Unifying Tests of GR
Burke Institute/Caltech
July 21, 2016

E.F.T. is Evil!

Niayesh Afshordi

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PERIMETER INSTITUTE
FOR THEORETICAL PHYSICS

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(i.e. very boring)

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Outline

- Why E.F.T. is Evil
- What ~~E.F.T.~~ is good for:
  - Neutron Stars and CC problem
  - Dark Energy, Black Holes, and LIGO
  - Pulsar Timing and Vacuum Gravity

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Locality and Unitarity had a good run, but ...

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- BH Information Paradox, a.k.a. Firewalls
- Quantum Gravity is non-local (light-cone not defined)
- no decoupling thm in QG: $e^- e^+$ have opposite electric charge, same gravitational charge
- EFT is boring! Think outside the Box!

Cosmological Constant (CC) Problem

- General Relativity

energy/momentum

$$G_{\mu\nu}(x) = \kappa\, T_{\mu\nu}(x)$$

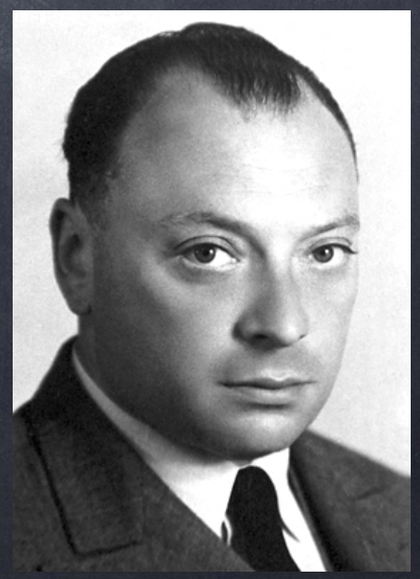
curvature

- Quantum Mechanics (Standard Model)

$$\langle T_{\mu\nu}(x)\rangle_{\rm SM} \sim \pm 10^{45}\ {\rm eV}^4 \times g_{\mu\nu}$$

- Real World!

$$\kappa^{-1}\langle G_{\mu\nu}(x)\rangle_{\rm cosm.} \sim 10^{-12}\ {\rm eV}^4 \times g_{\mu\nu}$$



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Gravitational Aether proposal (c.f. *unimodular* gravity)

- Let us propose (*NA 2008*):

$$(8\pi G')^{-1} G_{\mu\nu} = T_{\mu\nu} - \frac{1}{4} T^{\alpha}_{\alpha} g_{\mu\nu} + ...$$

- The metric is now blind to vacuum energy

$$T_{\mu\nu} = \rho_{\rm vac} g_{\mu\nu} + \text{excitations}$$

- In order to satisfy Bianchi identity:

$$(8\pi G')^{-1} G_{\mu\nu} = T_{\mu\nu} - \frac{1}{4} T^{\alpha}_{\alpha} g_{\mu\nu} + T'_{\mu\nu}, \quad T'^{\mu}_{\nu;\mu} = \frac{1}{4} T^{\alpha}_{\alpha,\nu}$$

- Further assume an *incompressible* fluid (or *gravitational aether*)

$$T'_{\mu\nu} = p' (u'_{\mu} u'_{\nu} - g_{\mu\nu})$$

- ***Disclaimer:* The field equations *do not* follow from an *Action principle*

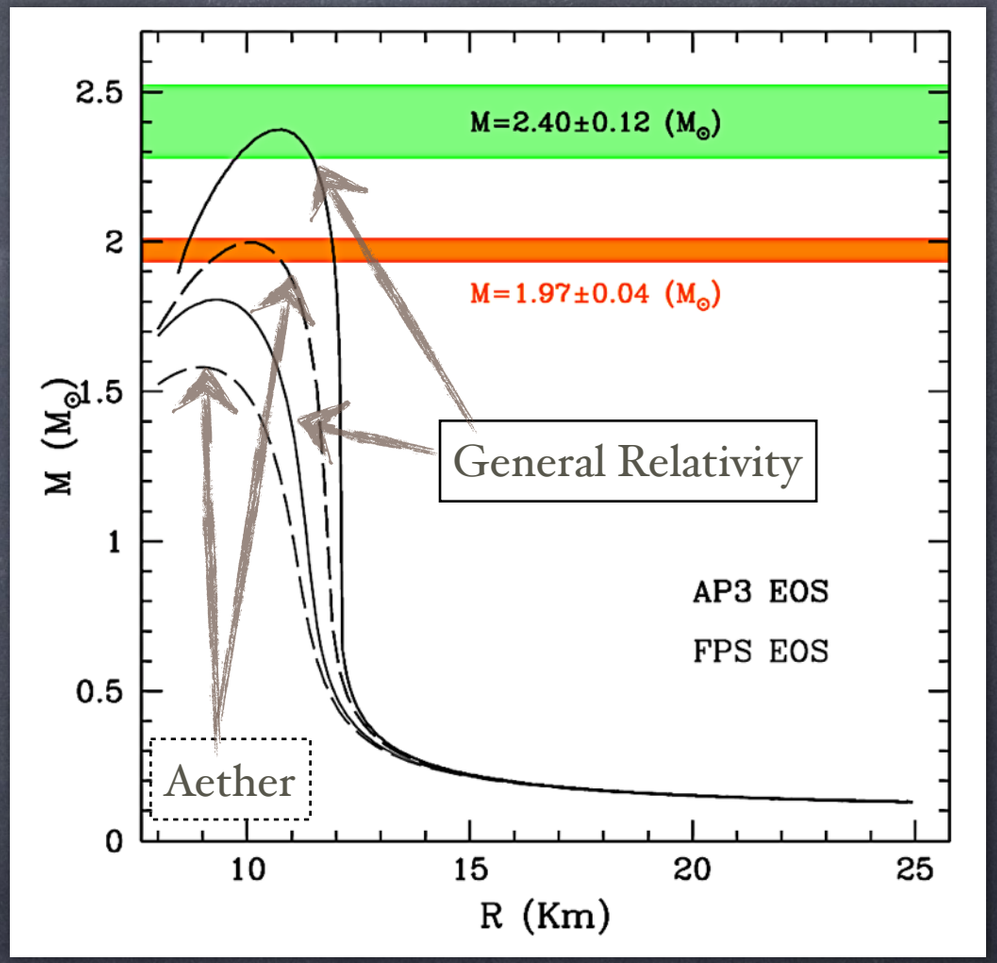
Deviations from GR sourced by Pressure

(Kamiab & NA, 2011)
(Aslanbeigi, Robbers, Foster, Kohri & NA, 2011)
(Narimani, NA & Scott, 2014)

- Neutron Star Structure (e.g. aLIGO)
- Cosmology (CMB, Big Bang Nucleosynthesis)
- Vacuum gravity identical to GR**

neutron stars and aether

- Aether decreases the maximum mass (effectively softens EOS), so discovery of very massive Neutron Stars can rule it out
- Uncertainty in nuclear E.O.S. ☹
- Can test with Gravitational Wave detection from NS-NS mergers ☺
- Strong Gravity Simulations?



Kamiab & NA 2011

Einstein was right!**

Tests of equivalence principle

Year	Investigator	Sensitivity	Method
500?	Philoponus [12]	"small"	Drop Tower
1585	Stevin [13]	5×10^{-2}	Drop Tower
1590?	Galileo [14]	2×10^{-2}	Pendulum, Drop Tower
1686	Newton [15]	10^{-3}	Pendulum
1832	Bessel [16]	2×10^{-5}	Pendulum
1910	Southerns [17]	5×10^{-6}	Pendulum
1918	Zeeman [18]	3×10^{-8}	Torsion Balance
1922	Eötvös [19]	5×10^{-9}	Torsion Balance
1923	Potter [20]	3×10^{-6}	Pendulum
1935	Renner [21]	2×10^{-9}	Torsion Balance
1964	Dicke,Roll,Krotkov [22]	3×10^{-11}	Torsion Balance
1972	Braginsky,Panov [23]	10^{-12}	Torsion Balance
1976	Shapiro, et al.[24]	10^{-12}	Lunar Laser Ranging
1981	Keiser,Faller [25]	4×10^{-11}	Fluid Support
1987	Niebauer, et al.[26]	10^{-10}	Drop Tower
1989	Heckel, et al.[27]	10^{-11}	Torsion Balance
1990	Adelberger, et al.[28]	10^{-12}	Torsion Balance
1999	Baessler, et al.[29]	5×10^{-14}	Torsion Balance
cancelled?	MiniSTEP	10^{-17}	Earth Orbit
2015?	MICROSCOPE	10^{-16}	Earth Orbit
2015?	Reasenberg/SR-POEM [30]	2×10^{-17}	vacuum free fall

Tests of strong gravity
(Parametrized Post Newtonian)

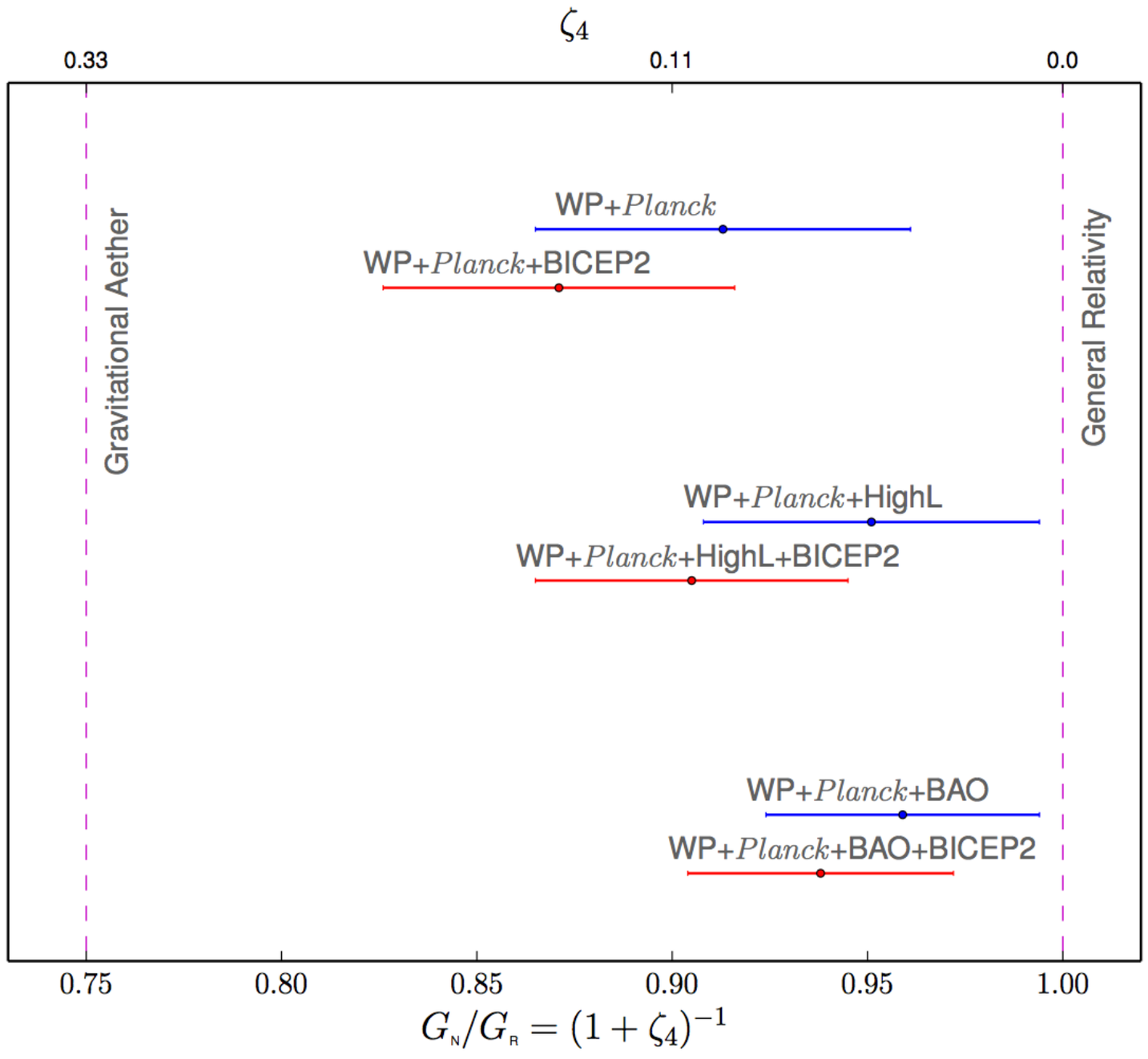
Bounds on the PPN parameters Will (2006)

Parameter	Bound	Effects	Experiment
$\gamma - 1$	2.3×10^{-5}	Time delay, Light deflection	Cassini tracking
$\beta - 1$	2.3×10^{-4}	Nordtvedt effect, Perihelion shift	Nordtvedt effect
ξ	0.001	Earth tides	Gravimeter data
α_1	10^{-4}	Orbit polarization	Lunar laser ranging
α_2	4×10^{-7}	Spin precession	Sun axis' alignment with ecliptic
α_3	4×10^{-20}	Self-acceleration	Pulsar spin-down statistics
ζ_1	0.02	-	Combined PPN bounds
ζ_2	4×10^{-5}†	Binary pulsar acceleration	PSR 1913+16
ζ_3	10^{-8}	Newton's 3rd law	Lunar acceleration
ζ_4	0.006‡	-	Kreuzer experiment

† Will, C.M. *Is momentum conserved? A test in the binary system PSR 1913 + 16*, Astrophysical Journal, Part 2 - Letters (ISSN 0004-637X), vol. 393, no. 2, July 10, 1992, p. L59-L61.

‡ Based on $6\zeta_4 = 3\alpha_3 + 2\zeta_1 - 3\zeta_3$ from Will (1976, 2006). It is theoretically possible for an alternative model of gravity to bypass this bound, in which case the bound is $|\zeta_4| < 0.4$ from Ni (1972).

How does pressure gravitate?

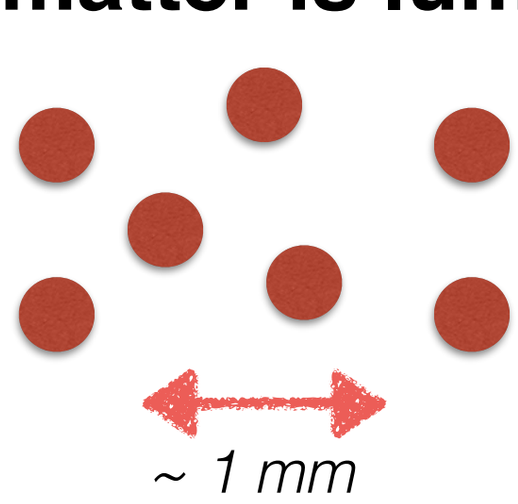


(Narimani, NA & Scott 2014)

What now?

- Original Gravitational Aether proposal (NA 2008) is ruled out at 3-4σ (still better than 10^{60}-10^{120}σ!)

- **But, vacuum is smooth** **matter is lumpy**



- Does that make a difference?

- The theory ***must*** have a cut-off/coarse-graining scale

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aether and black holes

- We can solve for the black hole spacetime in this theory

$$ds^2 = \left(1 - \frac{2m}{r}\right)\left[1 + 4\pi p_0 f(r)\right]^2 dt^2 - \left(1 - \frac{2m}{r}\right)^{-1} dr^2 - r^2 d\Omega^2$$

- p_0 is the aether pressure at infinity
- *f(r):* analytic function of *r* diverging at $r \approx 2m$ & $r \to \infty$
- ➥ *UV-IR coupling thru aether pressure, p_0*
- ➥ *Finite redshift at r=2m*
- ➥ *No Horizon (similar to Fuzzball models)*

$$f(r) = \frac{1}{2}\left(1 - \frac{2m}{r}\right)^{-1/2}\left(-30m^2 + 5mr + r^2\right) + \frac{15}{2}m^2 \ln\left[\frac{r}{m} - 1 + \frac{r}{m}\left(1 - \frac{2m}{r}\right)^{1/2}\right],$$

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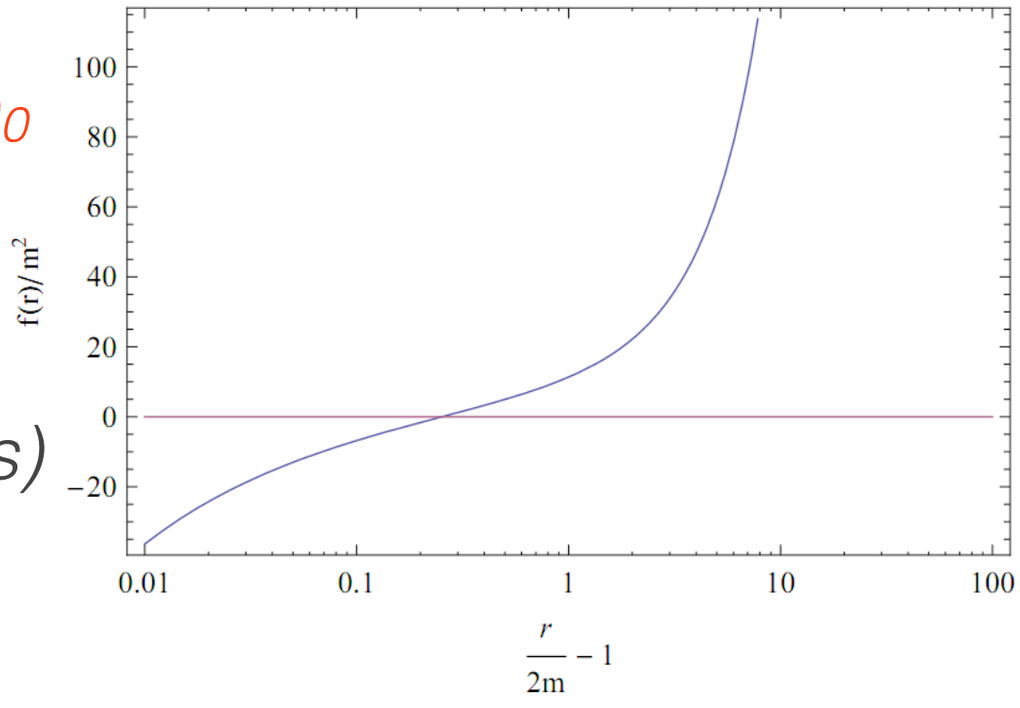


… and dark energy!

- Assume:

$$\boxed{1 + z_{\max} \sim \frac{\text{Planck temperature}}{\text{Hawking temperature}}}$$

- then we get

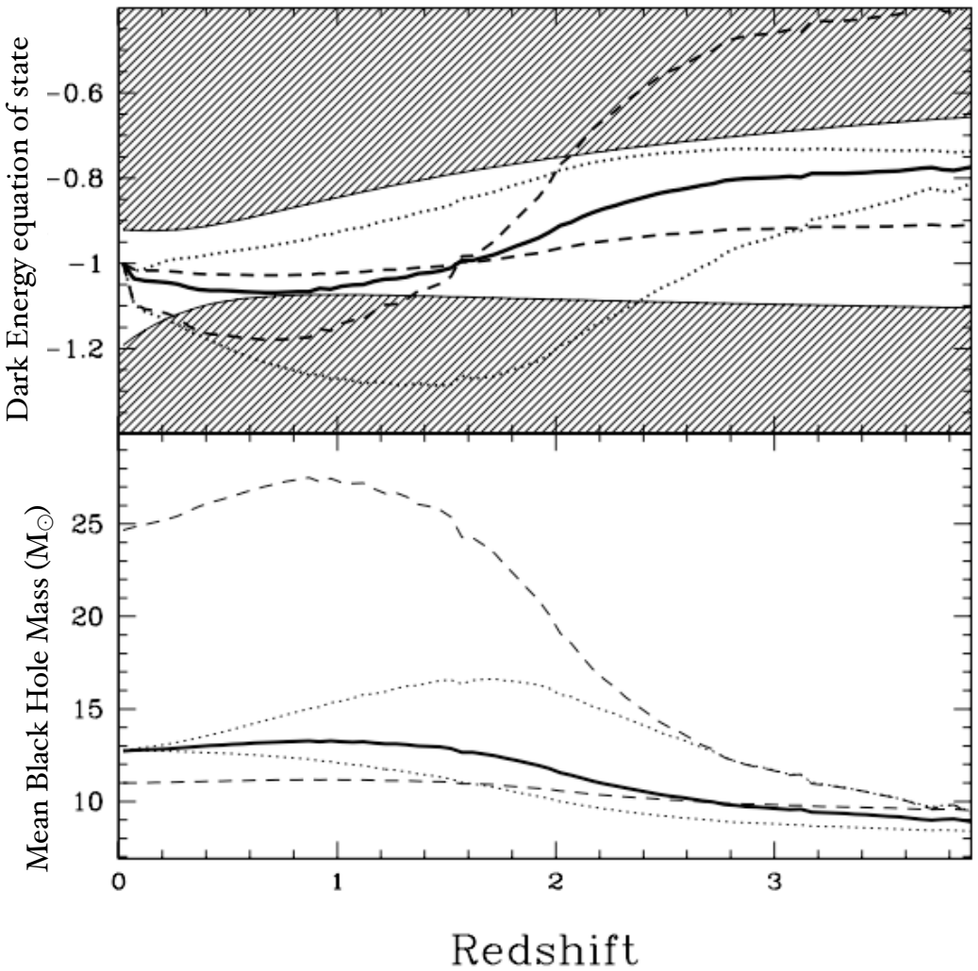
$$\boxed{p_0 = -\frac{1}{256\pi^2 m^3} \simeq \left(\frac{m}{74\ M_\odot}\right)^{-3} p_{\rm DE,obs}!!}$$

- *Pressure* has the same sign and magnitude as *Dark Energy* for stellar mass black holes!

- ➥Conjecture: Formation of stellar black holes causes cosmic acceleration

- ➥Conjecture: Evolution of Astrophysical black holes leads to dynamical Dark Energy

Prescod-Weinstein, NA, Balogh 2009



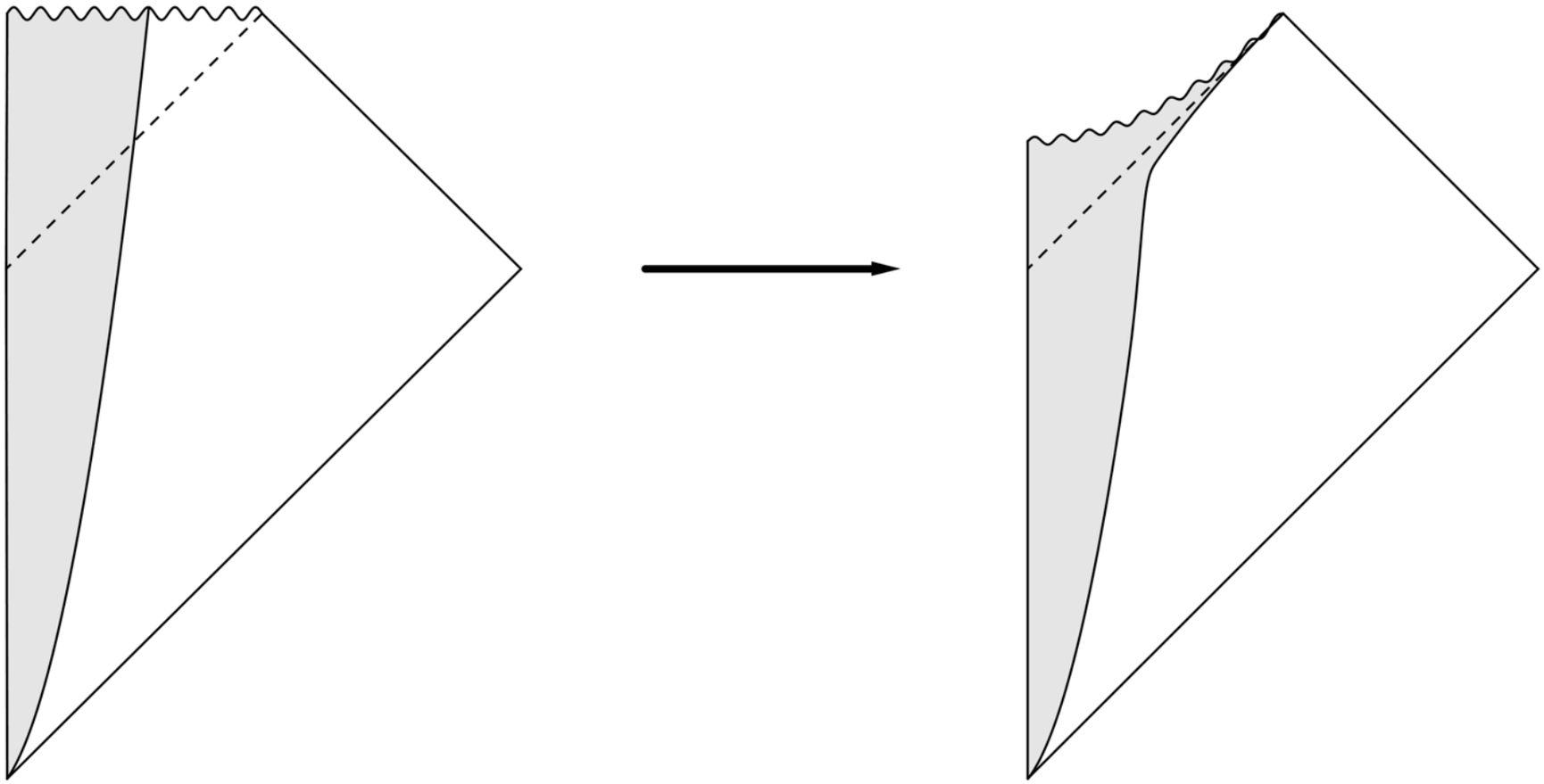
why EFT fails at “horizon”

- **Information paradox:** unitary black hole evaporation, not consistent with <u>local physics</u> +<u>smooth horizon</u> *(Hawking … AMPS 2013)*

- **Quantum Tunnelling:** $exp(-S_E) x\ exp(entropy) \sim 1$

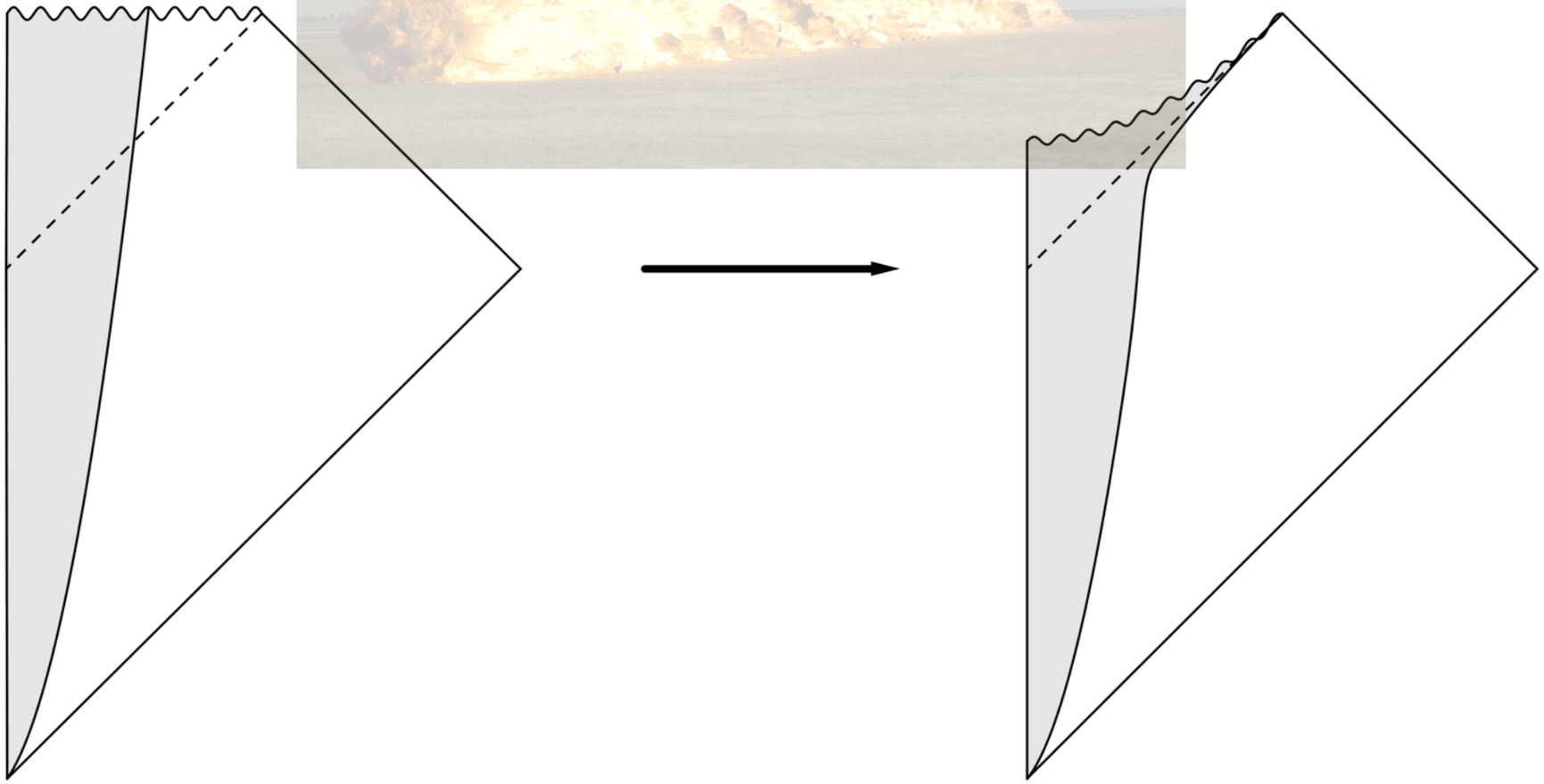
- **Fuzzballs:** Classical horizon-less spacetimes, that account for BH entropy *(Mathur; Saravani, NA, Mann 2015)*

- **Dark Energy:** pressure eq. with stellar BH firewalls, → scale of dark energy *(Presocd-Weinstein, NA, Balogh 2009)*



How to form a Black Hole

How to form a Firewall?!



How to form a Black Hole

How to form a Firewall?!

Echoes from the Abyss!

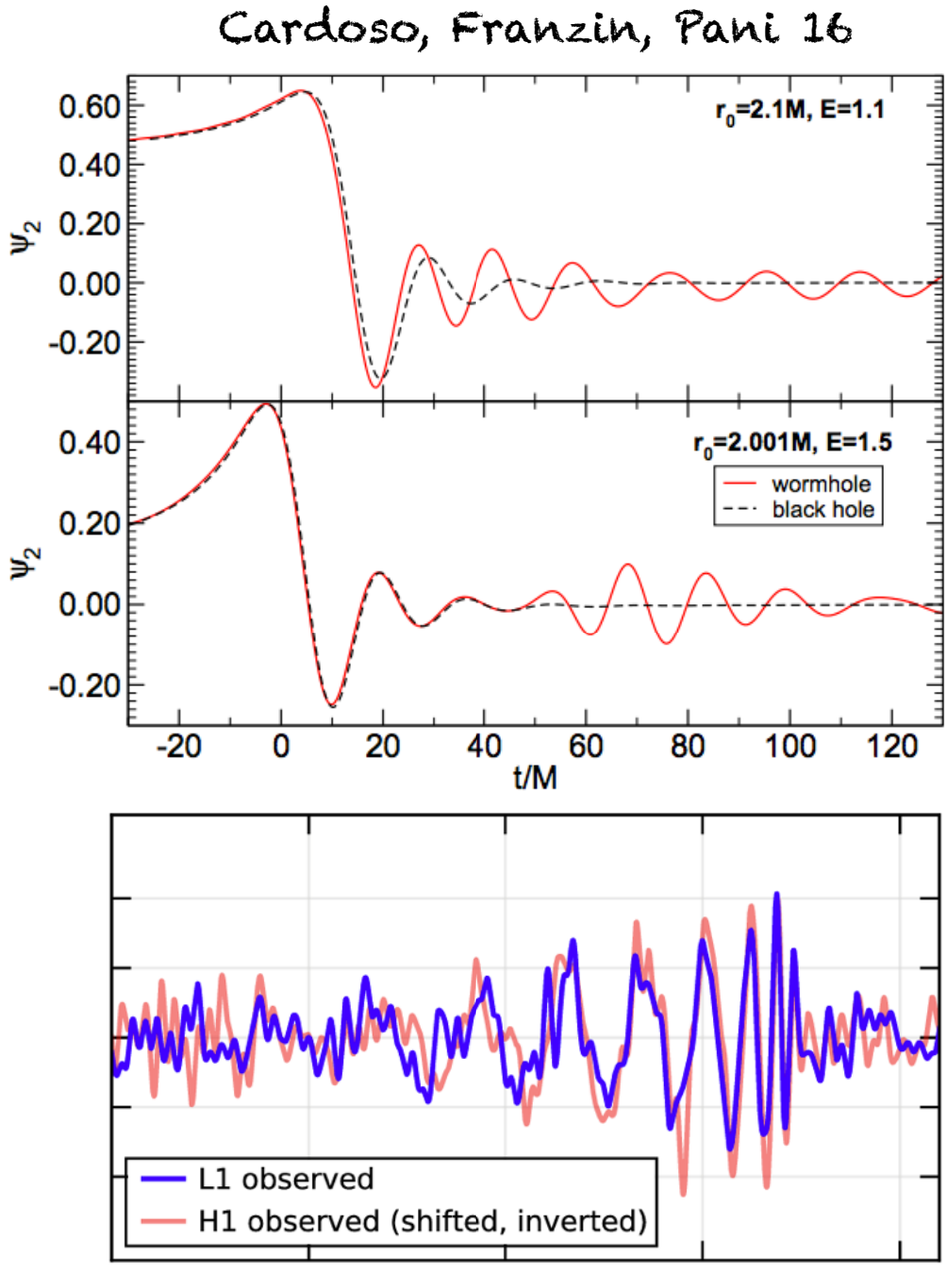
- Late echoes from Planckian structure near horizon

$$\boxed{\Delta t \simeq 8 M_{BH} \log\left(\frac{M_{BH}}{M_P}\right) \simeq 0.22 \text{ sec}}$$

- Including the the spin-dependence

$$\boxed{\Delta t \simeq 0.25 - 0.28 \text{ sec}}$$

- for **GW150914**



Preliminary!

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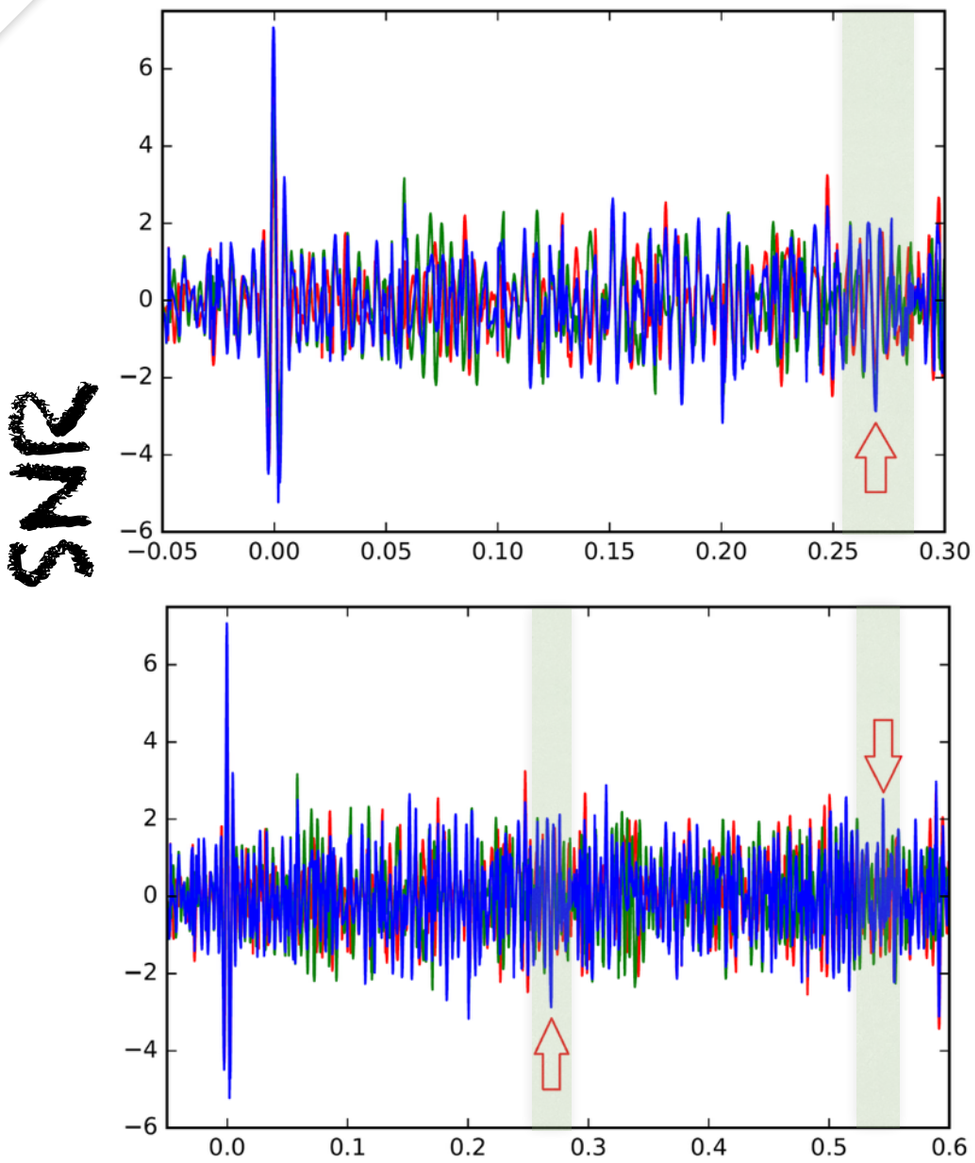
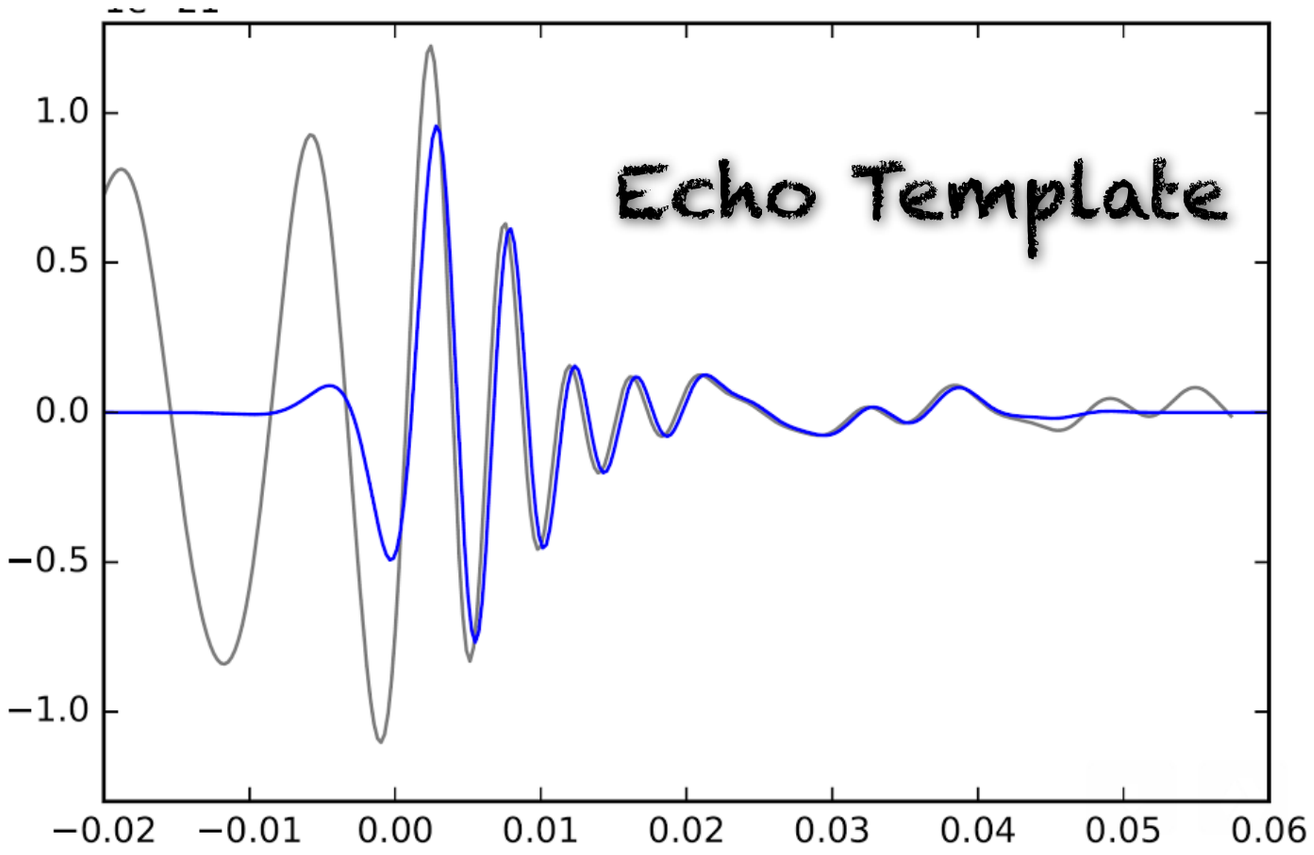


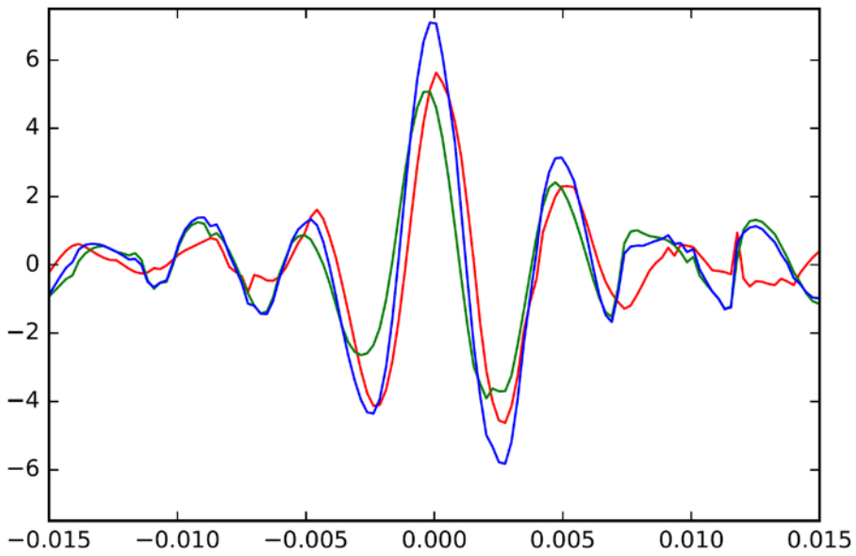


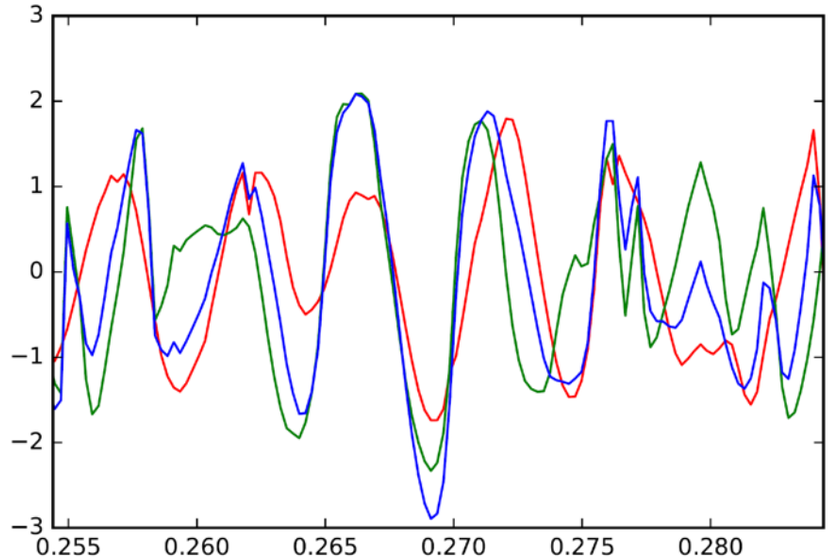
Abedi, Dykaar, & NA, in prep

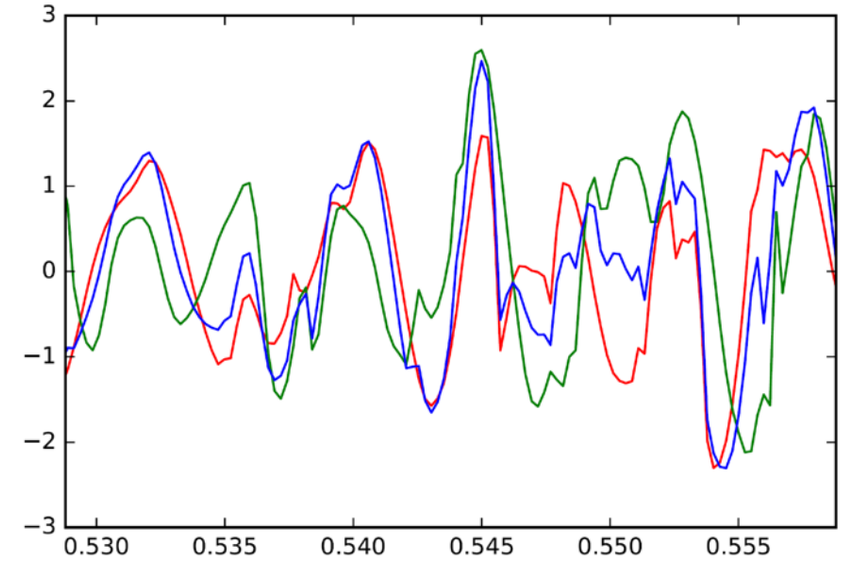
Preliminary!

Echoes from the Abyss!

chance probability < 6 x 10^{-4} or 3.4σ







SNR=−2.9

SNR=+2.5

Abedi, Dykaar, & NA, in prep

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with Elliot Nelson, Phys. Rev. D 93, 083505, and in prep.

HEP Hierarchy problem(s)

old cosmological constant (CC) problem

Higgs hierarchy problem

CnC problem!

- neutrino mass — Higgs, Electroweak — GUT…Planck
- dark energy — LHC

$10^{-3}\mathrm{eV}$ $10^{12}\mathrm{eV}$ $10^{28}\mathrm{eV}$

$\rho_{\mathrm{DE}} \sim \Lambda^4$ $\delta m_H^2 \sim \Lambda^2$ $\Lambda?$

Punchline!

- Gravity is different! Observables non-local
- UV physics -> IR noise in geometry
- No new scale in QFT+GR $\gtrsim$ TeV!

→ ~~High scale SUSY, GUT, (almost all) Inflation models~~

→ TeV-scale QG, Large Extra Dimensions

→ Strongly coupled UV completion (technicolor?, bootstrap?, Conformal Higgs?)

A very vibrant vacuum

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- Quantum Fluctuations do fluctuate!

$$\langle T_{\mu\nu} T_{\alpha\beta} \rangle \neq \langle T_{\mu\nu} \rangle \langle T_{\alpha\beta} \rangle$$

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- Quantum Fluctuations do fluctuate!

$$\langle T_{\mu\nu} T_{\alpha\beta} \rangle \neq \langle T_{\mu\nu} \rangle \langle T_{\alpha\beta} \rangle$$

- What is the analog of CC for the covariance of stress fluctuations?

A very vibrant vacuum

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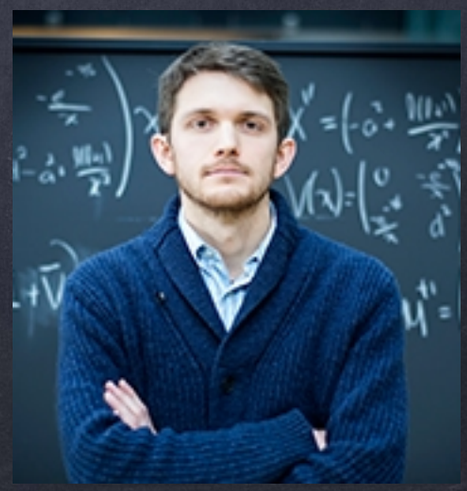
$$\langle T_{\mu\nu} T_{\alpha\beta} \rangle \neq \langle T_{\mu\nu} \rangle \langle T_{\alpha\beta} \rangle$$

- What is the analog of CC for the covariance of stress fluctuations?

- Can these fluctuations have an observable gravitational signature on large scales?

with Elliot Nelson, Phys. Rev. D 93, 083505



CnC: *the upshot!*

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- Random stress fluctuations at UV scale Λ

$$\langle T_{ij}^{(V)}(\mathbf{x}) T_{kl}^{(V)}(\mathbf{y}) \rangle \sim \delta^3(\mathbf{x}-\mathbf{y}) \Lambda^5$$

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- Einstein eq. for anisotropic stress

$$k^2 \Phi \sim M_{\rm p}^{-2} A^{ij} T_{ij}$$

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- Variance of Metric perturbations grows as distance

$$\left(\Delta_\Phi^{(V)}\right)^2 \sim \frac{\Lambda^5}{M_p^4 k}$$

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- A UV/IR Heisenberg uncertainty relation

$$\Lambda_{\rm IR} = \frac{\Lambda_{\rm UV}^5}{M_p^4}$$

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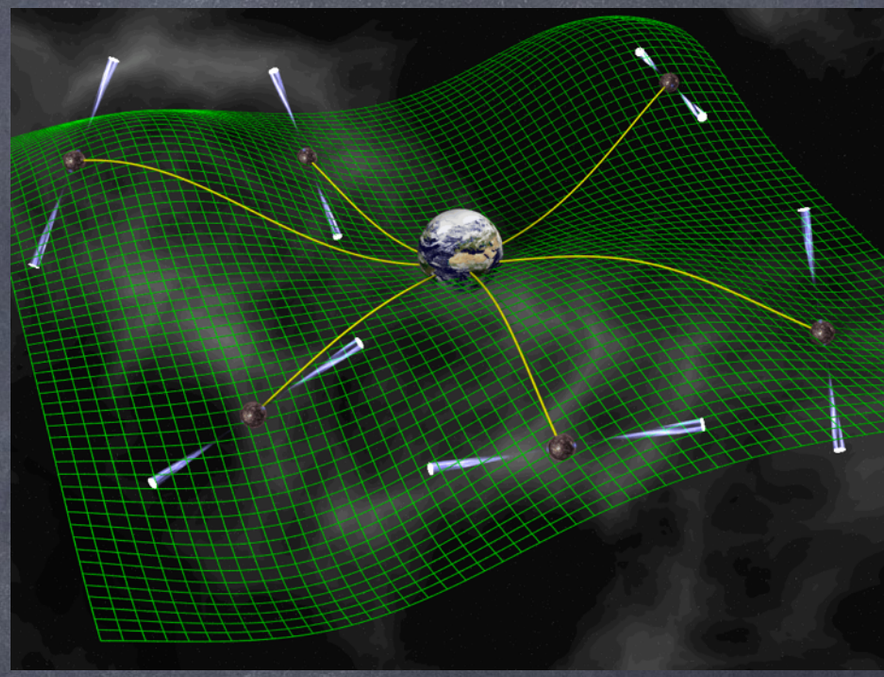
- Cosmology limits the UV scale

$$\Lambda \lesssim (M_{\rm p}^4 H_0)^{1/5} \approx 2\ {\rm PeV}$$

Preliminary!

Pulsar Timing

- Same as ISW effect, exc. @ different times, not diametrical directions



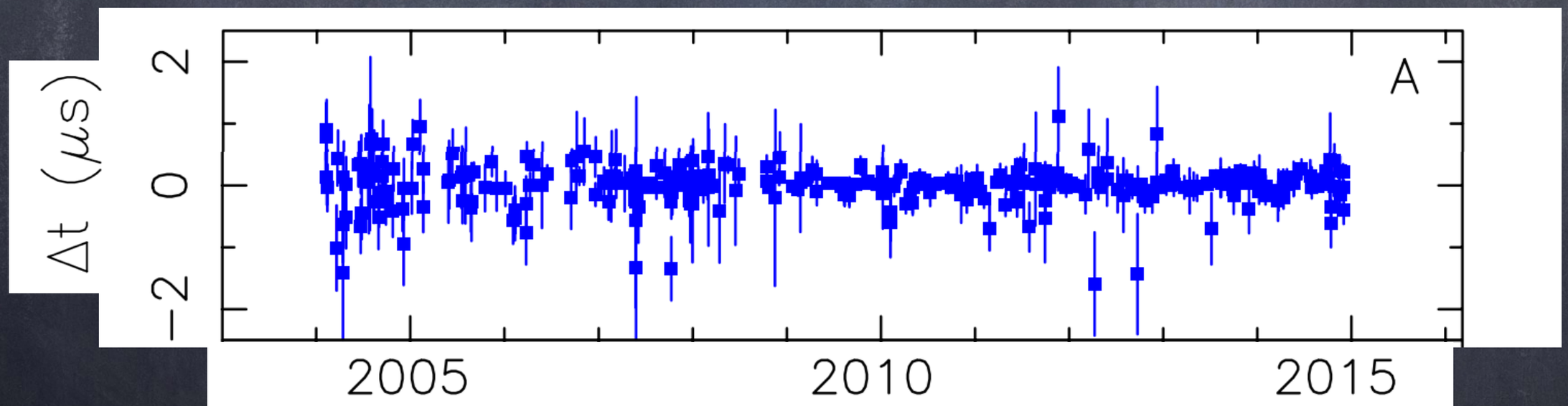
$$P^2 f^3 \Phi_{TN}(f) = \frac{h^2_{c,\mathrm{eff}}}{12\pi^2} = \frac{7}{1920\pi^2}\frac{m^5 d}{M_p^4}$$

$$= 2.6 \times 10^{-28} m^5(\mathrm{TeV}) d(\mathrm{kpc})$$

Preliminary!

Meet PSR J1909-3744!

- P=2.947 ms, d=1.26 kpc
- $h_c < 3.2 \times 10^{-15}$ @2σ

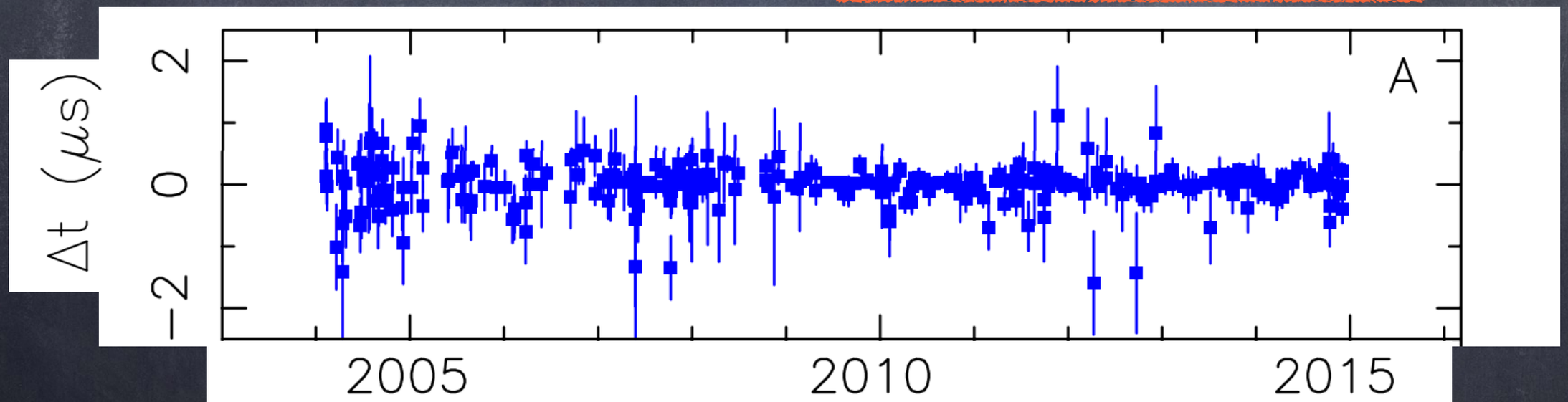


Shannon, et al 2015

Preliminary!

Meet PSR J1909-3744!

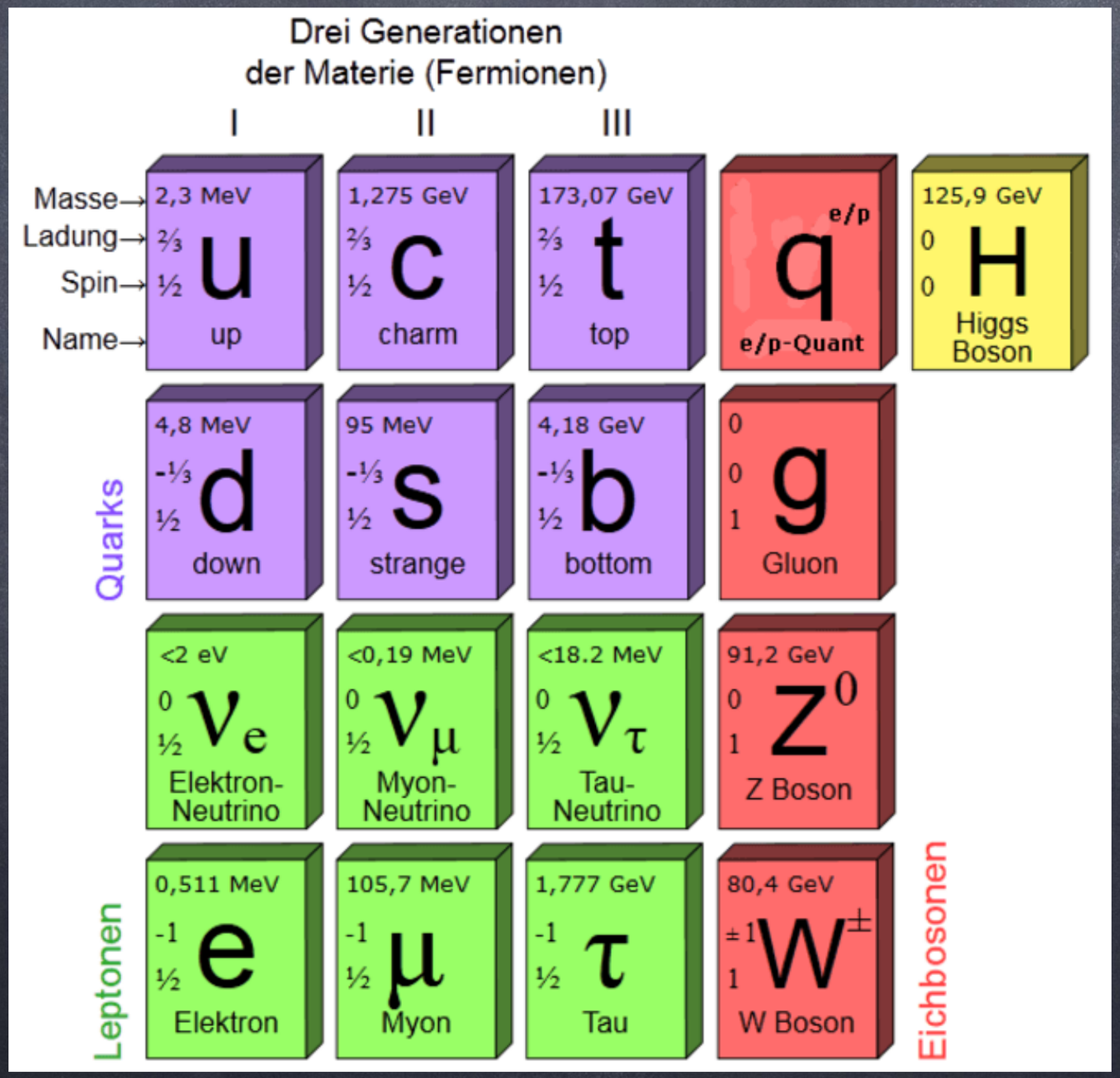
- P=2.947 ms, d=1.26 kpc
- $h_c < 3.2 \times 10^{-15}$ @2σ → $m_\varphi < 192$ GeV



Shannon, et al 2015

Preliminary:

No Physics "beyond" Standard Model!



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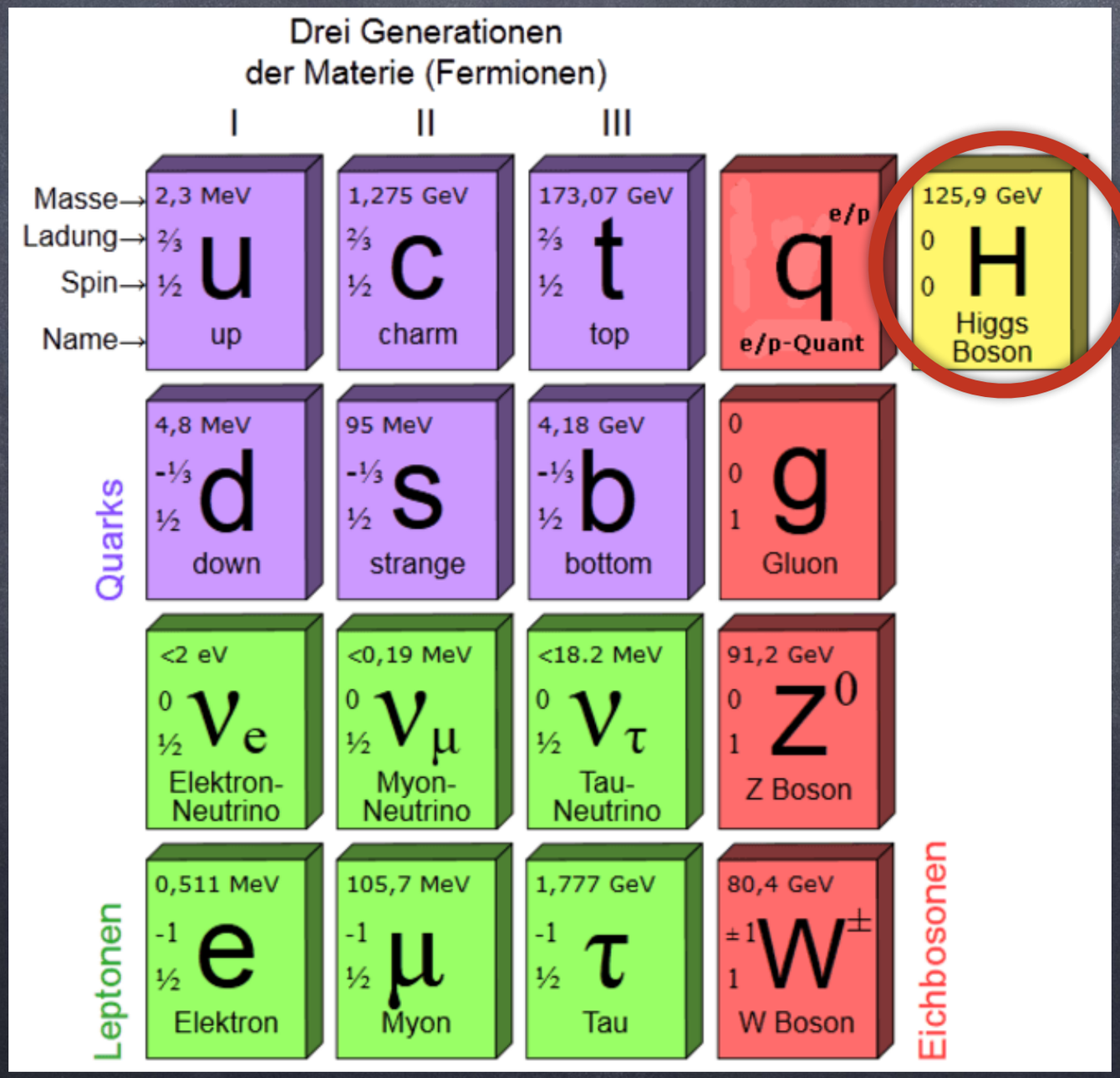

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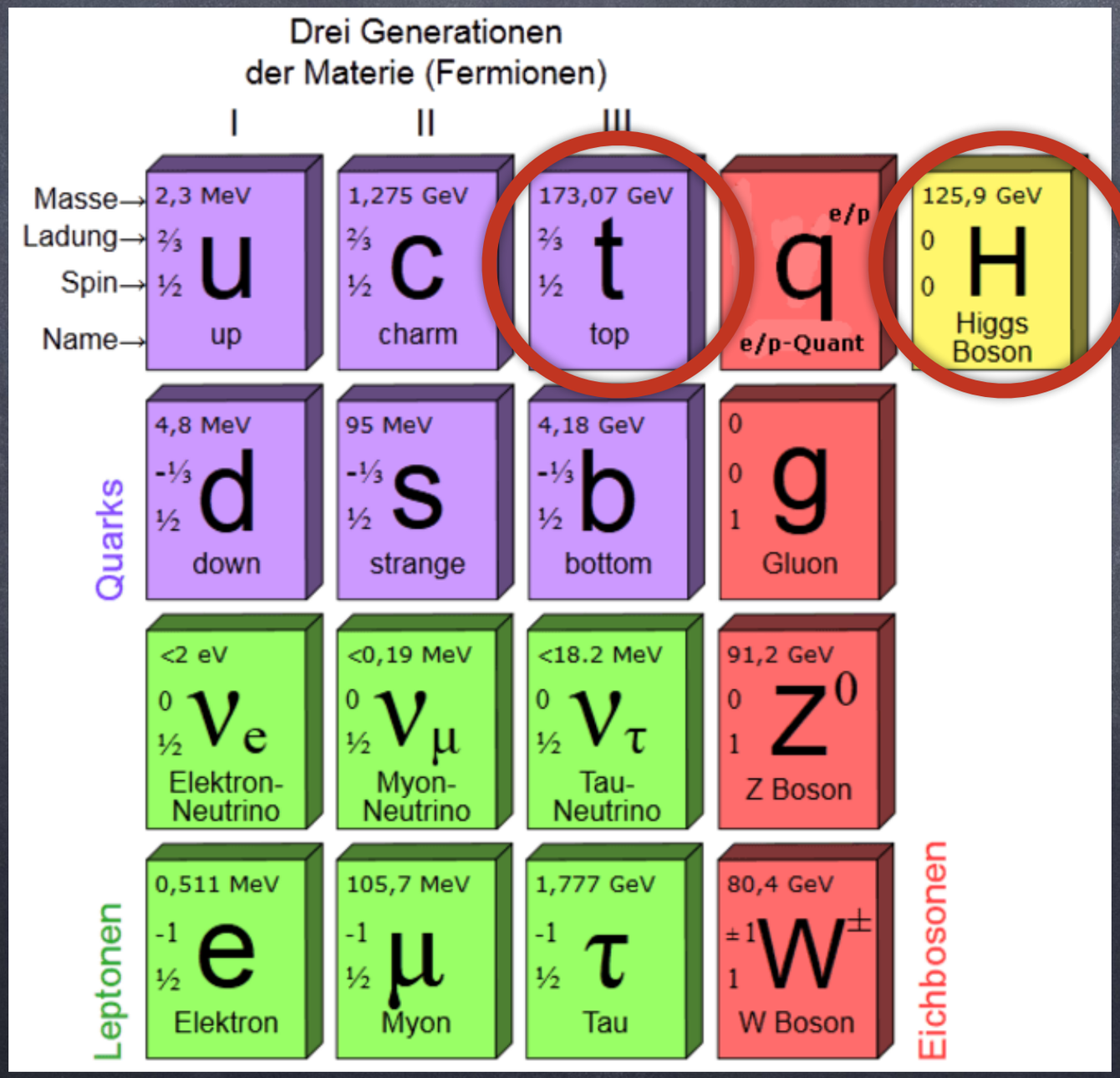

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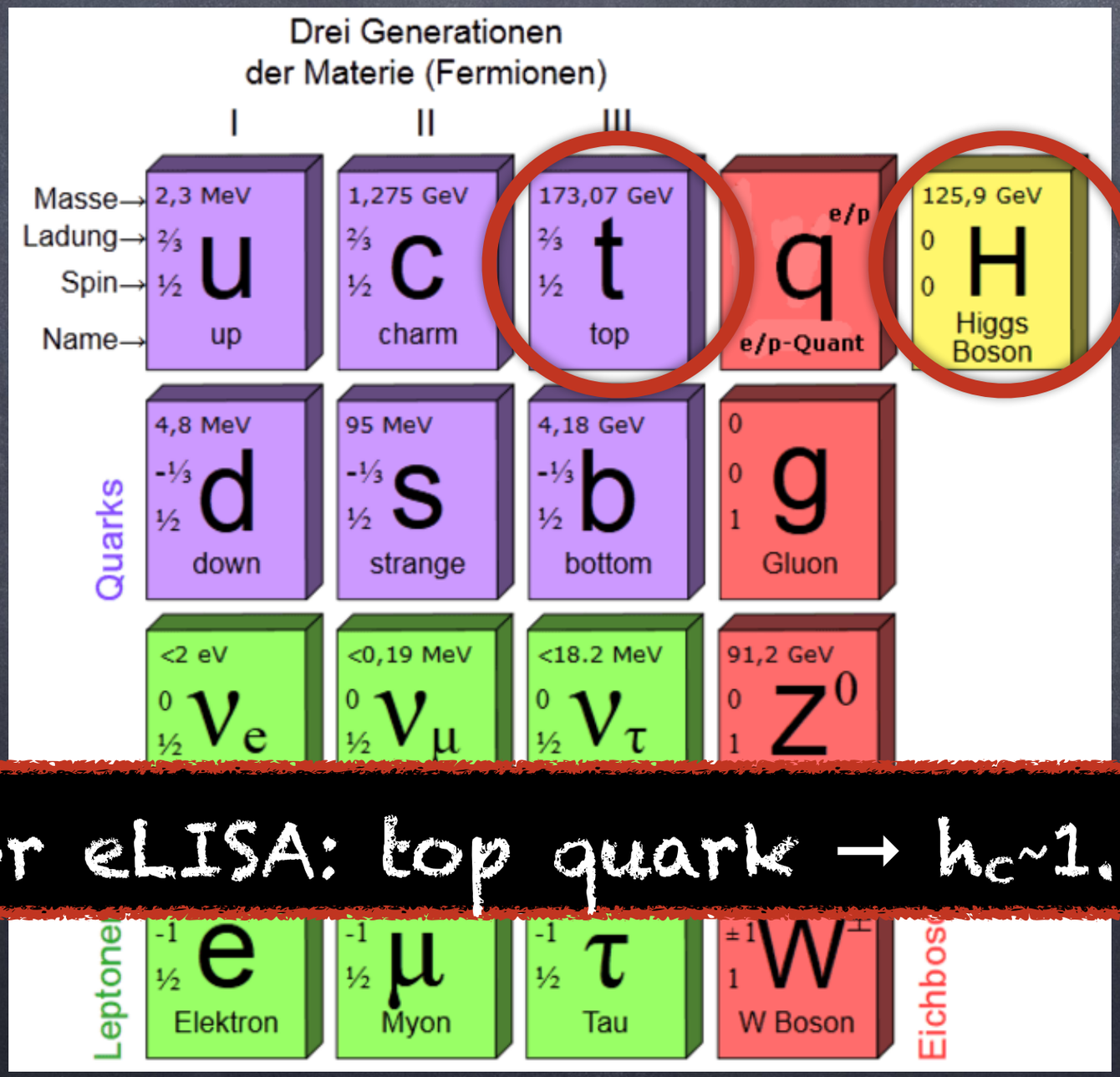
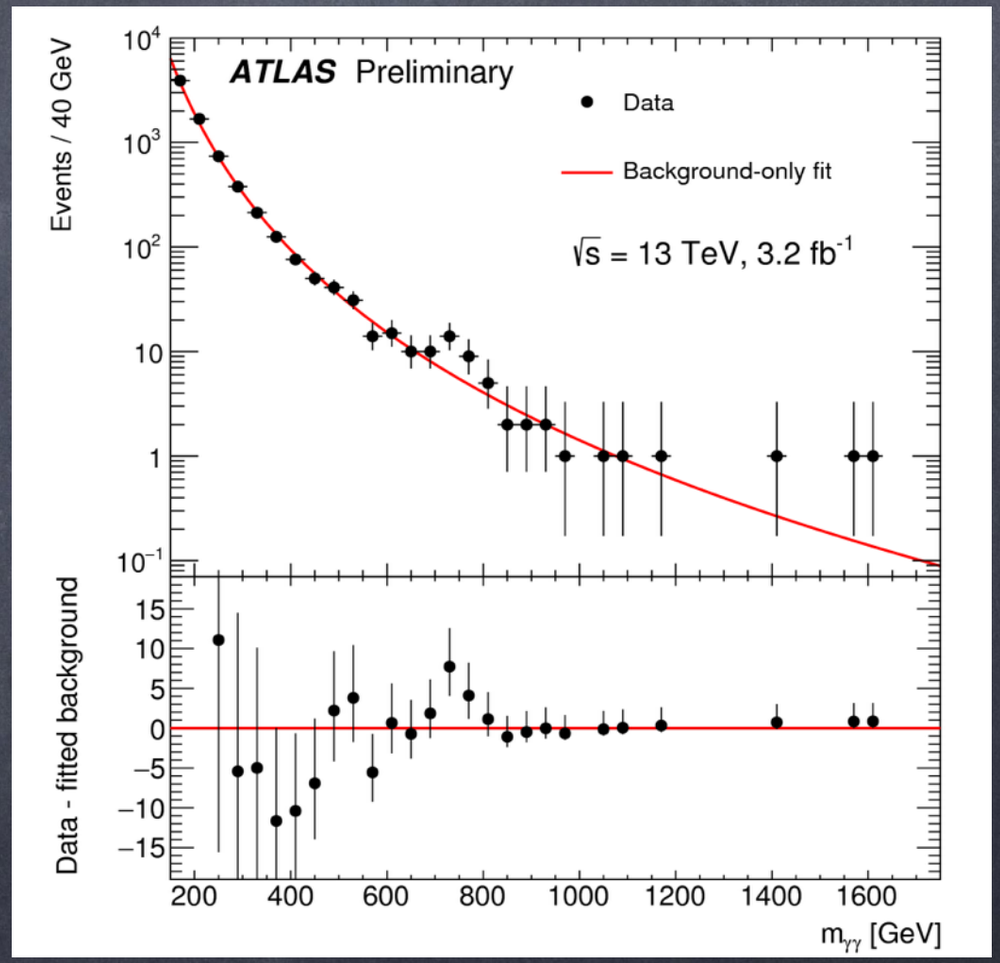


Target for eLISA: top quark → $h_c \sim 1.2 \times 10^{-20}$

Preliminary!

Di-photon excess?

- 3σ di-photon excess in LHC/CMS
- A new particle at 750 GeV?
- If so, in contrast with CnC constraint from pulsar timing!



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