Gravitational Waves as Probes of Extreme Gravity

Nicolas Yunes
Montana State University

Testing Gravity 2015, January 15th, 2015

Yunes & Siemens, Living Reviews in Relativity 2014,
http://arxiv.org/abs/1304.3473

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, Paolo Pani, Antoine Klein, Kent Yagi, Laura Sampson, Luis Lehner, Masaru Shibata, Curt Cutler, Haris Apostolatos,

An <u>incomplete</u> summary of what GWs will tell us about gravity

Leo Stein, Sarah Vigeland, Katerina Chatziioannou, Philippe Jetzer, Leor Barack, 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, Devin Hansen, Enrico Barausse, Carlos Palenzuela, Marcelo Ponce, etc.

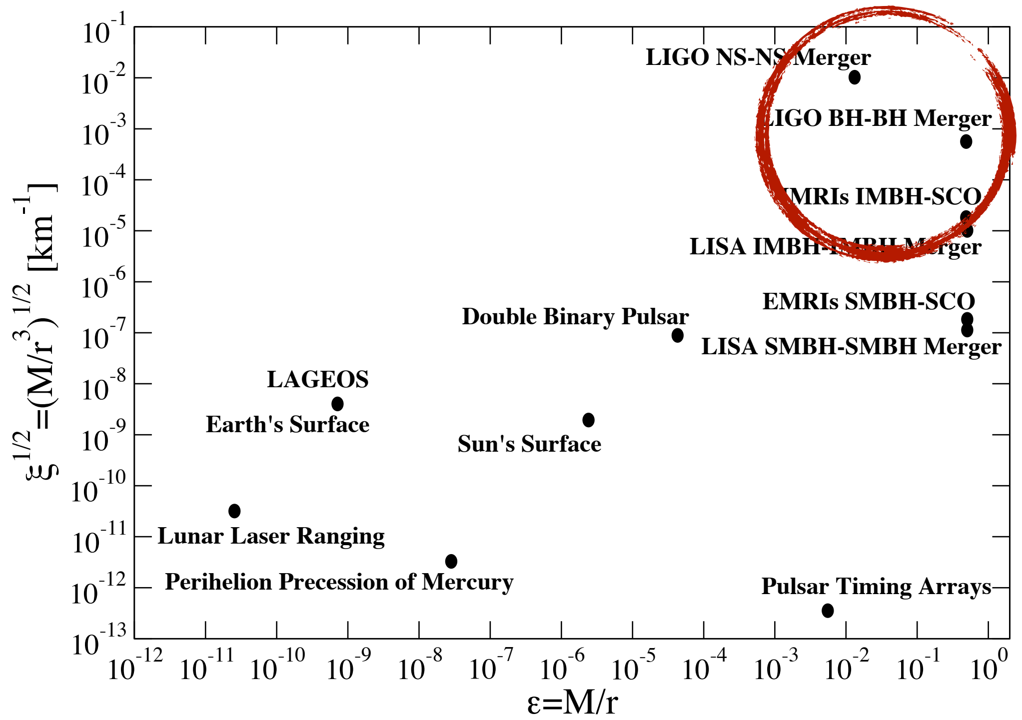
Roadmap

How do GW tests differ from other tests?

How do we use GWs to test GR?

What will we learn from GW tests of GR?

How do GW tests Differ from Other Tests?



[Baker, et al, Psaltis LRR]

1. <u>Extreme Gravity</u>:

<u>Sources</u>: **Compact Object Coalescence**
Supernova, deformed NSs, etc.
(excluding pulsar timing in this talk)

<u>Phases</u>: **Late Inspiral**, Merger, Ringdown.

<u>Processes</u>: Generation and Propagation of metric perturbation.

2. <u>Clean</u>:

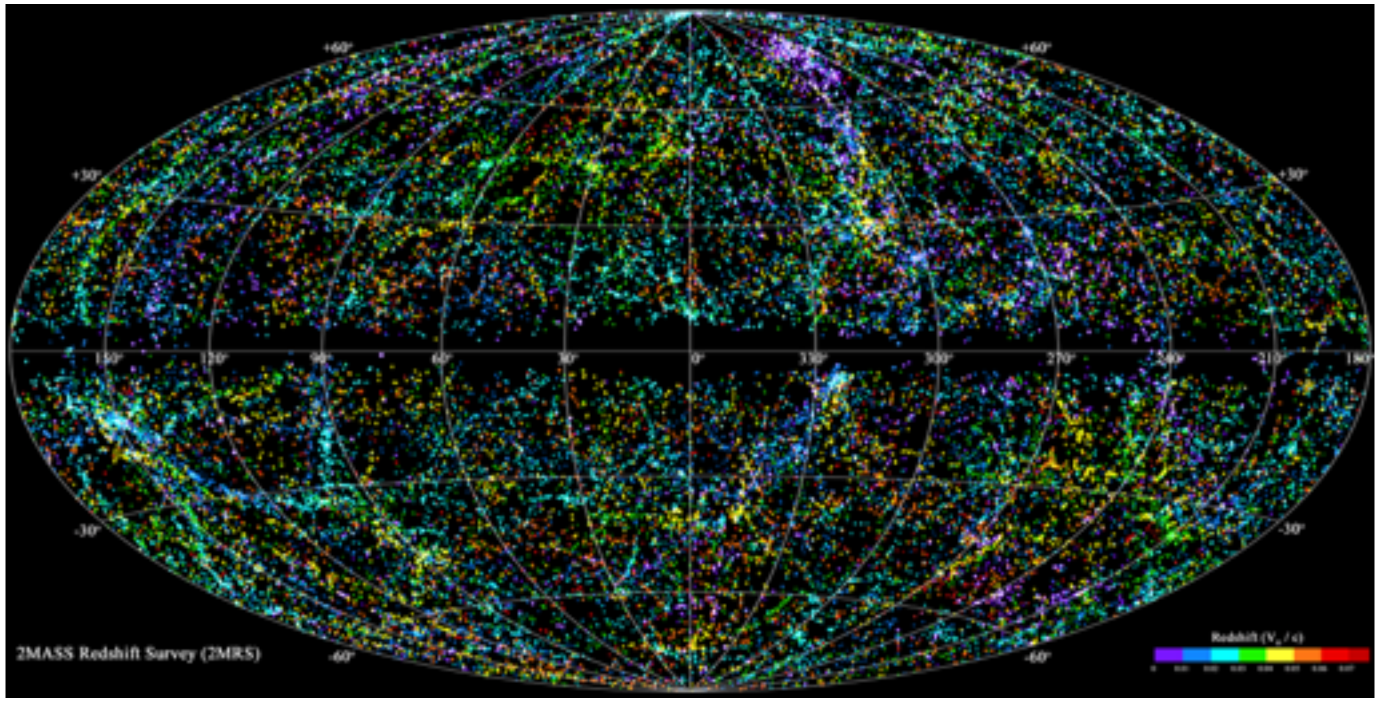
Absorption is negligible, lensing unimportant at low z, accretion disk and magnetic fields unimportant during inspiral.

How do GW tests Differ from Other Tests?

3. <u>Localized</u>: Distinct point sources in spacetime (not a background)

4. <u>Constraint Maps</u>:

If large # of sources detected.
eg. preferred position tests.

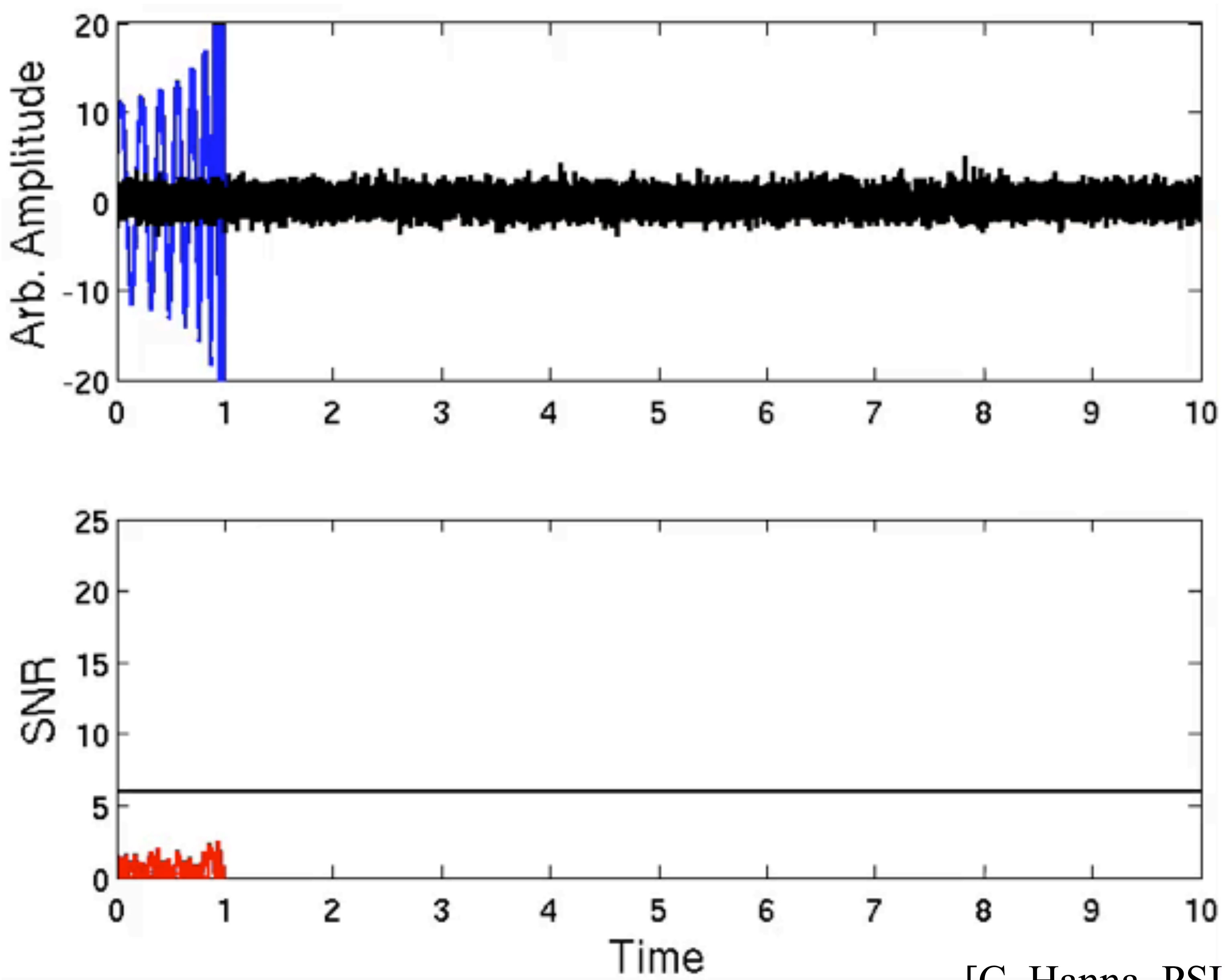


5. <u>Very Local Universe</u>: $z < 0.07$ or $D < 300$ Mpc for NS/NS inspiral.

How do use GWs to test GR? Matched Filtering

Matched Filtering:

- Create template "filters"
- Cross-correlate filters & data
- Find filter that maximizes the cross-correlation.



[C. Hanna, PSU]

$$\rho^2 \sim \int \frac{\tilde{s}(f)\tilde{h}(f,\lambda^\mu)}{S_n(f)} df$$

signal-to-noise ratio (SNR)

data

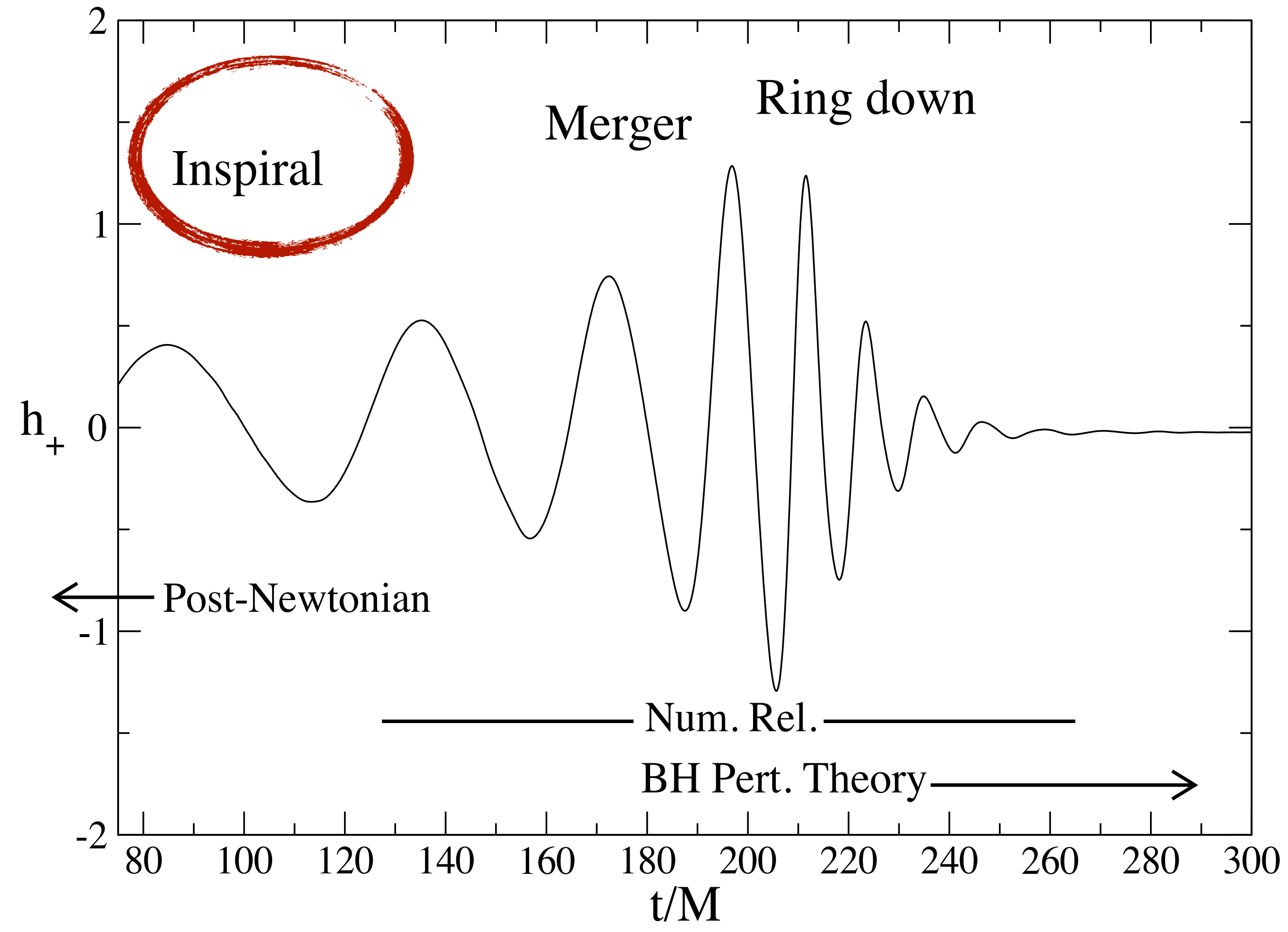
template param that characterize system

detector noise (spectral noise density)

template (projection of GW metric perturbation)

How do use GWs to test GR? Source Modeling

Inspiral: thousands of cycles, most SNR at low masses.



Approximations: PN + PM

Accuracy: 3.5 PN ("3 loop" order)

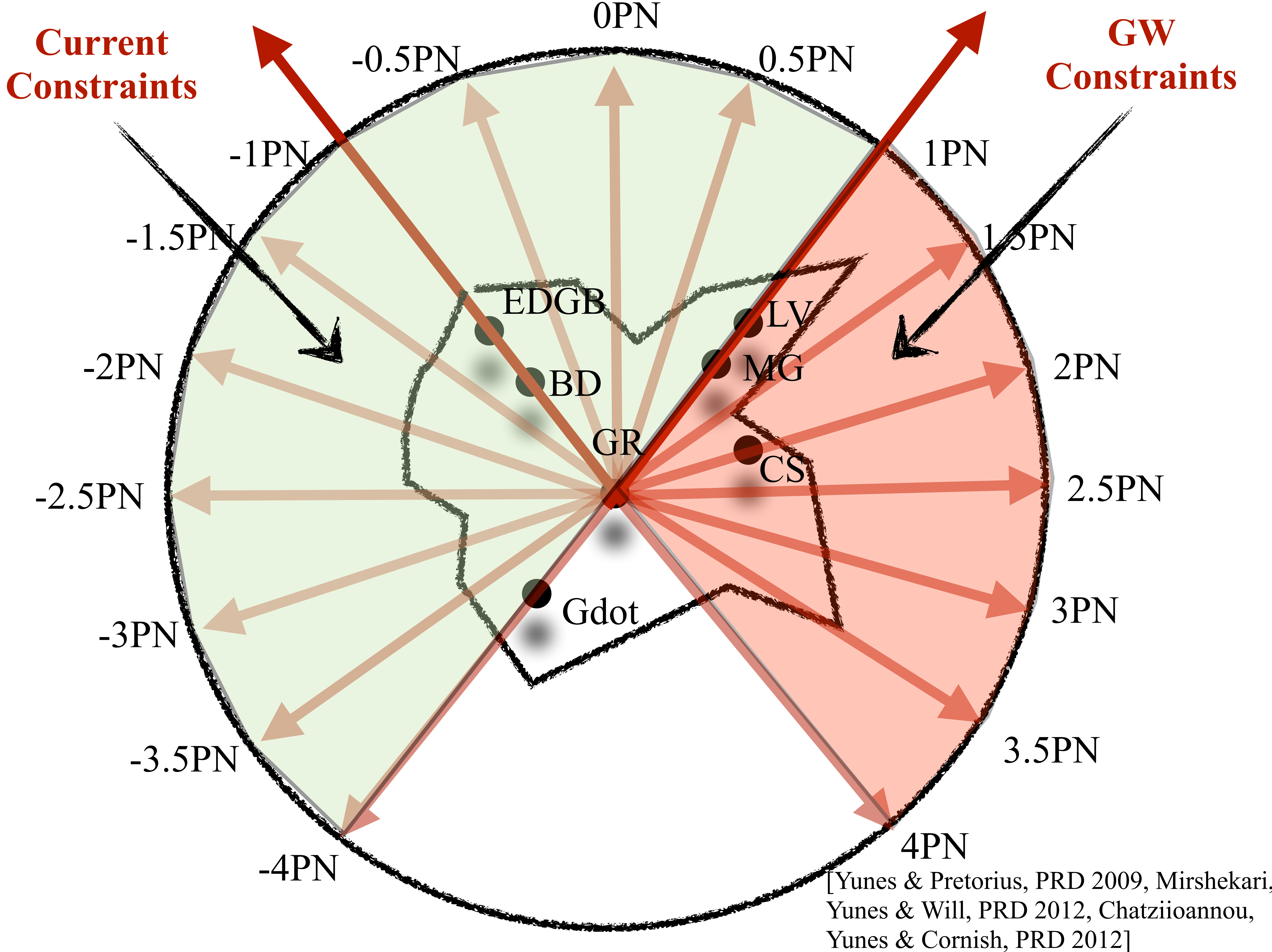
Template:

$$h_\times(t) \sim \frac{\eta M}{D_L} \cos\iota \, (M\omega)^{2/3} \cos 2\Phi + \ldots$$

- $h_\times(t)$: gravitational wave
- η: symmetric mass ratio
- D_L: distance to the source
- ι: inclination angle
- M: total mass
- ω: orbital freq.
- Φ: orbital phase

How do use GWs to test GR?

Top-Down (test specific theory) vs. Bottom-Up (search for deviations).


Current Constraints
GW Constraints
0PN
-0.5PN
0.5PN
-1PN
1PN
-1.5PN
1.5PN
-2PN
2PN
-2.5PN
2.5PN
-3PN
3PN
-3.5PN
3.5PN
-4PN
4PN
EDGB
BD
GR
LV
MG
CS
Gdot
[Yunes & Pretorius, PRD 2009, Mirshekari, Yunes & Will, PRD 2012, Chatziioannou, Yunes & Cornish, PRD 2012]

What will we learn from GW tests of GR?

<u>Search for Generic Deviations</u>: Parameterize post-Einsteinian (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.

[Yunes & Pretorius, PRD 2009,
Chatziioannou, Yunes & Cornish, PRD 2012]

What will we learn from GW tests of GR?

1. **Gravitational Lorentz Violation**: Primarily from propagation speed w/coincident EM

$$\frac{v_g}{c} - 1 \lesssim 10^{-14}$$

[Nishizawa & Nakamura, 2014,
Jacobson, 2004,
Yagi, Blas, Barausse, Yunes, PRD 2013,
Hansen, Yunes, Yagi, 2014]

2. **Graviton Mass**: Primarily from modification of dispersion relation.

$$\lambda_g^{\rm Pul.Tim.} \gtrsim 10^{13} \text{ km} \qquad \lambda_g^{\rm GW} \gtrsim 10^{14} - 10^{16} \text{ km}$$

[Finn & Sutton PRD 2002,
Baskaran, et al, PRD 2008,
Will, PRD 1998,
Will & Yunes, CQG 2004,
Berti, Buonanno & Will, CQG 2005]

3. **Dipolar Emission**: From activation of scalar or vectorial modes.

[Will, PRD 1994,
Yagi, et al PRL 2013,
Hansen, Yunes, Yagi 2014]

What will we learn from GW tests of GR?

4. **Higher Curvature Action**: Effective theories (EDGB, CS)

$$\xi_{\rm CS}^{\rm LAGEOS} \lesssim 10^7 \text{ km} \qquad \xi_{\rm CS}^{\rm GW} \lesssim 10 \text{ km}$$

[Alexander & Yunes, Phys. Rept, 2009
Yagi, PRD 2012,
Yagi, et al, PRD 2012]

5. **Screening Strong-Field Mechanism**: Scalarization

$$\beta_{\rm ST}^{\rm Bin.Pul.} \gtrsim (-4.75, -4.5) \qquad \beta_{\rm ST}^{\rm GW} \gtrsim -4.5$$

[Damour & Esposito-Farese, CQG, 1992,
Freire et al, MNRAS 2012,
Sampson et al, PRD 2014]

6. **No-Hair Theorem**: From binary black hole ringdown.
(more difficult, requires high SNR)

[Dreyer, et al, CQG, 2004,
Berti et al, PRD 2006,
Gossan et al, PRD 2012]

What does it all mean?

GW tests of GR differ from other tests in a variety of ways:
probe extreme gravity, clean, localized, constraint maps, present day.

GW tests will constrain a variety of phenomena:
Lorentz violation, graviton mass, dipole emission, higher curvature action, screening mechanisms, no-hair theorem.

Doveryai, no proveryai

What will we learn from GW tests of GR?

Nico's (GW-Biased) GW
Modified Theory Classification:

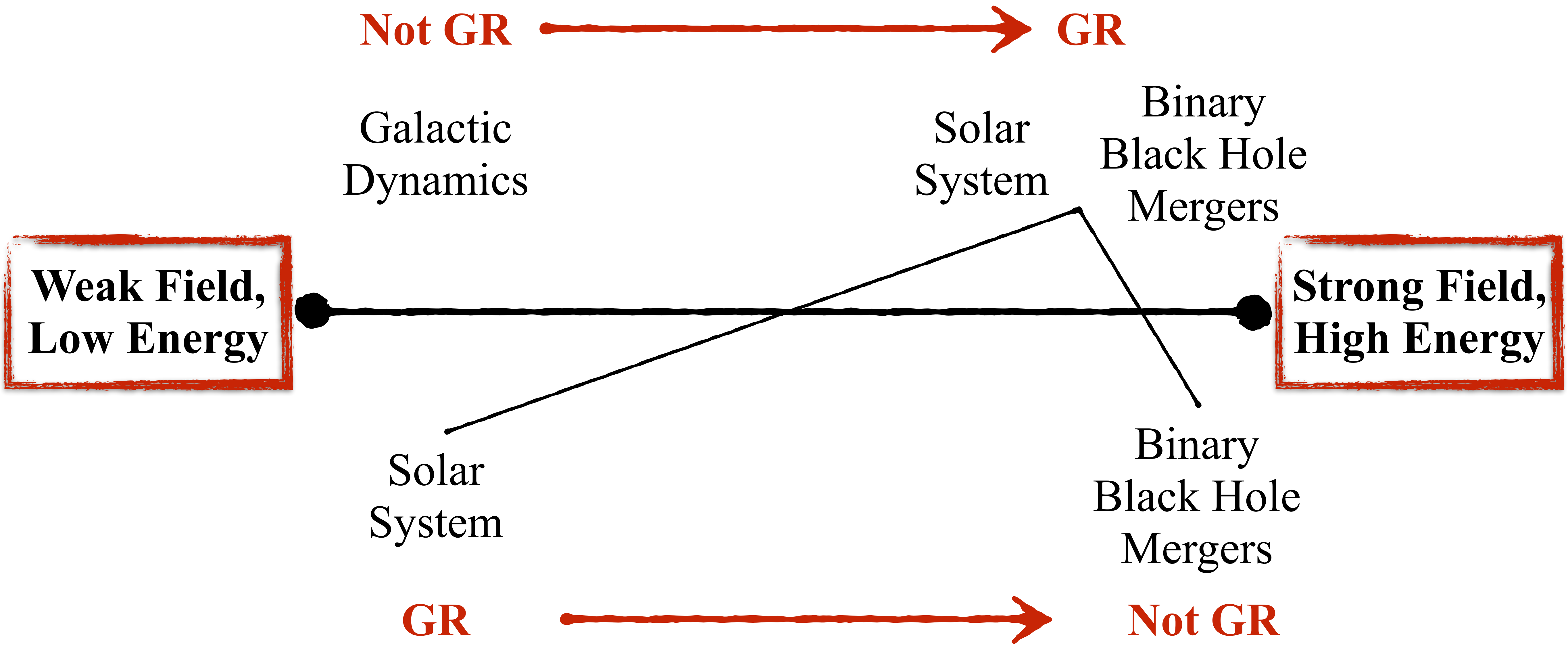
"Weak Field"	**Strong-Field**
Well-constrained by binary pulsars, so need screening	Constrainable with GW observations, natural suppression without screening
Eg, Scalar-Tensor theories	Eg, Chern-Simons, Gauss-Bonnet, etc.

Nico's (GW-Biased) Cosmological
Modified Theory Classification:

Screened	**Unscreened**
Late-time expansion, DE	Early-time cosmology, inflation
Eg, chameleon, Vainshtein, etc.	Eg, Chern-Simons, Gauss-Bonnet, etc.

Screening in Cosmology ≉ Screening in GWs

In Cosmology



In Gravitational Wave Physics

Weak Field Theories

Example: Scalar Tensor Theories

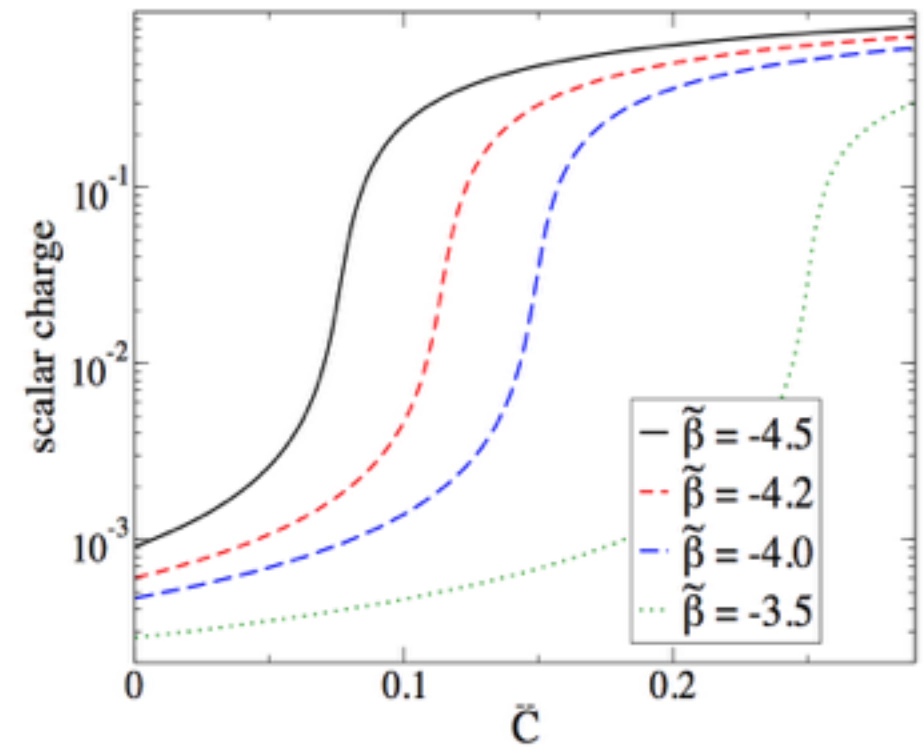
Definition:

$$S_{\text{Jordan}} \sim \int d^4x\sqrt{-g}\left[\phi R - \frac{\omega(\phi)}{\phi}\left(\partial^\mu\phi\right)\left(\partial_\mu\phi\right) + \mathcal{L}_{\text{matter}}\right]$$

$$\phi \to g_{\mu\nu} \to T_{\mu\nu}$$

Effective Coupling to Matter: $\alpha \sim \frac{1}{\sqrt{3+2\omega_{BD}}}$ / $\alpha \sim \alpha_0 - \beta(\phi - \phi_0)$

Main Effect: Stars acquire scalar charge + Spontaneous Scalarization

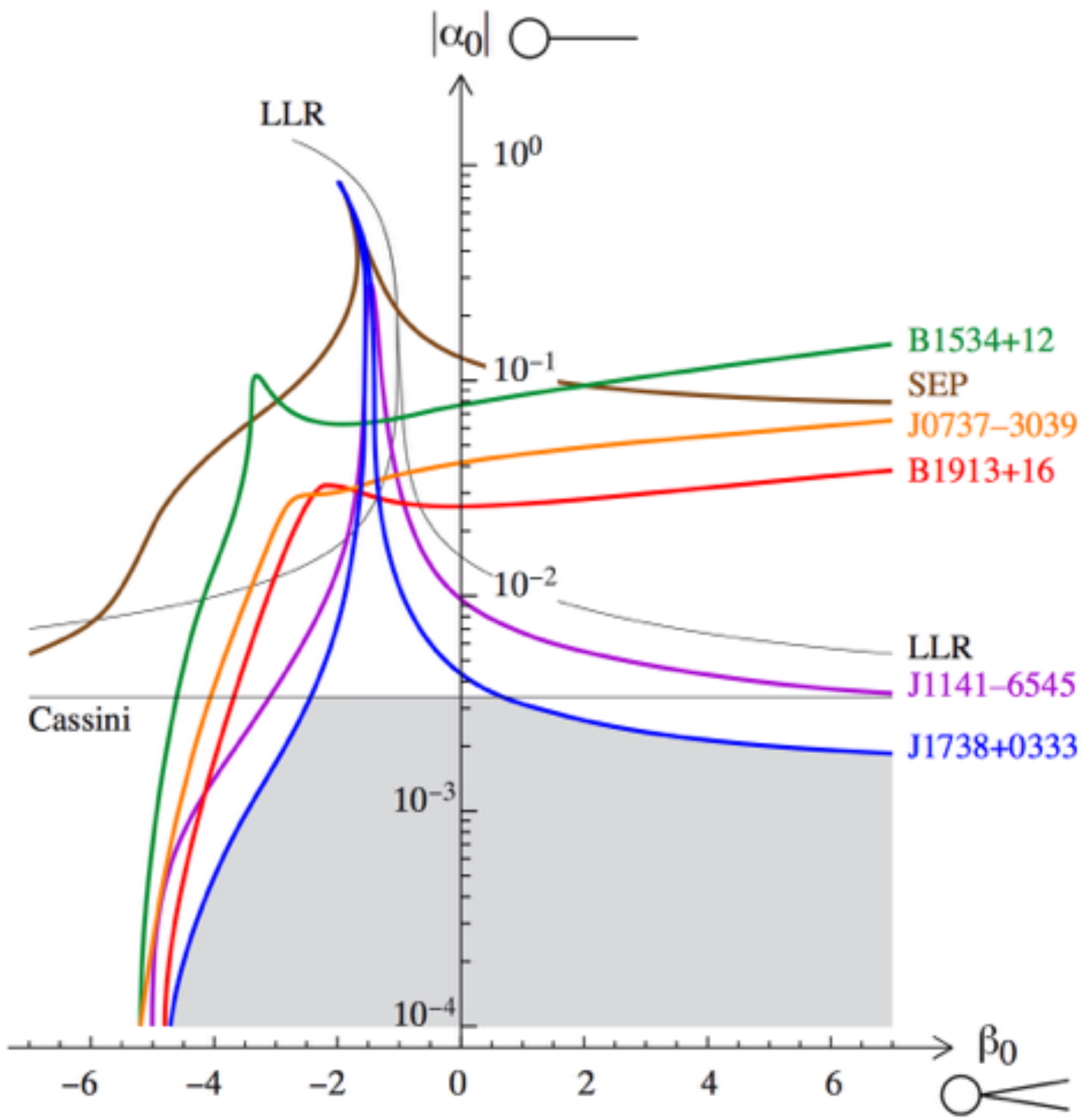


Dominant Observables: Grav. and Inertial center of mass do not coincide → **Screened** Dipole Gravitational Wave Emission → Faster Orbital Decay

Damour+Esposito-Farese, PRD 54 ('96)
Palenzuela, et al, PRD 97 ('13), 89 ('14).

Constraints on Weak Field Theories

Scalarizable Scalar-Tensor:



(similar constraints for TeVeS and for massive Brans-Dicke)

Freire, et al, MRAS 18 ('12).
Alsing, et al, PRD 85, ('12).

Strong Field Theories

Example: Quadratic Gravity

Definition:

$$S_{\rm Quad} \sim \int d^4x \sqrt{-g} \left[R - \frac{1}{2} \left(\partial_\mu \vartheta\right) \left(\partial^\mu \vartheta\right) + \alpha_1 \vartheta R^2 + \alpha_2 \vartheta R_{\mu\nu} R^{\mu\nu} + \alpha_3 \vartheta R_{\mu\nu\delta\sigma} R^{\mu\nu\delta\sigma} + \alpha_4 \vartheta R_{\mu\nu\delta\sigma} \, {}^*R^{\mu\nu\delta\sigma} \right]$$

certain choices of couplings lead to Einstein-Dilaton-Gauss-Bonnet theory or dynamical Chern-Simons gravity.

Main Effects: dCS. Gravitational Parity Violation, inverse no-hair theorem.

Dominant Observables: Chirping of Gravitational Wave Phase → Requires observation of late inspiral & merger

Alexander & Yunes, Phys. Rept 480 ('09)
Yunes & Stein, PRD 83 ('11)

Constraints on Strong Field Theories

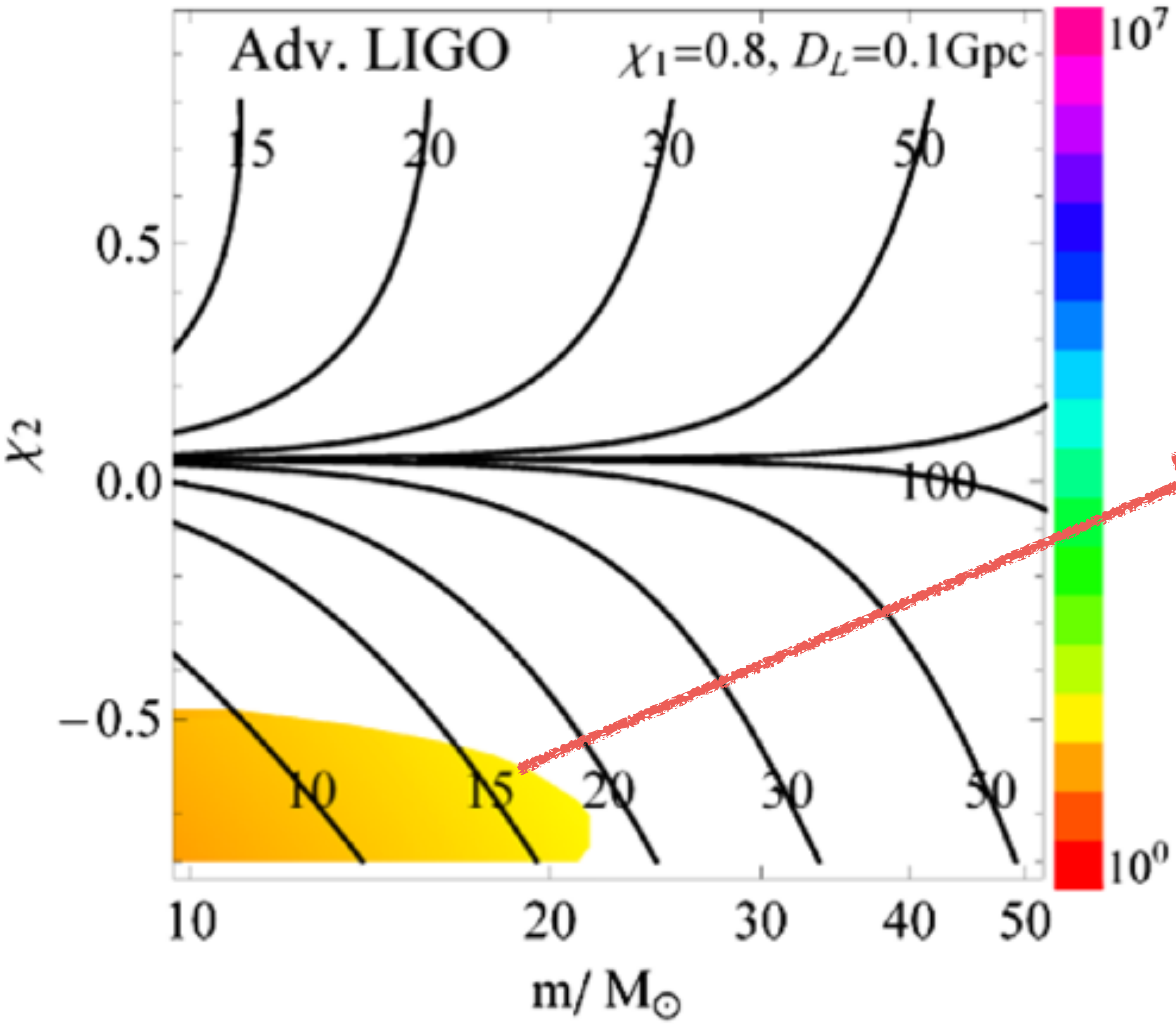
dCS

Current constraints

Extremely weak from Solar System (GPB)

$\alpha_4^{1/2} < \mathcal{O}(10^8 \text{ km})$

Projected GW constraints



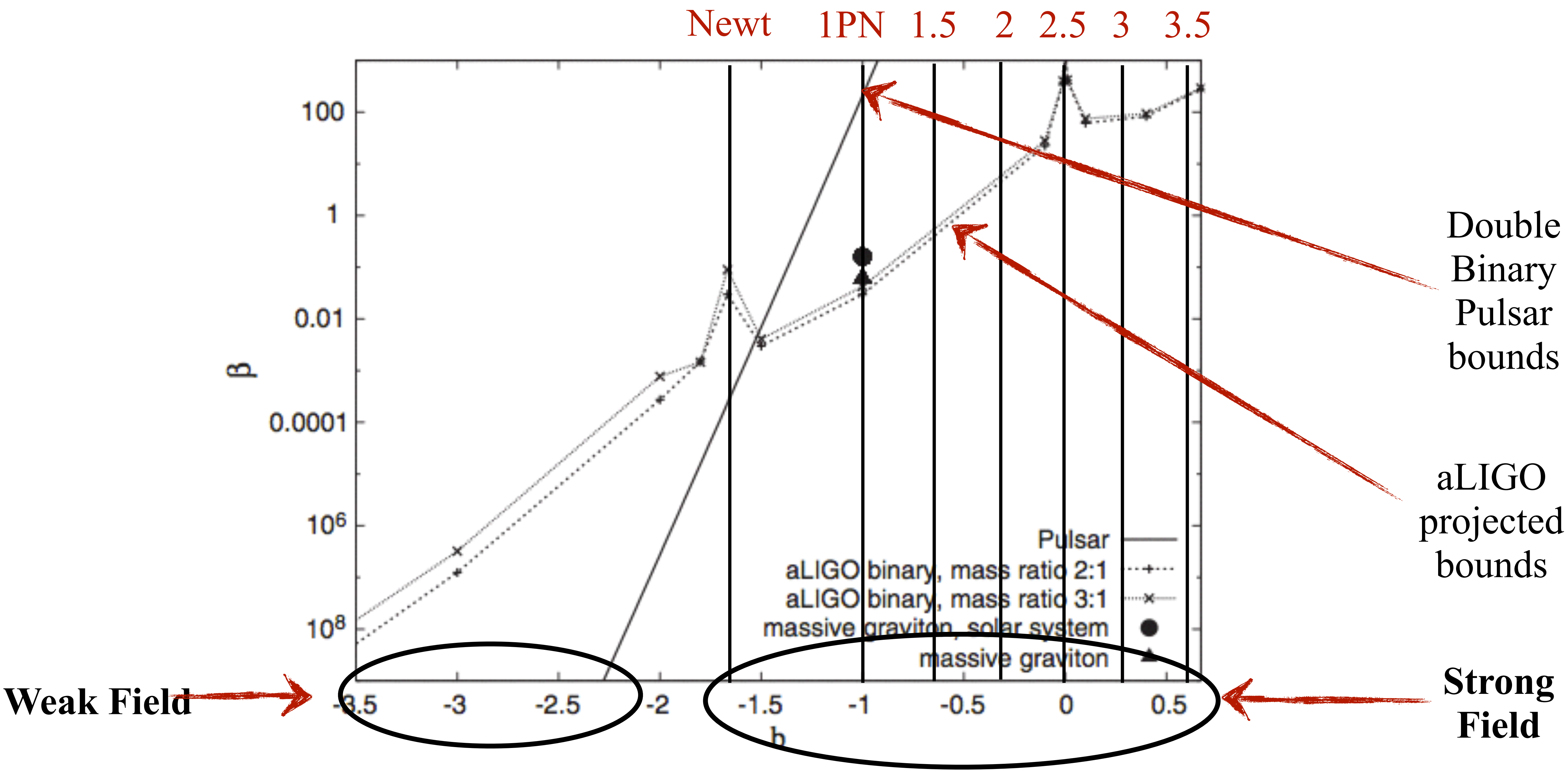
Constraint Contours on $\alpha_4^{1/2}$ in km.

Yagi, Yunes & Tanaka, PRL 109 ('12)

Parametrized Post-Einsteinian

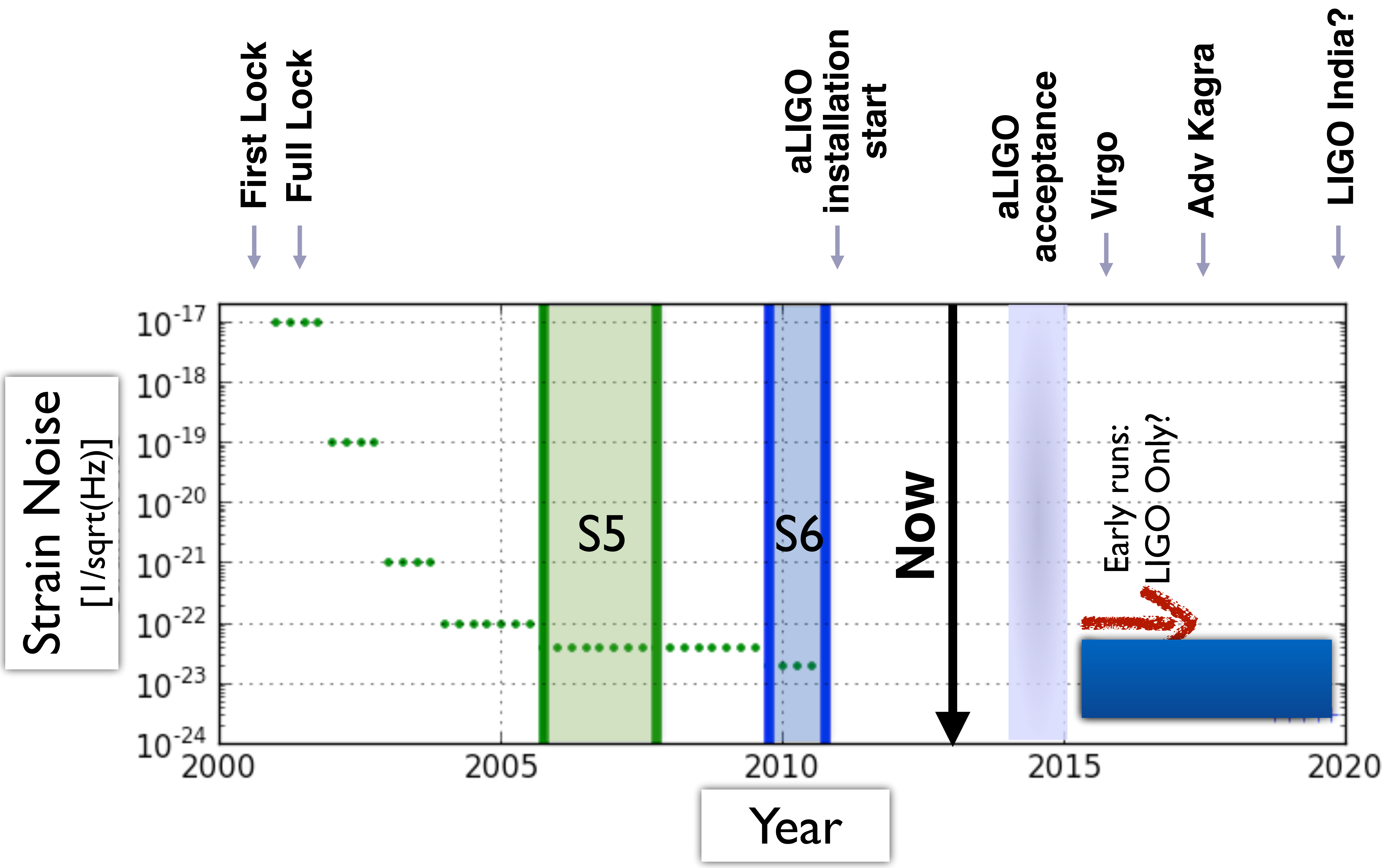
Projected Gravitational Wave Constraints

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



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

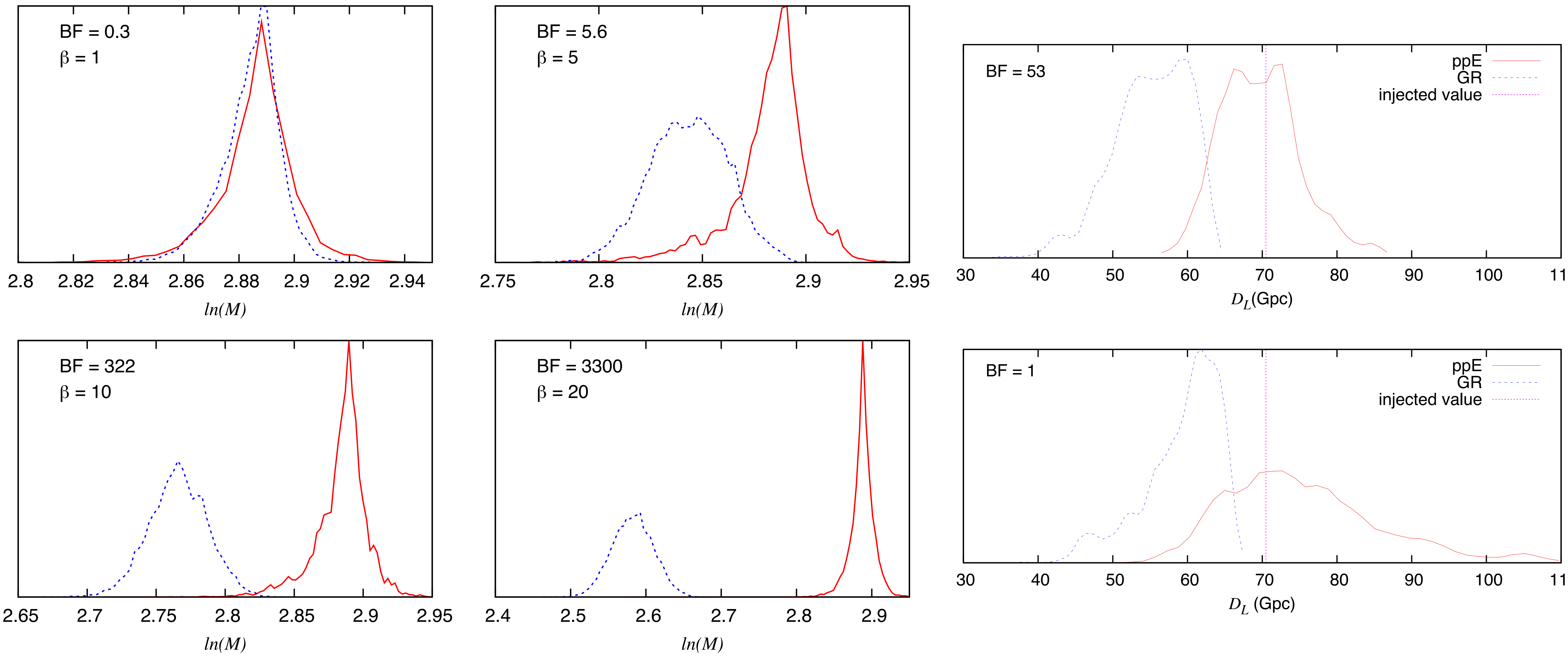
Yunes & Hughes, 2010,
Cornish, Sampson, Yunes & Pretorius, 2011
Sampson, Cornish, Yunes 2013.


First Lock
Full Lock
aLIGO installation start
aLIGO acceptance
Virgo
Adv Kagra
LIGO India?
Strain Noise
[1/sqrt(Hz)]
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
S5
S6
Now
Early runs: LIGO Only?
2000
2005
2010
2015
2020
Year

Fundamental Bias

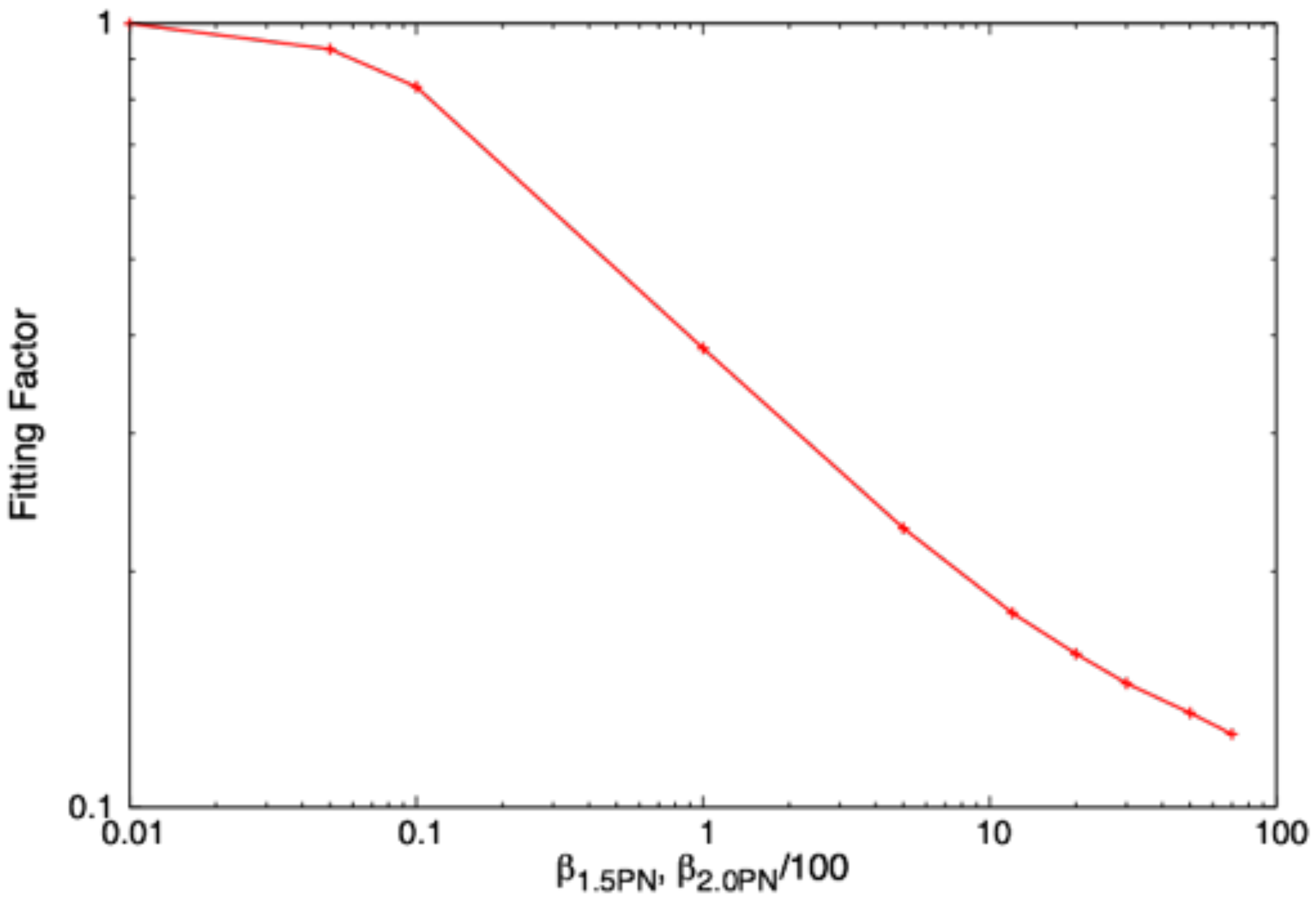
Non-GR Signal/GR Templates, SNR = 20

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

Ignoring Fundamental Bias...

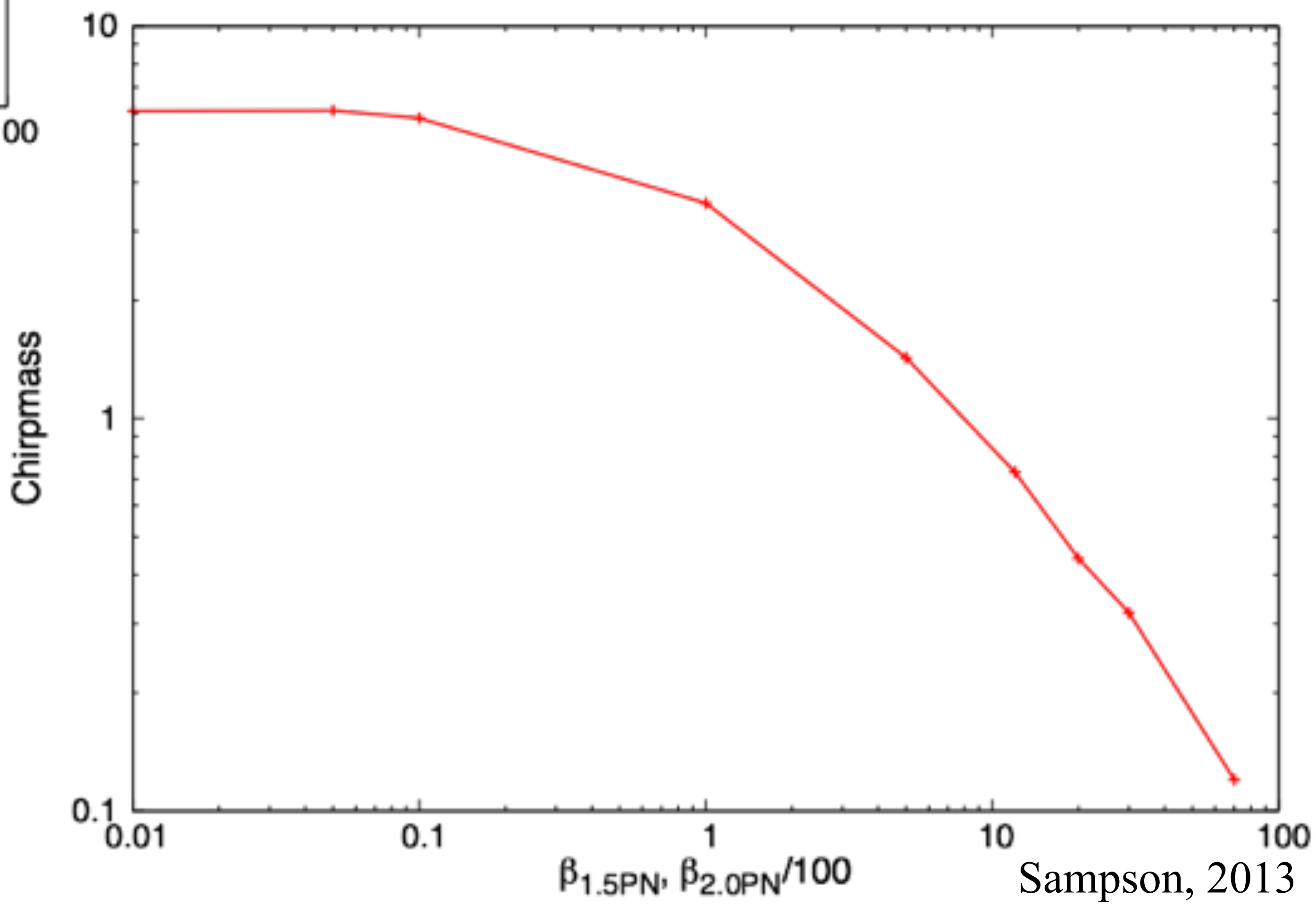


injection=(not-ruled out) ppE

template=GR

Fitting Factor Deteriorates

Physical Parameters Completely Biased



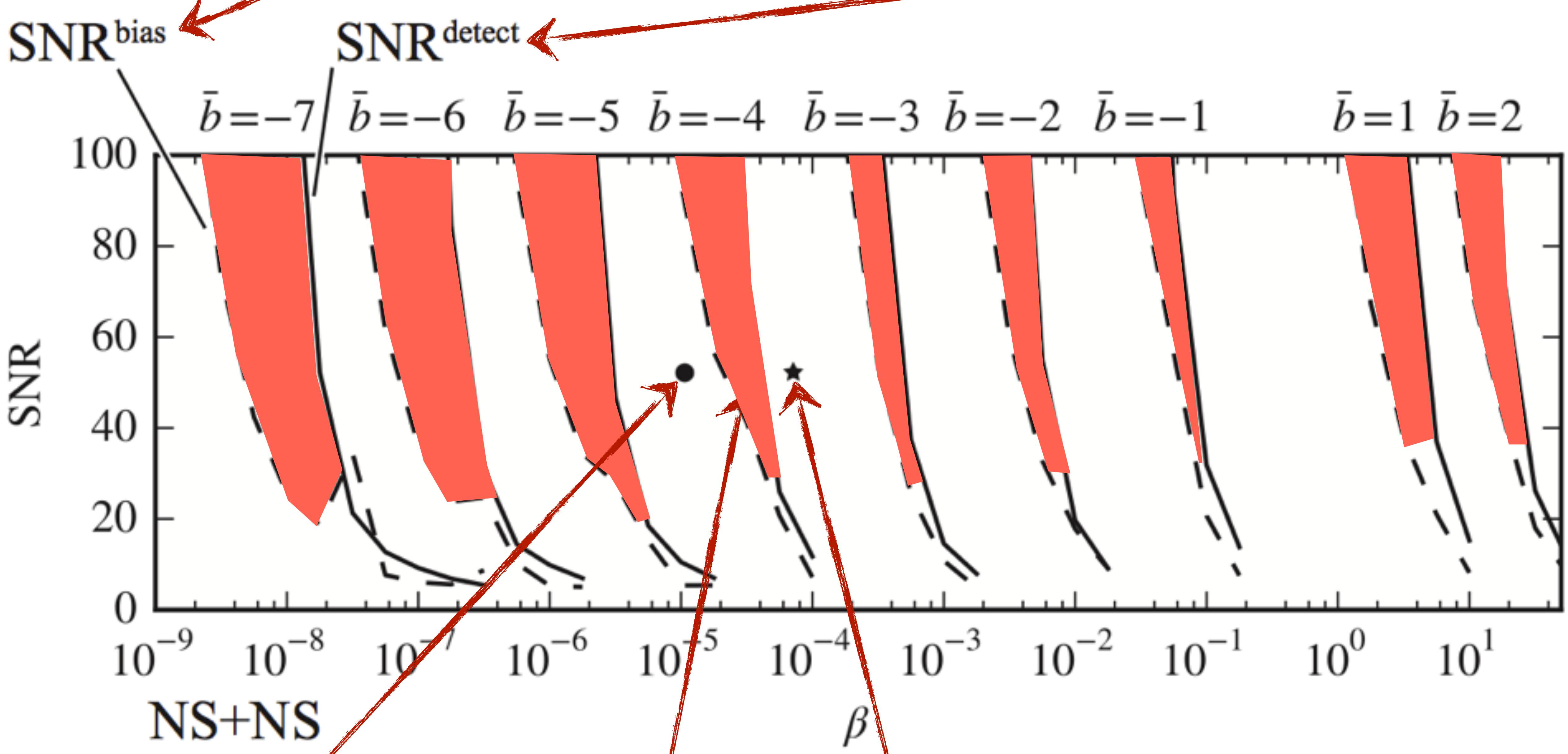
Sampson, 2013

Stealth Bias

Fundamental Bias that we can't detect!

SNR needed for fundamental bias error to be larger than systematic error

SNR needed to detect a GR deviation

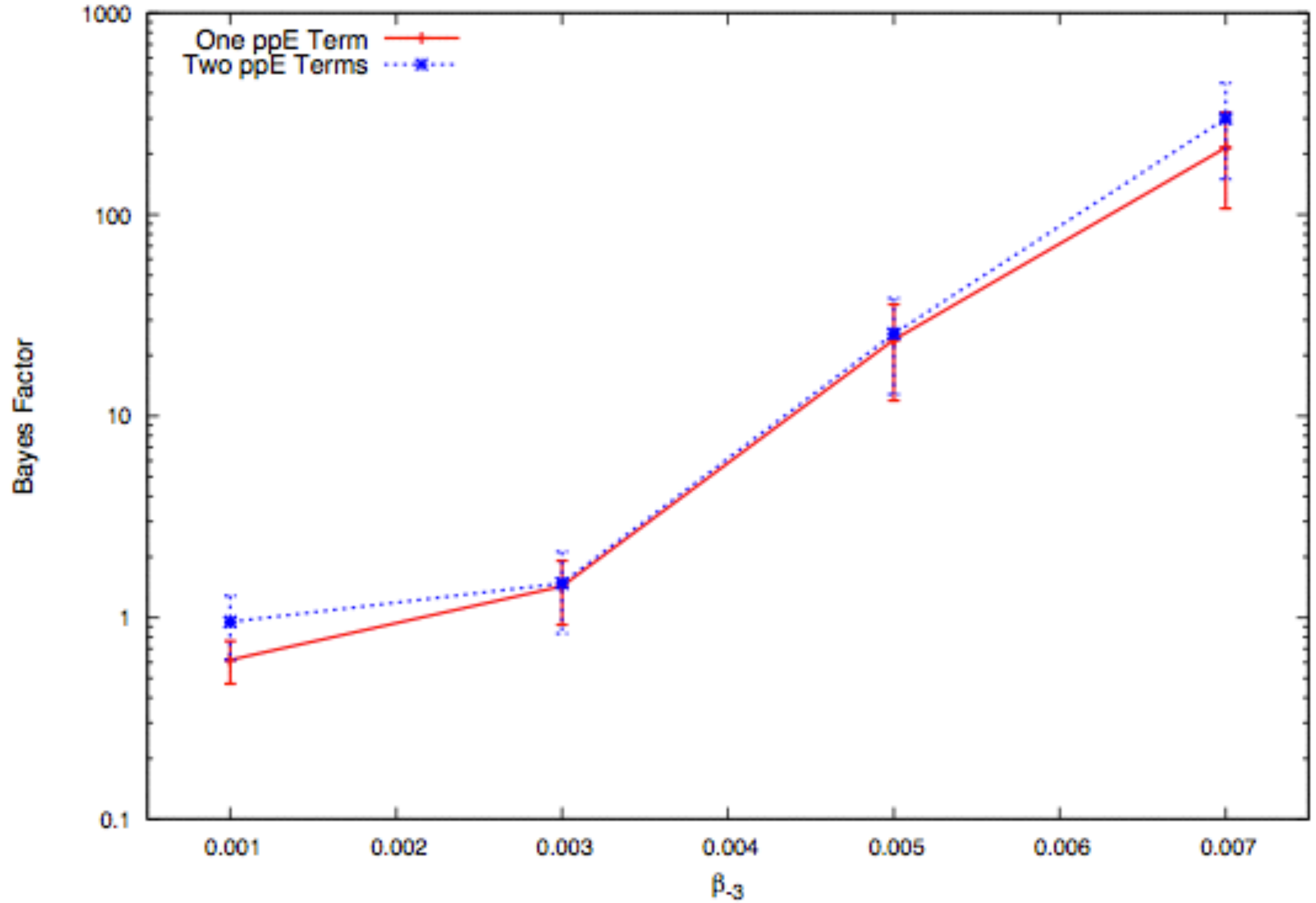


Negligible Bias

Stealth Bias

Overt Bias

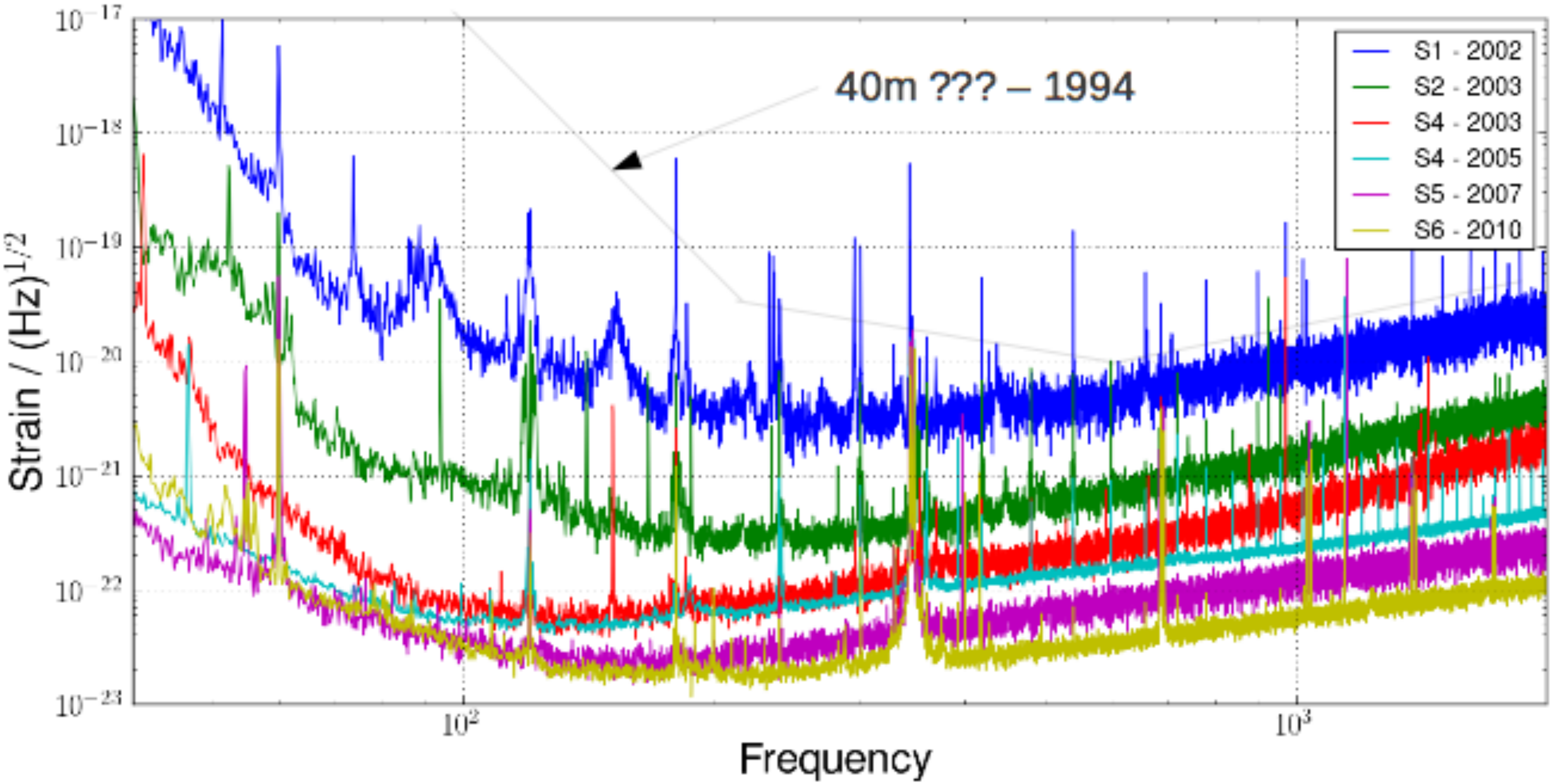
Simple ppE Performance



Bayes Factor between a 1-parameter ppE template and a GR template (red) and between a 2-parameter ppE template and a GR template (blue), given a non-GR injection with 3 phase deformations, as a function of the magnitude of the leading-order phase deformation.

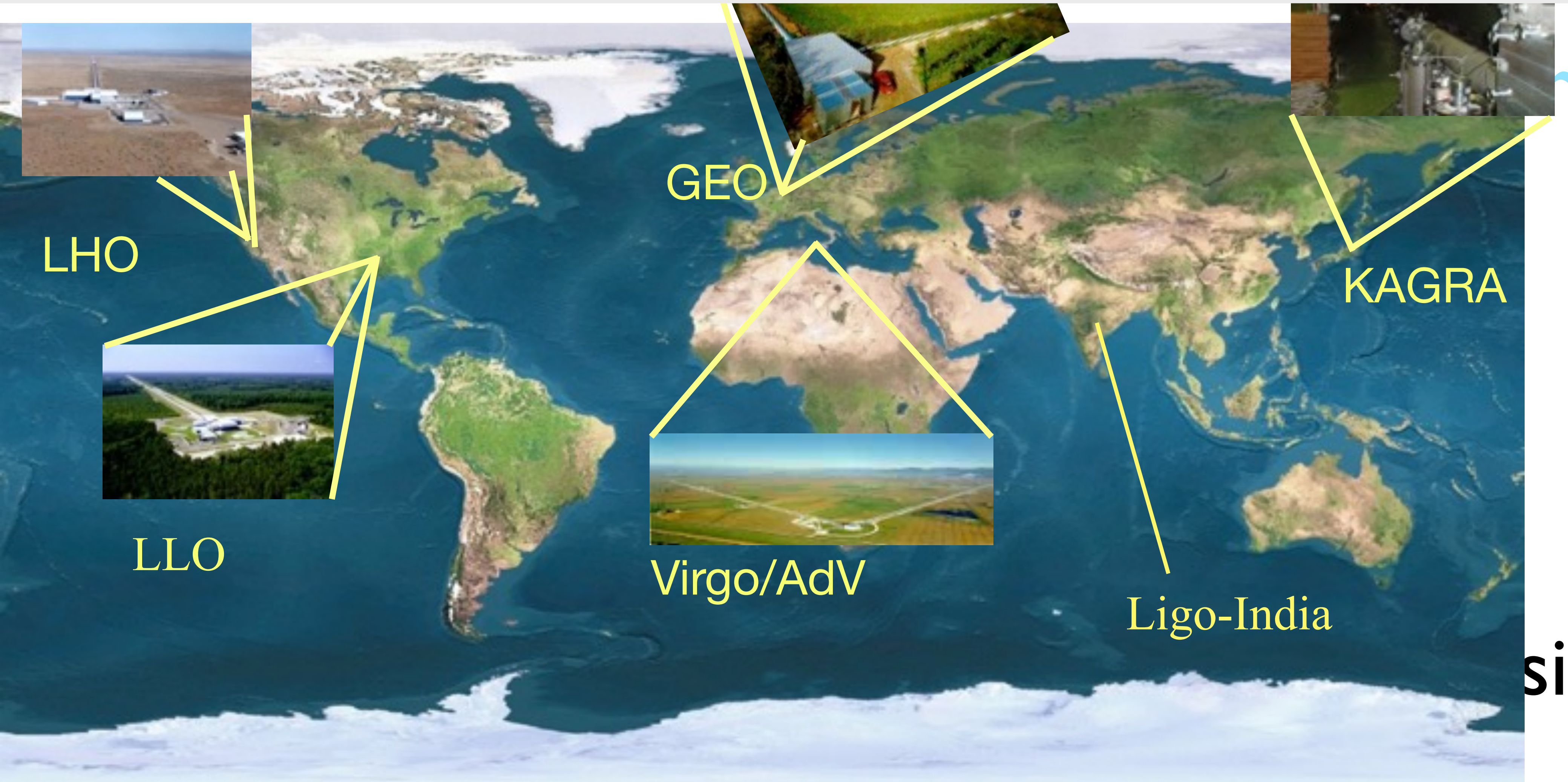
Sampson, Cornish & Yunes, 2013

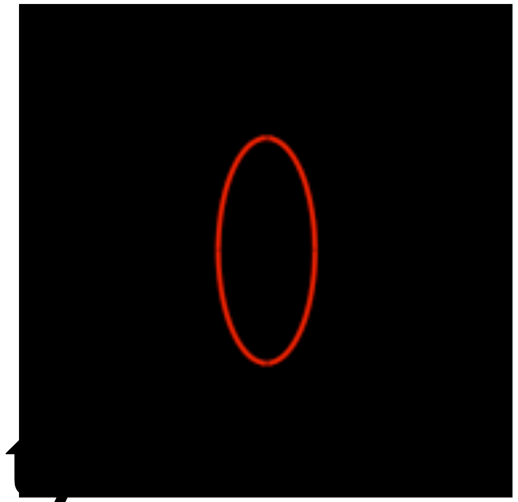
The Need for Accuracy



Quantum Noise (Amelino-Camelia)

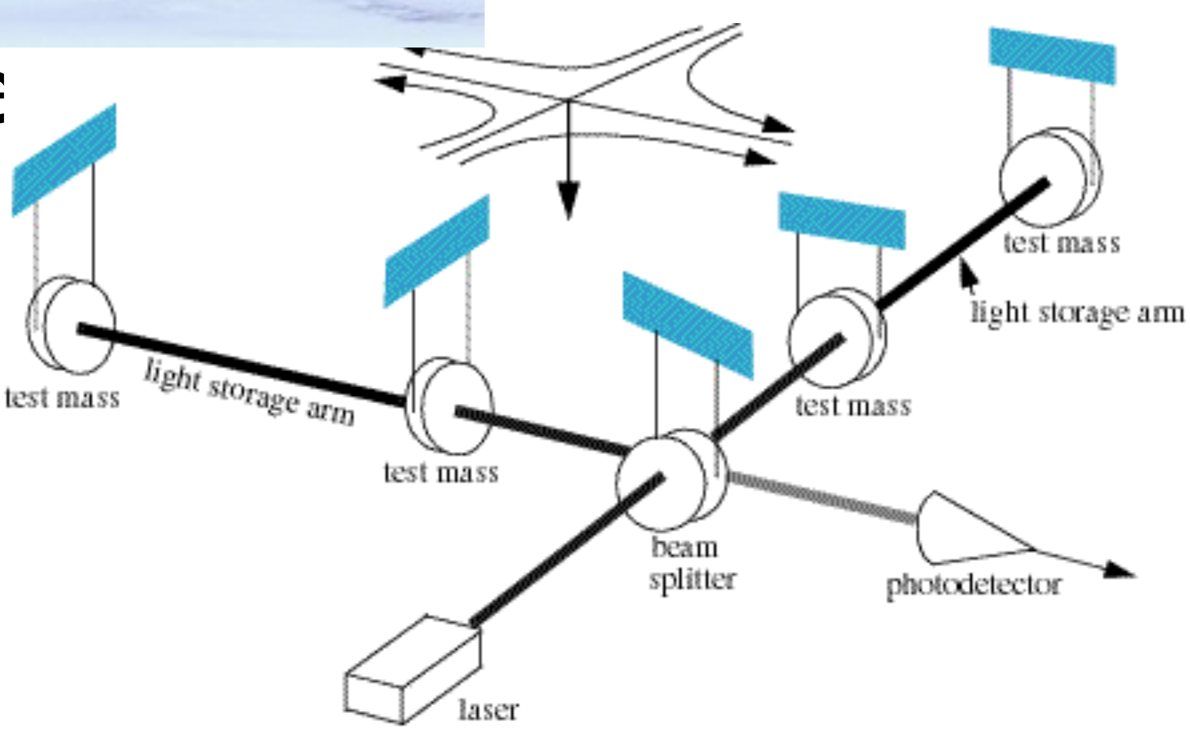
Detectors





- is either a dynamical fie

Bounce light off mirrors and look for interference pattern when the light recombines.



Parameterized post-Einsteinian Framework

I. Parametrically deform the Hamiltonian.

II. Parametrically deform the RR force.

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

III. Deform waveform generation.

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

IV. Parametrically deform g propagation.

$$E_g^2 = p_g^2 c^4 + \tilde{\alpha} p_g^{\tilde{\alpha}}$$

Result: To leading PN order and leading GR deformation

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

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