The Cosmological Standard Model

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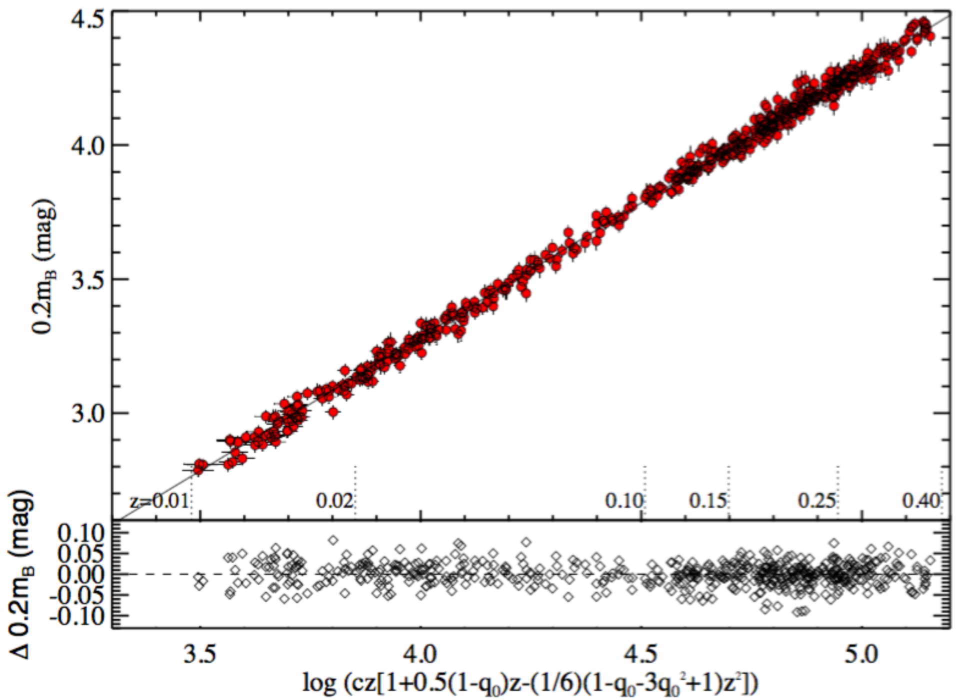
What any successful cosmological model should do

- Provide a satisfactory prediction of the physics of the early Universe
- Provide initial conditions for the origin of the cosmological perturbations, explain their evolution and the statistical properties of the cosmic structure we observe in the Universe
- Correctly describe the dynamics of the Universe
- Determine the cosmological parameters and provide a *fundamental understanding* of such quantities

Kinematical tests

- Probe of the content of the Universe and its geometry

- Measurements of the expansion rate, the luminosity and angular diameter distance

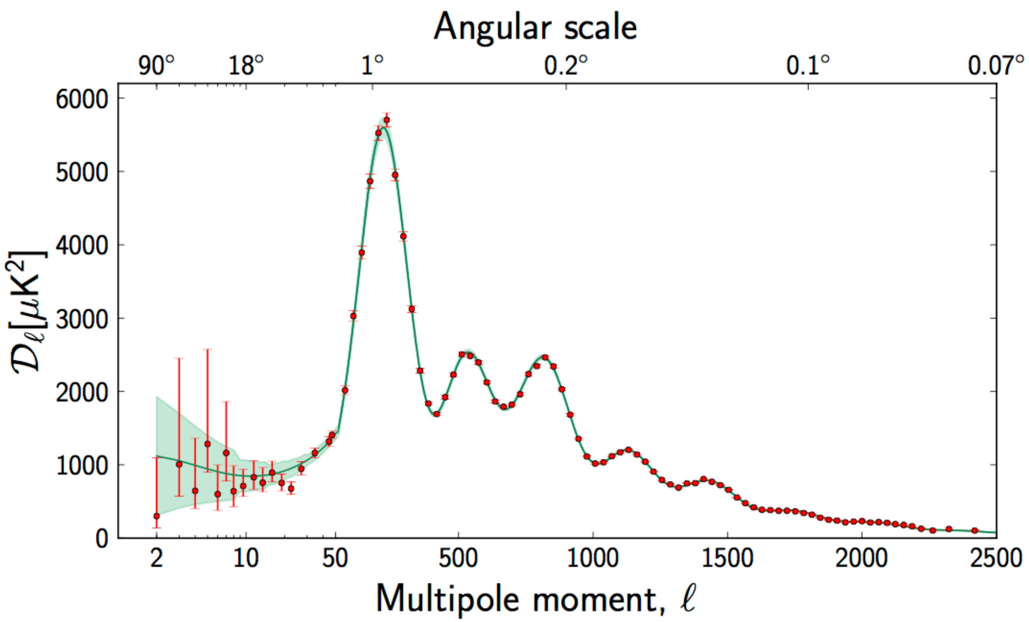


Riess et al., 2016

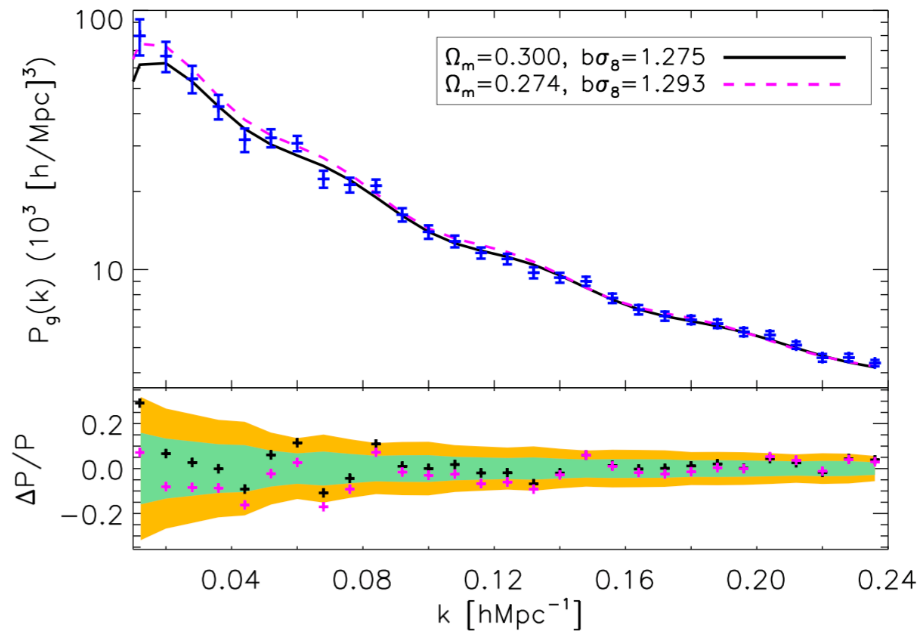
Structure formation tests

- Probe of the content of the Universe and the nature of the perturbations

- Measurements of the CMB anisotropies and the LSS

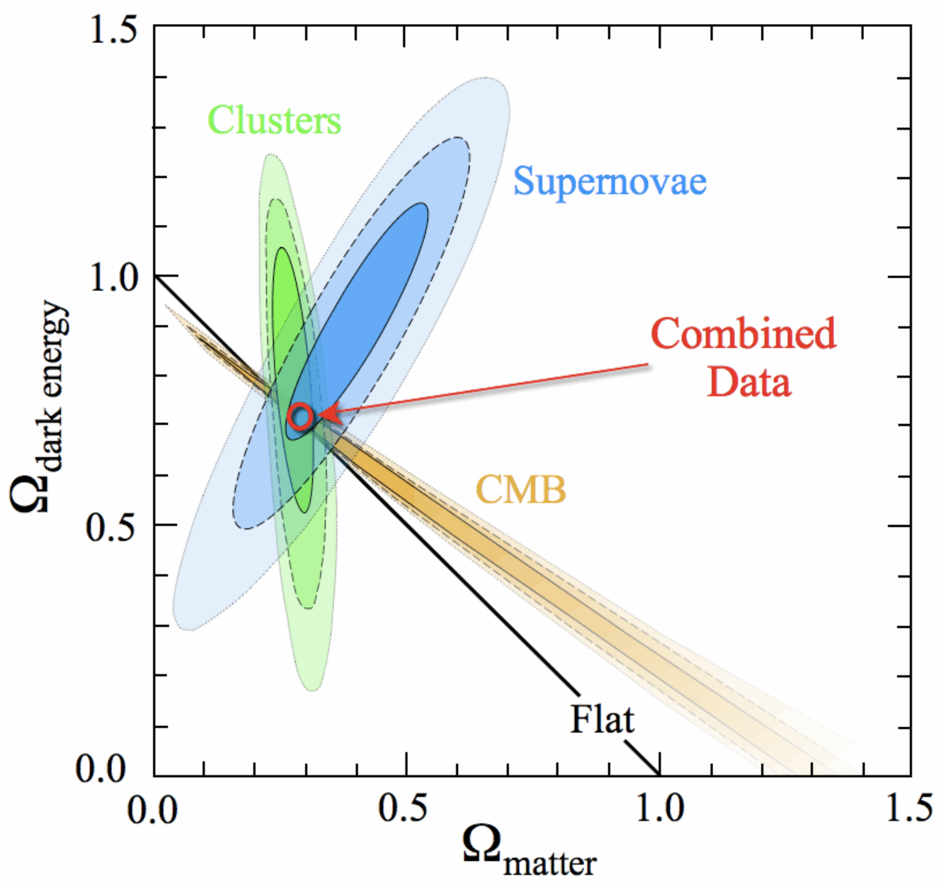


Planck, 2015



Boss, 2016

The ΛCDM concordance model

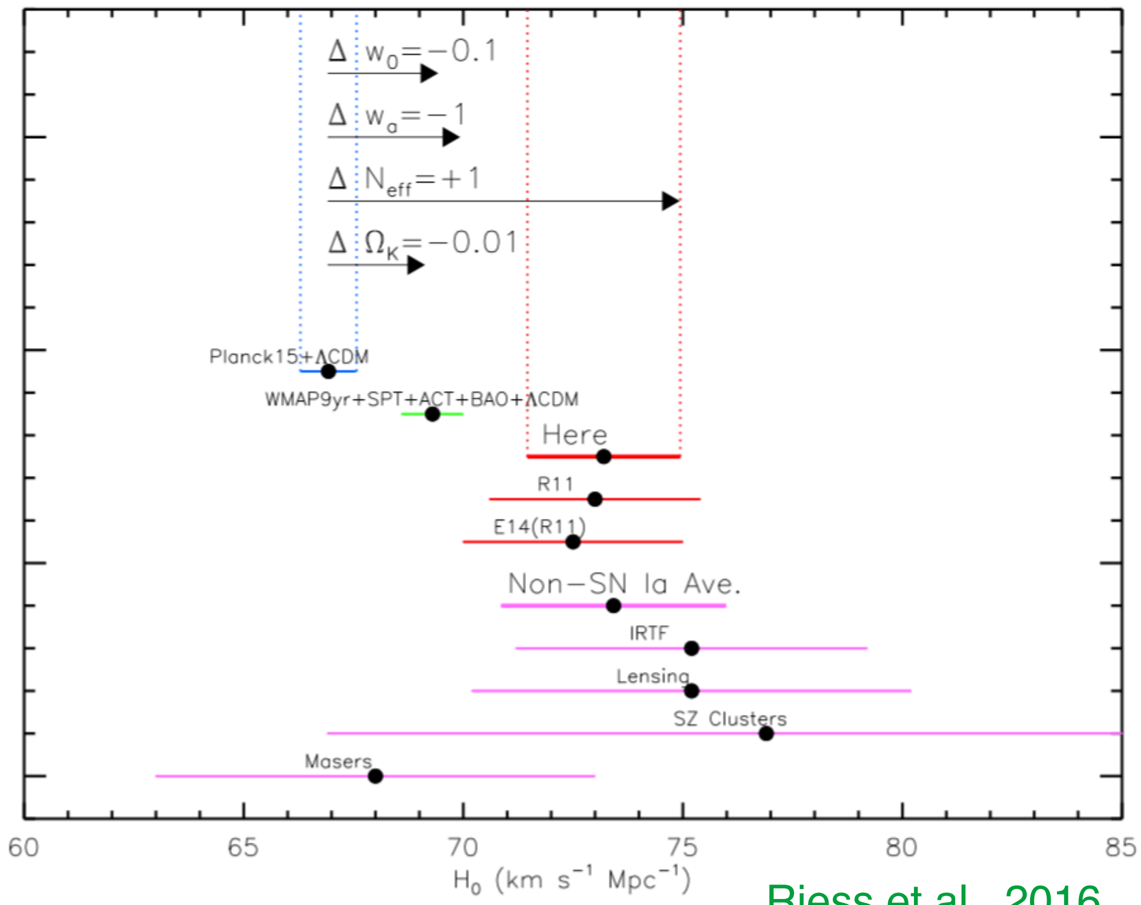


Six parameters (flat universe + CC):

$$\{\Omega_{\mathrm{DM}}, \Omega_{\mathrm{b}}, n_\zeta, A_\zeta, H_0, \tau\}$$

Some recent tension within the concordance model..

- Probably not due to sample variance
- If not systematics, can be explained by fluids with $P/\rho < -1$ or interacting DE, in any case new physics (= *beyond the concordance model*)



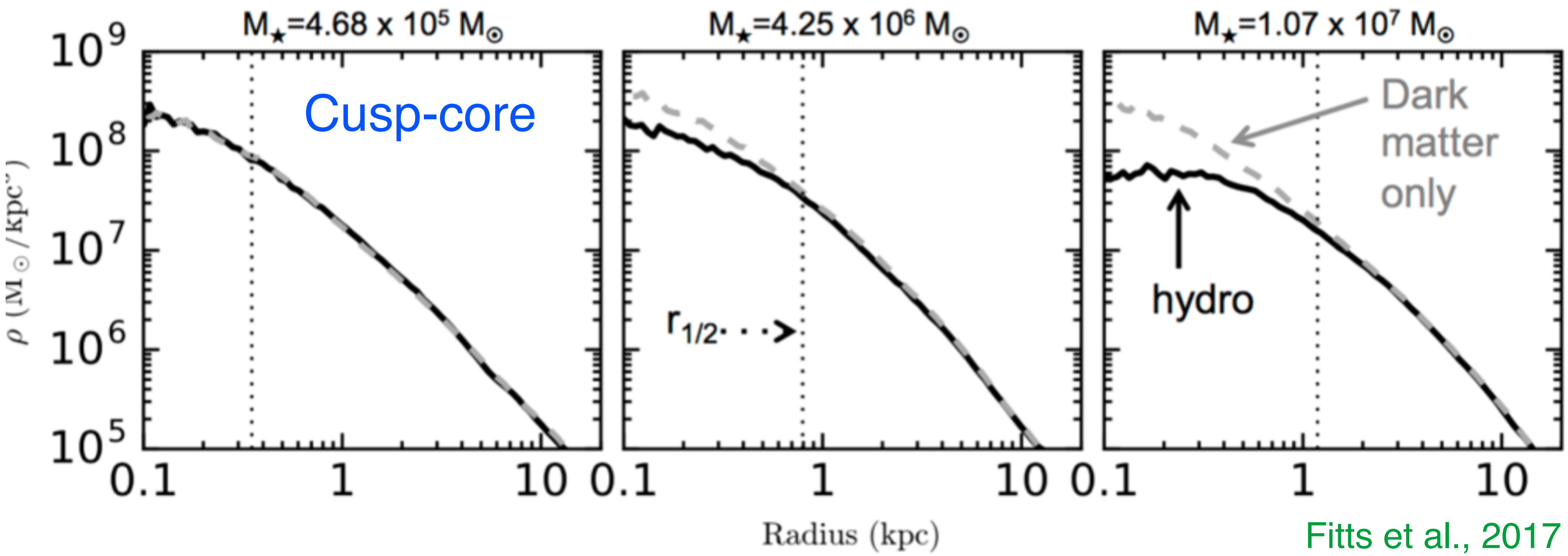
Riess et al., 2016

$$H_0 = 73.24 \pm 1.74 \text{ Km sec}^{-1} \text{ Mpc}^{-1}$$

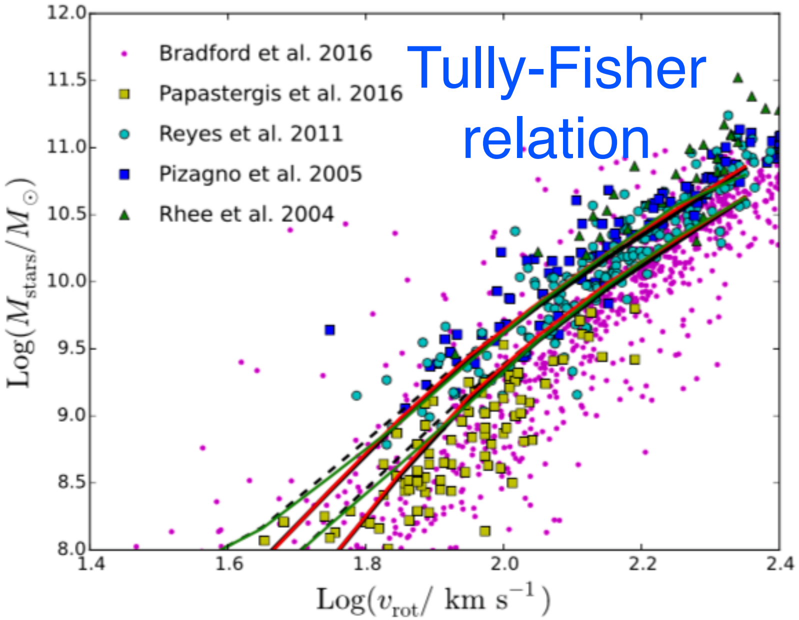
vs

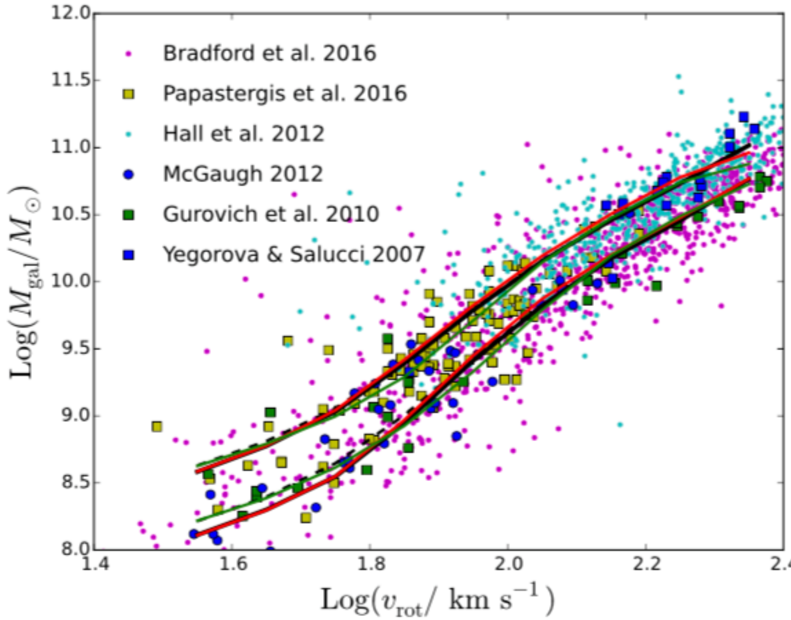
$$H_0 = 66.93 \pm 0.62 \text{ Km sec}^{-1} \text{ Mpc}^{-1}$$

..but also some recent progress



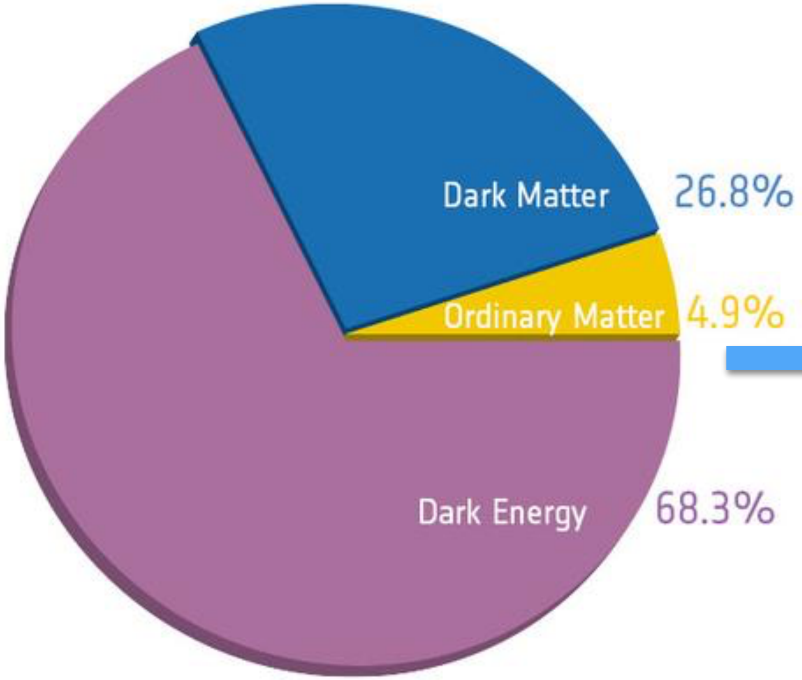
Fitts et al., 2017





Cattaneo et al., 2017

The fundamental understanding problem



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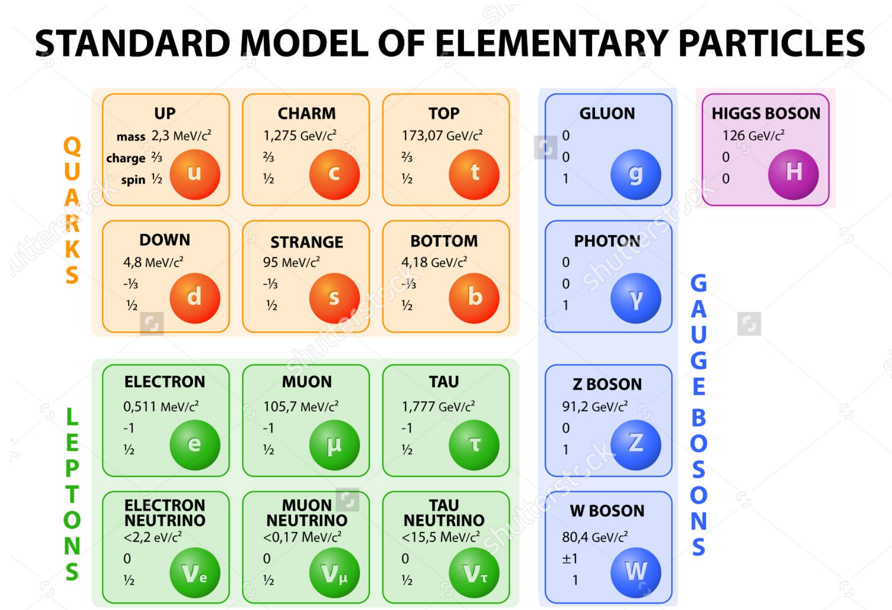
Initial conditions (inflation?)
Dark Matter
Dark Energy



?

Baryon asymmetry
Dark matter
Neutrino masses
Flavour structure
Hierarchy problem
Naturalness

The *fundamental understanding problem* makes modern cosmology a fantastic playground for high-energy physicists

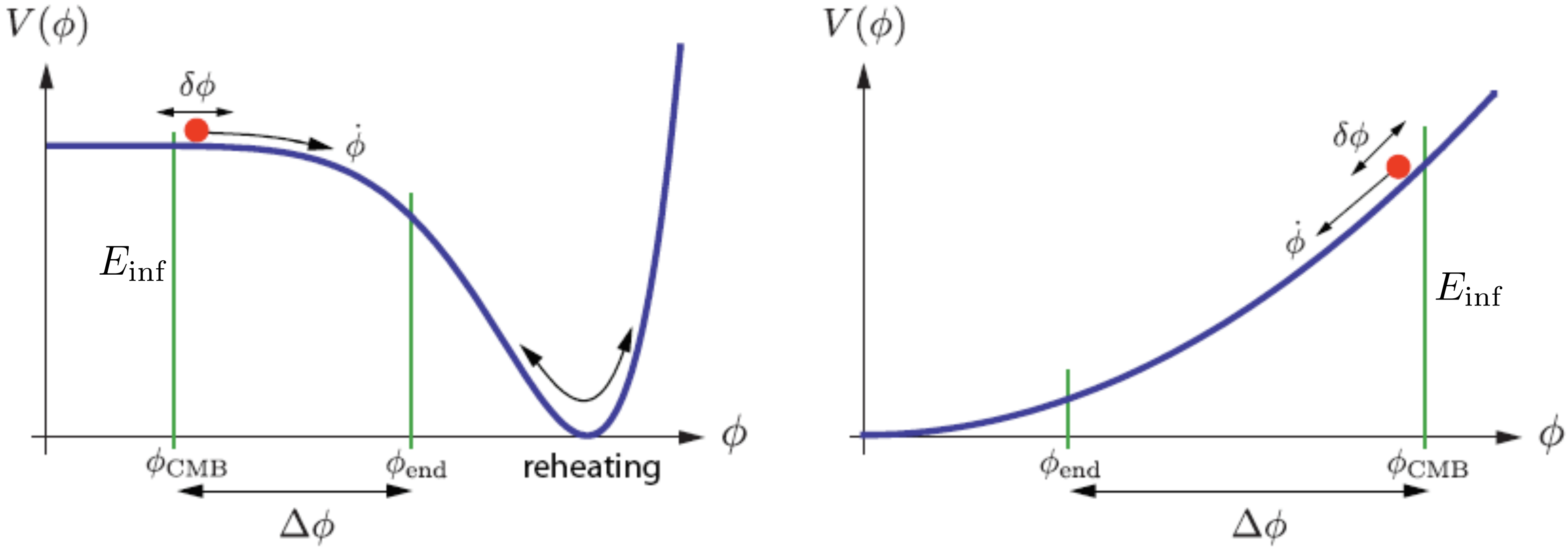
Plan of the talk

Discuss (with some bias) two pillars of the cosmological standard model

- Inflation (initial conditions)
- Dark Matter

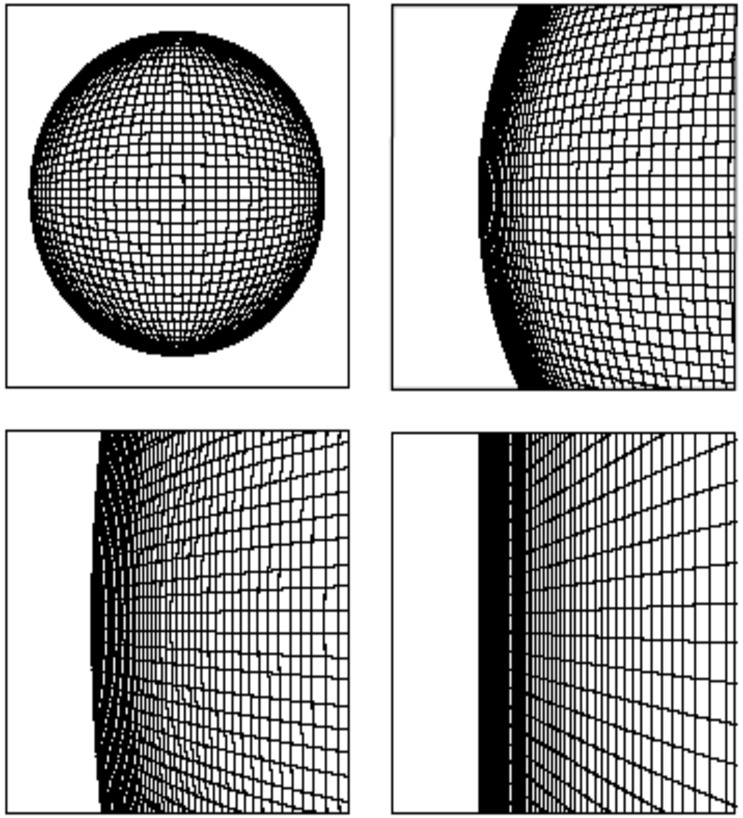
and what we could learn more from them in the next future about HEP

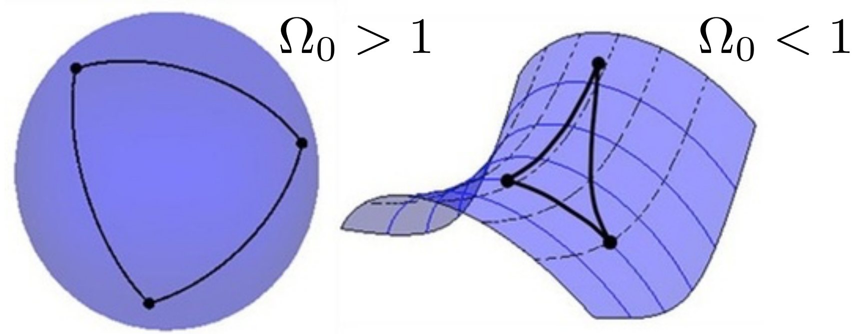
First pillar: Inflation



$$\left(\frac{\dot a}{a}\right)^2 = H^2 = \frac{\rho}{3M_{\rm Pl}^2} = \frac{E_{\rm inf}^4}{3M_{\rm Pl}^2} \Rightarrow a(t) \sim e^{Ht}$$

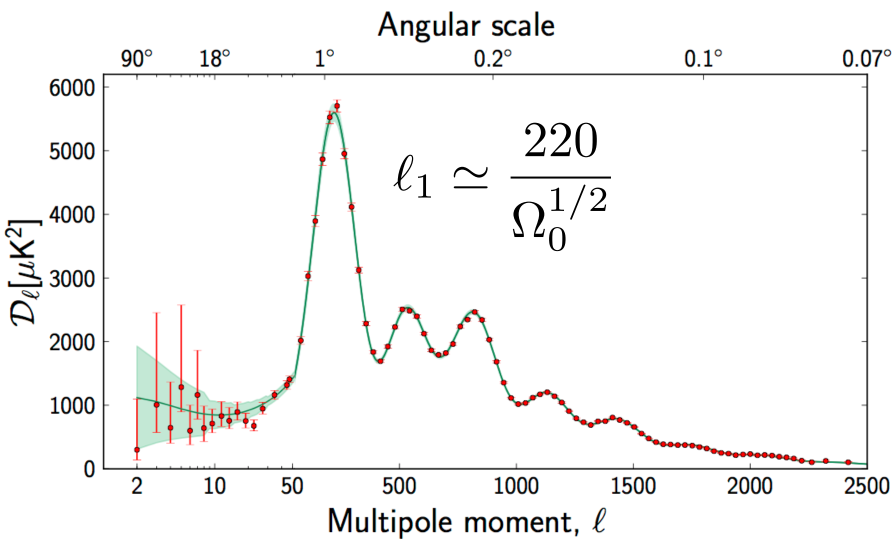
Inflation makes the *local* Universe spatially flat





positive curvature

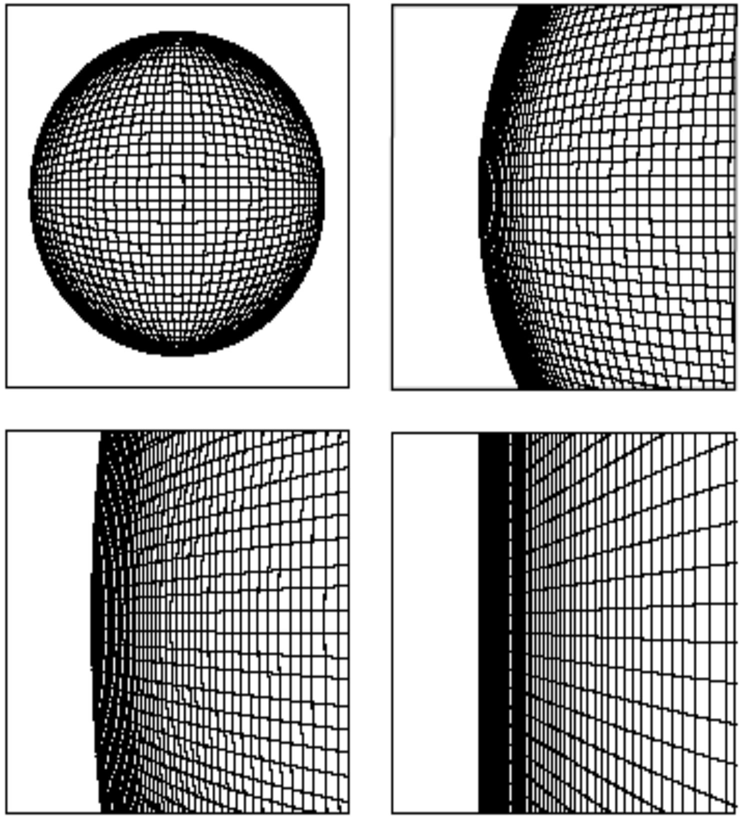
negative curvature

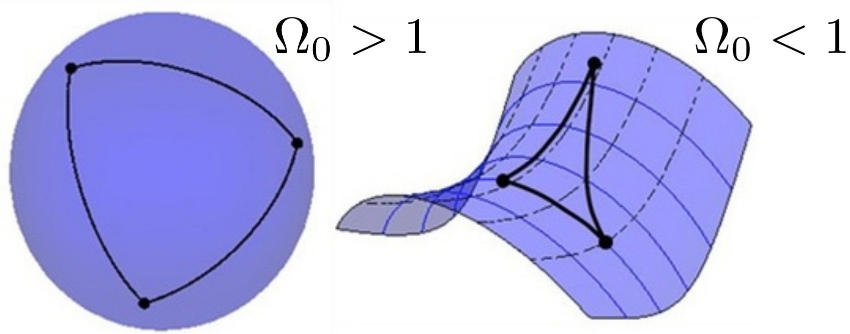


Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040
H_0	67.31 ± 0.96	67.81 ± 0.92	67.90 ± 0.55	67.27 ± 0.66	67.51 ± 0.64	67.74 ± 0.46
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012	0.6935 ± 0.0072	0.6844 ± 0.0091	0.6879 ± 0.0087	0.6911 ± 0.0062
Ω_m	0.315 ± 0.013	0.308 ± 0.012	0.3065 ± 0.0072	0.3156 ± 0.0091	0.3121 ± 0.0087	0.3089 ± 0.0062
$\Omega_m h^2$	0.1426 ± 0.0020	0.1415 ± 0.0019	0.1413 ± 0.0011	0.1427 ± 0.0014	0.1422 ± 0.0013	0.14170 ± 0.00097
$\Omega_m h^3$	0.09597 ± 0.00045	0.09591 ± 0.00045	0.09593 ± 0.00045	0.09601 ± 0.00029	0.09596 ± 0.00030	0.09598 ± 0.00029
σ_8	0.829 ± 0.014	0.8149 ± 0.0093	0.8154 ± 0.0090	0.831 ± 0.013	0.8150 ± 0.0087	0.8159 ± 0.0086
$\sigma_8 \Omega_m^{0.5}$	0.466 ± 0.013	0.4521 ± 0.0088	0.4514 ± 0.0066	0.4668 ± 0.0098	0.4553 ± 0.0068	0.4535 ± 0.0059
$\sigma_8 \Omega_m^{0.25}$	0.621 ± 0.013	0.6069 ± 0.0076	0.6066 ± 0.0070	0.623 ± 0.011	0.6091 ± 0.0067	0.6083 ± 0.0066
z_{re}	$9.9^{+1.8}_{-1.6}$	$8.8^{+1.7}_{-1.4}$	$8.9^{+1.3}_{-1.2}$	$10.0^{+1.7}_{-1.5}$	$8.5^{+1.4}_{-1.2}$	$8.8^{+1.2}_{-1.1}$
$10^9 A_s$	$2.198^{+0.076}_{-0.085}$	2.139 ± 0.063	2.143 ± 0.051	2.207 ± 0.074	2.130 ± 0.053	2.142 ± 0.049
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.874 ± 0.013	1.873 ± 0.011	1.882 ± 0.012	1.878 ± 0.011	1.876 ± 0.011
Age/Gyr	13.813 ± 0.038	13.799 ± 0.038	13.796 ± 0.029	13.813 ± 0.026	13.807 ± 0.026	13.799 ± 0.021
z_*	1090.09 ± 0.42	1089.94 ± 0.42	1089.90 ± 0.30	1090.06 ± 0.30	1090.00 ± 0.29	1089.90 ± 0.23
r_*	144.61 ± 0.49	144.89 ± 0.44	144.93 ± 0.30	144.57 ± 0.32	144.71 ± 0.31	144.81 ± 0.24
$100\theta_*$	1.04105 ± 0.00046	1.04122 ± 0.00045	1.04126 ± 0.00041	1.04096 ± 0.00032	1.04106 ± 0.00031	1.04112 ± 0.00029
z_{drag}	1059.57 ± 0.46	1059.57 ± 0.47	1059.60 ± 0.44	1059.65 ± 0.31	1059.62 ± 0.31	1059.68 ± 0.29
r_{drag}	147.33 ± 0.49	147.60 ± 0.43	147.63 ± 0.32	147.27 ± 0.31	147.41 ± 0.30	147.50 ± 0.24
k_D	0.14050 ± 0.00052	0.14024 ± 0.00047	0.14022 ± 0.00042	0.14059 ± 0.00032	0.14044 ± 0.00032	0.14038 ± 0.00029
z_{eq}	3393 ± 49	3365 ± 44	3361 ± 27	3395 ± 33	3382 ± 32	3371 ± 23
k_{eq}	0.01035 ± 0.00015	0.01027 ± 0.00014	0.010258 ± 0.000083	0.01036 ± 0.00010	0.010322 ± 0.000096	0.010288 ± 0.000071
$100\theta_{s,eq}$	0.4502 ± 0.0047	0.4529 ± 0.0044	0.4533 ± 0.0026	0.4499 ± 0.0032	0.4512 ± 0.0031	0.4523 ± 0.0023
f_{2000}^{143}	29.9 ± 2.9	30.4 ± 2.9	30.3 ± 2.8	29.5 ± 2.7	30.2 ± 2.7	30.0 ± 2.7
$f_{2000}^{143\times217}$	32.4 ± 2.1	32.8 ± 2.1	32.7 ± 2.0	32.2 ± 1.9	32.8 ± 1.9	32.6 ± 1.9
f_{2000}^{217}	106.0 ± 2.0	106.3 ± 2.0	106.2 ± 2.0	105.8 ± 1.9	106.2 ± 1.9	106.1 ± 1.8

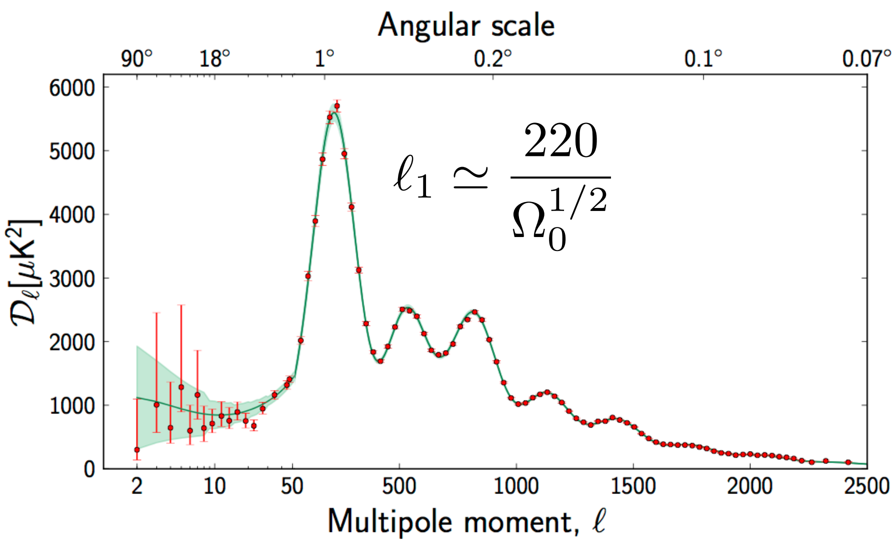
Inflation makes the *local* Universe spatially flat

$$\Omega_0 = \Omega_\Lambda + \Omega_m = 0.685 + 0.315 = 1$$

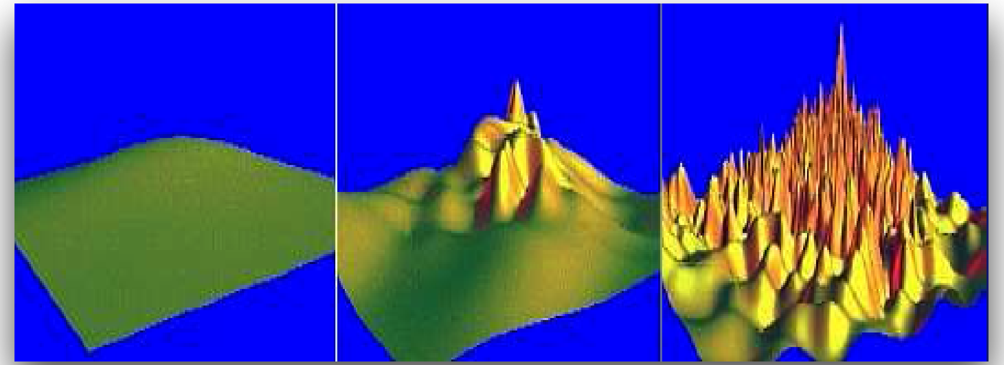




positive curvature negative curvature

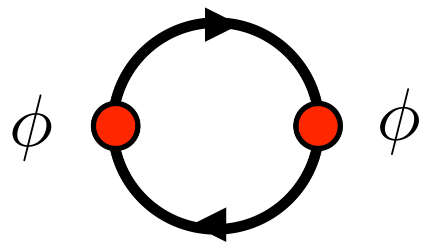


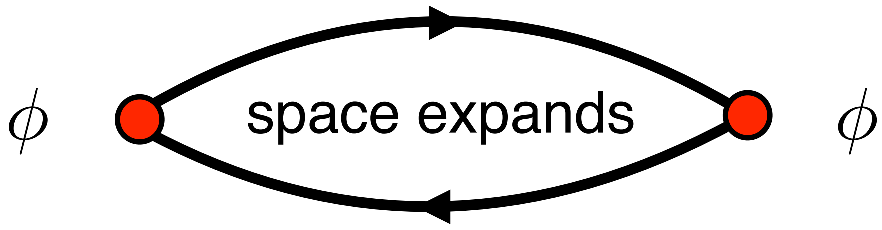
Inflation explains the cosmological structure from quantum fluctuations



Quantum —gravity→ Classical

Particle production in the early Universe





All massless states are excited during inflation

$$S = \int \mathrm{d}^4x \sqrt{-g}\, \frac{1}{2} \left(\partial\phi\right)^2$$

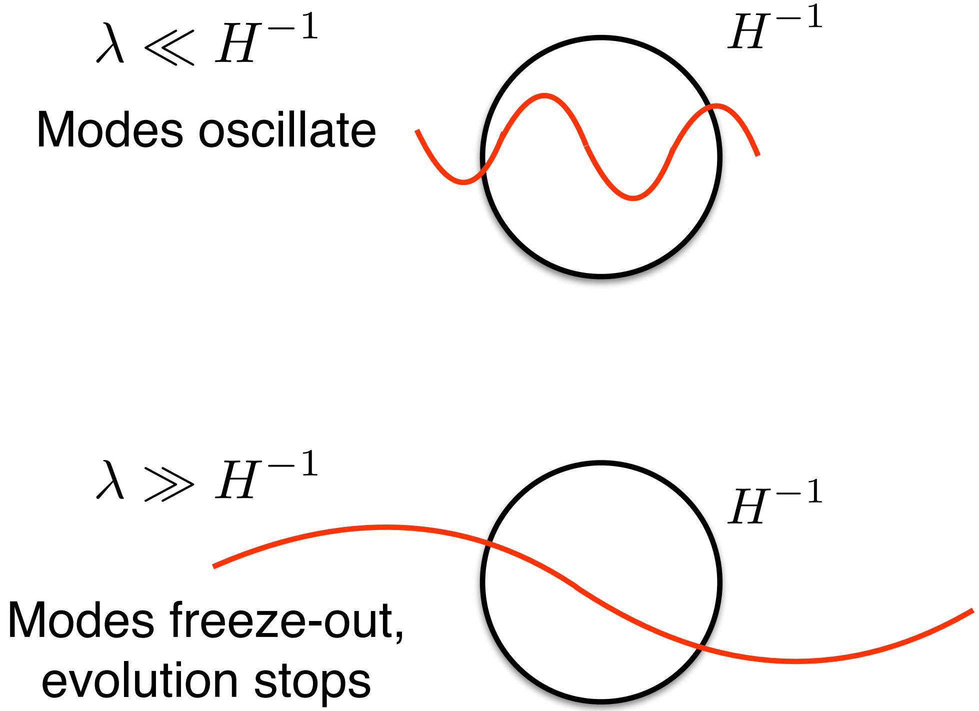
$$\phi(\mathbf{x}, t) = \phi_0(t) + \delta\phi(\mathbf{x}, t)$$

$$\mathrm{d}\tau = \mathrm{d}t / a(t)$$

$$u_{\mathbf{k}}(\tau) = a(\tau)\delta\phi_{\mathbf{k}}(\tau)$$

$$u''_{\mathbf{k}} + \left(k^2 - \frac{a''}{a}\right) u_{\mathbf{k}} = 0$$

Oscillator with time-dependent frequency



$$\mathcal{P}_{\delta\phi}(k) = \frac{k^3}{2\pi^2}\,|\delta\phi_{\mathbf{k}}|^2 = \left(\frac{H}{2\pi}\right)^2 k^0$$

dS/CFT Correspondance

$$\mathrm{d}s^2 = \mathrm{d}t^2 - e^{2Ht}\mathrm{d}\mathbf{x}^2 = \frac{1}{H^2\tau^2}\left(\mathrm{d}\tau^2 - \mathrm{d}\mathbf{x}^2\right)$$

4D bulk isometries

Translations

Spatial rotations

Dilations

$$\tau \to \lambda\,\tau,\;\; \mathbf{x} \to \lambda\,\mathbf{x}$$

Special conformal transformations

$$\begin{aligned} \tau &\to \tau - 2\,\tau\,(\mathbf{b}\cdot\mathbf{x}), \\ \mathbf{x} &\to \mathbf{x} + \mathbf{b}\,(-\tau^2 + \mathbf{x}^2) - 2\,\mathbf{x}\,(\mathbf{b}\cdot\mathbf{x}) \end{aligned}$$

3D boundary

$\tau = 0$

CFT_3

Translations

Spatial rotations

Spatial dilations

$$\mathbf{x} \to \lambda\,\mathbf{x}$$

Special conformal transformations

$$\mathbf{x} \to \mathbf{x} + \mathbf{b}\,\mathbf{x}^2 - 2\,\mathbf{x}\,(\mathbf{b}\cdot\mathbf{x})$$

Spatial dilations are isometries of the dS

$$\mathbf{x} \to \lambda\,\mathbf{x}$$

$$\phi_{\mathbf{k}} \to \lambda^{-3}\phi_{\mathbf{k}/\lambda}$$

$$\langle \phi_{\mathbf{k}_1}\phi_{\mathbf{k}_2}\rangle = (2\pi)^3\delta(\mathbf{k}_1+\mathbf{k}_2)\cdot\frac{1}{k_1^3}$$

$$\mathcal{P}_\phi \sim k^3|\phi_{\mathbf{k}}|^2 \sim k^0$$

The power spectrum is scale-invariant for a massless field

Single-field models

Only one scalar field: it drives inflation
and is quantum-mechanically excited

$$\int \mathrm{d}^4x \sqrt{-g} \left[\frac{1}{2} (\partial\phi)^2 - V(\phi) \right]$$

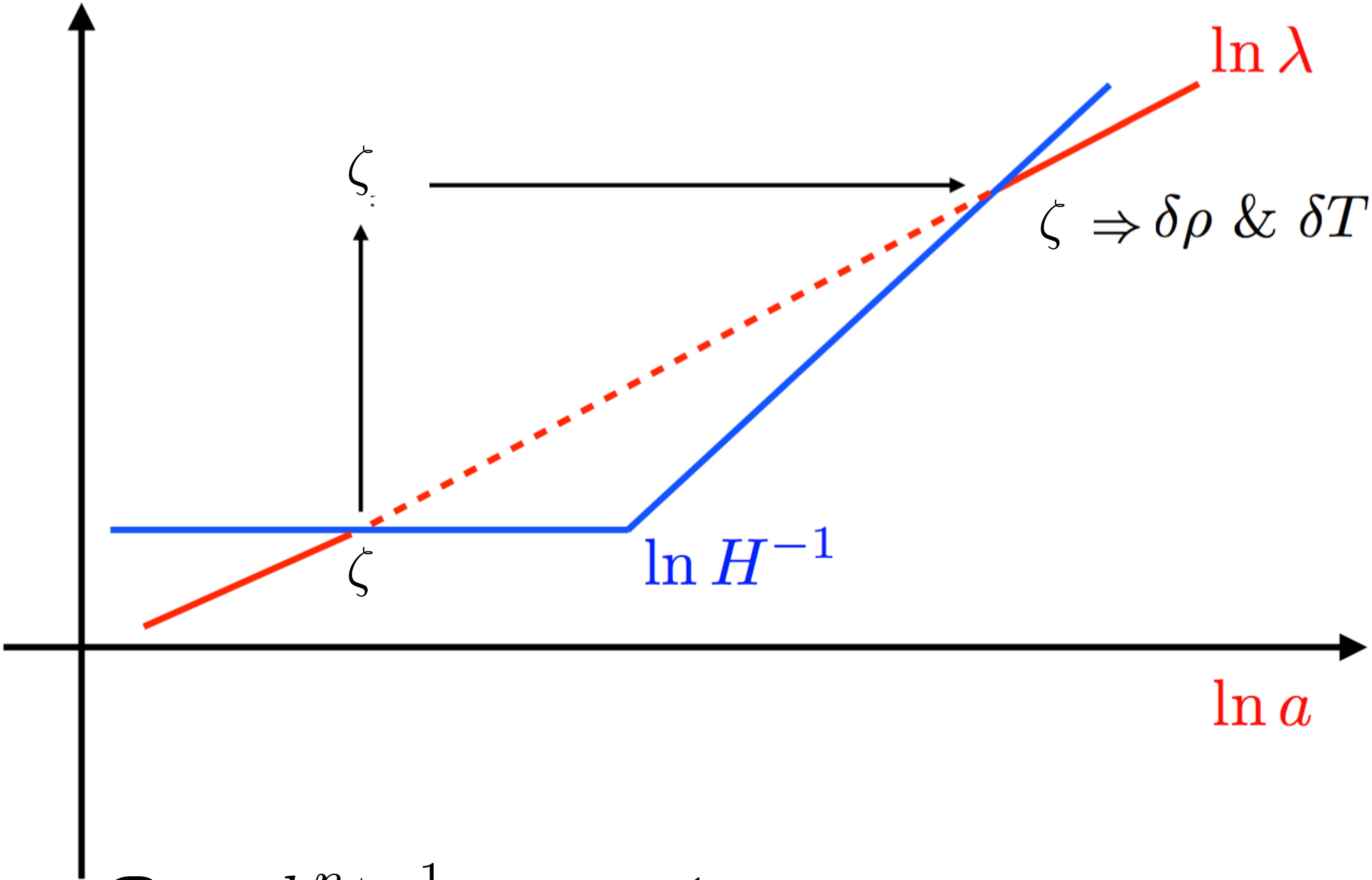
De Sitter slightly broken:
expect small breaking of scale-invariance

$$-\dot{H} \ll H^2$$

- In the high energy physics language, the slightly broken scale invariance is associated to a *pseudo Nambu-Goldstone boson* representing fluctuations in the clock

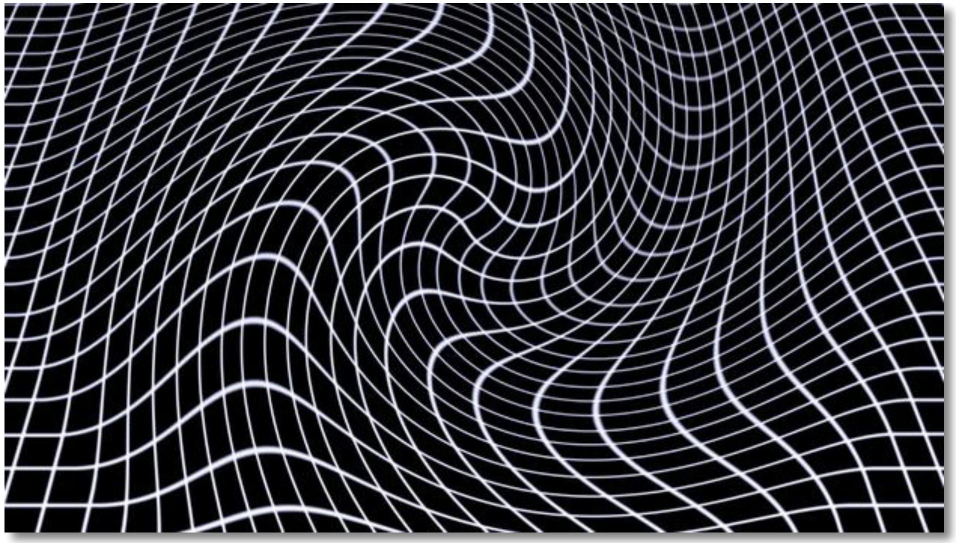
- Different regions have

$$\zeta \sim \frac{\delta a}{a} \sim H\delta t \sim H\frac{\delta\phi}{\dot{\phi}_0}$$



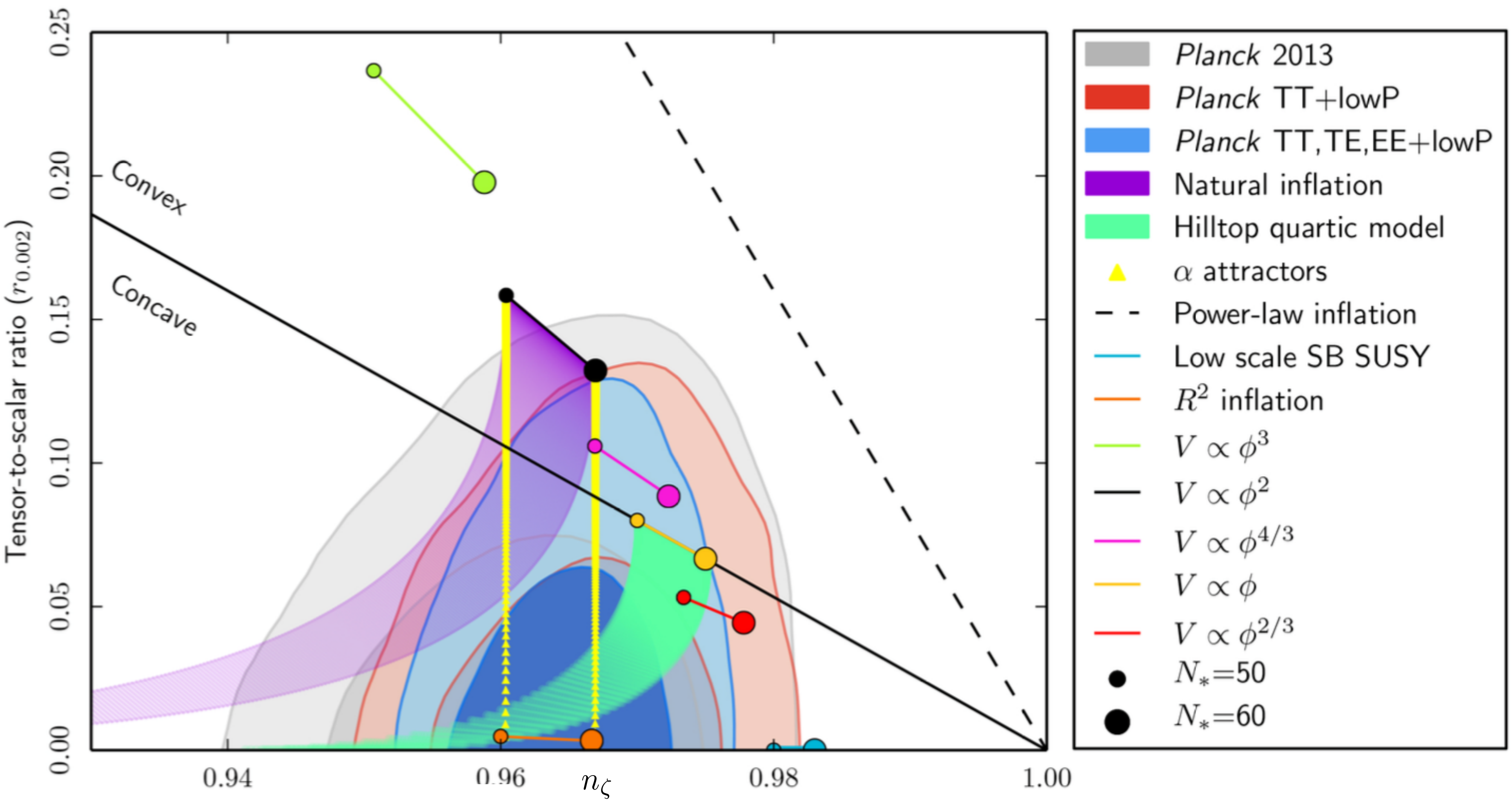
$\mathcal{P}_\zeta \sim k^{n_\zeta - 1}, \quad n_\zeta - 1$ small, but *not* zero

Inflation predicts gravity waves



$$\mathrm{d}s^2 = \frac{1}{H^2\tau^2}\left[\mathrm{d}\tau^2 - (\delta_{ij} + h_{ij})\,\mathrm{d}x^i\mathrm{d}x^j\right]$$

$$\mathcal{P}_h(k) = \frac{k^3}{2\pi^2}\,|h_{\mathbf{k}}|^2 \sim \frac{H^2}{M_{\mathrm{Pl}}^2} \sim \frac{E_{\mathrm{inf}}^4}{M_{\mathrm{Pl}}^4}$$

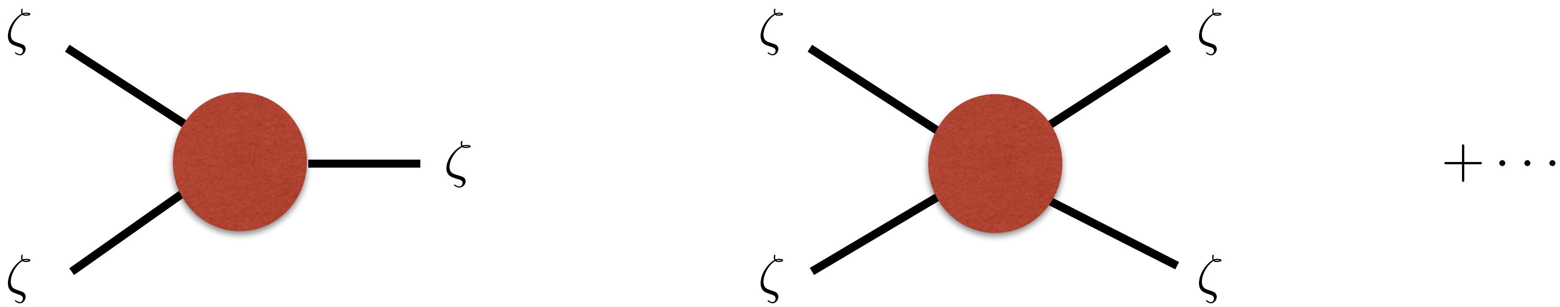


Tensor-to-scalar ratio ($r_{0.002}$)
0.25
0.20
0.15
0.10
0.05
0.00
0.94
0.96
0.98
1.00
n_ζ
Convex
Concave
Planck 2013
Planck TT+lowP
Planck TT,TE,EE+lowP
Natural inflation
Hilltop quartic model
α attractors
Power-law inflation
Low scale SB SUSY
R^2 inflation
$V \propto \phi^3$
$V \propto \phi^2$
$V \propto \phi^{4/3}$
$V \propto \phi$
$V \propto \phi^{2/3}$
N_*=50
N_*=60

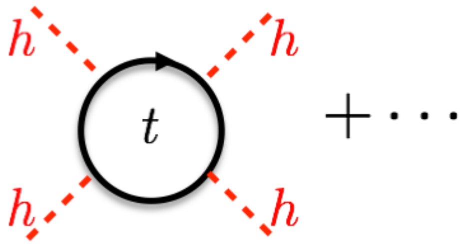
Planck 2015

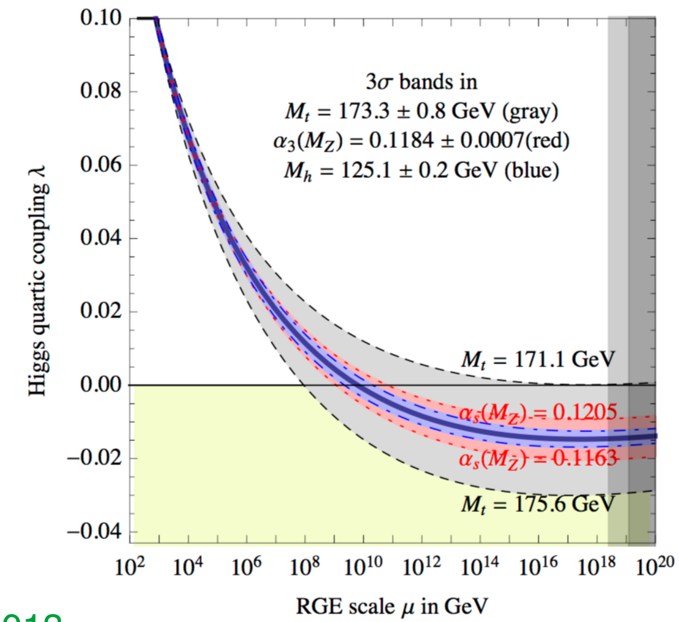
Inflation as a cosmological collider

Higher-order correlation functions



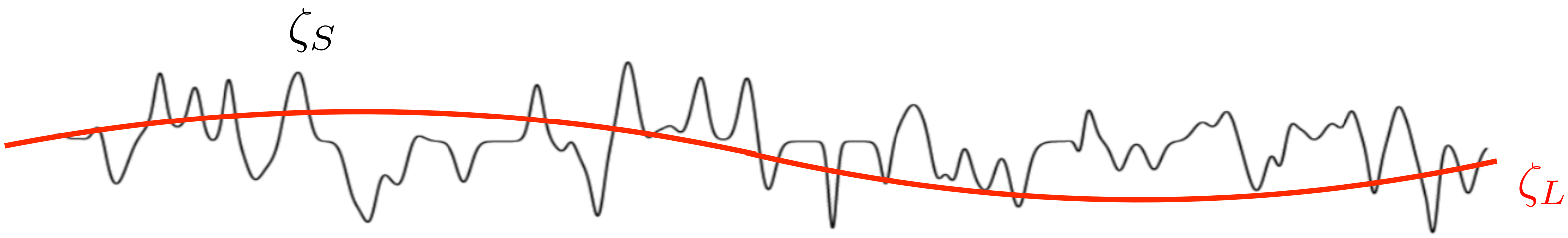
Similar to the SM
self-interaction coupling





D. Buttazzo et al., 2013

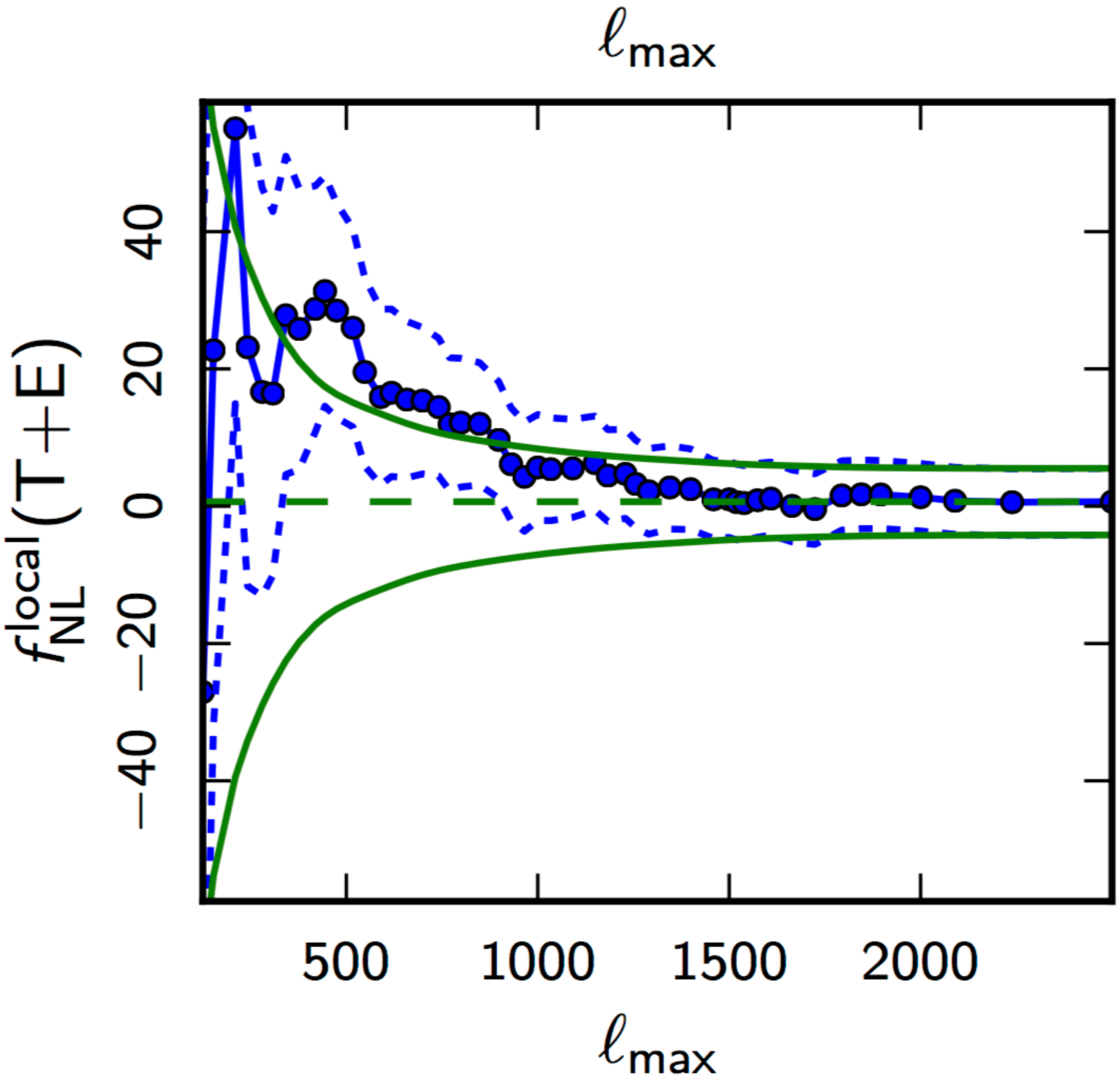
Non-Gaussian three-point statistics



In single-field models the long mode is already classical when the short ones are produced and it acts as a rescaling of the coordinates (dilation)

$$\langle \zeta_L \zeta_S \zeta_S \rangle \sim (n_\zeta - 1) \langle \zeta_L \zeta_L \rangle \langle \zeta_S \zeta_S \rangle$$

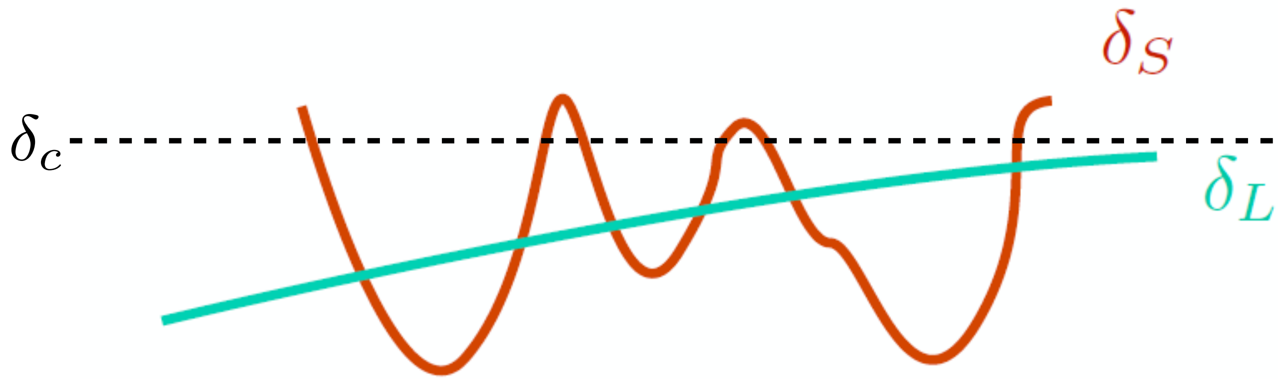
Small NG in the simplest scenario, but not true in general: smoking gun for extra-degrees of freedom



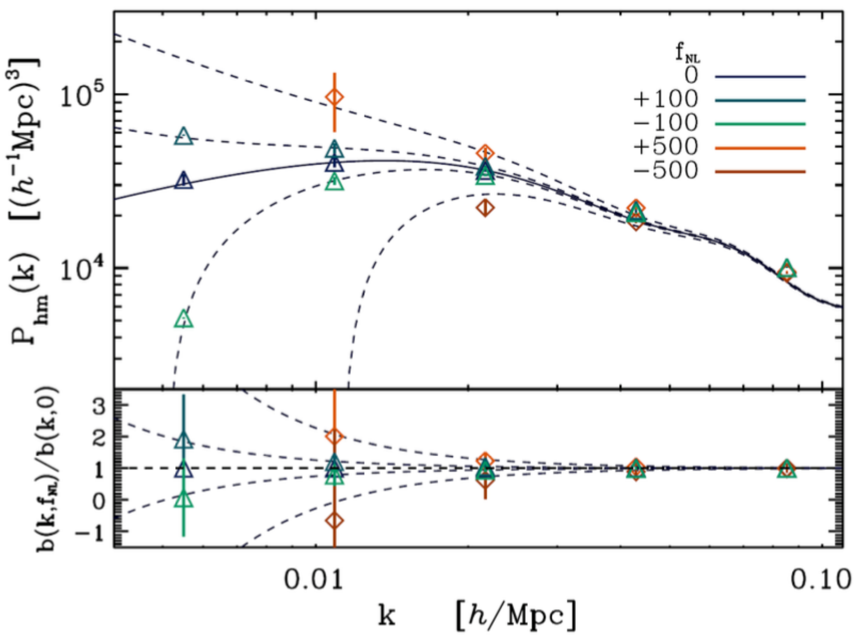
Planck 2015

$$f_{\rm NL}^{\rm local} = \frac{\text{three−point}}{(\text{two−point})^2} = 0.6 \pm 5$$

Galaxies are *biased* peaks in the DM distribution



$$P_h(k) = [b + \Delta b(k)]^2 P_{\rm CDM}(k) \qquad \Delta b(k) \sim \frac{f_{\rm NL}^{\rm loc}}{k^2}$$

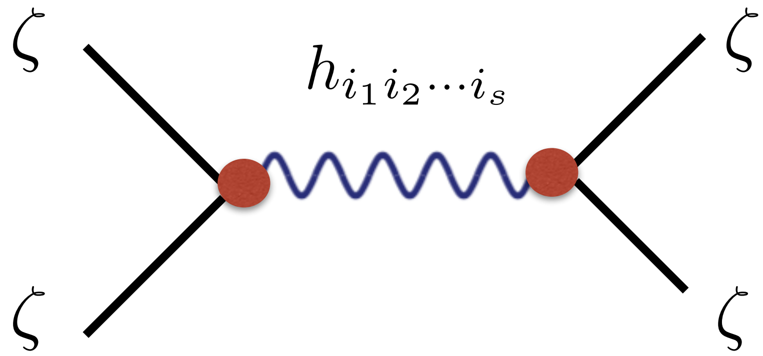


Dalal et al., 2007

Bispectrum shape	local
Fiducial $f_{\rm NL}$	0
Galaxy clustering (spectr. z)	4.1 (4.0)
Galaxy clustering (photom. z)	5.8 (5.5)
Weak lensing	73 (27)
Combined	4.7 (4.5)

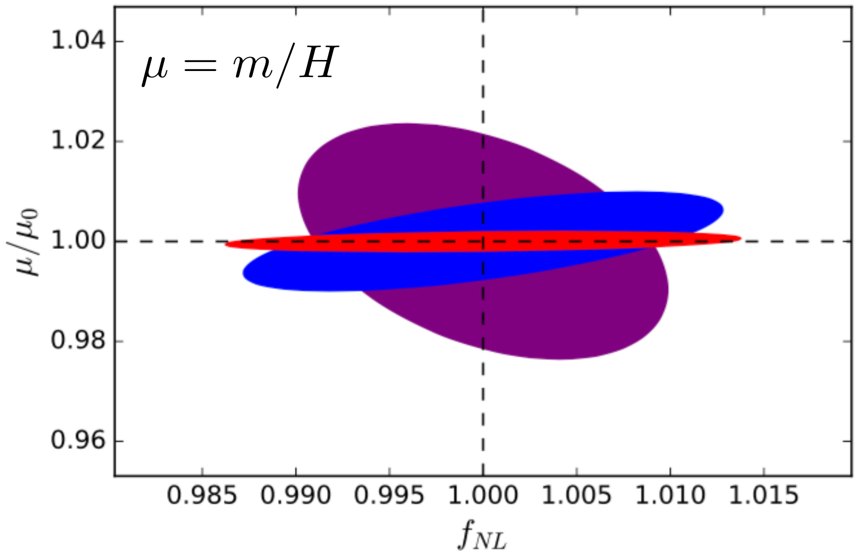
Euclid, 2016

Massive Higher-Spin fields



$$\langle \zeta_L \zeta_S \zeta_S \rangle \sim \left(\frac{k_L}{k_S} \right)^{1/2 \pm im/H} P_s(\cos\theta_k)$$

Arkani-Hamed and Maldacena, 2015



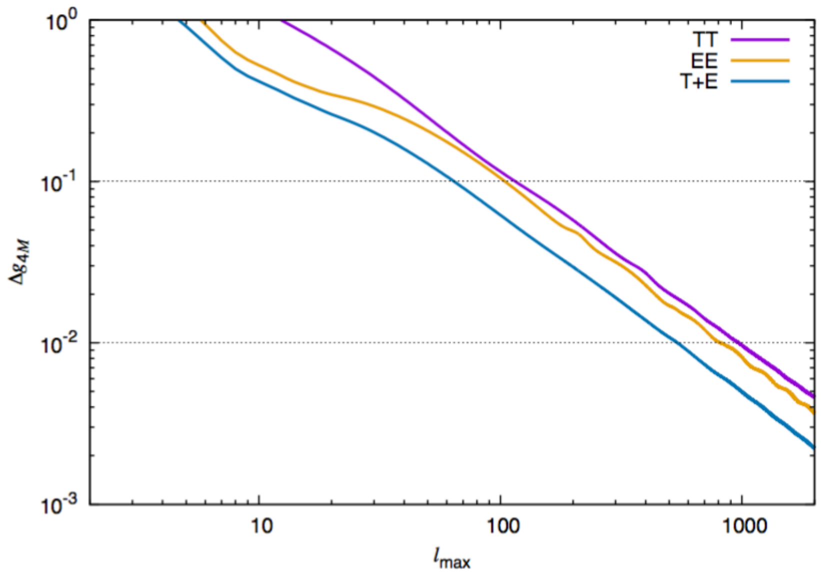
Meerburg et al., 2016

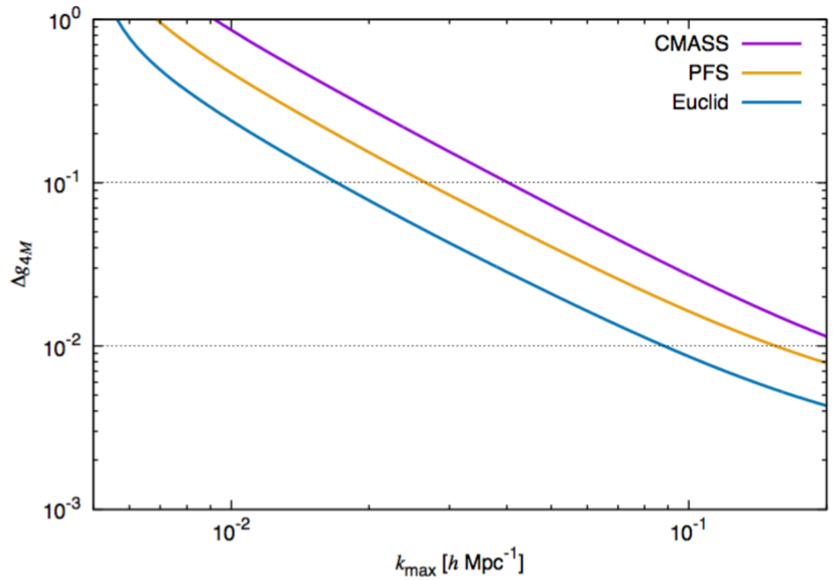
Massless Higher-Spin fields

- Massless HS fields (difficult in Minkowski but consistent in dS)
- Use techniques from dS/CFT correspondence

$$P_\zeta(k) = P_\zeta^{\rm iso}(k)\left(1 + C_s \sin^{2s}\theta_k\right)$$

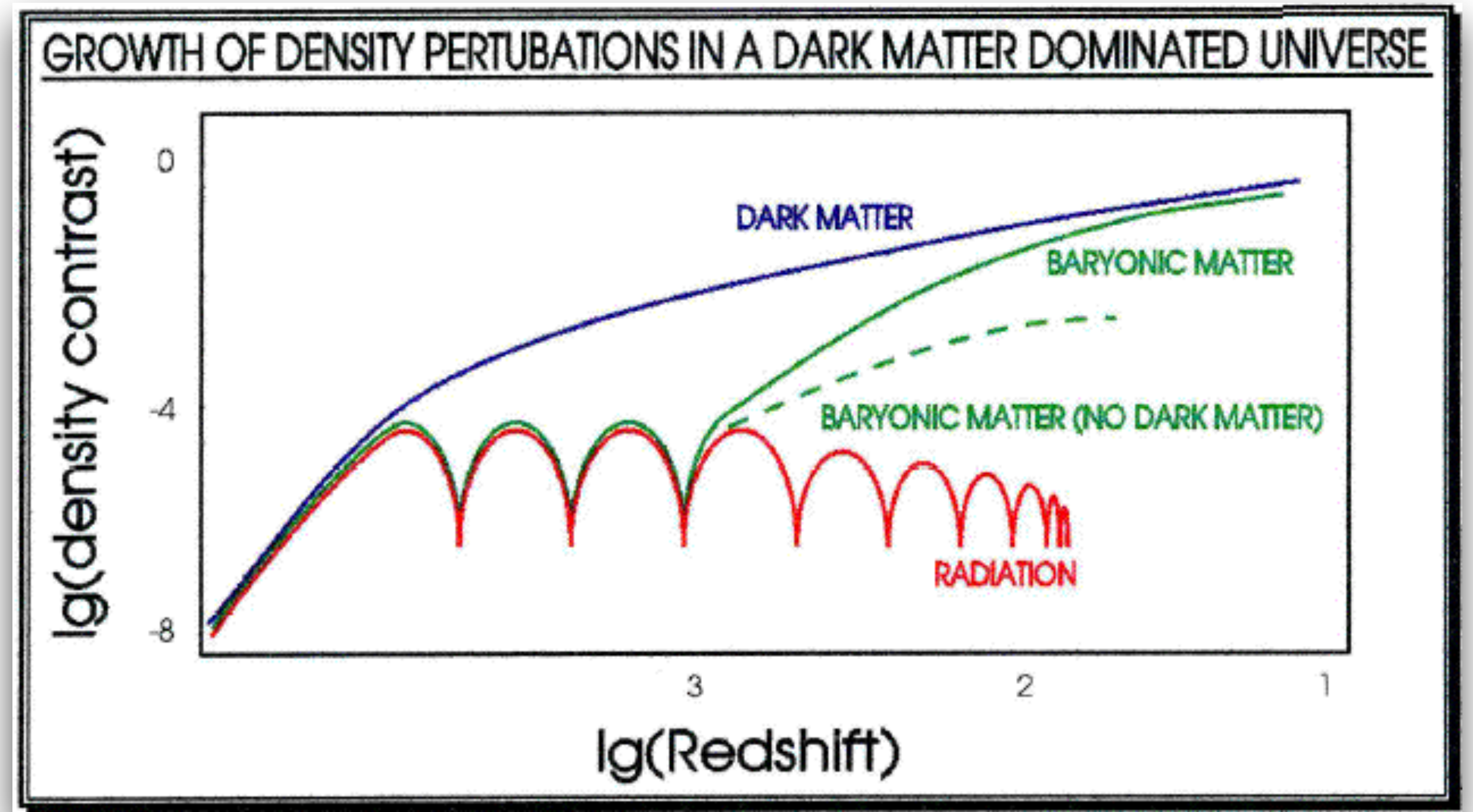
Kehagias and AR, 2017





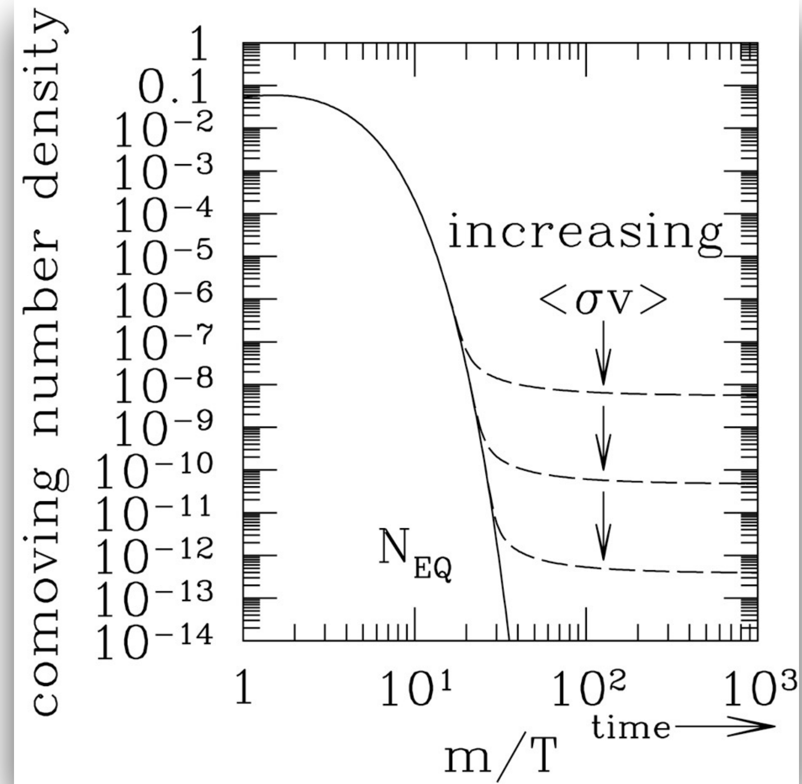
Bartolo et al., in preparation

Second pillar:
Cold Dark Matter



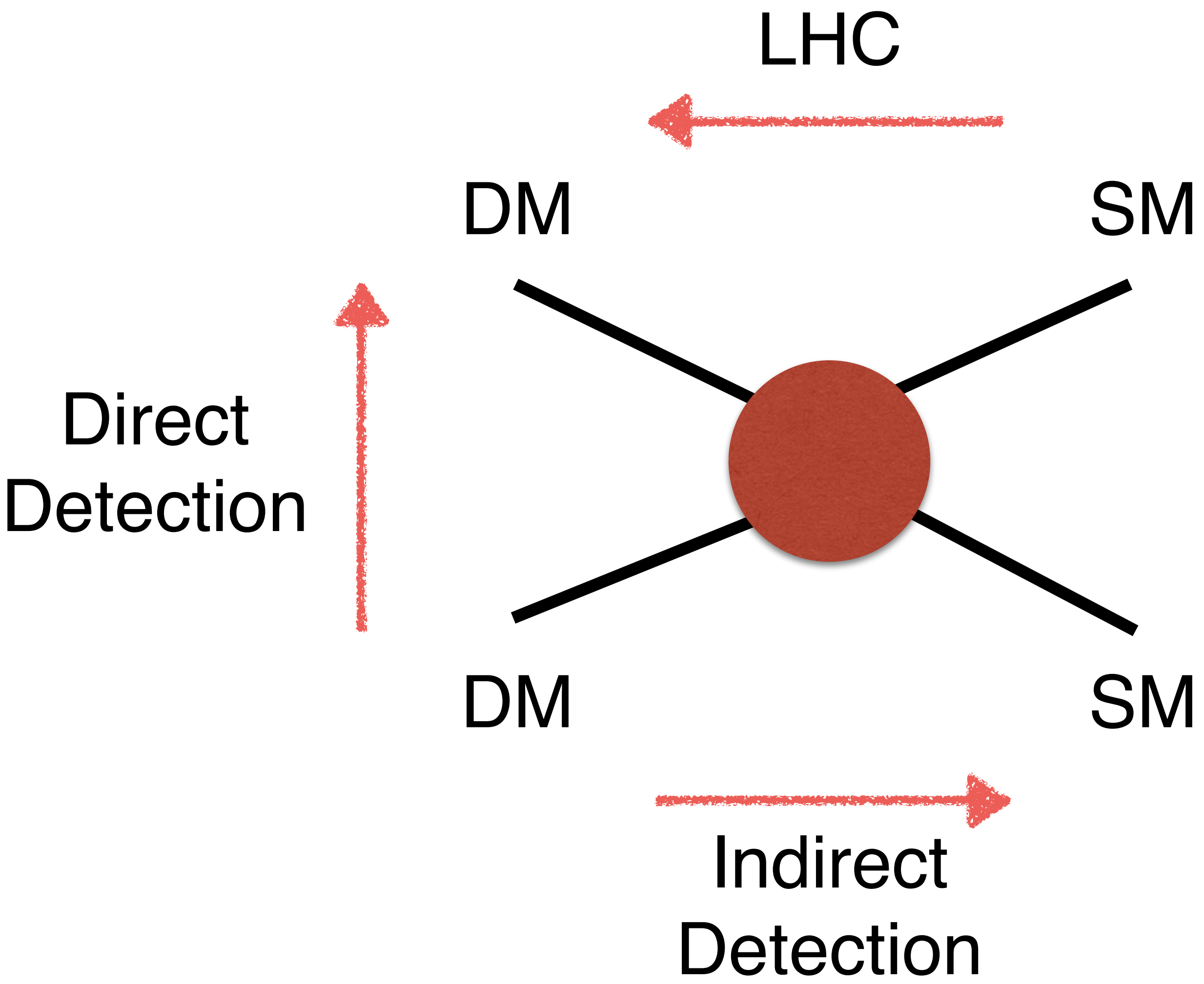
Standard CDM candidate: WIMP

- Abundance independent from initial conditions
- Neutral
- Stable on cosmological scales
- Dynamics governed by Boltzmann equations
- Cold



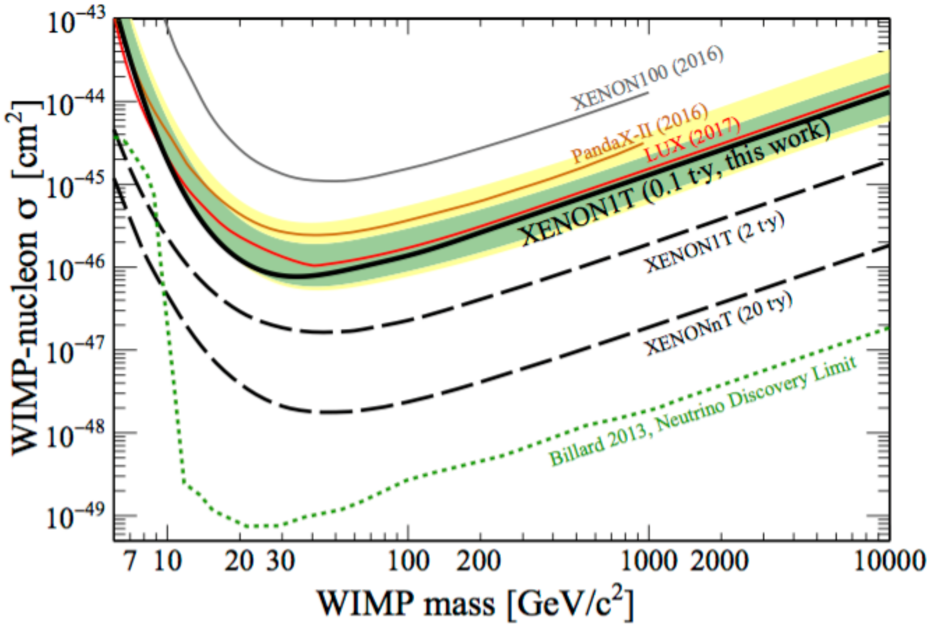
$$\Omega_{\rm WIMP} h^2 \simeq \frac{3 \cdot 10^{-27}\,{\rm cm}^3\,{\rm s}^{-1}}{\langle \sigma_{\rm A} v \rangle}$$

WIMP strength: search complementarity

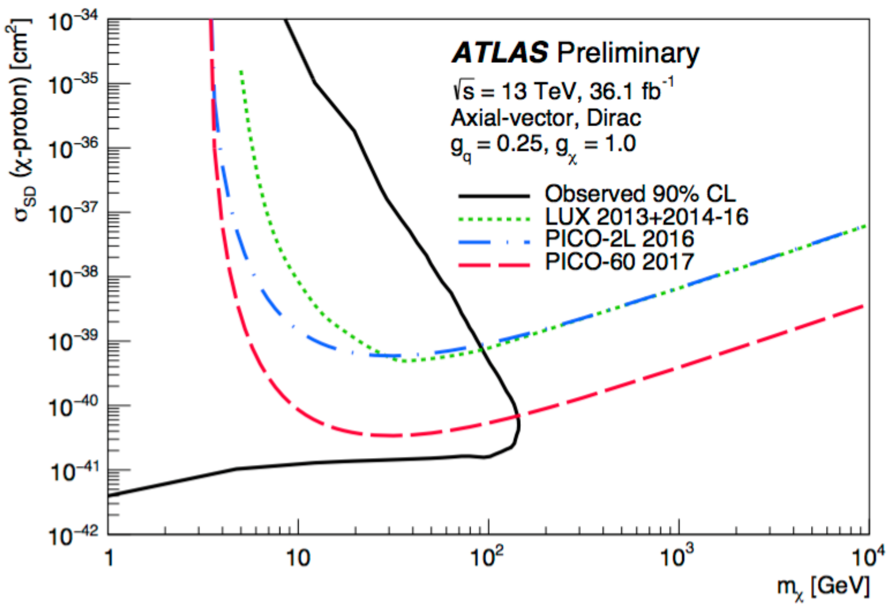


Strategy

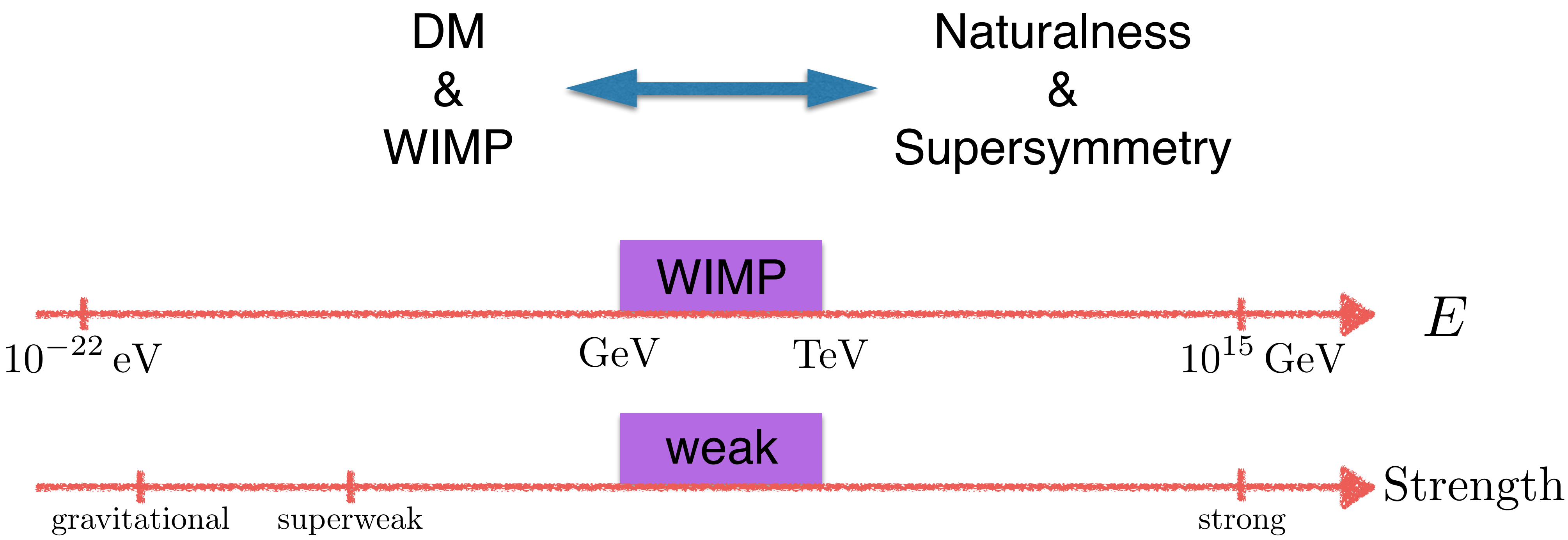
- Full model (e.g. supersymmetric)
- EFT (not working at colliders)
- Simplified models
- Consistent simplified models
- Full model?



M. Galloway, this conference



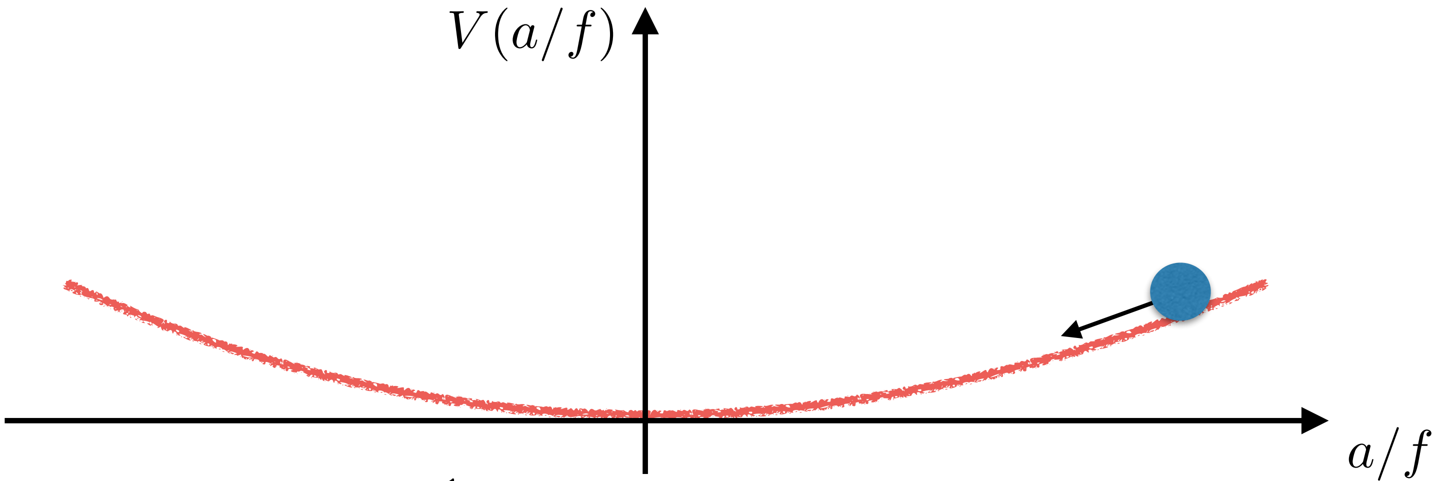
V. Ippolito, this conference



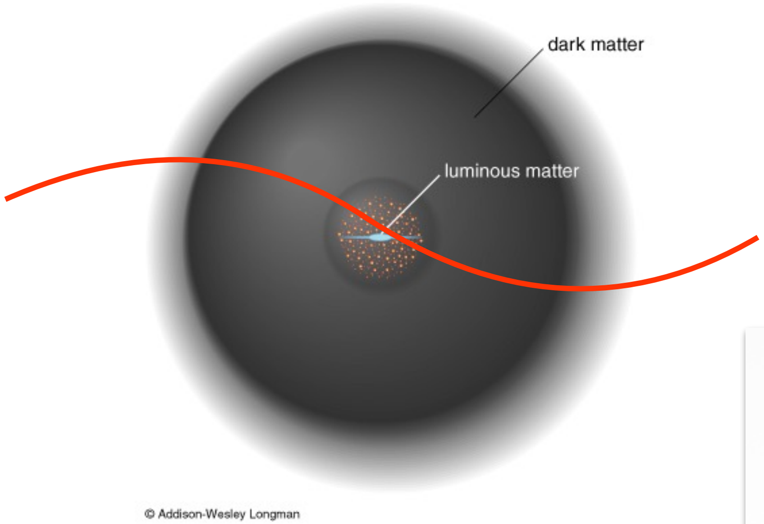
WIMP’s maybe around the corner, but healthy to cope with

- the moderate idea that DM might have another origin, other interactions, production mechanisms (good for HEP’s)
- and maybe with the extreme (and hopefully wrong idea) that it manifests itself only through gravitational effects

Moderate: the ultra-light axion



$$\mathcal{L} = \frac{1}{2}(\partial a)^2 - \Lambda^4(1 - \cos a/f)$$

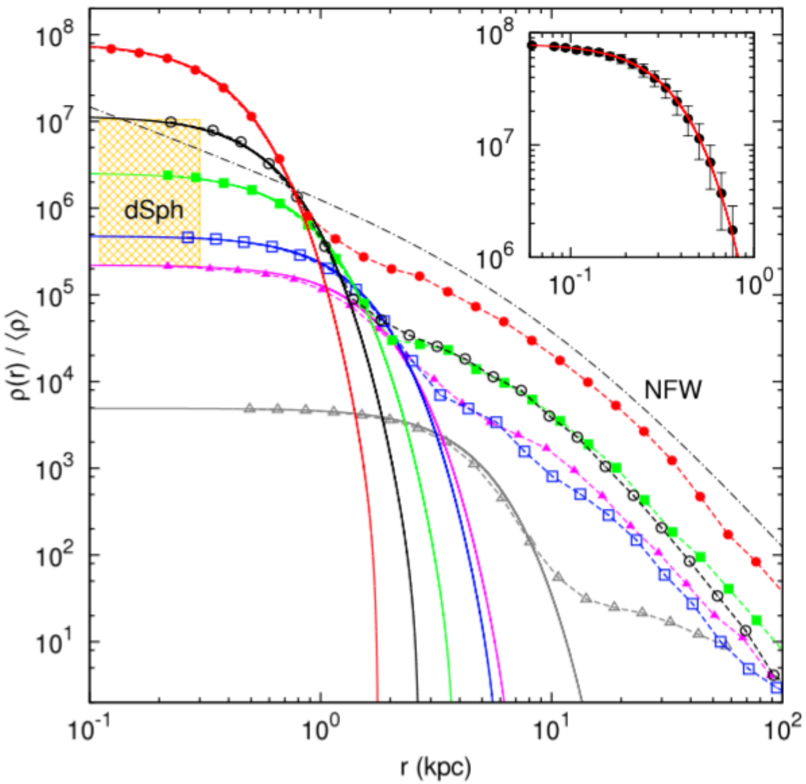


$$\lambda_{\rm dB} \sim (10^{-22}\,{\rm eV}\,v)^{-1} = \mathcal{O}({\rm Kpc})$$

$$\Omega_a \sim \left(\frac{f}{10^{17}\,{\rm GeV}}\right)^2 \left(\frac{m_a}{10^{-22}\,{\rm eV}}\right)^{1/2}$$

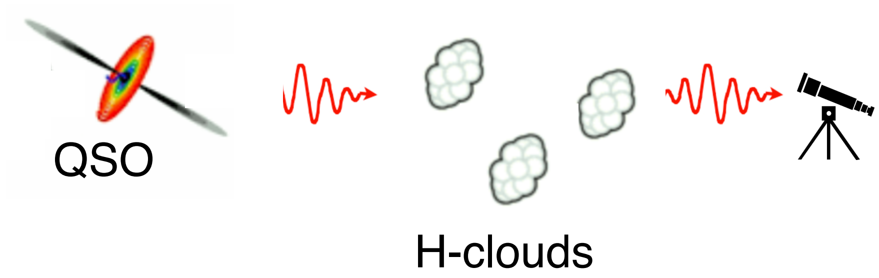
Gross-Pitaevskii-Poisson dynamics
(BEC in the cosmo)

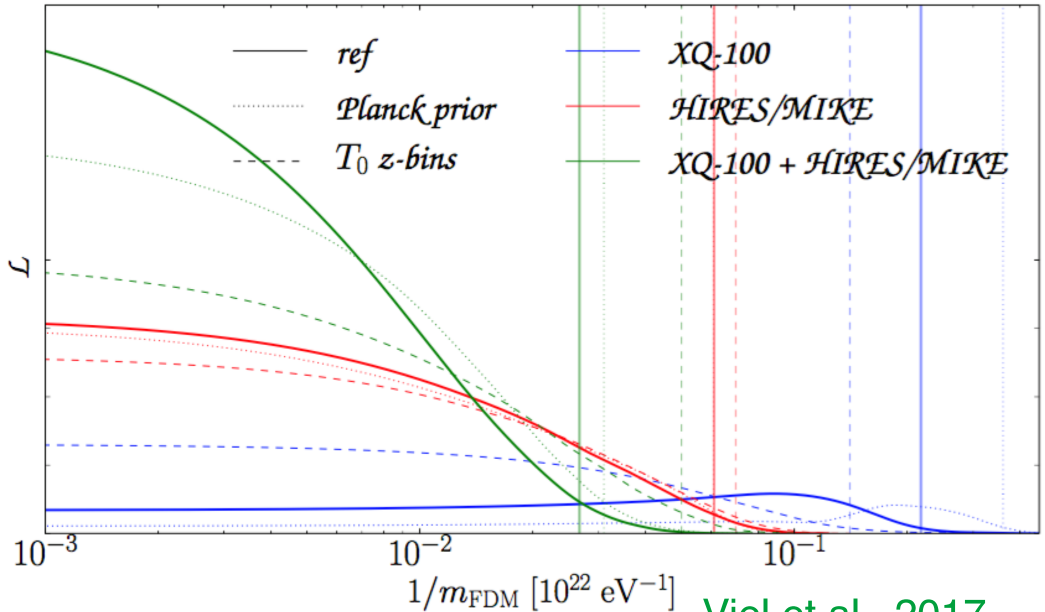
$$\begin{aligned} a/f &= \sqrt{2}\mathrm{Re}(\psi e^{-im_a t}) \\ i\partial_t \psi &= -\nabla^2\psi/2m_a + m_a(\Phi - g|\psi|^2/8)\psi \\ \nabla^2\Phi &= 4\pi\rho/M_{\mathrm{pl}}^2 \end{aligned}$$



Schive et al., 2014

Lyman-alpha forest





Viel et al., 2017

$$m_a > 37.5 \cdot 10^{-22}\,\mathrm{eV}$$

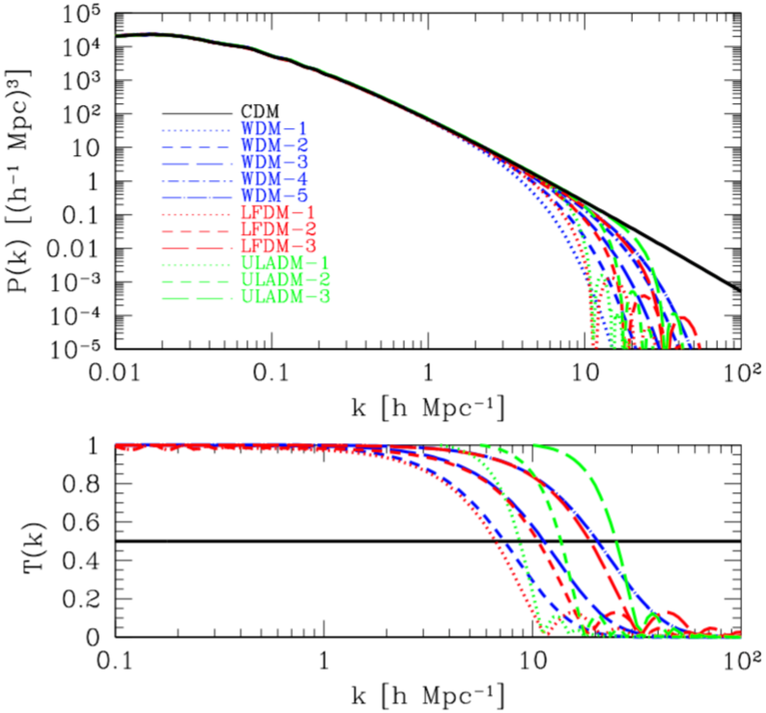
Excluded as DM candidate?

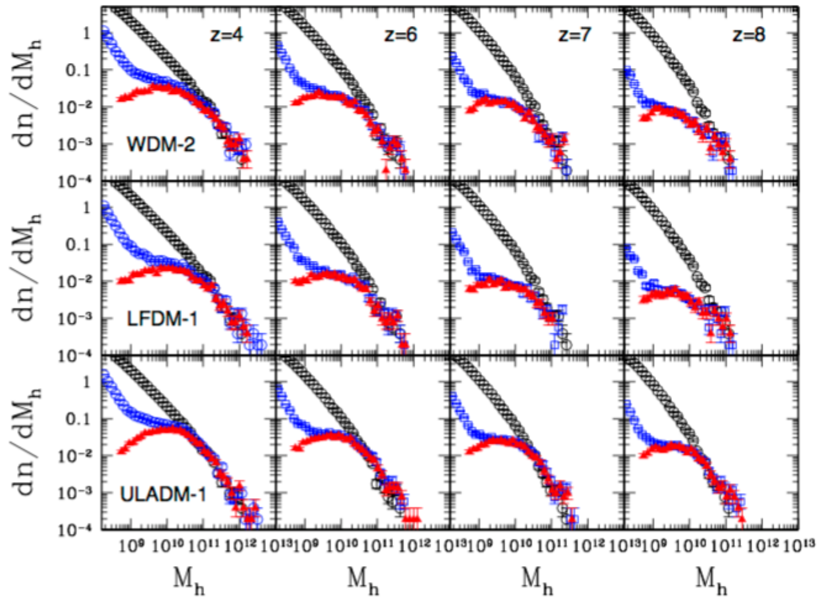
Self-interactions cannot be neglected despite the smallness of the coupling: cosmic web affected. Interesting non-linear physics in action

Desjacques et al., in preparation

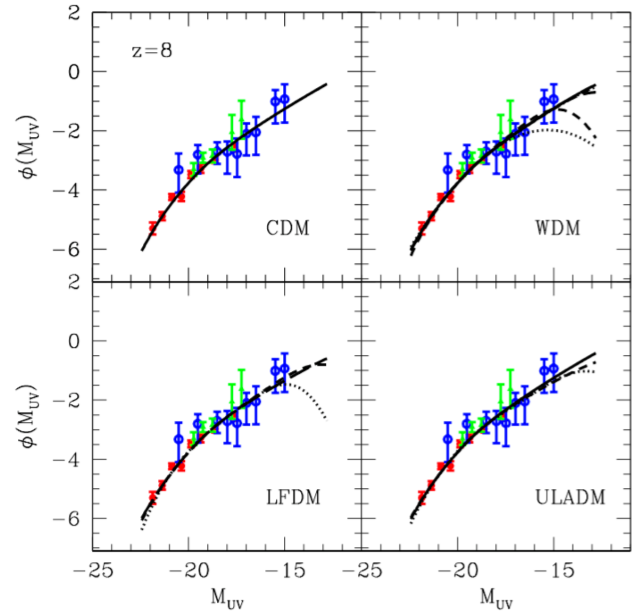
Extreme: only gravity

From the linear PS → to the N-body halo-mass function





→ to measured luminosity functions



Corasaniti et al., 2016

Conclusions

It was the best of times, it was the worst of times,
it was the age of wisdom, it was the age of foolishness,
it was the epoch of belief, it was the epoch of incredulity,
it was the season of (*observational*) Light, it was the season of (*theoretical*) *Darkness*..

Charles Dickens
A Tale of Two Cities