Gravitational Waves as Strong Field Probes of the Universe

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APC Invited Talk, June 12th, 2014
Yunes & Siemens, Living Reviews in Relativity 2014,
http://arxiv.org/abs/1304.3473

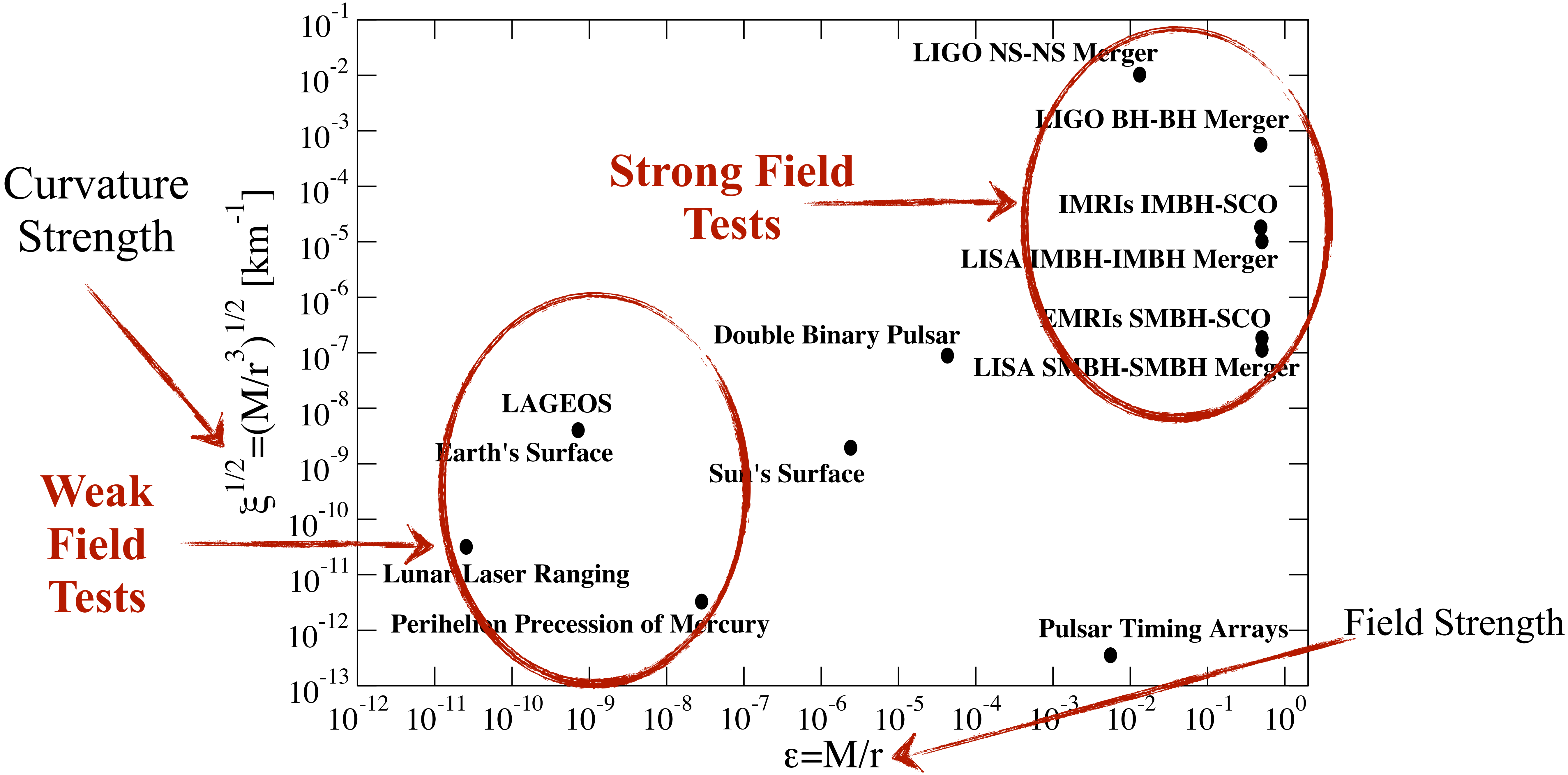
Standing on the Shoulders of...

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 incomplete summary of what GWs will tell us about gravity in the cosmology context

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.

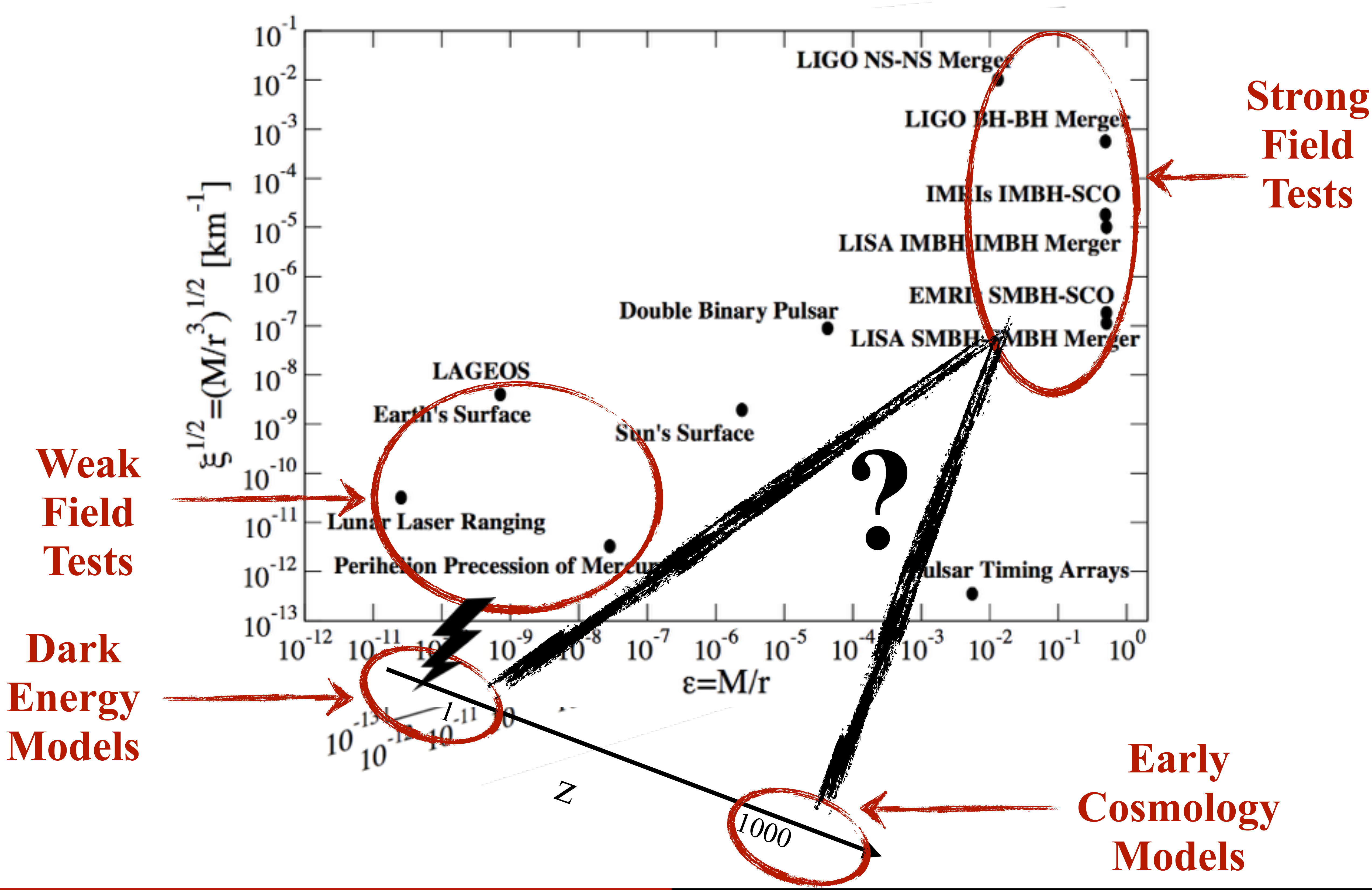
Testing Phase Space



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

Will, Liv. Rev., 2005, Psaltis, Liv. Rev., 2008, Siemens & Yunes, Liv. Rev. 2013.

Enlarging Phase Space



Divide and Conquer

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

"Weak Field"

Well-constrained by binary pulsars, so need screening

Eg, Scalar-Tensor theories

Strong-Field

Constrainable with GW observations, natural suppression without screening

Eg, Chern-Simons, Gauss-Bonnet, etc.

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

Screened

Late-time expansion, DE

Eg, chameleon, Vainshtein, etc.

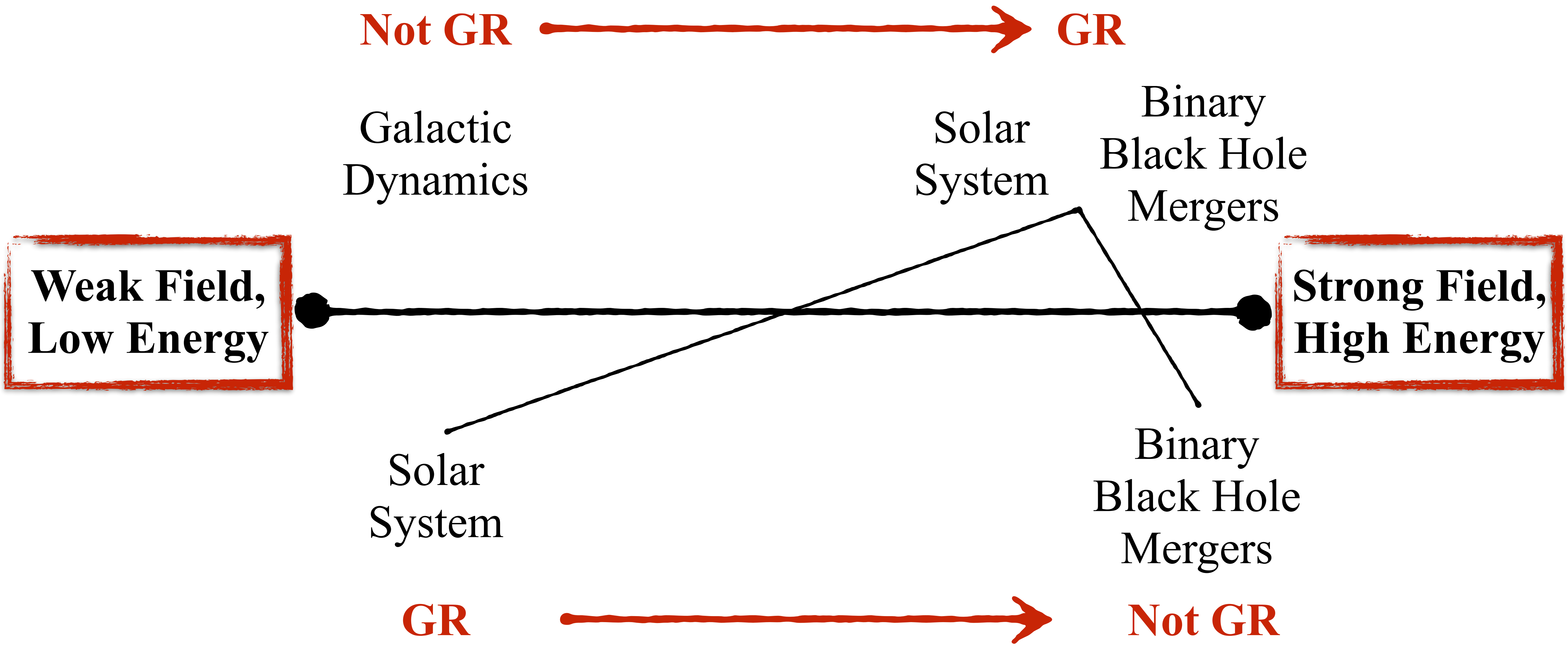
Unscreened

Early-time cosmology, inflation

Eg, Chern-Simons, Gauss-Bonnet, etc.

Screening in Cosmology ≠ Screening in GWs

In Cosmology



In Gravitational Wave Physics

Roadmap


Weak Field Theories
Parametrized post-Einsteinian
Strong Field Theories
FORODWAITH
RHÛN
ERED MITHRIN
IRON HILLS
Carn Dûm
Here was of old the Witch-realm of Angmar
The Lost Realm of
SHIRE
Hobbiton
LORIEN
ROHAN
FANGORN
MORDOR
Gorgoroth
ENEDWAITH
MINHIRIATH
ERED LITHUI (Ash Mountains)
Sea of Rhûn
Rivendell
Isengard
Bree
Tharbad
Harlond
Gulf of Lhûn
Miles
50 100 150 200

Weak Field Theories

Example: Scalar Tensor Theories

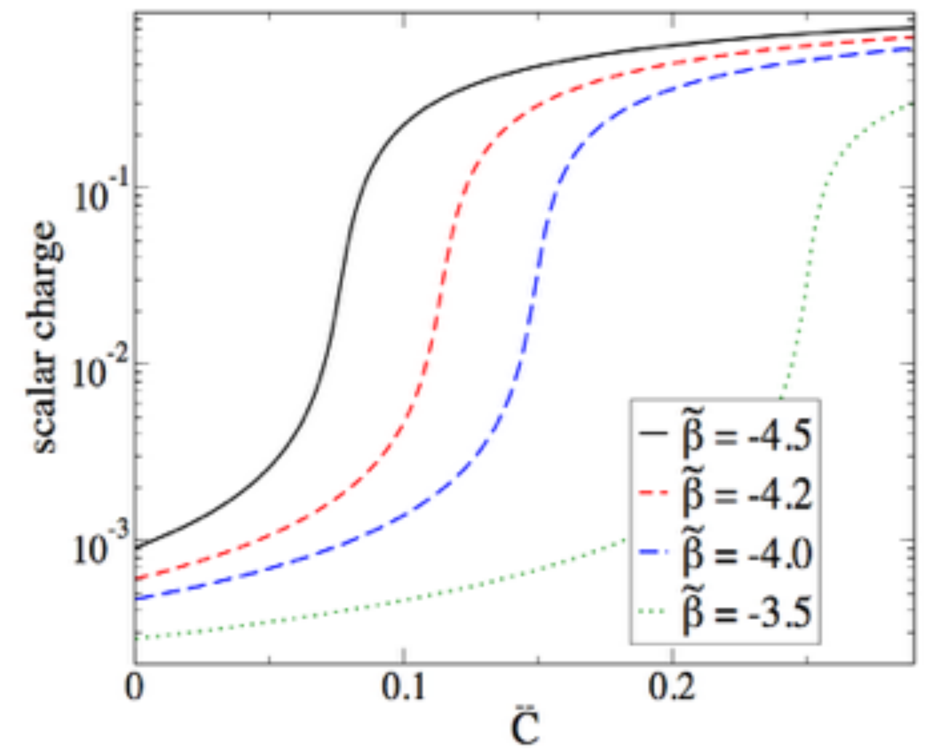
Definition:

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

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

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

Main Effect: Stars acquire scalar charge + Spontaneous Scalarization

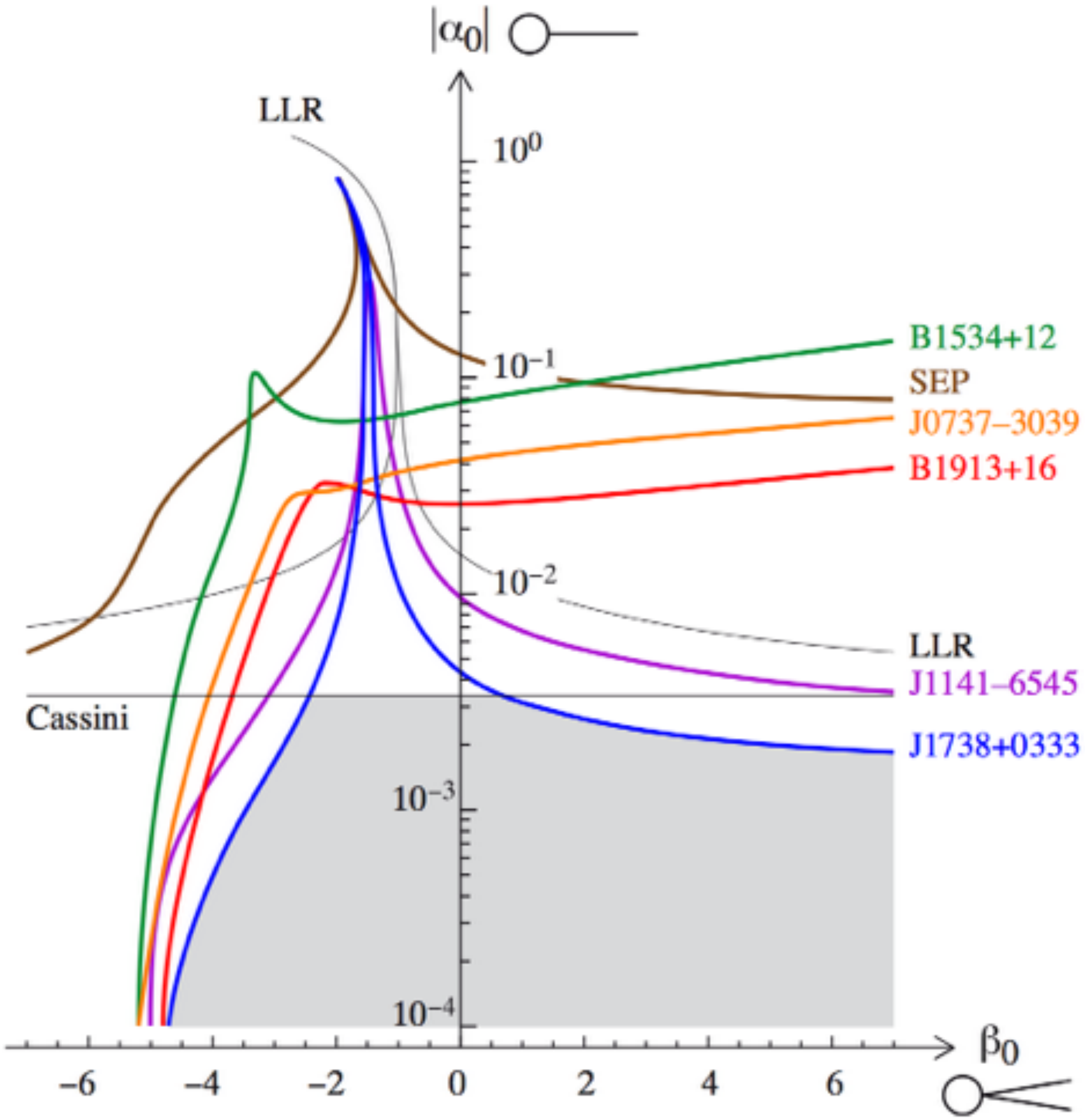


Dominant Observables: Grav. and Inertial center of mass do not coincide → **Screened** Dipole Gravitational Wave Emission → Faster Orbital Decay

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

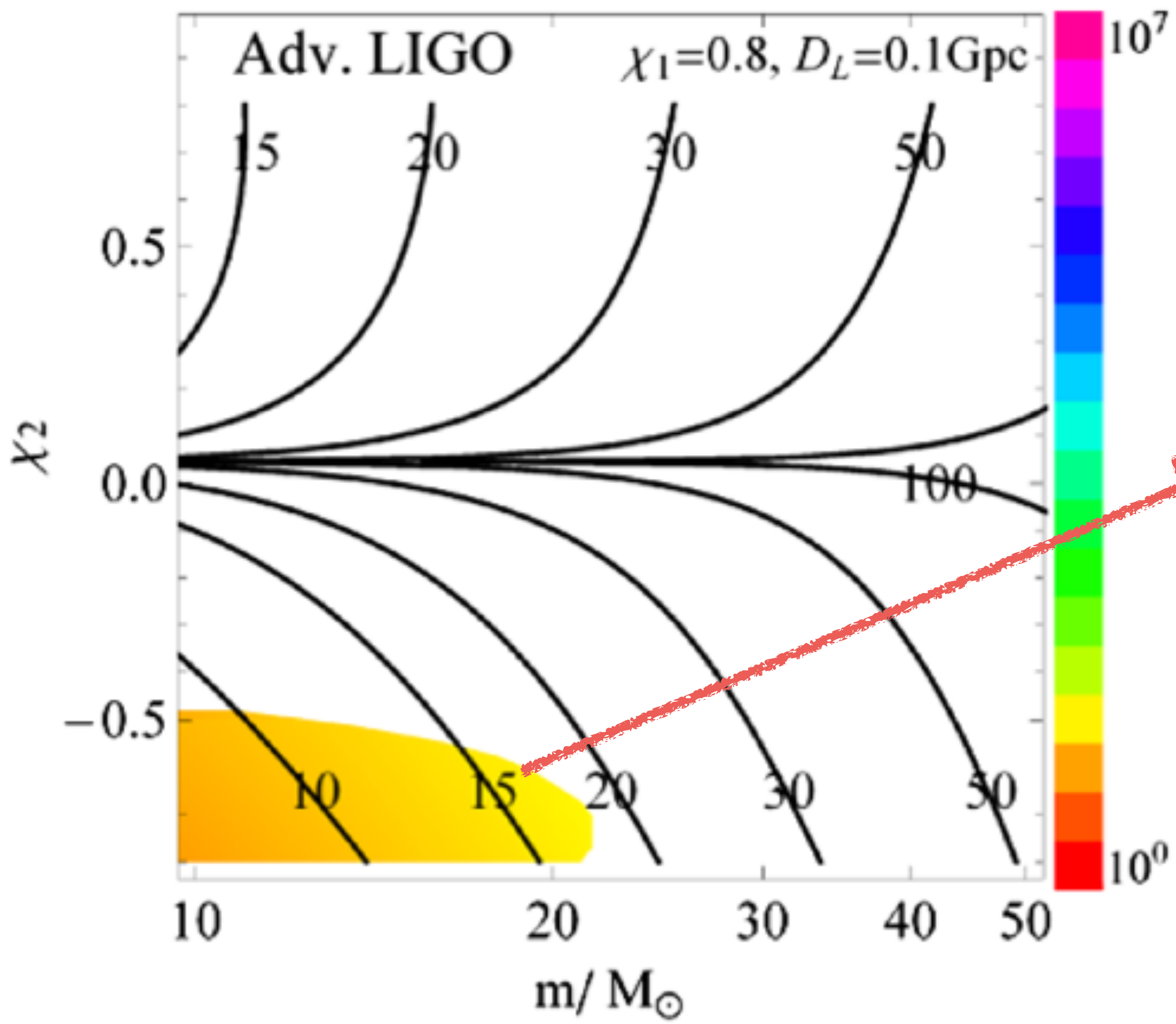
dCS

Current constraints

Extremely weak from Solar System (GPB)

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

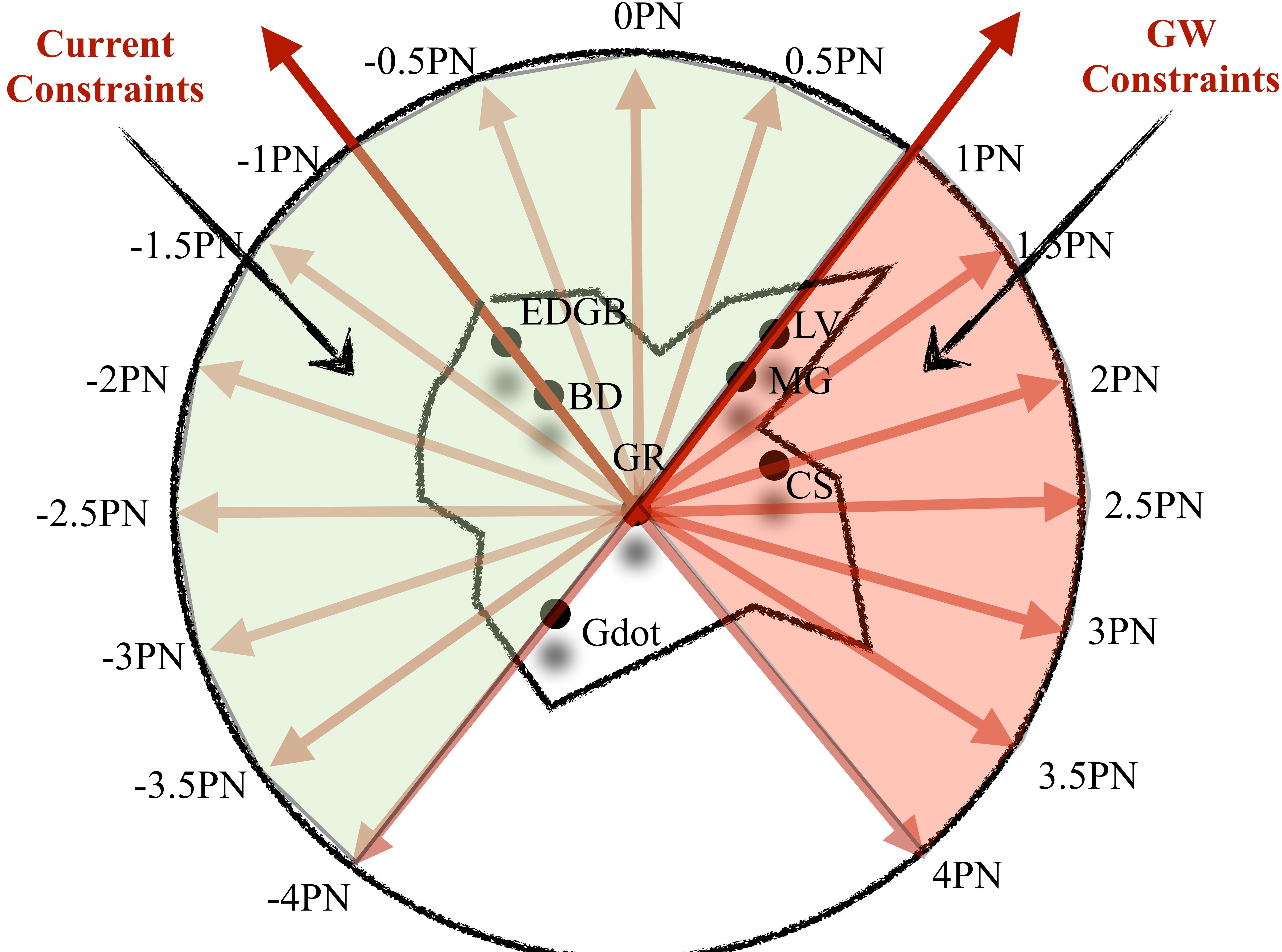
Projected GW constraints



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

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

Parametrized Post-Einsteinian



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

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

Questions to Ask

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.

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

$a_{\rm ppE}$	$b_{\rm ppE}$	Interpretation
1	·	Parity Violation
-8	-13	Anomalous Acceleration, Extra Dimensions, Violation of Position Invariance
·	-7	Dipole Gravitational Radiation, Electric Dipole Scalar Radiation
·	-3	Massive Graviton Propagation
$\propto$ spin	-1	Magnetic Dipole Scalar Radiation, Quadrupole Moment Correction, Scalar Dipole Force

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

What does it all mean?

Clear difference between "Cosmological Modified Theories" and "GW Modified Theories". More cross-pollination needed.

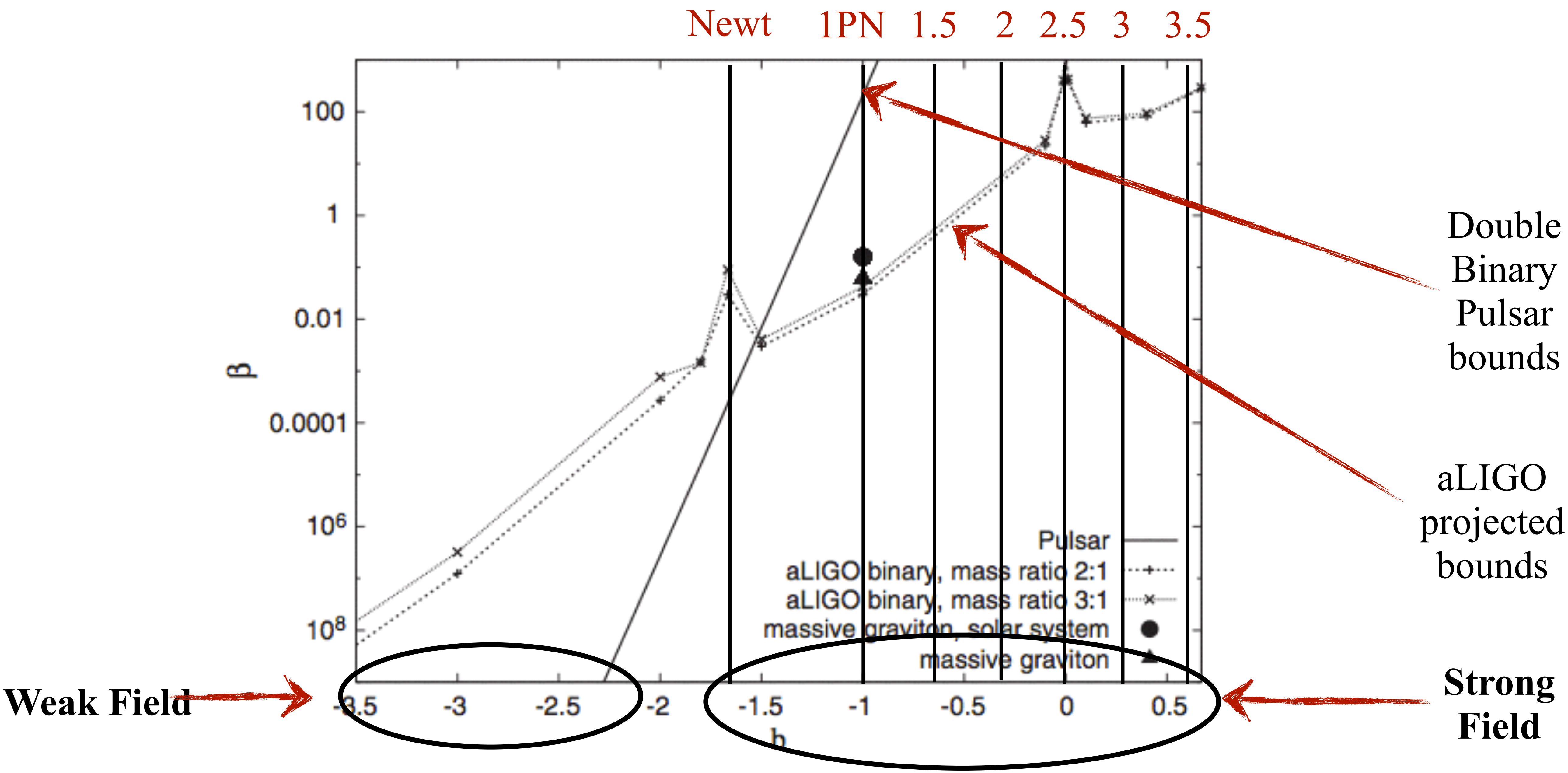
Weak Field Modified Theories best constrained with binary pulsars (they will be hard to constrain with gravitational waves)

Strong Field Theories are only strongly constrained by gravitational waves from binary mergers.

Doveryai, no proveryai

Projected Gravitational Wave Constraints

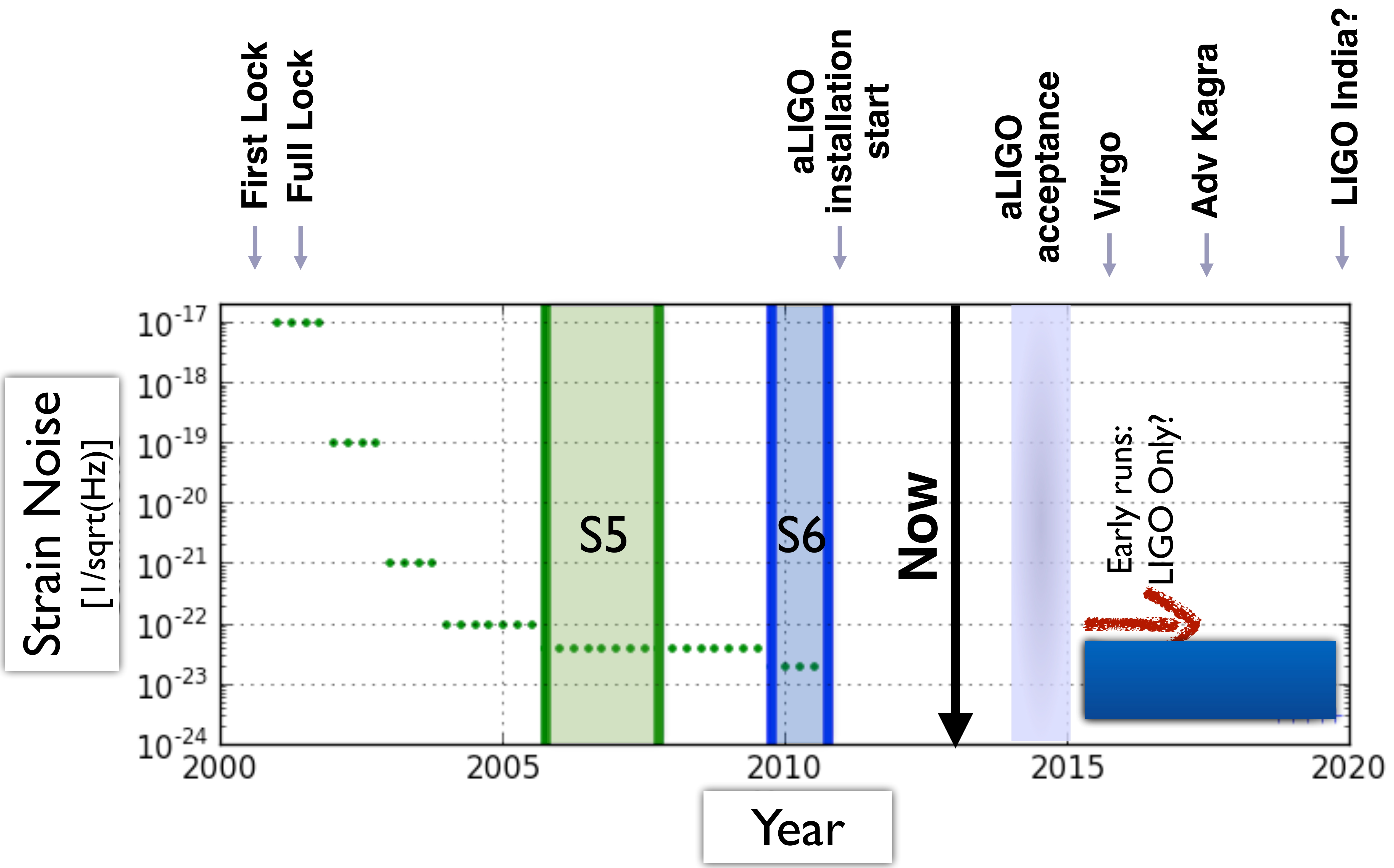
GR Signal/ppE Templates, 3-sigma constraints, SNR = 20



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

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

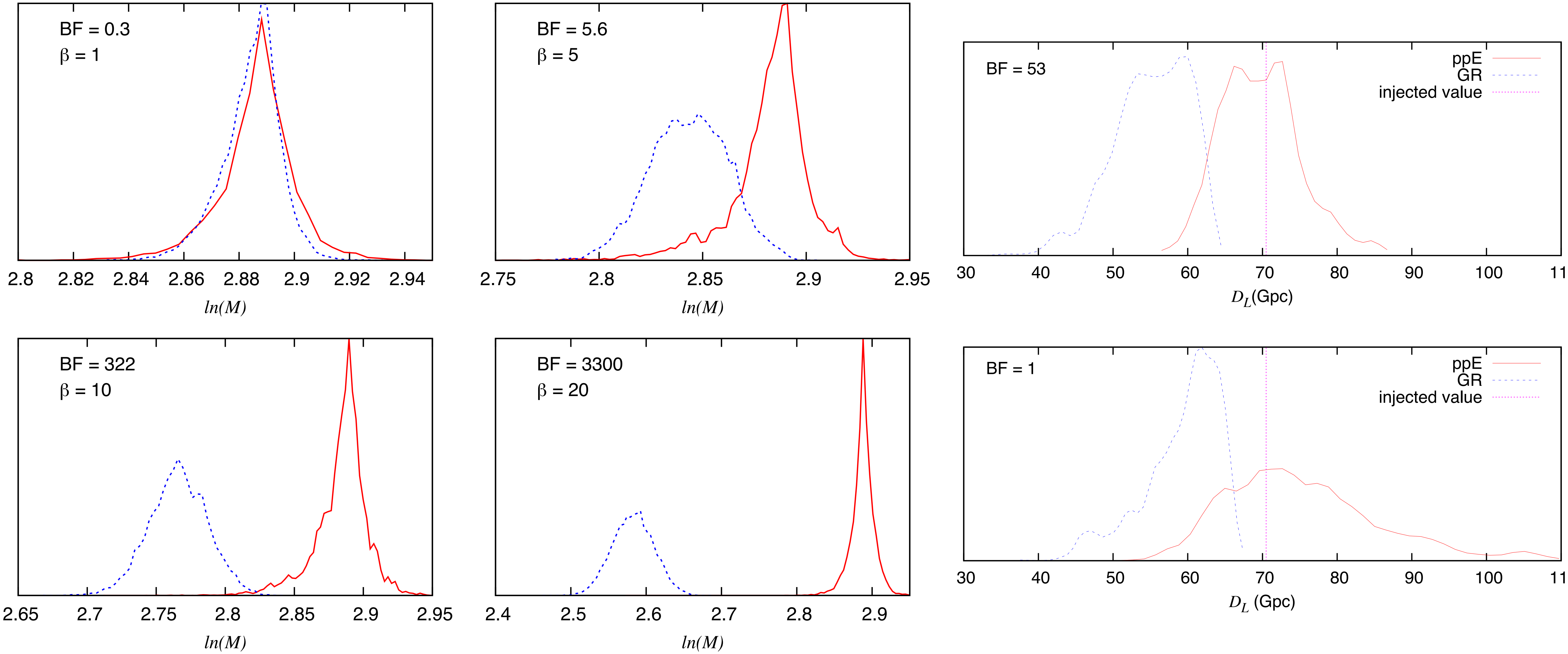
At our doorstep...



Fundamental Bias

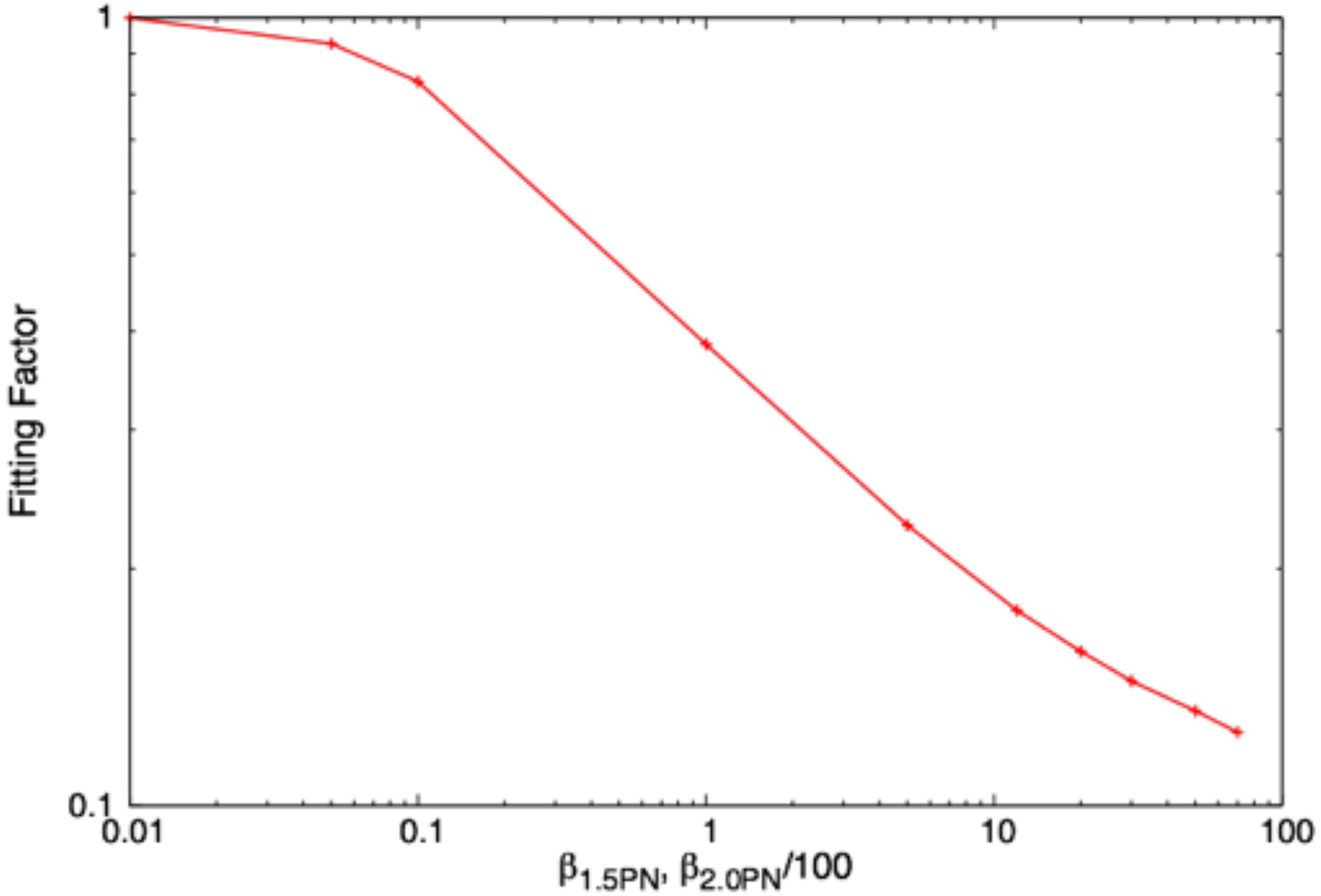
Non-GR Signal/GR Templates, SNR = 20

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...

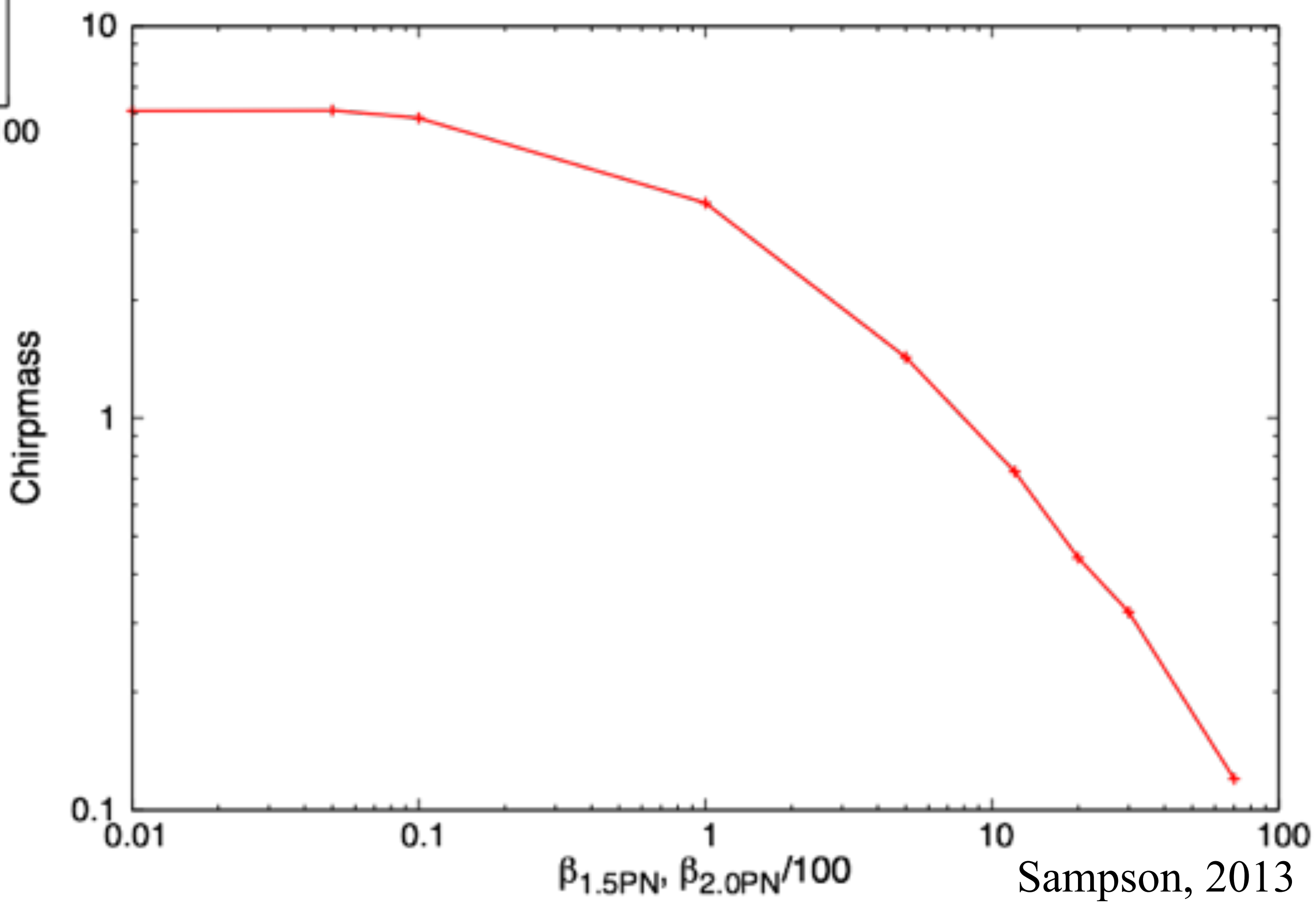


injection=(not-ruled out) ppE

template=GR

Fitting Factor Deteriorates

Physical Parameters Completely Biased



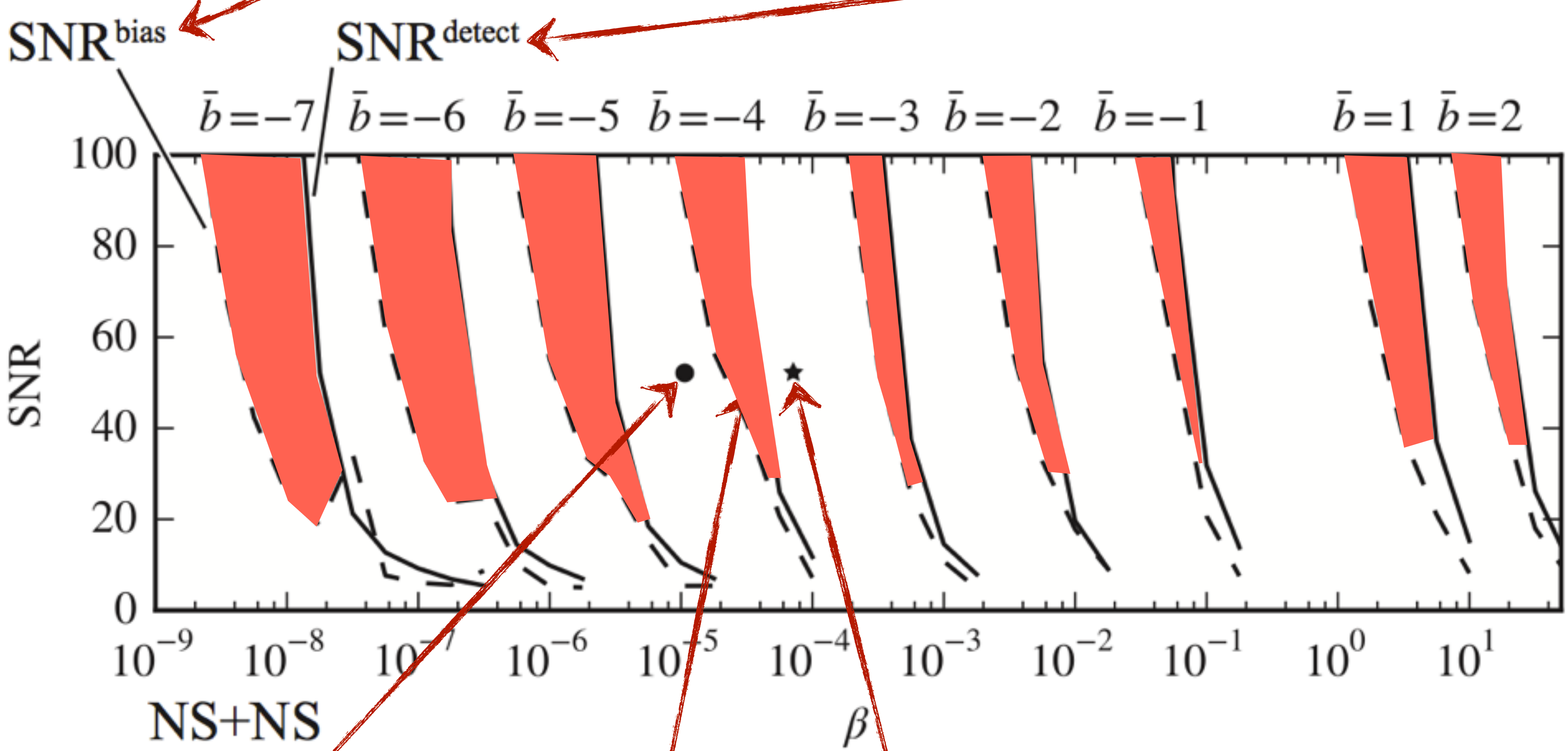
Sampson, 2013

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

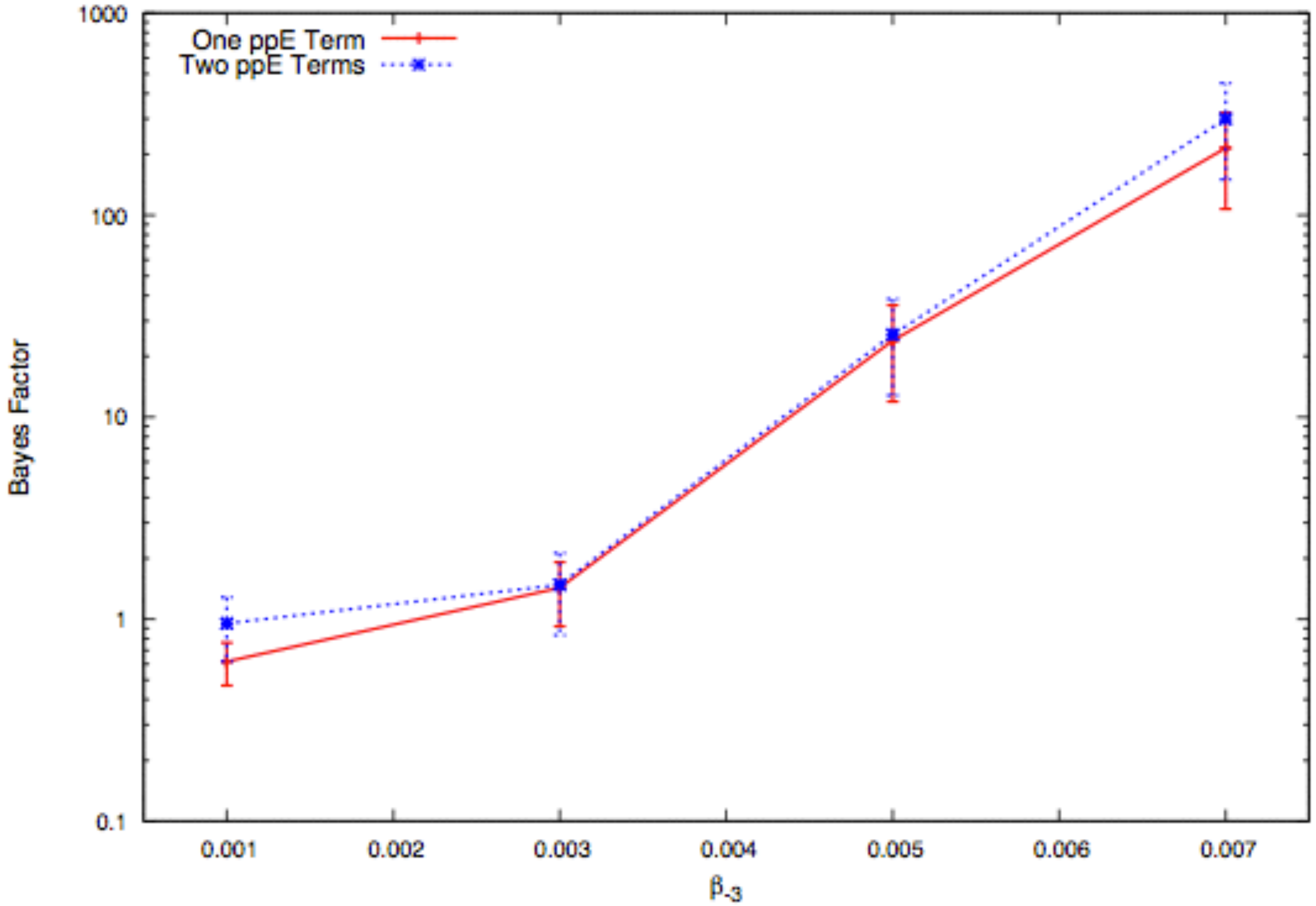


Negligible Bias

Stealth Bias

Overt Bias

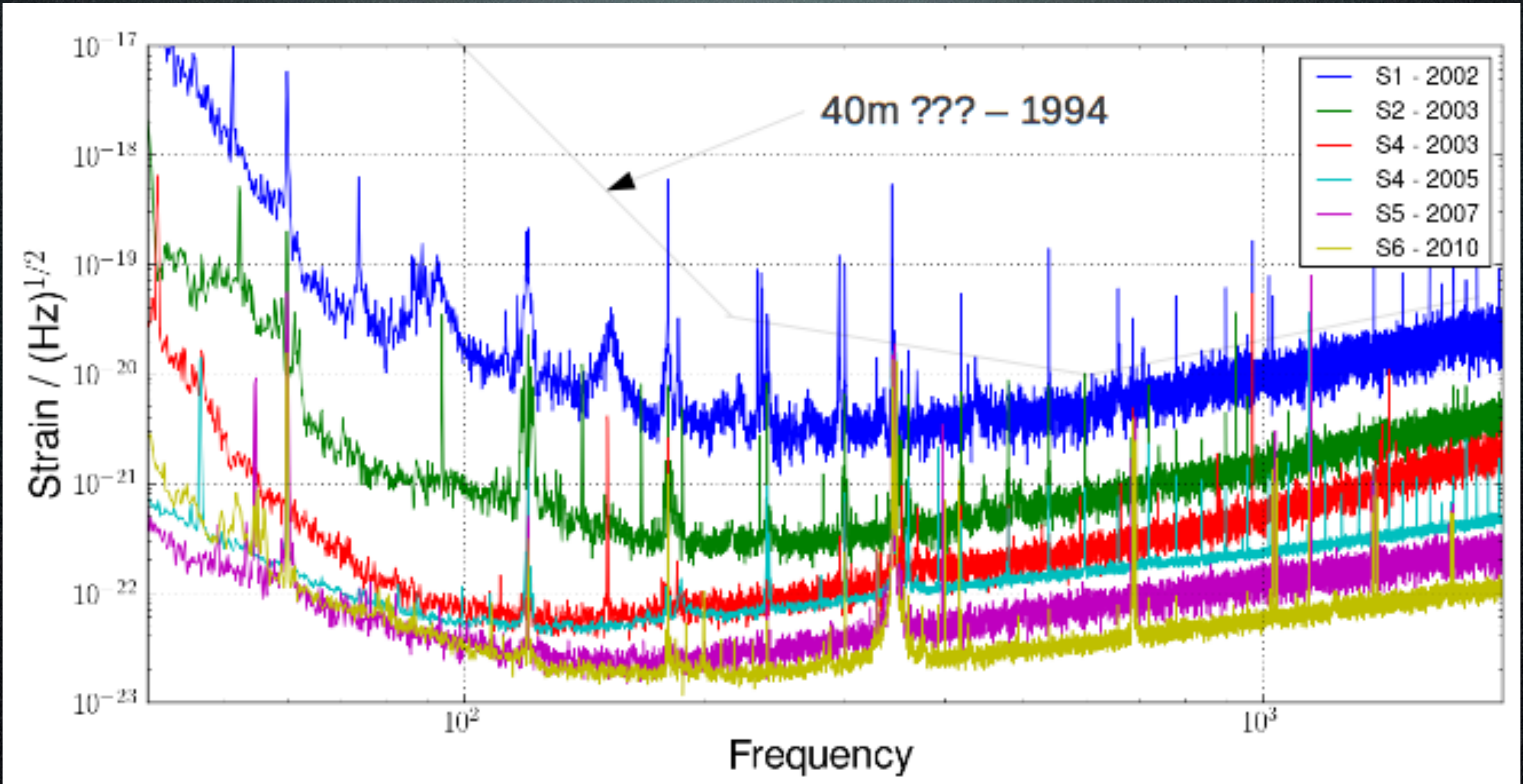
Simple ppE Performance



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.

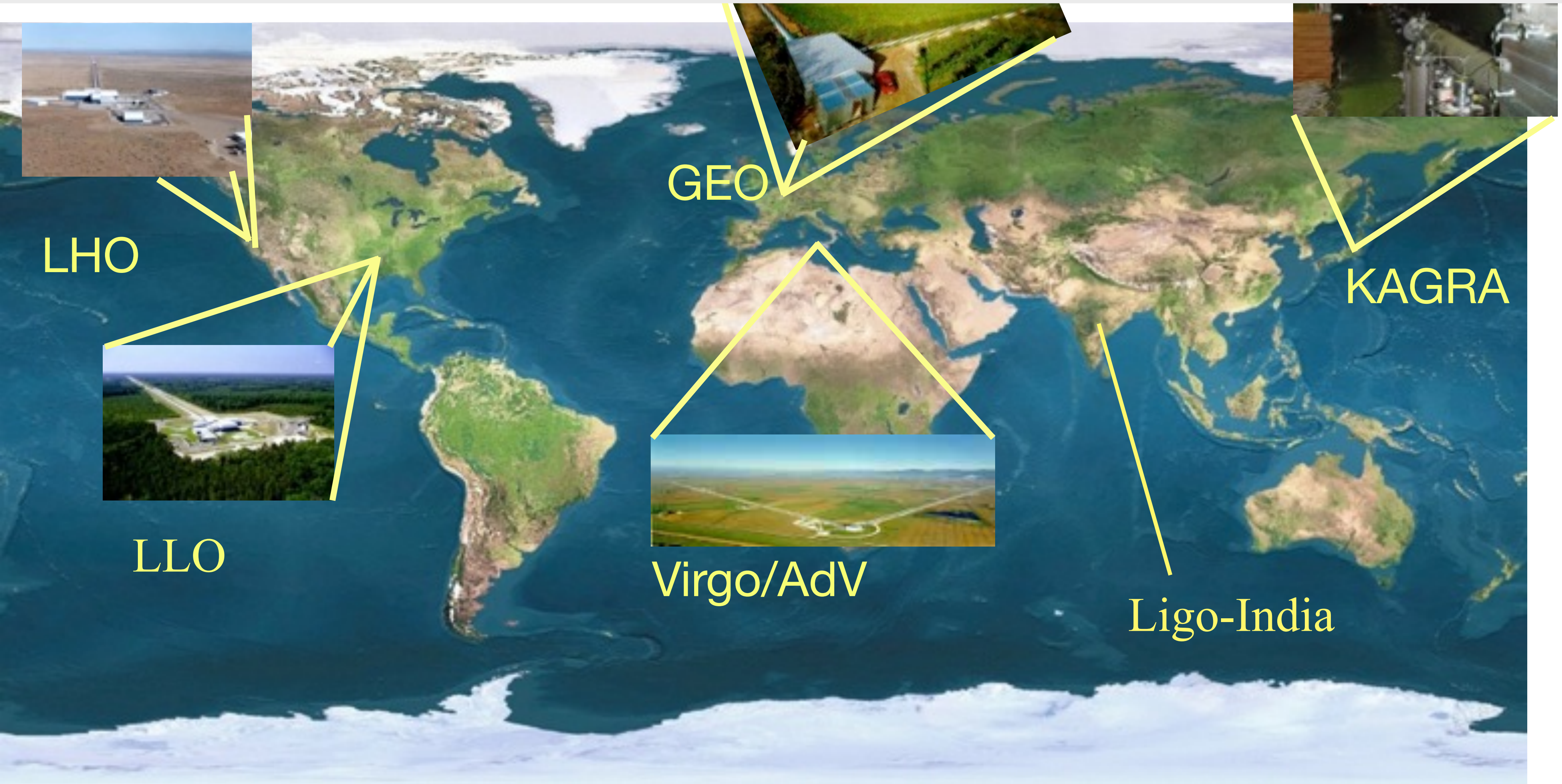
Sampson, Cornish & Yunes, 2013

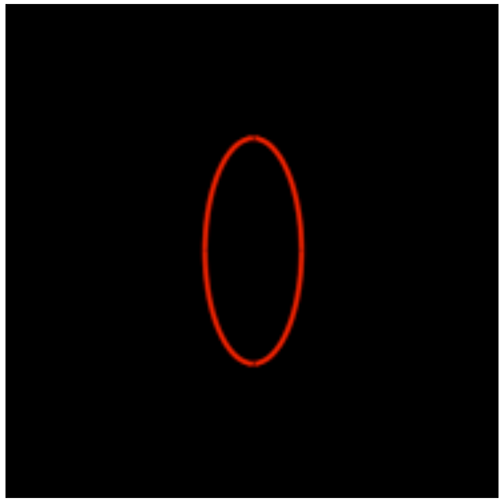
The Need for Accuracy



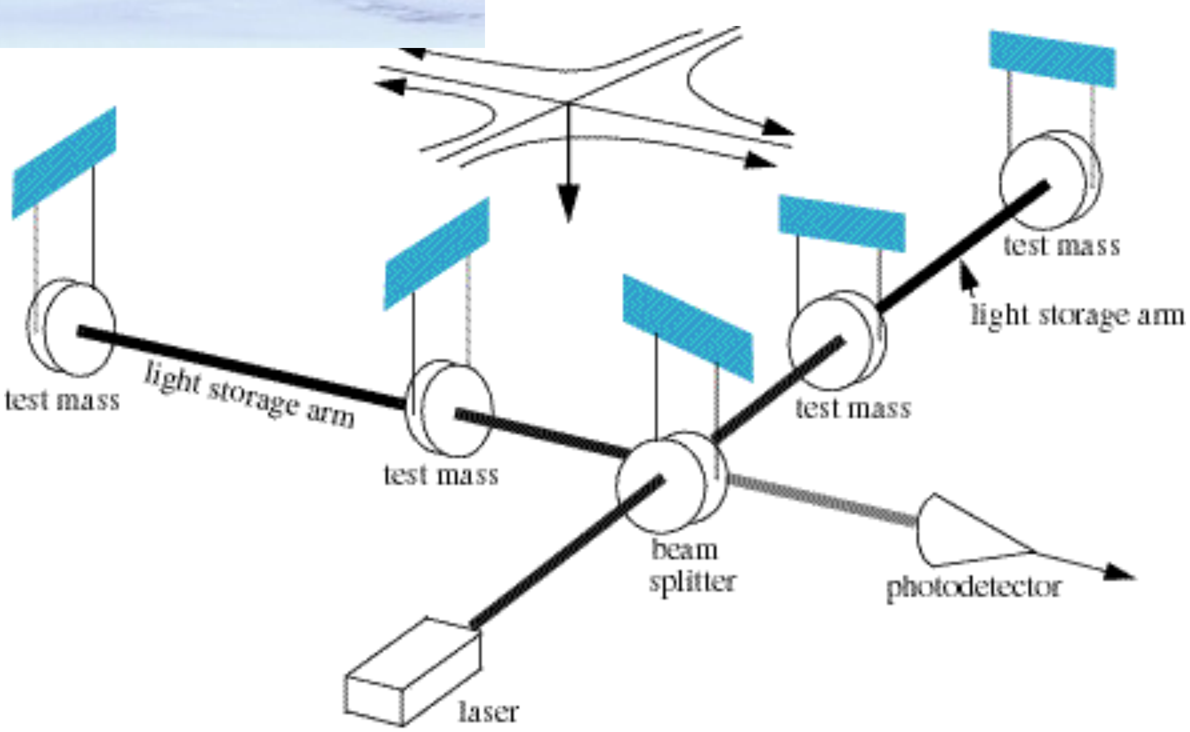
Quantum Noise (Amelino-Camelia)

Detectors



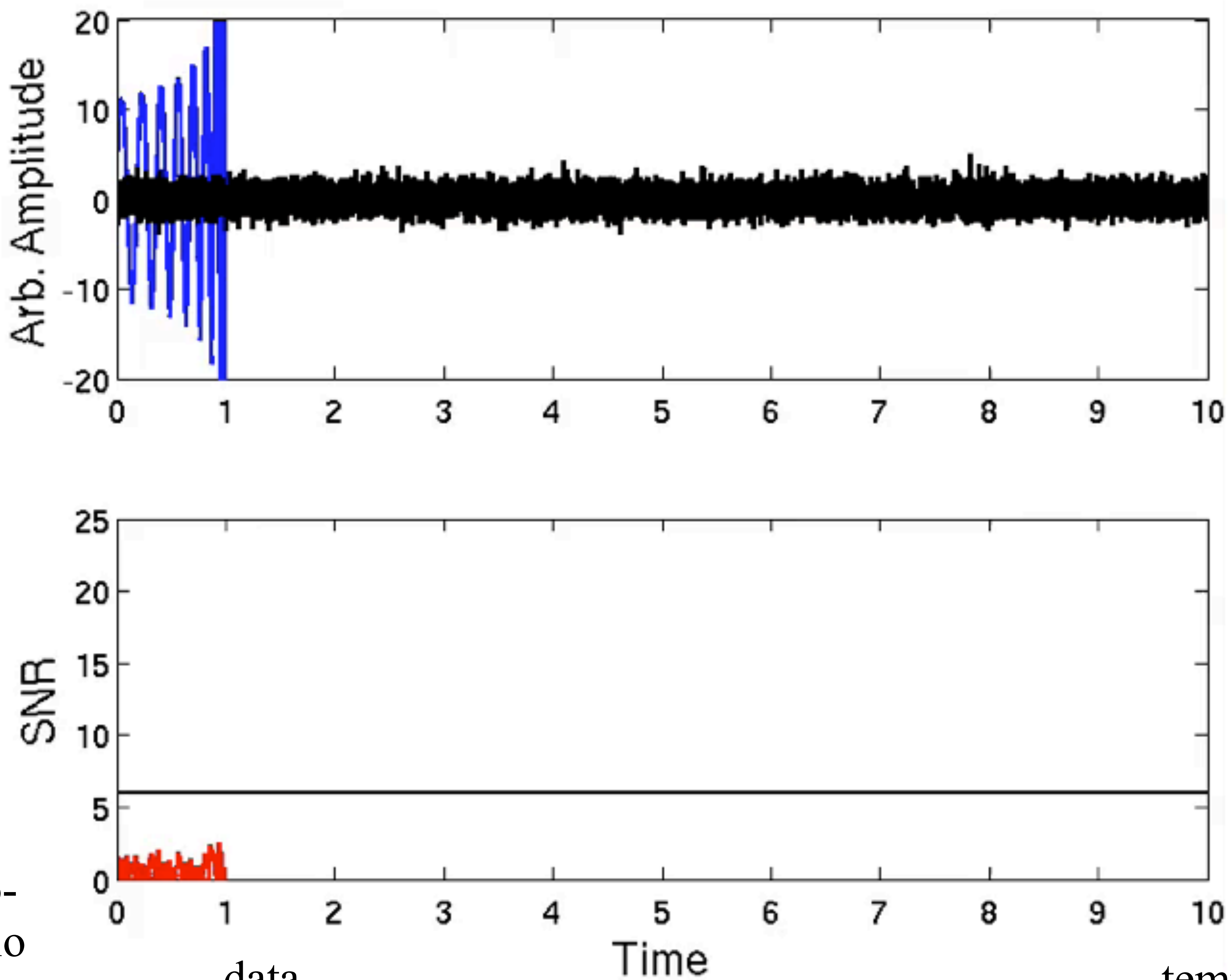


Bounce light off mirrors and look for interference pattern when the light recombines.



Data Analysis at work

C. Hanna, LSC/PI



Matched Filtering: Maximize the SNR over all template parameters

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

- signal-to-noise ratio (SNR) → ρ^2
- data → $\tilde{s}(f)$
- template param that characterize system → λ^μ
- template (projection of GW metric perturbation) → $\tilde{h}$
- detector noise (spectral noise density) → $S_n(f)$