Probing strong gravity when gravity waves

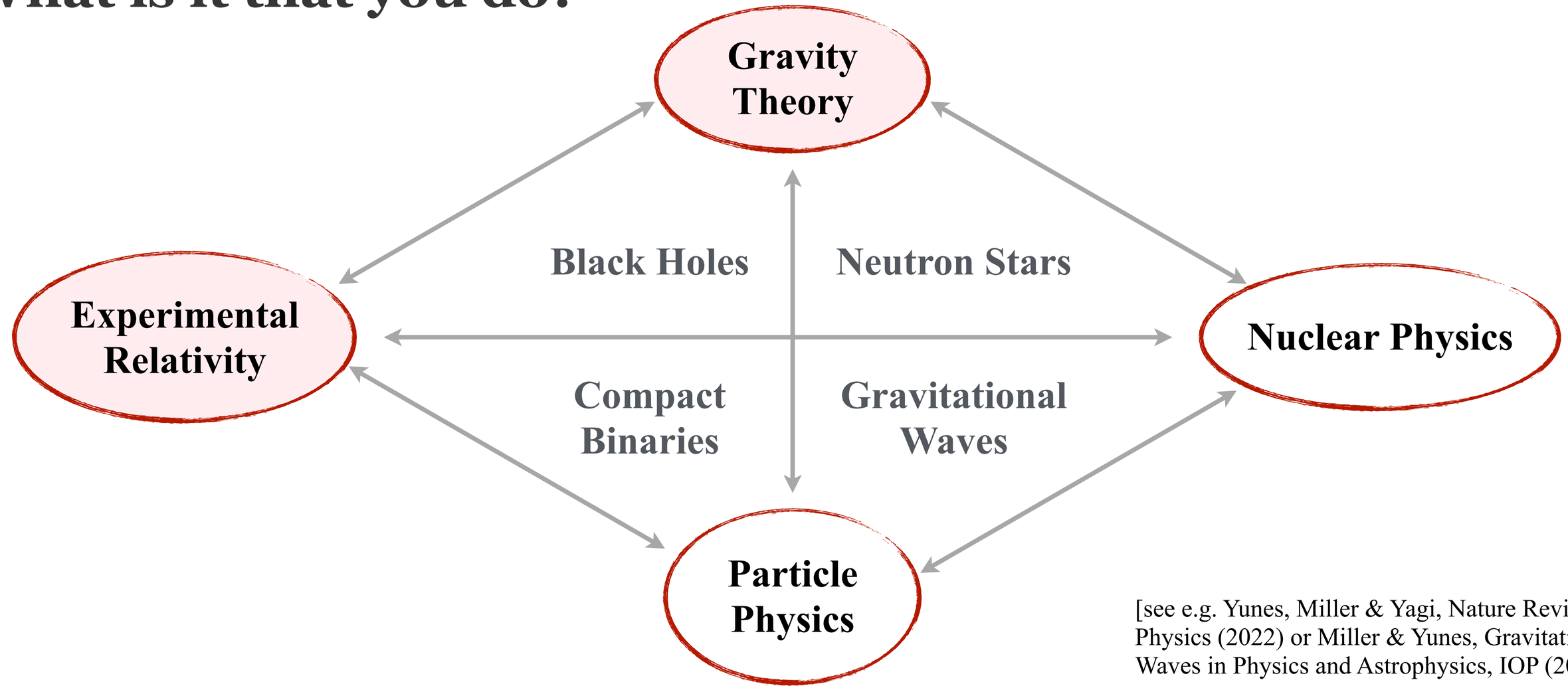
Nicolás Yunes
Illinois Center for Advanced Studies of the Universe
Department of Physics
University of Illinois at Urbana-Champaign

December 1st, 2023

Nico's Graviteers

Illinois Center for Advanced Studies of the Universe

What is it that you do?



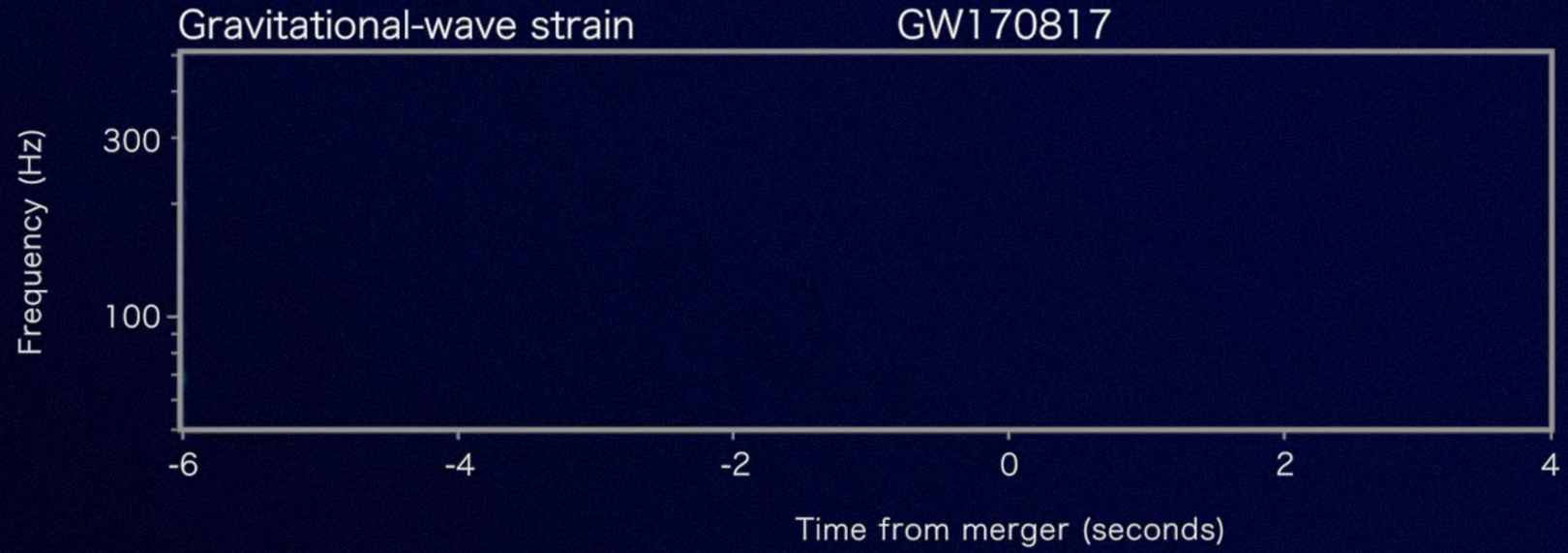
[see e.g. Yunes, Miller & Yagi, Nature Reviews Physics (2022) or Miller & Yunes, Gravitational Waves in Physics and Astrophysics, IOP (2022)]

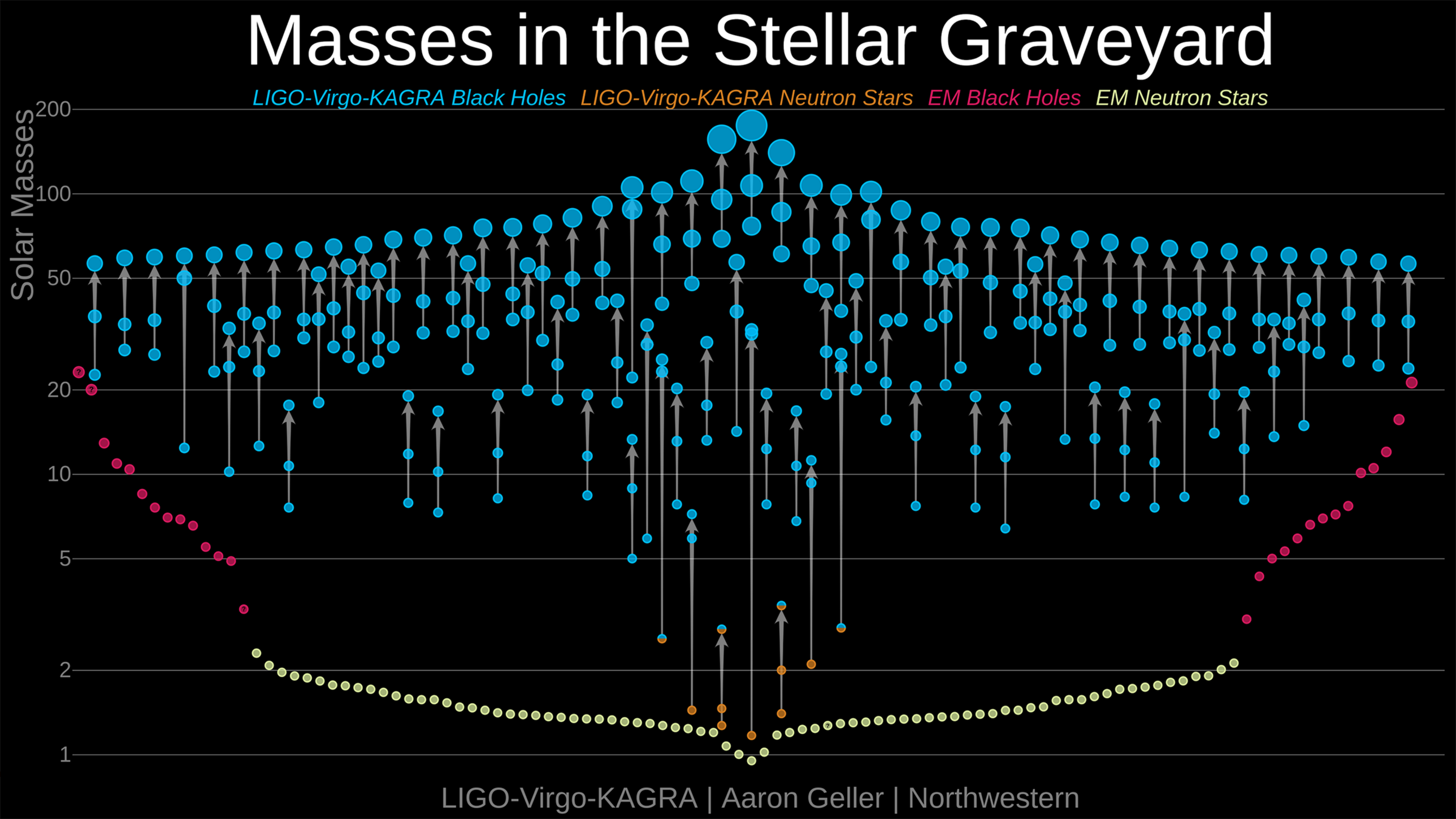
What "fundamental" physics have we/will we learn from gravitational wave observations?

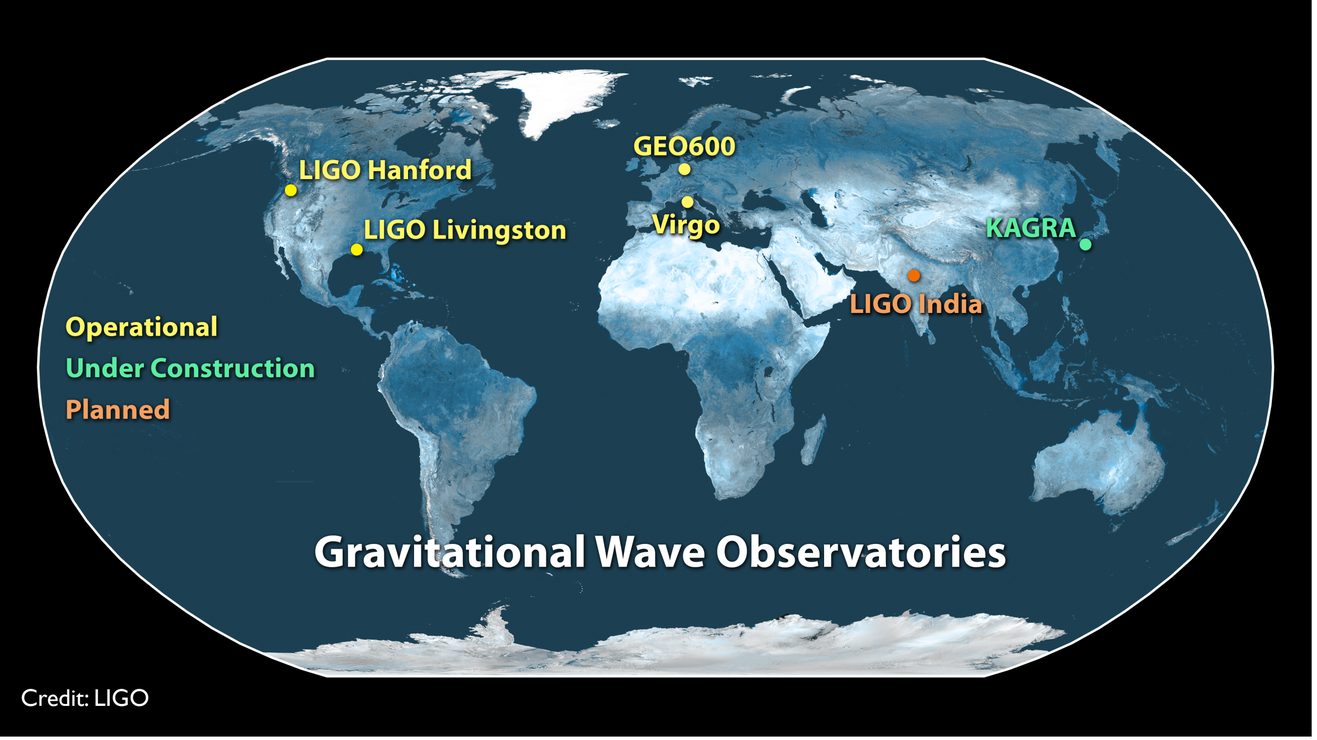
Fermi


Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500

LIGO


Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

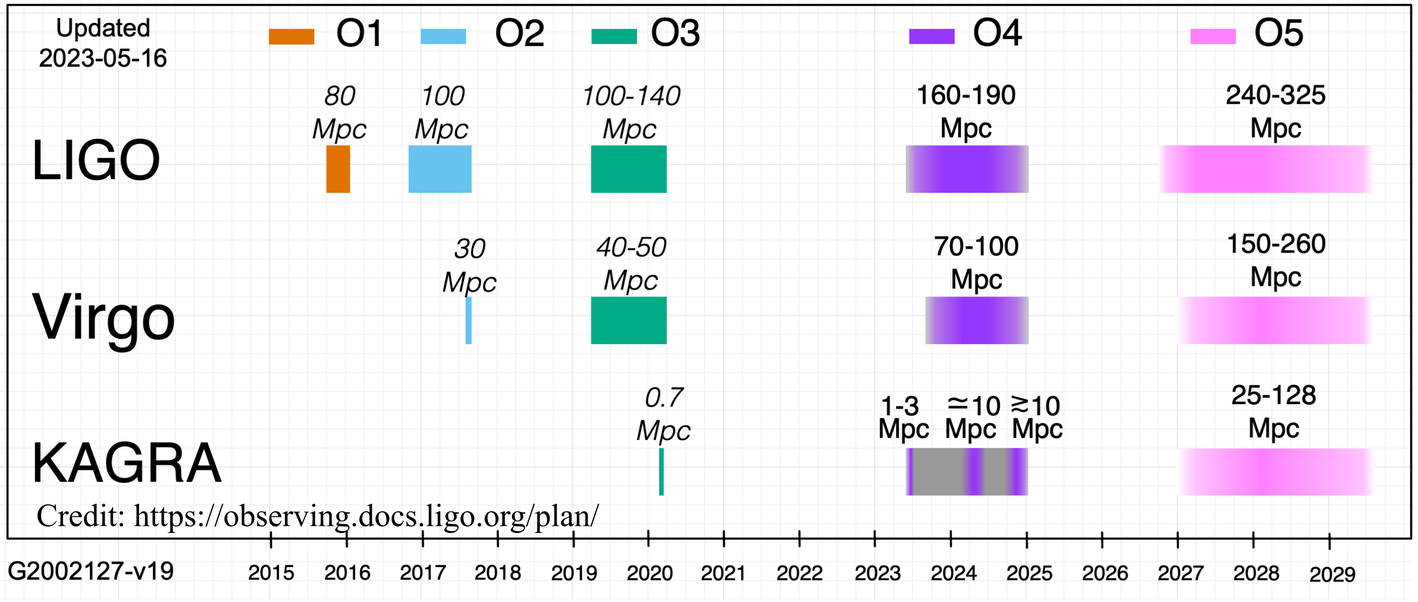


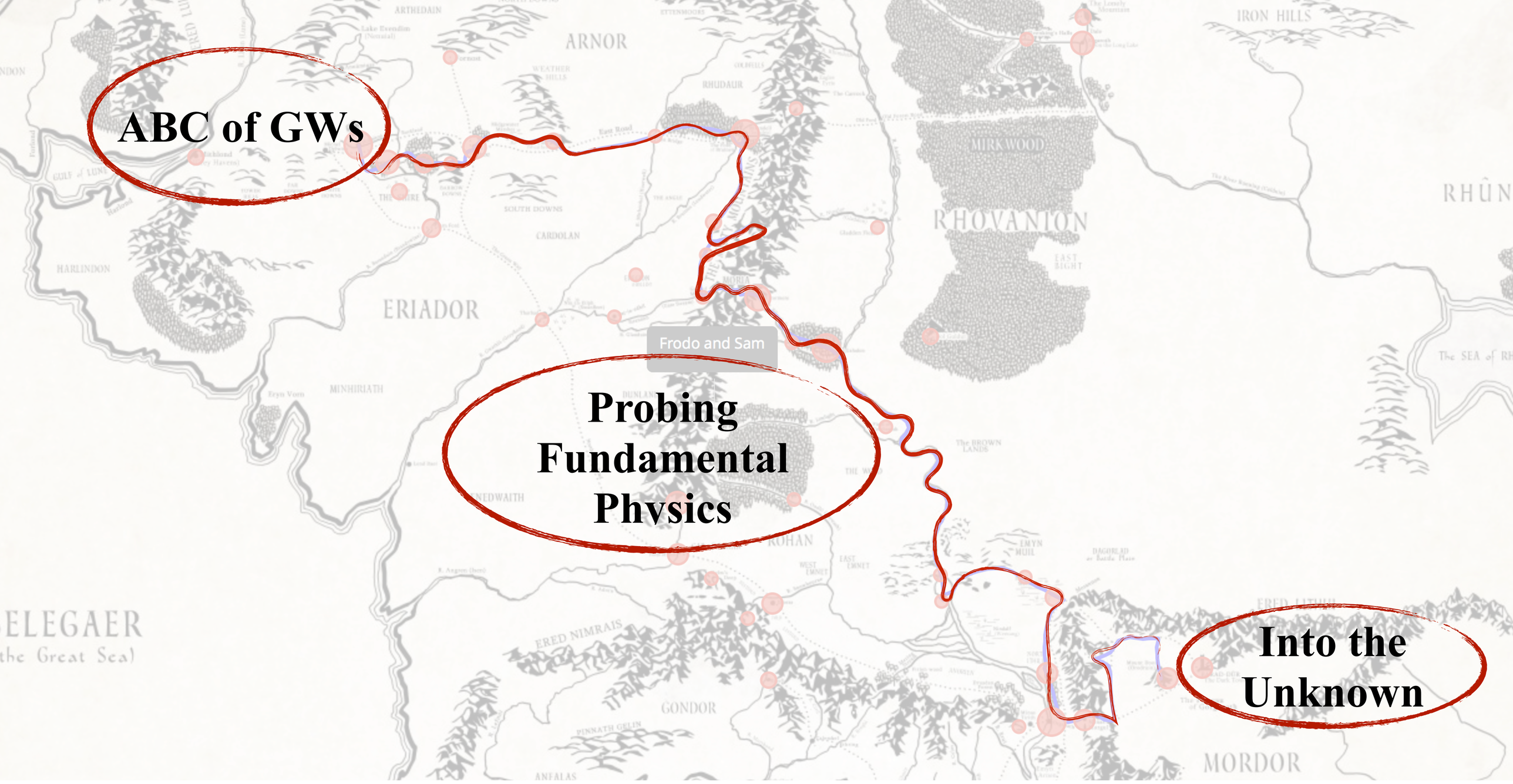
Fact

The future is loud

Challenge

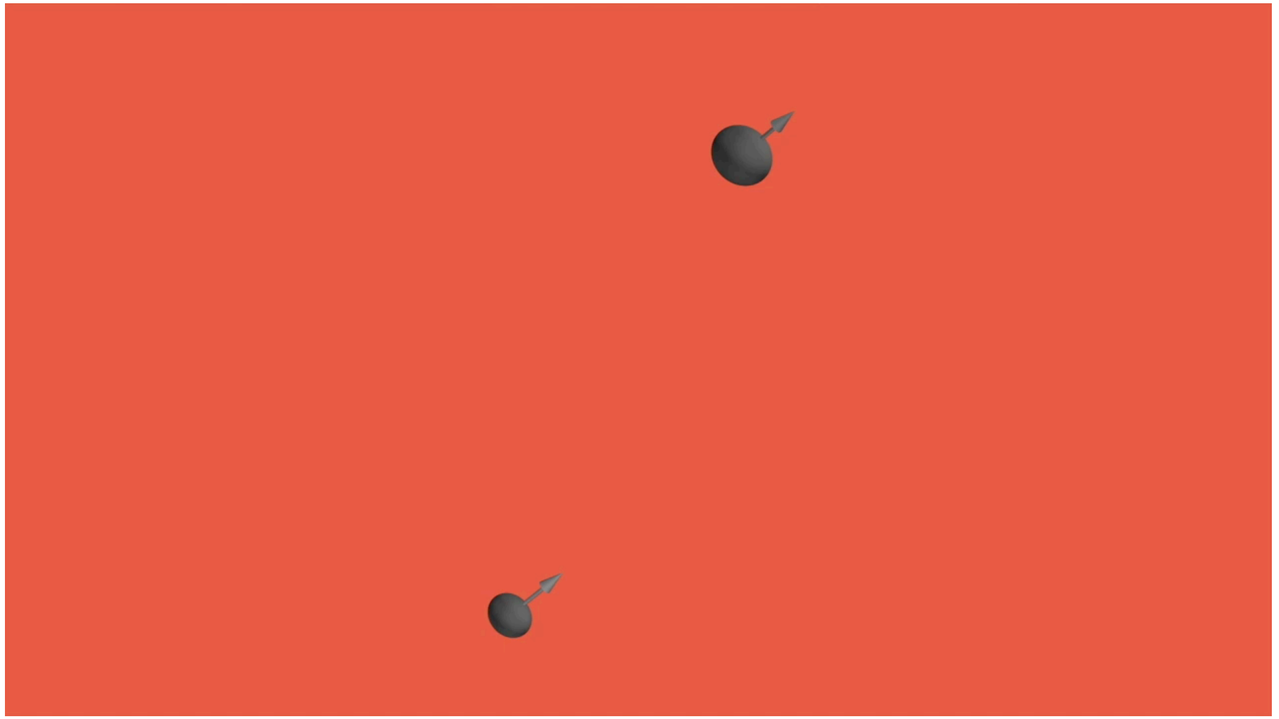
So what are you going to do with all this data?




ABC of GWs
Frodo and Sam
Probing Fundamental Phvsics
Into the Unknown
ARNOR
RHUDAUR
MIRKWOOD
RHOVANION
IRON HILLS
ERIADOR
HARLINDON
CARDOLAN
SOUTH DOWNS
MINHIRIATH
ROHAN
GONDOR
MORDOR
ELEGAER
the Great Sea)

What are gravitational waves and how are they generated?

eXtreme Gravity: where gravity is
(a) non-linear *and*
(b) dynamical



Gravitational Waves (GWs):

Wave-like perturbation
of the gravitational field.

Generation of GWs: Accelerating masses
(t-variation in multipoles)

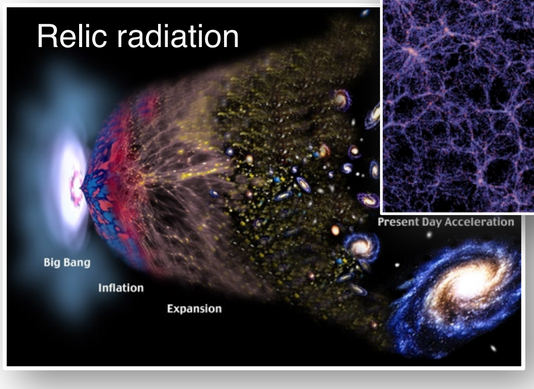
Propagation of GWs:

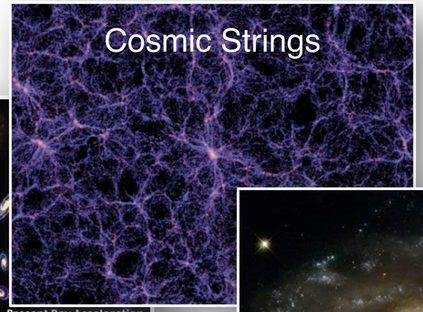
Light speed, weakly
interacting, 1/R decay.

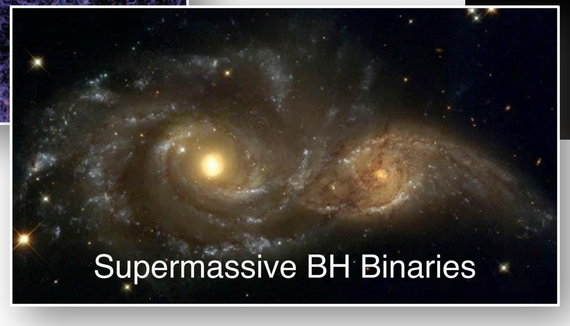
GW Spectrum: Kepler 3rd Law!

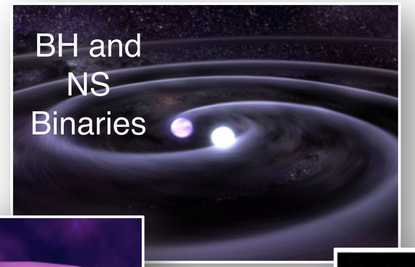
$$\frac{f}{2\pi} = \sqrt{\frac{G\,m_{\rm tot}}{r_{12}^3}} = \sqrt{\frac{c^6}{8G^2 m_{\rm tot}^2}} \sim \frac{1}{m_{\rm tot}}$$

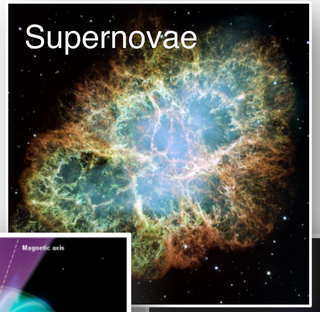
What are the sources of gravitational waves?

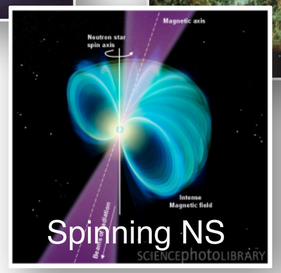








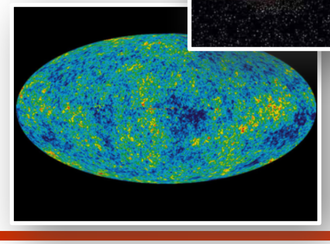


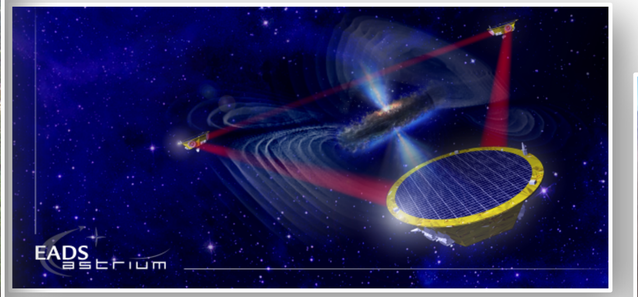


T_{GW} *10^{-16} Hz* *100 years* *year* *days* *hours* *seconds* *milliseconds*

f_{GW} *10^{-16} Hz* *10^{-9} Hz* *10^{-7} Hz* *10^{-6} Hz* *10^{-4} Hz* *10^{1} Hz* *10^{3} Hz*

Inflation Probe | **Pulsar timing** | **Space detectors** | **Ground interferometers**





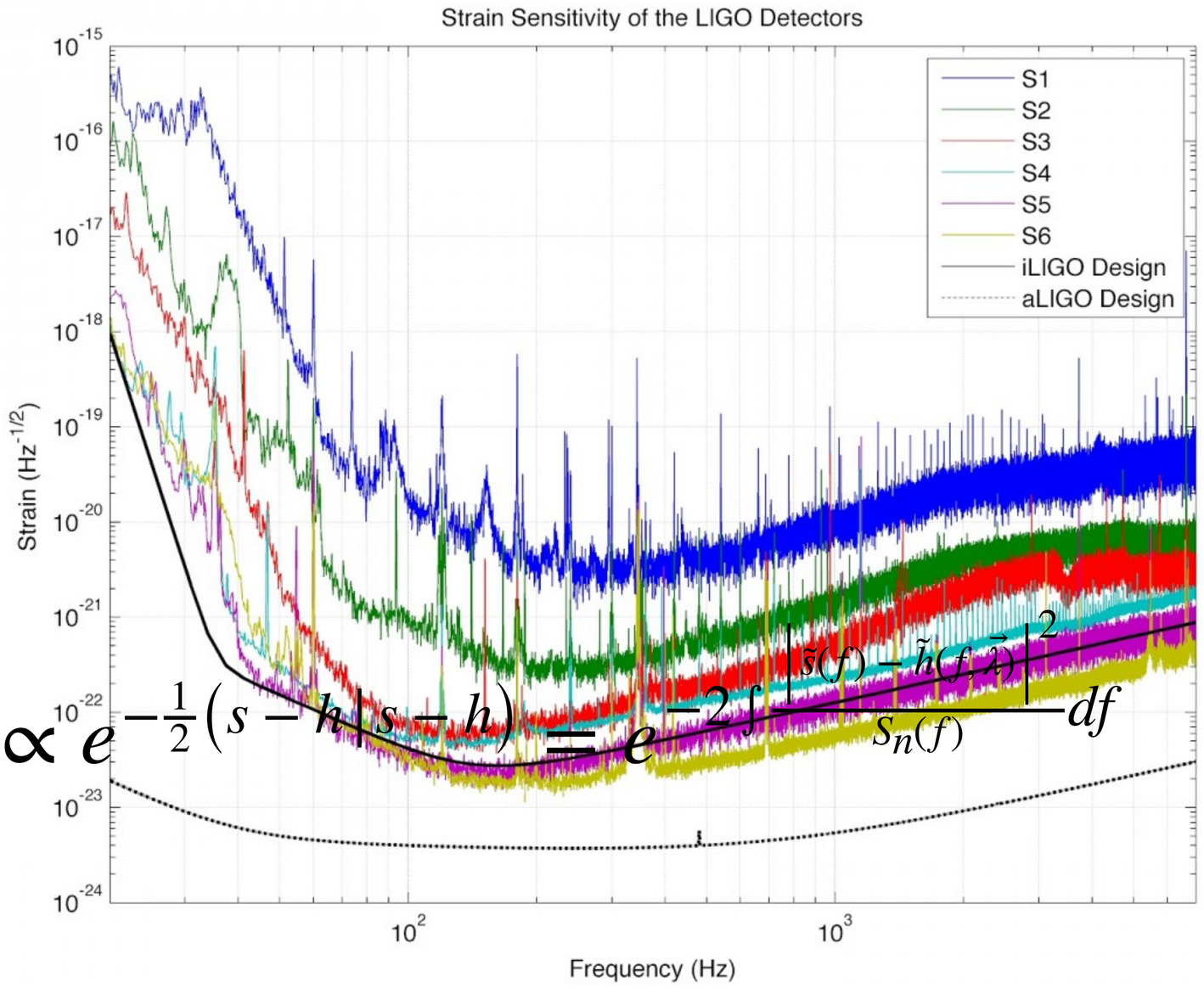
Credit: Cornish

How do you extract information from gravitational waves?

Modelling 1. C

Data Analysis 2. C

3. Fi



template param that characterize system

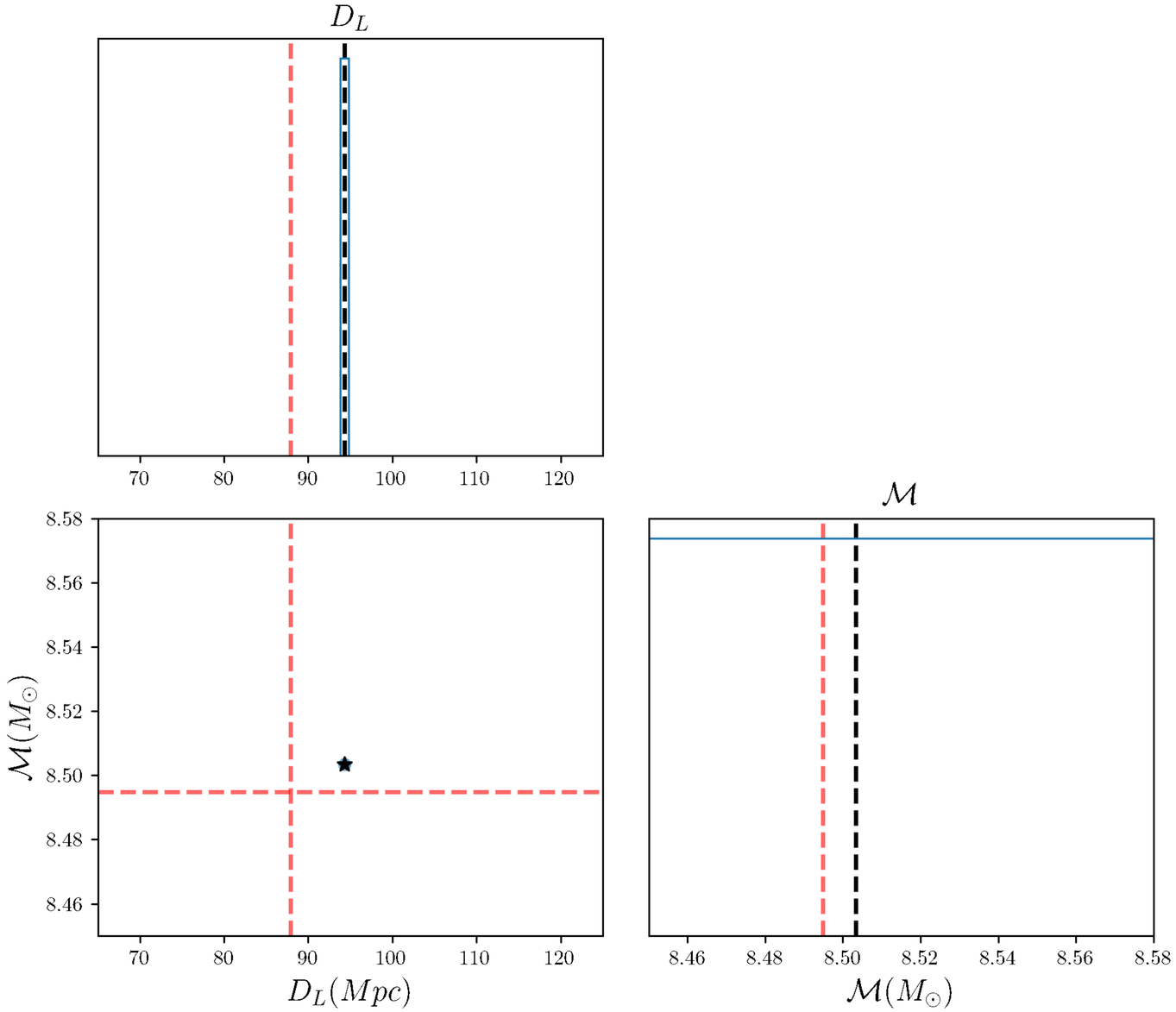
Likelihood function →

$$\mathscr{L} \propto e^{-\frac{1}{2}(s-h|s-h)} = e^{-2\int \frac{|\tilde{s}(f)-\tilde{h}(f;\vec{\lambda})|^2}{S_n(f)}df}$$

nplate (projection of metric perturbation)

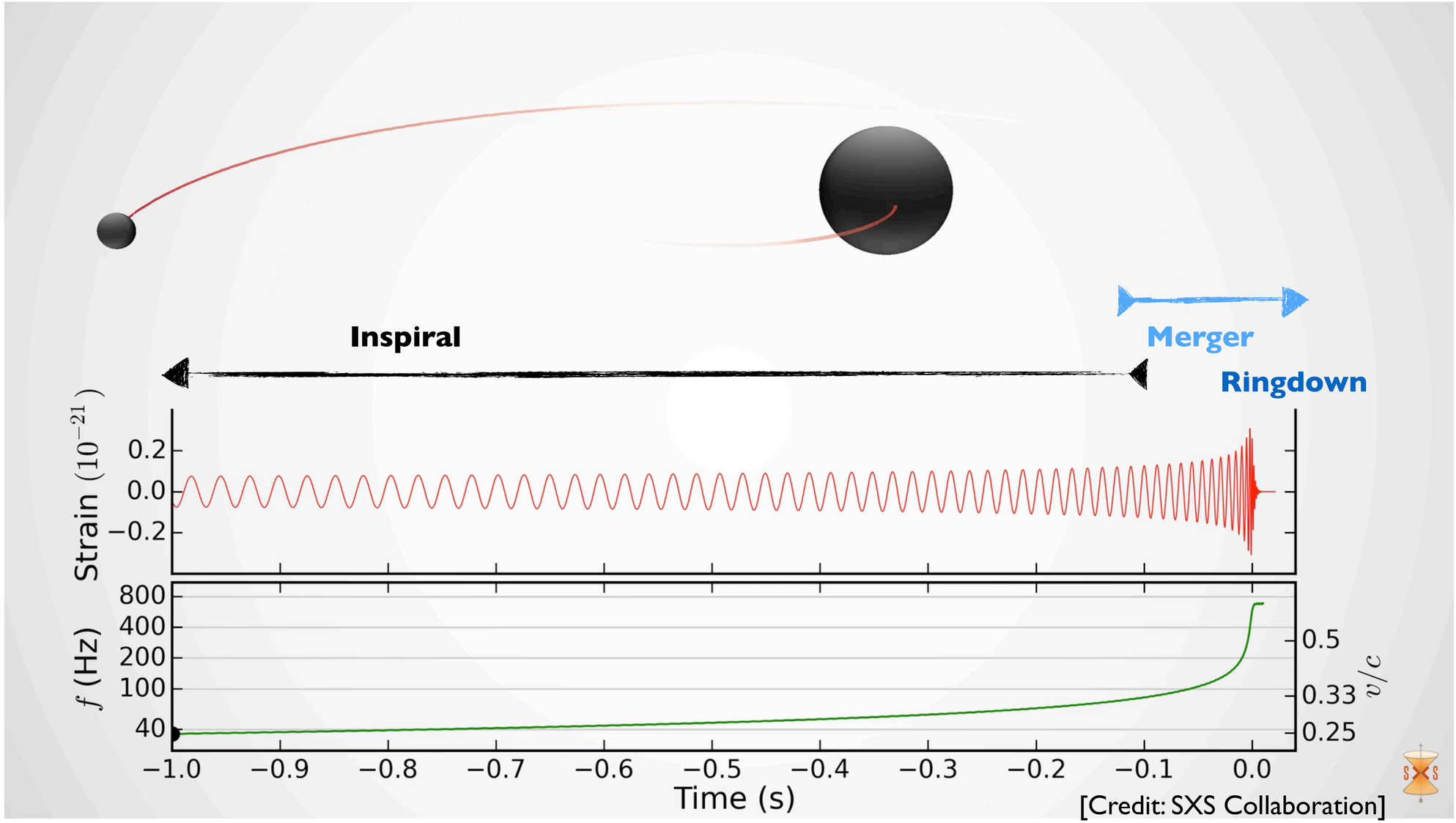
inner p

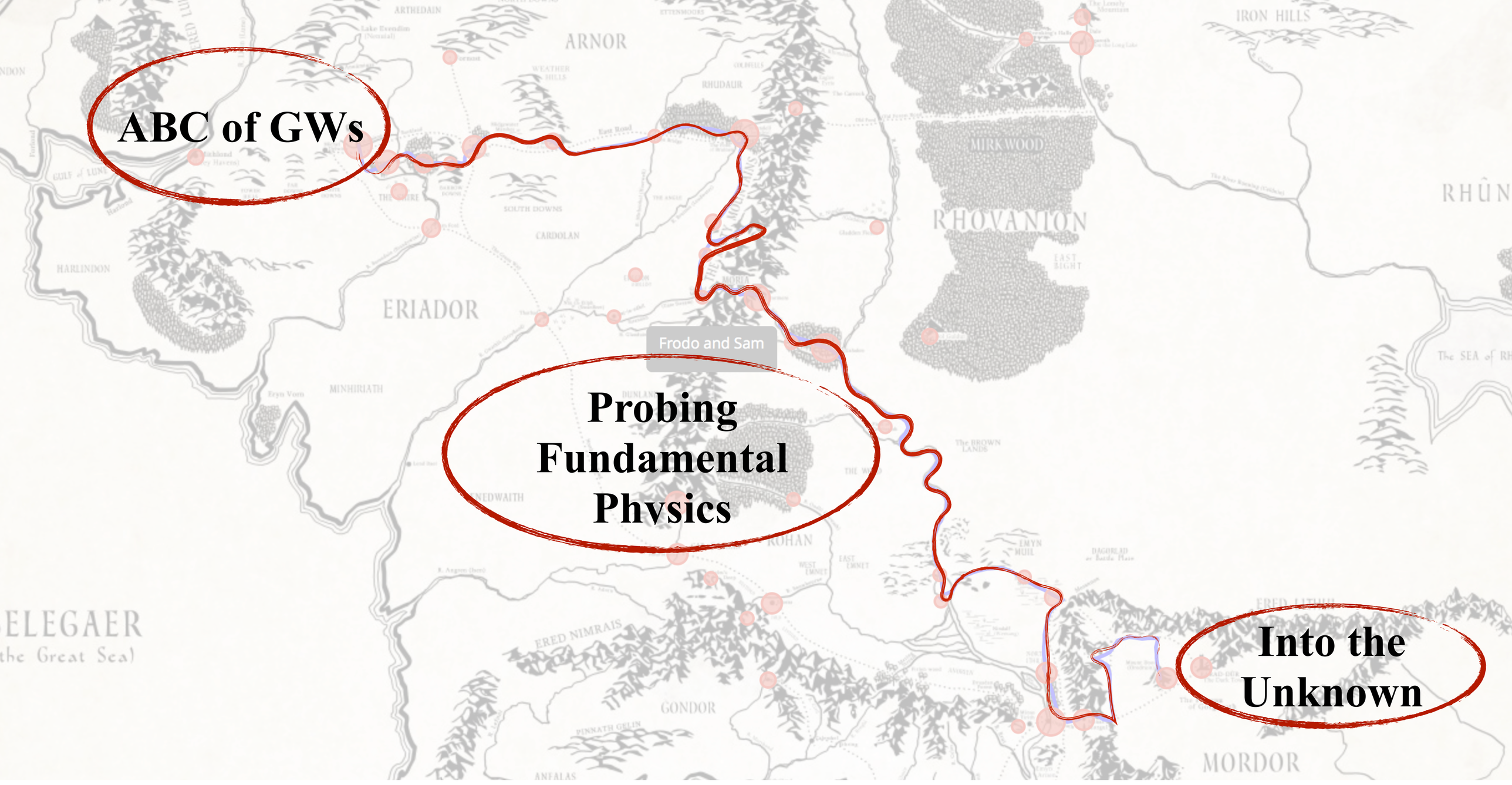
Searching for needles in a haystack...



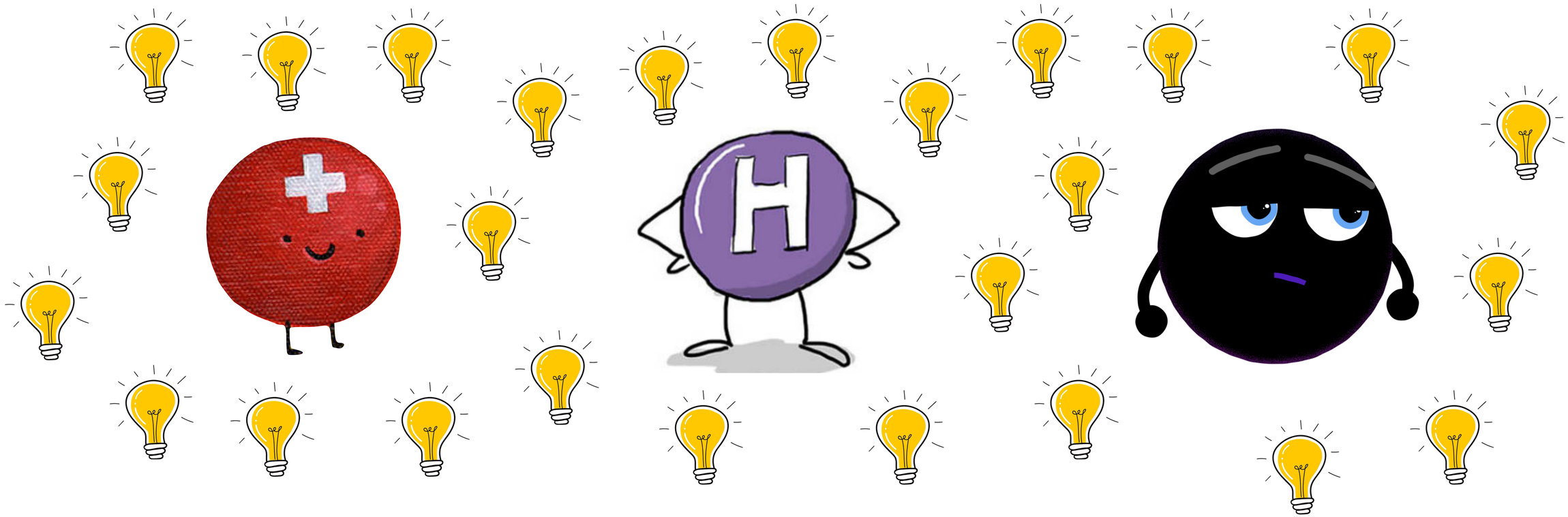
[Credit: Rohit Chandramouli]

The model used in matched filtering is crucial



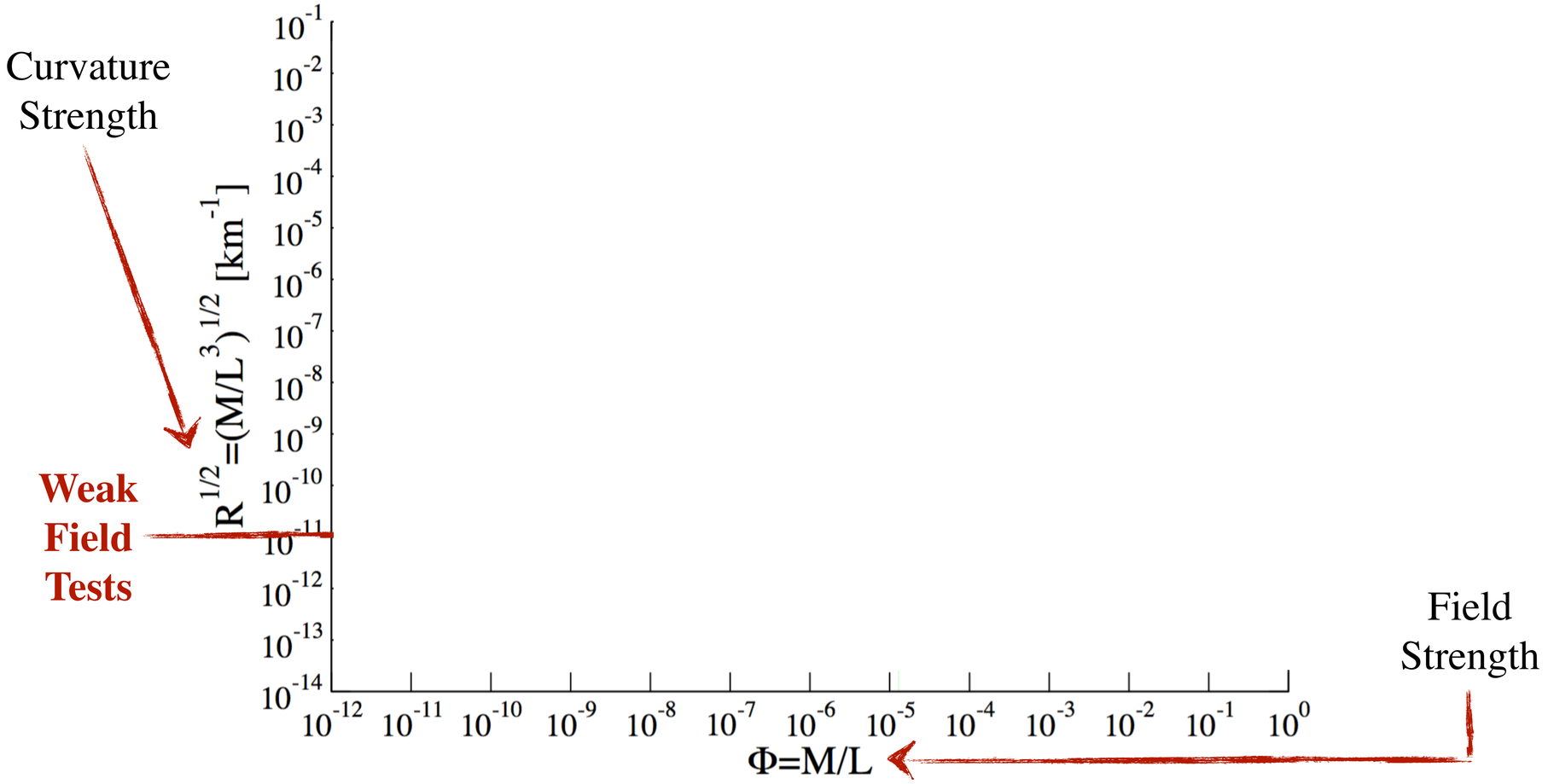

ABC of GWs
Frodo and Sam
Probing Fundamental Phvsics
Into the Unknown
ARNOR
RHUDAUR
MIRKWOOD
RHOVANION
IRON HILLS
ERIADOR
HARLINDON
CARDOLAN
SOUTH DOWNS
MINHIRIATH
ROHAN
GONDOR
MORDOR
ELEGAER
the Great Sea)

What is fundamental physics?



For this talk: “fundamental physics” are deviations from general relativity that can be probed with gravitational waves

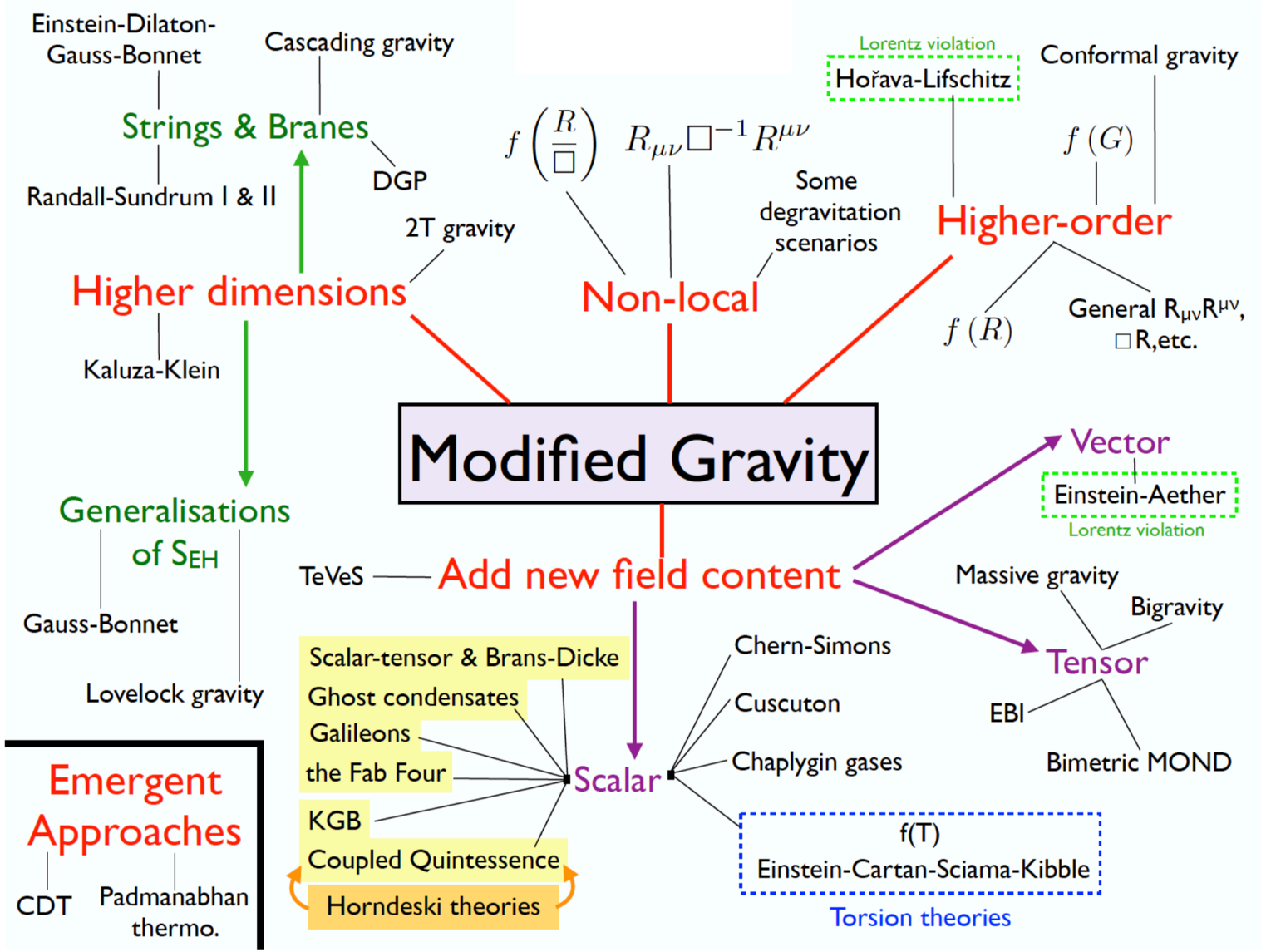
Why probe “fundamental physics” when gravity waves?



GWs probe e$\mathcal{X}$treme Gravity

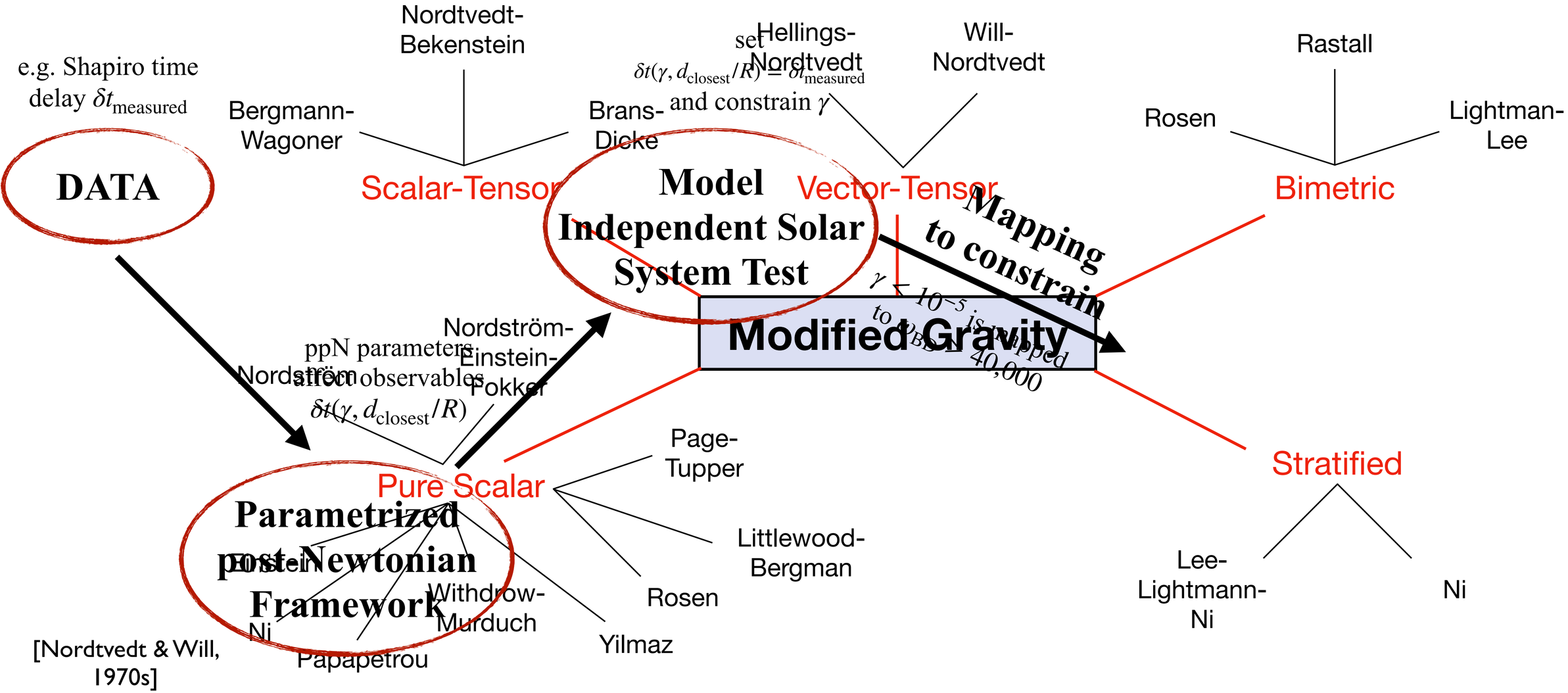
[Will, Liv. Rev., 2005, Psaltis, Liv. Rev., 2008, Baker, et al, Siemens & Yunes, Liv. Rev. 2013, Yunes, et al PRD 2016]

How do we probe the modified gravity bestiary?

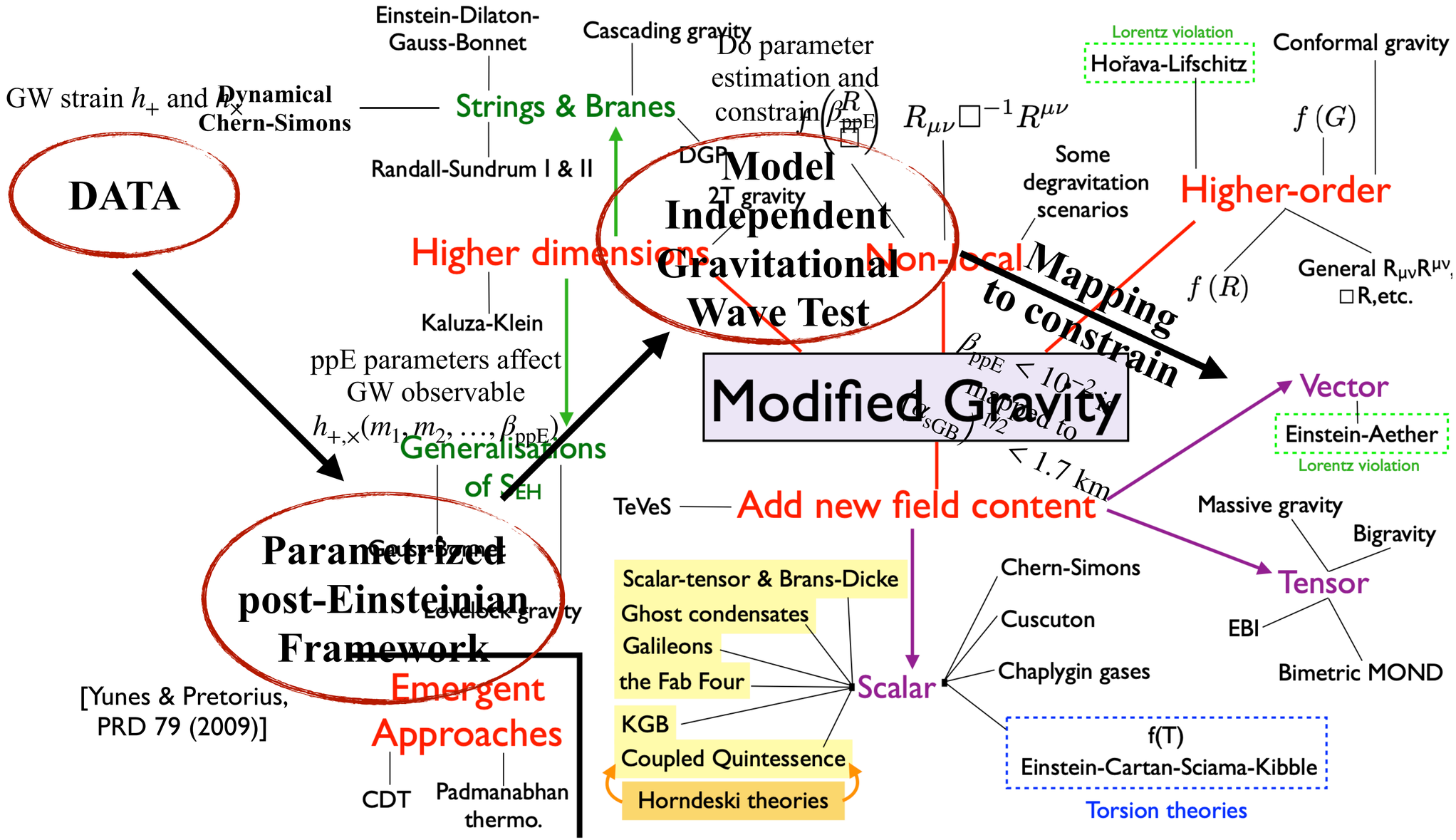


[Credit: Tessa Baker]

A page from the past



Taming the bestiary



Effectively deforming away from general relativity

Principle of Equivalence | massless spin-2 field | Lorentz Invariance | Parity Invariance | Diffeomorphism Invariance | Dispersionless Propagation | ...

<u>One</u> example: $S = \int \sqrt{-g} \quad \kappa R$

Test properties of General Relativity by constructing theories that violate its pillars

Dynamical Chern-Simons

Scalar-tensor theories

Horava gravity

Einstein-dilaton-Gauss-Bonnet

Einstein-AEther theory

Massive gravity

...

[Yunes & Pretorius, PRD 80 ('09)]
[Endlich, Gorbenko, Huang, Senatore, JHEP 09 ('17)]
[Yunes & Siemens, Liv. Rev. in Rel ('13)]

Calculate ppE observable through deformations of GR

I. Parametrically deform the Hamiltonian.

II. Parametrically deform the RR force.

$$H = H_{\rm GR} + \delta H \qquad \delta H = \alpha_H v^{a_H}$$

$$\vec{F}_{\rm RR} = \vec{F}_{\rm RR,GR} + \delta\vec{F}_{\rm RR} \qquad \delta\vec{F}_{\rm RR} = \vec{\alpha}_{RR} v^{a_{RR}}$$

III. Deform waveform generation.

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

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

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

[Yunes & Pretorius, PRD 80 ('09)
Mirshekari, Yunes & Will, PRD 85 ('12)
Chatziioannou, Yunes & Cornish, PRD 86 ('12)]

Parameterized post-Einsteinian Framework

Parameterized post-Einsteinian theory

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

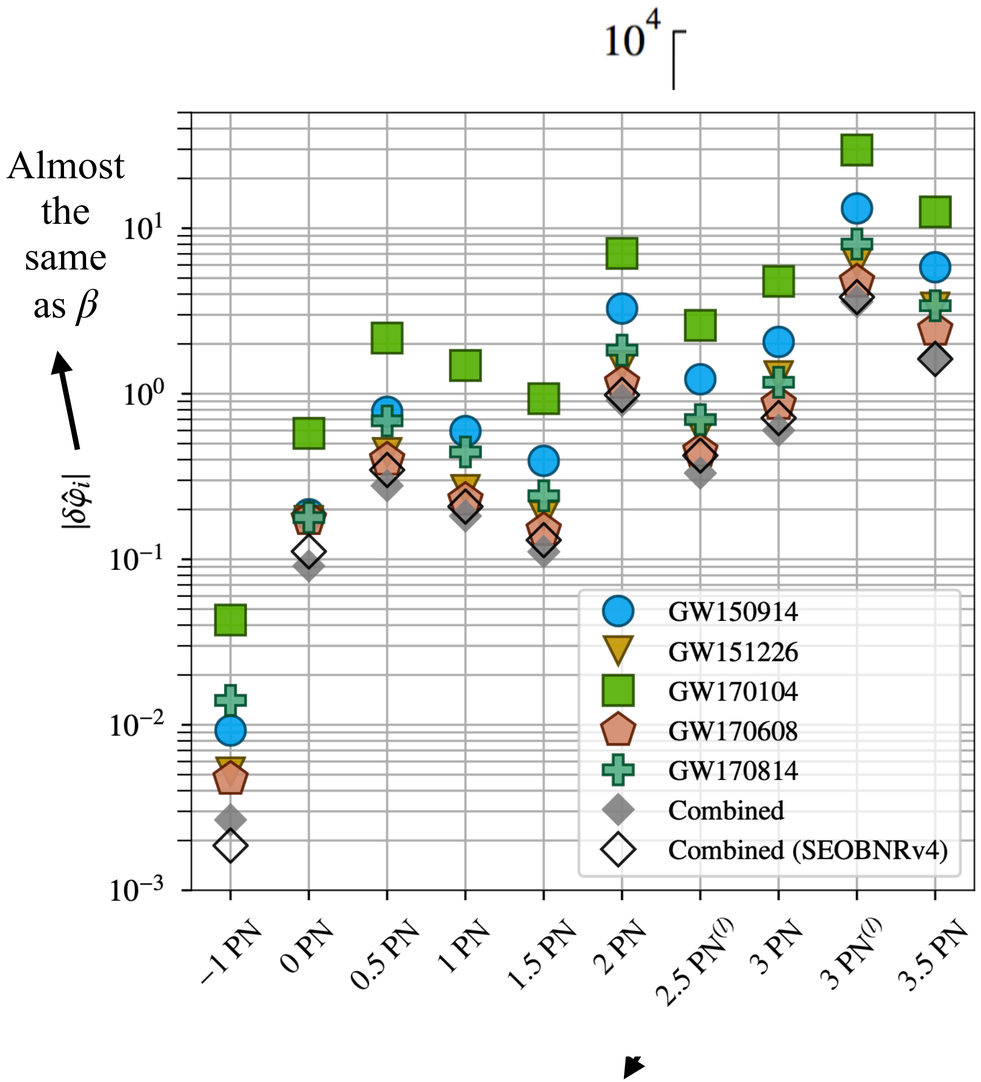
[Yunes & Pretorius, PRD 80 ('09)]

Mapping between ppE parameters (β, b) to specific modified theories

Theoretical Effect	Theoretical Mechanism	Theories	ppE b	Order	Mapping
Scalar Dipolar Radiation	Scalar Monopole Field Activation	EdGB [140, 142, 149, 150]	-7	-1PN	$\beta_{\rm EdGB}$ [140]
	BH Hair Growth	Scalar-Tensor Theories [59, 151]	-7	-1PN	$\beta_{\rm ST}$ [59, 151]
Anomalous Acceleration	Extra Dimension Mass Leakage	RS-II Braneworld [152, 153]	-13	-4PN	$\beta_{\rm ED}$ [141]
	Time-Variation of G	Phenomenological [137, 154]	-13	-4PN	$\beta_{\dot{G}}$ [137]
Scalar Quadrupolar Radiation Scalar Dipole Force Quadrupole Moment Deformation	Scalar Dipole Field Activation due to Gravitational Parity Violation	dCS [140, 155]	-1	$+2$PN	$\beta_{\rm dCS}$ [146]
Scalar/Vector Dipolar Radiation	Vector Field Activation due to Lorentz Violation	EA [109, 110], Khronometric [111, 112]	-7	-1PN	$\beta_{\text{Æ}}^{(-1)}$ [113]
Modified Quadrupolar Radiation			-5	0PN	$\beta_{\text{Æ}}^{(0)}$ [113]
Modified Dispersion Relation	GW Propagation/Kinematics	Massive Gravity [156–159]	-3	$+1$PN	$\beta_{\rm MDR}$ [145, 156]
		Double Special Relativity [160–163]	$+6$	$+5.5$PN	
		Extra Dim. [164], Horava-Lifshitz [165–167],	$+9$	$+7$PN	
		gravitational SME ($d=4$) [179]	$+3$	$+4$PN	
		gravitational SME ($d=5$) [179]	$+6$	$+5.5$PN	
		gravitational SME ($d=6$) [179]	$+9$	$+7$PN	
		Multifractional Spacetime [168–170]	3–6	4–5.5PN	

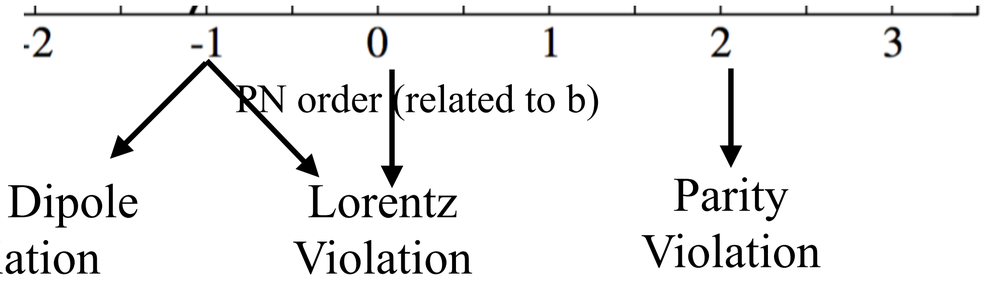
[Cornish et al PRD 84 ('11), Gair & Yunes PRD 84 ('11), Chatziioannou et al PRD 86 ('12), Sampson et al PRD 87 ('13), Sampson, et al PRD 88 ('13), Sampson et al PRD 89 ('14), Huwyler et al PRD 91 ('14), Yunes, Yagi & Pretorius PRD 94 ('16), Tahura & Yagi PRD 98 ('16), Quiao et al PRD 100 ('19), Zhang et al PRD 100 ('19), Moore & Yunes CQG 37 ('20), Bonilla, Kumar & Teukolsky ('22), Mezzasoma & Yunes PRD ('22), …]

ppE constraints with gravitational waves



[LIGO, PRD 100 ’(19)]

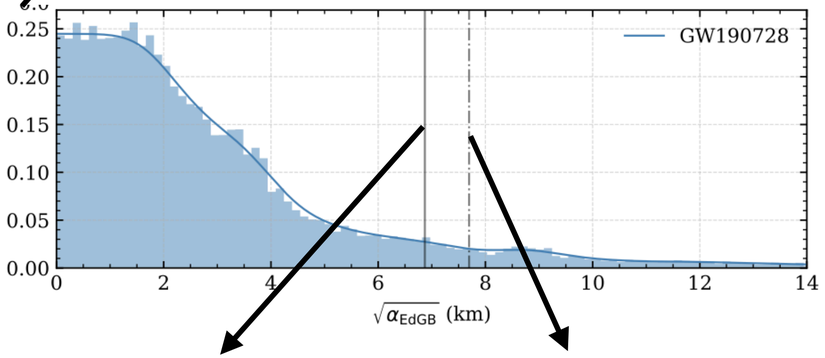
$$\tilde{h}(f) = \tilde{h}_{\rm GR}(f)\, e^{i\beta f^b}$$



[Yunes, Yagi, Pretorius, PRD 94 ’(16), Editor’s suggestion]

Mapping ppE constraints to specific theories

Marginalized posterior distribution of $\sqrt{\alpha_{\rm EdGB}}$



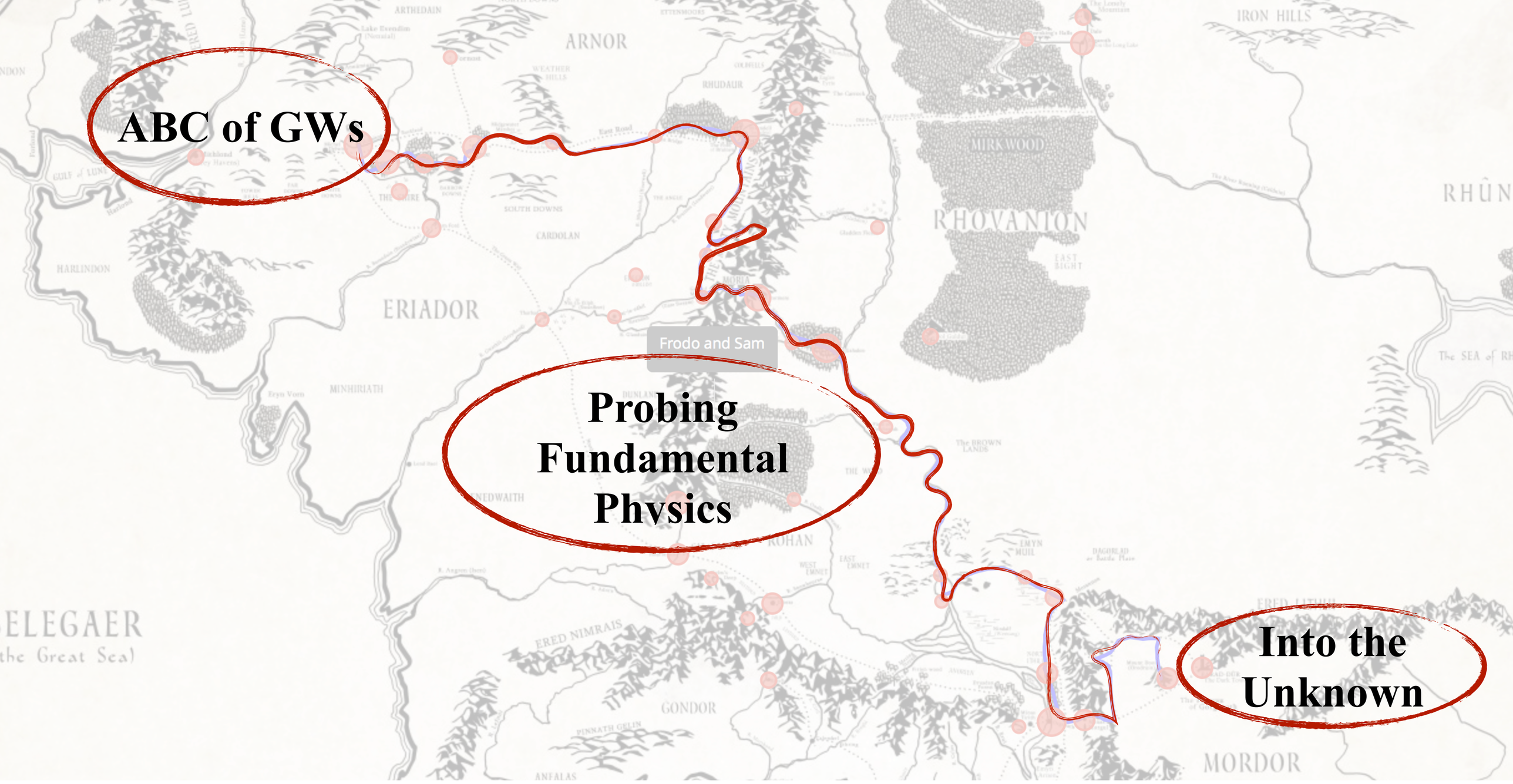
90% confidence limit

Max $\sqrt{\alpha_{\rm EdGB}}$ for validity of small coupling approximation

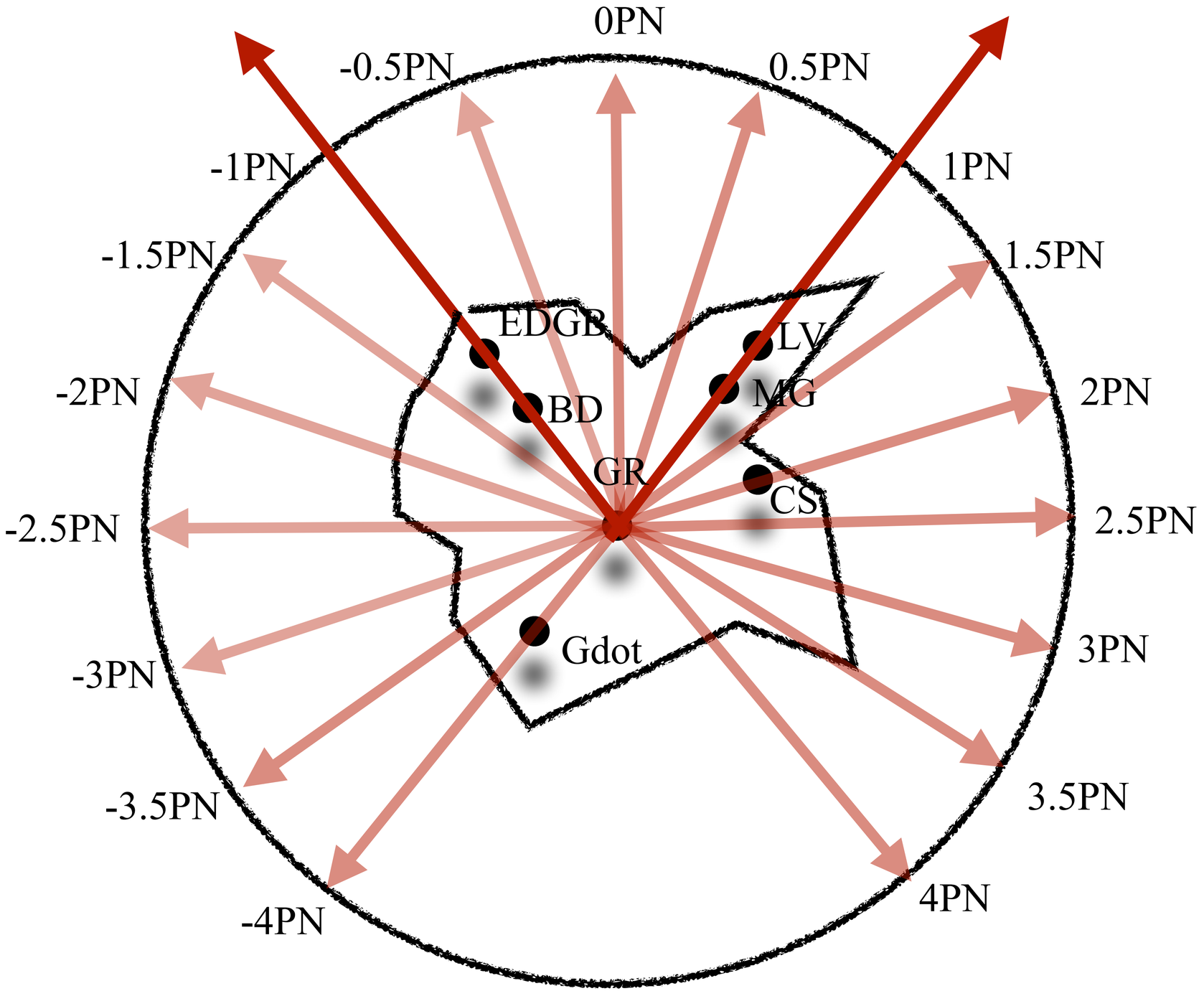
First constraints on quadratic gravity with gravitational waves!

$$\sqrt{\alpha_{\rm EdGB}} \leq 1.7 \text{ km}$$

[Nair, Perkins, Silva & Yunes, *Phys.Rev.Lett.* 123 (2019) 19, 191101, Perkins, Nair, Silva & Yunes, *Phys.Rev.D* 104 (2021) 2, 024060, Lyu, et al, *Phys.Rev.D* 105 (2022]

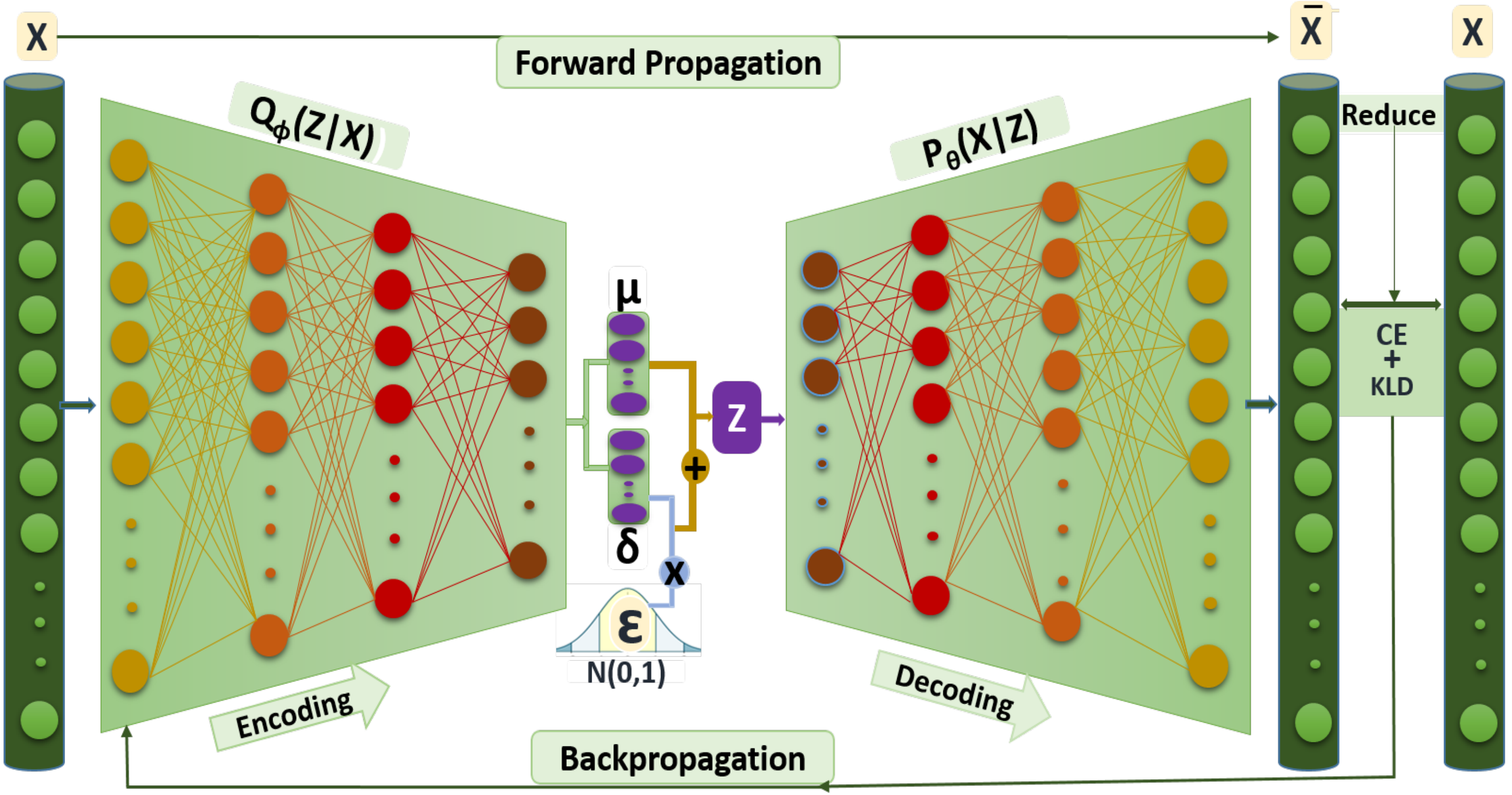

ABC of GWs
Frodo and Sam
Probing Fundamental Phvsics
Into the Unknown
ARNOR
RHUDAUR
MIRKWOOD
RHOVANION
IRON HILLS
ERIADOR
CARDOLAN
HARLINDON
MINHIRIATH
ROHAN
GONDOR
MORDOR
ELEGAER
the Great Sea)

Understanding

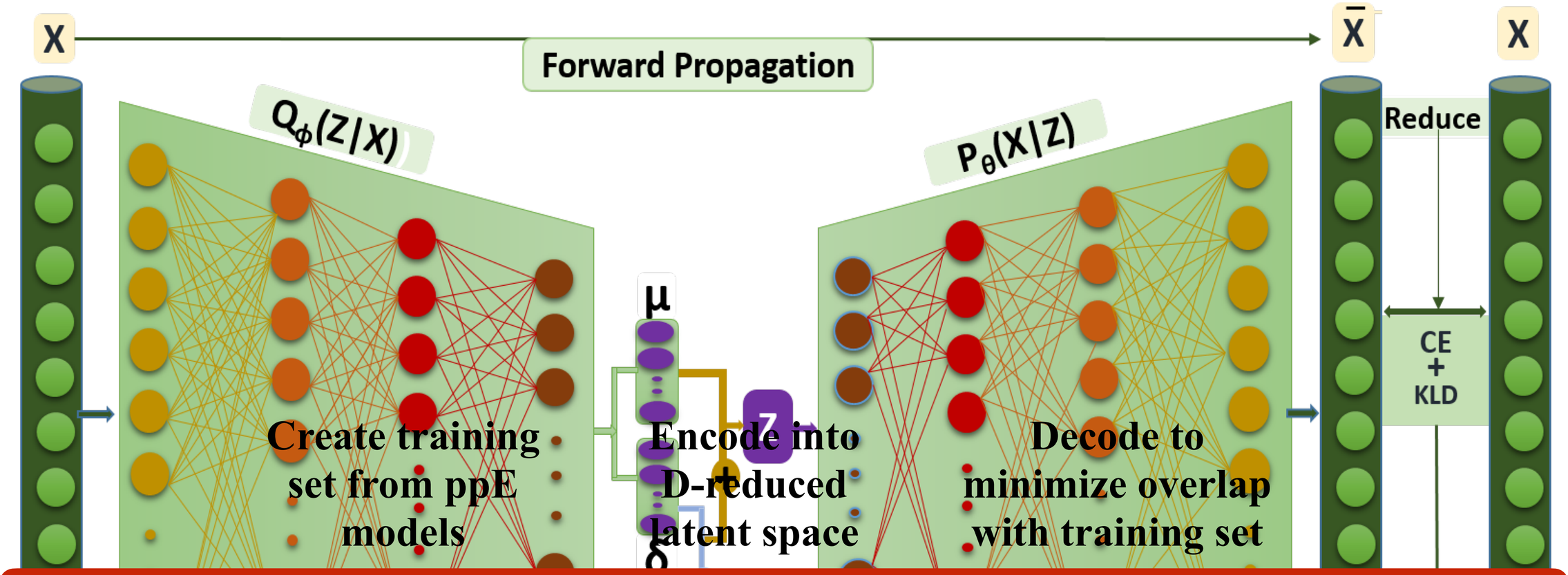


ppE

Beyond ppE tests of general relativity



Neural post-Einsteinian (NPE) framework



VAE-ppE should be able to:

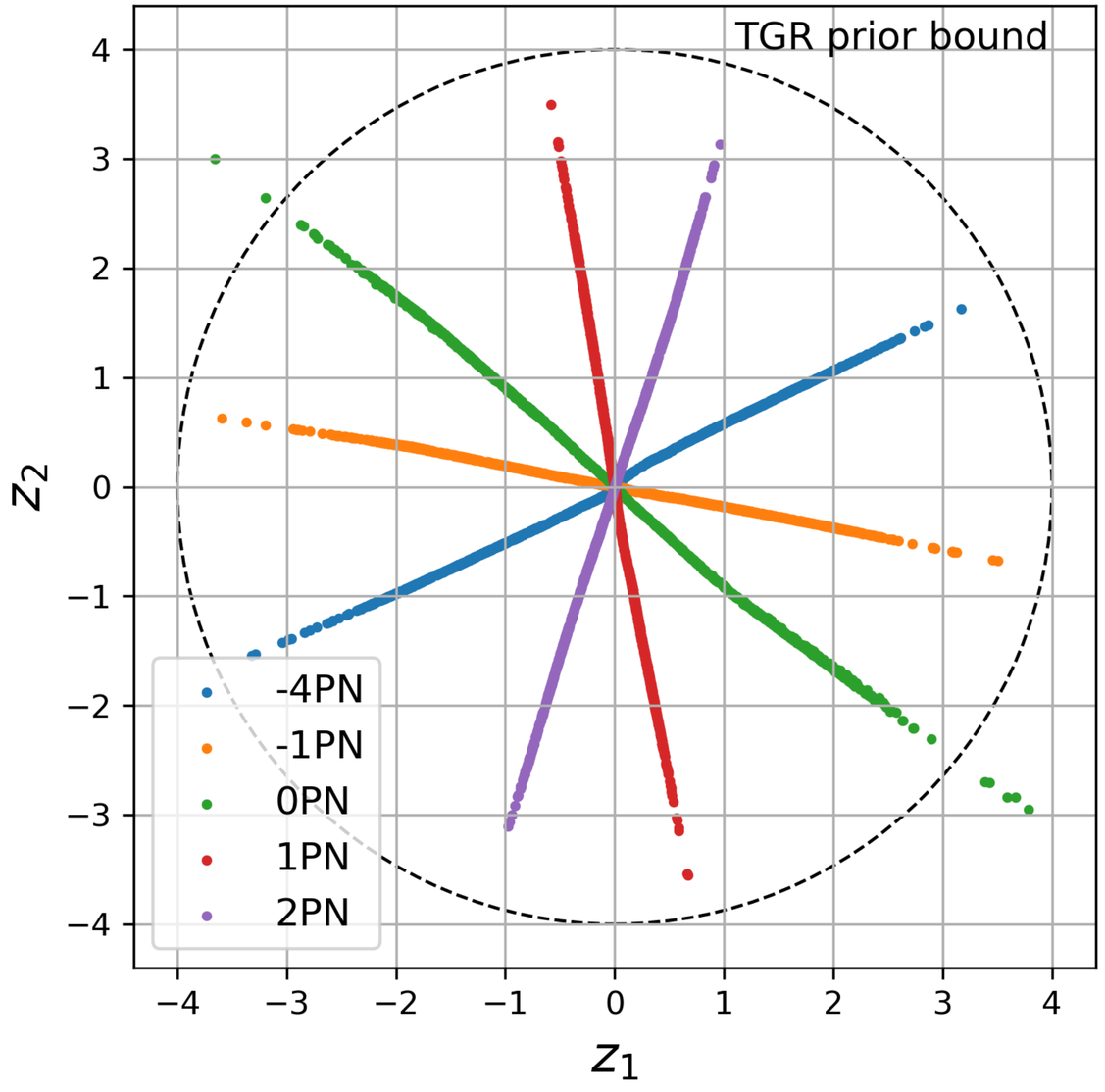
(i) detect (leading-PN order) ppE deviations efficiently,

(ii) detect untrained higher-PN order deviations,

(iii) detect untrained non-polynomial deviations.

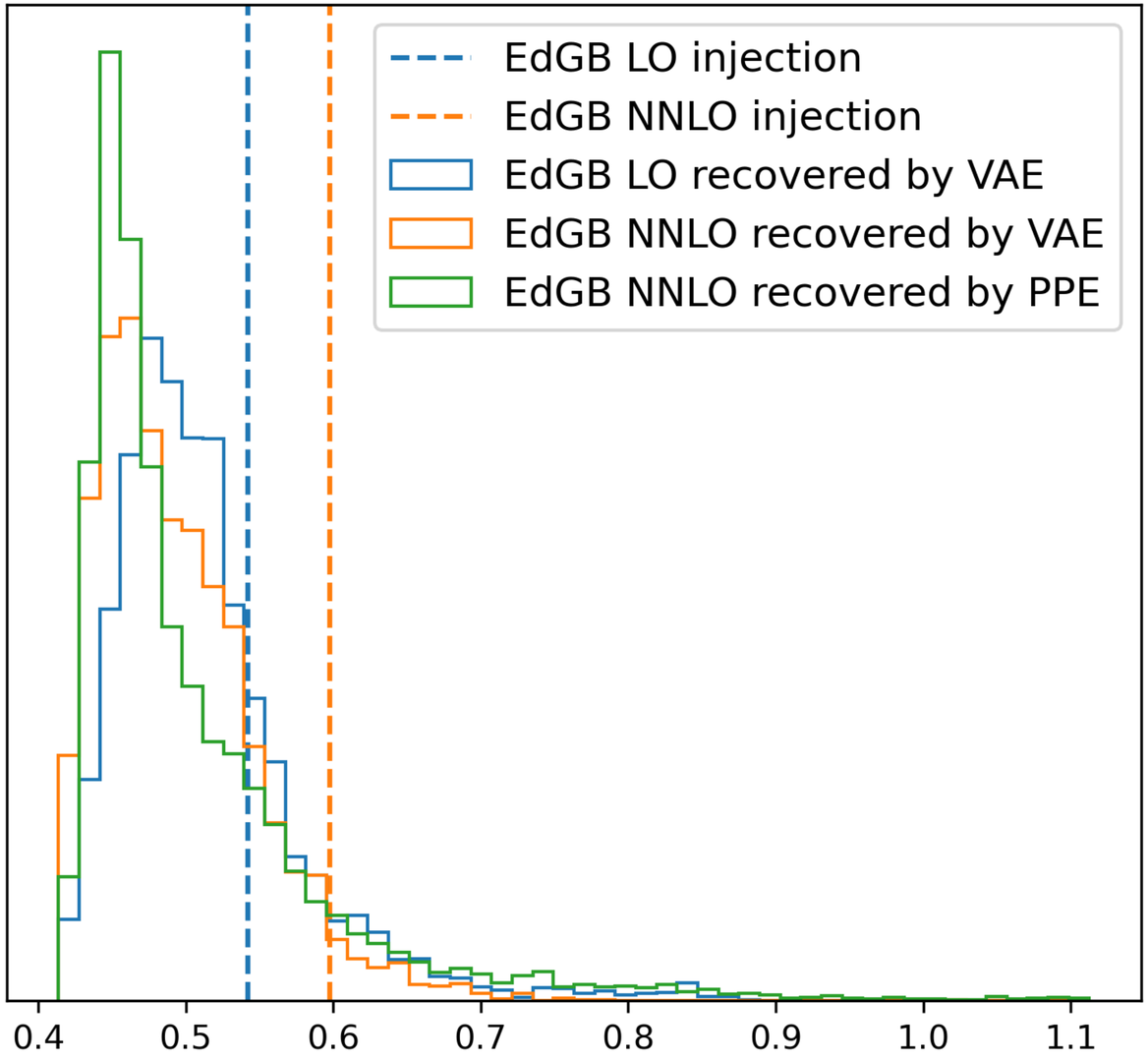
[Xi, Narayan & Yunes, in prep]

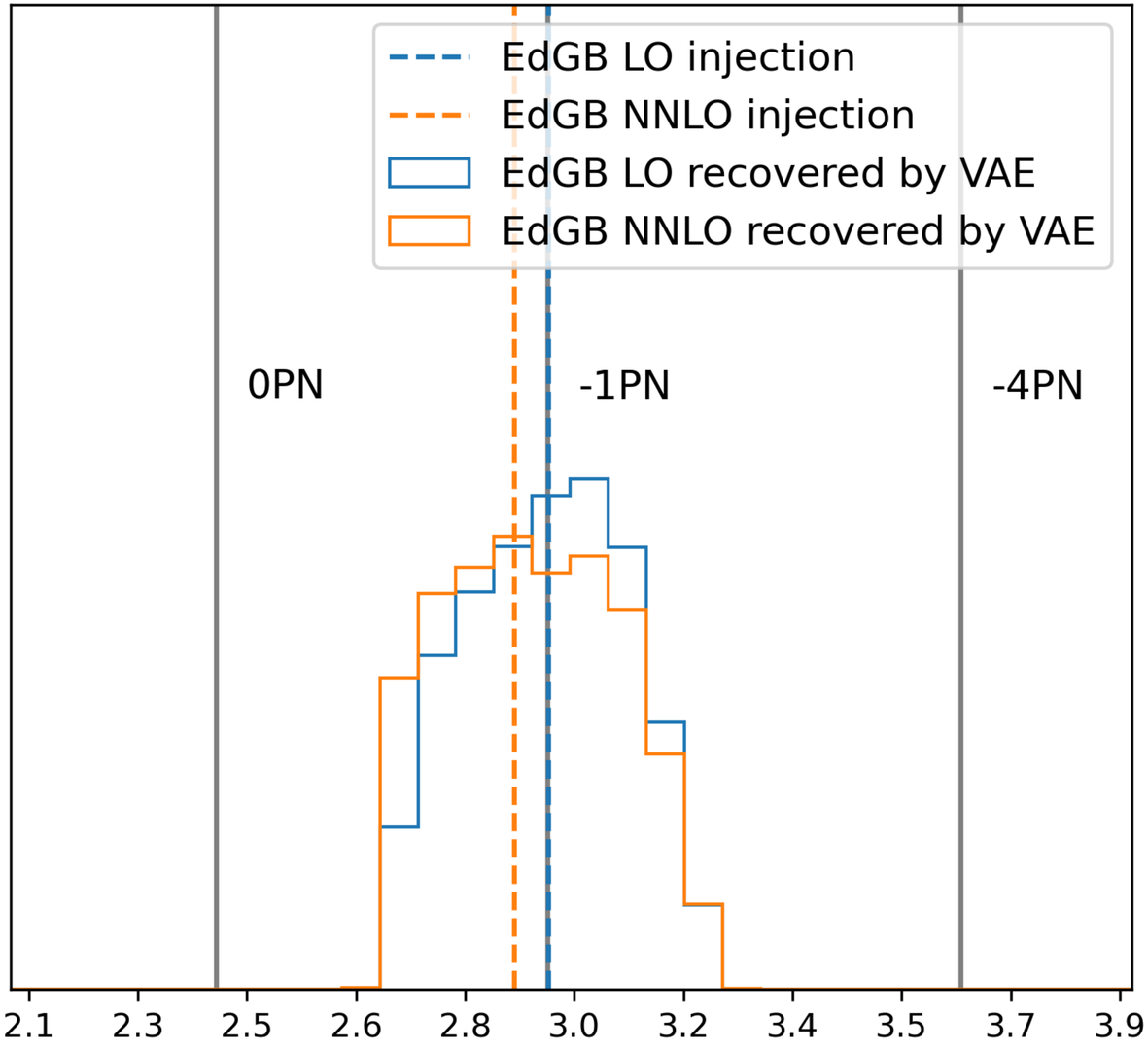
NPE in action



[Xi, Narayan & Yunes, in prep]

Bayesian Parameter Estimation with NPE





Summary and Outlook

Gravitational waves are beginning to place strong constraints on "fundamental" physics in extreme gravity

But what's next?

Detectors with higher sensitivity (2021-2028)

- Many more detections (stacking)
- A few very loud detections (SNRs in low 100s)

- Look for new physics (e.g. screening mechanisms)
- Look for physics in new sources (e.g. dipoles in EMRIs)
- Look at new agonistic tests (e.g. polarization tests)
- and much more!