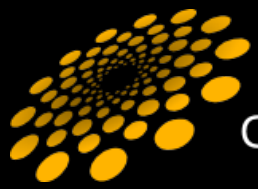
# Dark Matter and Dark Energy in the Era of Gravitational Wave Astronomy

Miguel Zumalacárregui



BERKELEY CENTER *for* COSMOLOGICAL PHYSICS



Very High Energy Phenomena in the Universe

Aug 2018 (170817 + 1year)

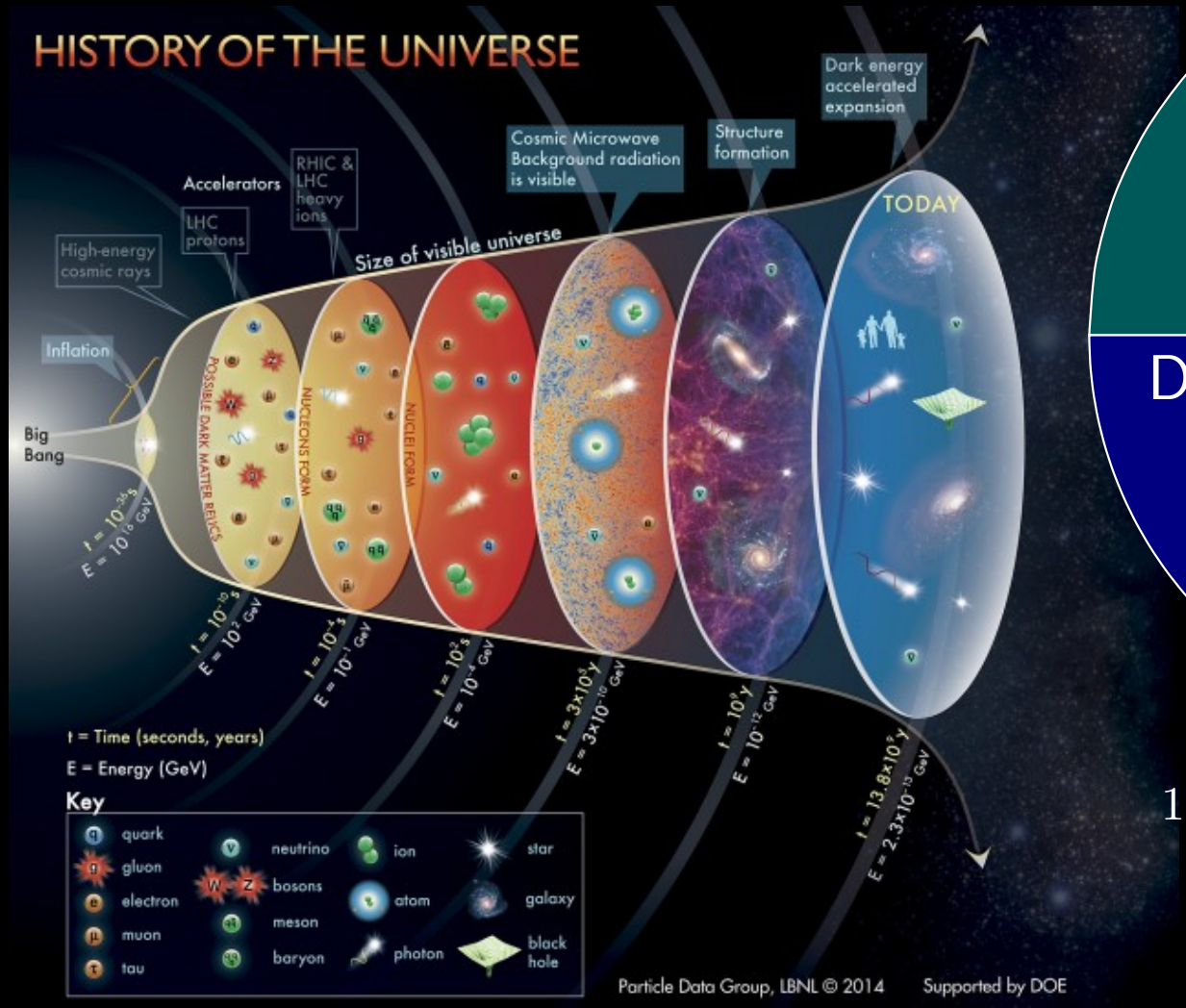
MZ, Seljak (1712.02240)

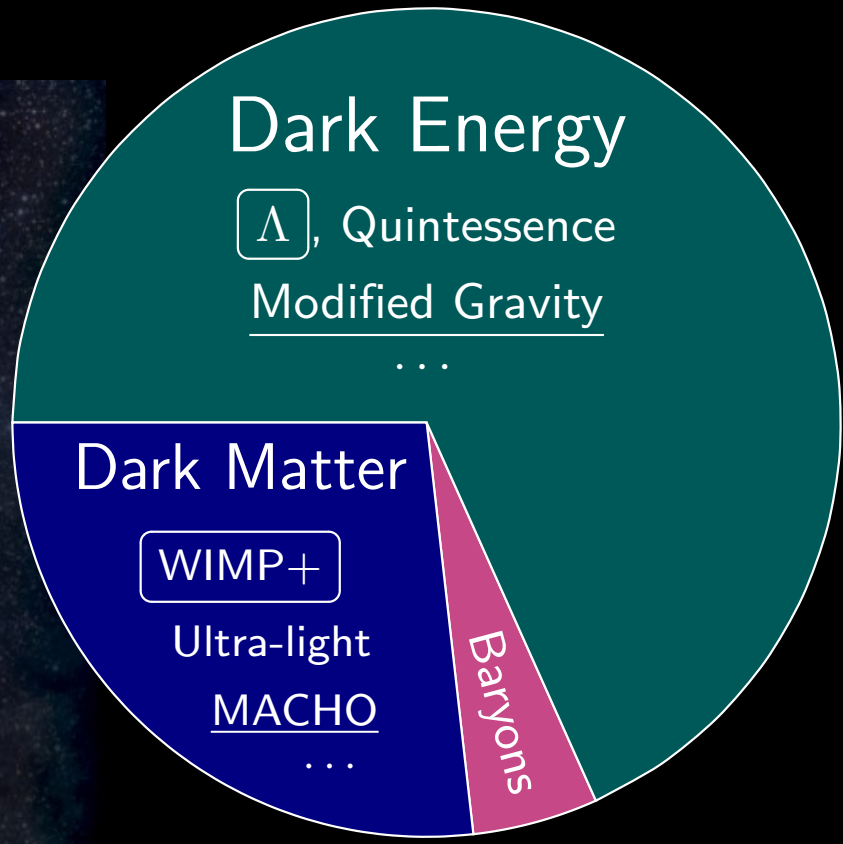
Ezquiaga, MZ, (1807.09241 Review), Ezquiaga, MZ, (1710.05901 PRL)

Bettoni, Ezquiaga, Hinterbichler, MZ (1607.901982 PRD)

Renk, MZ, Montanari, Barreira (1707.02263 JCAP)

# The Dark Universe



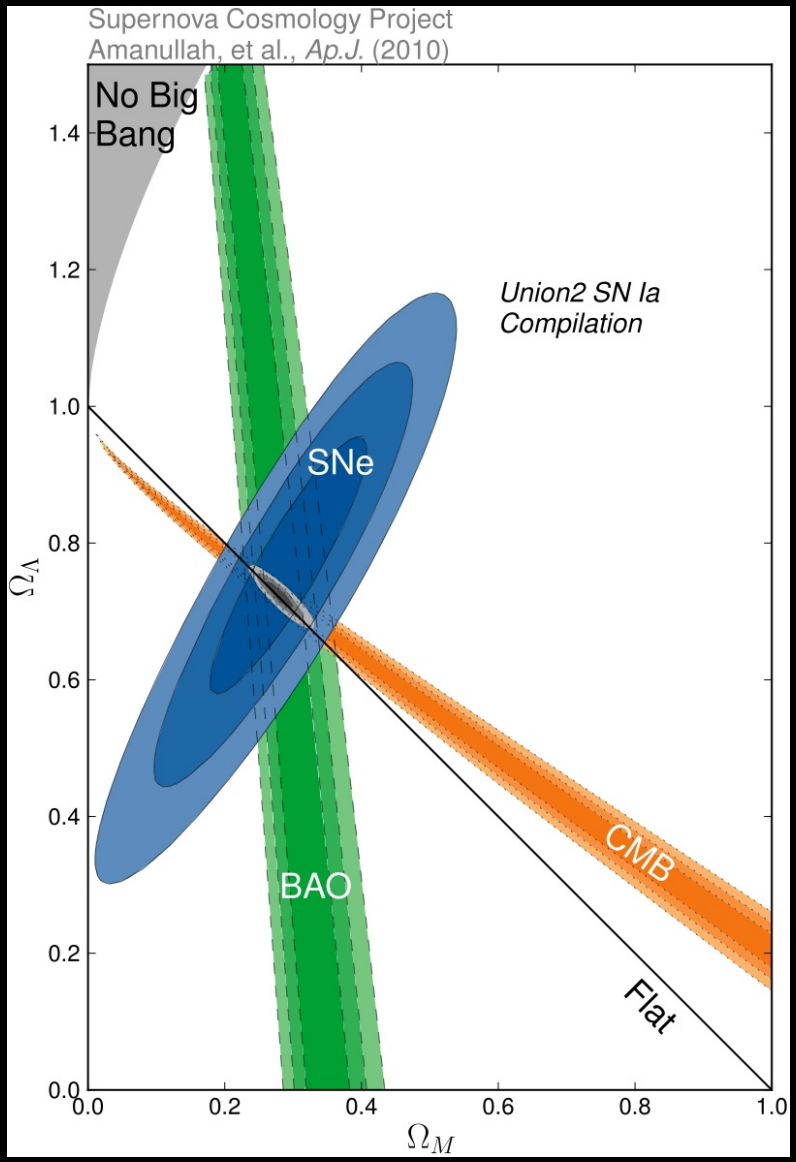




$$100\Omega_b h^2 = 2.222 \pm 0.023\ (1.0\%)$$
$$\Omega_c h^2 = 0.1197 \pm 0.0022\ (1.8\%)$$
$$\Omega_\Lambda = 0.685 \pm 0.013\ (1.9\%)$$

Planck '15 (T+lowP only!)

Well understood laws and history

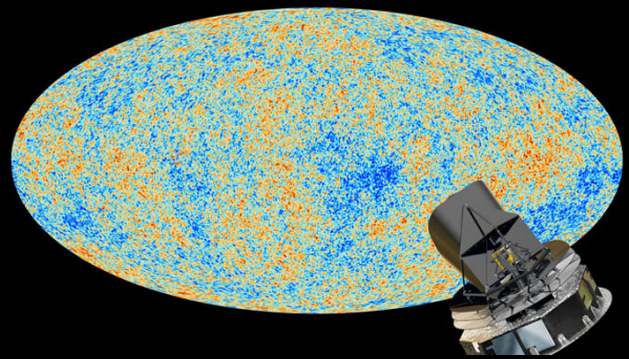
# Cosmic Concordance



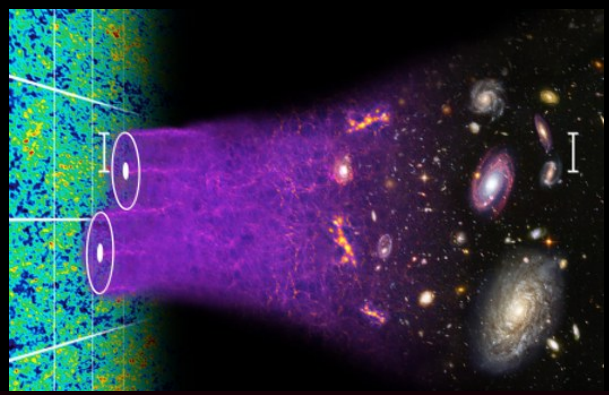

(Perlmutter+ 99, Amanullah+ 2010, Scolnic+ 2017)

## Type IA Supernovae

## Cosmic Microwave Background

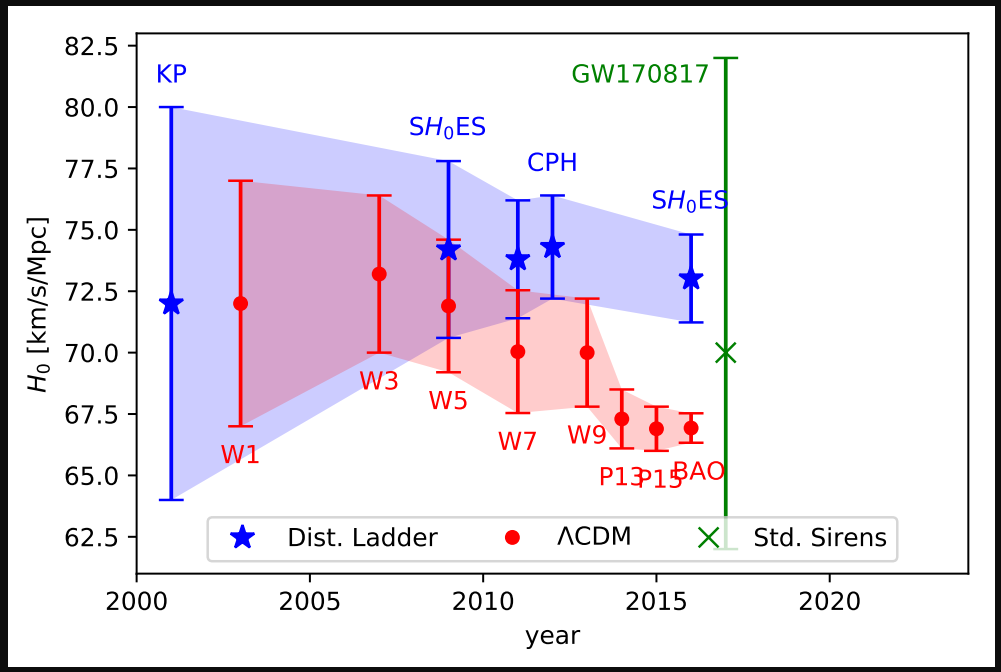


## Baryon Acoustic Oscillations



# $\Lambda$CDM tensions $\rightarrow$ systematics or new physics?

## Cosmic expansion: $3.4\sigma$ tension in $H_0$




(Adapted from Freedman '17, 1604.01788, 1710.05835)

- Distance ladder
  - + several reanalyses
  - + lensing time delays
- CMB (+BAO)
  - $\rightarrow$ assumes $\Lambda$CDM
- Standard Sirens
  - $\rightarrow$ fully independent
  - $\rightarrow$ (E. Burns' talk)

No simple explanation (Bernal+ '16, Poulin+ '18)

Also: Weak Gravitational Lensing (KiDS: $2.9\sigma$, DES: OK?)
Clusters, Planck lensing...

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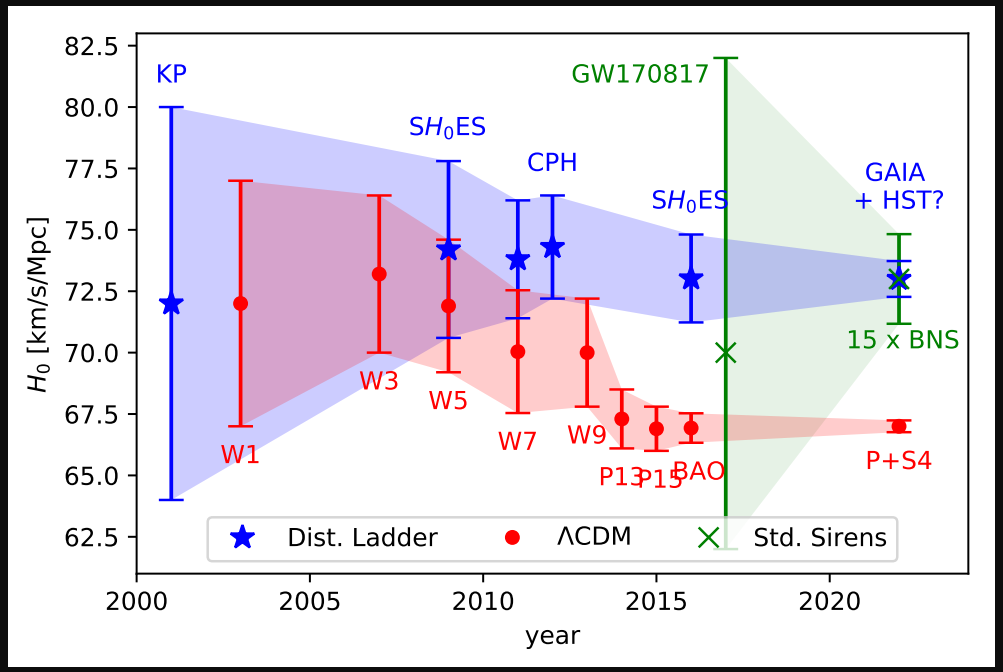


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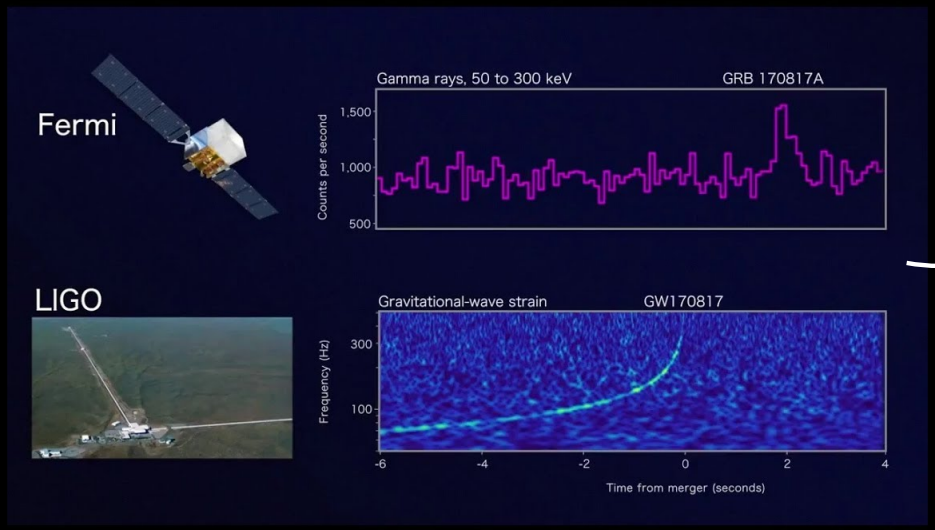
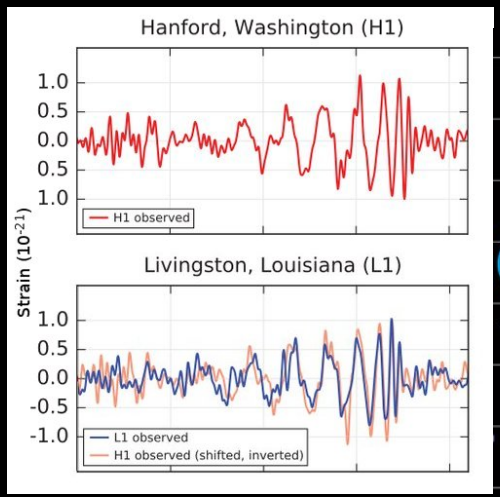
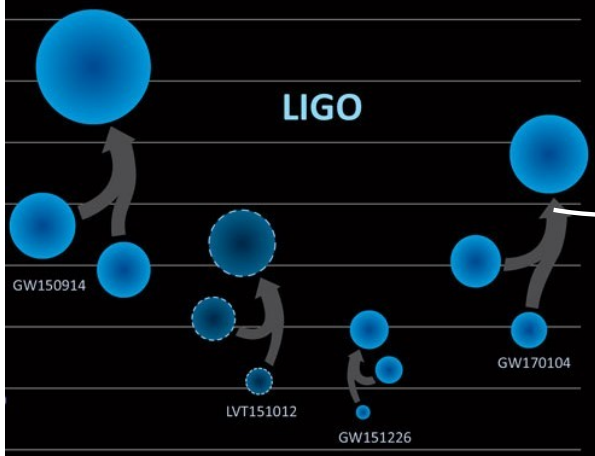
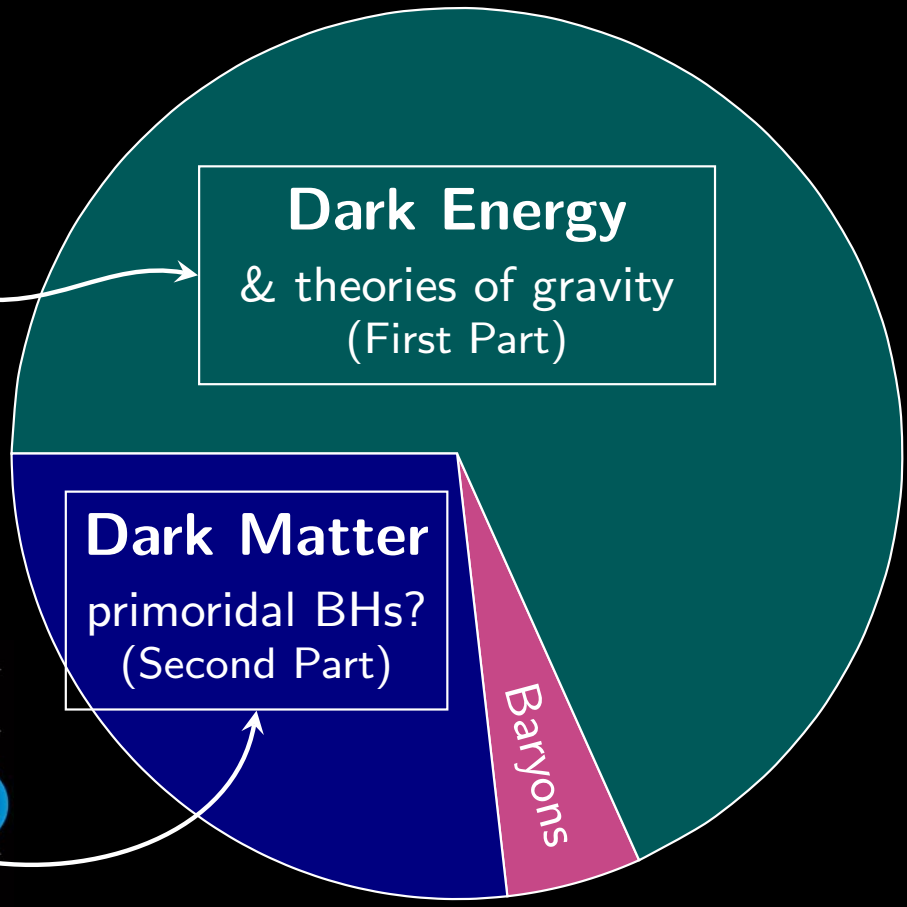
# Gravitational Waves vs $\Lambda$CDM

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Planck '15 (T+lowP only!)

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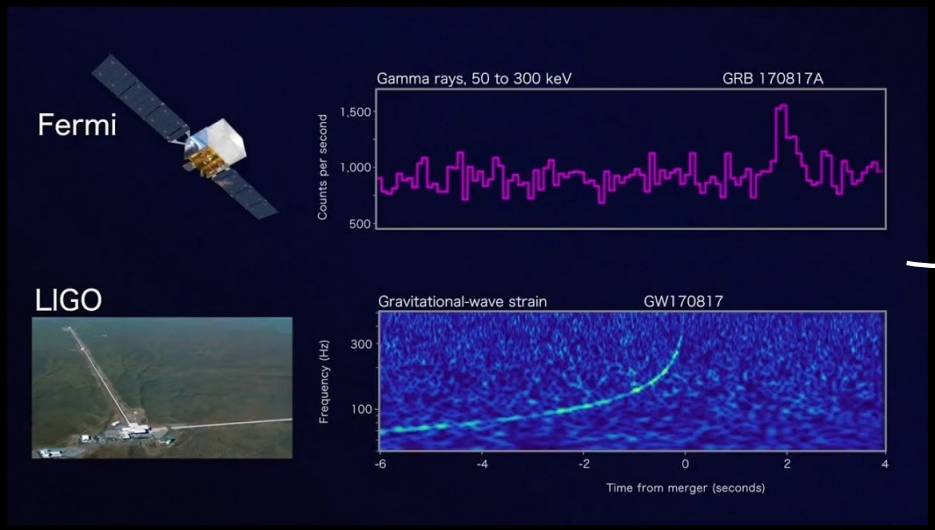


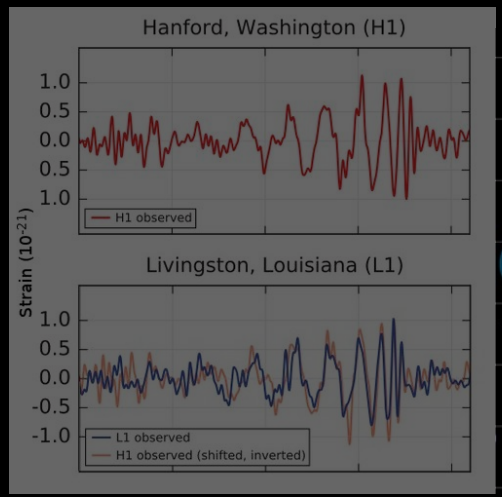


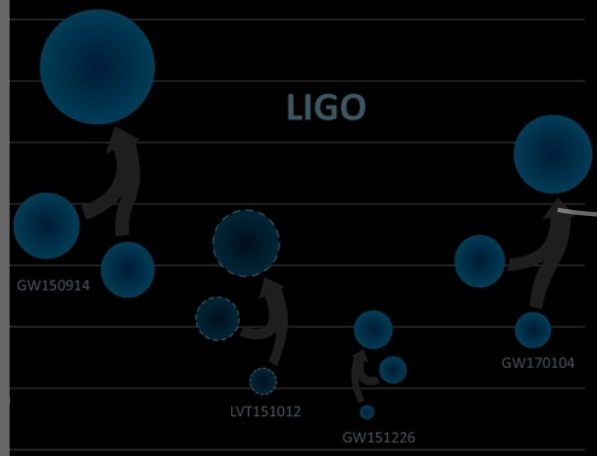


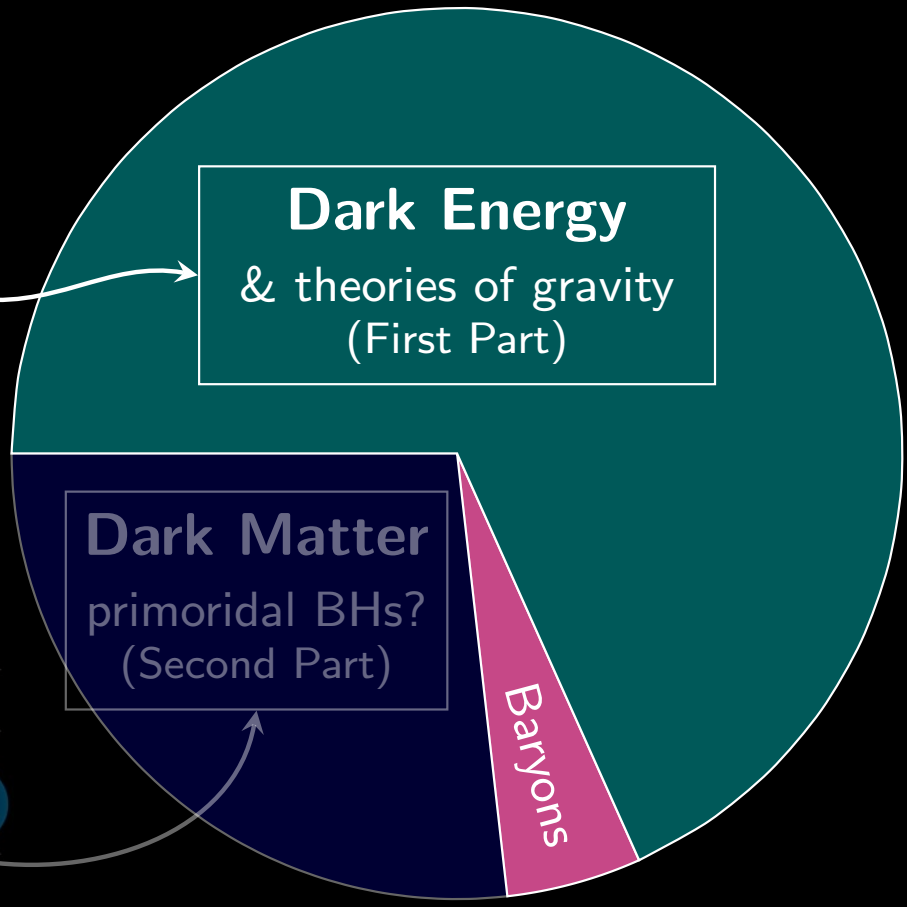


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# gravity

'gravɪti/

*noun*

1. [Physics]
   the force that attracts a body towards the centre of the earth, or towards any other physical body having mass.

2. extreme importance; seriousness.

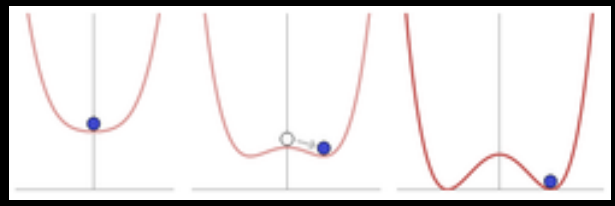
Sources: google (1,2)

# The case for modified gravity

- Interesting theoretical questions:

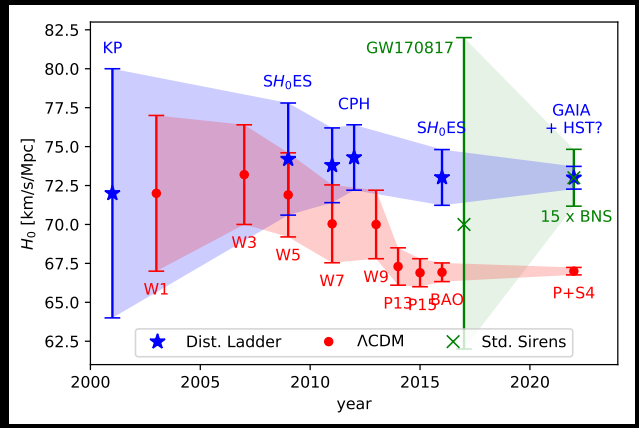
  $\sim 36\%$ *of open problems in physics involve gravity*

  (see www.wikipedia.org/wiki/List_of_unsolved_problems_in_physics)



  - *cosmological constant problems?*
  - *proxy for inflation/quantum gravity?*

- Alternatives to $\Lambda$
  - Inflation again? $n_s \neq 1$
  - $\Lambda$CDM tensions $\longrightarrow$

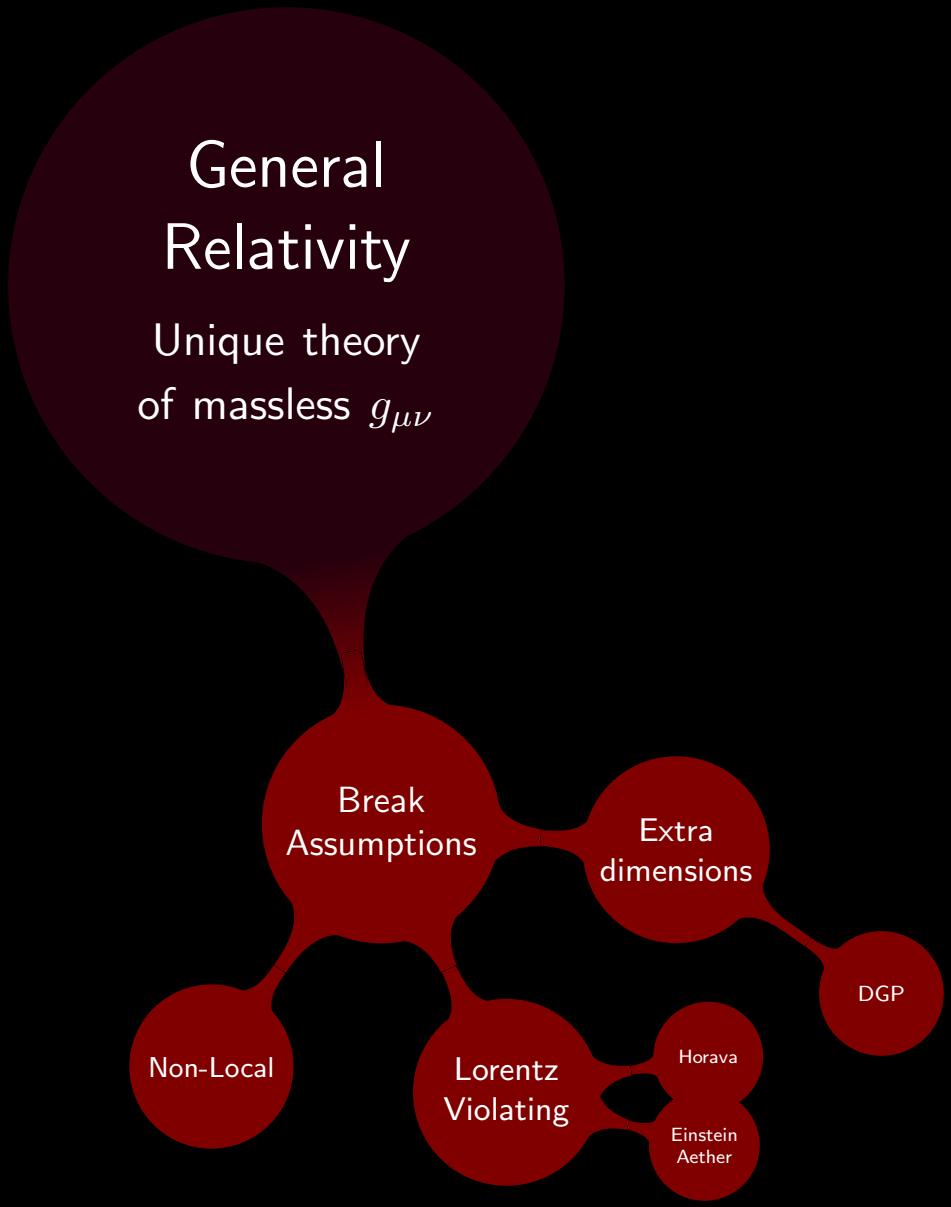



(Adapted from Fredman '17)

- Test gravity on all regimes

# How to modify gravity

(Review Ezquiaga & MZ '18)



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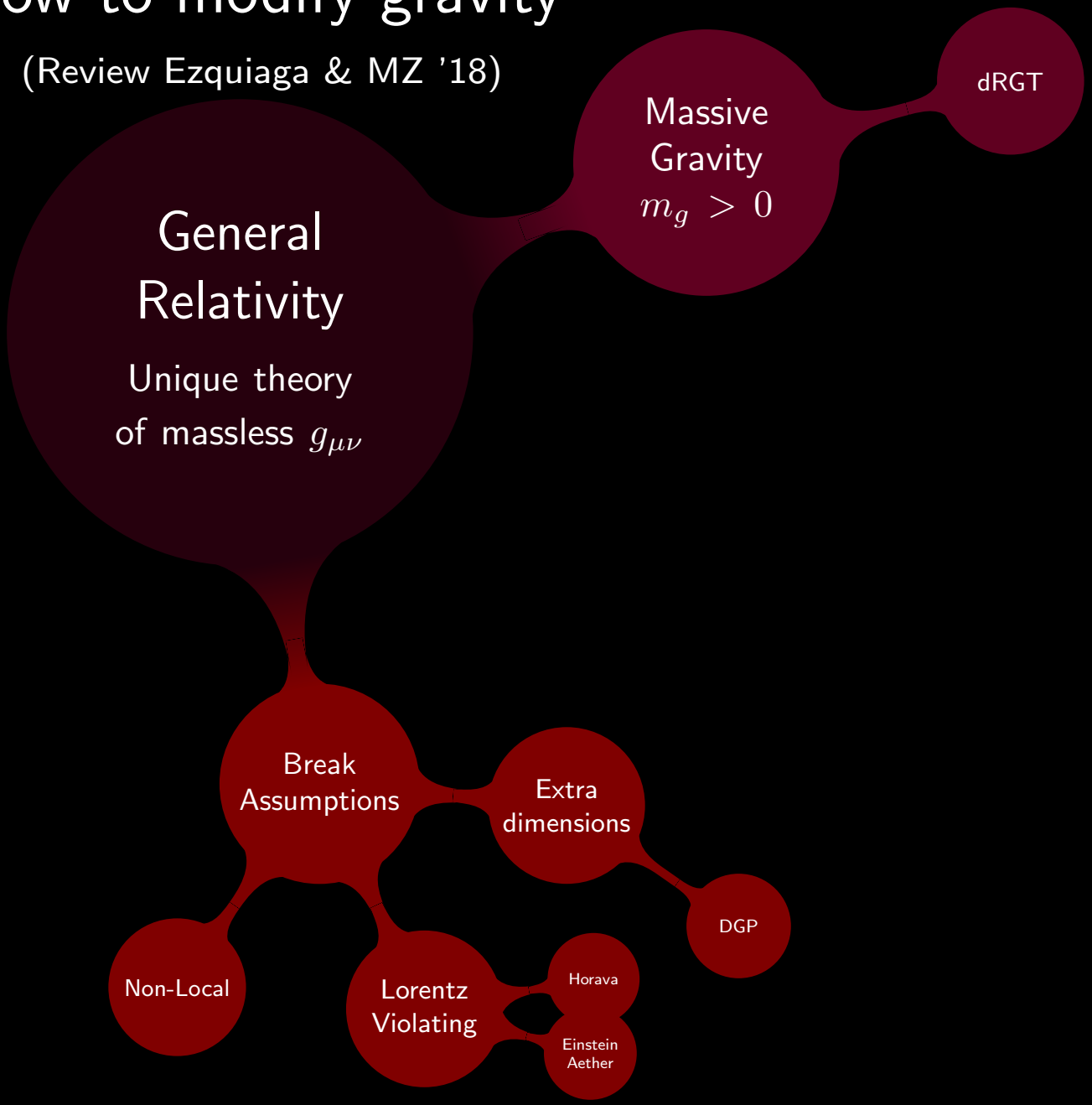

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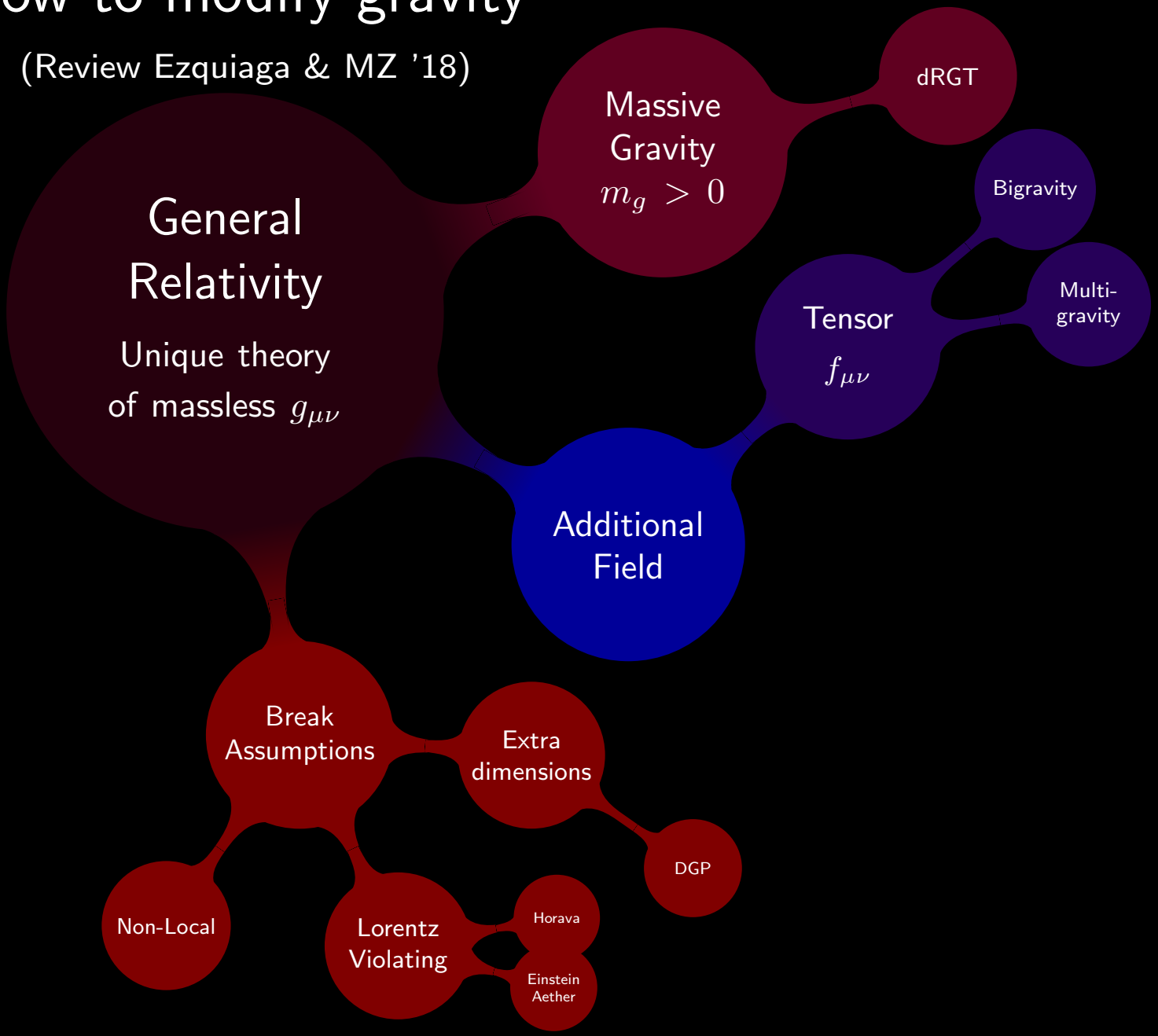

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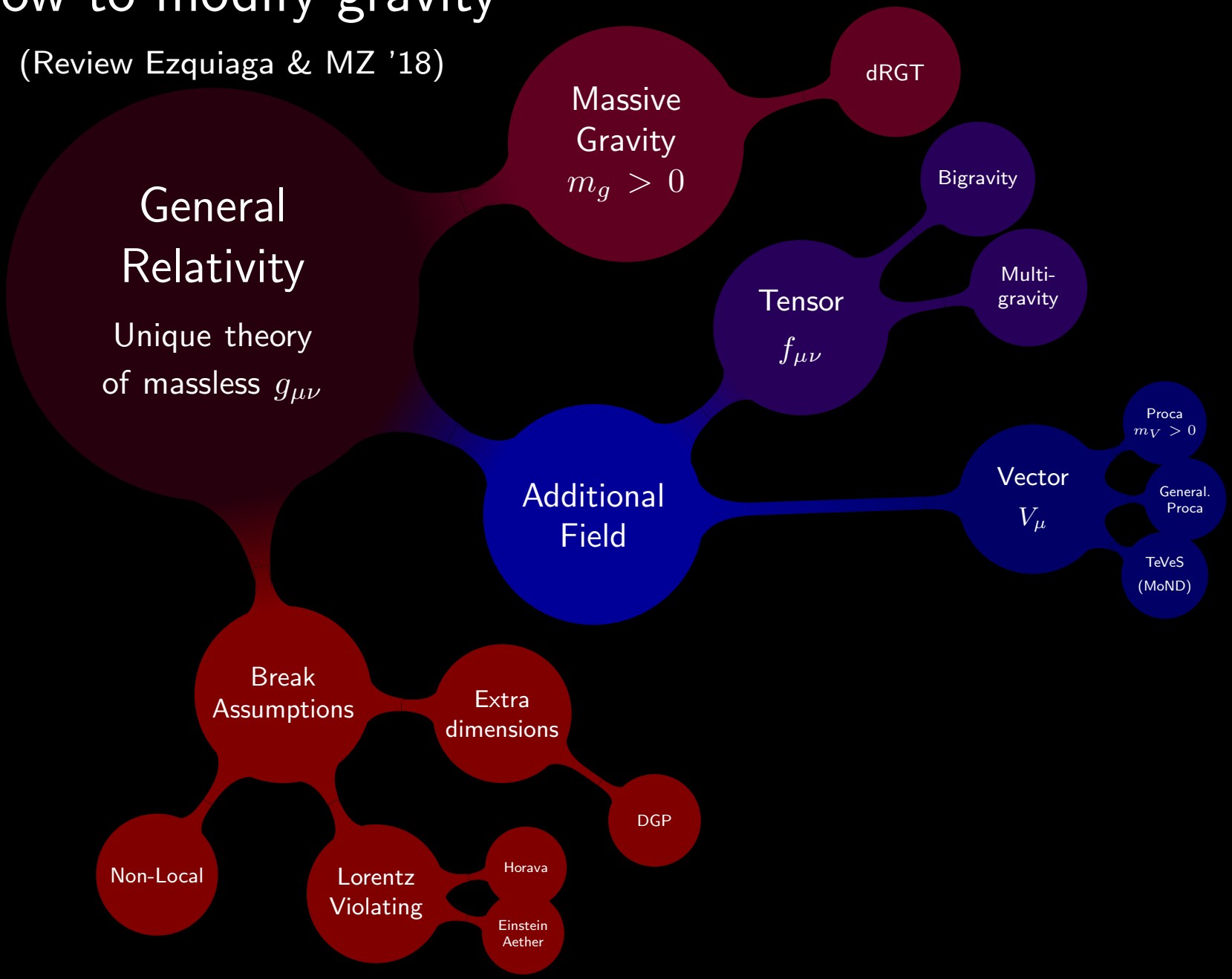

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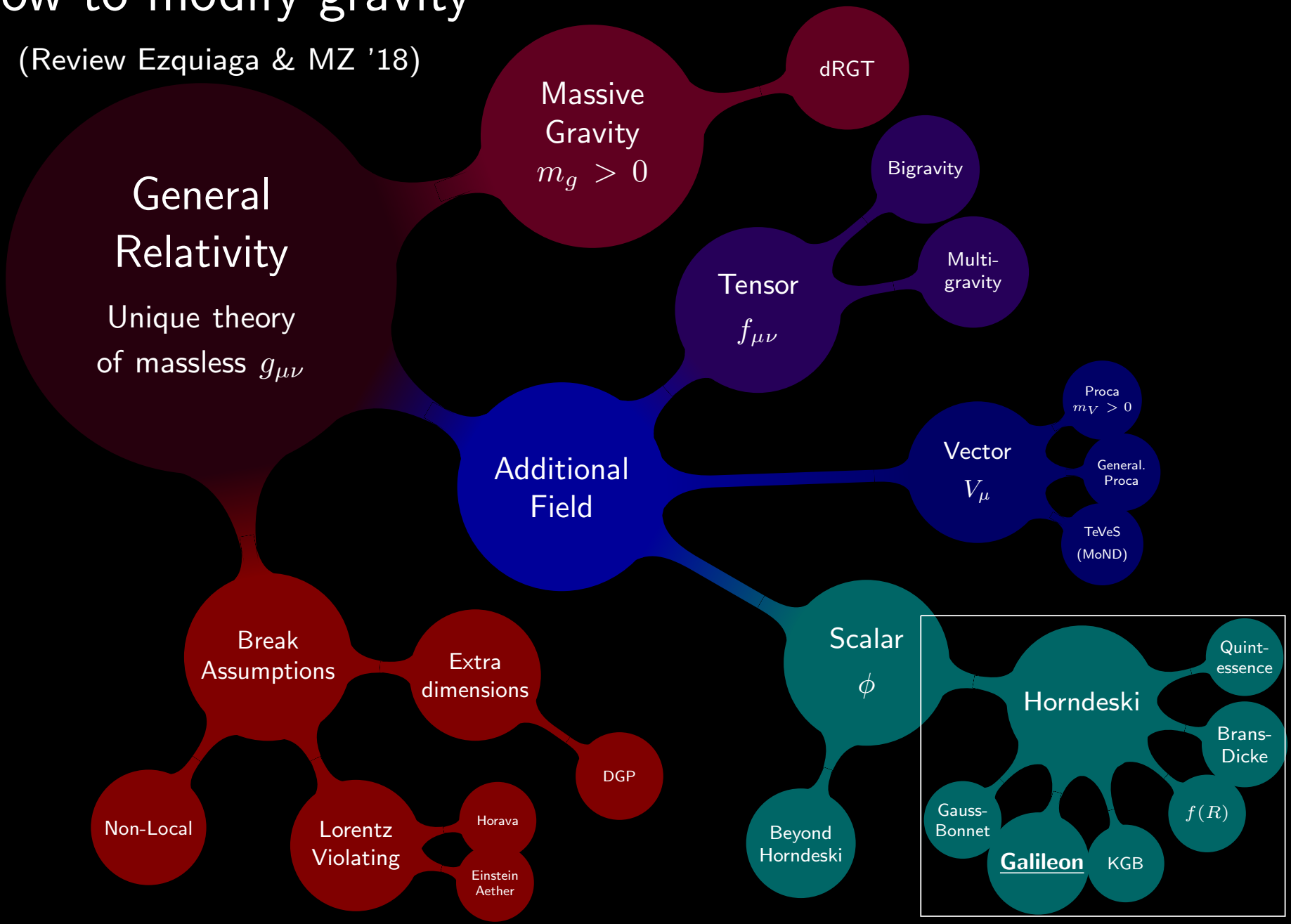
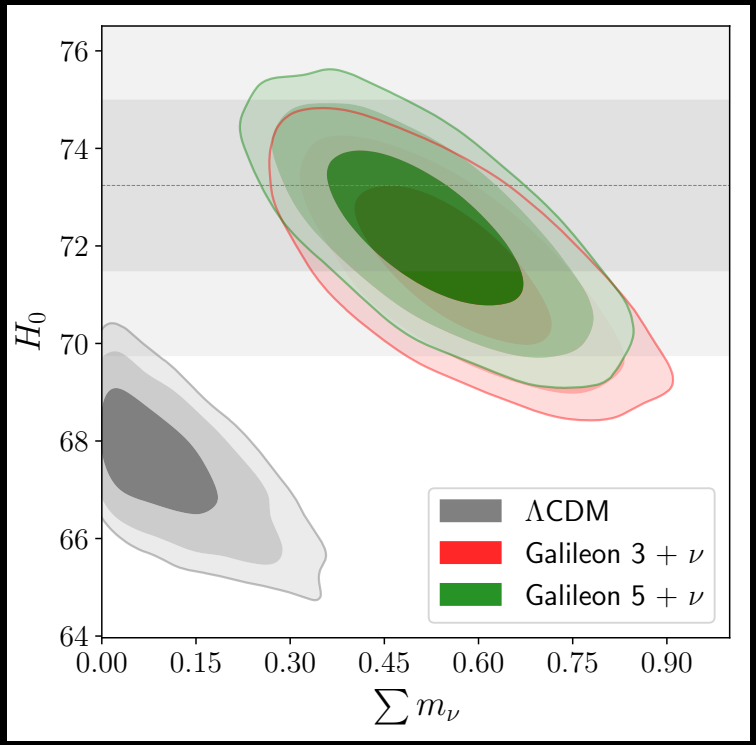


# $\Lambda = 0$ Galileon Gravity

(Barreira+ '14, Renk, MZ+ 17')

Planck+BAO:




- $H_0$ compatible ($\Lambda$CDM $3.4\sigma$!)
- if $\Sigma m_\nu \approx 0.6$ eV
- slight tension with other data

# $\Lambda = 0$ Galileon Gravity $\longrightarrow$ modifies GW propagation

(Barreira+ '14, Renk, MZ+ 17')

$$\ddot{h}_{ij} + \underbrace{(1+\alpha_T)}_{c_g^2,\ \text{GW}} \vec{\nabla}^2 h_{ij} + 3H(1+\alpha_M)\dot{h}_{ij} = 0$$

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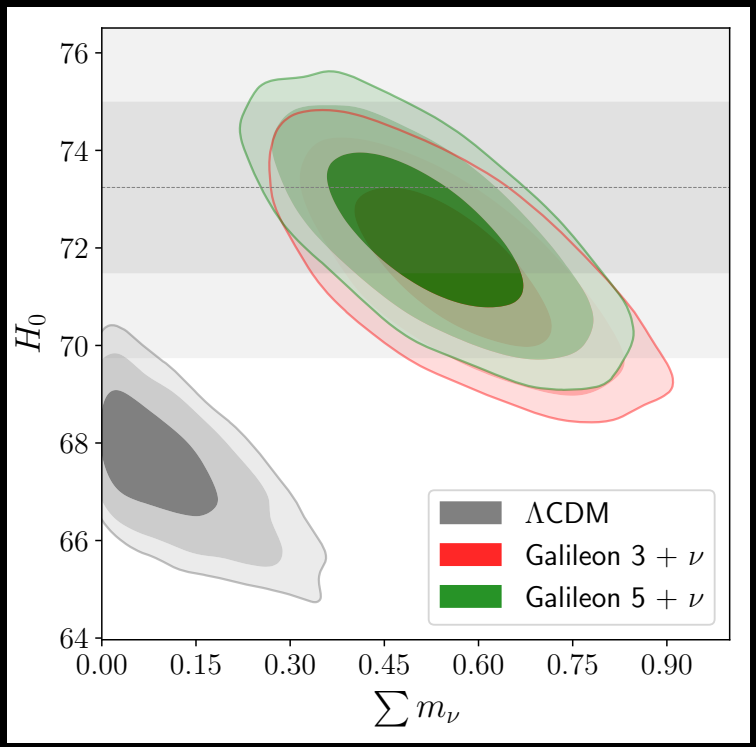


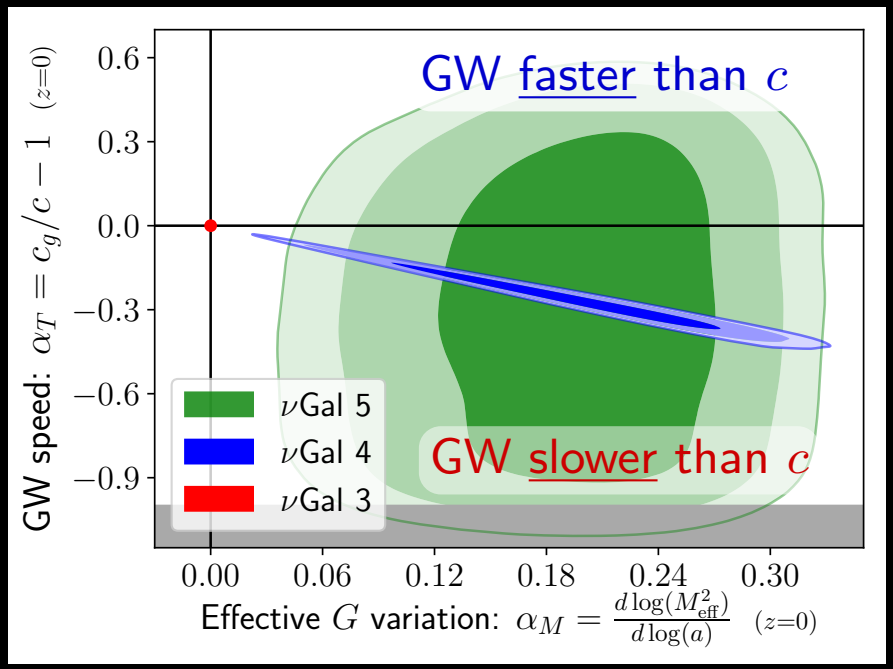


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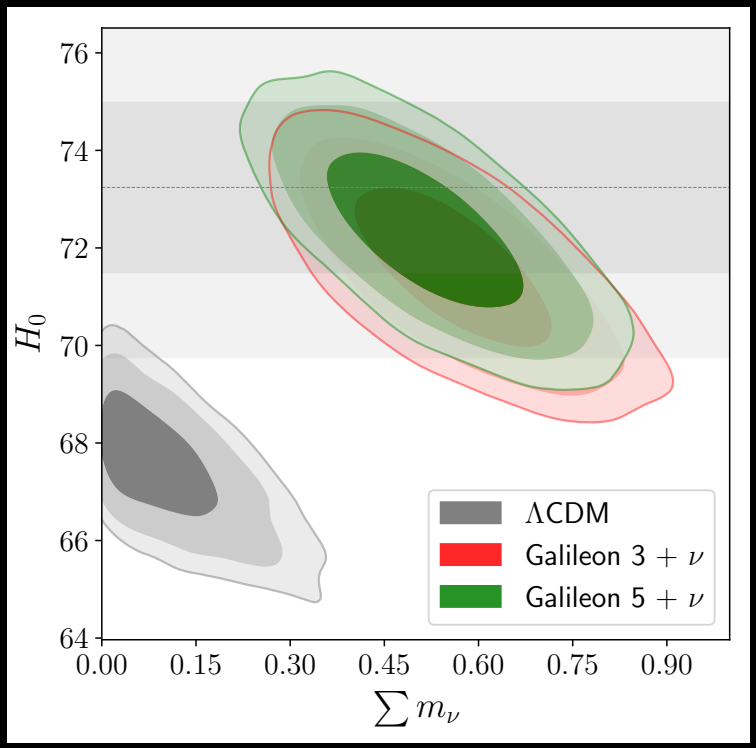


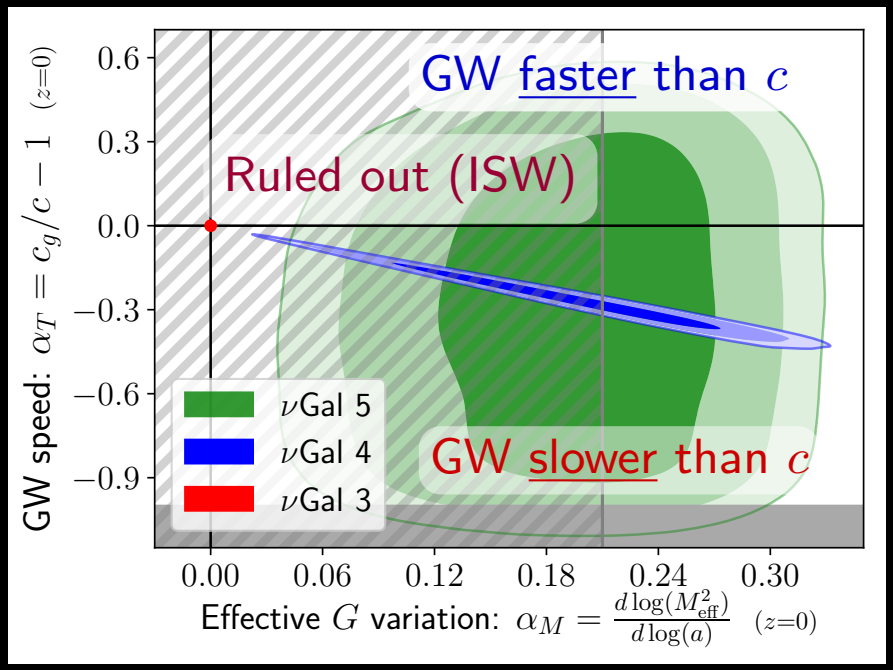


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- ISW effect (from Planck×WISE):
  - $\rightarrow$ kills $\nu$Gal3 ($7.92\sigma$)
  - $\rightarrow$ non-standard GW propagation

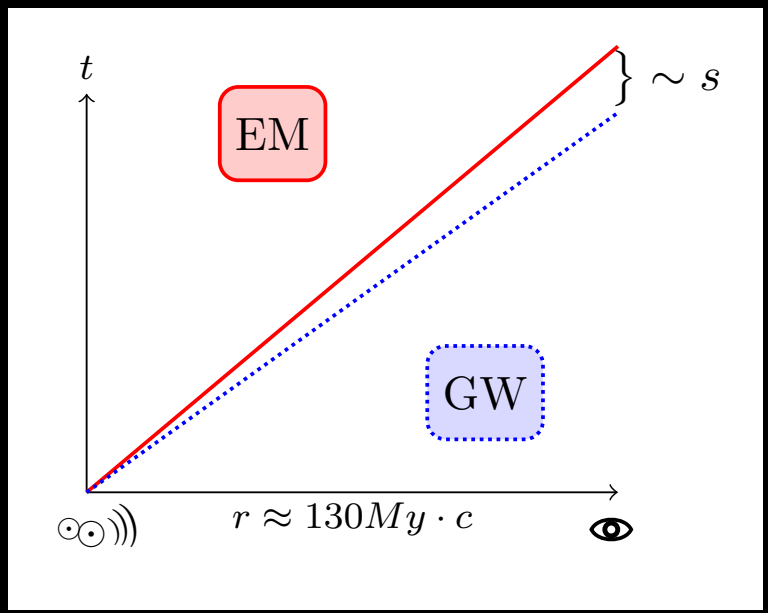
# Universal speed limit

## GW170817 + GRB170817A

Bound on the GW speed:

$$-3\cdot 10^{-15} \leq \frac{c_g}{c} - 1 \leq 6\cdot 10^{-16}$$

(LIGO+Fermi+$\cdots$ 1710.05834)




# Coincident Signals: GW170817 and its Aftermath

## GW170817 + GRB170817A

Bounds: $\left|\leq \frac{c_g}{c} - 1\right| \lesssim 10^{-15}$

(LIGO+Fermi+$\cdots$ 1710.05834)

Theories: $\Delta c_g/c \sim 0.1 - 1\%$


Strongest constraints on DE & Modified Gravity

[2] arXiv:1710.05901 [pdf, other]

**Dark Energy after GW170817**

Jose María Ezquiaga (1 and 2), Miguel Zumalacárregui (2 and 3) ((1) Madrid IFT, (2) UC Berkeley, (3)

Comments: 9 pages, 3 figures

Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; General Relativity and Quantum Cosmology (gr-qc); H

[3] arXiv:1710.05893 [pdf, other]

**Implications of the Neutron Star Merger GW170817 for Cosmological Scalar-Tensor**

Jeremy Sakstein, Bhuvnesh Jain

Comments: five pages, two figures

Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; General Relativity and Quantum Cosmology (gr-qc); H

[4] arXiv:1710.05877 [pdf, ps, other]

**Dark Energy after GW170817**

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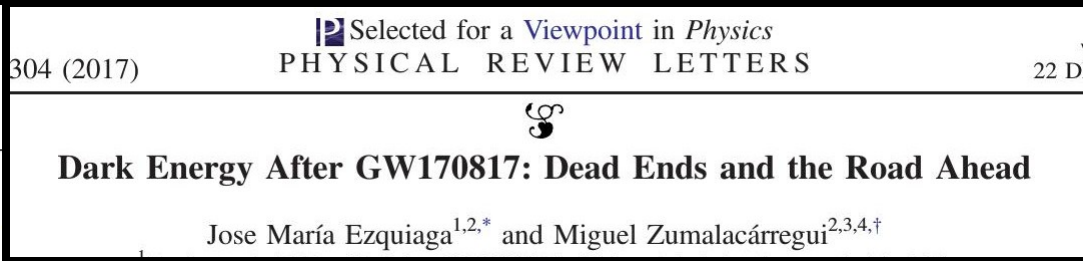
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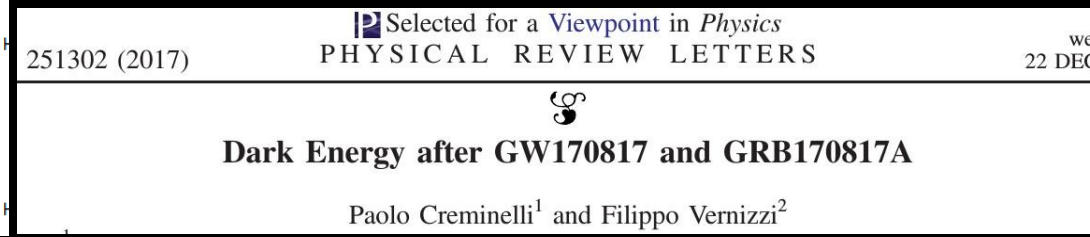
**Dark Energy After GW170817: Dead Ends and the Road Ahead**

Jose María Ezquiaga[1,2,*] and Miguel Zumalacárregui[2,3,4,†]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**Dark Energy after GW170817 and GRB170817A**

Paolo Creminelli[1] and Filippo Vernizzi[2]

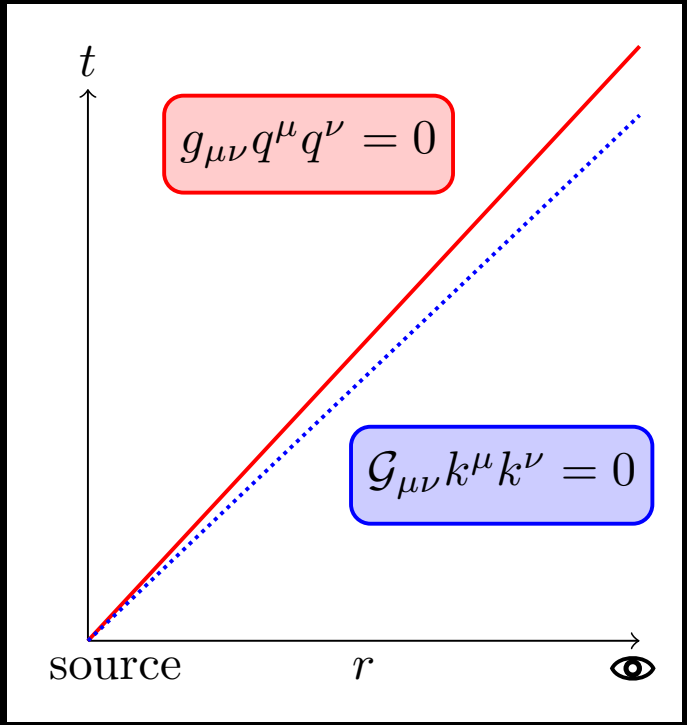
See also Baker, Bellini, Ferreira+ '17 (and many many others)

# Conditions for variable $c_g$ (Bettoni, Ezquiaga, Hinterbichler & MZ '16)

Operationally: $\ddot{h}_{ij} + c_g^2 \vec{\nabla}^2 h_{ij} + \cdots = 0$

**GW effective metric** - any background, $k^2 \gg |R_{\mu\nu}|$

$$\text{GW eq} \propto \big( \underbrace{\mathcal{C}\Box + \mathcal{D}_{\mu\nu}\partial^\mu\partial^\nu}_{\mathcal{G}_{\mu\nu}\partial^\mu\partial^\nu} \big) h_{ij}$$

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(2) $\Rightarrow$ binary classification of theories

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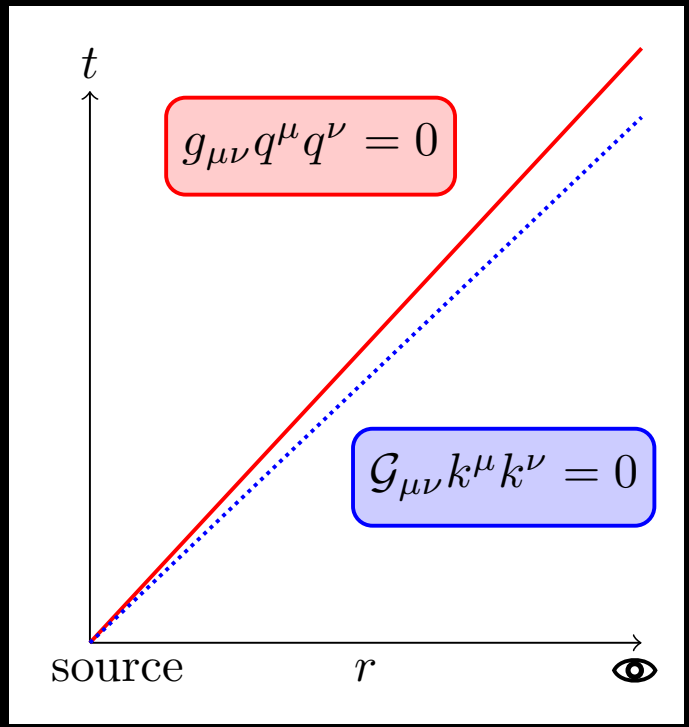


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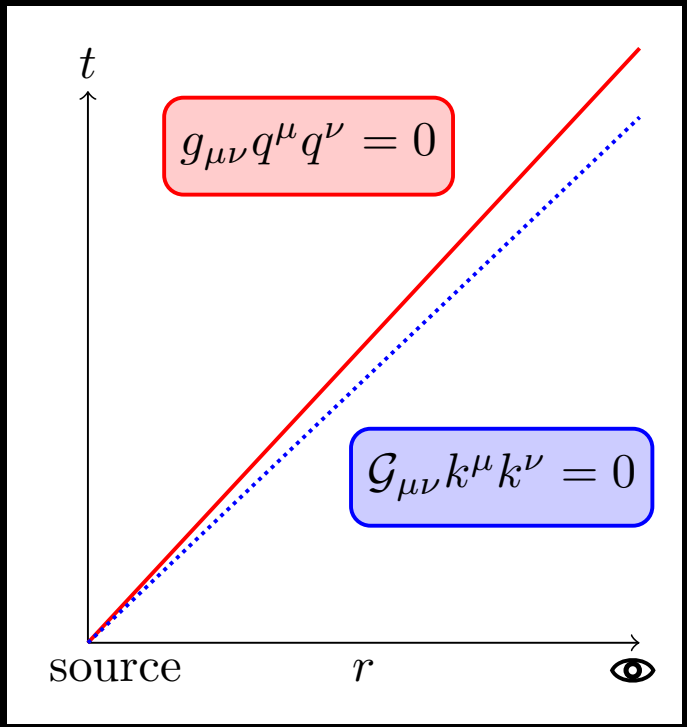
   Cosmology $\to \dot{\phi} \sim H_0$

2) $\phi$-derivatives couple to Riemann Curvature

   $R_{\mu\alpha\nu\beta} \to \underline{\partial_\mu\partial_\nu}\, h^{\rm TT}_{\alpha\beta}$ $\qquad (R_{\mu\nu} \to \Box h^{\rm TT}_{\mu\nu})$

   i.e. non-canonical kinetic term

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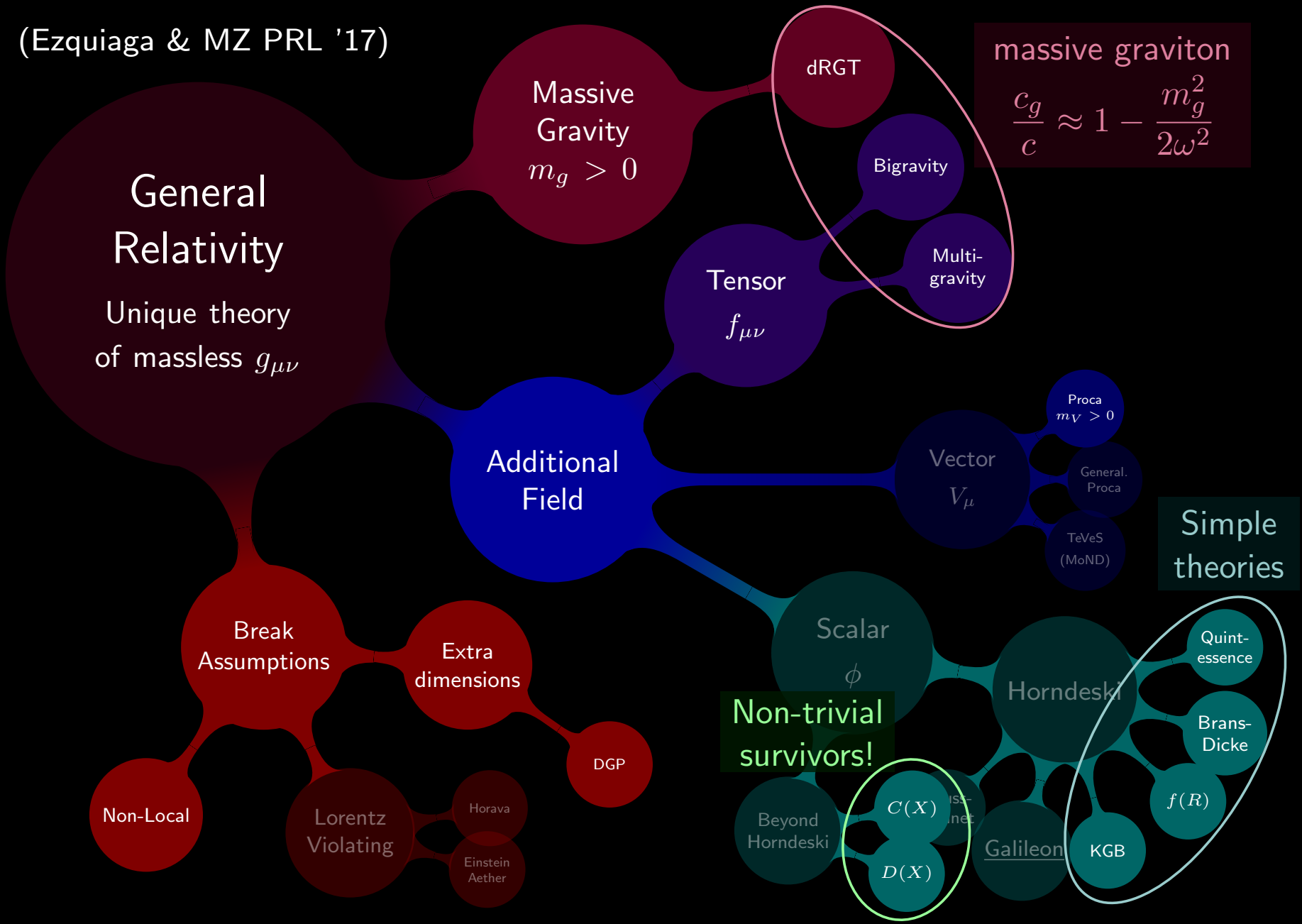
# DE after GW170817

(Ezquiaga & MZ PRL '17)



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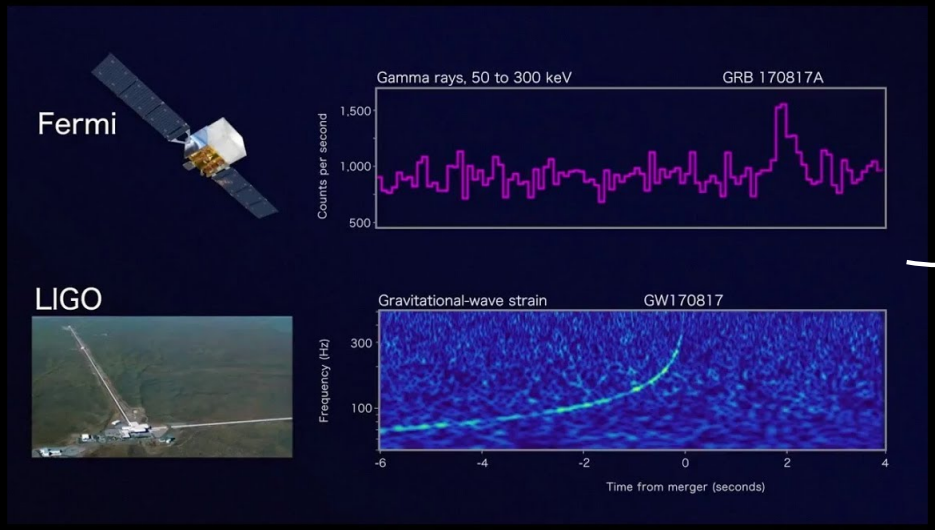
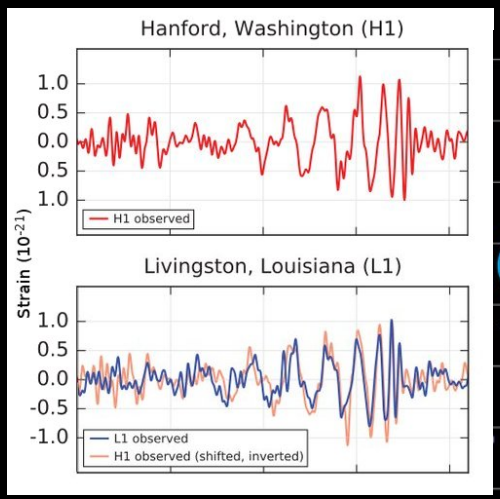
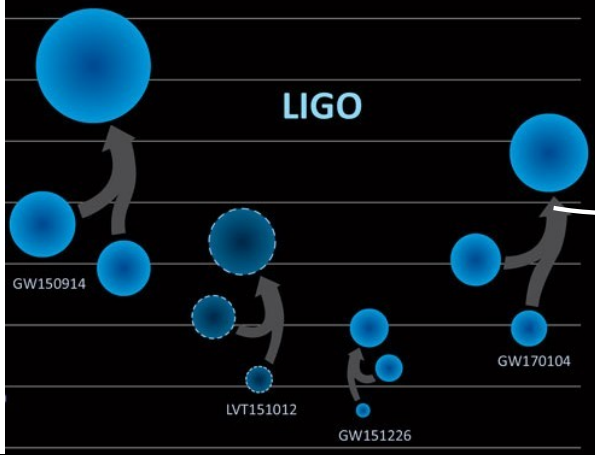
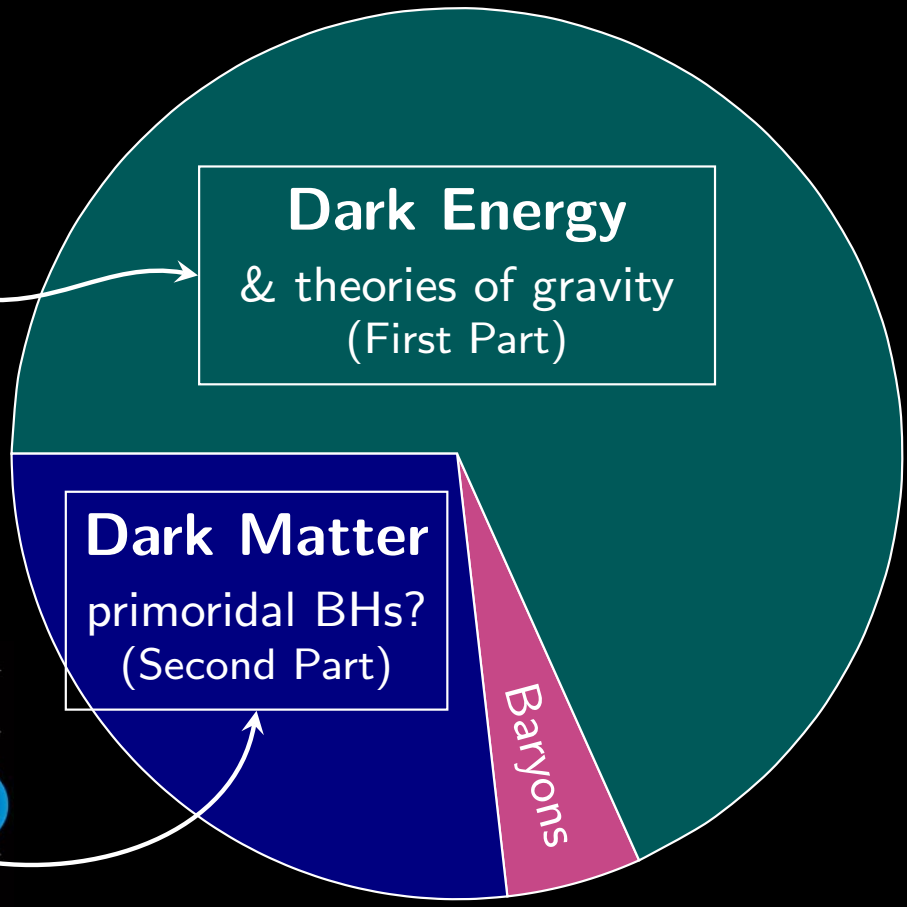


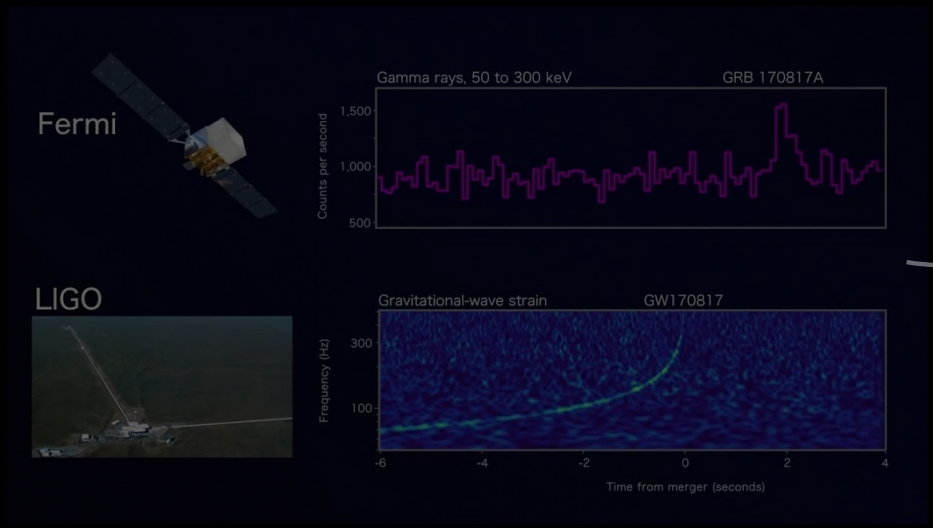



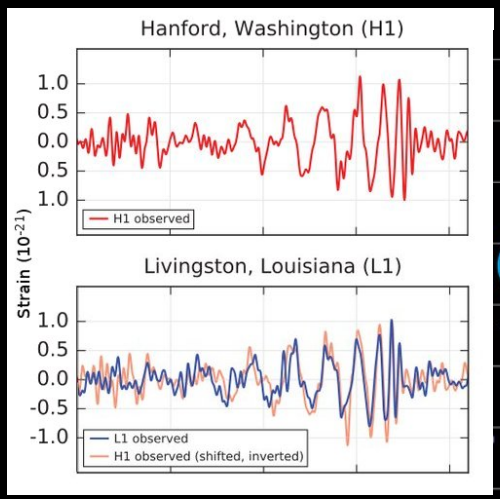



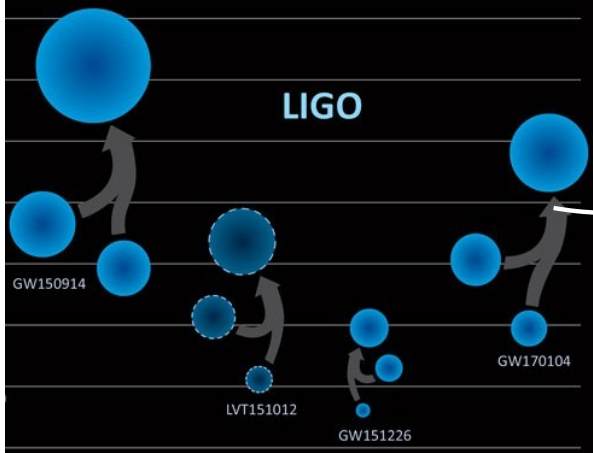

$$
\begin{aligned}
100\Omega_b h^2 &= 2.222 \pm 0.023\ (1.0\%) \\
\Omega_c h^2 &= 0.1197 \pm 0.0022\ (1.8\%) \\
\Omega_\Lambda &= 0.685 \pm 0.013\ (1.9\%)
\end{aligned}
$$

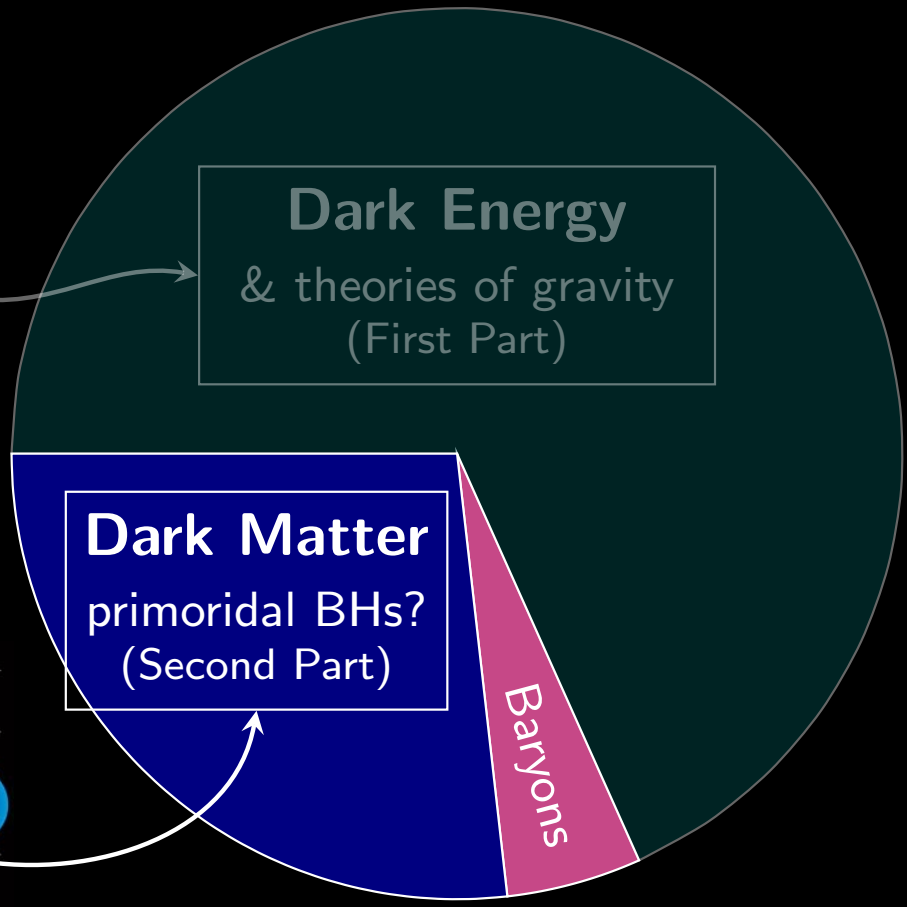
Planck '15 (T+lowP only!)

# Gravitational Waves vs $\Lambda$CDM

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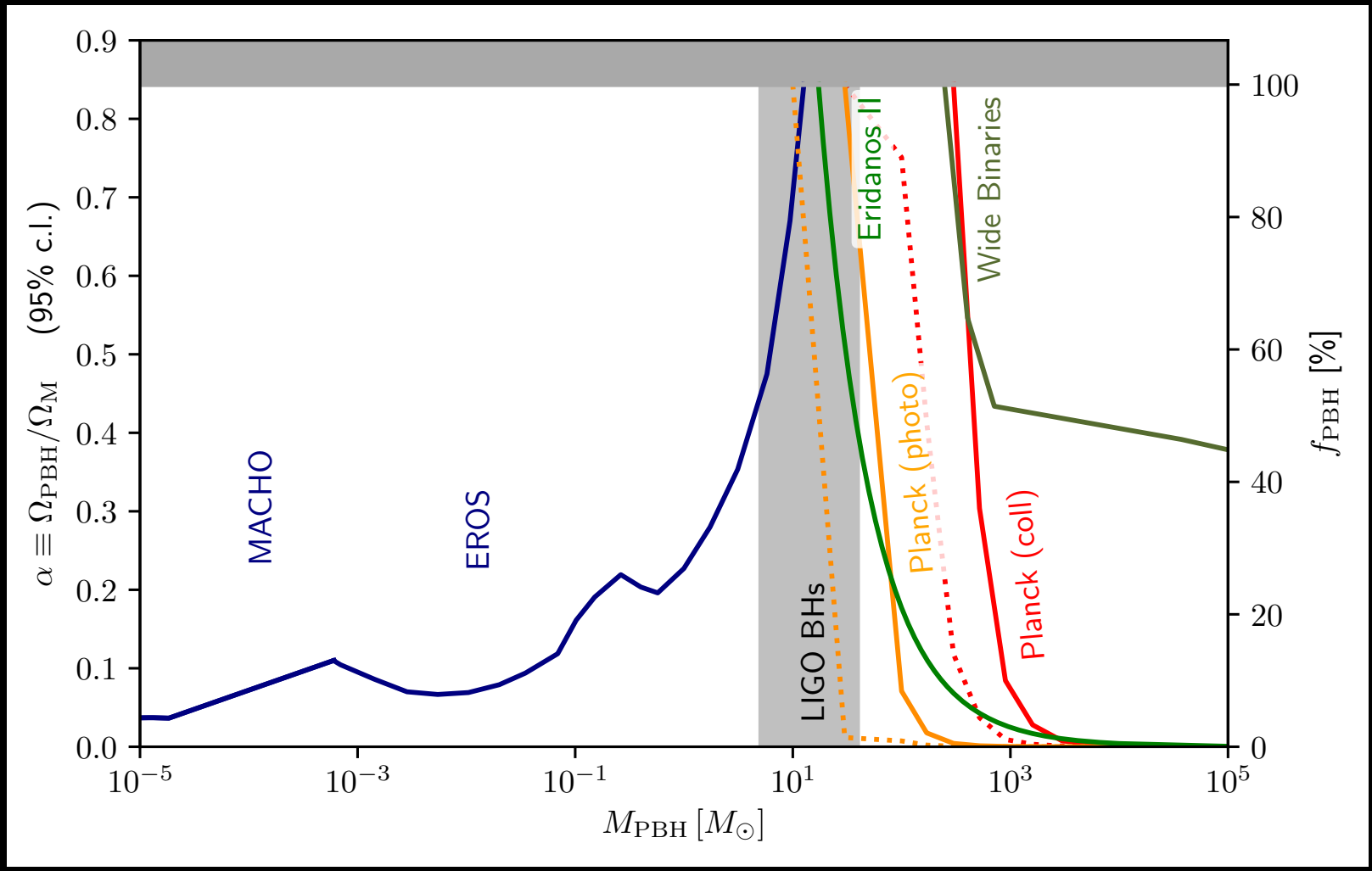
Planck '15 (T+lowP only!)

(S. Bird's talk, see also C. Johnson's talk)

# LIGO MACHO miracle?

(S. Bird's talk, see also C. Johnson's talk)




SNe lensing → MZ & Seljak '17

CMB → Bernal+ '17

(Tisserand+ EROS-2 '07)

(Reviews: Carr+ '16, Sasaki+ '18)

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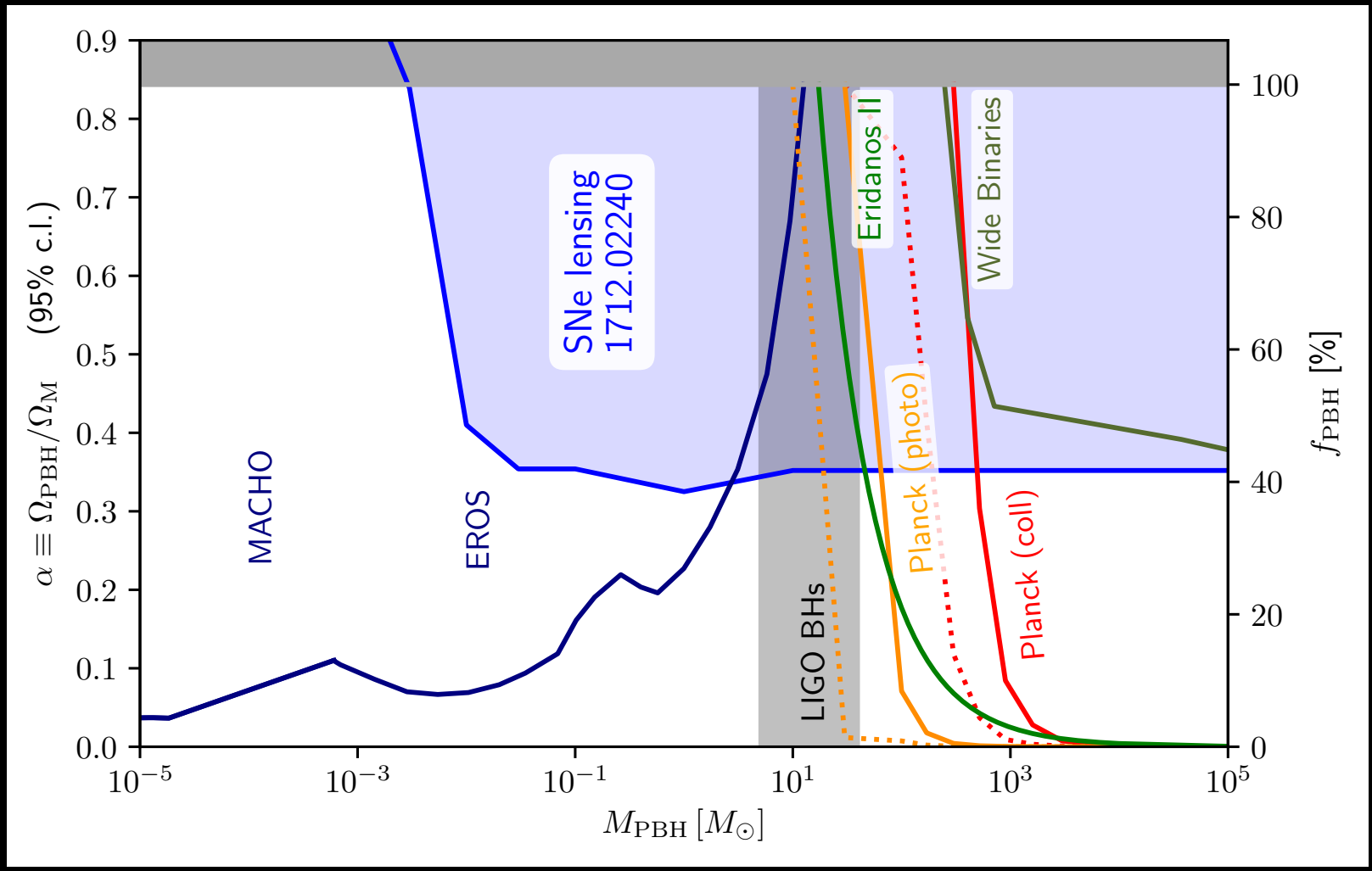


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# No LIGO MACHO?

ligar *(verb)*

1. Bind, connnect.
2. [Colloquial] Flirt.

*(yo) ligo* $\rightarrow$ *I flirt*

macho *(noun)*

1. Male.
2. [Colloquial] Dude, bro.

# No LIGO MACHO?

*No LIGO MACHO*

(MZ & Seljak 1712.02240)

*my love life sucks, bro*

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(credit: Paramount Pictures 1972, Warner Bros. 1949)

# No LIGO MACHO?

*No LIGO MACHO*

(MZ & Seljak 1712.02240)

*LIGO Lo(g)-normal MACHO*

(Garcia-Bellido+ 1712.06574)

**ligar** *(verb)*

1. Bind, connnect.
2. [Colloquial] Flirt.

*(yo) ligo → I flirt*

**macho** *(noun)*

1. Male.
2. [Colloquial] Dude, bro.

*my love life sucks, bro*


*mine's normal, bro*



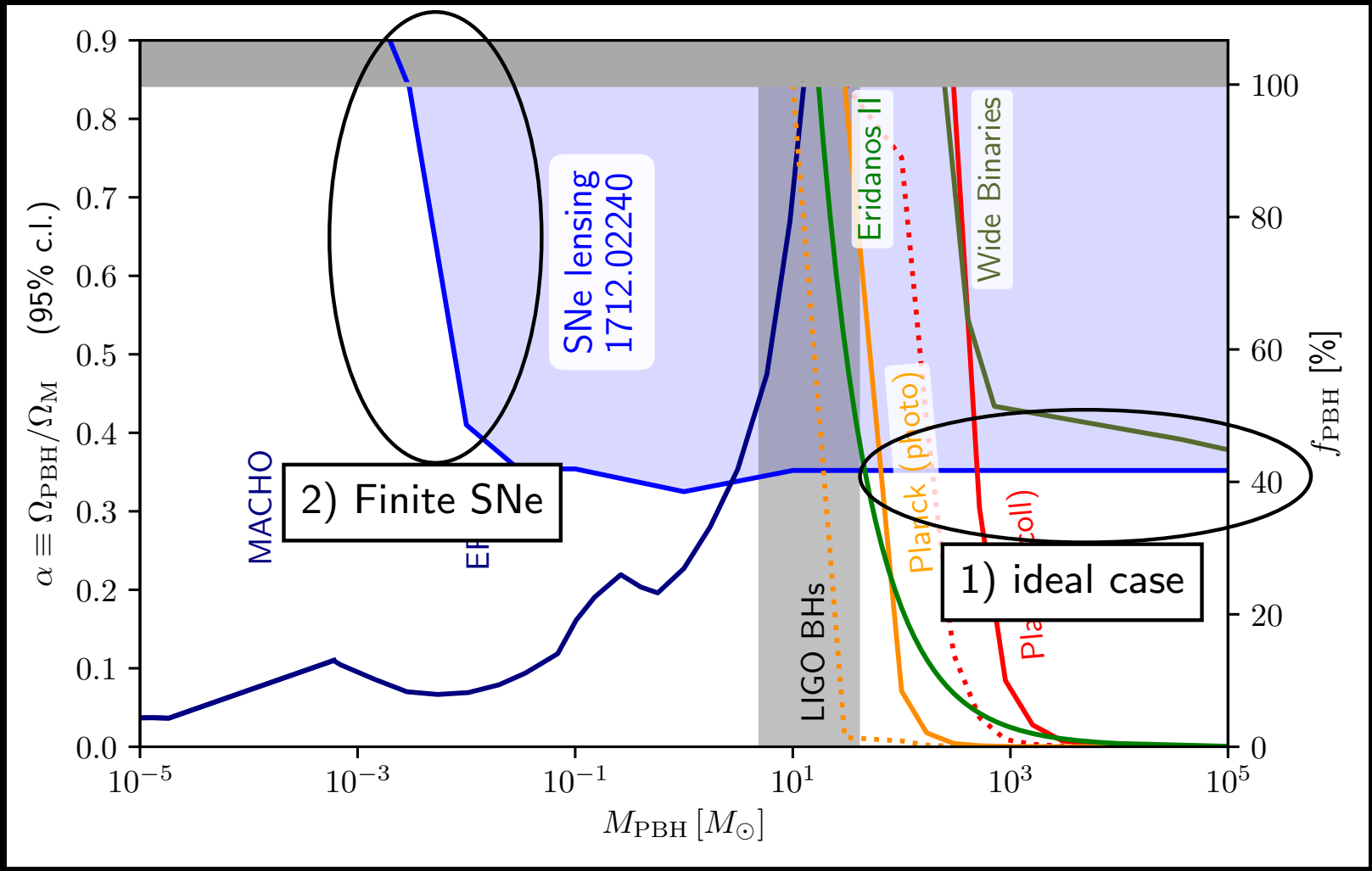
Discussion session (MZ+Fleury)
CERN PBH Workshop '18

Video → https://cds.cern.ch/record/2320183

(credit: Paramount Pictures 1972, Warner Bros. 1949)

# LIGO MACHO miracle?

(S. Bird's talk, see also C. Johnson's talk)

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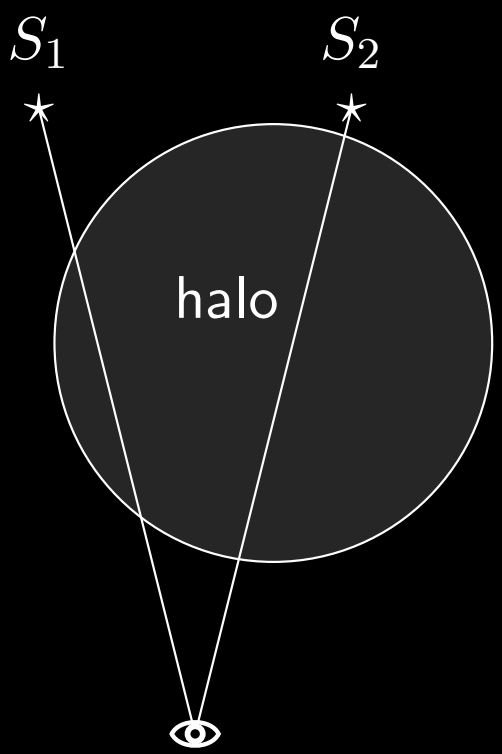
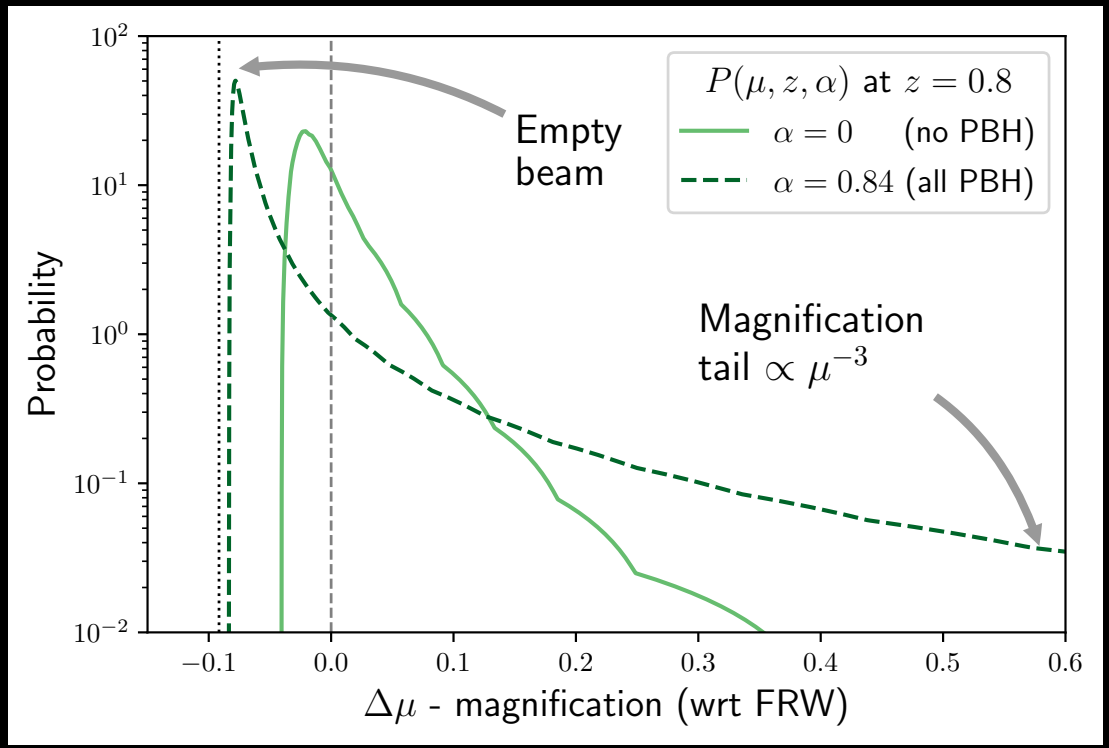
# Lensing by compact objects (Rauch '91, Seljak & Holz '99, Metcalf & Silk '06)

$$D(z, \Delta\mu) = \frac{\bar{D}(z)}{\sqrt{1 + \Delta\mu}}$$

Distance (perceived vs average)
Magnification




PBH signatures: { slight demagnification (most SNe)
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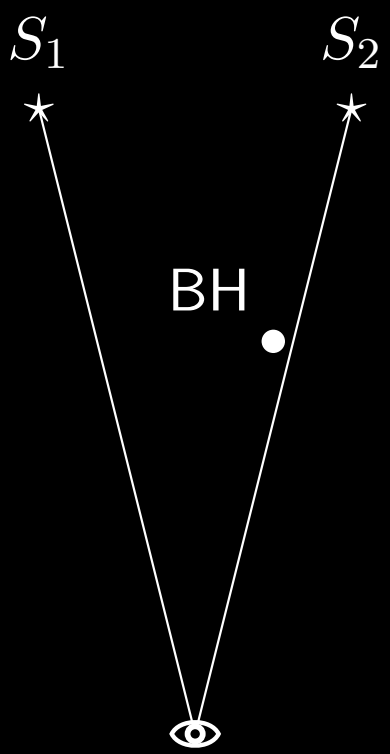


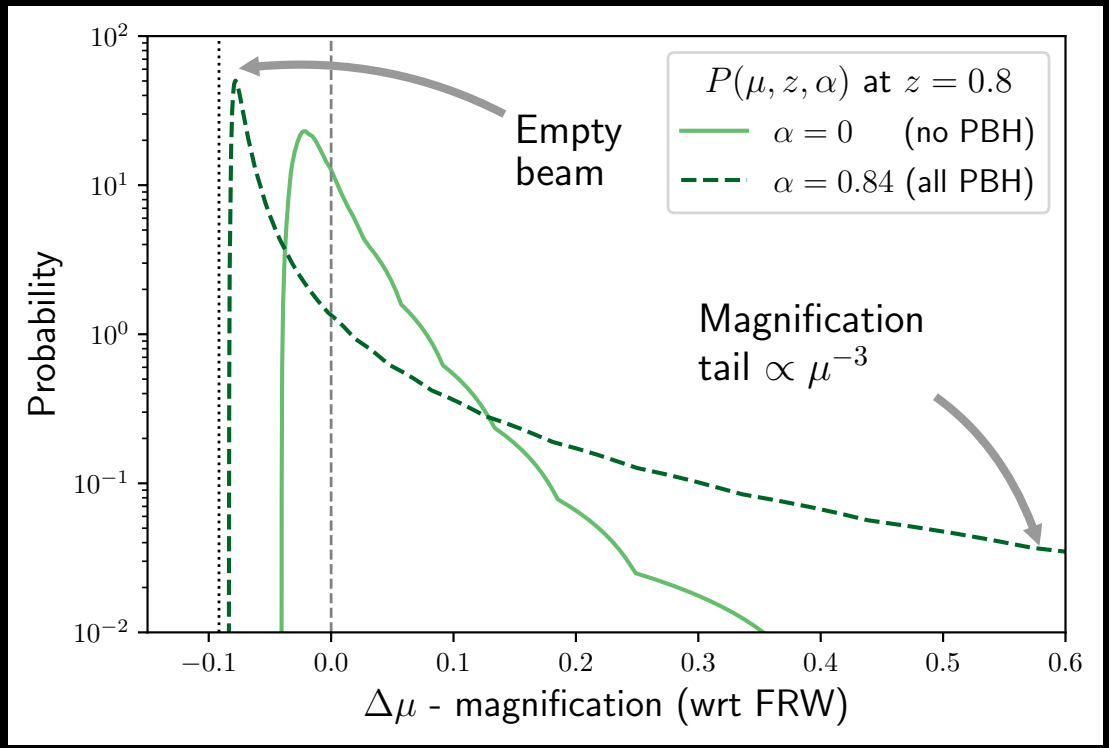


PBH signatures: { slight demagnification (most SNe)
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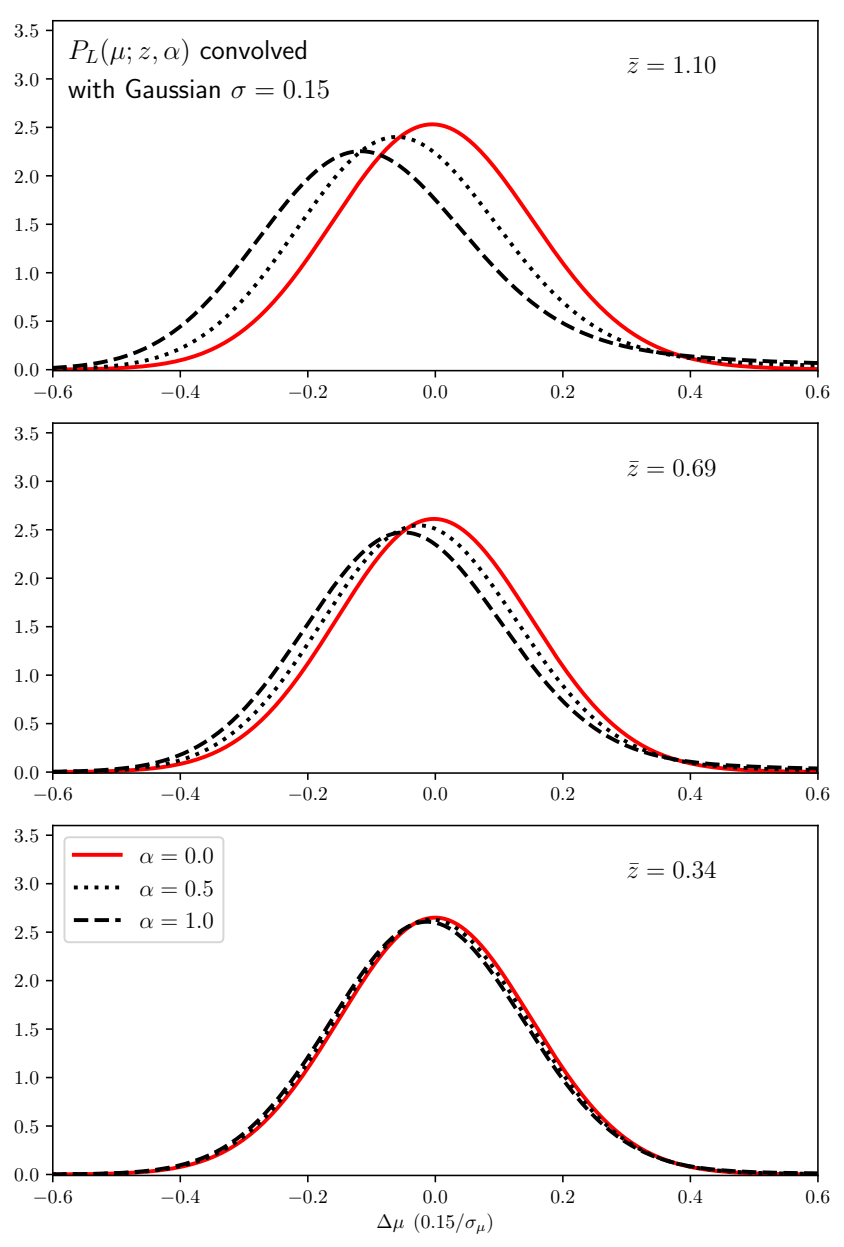
# SNe Magnification

(MZ & Seljak '17)



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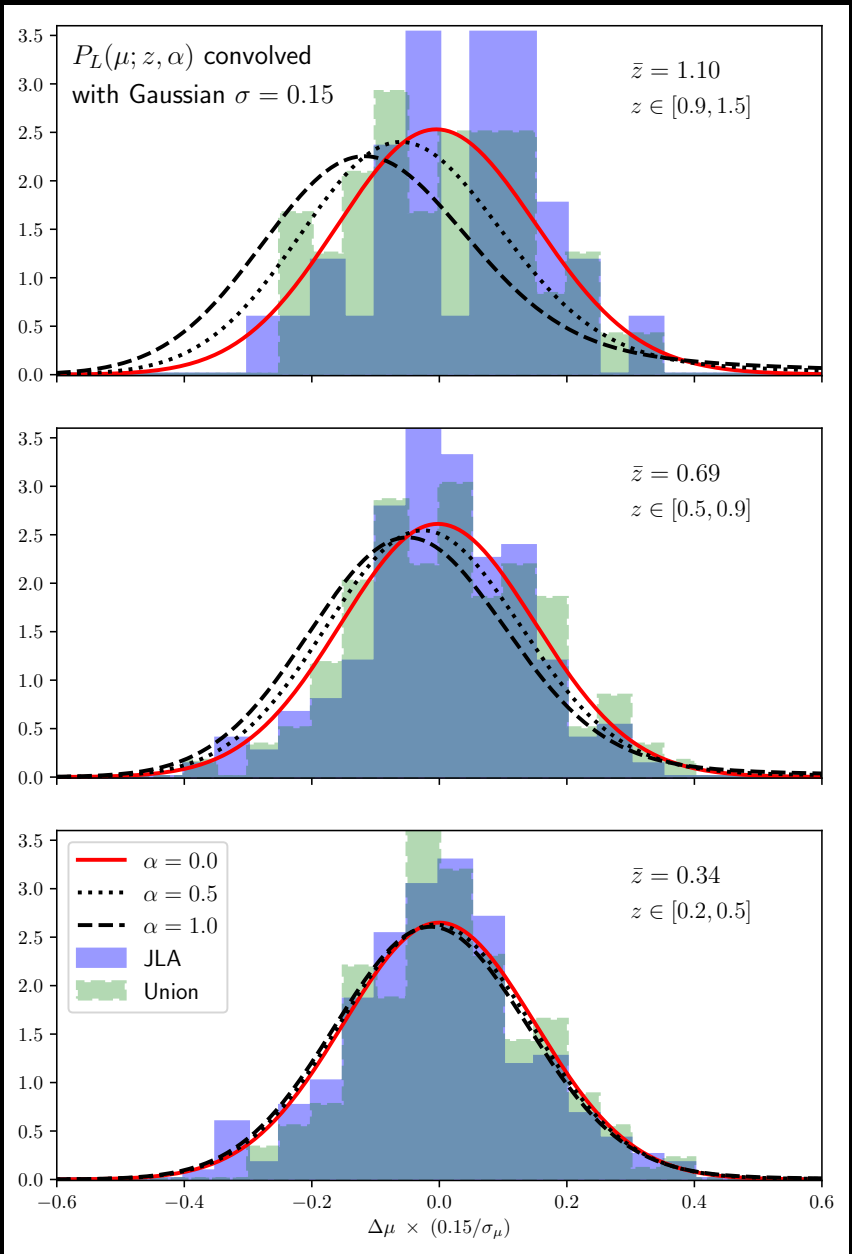

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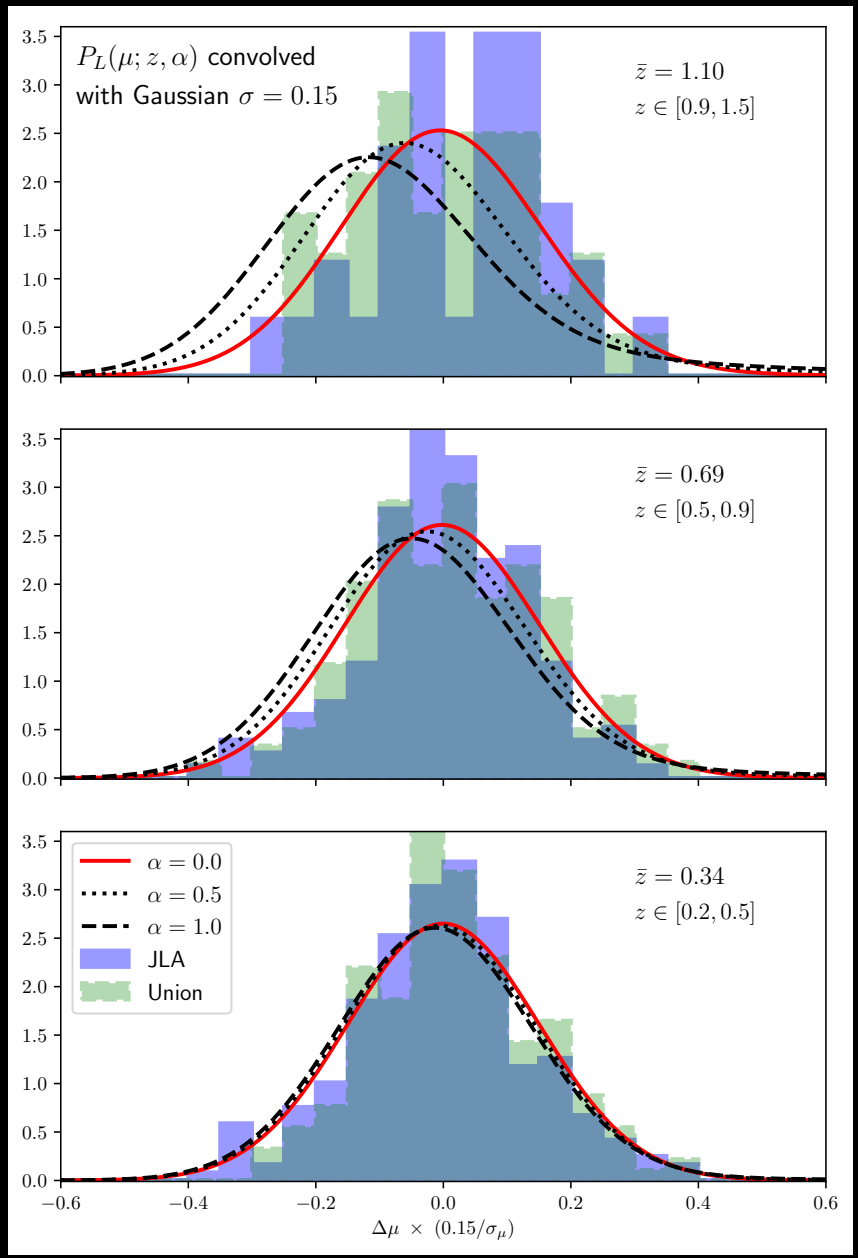
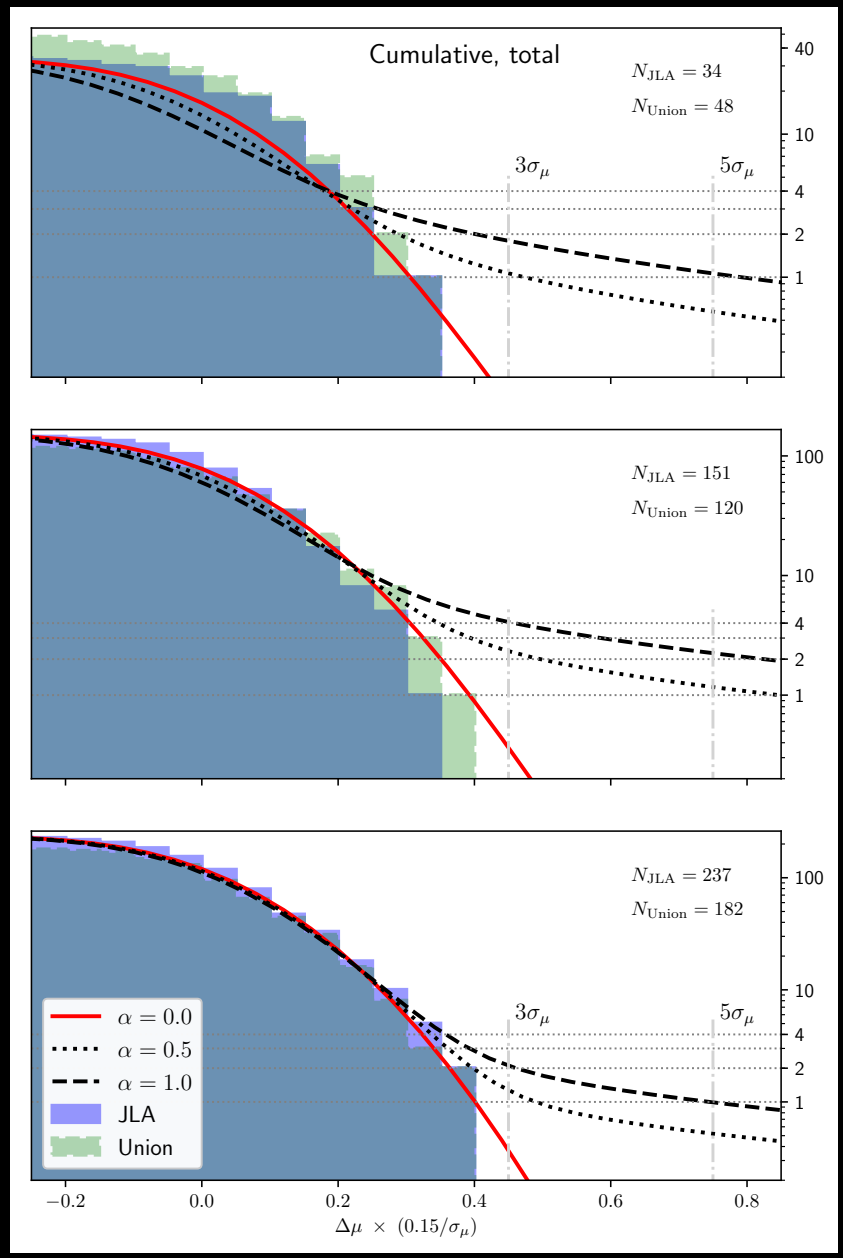
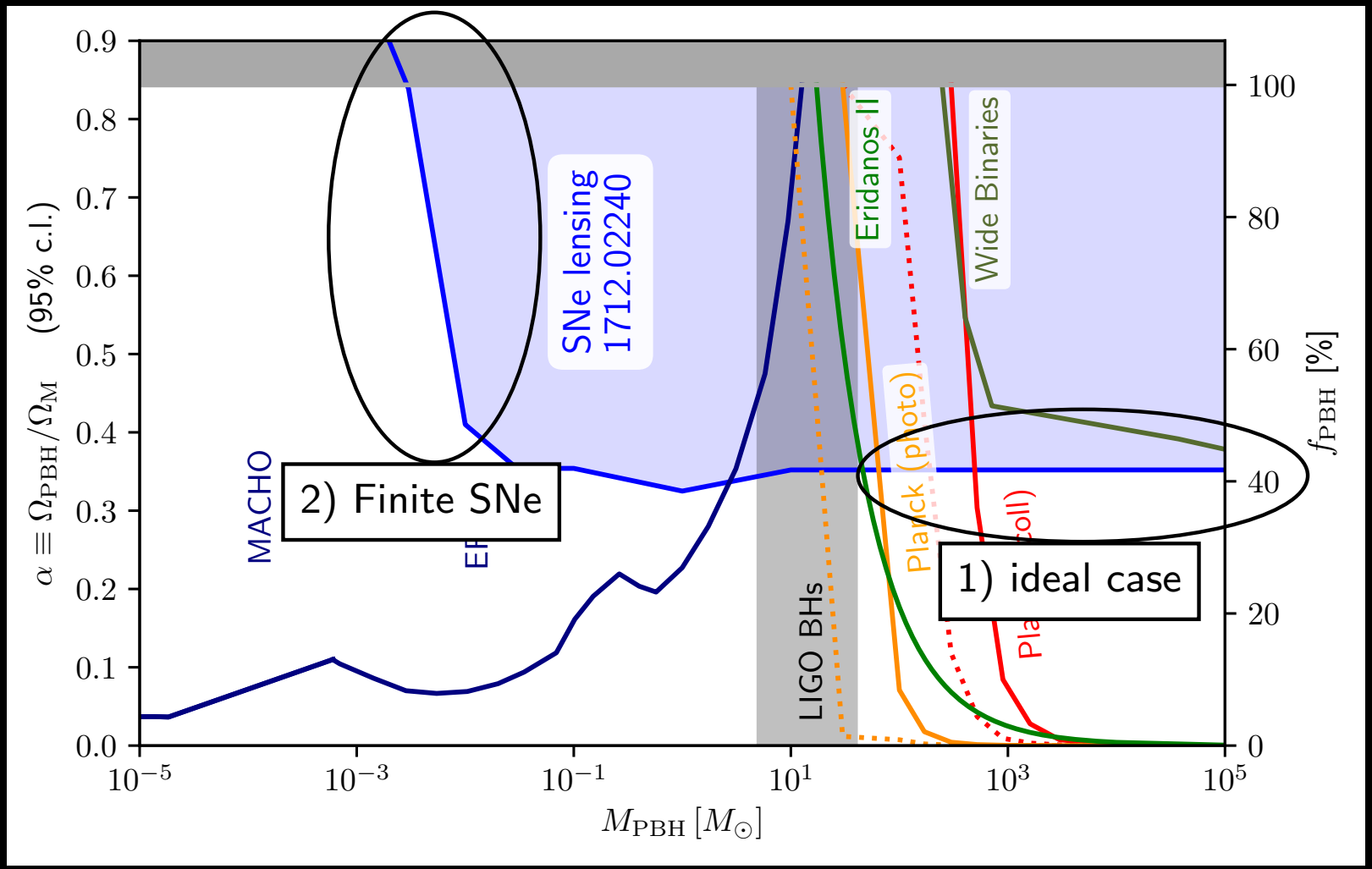


# LIGO MACHO miracle?




Errors/typos in arxiv version 

New version coming ⇒ basic results hold

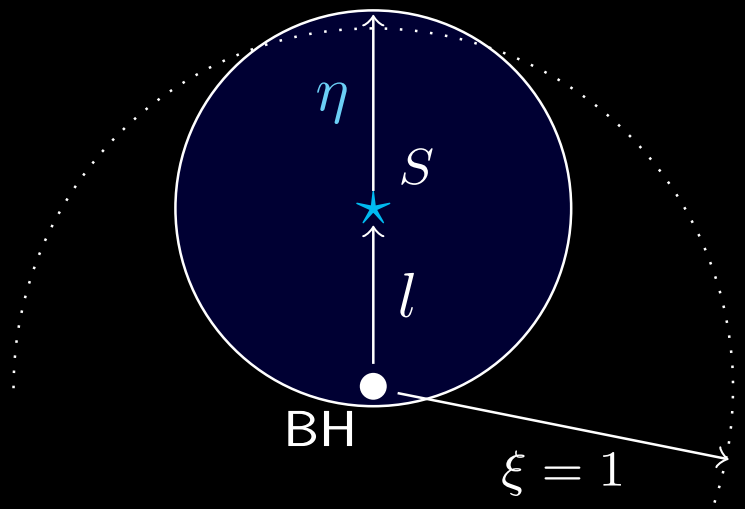
# Finite sources → size matters, conclusion stands

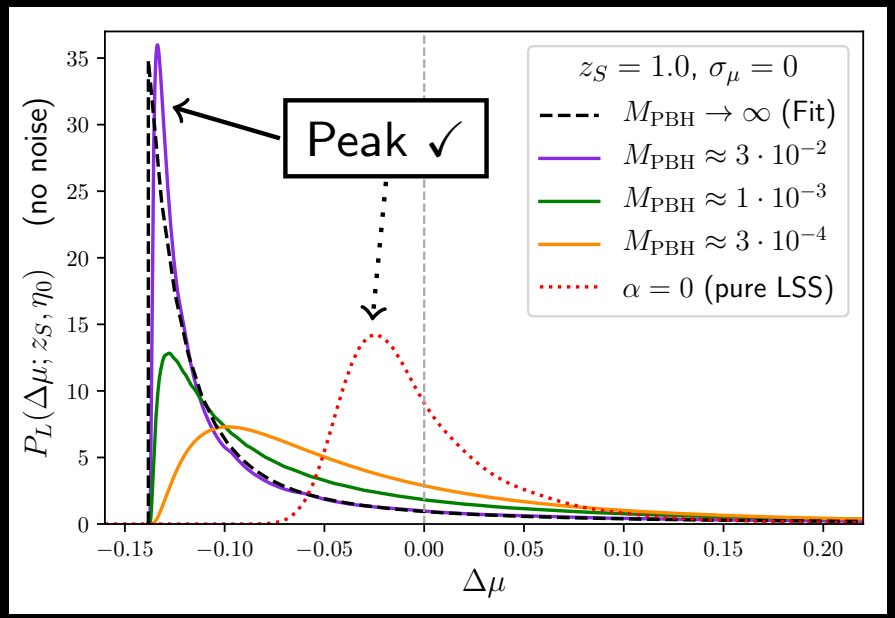
- Point lens + point source

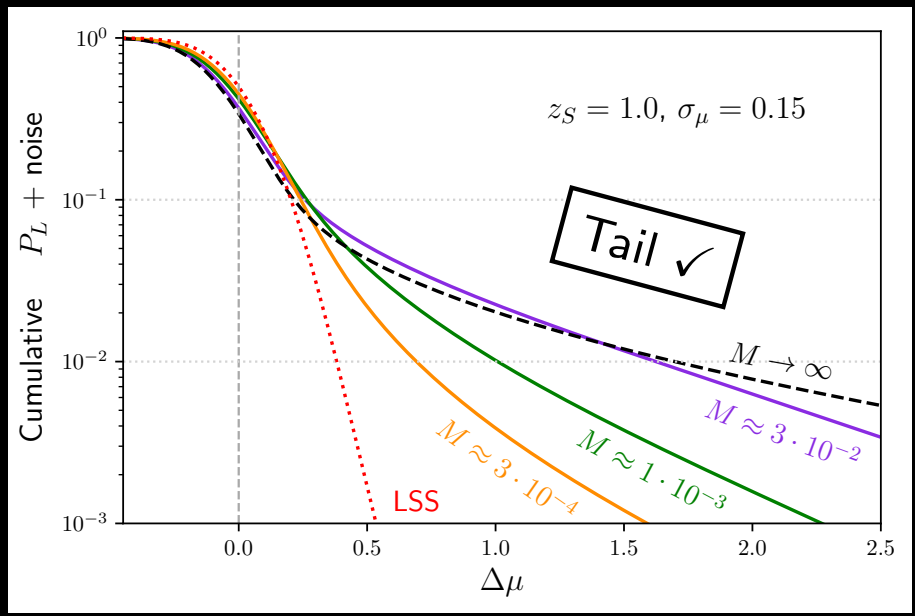
$$\mu = \frac{1}{l}\frac{l^2 + 2\xi^2}{\sqrt{l^2 + 4\xi^2}} - 1$$

- Finite source $\eta \equiv \dfrac{R_S}{\xi} = \dfrac{\text{source size}}{\text{Einstein radius}}$

$$\mu_{\max} = \sqrt{1 + 4\eta^{-2}} - 1$$



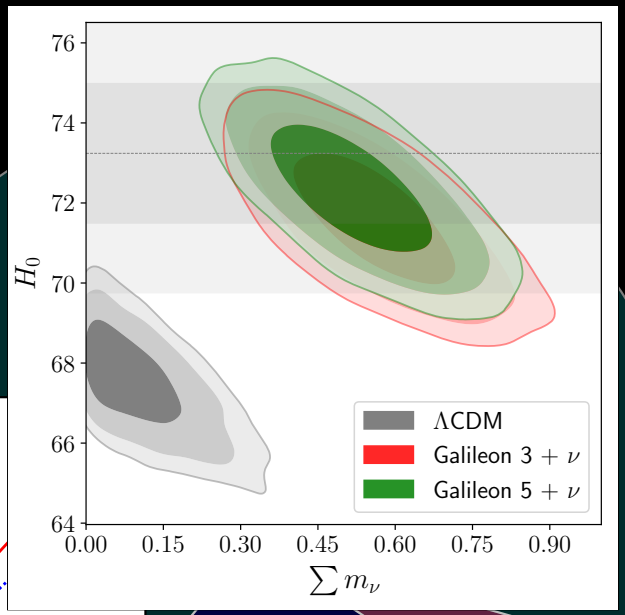



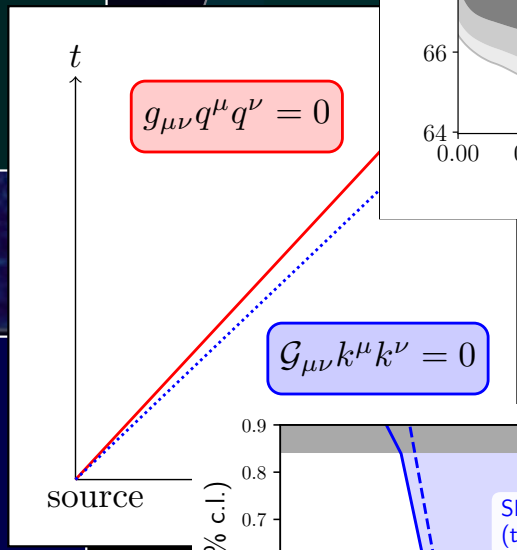



# Conclusions: exciting times to come!

## Dark Energy

- ⋆ $\exists$ Interesting DE models
- ⋆ GWs $\rightarrow$ new & powerful tests
- ⋆ LIGO could confirm $H_0$
  $\rightarrow$ rule out $\Lambda$CDM

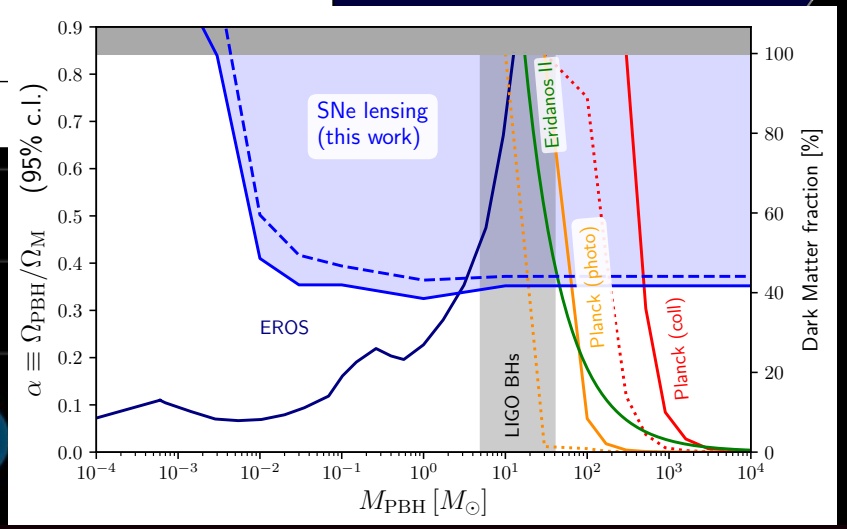



Baryons

## Dark Matter

- ⋆ PBH-DM with $M \gtrsim 0.01 M_\odot$
  - $\frac{\Omega_{\rm PBH}}{\Omega_M} < 0.35$ (95% c.l. JLA)
  - 100% DM excluded at $4.8\sigma$!
- ⋆ (some) BHs could be primordial



gravity

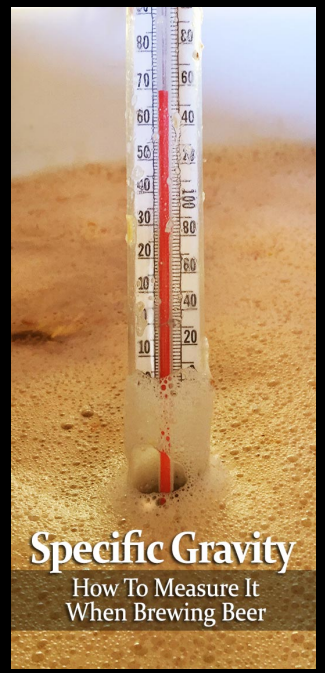
'gravɪti/

*noun*

Cảm ơn!

Thanks!

1. [Physics]
   the force that attracts a body towards the centre of the earth, or towards any other physical body having mass.
2. extreme importance; seriousness.
3. in the context of fermenting alcoholic beverages, refers to the specific gravity, or relative density compared to water, of the wort or must at various stages in the fermentation.

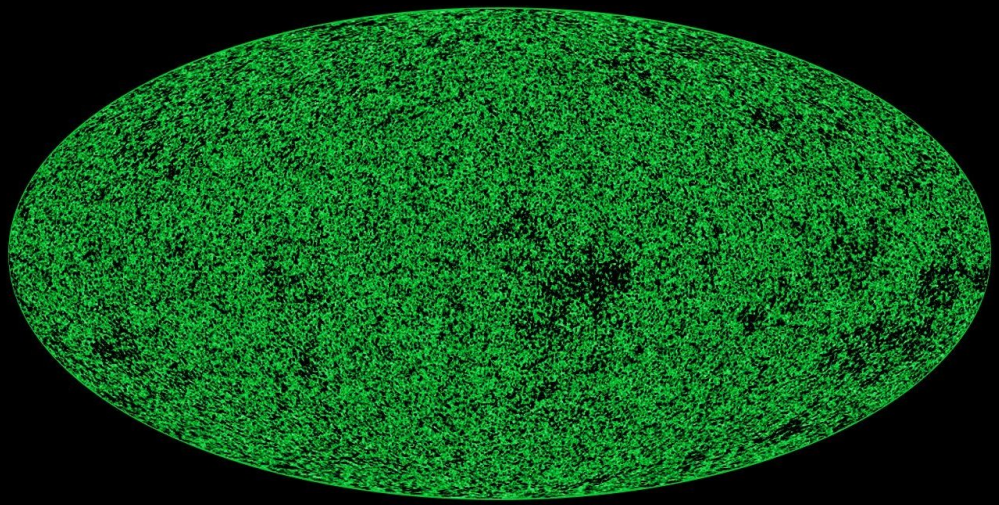



$$\boxed{\frac{d}{dt}\text{gravity} \propto \text{alcohol \%}}$$

$\Rightarrow \exists$ at least a useful "test" of gravity!

Sources: google (1,2), wikipedia (3)

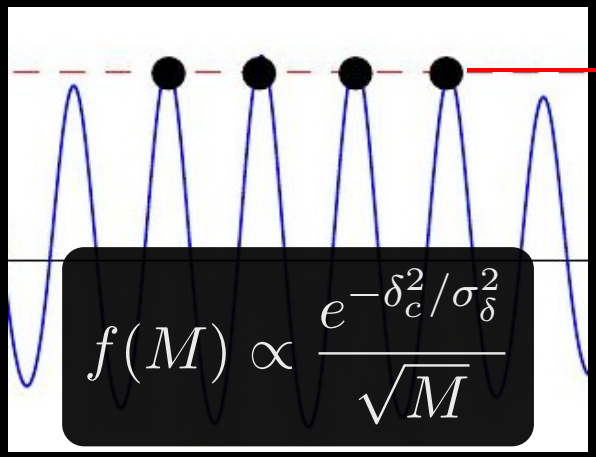
# Backup Slides

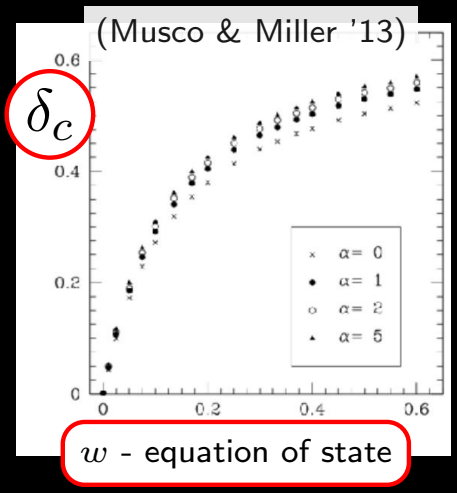


PLANCK

# LIGO MACHO miracle? (Byrnes, Hindmarsh, Young, Hawkings '18)

PBH formation $\rightarrow$ collapse of high-contrast density fluctuations




(Jedamizik '97, Widerin & Schmidt '98, Jedamzik & Niemeyer '99, Sobrinho '16...)

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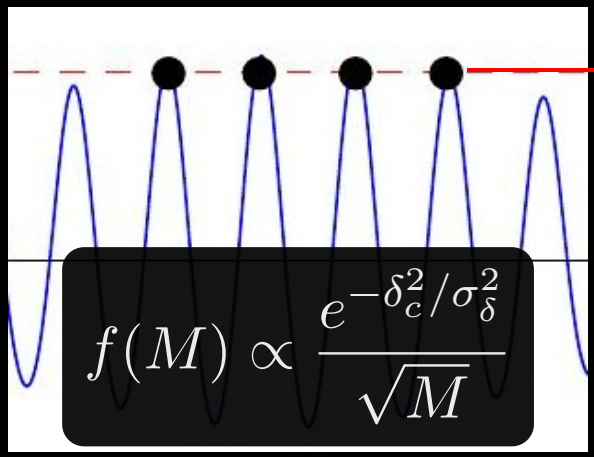
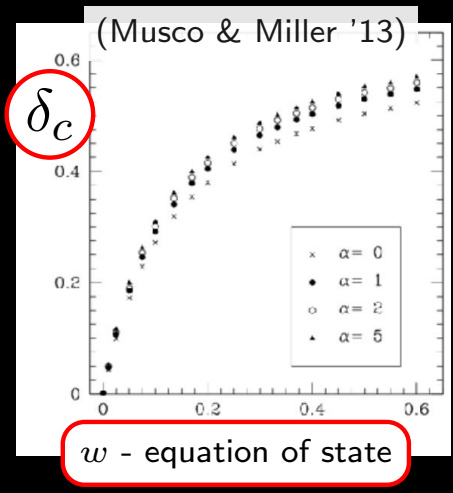
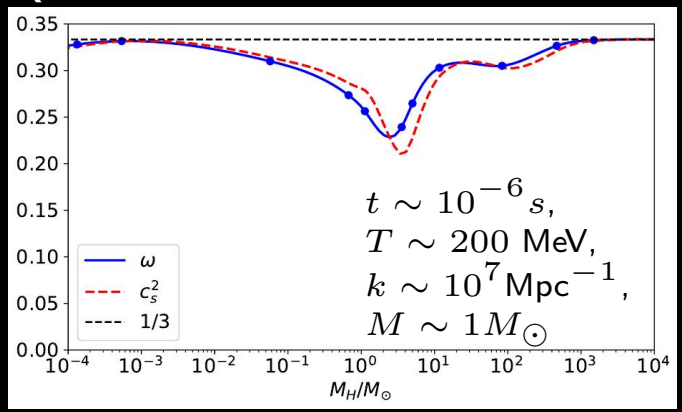
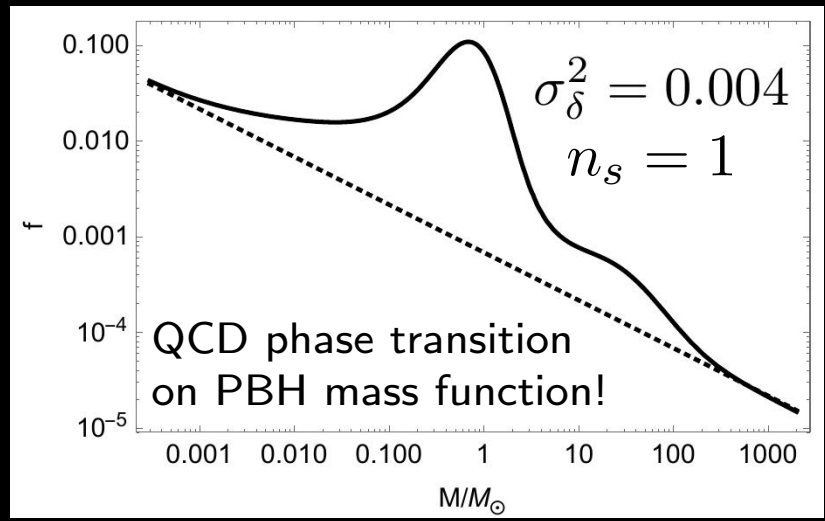



QCD Phase Transition




$\sim$ 1% accurate! (Borsanyi+ '16)

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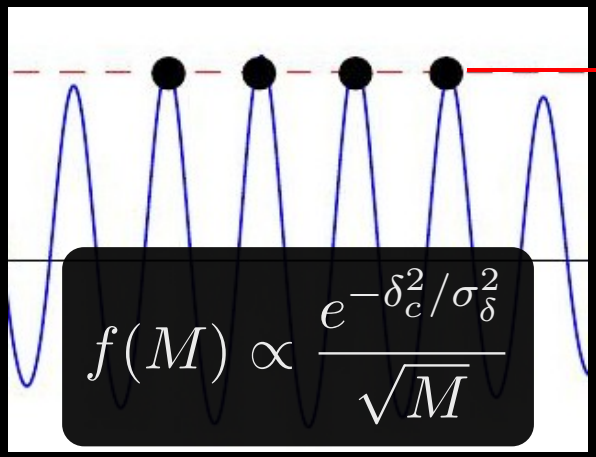


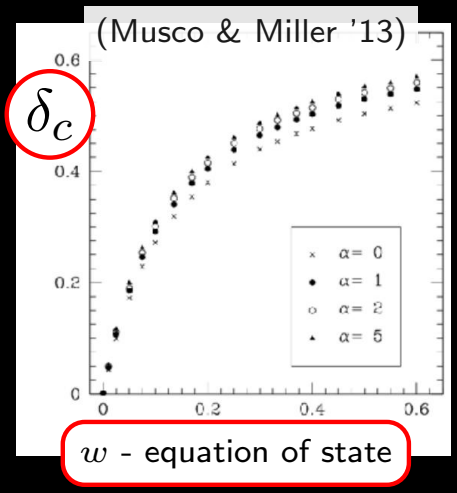


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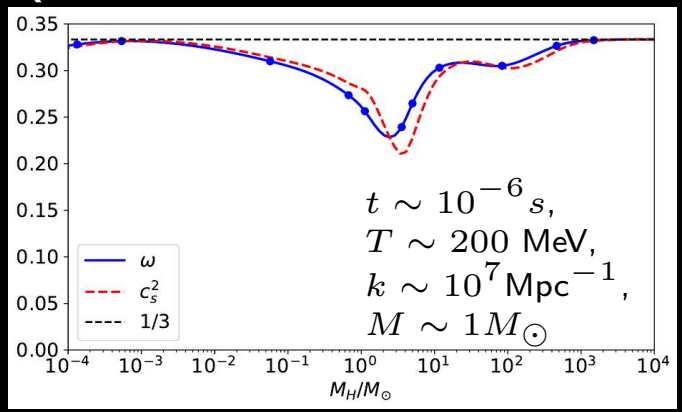


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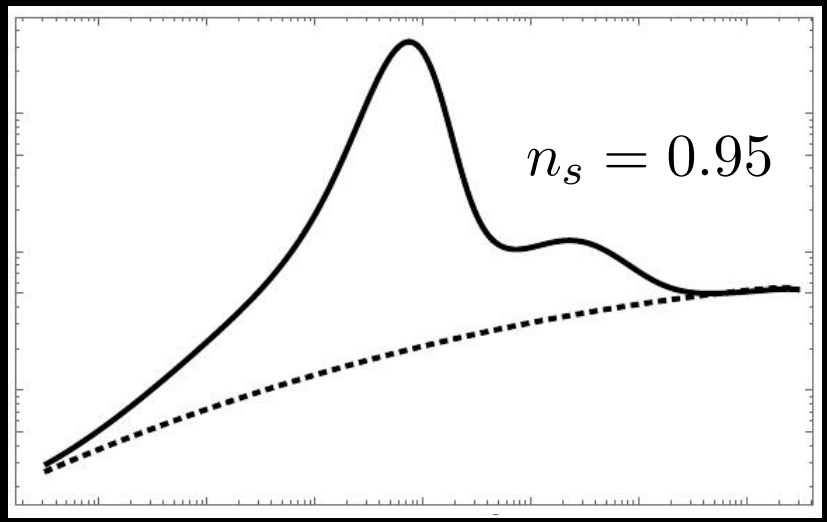


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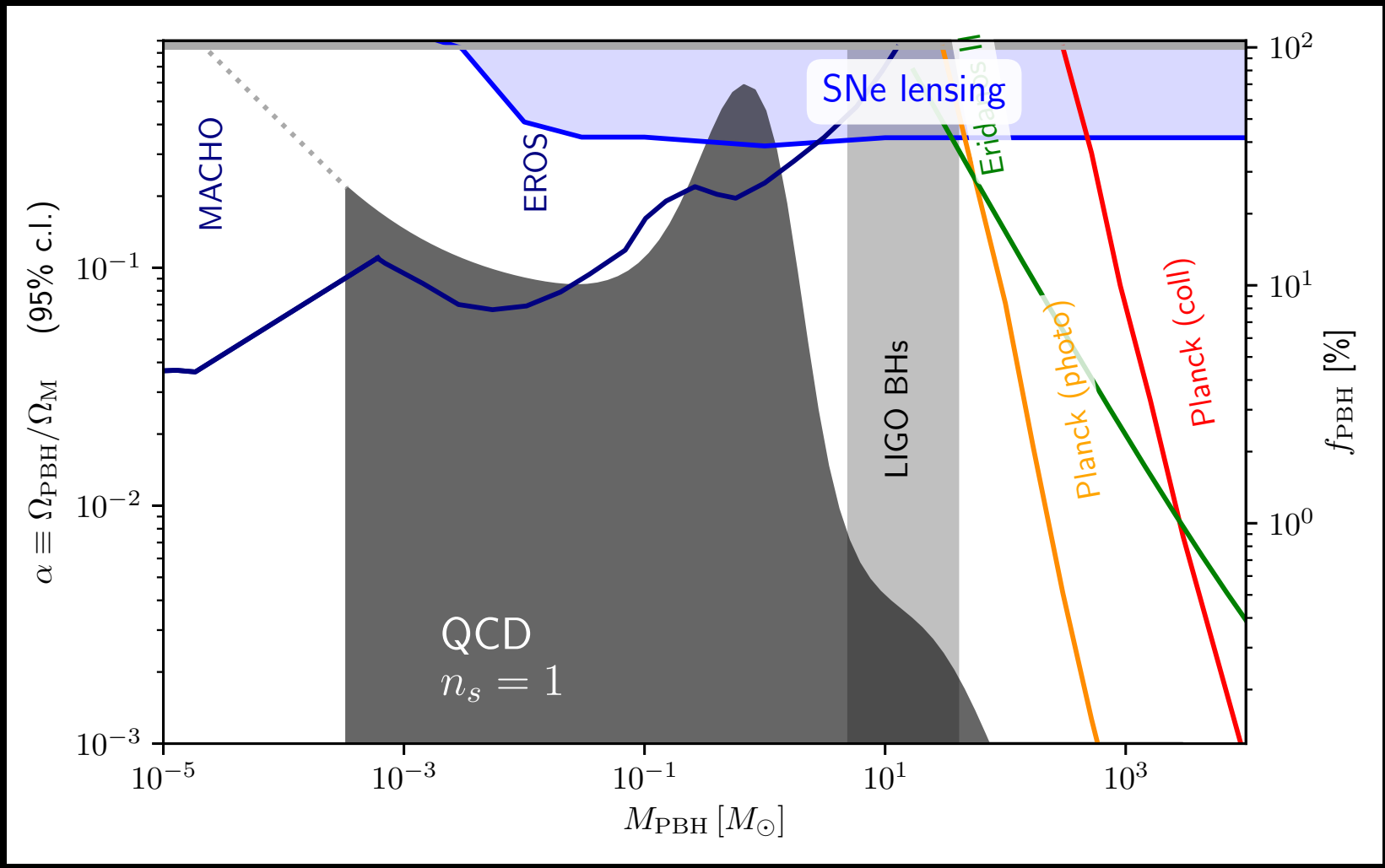


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LIGO merger rates → Nakamura+ '97, Sasaki+ '16, Ali-Haimoud+ '17

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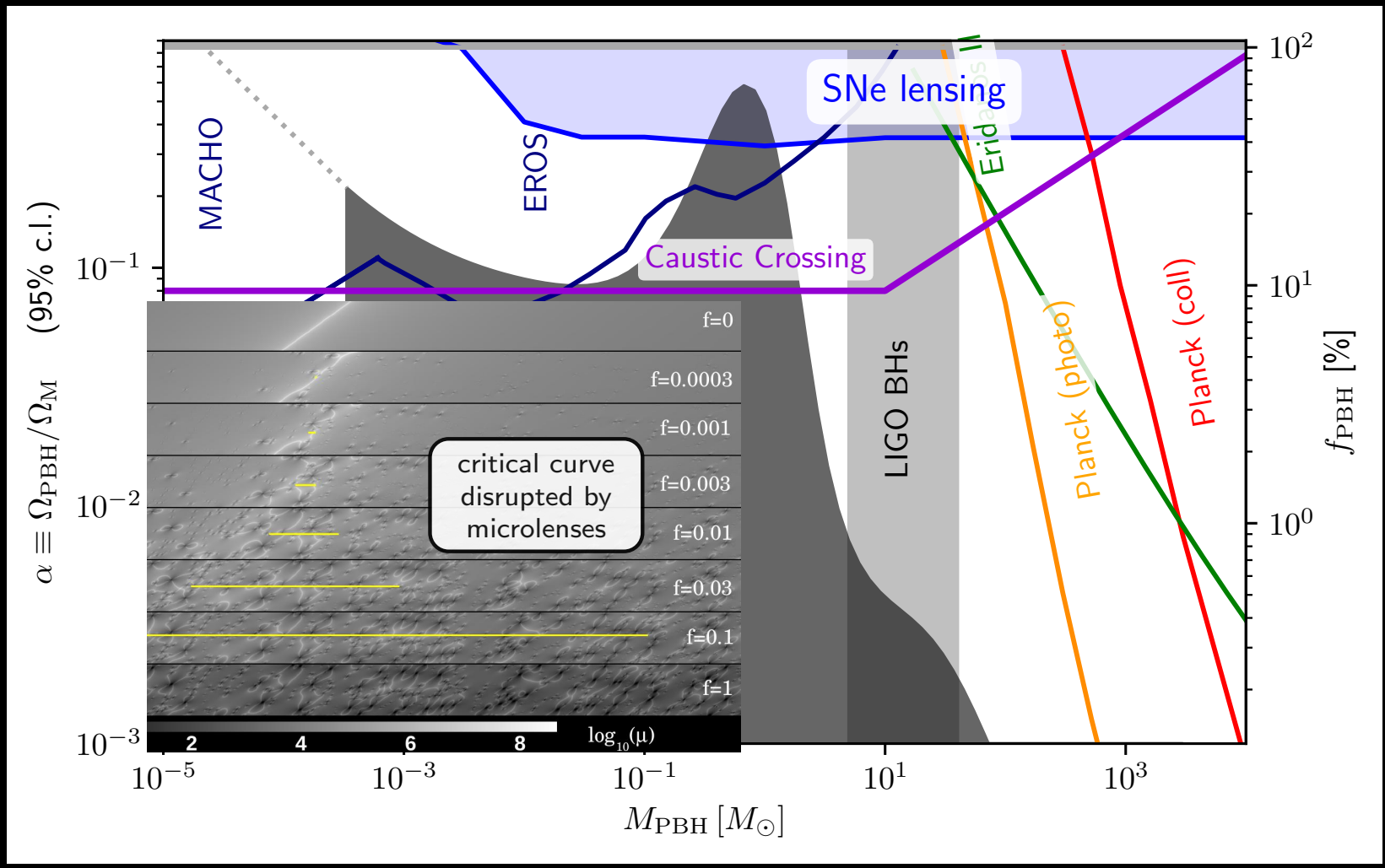


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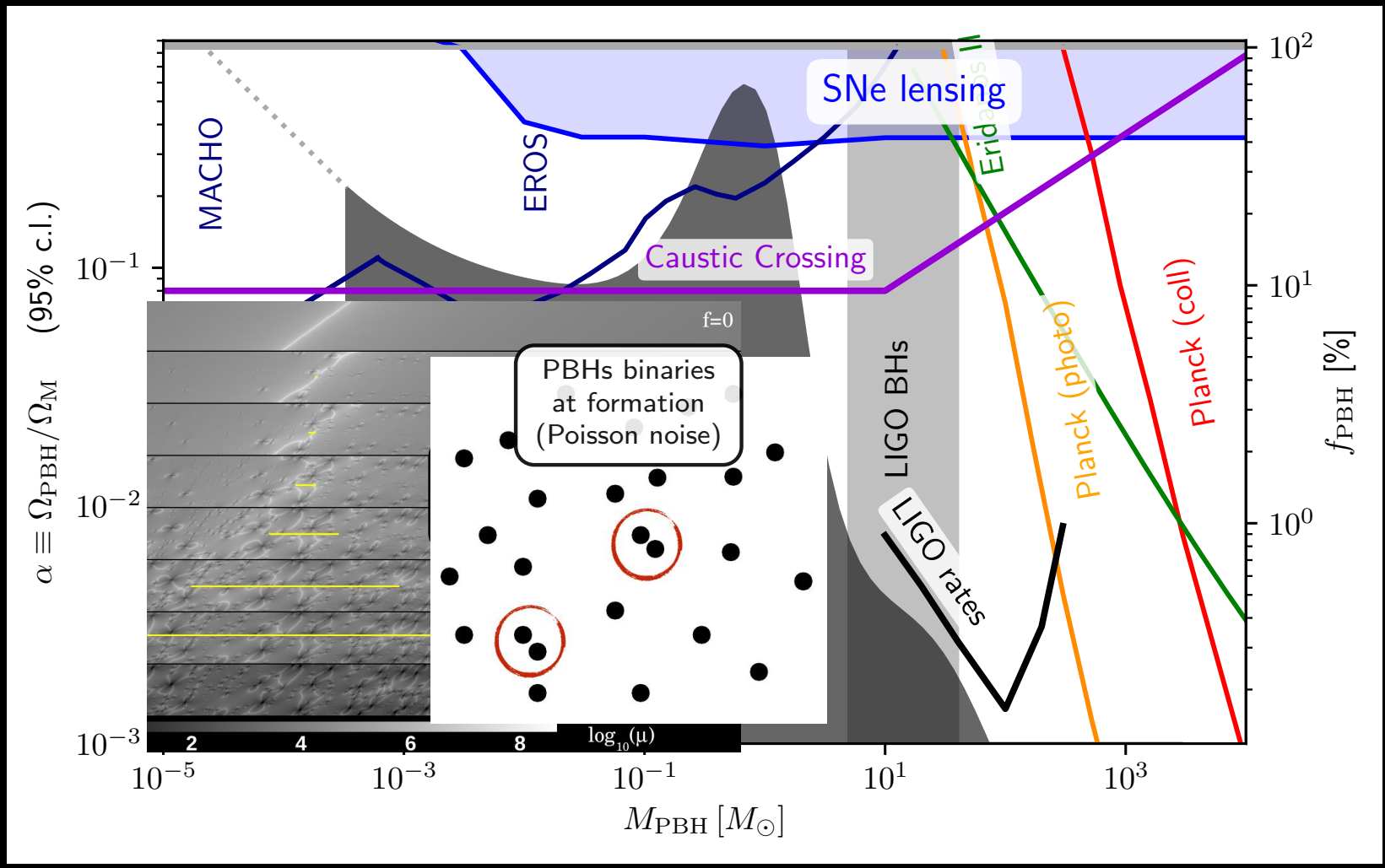


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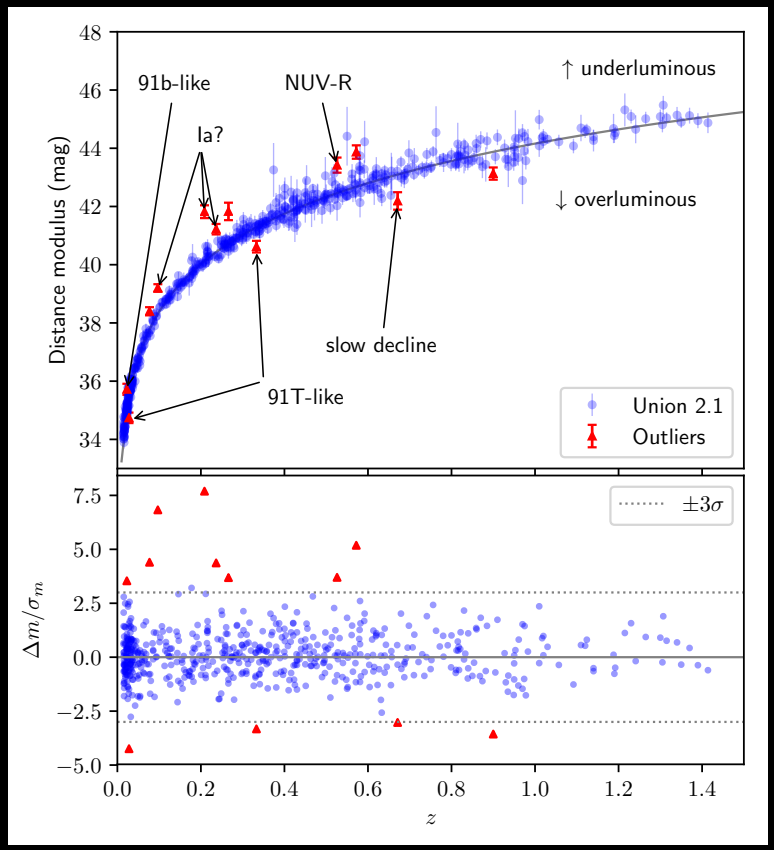
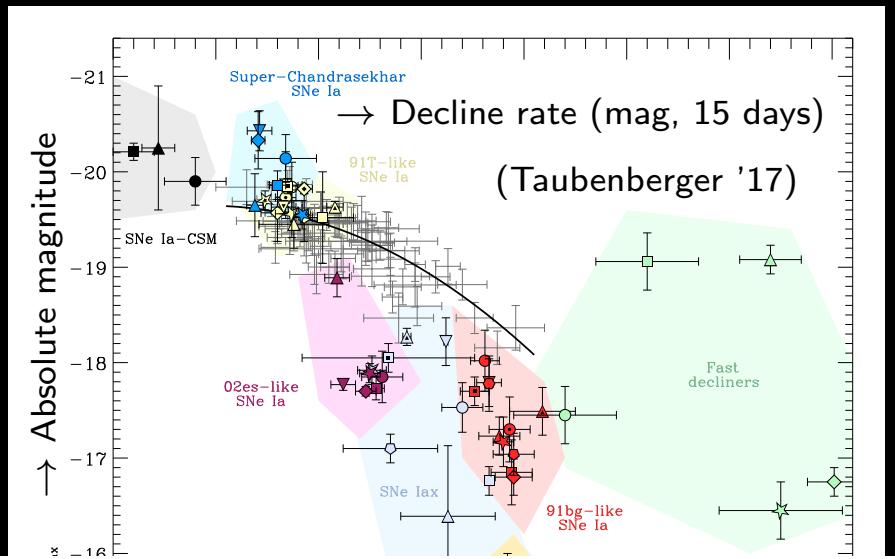
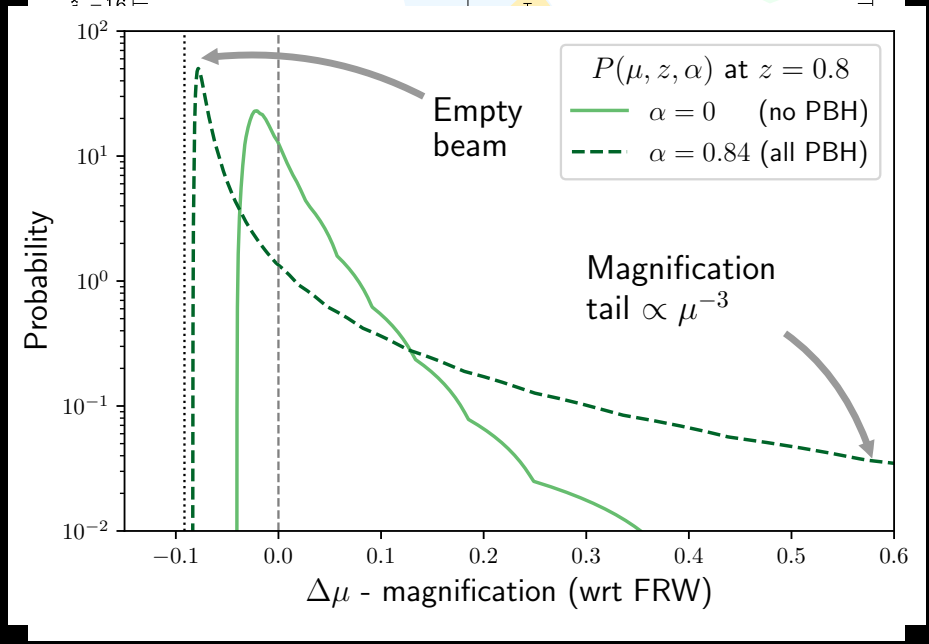
# Highly-magnified events or peculiar SNe?



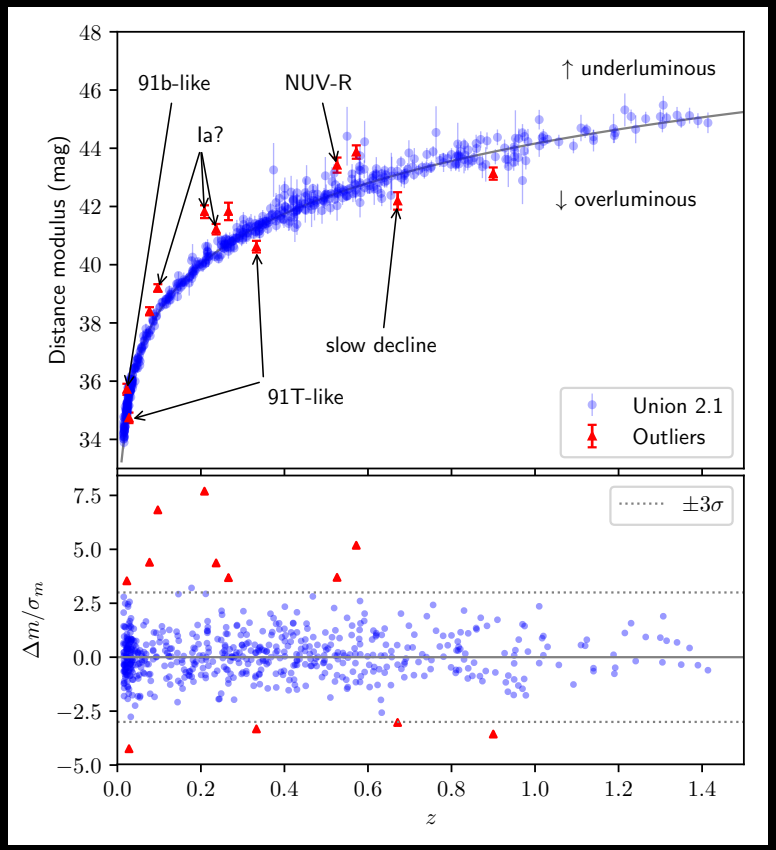



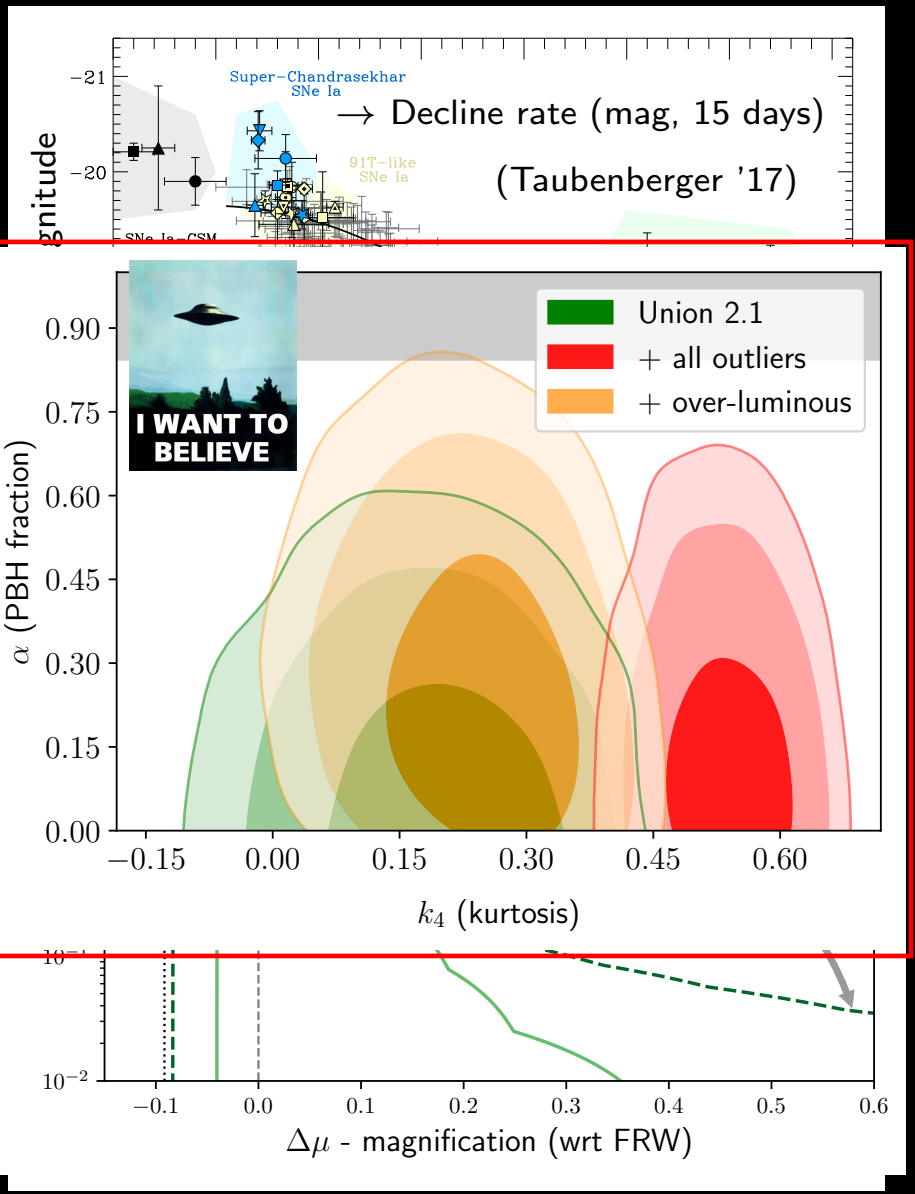

## Outliers in Union 2.1

- 4 overluminous → 3 peculiar
- 8 subluminous → 5 peculiar

Thanks to D. Rubin (sample) & Ll. Galbany (assesment)

# Highly-magnified events or peculiar SNe?




## Outliers in Union 2.1

- 4 overluminous $\rightarrow$ 3 peculiar
- 8 subluminous $\rightarrow$ 5 peculiar

Thanks to D. Rubin (sample) & Ll. Galbany (assesment)

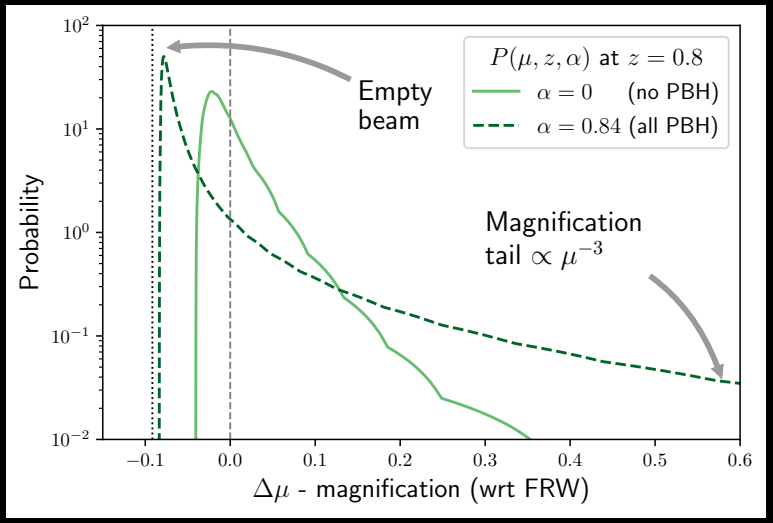
# Cosmology Dependence

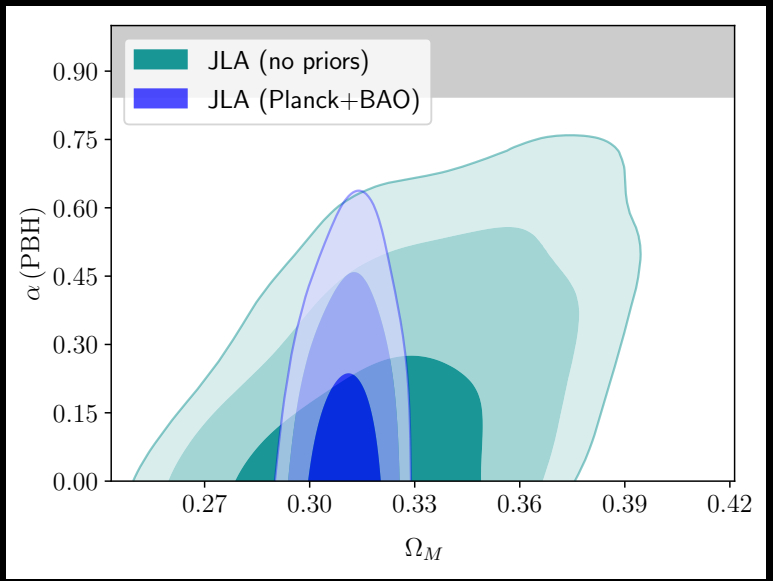
Assumed flat $\Lambda$CDM

- Planck+BOSS: $\Omega_M = 0.309 \pm 0.006$ (Alam+ '17)
- Weak effect of perturbations

  SNe: $\sigma_8 = 1.07^{+0.50}_{-0.76}$ (Macaulay+ '17)
- Degeneracy:

  empty-beam shift $\leftrightarrow$ expansion




## No $\Omega_M$ prior

- slightly weaker results
- "best" case PBH

  Tension $\begin{cases} \alpha \approx 0.8 & \rightarrow 3\sigma \text{ w. SNe} \\ \Omega_M \approx 0.36 & \rightarrow 8\sigma \text{ w. P+B} \end{cases}$
- Lack of outliers!

# Galileon gravity (Nicolis+ '08, de Rham Tolley '10...)

## Horndeski's Theory, with

$\boxed{\Lambda = 0}$ + scalar $\phi$ + derivative interactions $\quad (X \equiv -\frac{1}{2}(\partial\phi)^2)$

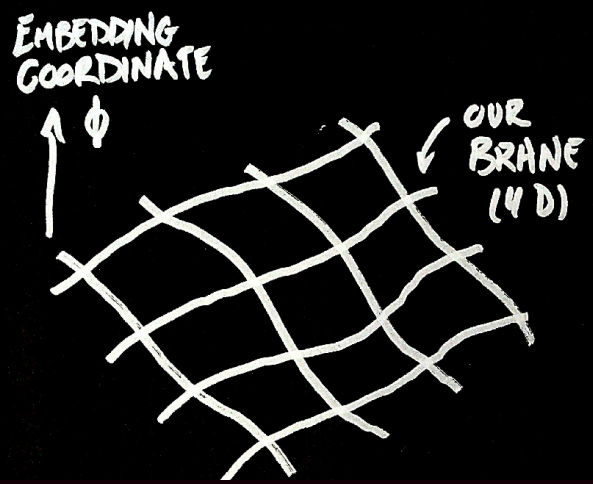
$$\frac{M_p^2}{2}R - X - c_3\frac{X}{M^3}\nabla^2\phi \qquad \rightarrow \text{Gal3: 0 extra params}$$

$$+ c_4\frac{X^2}{M^6}\left(\frac{M_p^2}{2}R + \frac{2}{X}\left[\nabla\nabla\phi\right]^2\right) \qquad \rightarrow \text{Gal4: 1 extra params}$$

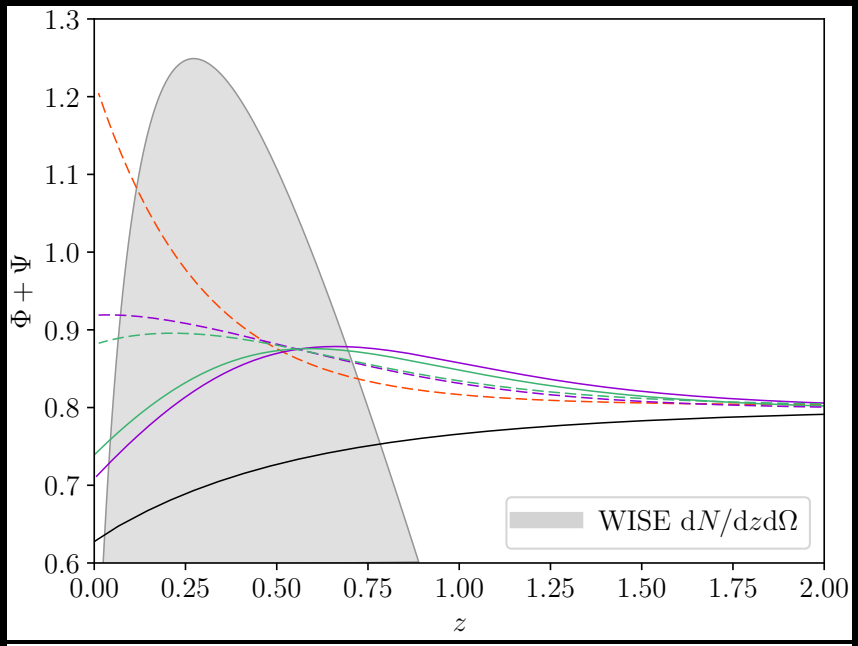
$$+ c_5\frac{X^2}{M^9}\left(G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{3X}\left[\nabla\nabla\phi\right]^3\right) \qquad \rightarrow \text{Gal5: 2 extra params}$$

- Related to
  - ⋆ Massive Gravity: $\phi \rightarrow$ helicity 0
  - ⋆ DGP/extra dim: $\phi \leftrightarrow x^5$ coord.
- Vainshtein: $\Rightarrow \sim$ GR on small scales
- Self-accelerating solutions ($\Lambda = 0$)

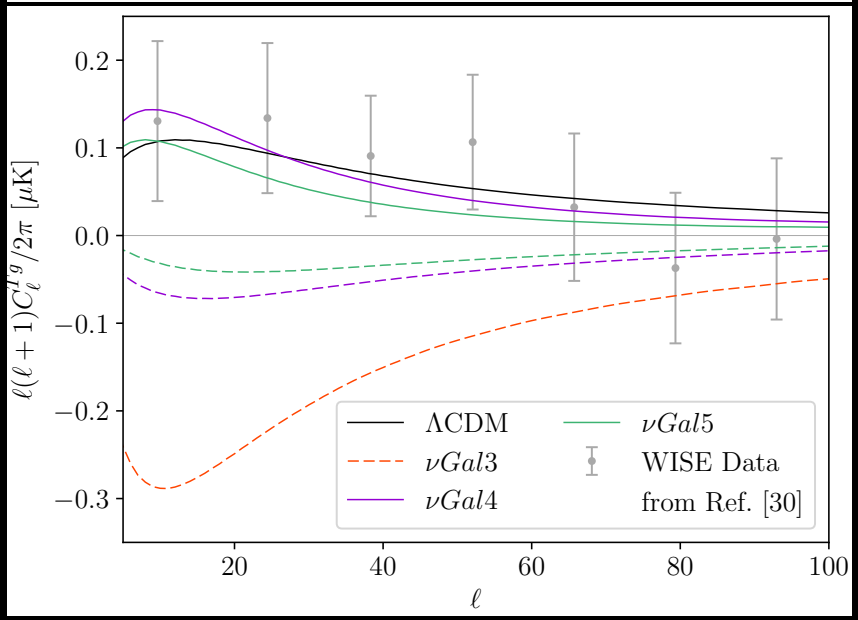
(de Felice Tsujikawa '10, Barreira+ '14)

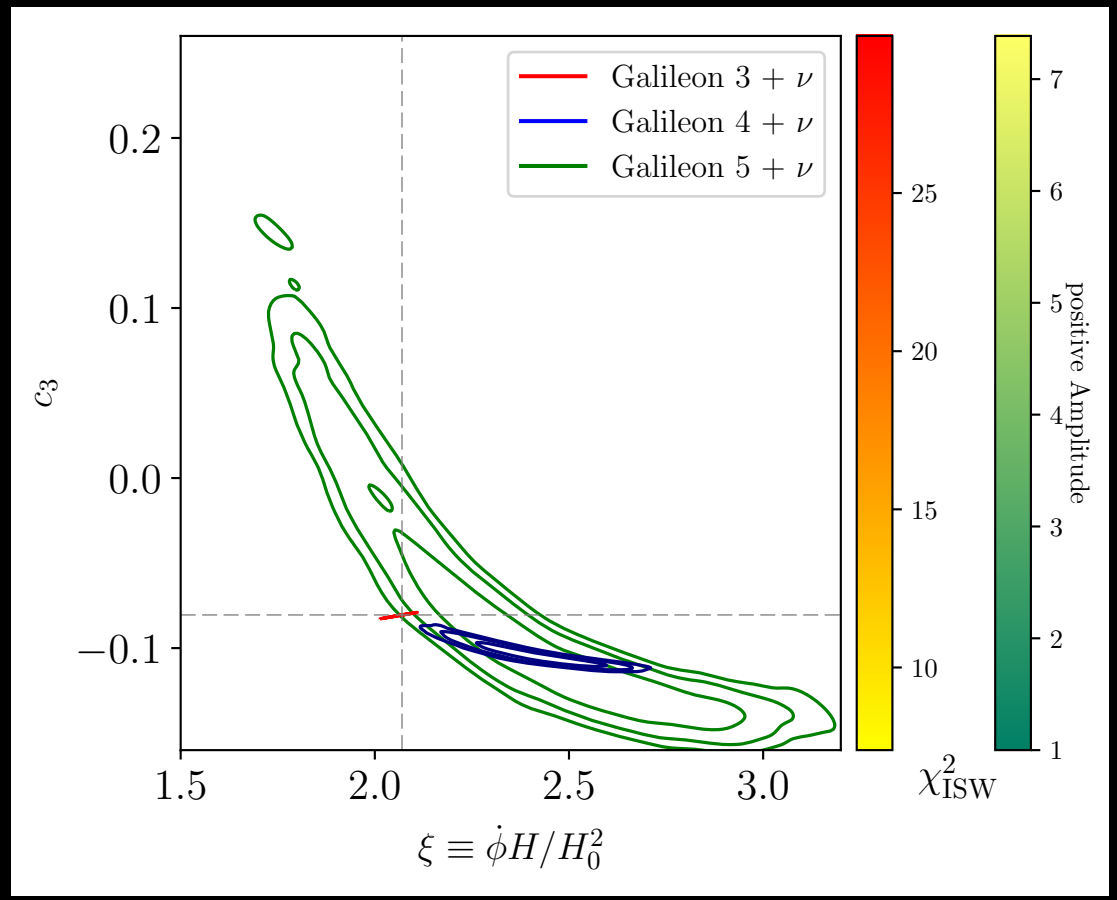


# Galileon and Integrated Sachs-Wolfe effect (Renk+ '17)

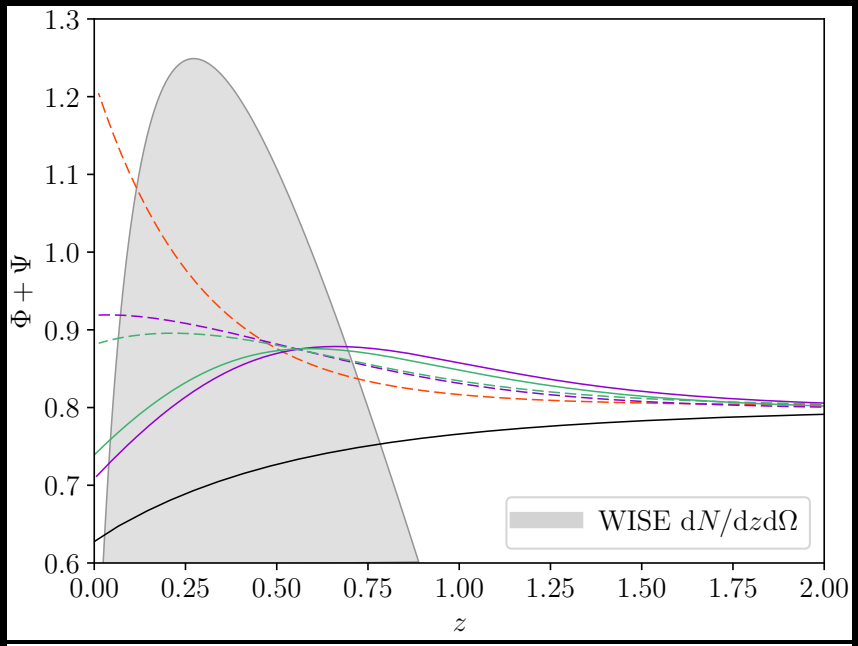



$$\Delta_\ell^{\rm ISW} = \int_{\tau_*}^{\tau_0} d\tau (\Phi' + \Psi') j_\ell$$



# Galileon and Integrated Sachs-Wolfe effect (Renk+ '17)

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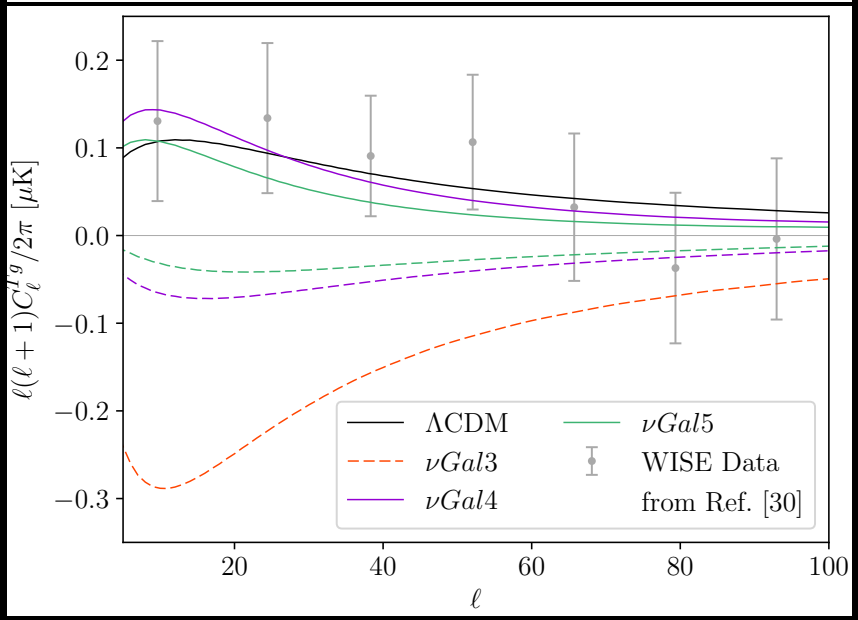
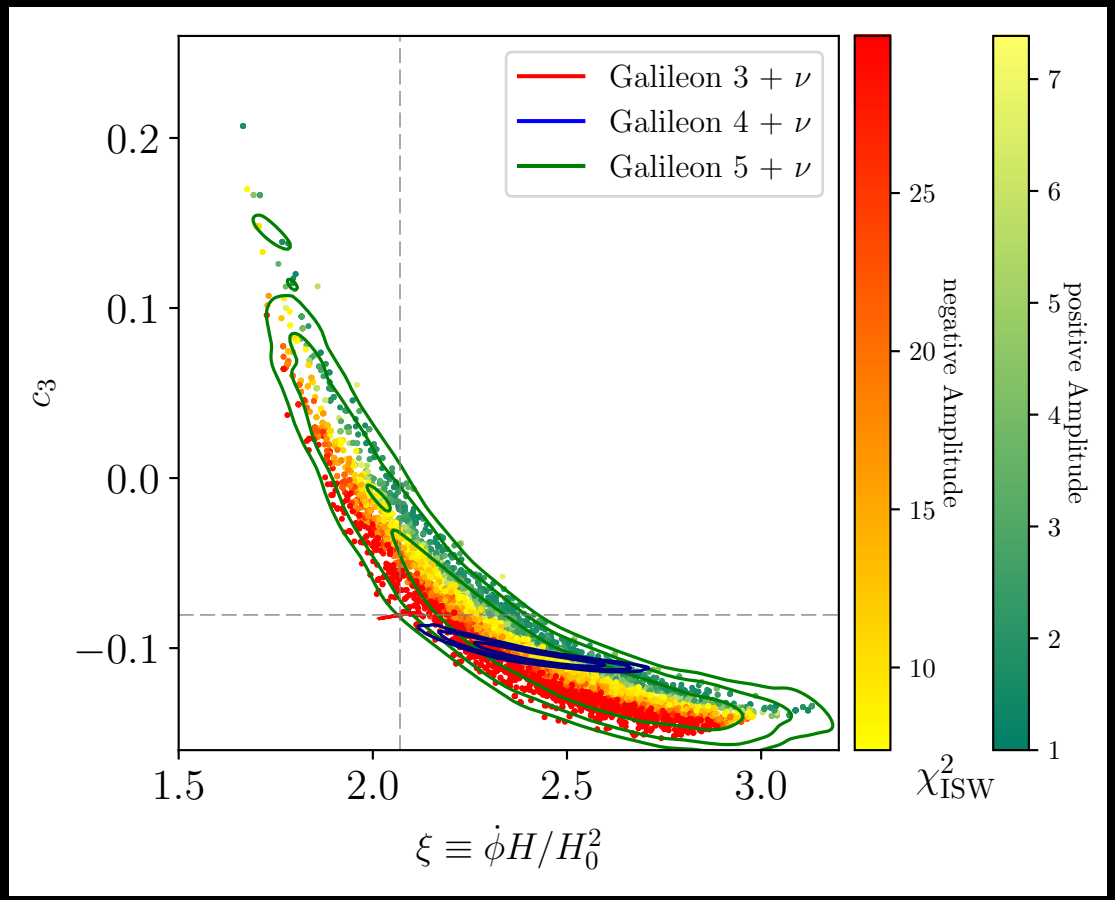
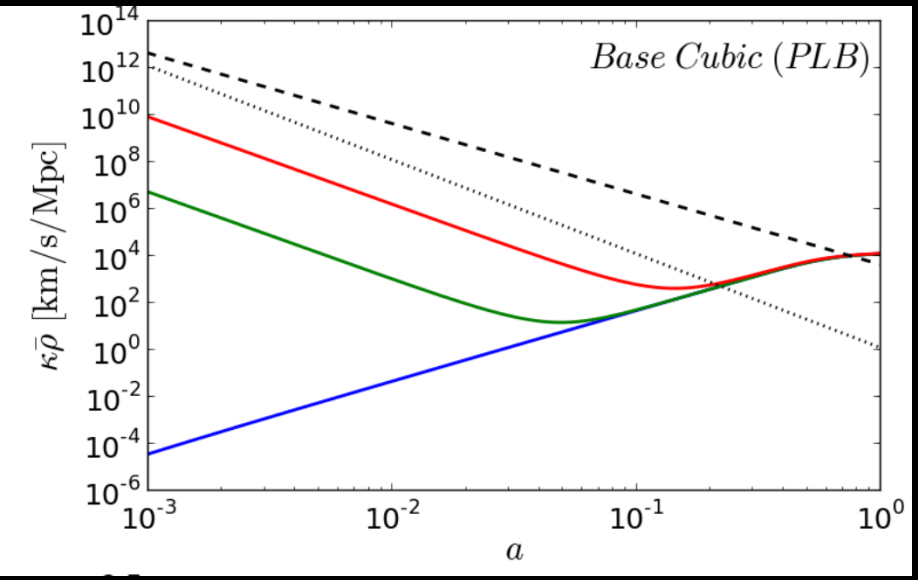


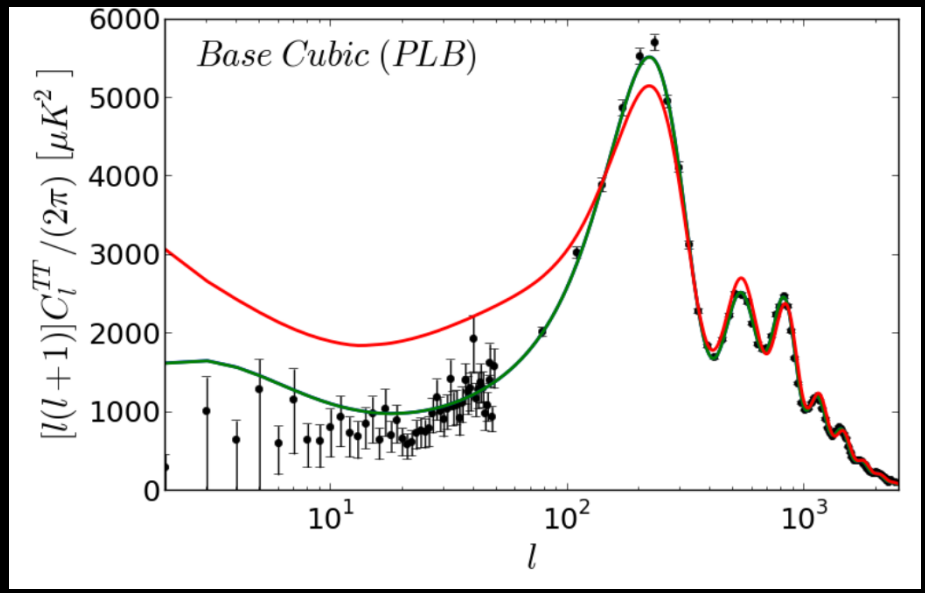



# Galileon: Tracker condition (Barreira+ '14)

Symmetry $\phi \to \phi + C$ $\Rightarrow$ conserved $\mathcal{J}^\mu$ $\Rightarrow \mathcal{J}^0 \propto a^{-3} \to 0$

$$\dot{\phi}(t)H(t) = \xi \cdot H_0^2 M_P = \text{constant}$$




- Evolution to tracker: no fine tuning
- Tracker by $z_T \sim \infty$, $z_T \approx 6$, $z_T \approx 2.5$ ($\Omega_{de}$ small but relevant)
- Inviable if out of tracker late (i.e. while $\Omega_{de}$ significant)
- Indistinguishable if reached earlier