Cosmological Gravity after GW170817

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Dark Interactions
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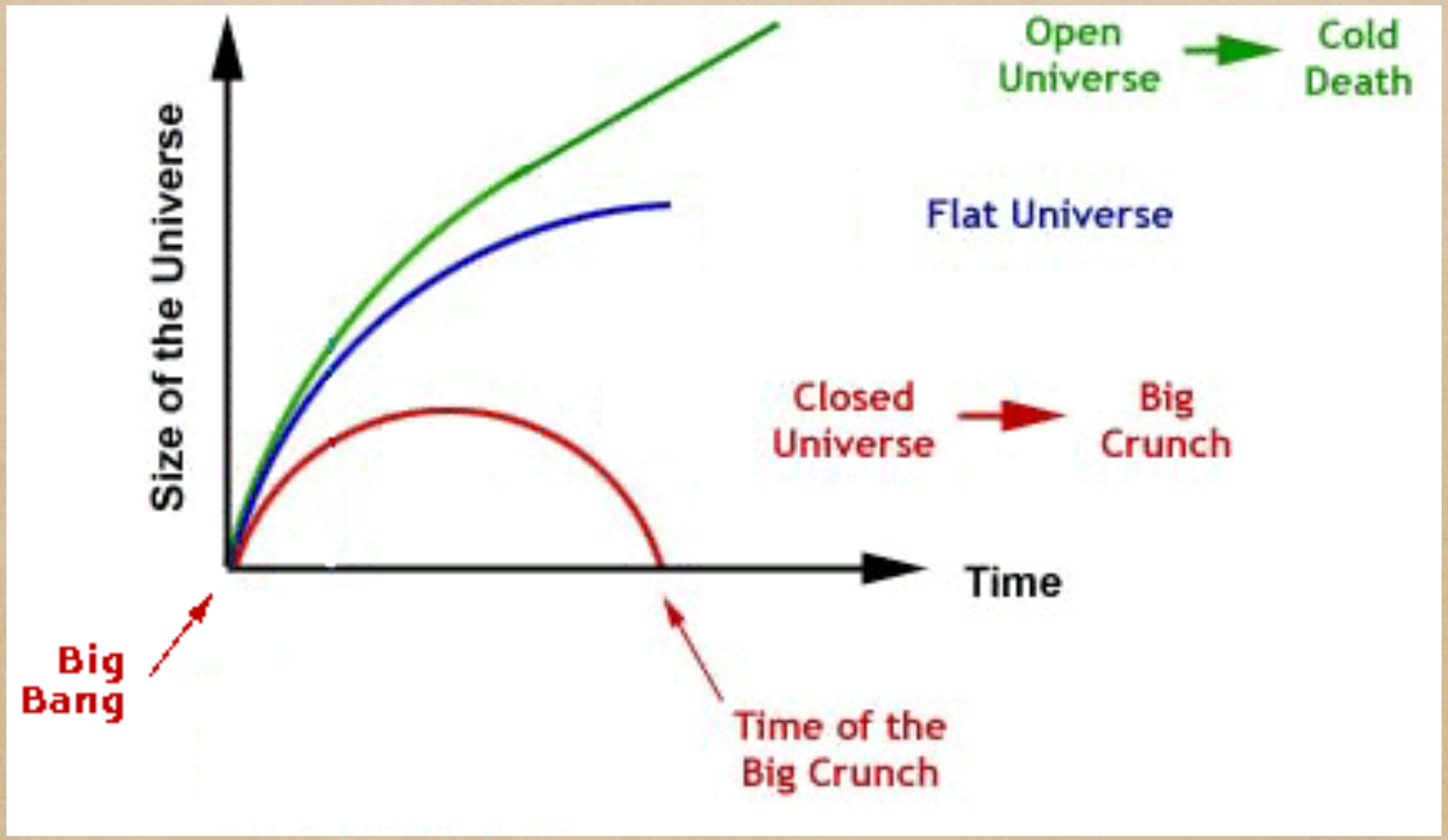
Modified Gravity $\neq$ MOND

(well defined EFTs valid on cosmological scales)

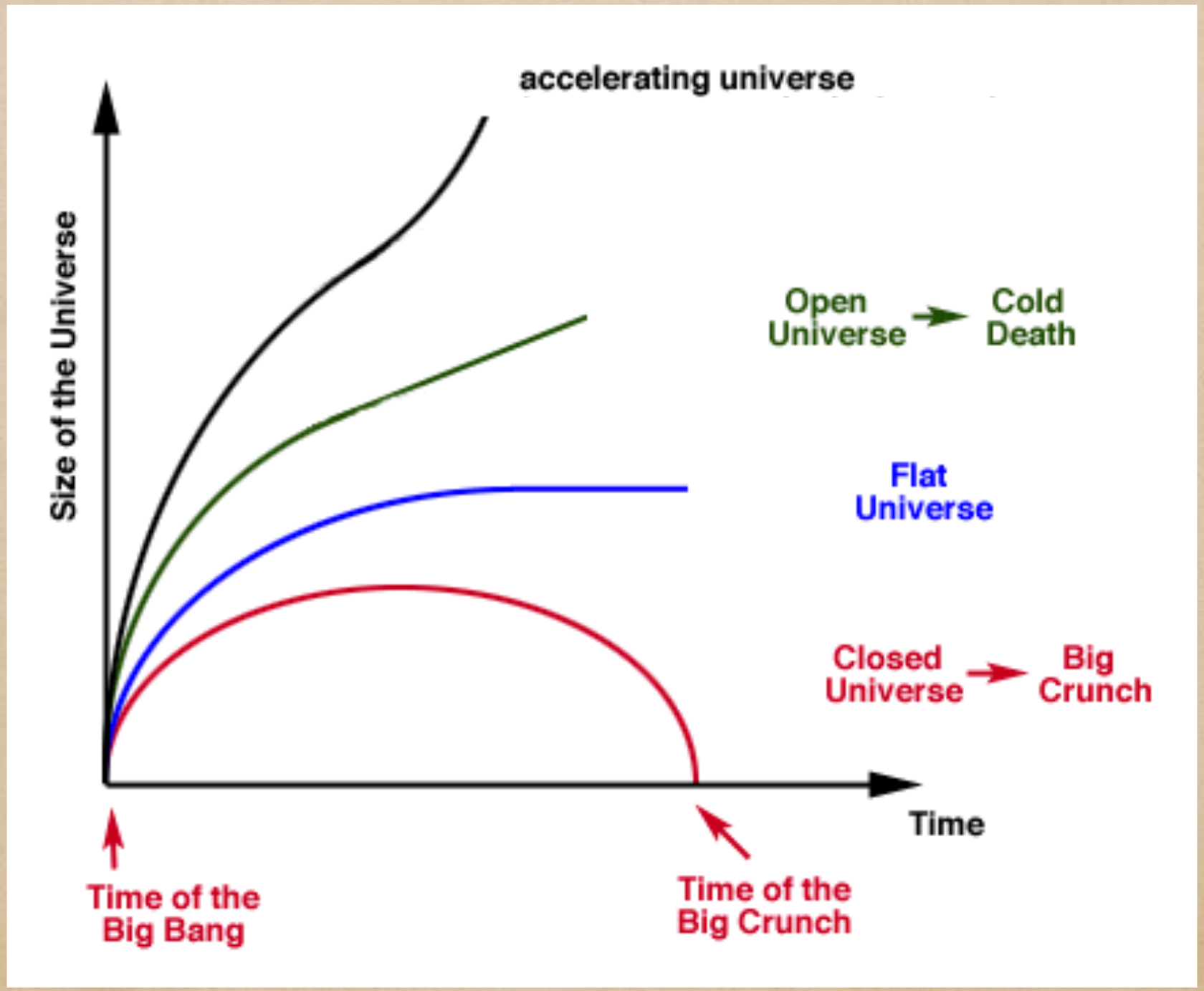
Overview

- Why cosmologists study MG?
- What is GW1701817?
- Where are we now?

Expansion of the universe

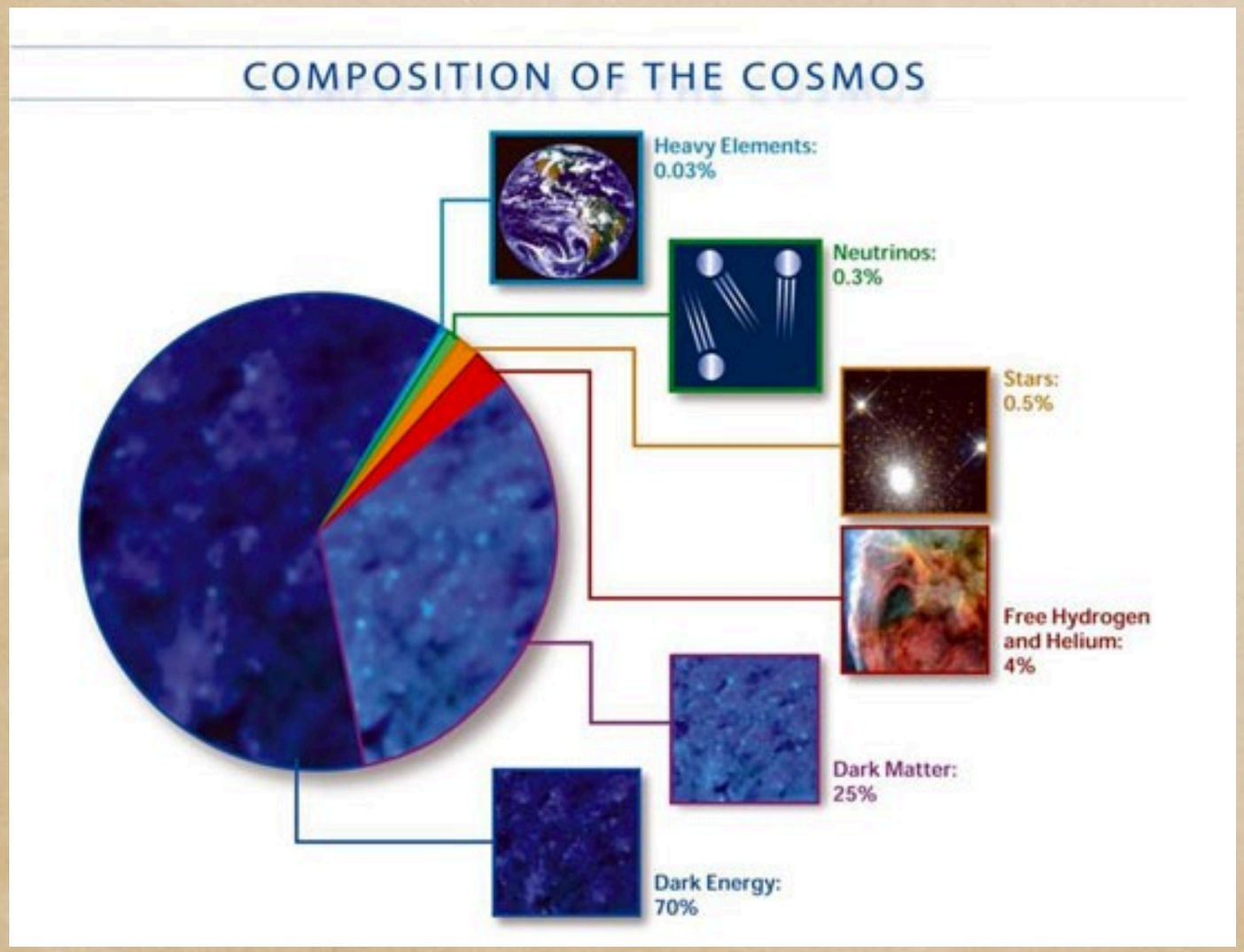


Acceleration of the universe



Why study MG?

Dark energy — acceleration of the cosmic expansion



DE vs MG

Geometry

MG: new terms/ DOF

Matter

DE: new exotic matter

(quintessence/ K-essence/…)

$$G_{\mu\nu} = -\Lambda g_{\mu\nu} + 8\pi G T_{\mu\nu}$$

Cosmological constant

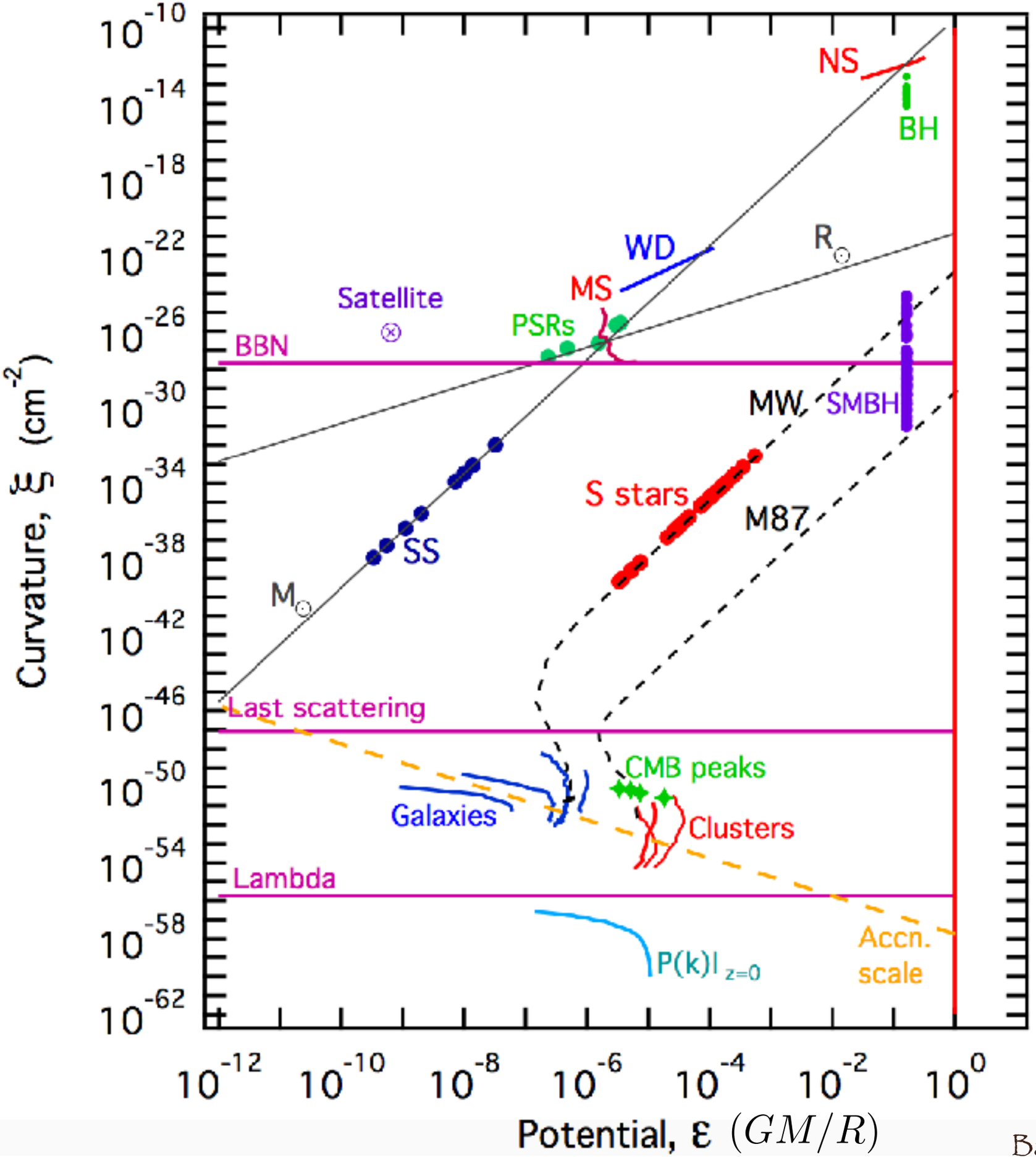
(drives acceleration but fine-tuned)

(DE: zero due to symmetry/dynamics)

If your life doesn't make sense, buy some Dark Energy and balance your equations. We won't promise that the rest of the world will make any more sense, but at least you'll have beer.

Other motivations

- Gravity not tested on all scales
- Need alternative theories to test GR
- Interesting new field theories
- Lessons for UV-modifications
- Cosmological constant problem



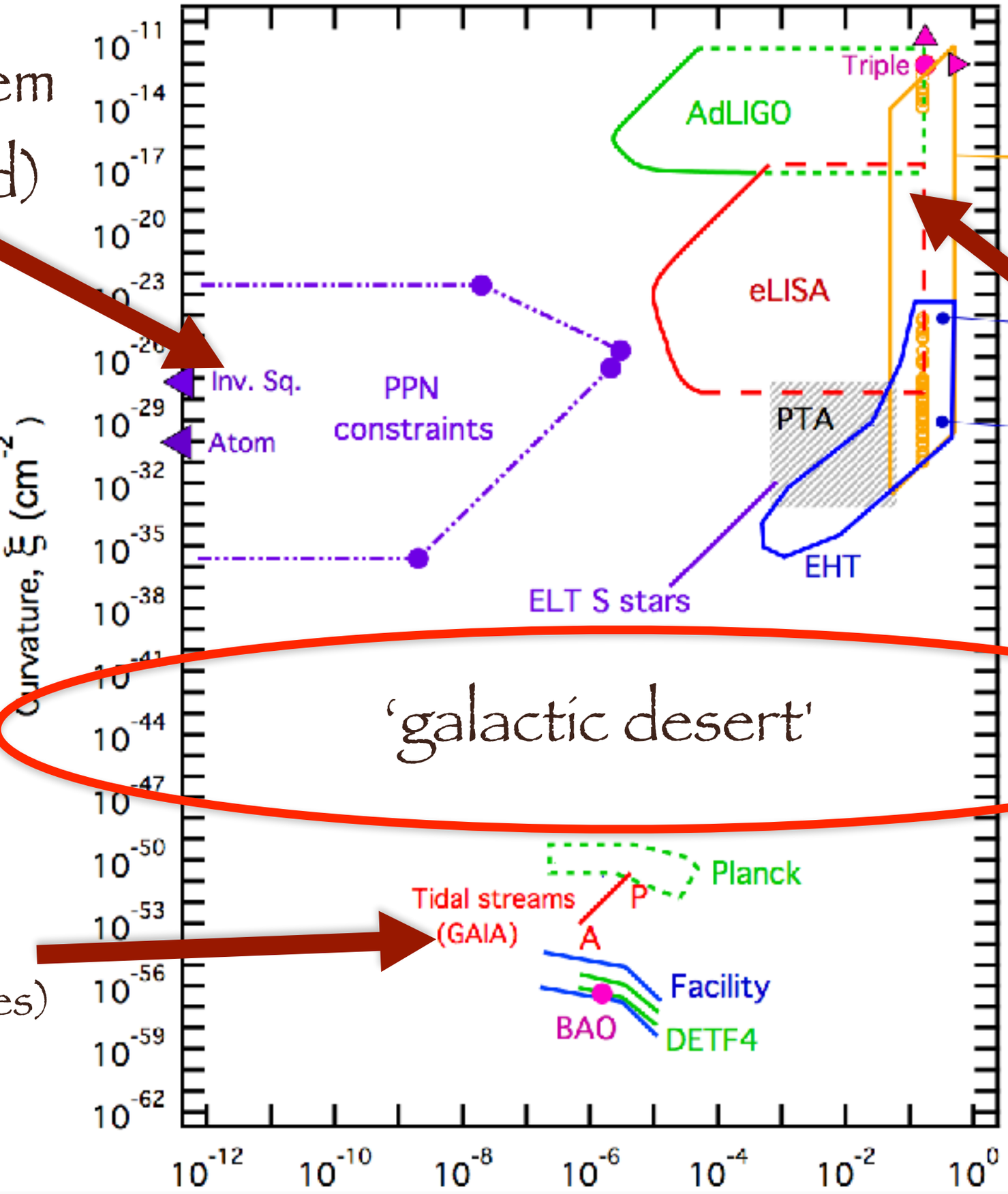
Baker, Psaltis, Skordis '14

solar system
(weak field)

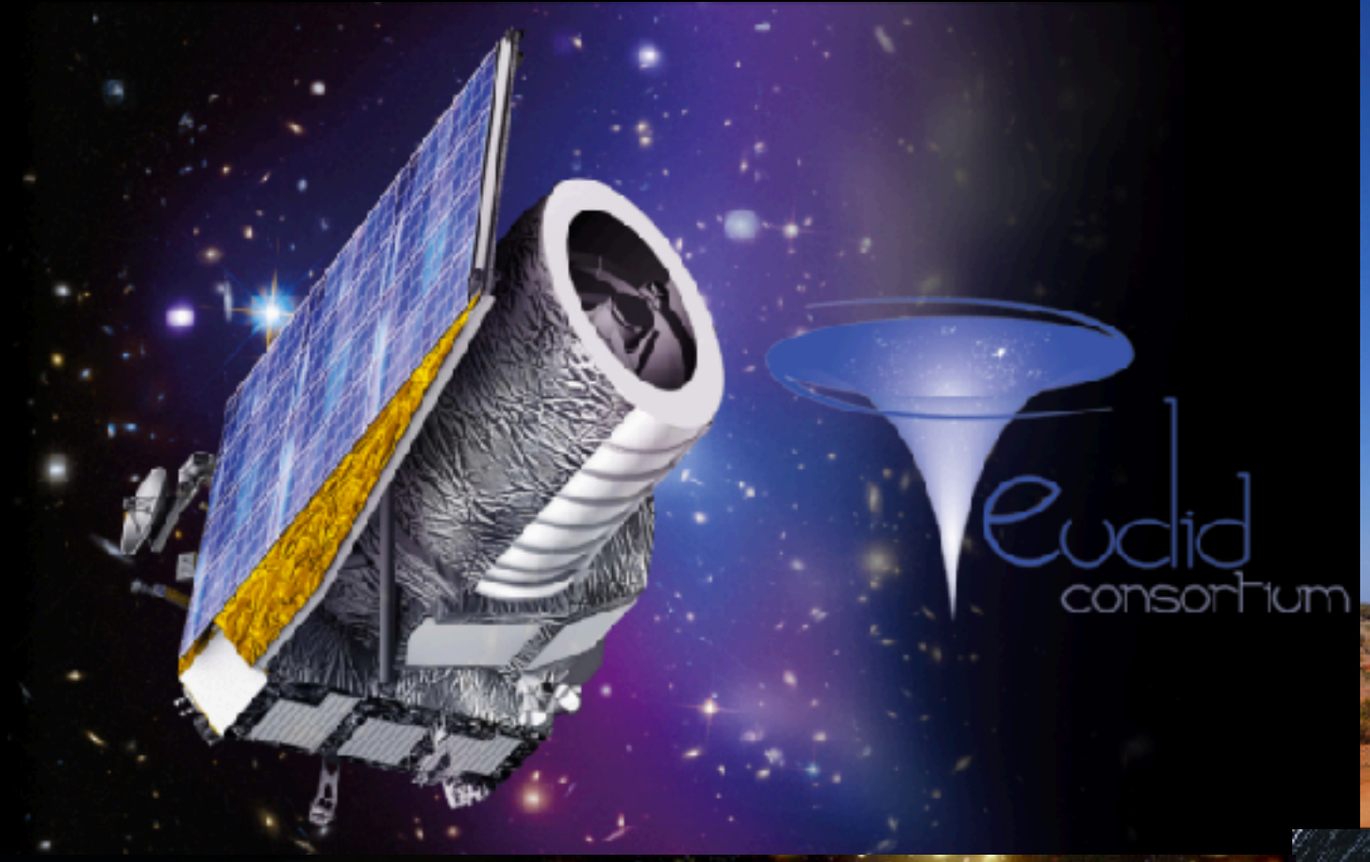
cosmology
(large distances)

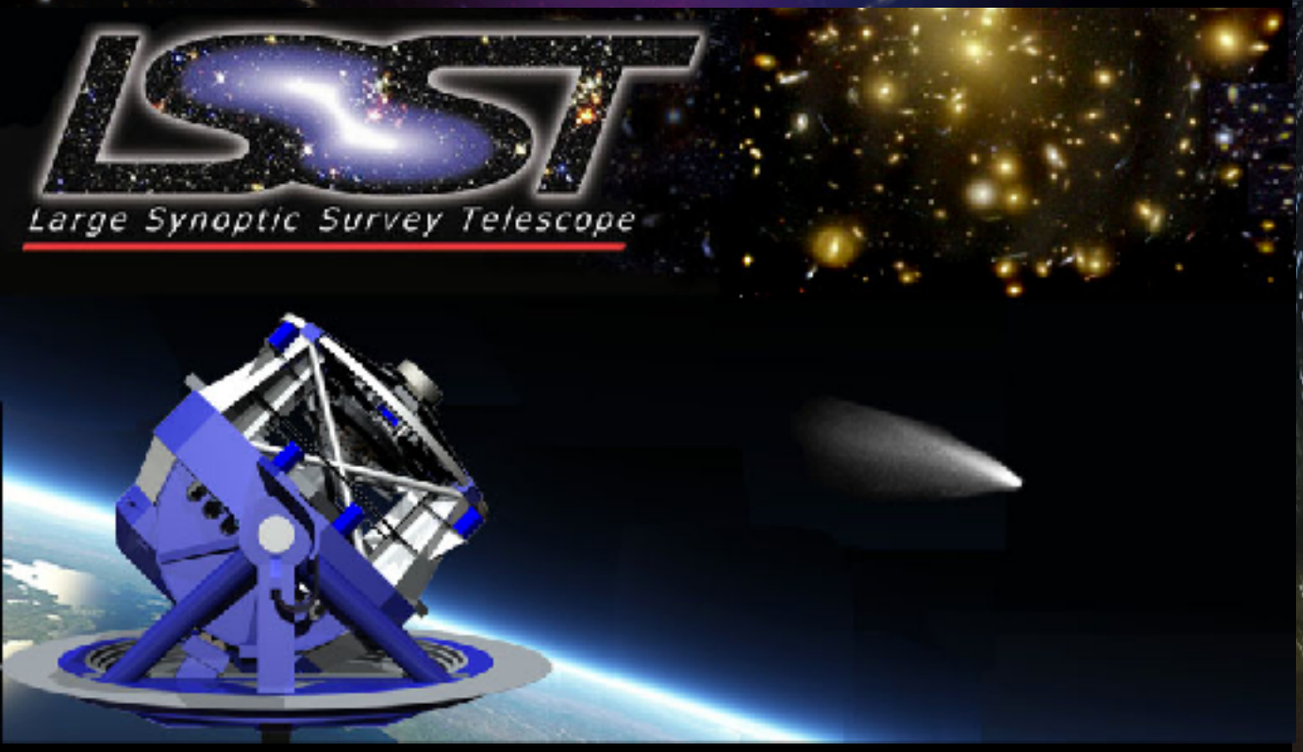
black holes
neutron stars
gravitational waves
(strong field)

'galactic desert'



Baker, Psaltis, Skordis '14





dark energy survey

MG and cosmology

Weinberg:

GR is unique low energy EFT for massless spin-2

(4D, Lorentz-invariant)

Break assumptions:

- Extra DOF - scalar-tensor, vector-tensor
- Break Lorentz - TeVeS, Einstein Aether
- Add mass - massive gravity
- Extra dimensions - braneworld, compact dimensions

Weinberg '65

Modified gravity frameworks

Typically use Horndeski + extensions:

$$\frac{\mathcal{L}}{\sqrt{-g}} = K(\phi, X) + G_3(\phi, X)\Box\phi + G_4(\phi, X)R$$
$$+G_{4,X}\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right] + G_5(\phi, X)G^{\mu\nu}\nabla_\mu\nabla_\nu\phi$$
$$-\frac{1}{6}G_{5,X}\left[(\Box\phi)^3 - 3\nabla^\mu\nabla^\nu\phi\nabla_\mu\nabla_\nu\Box\phi + 2\nabla^\nu\nabla_\mu\phi + \nabla^\alpha\nabla_\nu\phi\nabla^\mu\nabla_\alpha\phi\right]$$

free functions ~ model building

+ beyond Horndeski
+ DHOST
+ .....

$$\left(X = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi\right)$$

(Horndeski '74)

Motivations

- Simple (only one extra scalar)

- EOM is second order (no ghosts)

- Symmetries/EFT (depends on precise form)

- Hide fifth-forces with 'Vainshtein Mechanism'

EFT with cut-off $\Lambda_3 = (M_{\rm pl} H_0^2)^{1/3} \sim (1000\ {\rm km})^{-1}$

Gravitational waves

$$g_{\mu\nu} = (\mathrm{FLRW})_{\mu\nu} + h_{\mu\nu}$$

(space-time) (expanding universe) (GWs)

speed of GWs

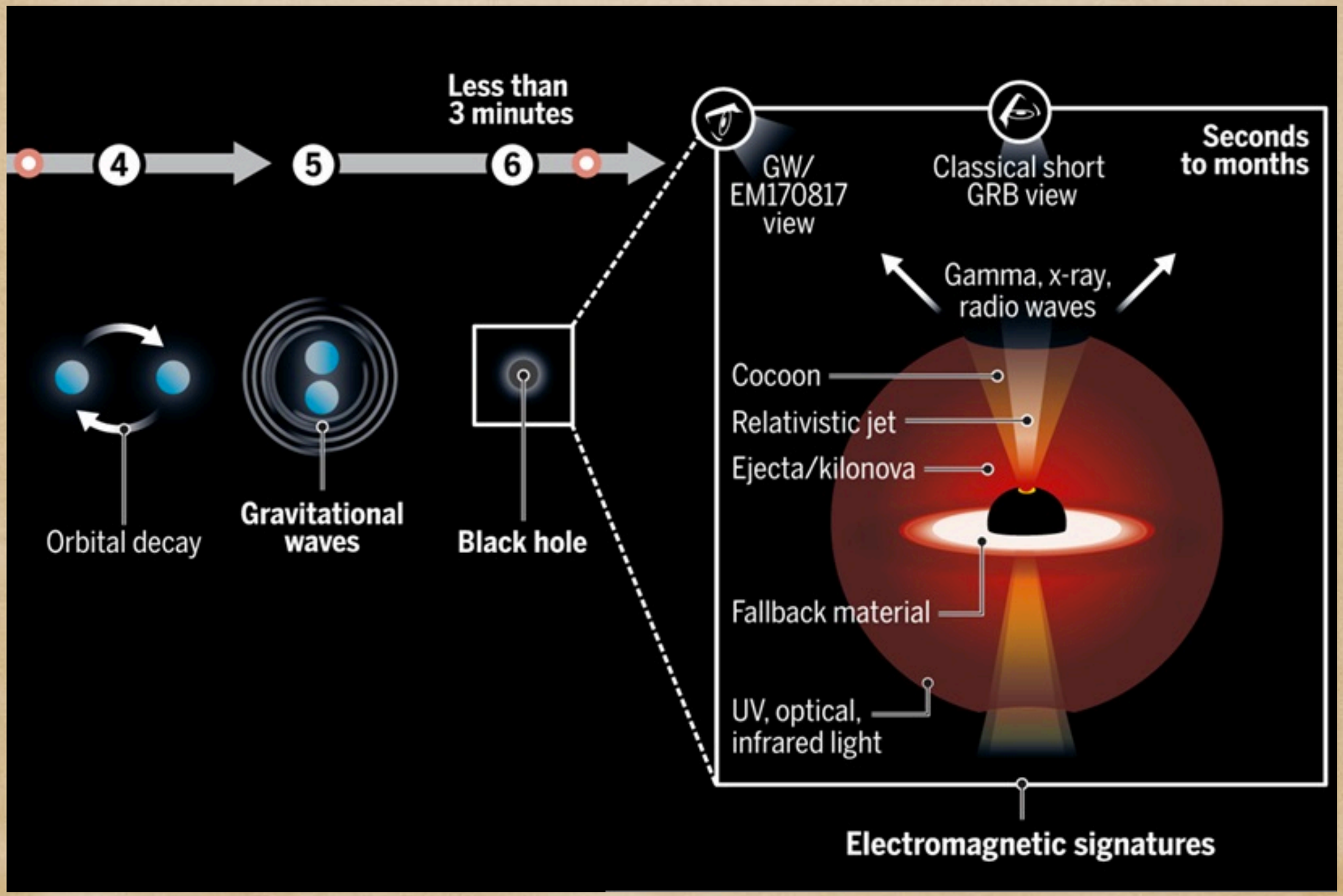
$$S_{\mathrm{GW}} \propto \int \mathrm{d}t\, \mathrm{d}^3\vec{x} a^3 \left[\dot{h}_{ij}^2 - \frac{c_T^2}{a^2}(\partial_k h_{ij})^2\right]$$

speed of GWs ≠ speed of photons

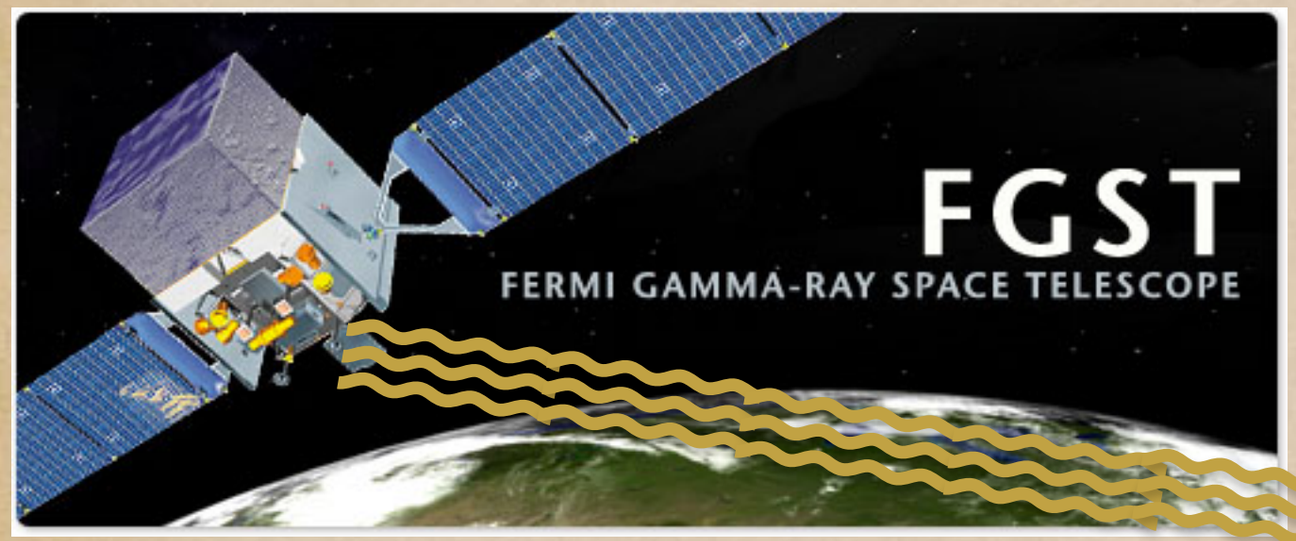
(on distances above cut-off i.e. cosmological)

(Bellini & Sawicki '14)

GW170817


Less than
3 minutes
4
5
6
Orbital decay
Gravitational
waves
Black hole
GW/
EM170817
view
Classical short
GRB view
Seconds
to months
Gamma, x-ray,
radio waves
Cocoon
Relativistic jet
Ejecta/kilonova
Fallback material
UV, optical,
infrared light
Electromagnetic signatures

What did we measure?

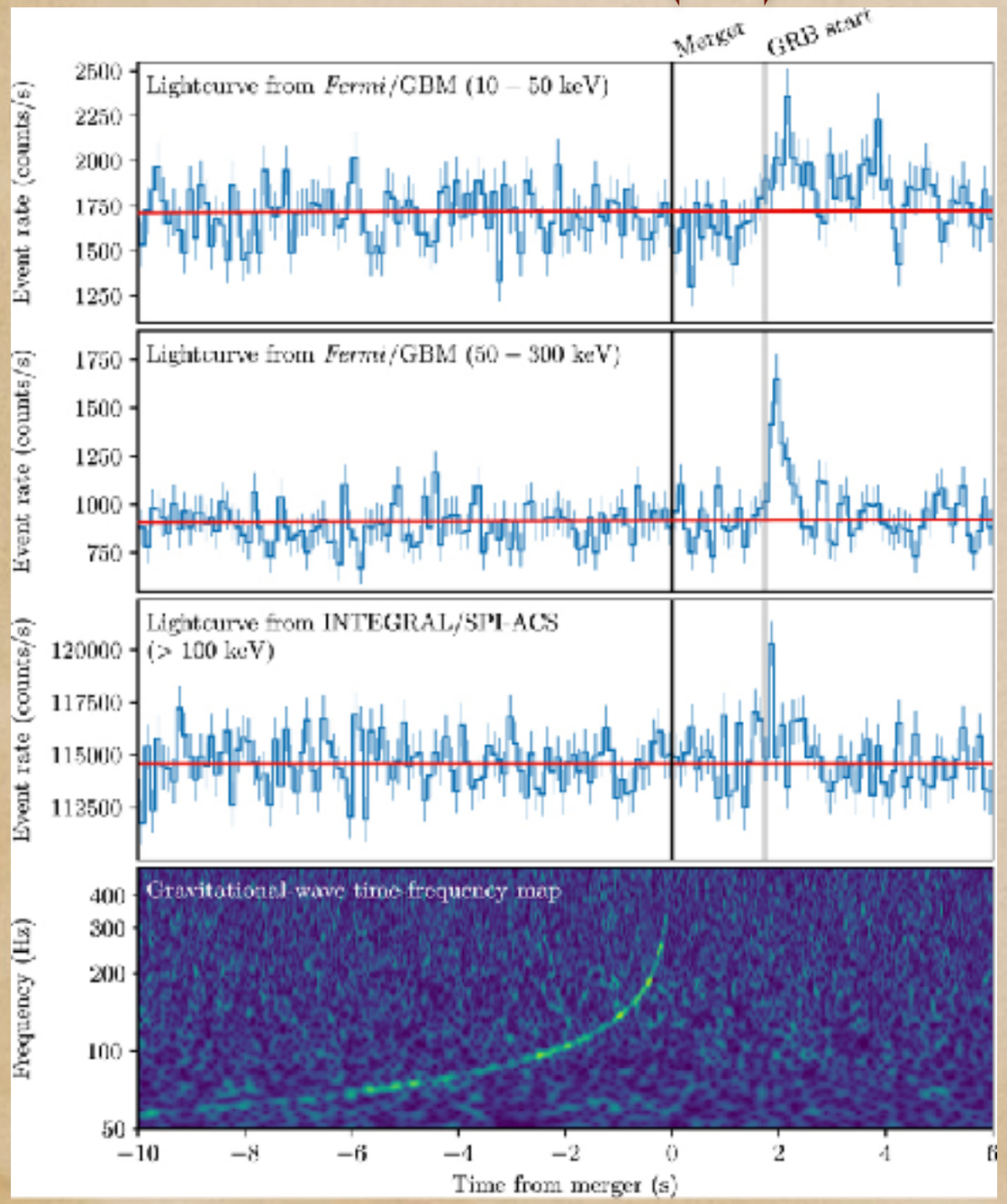


γ

$h_{\mu\nu}$

GW170817

$\Delta t \leq 1.7s$



uncertainty due to NS physics

different models for GRB production

Geometry of GW170817

40 Mpc

$$\Rightarrow \frac{c_T - c}{c} < 10^{-15}$$

Constraints on new DOF

Horndeski:

$$c_T = c$$

$$\frac{\mathcal{L}}{\sqrt{-g}} = K(\phi, X) + G_3(\phi, X)\Box\phi + G_4(\phi, X)R$$

$$+G_{4,X}\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right] + G_5(\phi, X)G^{\mu\nu}\nabla_\mu\nabla_\nu\phi$$

$$-\frac{1}{6}G_{5,X}\left[(\Box\phi)^3 - 3\nabla^\mu\nabla^\nu\phi\nabla_\mu\nabla_\nu\Box\phi + 2\nabla^\nu\nabla_\mu\phi + \nabla^\alpha\nabla_\nu\phi\nabla^\mu\nabla_\alpha\phi\right]$$

$$c_T \neq c$$

Strong constraints on: beyond Horndeski, DHOST, vector-tensor

JS & Jain '17, Baker et al. '17, Ezquiaga & Zumalacárregui '17, Creminelli & Vernizzi '17

Implications for DE

$$\frac{\mathcal{L}}{\sqrt{-g}} = K(\phi, X) + G_3(\phi, X)\Box\phi + G_4(\phi)R$$

quintessence
K-essence
(DE not MG)

can get acceleration
strongly disfavoured (7σ)
(Renk et al. '17)

no self-acceleration

preserves light-cone

Other theories: $g_{\mu\nu} = \Omega^2(\phi, X)\tilde{g}_{\mu\nu}$

(can tune functions too)

Baker et al. '17, Ezquiaga & Zumalacárregui '17

Constraints on massive gravity

$$\omega^2 = c_T^2 p^2 + m_{\rm g}^2$$

Constrained by GW170817

Constrained by most LIGO events

$$m_g < 10^{-22}\ \mathrm{eV}$$

not competitive with solar system tests

$(m_g < 10^{-32}\ \mathrm{eV})$

Important caveats

1) Non-cosmological modifications are unconstrained:

Treat as UV-modification: $\Lambda_{\rm UV} \gg \Lambda_3$

GW170817 constrains MG as dark energy

Okay to study:

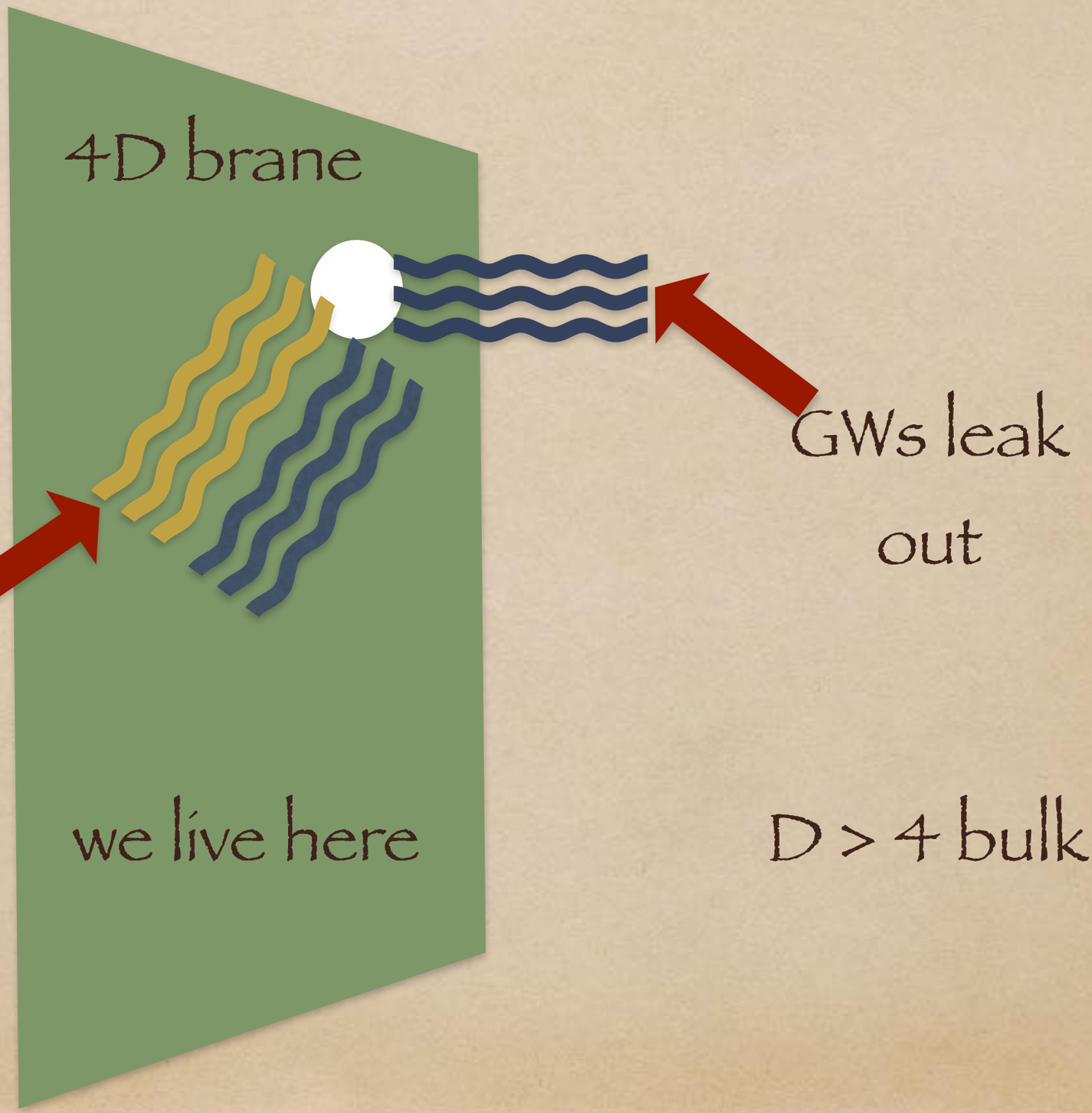
- Black holes
- Neutron stars
- High-energy phenomena

(constraining UV-modifications of GR not DE)

Summary

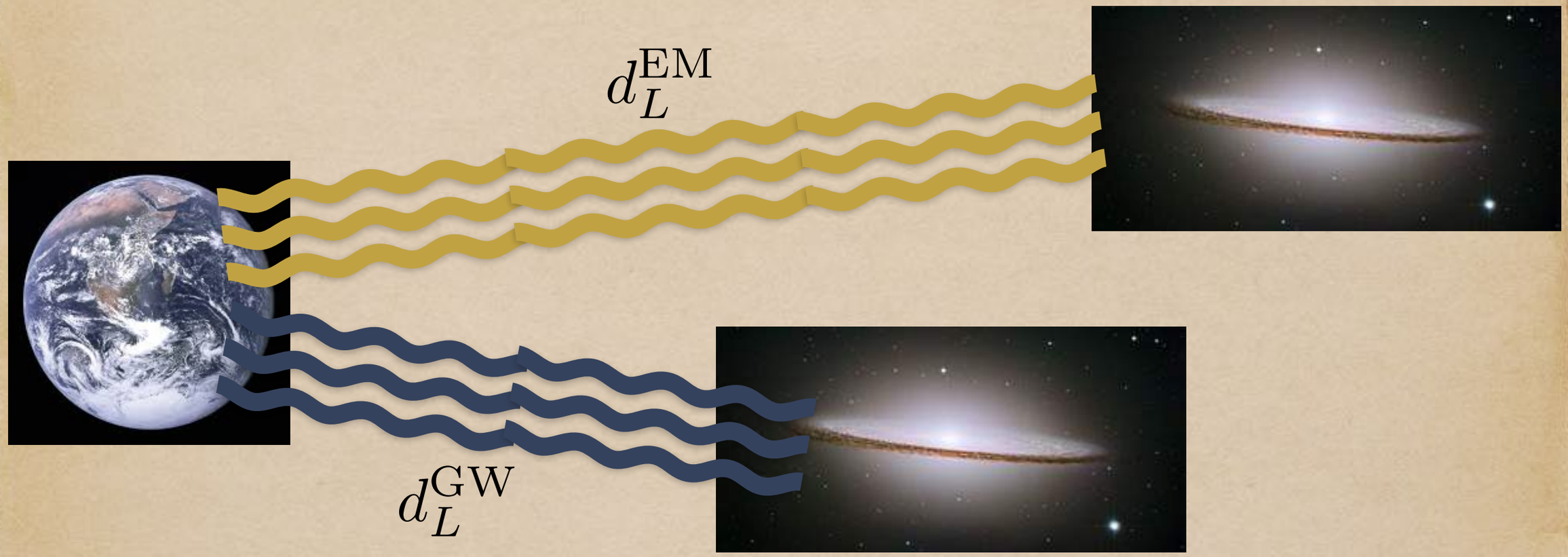
- Dark energy ~ universe is accelerating
  (new physics, MG?)
- GW170817 changed the face of dark energy research
- New (dark energy) DOF highly constrained
- Graviton mass < 10^{-22} eV (<10^{-32} from SS)

Constraints on large extra dimensions



Deffayet & Menou '07

Constraints on large extra dimensions



$$h \propto \frac{1}{{d_L^{\rm GW}}^{\frac{D-2}{2}}}$$

$$D = 4.02^{+0.07}_{-0.1}$$

Deffayet & Menou '07 Pardo, Fishbach, Holz & Spergel '18

Summary

- GW170817 changed the face of dark energy research
- New (dark energy) DOF highly constrained
- Graviton mass < 10^{-22} eV (<10^{-32} from SS)
- D = 4 (large extra dimensions only)