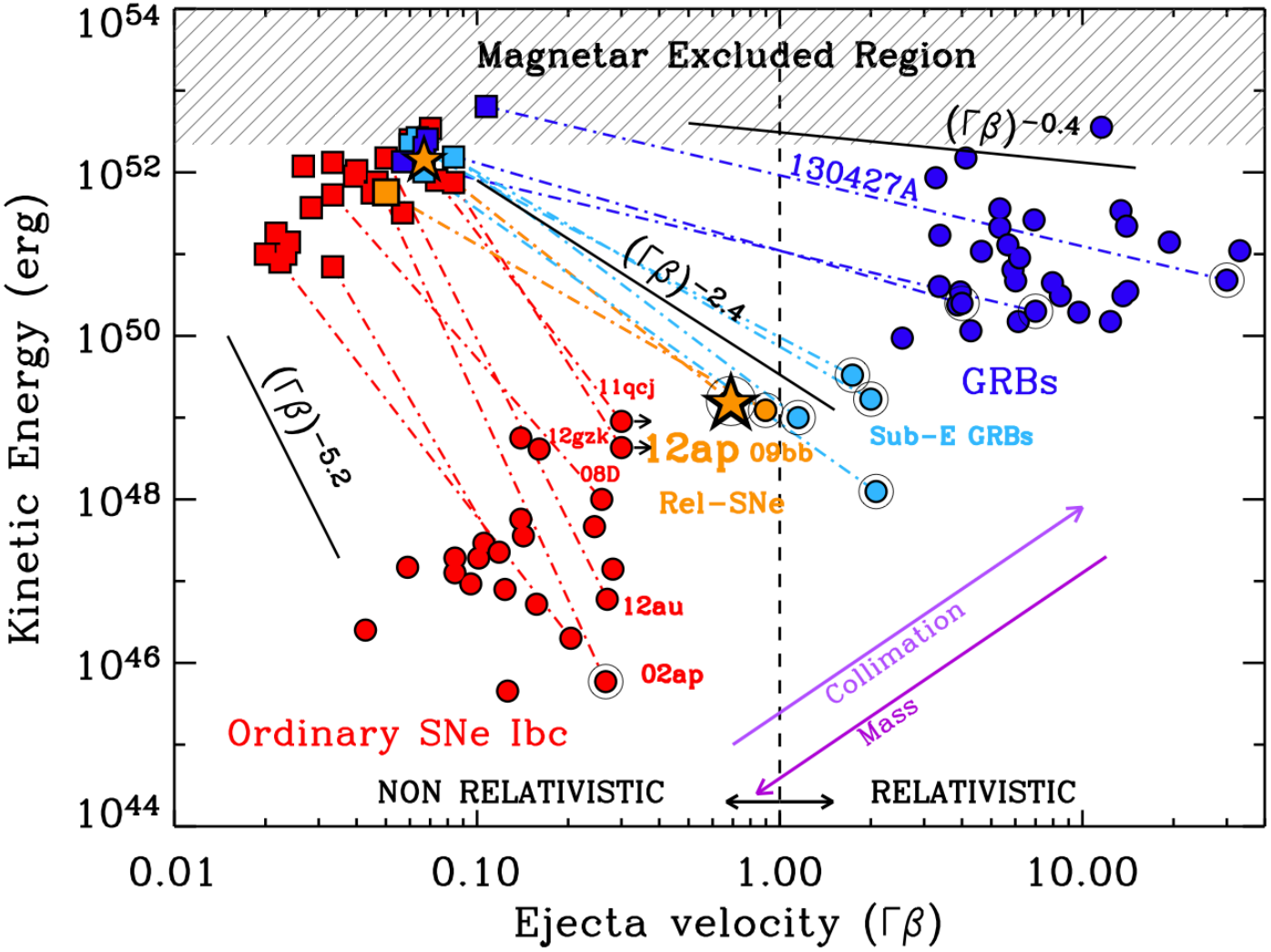
← with super-soft (Γ>3)
late-time (>0.5 days)
X-ray emission
(not external shock)

1. Recent mass loss

⇒ Dust echo (late X) &
Wind-Jet shock (Long T)?

2. Large envelope

Relativistic Supernova = Failed GRB?



GRB-SNIbc gap is being filled

Relativistic SN = Failed GRB?

Short-lived jet?

Large envelope?

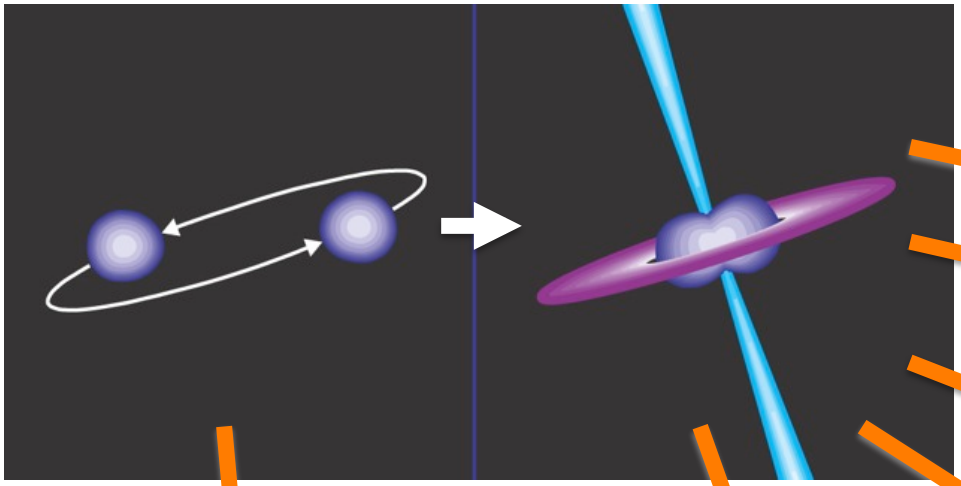
Margutti+ 14

Contents for GRB

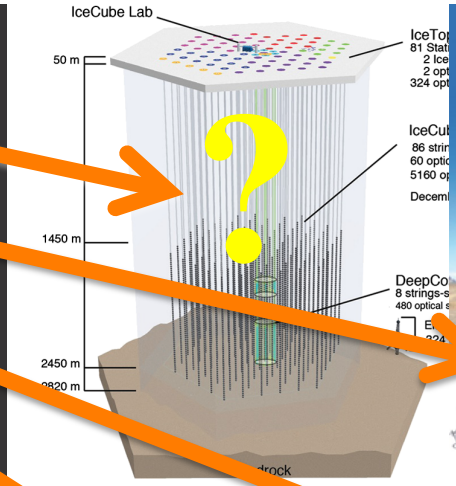
- GRB Cosmology
- Pop III GRB
- Ultralong GRB
- ***Short GRB***
- Other topics

Counterparts to GW

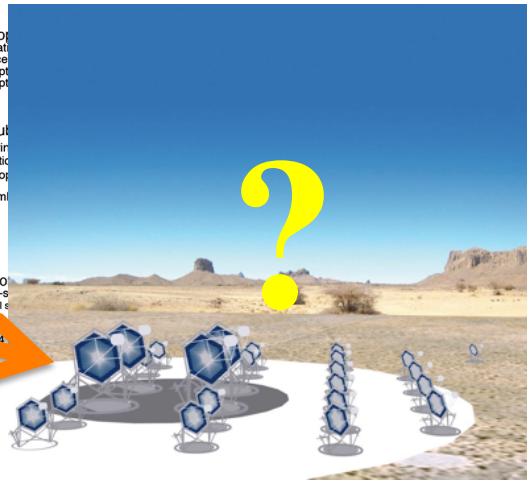
Gravitational Wave Sources

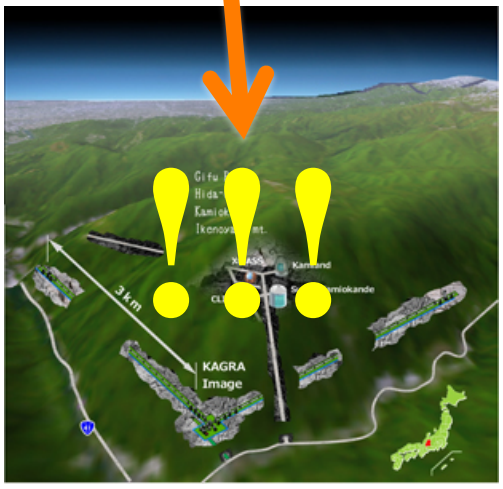


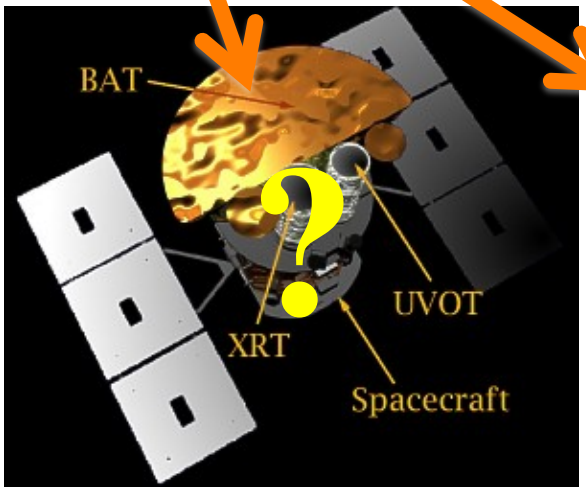
Neutrino



Gamma-ray



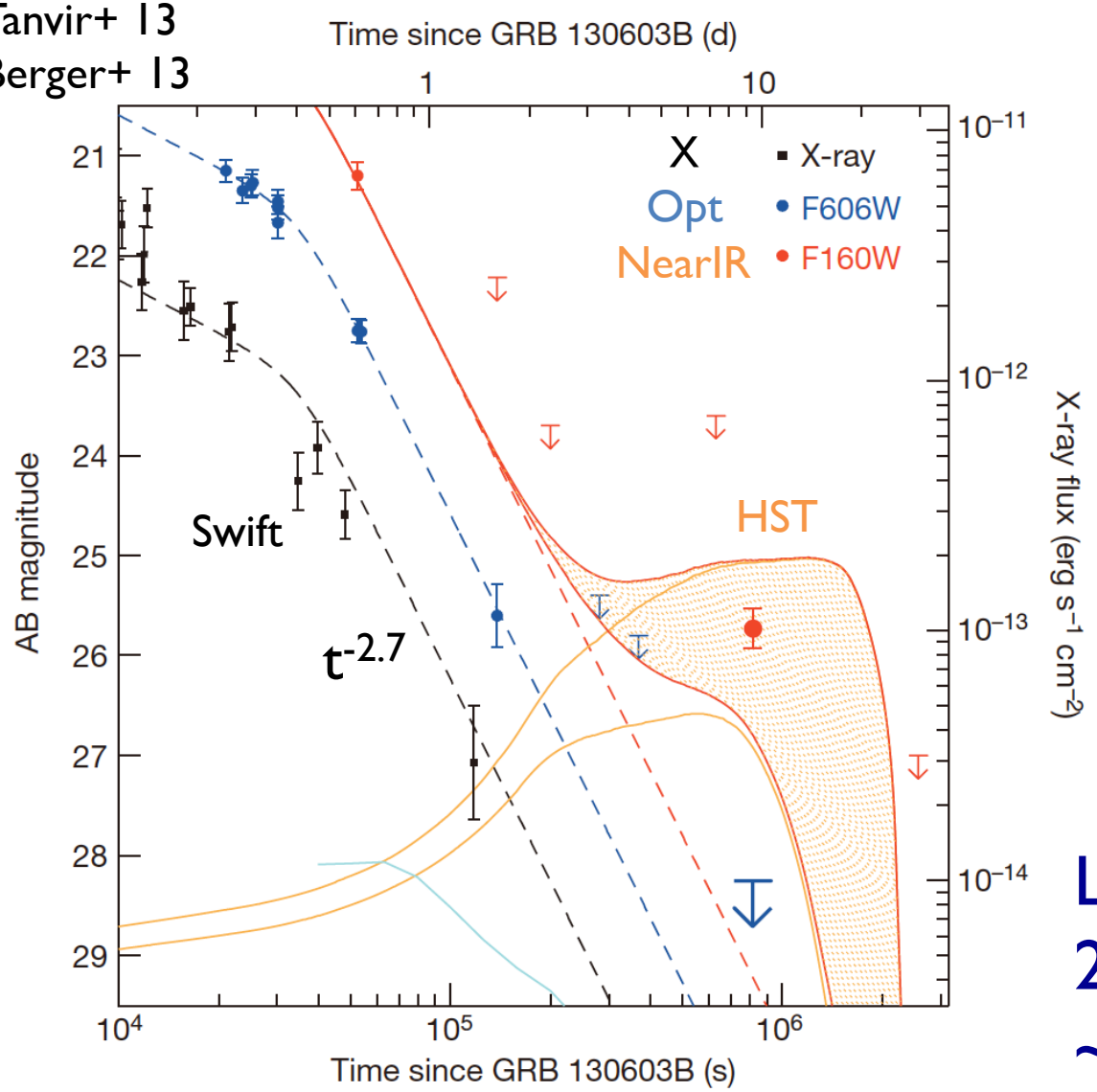




Gravitational wave X-ray IR-Opt Radio

Macro/Kilo/r-Process-Nova?

Tanvir+ 13
Berger+ 13



Ejecta with
~0.01-0.1$M_\odot$
~0.1-0.3c
~10^{50}-10^{52}erg
Radioactivity
$f \sim \varepsilon_r/mc^2 \sim 3e\text{-}6$

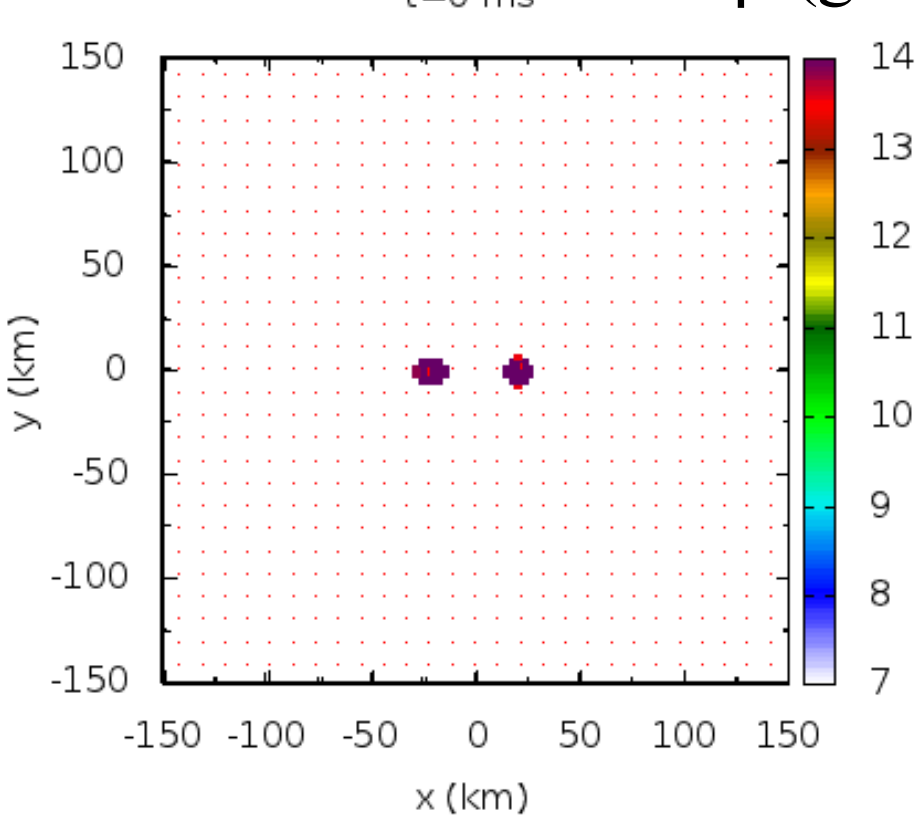
Li & Paczynski 98
Kulkarni 05

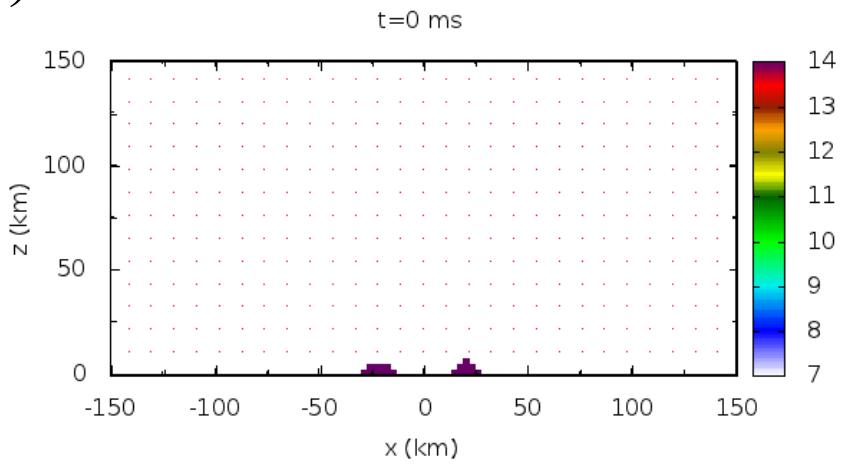
L~10^{41}erg/s @z~0.356
22-23 mag if @200Mpc
~10 days

Merger of 1.3-1.4 M_{sun} NS:

EOS=APR4: stiff but relatively soft

ρ (g/cm^3)





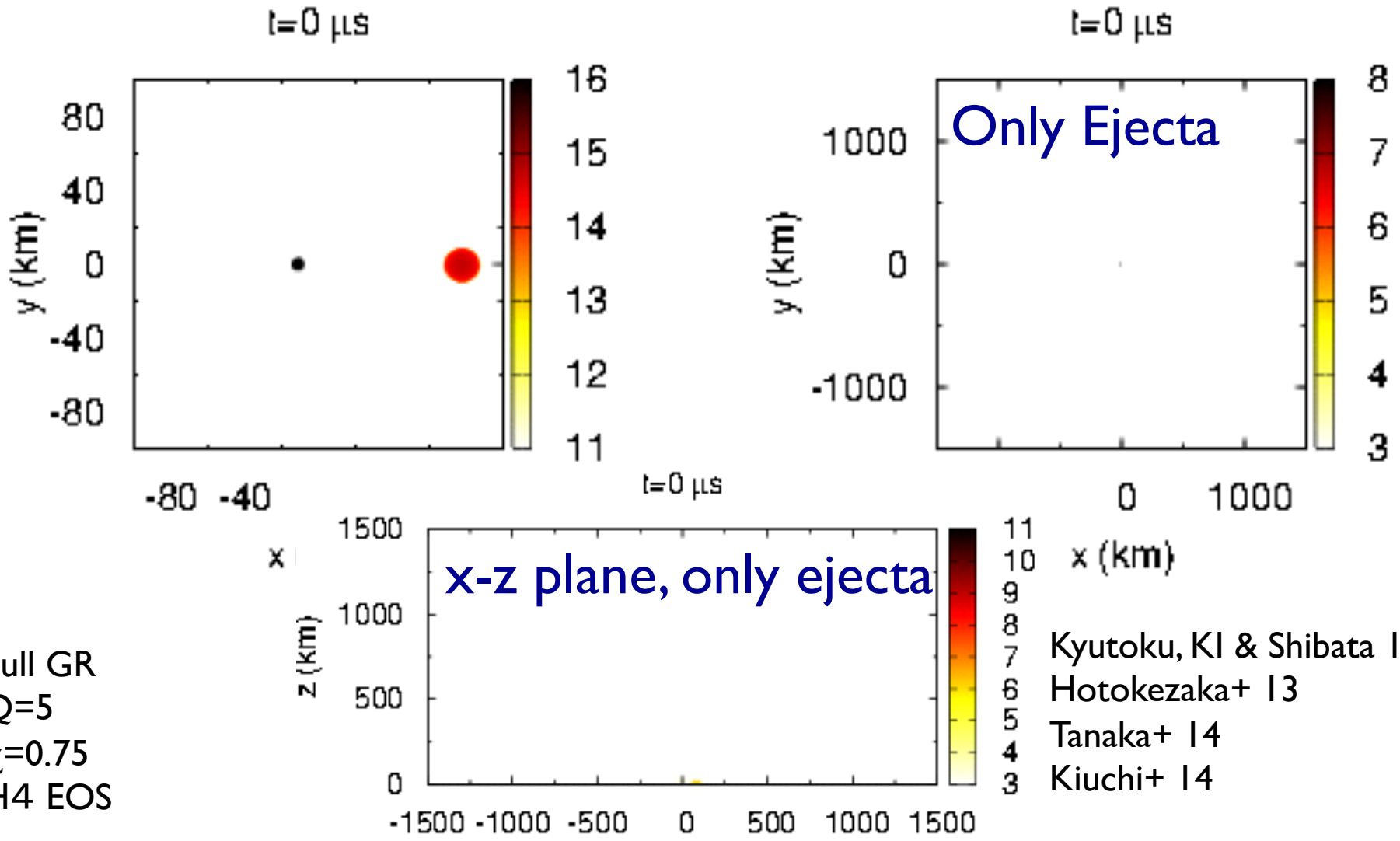
Relatively wider view

Orbital plane

***X-Z* plane**

BH-NS Merger

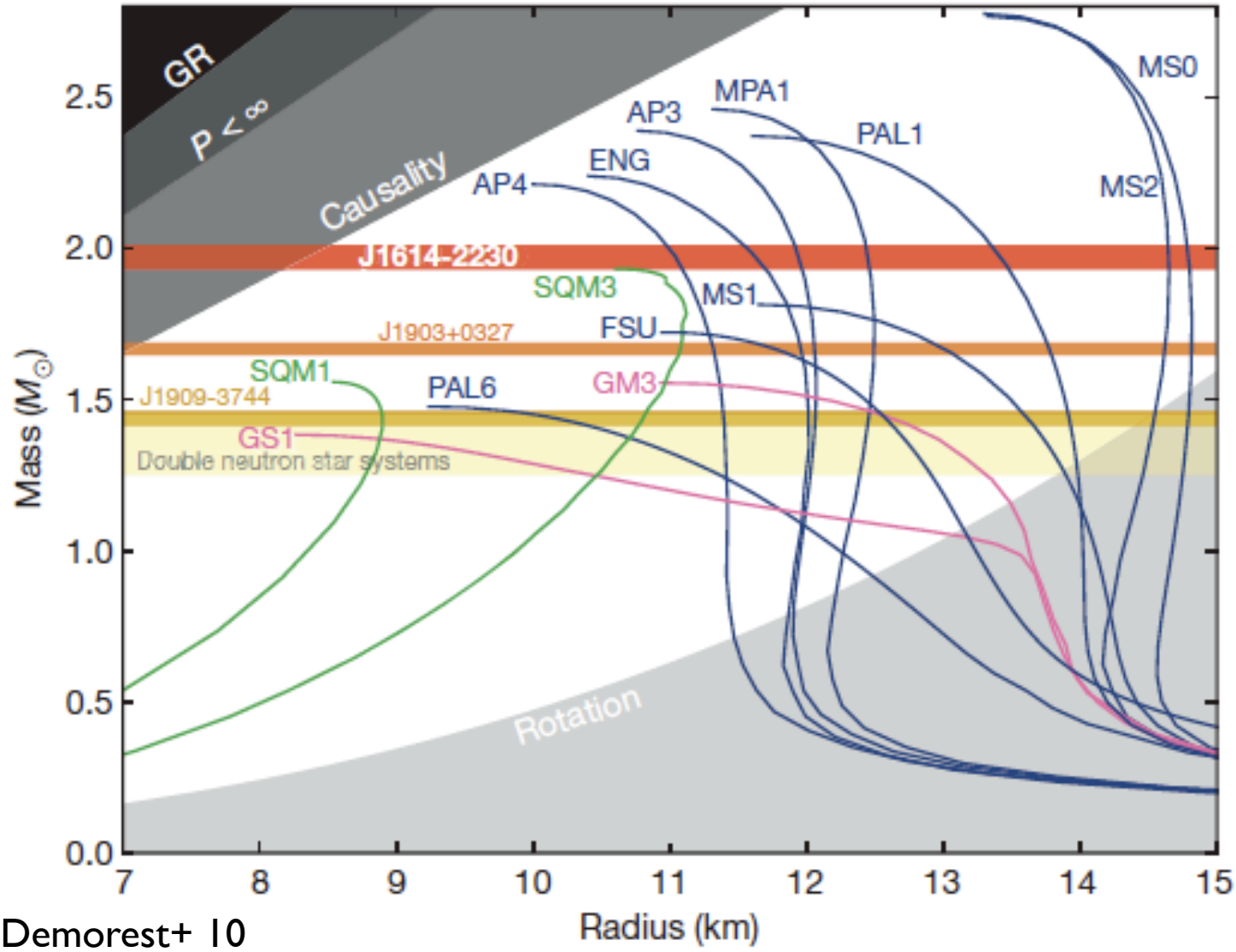
©Kyutoku



Full GR
Q=5
χ=0.75
H4 EOS

Kyutoku, KI & Shibata 13
Hotokezaka+ 13
Tanaka+ 14
Kiuchi+ 14

Maximum Mass



Demorest+ 10

$2M_\odot$

msec NS + $0.5M_\odot$ WD

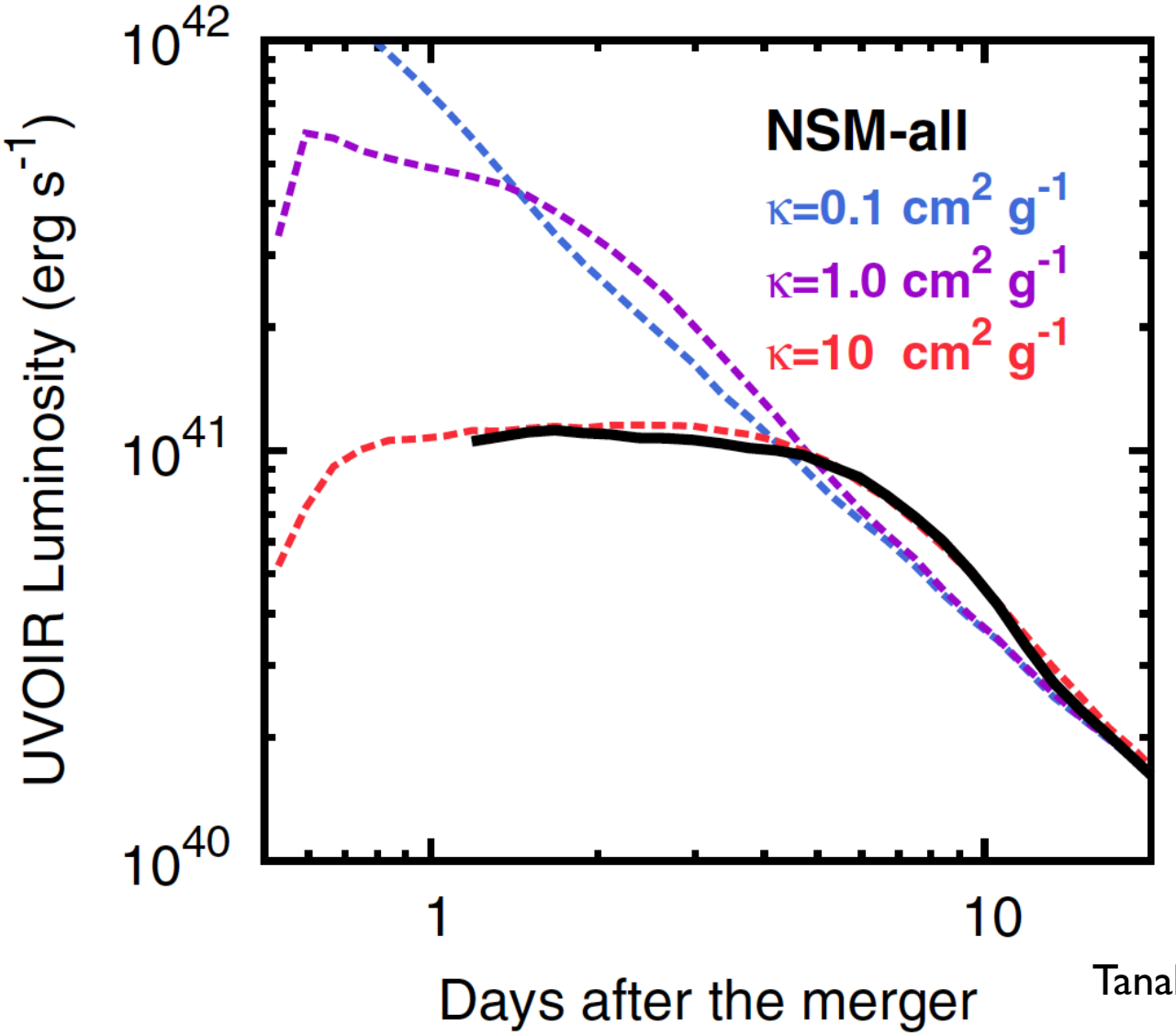
Shapiro delay

$\sim(1.97\pm0.04)M_\odot$

Stiff EOS

(No hyperon?
3-body?
vector force?)

High Opacity



Supernova

Fe

$\kappa \sim 0.1$ cm^2/g

Macronova

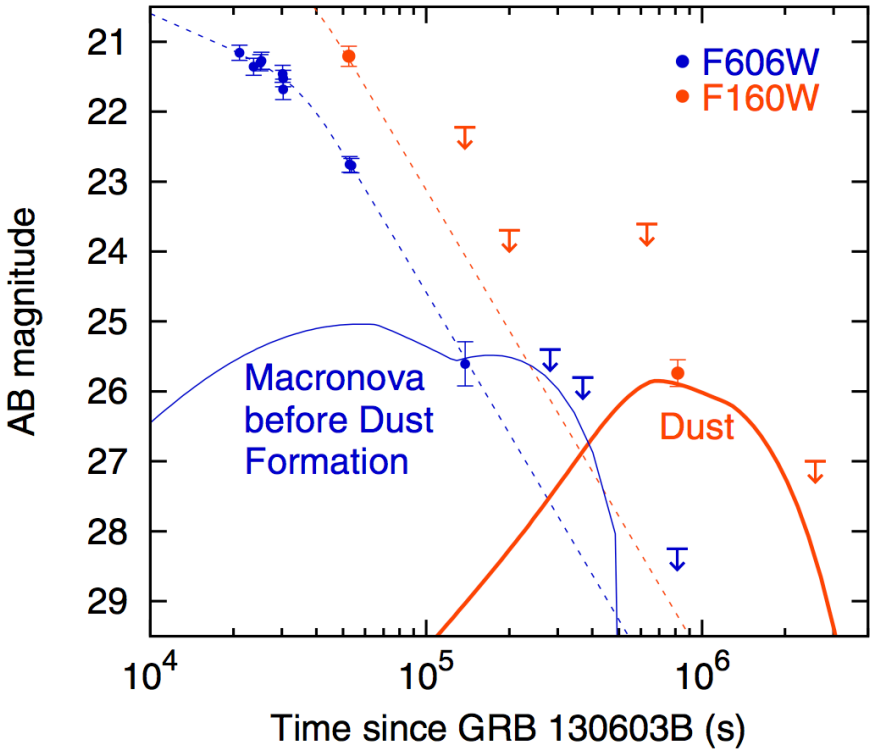
r-process

$\kappa \sim 10$ cm^2/g

Tanaka & Hotokezaka 13

Alternative Models

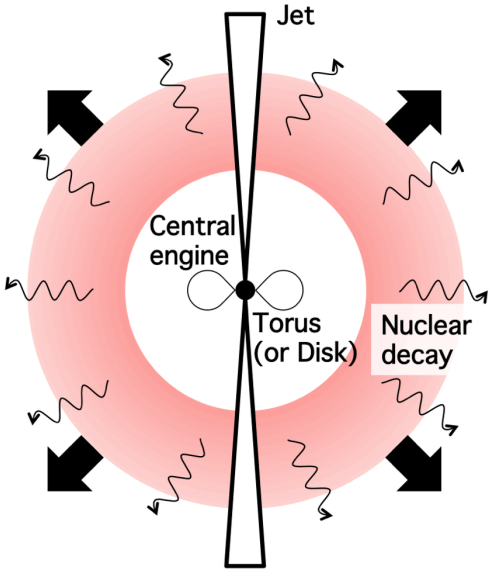
Dust for high opacity?



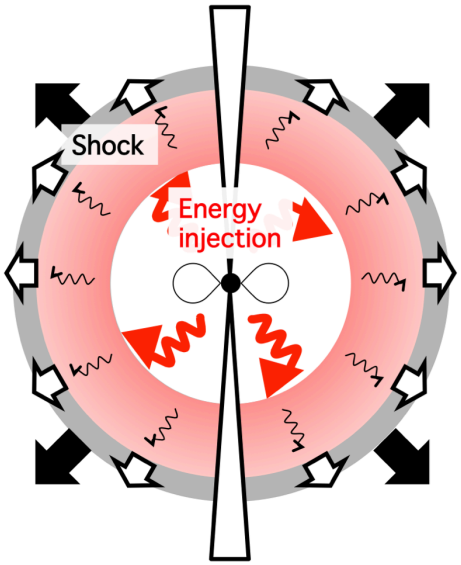
$$\kappa_{geometrical} = \frac{\pi r_{dust}^2}{m_{dust}} \sim \frac{\pi \left(N^{1/3} r_A \right)^2}{N m_A} \sim 10^6 N^{-\frac{1}{3}} \ \mathrm{cm}^2 \ \mathrm{g}^{-1}$$

Takami, Nozawa & KI 14

Engine-Powered?



R-process model



Engine model

$$L \sim \frac{E_{\rm int0}}{t} \left(\frac{t}{t_{\rm inj}} \right)^{-1}$$

$$\sim 10^{41} \left(\frac{E_{\rm int0}}{10^{51}\rm erg} \right) \left(\frac{t_{\rm inj}}{10^2\rm s} \right) \left(\frac{t}{10^6\rm s} \right)^{-2} \ \rm erg\ s^{-1}$$

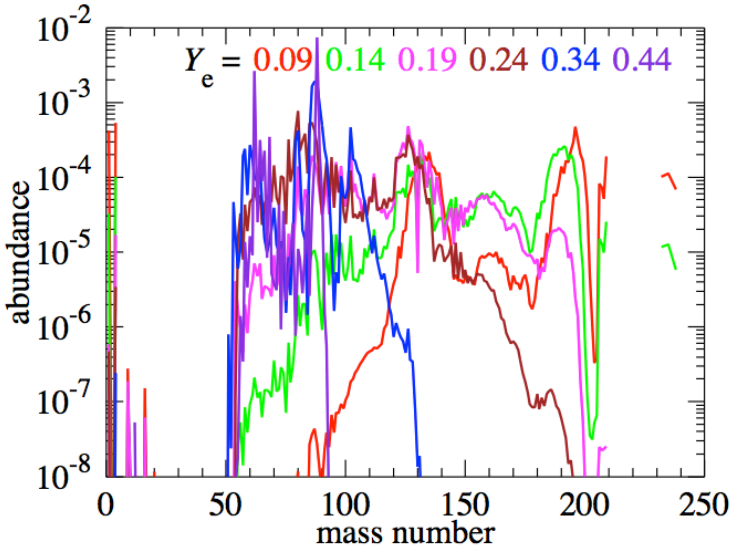
$$T \sim T_0 \left(\frac{t}{t_{\rm inj}} \right)^{-1}$$

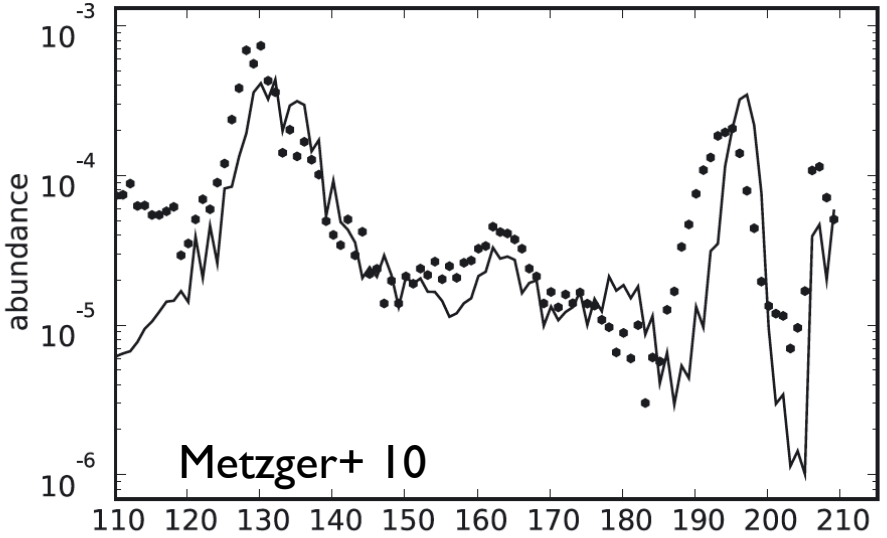
$$\sim 2 \times 10^3 \left(\frac{E_{\rm int0}}{10^{51}\rm erg} \right)^{1/4} \left(\frac{t_{\rm inj}}{10^2\rm s} \right)^{1/4}$$

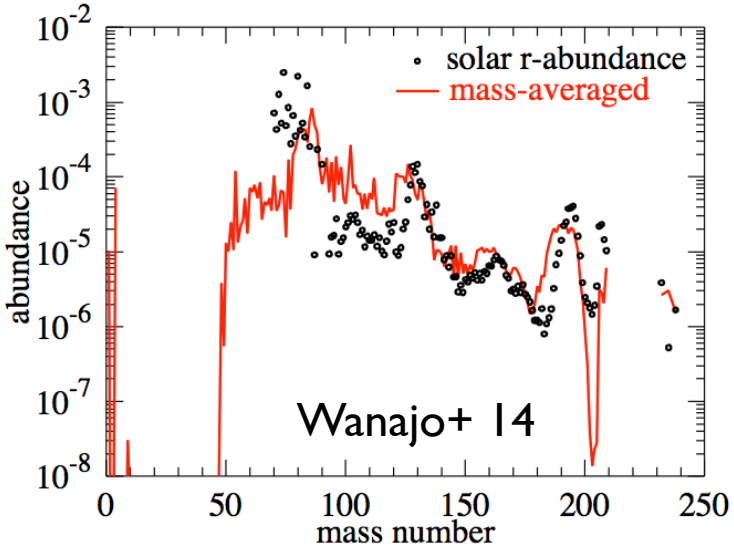
$$\times \left(\frac{v}{10^{10}\rm cm\ s^{-1}} \right)^{-3/4} \left(\frac{t}{10^6\rm s} \right)^{-1} \ \rm K.$$

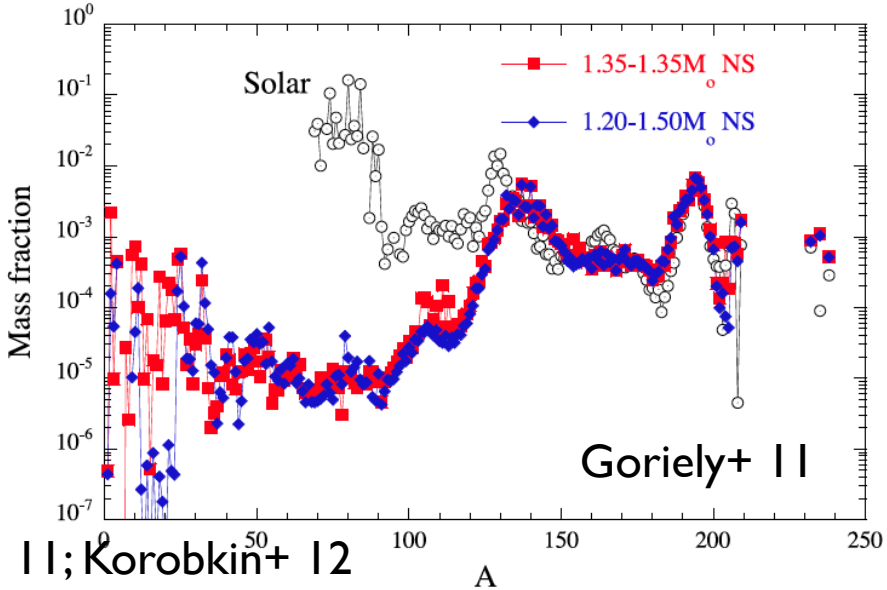
Kisaka, Takami & KI 14

r-Process Nucleosynthesis



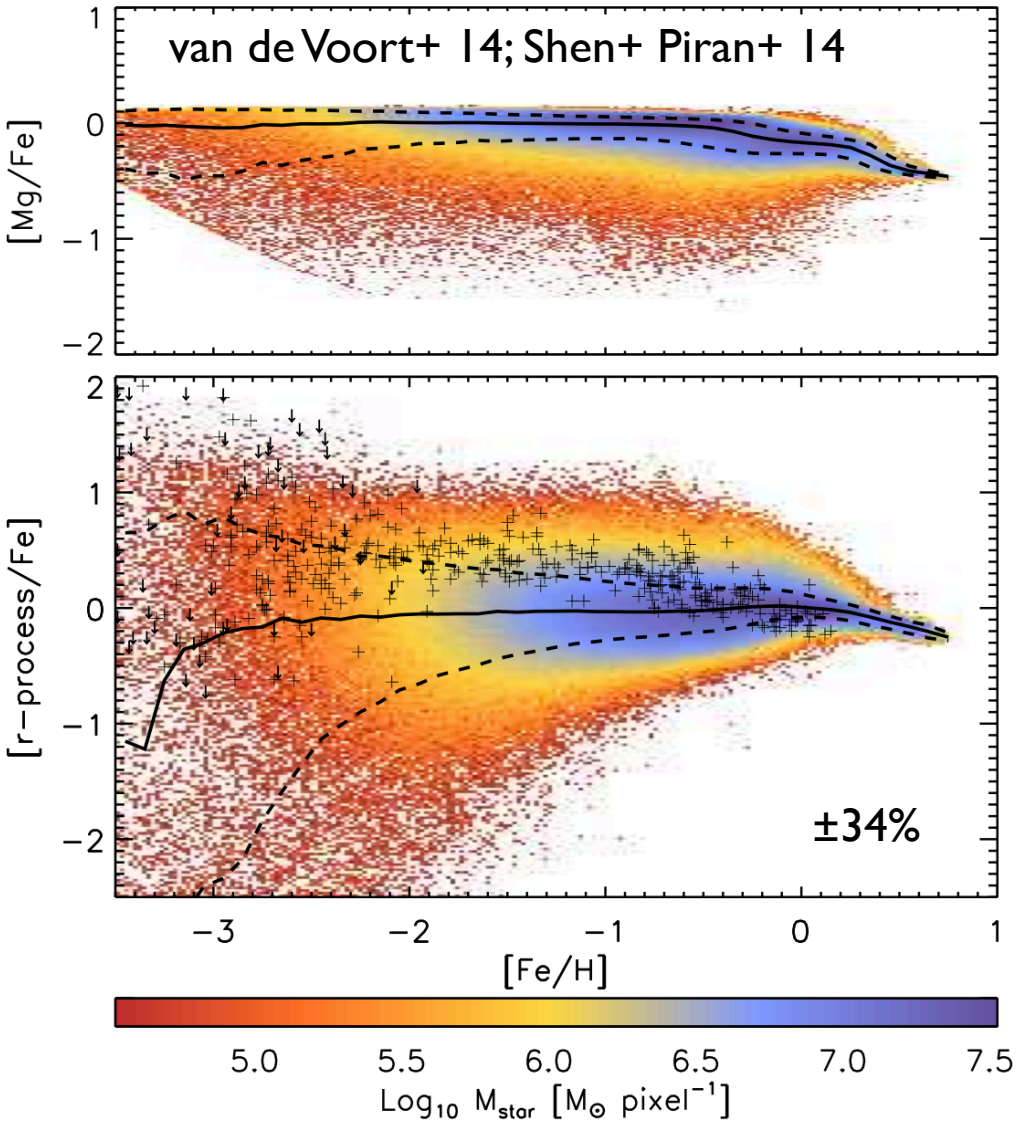






Roberts+ 11; Korobkin+ 12

r-Process Abundance



Cosmological zoom-in simulation FIRE

Fe: Supernova

r-process: NS mergers

Mixing: wind, disk, …

Less scatter in low metal

[r/Fe] decreases at large R_{gal}

Not converged yet at Fe<-2

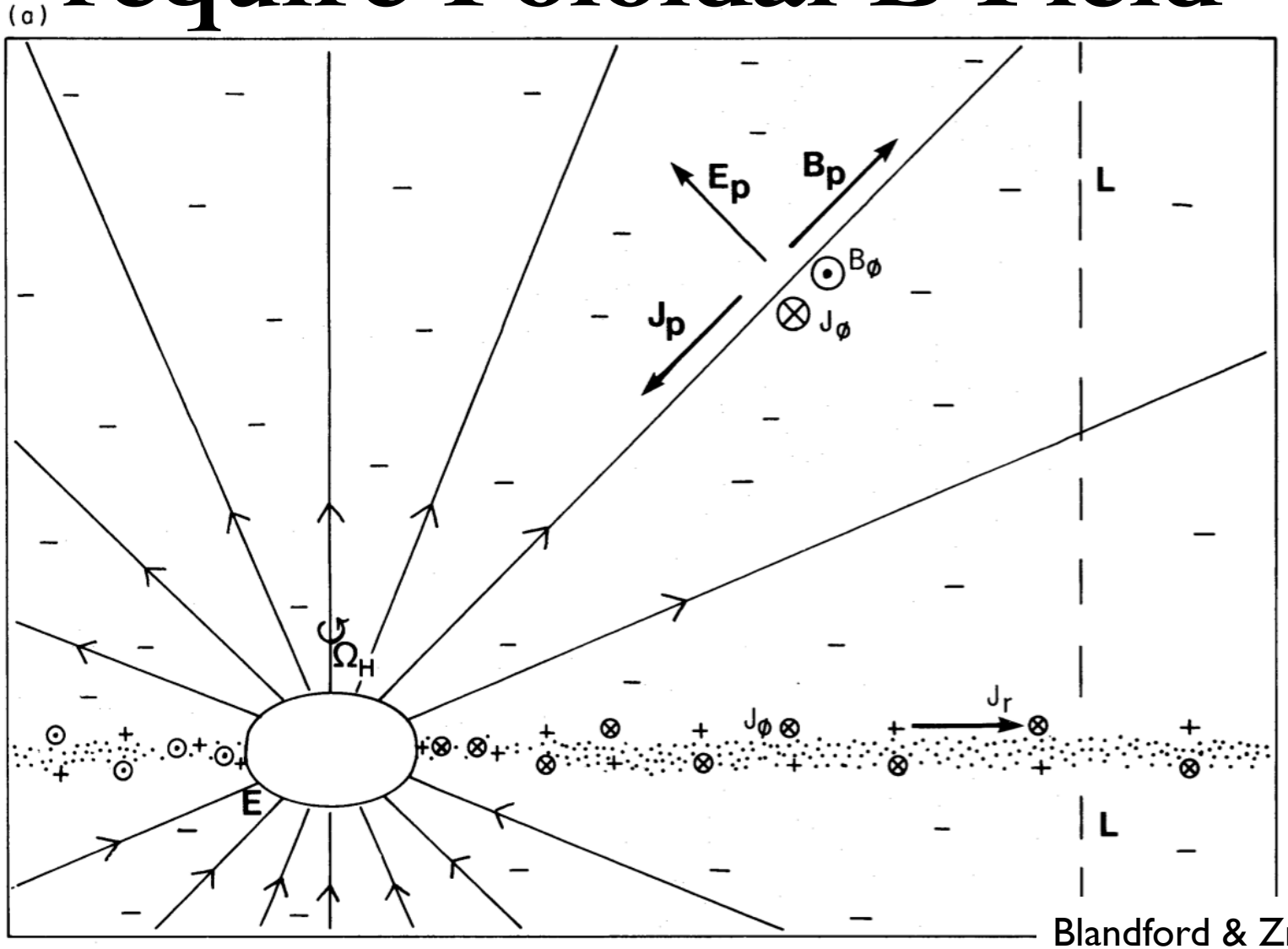
< NS merger uncertainties

(Rate~1e-4/yr, t_{delay}~3e7 yr)

Contents for GRB

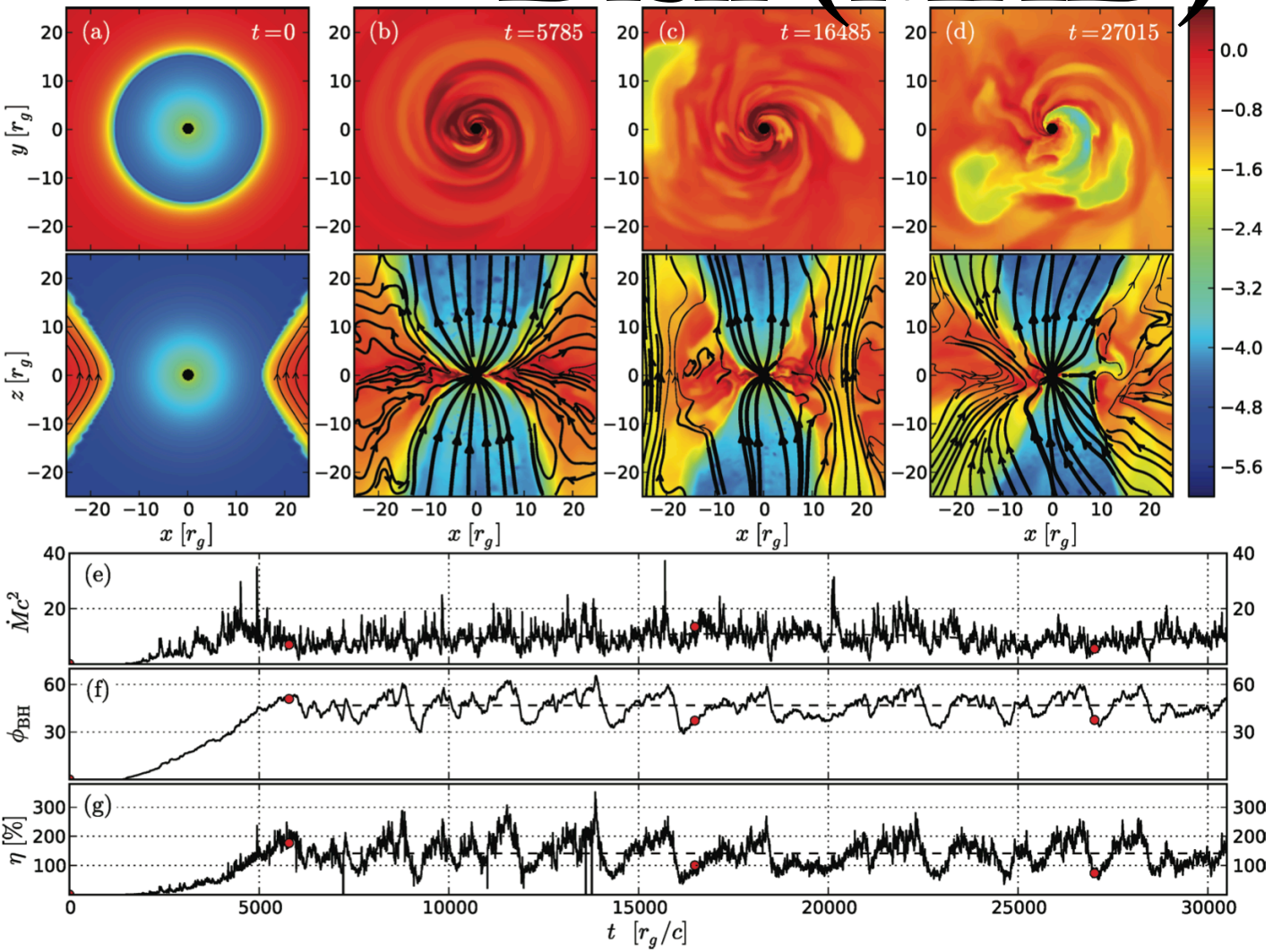
- GRB Cosmology
- Pop III GRB
- Ultralong GRB
- Short GRB
- ***Other topics***

Blandford-Znajek Jets require Poloidal B Field



Blandford & Znajek 77

Magnetically Arrested Disk (MAD)



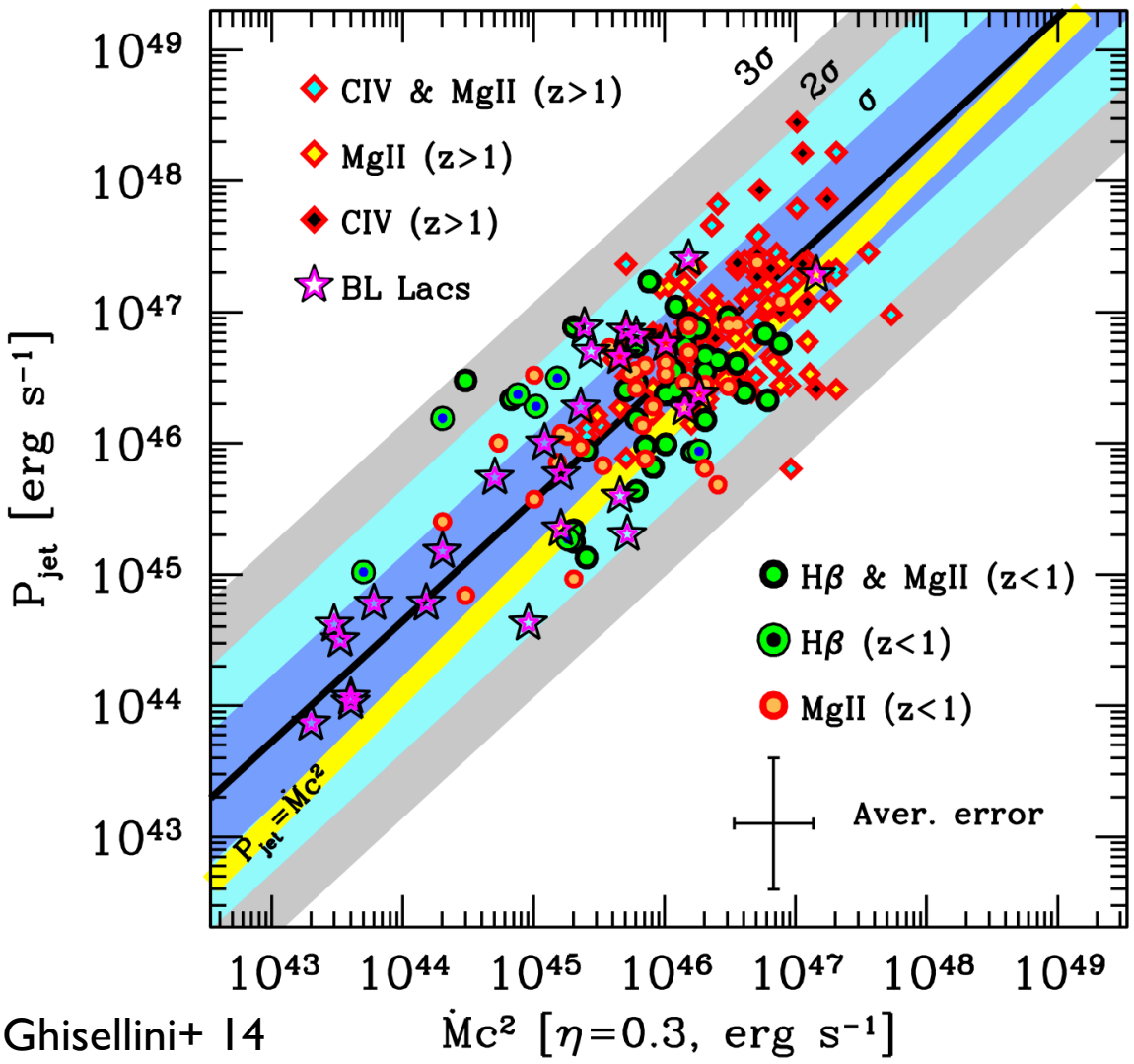
Poloidal
B-dominated
$P_B > P_{gas}$

$P_{jet} > M_{dot}\ c^2$
$\eta > 100\%!!!$

GR-MHD

Tchekhovskoy+ 11
McKinney+ 12
Narayan & Abramowicz 03

Observations of MAD



Ghisellini+ 14

$P_{jet} > M_{dot}c^2$

$\eta = L_{disk}/M_{dot}c^2 = 0.3$

$P_{\rm jet} \approx 10 P_{\rm rad}$

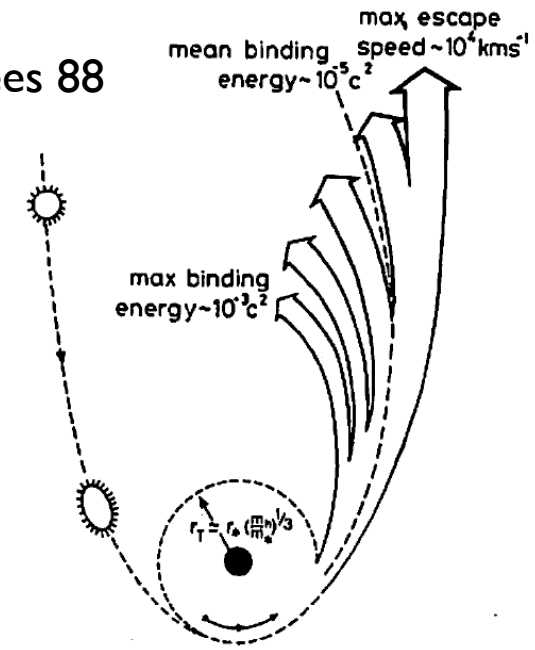
(one p per one e)

$\log(P_{\rm jet}) = 0.92\log(\dot{M}c^2) + 4.09$

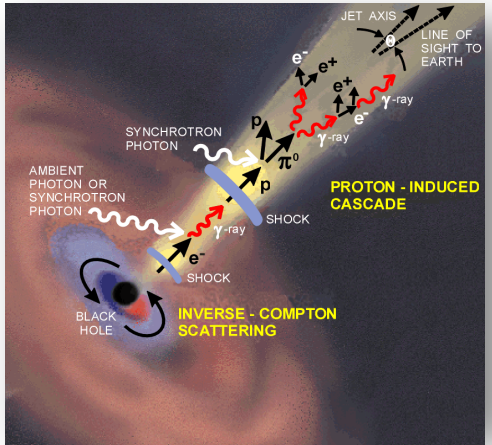
$\sigma = 0.5\,{\rm dex}$

Tidal Disruption Jet

Rees 88

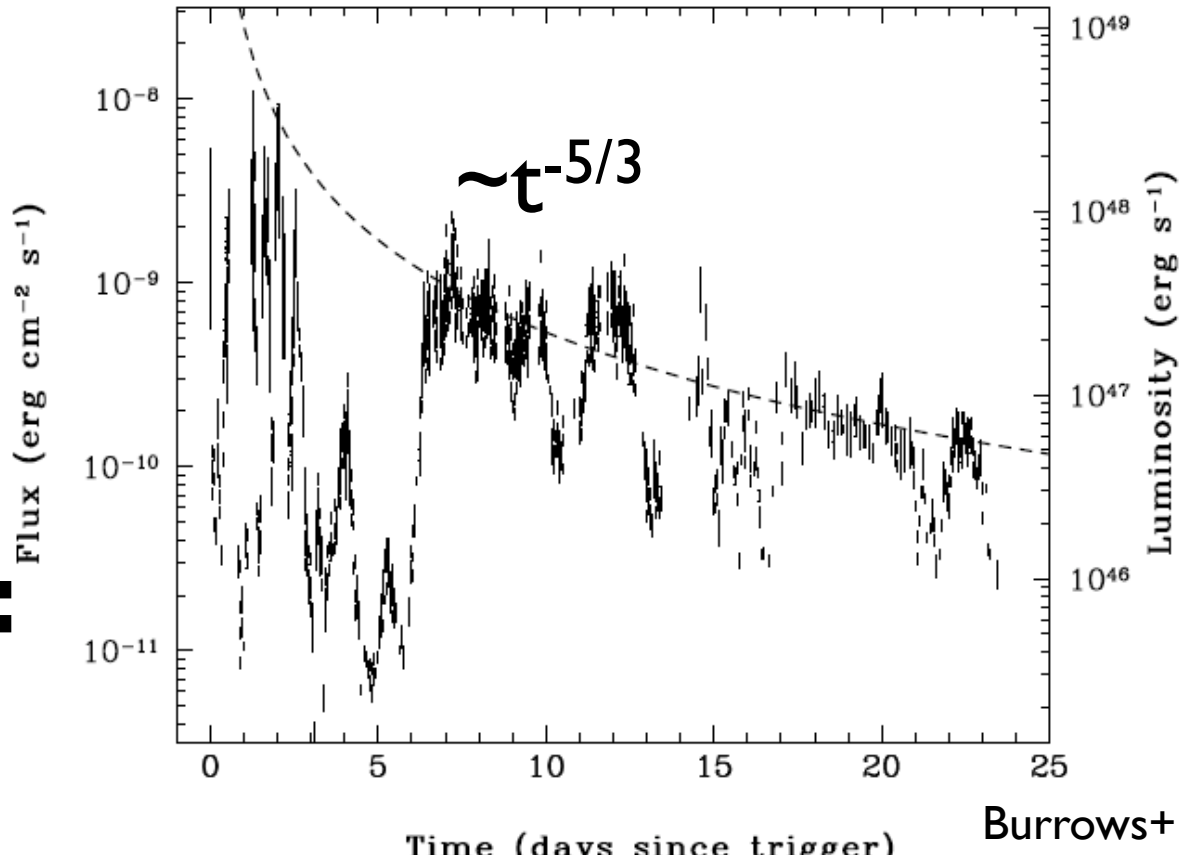


+



=

Massive BH tidally disrupt a star



Burrows+ 11

Jet formation (unexpected)

First 2 PeV νs

PeV=10^{15}eV

"Bert" 8 Aug 2011 3 Jan 2012 "Ernie"

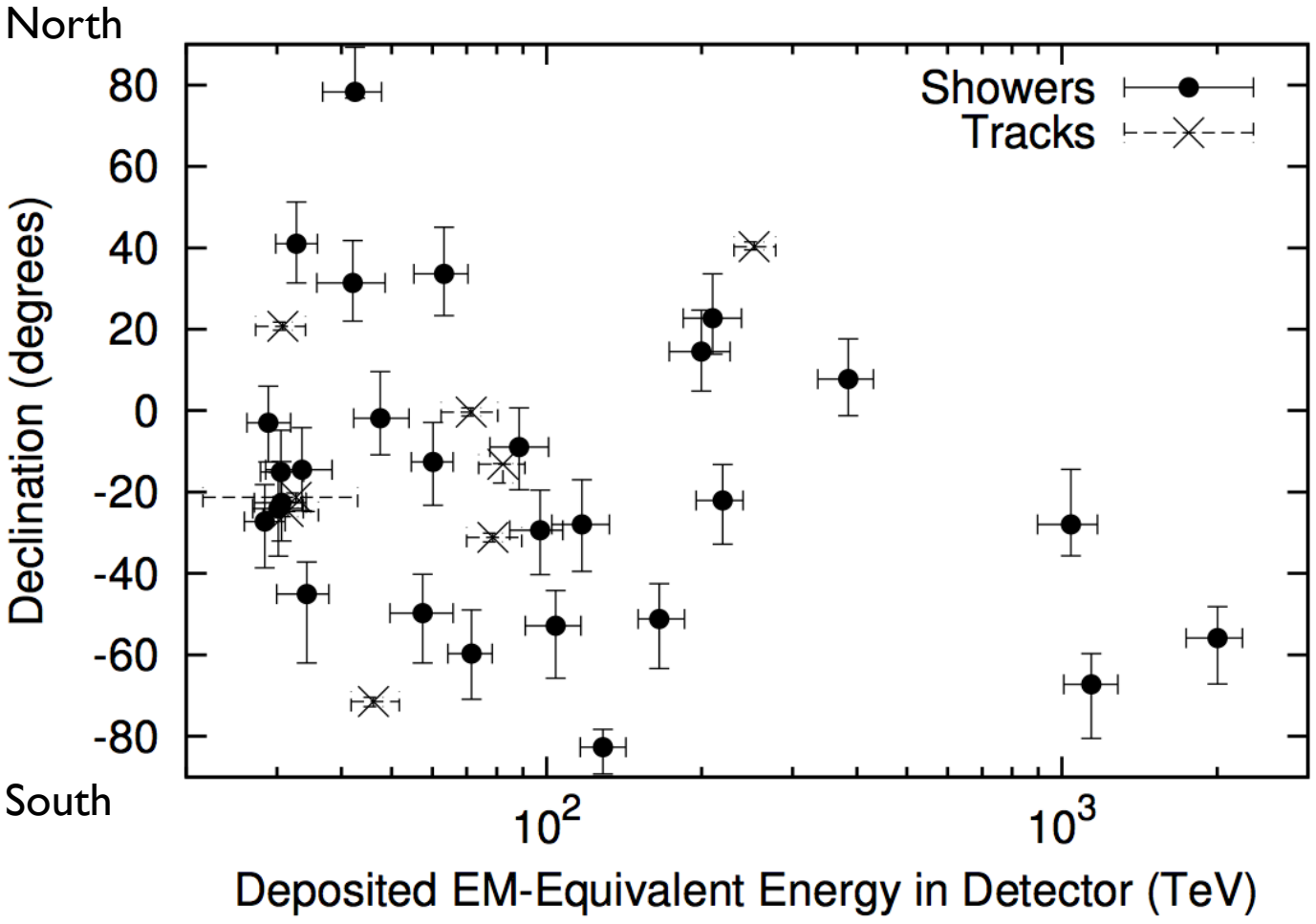
1.04±0.16 PeV 1.14±0.17 PeV

Reported in Kyoto ν 2012

Aartsen+(IceCube), arXiv:1304.5356

Dawn of High-Energy ν Astronomy!!!

More Events



May 2010-May 2011 (79 strings)
May 2011-May 2012 (86 strings)
May 2012-May 2013 (86 strings)
~988 days

Big Bird

IceCube
1405.5303

Reject a purely atmospheric explanation at **5.7σ**

37 (9 μ + 28 showers), Background 8.4±4.2 μ & $6.6^{+5.9}_{-1.6}$ ν

ν from GRBs

$$p\gamma \rightarrow n\pi^+,\ p\pi^0$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

$$\pi^0 \rightarrow \gamma\gamma$$

At Δ-resonance

$$\varepsilon_p \varepsilon_\gamma \approx 0.2\Gamma^2\ \mathrm{GeV}^2$$

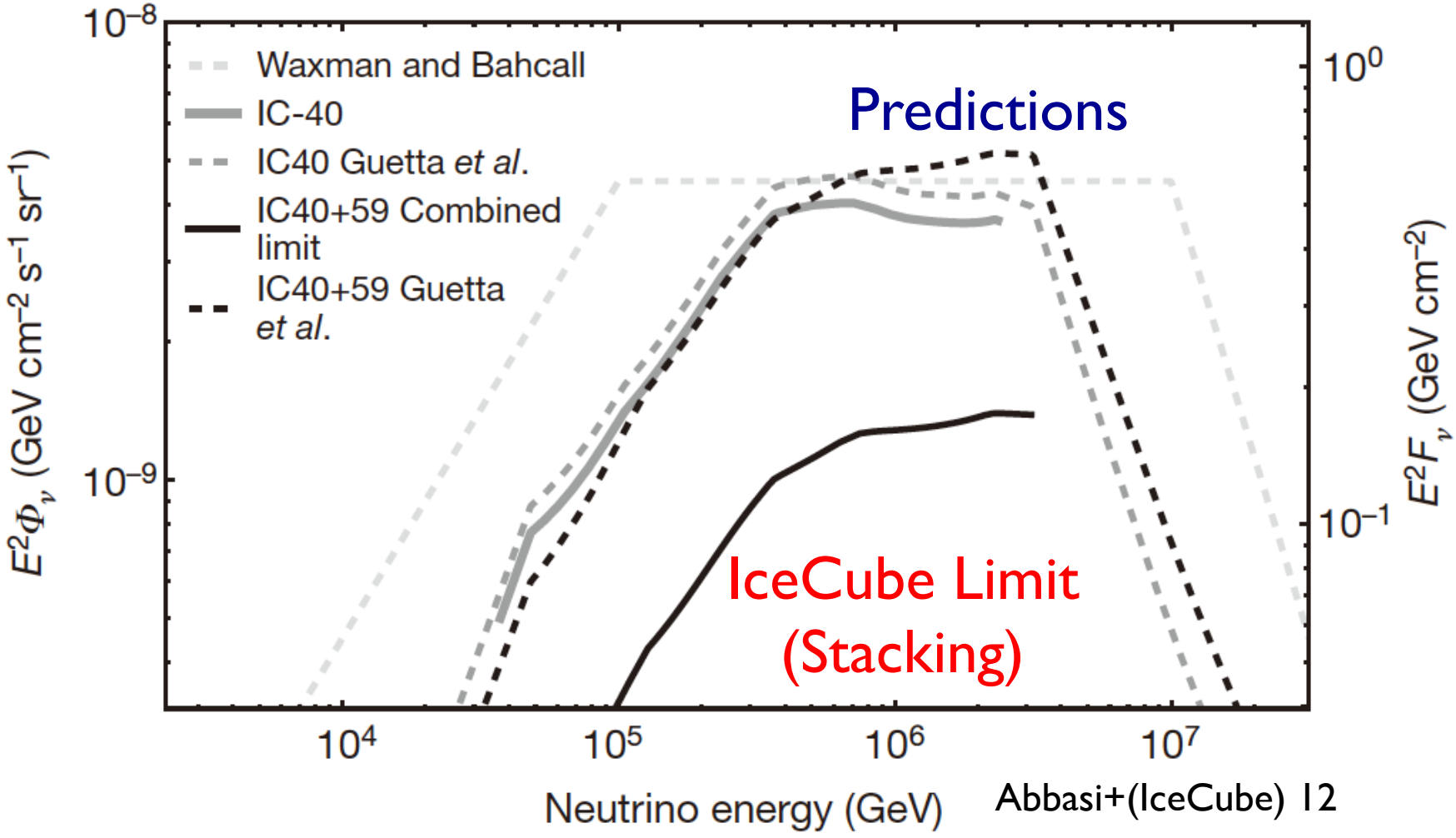
$$\varepsilon_\nu \approx 0.05\varepsilon_p$$

ε_γ~1MeV, Γ~1000 (from obs.)

$\Rightarrow \varepsilon_p$~$10^{17}$eV $\Rightarrow \varepsilon_\nu$~PeV

pγ efficiency can be $f_{p\gamma}$~O(1) [for $\sigma_{p\gamma}$~3×10^{-28}cm^2]

Limits on ν from GRBs



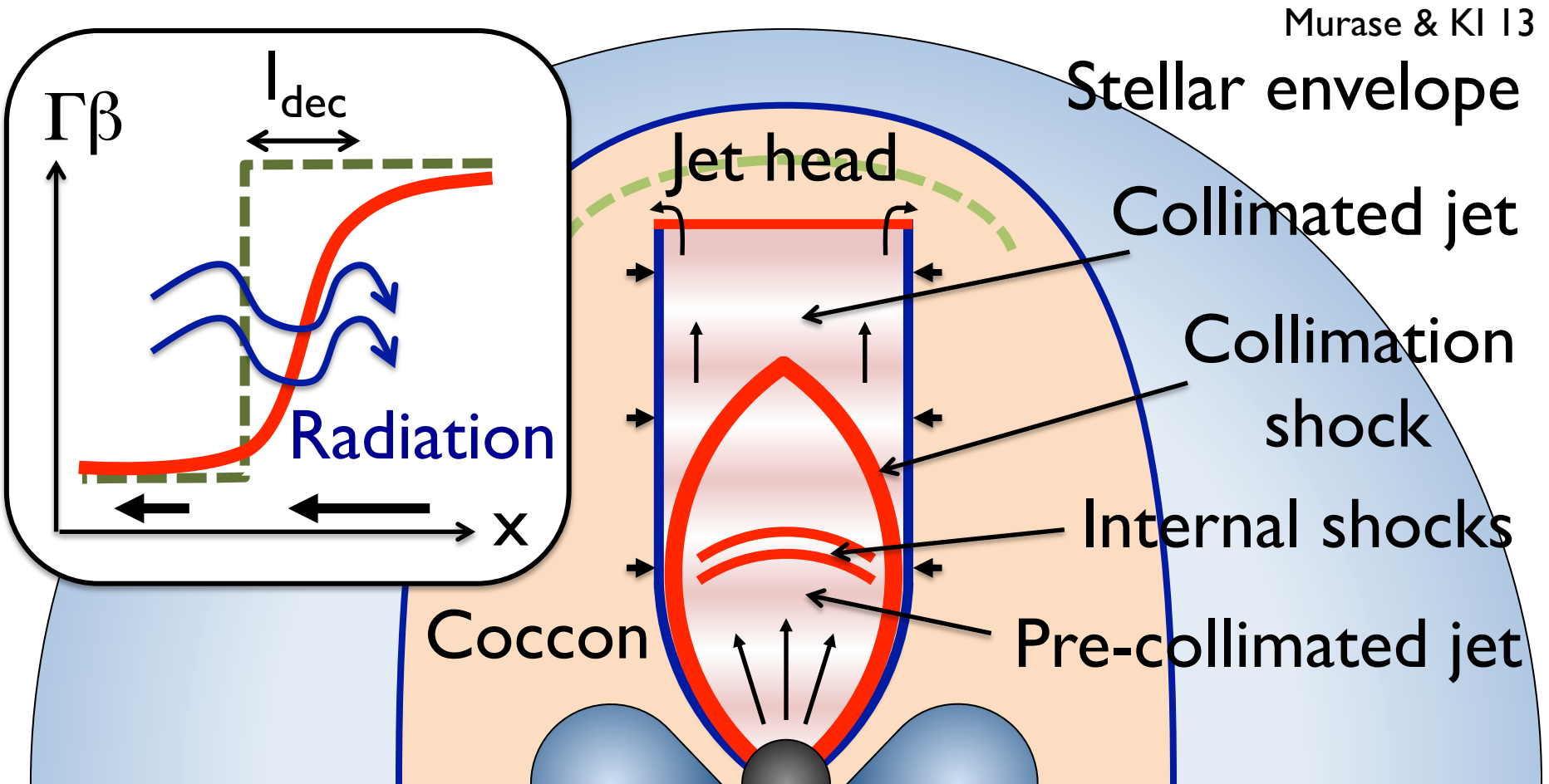
Abbasi+(IceCube) 12

GRBs ≠ PeV ν Sources? ~10^{-8}GeV cm^{-2} s^{-1} sr^{-1}

GRB inside a Star?

Low-power GRB (Low-luminosity GRB, Ultra-long GRB)

Cutoff by E_{max}, π/μ Cooling, or Absorption by envelope



Contents

- ***GRB***
  - GRB Cosmology
  - Pop III GRB
  - Ultralong GRB
  - Short GRB
  - Other topics
- ***FRB***
  - Possible origins
  - Real cosmic signal?
  - Galactic?
  - FRB cosmology

Cosmic Transients for Probing High-z!

Thank You

Localization

- Single dish
  - ~(c/GHz)x(64 m)$^{-1}$>0.1 deg
- Long-baseline Interferometer
  - Not yet
  - will prove the extragalactic origin
  - will improve the counterpart searches

Table 1. Observed properties of FRB 140514

Event date UTC	14 May, 2014
Event time UTC, $\nu_{1.4\ \mathrm{GHz}}$	17:14:11.06
Event time, ν_∞	17:14:09.83
Local date AEST	15 May, 2014
Local time AEST	03:14:11.06
RA	22:34:06.2
Dec	−12:18:46.5
(ℓ,b)	(50.8°, −54.6°)
Beam diameter	14.4′
$\mathrm{DM_{FRB}}$ (pc cm^{-3})	562.7(6)
$\mathrm{DM_{MW}}$ (pc cm^{-3})	34.9
Detection S/N	16(1)
Observed width, Δt (ms)	$2.8\ ^{+3.5}_{-0.7}$
Scattering timescale, $\tau_{1\mathrm{GHz}}$ (ms)	5.4(1)
Dispersion index, α	-2.000(4)
Peak flux density, $S_{\nu,1400\mathrm{MHz}}$ (Jy)	$0.47\ ^{+0.11}_{-0.08}$
Fluence, $\mathcal{F}$ (Jy ms)	$1.3\ ^{+2.3}_{-0.5}$

Table 2. Derived cosmological properties of FRB 140514

z	$< 0.44(1)$
Co-moving distance (Gpc)	$< 1.71(3)$
Luminosity distance (Gpc)	$< 2.46^{+0.04}_{-0.06}$
Energy (erg)	$< 3.7^{+4.7}_{-2.0} \times 10^{38}$
Distance modulus (mag)	< 42.2

Luminosity-Rise time

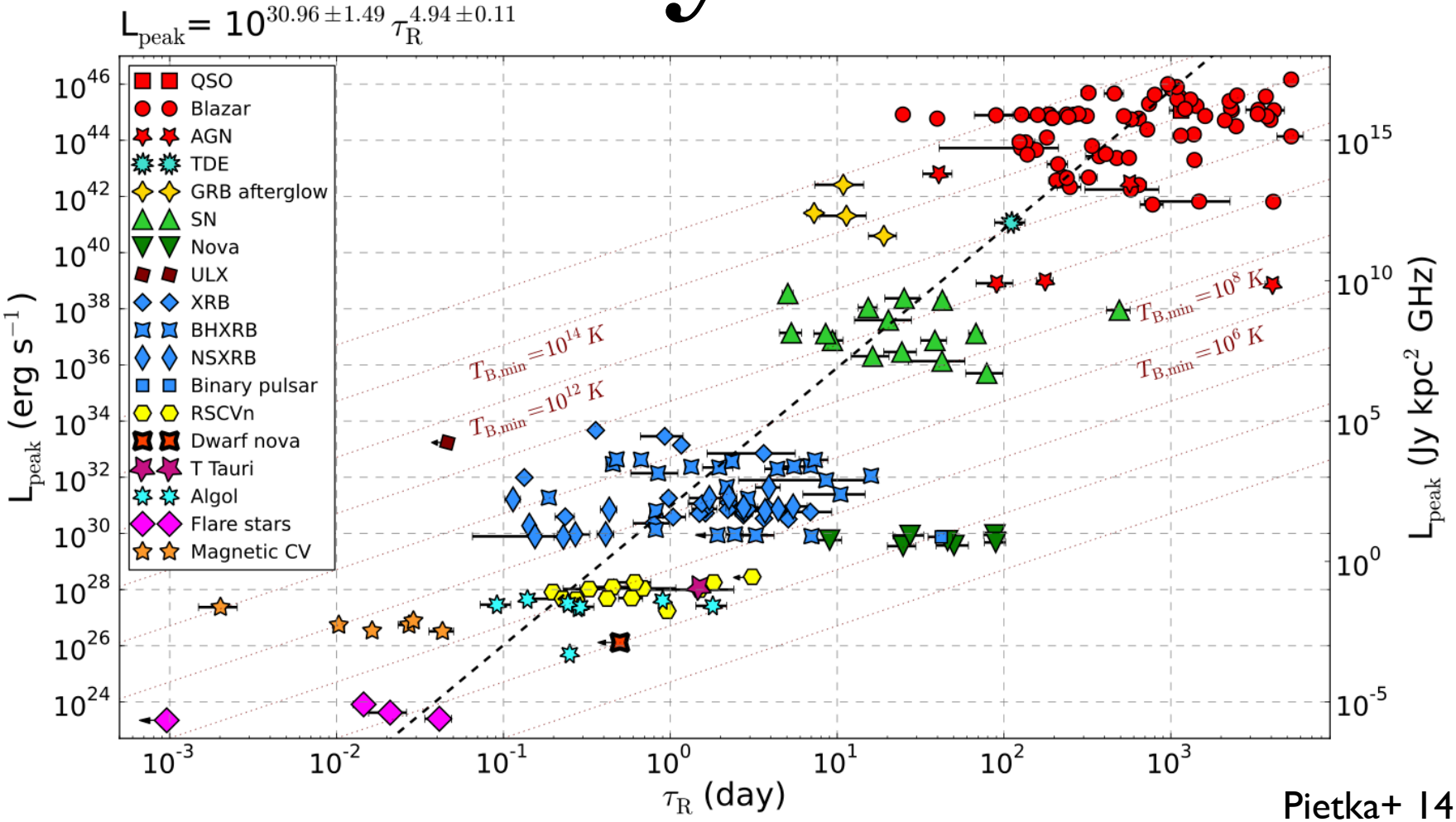


Figure 3. Exponential rise timescale as a function of peak radio luminosity for the entire set of radio flares studied. The overall relation is of the form $L \propto \tau^{4.94 \pm 0.11}$. Overplotted are lines corresponding to a fixed minimum brightness temperature ($T_{B,min}$), under the assumption that the size of the emitting region $r = c\tau$, which have a form $L \propto \tau^2$, demonstrating clearly that $T_{B,min}$ is an increasing function of luminosity, peaking just above the theoretical limit of 10^{12}K for the most luminous AGN (which are also likely to be beamed).

Brightness Temperature

$$F_\nu = \frac{\pi r_\perp^2}{d^2}\frac{2\nu^2}{c^2}kT$$

$$T \sim 3\times10^{41}\,\mathrm{K}\; L_{43} r_{emi,10}^{-2}$$

⇒ Coherent emission

$P \sim |E|^2 \sim |E_1+E_2+E_3+\ldots+E_N|^2$
$\sim N|E_1|^2$ (incoherent)
$\sim N^2|E_1|^2$ (coherent)

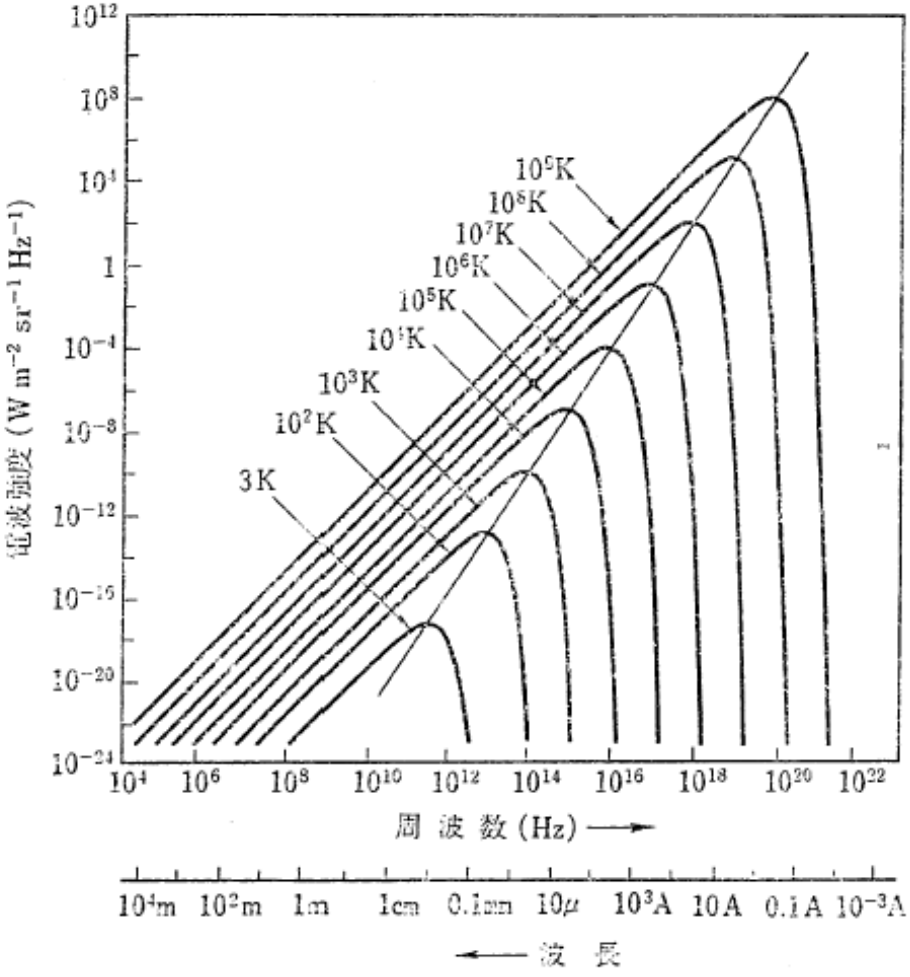


図 2·6 熱放射（プランク放射）の強度スペクトル

FRB 010621 is Galactic?

Bannister & Madsen 14

- Keane FRB 010621
- Galactic?
- H_α, H_β towards FRB

⇒ Emission measure (with dust correction)

⇒ Contribution to DM

⇒ Galactic

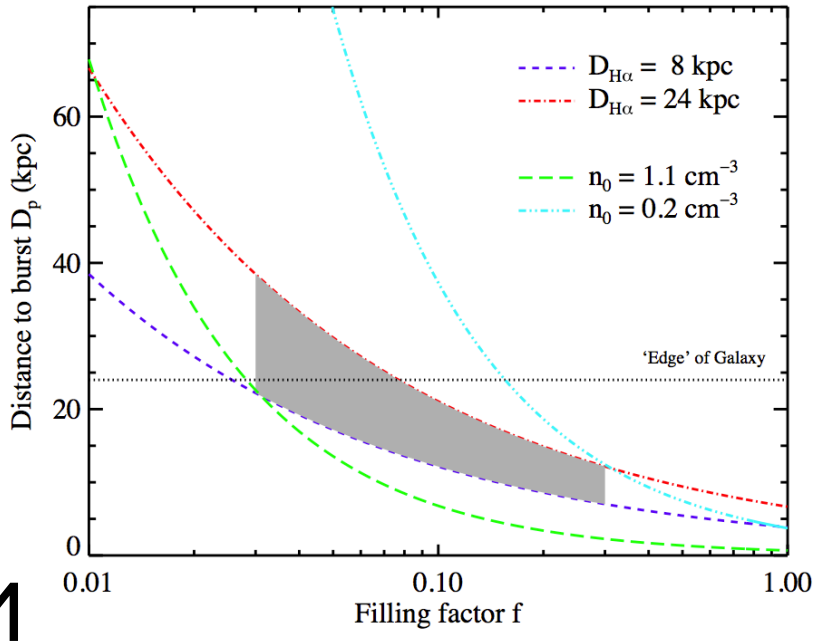
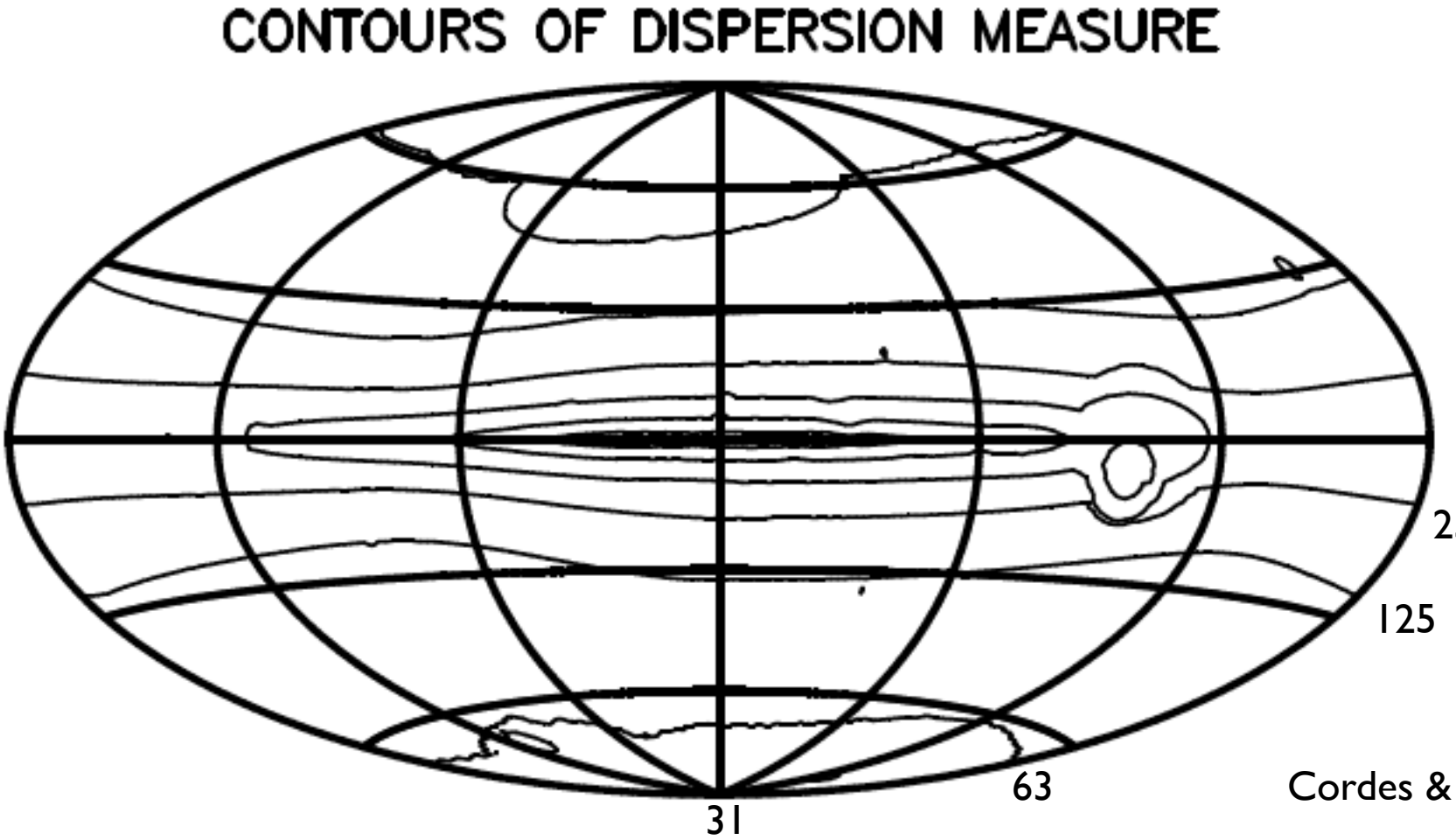


Figure 2. Distance to the burst as a function of filling factor of the ionised gas using an extinction corrected EM of 276 cm^{-6}pc. The grey shaded area shows the range of possible values of D_p bounded by 8 kpc $< D_{H\alpha} <$ 24 kpc and $0.03 < f < 0.30$. The black horizontal dotted line is placed at the canonical 'edge' of the Galaxy along the line of sight to the burst (24 kpc). The lower and upper limits on the average electron density over the corresponding range of values of D_p are $0.2 < n < 1.1$; lines with these values of constant density are shown in aqua and green, respectively.



Cordes & Lazio 02

FIG. 15.— Contours of DM integrated to infinite distance and plotted against Galactic latitude and longitude on an Aitoff projection with the Galactic center in the middle and negative longitudes to the right. Contours are at $4000/2^n$ pc cm^{-3} for $n = 0, 1, \ldots, 7$, with the lowest contour at the Galactic poles.

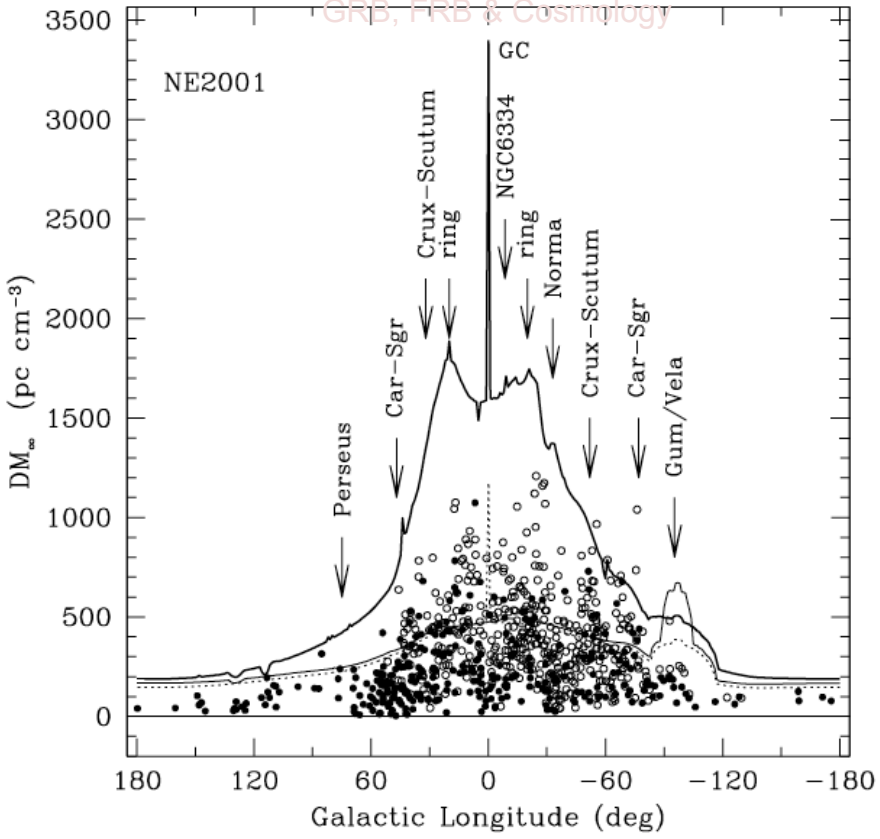


FIG. 11.— Plot of $DM_\infty(\ell, b)$, the maximum DM obtained by integrating the NE2001 model. Heavy solid line: $b = 0°$. Light solid line: $b = -5°$. Dotted line: $b = +5°$ (offset by -20 pc cm^{-3} in the vertical direction for clarity). Plotted points are pulsars with $|b| < 5°$. Filled circles: pulsars from the Princeton catalog. Open circles: pulsars from the public Parkes Multibeam catalog. Labelled features include tangents to the spiral arms and maxima associated with the ring component, the Gum Nebula and Vela supernova remnant, and the H II complex NGC 6334. The gaps near $\ell = +15°$ and $-20°$ and DM $\lesssim$ 200 pc cm^{-3} are real, appearing in both samples, and signify either the real absence of pulsars in the corresponding volume or the presence of large electron densities in these directions fairly close to the solar system. The absence of pulsars above $\sim$ 1200 pc cm^{-3} is due to selection against such objects by pulse broadening from dispersion smearing and scattering.

Cordes & Lazio 02

Name	FRB 110220	FRB 110627	FRB 110703	FRB 120127
Beam Right Ascension (J2000)	$22^h\ 34^m$	$21^h\ 03^m$	$23^h\ 30^m$	$23^h\ 15^m$
Beam Declination (J2000)	−12° 24’	−44° 44’	−02° 52’	−18° 25’
Galactic Latitude, b (°)	−54.7	−41.7	−59.0	−66.2
Galactic Longitude, l (°)	+50.8	+355.8	+81.0	+49.2
UTC (dd/mm/yyyy hh:mm:ss.sss)	20/02/2011 01:55:48.957	27/06/2011 21:33:17.474	03/07/2011 18:59:40.591	27/01/2012 08:11:21.723
DM (cm^{-3} pc)	944.38 ± 0.05	723.0 ± 0.3	1103.6 ± 0.7	553.3 ± 0.3
DM_E (cm^{-3} pc)	910	677	1072	521
Redshift, z (DM_{Host} = 100 cm^{-3} pc)	0.81	0.61	0.96	0.45
Co-moving Distance, D (Gpc) at z	2.8	2.2	3.2	1.7
Dispersion Index, α	−2.003 ± 0.006	–	−2.000 ± 0.006	–
Scattering Index, β	−4.0 ± 0.4	–	–	–
Observed Width at 1.3 GHz, W (ms)	5.6 ± 0.1	< 1.4	< 4.3	< 1.1
SNR	49	11	16	11
Minimum Peak Flux Density S_ν (Jy)	1.3	0.4	0.5	0.5
Fluence at 1.3 GHz, F (Jy ms)	8.0	0.7	1.8	0.6
$S_\nu D^2$ (× 10^{12} Jy kpc^2)	10.2	1.9	5.1	1.4
Energy Released, E (J)	~10^{33}	~10^{31}	~10^{32}	~10^{31}

Spectral index is difficult to infer due to position uncertainties

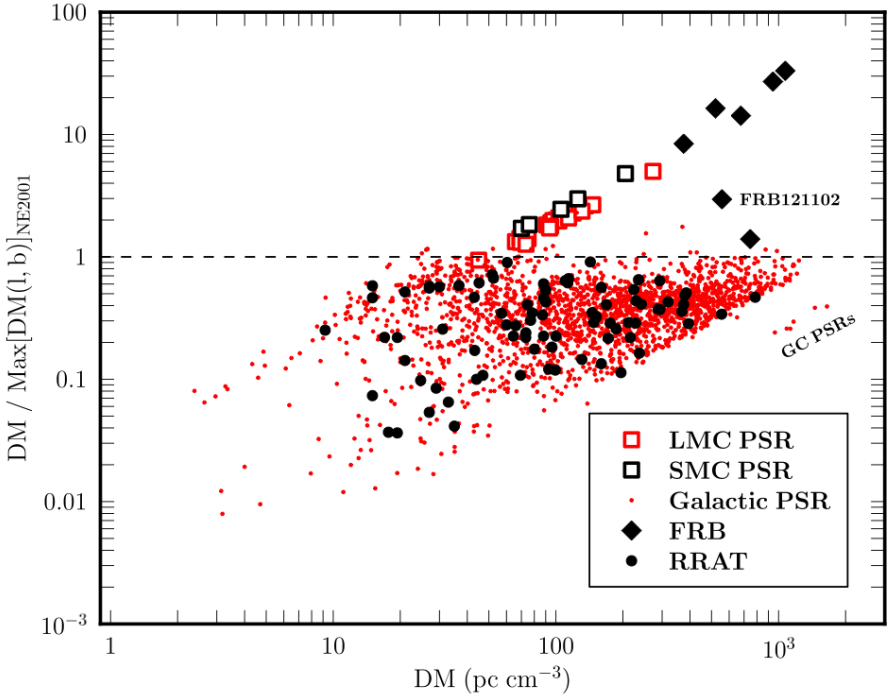


Figure 3. DM ratio (r_{DM}) of measured DM to maximum Galactic dispersion measure plotted against measured DM. The maximum Galactic DM is calculated by integrating the NE2001 model to the edge of the Galaxy for each pulsar line-of-sight. The dashed line shows the maximum unity ratio expected for Galactic objects if the electron density is accurate for all lines of sight. The six pulsars near the Galactic center are clustered on the far right of the plot. The RRATs have DM ratios consistent with the rest of the Galactic pulsar population. Known pulsars in the LMC and SMC have $r_{DM} \sim 1-5$, and the seven FRBs have ratios from 1.2 to 33. The Keane et al. (2012) burst has the lowest DM ratio of the FRBs and is located to the lower right of FRB 121102. The Lorimer et al. (2007) burst and Thornton et al. (2013) bursts fall along the line that extends from the LMC and SMC pulsars with the Lorimer et al. (2007) burst being the left-most point. (See Section 5 for data source references.)

Table 1
Observational Parameters of FRB 121102

Parameter	Value
Date	2012 Nov 02
Time	06:35:53 UT
MJD arrival time[a]	56233.27492180
Right Ascension[b]	$05^h32^m09.6^s$
Declination[b]	$33°05'13.4''$
Gal. long.[b]	174.95°
Gal. lat.[b]	−0.223°
DM (pc cm^{-3})	557.4 ± 2.0
$DM_{NE2001,max}$ (pc cm^{-3})	188
Dispersion index[c]	-2.01 ± 0.05
Pulse width (ms)	3.0 ± 0.5
Pulse broadening (ms)[d]	< 1.5
Flux density (Jy)[e]	$0.4^{+0.4}_{-0.1}$
Spectral index range(α) [f]	7 to 11

[a] Barycentered arrival time referenced to infinite frequency.
[b] The J2000 position of the center of beam 4.
[c] DM $\propto \nu^{\beta}$
[d] Flux density at 1 GHz
[e] Flux estimation at 1.4 GHz assumes a sidelobe detection and a corresponding gain of 0.7 ± 0.3 K Jy^{-1}.
[f] $S(\nu) \propto \nu^{\alpha}$

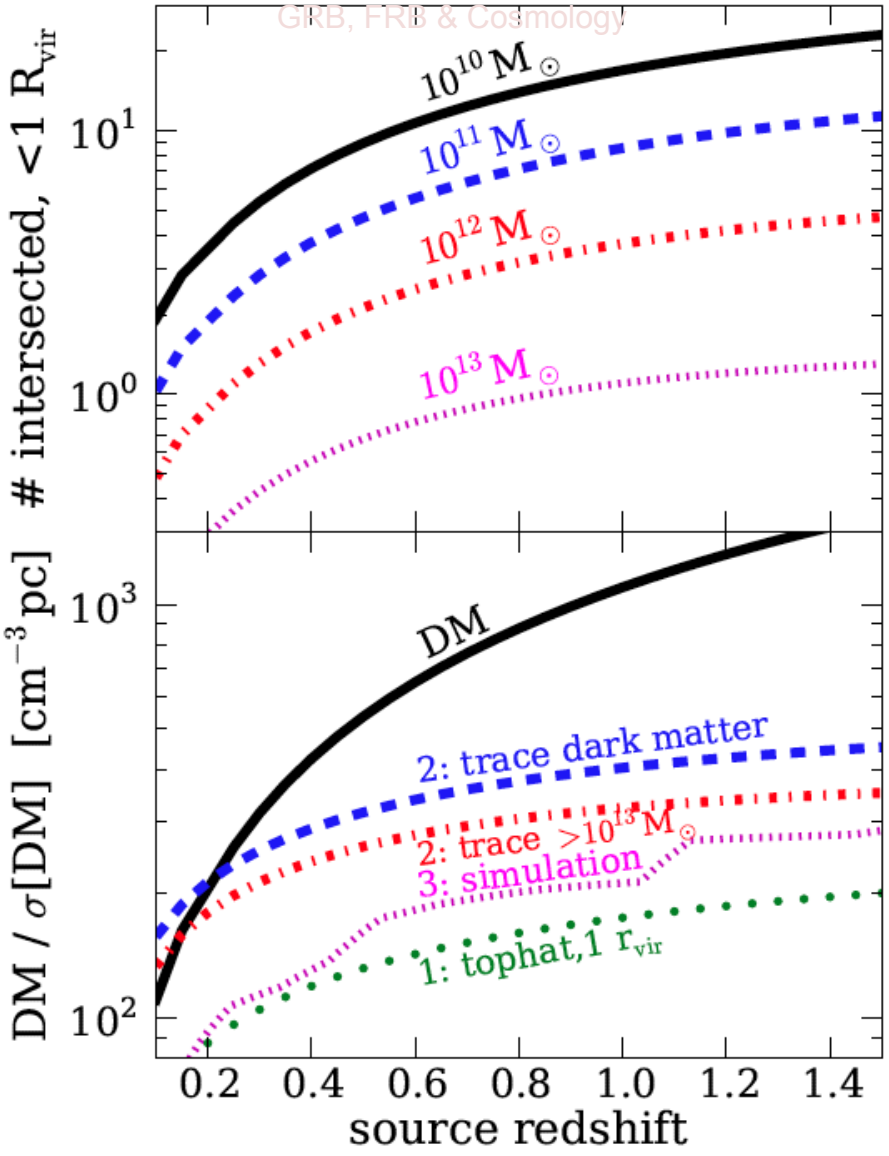


FIG. 1.— Top panel: The average number of halos above the specified mass thresholds that a sightline intersects within $1\,r_{vir}$. Bottom panel: The mean dispersion measure (solid curve) as well as the standard deviation in its value for the considered models (other curves).

Table 2

Volumetric Rates of Selected Cosmic Explosions

Class	Type	Φ ($\mathrm{Gpc^{-3}\ yr^{-1}}$)	Ref
LSB (low)	BC	100–1800	(1,2)
LSB(high)	Obs	1	(1)
	BC	100–550	(1)
SHB	Obs	>10	(3a)
	BC	500–2000	(3b)
In-spiral	Th	3×10^3	(4)
SGR	Obs	$<2.5 \times 10^4$	(5)
Type Ia	Obs	10^5	(6)
Core Collapse	Obs	2×10^5	(7)
FRB	Obs	$\approx 2 \times 10^4$	(8,9)

Notes. "Obs" is the annual rate inferred from observations. "BC" is the observed rate corrected for beaming. "Th" is the rate deduced from stellar models. LSB stands for GRBs of the long duration and soft spectrum variety. A gamma-ray luminosity of 10^{49} erg $\mathrm{s^{-1}}$ divides the "low" and "high" subclasses (see Guetta & Della Valle 2007). SHB stands for GRBs of the short duration and hard spectrum class. SGR stands for soft gamma repeaters. Here we only include those giant flares with isotropic energy release $>4 \times 10^{46}$ erg.

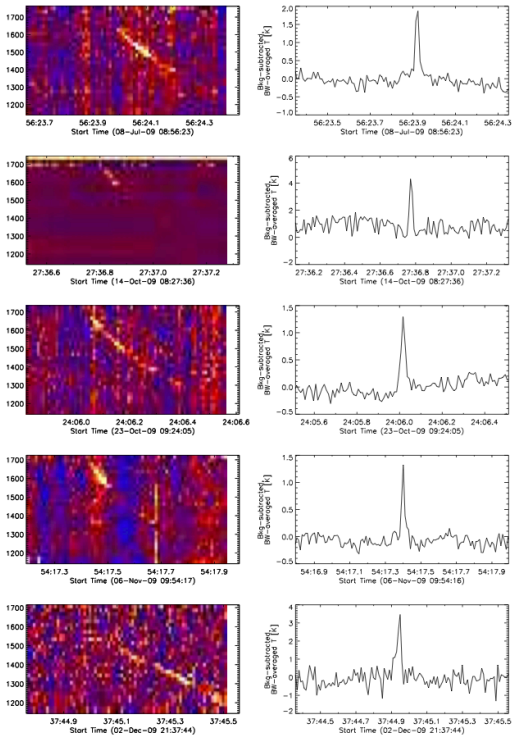
References. (1) Guetta & Della Valle 2007; (2) Soderberg et al. 2006; (3a) Nakar et al. 2006; (3b) Coward et al. 2012; (4) Kalogera et al. 2004; (5) Ofek 2007; (6) Scannapieco & Bildsten 2005; (7) Li et al. 2011; (8) Lorimer et al. 2007; (9) Thornton et al. 2013.

Kulkarni+ 14

Peryton

- Detected in multiple receiver beams with approximately the same S/N ⇒ <10km
- ~10^{-4}(d/10km)^2 erg (cf. cell phone ~10^{-2}erg)
- DM~300pc/cc ~ 1mg/cc x cm
- Possible origins
  - Lightning
  - Aircraft, GPS, etc.
  - Electronics

Danish Kahn 14

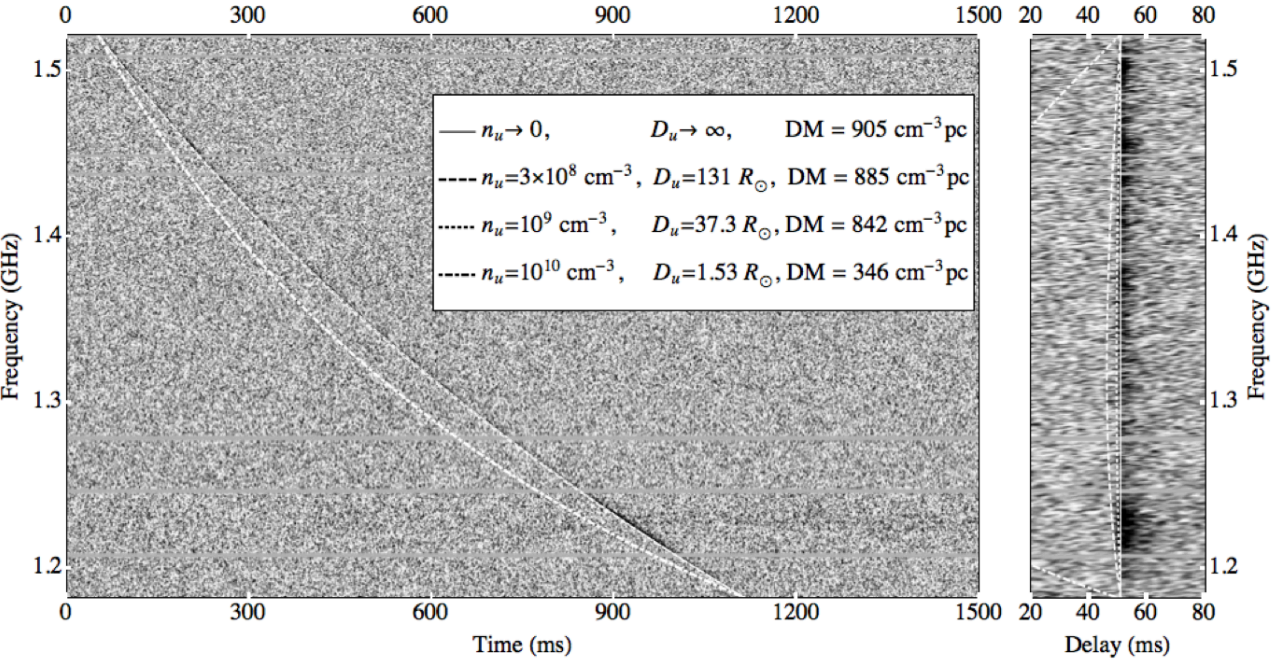


Saint-Hilaire+ 14

Dense Plasma Dispersion

$$t - t_0 \simeq \int \frac{\mathrm{d}D}{c} \left[\frac{1}{2}\frac{f_p^2}{f^2} + \frac{3}{8}\left(\frac{f_p^2}{f^2}\right)^2 + \frac{5}{16}\left(\frac{f_p^2}{f^2}\right)^3 + \ldots \right]$$

$$\approx \frac{c r_e}{2\pi f^2}\mathrm{DM}, \qquad \mathrm{DM} \equiv \int n_e(D)\,\mathrm{d}D.$$



$n_e < 10^{8\text{-}9}$/cc

Not nearby star

Tuntsov+ 14

Katz 14

No FRB-GRB Connection

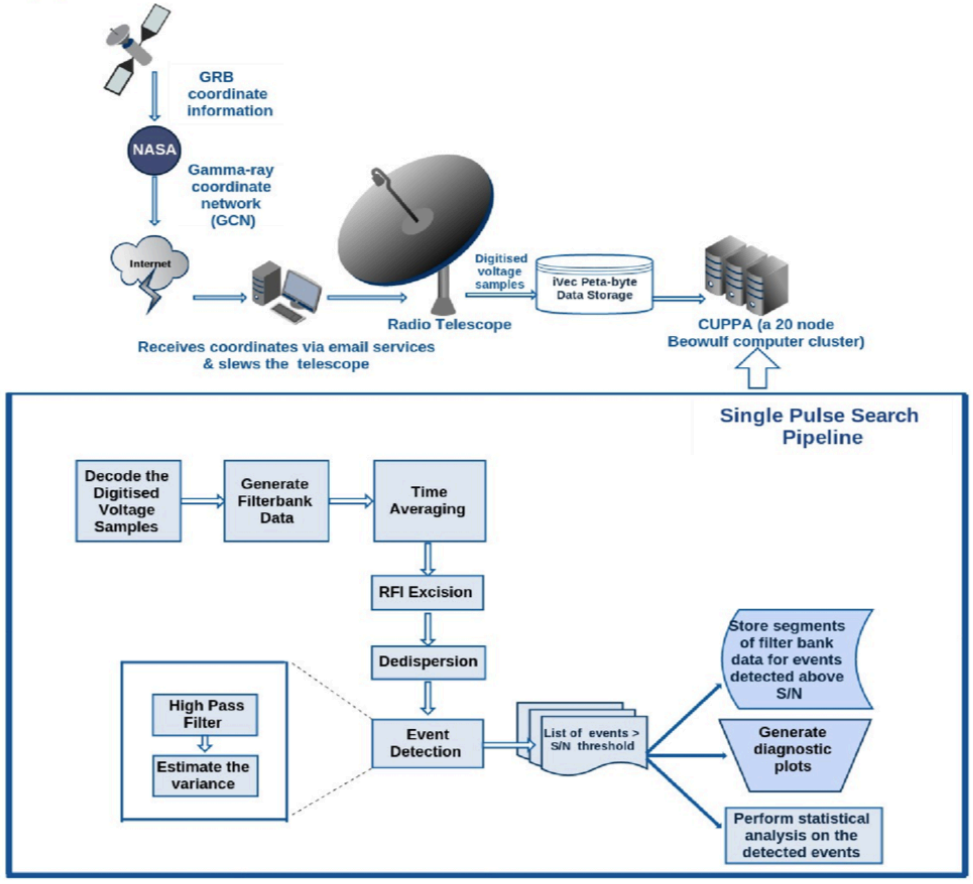


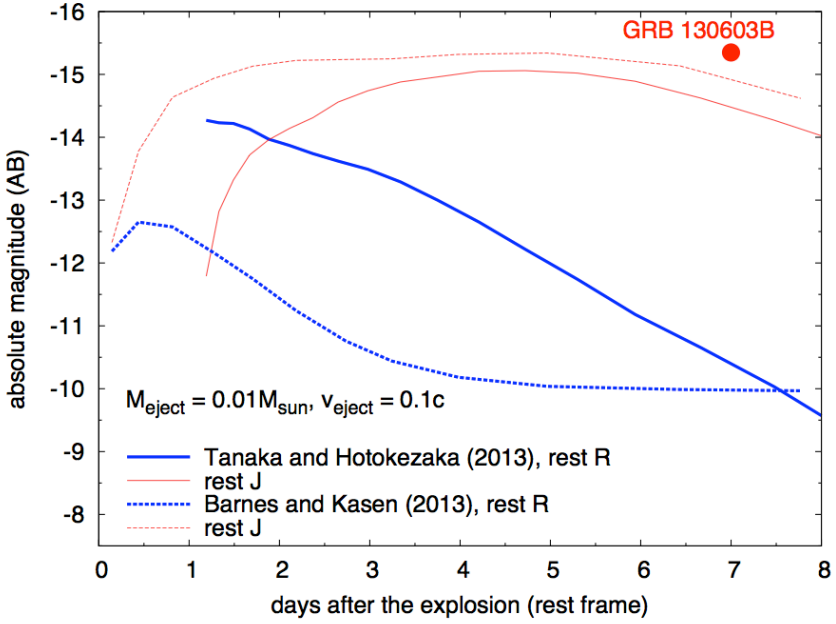
Fig. 1.— *Top panel*: A schematic representation of the system where the space-borne GRB telescope sends the position information for GRBs to our ground-based radio telescope through GCNs. The radio telescope is then slewed to the GRB positions and data are recorded. The recorded data are then transferred to the PetaByte data storage facility at iVEC, in Perth and processed on a 20 node Beowulf computer cluster, CUPPA. *Bottom panel*: Represents the single pulse search pipeline implemented in this paper, to search for FRBs from GRBs. The search pipeline has multiple stages: correlation; time averaging; radio frequency interference (RFI) excision; dedispersion; event detection and classification. In this experiment we generate time averages ranging from 640 μs to 25.60 ms (section 3.1.2). Each averaged time series go through the RFI excision, dedispersion, event detection and clasification stages independently.

2.3GHz
26 m radio telescope
Slew to GRB in ~140 s
No FRB detected

Palaniswamy+ 14

FRB-Macronova?

FRB-Macronova is detectable @z<~0.3 if exist



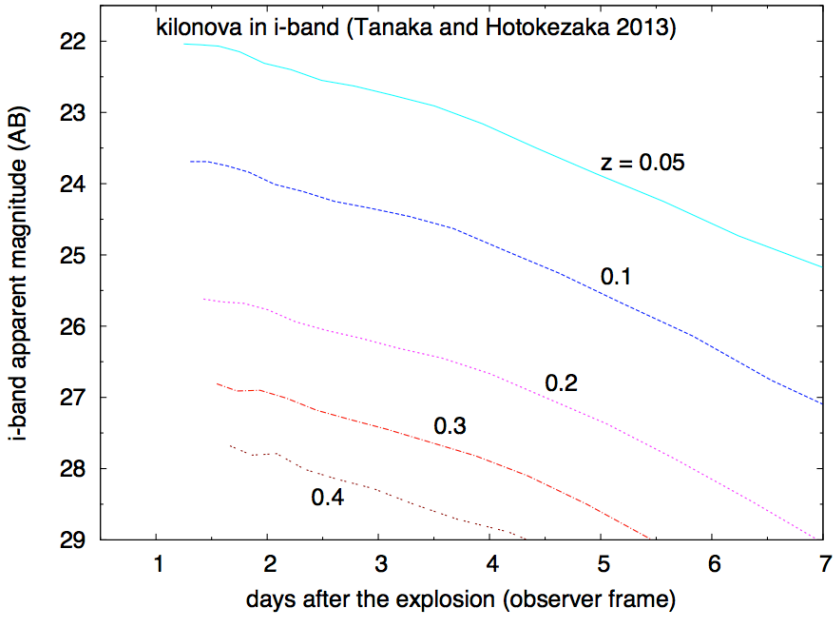
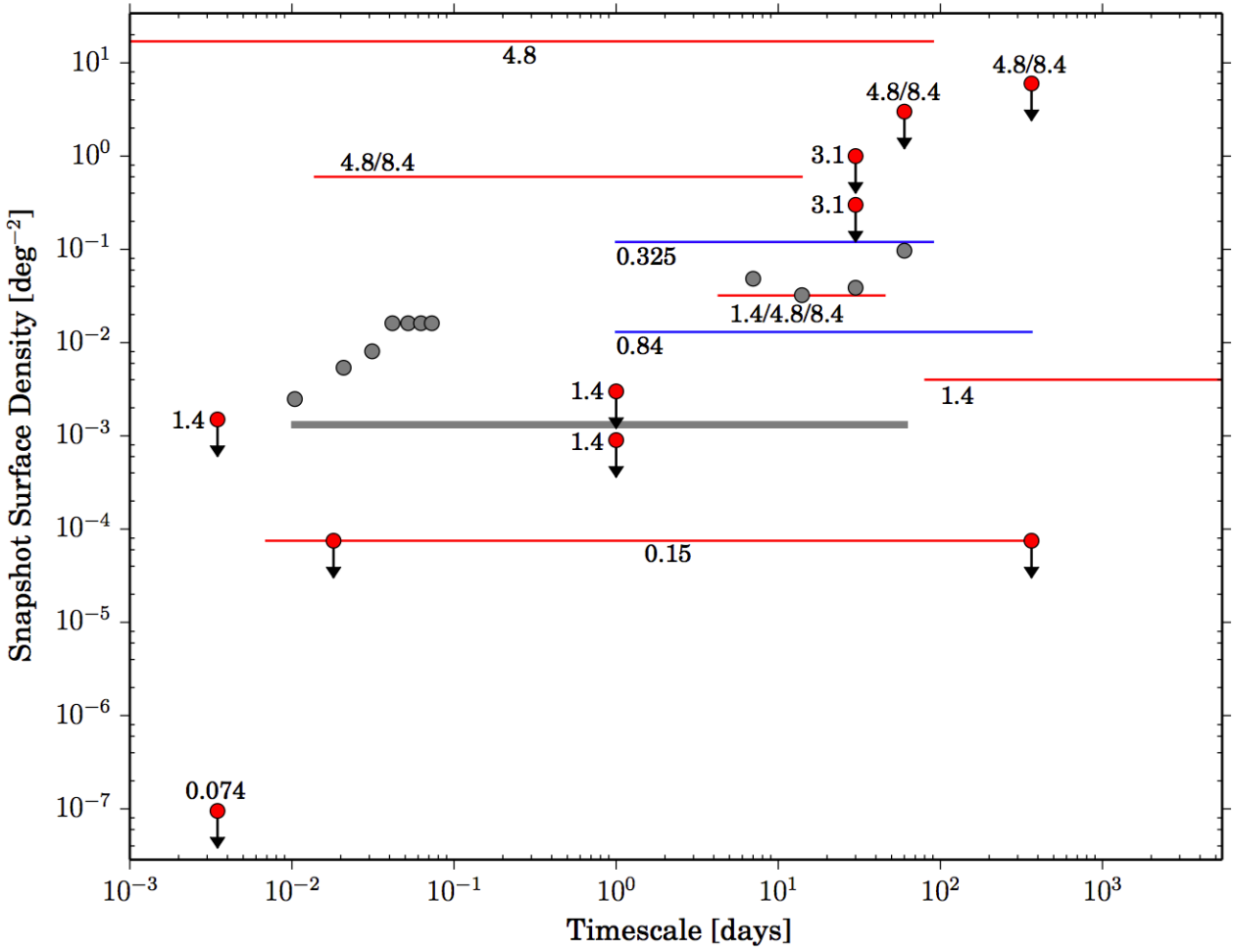


Fig. 1. Left panel: rest frame light curves of kilonovae in absolute magnitude predicted by the models of Tanaka & Hotokezaka (2013, TH13) and Barnes & Kasen (2013). The thick and thin lines represent the light curves in rest frame R-band and J-band, respectively. The circle at the top right indicates observing time and luminosity of the kilonova candidate associated with GRB 130603B ($z = 0.356$) in HST F160W filter which roughly corresponds to rest frame J-band. Right panel: apparent light curves in observer frame i-band predicted by the TH13 model at different redshifts.

Niino, Totani & Okumura 14

LOFAR

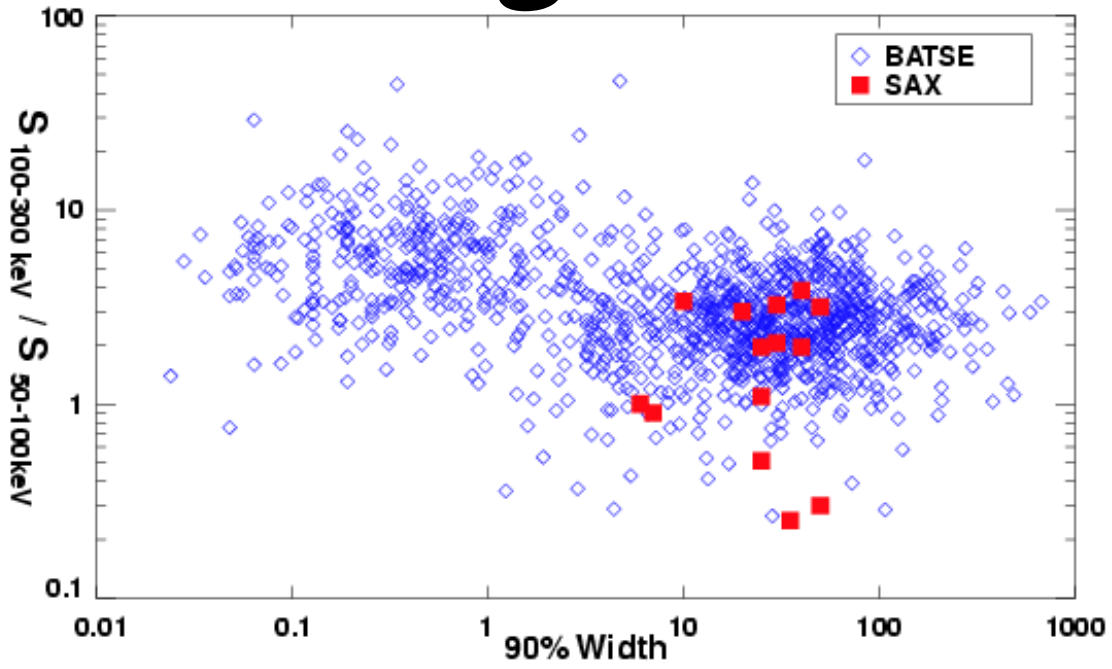


Carbone+ 14

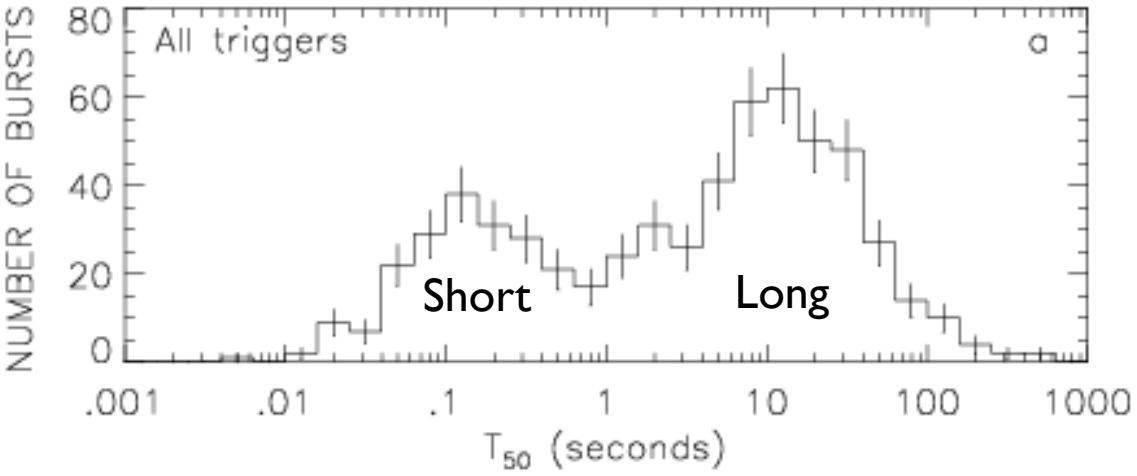
Figure 4. Snapshot surface density $\left(\mathrm{deg}^{-2}\right)$ against time-scale of detections of transients (blue diamonds and lines) and upper limits based on non detections (red circles and lines). The numbers indicates the frequency in GHz at which each survey was conducted. The surveys displayed here are listed in Table 5. The grey circles indicate the upper limits derived from this work while the grey line represents the result from this work as displayed for the other surveys. It is clear how the grey line is a very rough approximation for the grey circles.

Thank You

Long & Short GRB

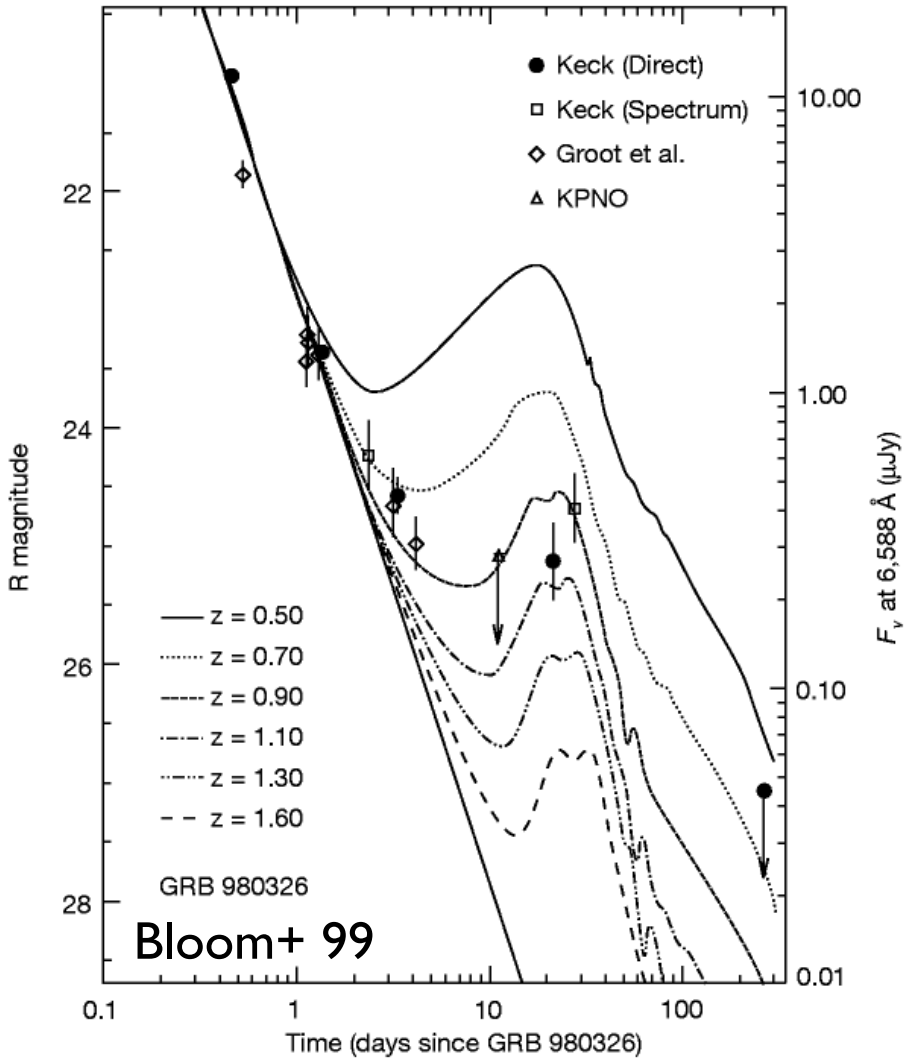


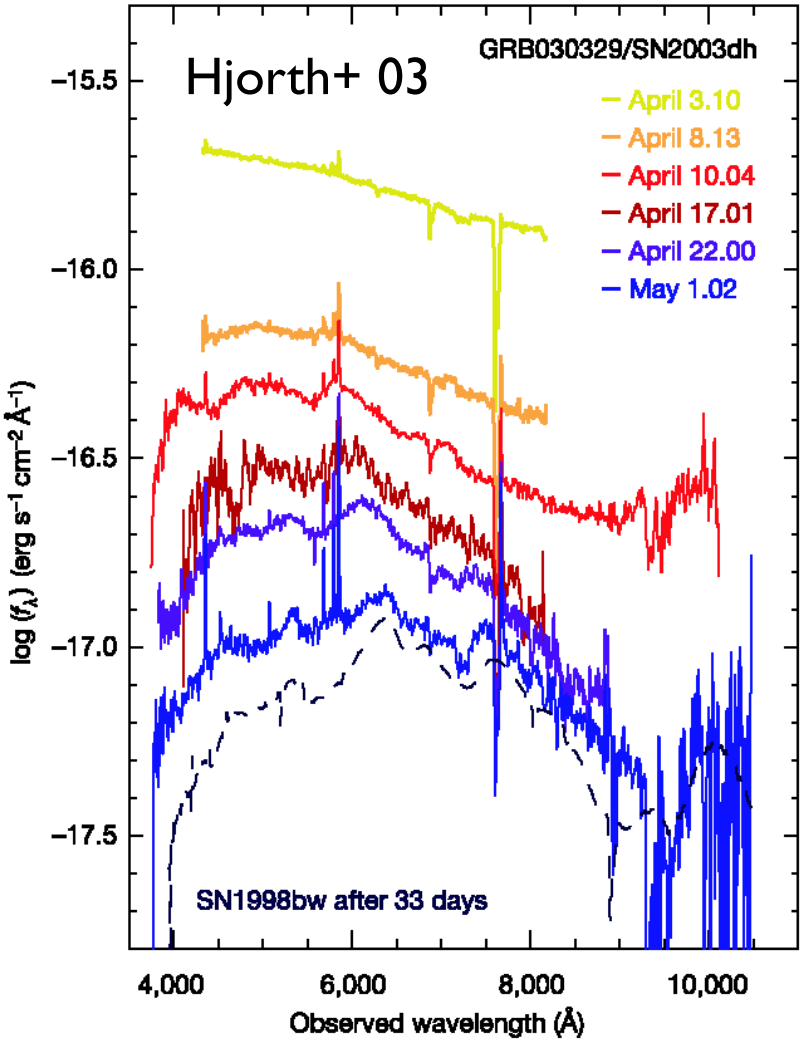
Long-soft
Short-hard



Long burst
Short burst

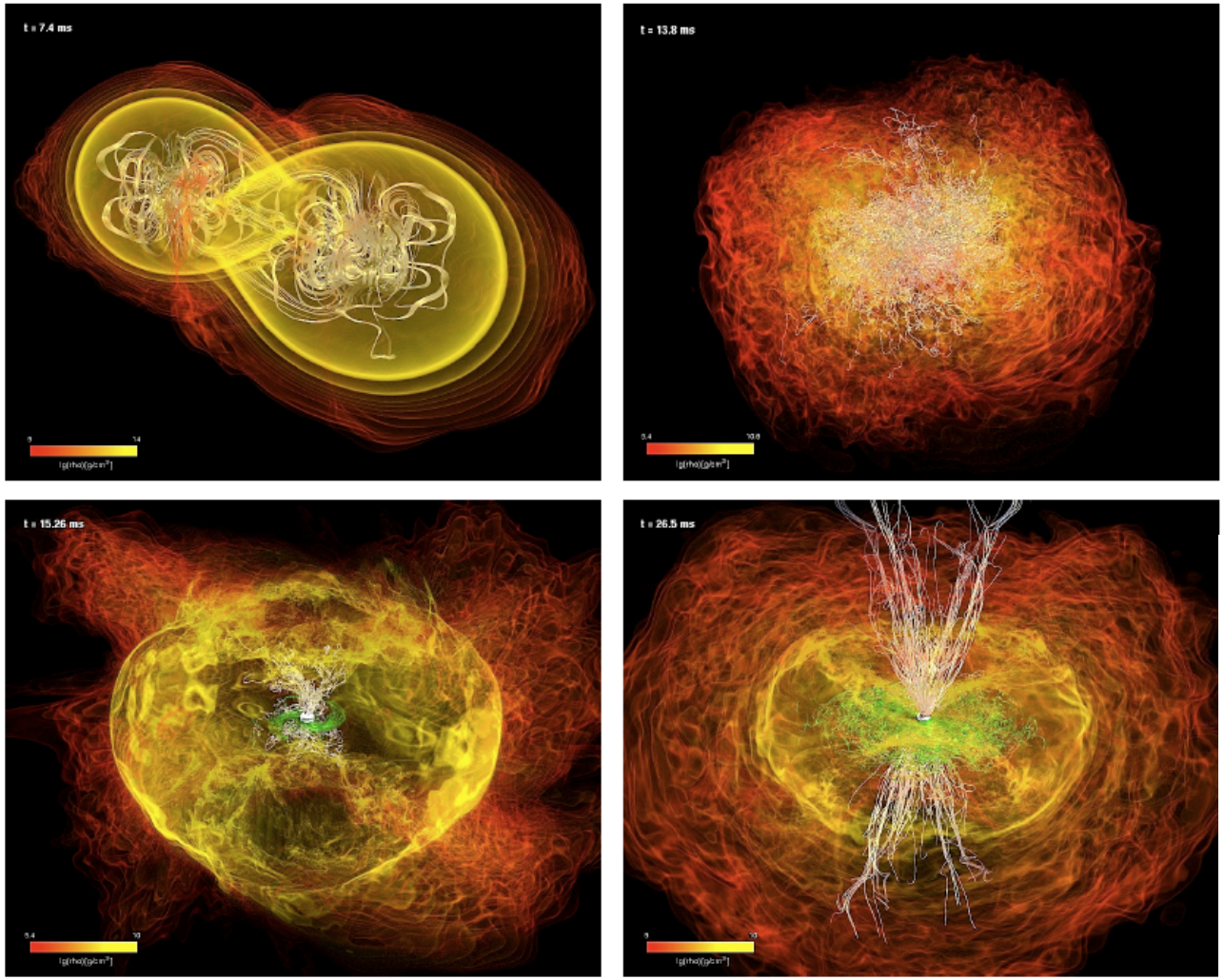
Supernova with Long GRB





Woosley 93 "Gamma-ray bursts from stellar mass accretion disks around black holes"

Short GRB



Rezzolla+ 11

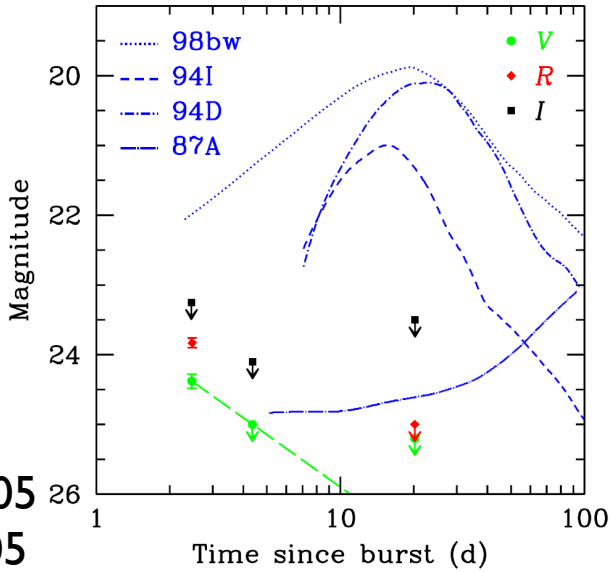
NS-NS / NS-BH

Magnetar (Svinkin+ 14)

WD/NS AIC

WD-WD

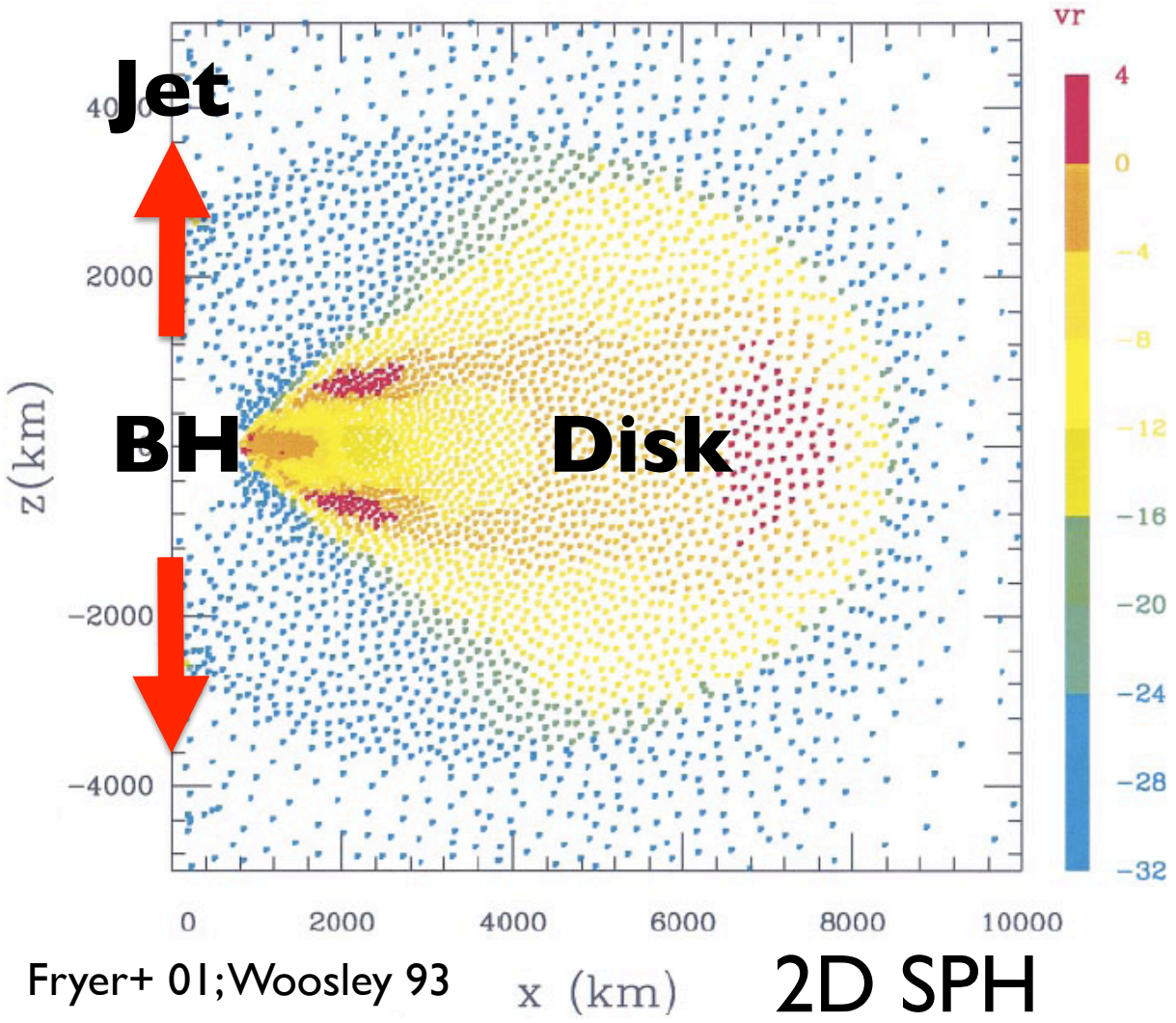
Not collapsar



Covino+ 05

Hjorth+ 05

Super Collapsar



Fryer+ 01; Woosley 93

2D SPH

$50M_\odot<M<160M_\odot$:
Black Hole

$160M_\odot<M<260M_\odot$:
Pair Instability SN

$260M_\odot<M$: BH

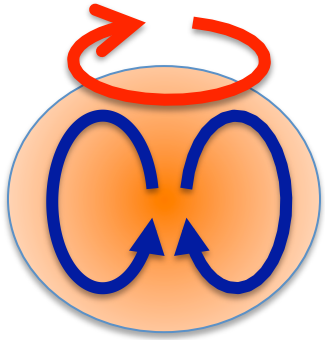
⇒ BH + Disk + Jet
like Collapsar

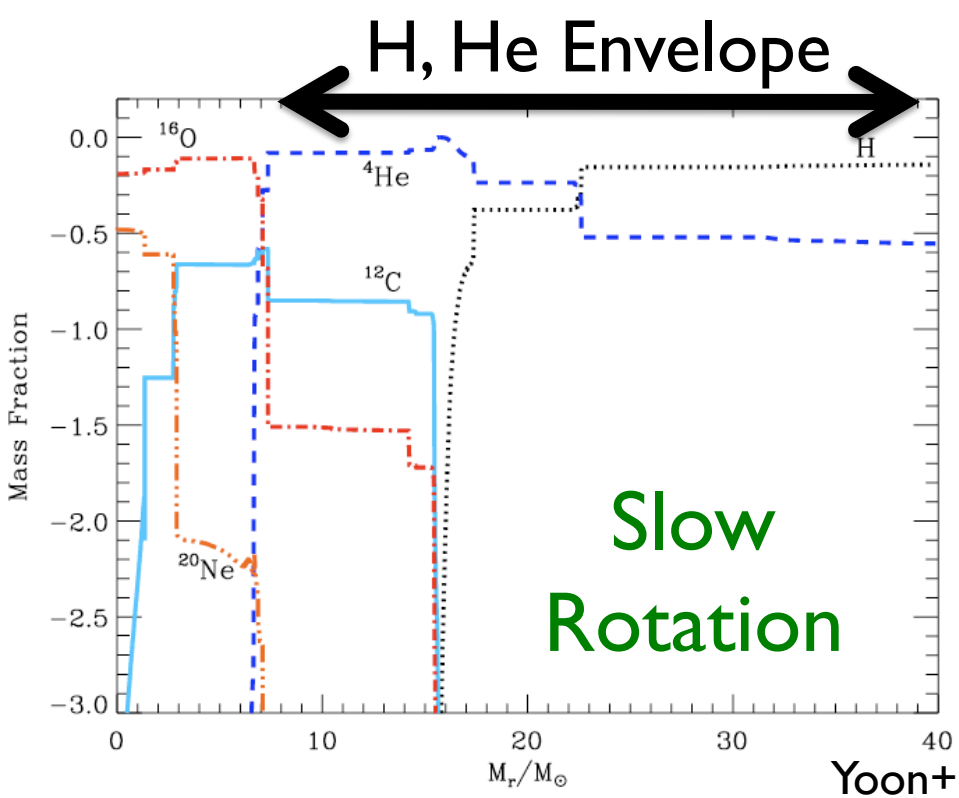
~100 times mass ⇒
Super Collapsar

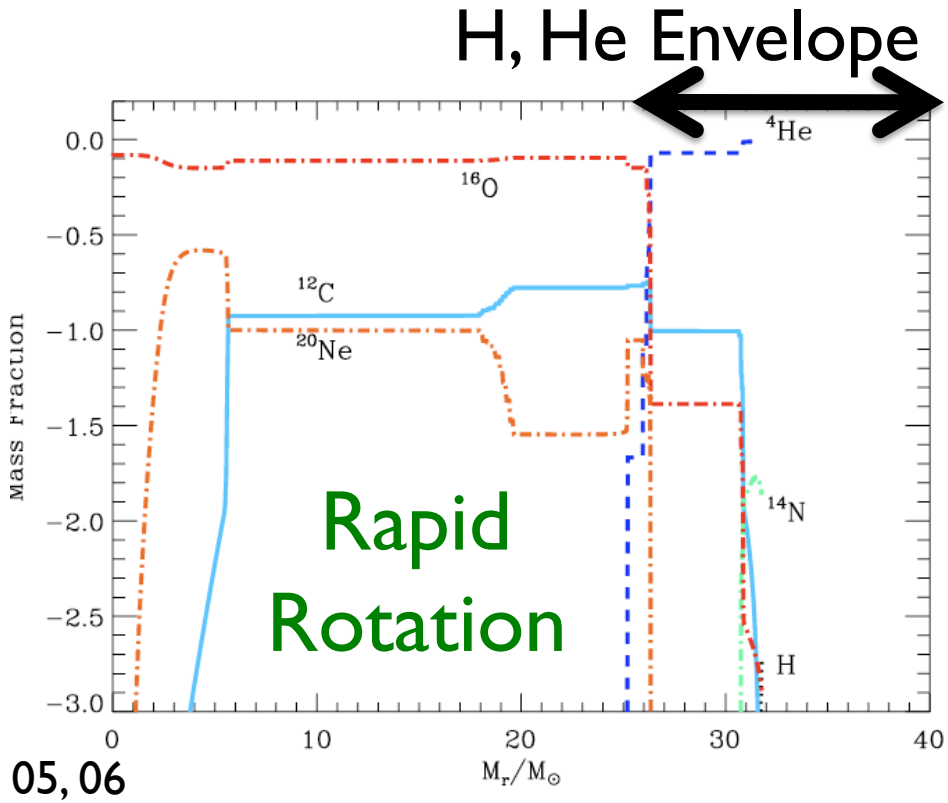
ν ann. is not effective
BZ could work

Chemically Homogeneous Evolution (CHE)?

- Rotation ⇒ Mixing
  ⇒ Large CO Core & **Small envelope**

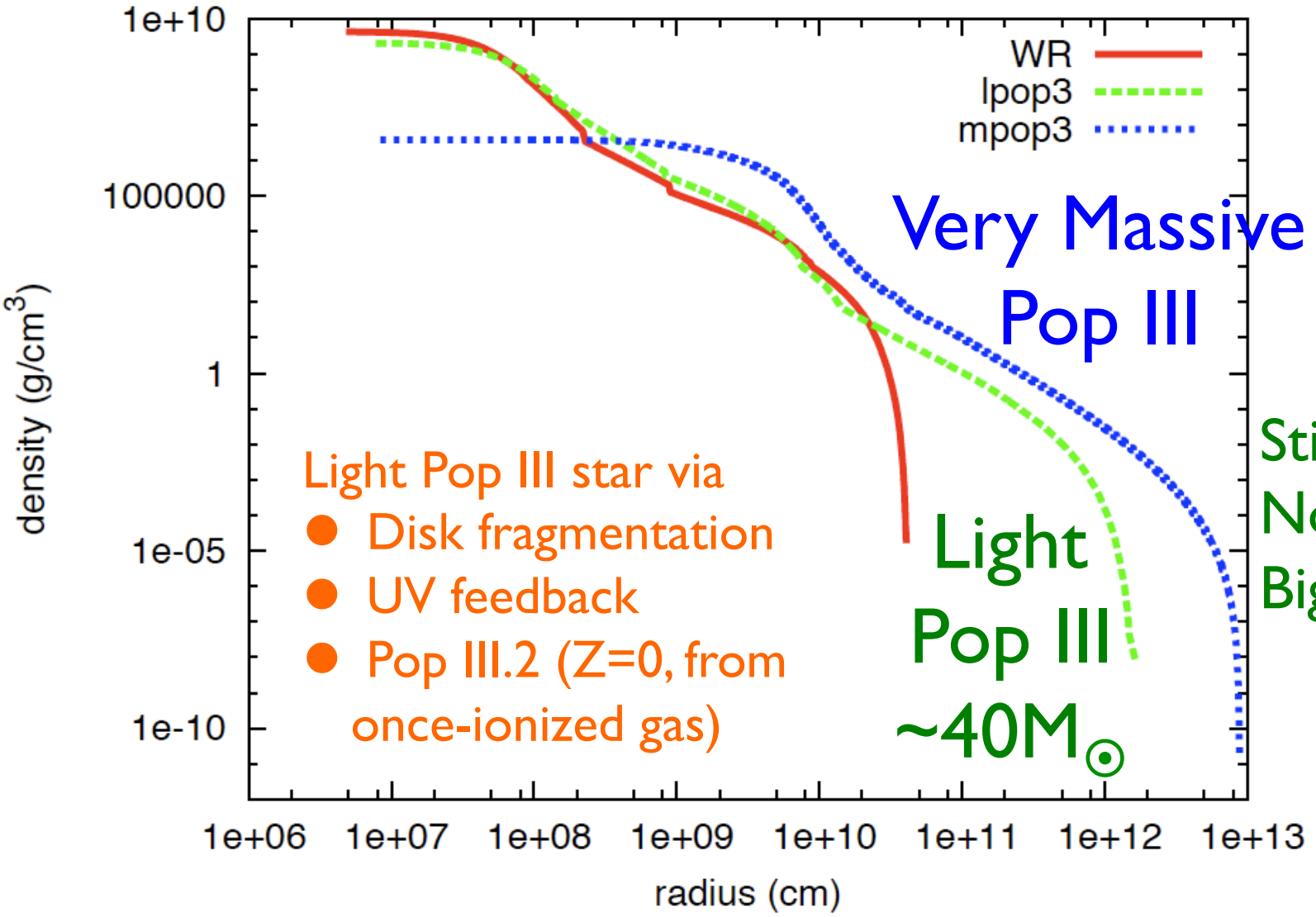




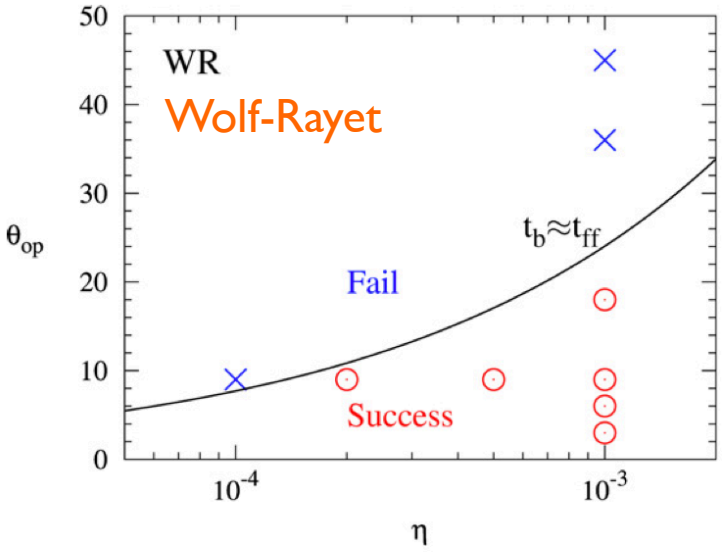


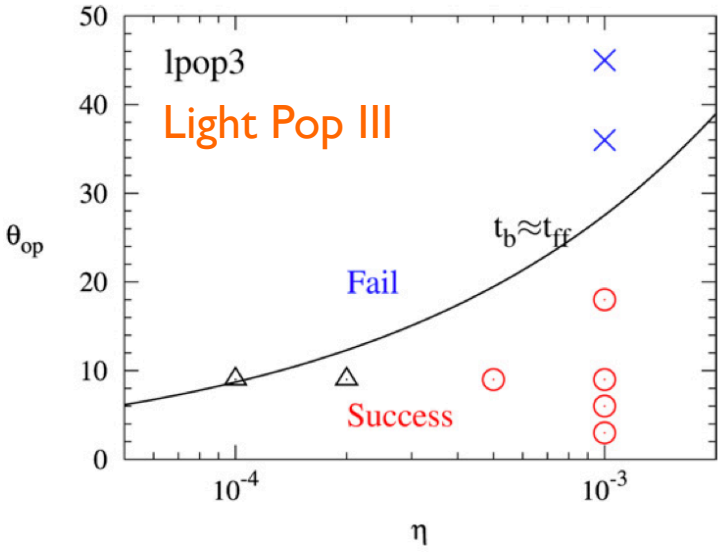
Yoon+ 05, 06

"Light" Pop III Star

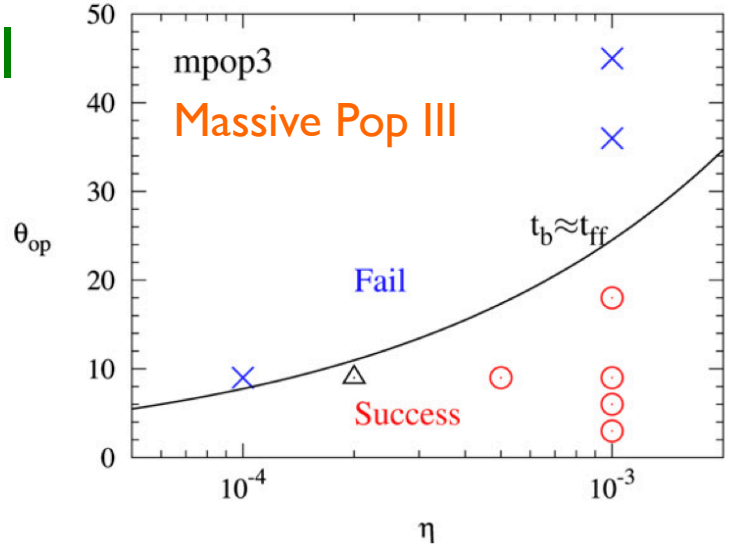


"Light" Pop III GRB





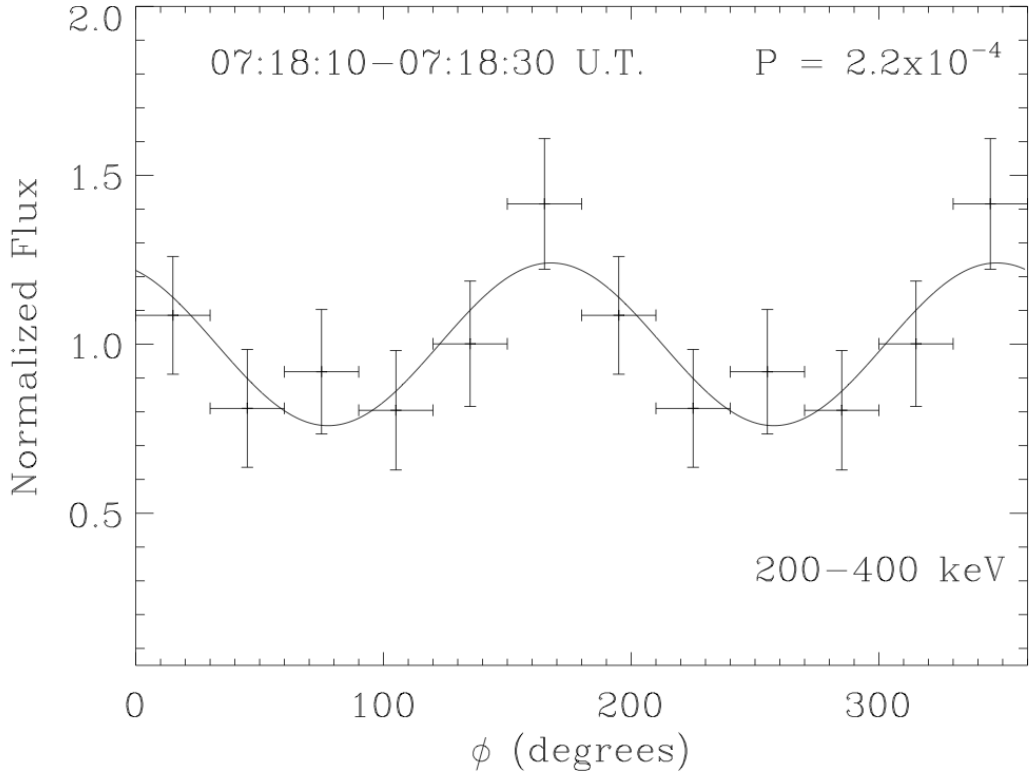
40 numerical calculations + Analytical



Nagakura+ 12

Breakout is possible also for "Light" Pop III

Polarized GRB 140206A



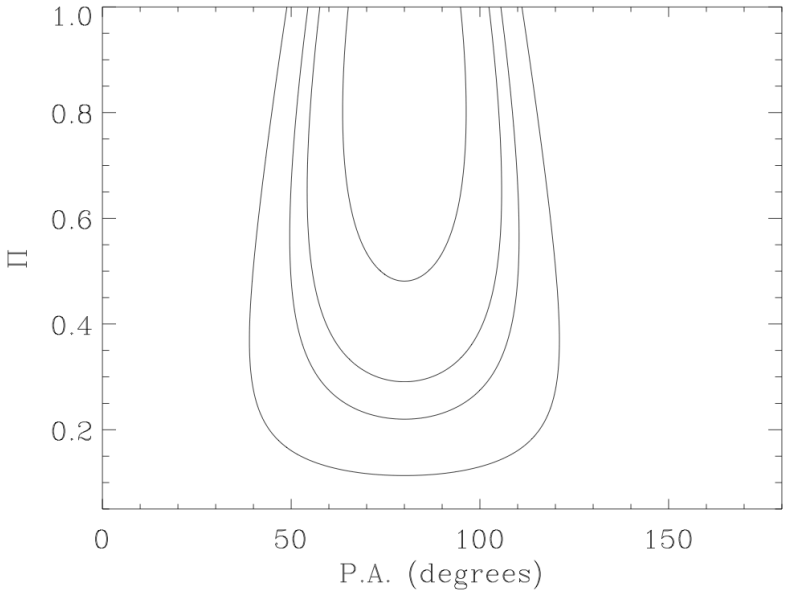


Table 2. Polarization measurements of GRB 140206A.

Energy band (keV)	Π (%) (68% c.l.)	P.A. (°) (68% c.l.)	Π (%) (90% c.l.)	P.A. (°) (90% c.l.)
200–400	>48	80±15	>28	80±25

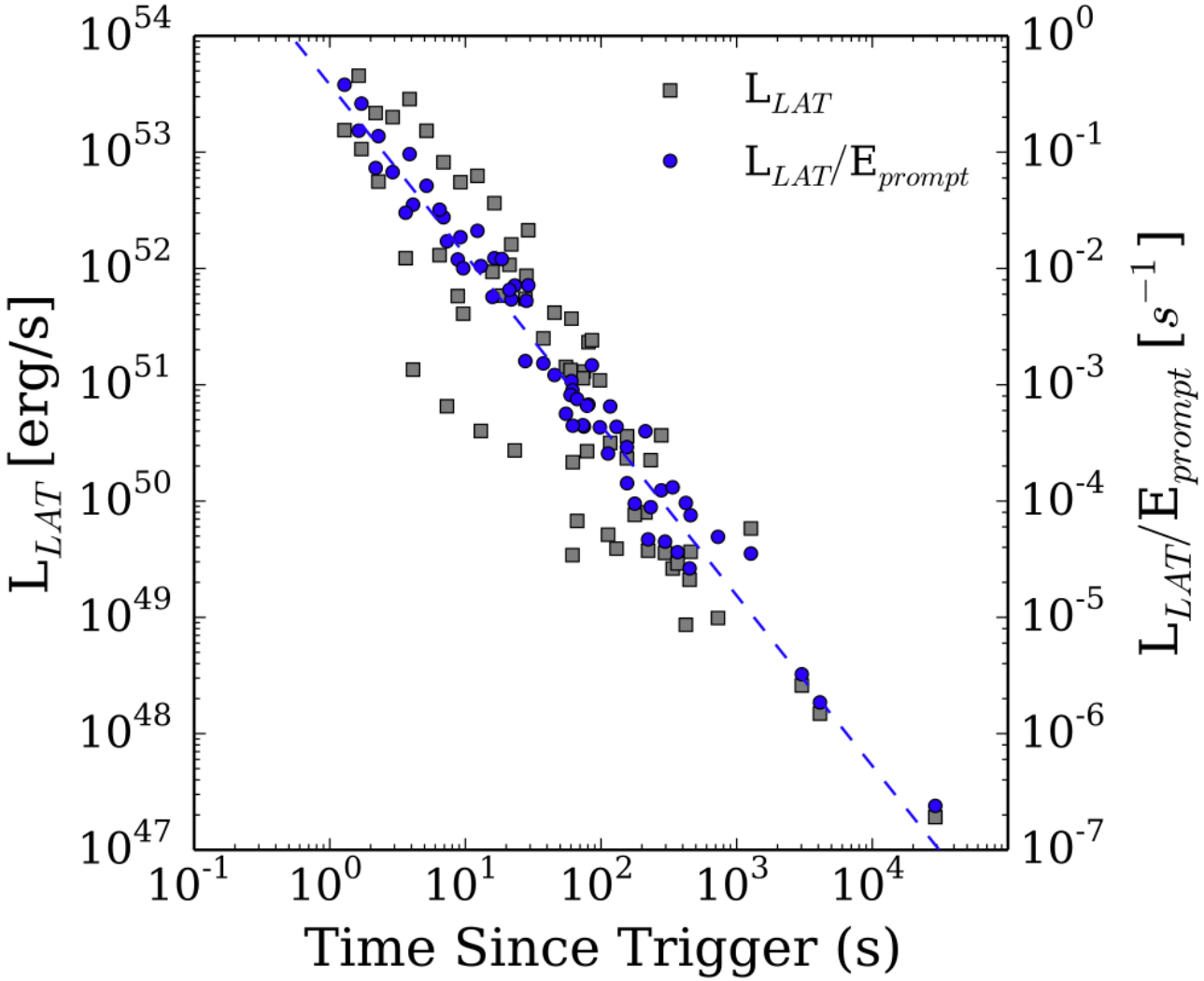
INTEGRAL/IBIS

z=2.739

ξ<1e-16 on LIV

Gotz+ 14

GeV Light Curve

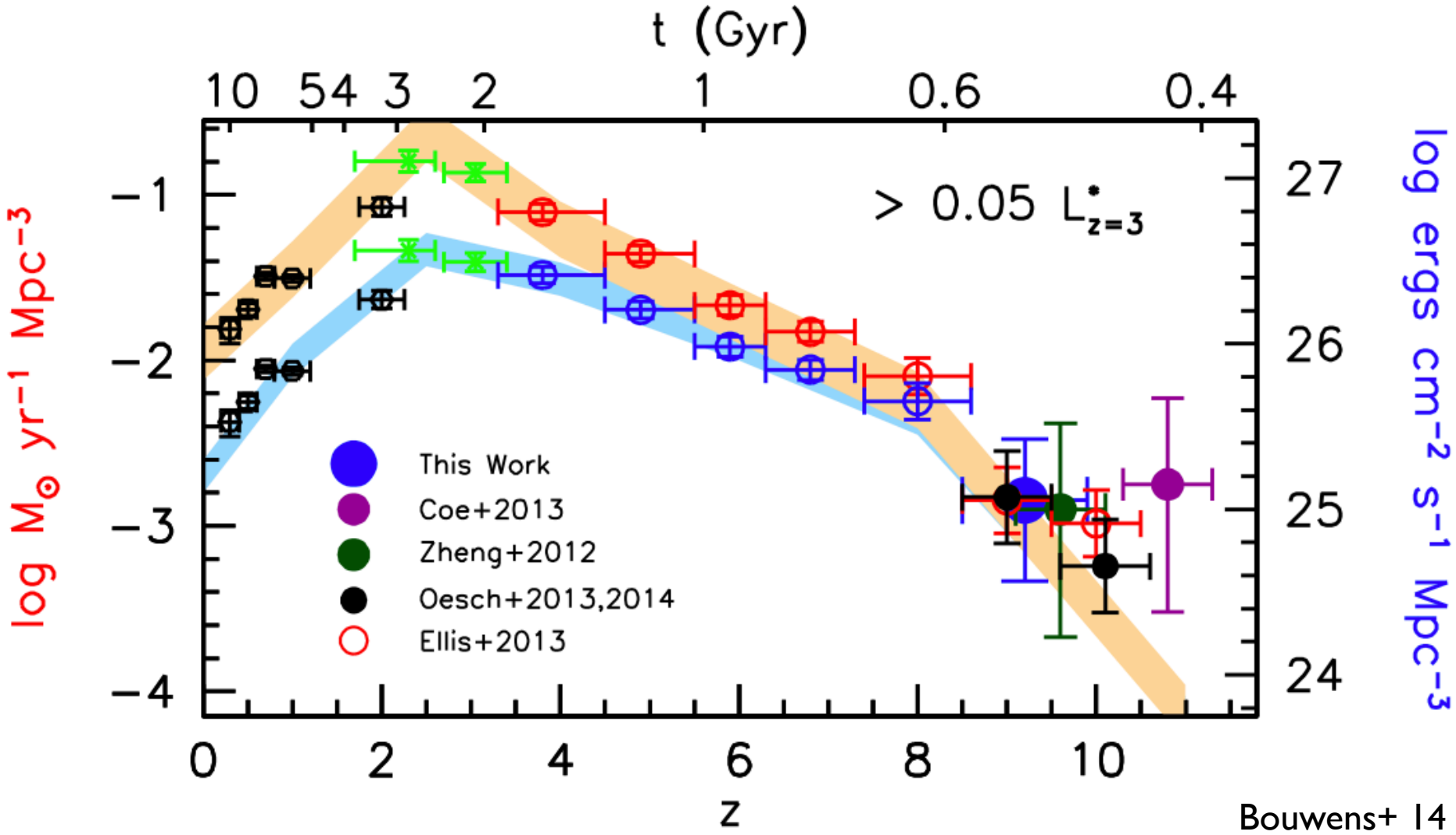


Clustering after normalization

⇒ Extended GeV emission from external shocks

Nava+ 14

SFR up to z~10



Bouwens+ 14

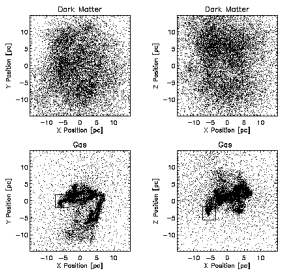
Mass Movement

1000M$_\odot$

100M$_\odot$

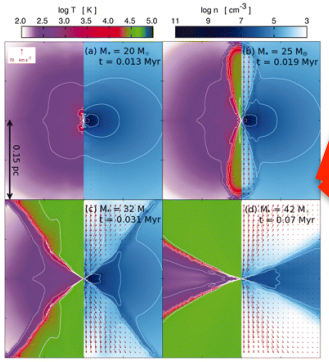
10M$_\odot$

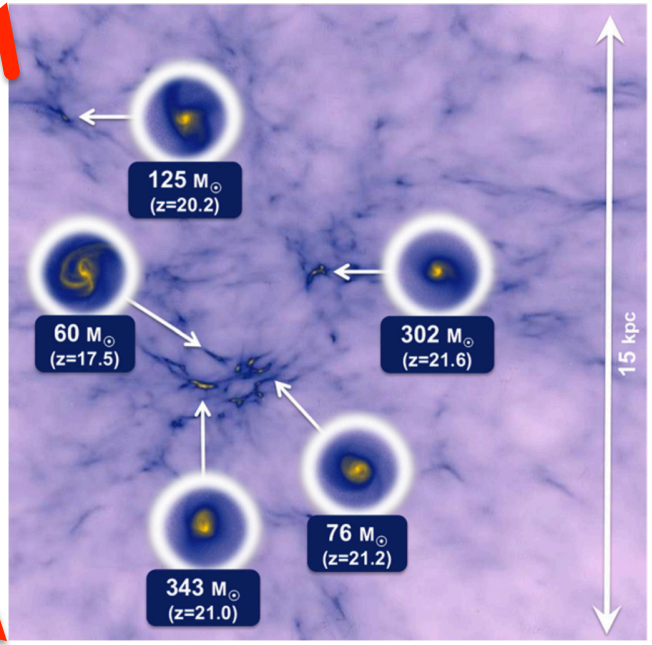
1M$_\odot$



Abel+ 02
Bromm+ 02
Omukai & Palla 03
Yoshida+ 08

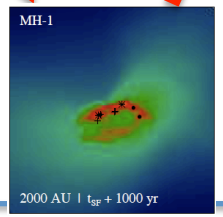
Hosokawa+ 11





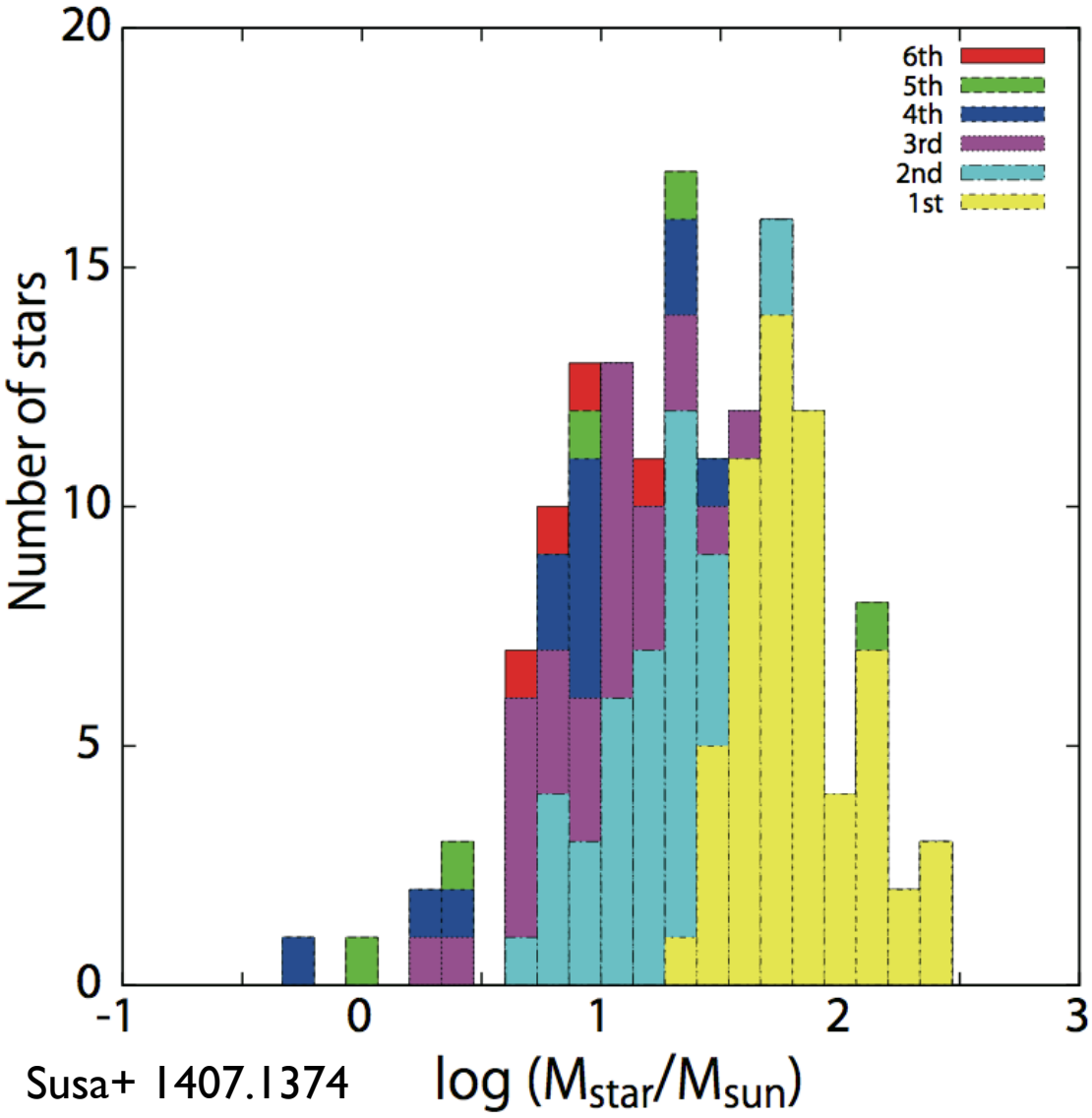
Hirano+ 14

Clark+ 11
Grief+ 11



~2002 ~2011 ~2014 Year

Pop III Mass Spectrum

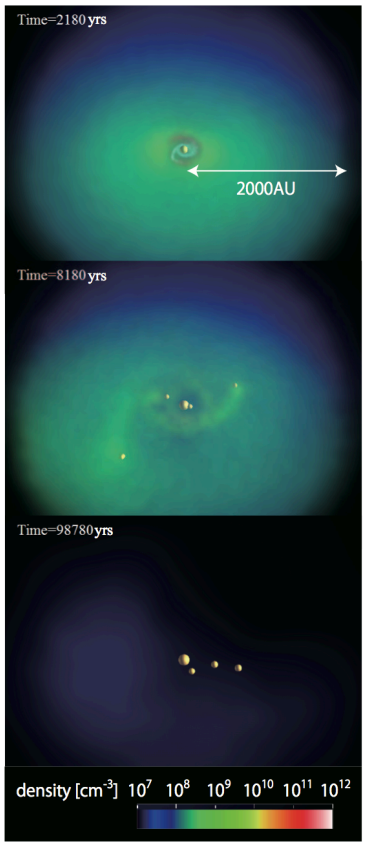


Susa+ 1407.1374

59 minihalos

3D Radiation Hydro

1M$_\odot$<M<300M$_\odot$



~30M$_\odot$ peak

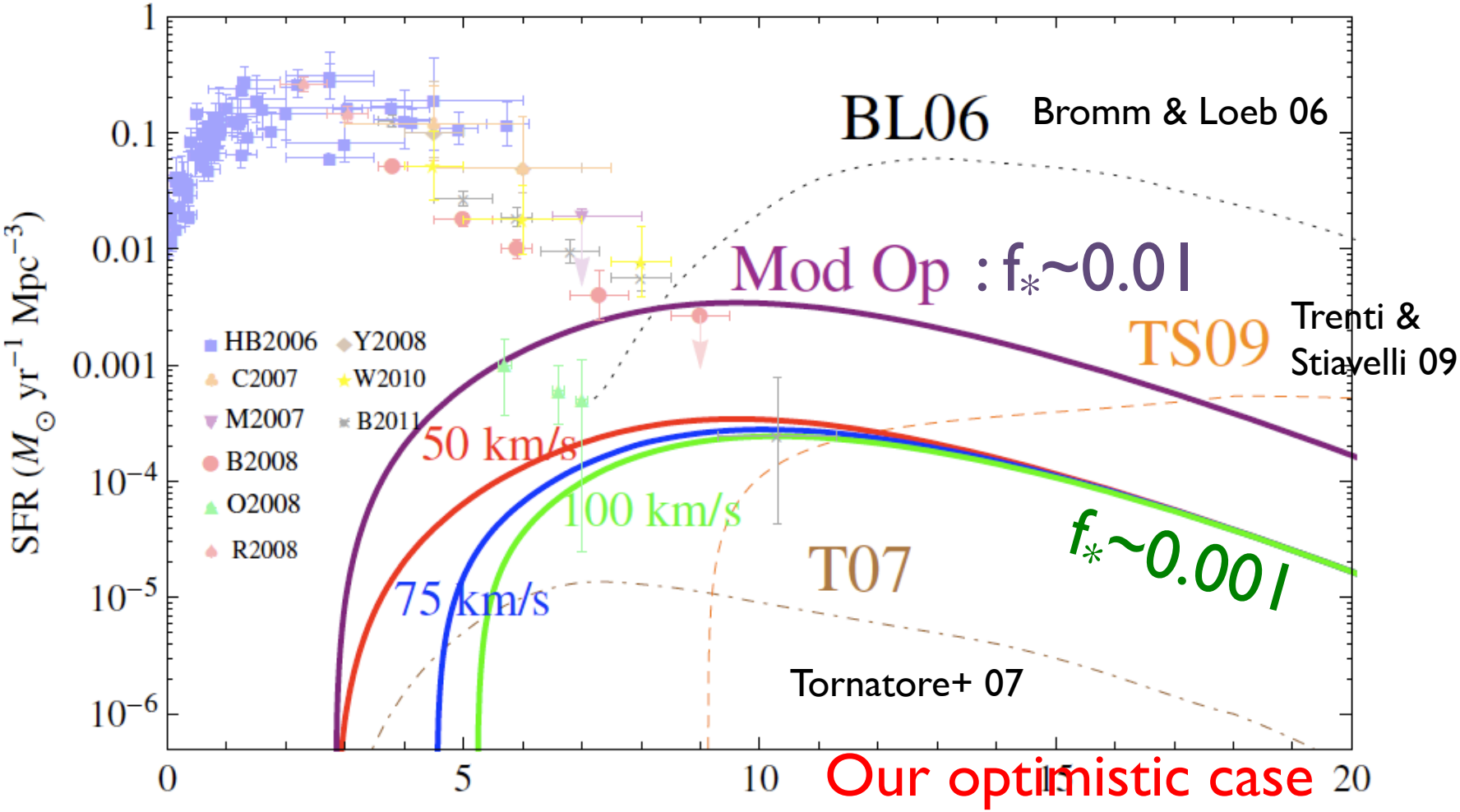
Disk frag.

UV feedback

2/3 minihalos host >2 stars separated by ~10-1000AU


GRB jet can breakout
the first star!

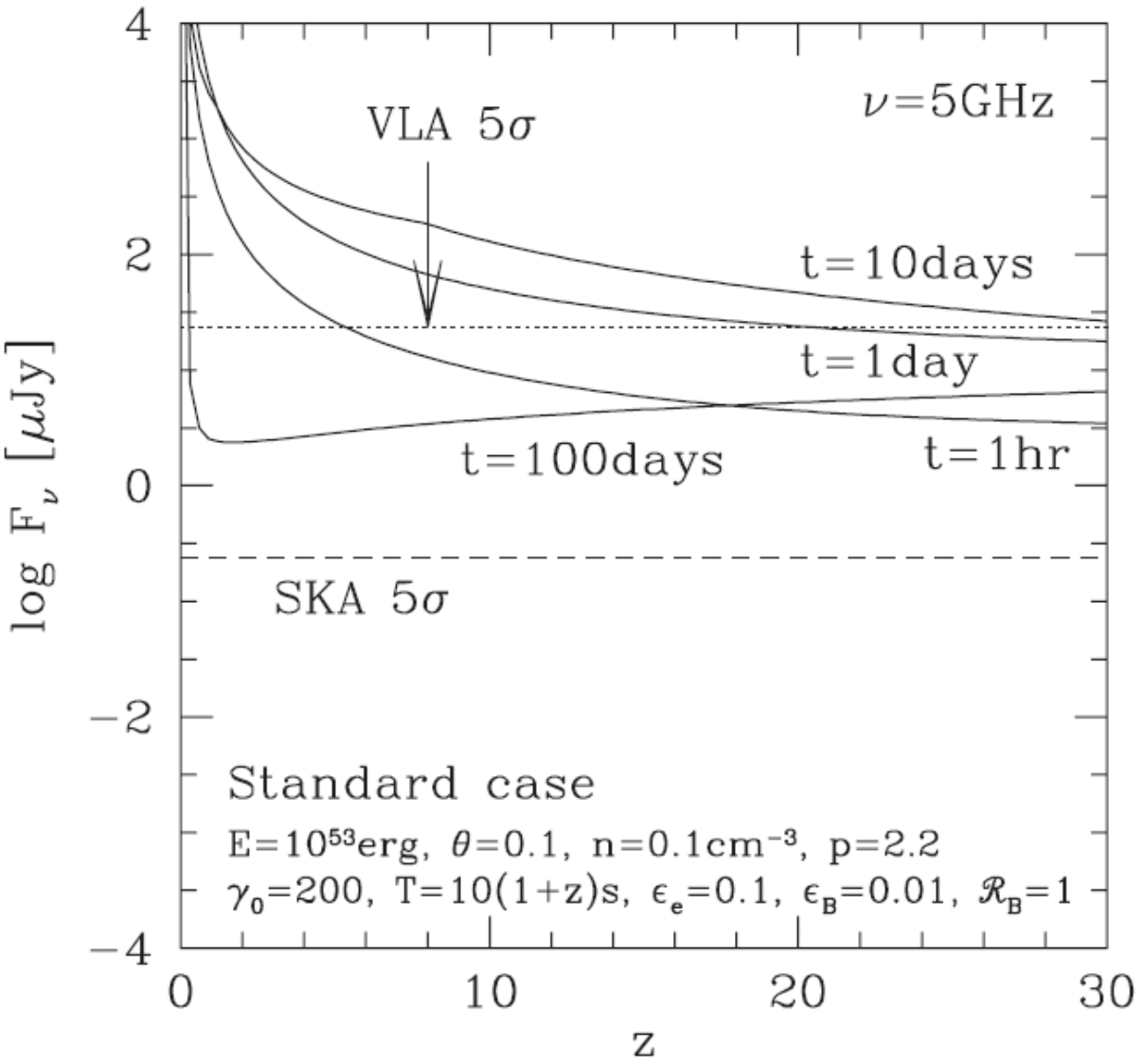
Pop III.1+III.2 Star Formation Rate

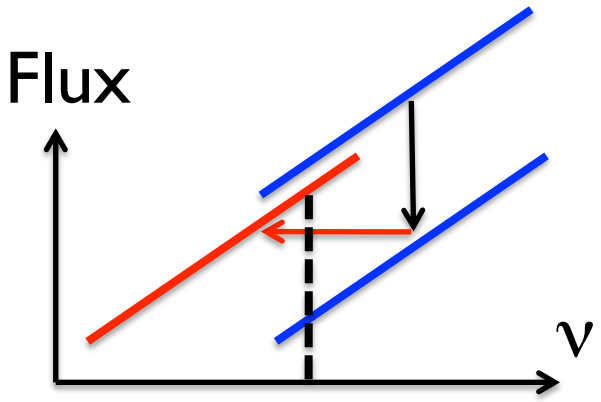


de Souza, Yoshida & KI 11

Our optimistic case is still conservative

Radio Afterglow





K-correction ⇒
Not dim @high-z

Spherical after jet break

KI & Meszaros 05
Inoue+ 07, Toma+ 10

Radio Transient Survey

Optimistic

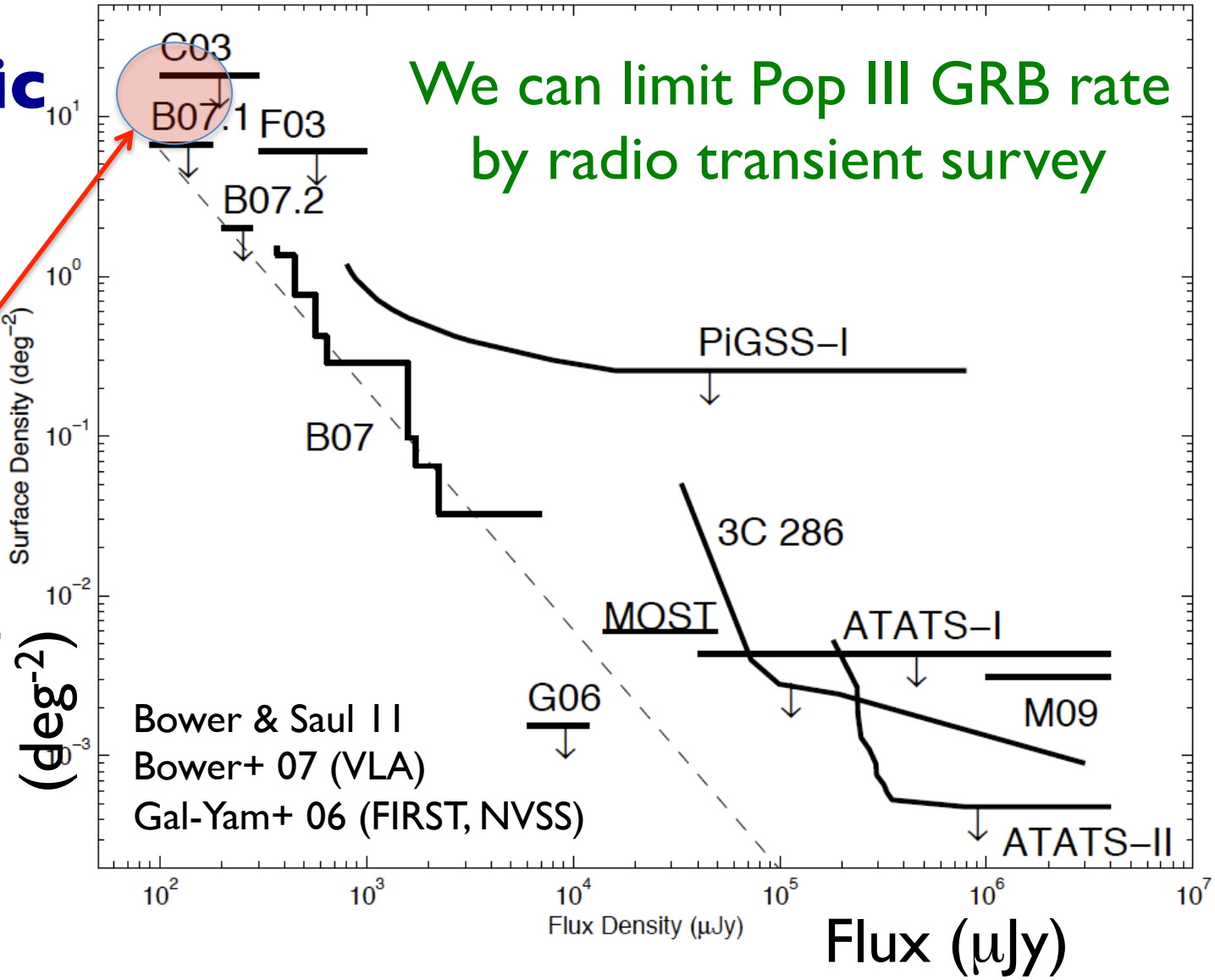
~10^5/yr/z

x (z~10)

x 100day

~3×10^5

on the sky



$\Delta t \sim 1yr$

Radio Transient Survey

Optimistic

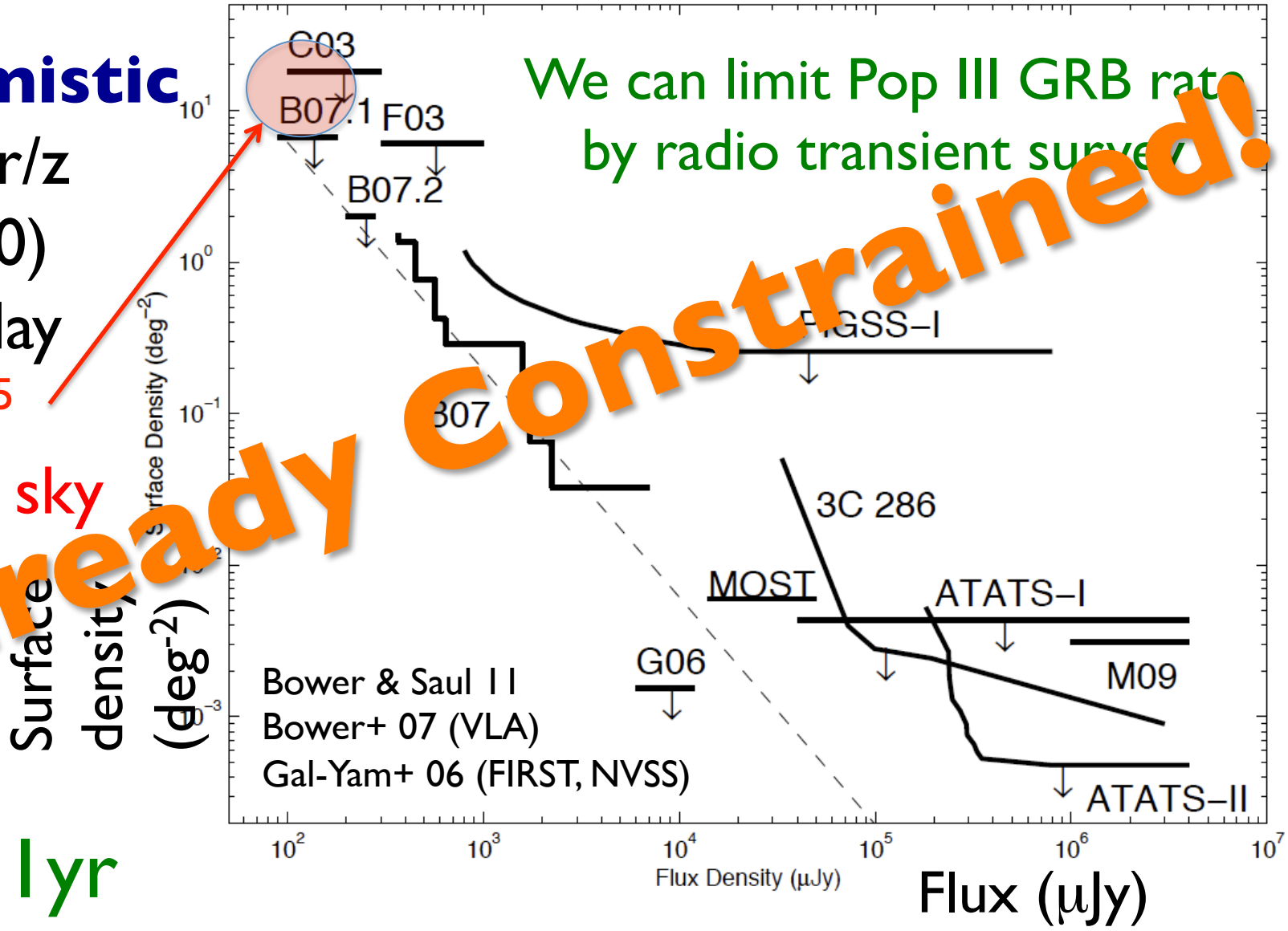
~10^5/yr/z

x (z~10)

x 100day

~3×10^5

on the sky

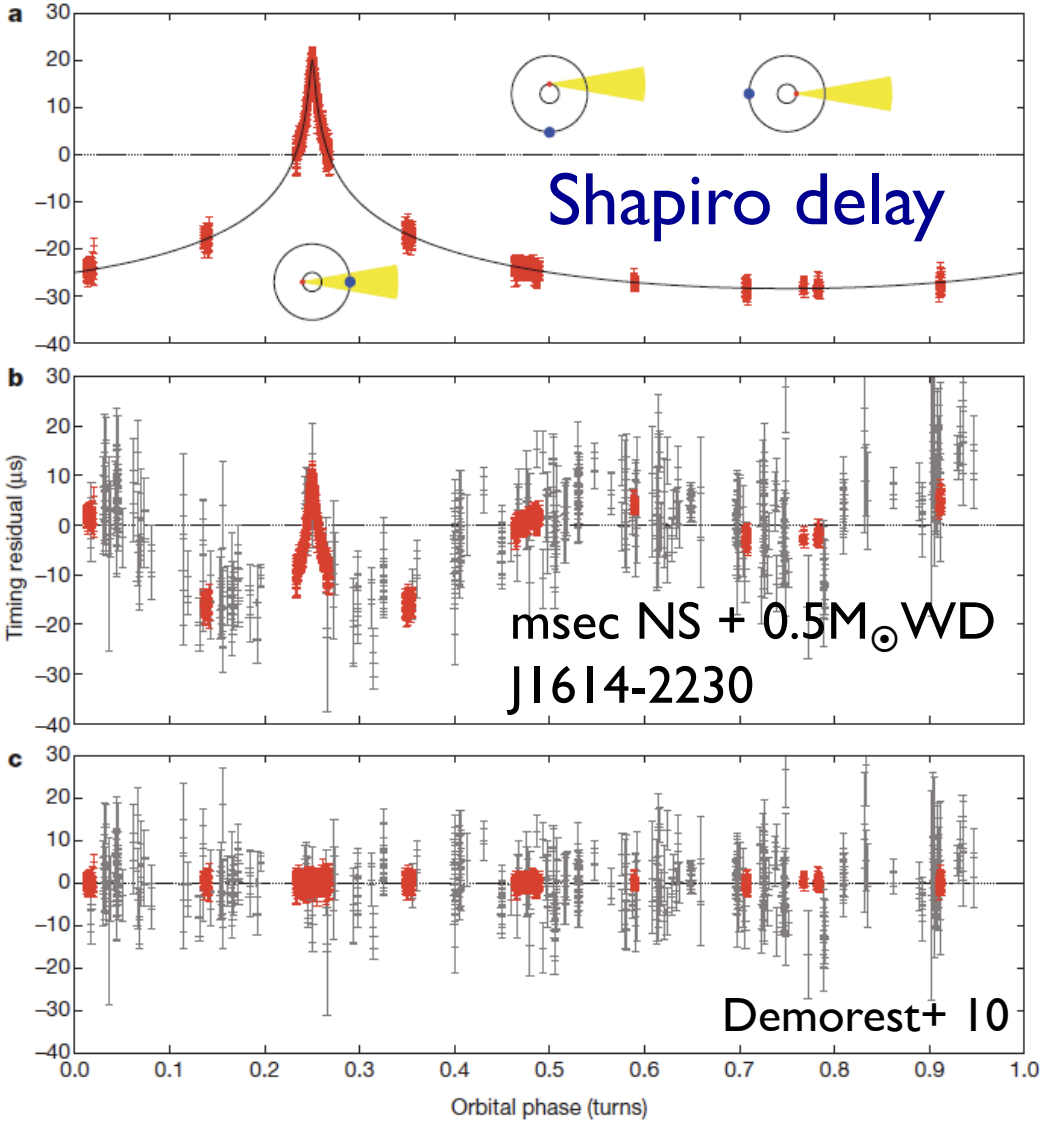


We can limit Pop III GRB rate by radio transient survey

Already Constrained!

$\Delta t \sim 1yr$

$2M_\odot$中性子星



- **~(1.97±0.04)$M_\odot$**
- 硬い状態方程式
- 中性子星がブラックホールに崩壊しにくい
- 連星中性子星合体
  ⇒ 超巨大中性子星
  ⇒ Short GRB
  の可能性を高める

See also Antoniadis+ 13

ULX

CIBER

Fermi Bubble

EBL, CIBER