Gravitational Waves from Binary Systems as Probes of the Universe

Nicolas Yunes
Assistant Professor
MSU

Sept 28th 2011,
JGRG 21 - Tohoku University

Standing on the Shoulders of...

Professors:

Clifford Will, Jim Gates, David Spergel, Stephon Alexander, Abhay Ashtekar, Sam Finn, Ben Owen, Bernd Bruegman, Pablo Laguna, Emanuele Berti, Alessandra Buonanno, Uli Sperhake, Dimitrios Psaltis, Avi Loeb, Scott Hughes, Carlos Sopuerta, Vitor Carodoso, Leonardo Gualtieri, **Takahiro Tanaka**, **Frans Pretorius, Neil Cornish**, **Cole Miller, Avi Loeb.**

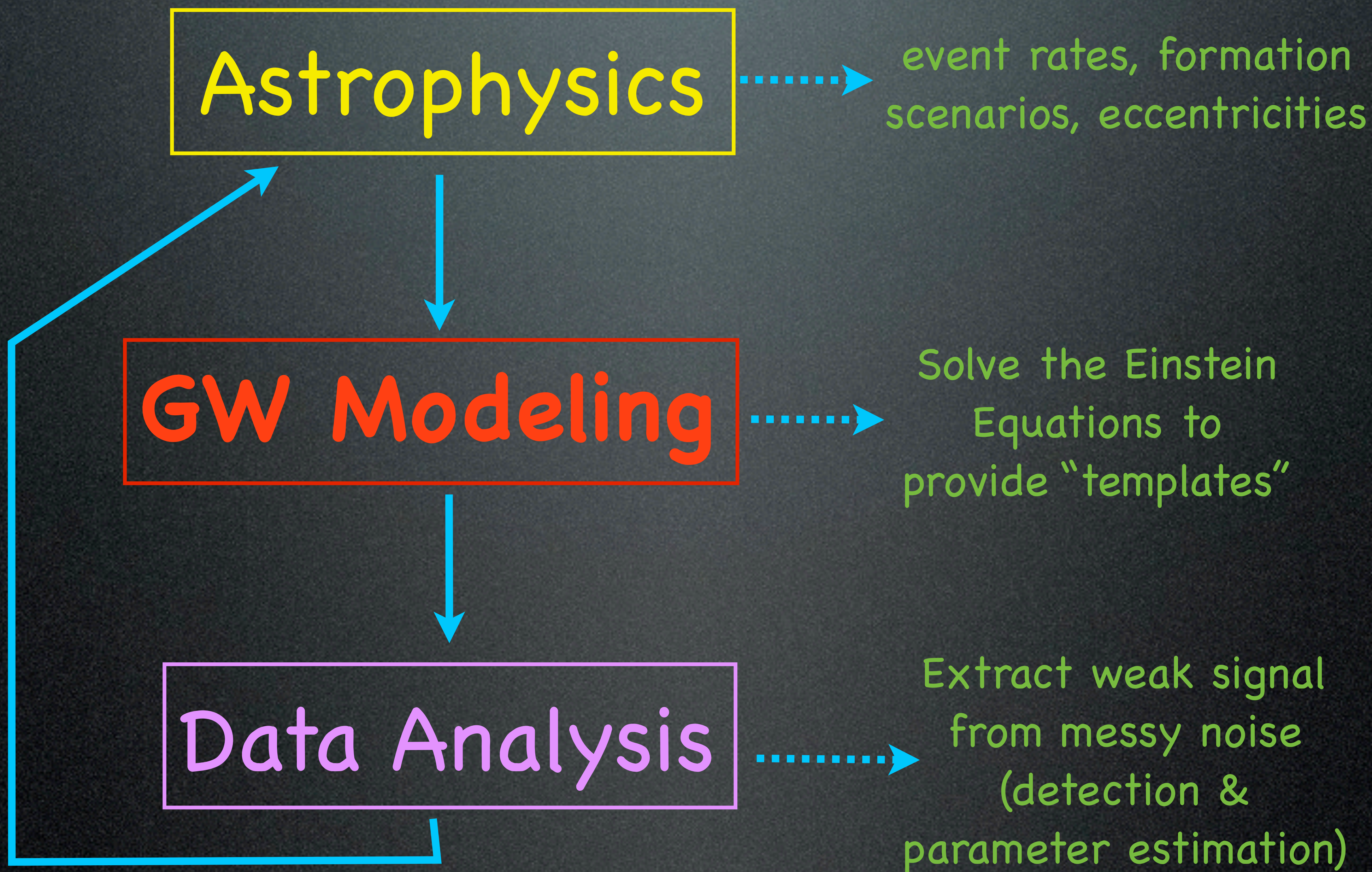
Post-Docs:

Victor Taveras, **Bence Kocsis**, Daniel Grumiller.

Graduate Students:

Laura Sampson, **Leo Stein**, **Sarah Vigeland**, **Kent Yagi**.

Multi-Messenger Astrophysics



GW Astrophysics: A two-way street

Astrophysical Environment

Electromagnetic Signal

Detection on Earth

Gravitational Environment

Gravitational Wave Event/ Signal

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Astrophysical Environment → Electromagnetic Signal → Detection on Earth

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Example: Accretion Disk flare

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Astrophysical Environment → Electromagnetic Signal → Detection on Earth

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Part of this talk is about how we can learn about astrophysics from gravitational wave detections.

Multi-Messenger Astrophysics

Astrophysics → event rates, formation scenarios, eccentricities

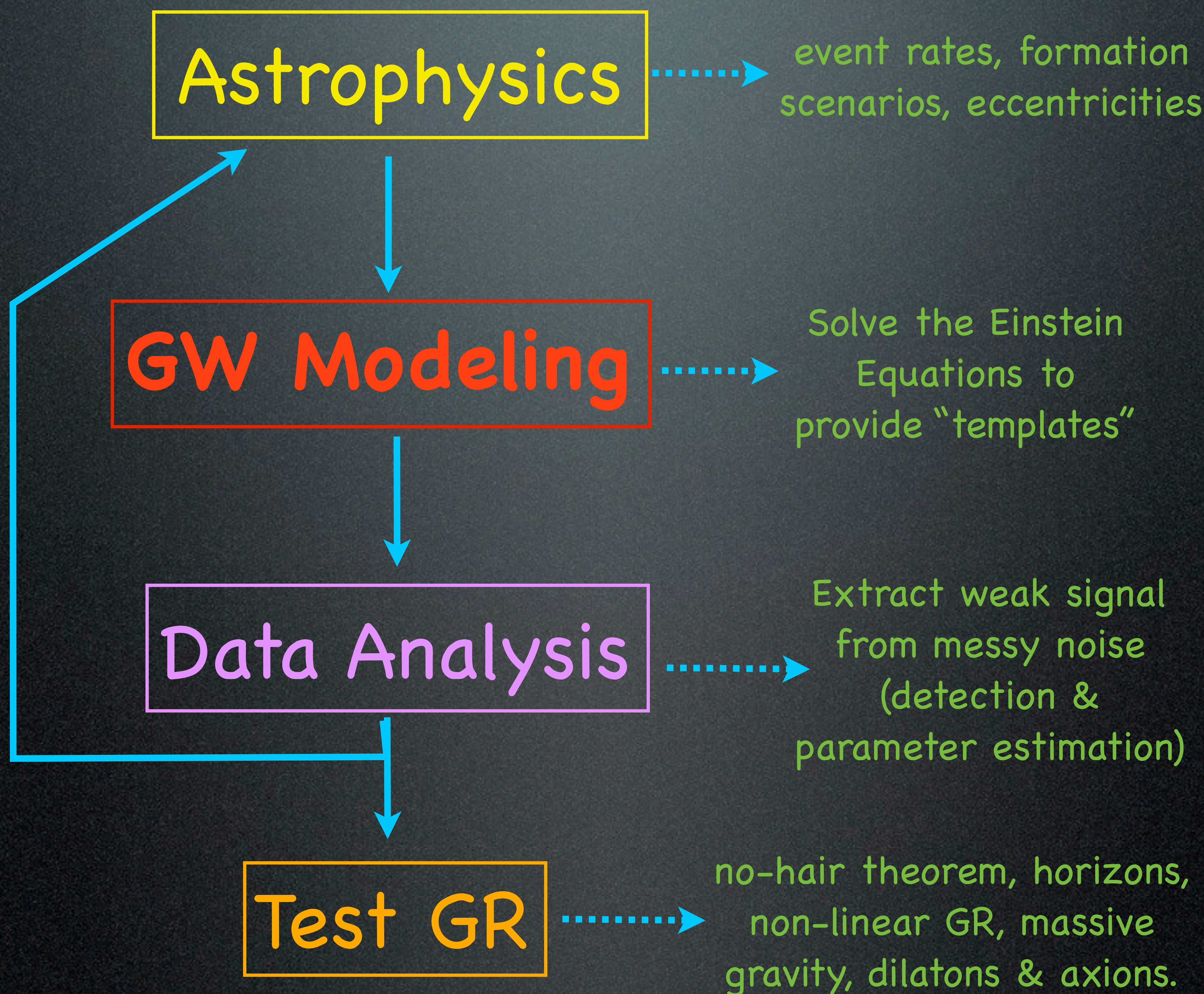
↓

GW Modeling → Solve the Einstein Equations to provide "templates"

↓

Data Analysis → Extract weak signal from messy noise (detection & parameter estimation)

Multi-Messenger Astrophysics



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Eg. Brans-Dicke Theory.

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- Find generic features and construct a "meta"-theory to test. Eg. ppN, ppK, **ppE**

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- Find generic features and construct a "meta"-theory to test. Eg. ppN, ppK, **ppE**
- Search for model-independent deviations from GR in the strong-field.

Road Map

I. Gravitational Wave Modeling

II. Connection to Astrophysics

III. Connection to Fundamental Theory

Part I: Gravitational Wave Modeling

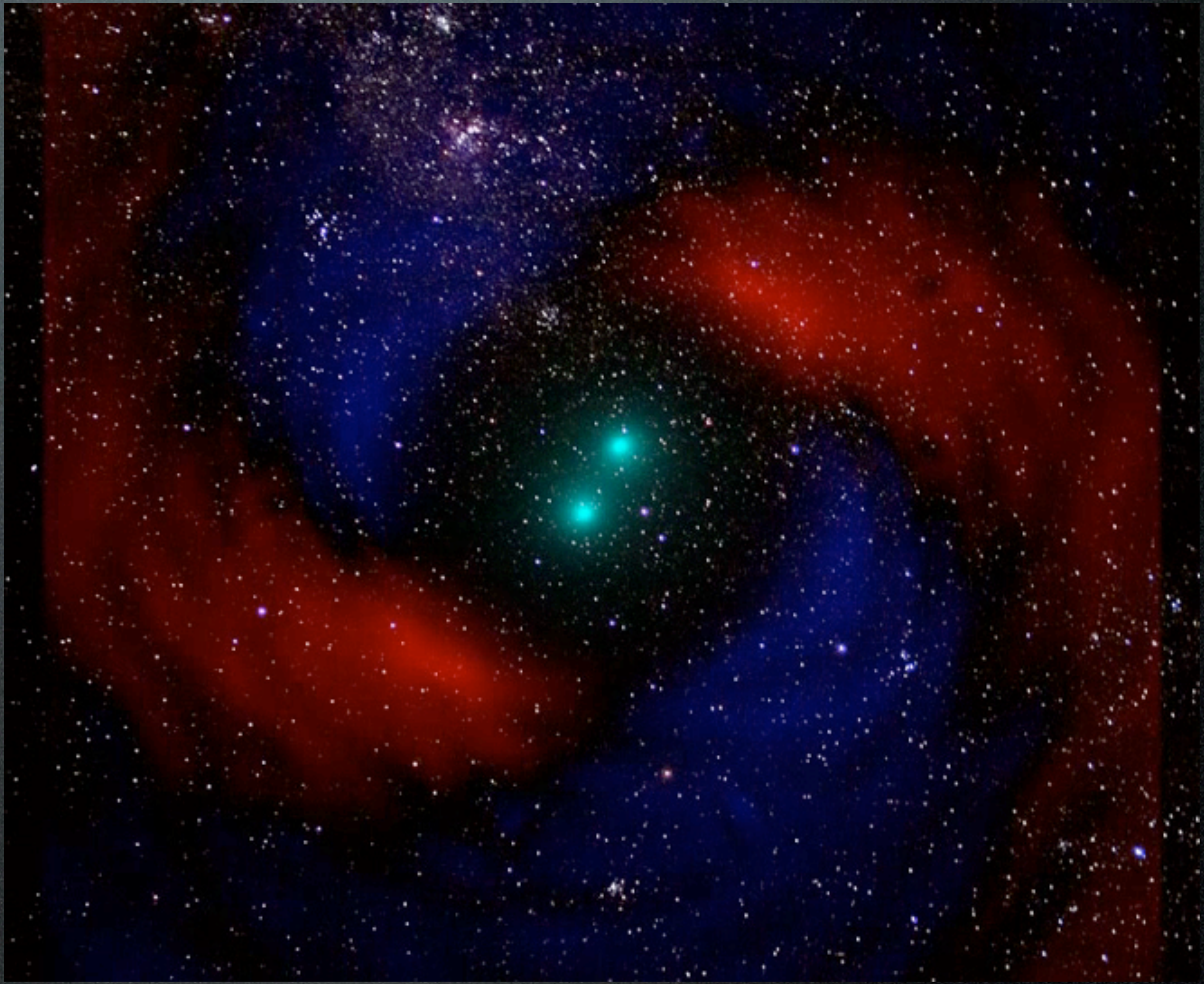
A Binary Black Hole Coalescence

m1=m2=4e6 Msun

10 M = 0.8 AU

(courtesy,
I. Hinder)

A Binary Black Hole Coalescence



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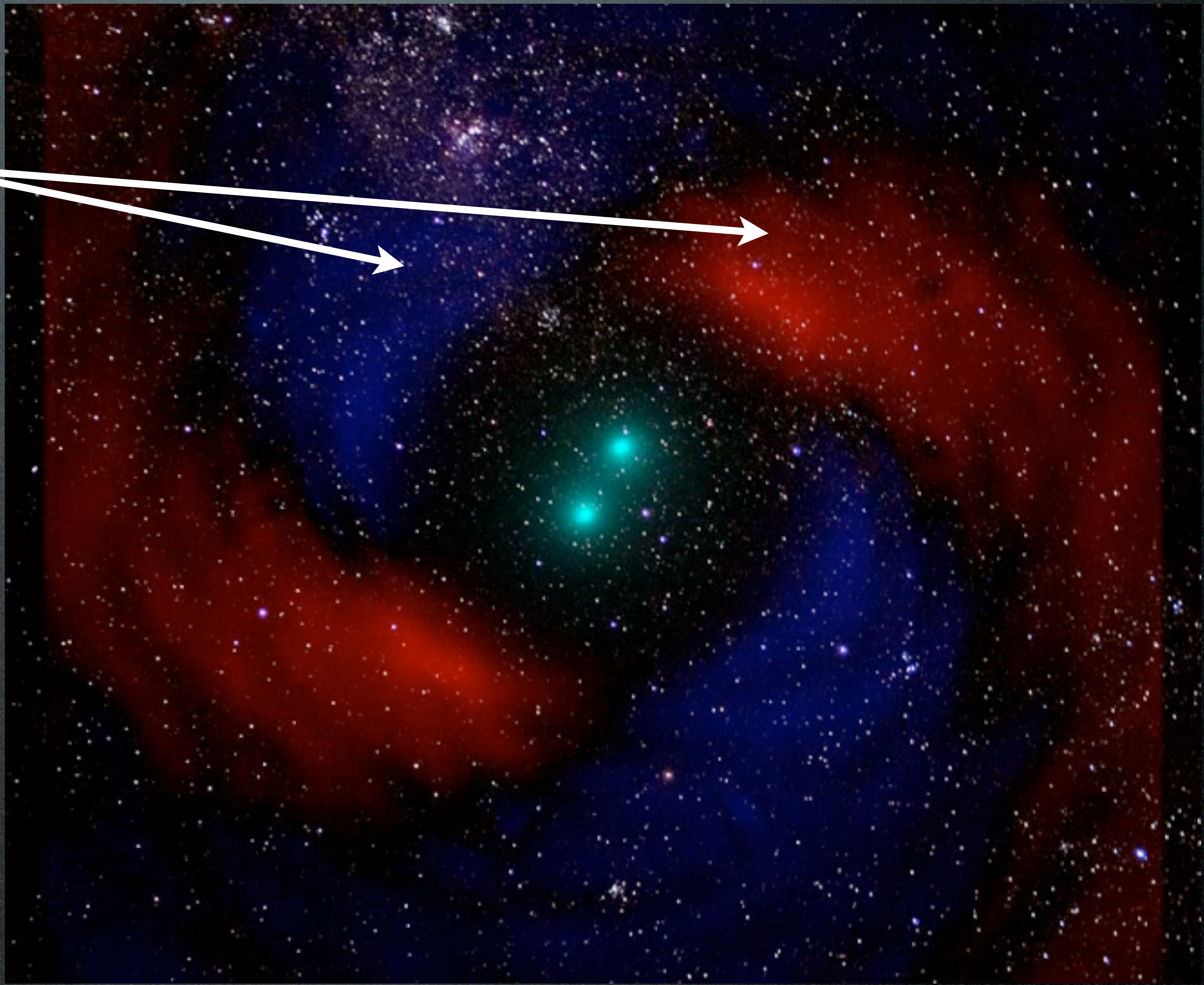
A Binary Black Hole Coalescence

Red/blue shows grav. waves := ripples in space and time, in the gravitational field



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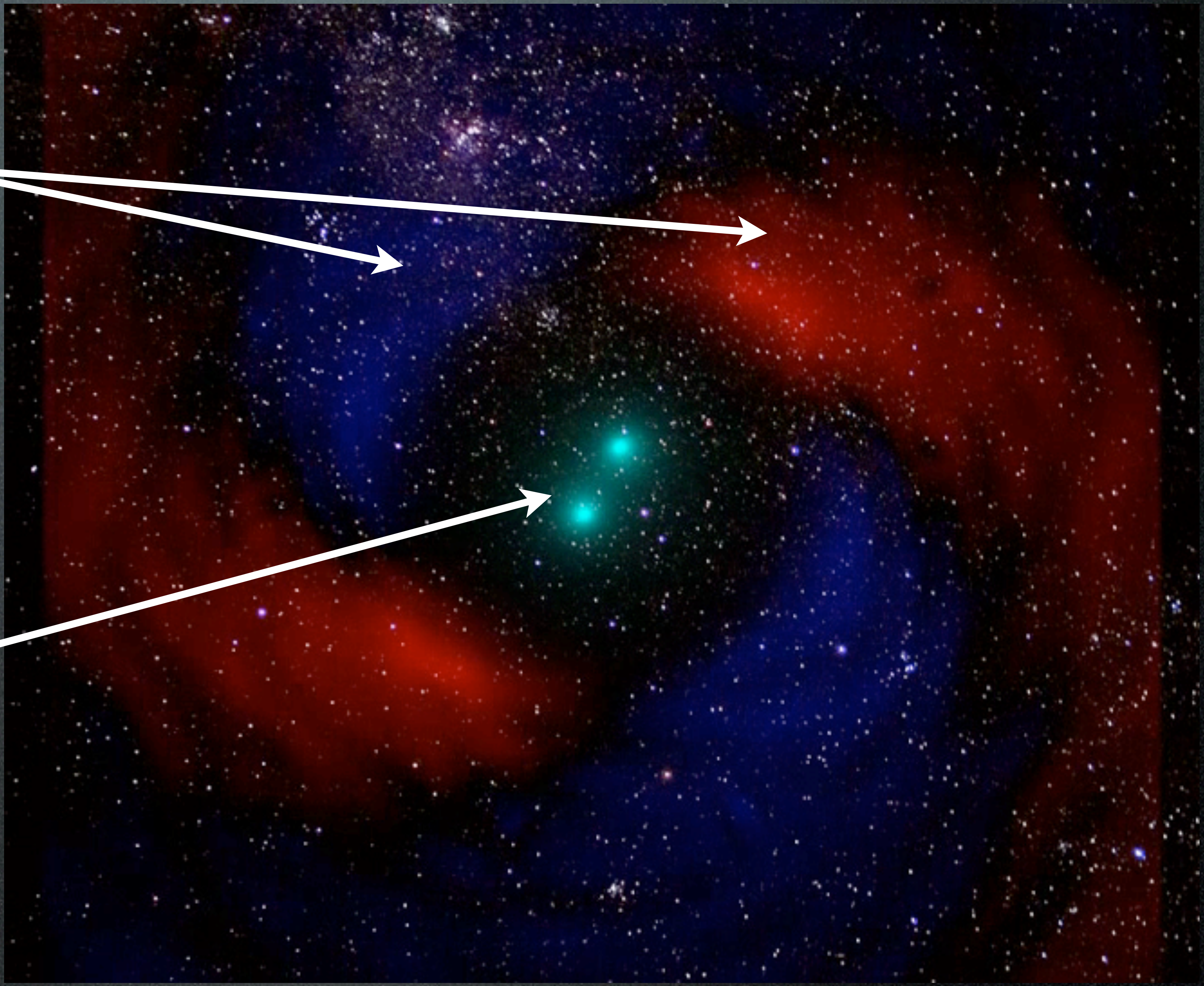
A Binary Black Hole Coalescence

Red/blue shows grav. waves := ripples in space and time, in the gravitational field

light cyan shows the strength of the grav. field



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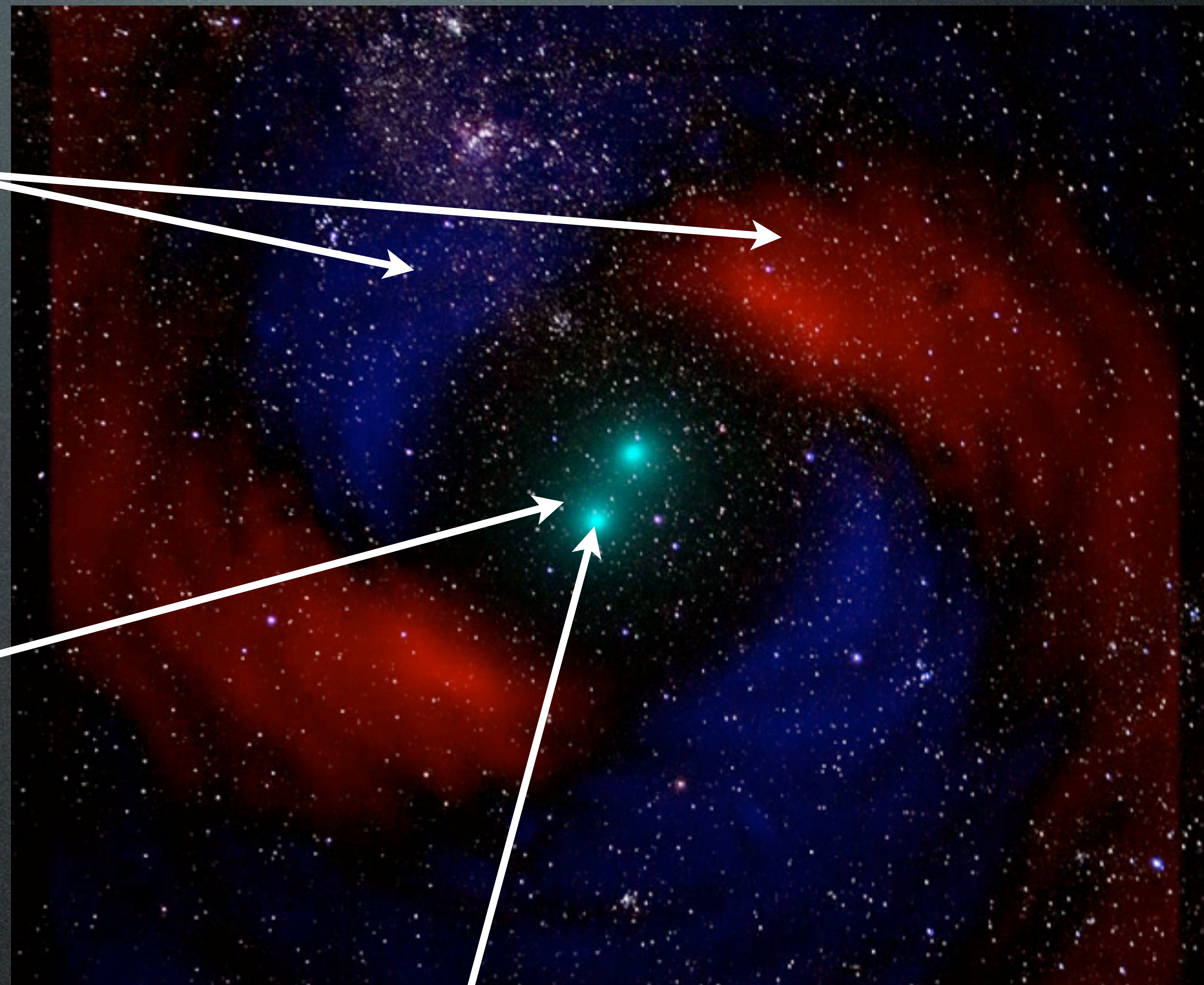

light cyan shows the strength of the grav. field

solid cyan shows (roughly) the location of the event horizon (BH surface)

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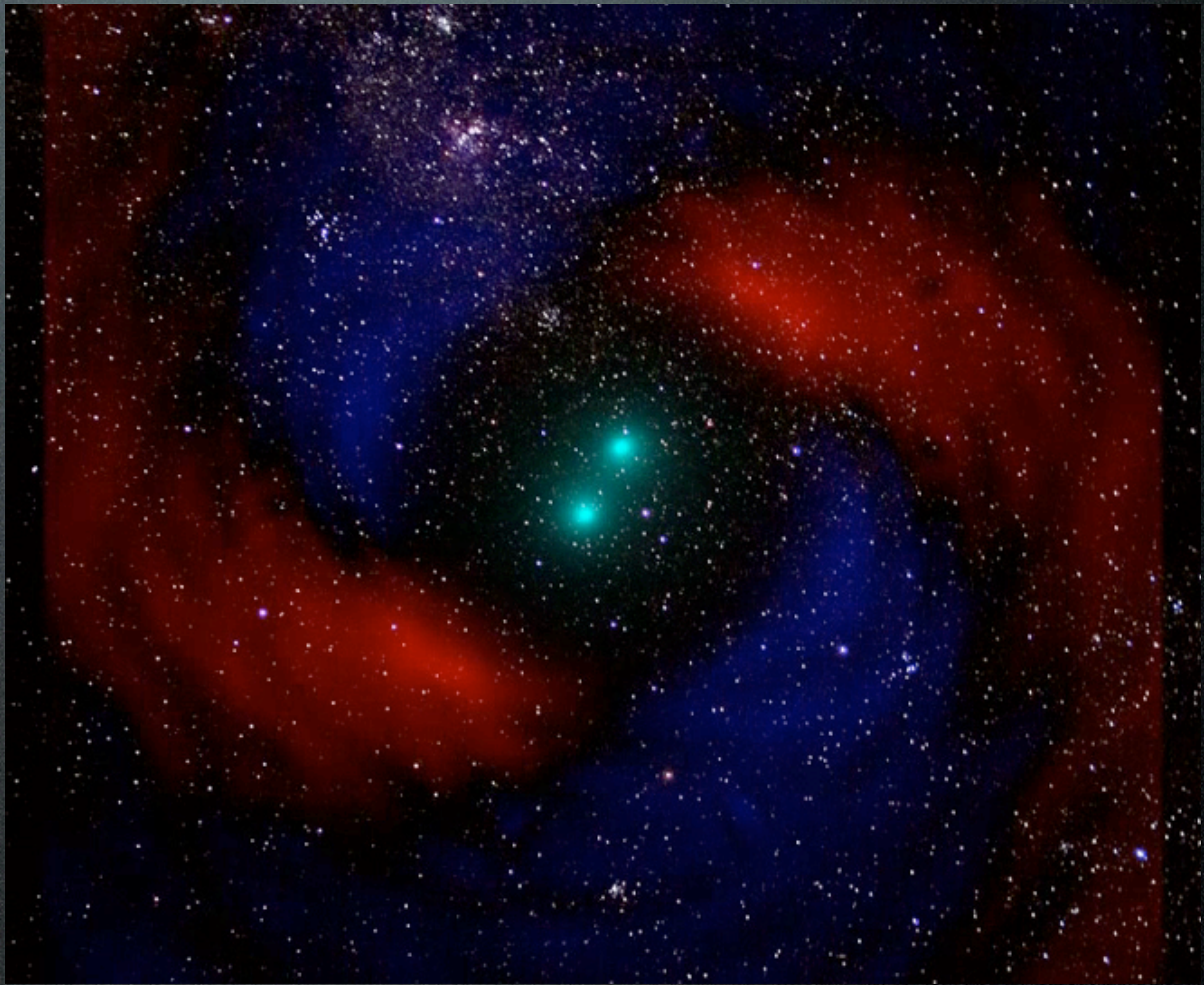

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Post-Newtonian Compact Binaries in GR

Metric Perturbation

$$\boxed{g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}}$$

(Futamase, Will, Damour, Blanchet, etc.)

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tensor

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Acceleration

$$\nabla^\mu \left(G_{\mu\nu} - 8\pi T_{\mu\nu}\right) = 0$$

Solve Perturbatively, assuming

Perfect Fluid

$$T_{\mu\nu} = (\rho + p) u_\mu u_\nu + p g_{\mu\nu}$$

(Futamase, Will, Damour, Blanchet, etc.)

Post-Newtonian Compact Binaries in GR

Metric Perturbation

$$\boxed{\underbrace{g_{\mu\nu}}_{\text{metric tensor}} = \underbrace{\eta_{\mu\nu}}_{\text{flat}} + \underbrace{h_{\mu\nu}}_{\text{GW metric pert.}}}$$

$$\boxed{\underbrace{G_{\mu\nu}}_{\text{Einstein tensor}} = 8\pi \underbrace{T_{\mu\nu}}_{\text{Stress-Energy tensor}}} \quad \rightarrow \quad \boxed{\underbrace{\Box_\eta}_{\text{Flat-space, diff. wave op.}} h_{\mu\nu} = \underbrace{\tau_{\mu\nu}[h^2]}_{\text{Annoying non-linearities}}}$$

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Point Particles

$$\boxed{\rho = m\, \delta^3(x^i - y^i)}$$

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Particle Location

orbital velocity

speed of light

$$\epsilon := \frac{v}{c} = \sqrt{\frac{m}{r}} \ll 1$$

total mass

orbital separation

(Futamase, Will, Damour, Blanchet, etc.)

Intimidation Slide

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Leading term: Newtonian gravity.

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$$+\frac{1}{c^2}\left\{\left[\frac{5G^2m_1m_2}{r_{12}^3}+\frac{4G^2m_2^2}{r_{12}^3}+\frac{Gm_2}{r_{12}^2}\left(\frac{3}{2}(n_{12}v_2)^2-v_1^2+4(v_1v_2)-2v_2^2\right)\right]n_{12}^i\right.$$
$$\left.+\frac{Gm_2}{r_{12}^2}\left(4(n_{12}v_1)-3(n_{12}v_2)\right)v_{12}^i\right\}$$

1 PN (Relativity corrections)

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1 PN (Relativity corrections)

$$+\frac{1}{c^4}\left\{\left[-\frac{57G^3m_1^2m_2}{4r_{12}^4}-\frac{69G^3m_1m_2^2}{2r_{12}^4}-\frac{9G^3m_2^3}{r_{12}^4}\right.\right.$$
$$+\frac{Gm_2}{r_{12}^2}\left(-\frac{15}{8}(n_{12}v_2)^4+\frac{3}{2}(n_{12}v_2)^2v_1^2-6(n_{12}v_2)^2(v_1v_2)-2(v_1v_2)^2+\frac{9}{2}(n_{12}v_2)^2v_2^2\right.$$
$$\left.+4(v_1v_2)v_2^2-2v_2^4\right)$$
$$+\frac{G^2m_1m_2}{r_{12}^3}\left(\frac{39}{2}(n_{12}v_1)^2-39(n_{12}v_1)(n_{12}v_2)+\frac{17}{2}(n_{12}v_2)^2-\frac{15}{4}v_1^2-\frac{5}{2}(v_1v_2)+\frac{5}{4}v_2^2\right)$$
$$\left.+\frac{G^2m_2^2}{r_{12}^3}\left(2(n_{12}v_1)^2-4(n_{12}v_1)(n_{12}v_2)-6(n_{12}v_2)^2-8(v_1v_2)+4v_2^2\right)\right]n_{12}^i$$
$$+\left[\frac{G^2m_2^2}{r_{12}^3}\left(-2(n_{12}v_1)-2(n_{12}v_2)\right)+\frac{G^2m_1m_2}{r_{12}^3}\left(-\frac{63}{4}(n_{12}v_1)+\frac{55}{4}(n_{12}v_2)\right)\right.$$
$$+\frac{Gm_2}{r_{12}^2}\left(-6(n_{12}v_1)(n_{12}v_2)^2+\frac{9}{2}(n_{12}v_2)^3+(n_{12}v_2)v_1^2-4(n_{12}v_1)(v_1v_2)\right.$$
$$\left.\left.\left.+4(n_{12}v_2)(v_1v_2)+4(n_{12}v_1)v_2^2-5(n_{12}v_2)v_2^2\right)\right]v_{12}^i\right\}$$

$$+\frac{1}{c^5}\left\{\left[\frac{208G^3m_1m_2^2}{15r_{12}^4}(n_{12}v_{12})-\frac{24G^3m_1^2m_2}{5r_{12}^4}(n_{12}v_{12})+\frac{12G^2m_1m_2}{5r_{12}^3}(n_{12}v_{12})v_{12}^2\right]n_{12}^i\right.$$
$$\left.+\left[\frac{8G^3m_1^2m_2}{5r_{12}^4}-\frac{32G^3m_1m_2^2}{5r_{12}^4}-\frac{4G^2m_1m_2}{5r_{12}^3}v_{12}^2\right]v_{12}^i\right\}$$

2 PN (more corrections ...)

and craziness ensues...

and craziness ensues...

3 PN (yet more corrections ...)

$$+\frac{1}{c^6}\Bigg\{\Bigg[\frac{Gm_2}{r_{12}^2}\Big(\frac{35}{16}(n_{12}v_2)^6-\frac{15}{8}(n_{12}v_2)^4v_1^2+\frac{15}{2}(n_{12}v_2)^4(v_1v_2)+3(n_{12}v_2)^2(v_1v_2)^2$$

$$-\frac{15}{2}(n_{12}v_2)^4v_2^2+\frac{3}{2}(n_{12}v_2)^2v_1^2v_2^2-12(n_{12}v_2)^2(v_1v_2)v_2^2-2(v_1v_2)^2v_2^2$$

$$+\frac{15}{2}(n_{12}v_2)^2v_2^4+4(v_1v_2)v_2^4-2v_2^6\Big)$$

$$+\frac{G^2m_1m_2}{r_{12}^3}\Big(-\frac{171}{8}(n_{12}v_1)^4+\frac{171}{2}(n_{12}v_1)^3(n_{12}v_2)-\frac{723}{4}(n_{12}v_1)^2(n_{12}v_2)^2$$

$$+\frac{383}{2}(n_{12}v_1)(n_{12}v_2)^3-\frac{455}{8}(n_{12}v_2)^4+\frac{229}{4}(n_{12}v_1)^2v_1^2$$

$$-\frac{205}{2}(n_{12}v_1)(n_{12}v_2)v_1^2+\frac{191}{4}(n_{12}v_2)^2v_1^2-\frac{91}{8}v_1^4-\frac{229}{2}(n_{12}v_1)^2(v_1v_2)$$

$$+244(n_{12}v_1)(n_{12}v_2)(v_1v_2)-\frac{225}{2}(n_{12}v_2)^2(v_1v_2)+\frac{91}{2}v_1^2(v_1v_2)$$

$$-\frac{177}{4}(v_1v_2)^2+\frac{229}{4}(n_{12}v_1)^2v_2^2-\frac{283}{2}(n_{12}v_1)(n_{12}v_2)v_2^2$$

$$+\frac{259}{4}(n_{12}v_2)^2v_2^2-\frac{91}{4}v_1^2v_2^2+43(v_1v_2)v_2^2-\frac{81}{8}v_2^4\Big)$$

$$+\frac{G^2m_2^2}{r_{12}^3}\Big(-6(n_{12}v_1)^2(n_{12}v_2)^2+12(n_{12}v_1)(n_{12}v_2)^3+6(n_{12}v_2)^4$$

$$+4(n_{12}v_1)(n_{12}v_2)(v_1v_2)+12(n_{12}v_2)^2(v_1v_2)+4(v_1v_2)^2$$

$$-4(n_{12}v_1)(n_{12}v_2)v_2^2-12(n_{12}v_2)^2v_2^2-8(v_1v_2)v_2^2+4v_2^4\Big)$$

$$+\frac{G^3m_2^3}{r_{12}^4}\Big(-(n_{12}v_1)^2+2(n_{12}v_1)(n_{12}v_2)+\frac{43}{2}(n_{12}v_2)^2+18(v_1v_2)-9v_2^2\Big)$$

$$+\frac{G^3m_1m_2^2}{r_{12}^4}\Big(\frac{415}{8}(n_{12}v_1)^2-\frac{375}{4}(n_{12}v_1)(n_{12}v_2)+\frac{1113}{8}(n_{12}v_2)^2-\frac{615}{64}(n_{12}v_{12})^2\pi^2$$

$$+18v_1^2+\frac{123}{64}\pi^2v_{12}^2+33(v_1v_2)-\frac{33}{2}v_2^2\Big)$$

$$+\frac{G^3m_1^2m_2}{r_{12}^4}\Big(-\frac{45887}{168}(n_{12}v_1)^2+\frac{24025}{42}(n_{12}v_1)(n_{12}v_2)-\frac{10469}{42}(n_{12}v_2)^2+\frac{48197}{840}v_1^2$$

$$-\frac{36227}{420}(v_1v_2)+\frac{36227}{840}v_2^2+110(n_{12}v_{12})^2\ln\Big(\frac{r_{12}}{r_1'}\Big)-22v_{12}^2\ln\Big(\frac{r_{12}}{r_1'}\Big)\Big)$$

$$+\frac{16G^4m_2^4}{r_{12}^5}+\frac{G^4m_1^2m_2^2}{r_{12}^5}\Big(175-\frac{41}{16}\pi^2\Big)+\frac{G^4m_1^3m_2}{r_{12}^5}\Big(\frac{3187}{1260}+\frac{44}{3}\ln\Big(\frac{r_{12}}{r_1'}\Big)\Big)$$

$$+\frac{G^4m_1m_2^3}{r_{12}^5}\Big(\frac{110741}{630}-\frac{41}{16}\pi^2-\frac{44}{3}\ln\Big(\frac{r_{12}}{r_2'}\Big)\Big)\Bigg]n_{12}^i$$

$$+\Bigg[\frac{Gm_2}{r_{12}^2}\Big(\frac{15}{2}(n_{12}v_1)(n_{12}v_2)^4-\frac{45}{8}(n_{12}v_2)^5-\frac{3}{2}(n_{12}v_2)^3v_1^2+6(n_{12}v_1)(n_{12}v_2)^2(v_1v_2)$$

$$-6(n_{12}v_2)^3(v_1v_2)-2(n_{12}v_2)(v_1v_2)^2-12(n_{12}v_1)(n_{12}v_2)^2v_2^2+12(n_{12}v_2)^3v_2^2$$

$$+(n_{12}v_2)v_1^2v_2^2-4(n_{12}v_1)(v_1v_2)v_2^2+8(n_{12}v_2)(v_1v_2)v_2^2+4(n_{12}v_1)v_2^4$$

$$-7(n_{12}v_2)v_2^4\Big)$$

$$+\frac{G^2m_2^2}{r_{12}^3}\Big(-2(n_{12}v_1)^2(n_{12}v_2)+8(n_{12}v_1)(n_{12}v_2)^2+2(n_{12}v_2)^3+2(n_{12}v_1)(v_1v_2)$$

$$+4(n_{12}v_2)(v_1v_2)-2(n_{12}v_1)v_2^2-4(n_{12}v_2)v_2^2\Big)$$

$$+\frac{G^2m_1m_2}{r_{12}^3}\Big(-\frac{243}{4}(n_{12}v_1)^3+\frac{565}{4}(n_{12}v_1)^2(n_{12}v_2)-\frac{269}{4}(n_{12}v_1)(n_{12}v_2)^2$$

$$-\frac{95}{12}(n_{12}v_2)^3+\frac{207}{8}(n_{12}v_1)v_1^2-\frac{137}{8}(n_{12}v_2)v_1^2-36(n_{12}v_1)(v_1v_2)$$

$$+\frac{27}{4}(n_{12}v_2)(v_1v_2)+\frac{81}{8}(n_{12}v_1)v_2^2+\frac{83}{8}(n_{12}v_2)v_2^2\Big)$$

$$+\frac{G^3m_2^3}{r_{12}^4}(4(n_{12}v_1)+5(n_{12}v_2))$$

$$+\frac{G^3m_1m_2^2}{r_{12}^4}\Big(-\frac{307}{8}(n_{12}v_1)+\frac{479}{8}(n_{12}v_2)+\frac{123}{32}(n_{12}v_{12})\pi^2\Big)$$

$$+\frac{G^3m_1^2m_2}{r_{12}^4}\Big(\frac{31397}{420}(n_{12}v_1)-\frac{36227}{420}(n_{12}v_2)-44(n_{12}v_{12})\ln\Big(\frac{r_{12}}{r_1'}\Big)\Big)\Bigg]v_{12}^i\Bigg\}$$

$$+\frac{1}{c^7}\Bigg\{\Bigg[\frac{G^4m_1^3m_2}{r_{12}^5}\Big(\frac{3992}{105}(n_{12}v_1)-\frac{4328}{105}(n_{12}v_2)\Big)$$

$$+\frac{G^4m_1^2m_2^2}{r_{12}^6}\Big(-\frac{13576}{105}(n_{12}v_1)+\frac{2872}{21}(n_{12}v_2)\Big)-\frac{3172}{21}\frac{G^4m_1m_2^3}{r_{12}^6}(n_{12}v_{12})$$

$$+\frac{G^3m_1^2m_2}{r_{12}^4}\Big(48(n_{12}v_1)^3-\frac{696}{5}(n_{12}v_1)^2(n_{12}v_2)+\frac{744}{5}(n_{12}v_1)(n_{12}v_2)^2-\frac{288}{5}(n_{12}v_2)^3$$

$$-\frac{4888}{105}(n_{12}v_1)v_1^2+\frac{5056}{105}(n_{12}v_2)v_1^2+\frac{2056}{21}(n_{12}v_1)(v_1v_2)$$

$$-\frac{2224}{21}(n_{12}v_2)(v_1v_2)-\frac{1028}{21}(n_{12}v_1)v_2^2+\frac{5812}{105}(n_{12}v_2)v_2^2\Big)$$

$$+\frac{G^3m_1m_2^2}{r_{12}^4}\Big(-\frac{582}{5}(n_{12}v_1)^3+\frac{1746}{5}(n_{12}v_1)^2(n_{12}v_2)-\frac{1954}{5}(n_{12}v_1)(n_{12}v_2)^2$$

$$+158(n_{12}v_2)^3+\frac{3568}{105}(n_{12}v_{12})v_1^2-\frac{2864}{35}(n_{12}v_1)(v_1v_2)$$

$$+\frac{10048}{105}(n_{12}v_2)(v_1v_2)+\frac{1432}{35}(n_{12}v_1)v_2^2-\frac{5752}{105}(n_{12}v_2)v_2^2\Big)$$

$$+\frac{G^2m_1m_2}{r_{12}^3}\Big(-56(n_{12}v_{12})^5+60(n_{12}v_1)^3v_{12}^2-180(n_{12}v_1)^2(n_{12}v_2)v_{12}^2$$

$$+174(n_{12}v_1)(n_{12}v_2)^2v_{12}^2-54(n_{12}v_2)^3v_{12}^2-\frac{246}{35}(n_{12}v_{12})v_1^4$$

$$+\frac{1068}{35}(n_{12}v_1)v_1^2(v_1v_2)-\frac{984}{35}(n_{12}v_2)v_1^2(v_1v_2)-\frac{1068}{35}(n_{12}v_1)(v_1v_2)^2$$

$$+\frac{180}{7}(n_{12}v_2)(v_1v_2)^2-\frac{534}{35}(n_{12}v_1)v_1^2v_2^2+\frac{90}{7}(n_{12}v_2)v_1^2v_2^2$$

$$+\frac{984}{35}(n_{12}v_1)(v_1v_2)v_2^2-\frac{732}{35}(n_{12}v_2)(v_1v_2)v_2^2-\frac{204}{35}(n_{12}v_1)v_2^4$$

$$+\frac{24}{7}(n_{12}v_2)v_2^4\Big)\Bigg]n_{12}^i$$

$$+\Bigg[-\frac{184}{21}\frac{G^4m_1^3m_2}{r_{12}^5}+\frac{6224}{105}\frac{G^4m_1^2m_2^2}{r_{12}^6}+\frac{6388}{105}\frac{G^4m_1m_2^3}{r_{12}^6}$$

$$+\frac{G^3m_1^2m_2}{r_{12}^4}\Big(\frac{52}{15}(n_{12}v_1)^2-\frac{56}{15}(n_{12}v_1)(n_{12}v_2)-\frac{44}{15}(n_{12}v_2)^2-\frac{132}{35}v_1^2+\frac{152}{35}(v_1v_2)$$

$$-\frac{48}{35}v_2^2\Big)$$

$$+\frac{G^3m_1m_2^2}{r_{12}^4}\Big(\frac{454}{15}(n_{12}v_1)^2-\frac{372}{5}(n_{12}v_1)(n_{12}v_2)+\frac{854}{15}(n_{12}v_2)^2-\frac{152}{21}v_1^2$$

$$+\frac{2864}{105}(v_1v_2)-\frac{1768}{105}v_2^2\Big)$$

$$+\frac{G^2m_1m_2}{r_{12}^3}\Big(60(n_{12}v_{12})^4-\frac{348}{5}(n_{12}v_1)^2v_{12}^2+\frac{684}{5}(n_{12}v_1)(n_{12}v_2)v_{12}^2$$

$$-66(n_{12}v_2)^2v_{12}^2+\frac{334}{35}v_1^4-\frac{1336}{35}v_1^2(v_1v_2)+\frac{1308}{35}(v_1v_2)^2+\frac{654}{35}v_1^2v_2^2$$

$$-\frac{1252}{35}(v_1v_2)v_2^2+\frac{292}{35}v_2^4\Big)\Bigg]v_{12}^i\Bigg\}$$

$$+\mathcal{O}\Big(\frac{1}{c^8}\Big).$$

[Blanchet 2006, Liv Rev Rel 9, 4, Eq. (168)]

Compact Binaries in **Effective** Alternative Theories

$$\boxed{G_{\mu\nu} + \zeta\, C_{\mu\nu} = 8\pi T_{\mu\nu}}$$

Start with the modified field equations

(Yagi, Stein, Yunes and Tanaka '10)

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But be careful!!

The point-particle description of BHs works in GR (in part due to the Birkhoff theorem), but this need not be so in Alternative Theories. In fact, usually one must compensate for violations of this description.

(Yagi, Stein, Yunes and Tanaka '10)

Semi-Analytical Phase Modeling

If we know that the only thing modified is the Hamiltonian and the Radiation-Reaction force --> Modified Hamiltonian Evolution (effective-one-body approach)

Damour & Buonanno '08,
Yunes, et al, PRL '11,
PRD 83 '11, PRL 104 '10.

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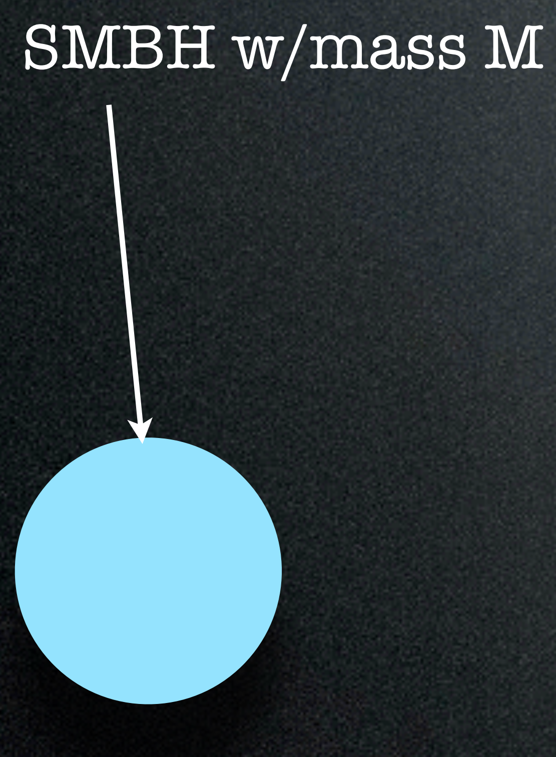
A modification to either of these components leads to a correction that we might observe.

Part II: Connection to Astrophysics

EMRIs and Massive Perturbers

Yunes, Miller, Thornburg, PRD 83 (2010)

EMRIs and Massive Perturbers



Yunes, Miller, Thornburg, PRD 83 (2010)

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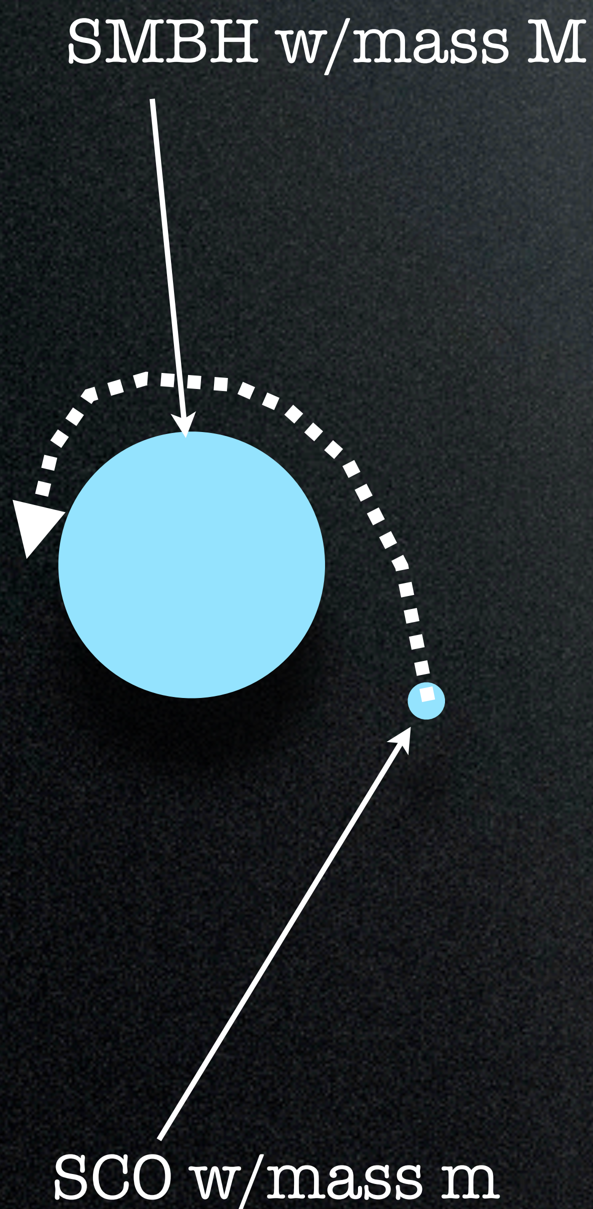

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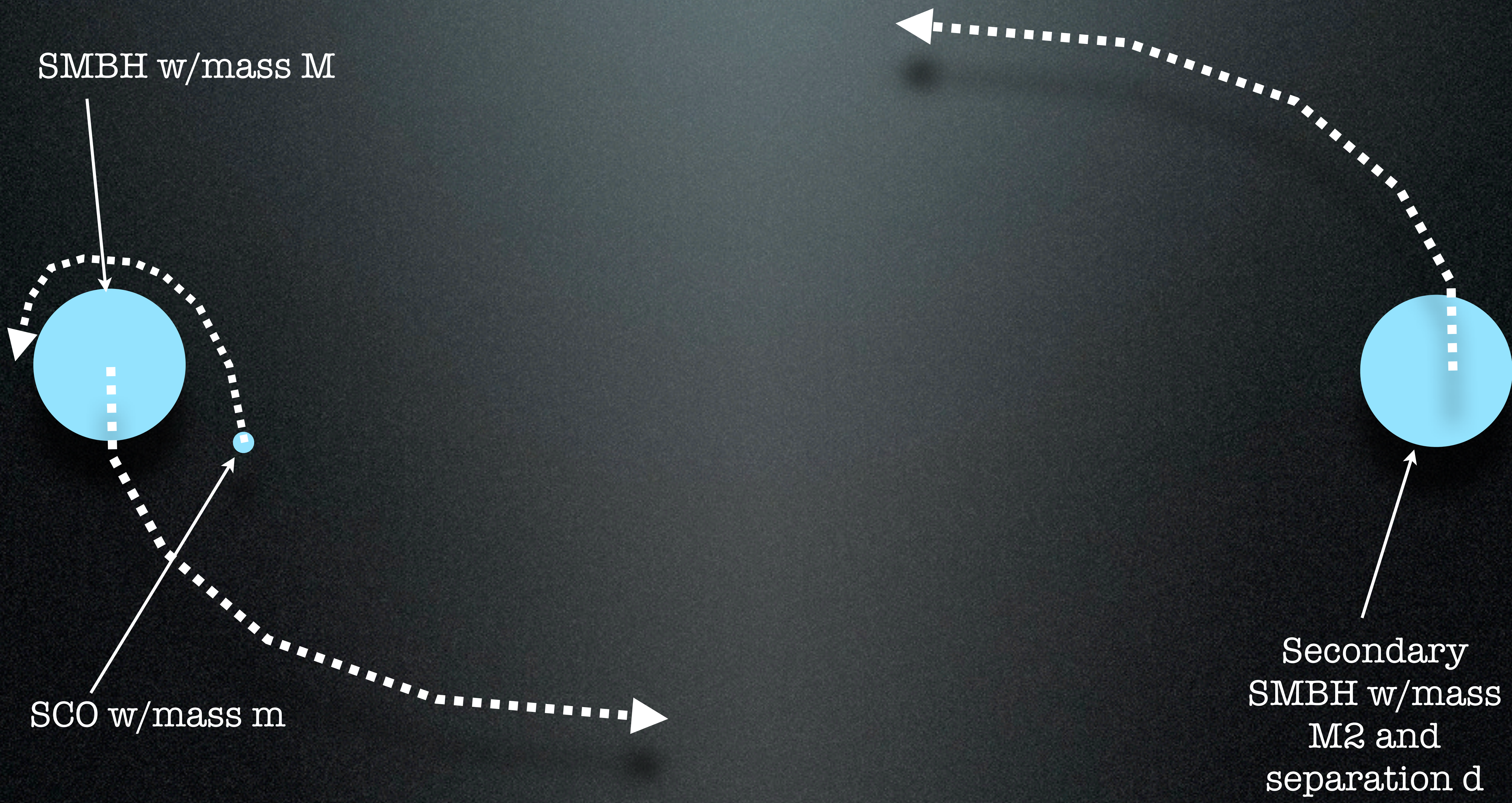
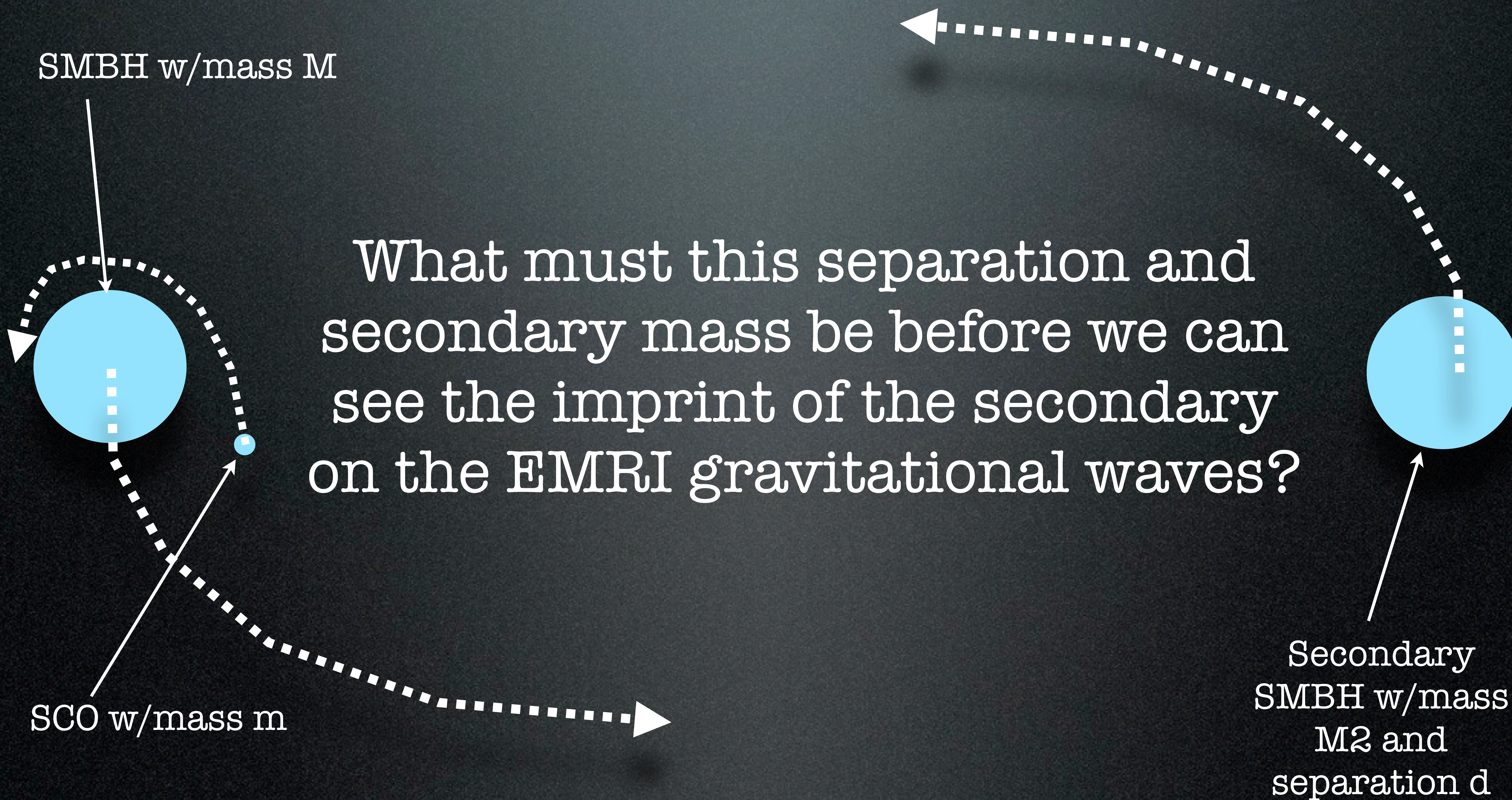
EMRIs and Massive Perturbers



Yunes, Miller, Thornburg, PRD 83 (2010)

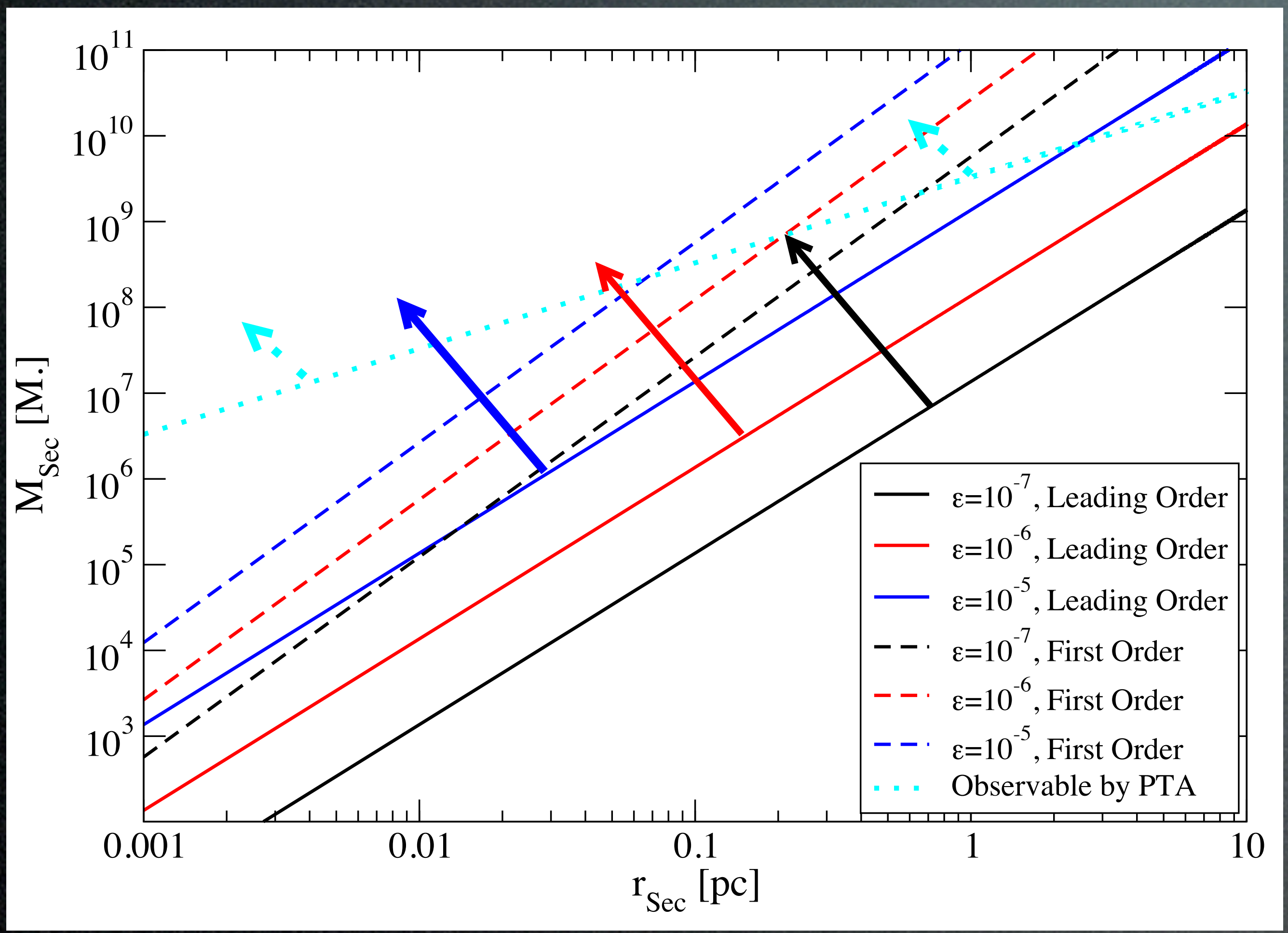
EMRIs and Massive Perturbers

What must this separation and secondary mass be before we can see the imprint of the secondary on the EMRI gravitational waves?



Yunes, Miller, Thornburg, PRD 83 (2010)

Detecting a Massive Companion



$$\Phi_{\rm GW} = \int F(t)\,(1 + v_{\rm los})\,dt$$

Yunes, Miller, Thornburg, PRD 83 (2010)

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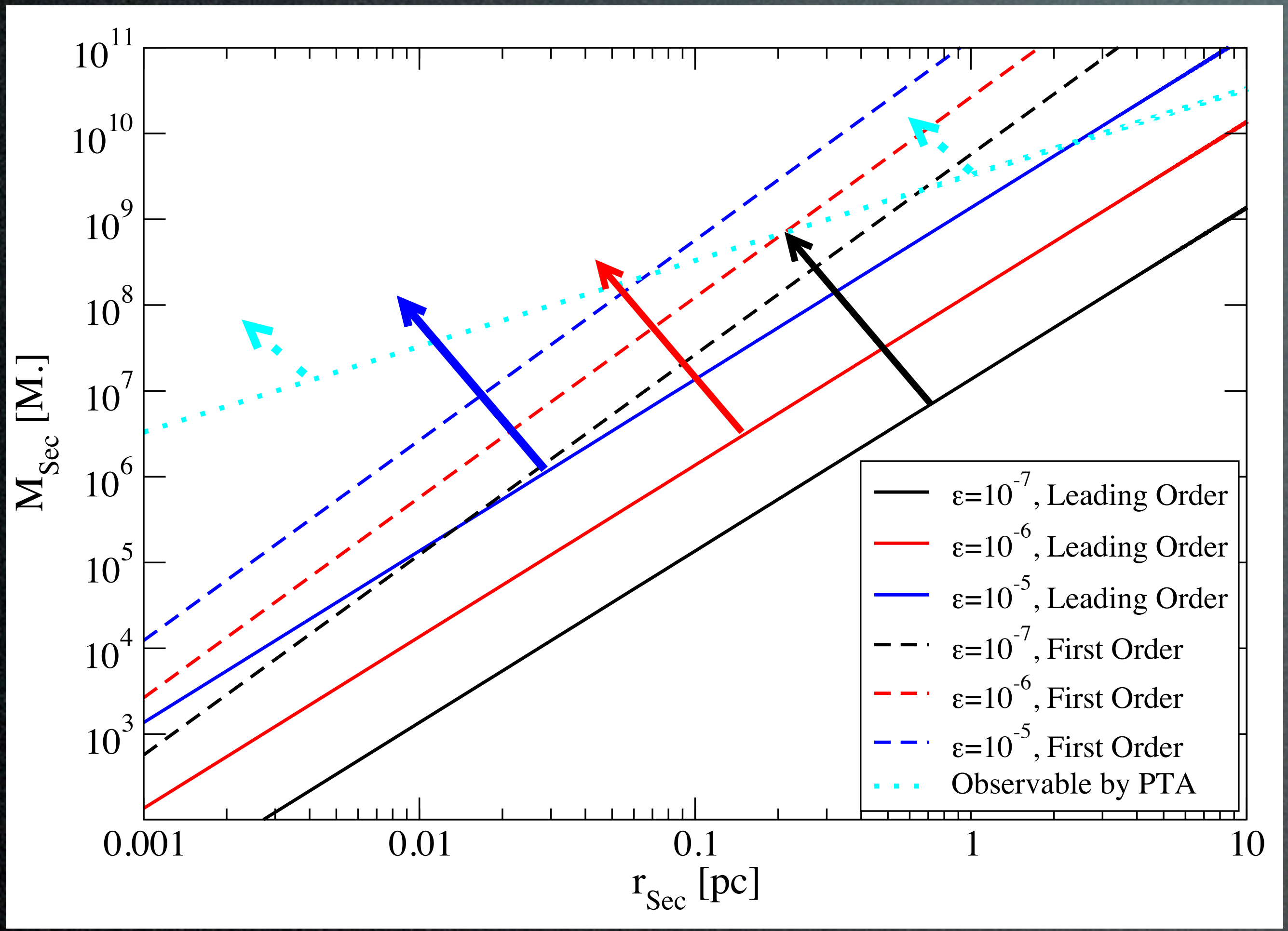

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GW Phase

GW Frequency

Velocity along the line of sight

Yunes, Miller, Thornburg, PRD 83 (2010)

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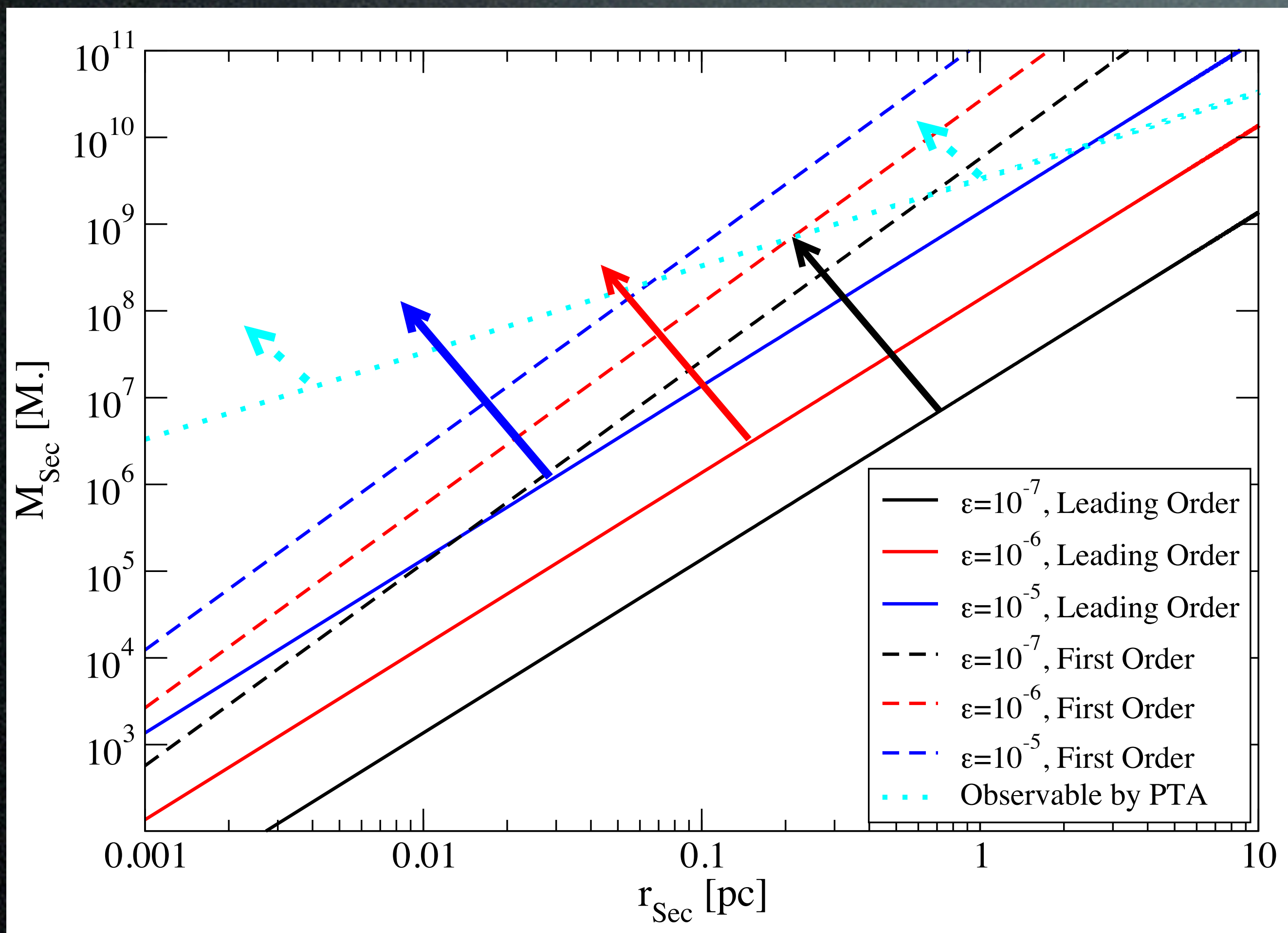

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Velocity along the line of sight

$$\delta\Phi_{\rm GW} \sim N_{\rm cycles}\left(\frac{M_{\rm Tot}}{r_{\rm Sec}^{2}}\right) T_{\rm obs}$$

# of Cycles

Acceleration

Observation Time

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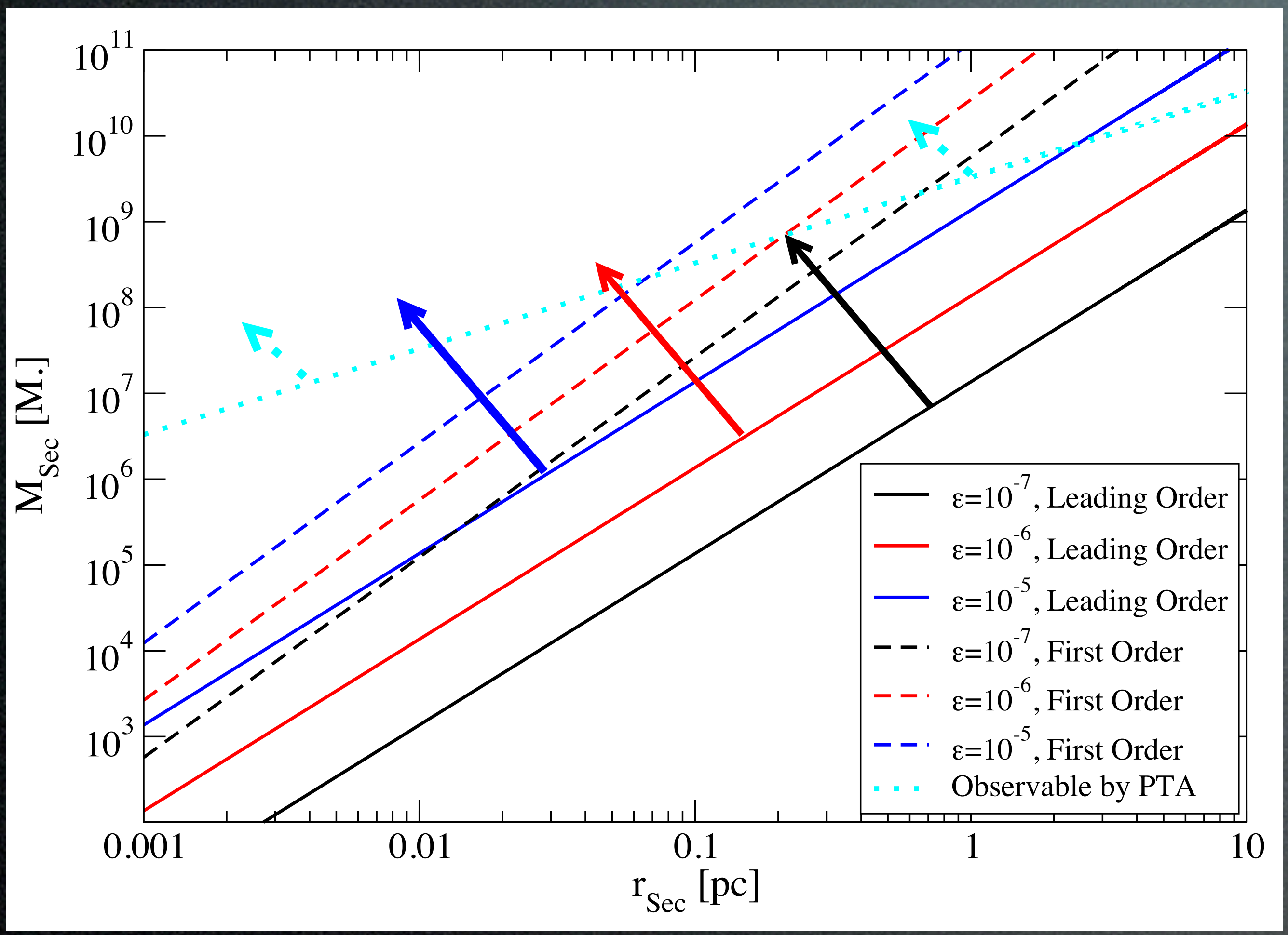

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If a sec. BH with mass 1e7 Msun is at about 1/10 pc from EMRI (acc about 1e-4 m/s^2) we might see it.

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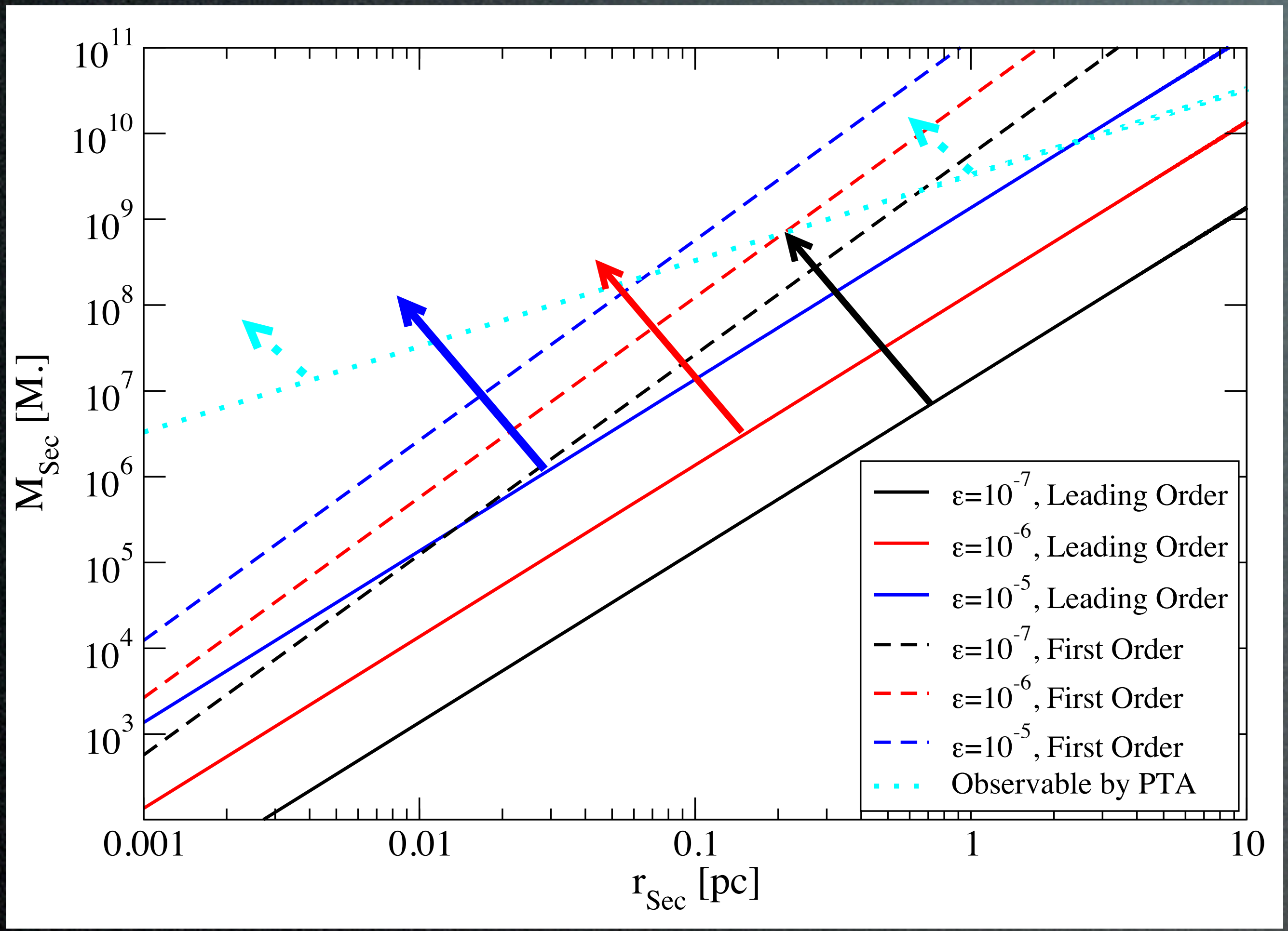

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$$\delta\Psi_{\rm FFT,GW} \sim \frac{3}{128}(\pi\mathcal{M}f)^{-5/3}\left[\frac{M_{\rm Sec}\mathcal{M}}{r^2_{\rm Sec}}(\pi\mathcal{M}f)^{-8/3}\right]$$

clear spectral signature

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Accretion Disks and EMRIs

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- Beta: viscosity proportional to gas pressure only.

Disk Effects Considered

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- Migration: Disk Spiral arms carry L away from the SCO, forcing it to inspiral into SMBH faster -> changes Edot. Two types: I (no gap forms) and II (a gap forms, gas pile up).

$$\delta\phi \in (1, 10^3) \text{ rads}$$

Part III: Connection to Fundamental Theory

Waveforms in Alternative Theories

Waveforms in Alternative Theories

(i) Scalar-Tensor theories:

(Will '94, Scharre & Will '02, Will & Yunes '04, Berti, Buonanno & Will '05, Yagi & Tanaka '09)

$$\boxed{\tilde{h} = \tilde{h}_{\rm GR} e^{i \, \beta_{\rm BD} \, \eta^{2/5} u^{-7/3}}}$$

because of dipolar energy emission

inversely related to the BD coupling parameter

reduced GW frequency (u = pi Mc f)

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(iv) G(t) theories:

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$$\boxed{\tilde{h} = \tilde{h}_{\rm GR} \left(1 + \alpha_{\dot{G}}\, \eta^{3/5} u^{-8/3}\right) e^{i\, \beta_{\dot{G}} \eta^{3/5} u^{-13/3}}}$$

related to $\dot{G}$

More Examples

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We have still not found any theories whose predicted gravitational wave correction cannot be mapped to such a phase and Amp corrections

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Strong-field GR remains completely untested

A modification to the Einstein Equations leads to corrections to the waveform that we can search for.

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Search GW Data with these templates and let the data decide what the parameters should be.

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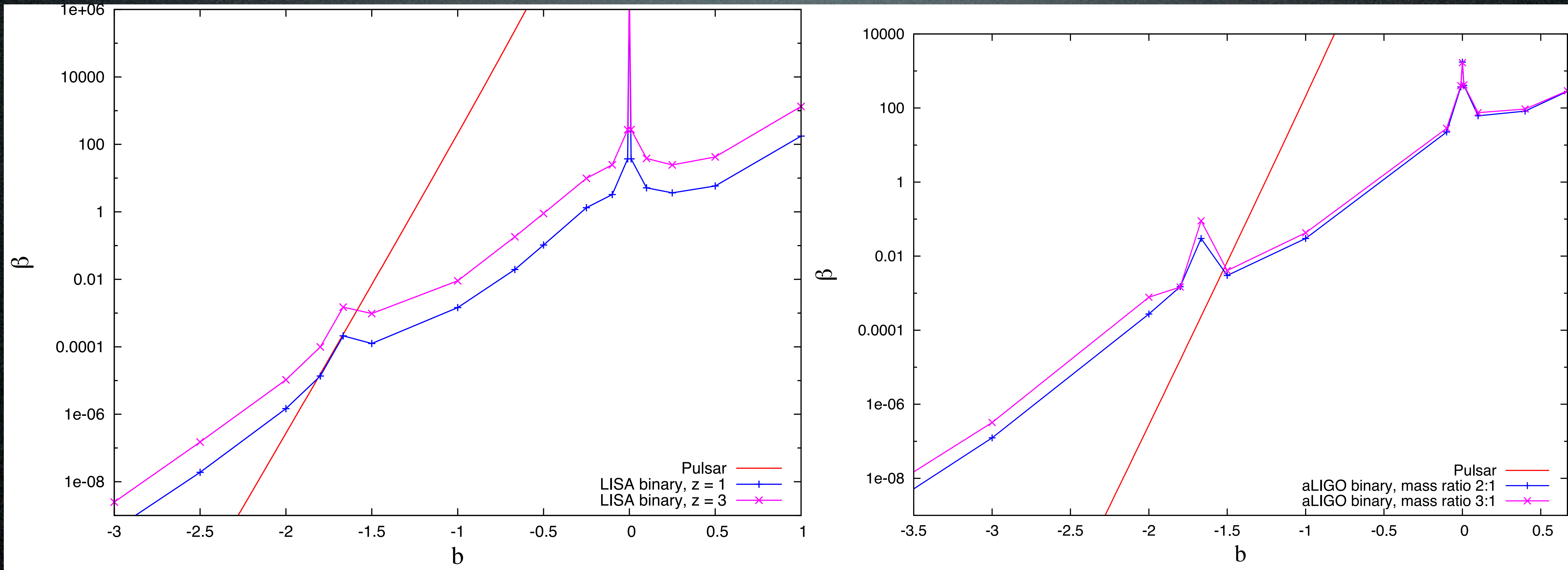
Templates/ Theories	GR	ppE
GR	Business as usual	**Quantify** the likelihood of GR being the underlying theory describing the detected event, within the class of alt. theories captured by ppE
Not GR	Understand the bias that could be introduced filtering non-GR events with GR templates	Measure deviations from GR characterized by non-GR ppE parameters.

Constraining GR Deviations

GR Signal/ppE Templates, 3-sigma constraints, SNR = 20



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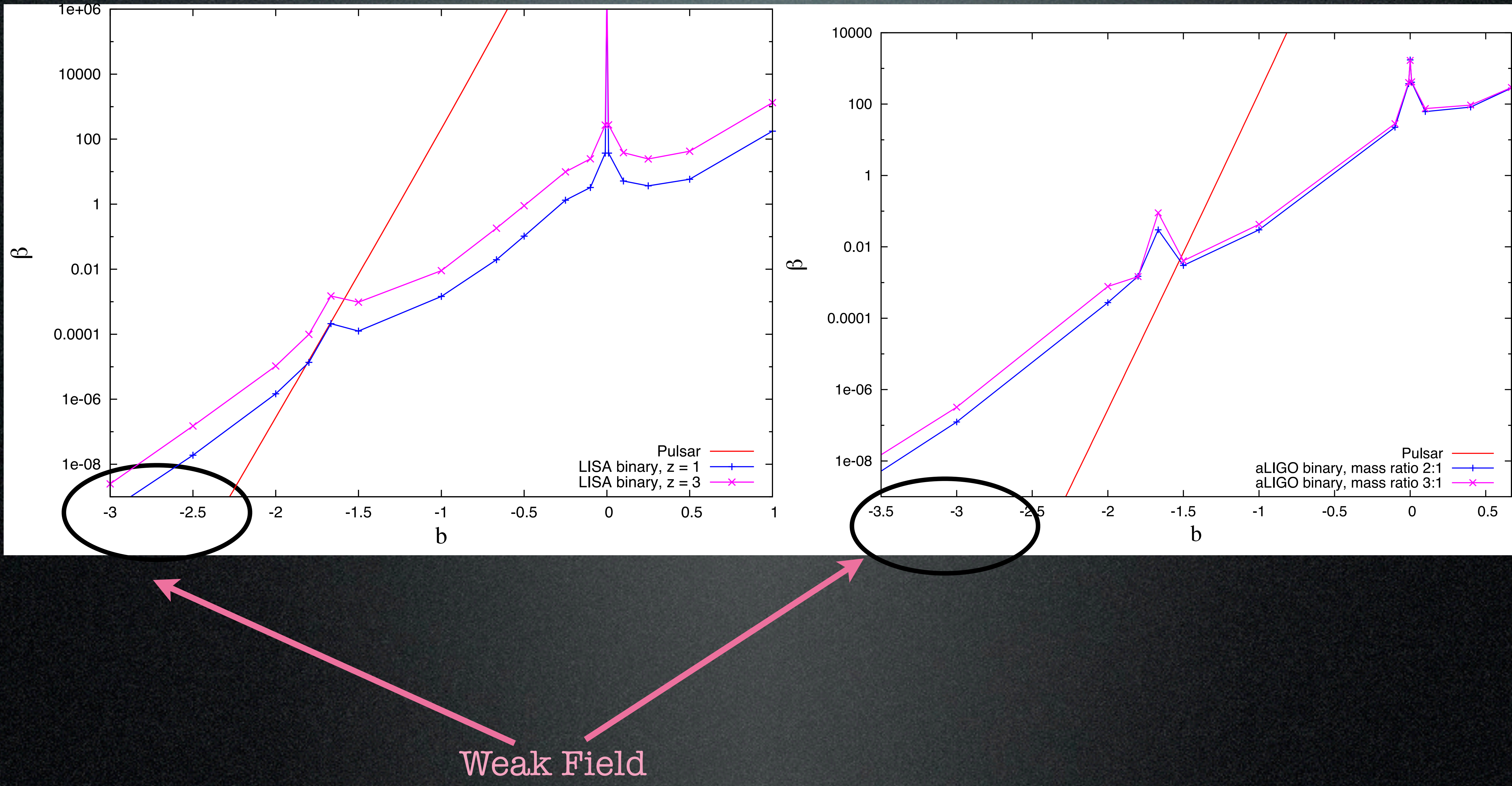

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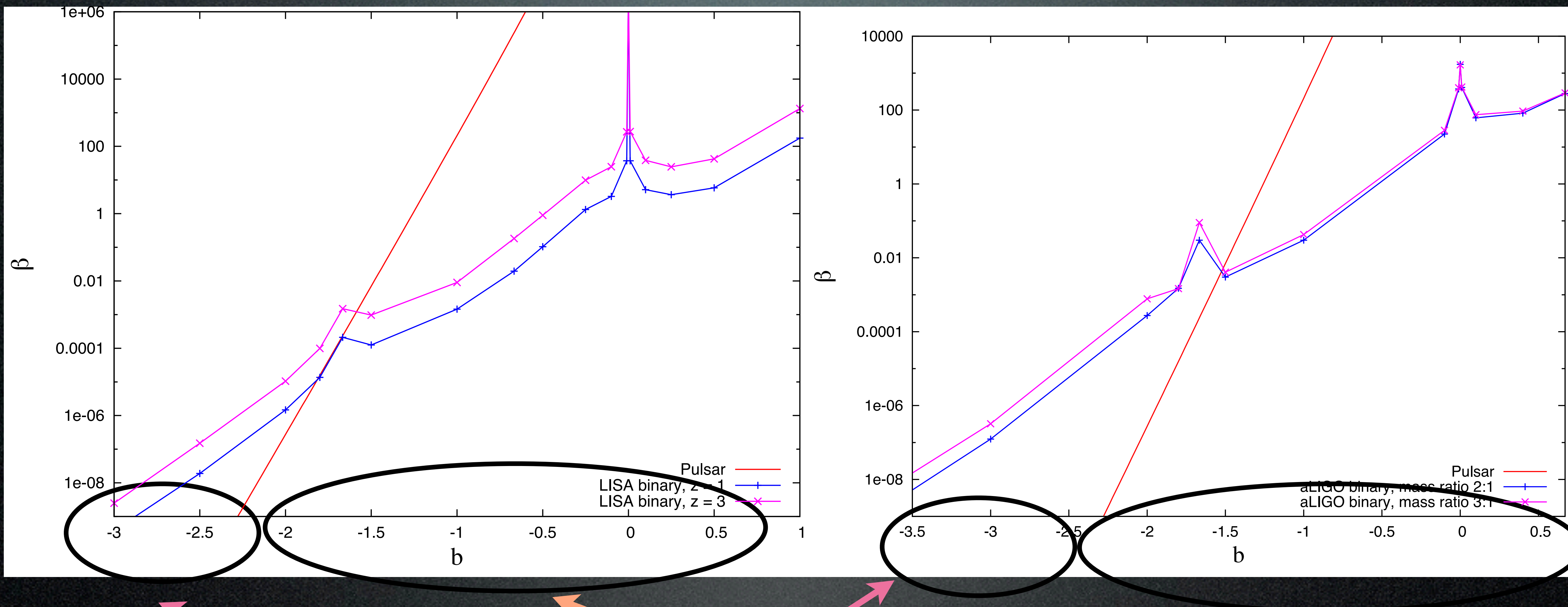

Weak Field

Strong Field

$$\tilde{h} = \tilde{h}_{\rm GR} \left(1 + \alpha f^{a}\right) e^{i\beta f^{b}}$$

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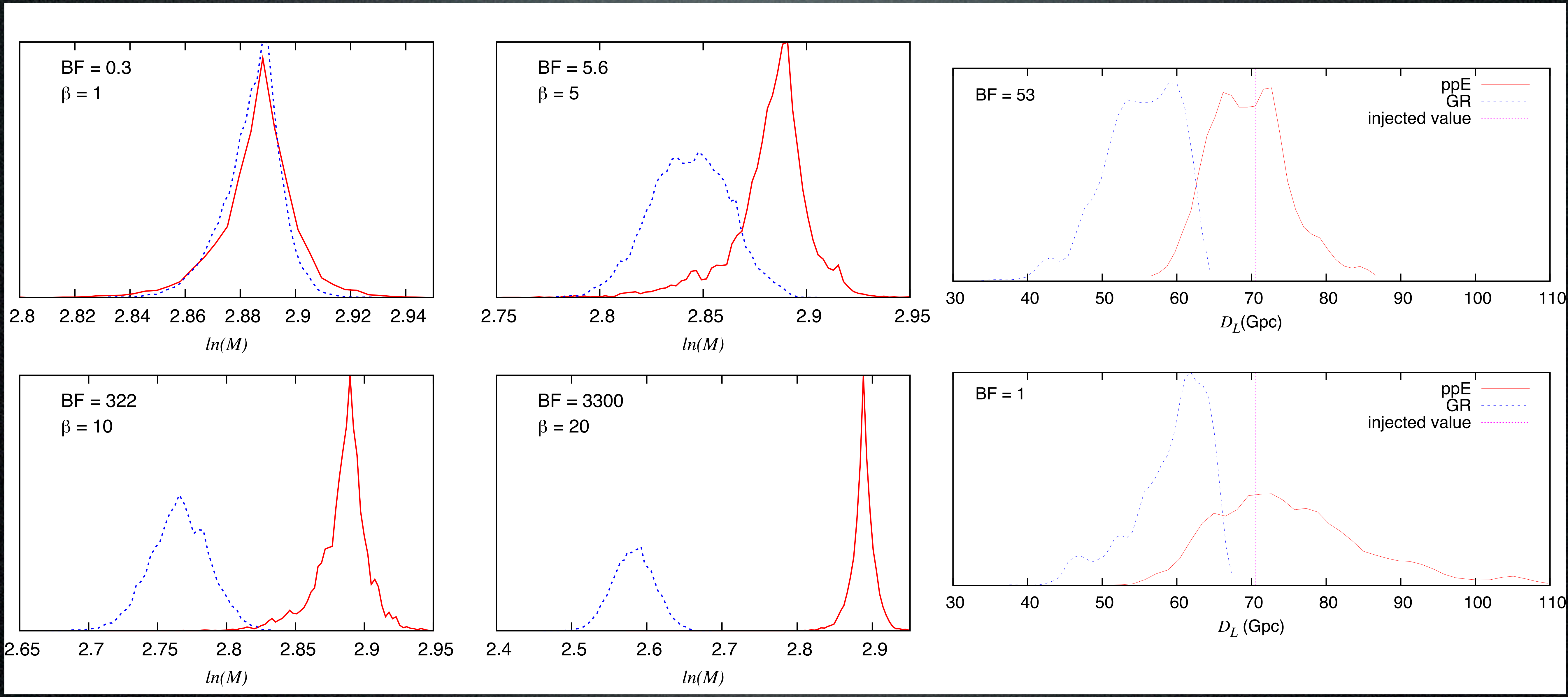
Parameter Bias

Non-GR Signal/GR Templates, SNR = 20

Non GR injection, extracted with GR templates (blue) and ppE templates (red). GR template extraction is “wrong” by much more than the systematic (statistical) error. “Fundamental Bias”

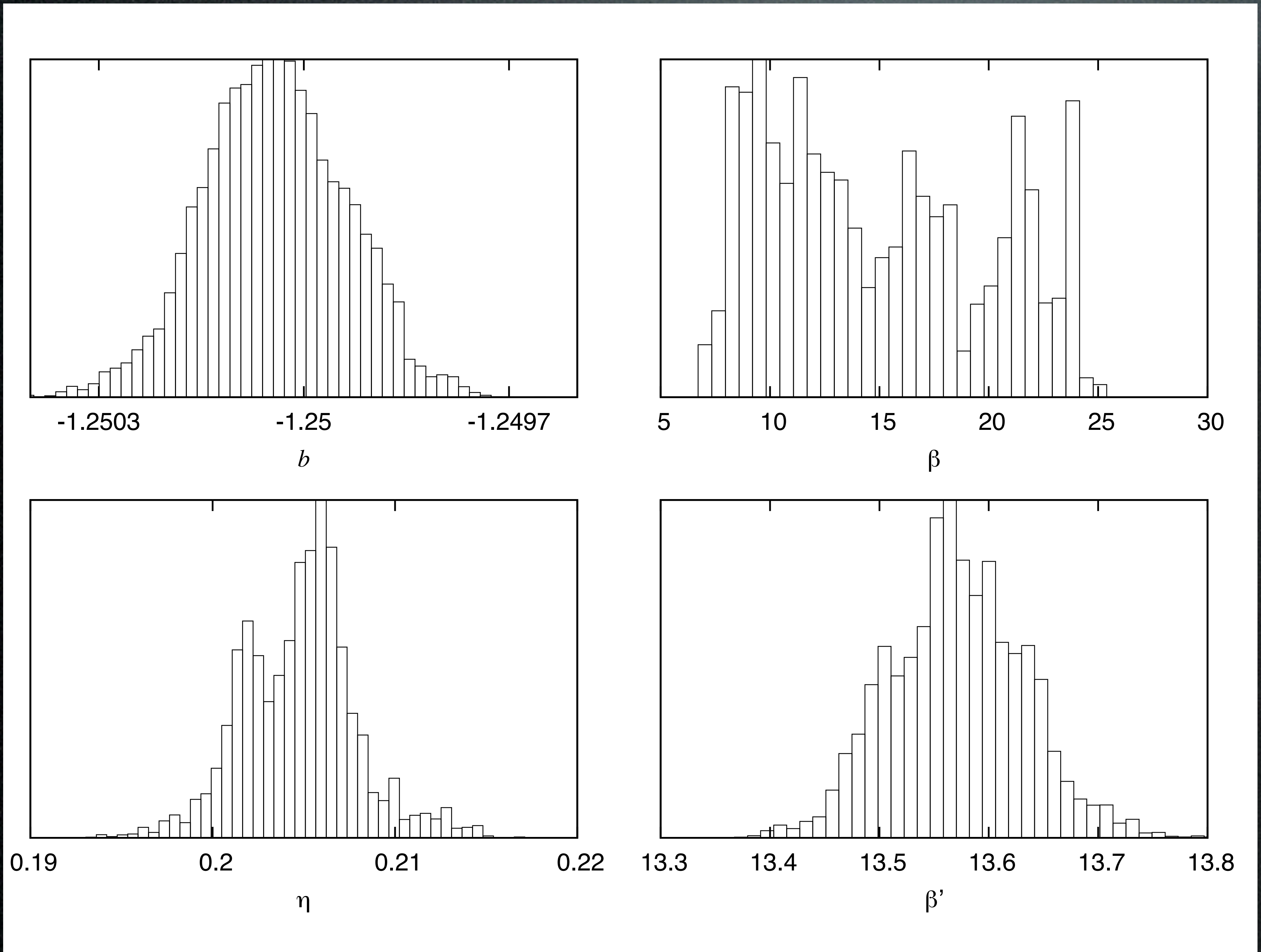


(Cornish, Sampson, Yunes & Pretorius, 2011.)

Identifying GR Deviations

Non-GR Signal/ppE Templates, Ad.LIGO, SNR = 20

Filter an injected ppE signal (a,alpha,b,beta)=(-0.5,4.0,1.25,10.0) with a ppE template family. The marginalized posterior for beta clearly shows a preference away from GR. LIGO (non-equal mass)



You can also compute the Bayes factor as a function of (b,beta). You would find a strong preference (BF > 100) for beta>2/10

(Cornish, Sampson, Yunes & Pretorius, 2011.)

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Masses, spins, sky location, inclination angle, etc.	Measure ppE parameters during Inspiral
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The Era of Precision GW Astrophysics is at our doorstep...

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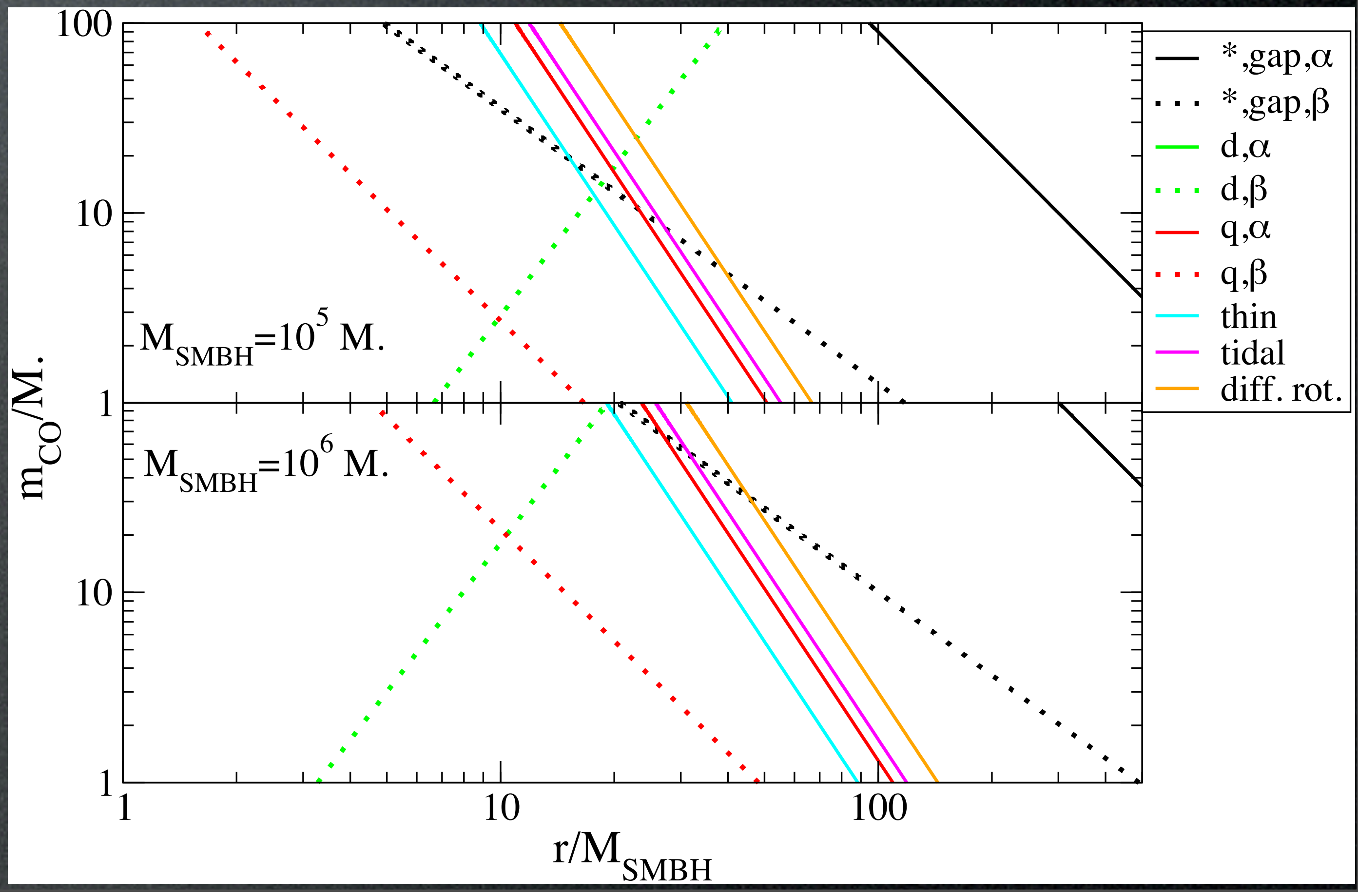

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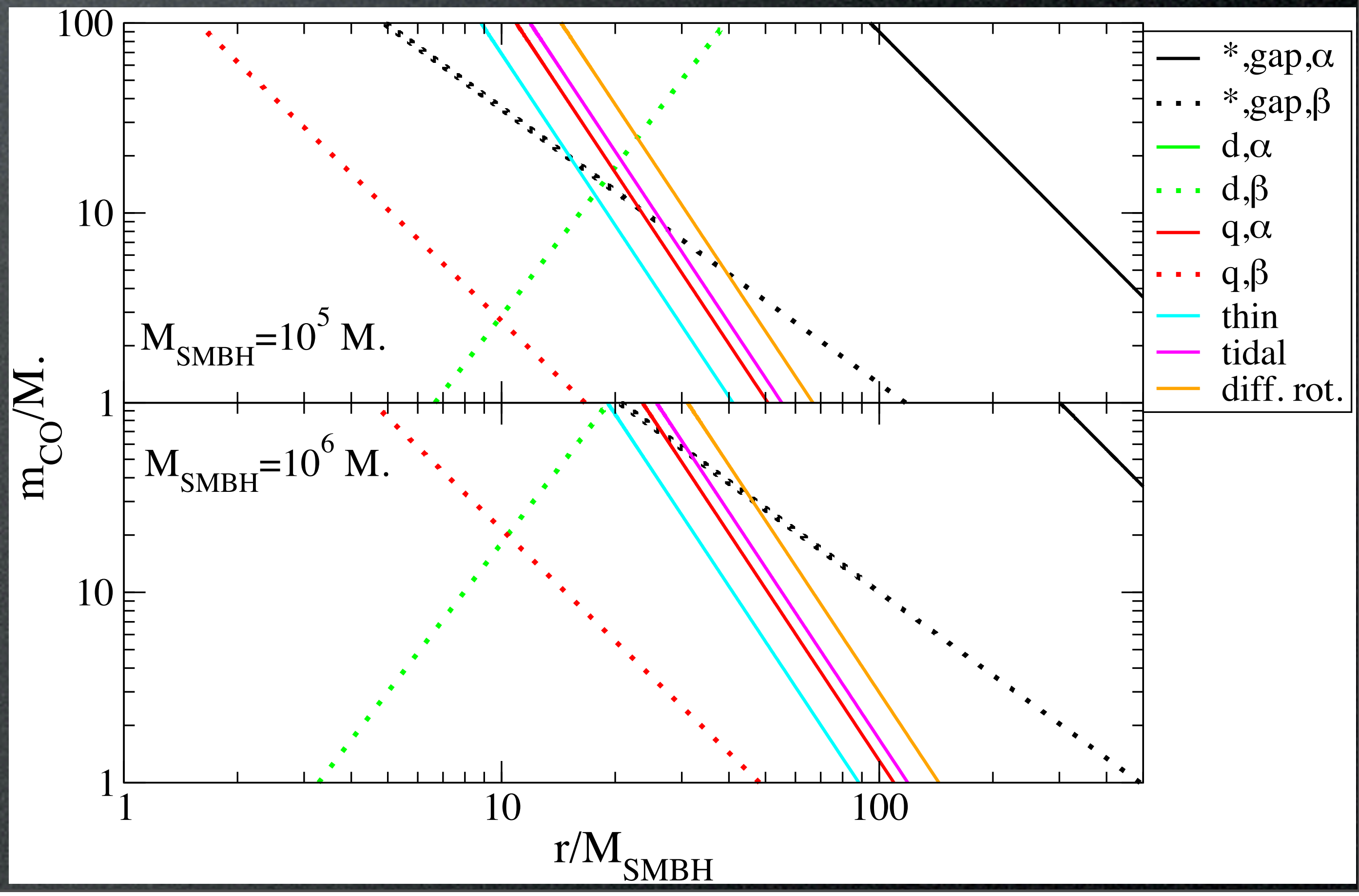

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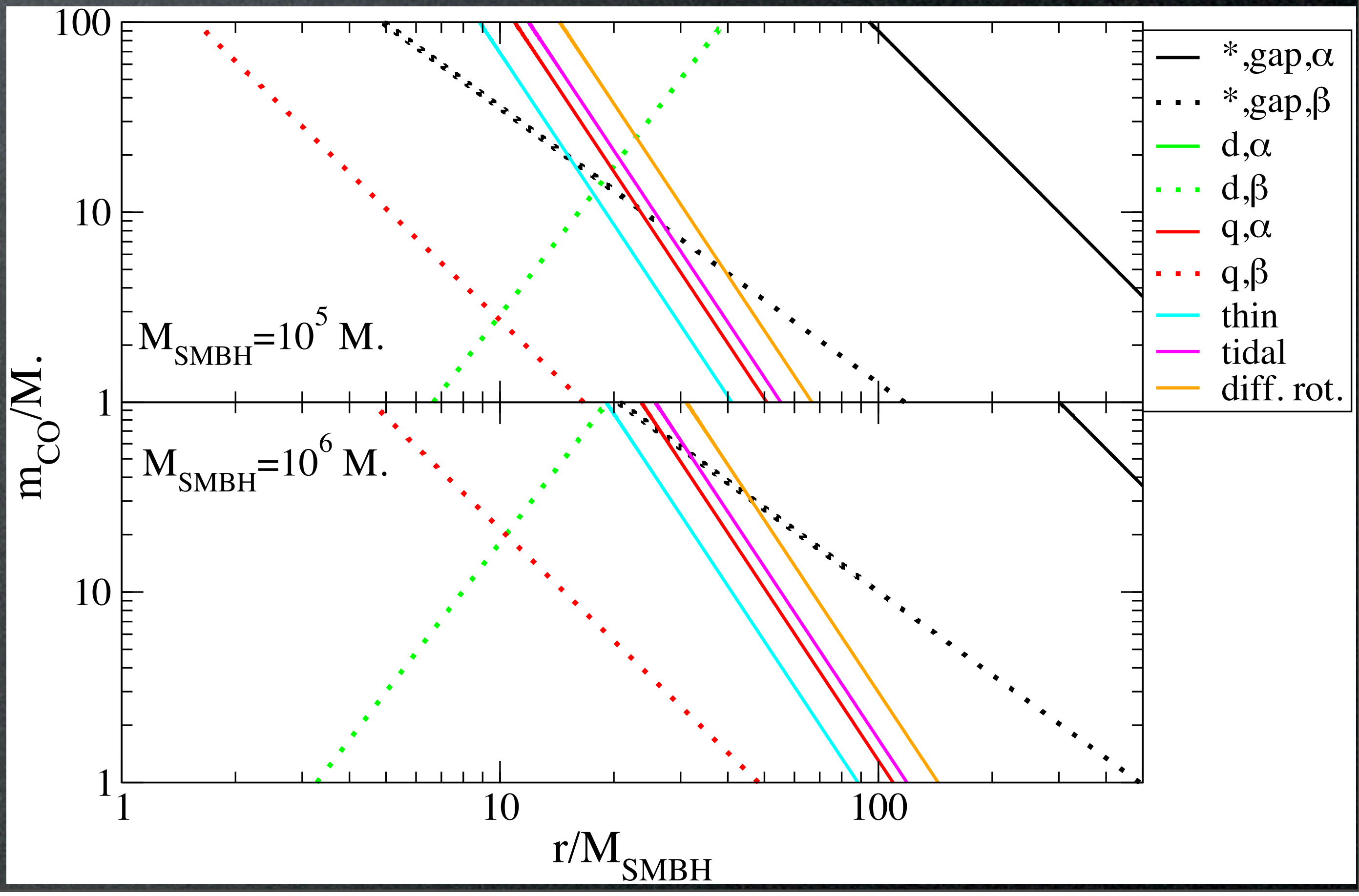

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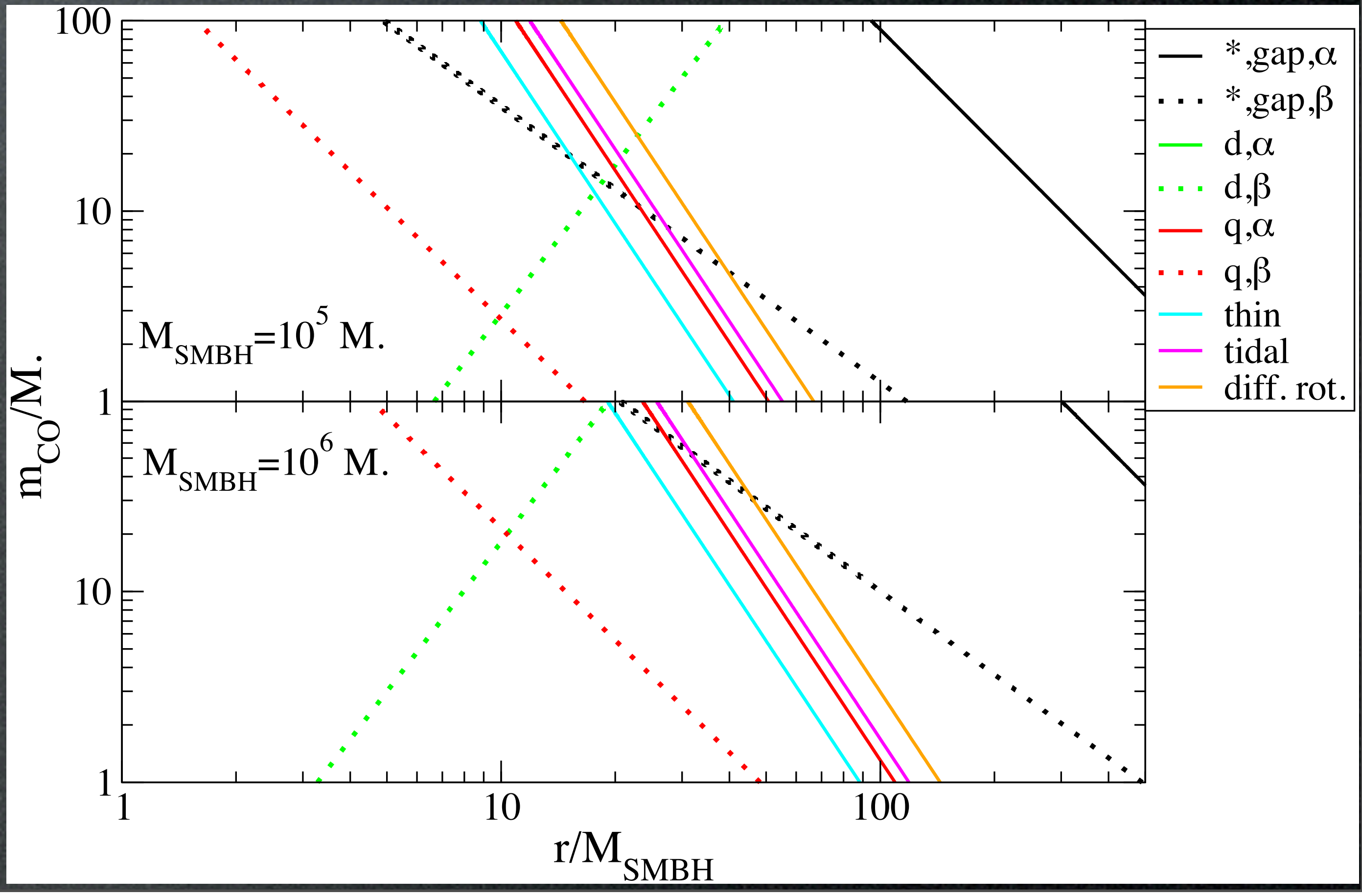

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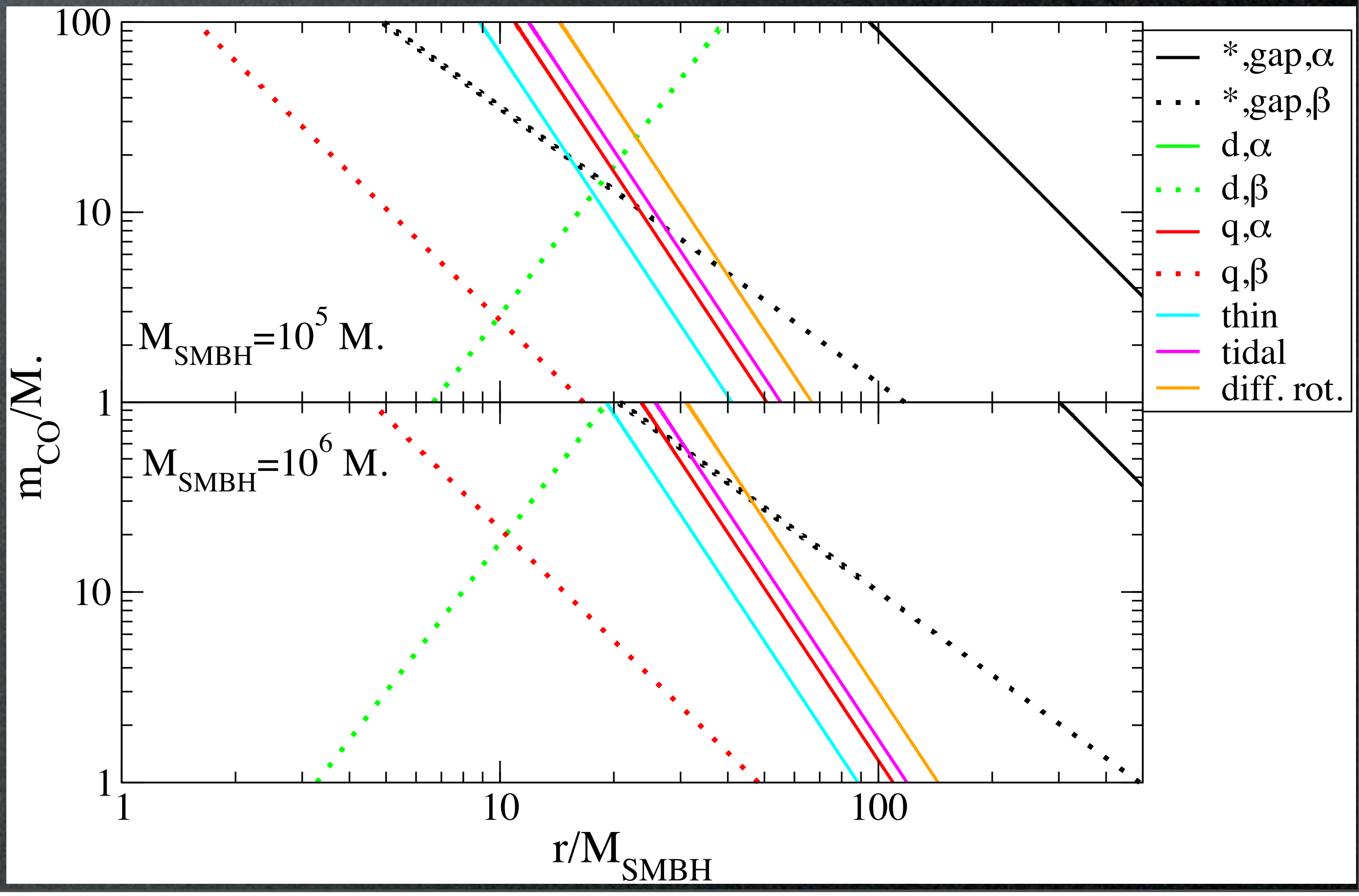

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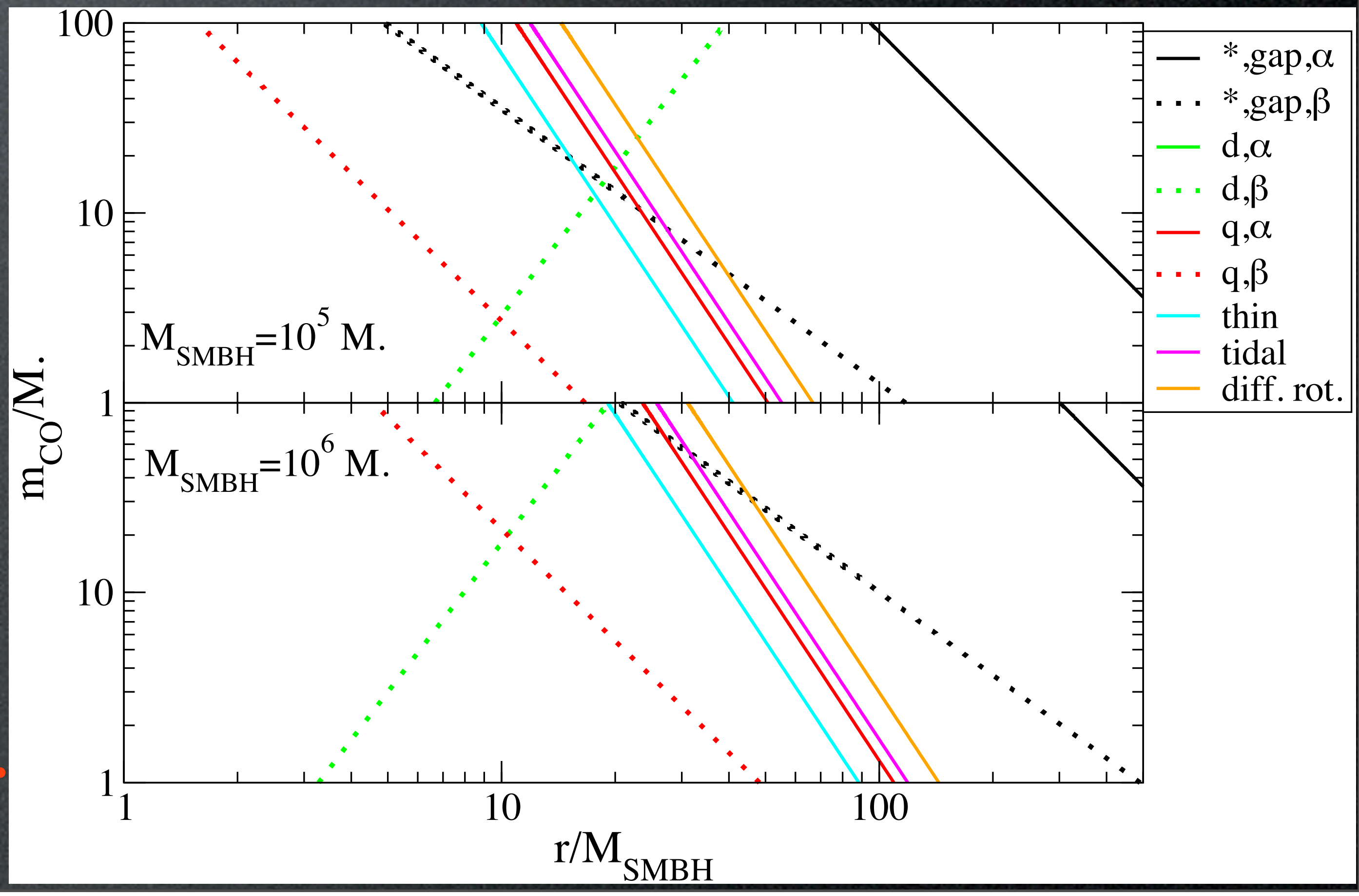
- Limited Gas Supply: If Bondi accretion rate>gas influx, then accretion limited by gas supply.



Accretion Disk-Induced Dephasings

Yunes, Kocsis, Haiman, Loeb (2011),
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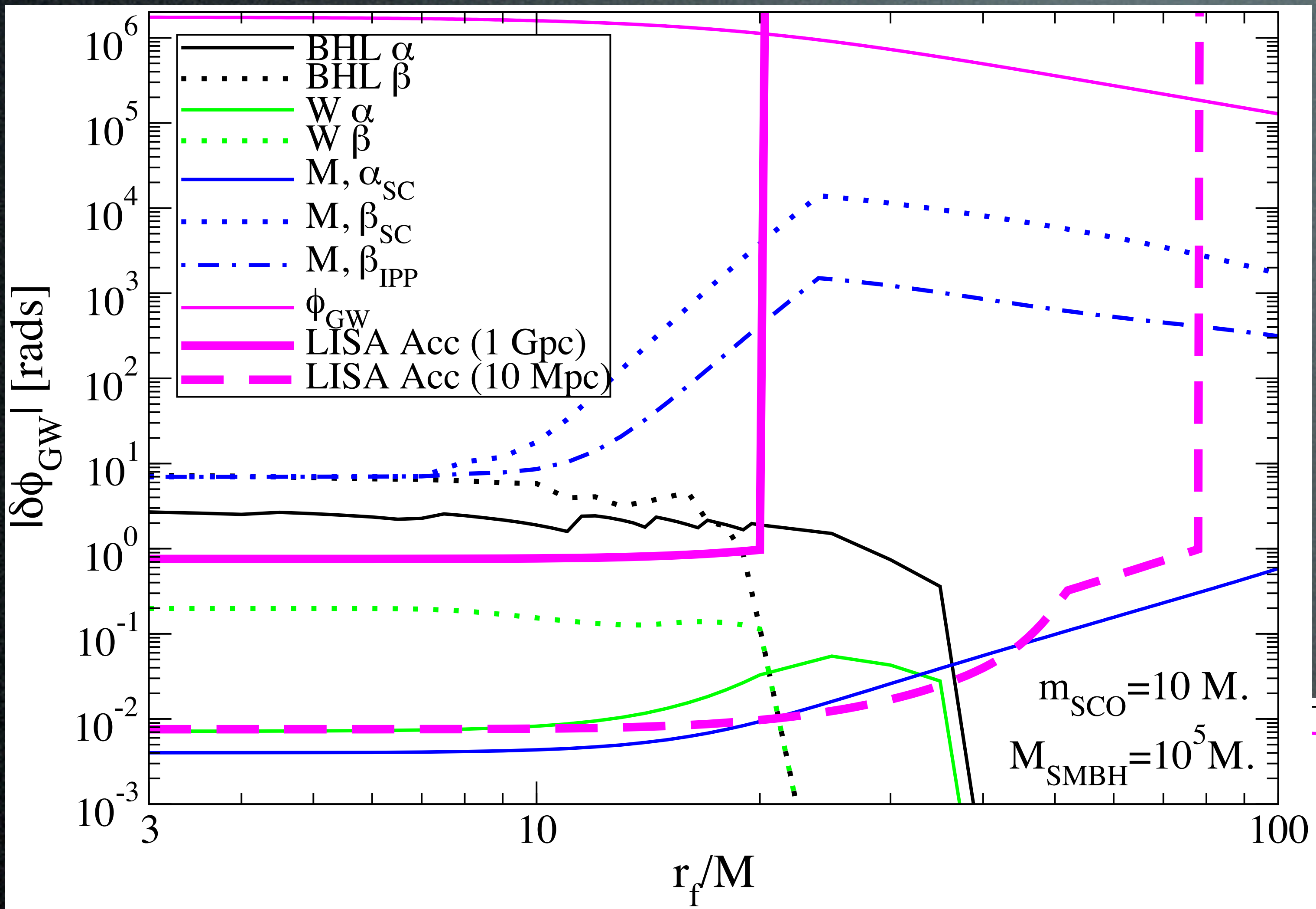
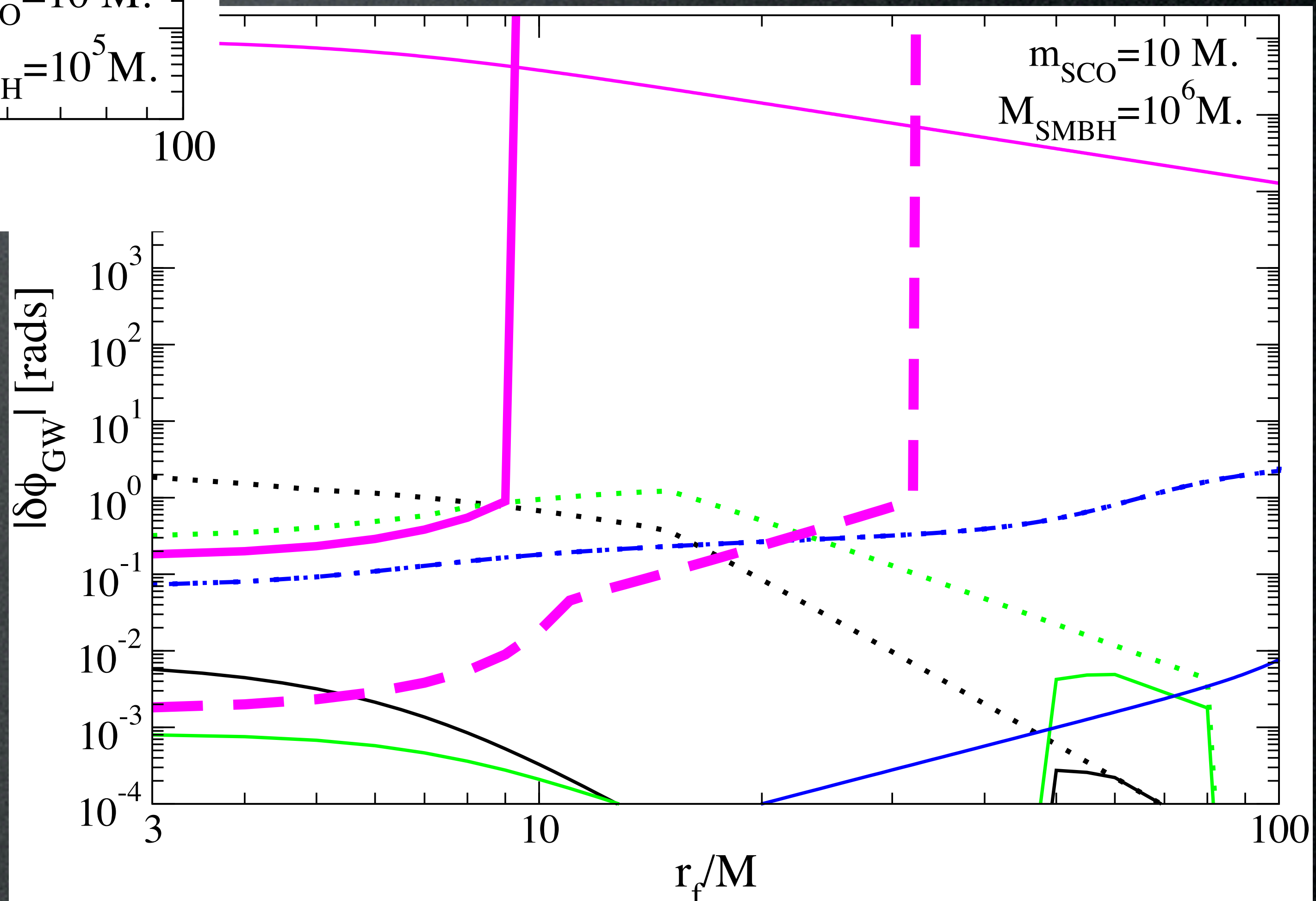
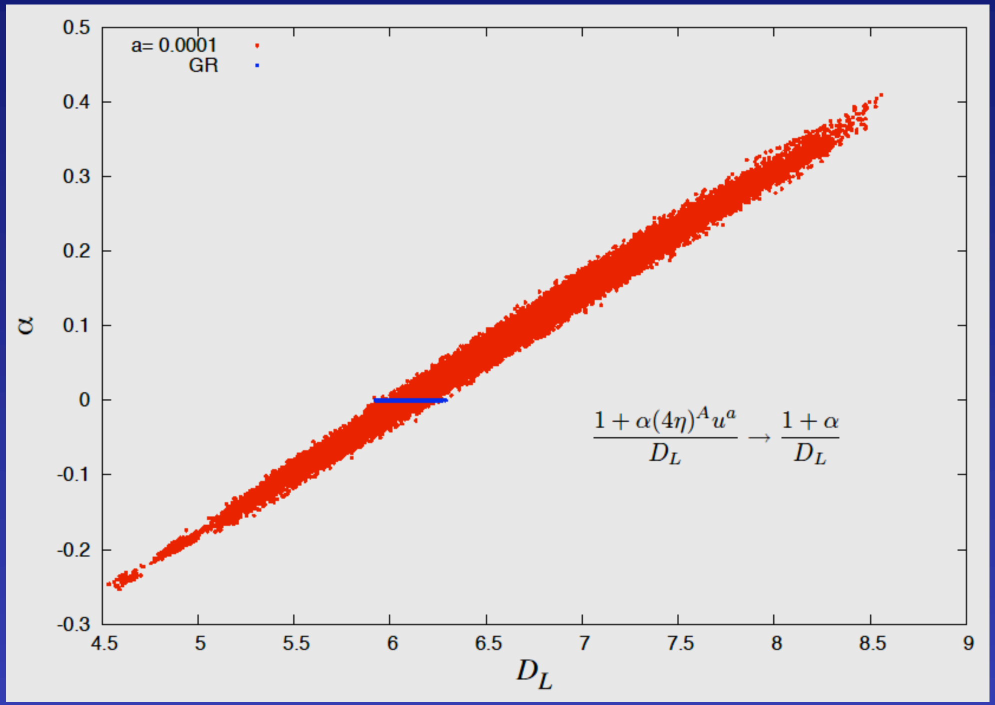


Curves above the thick magenta line can be detected by LISA. Thin magenta line is the vacuum GW phase.

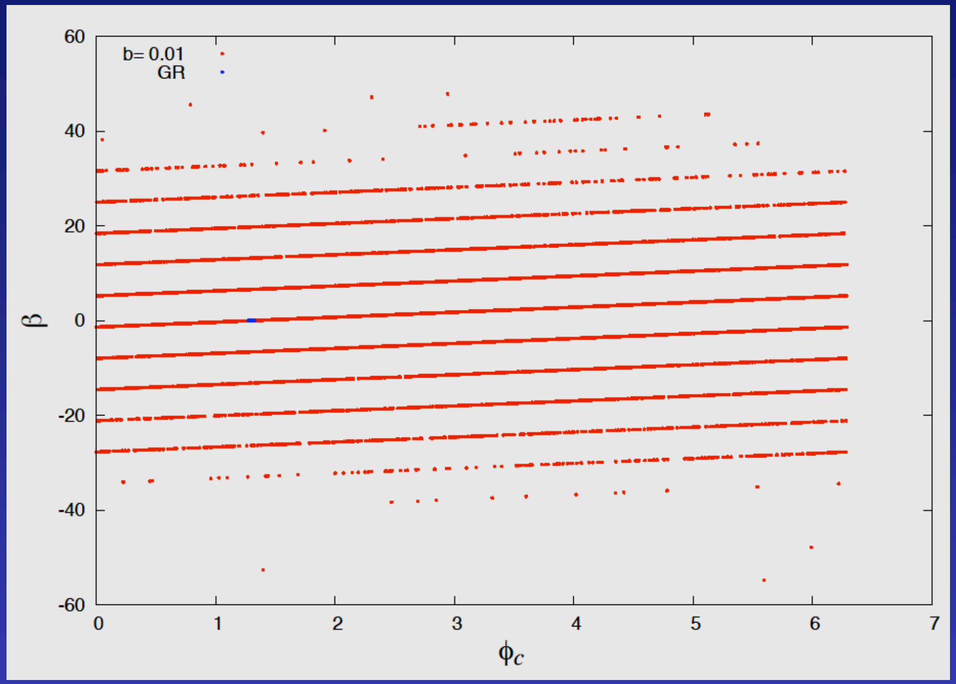
Each point in the figures is the dephasing after a 1-year inspiral, terminating at rf. Solid (dotted) lines are for alpha (beta) disks, diff. colors are for different disk effects.



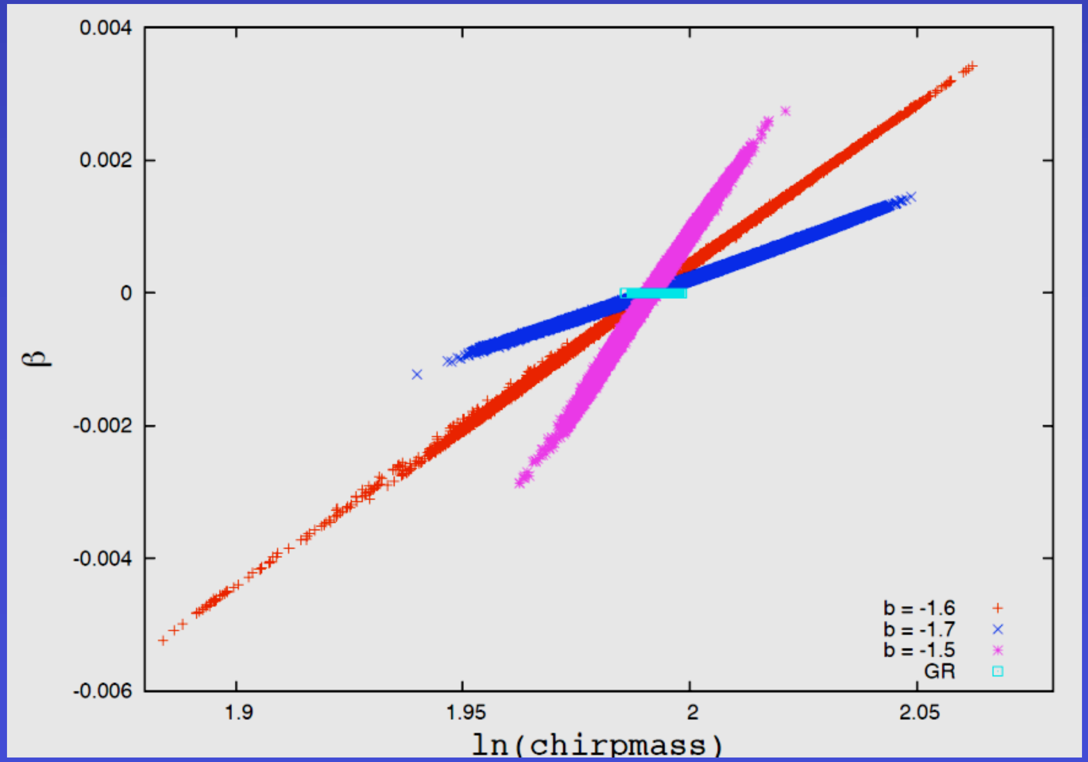
Correlations



peak at *a=0* is degeneracy between luminosity distance and effective α (LISA example)

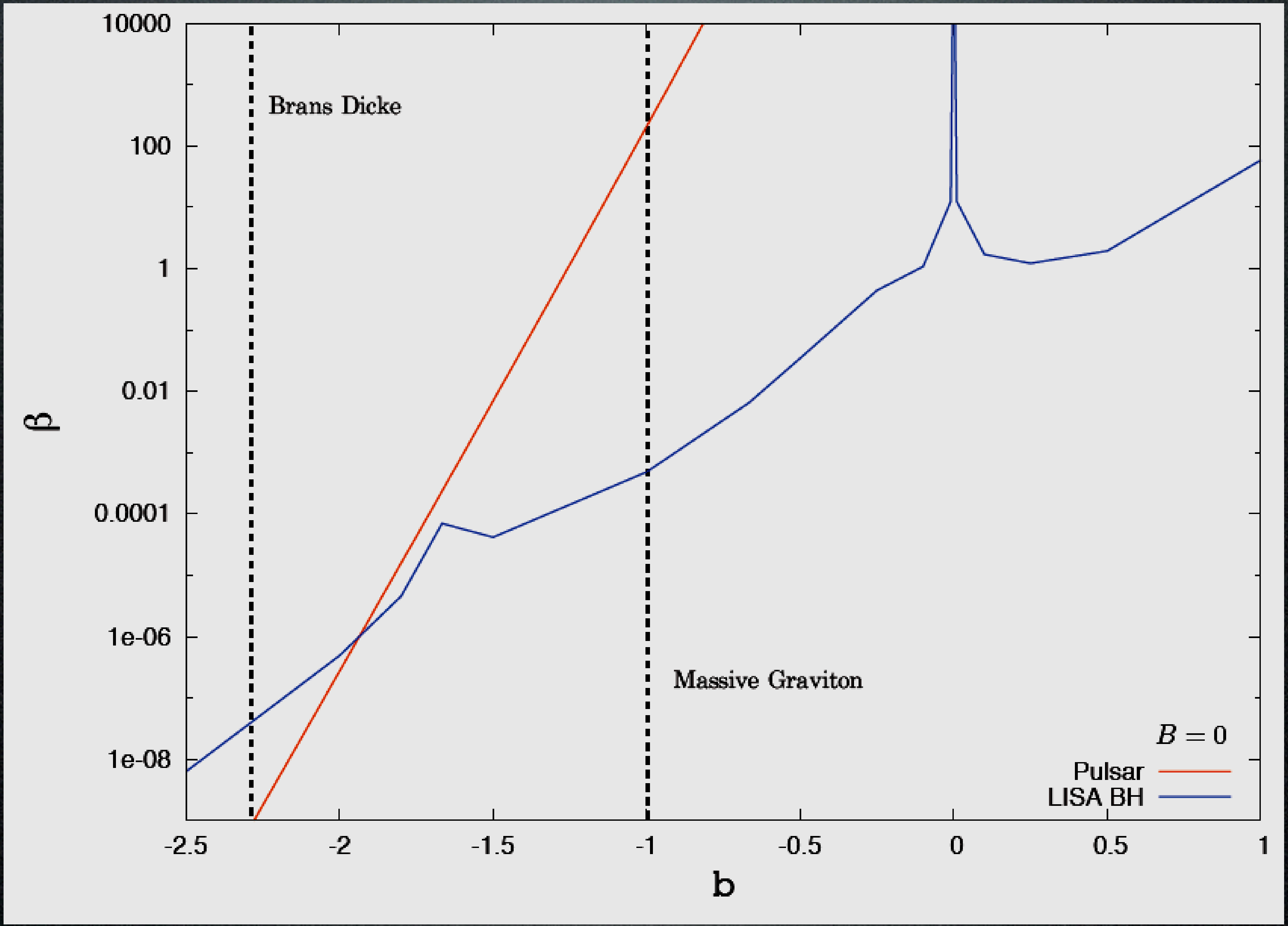


peak at *b=0* is degeneracy between phase of coalescence and β (LISA example)



bump at *b=-5/3* (PN value) is a partial degeneracy between chirp mass and β (LIGO example)

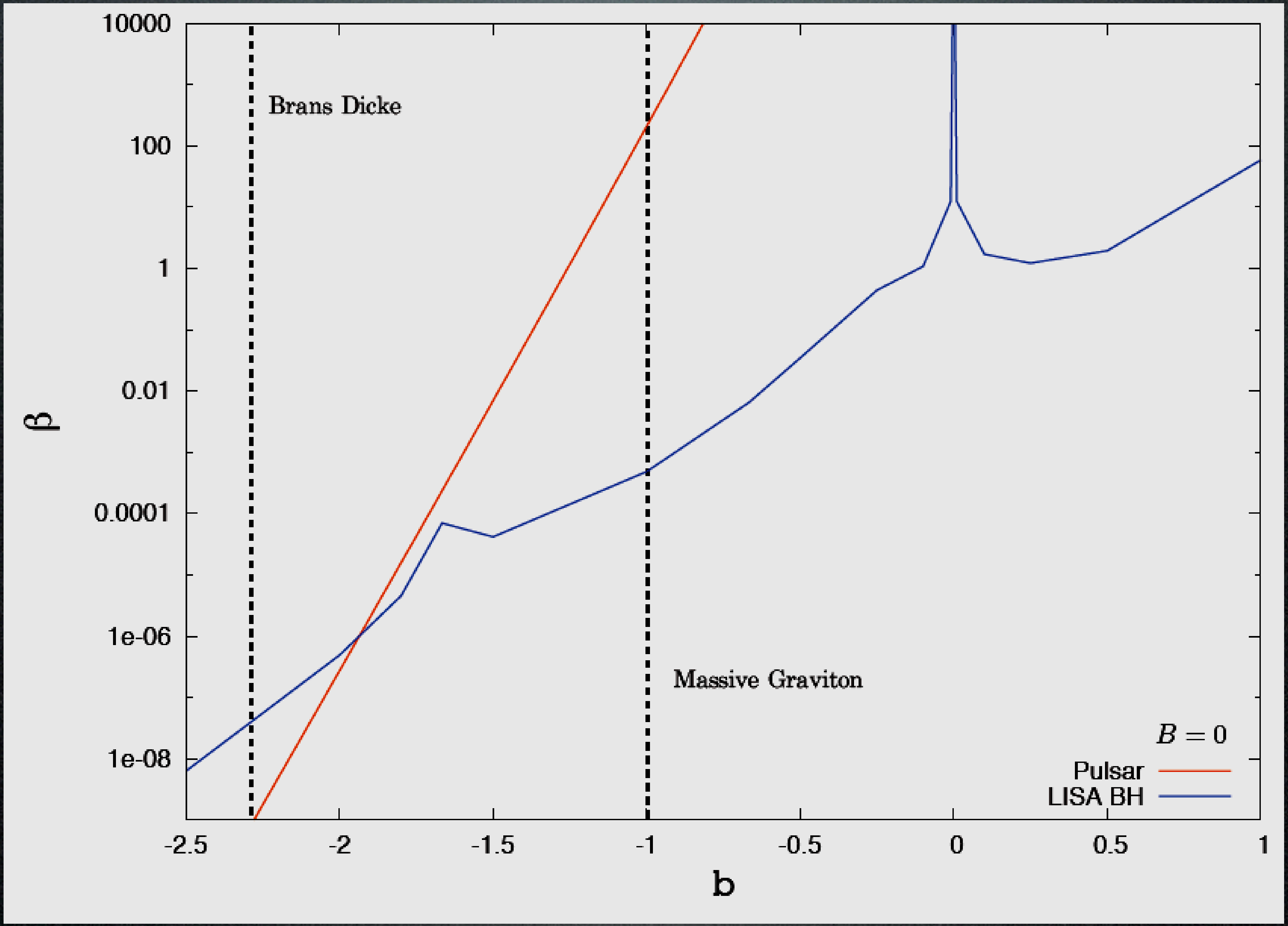
Resonances



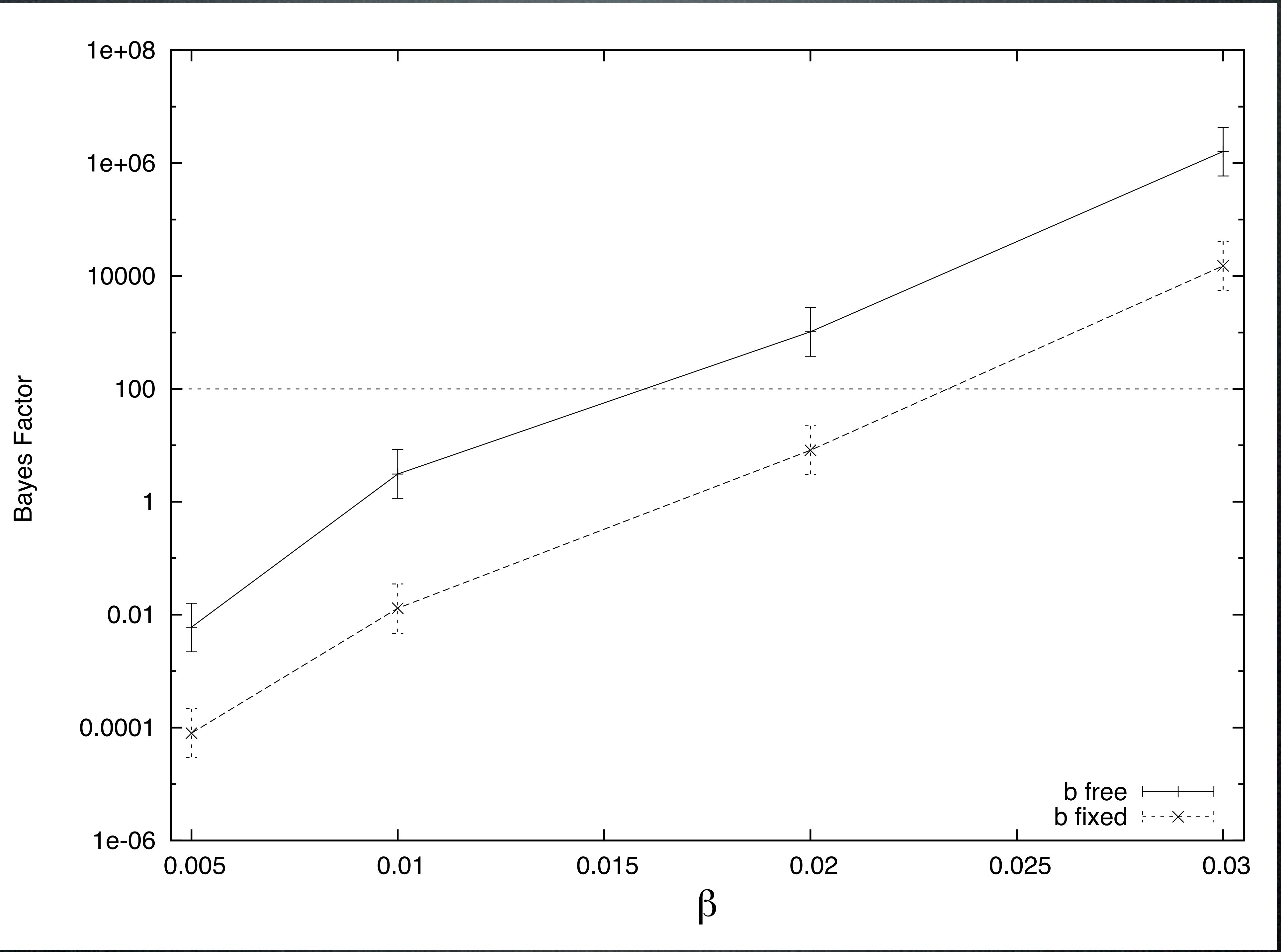
10000
100
1
0.01
0.0001
1e-06
1e-08
β
Brans Dicke
Massive Graviton
$B = 0$
Pulsar
LISA BH
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
b

Resonances

At certain "resonant" exponents, you cannot distinguish between GR and an alternative theory modification (spikes). (degeneracies not sampled in the previous plot)

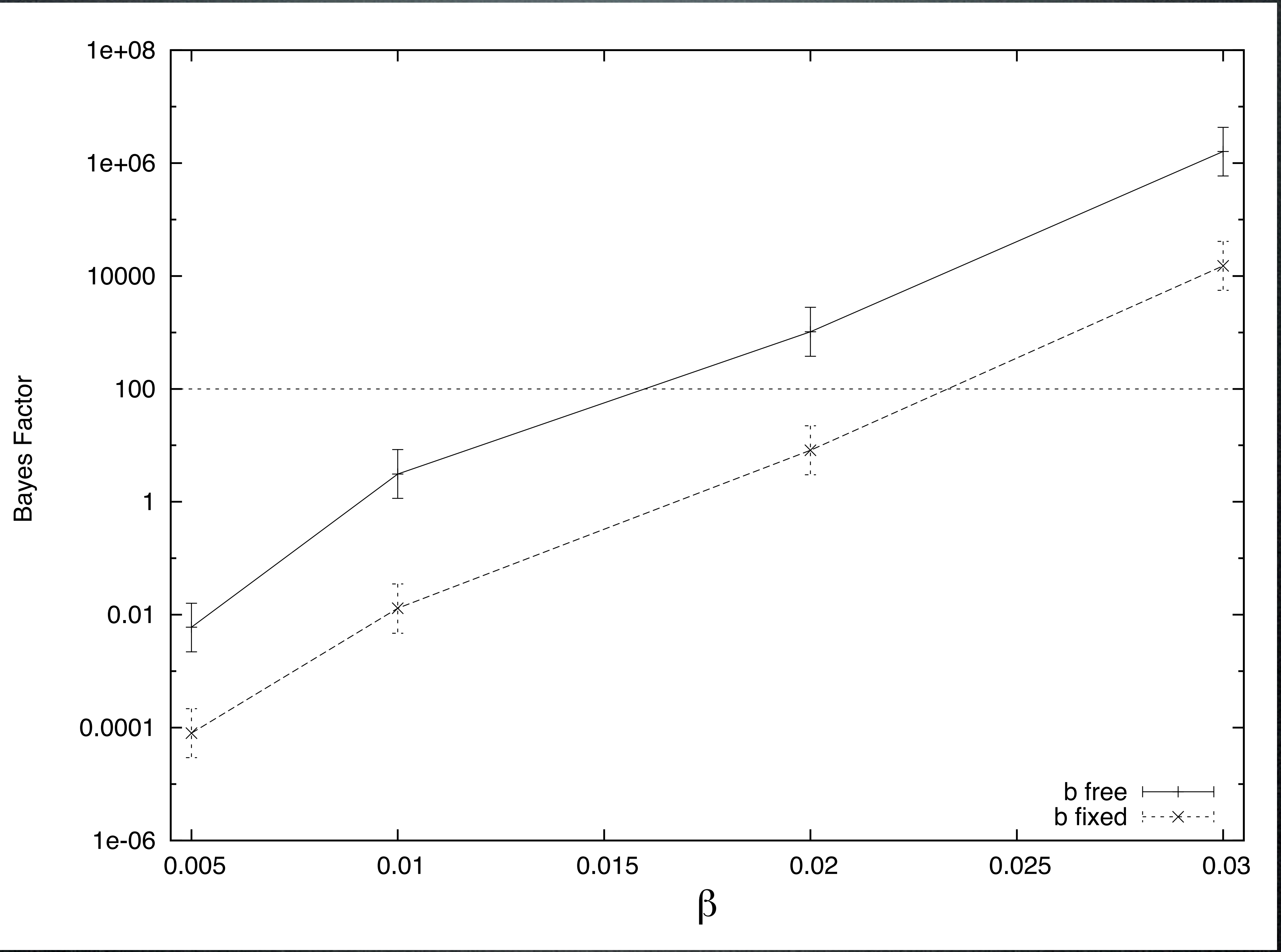


Bayes Factor

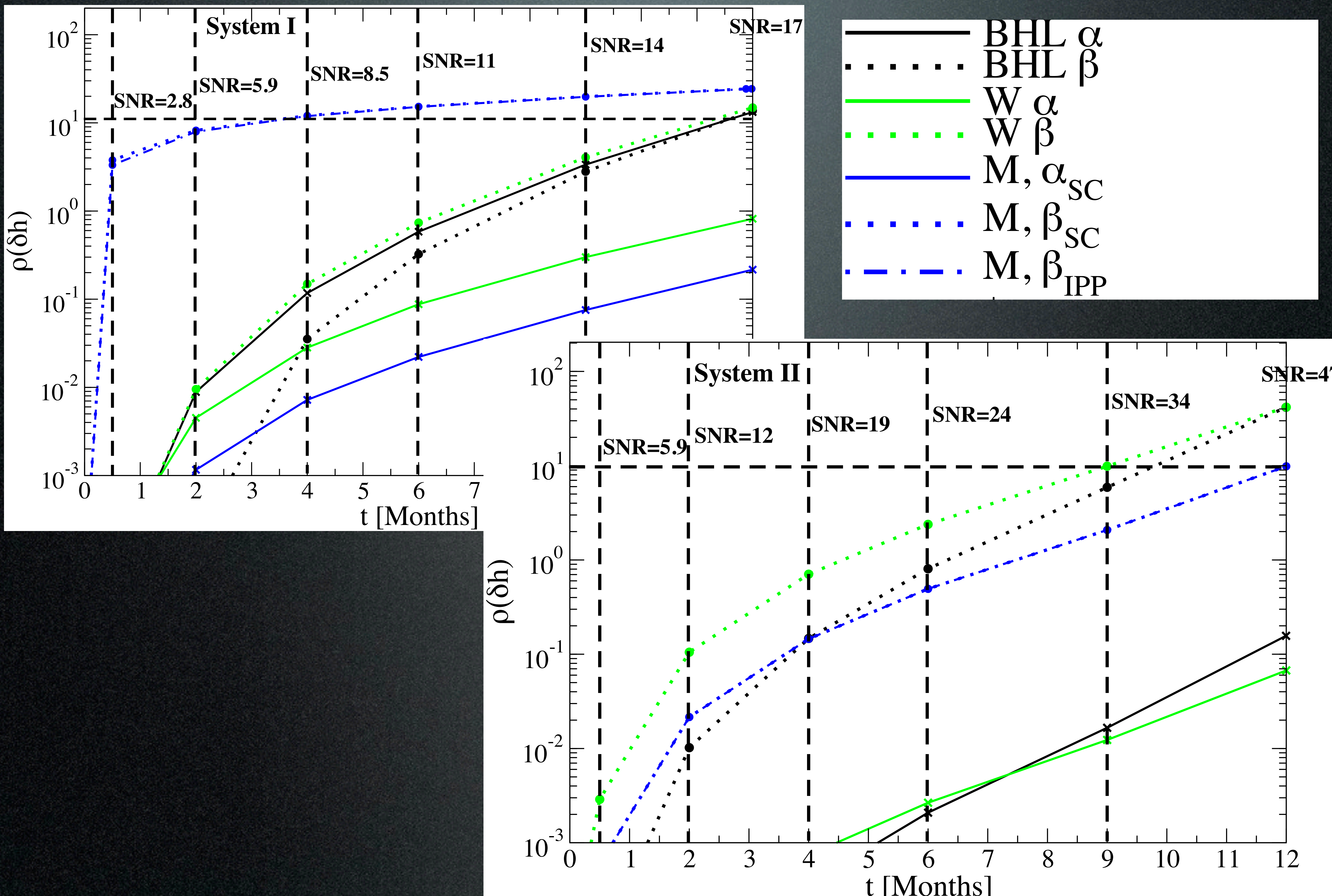


Bayes Factor

Odds ratio for ppE signal injection at different values of beta and (a,alpha,b)=(0,0,-1.25). Extraction with ppE template. Suggests beta > 2/10 can easily be observed.



SNR effects



System I
SNR=2.8
SNR=5.9
SNR=8.5
SNR=11
SNR=14
SNR=17
$\rho(\delta h)$
t [Months]
BHL α
BHL β
W α
W β
M, α_{SC}
M, β_{SC}
M, β_{IPP}
System II
SNR=5.9
SNR=12
SNR=19
SNR=24
SNR=34
SNR=47
$\rho(\delta h)$
t [Months]

Parameter Estimation Degeneracies

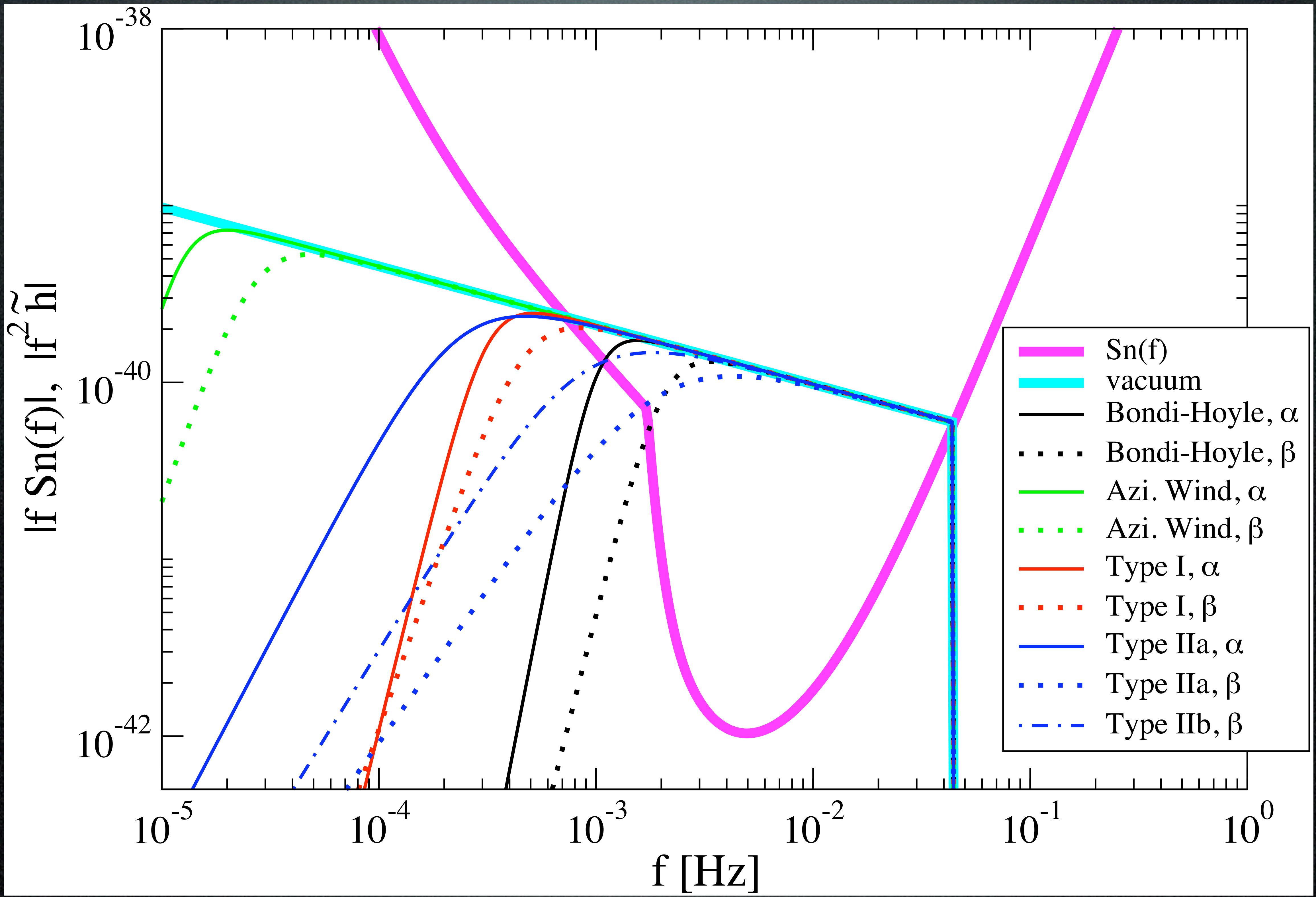
	$\tilde{A}_1$	$\tilde{B}_1$	$\tilde{a}_1$	$\tilde{a}_2$	$\tilde{a}_3$	$\tilde{a}_4$	$\tilde{a}_5$
BHα	$-1\,(-8)$	$-1\,(-7)$	-1	-5	1	4	$-20/3$
BHβ	$-2\,(-5)$	$-1\,(-4)$	$-4/5$	$-17/5$	$6/5$	$79/25$	$-79/15$
Wα	$2\,(-17)$	$1\,(-16)$	-1	-3	1	$16/5$	$-16/3$
Wβ	$9\,(-12)$	$3\,(-11)$	$-4/5$	$-7/5$	$6/5$	$59/25$	$-59/15$
MIα	$7\,(-10)$	$4\,(-9)$	-1	0	-2	$1/5$	$-16/3$
MIβ	$7\,(-7)$	$3\,(-6)$	$-4/5$	0	$-1/5$	$24/25$	$-59/15$
MIIaα	$8\,(-6)$	$2\,(-5)$	0	1	1	$-2/5$	$-8/3$
MIIaβ	$8\,(-3)$	$2\,(-2)$	$1/2$	$5/8$	$1/4$	$-1/8$	$-25/12$
MIIbβ	$7\,(-4)$	$2\,(-3)$	$2/7$	$11/14$	$4/7$	$-17/70$	$-7/3$

$$u \equiv \pi \mathcal{M} f$$

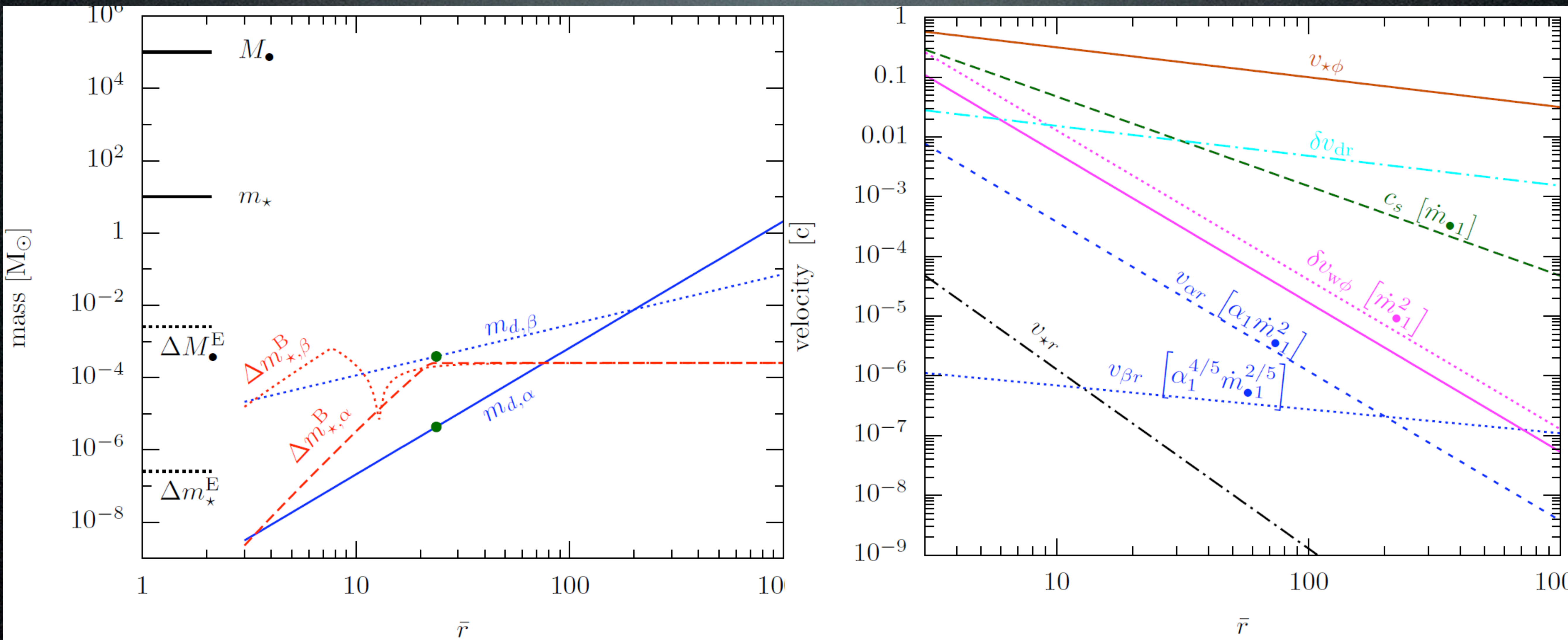
$$\psi/\psi_{\rm vac} = 1 - \tilde{A}_1 \alpha_1^{\tilde{a}_1} \dot{m}_{\bullet 1}^{\tilde{a}_2} M_{\bullet 5}^{\tilde{a}_3} q_0^{\tilde{a}_4} u_0^{\tilde{a}_5} \qquad \boxed{\frac{3}{128} u^{-5/3}}$$

$$|\tilde{h}|/|\tilde{h}|_{\rm vac} = 1 - \tilde{B}_1 \alpha_1^{\tilde{a}_1} \dot{m}_{\bullet 1}^{\tilde{a}_2} M_{\bullet 5}^{\tilde{a}_3} q_0^{\tilde{a}_4} u_0^{\tilde{a}_5} \qquad \boxed{\frac{\mathcal{M}^{5/6}}{\pi^{2/3}\sqrt{30}\, D_L} f^{-7/6}}$$

Amplitude Effects



Mass Scales



mass [M☉]
$M_\bullet$
$m_\star$
$\Delta M_\bullet^{\rm E}$
$\Delta m_\star^{\rm E}$
$\Delta m^{\rm B}_{\star,\beta}$
$\Delta m^{\rm B}_{\star,\alpha}$
$m_{d,\beta}$
$m_{d,\alpha}$
$\bar{r}$
velocity [c]
$v_{\star\phi}$
$\delta v_{\rm dr}$
$c_s\ [\dot{m}_{\bullet 1}]$
$\delta v_{w\phi}\ [\dot{m}^2_{\bullet 1}]$
$v_{\alpha r}\ [\alpha_1 \dot{m}^2_{\bullet 1}]$
$v_{\star r}$
$v_{\beta r}\ [\alpha_1^{4/5} \dot{m}^{2/5}_{\bullet 1}]$
$\bar{r}$

But What Theory Do We Pick?

A Minimal (?) Set of Criteria:

1. Weak-Field Consistency (existence and stability of physical solutions, satisfaction of precision tests).
2. Strong-Field Inconsistency (deviations only where experiments cannot currently rule out modifications)

Other Nice Criteria:

3. Well motivated from fundamental physics.
4. Well-posed theory ?? This is hard to do...

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It's not easy to fool Mother Nature! (Wald)

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Top-Down Accuracy Studies

	Will	Scharre, Will	Will, Yunes	Berti, Buonanno , Will	Arun, Will	Stravridis, Will	Yagi, Tanaka	Ajith, Keppel	Solar System
Binary Mass	x	1.4:1E3	1.4:1E3	1.4:1E3	x	x	1.4:1E3	x	x
BD Coupling Par. (e4)	x	24	20	10	x	x	0.7	x	4
Binary Mass	1E7: 1E6	x	1E6:1E6	1E6:1E6	2E6:1E7	1E6:1E6	1E7:1E6	5E7:5E7	x
Graviton Compton Wavelgth (e21 cm)	6.9	x	3.1	1.33	5	4	3.1	52	0.00028
Details	First MG study, no spin	First ST study, no spin	As a func. of Det.	non-prec., spinning	amp. corr.	spin + prec	spin + prec + ecc	IMR	Cassini, 3rd Law Solar Sys

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- One samples the "Strong-Field" regime of GR -> where gravity is strong and velocities close to c.

Now consider Alternative Theories s

Simplifications

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Dynamical Chern-Simons Theory

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Einstein-Dilaton-Gauss-Bonnet Theory

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