Probing Extreme Gravity with Black Holes & Neutron Stars

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Research Interest

Probing Fundamental Physics with Astrophysical Compact Objects

Gravitational Physics

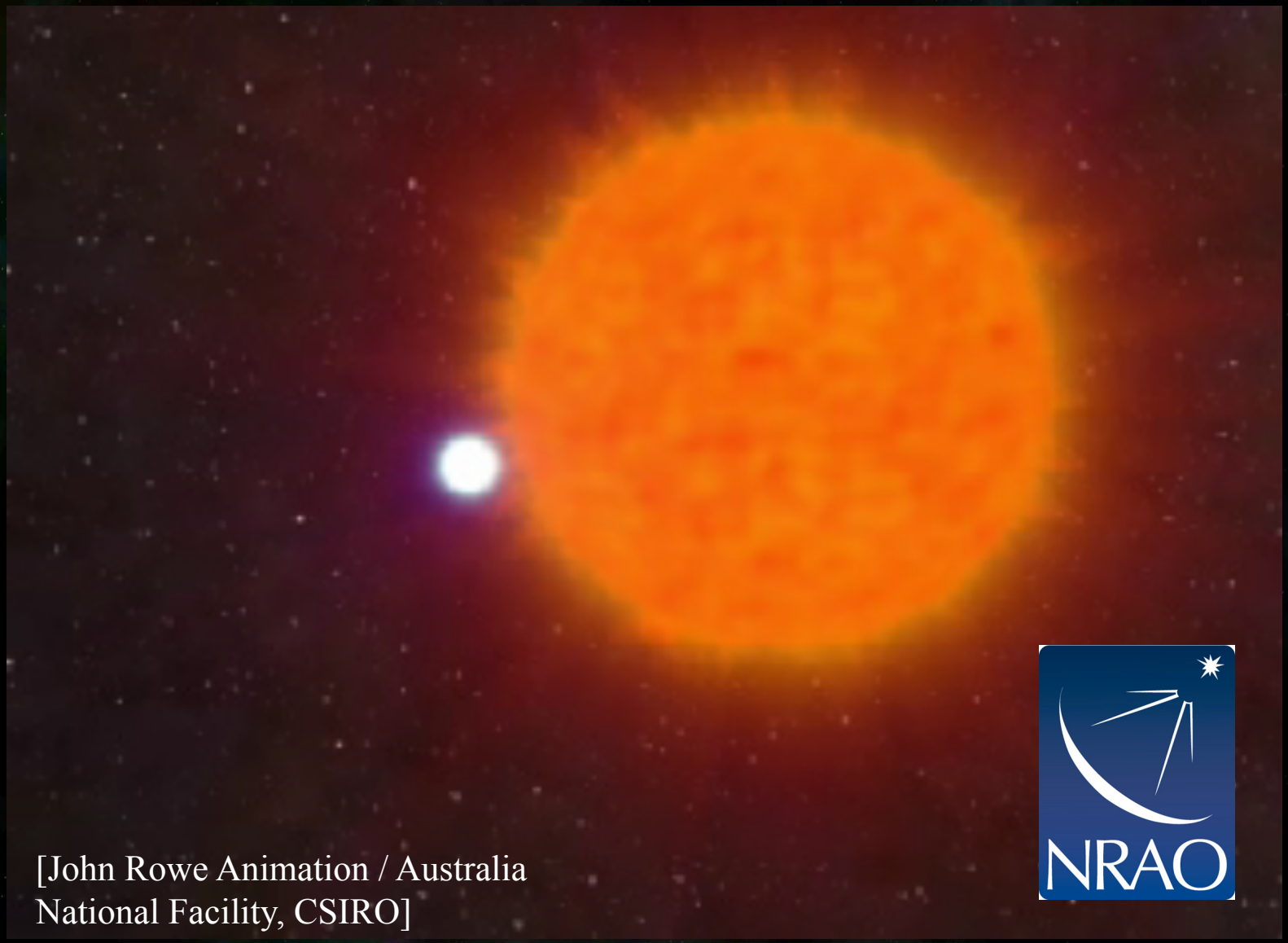
Black Holes
&
Neutron Stars

final fate of
massive stars

Nuclear Physics

Cosmology

Neutron Star Formation



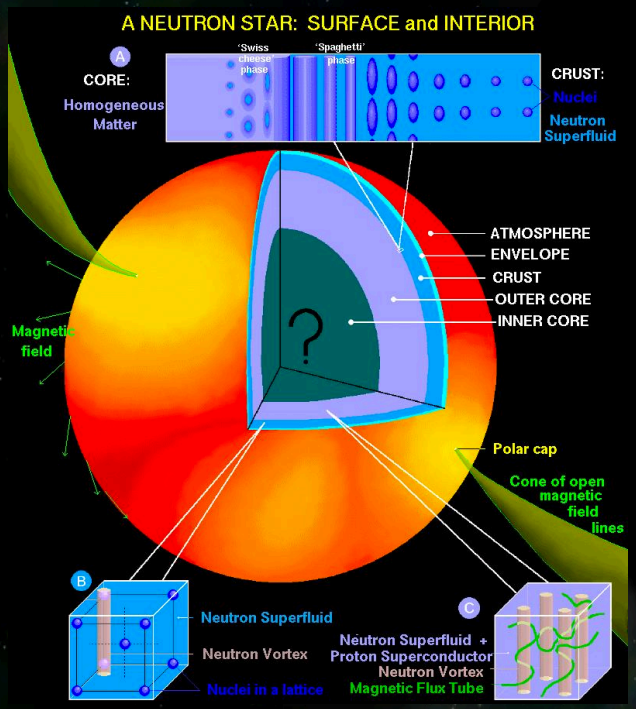
[John Rowe Animation / Australia National Facility, CSIRO]

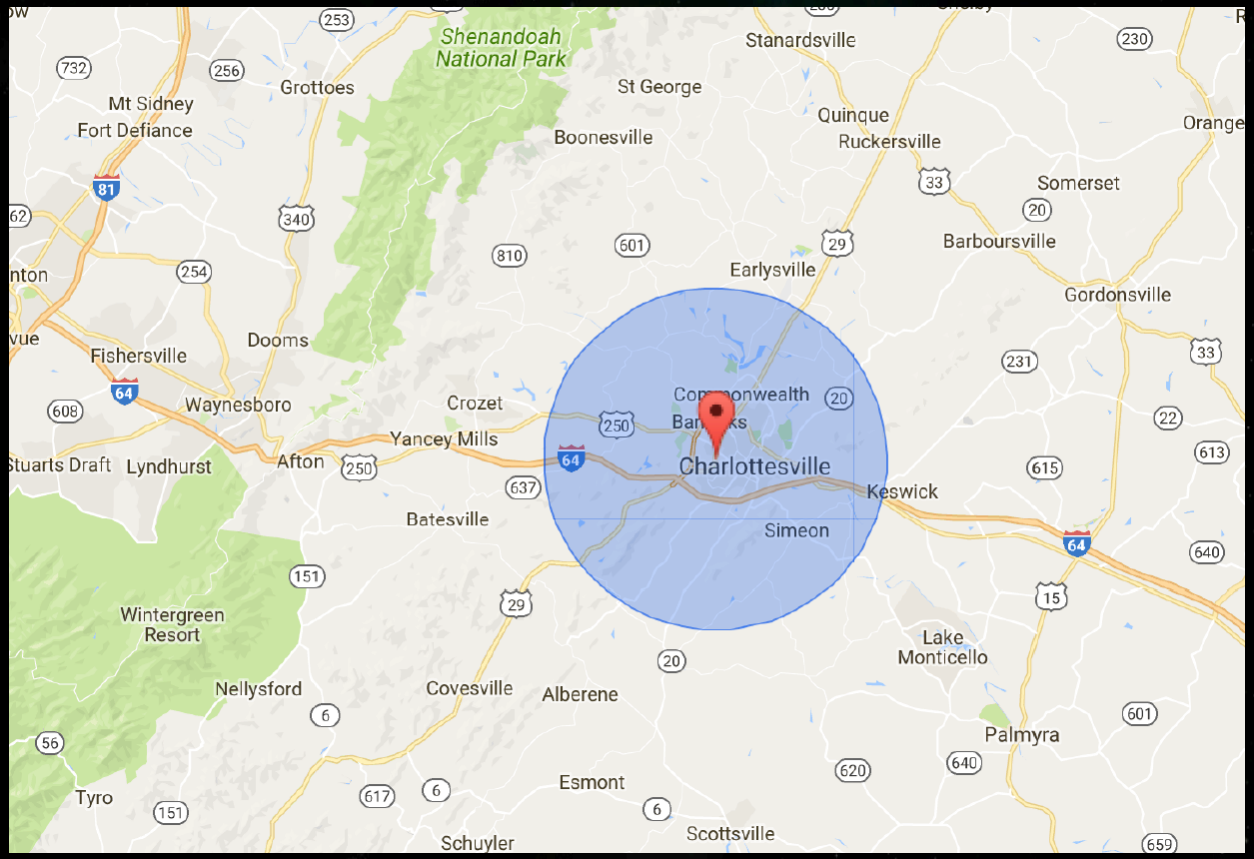
Neutron Star Basics

$$M_{\rm NS} = 1 - 2M_\odot$$

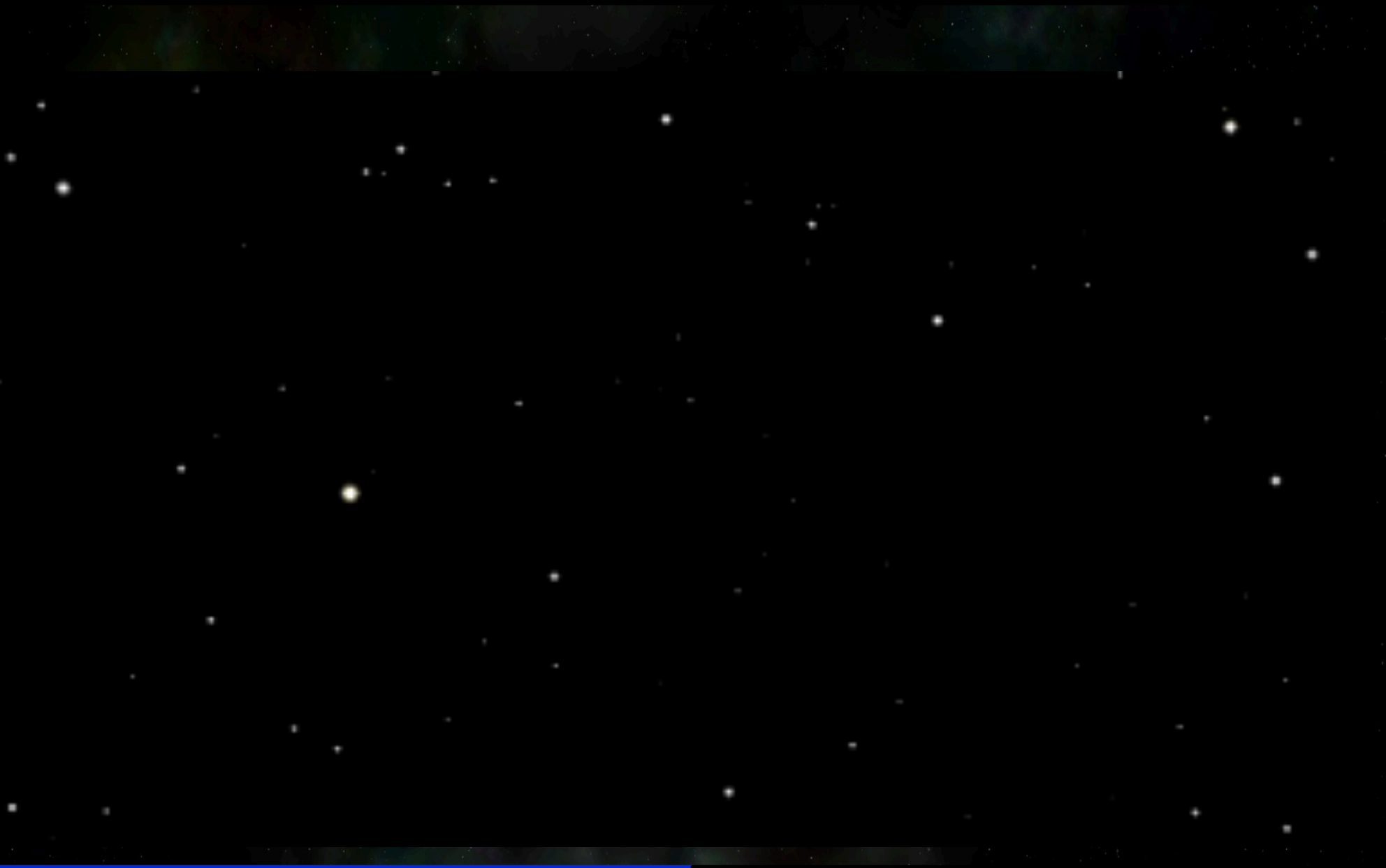
$$R_{\rm NS} \approx 12{\rm km}$$

$$\approx 7.5{\rm miles}$$

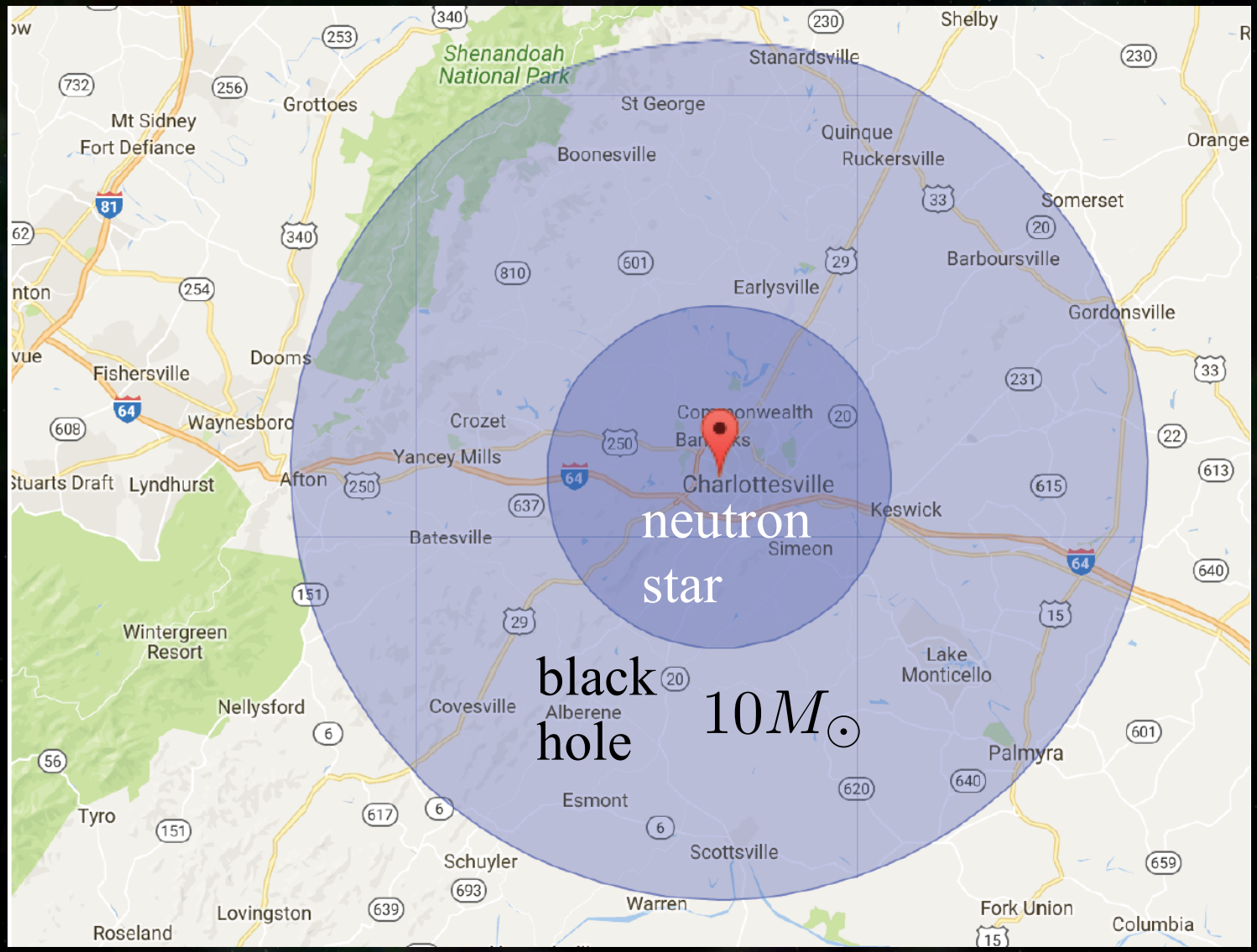




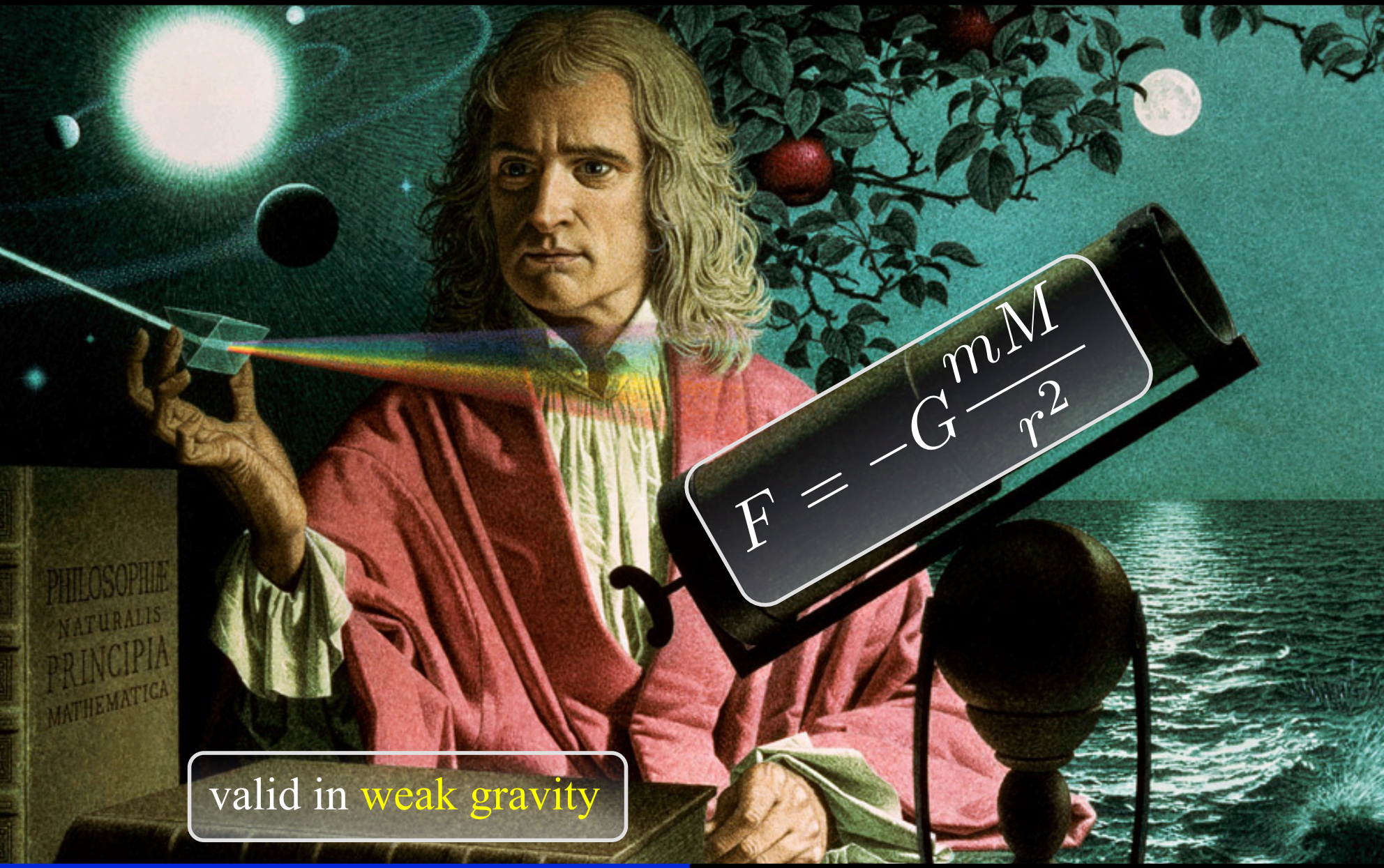
Black Hole Formation



Black Hole vs Neutron Star



Newtonian Gravity

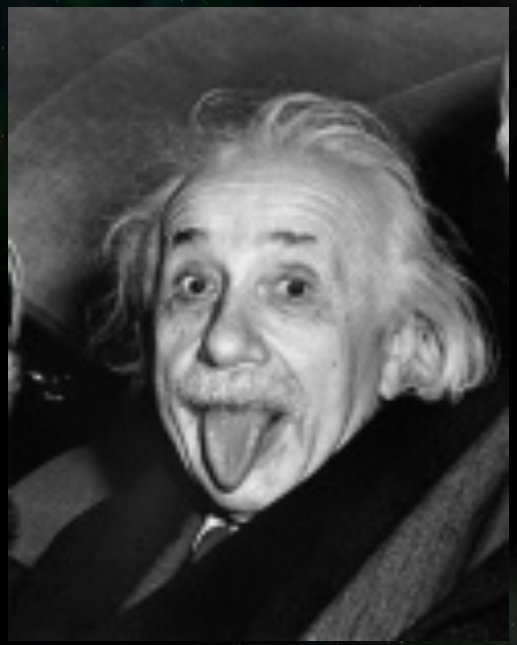


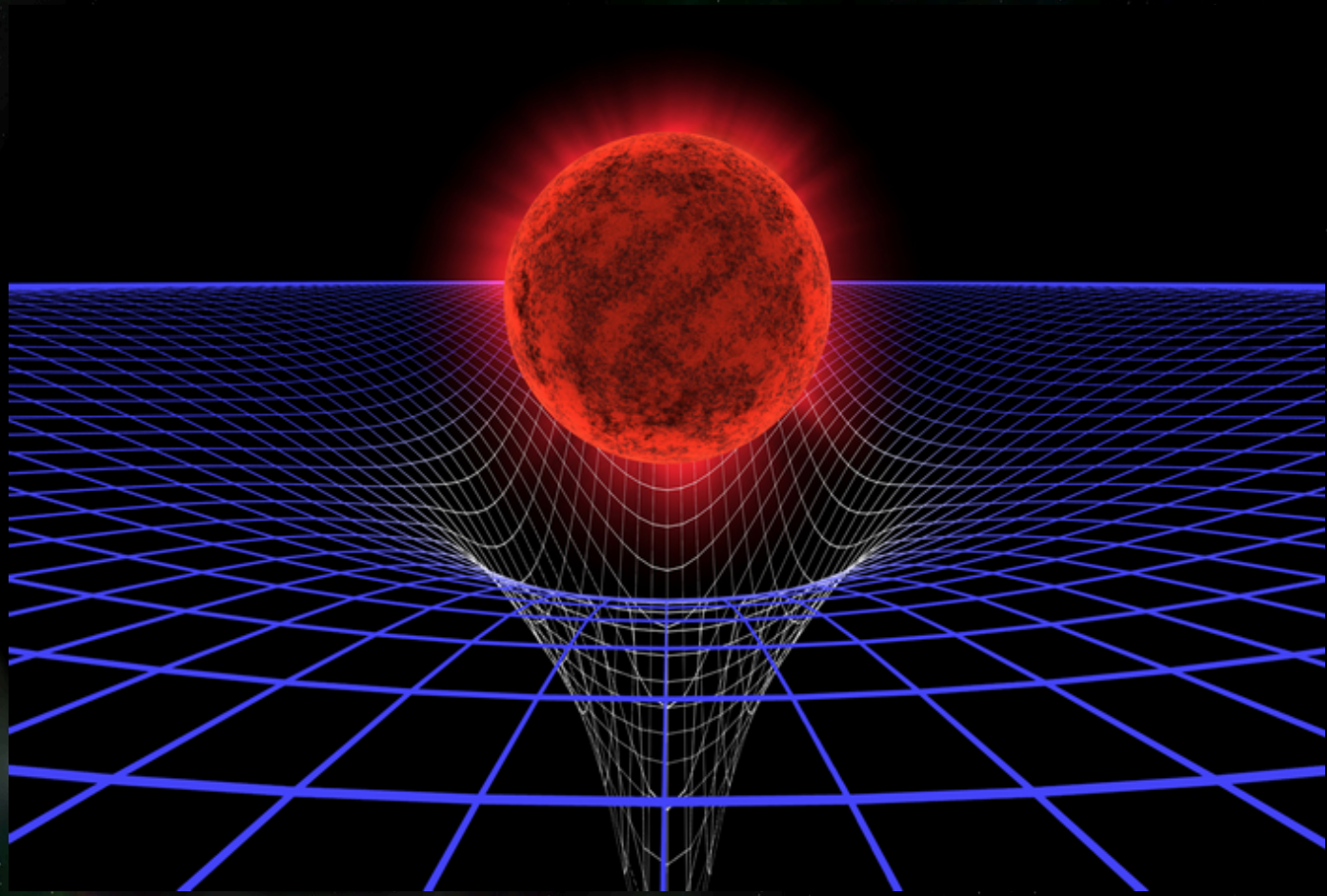
$$F = -G\frac{mM}{r^2}$$

valid in weak gravity

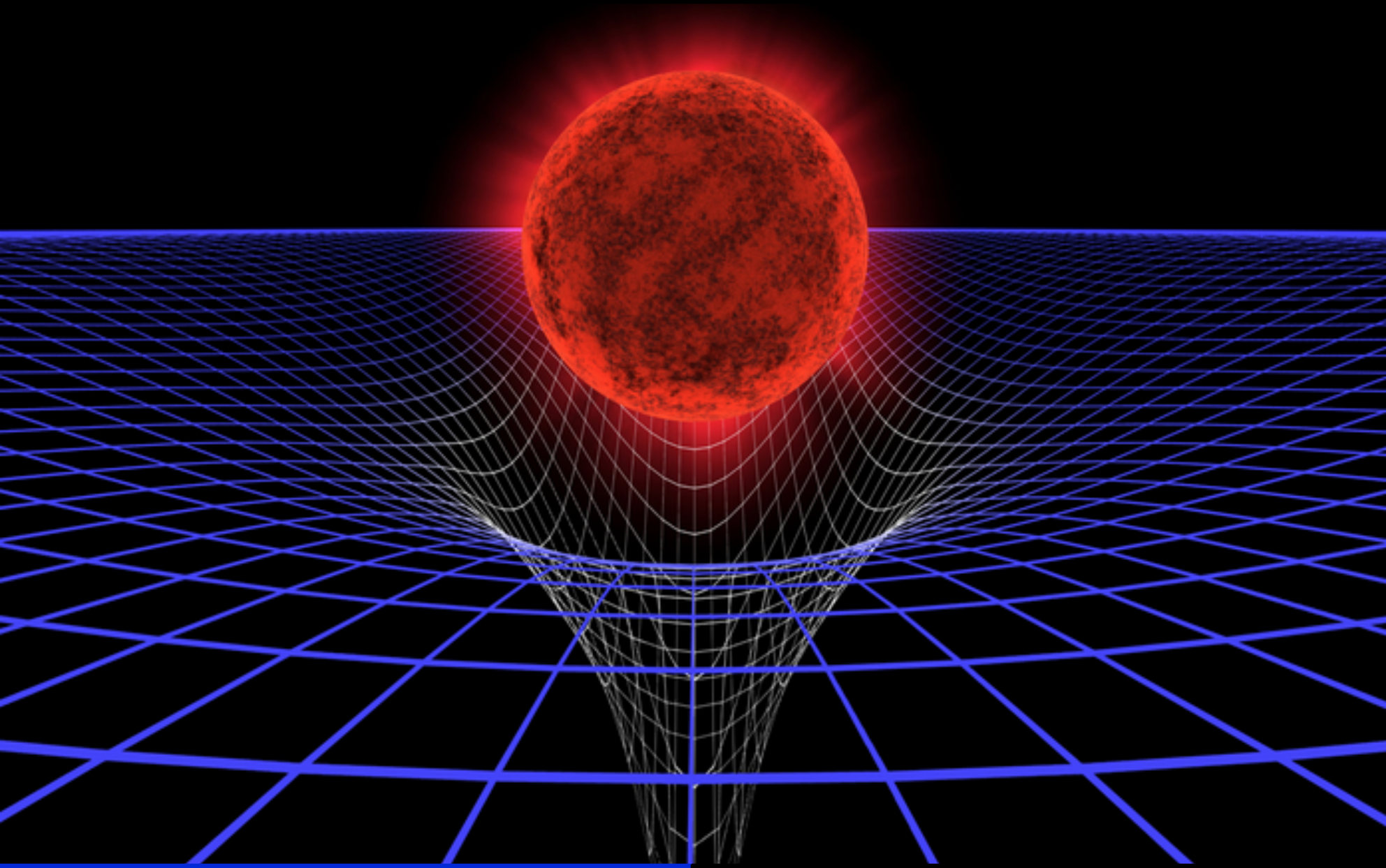
General Relativity

Gravity = Curvature of Spacetime



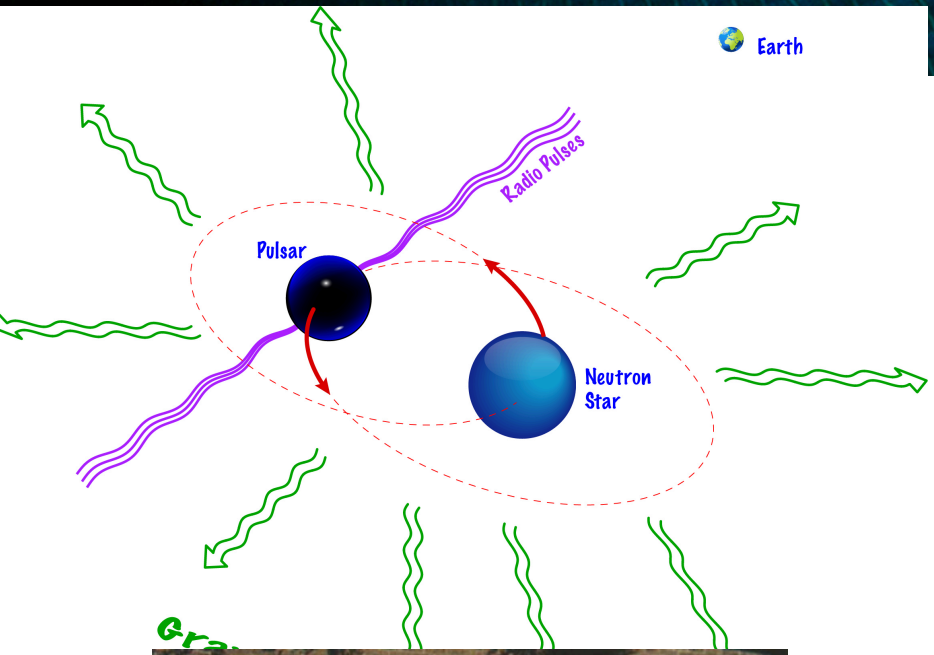


We feel spacetime curvature as gravity!

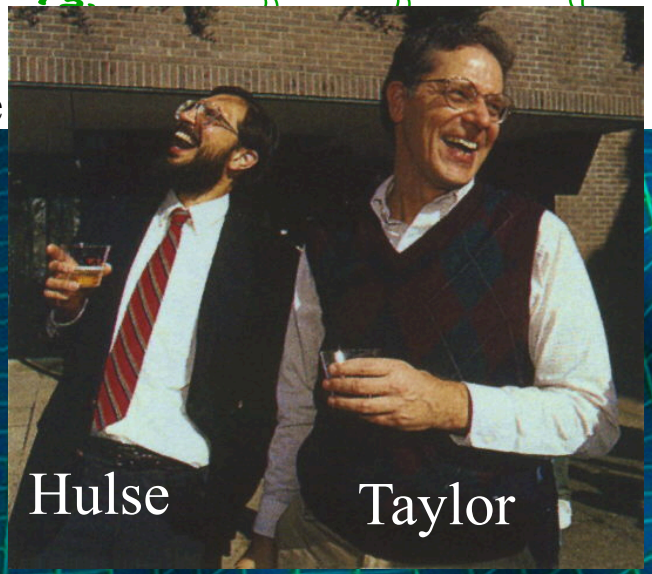


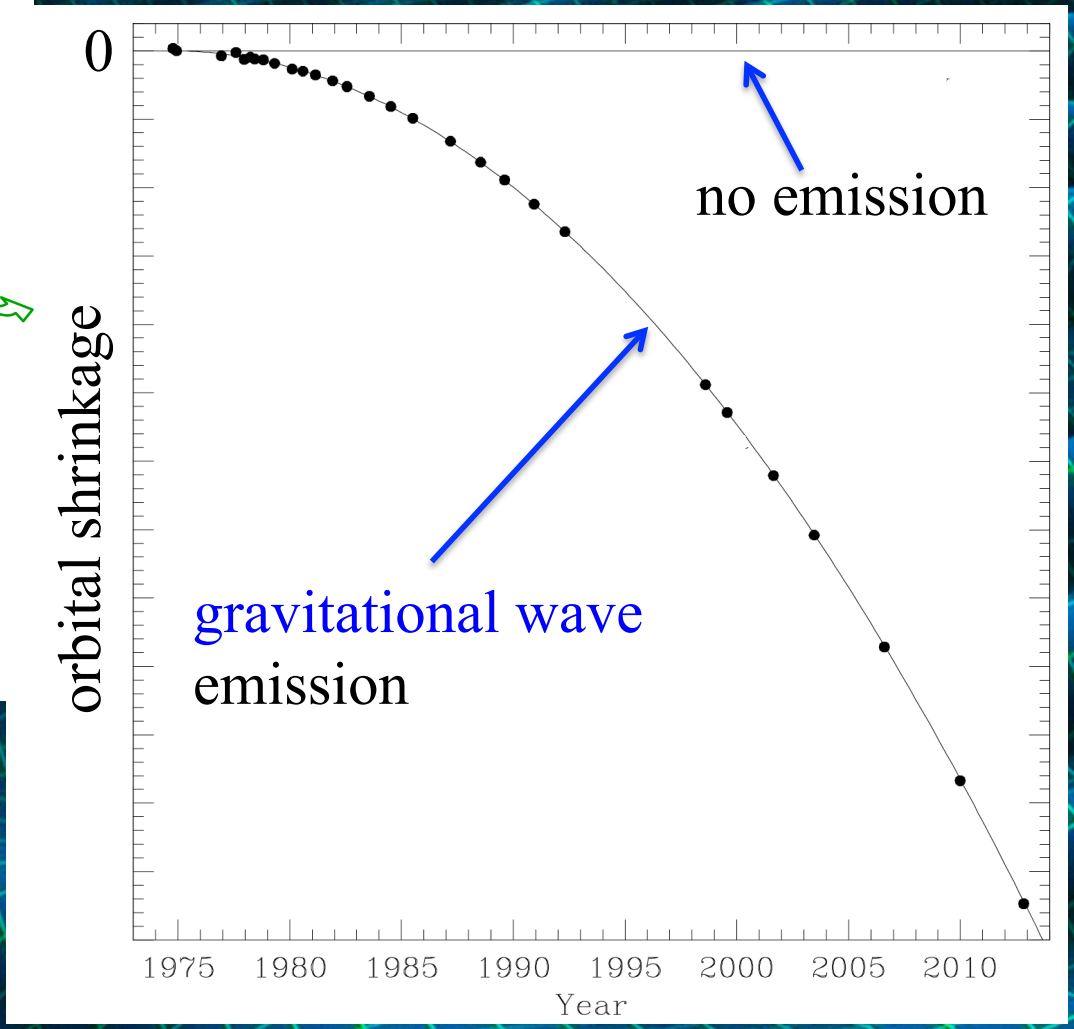
Ripples of Spacetime … Gravitational Waves!

Indirect Detection of Gravitational Waves



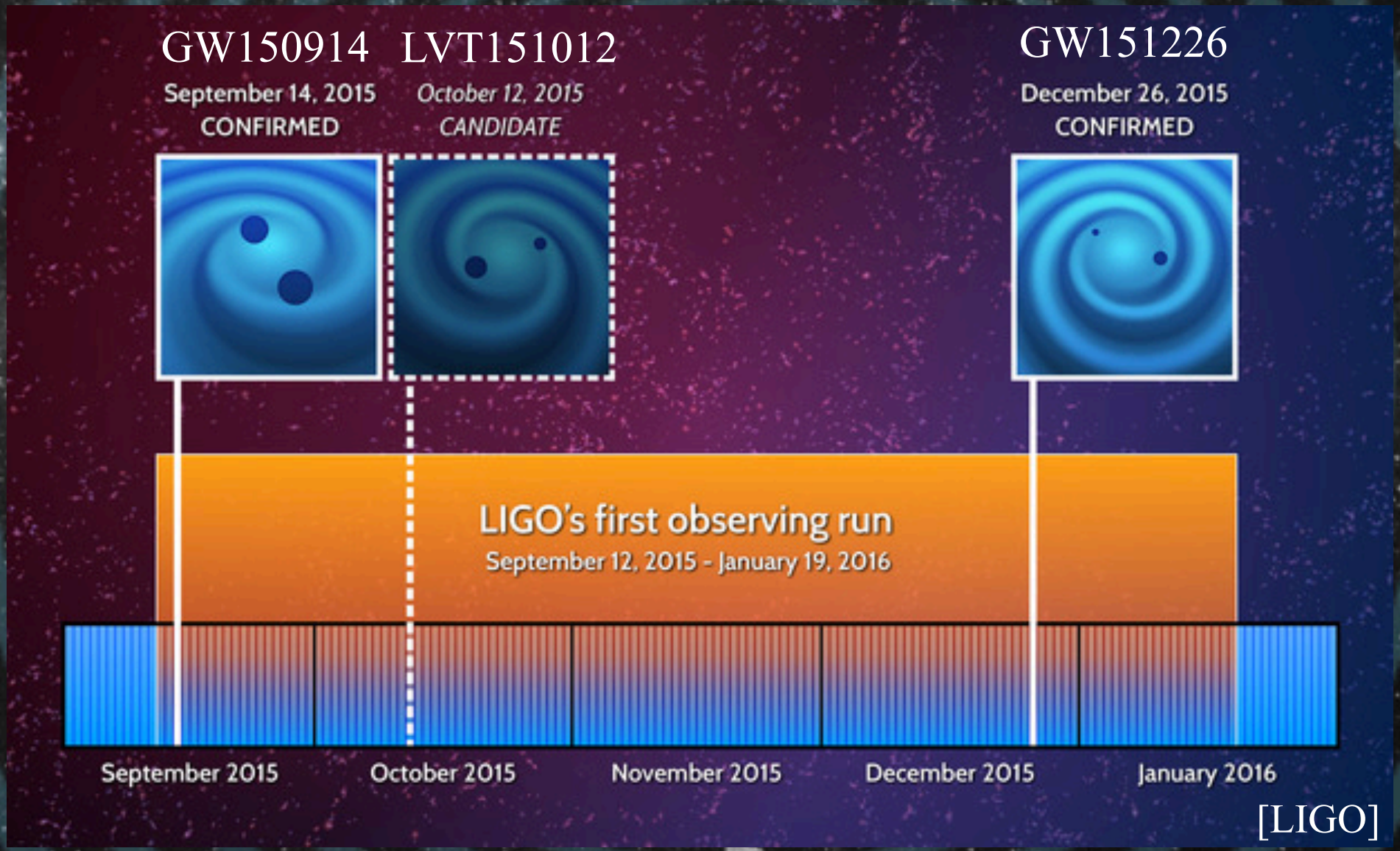
[Shane





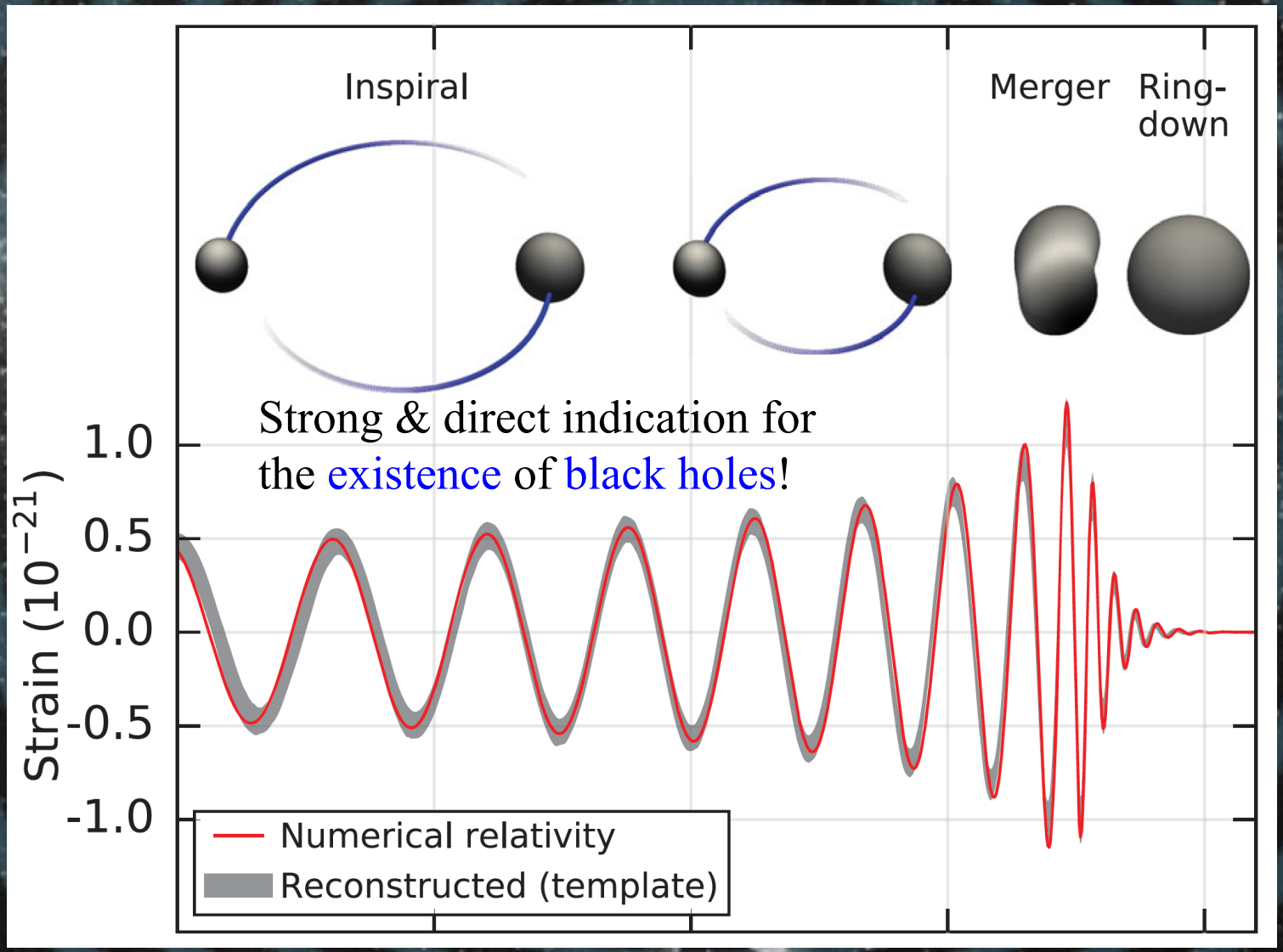
[Weisberg & Huang (2016)]

Direct Detection, At Last!!



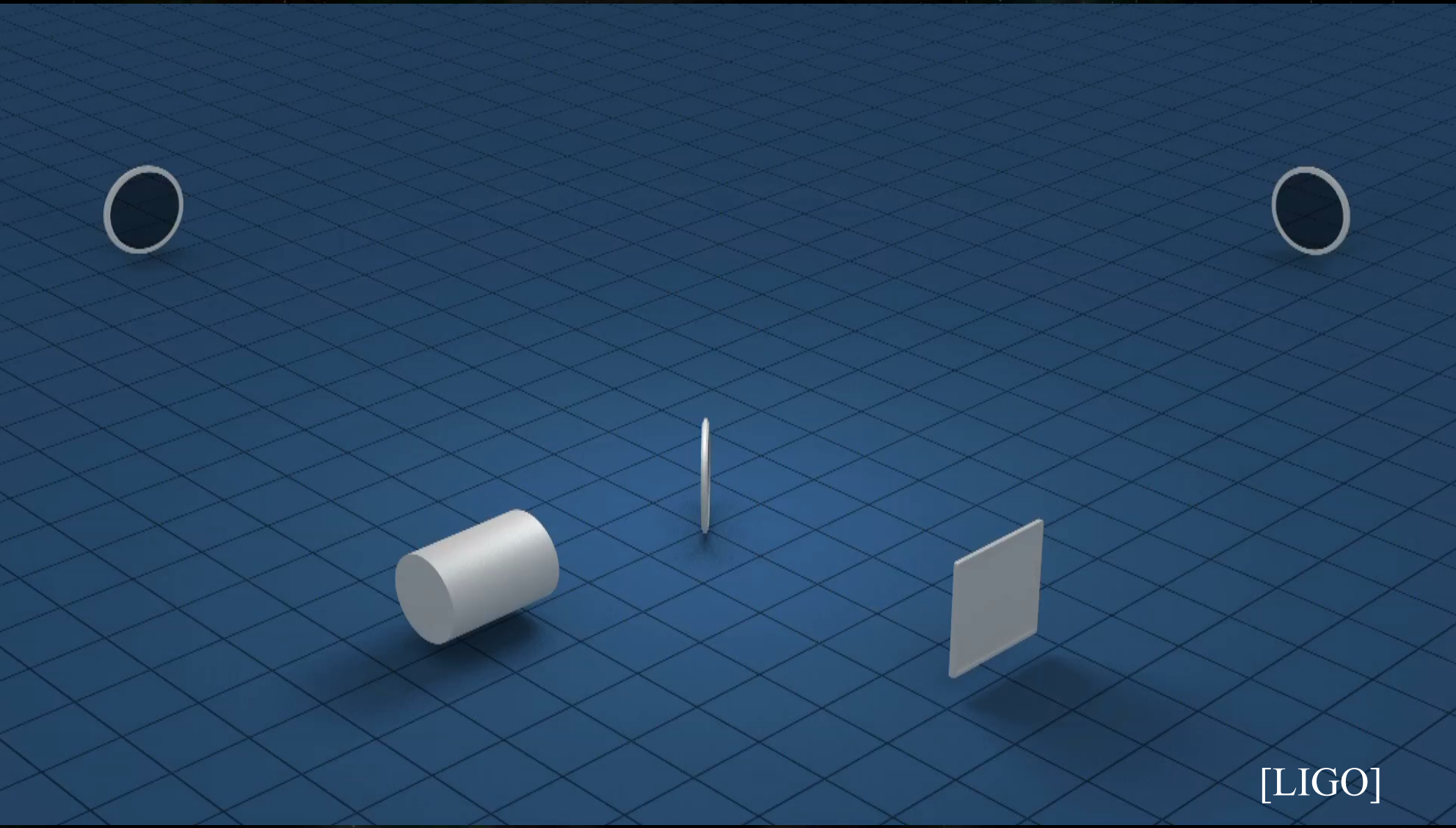
[LIGO]

GW150914 Waveform



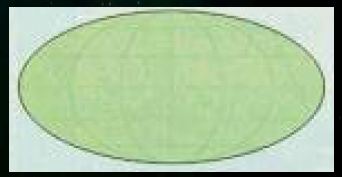
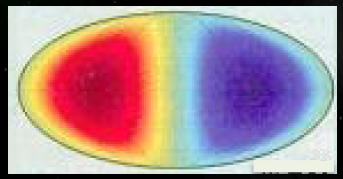
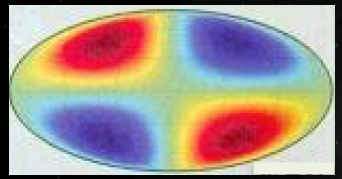
[Abbott et al. PRL 116 061102 (2016)]

How Does LIGO Work?



Analogy with Electromagnetism

multipolar structure of radiation

	electromagnetic	gravitational
monopole 	✗ charge conservation	✗ mass conservation
dipole 	✓	✗ momentum conservation
quadrupole 	✓	✓

Rough Estimate

gravitational wave amplitude (quadrupole formula)

$$h \sim \frac{G}{c^4}\frac{\ddot{Q}}{r} \qquad \ddot{Q} \sim m\,v^2$$

mass m

relative velocity v

$$\sim 10^{-21}\left(\frac{m}{30M_\odot}\right)\left(\frac{v}{0.4c}\right)^2\left(\frac{400\mathrm{Mpc}}{r}\right)$$

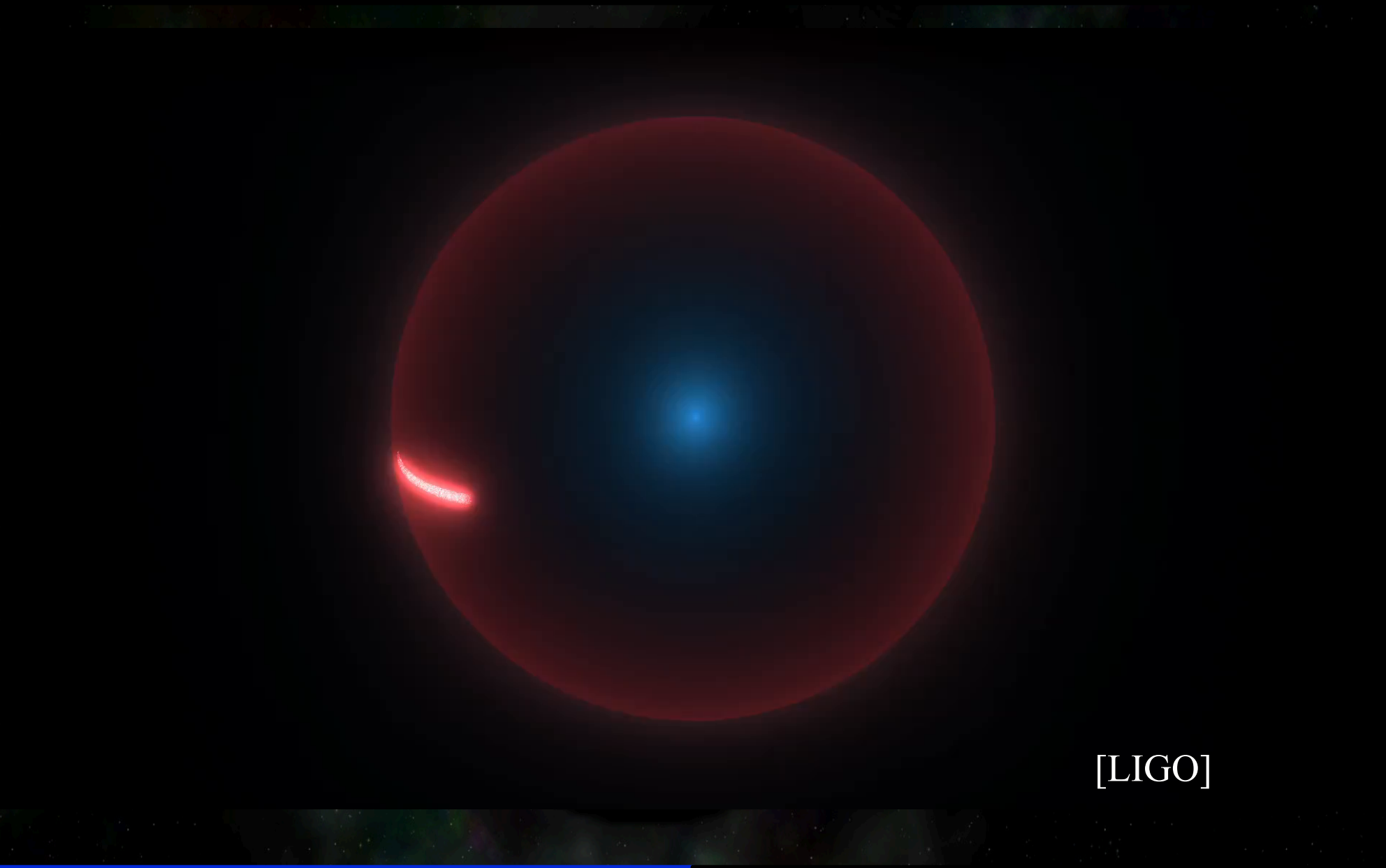
detector fluctuation

$$\Delta L \sim h\,L$$

$$\sim 4\times 10^{-18}\mathrm{m}\left(\frac{L}{4\mathrm{km}}\right)$$

r

It's Tiny!!



[LIGO]

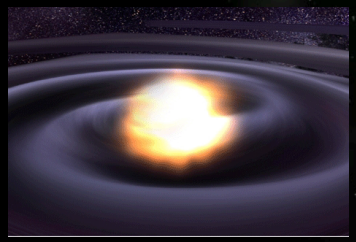
Most Energetic Event Observed Ever!

Luminosity (energy/time)

10^{59}erg/s Planck luminosity

$$L_{\rm Pl} = \frac{M_{\rm Pl}\, c^2}{t_{\rm Pl}} = \frac{c^5}{G}$$

10^{56}erg/s GW150914 GW151226



10^{54}erg/s ultraluminous gamma-ray burst

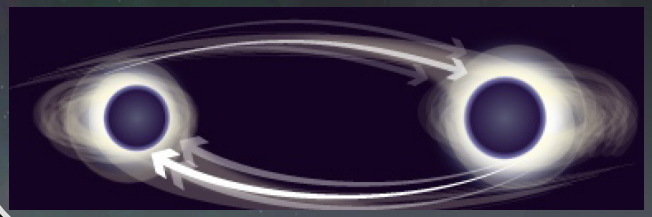
$\sim$

10^{33}erg/s Sun

Gravitational Waveform Template

Inspiral

Post-Newton (PN) approximation $\frac{v}{c} \ll 1$

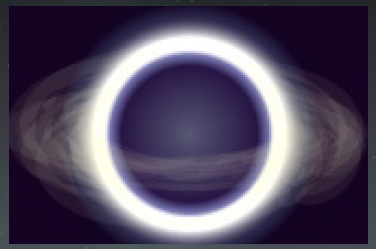


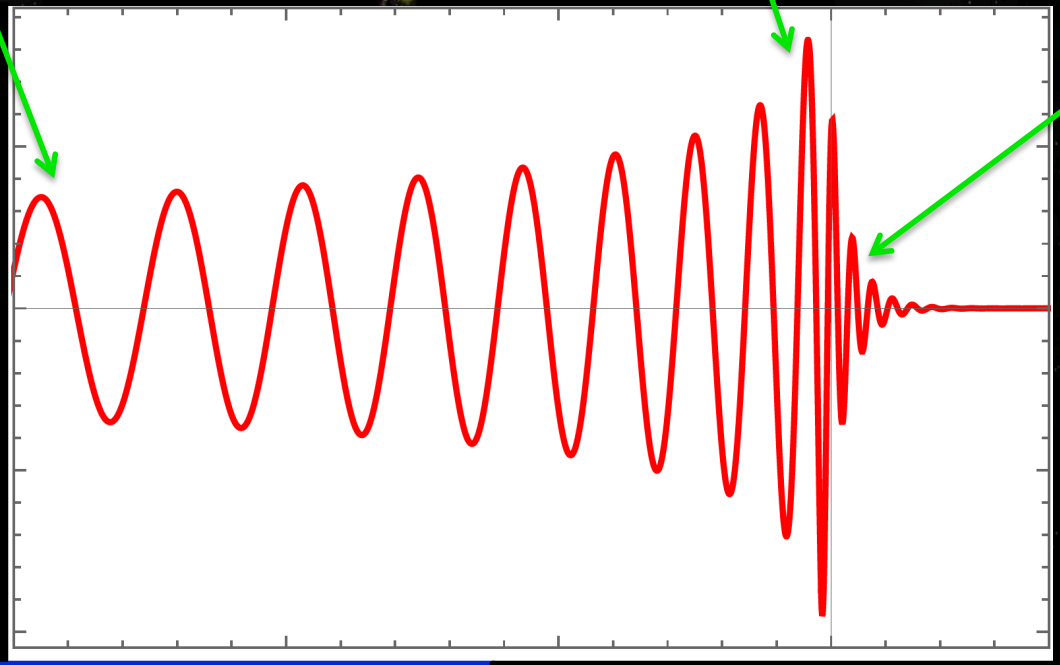
Merger

Numerical Relativity

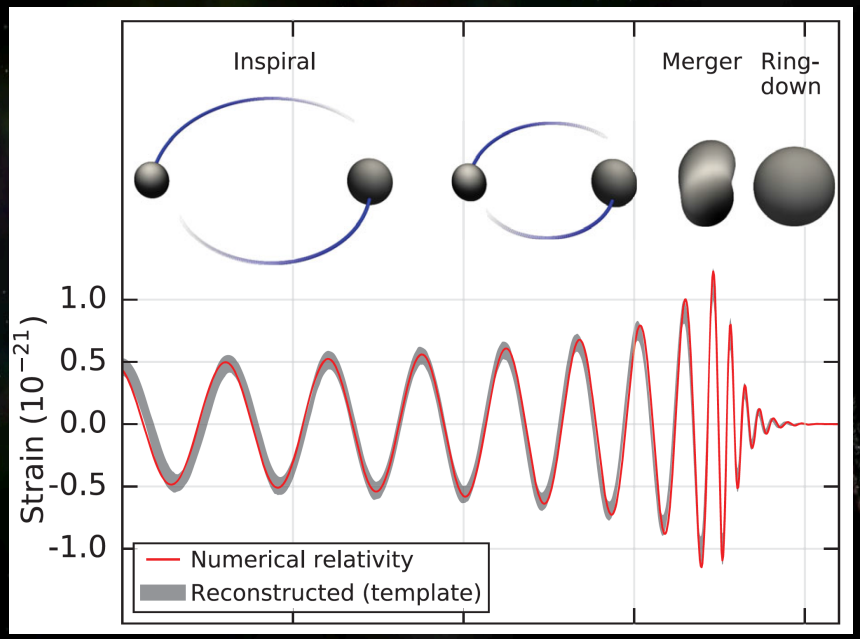
Ringdown

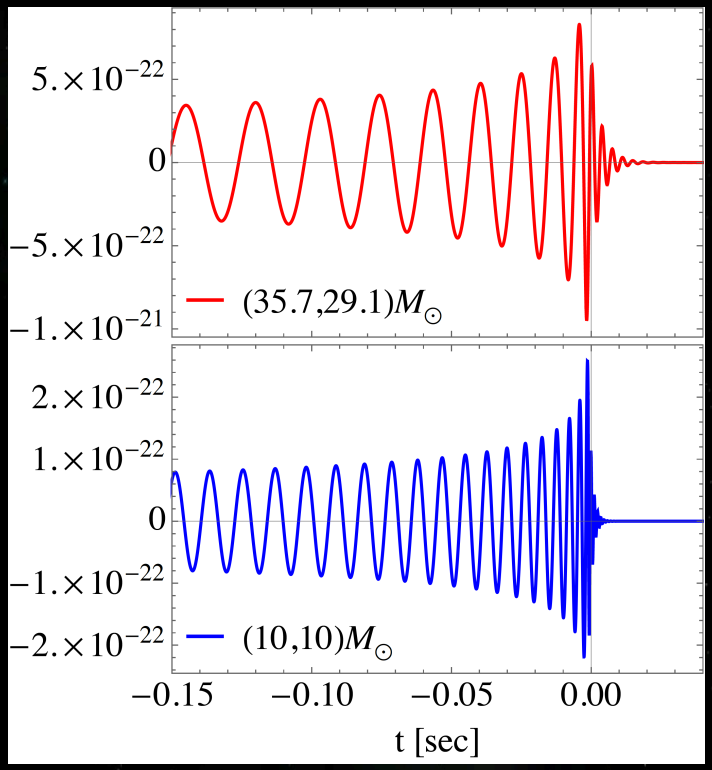
Black Hole Perturbation





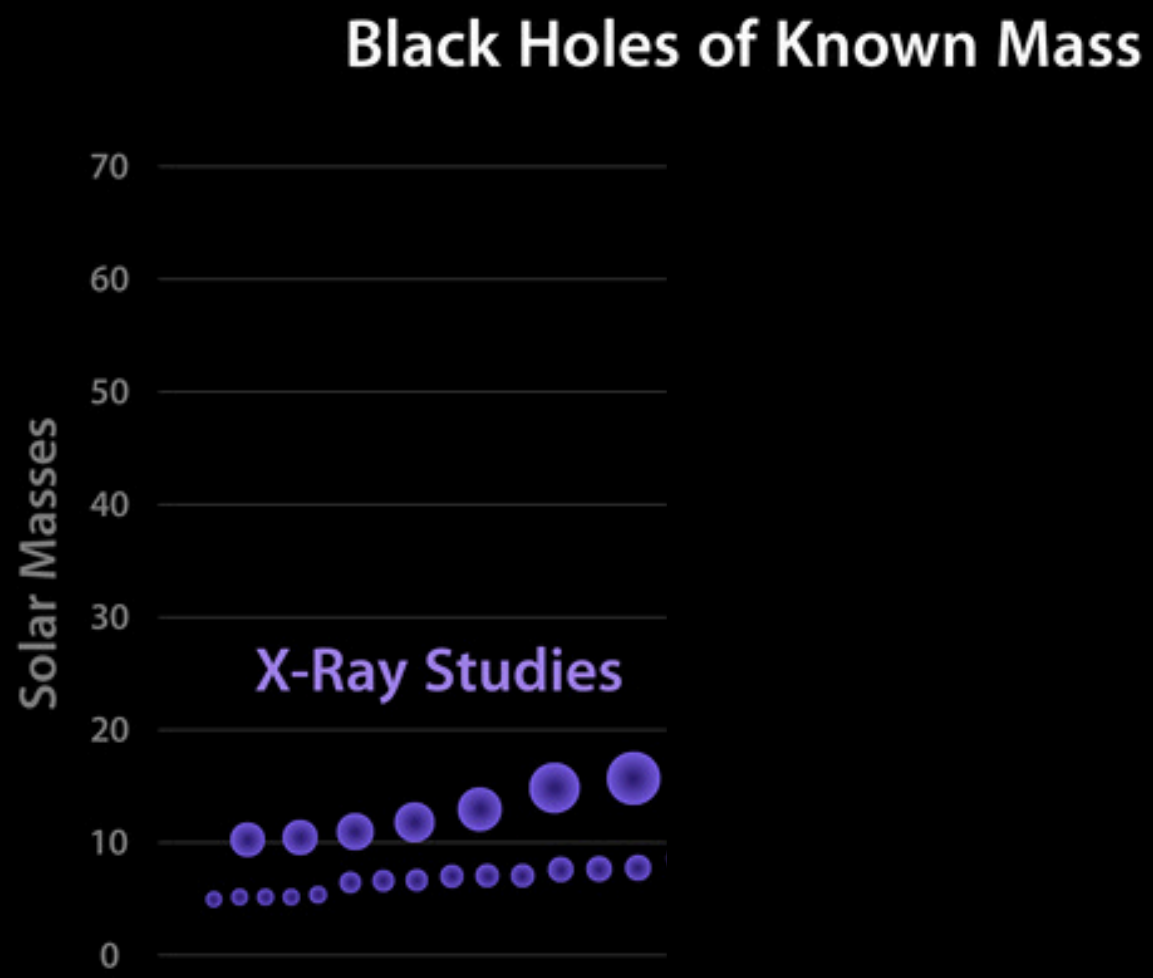
Gravitational Wave Data Analysis





1. Prepare template "filters"
2. Cross-correlate templates and data
3. Find parameters that maximize correlation

Most massive Stellar-mass Black Hole Ever!!



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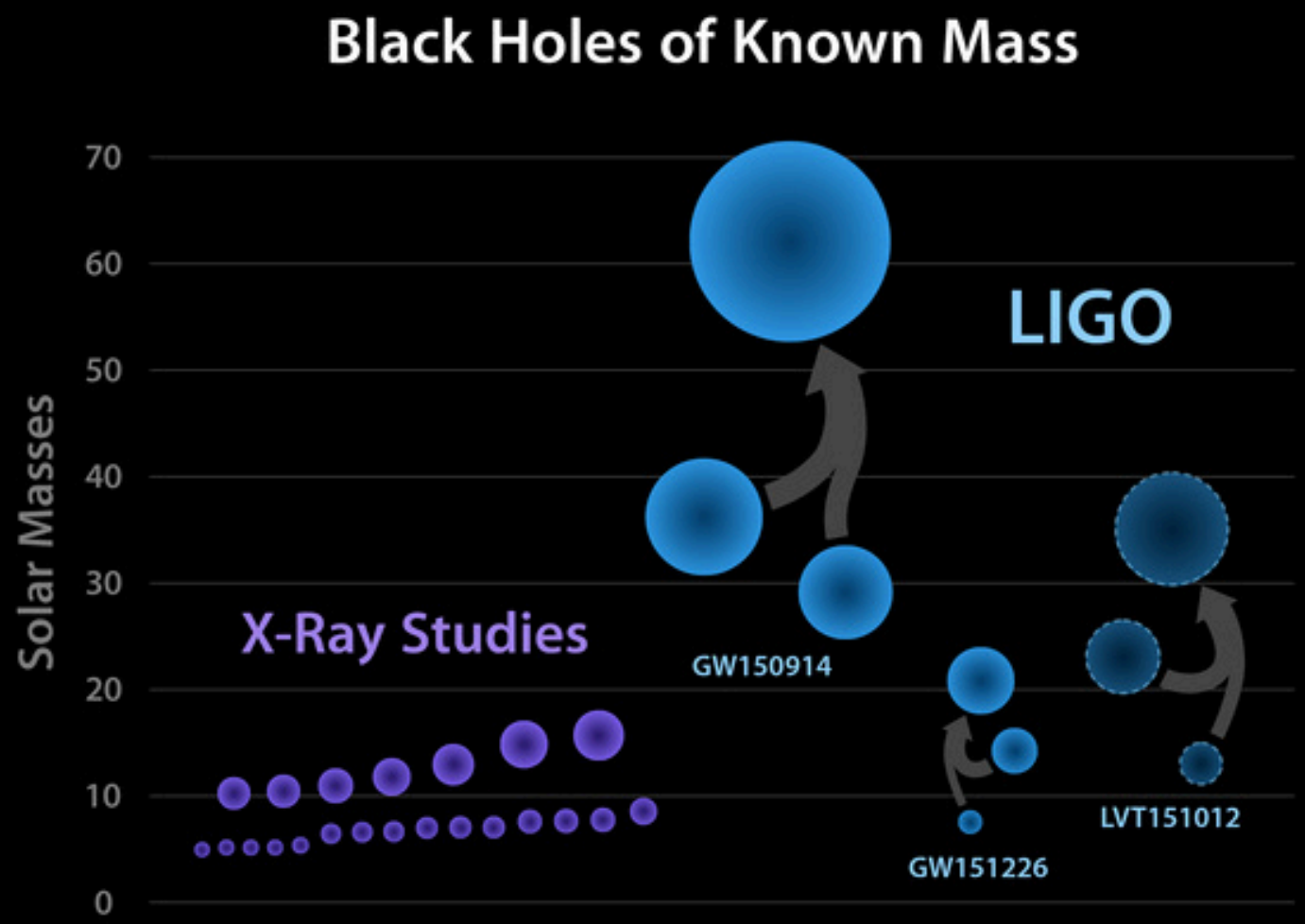


[LIGO]

LIGO was mainly designed for neutron star binaries...

Outline

Testing Gravity with Current Gravitational Wave Observations

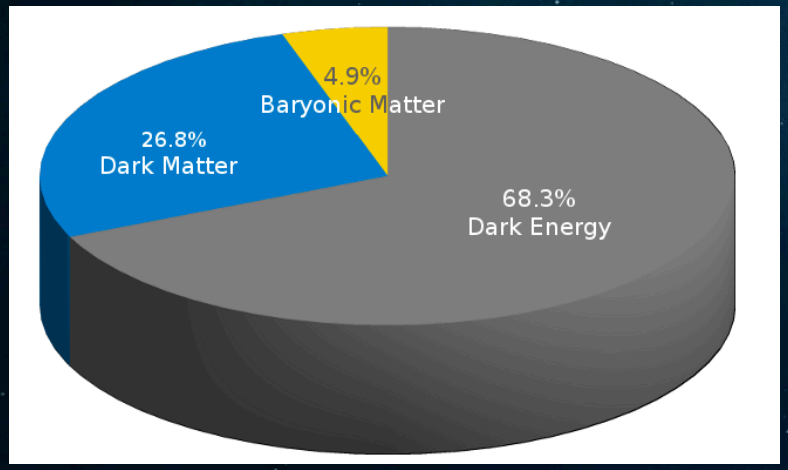
Looking into Future

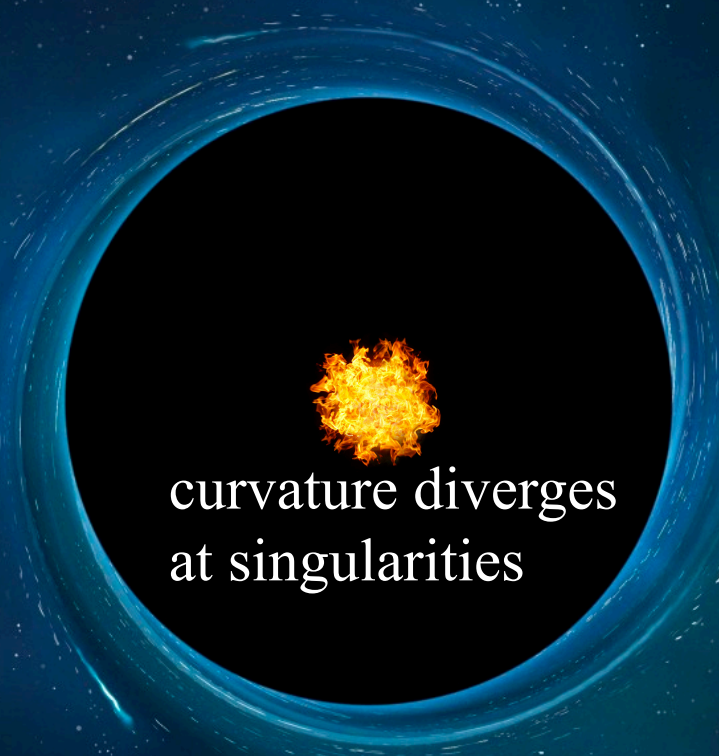
Outline

Testing Gravity with Current Gravitational Wave Observations

Why testing General Relativity?

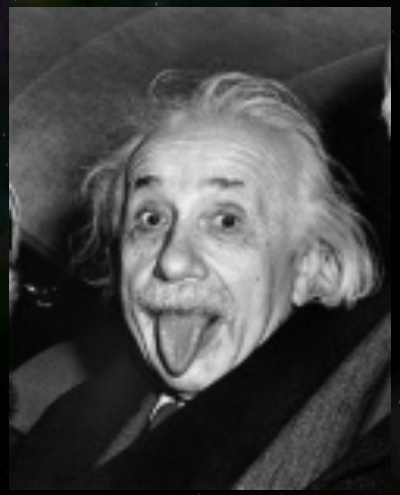
- missing mass
- accelerating expansion of the Universe
- quantum gravity? singularity…
- appreciate the beauty and simplicity of General Relativity





Lesson from History

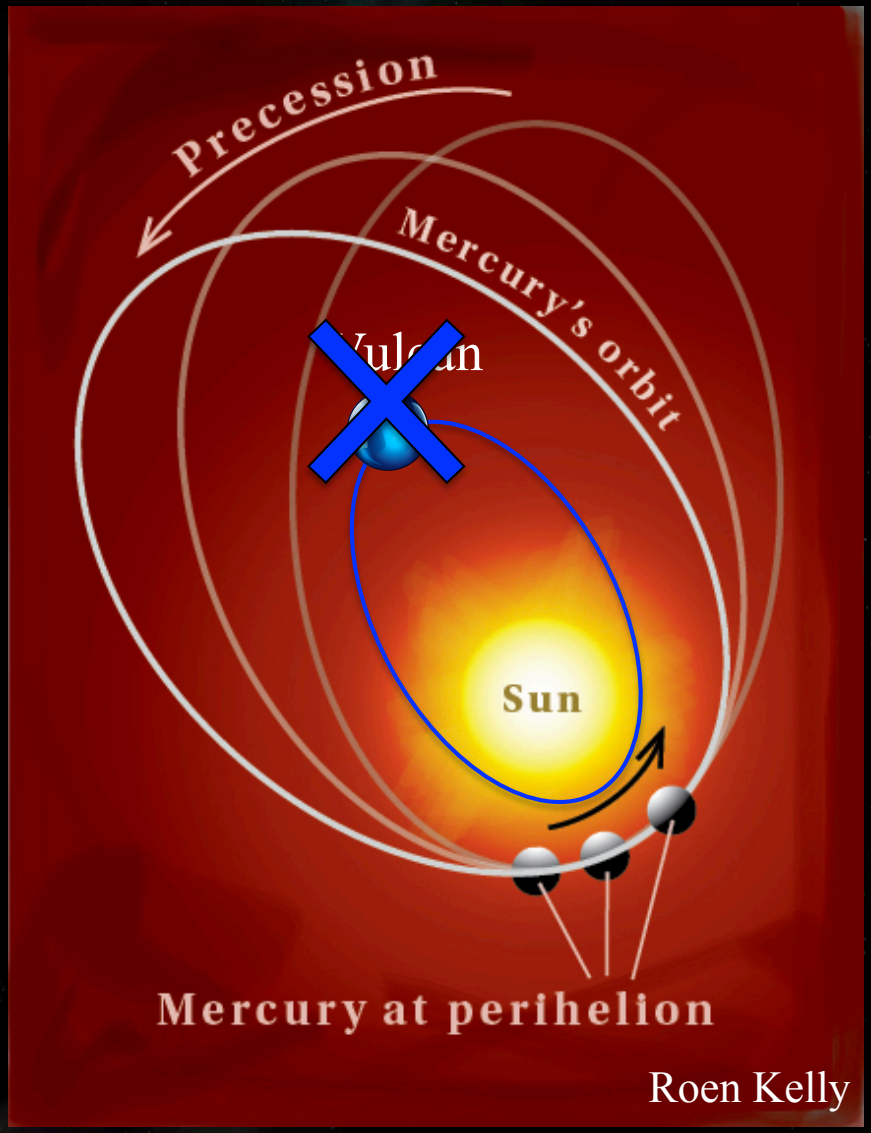
anomaly in perihelion precession of Mercury



General Relativity beautifully explains the anomalous precession!

Newtonian gravity

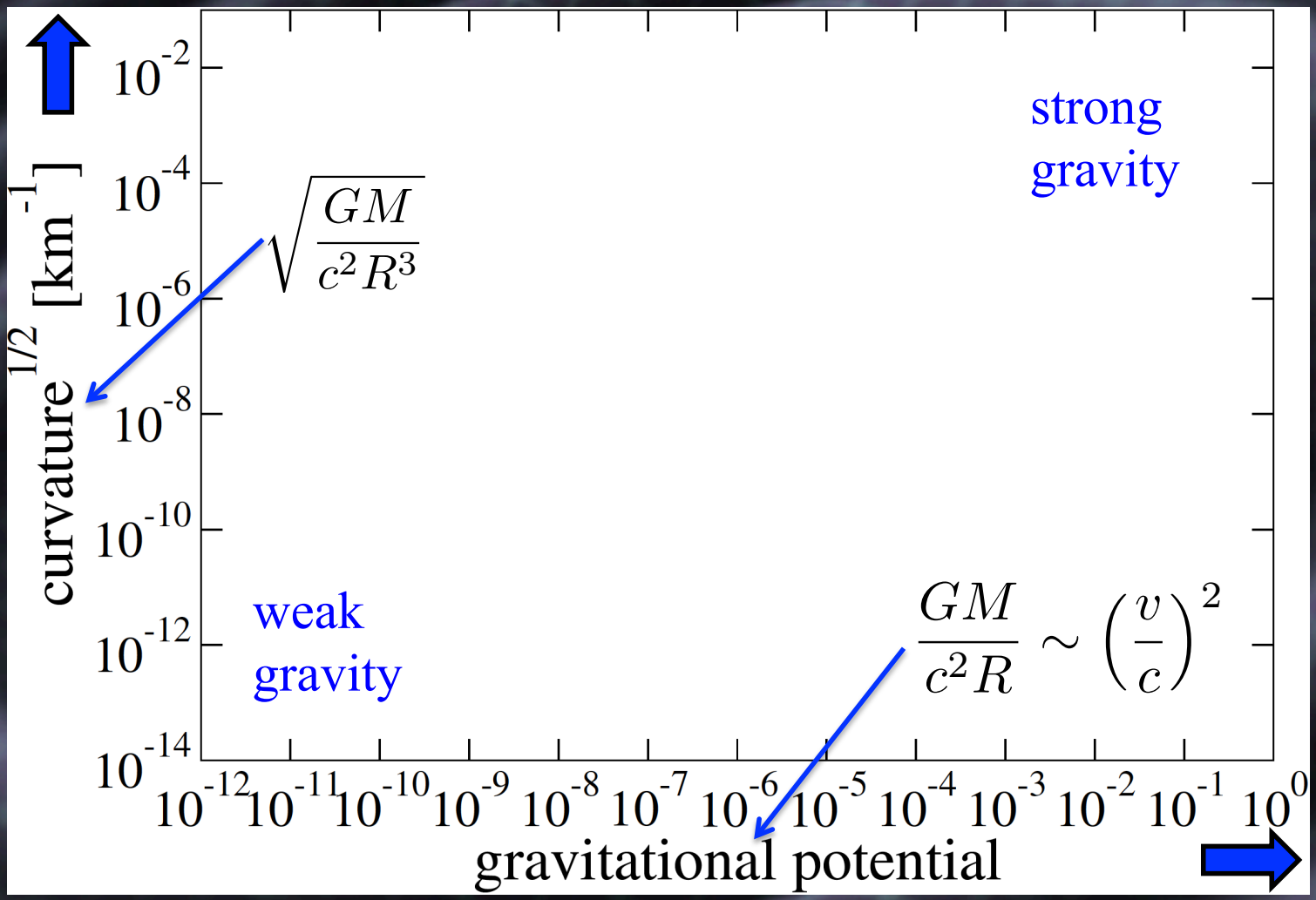
General Relativity



Roen Kelly

Is Einstein right…?

strong



[Yunes, KY & Pretorius PRD (2016)]

large

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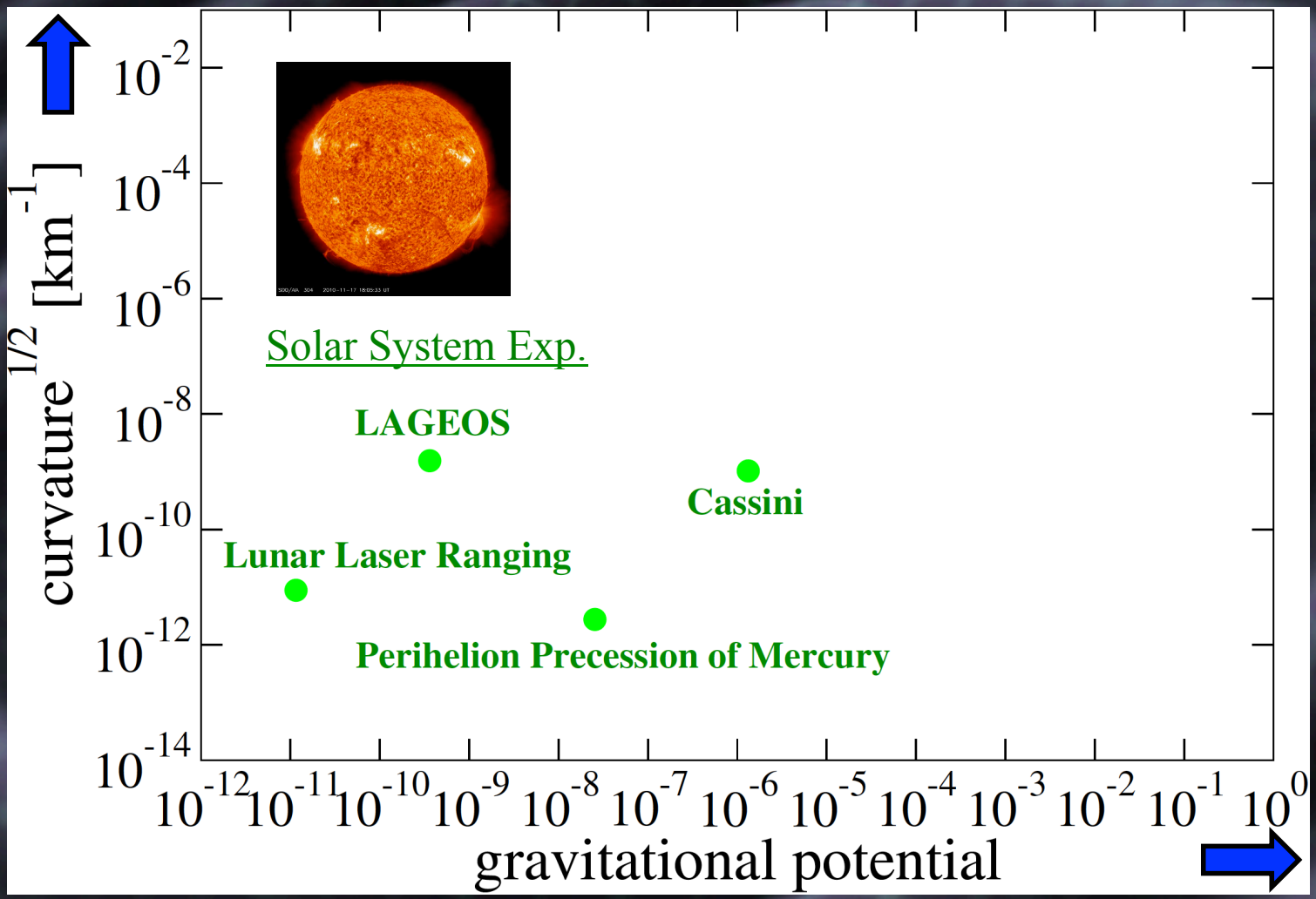

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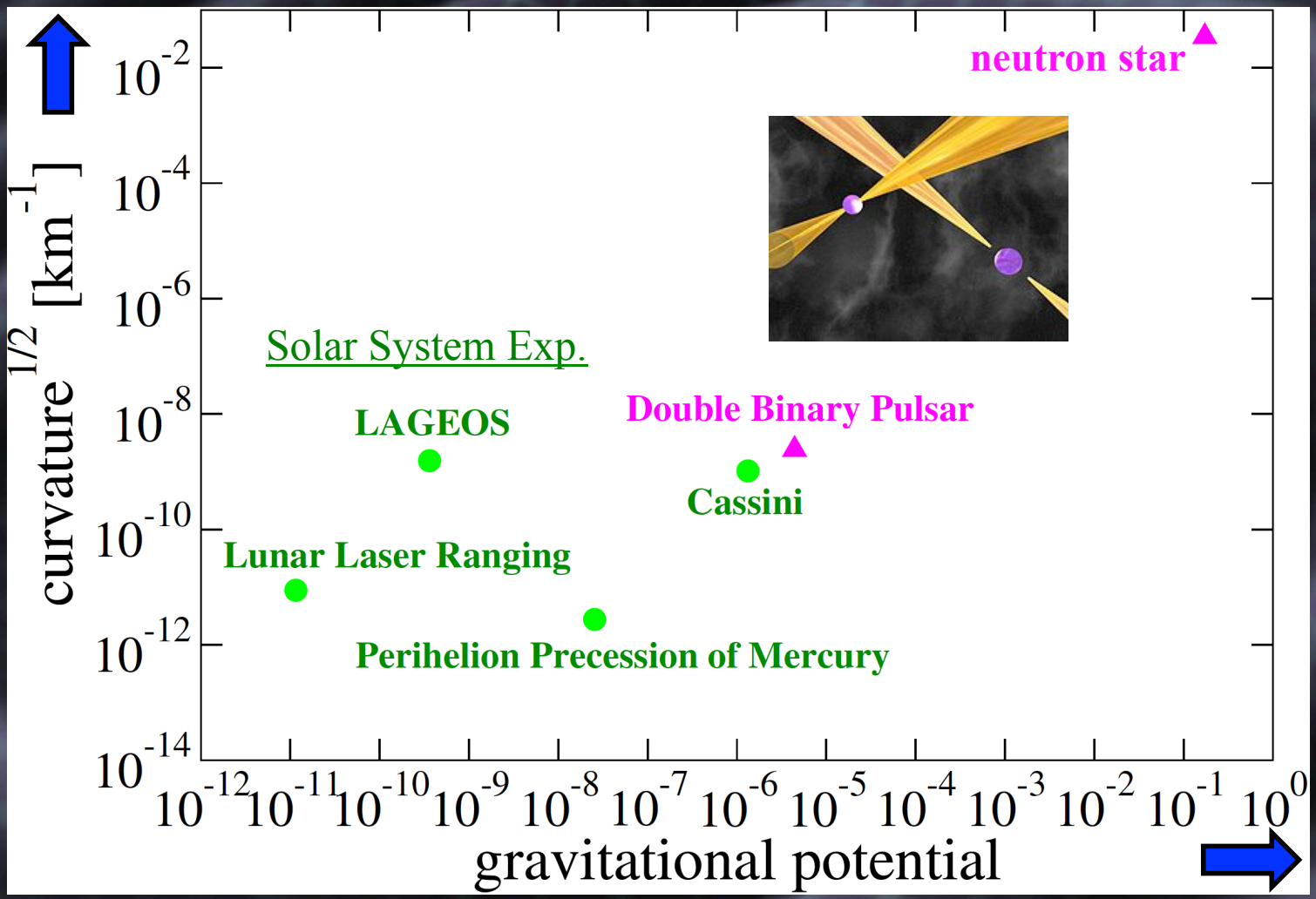


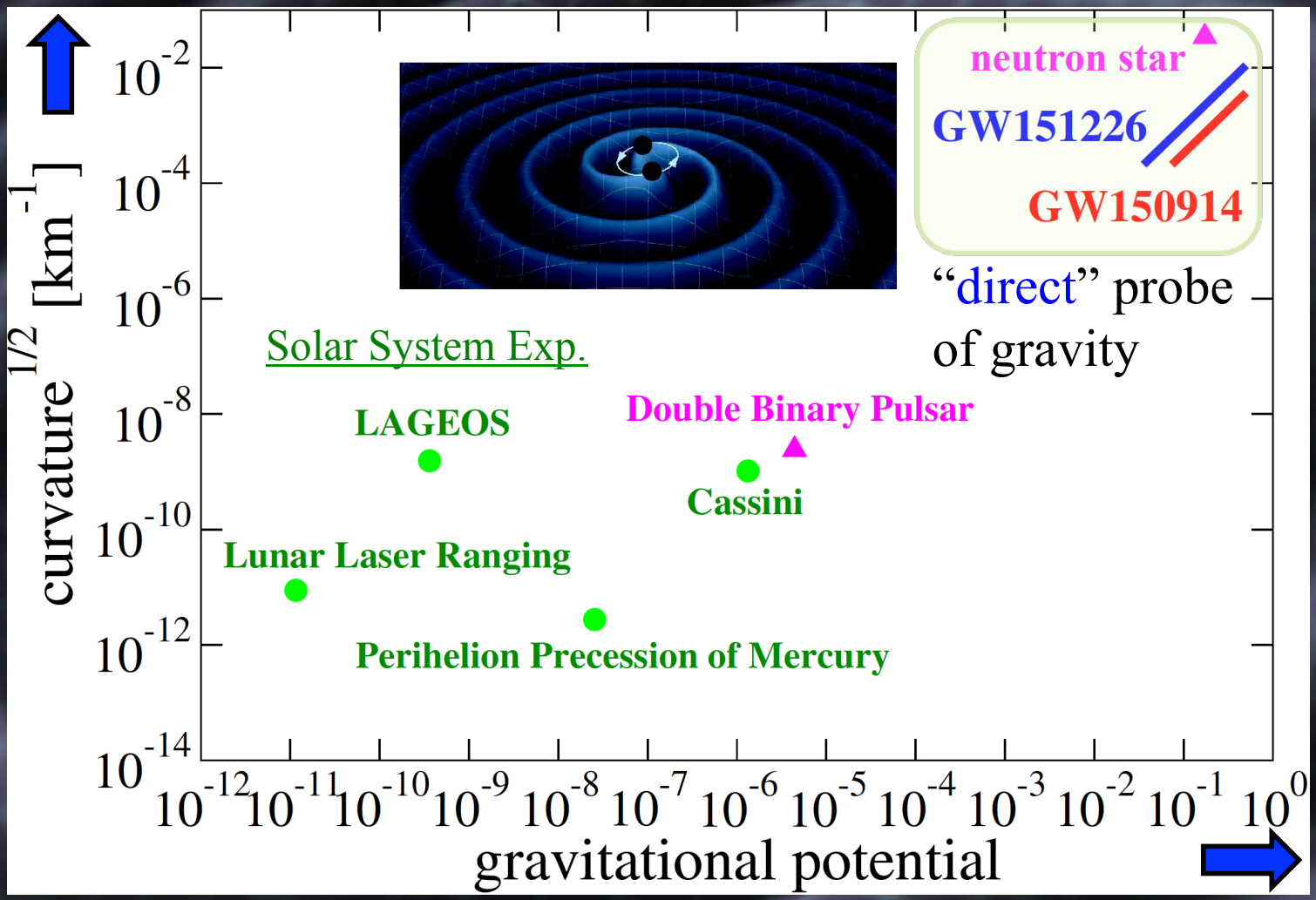
[Yunes, KY & Pretorius PRD (2016)]

large

Is Einstein right…?

Extreme Gravity = Strong & Dynamical Gravity

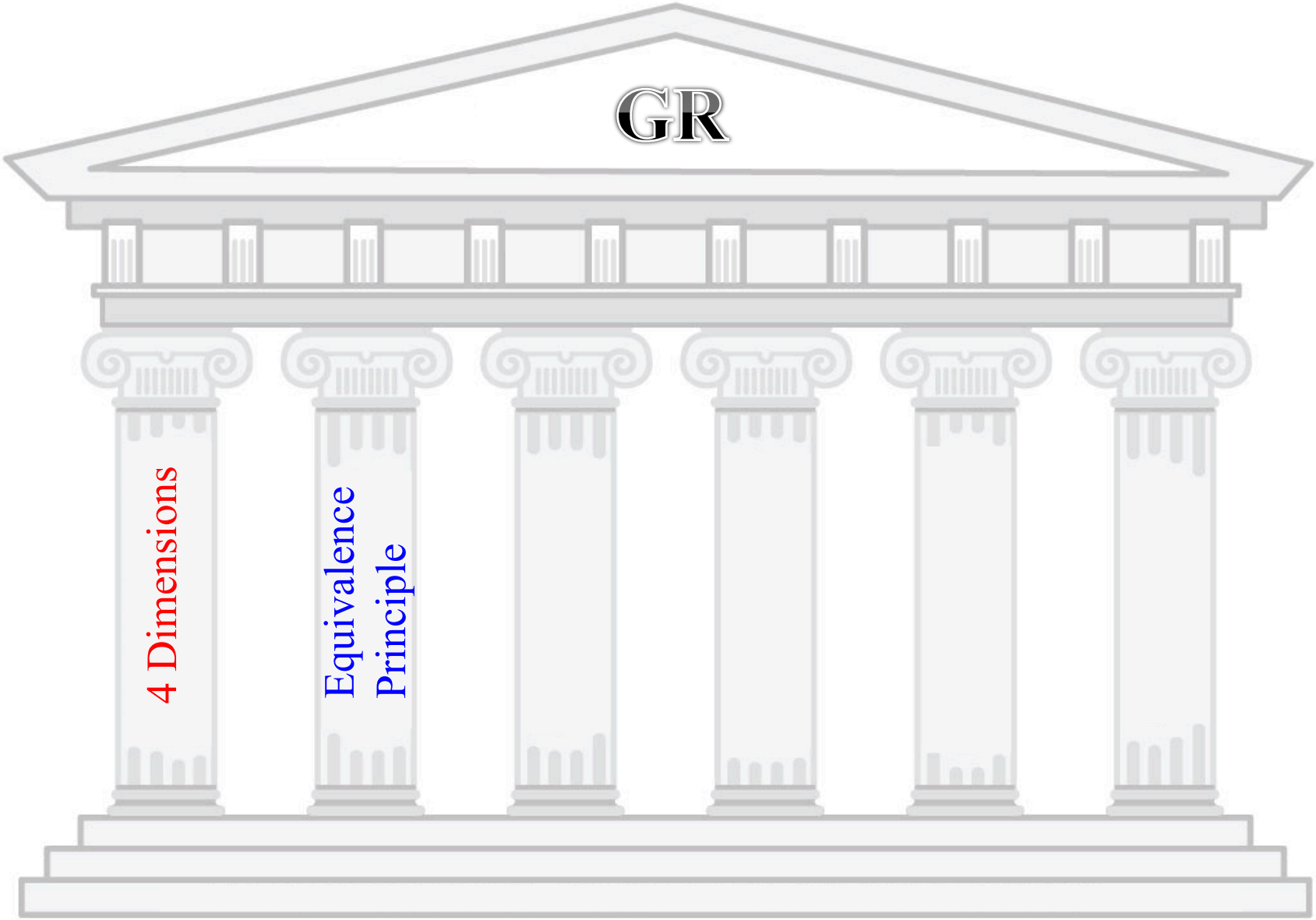
strong



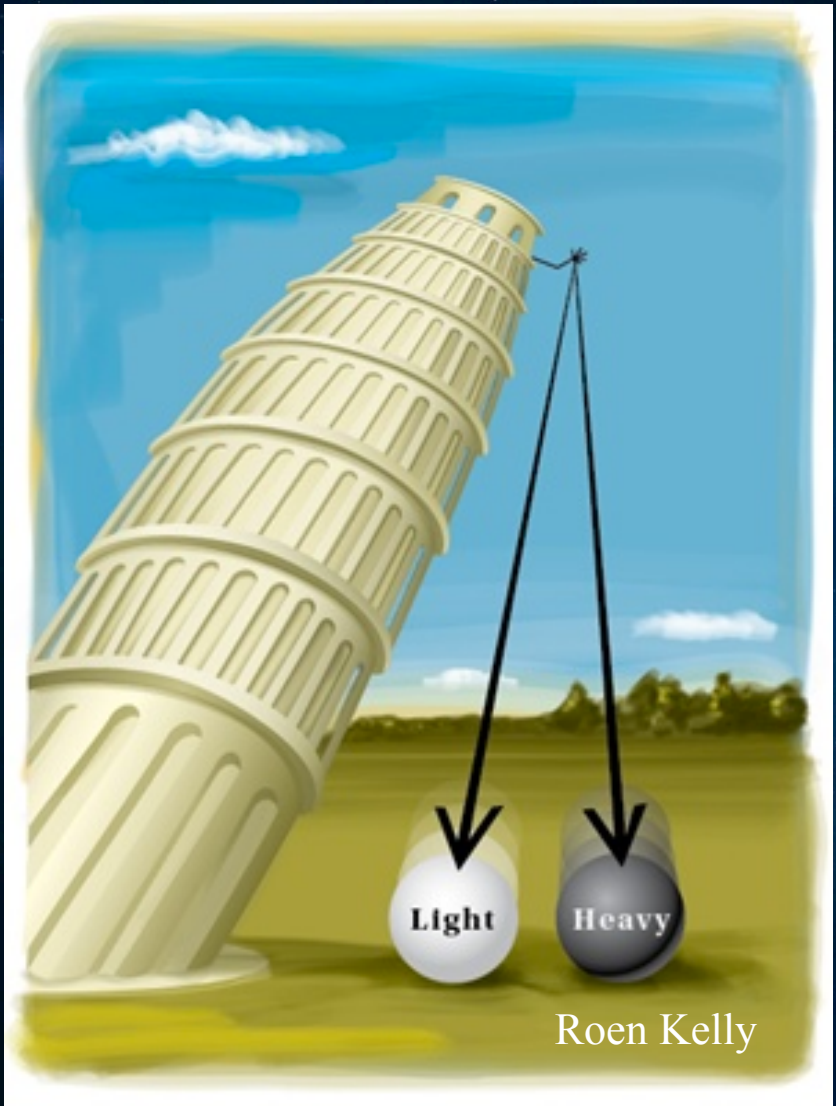
large

[Yunes, KY & Pretorius PRD (2016)]

Fundamental Pillars in General Relativity (GR)

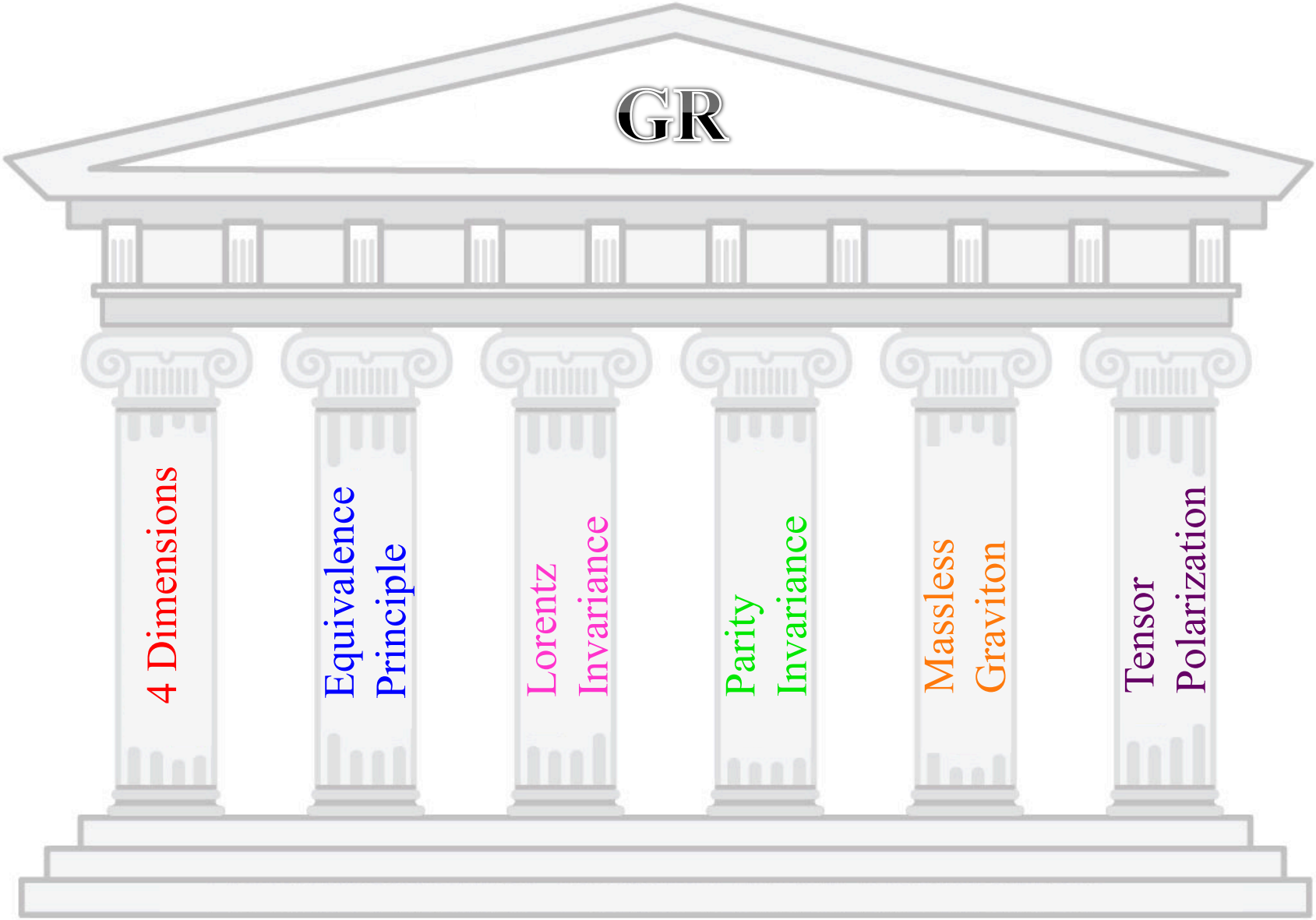


Equivalence Principle



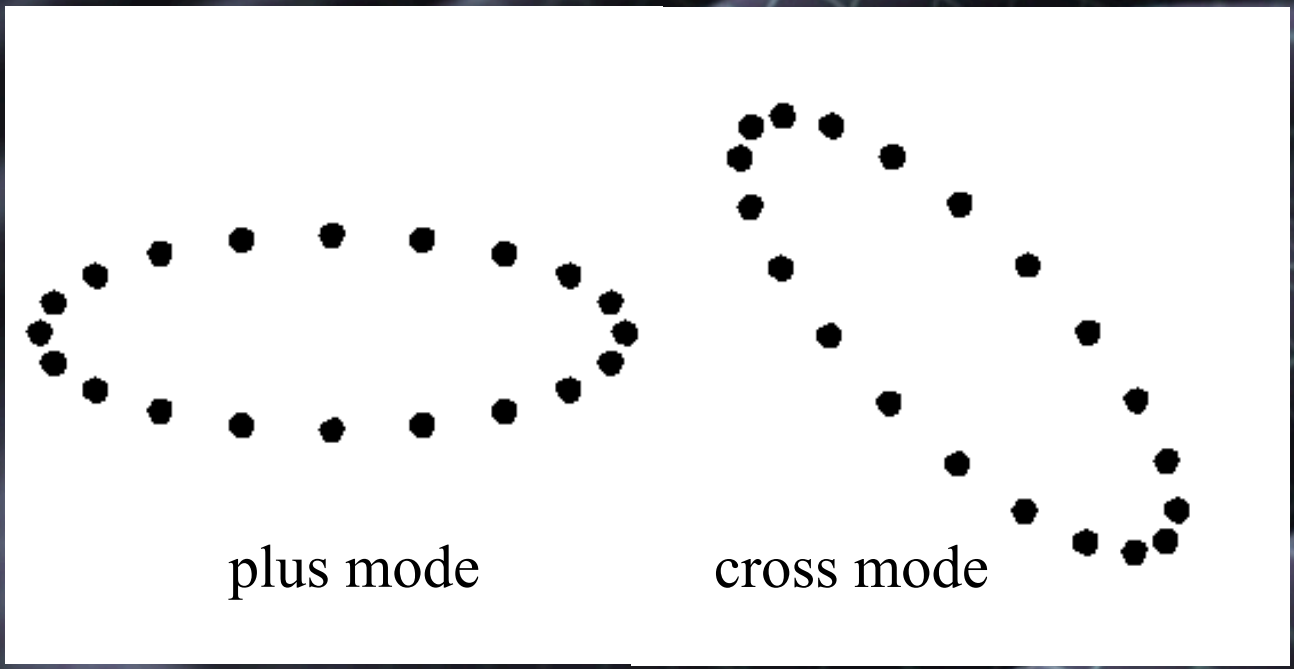
Universal
Free Fall

Fundamental Pillars in General Relativity (GR)

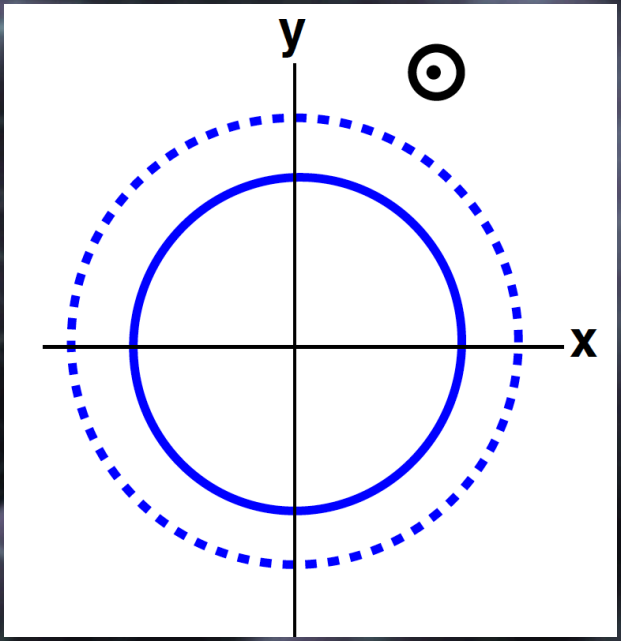


Polarizations

tensor polarizations

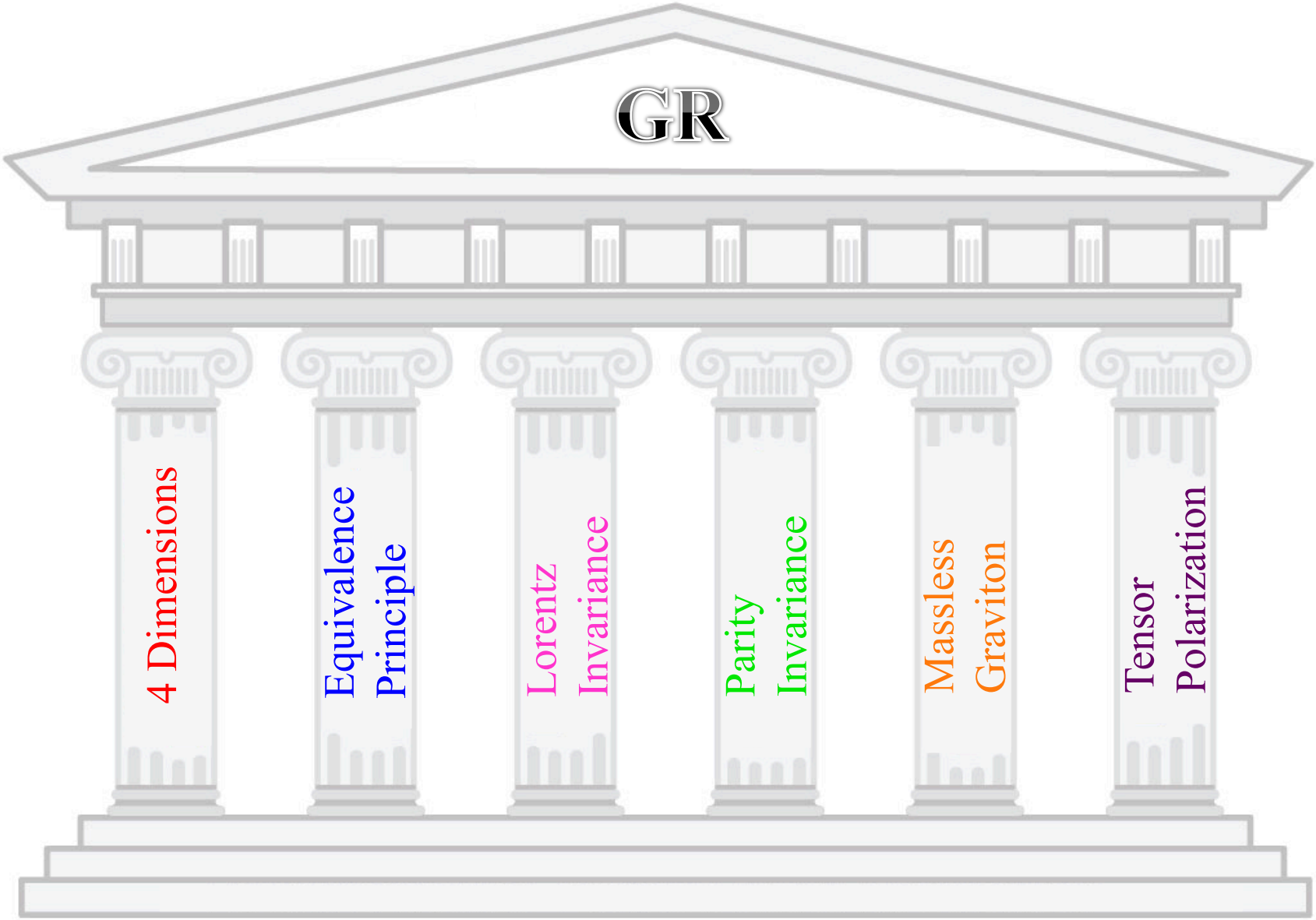


scalar polarization



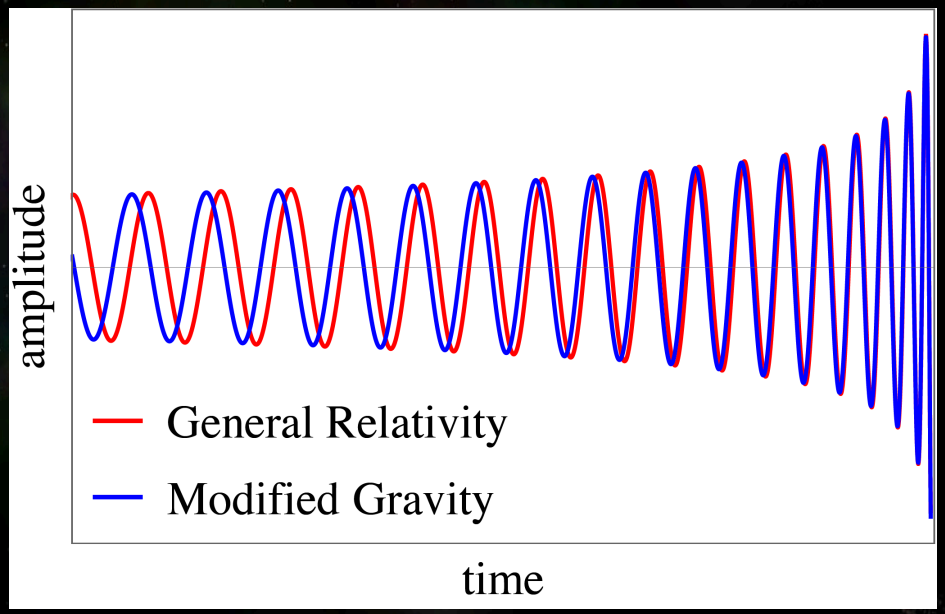
[Will Living Review]

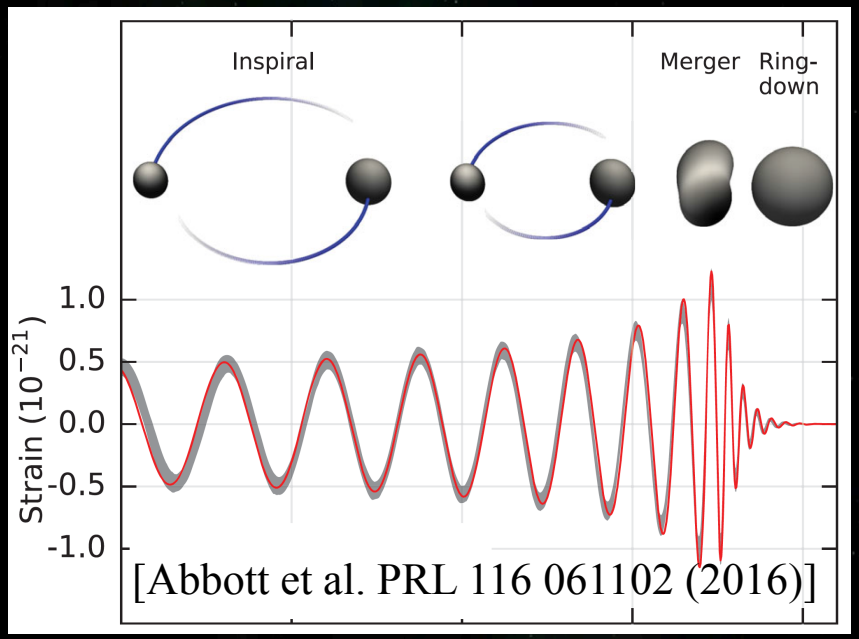
Fundamental Pillars in General Relativity (GR)



parameterized post-Einsteinian (ppE) Formalism

[Yunes & Pretorius (2009)]





<u>waveform phase:</u>

ppE parameter

relative velocity

$$\Psi^{(\mathrm{insp})} = \Psi^{(\mathrm{insp})}_{\mathrm{GR}} + \beta\,(v/c)^{2n-5}$$
$$\Psi^{(\mathrm{merg,ring})} = \Psi^{(\mathrm{merg,ring})}_{\mathrm{GR}}$$

nth post-Newton (PN) correction

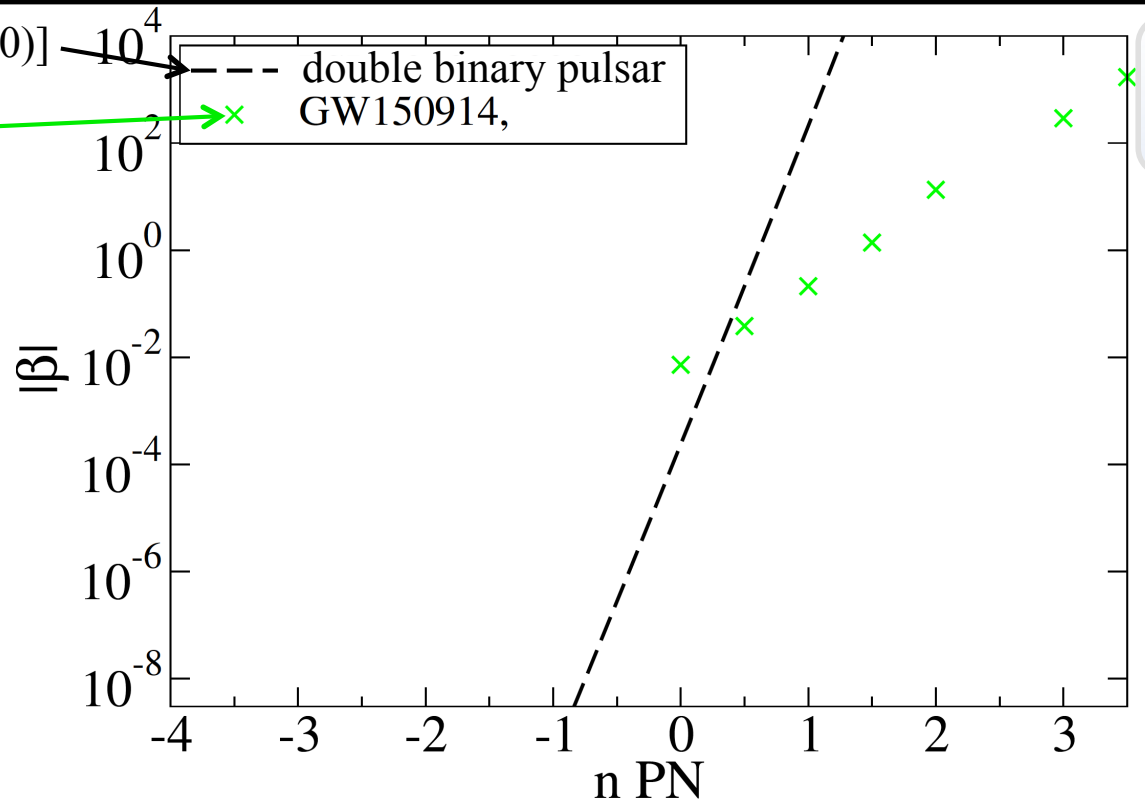
(lack of black hole binary merger simulations in non-Einsteinian theories)

Constraining GR Fundamental Pillars

[Yunes, KY & Pretorius PRD (2016)]

[Yunes & Hughes (2010)]

[LIGO-Virgo Collaboration (2016)]



$$\frac{\delta\Psi}{\Psi_{\rm GR}} = 1 + \beta\, v^{2n}$$

Be careful when comparing these bounds!!

Constraining GR Fundamental Pillars

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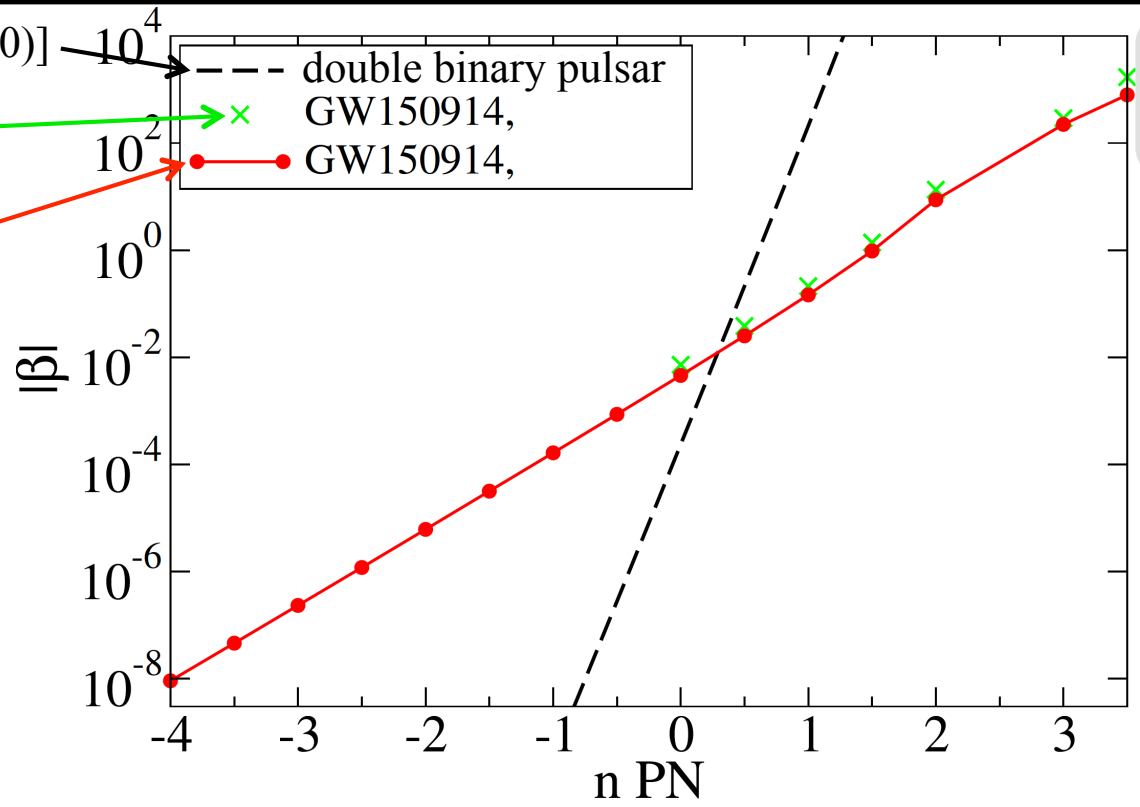

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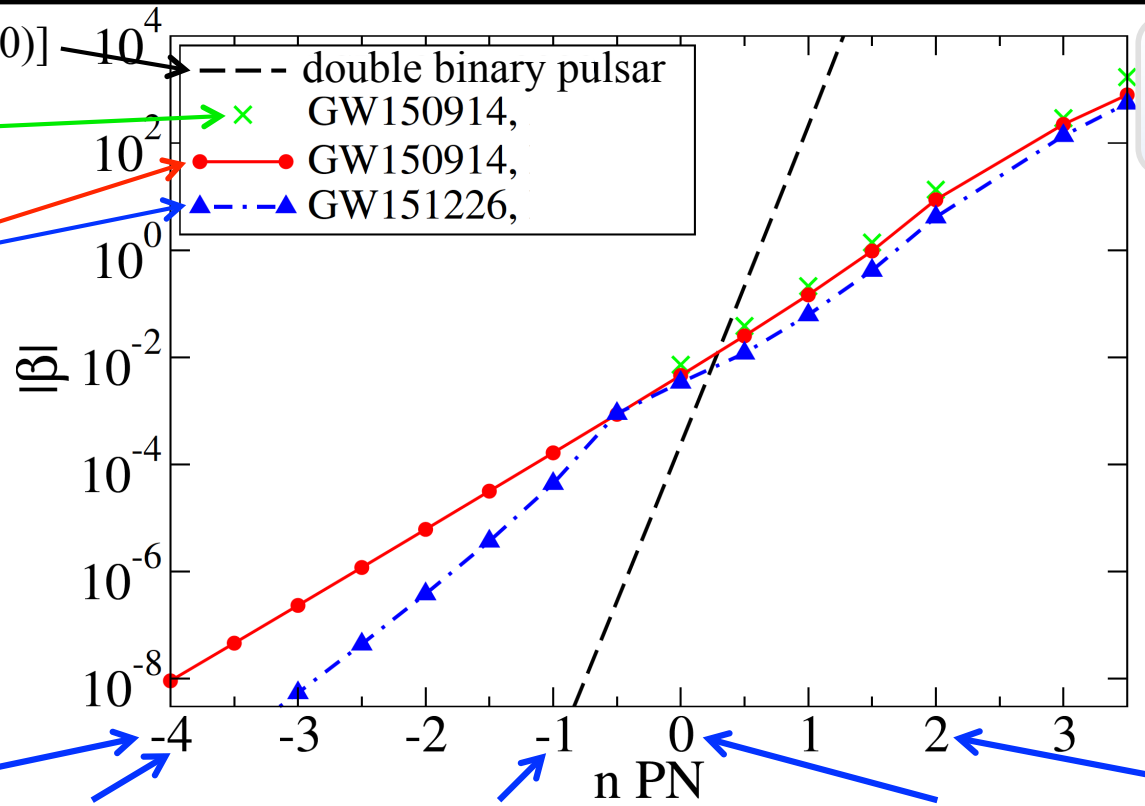


$$\frac{\delta\Psi}{\Psi_{\rm GR}} = 1 + \beta\, v^{2n}$$

Be careful when comparing these bounds!!

extra dimension	time varying G	scalar monopole activation	vector field activation	scalar dipole activation
⇓	⇓	⇓	⇓	⇓
4D	equivalence principle	equivalence principle	Lorentz invariance	parity invariance

Theoretical Constraints

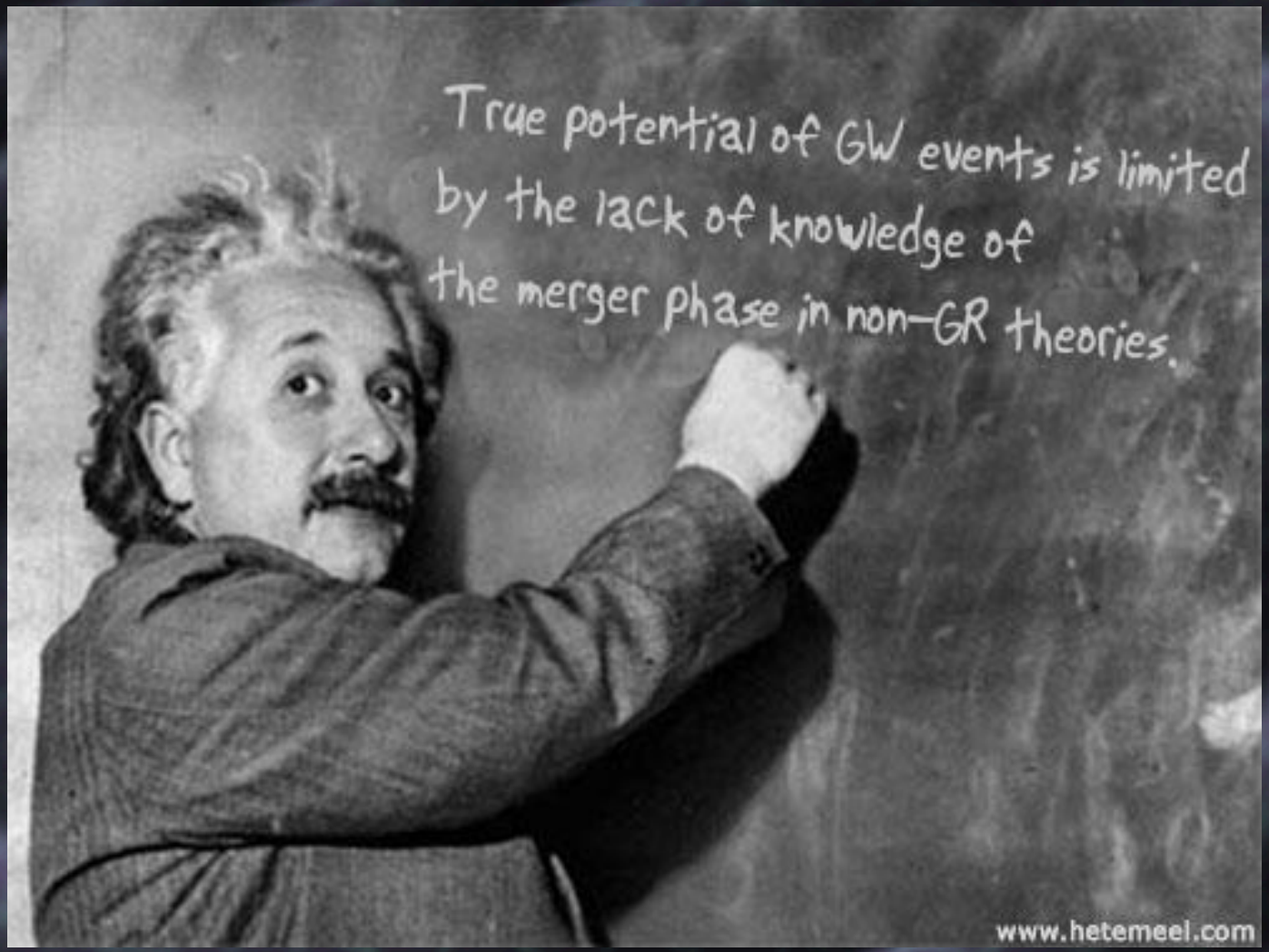
[Yunes, KY & Pretorius PRD (2016)]

no meaningful constraints
(beyond small-coupling approximation)

Example Theories (Theoretical Parameters)	GR Pillar	Example Theory Constraints		
		GW150914	**GW151226**	Current
Einstein-dilaton Gauss-Bonnet ($\sqrt{\lvert\alpha_{\rm EdGB}\rvert}$ [km])	Equiv. Princ.	—	—	10^7, 2
scalar-tensor ($\lvert\dot{\phi}\rvert$ [1/sec])	Equiv. Princ.	—	—	10^{-6}
dynamical Chern-Simons ($\sqrt{\lvert\alpha_{\rm dCS}\rvert}$ [km])	Parity Inv.	—	—	10^8
Einstein-Æther (c_+, c_-)	Lorentz Inv.	$(\mathbf{0.9}, \mathbf{2.1})$	$(\mathbf{0.8}, \mathbf{1.1})$	$(0.03, 0.003)$
RS-II Braneworld (ℓ [μm])	4D	$\mathbf{5.4 \times 10^{10}}$	$\mathbf{2.0 \times 10^{9}}$	10–10^3
time-varying G ($\lvert\dot{G}\rvert/G$ [10^{-12}/yr])	Equiv. Princ.	$\mathbf{5.4 \times 10^{18}}$	$\mathbf{1.7 \times 10^{17}}$	0.1–1

weaker than current bounds
first constraint in the strong/dynamical gravity regime

Important Message

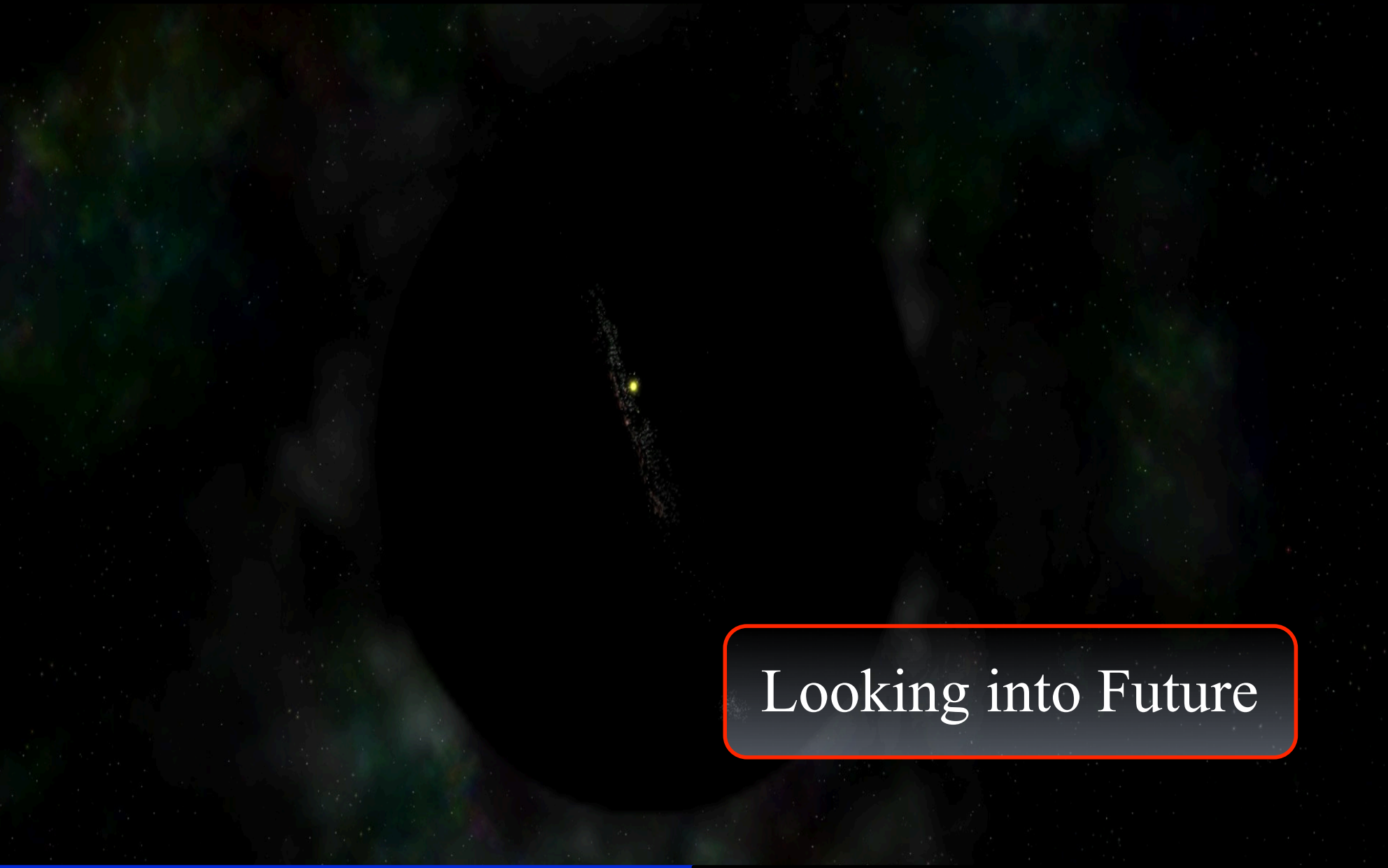


Outline

Testing Gravity with Current Gravitational Wave Observations

Looking into Future

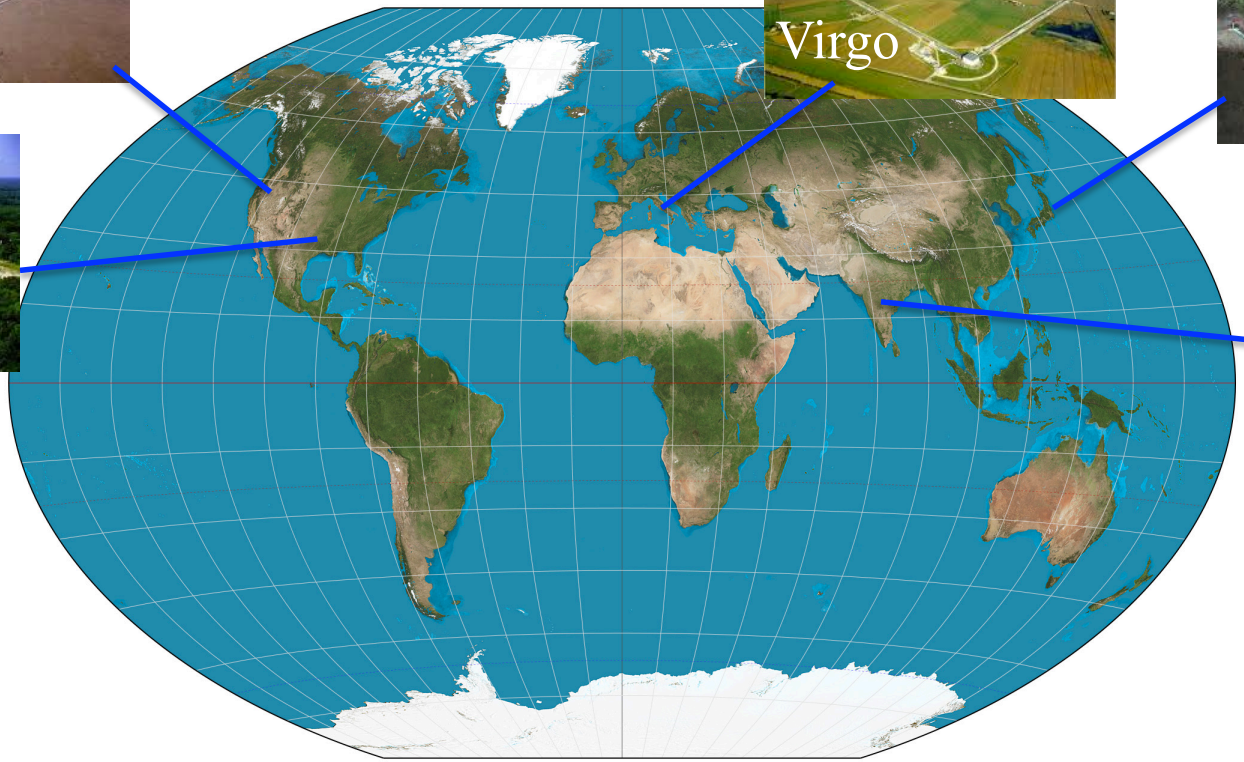
Outline



Looking into Future

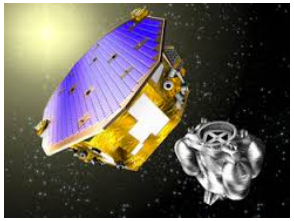
Very Bright Future!

2019?



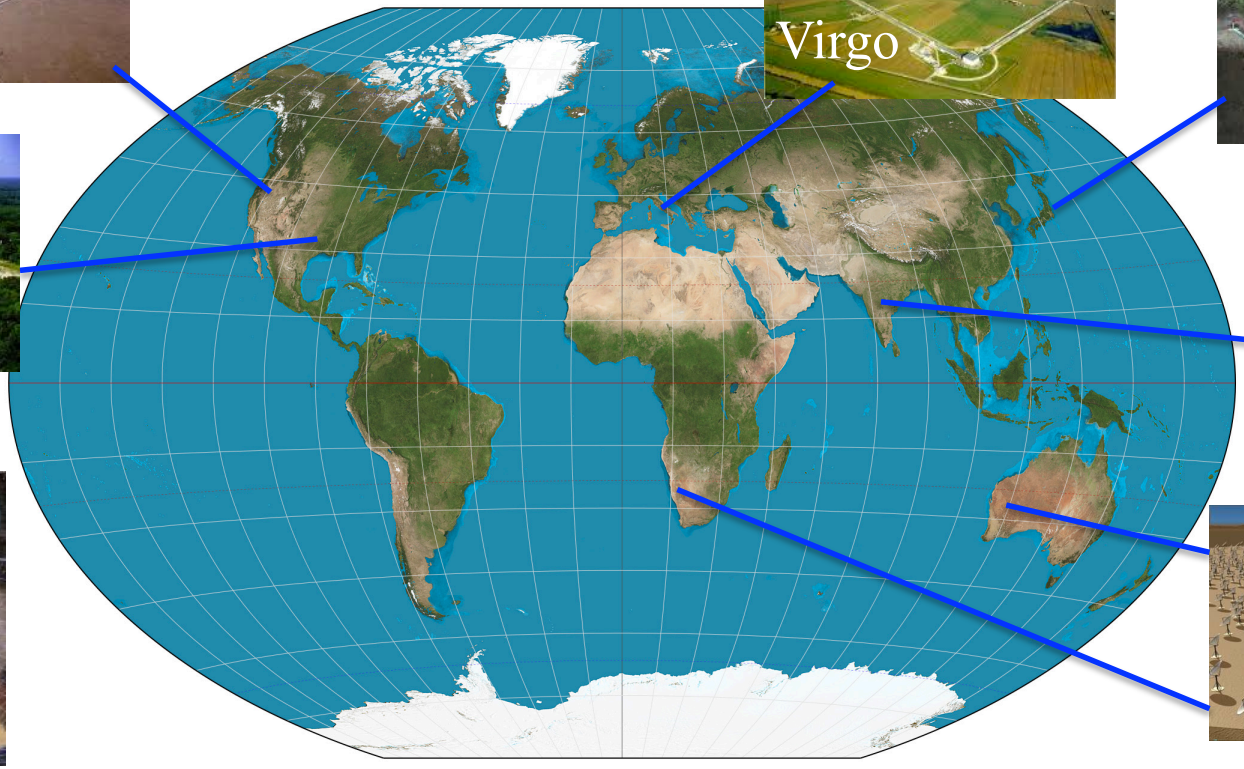
LIGO-India

LISA Pathfinder



Very Bright Future!

2019?

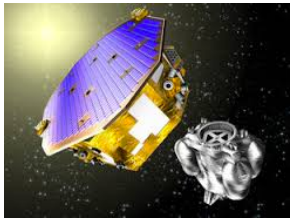


LIGO-India

2022-2024?

2020?

LISA Pathfinder

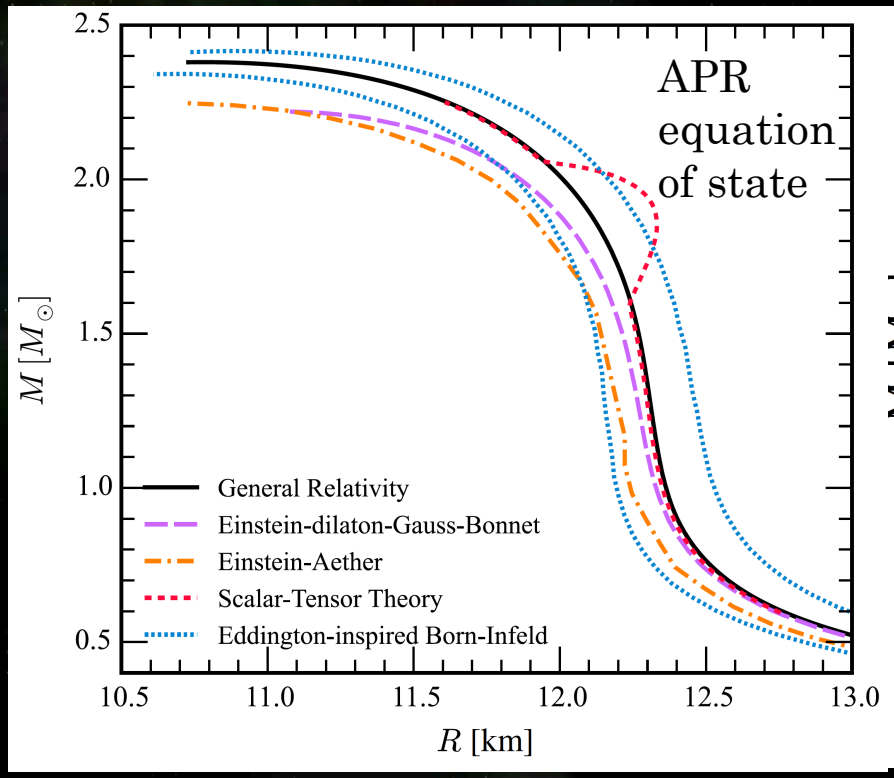


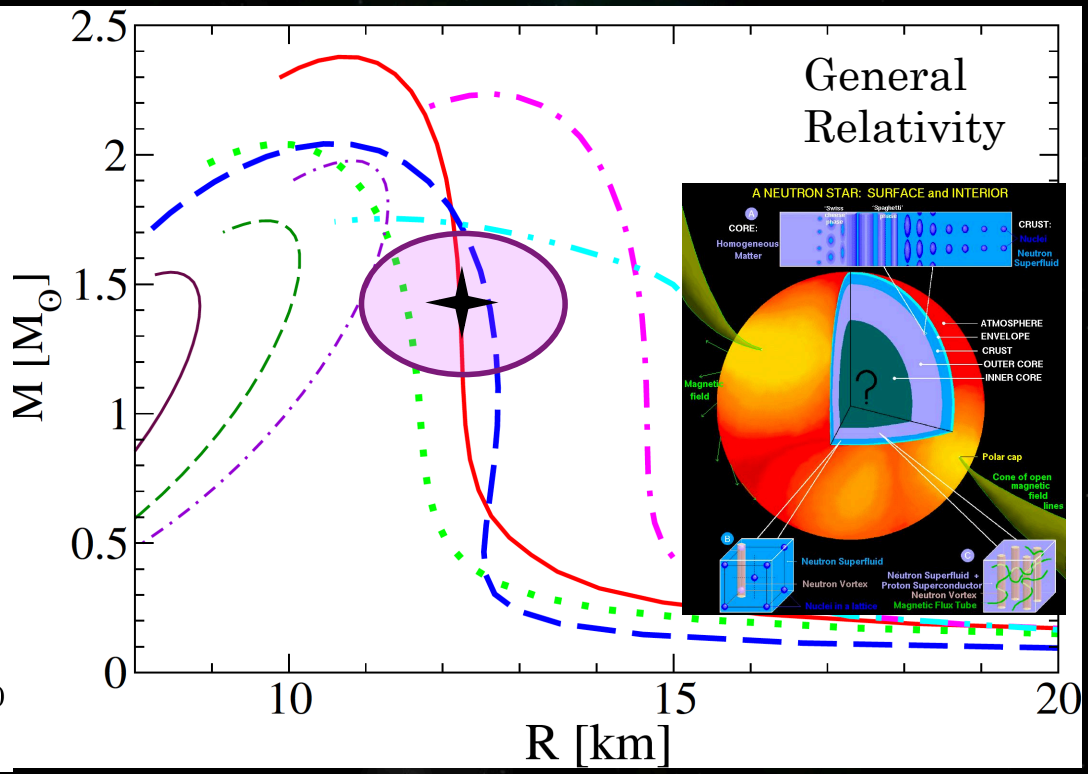
Multi-band / Multi-messenger Astronomy!

Neutron Star Based Tests of Gravity

sensitive to gravitational theory

sensitive to equation of state





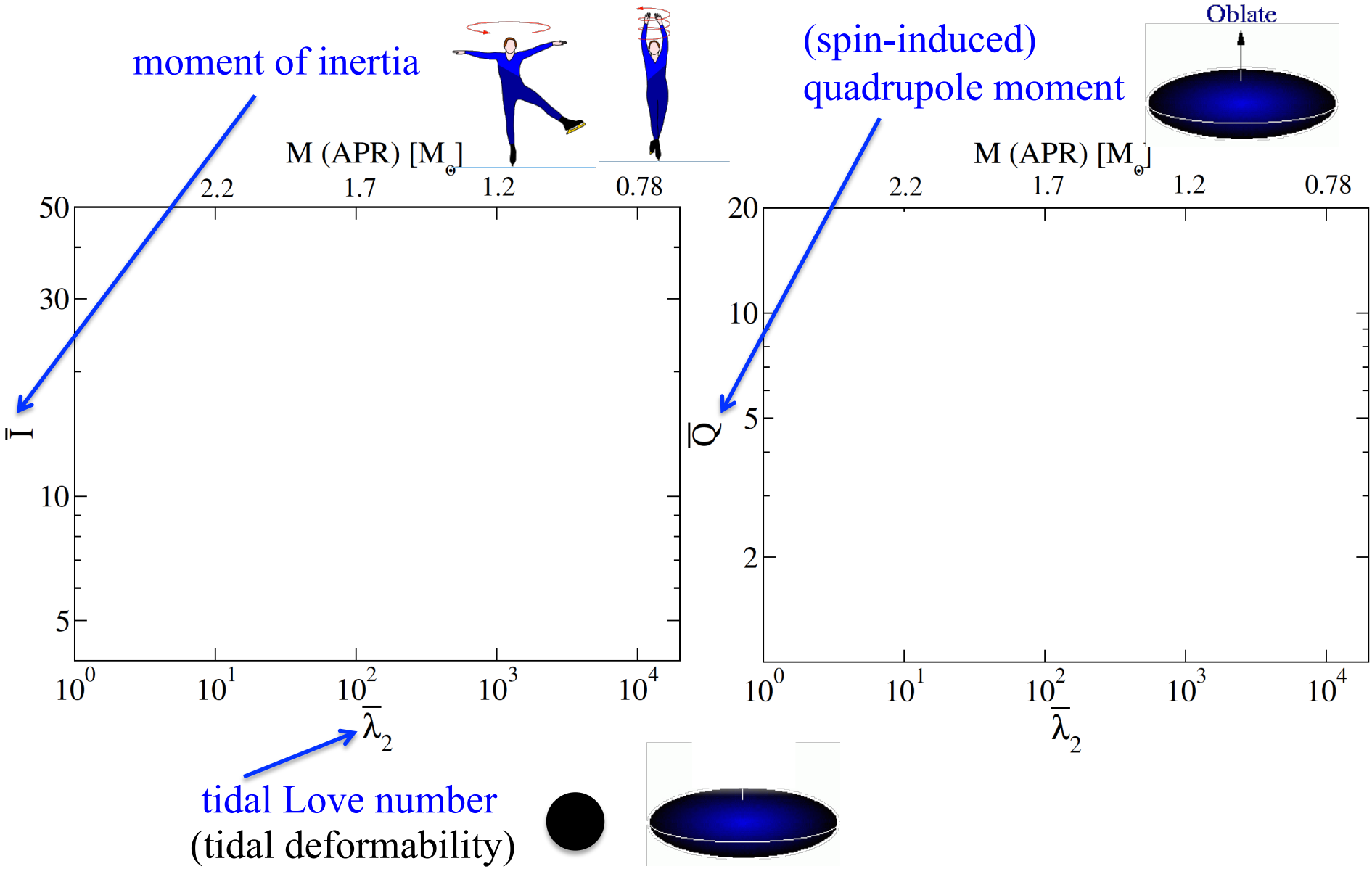
[Glampedakis et al. (2015)]

degeneracies between uncertainties in nuclear and gravitational physics

equation of state insensitive universal relations?

I-Love-Q Relations!

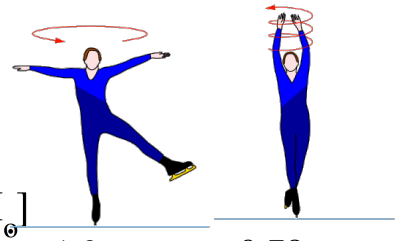
[KY & Yunes, Science 341 365 (2013)]



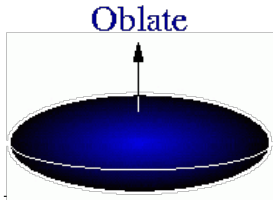
I-Love-Q Relations!

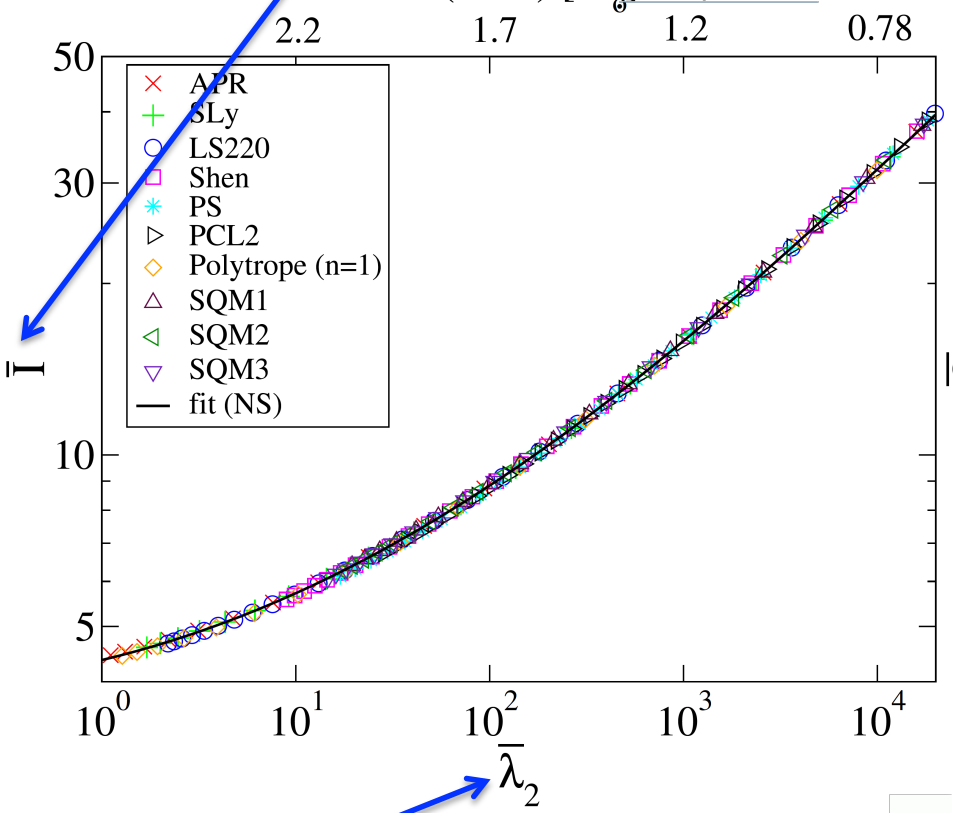
[KY & Yunes, Science 341 365 (2013)]

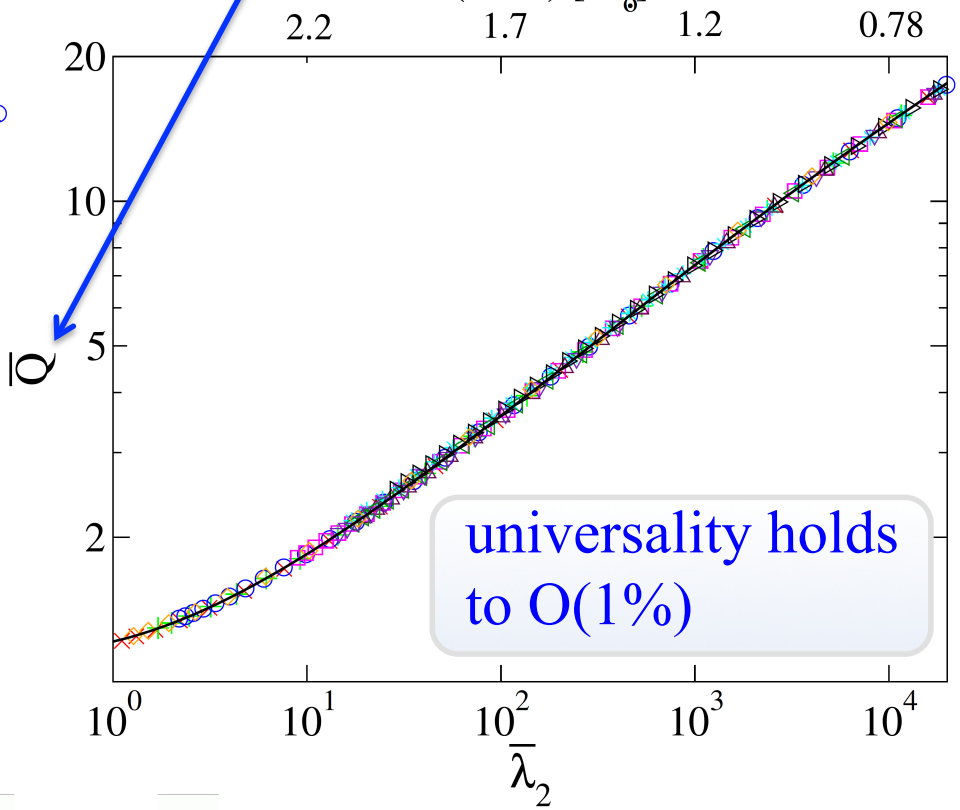
moment of inertia



(spin-induced) quadrupole moment

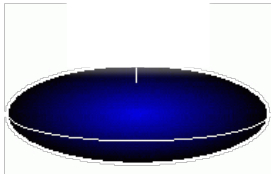






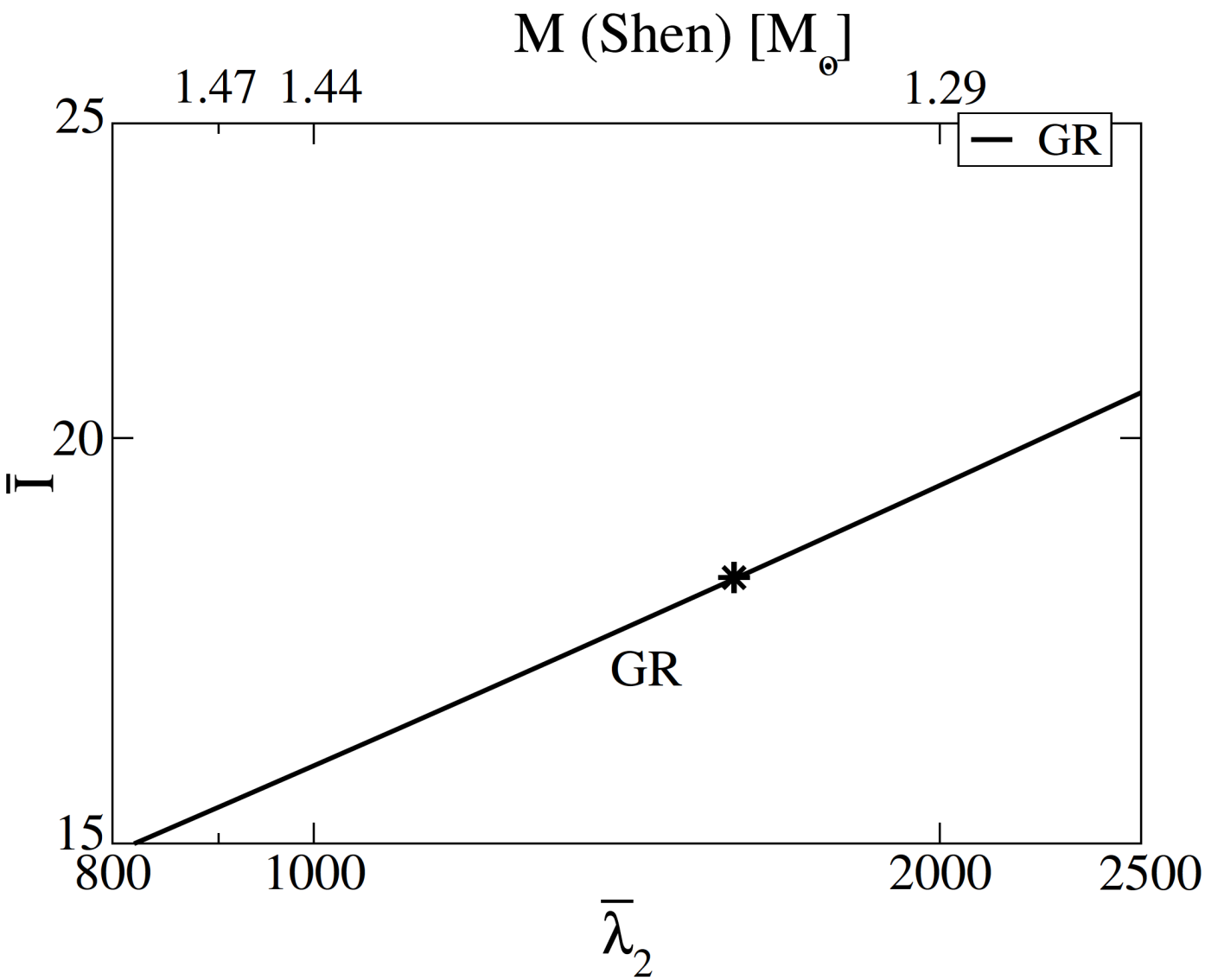
universality holds to O(1%)

tidal Love number
(tidal deformability)



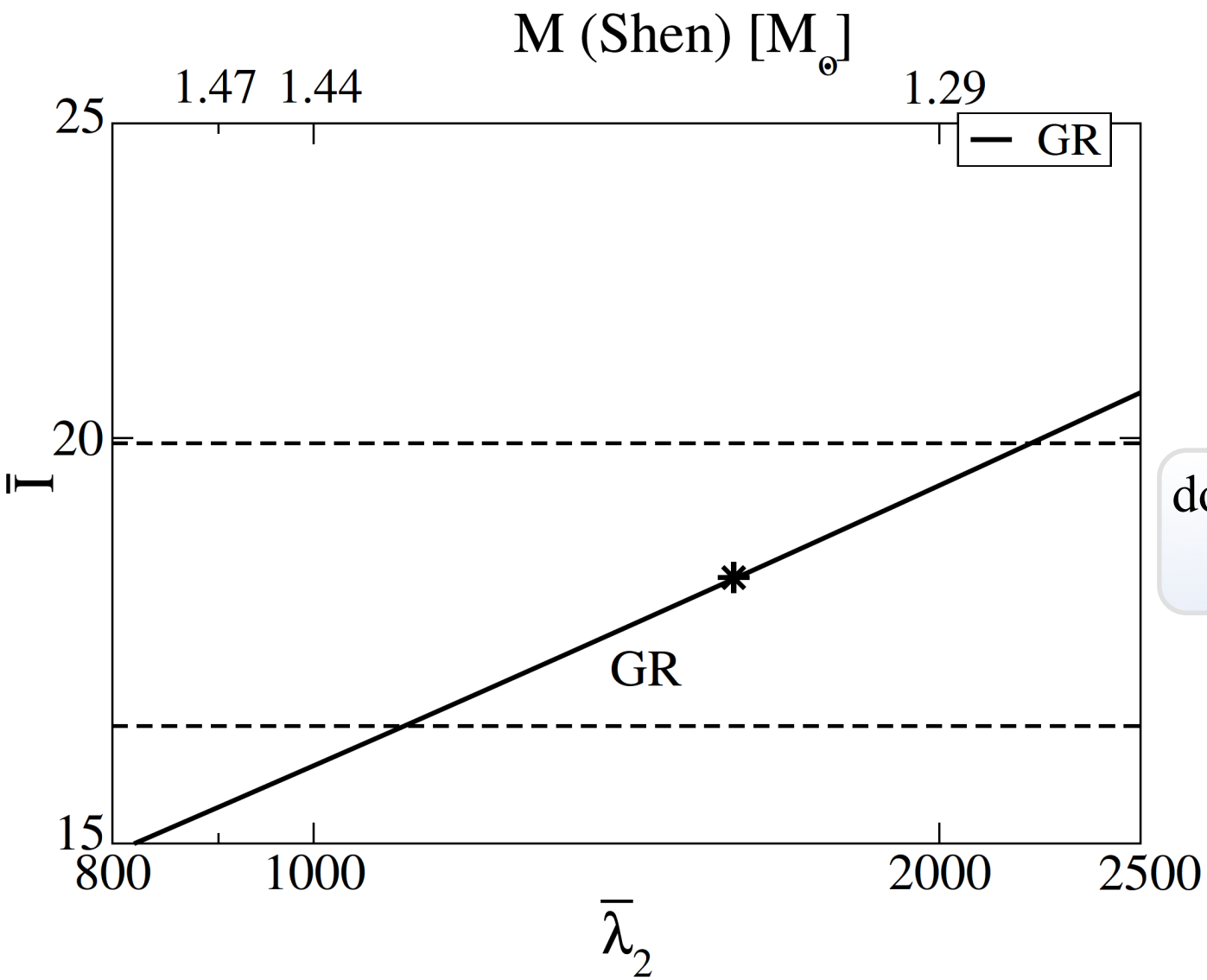
Extreme Gravity Tests

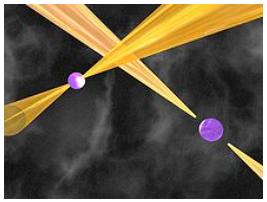
[KY & Yunes, Science 341 365 (2013)]



Extreme Gravity Tests

[KY & Yunes, Science 341 365 (2013)]



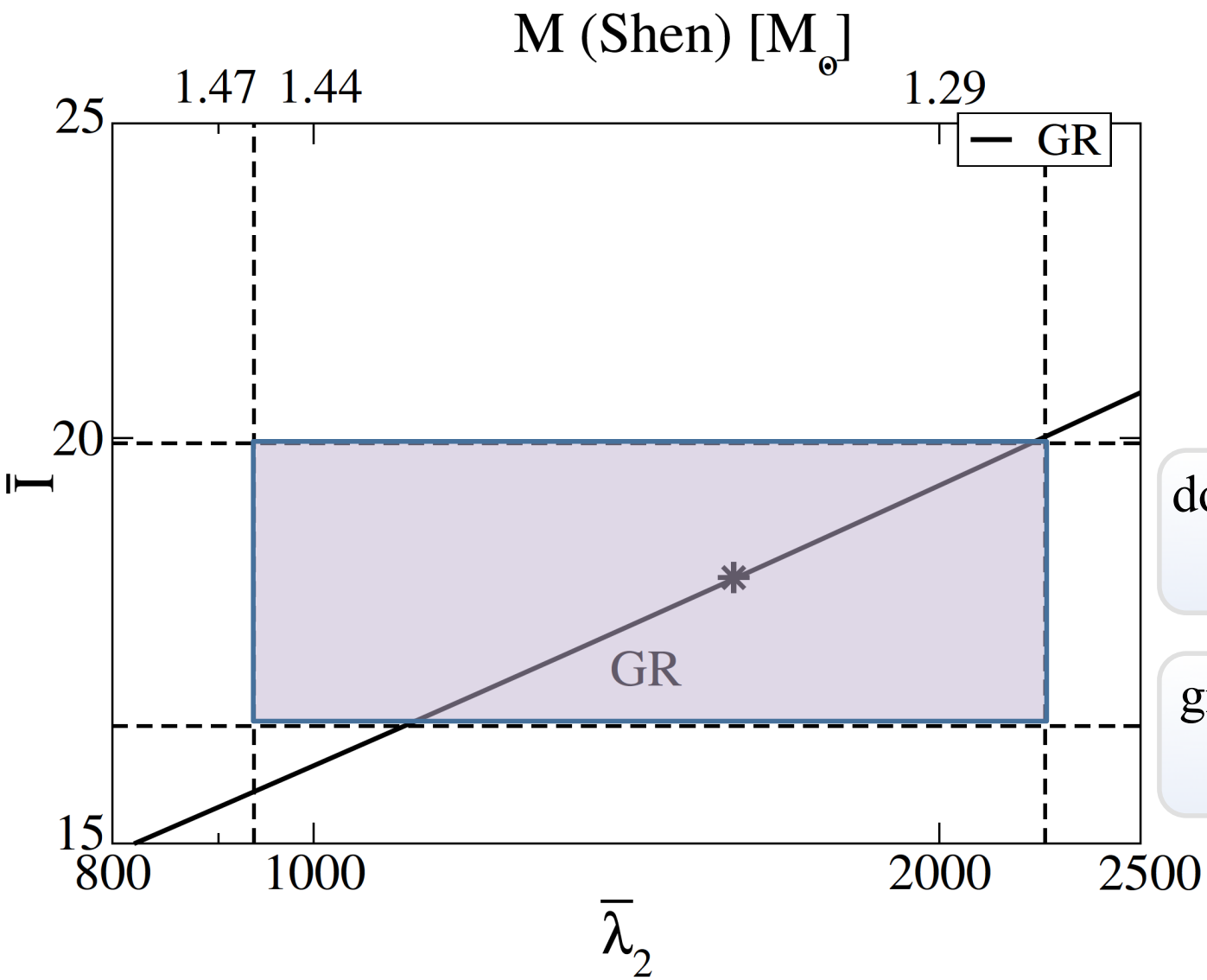


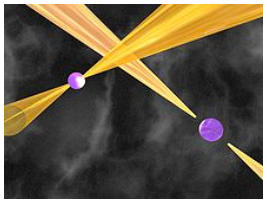
double binary pulsar

$\Delta\bar{I}/\bar{I} = 10\%$

Extreme Gravity Tests

[KY & Yunes, Science 341 365 (2013)]



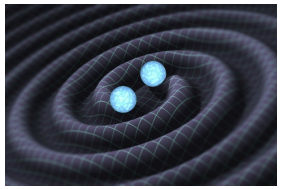


double binary pulsar

$\Delta\bar{I}/\bar{I} = 10\%$

gravitational waves

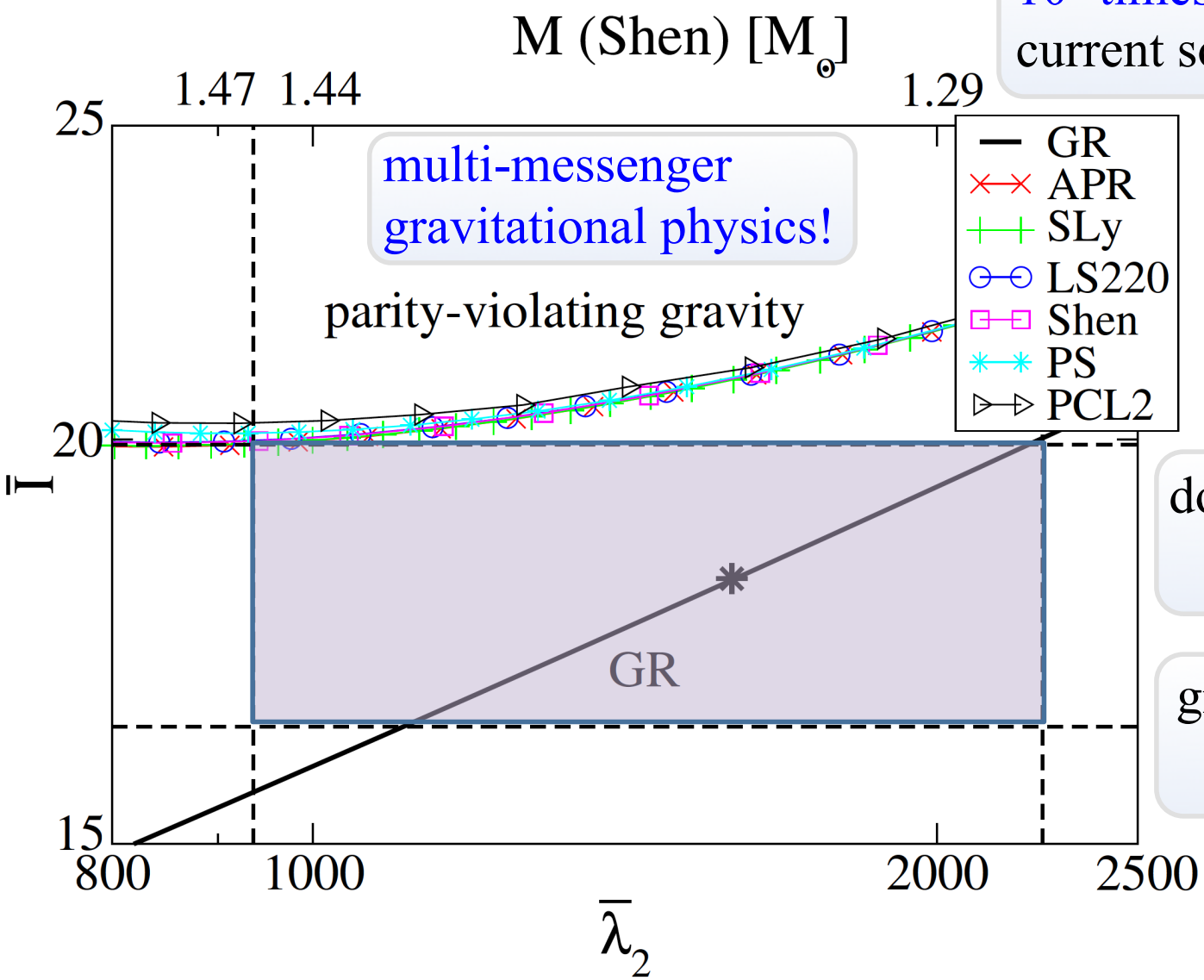
$\Delta\bar{\lambda}_2/\bar{\lambda}_2 = 40\%$



Extreme Gravity Tests

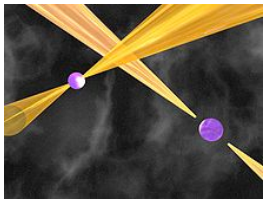
[KY & Yunes, Science 341 365 (2013)]

10^6 times stronger than the current solar system bound!



multi-messenger gravitational physics!

parity-violating gravity

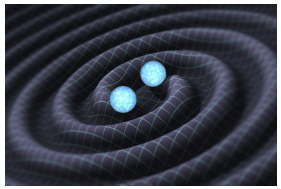


double binary pulsar

$\Delta\bar{I}/\bar{I} = 10\%$

gravitational waves

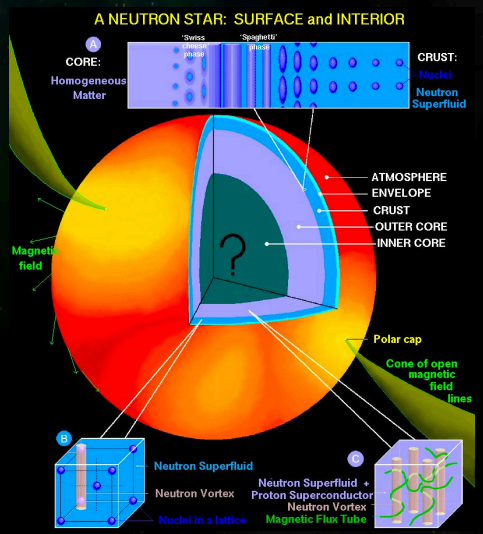
$\Delta\bar{\lambda}_2/\bar{\lambda}_2 = 40\%$



Other Applications

Astrophysics

[Newton, Steiner & KY (2016)]

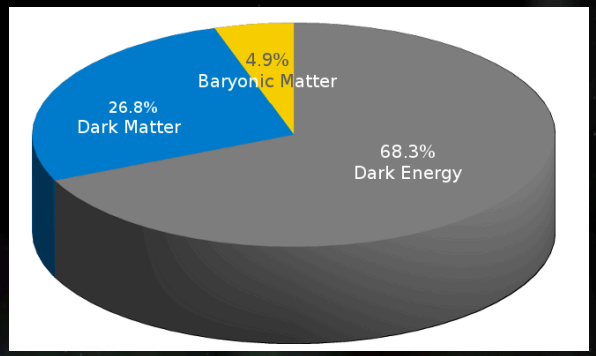


[KY & Yunes, PRD (2014)]
[KY & Yunes, CQG (2016)]

Nuclear Physics

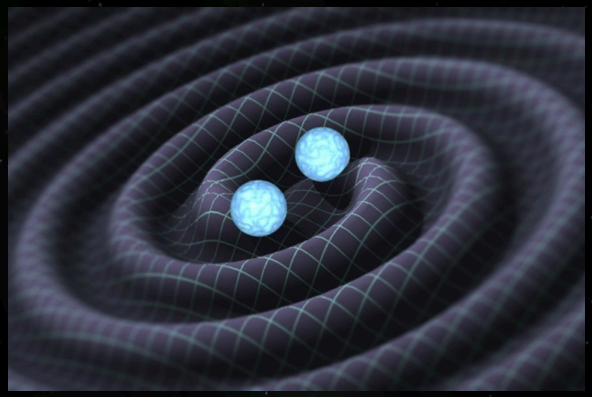
Universal Relations

review article [KY & Yunes arXiv:1608.02582]



Gravitational-wave Physics

[KY & Yunes, Science (2013)]
[KY & Yunes, PRD (2013)]



[KY & Yunes, CQG (2016)]
[KY & Yunes, CQG (2017)]

Cosmology

Future Directions

Maximize our ability of extracting fundamental physics information

Gravitational Physics

Black Holes
&
Neutron Stars

Nuclear Physics

Cosmology

Multi-band /
Multi-messenger
Fundamental
Physics!

Future Directions

Maximize our ability of extracting fundamental physics information

Gravitational Physics

construct parameterized non-Einsteinian waveform including the merger phase (effective one body approach)

stacking multiple signals

[Yang, KY et al., arXiv:1701.05808]

Black Holes & Neutron Stars

Multi-band / Multi-messenger Fundamental Physics!

Nuclear Physics

Cosmology

Future Directions

Maximize our ability of extracting fundamental physics information

stacking post-merger signals of neutron star coalescences

multiband gravitational-wave nuclear astrophysics

other universal relations for neutron stars

Gravitational Physics

Black Holes & Neutron Stars

Multi-band / Multi-messenger Fundamental Physics!

Nuclear Physics

Cosmology

Future Directions

Maximize our ability of extracting fundamental physics information

Gravitational Physics

gravitational wave
standard sirens
tidal effect
neutron star / black hole

redshift drift measurement
astrophysical systematics

Black Holes
&
Neutron Stars

Multi-band /
Multi-messenger
Fundamental
Physics!

Nuclear Physics

Cosmology

Conclusions

Summary

Current (Black Hole based) Tests of Extreme Gravity:
first strong/dynamical-field constraint on various gravitational theories

Future (Neutron Star based) Tests of Extreme Gravity:
universal I-Love-Q relations are a powerful tool to probe extreme gravity in future

Multi-band / Multi-messenger Fundamental Physics!

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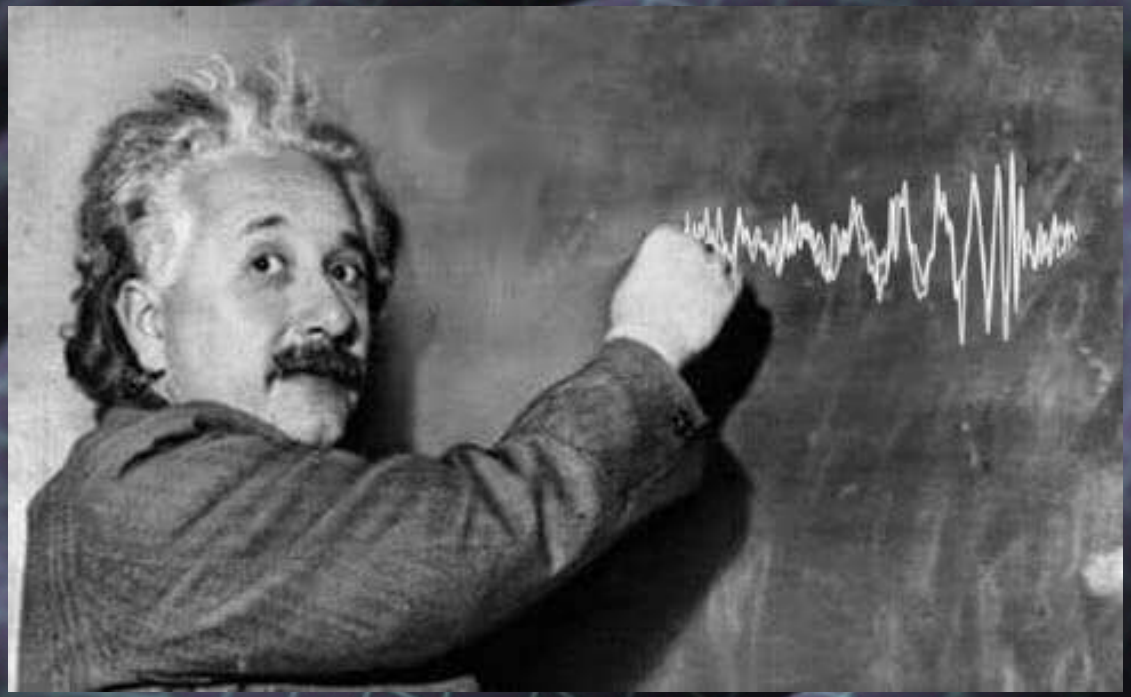
A. Taruya (Kyoto U.)
H. Yang (Princeton U.)
C. Yoo (Nagoya U.)
N. Yunes (Montana State U.)



Thank You