New Physics and Dark Energy

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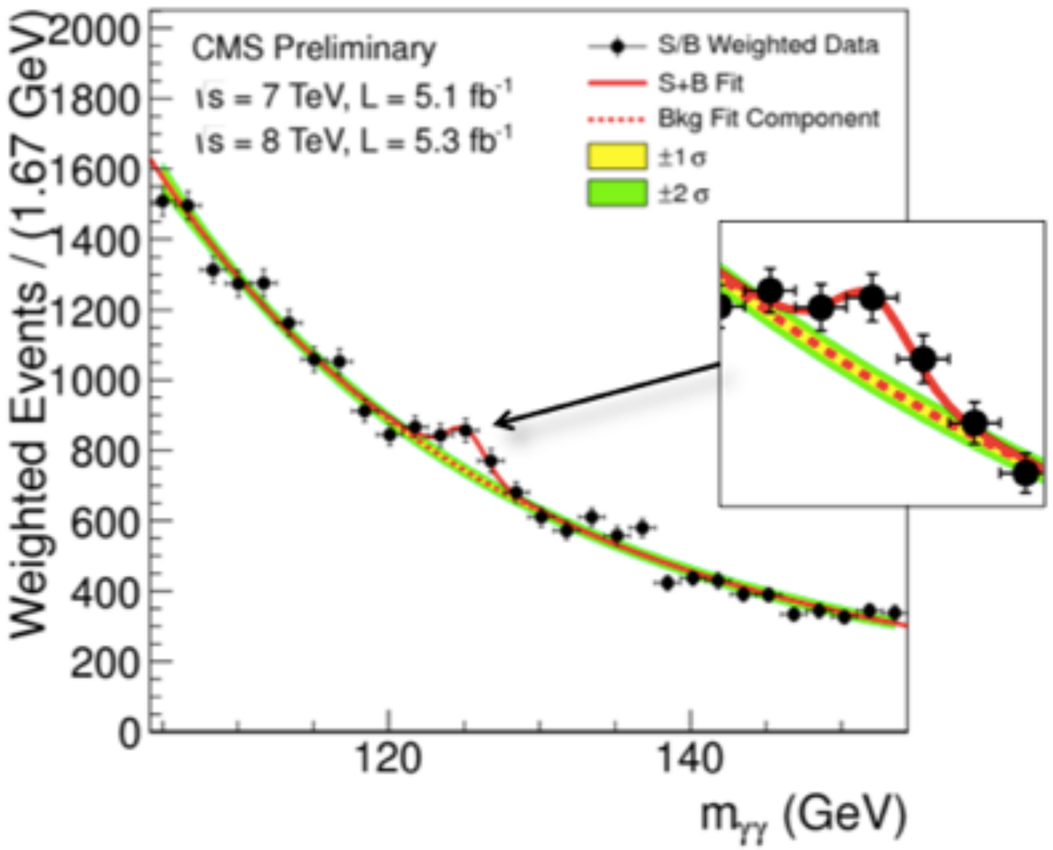
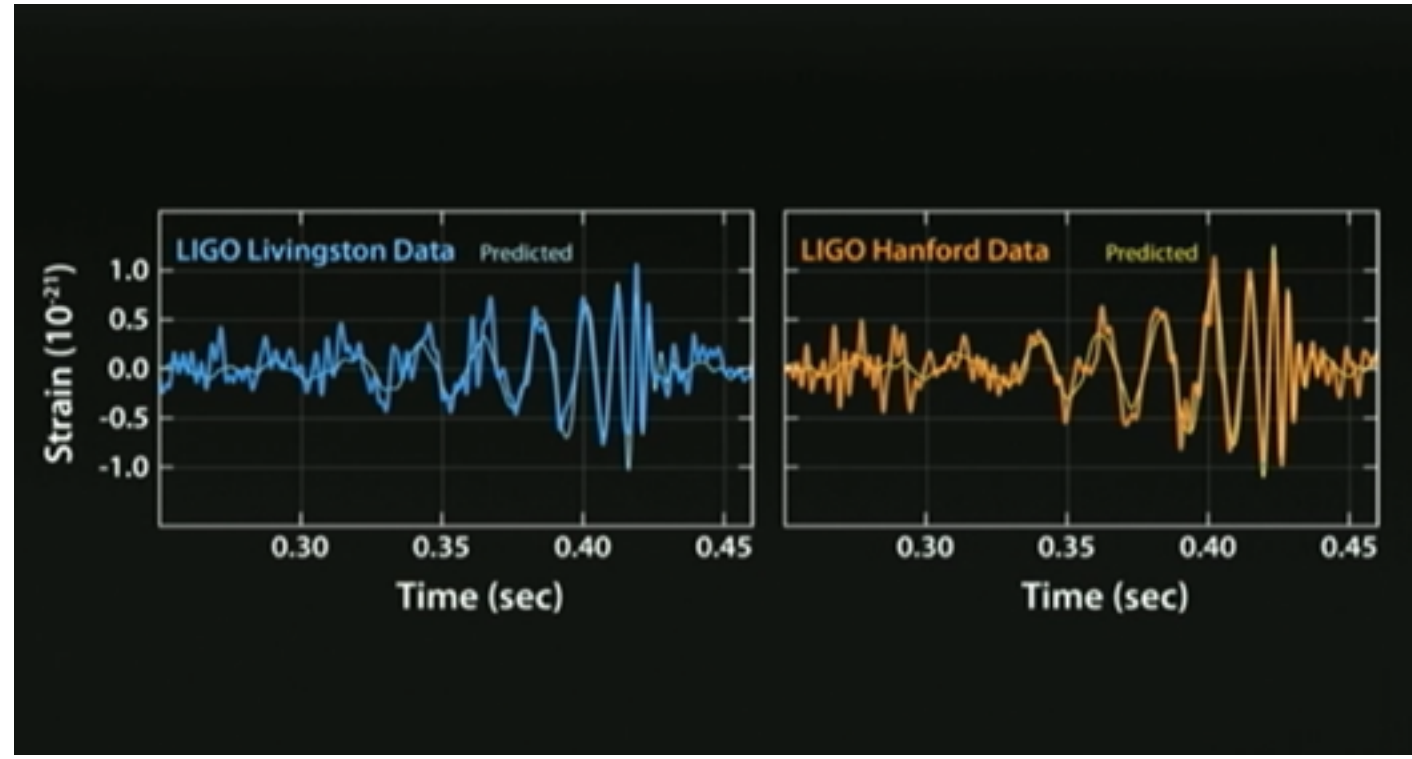
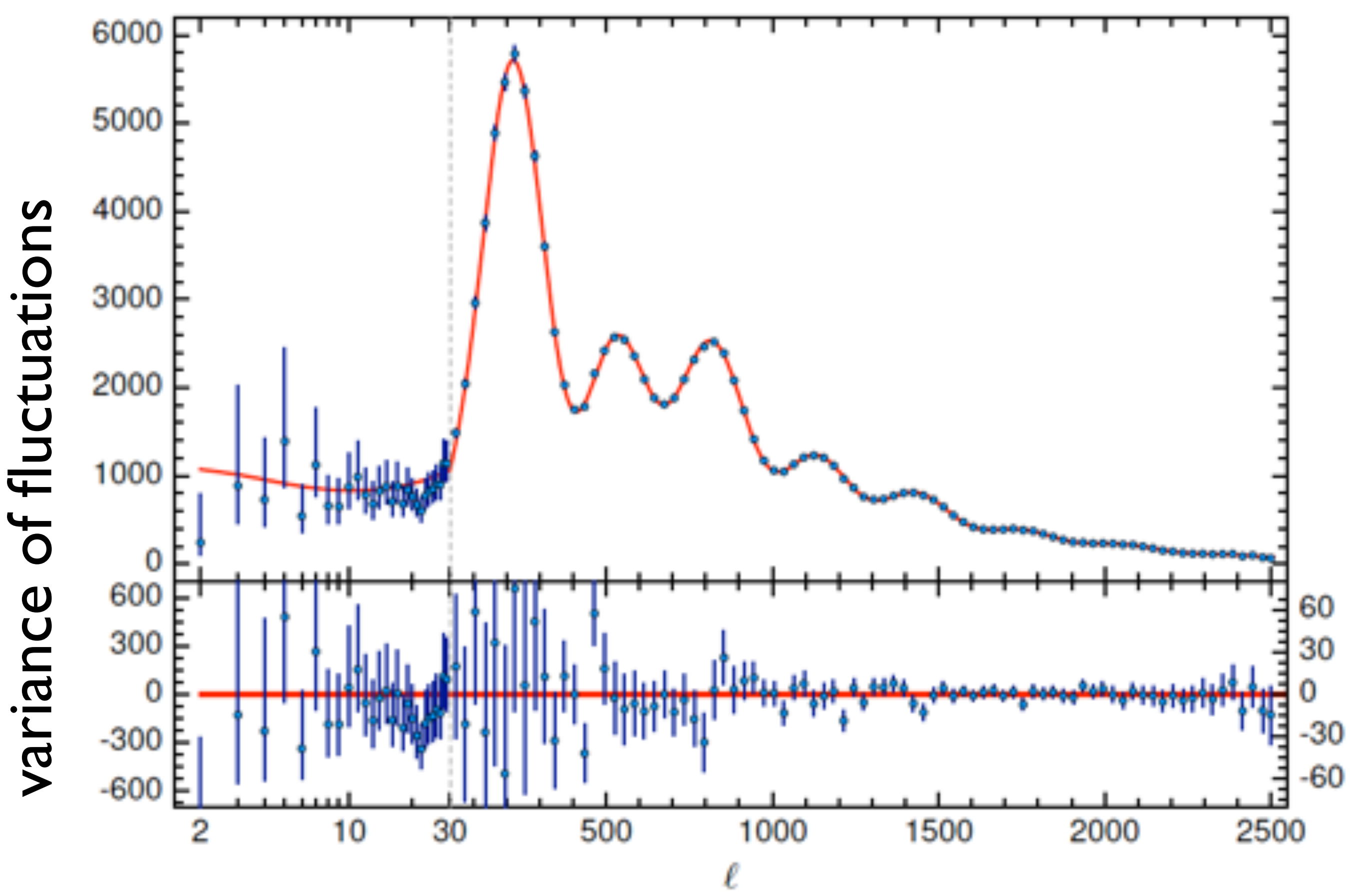
(University of Oxford)

Madrid (2019)


CMS Preliminary
√s = 7 TeV, L = 5.1 fb⁻¹
√s = 8 TeV, L = 5.3 fb⁻¹
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
Weighted Events / (1.67 GeV)
m_γγ (GeV)


LIGO Livingston Data
Predicted
LIGO Hanford Data
Predicted
Strain (10⁻²¹)
Time (sec)
Time (sec)


variance of fluctuations
ℓ

“There is nothing to be discovered in physics now.
All that remains is more and more precise measurement.”

Kelvin (1900)

Constants aren't Constants

- Higgs $\quad m\bar{\Psi}\Psi \rightarrow \lambda\phi\bar{\Psi}\Psi$
- Λ $\quad \Lambda \rightarrow V(\phi)$
- G $\quad$ "$\Box G \simeq \rho$"

$$\frac{1}{12}\alpha\phi^2 R$$

Fifth Forces

Define $M^2 = -\frac{\alpha}{6}\phi^2$

to get

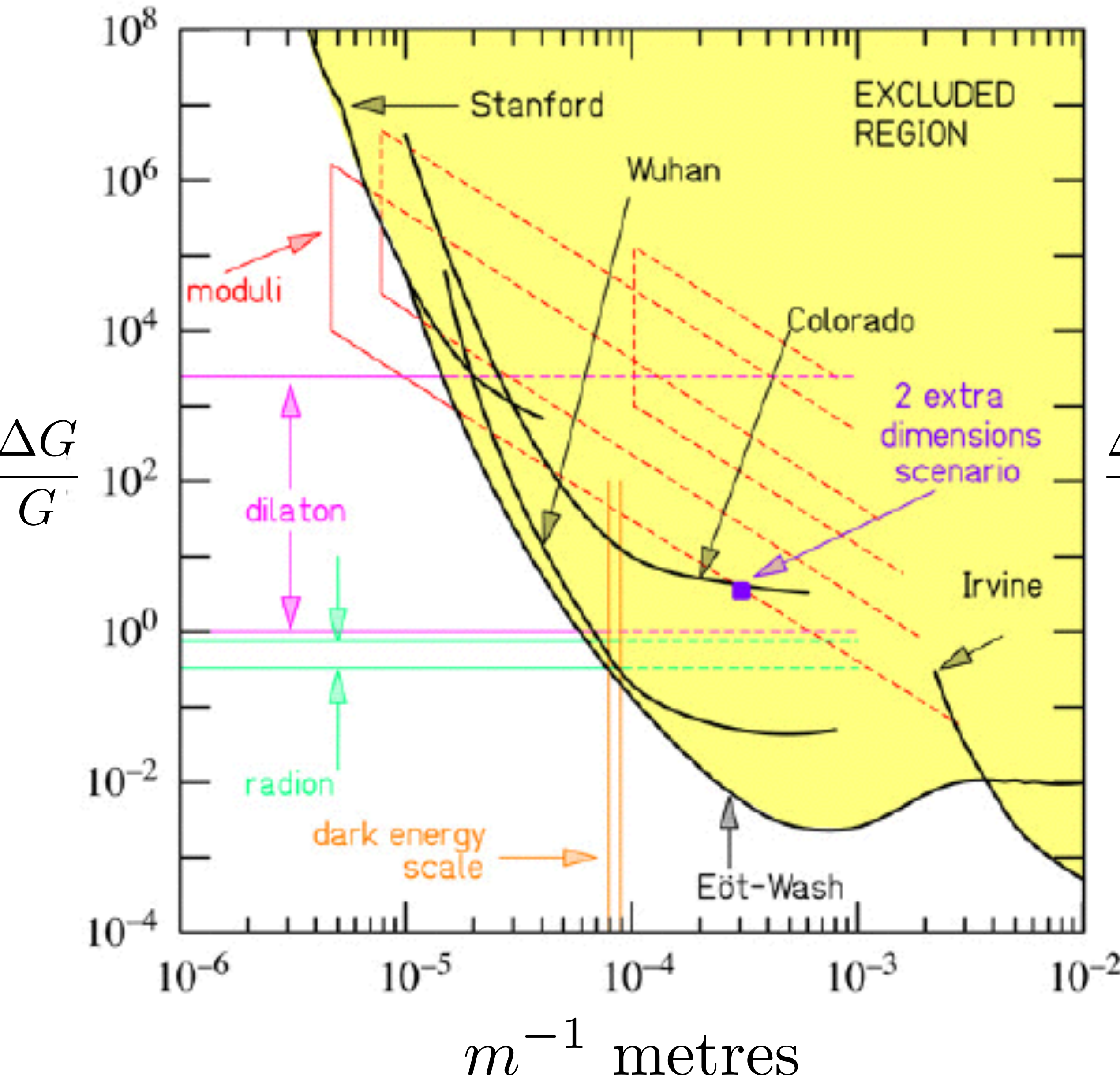
$$S_{BD} = -\int d^4x\sqrt{-g}\left[\frac{M^2}{2}R + \frac{\omega_{BD}}{M^2}\partial^\mu M^2 \partial_\mu M^2 + V + L_m\right]$$

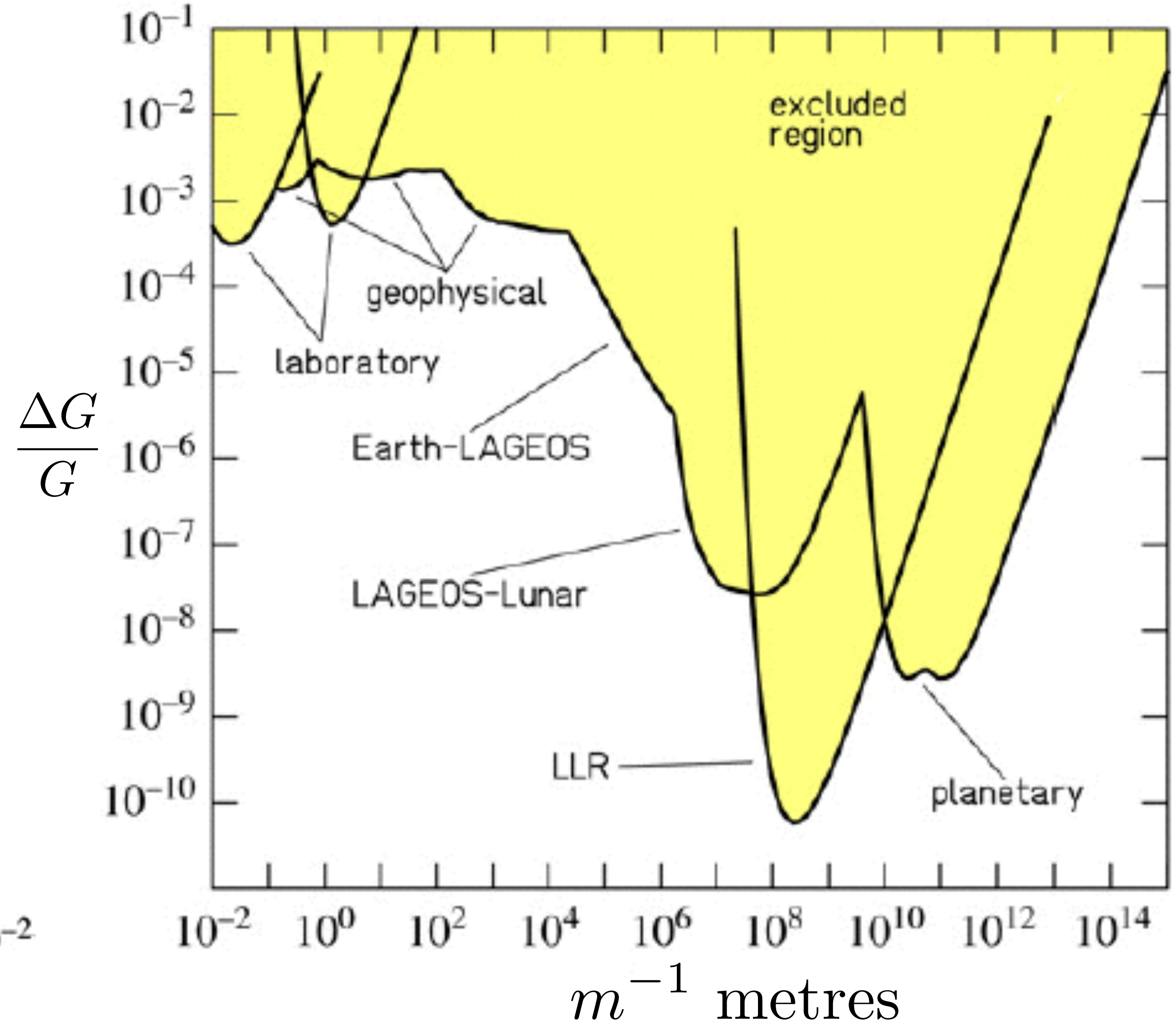
Einstein-Hilbert recovered when $\omega_{\rm BD} \sim 1/\alpha \to \infty$

Brans & Dicke 1961

Fifth Forces

Adelberger++ (2009)





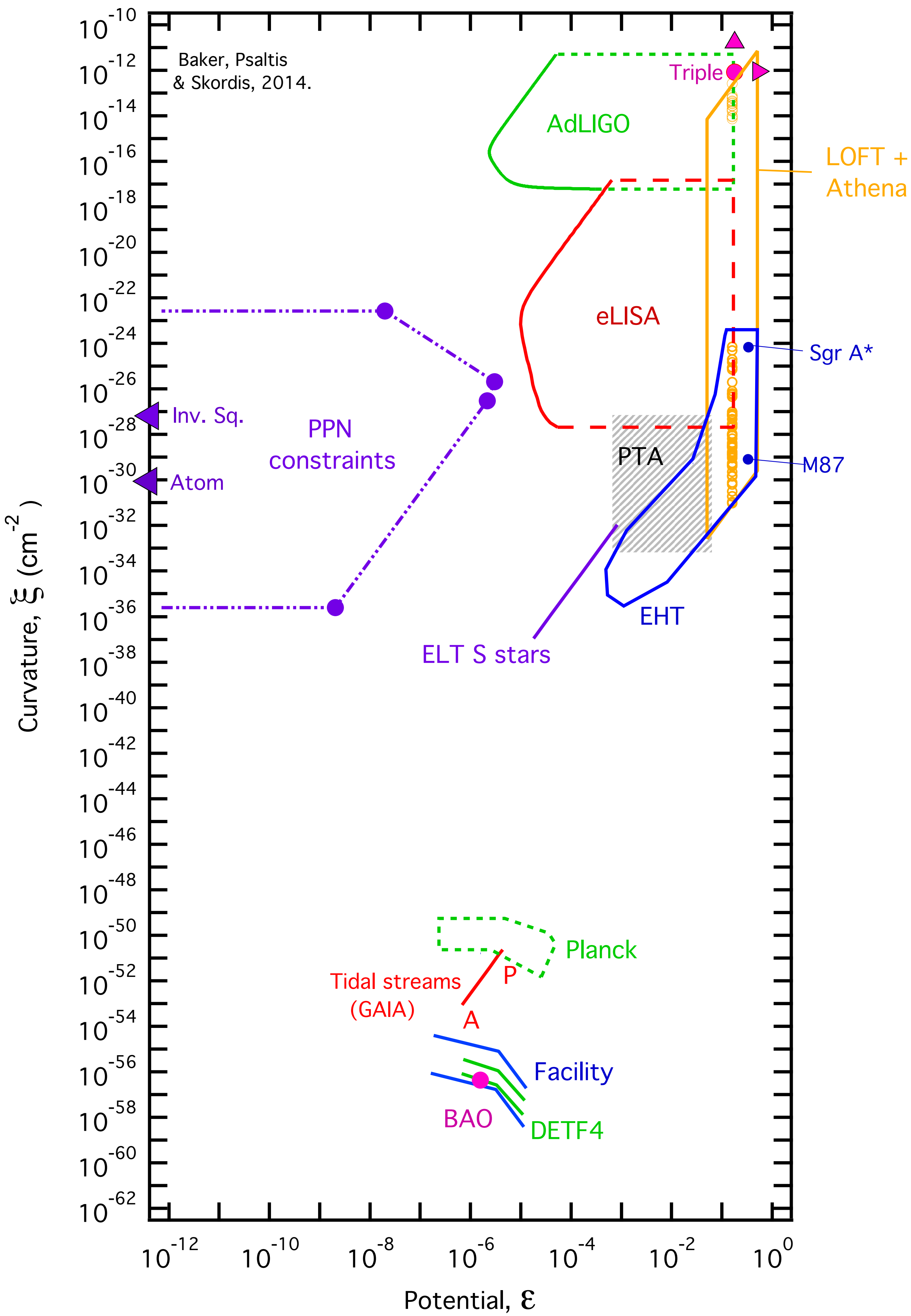
$$\Phi_{\rm tot} = \frac{GM}{r}\left(1 + \frac{\Delta G}{G} e^{-mr}\right)$$

$$\boxed{w_{\rm BD} > 40,000}$$

Look harder!

"By pushing a theory to its extremes, we also find out where the cracks in its structure might be hiding"

Wheeler 1960



Baker et al 2014
ArXiv:1412:3455

Gravitational Screening

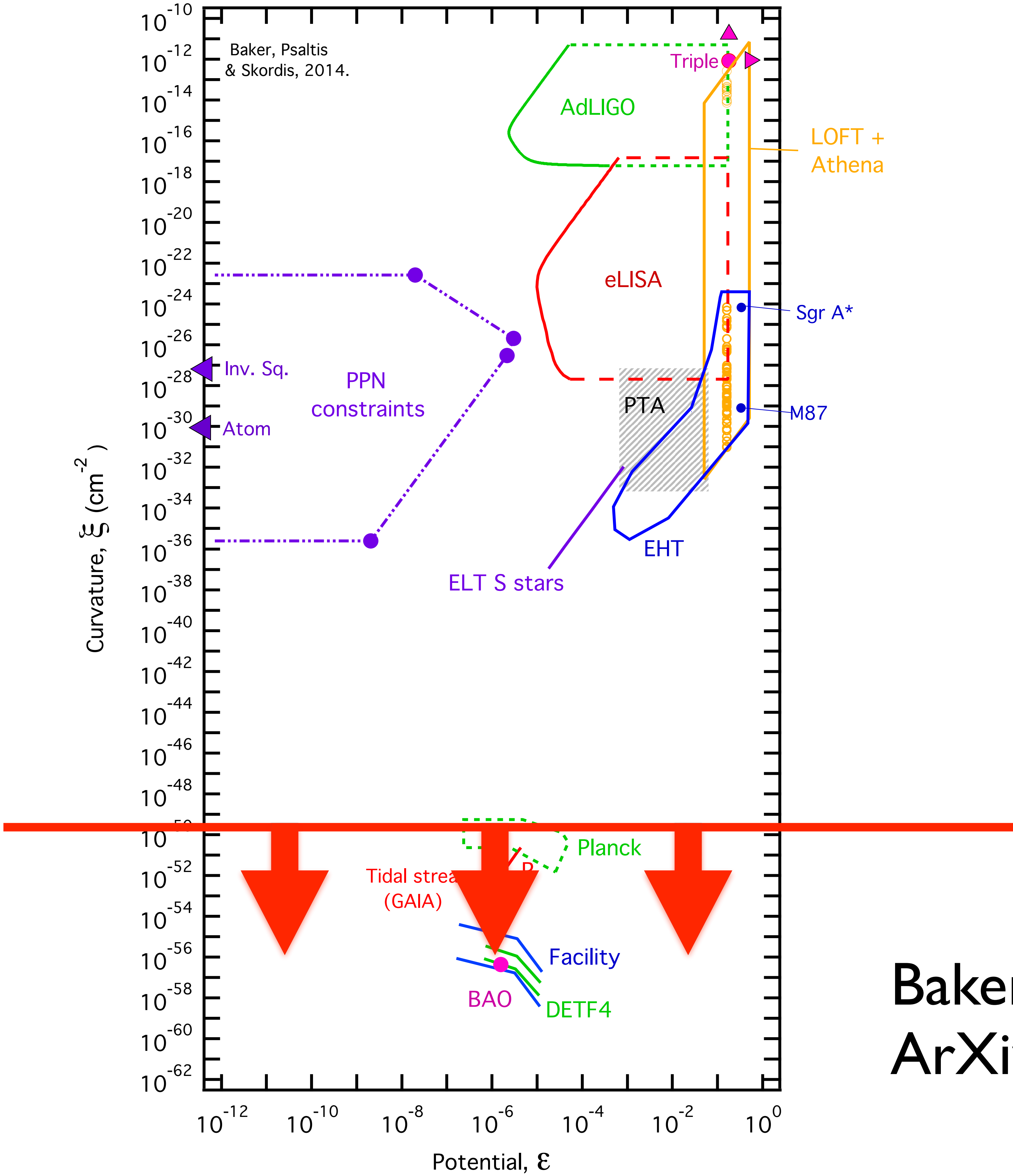
$$m \to \infty$$

in dense environments
(chameleon)

$$\Phi_{\rm tot} = \frac{GM}{r}\left(1 + \frac{\Delta G}{G} e^{-mr}\right)$$

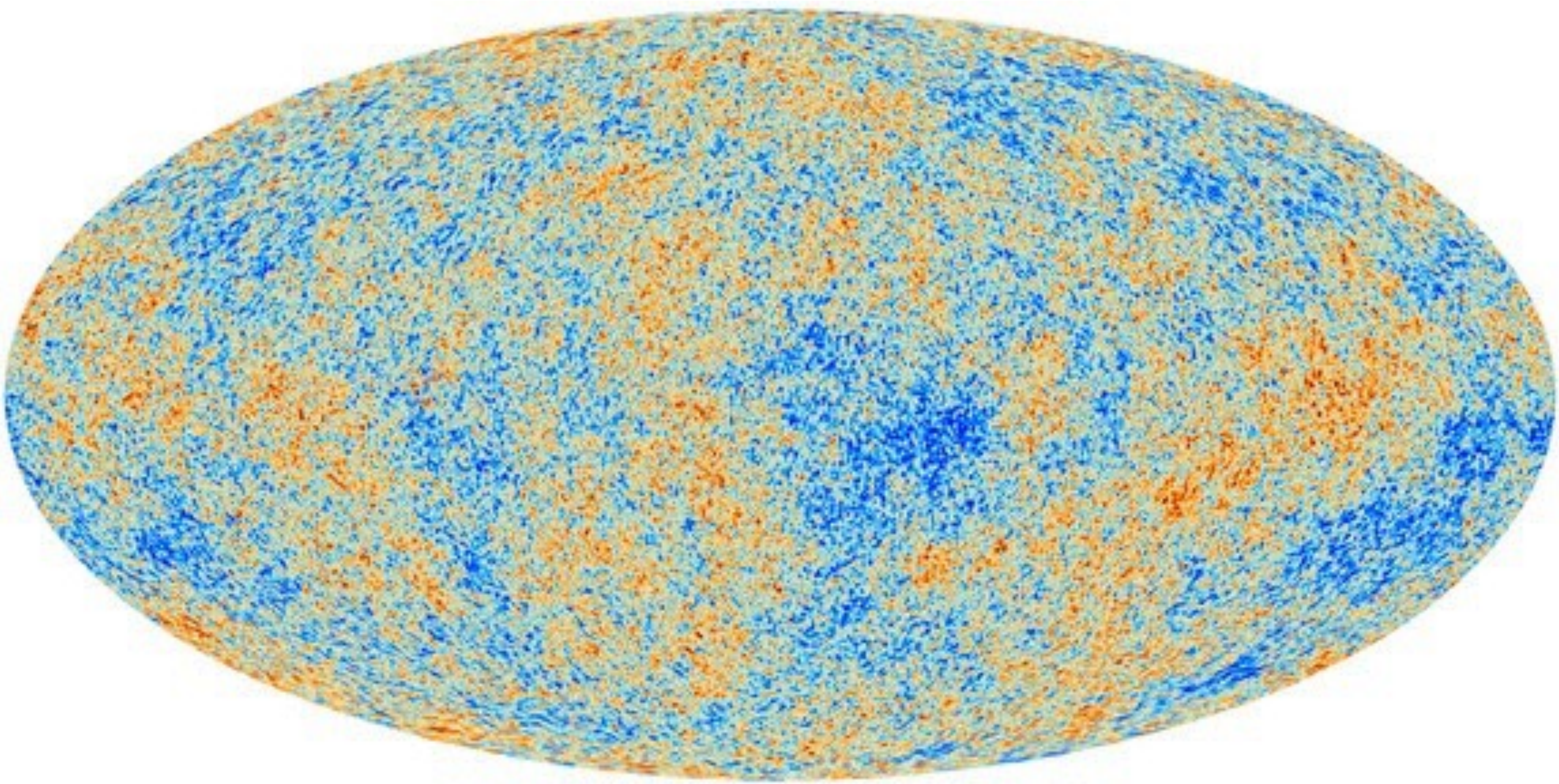
$$\frac{\Delta G}{G} \to 0$$

close to very massive objects
(Vainshtein)



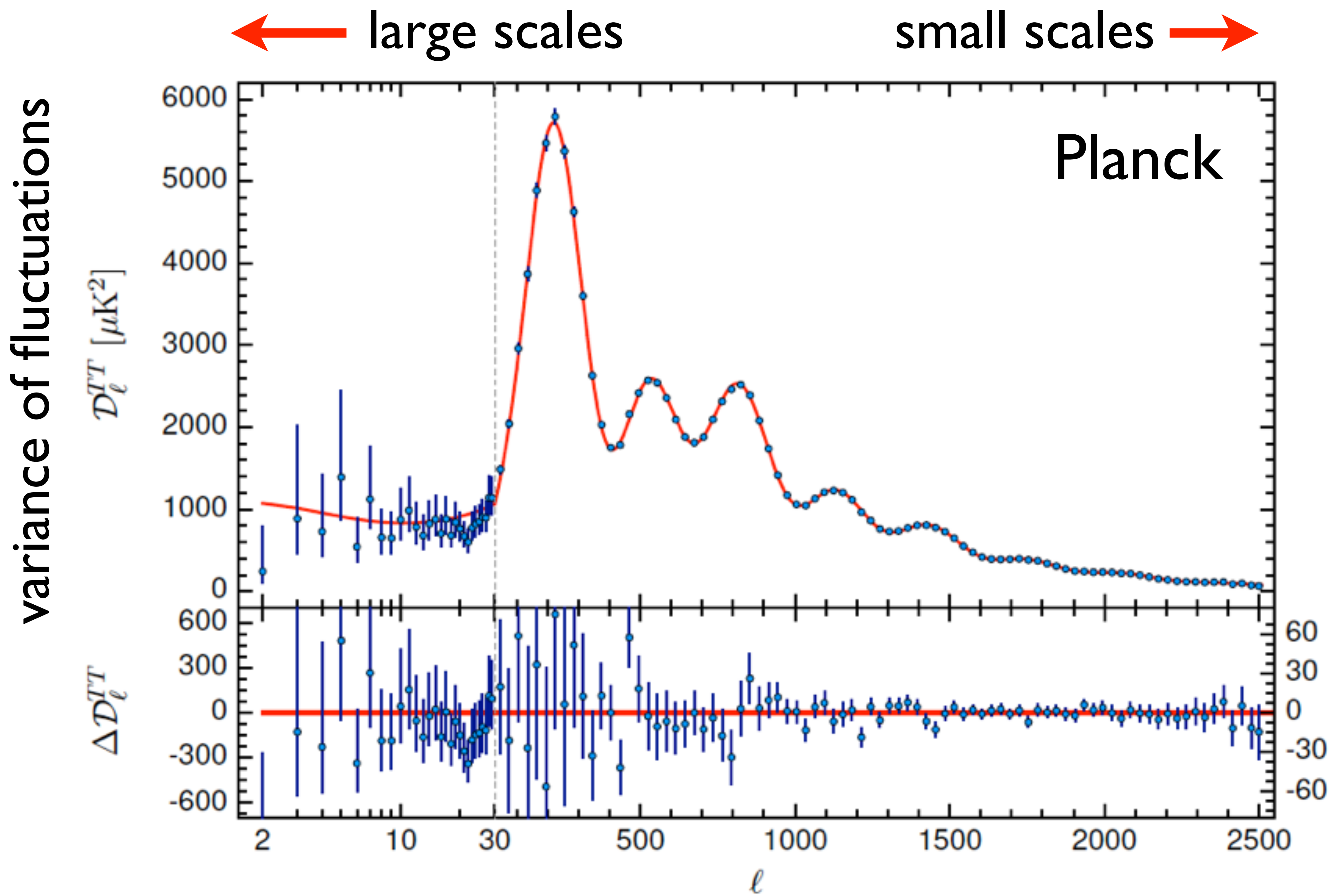
Baker et al 2014
ArXiv:1412:3455

CMB



Planck 2015

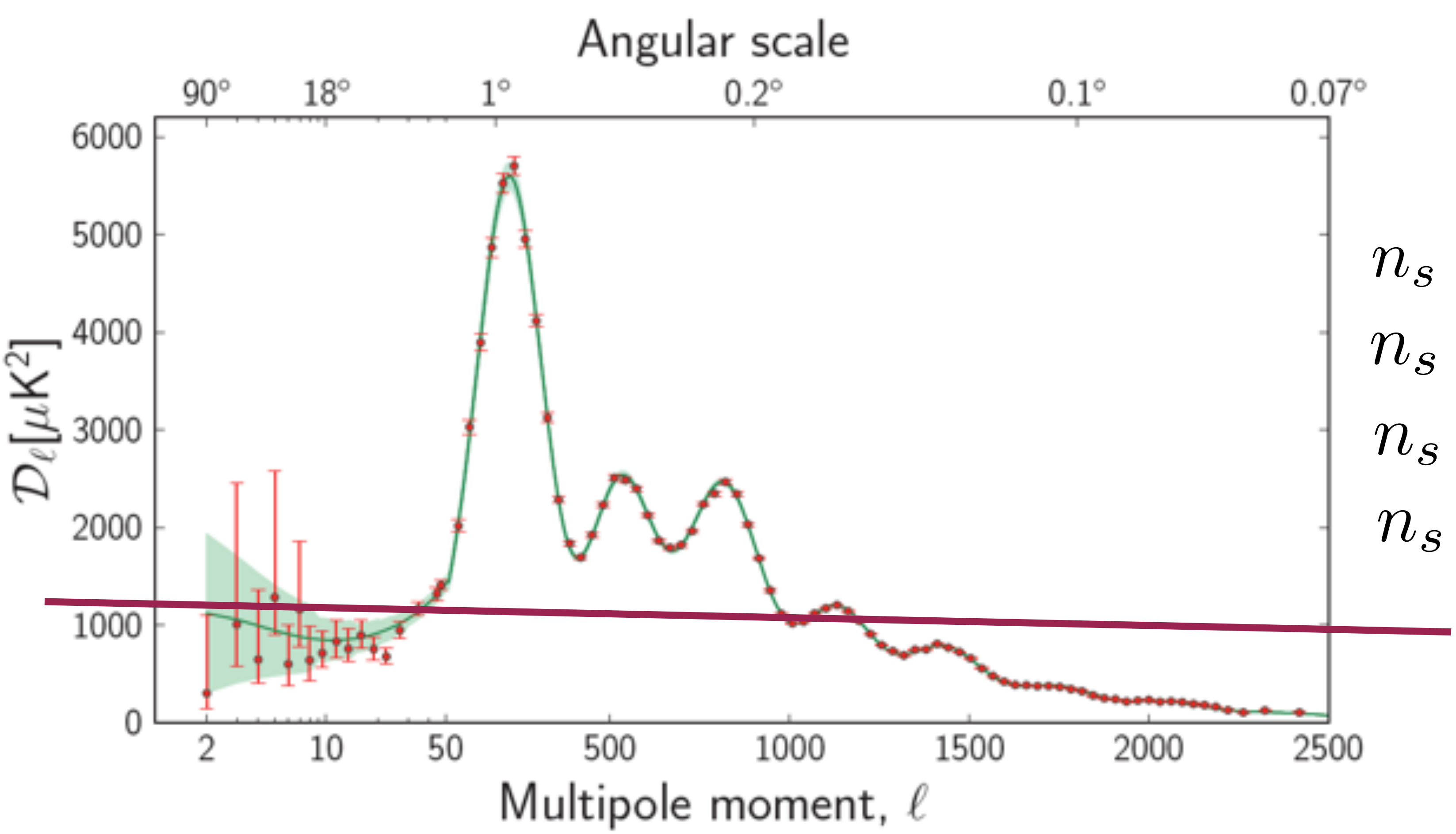
CMB


large scales
small scales
variance of fluctuations
Planck
$\mathcal{D}_\ell^{TT}$ [μK^2]
6000
5000
4000
3000
2000
1000
0
$\Delta\mathcal{D}_\ell^{TT}$
600
300
0
-300
-600
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ

CMB

Dramatic improvement in constraining power.

$$g_{ij} = a^2(\tau)\,[1 - 2\Phi]\,\gamma_{ij} \longrightarrow k^3\langle|\Phi|^2\rangle \propto k^{n_s-1}$$



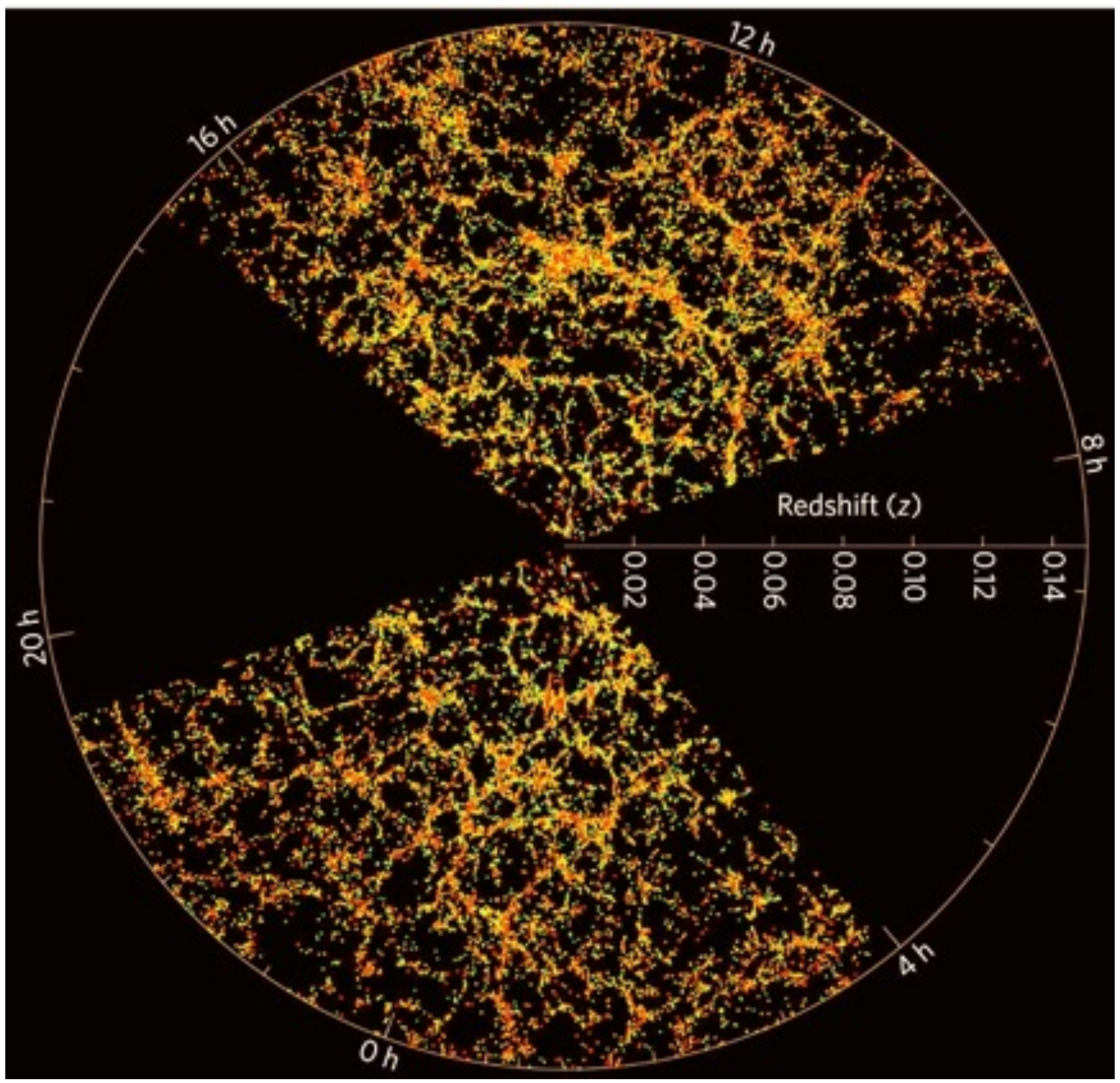
$n_s = 1 \pm 0.6$ 1992 (COBE)

$n_s = 1.03 \pm 0.09$ 2001 (MaxiBoom)

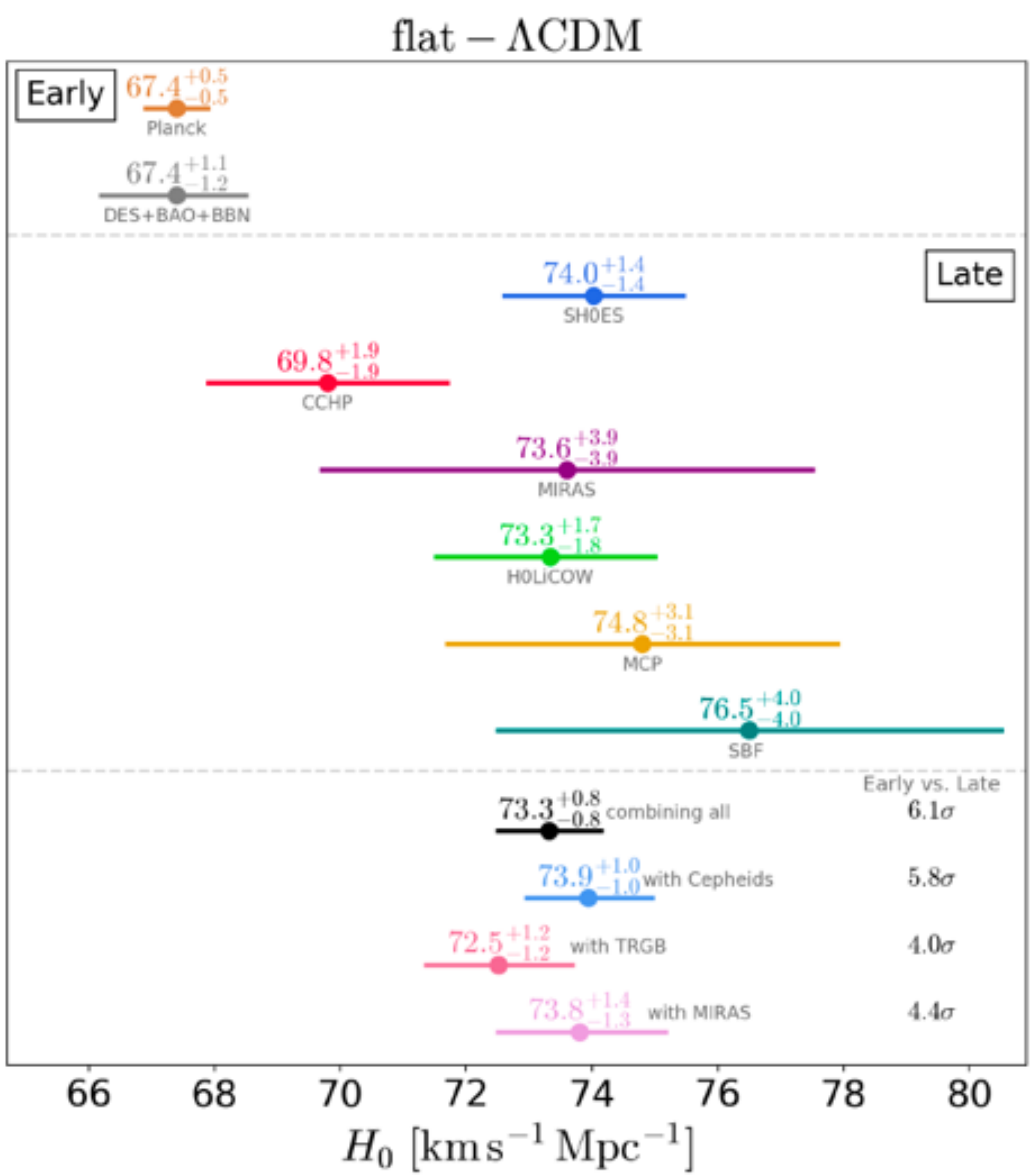
$n_s = 0.963 \pm 0.014$ 2009 (WMAP5)

$n_s = 0.9603 \pm 0.0073$ 2013 (Planck+)

Large Scale Structure



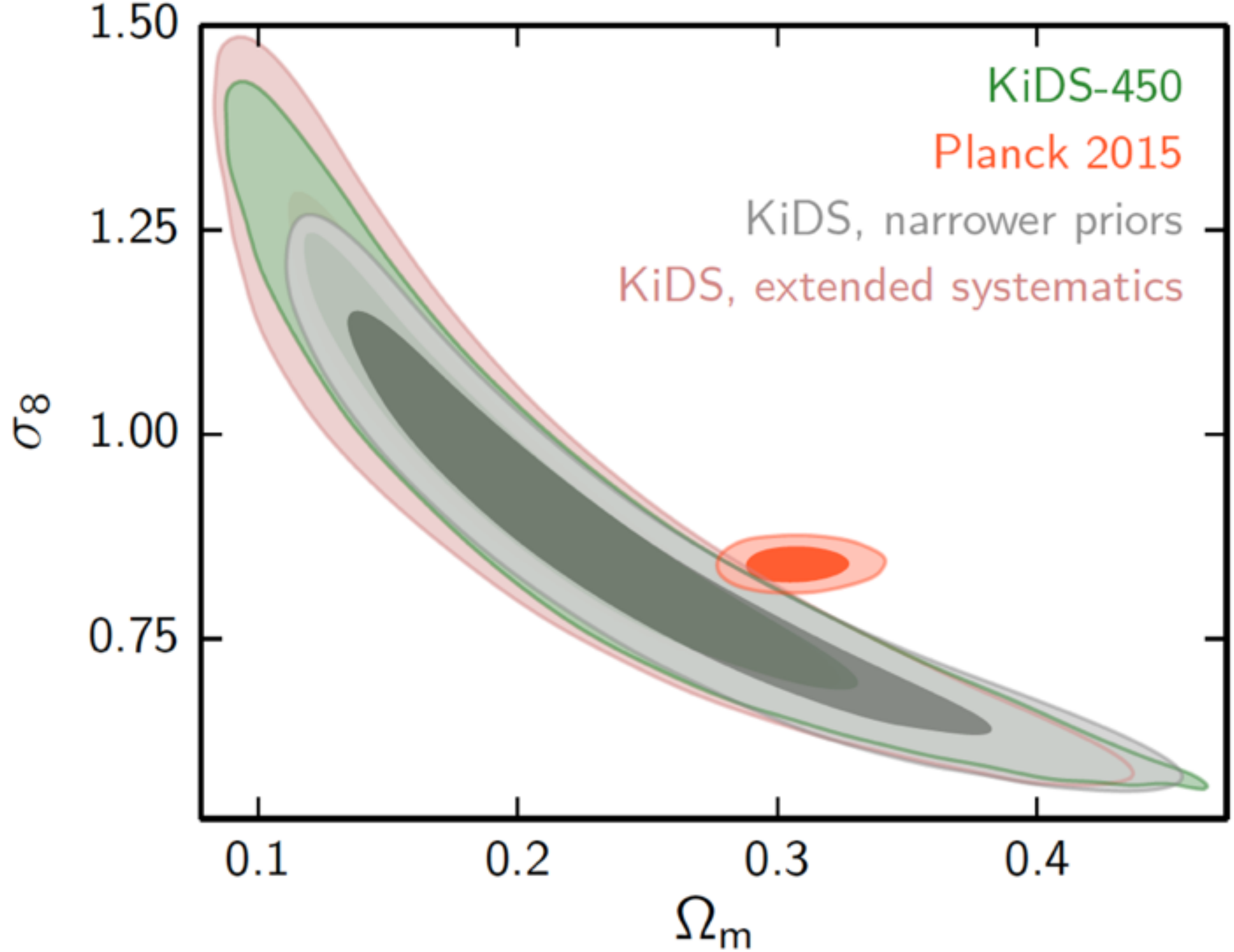
Hubble Tension



Vivien Bonvin 2019

Weak Lensing S_8 Tension

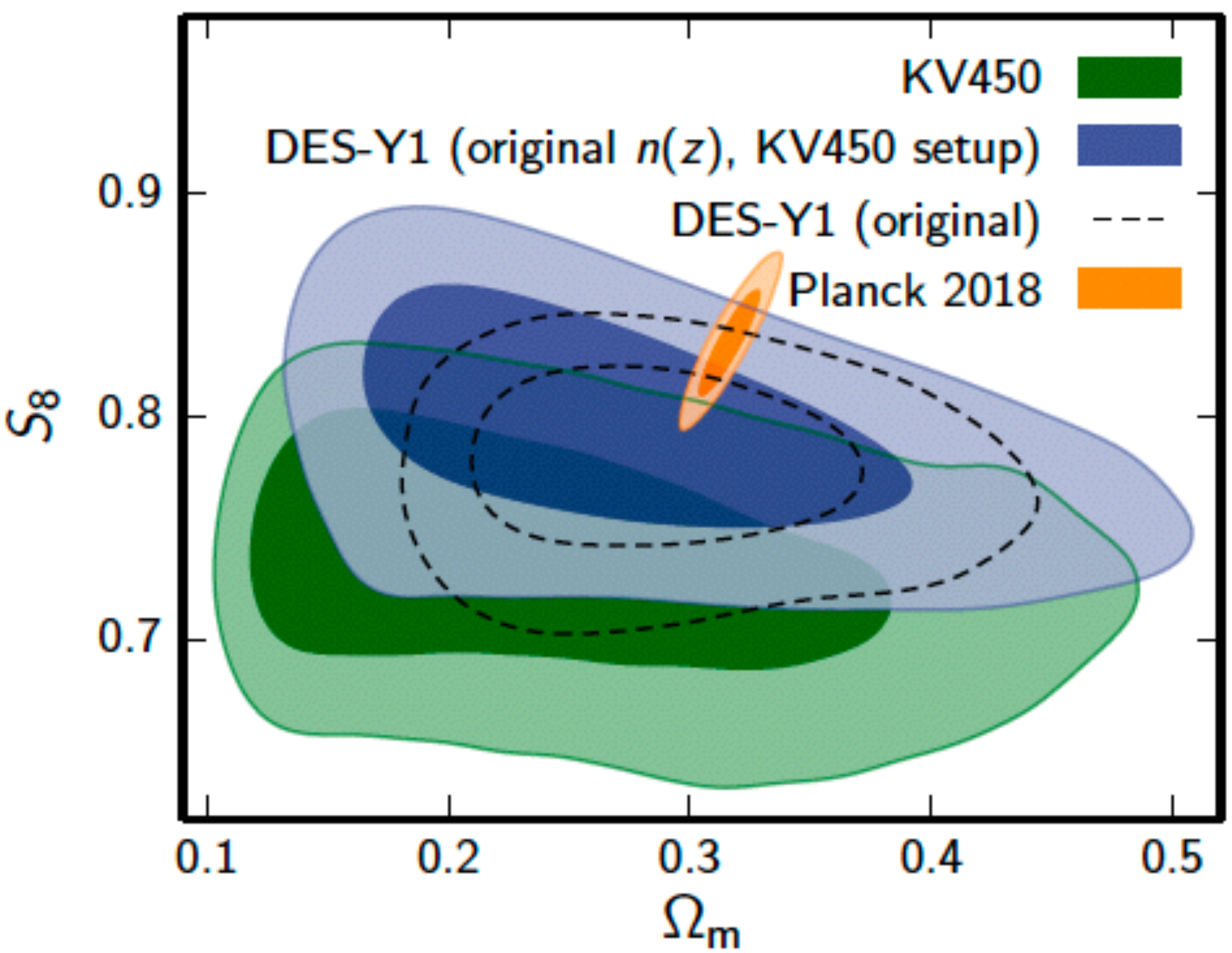
"amplitude of clustering at 8 h^{-1} Mpc"

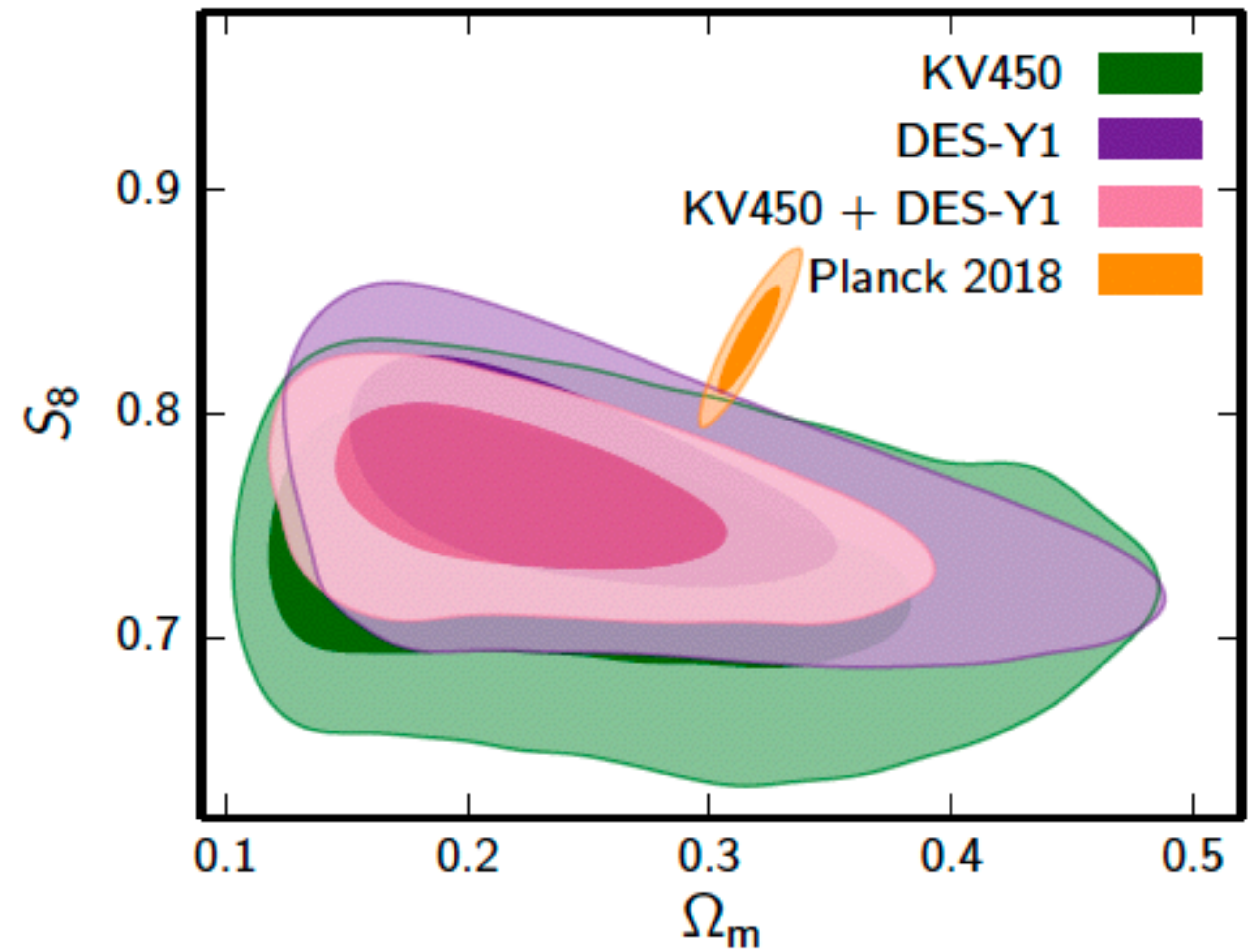


Joudaki et al 2016

"matter density"

Weak Lensing: S_8 Tension

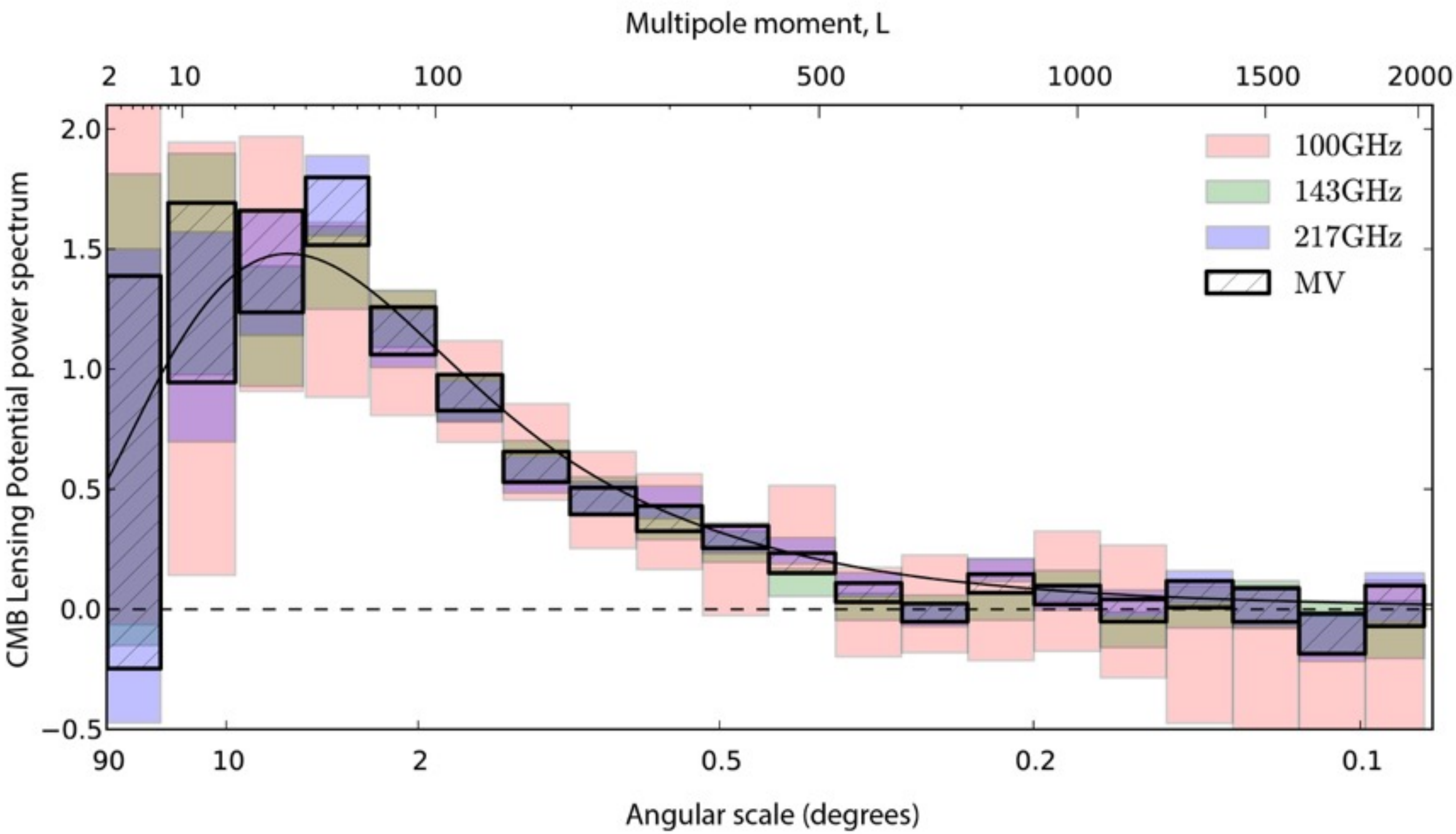




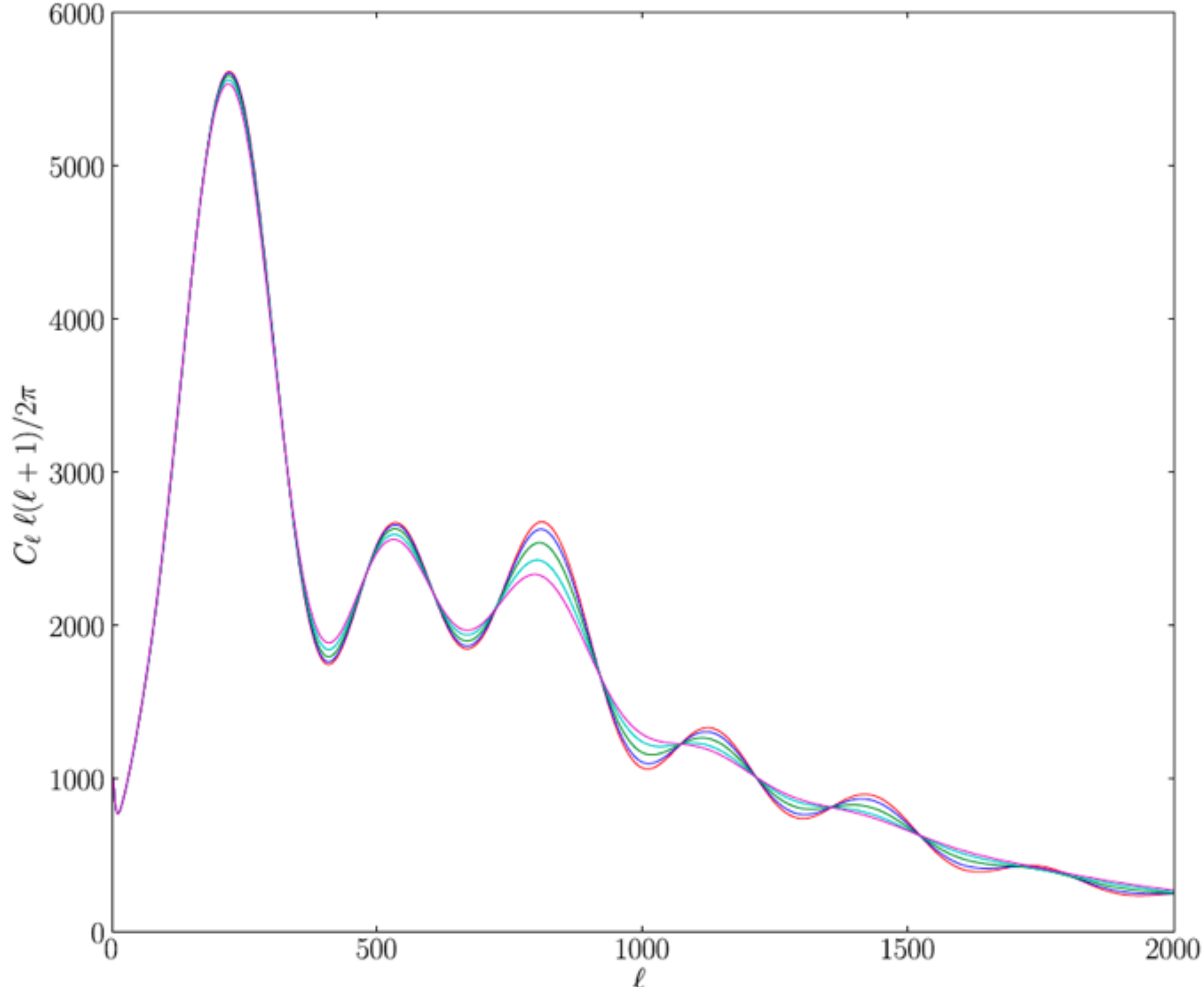
$$S_8 = \sigma_8(\Omega_M/0.3)^{0.5}$$

Joudaki et al 2019

Weak Lensing of CMB: A_L Tension



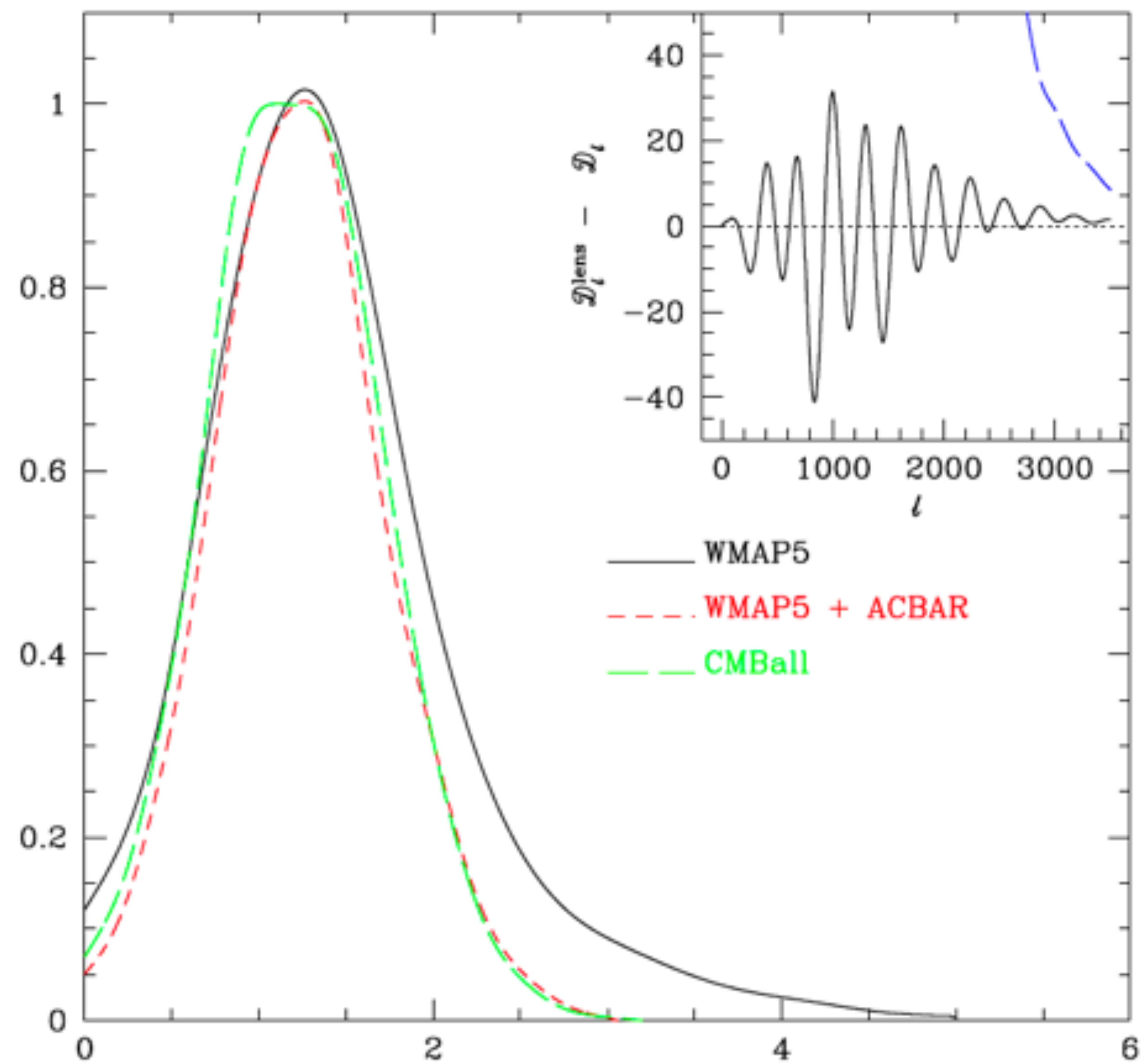
Weak Lensing of CMB: A_L Tension



Calabrese et al 2008

Weak Lensing of CMB: A_L Tension

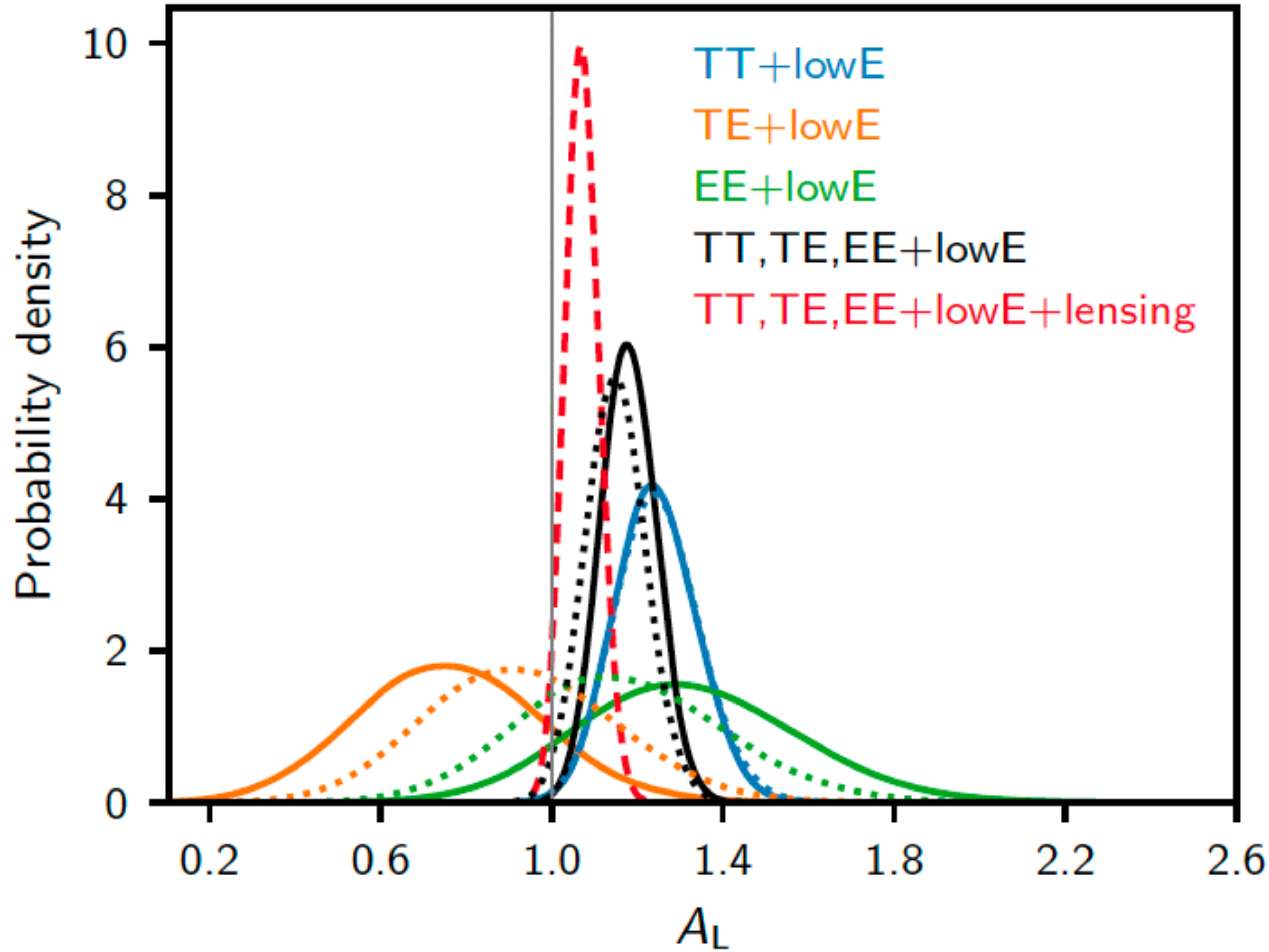
$$C_\ell^{\rm lens} = C_\ell^{\rm no-lens} + q_{\rm lens}\Delta C_\ell^{\rm lens}$$



$$A_L = q_{\rm lens}$$

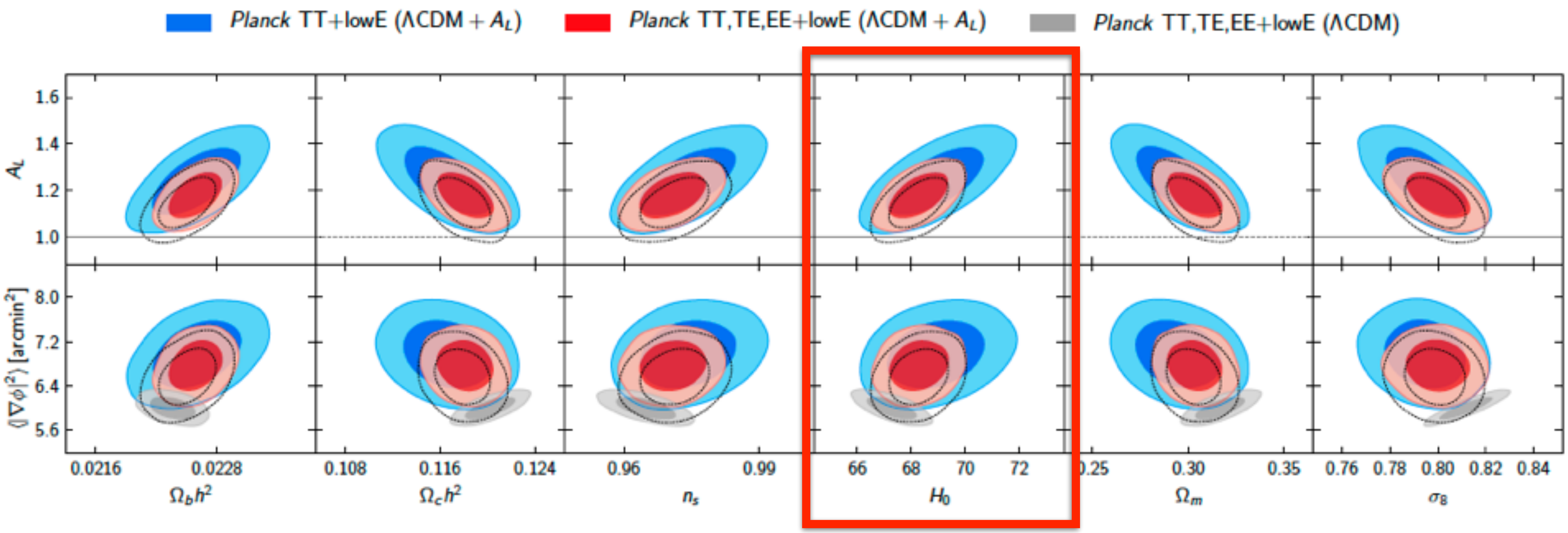
Reichardt et al (ACBAR) 2006

Weak Lensing of CMB: A_L Tension

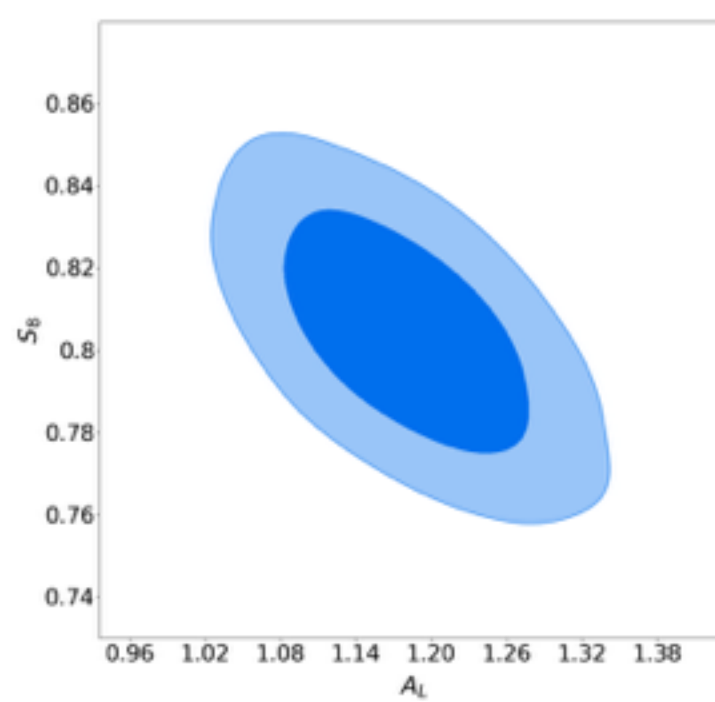


Planck 2018

Are the tensions all connected?



Planck 2018



Fifth forces on large scales

Most surveys very sub-horizon $\simeq 3000h^{-1}\mathrm{Mpc}$

Newtonian potentials: $h_{\alpha\beta} = 2\begin{pmatrix} \Phi & 0 \\ 0 & a^2\Psi\delta_{ij} \end{pmatrix}$

Assume $m \simeq 0$

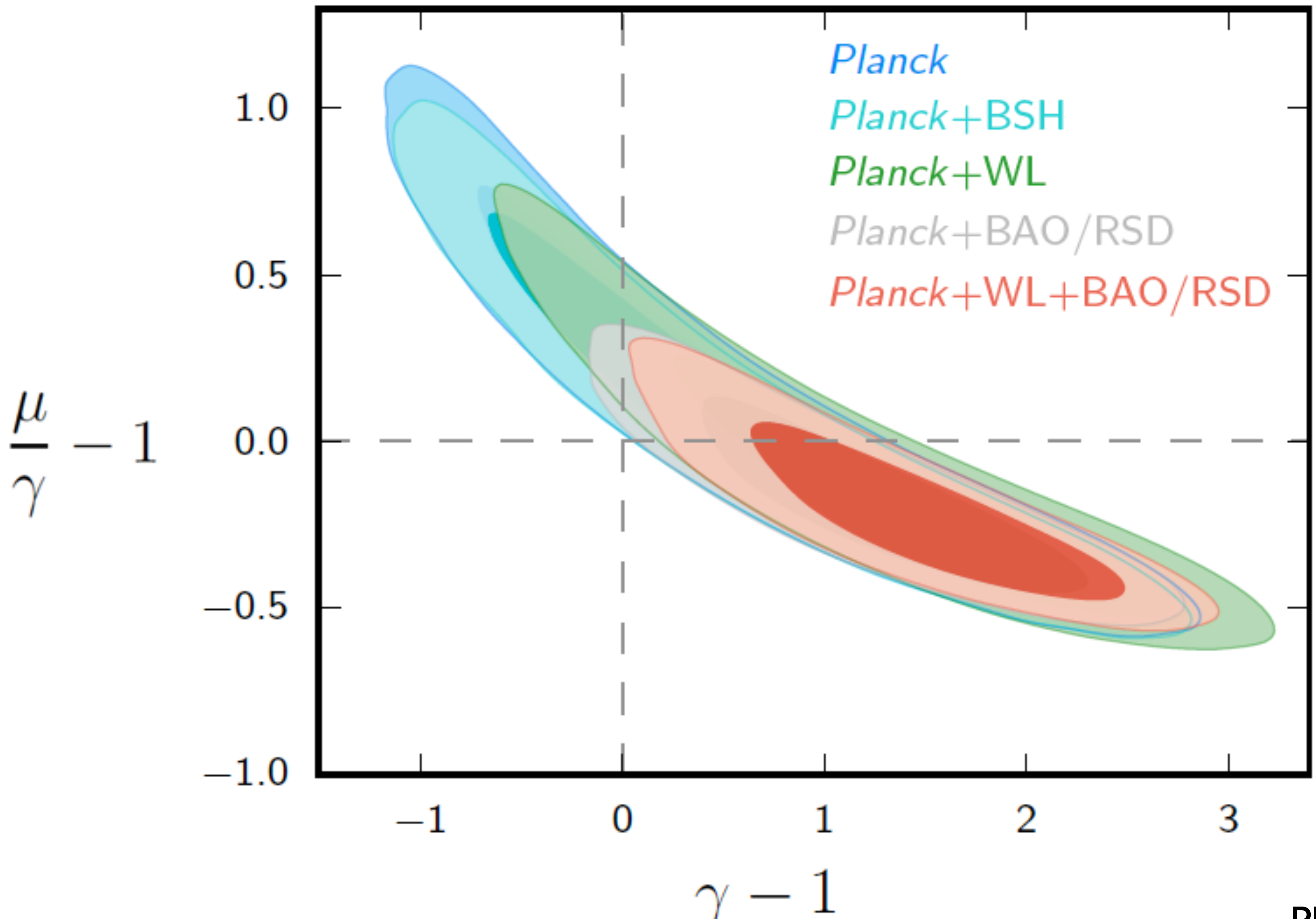
$$\boxed{\begin{aligned} \nabla^2(\Phi - \Psi) &= c_1\nabla^2\phi \\ \nabla^2\Phi &= 4\pi G\rho + c_2\nabla^2\phi \\ \nabla^2\phi &= 4\pi G c_3\rho \end{aligned}}$$

$$\Rightarrow$$

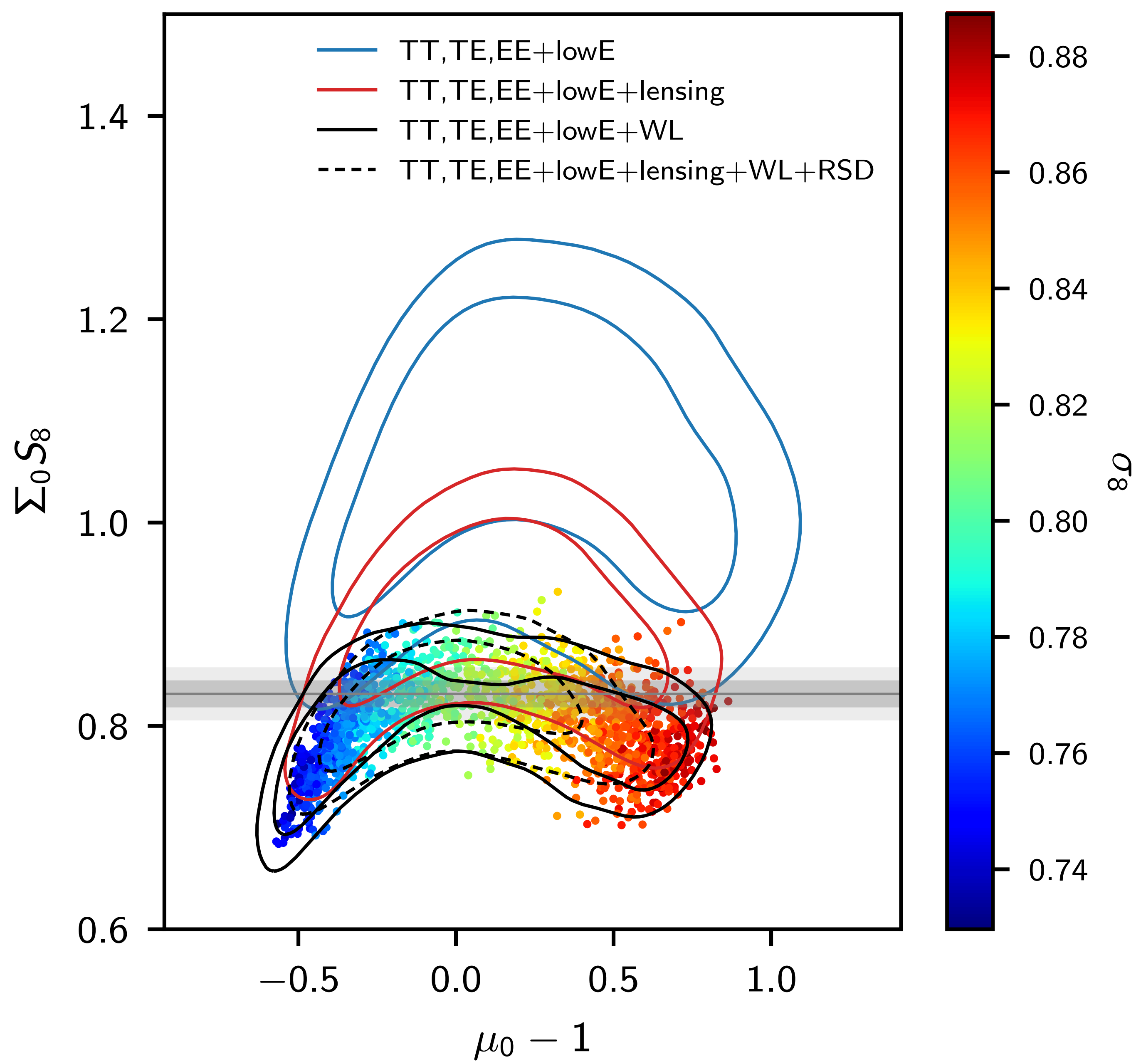
$$\mu = 1 + \frac{\Delta G}{G} = 1 + c_2c_3$$

$$\gamma = \left(1 + \frac{c_1c_3}{1 + c_2c_3}\right)^{-1}$$

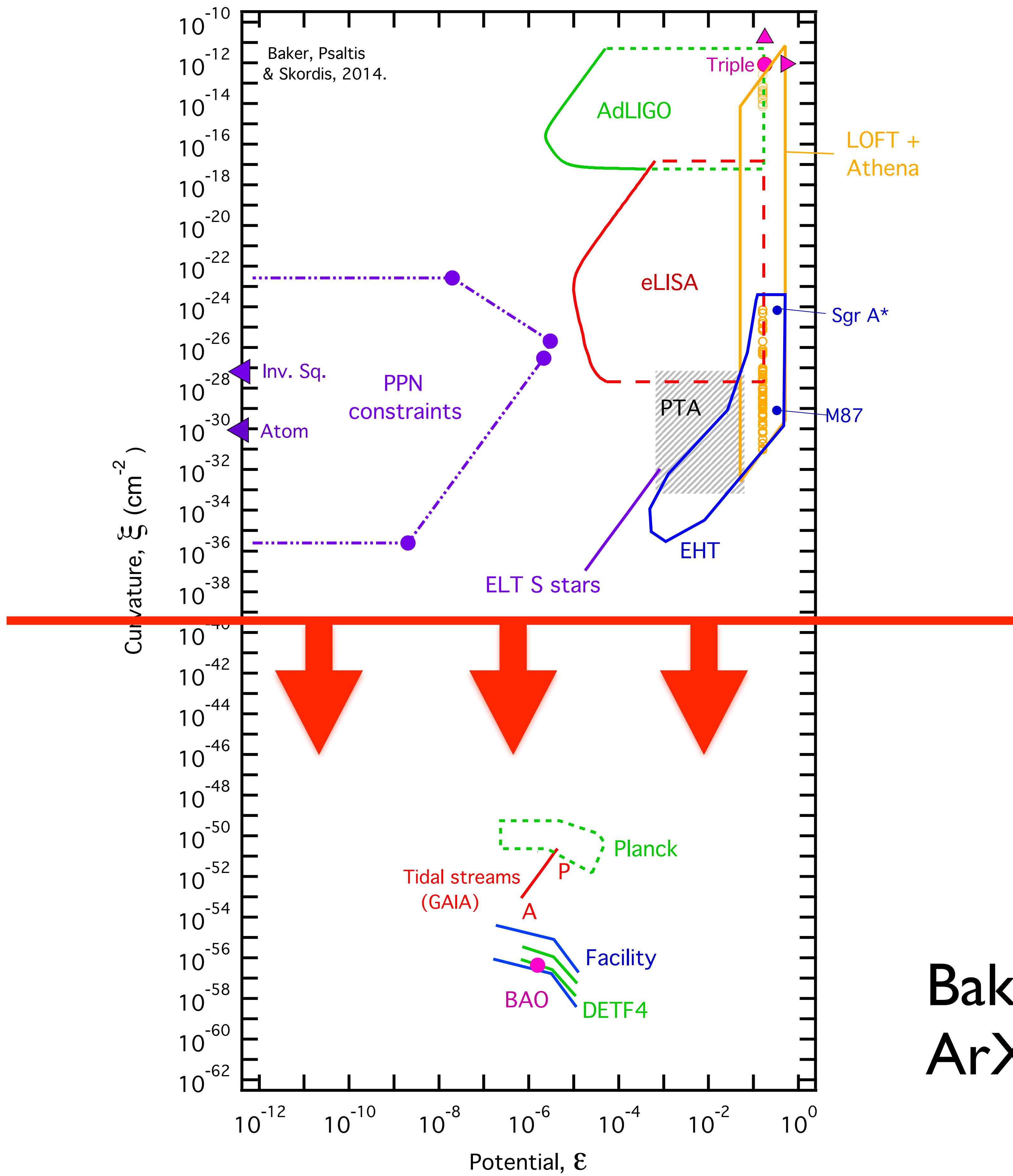
$$\nabla^2\Phi = 4\pi G\underline{\mu}\rho \qquad \underline{\gamma}\Psi = \Phi$$


Planck
Planck+BSH
Planck+WL
Planck+BAO/RSD
Planck+WL+BAO/RSD
1.0
0.5
0.0
−0.5
−1.0
−1
0
1
2
3
$\frac{\mu}{\gamma} - 1$
$\gamma - 1$

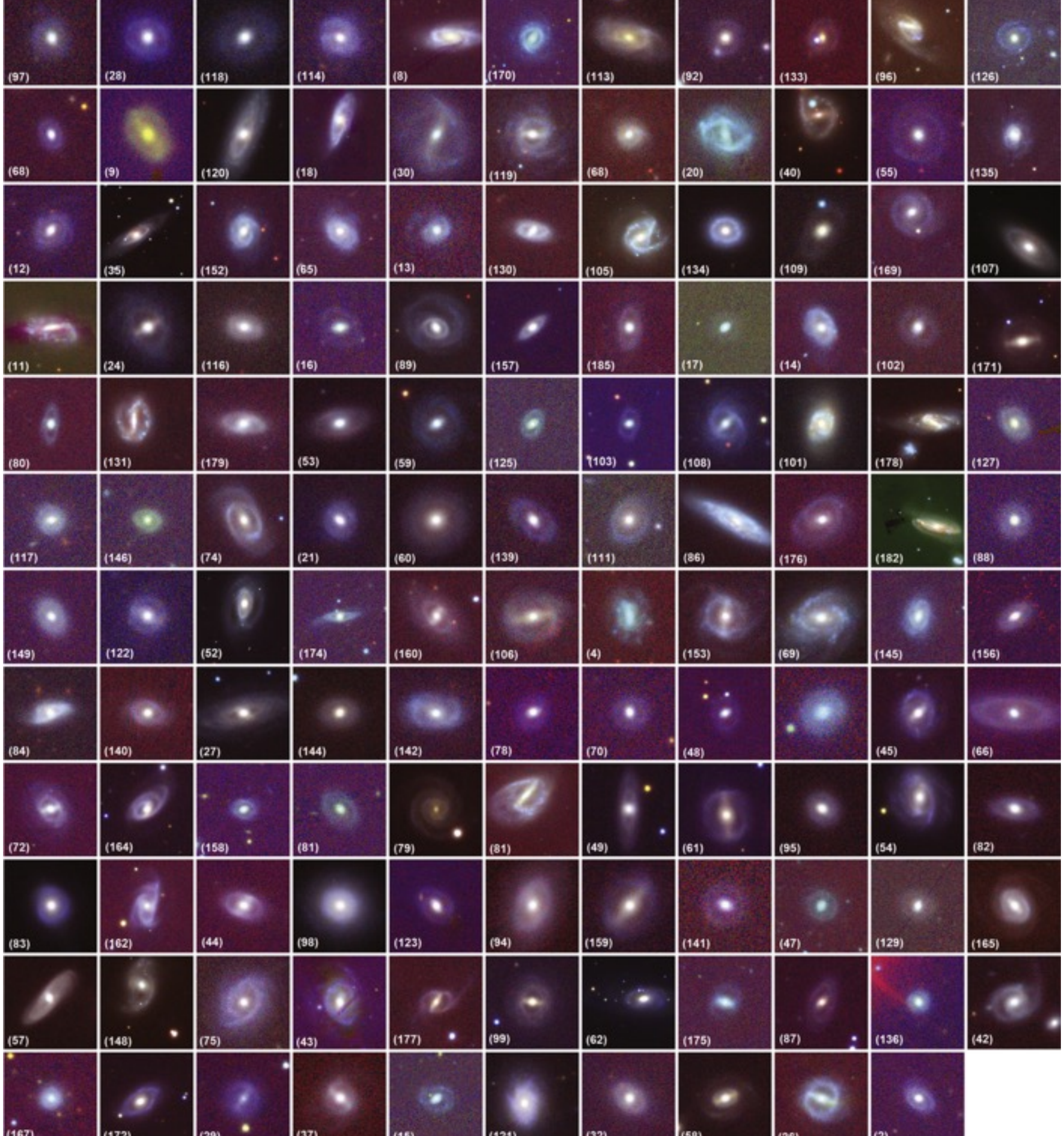
Planck 2015



$$\Sigma_0 = \mu \left(1 - \frac{1}{\gamma}\right)$$



Baker et al 2014
ArXiv:1412:3455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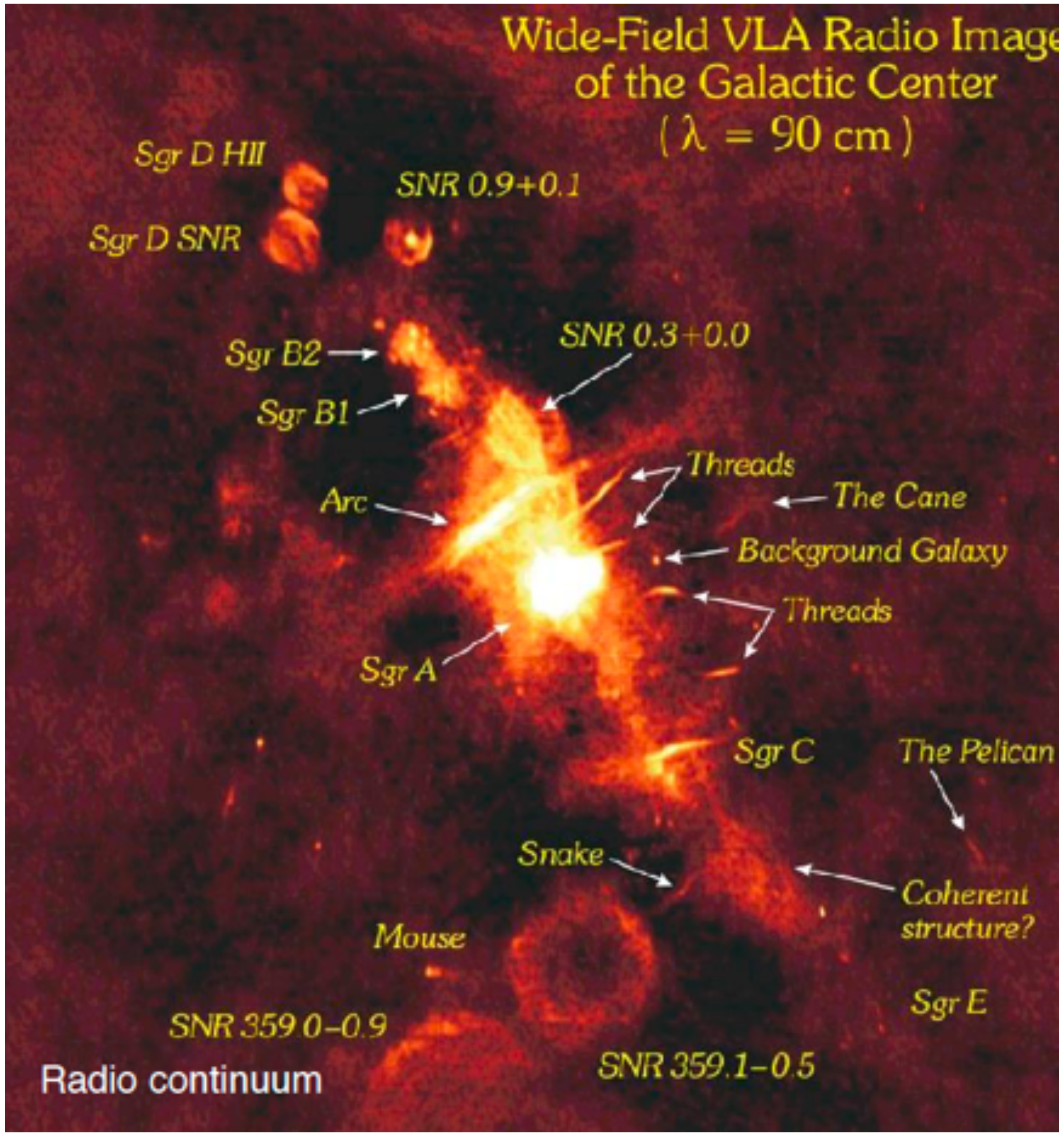
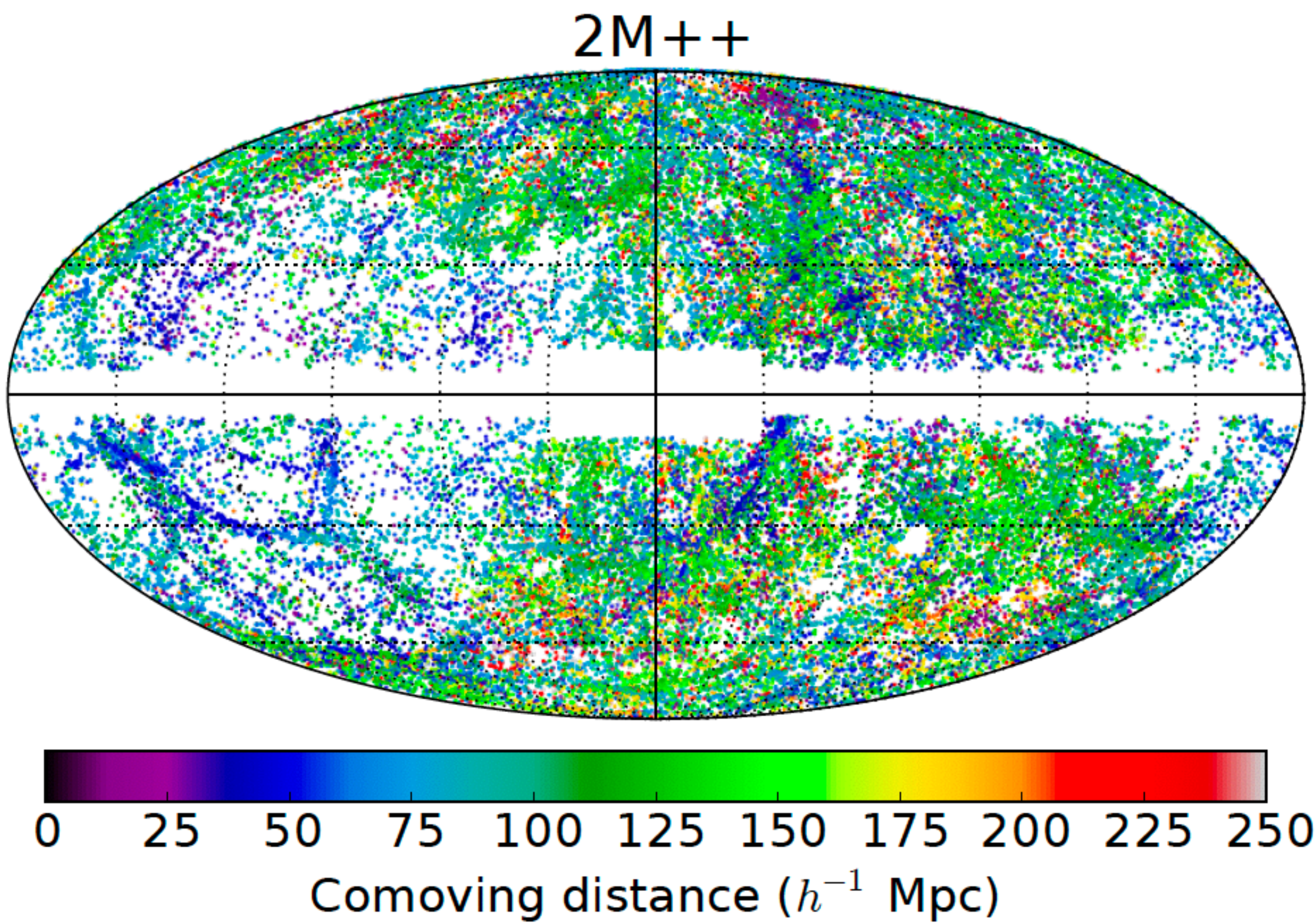
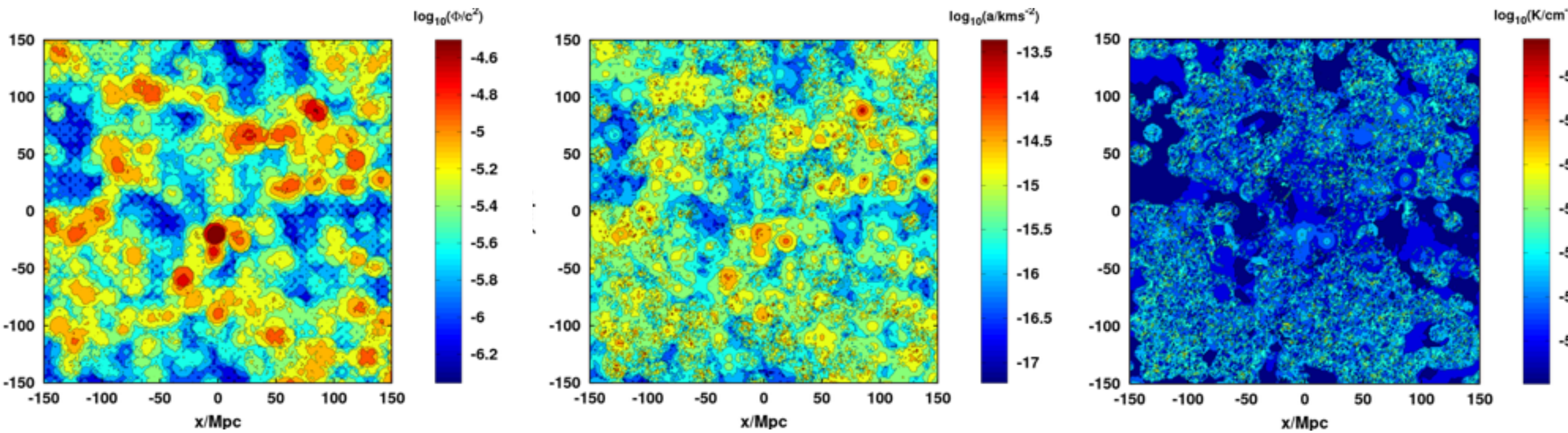


Wide-Field VLA Radio Image
of the Galactic Center
(λ = 90 cm)
Sgr D HII
SNR 0.9+0.1
Sgr D SNR
SNR 0.3+0.0
Sgr B2
Sgr B1
Threads
Arc
The Cane
Background Galaxy
Threads
Sgr A
Sgr C
The Pelican
Snake
Coherent
structure?
Mouse
Sgr E
SNR 359.0−0.9
SNR 359.1−0.5
Radio continuum


2M++
0
25
50
75
100
125
150
175
200
225
250
Comoving distance (h^{-1} Mpc)

Construct gravitational maps of the Universe



Desmond, Ferreira, Lavaux, Jasche 2017

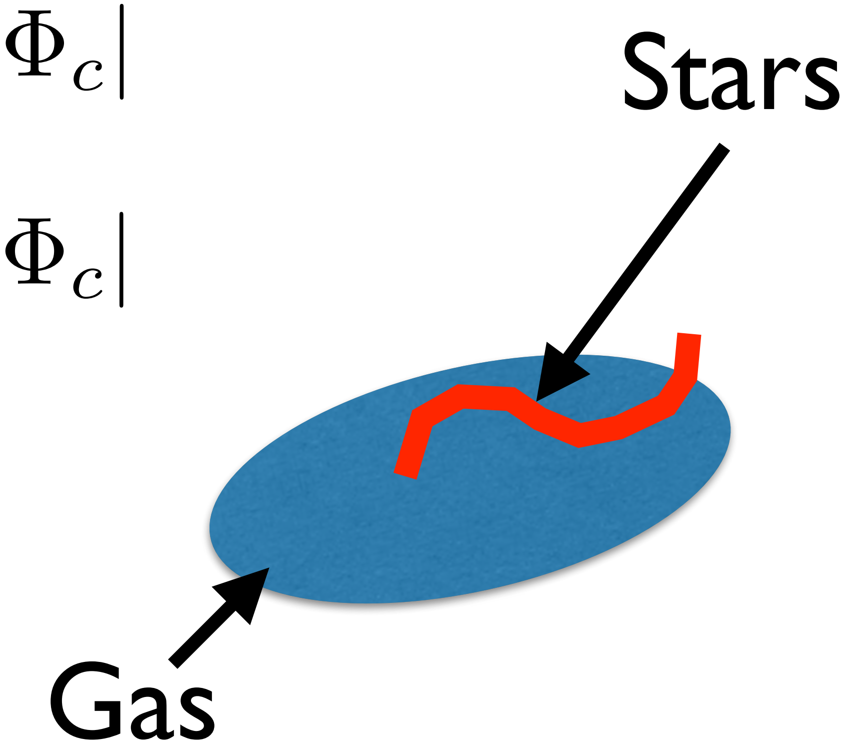
Galactic Offsets

$$a_{\text{unscreened}} = a_{\text{ext}} + \frac{\Delta G}{G} a_5$$ gas, dark matter

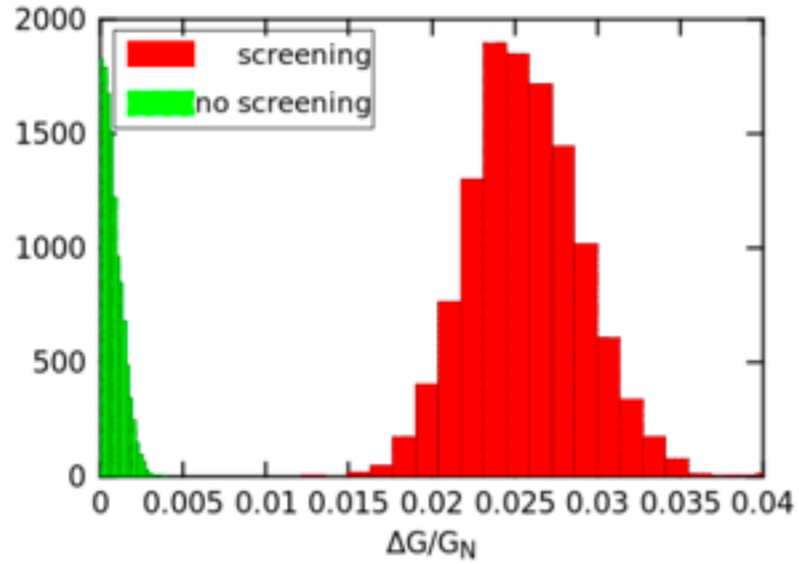
$$a_{\text{screened}} = a_{\text{ext}} + G\frac{M(r_*)}{r_*^2}$$ stars

$$\frac{M(r_*)}{r_*^2} = a_5 \frac{\Delta G}{G^2} \quad \text{if } |\Phi| < |\Phi_c|$$

$$r_* = 0 \qquad \text{if } |\Phi| > |\Phi_c|$$

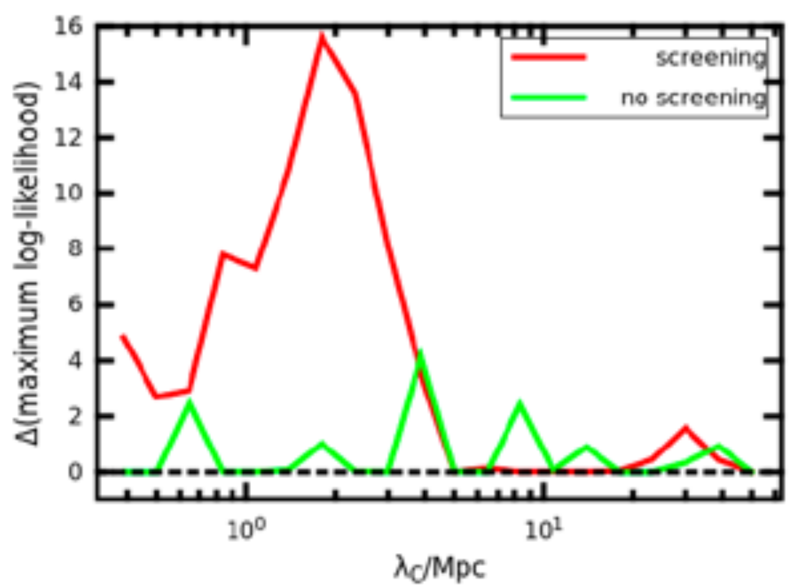


Galactic Offsets



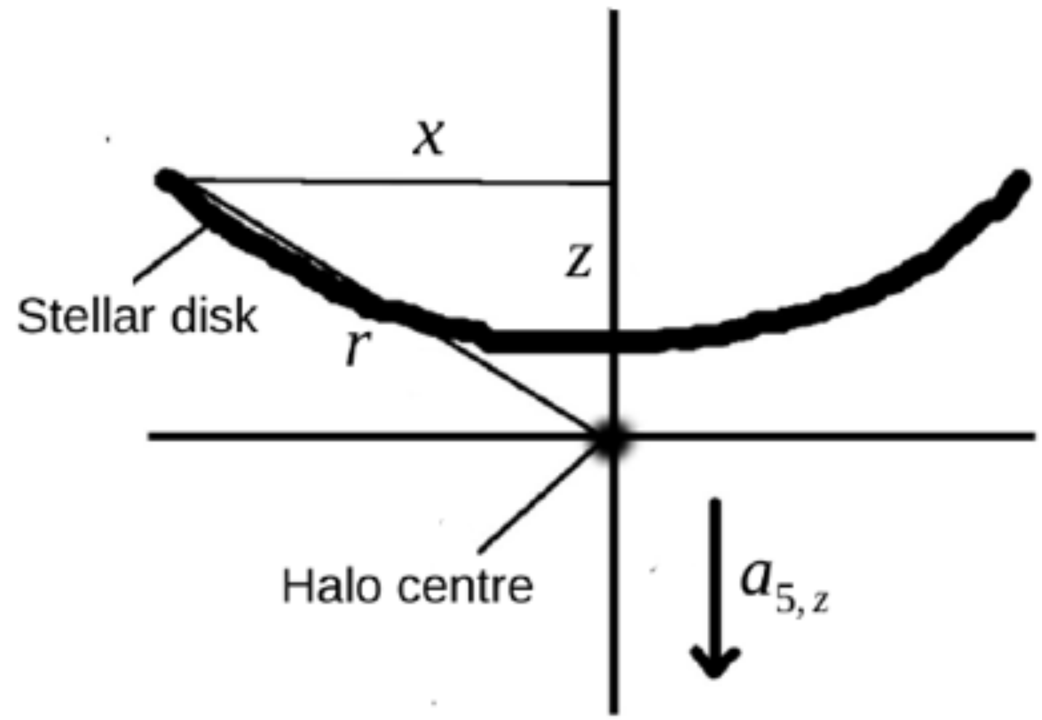
Displacement between SDSS and ALFALFA galaxies

at $\lambda_C = \frac{1}{m} = 1.8\mathrm{Mpc}$



Desmond, Ferreira, Lavaux, Jasche 2018

Galactic warps



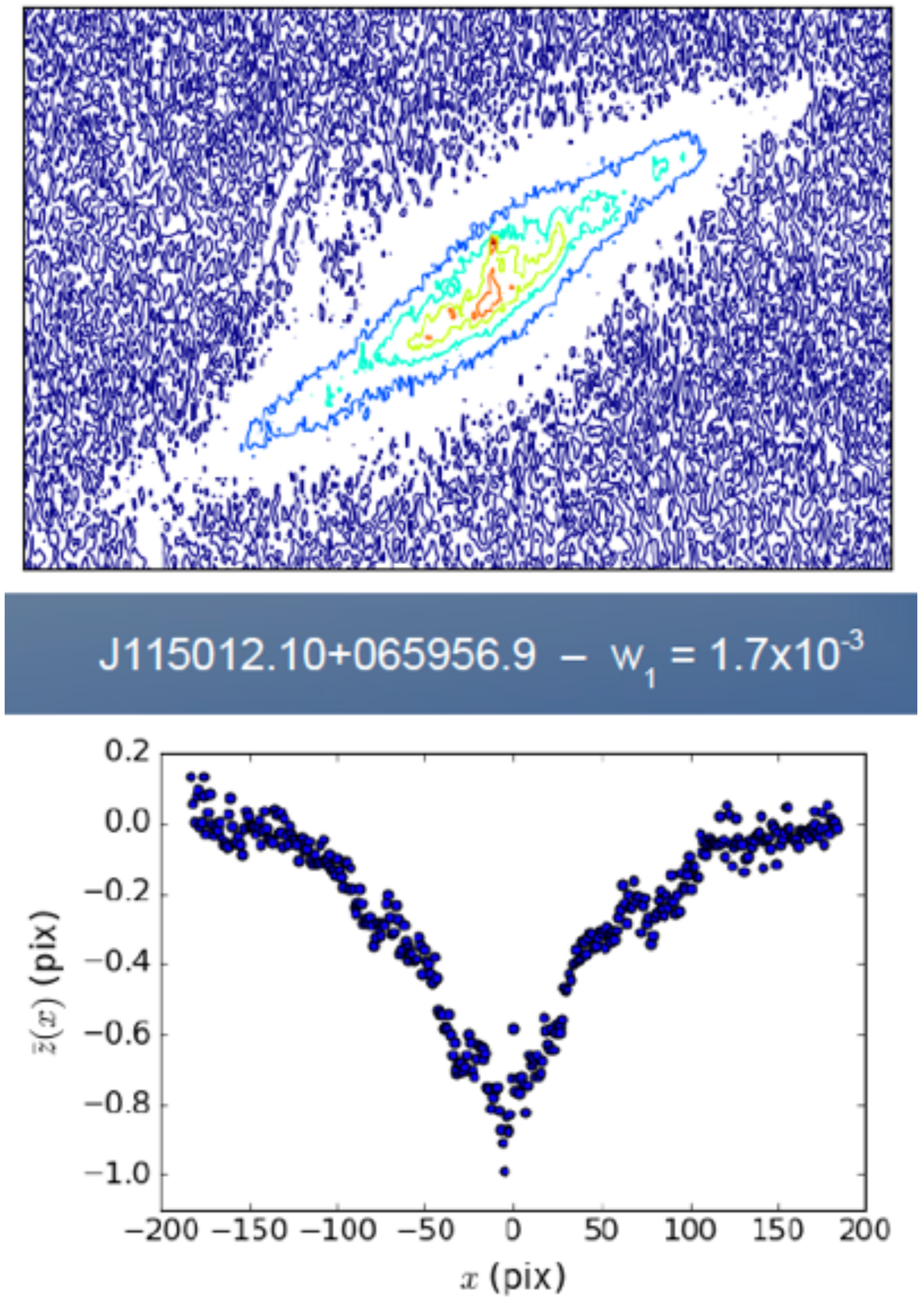
$$z(x) = -a_{5,z}\,\frac{\Delta G}{G_N^2}\,\frac{|x|^3}{M_{\rm halo}(<x)}.$$

$$w_1 \equiv \frac{1}{L_x^3}\int_{-L_x}^{L_x} |x|\, z(x)\, dx$$

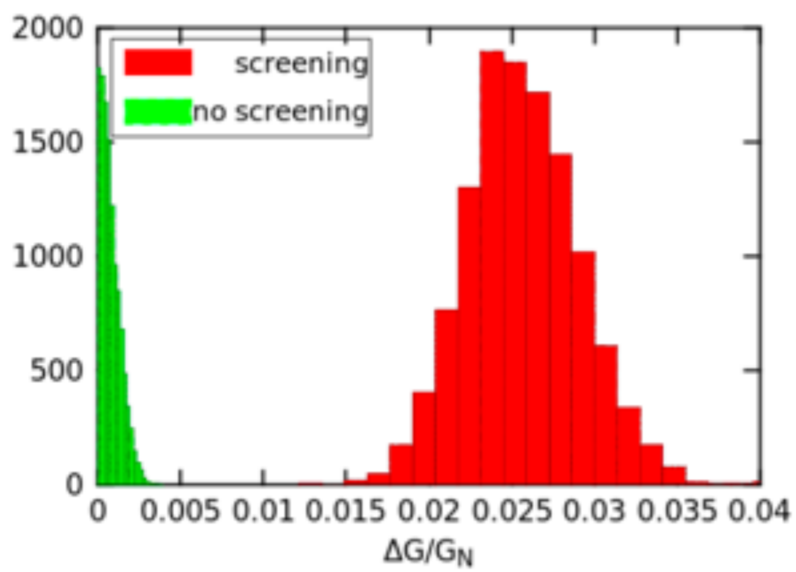
Galactic warps

Subsample from
Nasa Sloan Atlas
~ 4000

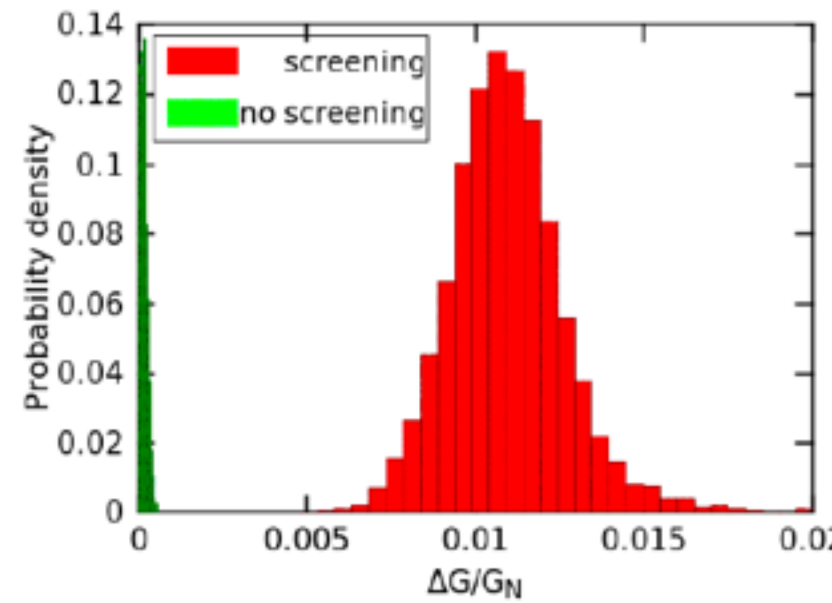
$M > 10^9 M_\odot$



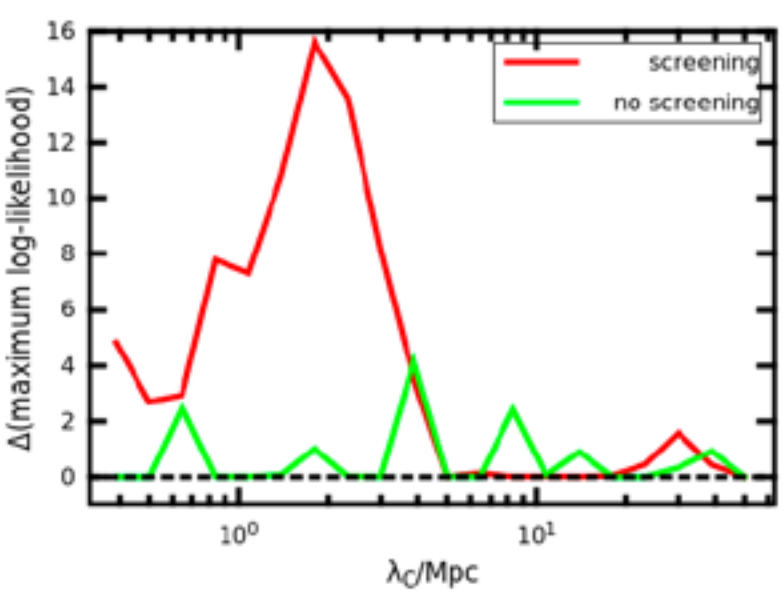
offsets + warps

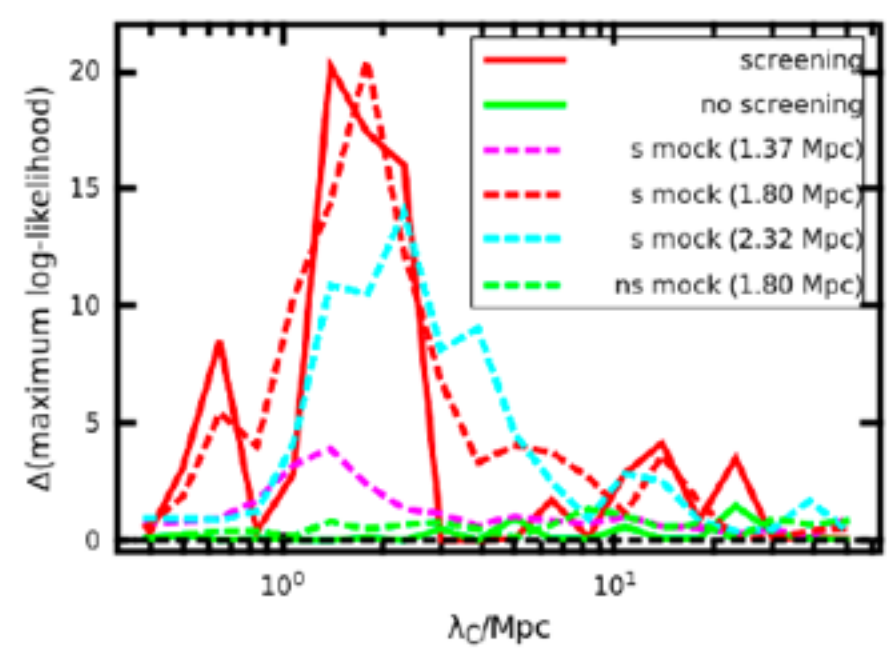


$\lambda_C = 1.8$ Mpc

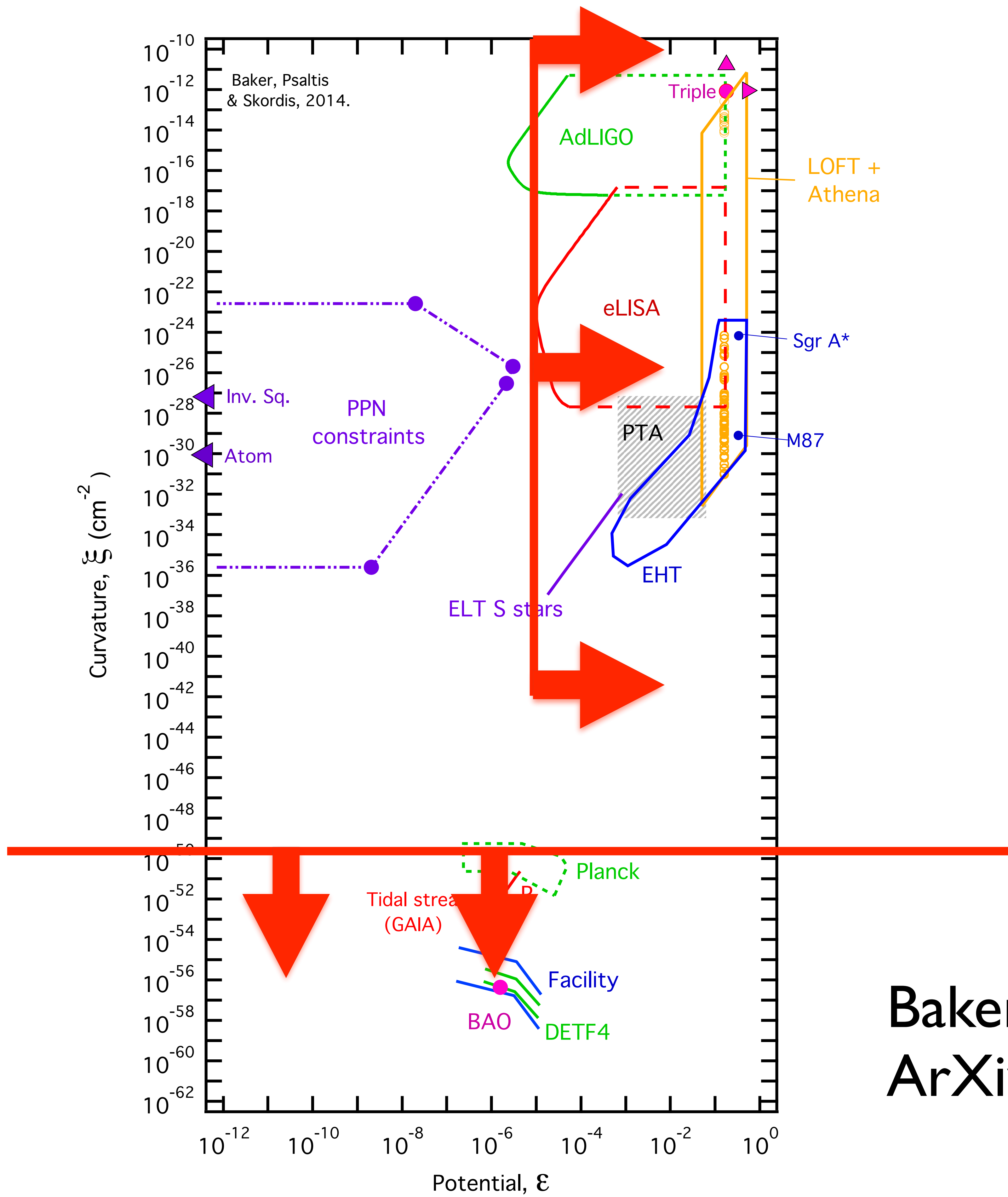


$\lambda_C = 1.8$ Mpc





Desmond, Ferreira, Lavaux, Jasche 2018



Baker et al 2014
ArXiv:1412:3455

Gravitational Waves

Extra fields can function as a medium

$$g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta}$$

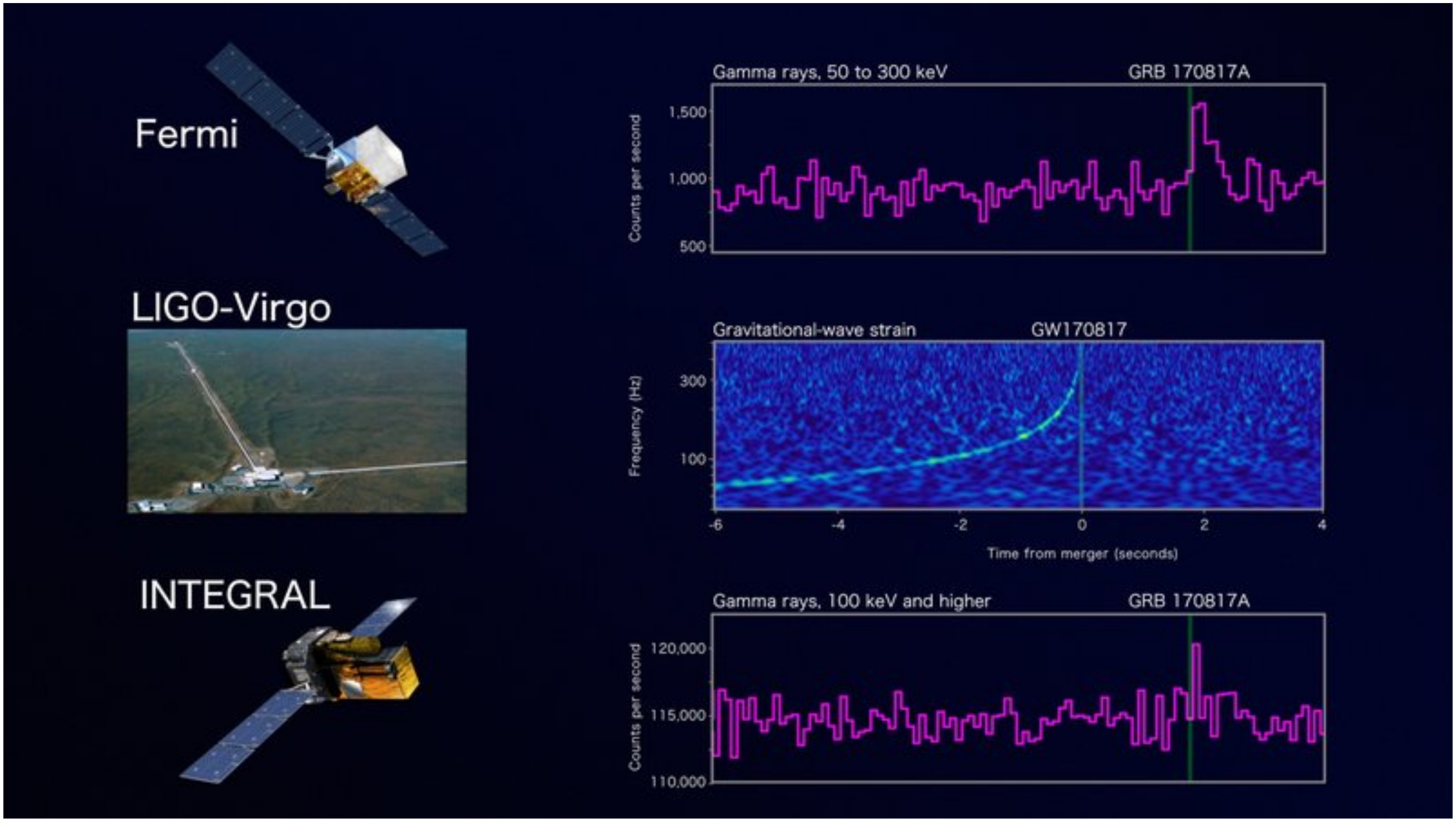
Minkowski

$$S_h = \frac{1}{2} \int d^3x dt M_*^2 [\dot{h}_{\times,+}^2 - c_T^2 (\nabla h_{\times,+})^2]$$

Speed of gravitational waves: $c_T^2 = 1 + \alpha_T$

In General Relativity $\alpha_T = 0$, $M_* = M_{\mathrm{Pl}}$

Gravitational Waves



$\alpha_T \simeq 2\Delta t / d_s$

$d_s \simeq 40 \text{ Mpc}$
$\Delta t \simeq 1.7 \text{ s}$

$|\alpha_T| \lesssim 1 \times 10^{-15}$

Box 33.1 A BLACK HOLE HAS NO "HAIR"

The following theorems come close to proving that *the external gravitational and electromagnetic fields of a stationary black hole* (a black hole that has settled down into its "final" state) *are determined uniquely by the hole's mass M, charge Q, and intrinsic angular momentum S*—i.e., the black hole can have no "hair" (no other independent characteristics). For a detailed review, see Carter (1973).

I. Stephen Hawking (1971b, 1972a): A stationary black hole must have a horizon with spherical topology; and it must either be static (zero angular momentum), or axially symmetric, or both.

II. Werner Israel (1967a, 1968): Any *static* black hole with event horizon of spherical topology has external fields determined uniquely by its mass M and charge Q; moreover, those external fields are the Schwarzschild solution if $Q = 0$, and the Reissner-Nordstrøm solution (exercises 31.8 and 32.1) if $Q \neq 0$ (both special cases of Kerr-Newman; see §33.2).

III. Brandon Carter (1970): "All uncharged, stationary, axially symmetric black holes with event horizons of spherical topology fall into disjoint families not deformable into each other. The black holes in each family have external gravitational fields determined uniquely by two parameters: the mass M and the angular momentum S." (Note: the "Kerr solutions"—i.e., "Kerr-Newman" with $Q = 0$—form one such family; it is very likely that there are no others, but this has not been proved as of December 1972. It is also likely that Carter's theorem can be extended to the case with charge; but this has also not yet been done.)

IV. Conclusions made by combining all three theorems:
- (a) All stationary black holes are axially symmetric.
- (b) All static (nonrotating) black holes are characterized uniquely by M and Q, and have the Reissner-Nordstrøm form.
- (c) All uncharged, rotating black holes fall into distinct and disjoint families, with each black hole in a given family characterized uniquely by M and S. The Kerr solutions form one such family. There may well be no other family.

V. Remarks and Caveats:
- (a) The above statements of the theorems are all somewhat heuristic. Each theorem makes several highly technical assumptions, not stated here, about the global properties of spacetime. These assumptions seem physically reasonable and innocuous, but they might not be.
- (b) Progress in black-hole physics is so rapid that, by the time this book is published, there may well exist theorems more powerful than the above, which really prove that "a black hole has no hair."
- (c) For insight into the techniques of "global geometry" used in proving the above theorems and others like them, see Chapter 34; for greater detail see the forthcoming book by Hawking and Ellis (1973).
- (d) For analyses which show that a black hole cannot exert any weak-interaction forces caused by the leptons which have gone down it, see Hartle (1971, 1972) and Teitelboim (1972b,c). For similar analyses which show absence of strong-interaction forces from baryons that have gone down the hole, see Bekenstein (1972a,b) and Teitelboim (1972a).

MTW 1973

Black Hole Hair

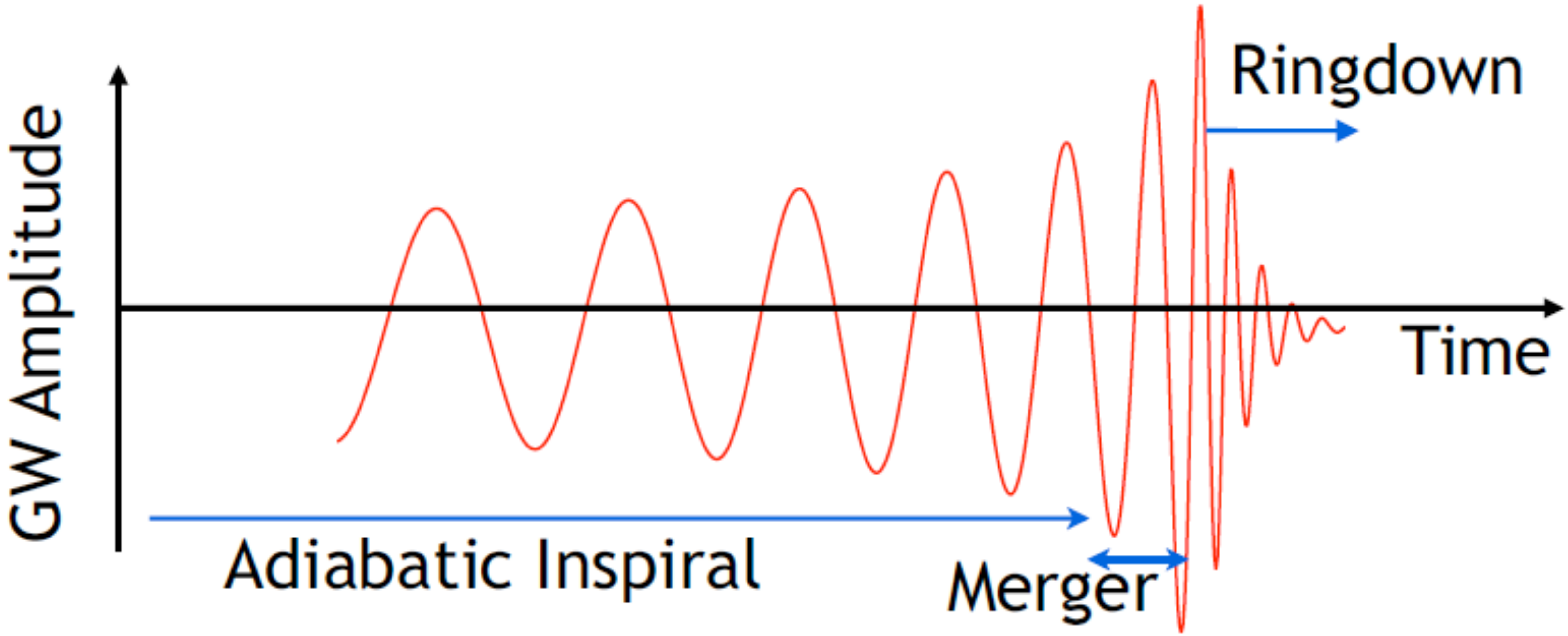
GW170817 takes an axe to black hole hair
for cosmologically relevant fields.

- Scalar-Tensor -“circumstantial” evidence BH are bald
- Vector-Tensor - BH hair allowed
- Tensor-Tensor - BH hair allowed

Tattersall, Ferreira & Lagos, 2018

Black Hole Hair

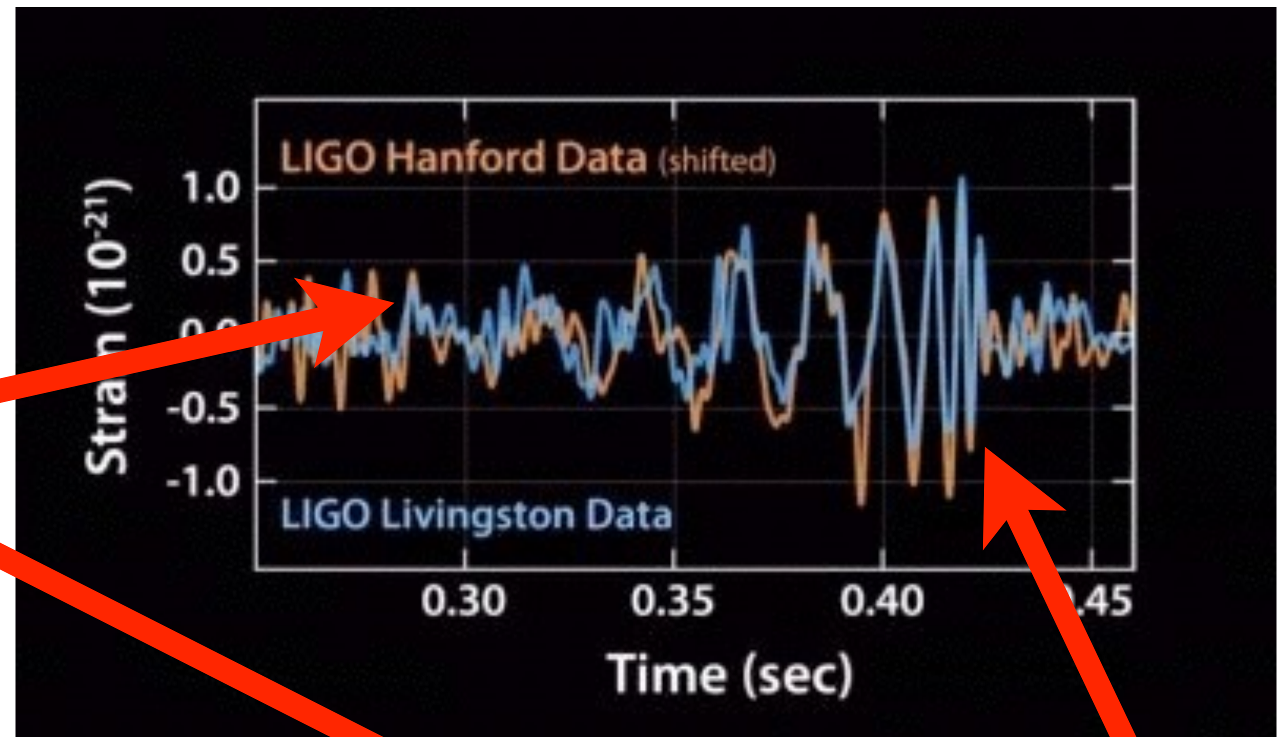
All is not lost … look at ring-down

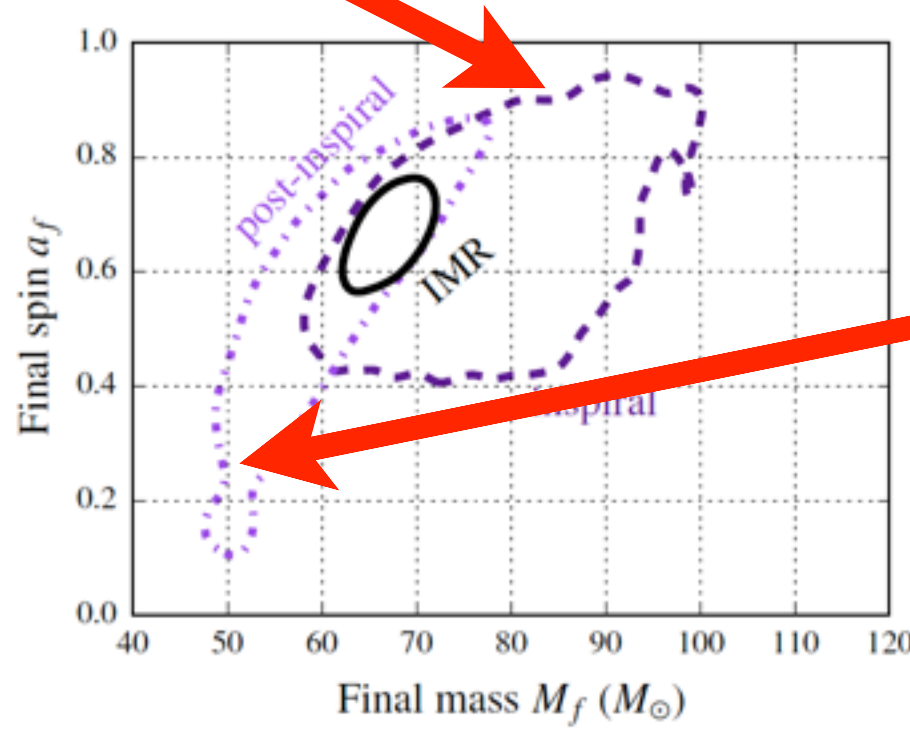


Quasi-normal-mode spectra is hugely informative

Black Hole Hair

Inspiral





"post-inspiral"

Modified Zerilli Equation

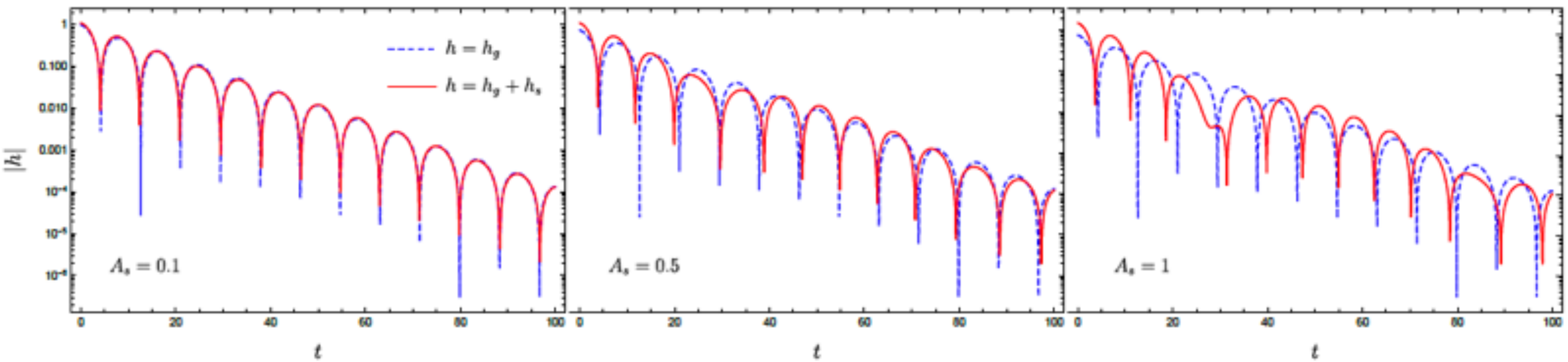
even parity gravitational wave

$$\frac{d^2\Psi}{dr_*^2} + \left[\omega^2 - V_Z(r)\right]\Psi = \frac{G_{4\phi}}{G_4} S_\varphi\left(\varphi, \varphi'\right)$$

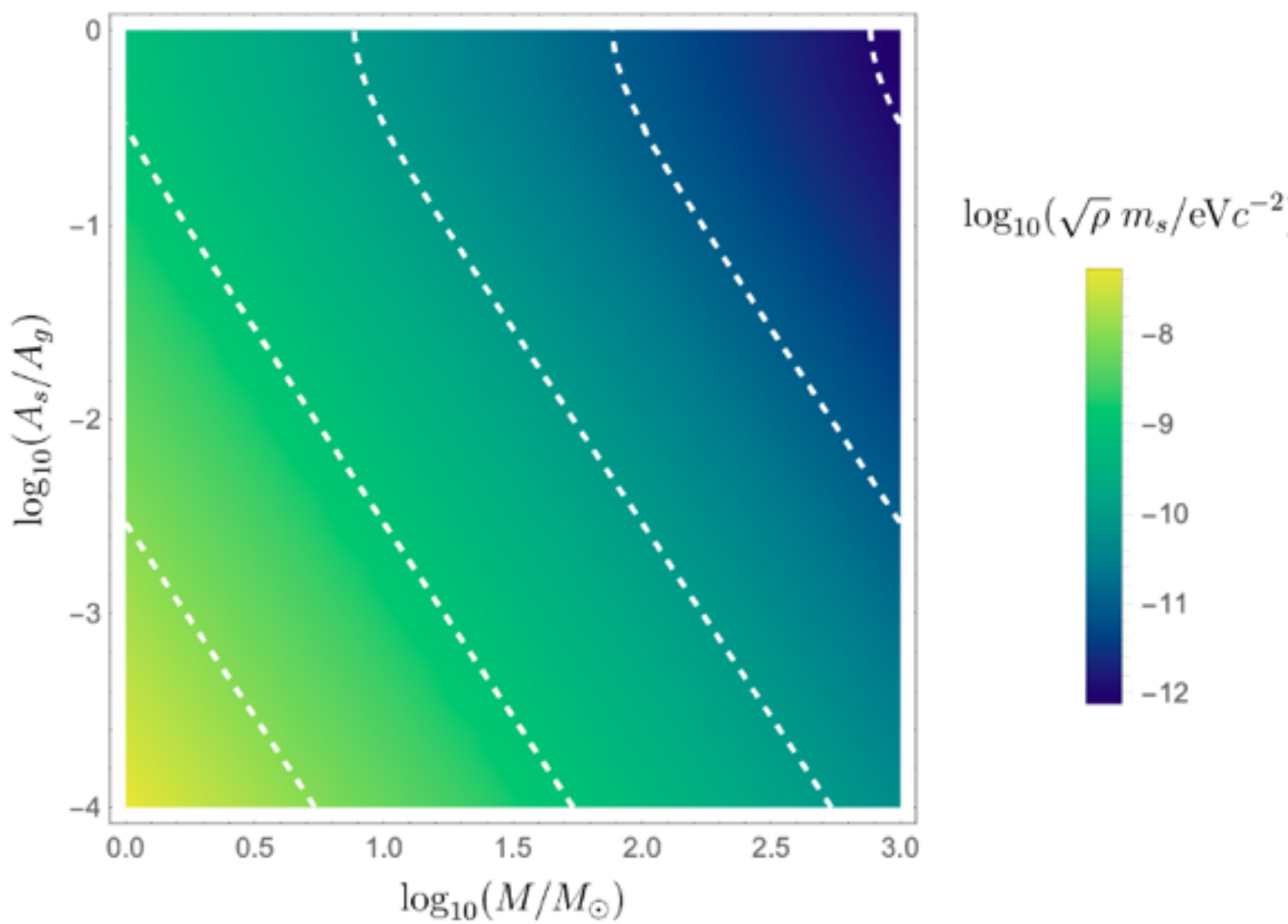
$$\frac{d^2\varphi}{dr_*^2} + \left[\omega^2 - V_S(r, \mu^2)\right]\varphi = 0,$$

non-minimal coupling

scalar field perturbation



$h = h_g$
$h = h_g + h_s$
$|h|$
$A_s = 0.1$
$A_s = 0.5$
$A_s = 1$
t



$\log_{10}(A_s/A_g)$
$\log_{10}(M/M_\odot)$
$\log_{10}(\sqrt{\rho}\, m_s/\mathrm{eV}c^{-2})$

Summary

- Large scale structure: next generation surveys!
- Galaxies: messy, difficult but lots of them!
- Black hole ringdown: clean probe, within reach!