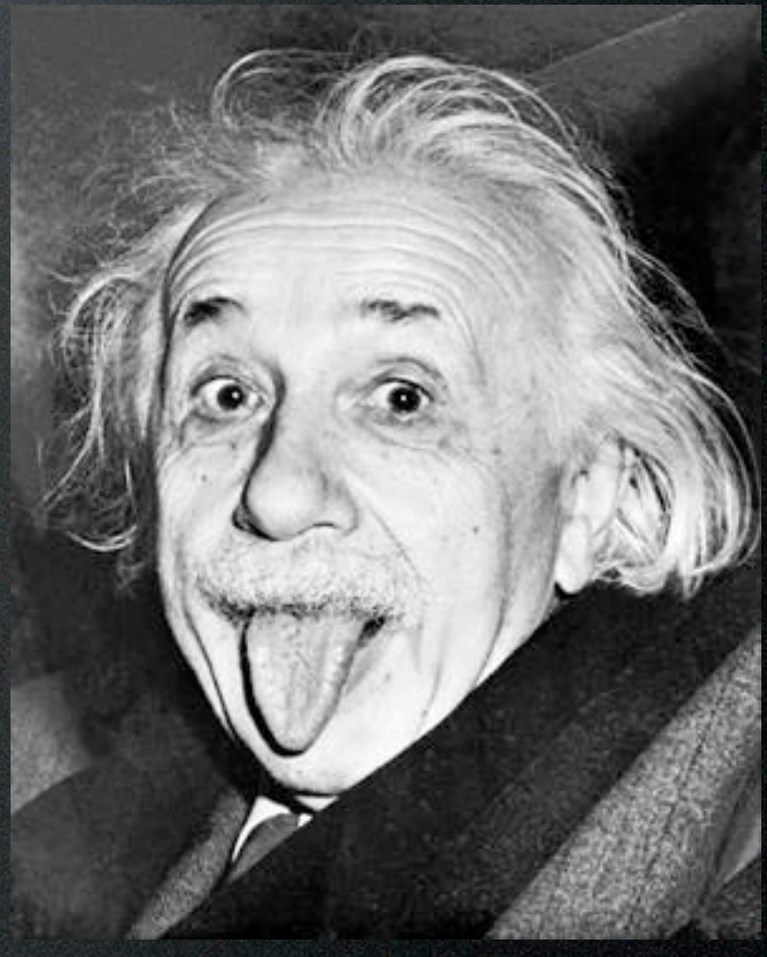
Testing General Relativity with Future GW Observations

Scientific Workshop
Montana State University,
April 5th-April 7th, 2013

http://www.physics.montana.edu/gravity/workshop/workshop.htm

Part of Celebrating Einstein

Mega-Outreach Event
Montana State University,
April 1st-April 6th, 2013



Testing General Relativity with Compact Binary Inspirals

Nico Yunes
Montana State University

Aug. 3rd, 2012,
KITP, UCSB

Standing on the shoulders of...

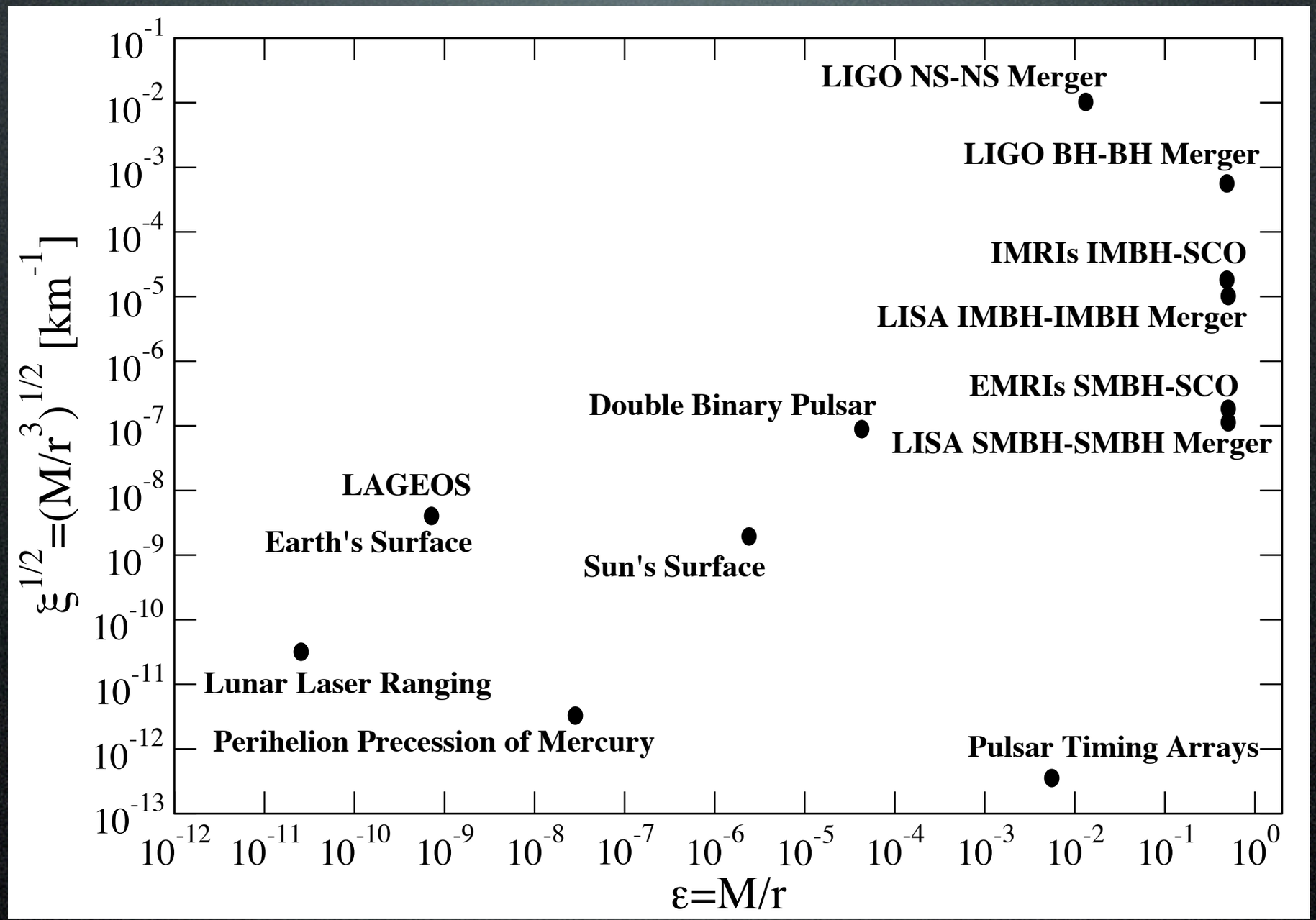
Clifford Will, Jim Gates, Stephon Alexander, Abhay Ashtekar, Sam Finn, Ben Owen, Pablo Laguna, Emanuele Berti, Uli Sperhake, Dimitrios Psaltis, Avi Loeb, Vitor Cardoso, Leonardo Gualtieri, Daniel Grumiller, David Spergel, **Frans Pretorius, Neil Cornish**, Scott Hughes, Carlos Sopuerta, Takahiro Tanaka, Jon Gair,

---

An incomplete summary of the Theory behind Inspiral GW tests of GR

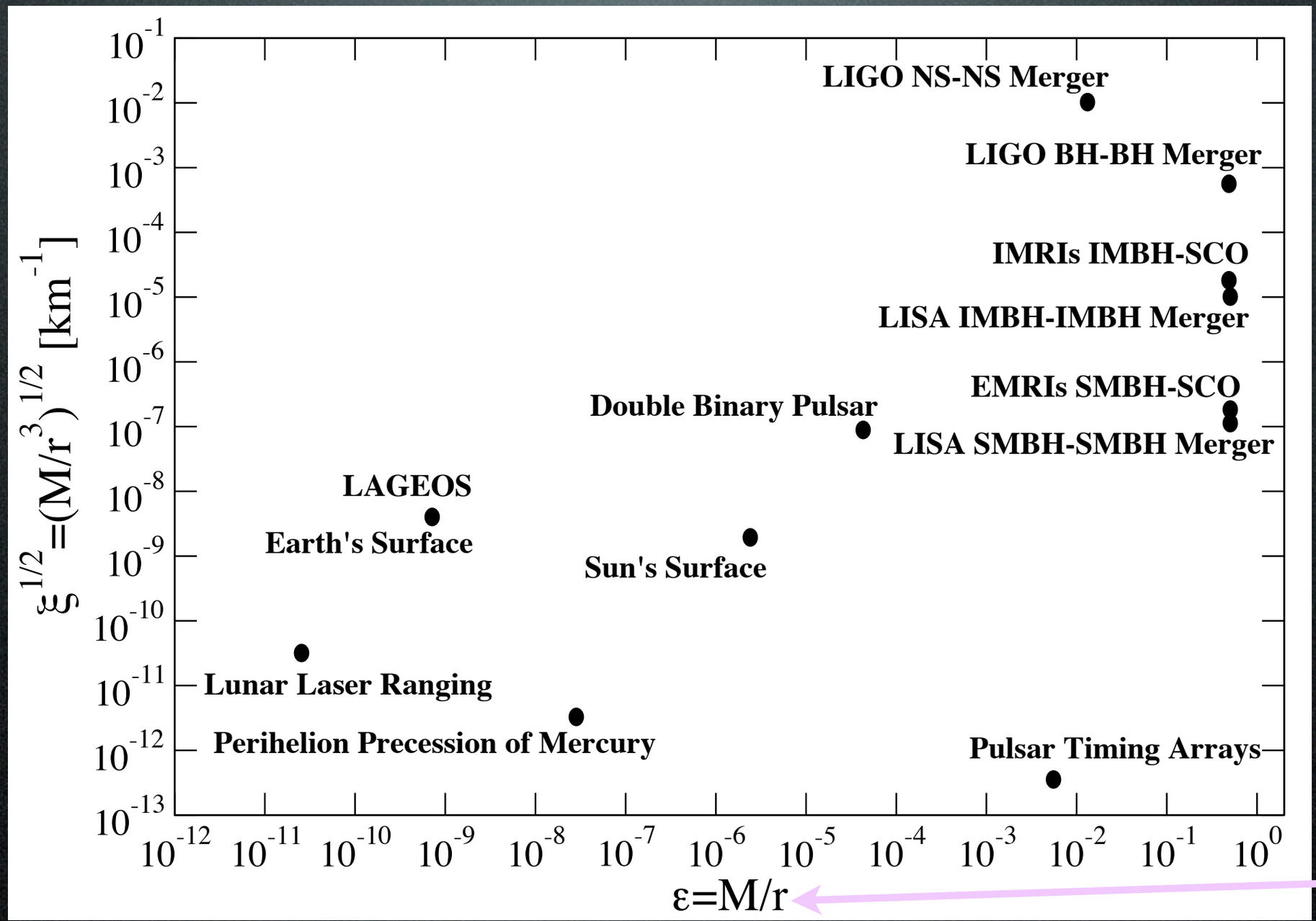
Paolo Pani, Antoine Klein, Kent Yagi, **Laura Sampson**, Leo Stein, Sarah Vigeland, **Katerina Chatziioannou**, Haris Apostolatos, Philippe Jetzer, Leor Barack, Curt Cutler, Kostas Glampedakis, Stanislav Babak, Ilya Mandel, Chao Li, Eliu Huerta, Chris Berry, Alberto Sesana, Carl Rodriguez, Georgios Lukes-Gerakopoulos, George Contopoulus, Chris van den Broeck, Walter del Pozzo, Jon Veitch, Nathan Collins, Deirdre Shoemaker, Sathyaprakash, etc.

Trust But Verify



Will, Liv. Rev., 2005, Psaltis, Liv. Rev., 2008, Siemens & Yunes, Liv. Rev. 2012 in prog.

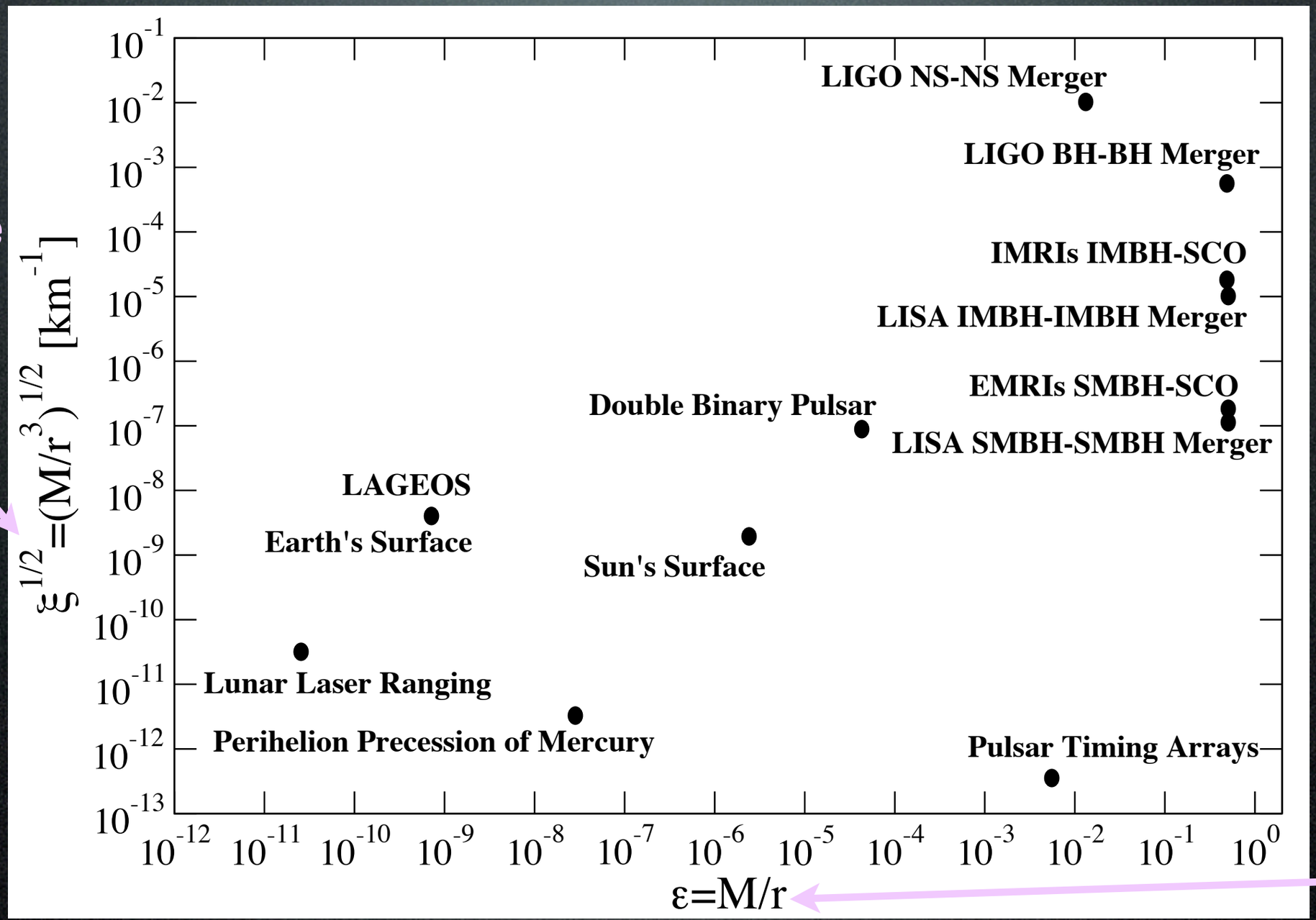
Trust But Verify



Will, Liv. Rev., 2005, Psaltis, Liv. Rev., 2008, Siemens & Yunes, Liv. Rev. 2012 in prog.

Trust But Verify

Curvature Strength



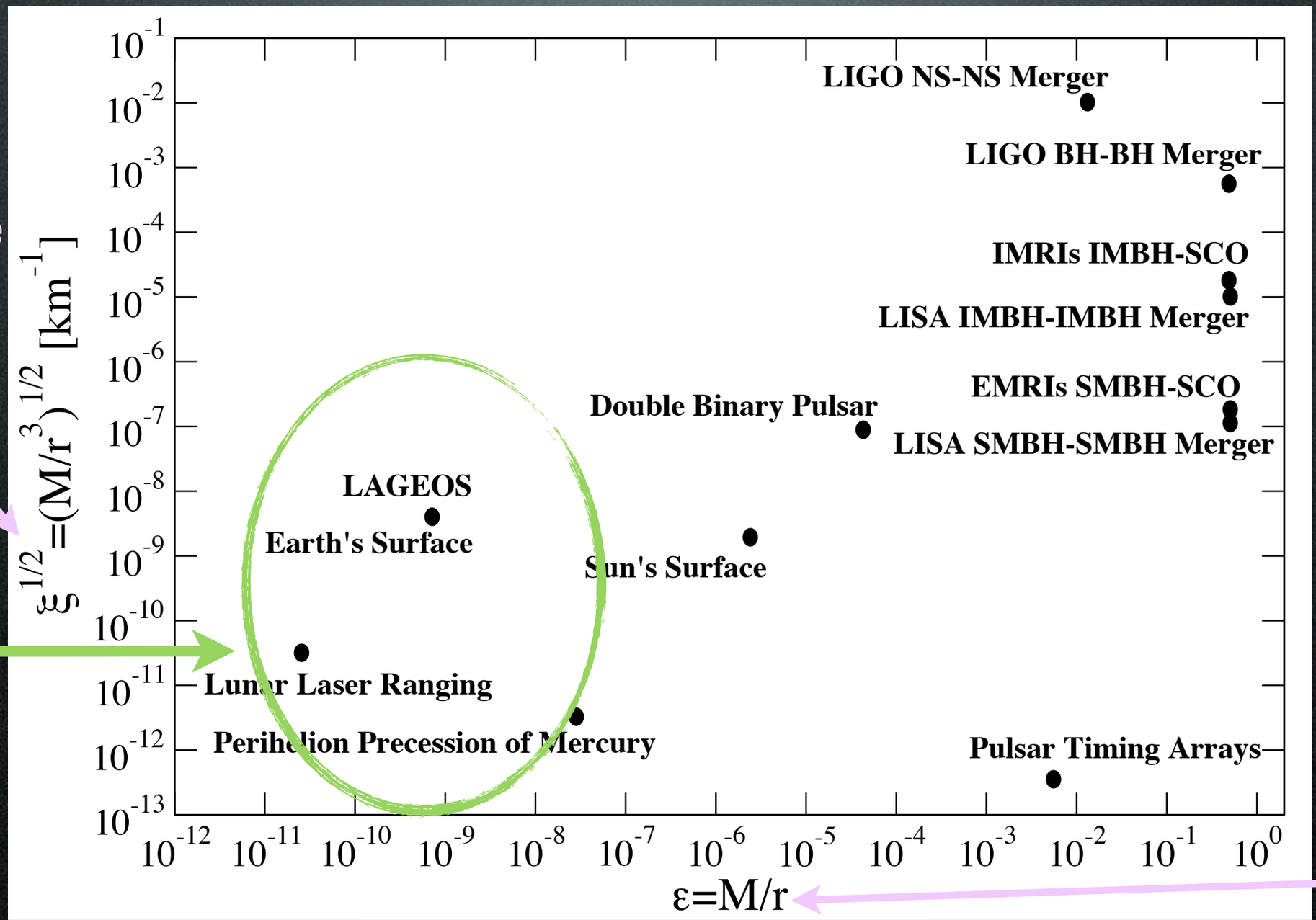
Field Strength

Will, Liv. Rev., 2005, Psaltis, Liv. Rev., 2008, Siemens & Yunes, Liv. Rev. 2012 in prog.

Trust But Verify

Curvature Strength

Weak Field Tests



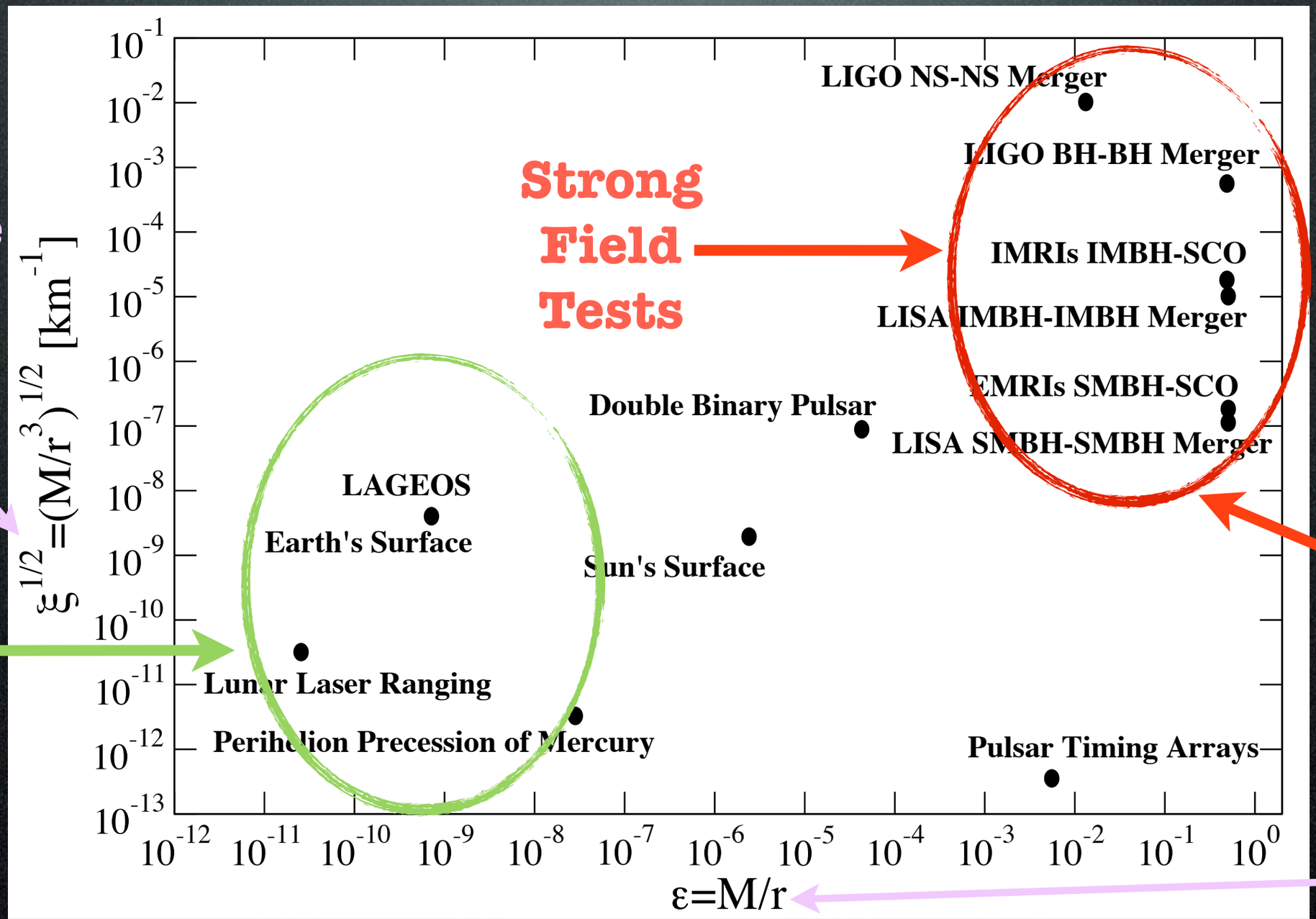
Field Strength

Will, Liv. Rev., 2005, Psaltis, Liv. Rev., 2008, Siemens & Yunes, Liv. Rev. 2012 in prog.

Trust But Verify

Curvature Strength

Weak Field Tests



Strong Field:

$\ell^2\zeta = \mathcal{O}(1)$

$\epsilon = \mathcal{O}(1)$

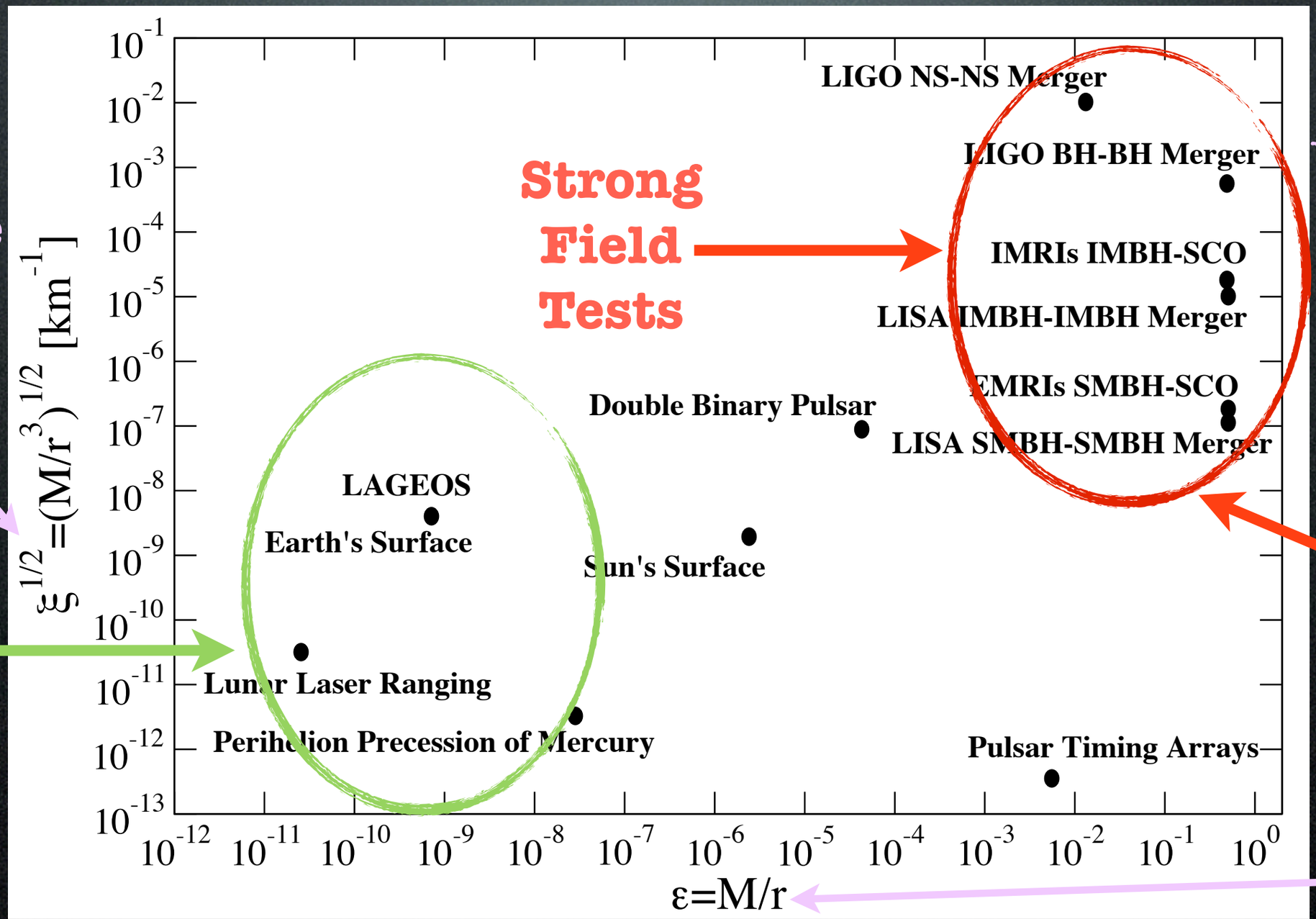
Field Strength

Will, Liv. Rev., 2005, Psaltis, Liv. Rev., 2008, Siemens & Yunes, Liv. Rev. 2012 in prog.

Trust But Verify

Curvature Strength

Weak Field Tests



with SNRs in the 10s

Strong Field:

$\ell^2\zeta = \mathcal{O}(1)$

$\epsilon = \mathcal{O}(1)$

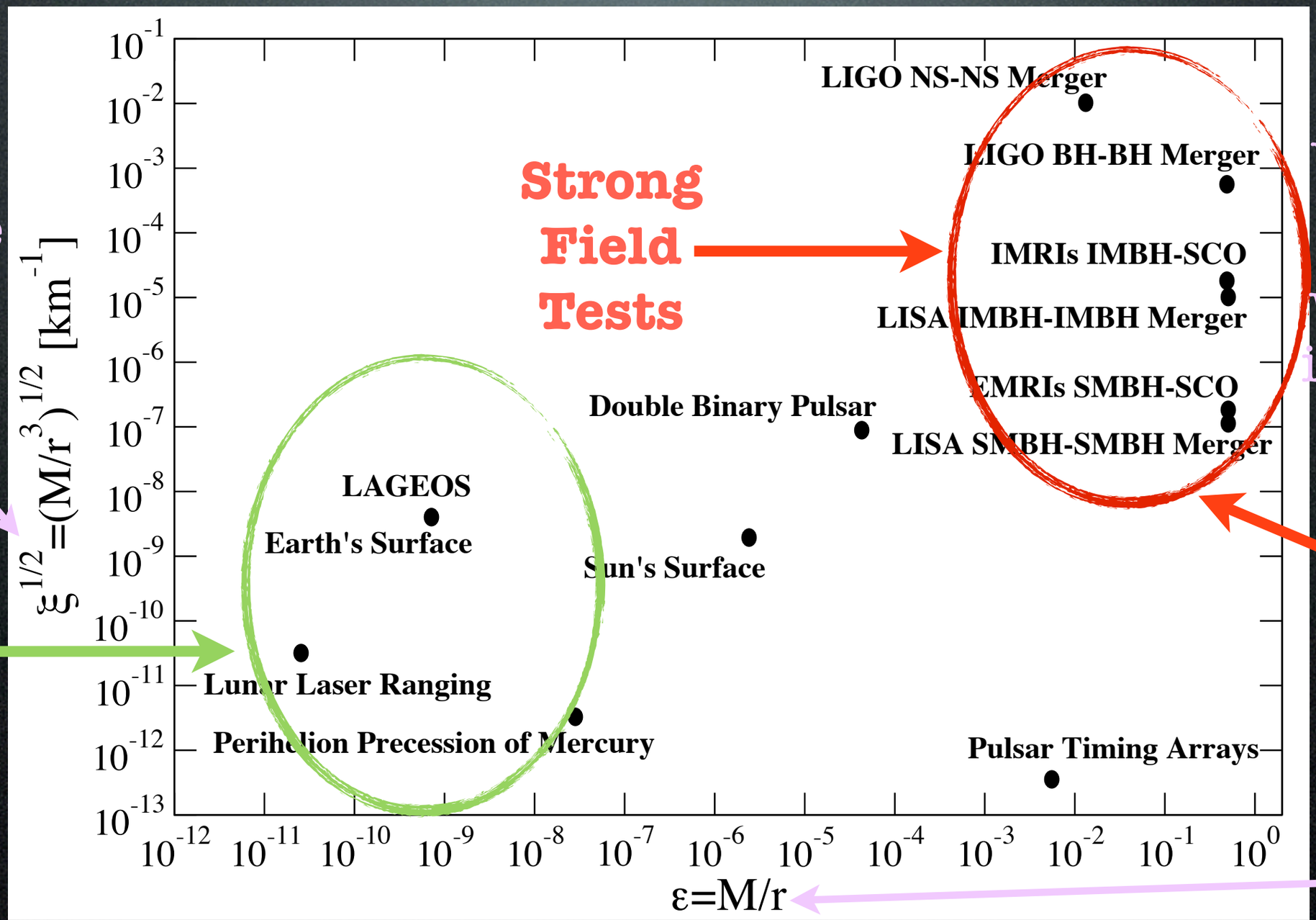
Field Strength

Will, Liv. Rev., 2005, Psaltis, Liv. Rev., 2008, Siemens & Yunes, Liv. Rev. 2012 in prog.

Trust But Verify

Curvature Strength

Weak Field Tests



Strong Field Tests

with SNRs in the 10s

with SNRs in the 1e3s

Strong Field:

$\ell^2\zeta = \mathcal{O}(1)$

$\epsilon = \mathcal{O}(1)$

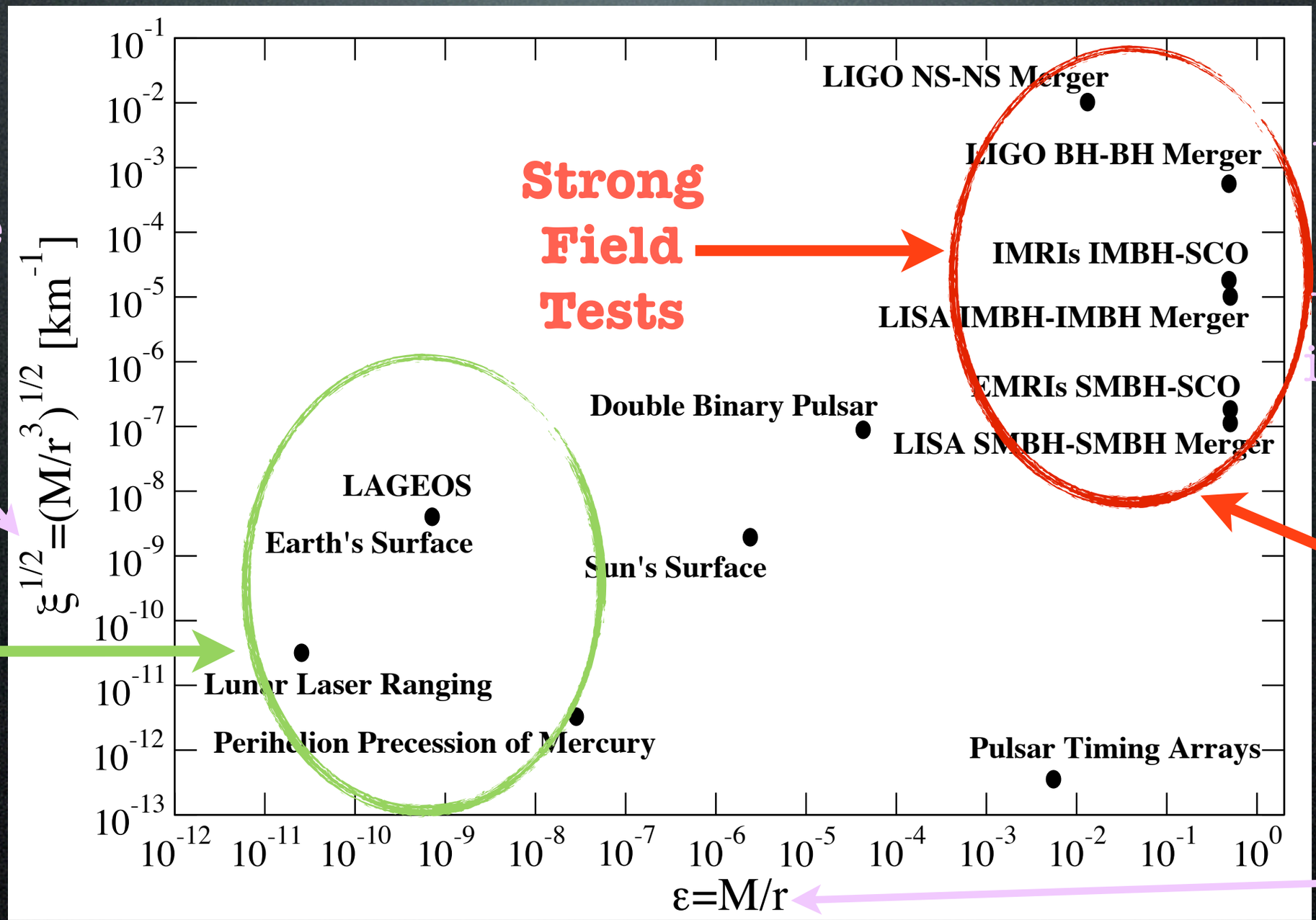
Field Strength

Will, Liv. Rev., 2005, Psaltis, Liv. Rev., 2008, Siemens & Yunes, Liv. Rev. 2012 in prog.

Trust But Verify

Curvature Strength

Weak Field Tests



with SNRs in the 10s

with SNRs in the 1e3s

Strong Field:

$\ell^2\zeta = \mathcal{O}(1)$

$\epsilon = \mathcal{O}(1)$

Field Strength

GWs can probe the non-linear, dynamical, strong-field regime

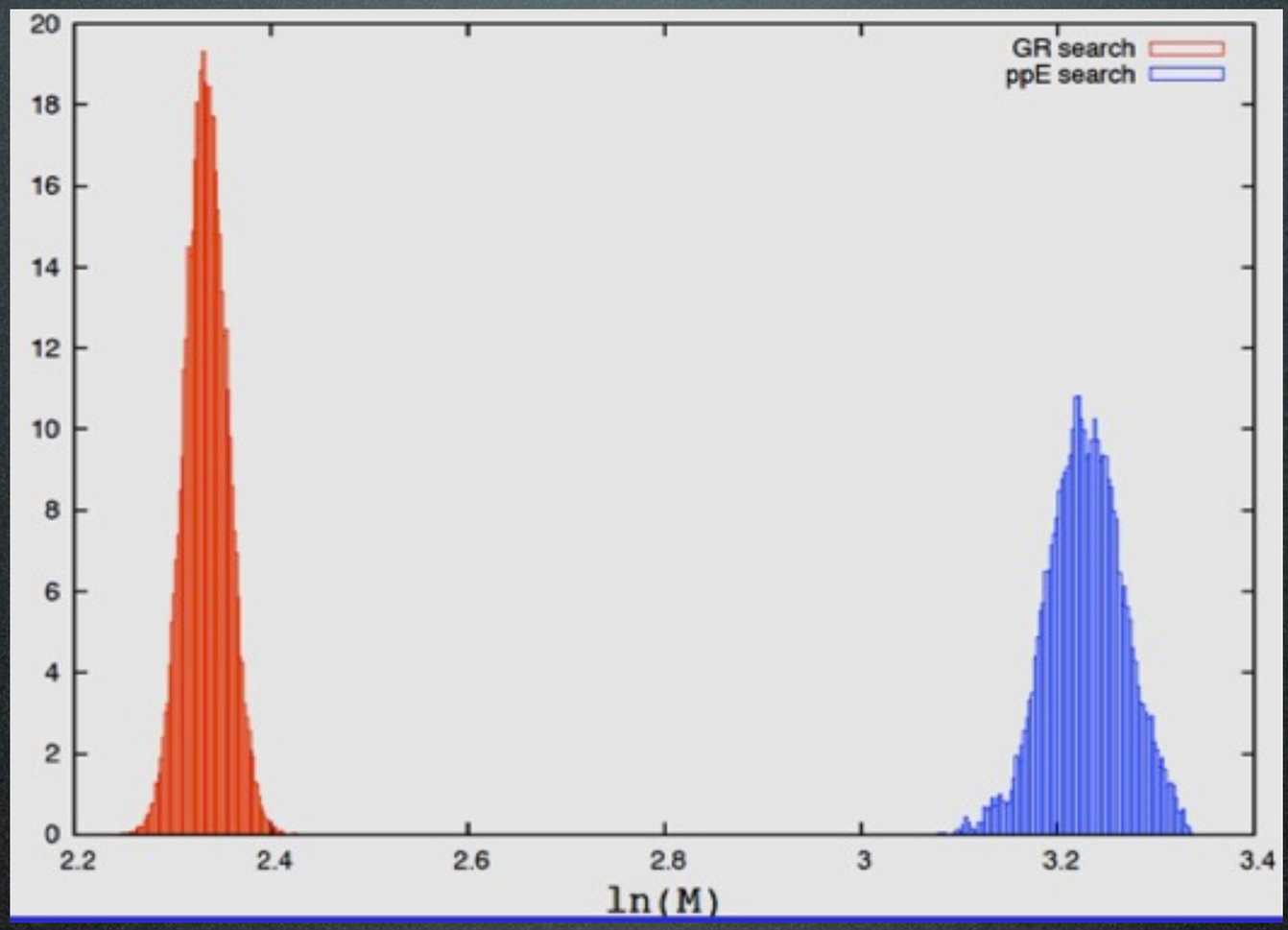
Will, Liv. Rev., 2005, Psaltis, Liv. Rev., 2008, Siemens & Yunes, Liv. Rev. 2012 in prog.

Verify and only then Trust

Unconstrained GR modifications can alter astrophysical inferences (fundamental bias).

Verify and only then Trust

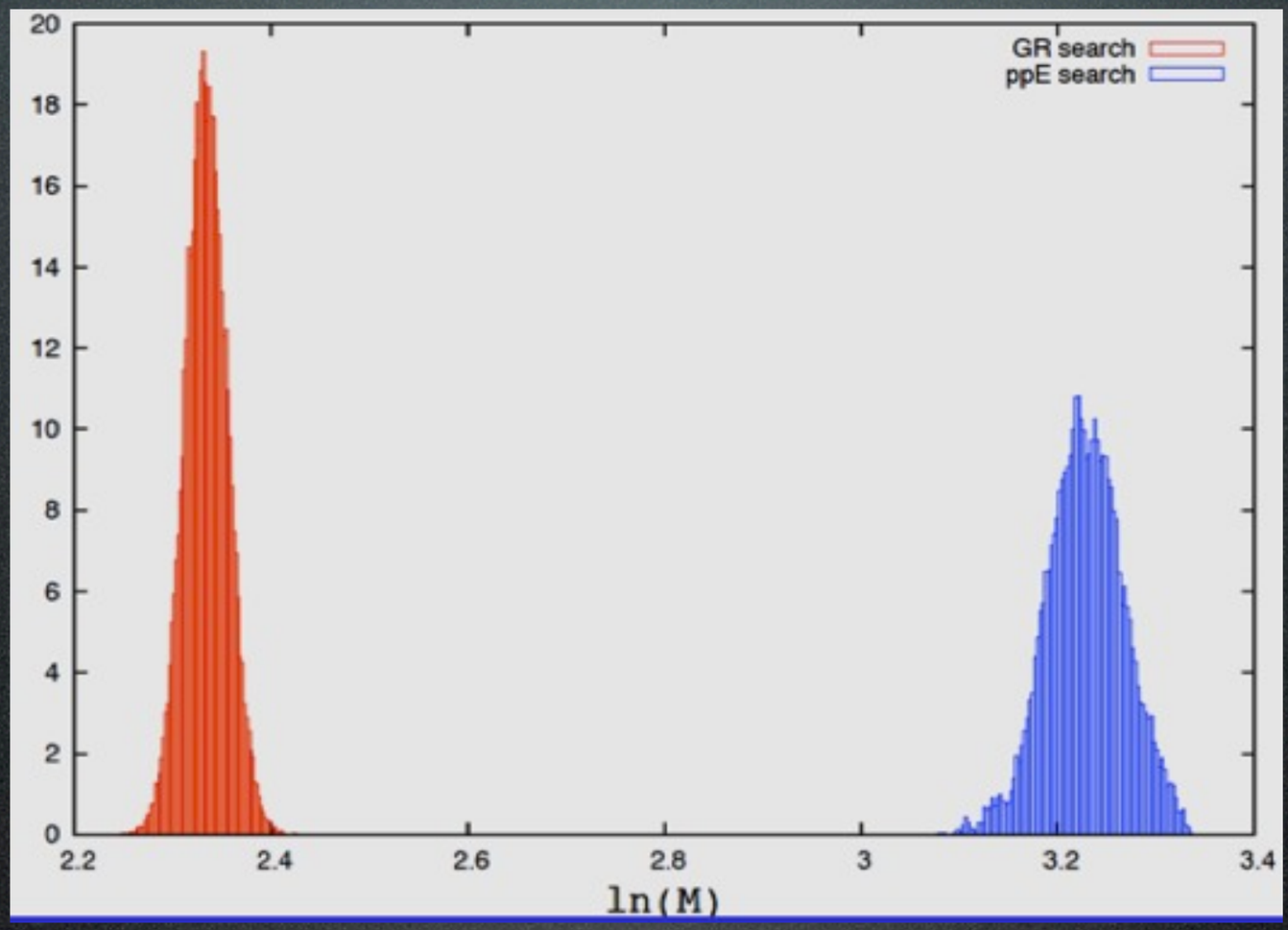
Unconstrained GR modifications can alter astrophysical inferences (fundamental bias).



Cornish, Sampson, Yunes & Pretorius, 2011

Verify and only then Trust

Unconstrained GR modifications can alter astrophysical inferences (fundamental bias).



Cornish, Sampson, Yunes & Pretorius, 2011

Modified theories can:

i) Change GW amplitude -> error in GW DL and inc. angle.

ii) Change GW phase -> error in GW Mchirp, mass ratio, EOS.

iii) Change ISCO -> error in EM spin measurement.

Road Map

I. ppE Theory

II. ppE Implementation

What I will leave out

- Data analysis [Veitch].
- Detailed waveform modeling within GR [Pan]
- Non-Integrable orbits, Chaos, Poincare Islands
- Cosmology.
- Quasi-normal ringdown and merger tests.

I. ppE Theory

Test Classification

Non-Generic Tests

- Pick a theory and test it.

Eg. Brans-Dicke Theory.

- Problem: what theory do you pick? Do we have to consider all possibilities?

Will, PRD 50, 1994,
Will, PRD 57, 1998,
Scharre & Will, PRD 65, 2002,
Will & Yunes, CQG 21, 2004,
Berti, et al PRD 71, 2005,
Stavridis & Will, CQG 28, 2009,
Arun & Will, CQG 26, 2009,
Yunes, Pretorius & Spergel, PRD 81, `10,
Mirshekari, Yunes & Will, PRD 85, `12.

Test Classification

Non-Generic Tests

- Pick a theory and test it.

Eg. Brans-Dicke Theory.

- Problem: what theory do you pick? Do we have to consider all possibilities?

Generic Tests

- Search for model-independent GR deviations.

Will, PRD 50, 1994,
Will, PRD 57, 1998,
Scharre & Will, PRD 65, 2002,
Will & Yunes, CQG 21, 2004,
Berti, et al PRD 71, 2005,
Stavridis & Will, CQG 28, 2009,
Arun & Will, CQG 26, 2009,
Yunes, Pretorius & Spergel, PRD 81, `10,
Mirshekari, Yunes & Will, PRD 85, `12.

Test Classification

Non-Generic Tests

- Pick a theory and test it.

Eg. Brans-Dicke Theory.

- Problem: what theory do you pick? Do we have to consider all possibilities?

Will, PRD 50, 1994,
Will, PRD 57, 1998,
Scharre & Will, PRD 65, 2002,
Will & Yunes, CQG 21, 2004,
Berti, et al PRD 71, 2005,
Stavridis & Will, CQG 28, 2009,
Arun & Will, CQG 26, 2009,
Yunes, Pretorius & Spergel, PRD 81, '10,
Mirshekari, Yunes & Will, PRD 85, '12.

Generic Tests

- Search for model-independent GR deviations.

- Develop a "meta"-model (e.g. ppN) but for GWs: **ppE**

Yunes & Pretorius, PRD 80, '09,
Yunes & Hughes, PRD 82, '10,
Yagi, Stein, Yunes and Tanaka '11,
Cornish, Sampson, Yunes & Pretorius, '11,
del Pozzo, et al, PRD 83, '11
Li, et al, '12,
Arun, CQG '12
Chatziioannou, Yunes & Cornish, '12,

“Penrose-Like Diagram”

"Penrose-Like Diagram"

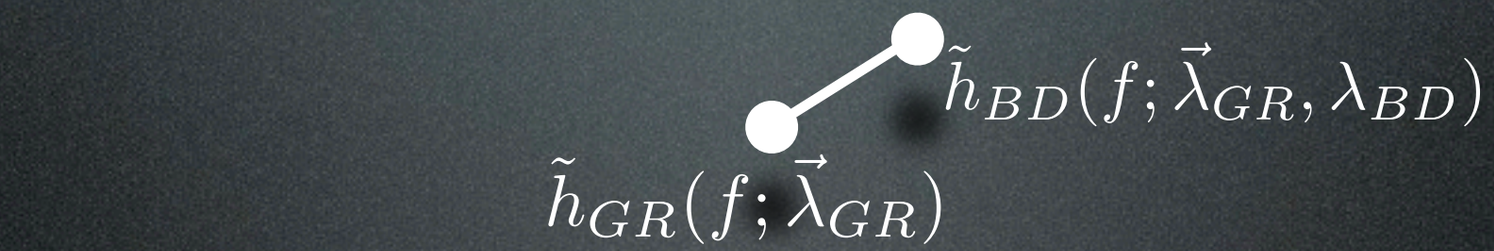
$$h_{GR}(f;\lambda_{GR})$$

"Penrose-Like Diagram"

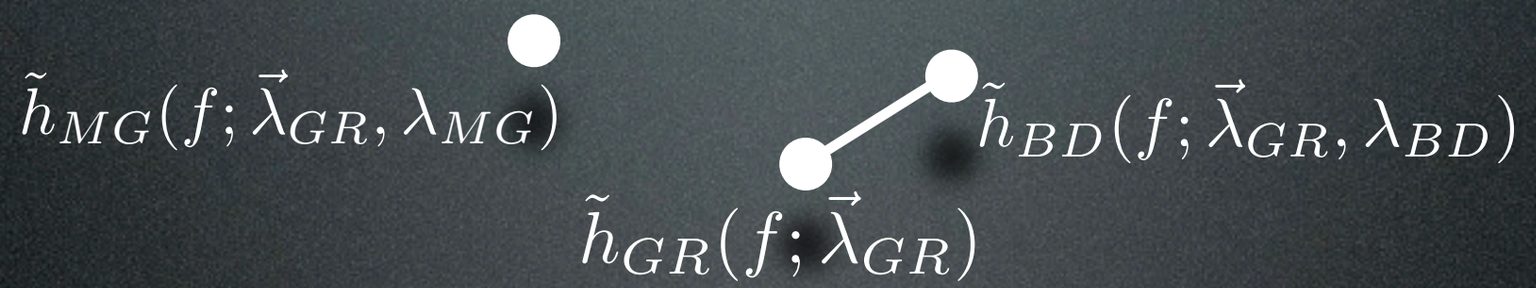
$\tilde{h}_{BD}(f;\vec{\lambda}_{GR},\lambda_{BD})$

$\tilde{h}_{GR}(f;\vec{\lambda}_{GR})$

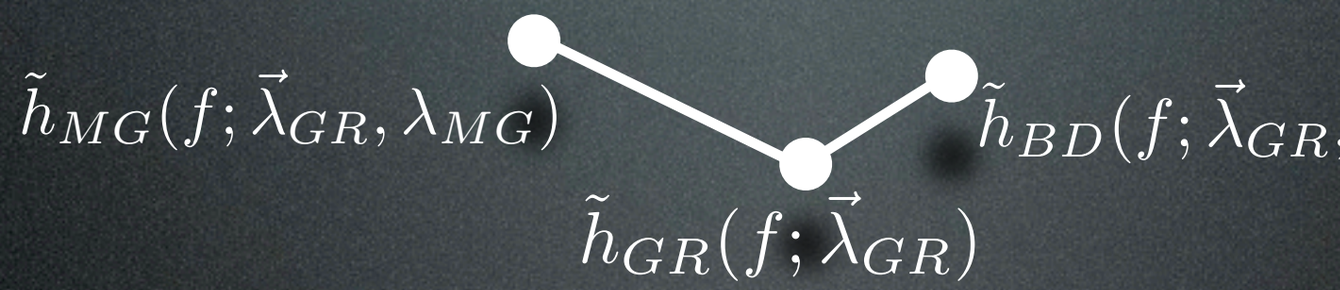
"Penrose-Like Diagram"



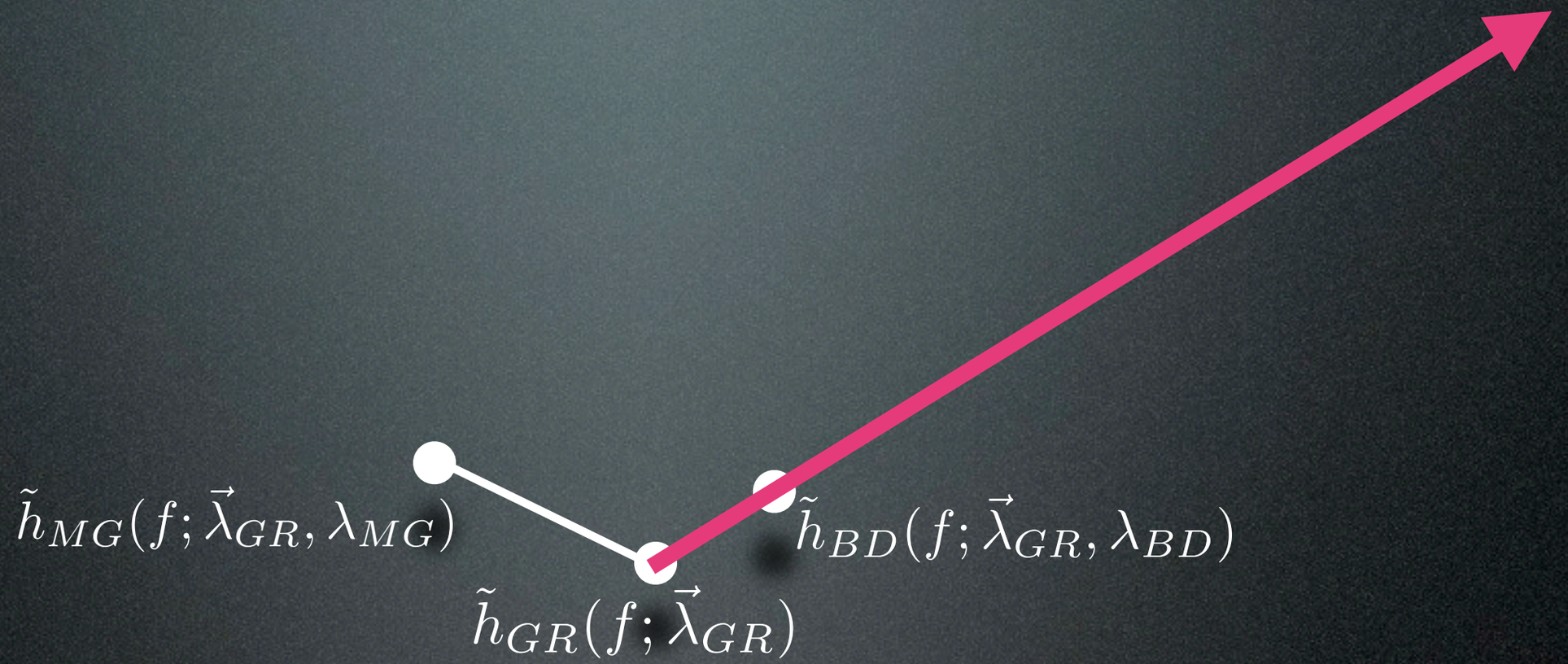
"Penrose-Like Diagram"



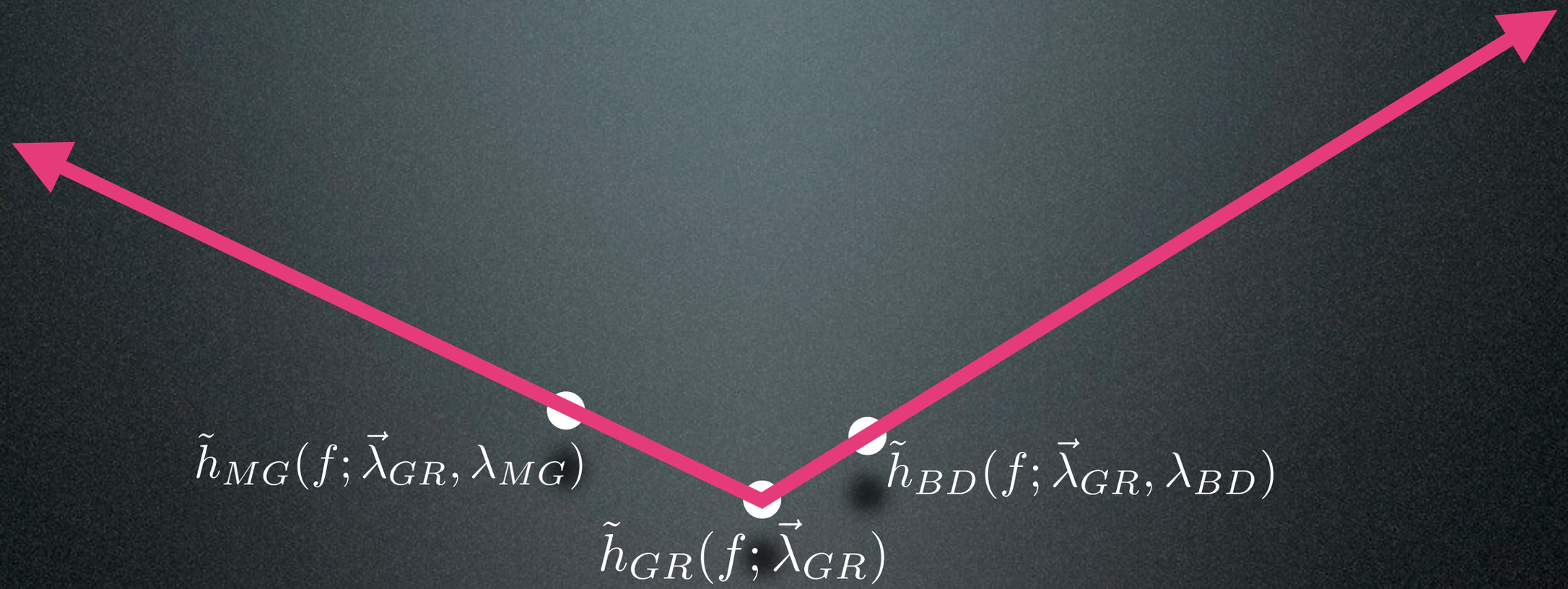
"Penrose-Like Diagram"



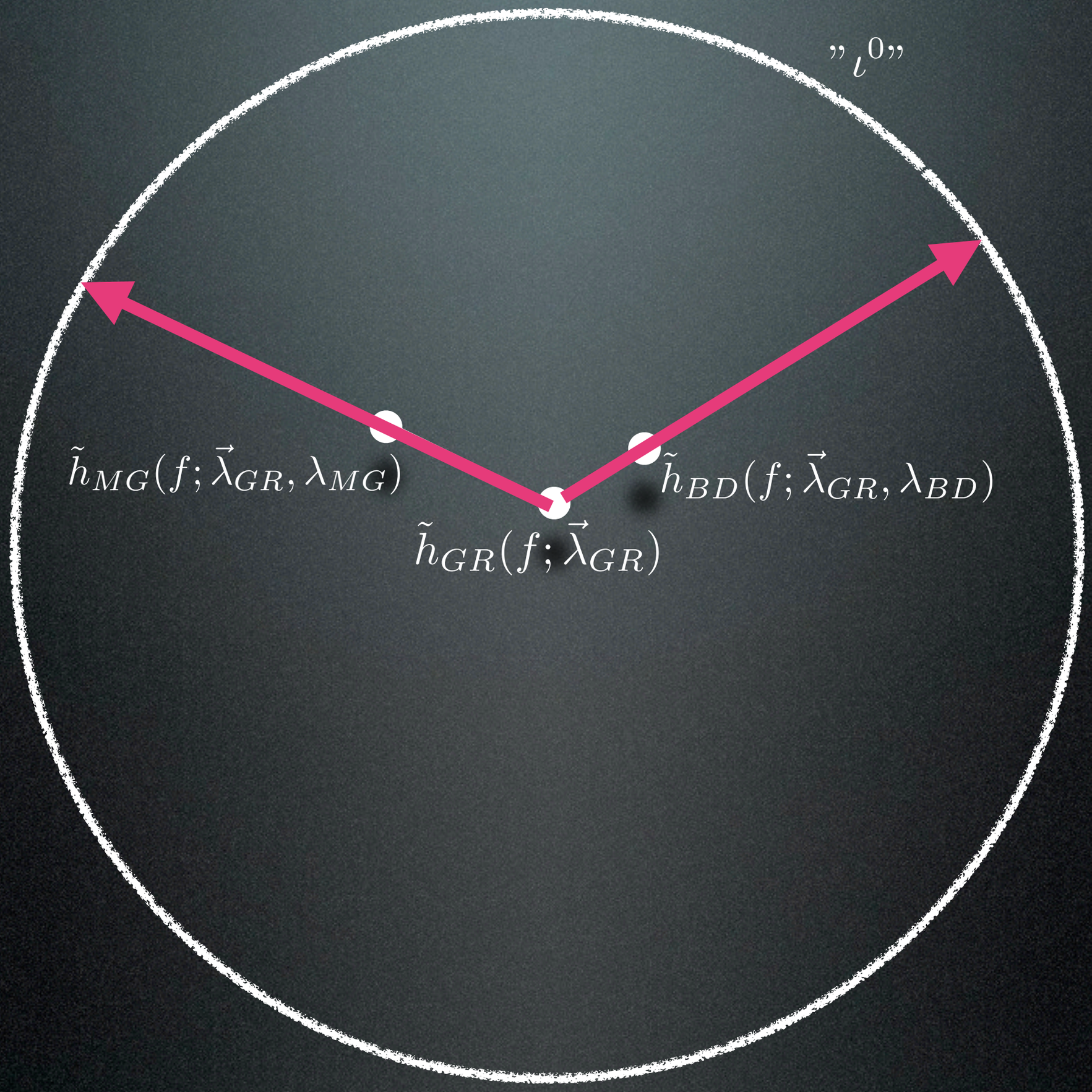
"Penrose-Like Diagram"



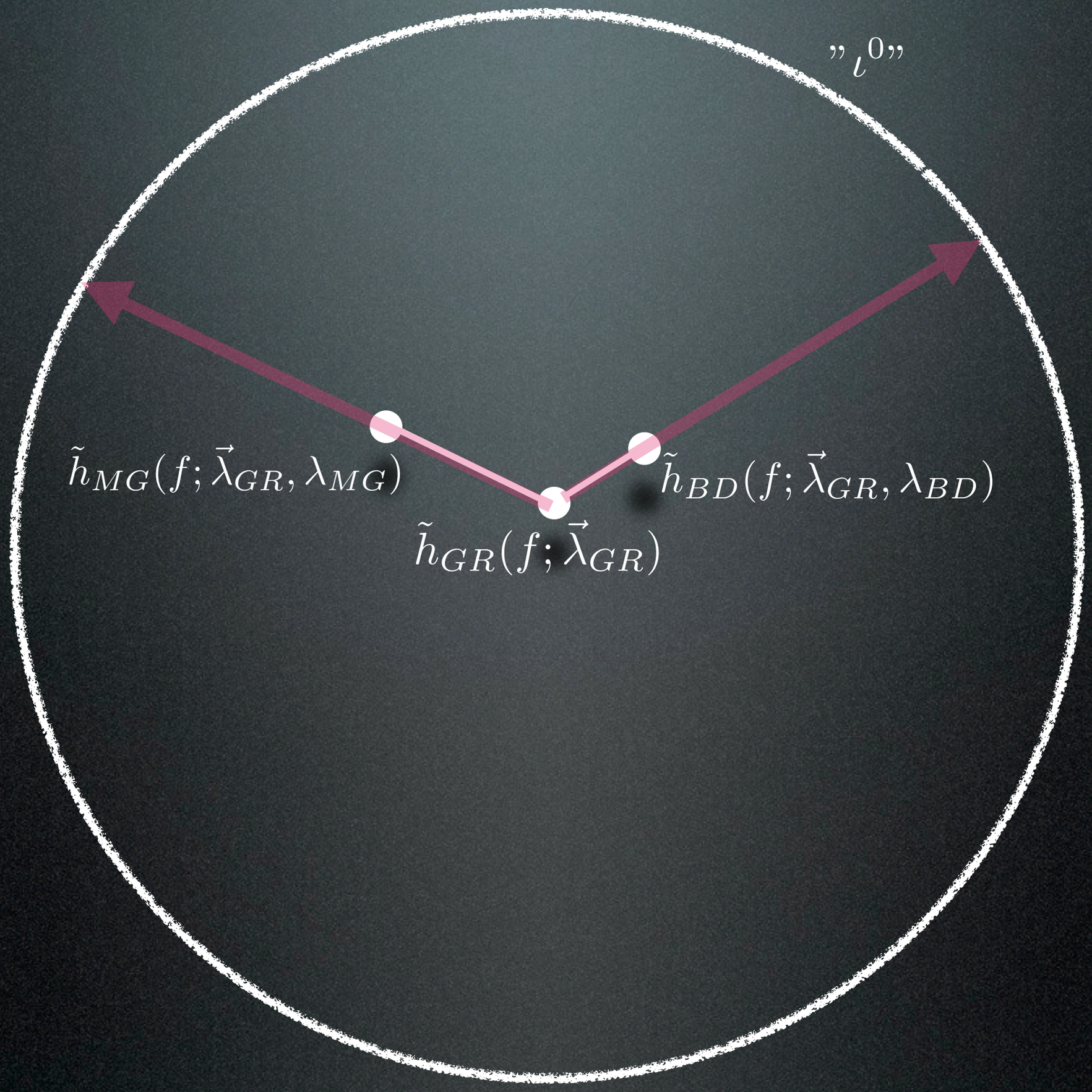
"Penrose-Like Diagram"



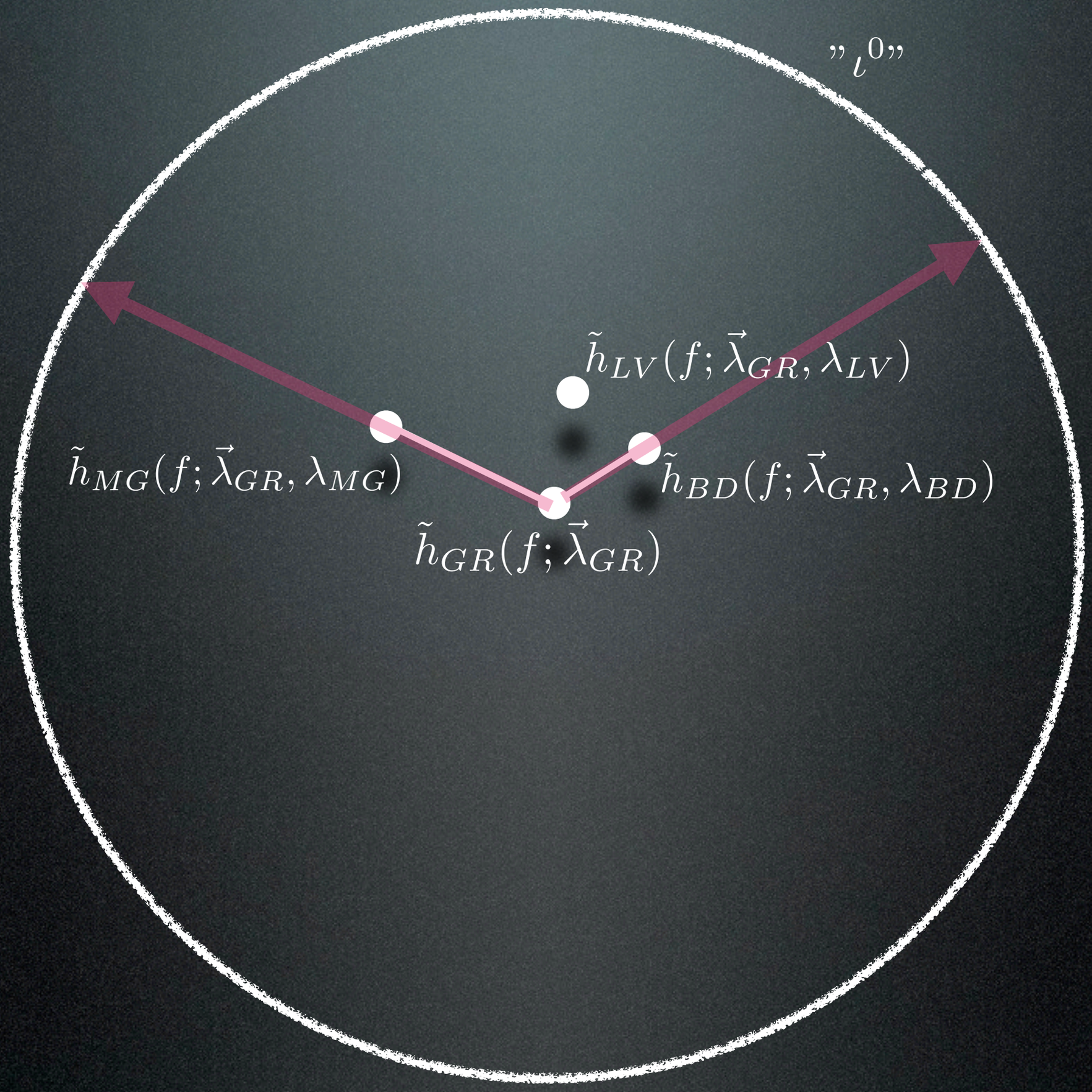
"Penrose-Like Diagram"



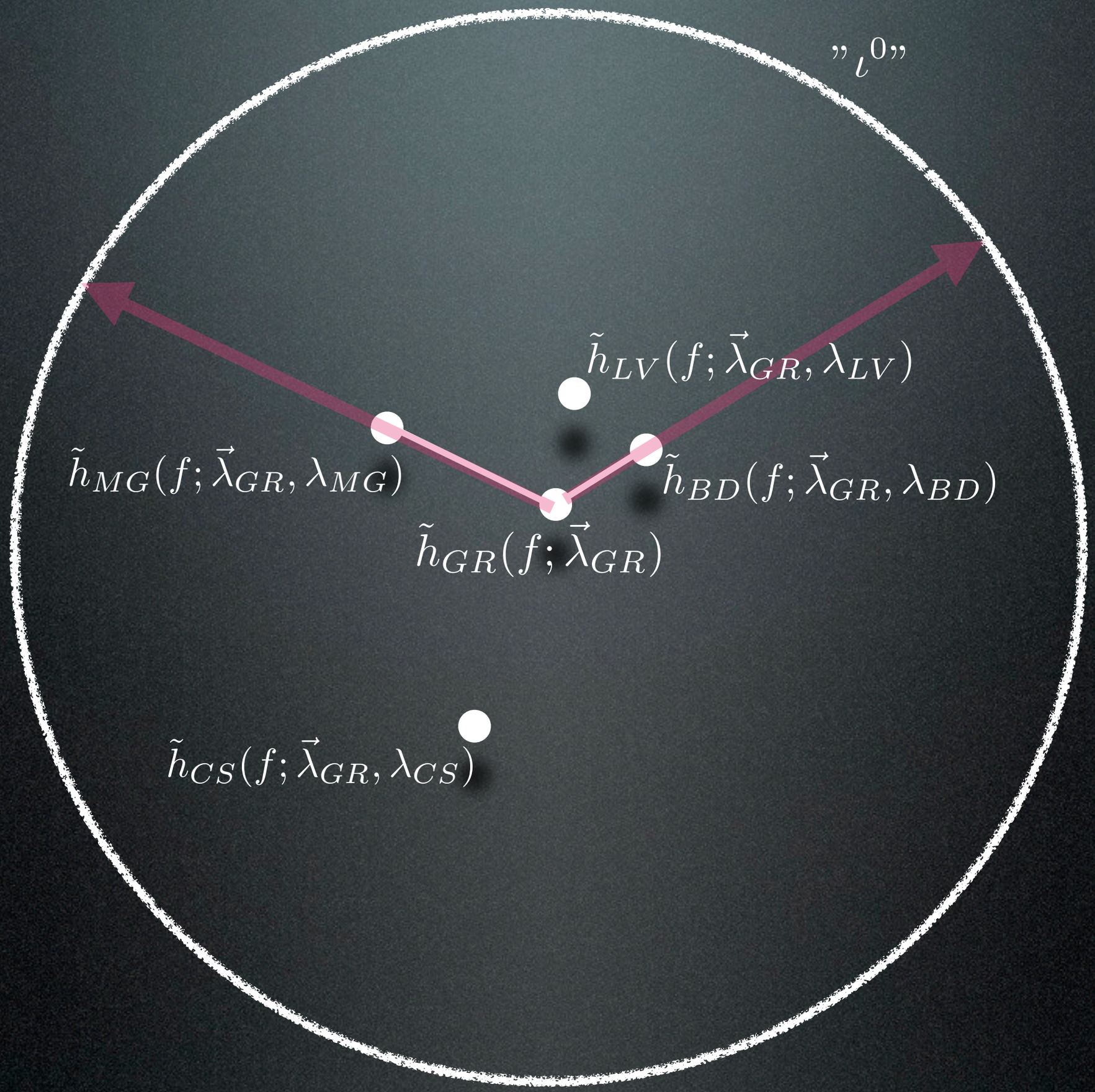
"Penrose-Like Diagram"



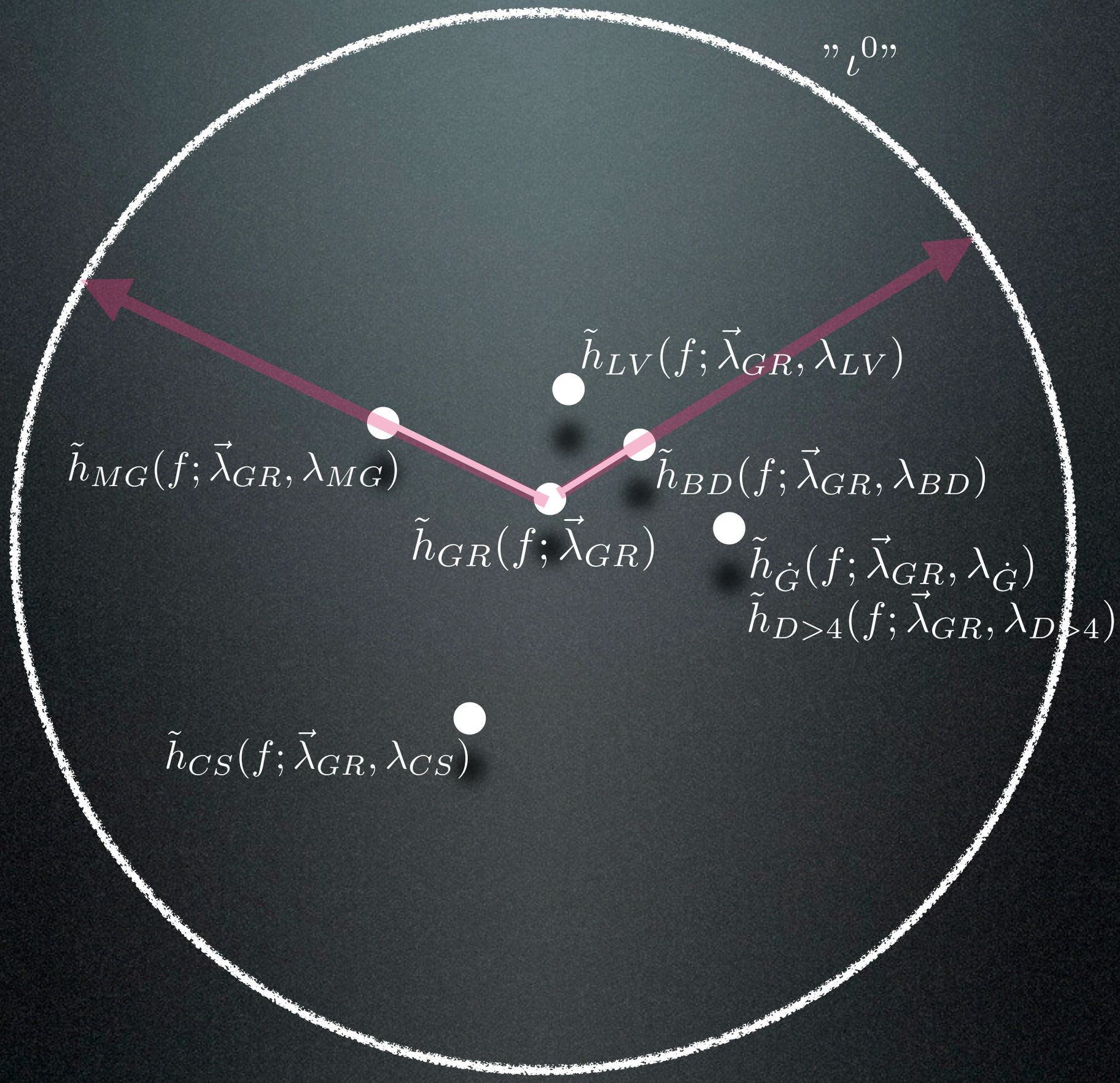
"Penrose-Like Diagram"



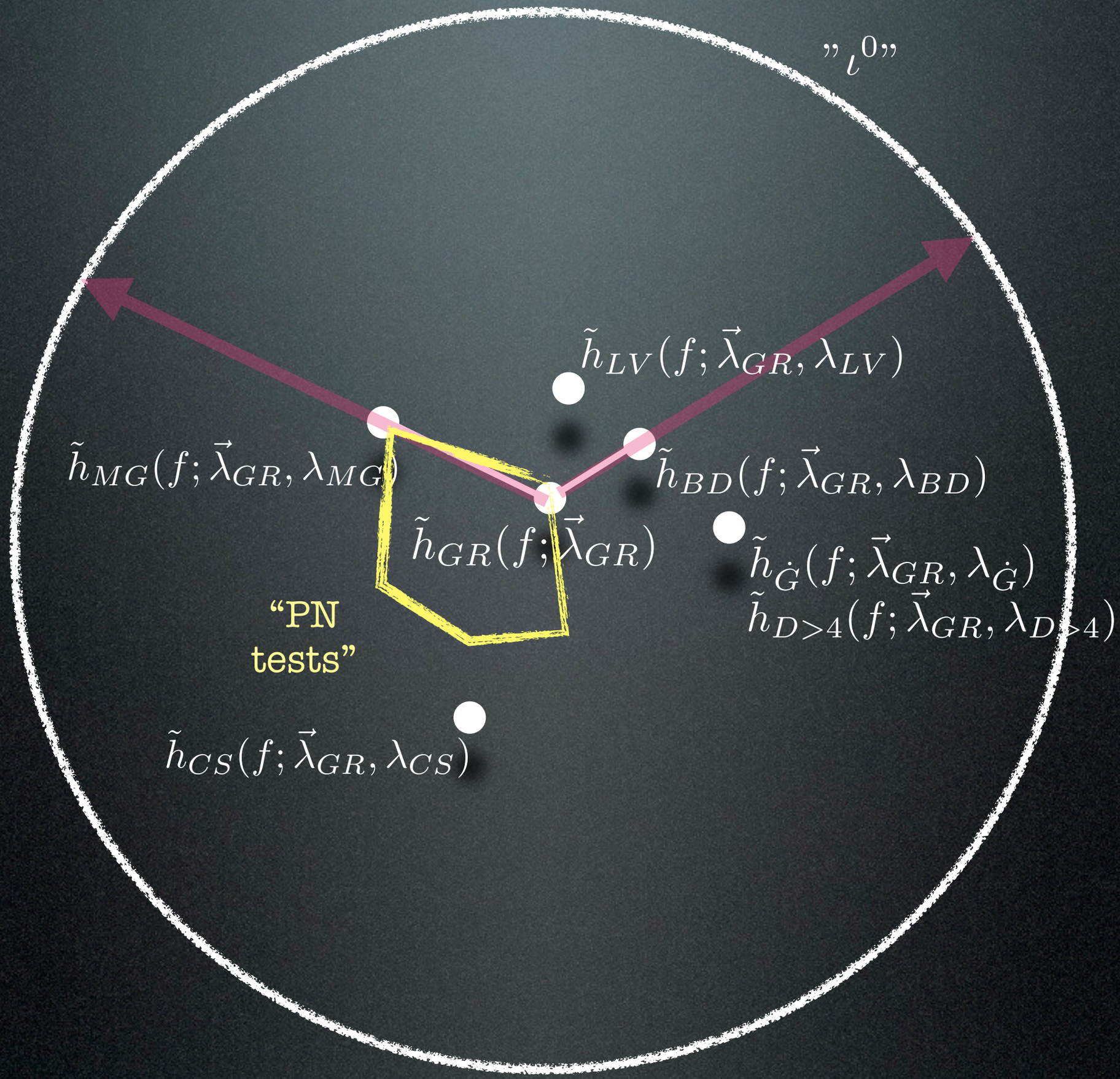
"Penrose-Like Diagram"



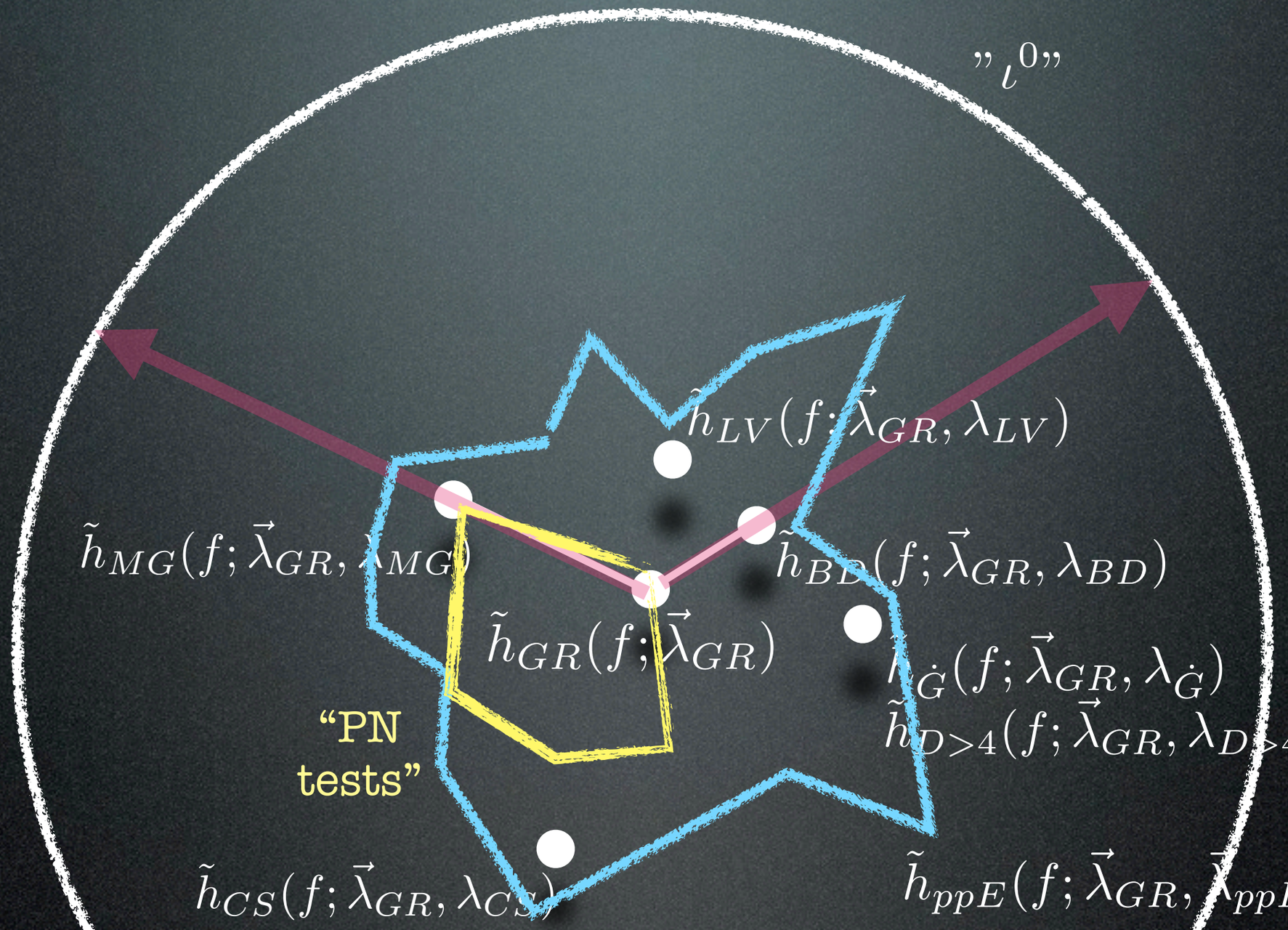
"Penrose-Like Diagram"



"Penrose-Like Diagram"



"Penrose-Like Diagram"



Theoretical ppE Construction

Yunes & Pretorius, PRD 2009
Mirshekari, Yunes & Will, PRD 2012
Chatziioannou, Yunes & Cornish, PRD 2012

Theoretical ppE Construction

> 0. (Consider comparable-mass, non-spinning compact inspirals.)

Yunes & Pretorius, PRD 2009
Mirshekari, Yunes & Will, PRD 2012
Chatziioannou, Yunes & Cornish, PRD 2012

Theoretical ppE Construction

> 0. (Consider comparable-mass, non-spinning compact inspirals.)

> I. Parametrically deform the Hamiltonian.

$$A = A_{\rm GR} + \delta A$$
$$\delta A_{H,RR} = \bar{\alpha}_{\rm H,RR}\, v^{\bar{a}_{\rm H,RR}}$$

Yunes & Pretorius, PRD 2009
Mirshekari, Yunes & Will, PRD 2012
Chatziioannou, Yunes & Cornish, PRD 2012

Theoretical ppE Construction

> 0. (Consider comparable-mass, non-spinning compact inspirals.)

> I. Parametrically deform the Hamiltonian.

> II. Parametrically deform the RR force.

$$A = A_{\rm GR} + \delta A$$
$$\delta A_{H,RR} = \bar{\alpha}_{\rm H,RR}\, v^{\bar{a}_{\rm H,RR}}$$

Yunes & Pretorius, PRD 2009
Mirshekari, Yunes & Will, PRD 2012
Chatziioannou, Yunes & Cornish, PRD 2012

Theoretical ppE Construction

> 0. (Consider comparable-mass, non-spinning compact inspirals.)

> I. Parametrically deform the Hamiltonian.

> II. Parametrically deform the RR force.

$$A = A_{\rm GR} + \delta A$$
$$\delta A_{H,RR} = \bar{\alpha}_{\rm H,RR}\, v^{\bar{a}_{\rm H,RR}}$$

> III. Deform waveform generation.

$$h = F_+ h_+ + F_\times h_\times + F_s h_s + \ldots$$

Yunes & Pretorius, PRD 2009
Mirshekari, Yunes & Will, PRD 2012
Chatziioannou, Yunes & Cornish, PRD 2012

Theoretical ppE Construction

> 0. (Consider comparable-mass, non-spinning compact inspirals.)

> I. Parametrically deform the Hamiltonian.

> II. Parametrically deform the RR force.

$$A = A_{\rm GR} + \delta A$$
$$\delta A_{H,RR} = \bar{\alpha}_{\rm H,RR}\, v^{\bar{a}_{\rm H,RR}}$$

> III. Deform waveform generation. $h = F_+ h_+ + F_\times h_\times + F_s h_s + \ldots$

> IV. Parametrically deform g propagation. $E_g^2 = p_g^2 c^4 + \tilde{\alpha}\, p_g^{\tilde{a}}$

Yunes & Pretorius, PRD 2009
Mirshekari, Yunes & Will, PRD 2012
Chatziioannou, Yunes & Cornish, PRD 2012

Theoretical ppE Construction

> 0. (Consider comparable-mass, non-spinning compact inspirals.)

> I. Parametrically deform the Hamiltonian.

> II. Parametrically deform the RR force.

$$A = A_{\rm GR} + \delta A$$
$$\delta A_{H,RR} = \bar{\alpha}_{\rm H,RR}\, v^{\bar{a}_{\rm H,RR}}$$

> III. Deform waveform generation. $h = F_+ h_+ + F_\times h_\times + F_s h_s + \ldots$

> IV. Parametrically deform g propagation. $E_g^2 = p_g^2 c^4 + \tilde{\alpha}\, p_g^{\tilde{a}}$

> Result: To leading PN order and leading GR deformation

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

Yunes & Pretorius, PRD 2009
Mirshekari, Yunes & Will, PRD 2012
Chatziioannou, Yunes & Cornish, PRD 2012

ppE Recovery of Theories

$$\tilde{h} = \tilde{h}_{\rm GR}\left[1+\alpha_{\rm ppE}\left(\pi\mathcal{M}f\right)^{a_{\rm ppE}/3}\right]e^{i\beta_{\rm ppE}\left(\pi\mathcal{M}f\right)^{b_{\rm ppE}/3}}$$

Theory	$\alpha_{\rm ppE}$	$a_{\rm ppE}$	$\beta_{\rm ppE}$	$b_{\rm ppE}$
Jordan-Brans-Dicke-Fierz	$-\frac{5}{96}\frac{S^2}{\omega_{\rm BD}}\eta^{2/5}$	-2	$-\frac{5}{3584}\frac{S^2}{\omega_{\rm BD}}\eta^{2/5}$	-7
Conservative Einstein-Dilaton-Gauss-Bonnet gravity	$\frac{5}{6}\eta^{-4/5}\zeta_3$	4	$\frac{25}{64}\eta^{-4/5}\zeta_{\rm EDGB}$	-1
Dissipative Einstein-Dilaton-Gauss-Bonnet gravity	0	·	$-\frac{5}{7168}\zeta_3\eta^{-18/5}\frac{(m_1-m_2)^2}{m^2}$	-7
Massive Graviton	0	·	$-\frac{\pi^2 D\mathcal{M}}{\lambda_g^2(1+z)}$	-3
Lorentz Violation	0	·	$-\frac{\pi^{2-\gamma}}{(1-\gamma)}\frac{D_\gamma}{\lambda_{\rm LV}^{2-\gamma}}\frac{\mathcal{M}^{1-\gamma}}{(1+z)^{1-\gamma}}$	$-3\alpha_{\rm LV}-3$
$G(t)$ Theory	$-\frac{5}{512}\dot{G}\mathcal{M}$	-8	$-\frac{25}{65536}\dot{G}_c\mathcal{M}$	-13
Extra Dimensions	·	·	$-\frac{75}{2554344}\frac{dM}{dt}\eta^{-4}(3-26\eta+24\eta^2)$	-13
Non-Dynamical Chern-Simons Gravity	$\alpha_{\rm PV}$	3	$\beta_{\rm PV}$	6

Siemens & Yunes, LRR '13

II. ppE Implementation

Questions for ppE

Questions for ppE

Questions for ppE

Templates/ Theories		

Questions for ppE

Templates/ Theories	GR	

Questions for ppE

Templates/ Theories	GR	ppE

Questions for ppE

Templates/ Theories	GR	ppE
GR		

Questions for ppE

Templates/ Theories	GR	ppE
GR	Business as usual	

Questions for ppE

Templates/ Theories	GR	ppE
GR	Business as usual	Quantify the statistical significance that the detected event is within GR. Anomalies?

Questions for ppE

Templates/ Theories	GR	ppE
GR	Business as usual	Quantify the statistical significance that the detected event is within GR. Anomalies?
Not GR		

Questions for ppE

Templates/ Theories	GR	ppE
GR	Business as usual	Quantify the statistical significance that the detected event is within GR. Anomalies?
Not GR	Quantify **fundamental bias** introduced by filtering non-GR events with GR templates	

Questions for ppE

Templates/ Theories	GR	ppE
GR	Business as usual	Quantify the statistical significance that the detected event is within GR. Anomalies?
Not GR	Quantify **fundamental bias** introduced by filtering non-GR events with GR templates	Can we measure deviations from GR characterized by non-GR signals? Model Evidence.

Questions for ppE

Templates/ Theories	GR	ppE
GR	Business as usual	Quantify the statistical significance that the detected event is within GR. Anomalies?
Not GR	Quantify **fundamental bias** introduced by filtering non-GR events with GR templates	Can we measure deviations from GR characterized by non-GR signals? Model Evidence.

- Confusion I: Astrophysical Environment -> b < -7 and non-integer.

  Yunes & Miller & Thornburg, 2011, Yunes, Kocsis & Loeb, 2011, Kocsis, Yunes & Loeb, 2011.

Questions for ppE

Templates/ Theories	GR	ppE
GR	Business as usual	Quantify the statistical significance that the detected event is within GR. Anomalies?
Not GR	Quantify **fundamental bias** introduced by filtering non-GR events with GR templates	Can we measure deviations from GR characterized by non-GR signals? Model Evidence.

- Confusion I: Astrophysical Environment -> b < -7 and non-integer.

  Yunes & Miller & Thornburg, 2011, Yunes, Kocsis & Loeb, 2011, Kocsis, Yunes & Loeb, 2011.

- Confusion II: Noise Environment -> different b for different sources

Questions for ppE

Templates/ Theories	GR	ppE
GR	Business as usual	Quantify the statistical significance that the detected event is within GR. Anomalies?
Not GR	Quantify **fundamental bias** introduced by filtering non-GR events with GR templates	Can we measure deviations from GR characterized by non-GR signals? Model Evidence.

- Confusion I: Astrophysical Environment -> b < -7 and non-integer.

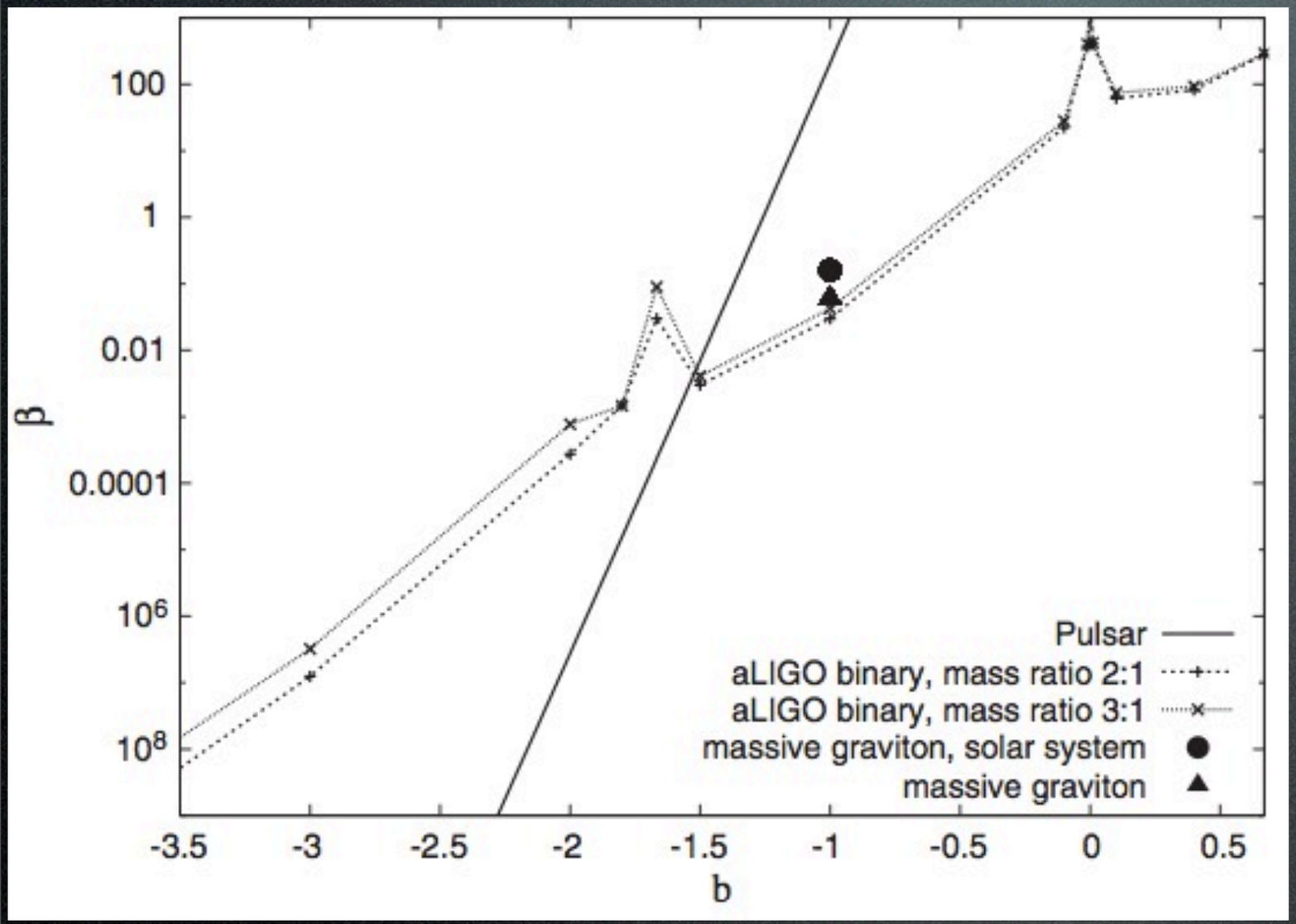
  Yunes & Miller & Thornburg, 2011, Yunes, Kocsis & Loeb, 2011, Kocsis, Yunes & Loeb, 2011.

- Confusion II: Noise Environment -> different b for different sources

- Confusion III: Mismodeling -> Only a problem for sys with large M

Constraining GR Deviations

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

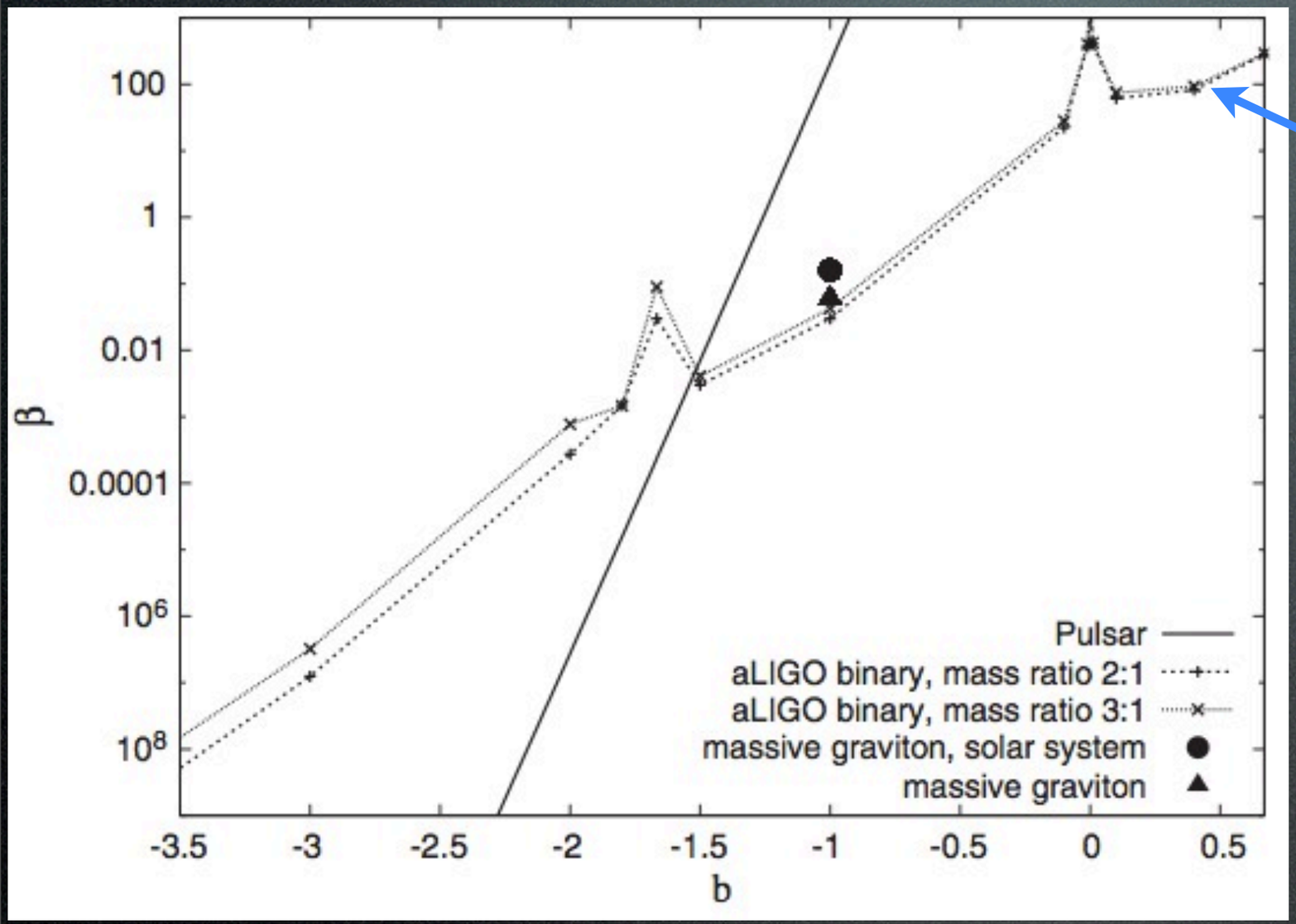


$$\tilde{h} = \tilde{h}_{\rm GR}\left(1+\alpha f^{a}\right)e^{i\beta f^{b}}$$

Yunes & Hughes, 2010,
Cornish, Sampson, Yunes & Pretorius, 2011
Li, et al, 2011.

Constraining GR Deviations

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



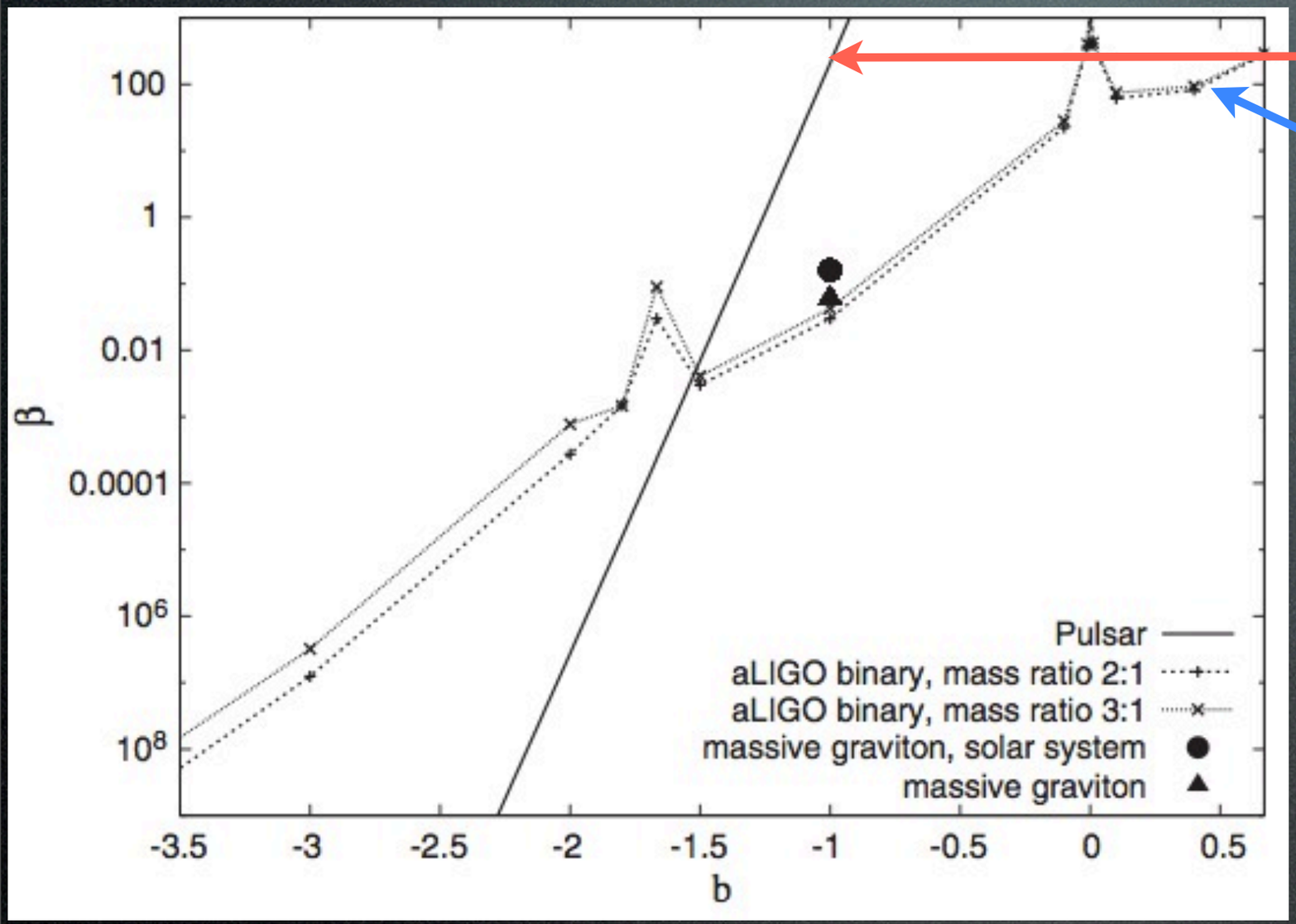
aLIGO projected bounds

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

Yunes & Hughes, 2010,
Cornish, Sampson, Yunes & Pretorius, 2011
Li, et al, 2011.

Constraining GR Deviations

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



Double Binary Pulsar bounds

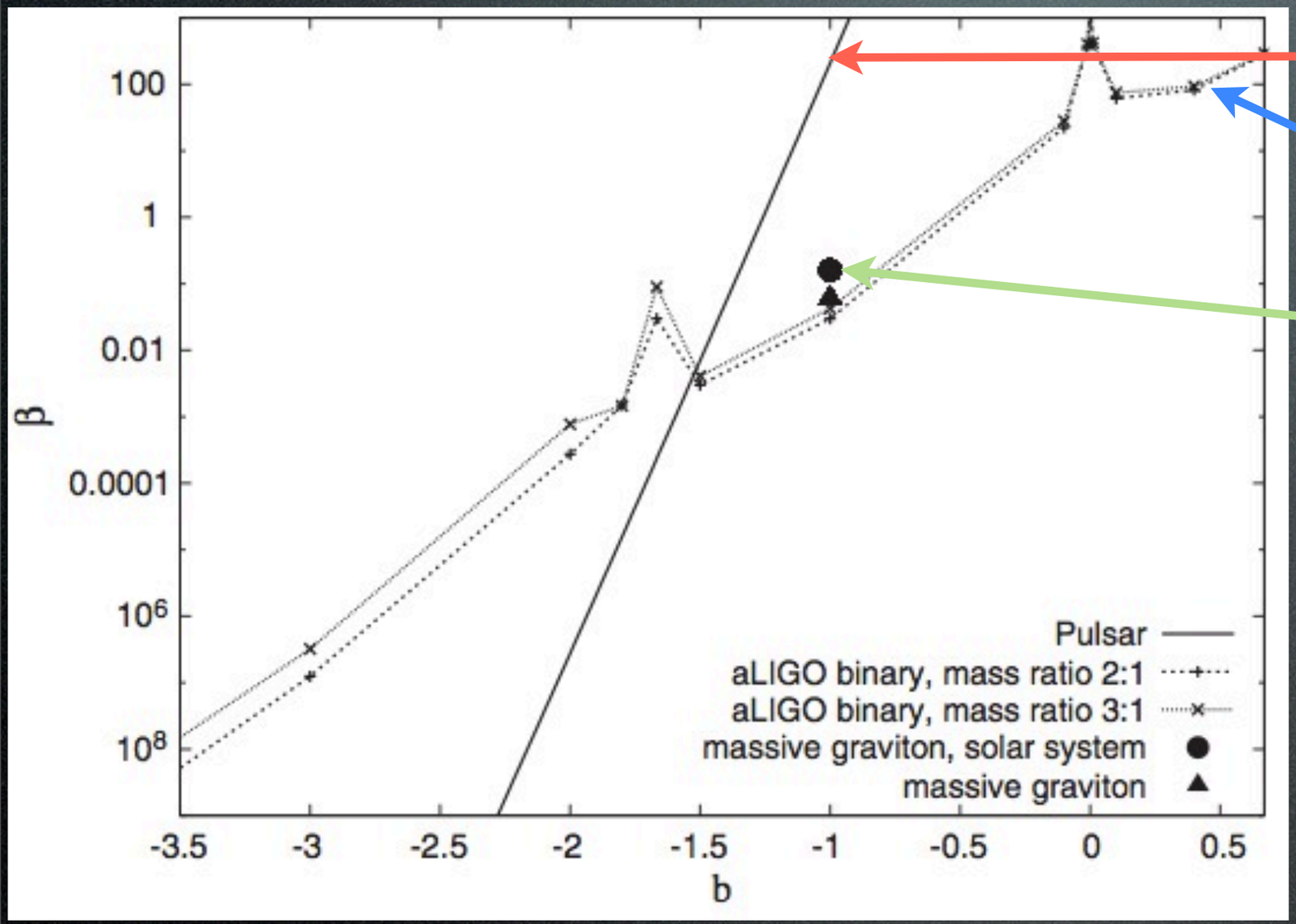
aLIGO projected bounds

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

Yunes & Hughes, 2010,
Cornish, Sampson, Yunes & Pretorius, 2011
Li, et al, 2011.

Constraining GR Deviations

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



Double Binary Pulsar bounds

aLIGO projected bounds

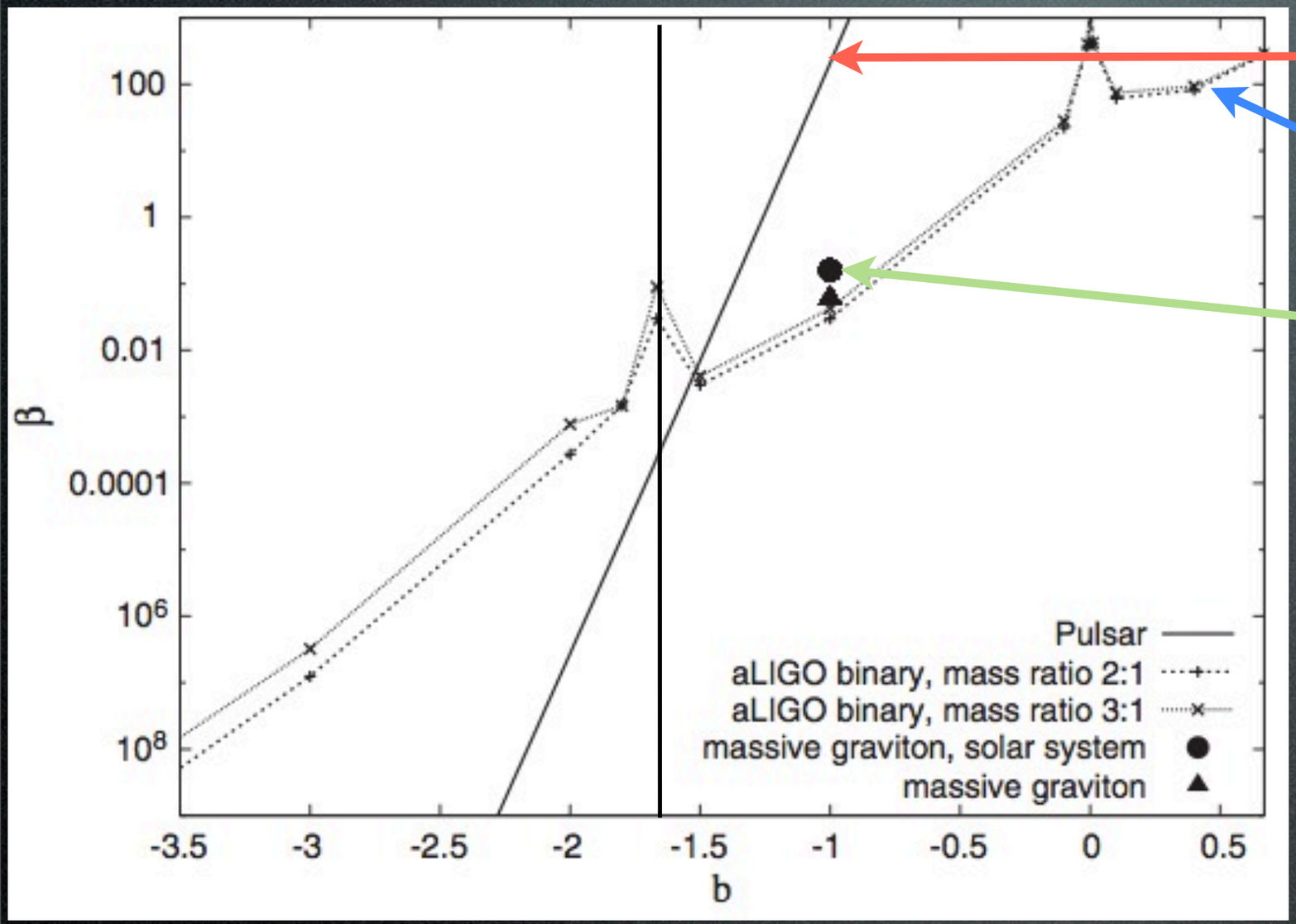
Solar Sys Massive Graviton Bound

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

Yunes & Hughes, 2010,
Cornish, Sampson, Yunes & Pretorius, 2011
Li, et al, 2011.

Constraining GR Deviations

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



Double Binary Pulsar bounds

aLIGO projected bounds

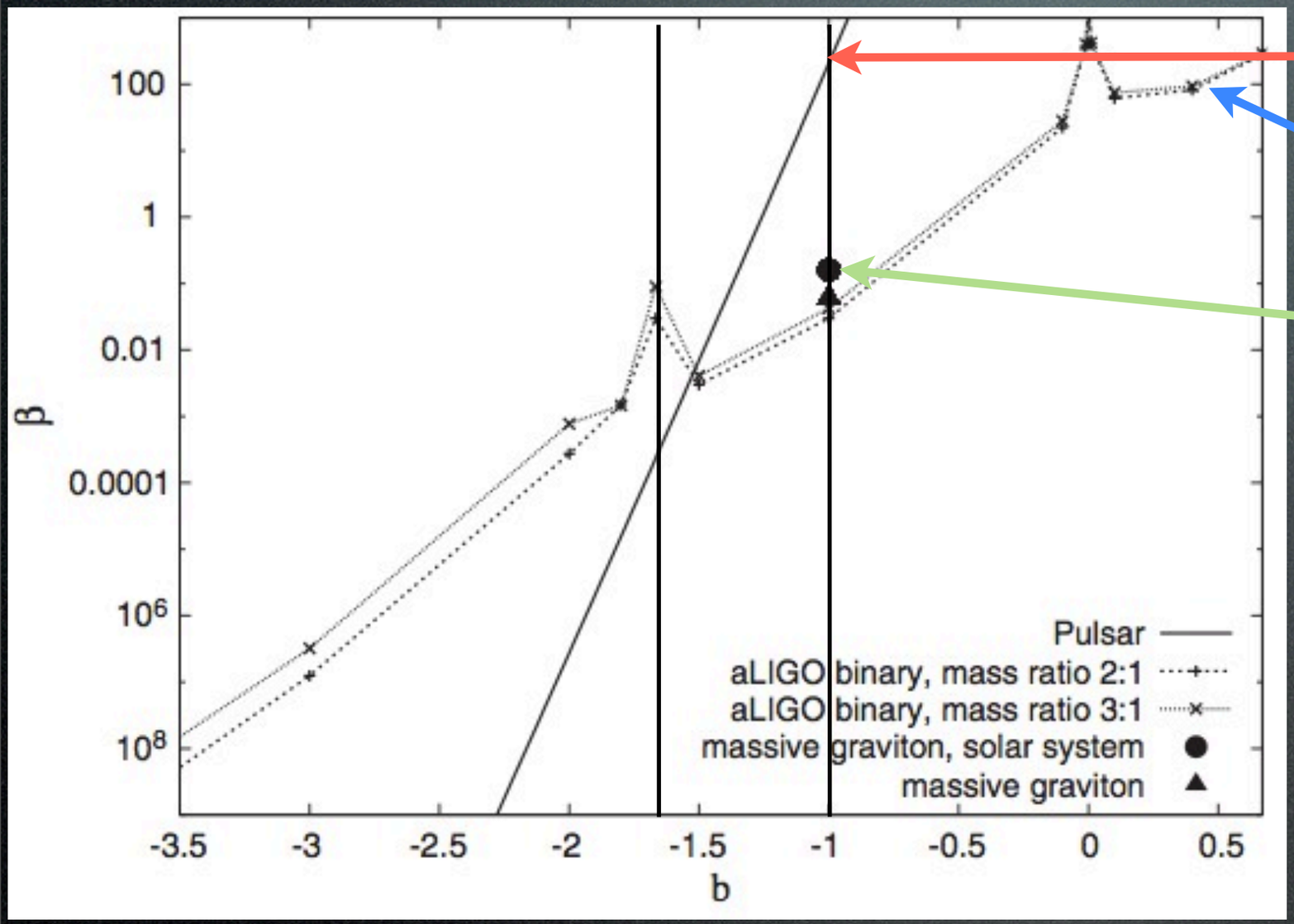
Solar Sys Massive Graviton Bound

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

Yunes & Hughes, 2010,
Cornish, Sampson, Yunes & Pretorius, 2011
Li, et al, 2011.

Constraining GR Deviations

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



Double Binary Pulsar bounds

aLIGO projected bounds

Solar Sys Massive Graviton Bound

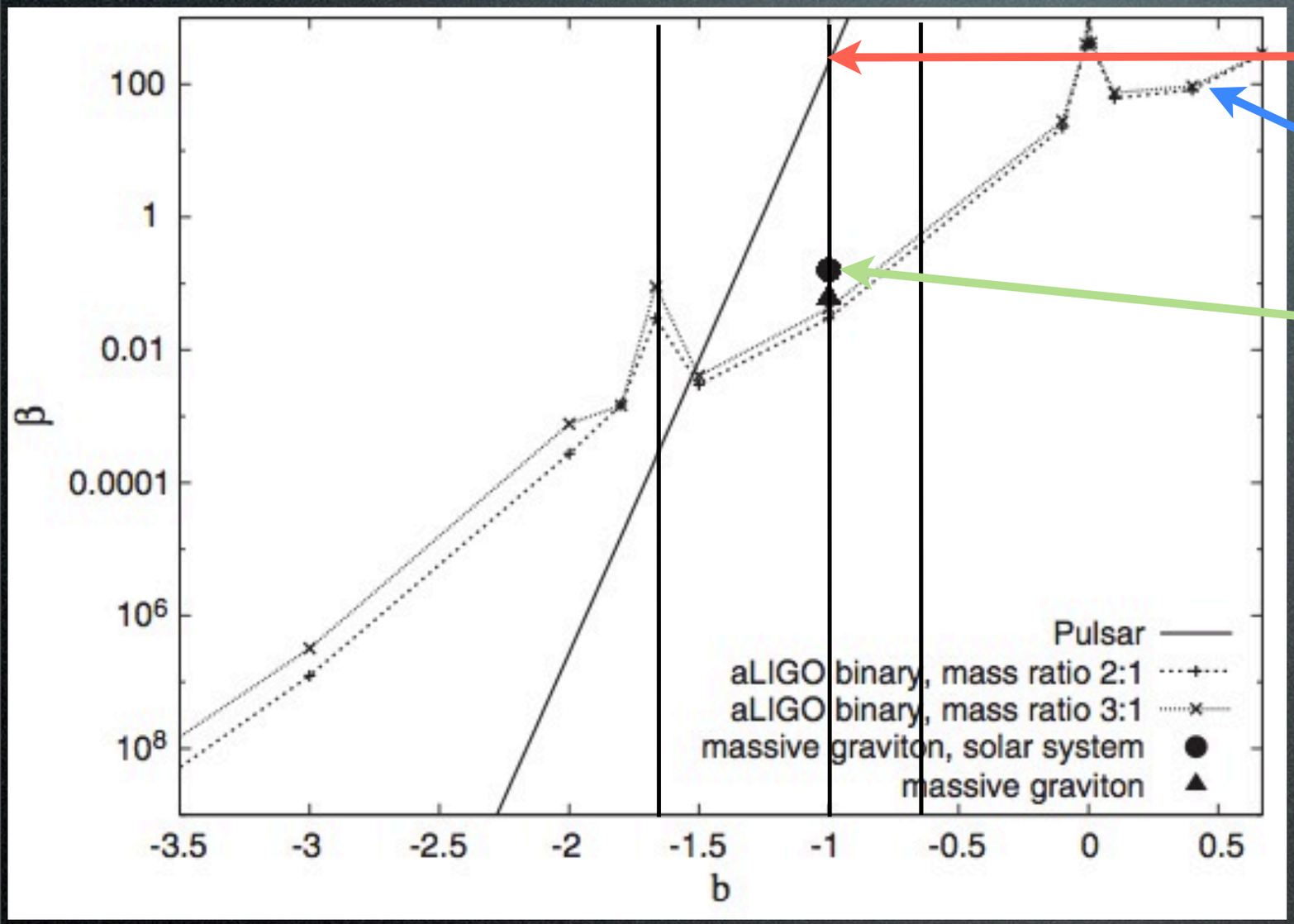
$$\tilde{h} = \tilde{h}_{\rm GR}\left(1 + \alpha f^a\right) e^{i\beta f^b}$$

Yunes & Hughes, 2010,
Cornish, Sampson, Yunes & Pretorius, 2011
Li, et al, 2011.

Constraining GR Deviations

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

Newt 1PN 1.5



Double Binary Pulsar bounds

aLIGO projected bounds

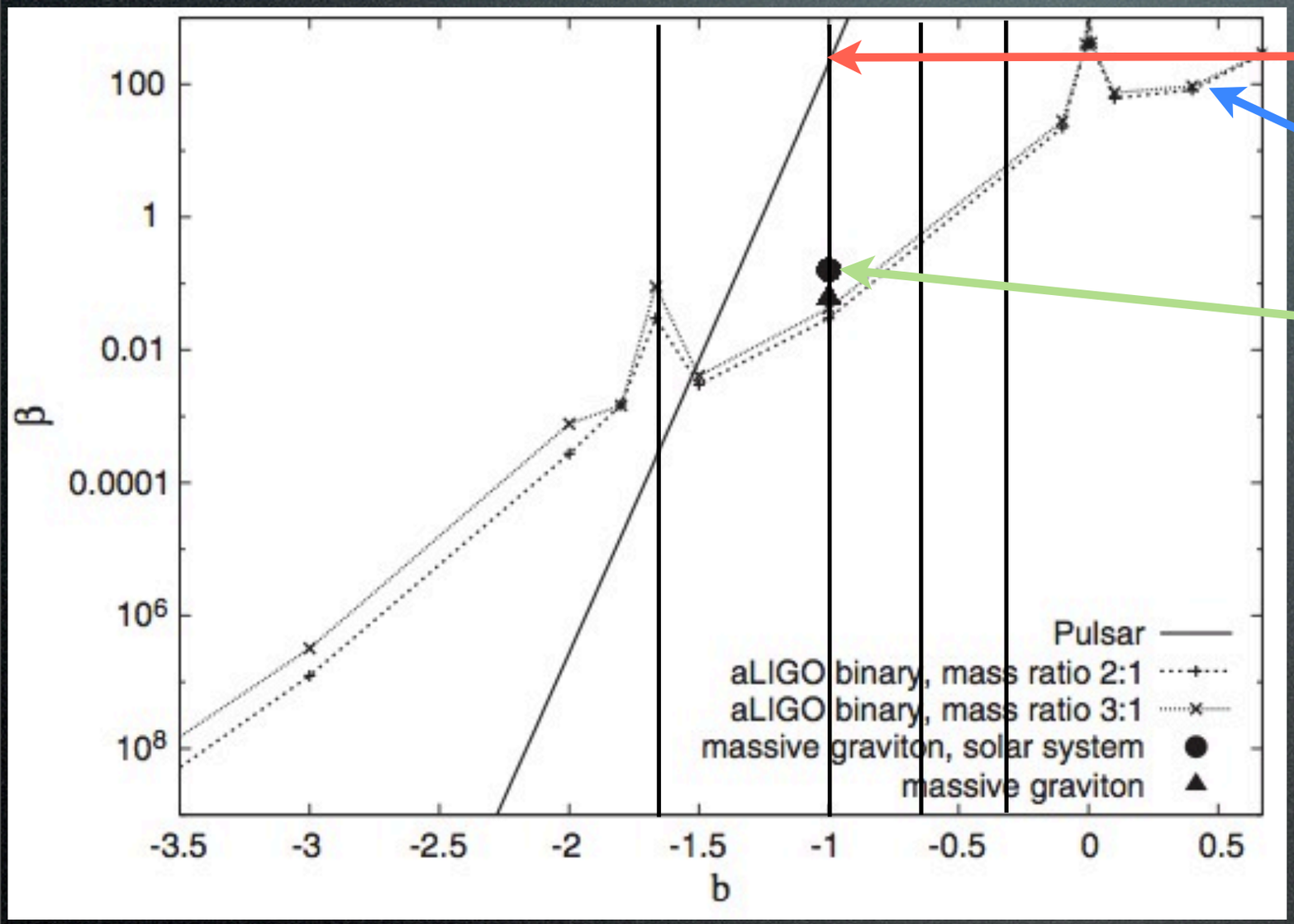
Solar Sys Massive Graviton Bound

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

Yunes & Hughes, 2010,
Cornish, Sampson, Yunes & Pretorius, 2011
Li, et al, 2011.

Constraining GR Deviations

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



Double Binary Pulsar bounds

aLIGO projected bounds

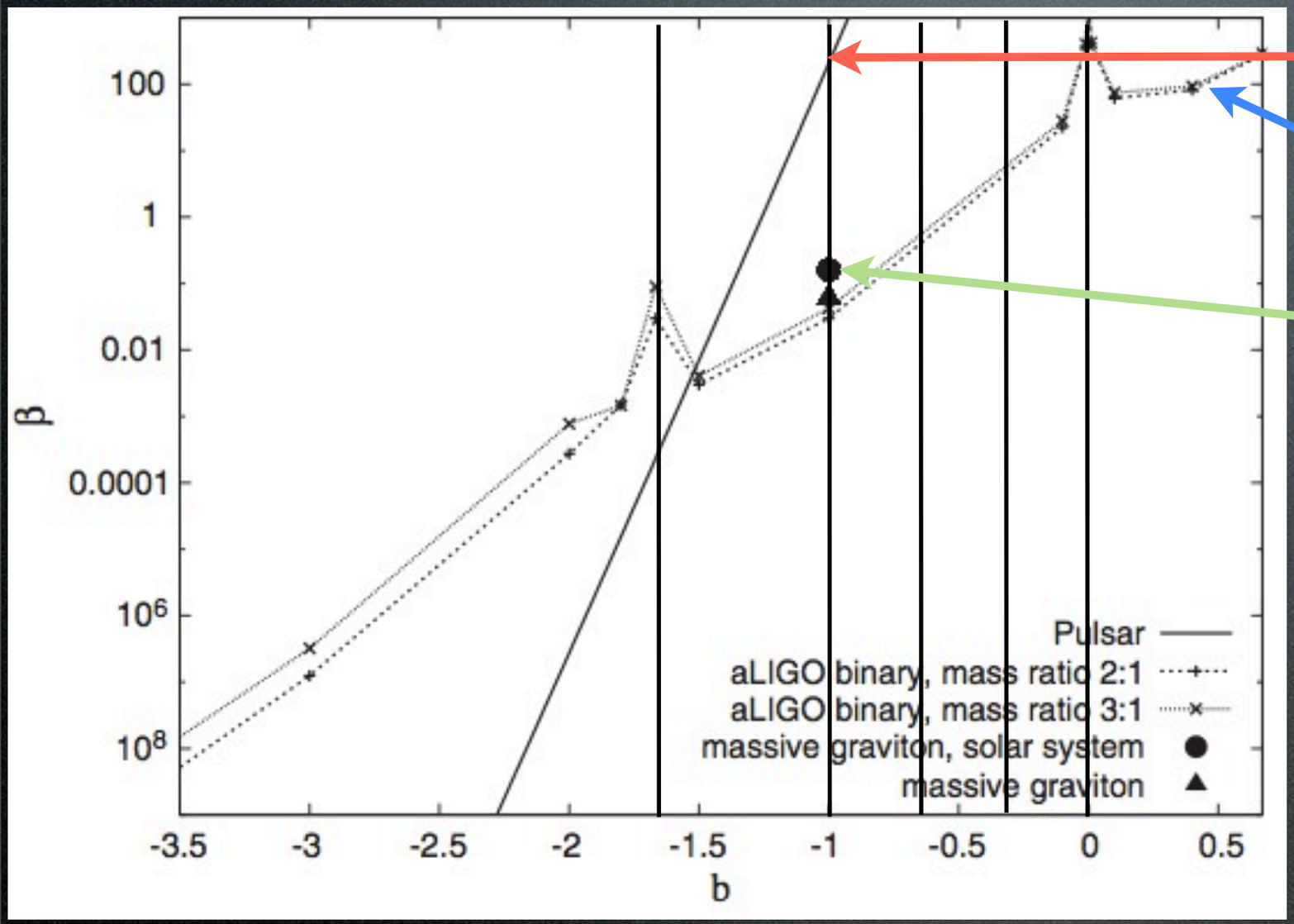
Solar Sys Massive Graviton Bound

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

Yunes & Hughes, 2010,
Cornish, Sampson, Yunes & Pretorius, 2011
Li, et al, 2011.

Constraining GR Deviations

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



Double Binary Pulsar bounds

aLIGO projected bounds

Solar Sys Massive Graviton Bound

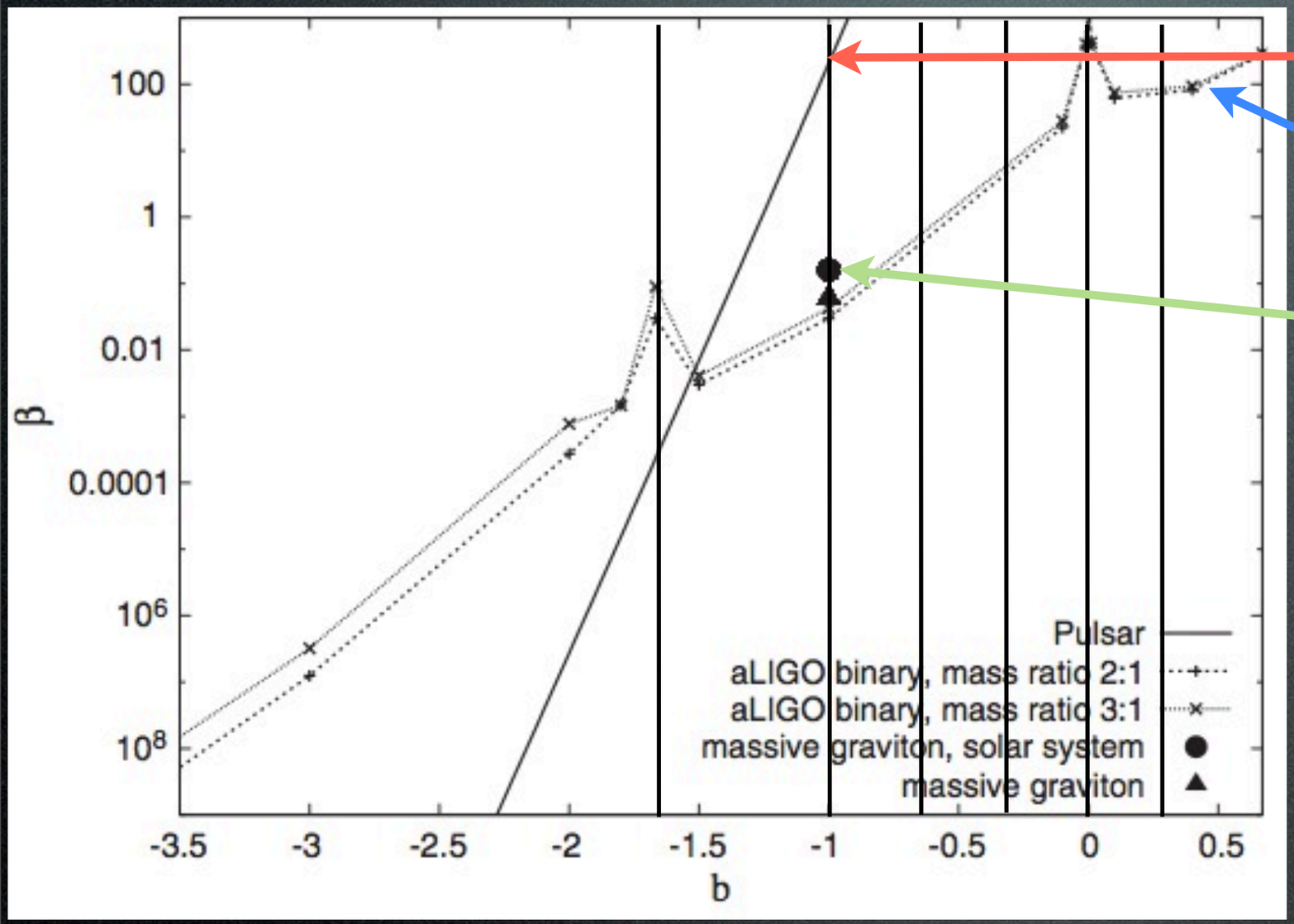
$$\tilde{h} = \tilde{h}_{\rm GR}\left(1+\alpha f^{a}\right)e^{i\beta f^{b}}$$

Yunes & Hughes, 2010,
Cornish, Sampson, Yunes & Pretorius, 2011
Li, et al, 2011.

Constraining GR Deviations

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

Newt 1PN 1.5 2 2.5 3



Double Binary Pulsar bounds

aLIGO projected bounds

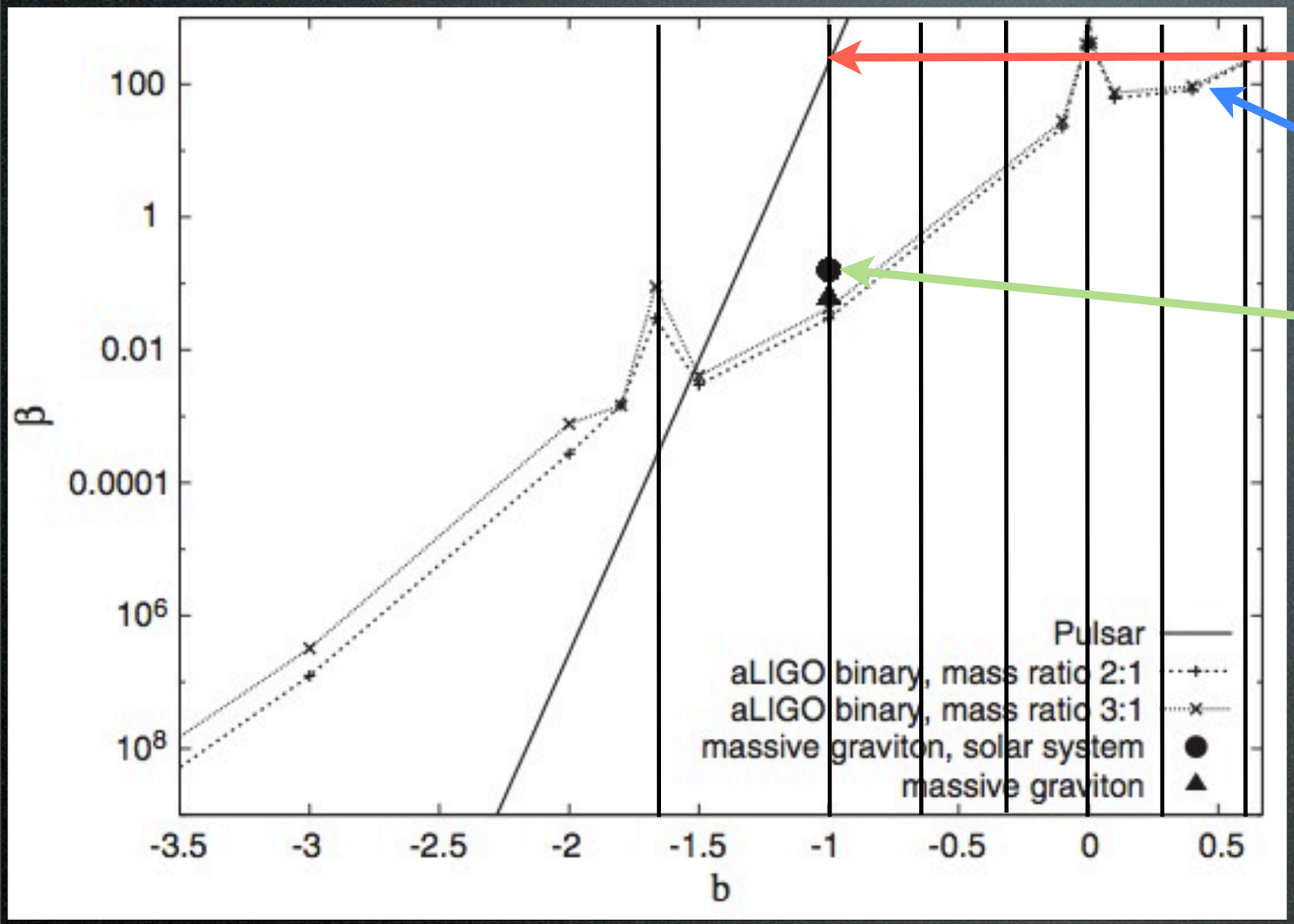
Solar Sys Massive Graviton Bound

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

Yunes & Hughes, 2010,
Cornish, Sampson, Yunes & Pretorius, 2011
Li, et al, 2011.

Constraining GR Deviations

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



Double Binary Pulsar bounds

aLIGO projected bounds

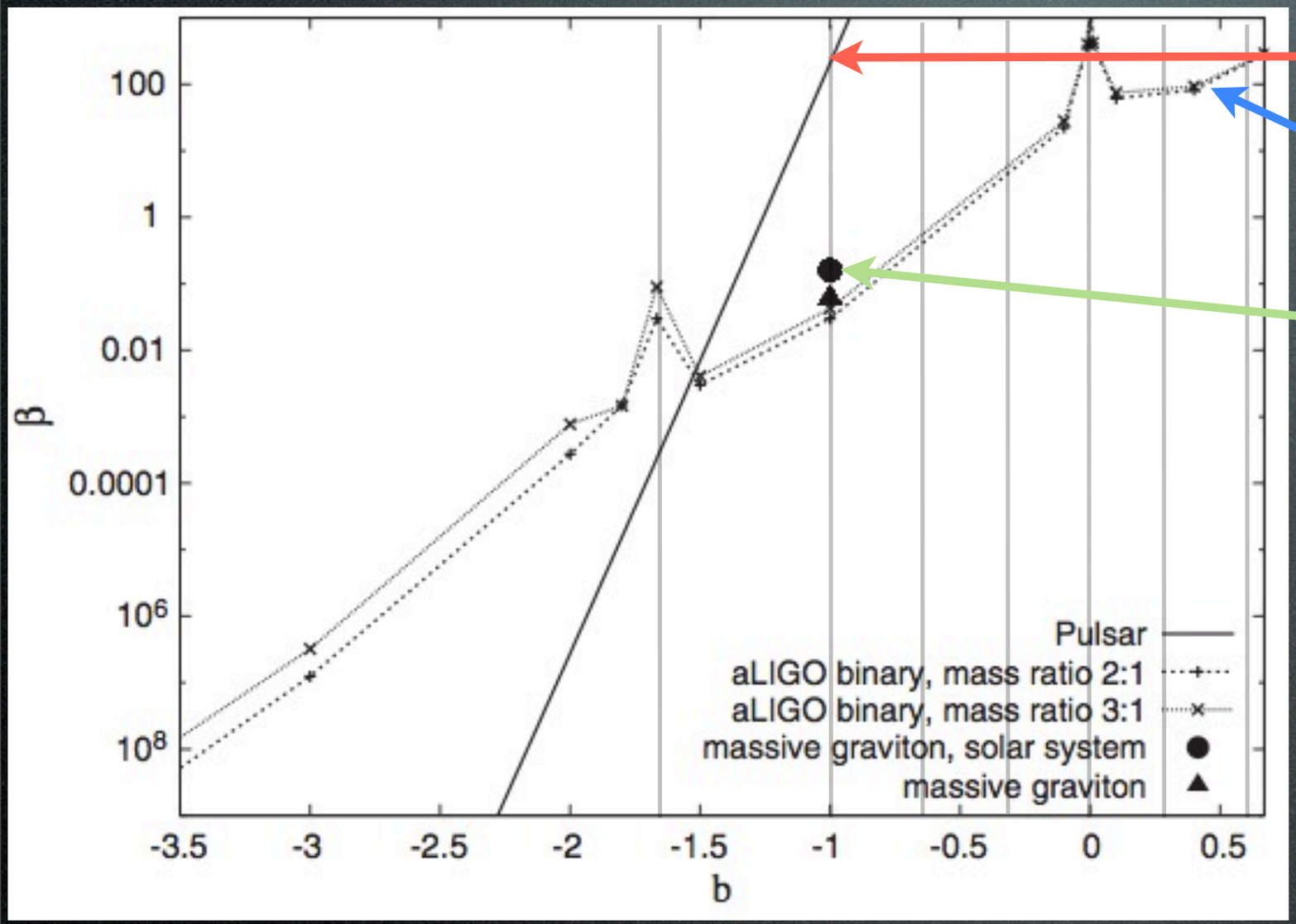
Solar Sys Massive Graviton Bound

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

Yunes & Hughes, 2010,
Cornish, Sampson, Yunes & Pretorius, 2011
Li, et al, 2011.

Constraining GR Deviations

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



Double Binary Pulsar bounds

aLIGO projected bounds

Solar Sys Massive Graviton Bound

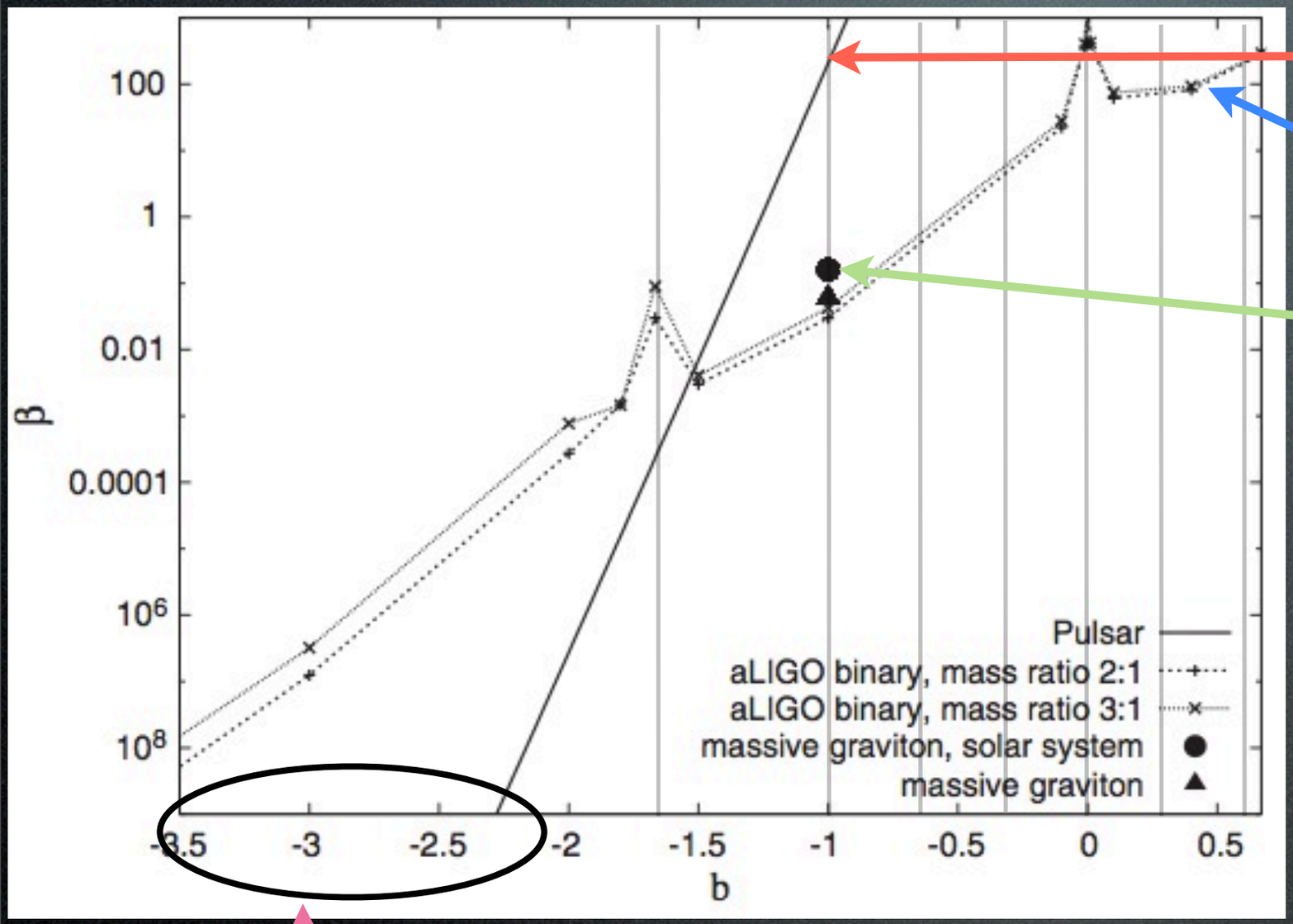
$$\tilde{h} = \tilde{h}_{\rm GR}\left(1+\alpha f^{a}\right)e^{i\beta f^{b}}$$

Yunes & Hughes, 2010,
Cornish, Sampson, Yunes & Pretorius, 2011
Li, et al, 2011.

Constraining GR Deviations

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

Newt 1PN 1.5 2 2.5 3 3.5



Double Binary Pulsar bounds

aLIGO projected bounds

Solar Sys Massive Graviton Bound

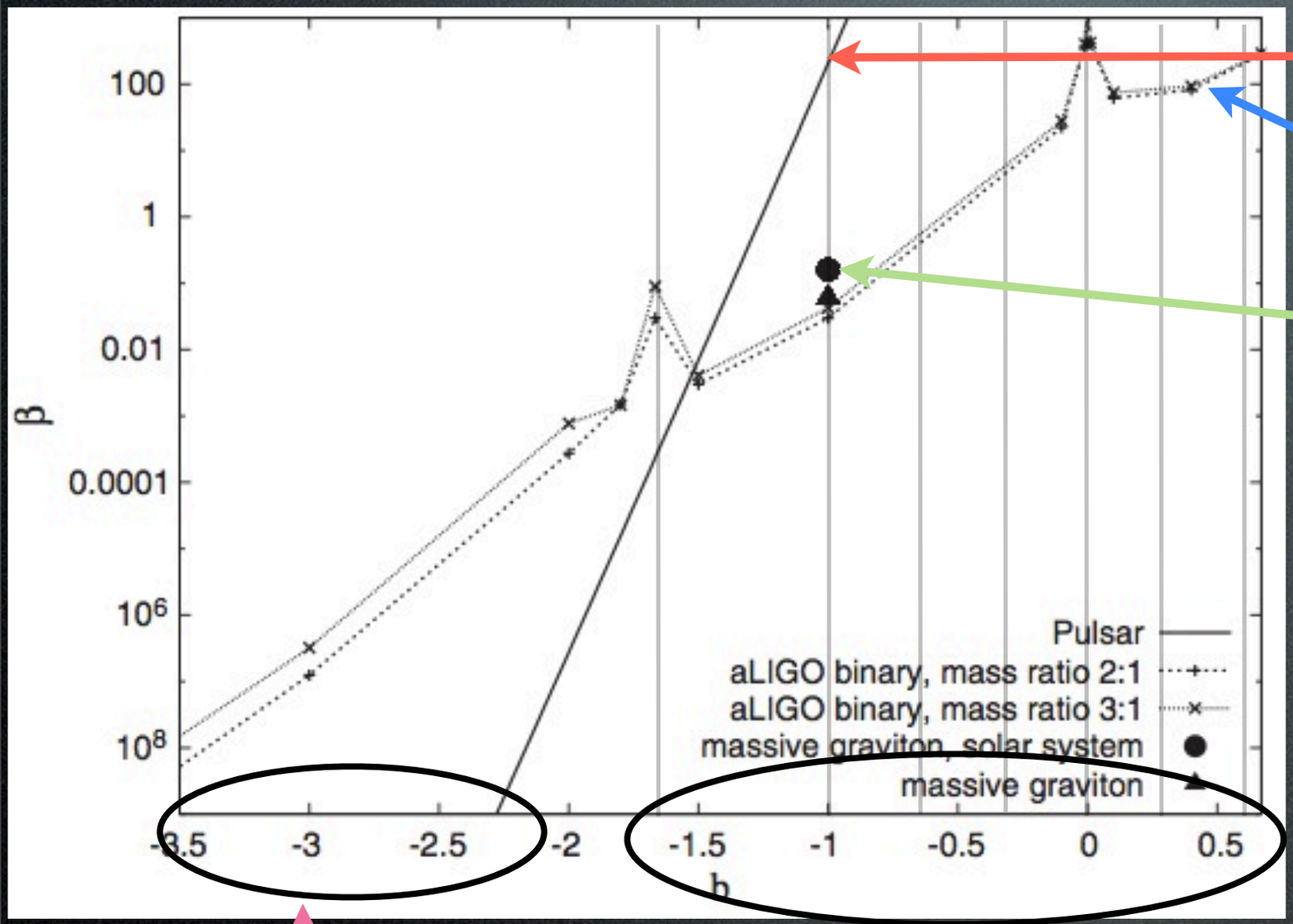
Weak Field

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

Yunes & Hughes, 2010,
Cornish, Sampson, Yunes & Pretorius, 2011
Li, et al, 2011.

Constraining GR Deviations

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



Double Binary Pulsar bounds

aLIGO projected bounds

Solar Sys Massive Graviton Bound

Weak Field

Strong Field

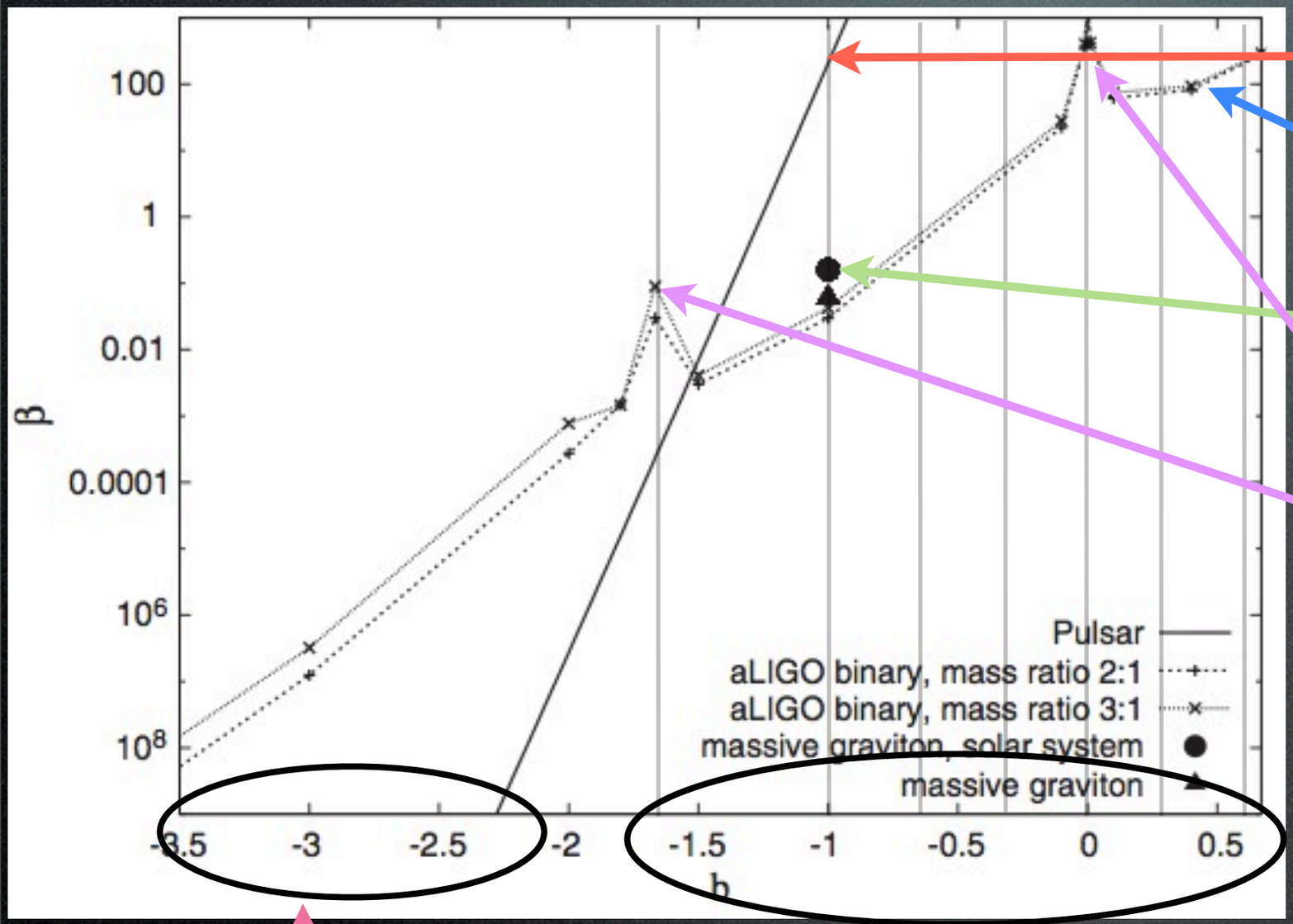
$$\tilde{h} = \tilde{h}_{\rm GR}\left(1+\alpha f^{a}\right) e^{i\beta f^{b}}$$

Yunes & Hughes, 2010,
Cornish, Sampson, Yunes & Pretorius, 2011
Li, et al, 2011.

Constraining GR Deviations

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

Newt 1PN 1.5 2 2.5 3 3.5



Double Binary Pulsar bounds

aLIGO projected bounds

Solar Sys Massive Graviton Bound

"Resonances" occur at 2 GR PN coefficients, where ppE and GR system parameters become correlated. The width of the resonance is narrow.

Weak Field

Strong Field

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

Yunes & Hughes, 2010,
Cornish, Sampson, Yunes & Pretorius, 2011
Li, et al, 2011.

Learning How to Breath before How to Crawl

Learning How to Breath before How to Crawl

Can we extend the ppE framework to constrain the existence of additional non-GR polarizations?

✓

Yes

Arun 2012, Chatziioannou, Yunes & Cornish, 2012.

Learning How to Breath before How to Crawl

Can we extend the ppE framework to constrain the existence of additional non-GR polarizations?

✓

Yes

Arun 2012, Chatziioannou, Yunes & Cornish, 2012.

Given a non-GR ppE detection, can we identify what type of GR correction such a detection corresponds to?

✓

Yes

Yunes, et al., 2010, 2011, 2012

Learning How to Breath before How to Crawl

Can we extend the ppE framework to constrain the existence of additional non-GR polarizations?

✓

Yes

Arun 2012, Chatziioannou, Yunes & Cornish, 2012.

Given a non-GR ppE detection, can we identify what type of GR correction such a detection corresponds to?

✓

Yes

Yunes, et al., 2010, 2011, 2012

Given multiple detectors, how do we leverge the ppE Scheme?

Sampson , Cornish, & Yunes, 2012.

Learning How to Breath before How to Crawl

Can we extend the ppE framework to constrain the existence of additional non-GR polarizations?

✓

Yes

Arun 2012, Chatziioannou, Yunes & Cornish, 2012.

Given a non-GR ppE detection, can we identify what type of GR correction such a detection corresponds to?

✓

Yes

Yunes, et al., 2010, 2011, 2012

Given multiple detectors, how do we leverge the ppE Scheme?

Sampson , Cornish, & Yunes, 2012.

If we observe a non-GR signal with all its PN corrections or with a non-analytic deformation, like a Heavisde function, can a simple leading-order ppE search signal a departure from GR?

Sampson , Cornish, & Yunes, 2012.

Learning How to Breath before How to Crawl

Can we extend the ppE framework to constrain the existence of additional non-GR polarizations?

✓

Yes

Arun 2012, Chatziioannou, Yunes & Cornish, 2012.

Given a non-GR ppE detection, can we identify what type of GR correction such a detection corresponds to?

✓

Yes

Yunes, et al., 2010, 2011, 2012

Given multiple detectors, how do we leverge the ppE Scheme?

Sampson , Cornish, & Yunes, 2012.

If we observe a non-GR signal with all its PN corrections or with a non-analytic deformation, like a Heavisde function, can a simple leading-order ppE search signal a departure from GR?

Sampson , Cornish, & Yunes, 2012.

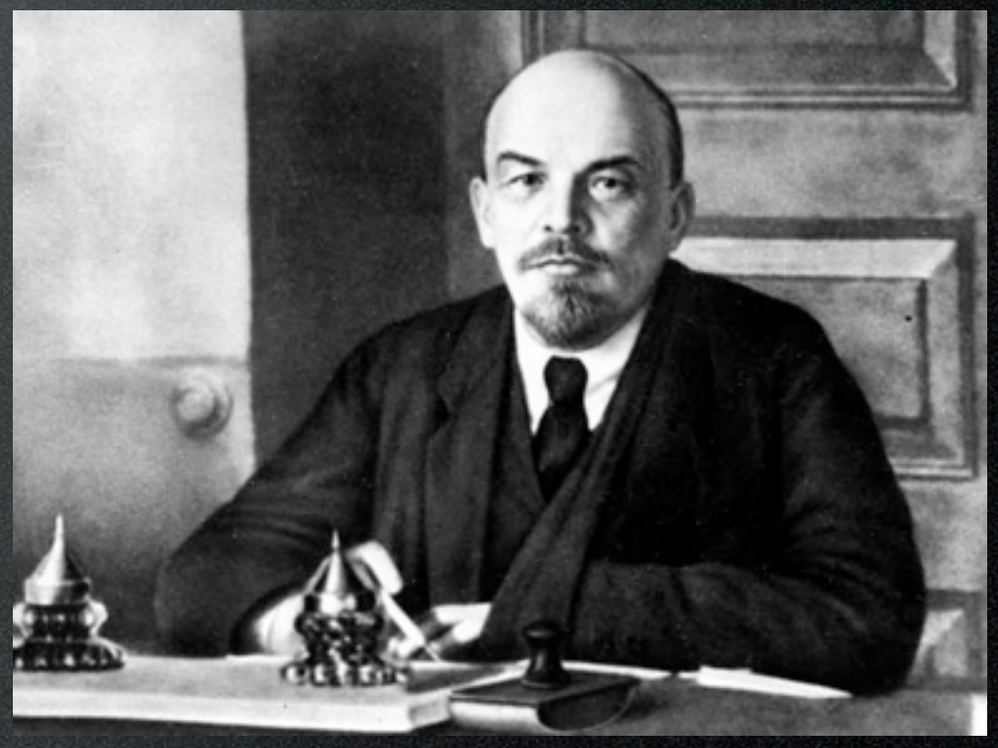
How do Systematics Affect the ppE Implementation?

We'll see...

Yagi , Yunes & Cornish, 2012.

What does it all Mean?

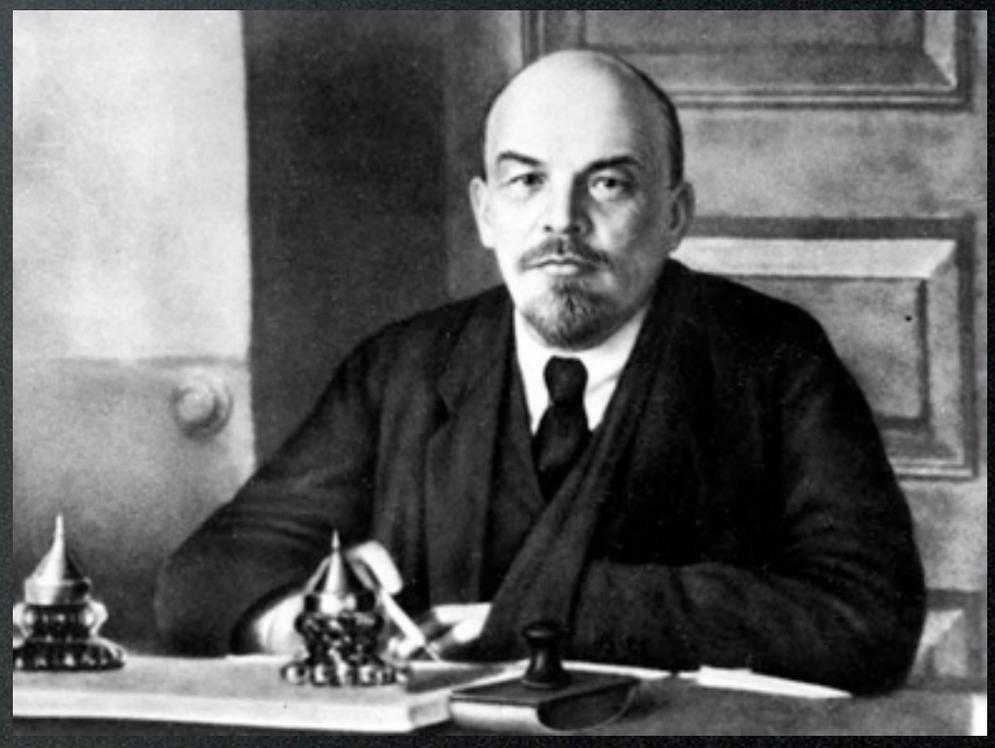
Doveryai, no proveryai



What does it all Mean?

GW Observations of compact binary inspirals will provide unparalleled information about fundamental physics. It is our responsibility to leverage this information to learn about physics:

Doveryai, no proveryai

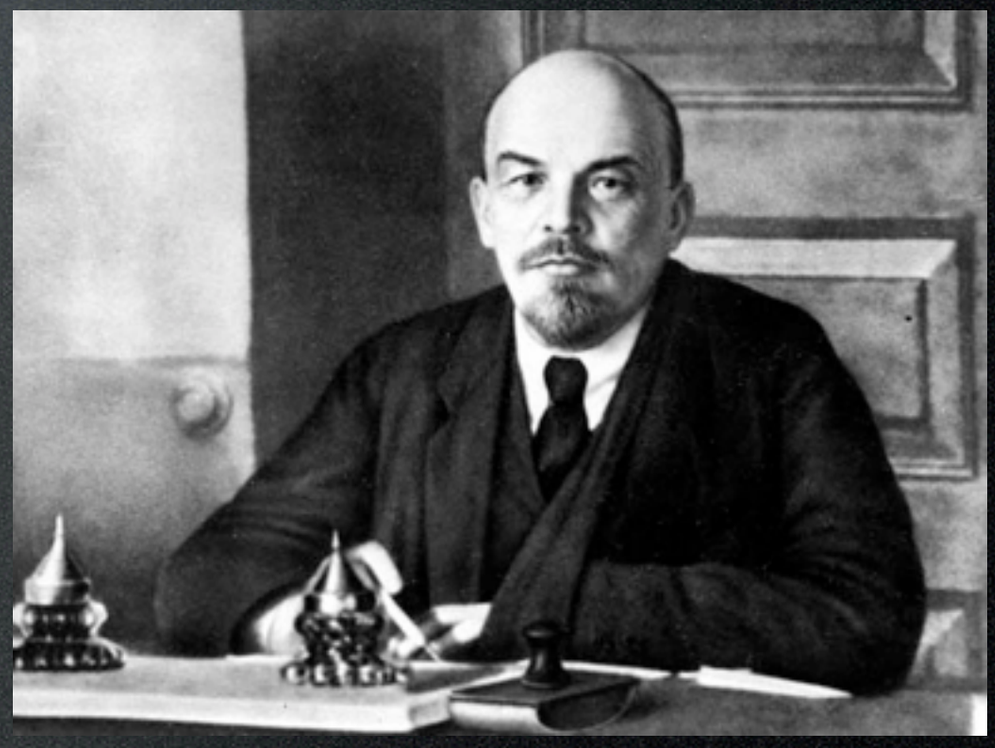


What does it all Mean?

GW Observations of compact binary inspirals will provide unparalleled information about fundamental physics. It is our responsibility to leverage this information to learn about physics:

Are the Einstein equations correct in the late inspiral/strong-field?

Doveryai, no proveryai



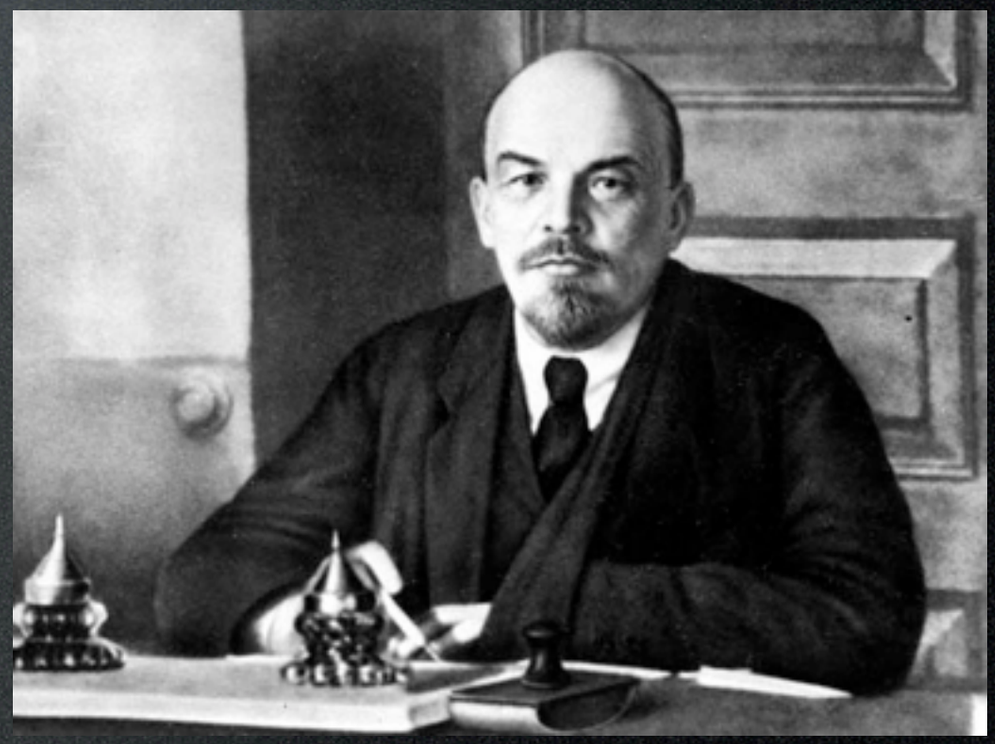
What does it all Mean?

GW Observations of compact binary inspirals will provide unparalleled information about fundamental physics. It is our responsibility to leverage this information to learn about physics:

Are the Einstein equations correct in the late inspiral/strong-field?

Are black holes described by the Kerr metric?

Doveryai, no proveryai



What does it all Mean?

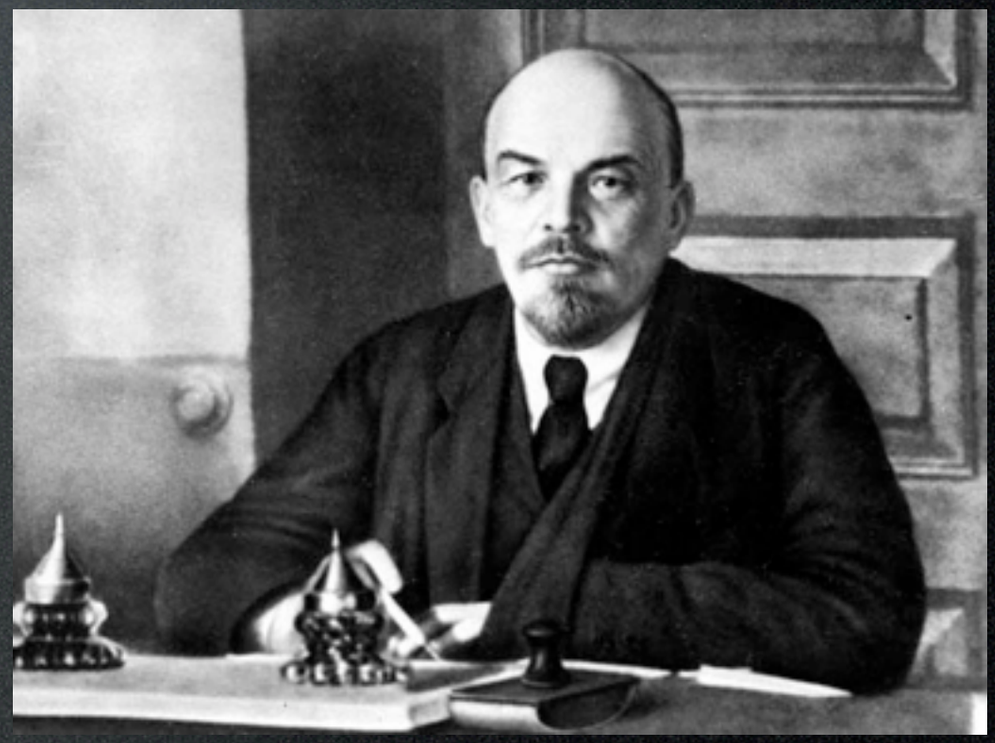
GW Observations of compact binary inspirals will provide unparalleled information about fundamental physics. It is our responsibility to leverage this information to learn about physics:

Are the Einstein equations correct in the late inspiral/strong-field?

Are black holes described by the Kerr metric?

Do GWs have only two massless polarizations?

Doveryai, no proveryai



What does it all Mean?

GW Observations of compact binary inspirals will provide unparalleled information about fundamental physics. It is our responsibility to leverage this information to learn about physics:

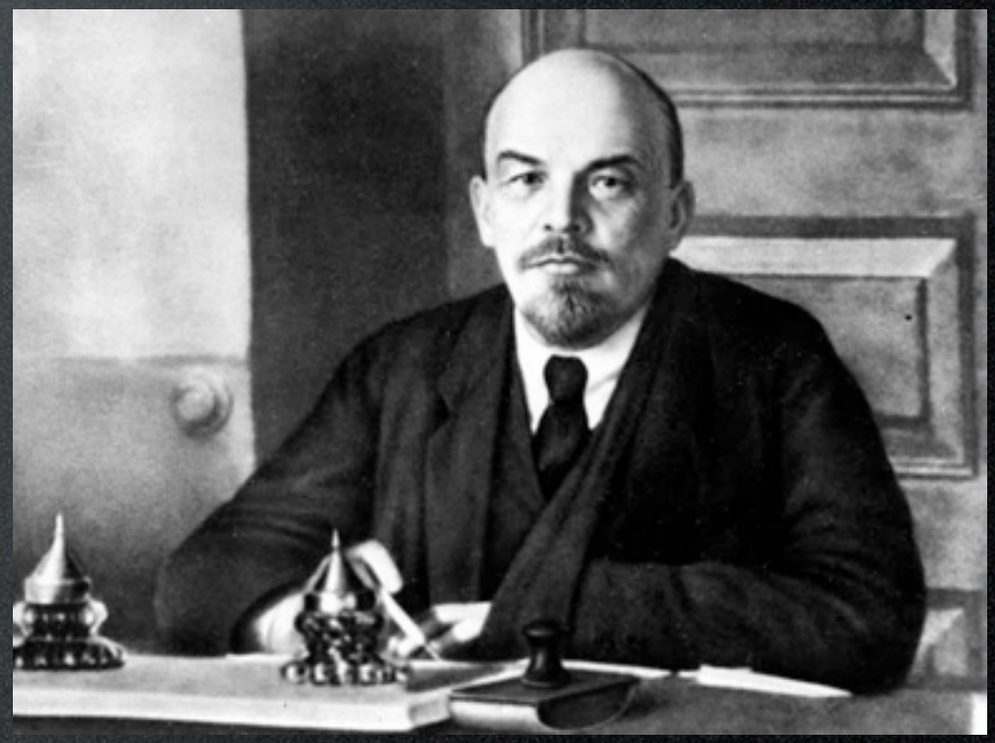
Are the Einstein equations correct in the late inspiral/strong-field?

Are black holes described by the Kerr metric?

Do GWs have only two massless polarizations?

And all of this will allow us to heavily constrain modified theories to unparalleled levels.

Doveryai, no proveryai



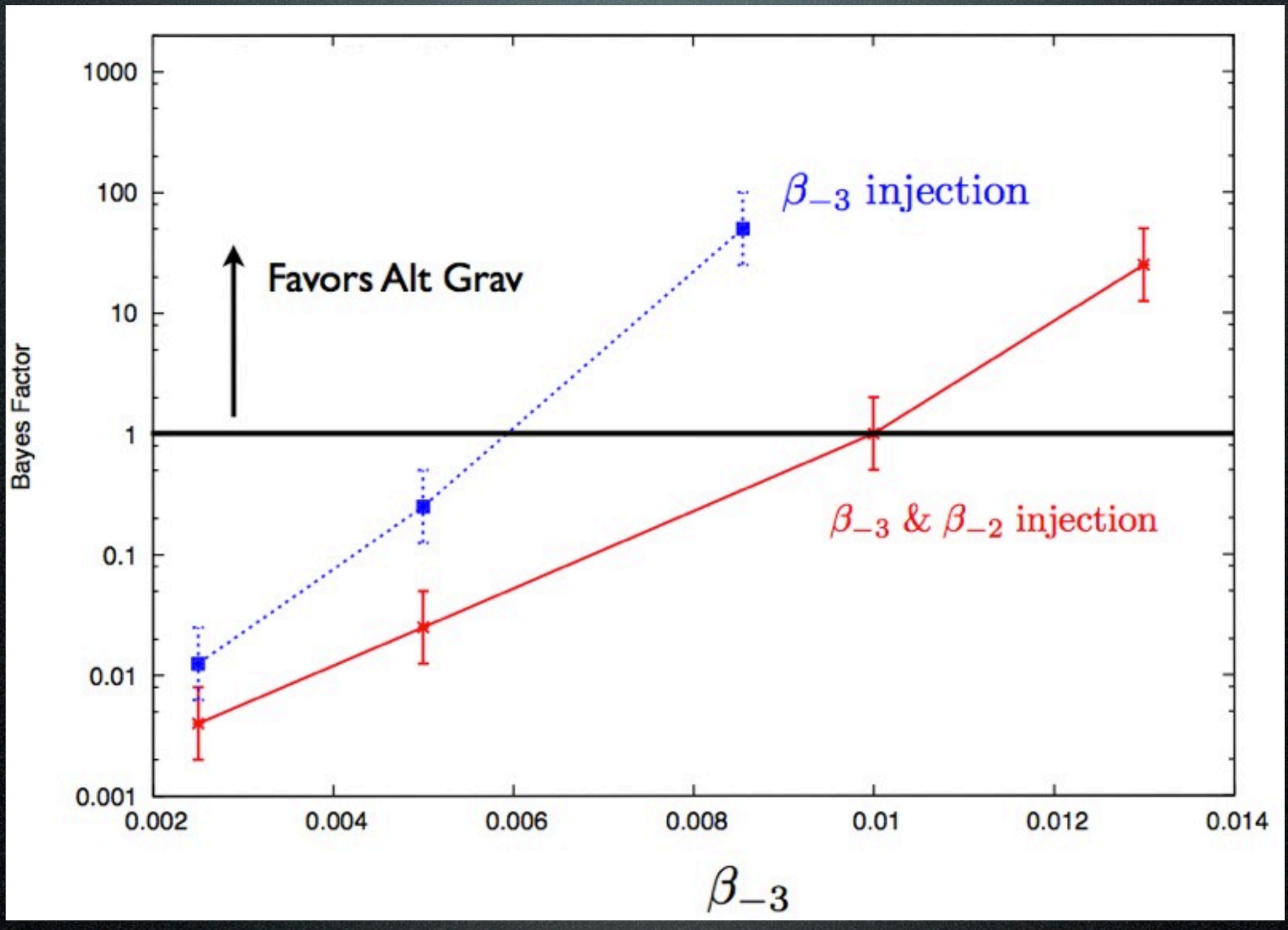
We can't solve problems by using the same kind of thinking we used when we created them...Common sense is a collection of prejudices...

We can't solve problems by using the same kind of thinking we used when we created them...Common sense is a collection of prejudices...

- Albert Einstein

Bayes Factors

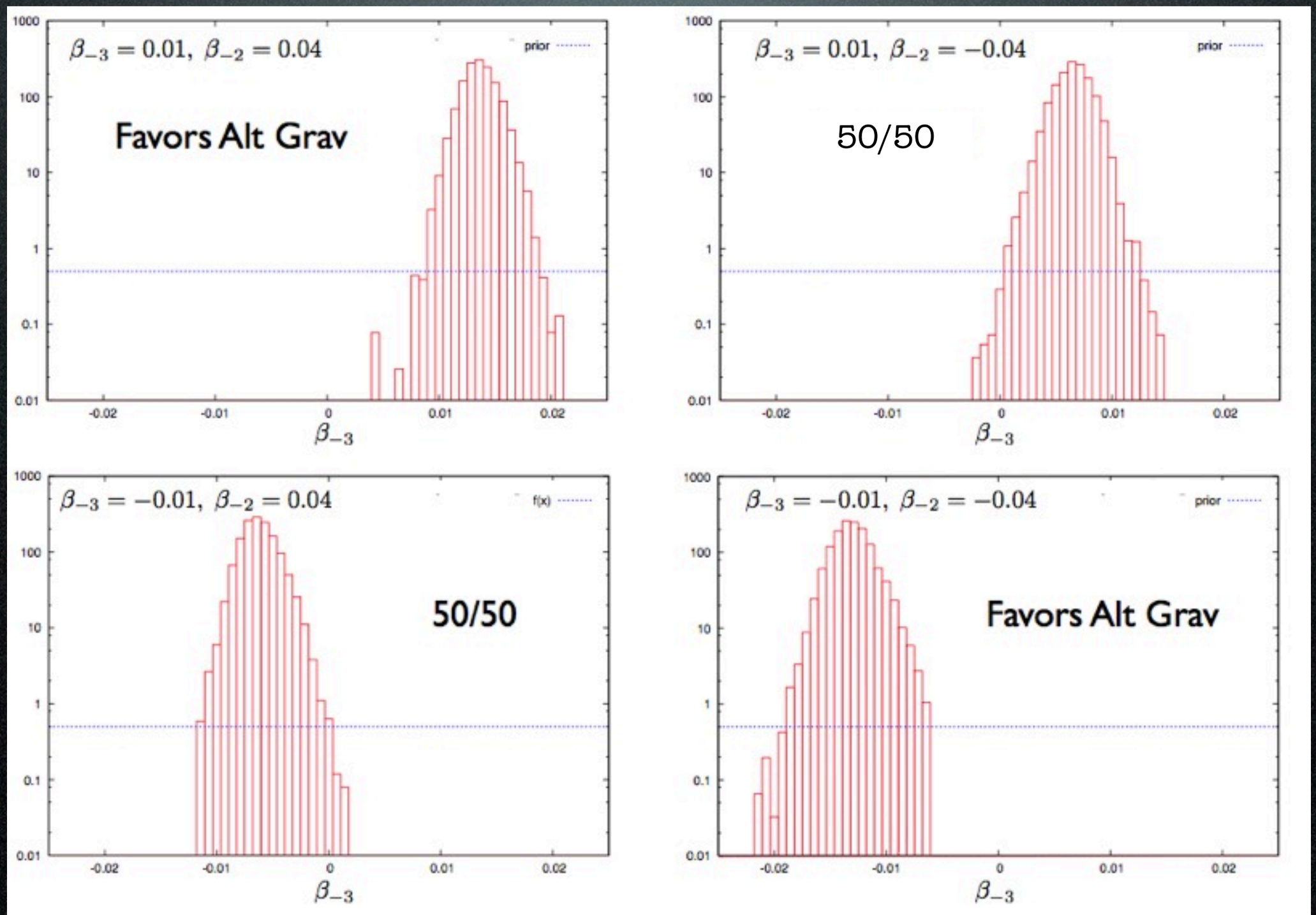
Single ppE template search β_{-3}



Sampson, Cornish & Yunes, 2012

High-Order PN Effects

Alt Grav NS-NS injection with $\beta_{-3} \neq 0 \neq \beta_{-2}$ single ppE template search β_{-3}

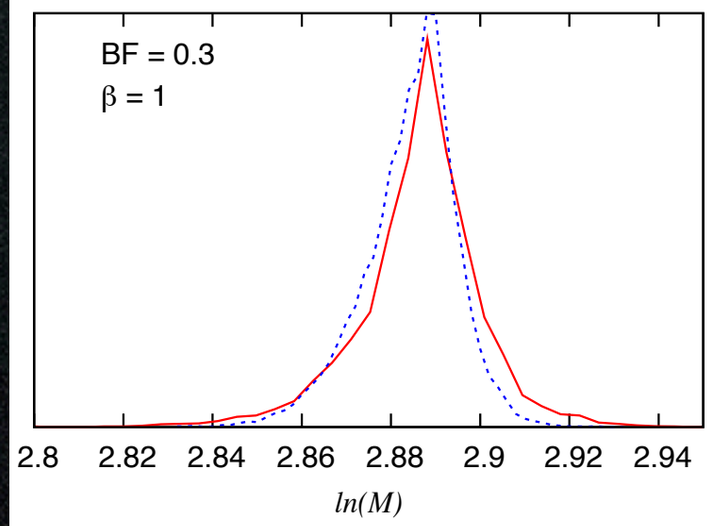


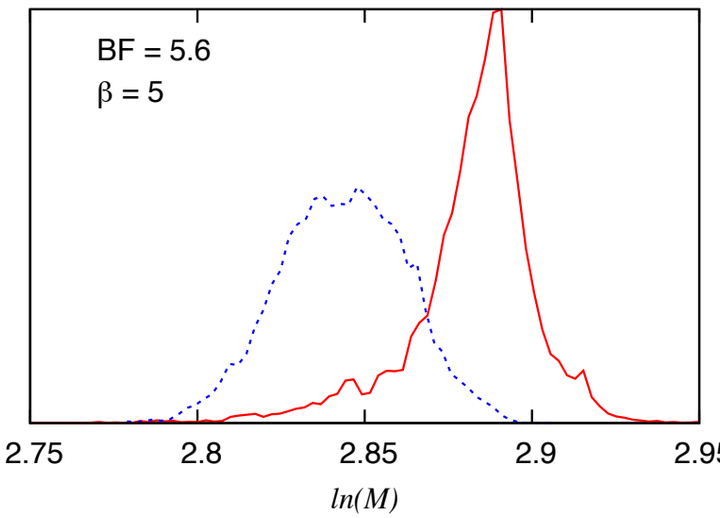
Sampson, Cornish & Yunes, 2012

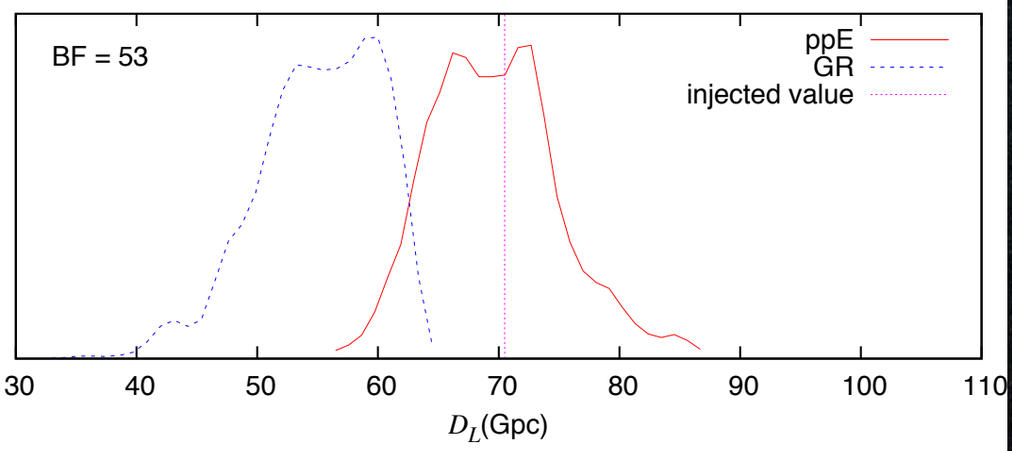
Fundamental Bias and Deviations

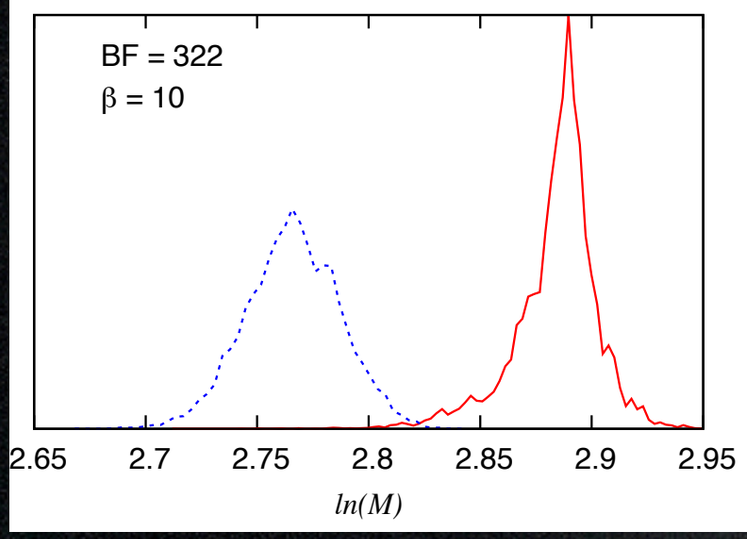
Non-GR Signal/GR Templates, SNR = 20

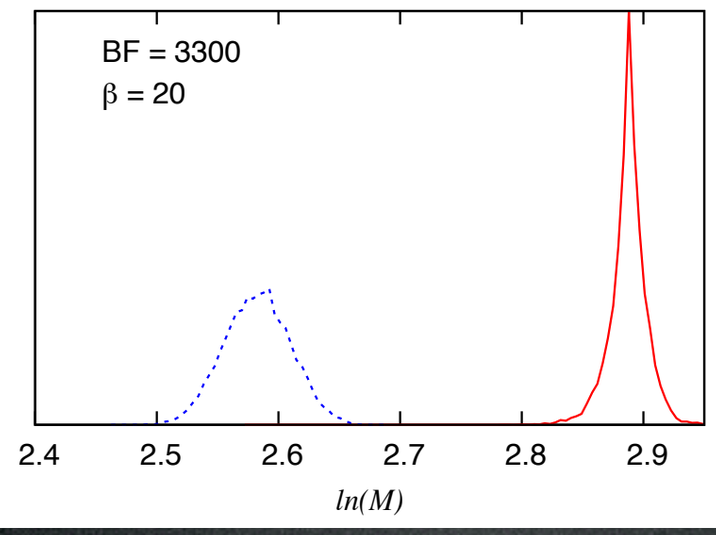
Non GR injection, extracted with GR templates (blue) and ppE templates (red). GR template extraction is "wrong" by much more than the systematic (statistical) error. "Fundamental Bias"

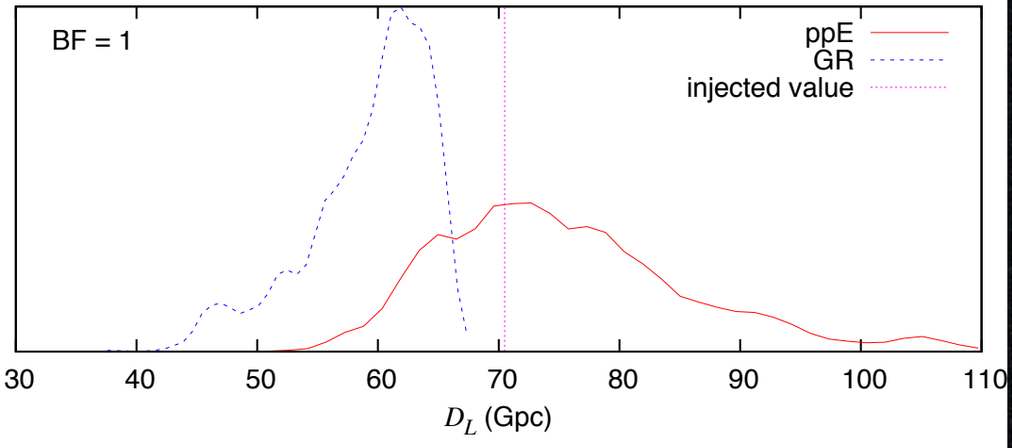






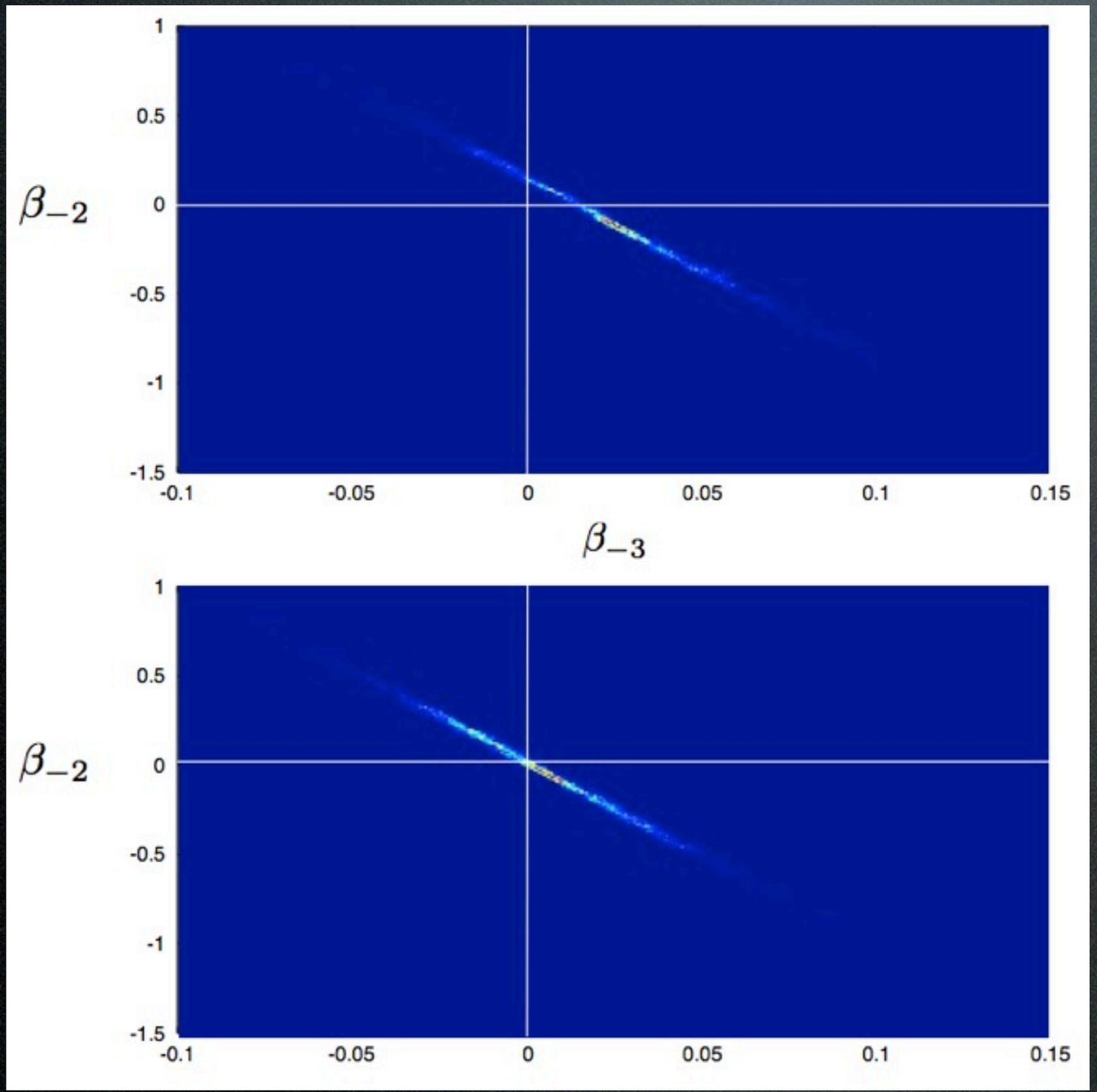






Cornish, Sampson, Yunes & Pretorius, 2011

2-Parameter ppE Effectiveness



$\beta_{-3} = 0.025, \beta_{-2} = -0.1$

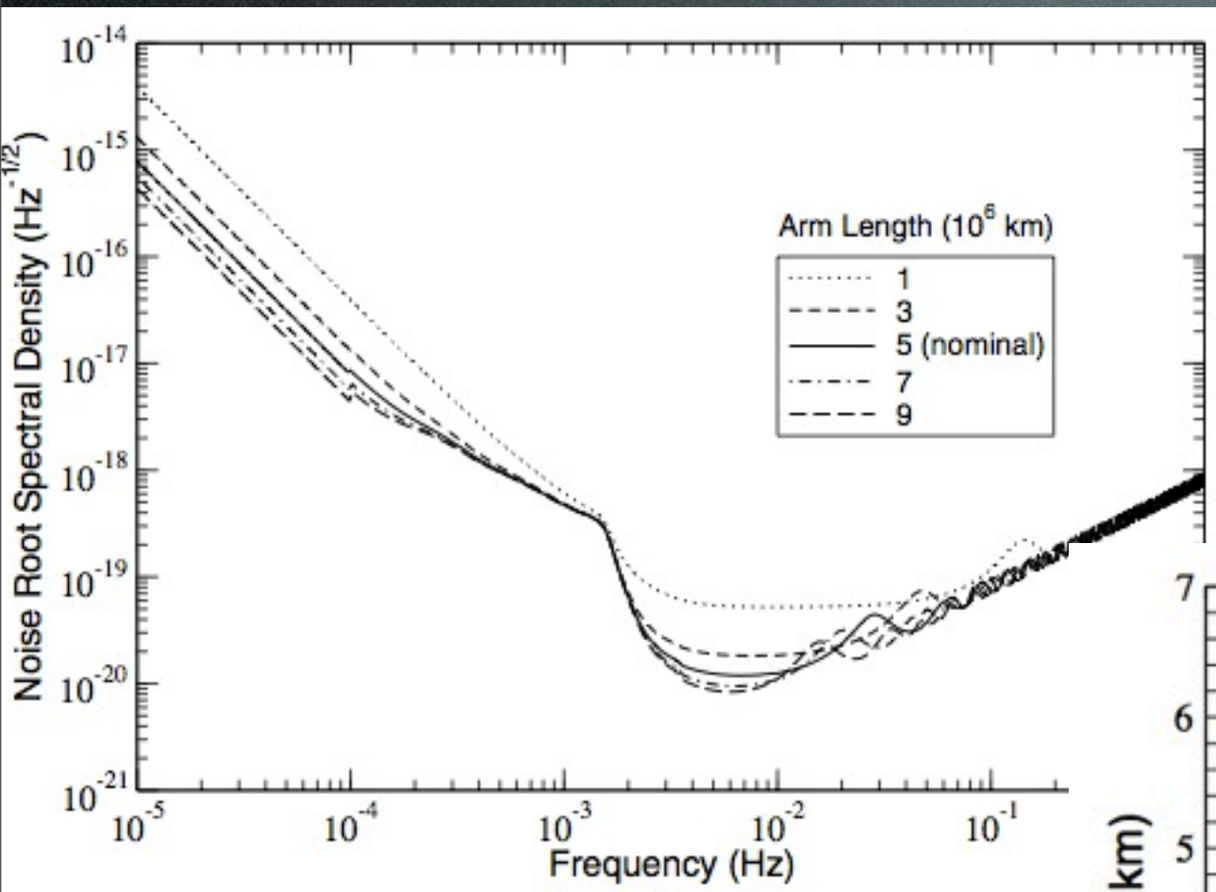
Detectable GR departure

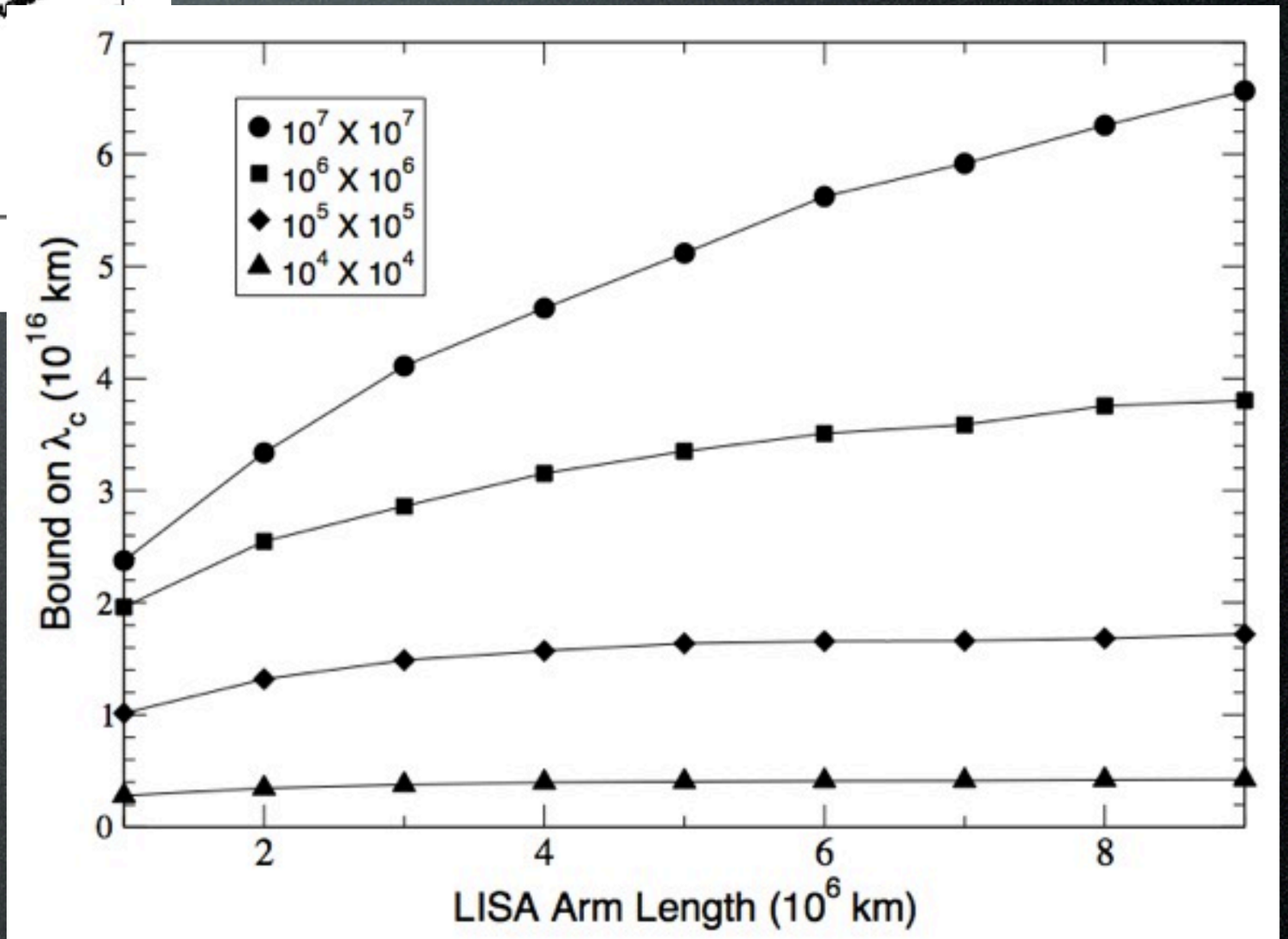
$\beta_{-3} = 0.005, \beta_{-2} = -0.02$

Consistent with GR

Sampson, Cornish & Yunes, 2012

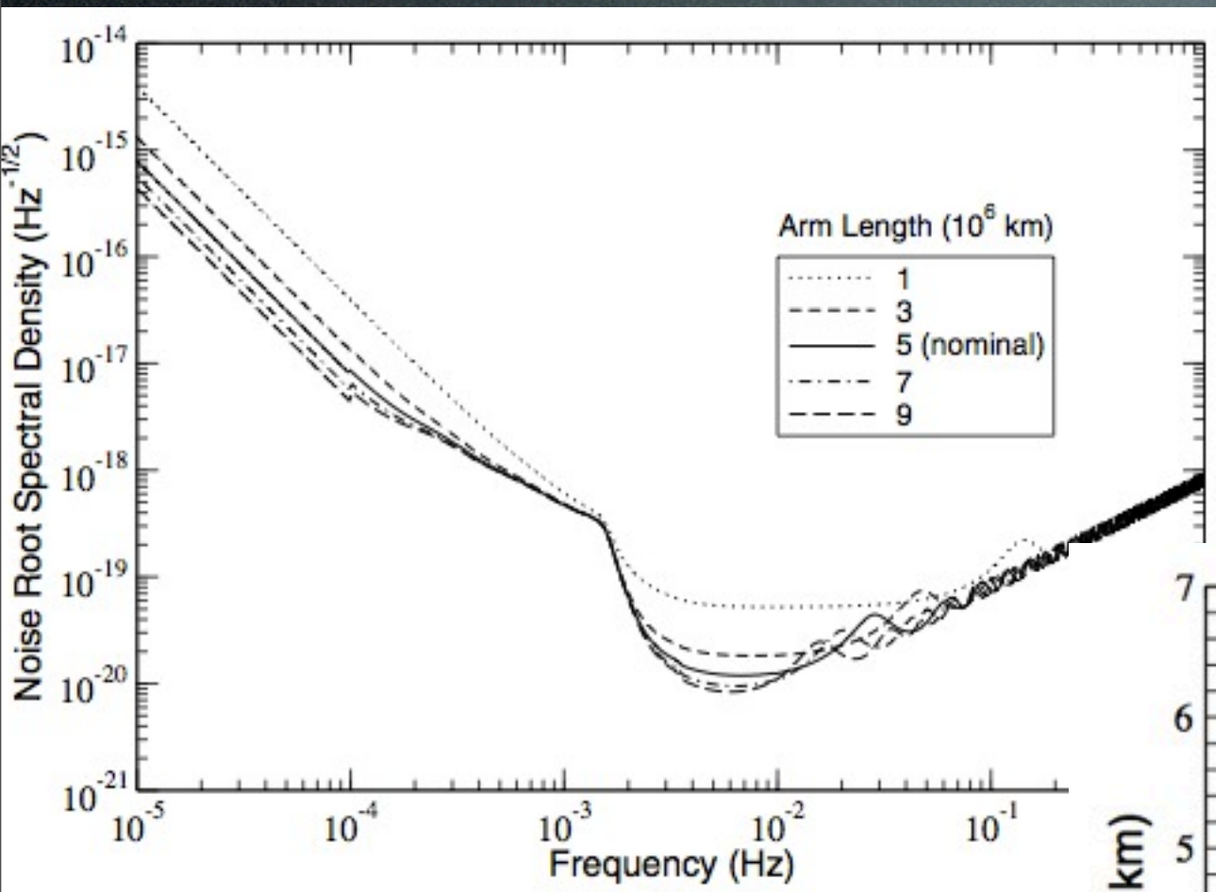
Example of Non-Generic Tests



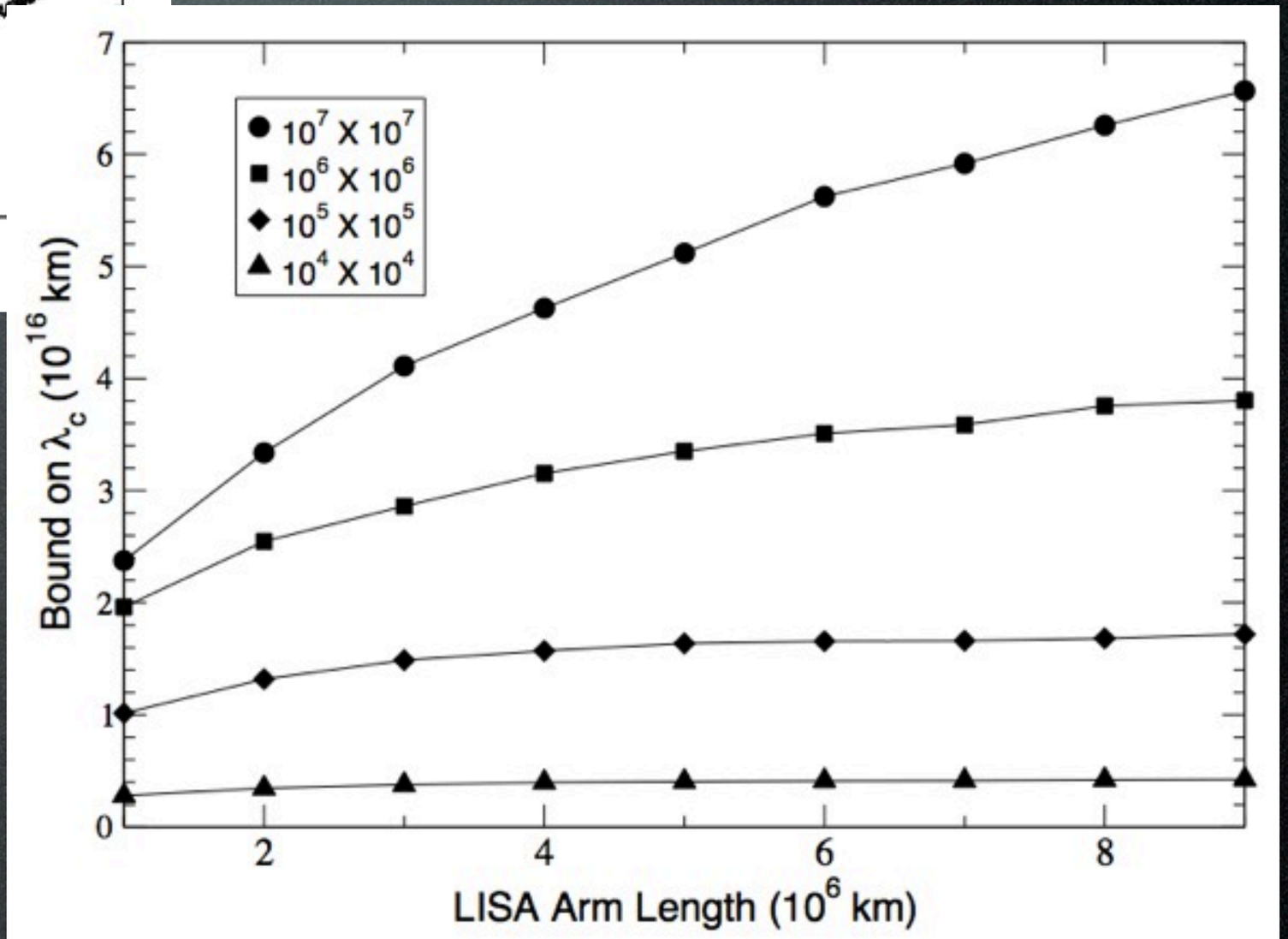


Will & Yunes, 2004

Example of Non-Generic Tests

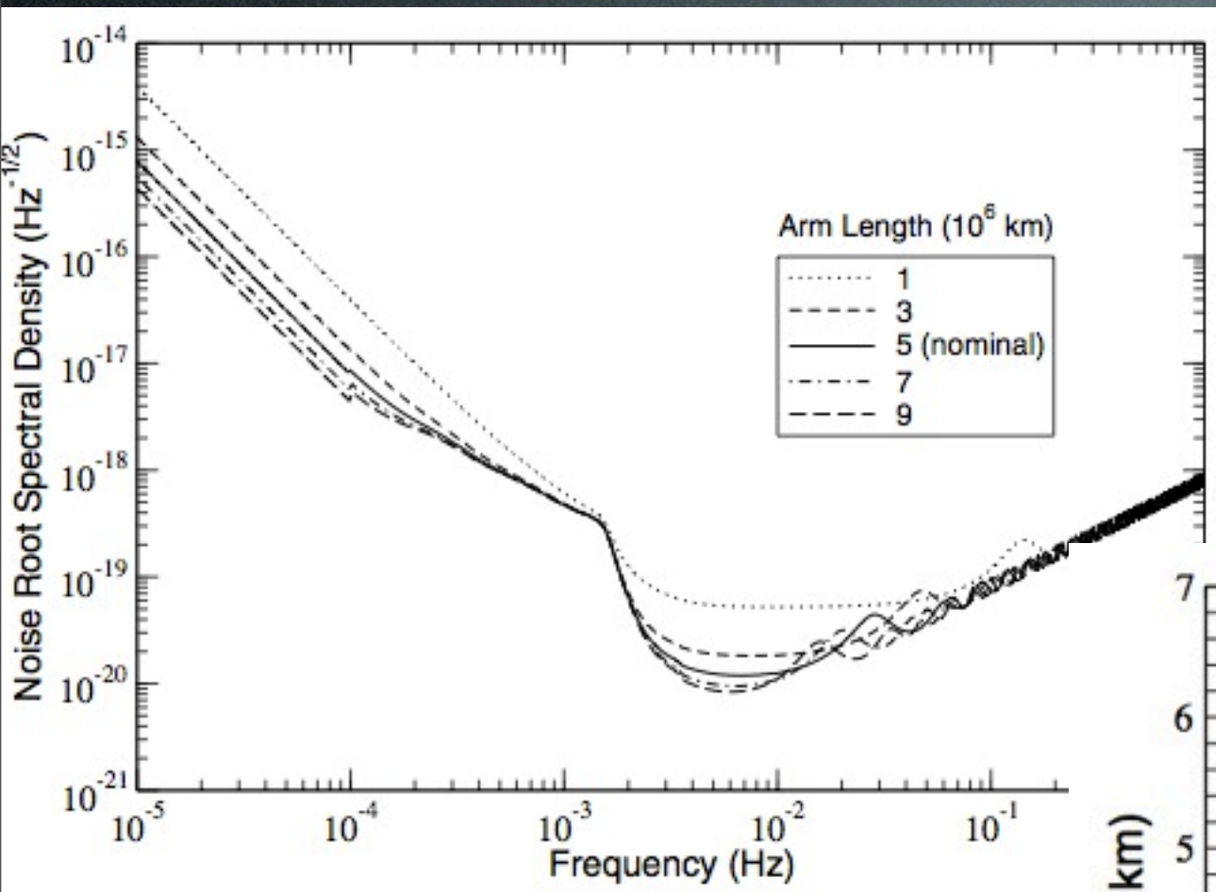


Changes in the arm length (classic LISA) affect the low-f and bucket noise spectrum.



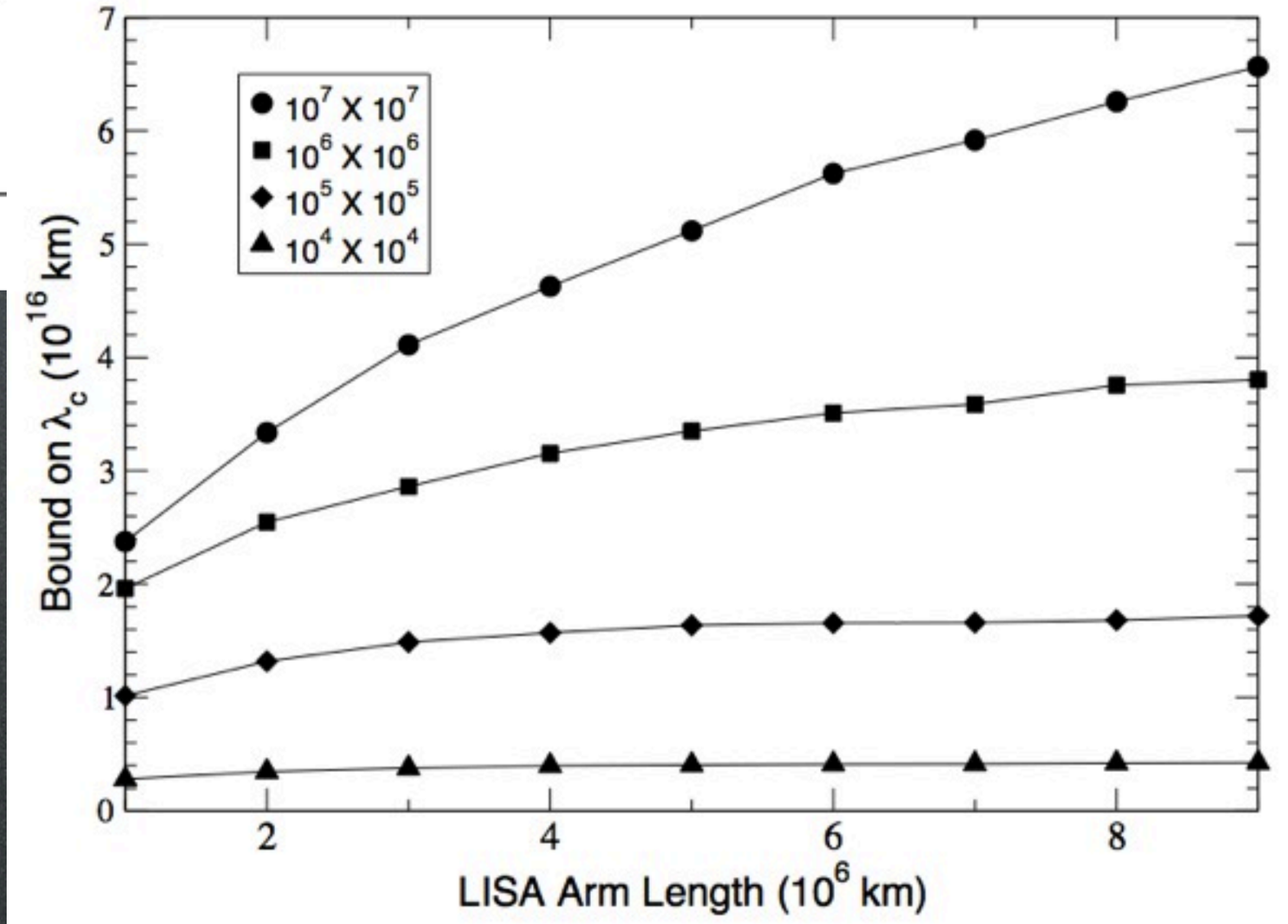
Will & Yunes, 2004

Example of Non-Generic Tests



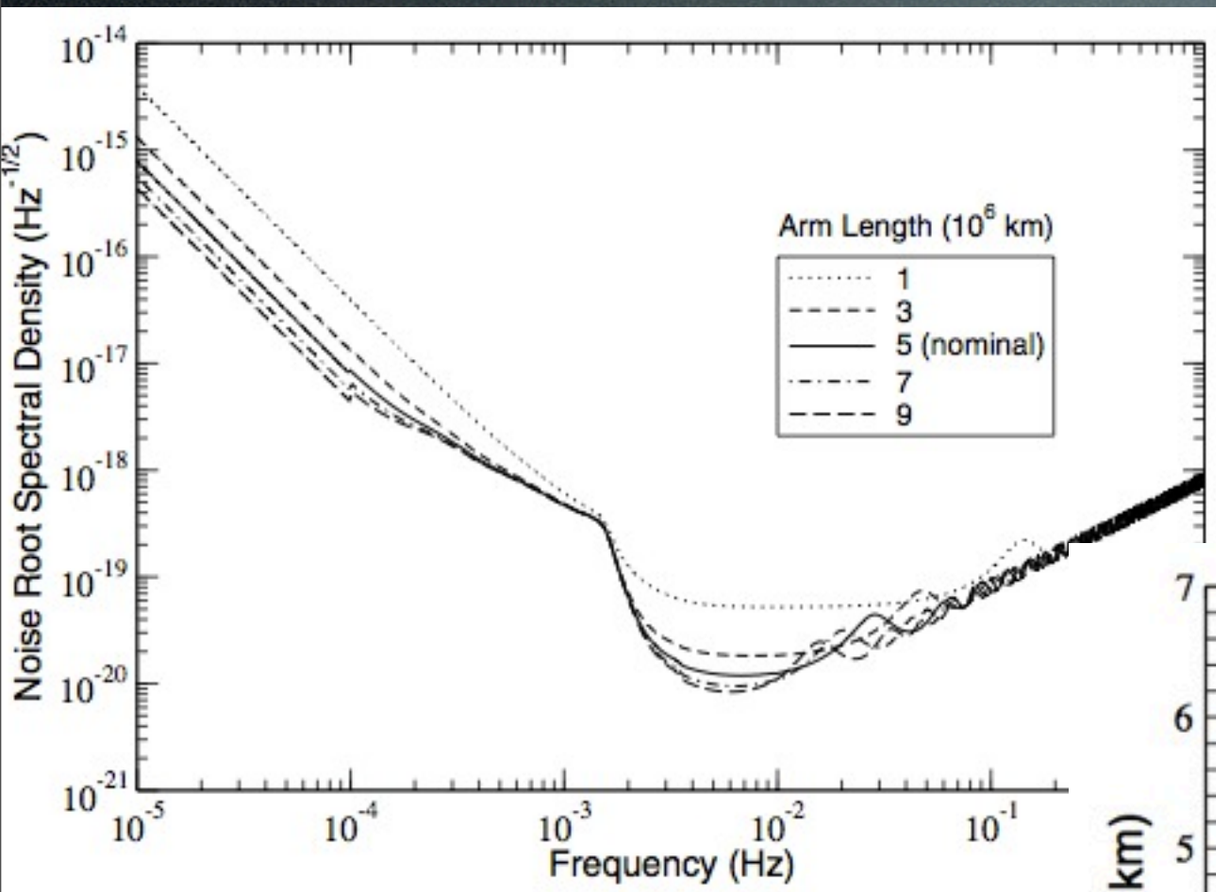
Changes in the arm length (classic LISA) affect the low-f and bucket noise spectrum.

For hi-M sys, bound goes as sqrt(L) because the noise goes as 1/L.



Will & Yunes, 2004

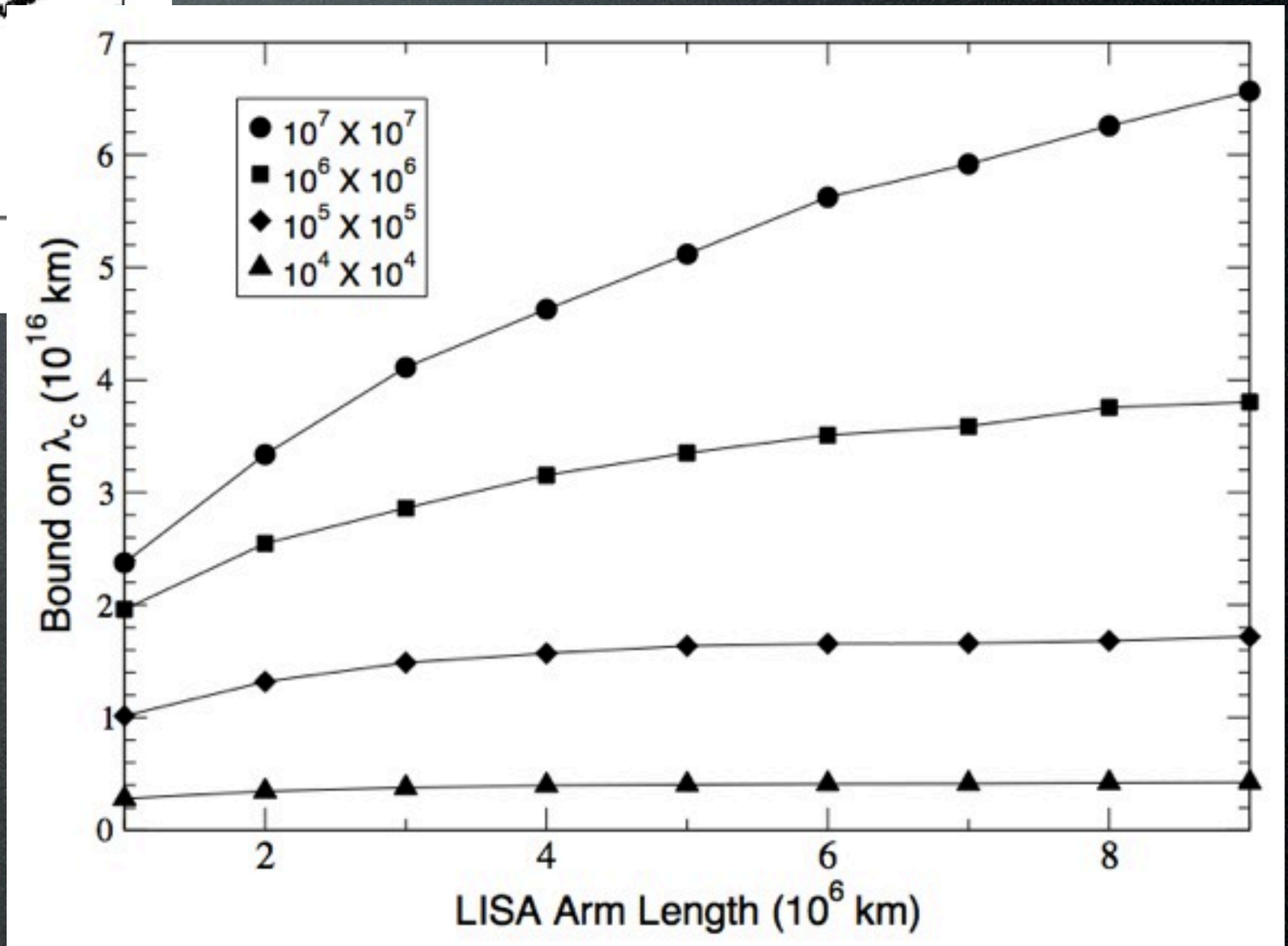
Example of Non-Generic Tests



Changes in the arm length (classic LISA) affect the low-f and bucket noise spectrum.

For hi-M sys, bound goes as sqrt(L) because the noise goes as 1/L.

For lo-M sys, low-f noise has little effect because signal dominated by WD confusion noise.



Will & Yunes, 2004