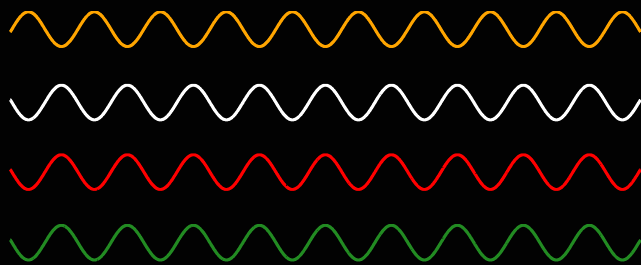
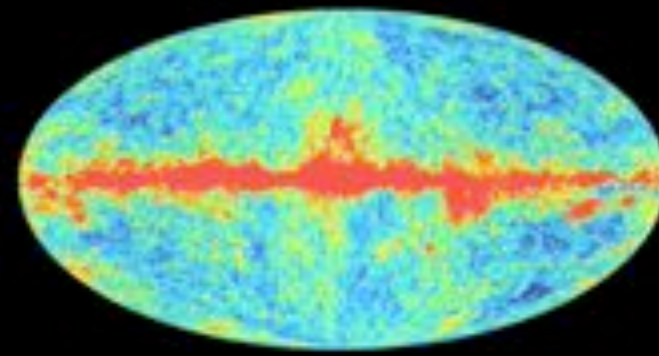




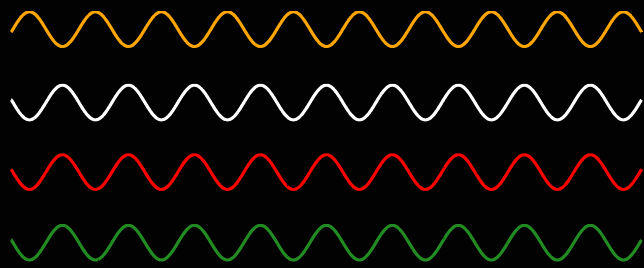
LIGHT SPECTATOR FIELDS AND THE DARK SECTOR

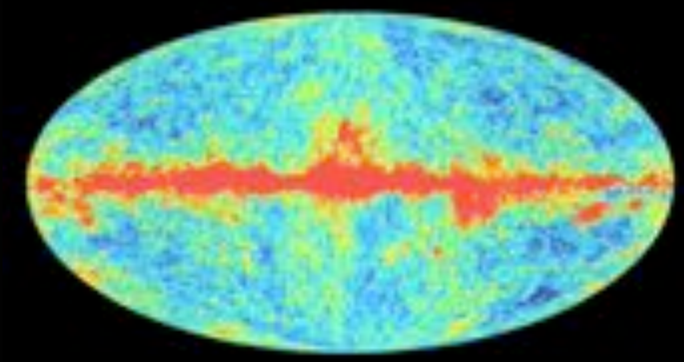
Daniel Grin

Haverford College

IAS informal seminar

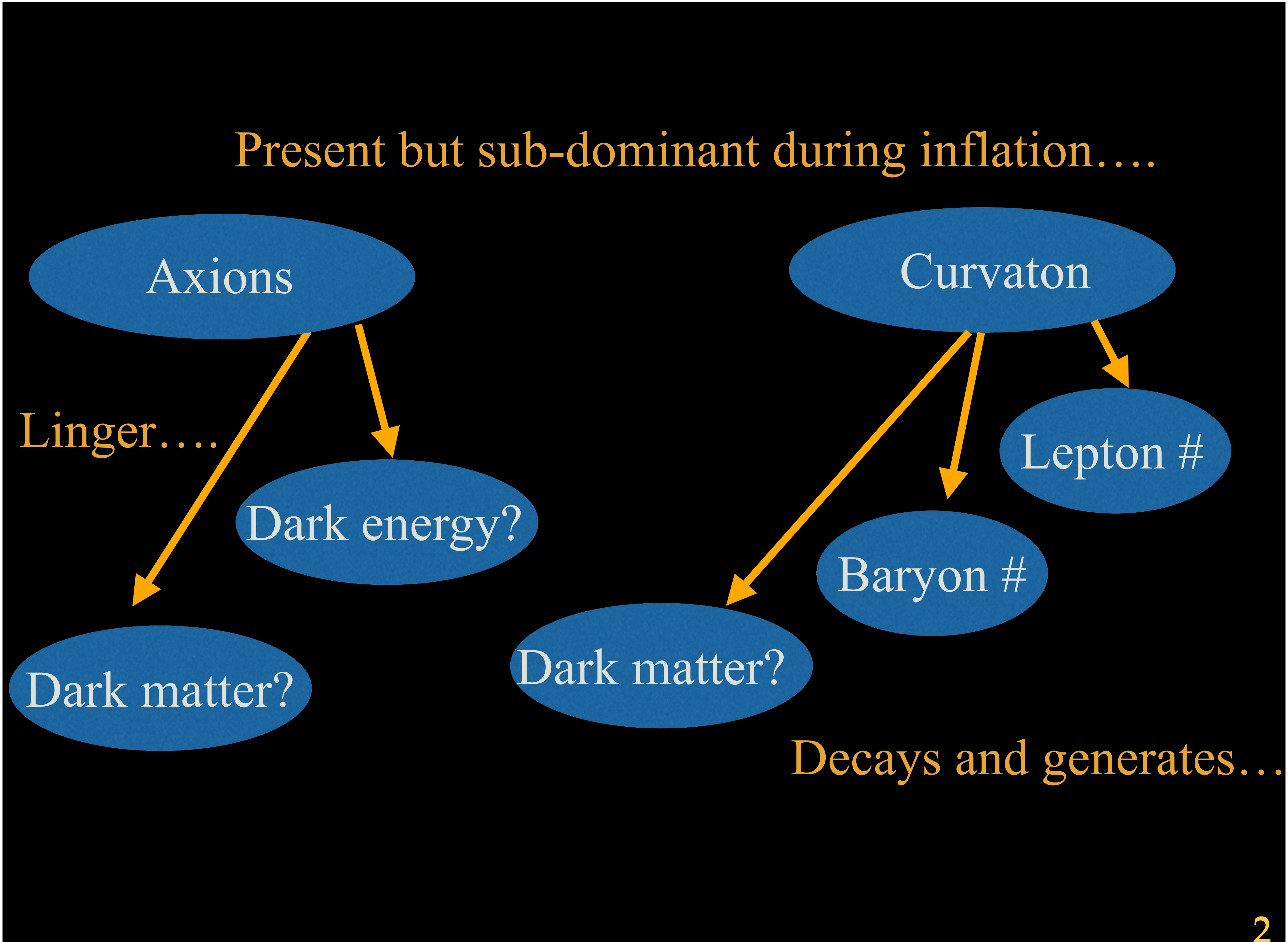
December 15, 2016





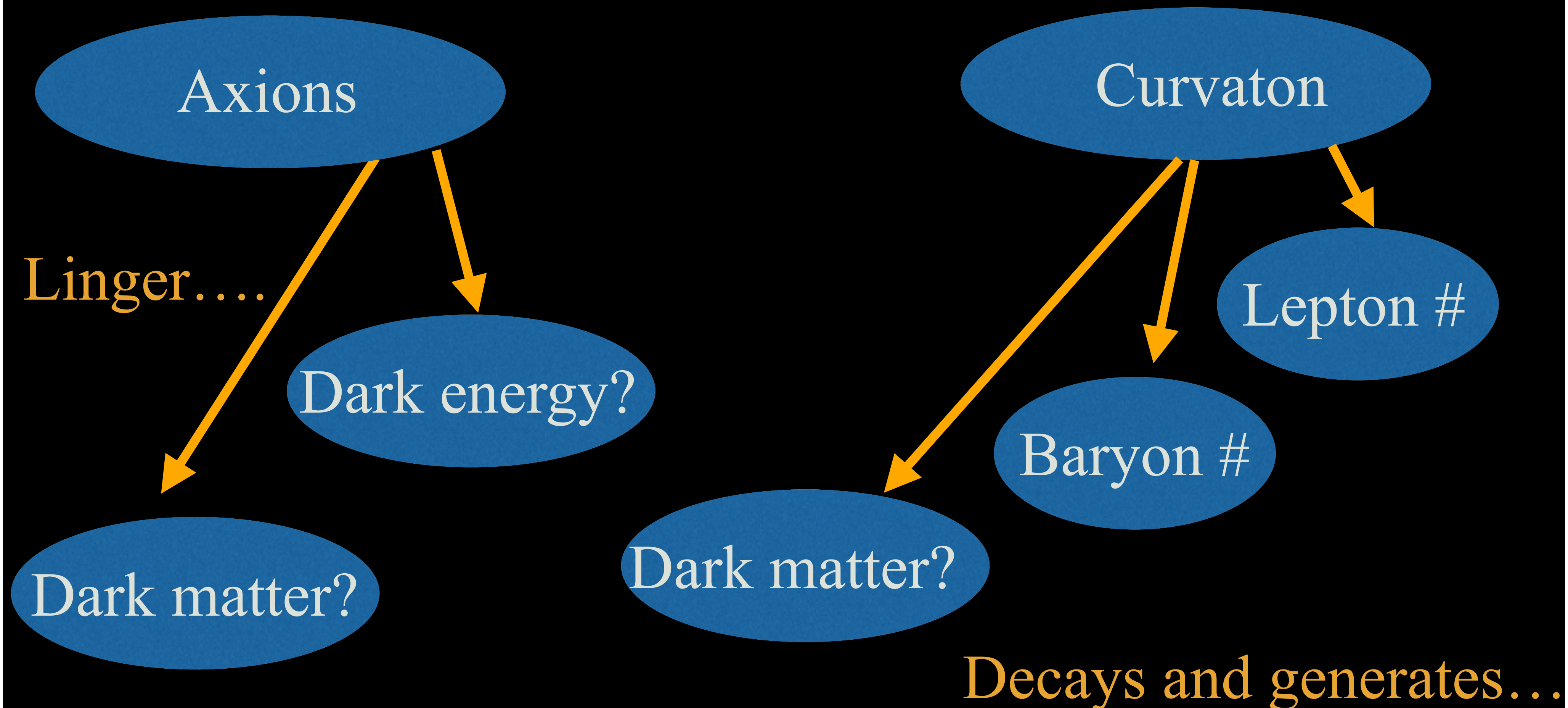
LIGHT SPECTATOR FIELDS AND THE DARK SECTOR

DANIEL GRIN
HAVERFORD COLLEGE
IAS informal seminar
December 15, 2016


Present but sub-dominant during inflation….
Axions
Curvaton
Linger….
Dark energy?
Lepton #
Baryon #
Dark matter?
Dark matter?
Decays and generates….

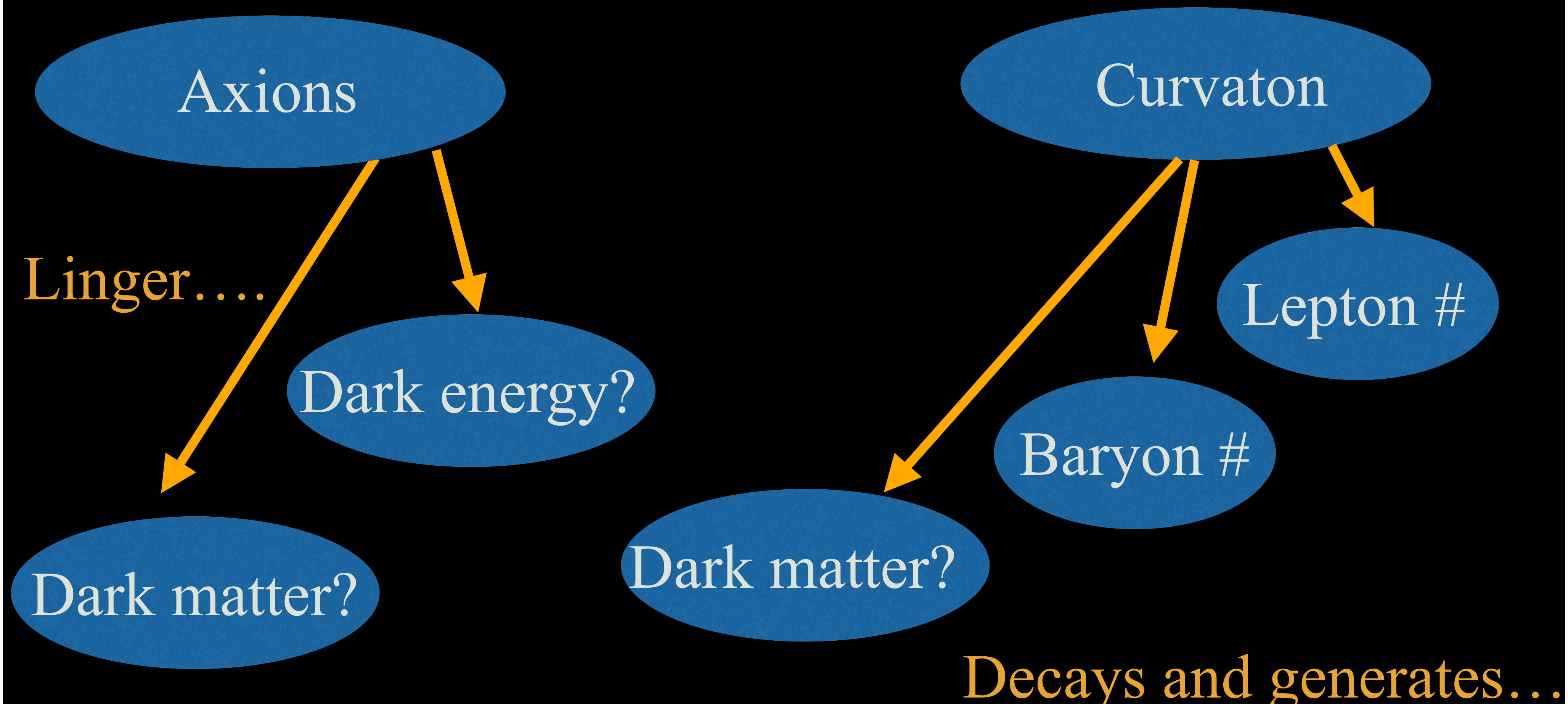
A TALE OF TWO FIELDS

Present but sub-dominant during inflation….



A TALE OF TWO FIELDS

Present but sub-dominant during inflation….



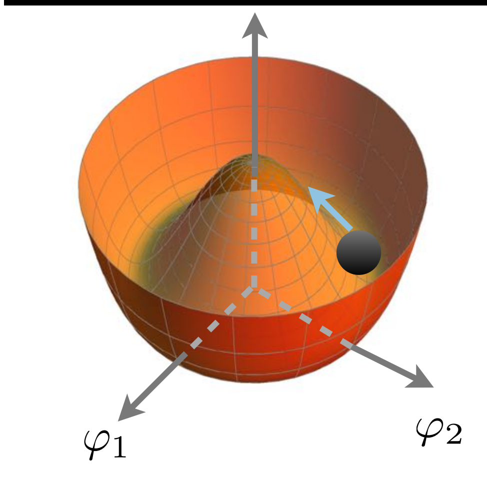
The answer, my friend, is ~~blowing in the wind~~

… encoded in the distribution of cosmological density perturbations

Outline

- Ultra-light axions
  - Motivation, observational imprint, tools
  - Constraints
  - Future work
- Curvaton-sourced isocurvature perturbations
  - Linearly observable isocurvature
  - Compensated isocurvature perturbations

What are axions?

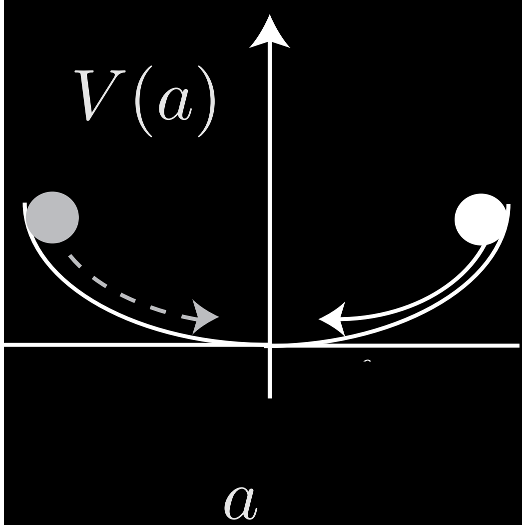


New scalar field with global U(1) symmetry!

Broken at scale f_a

$$\mathcal{L}_{\mathrm{CPV}} = \frac{\theta g^2}{32\pi^2} G\tilde{G} - \boxed{\frac{a}{f_{\mathrm{a}}} g^2 G\tilde{G}}$$

$$m_a \sim \frac{\Lambda_{\mathrm{QCD}}^2}{f_a}$$

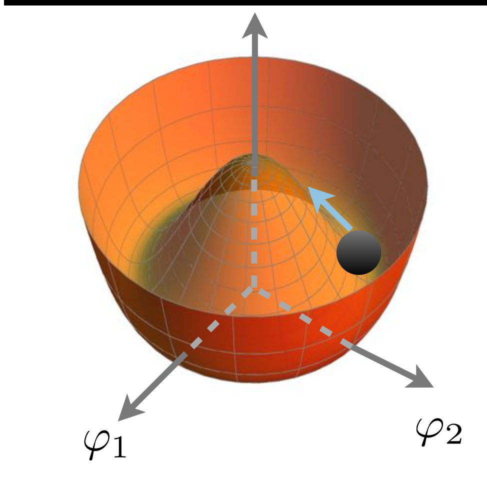


✳ Field misaligned $m_a \gg 3H \rightarrow$ oscillation

✳ $\rho_a \propto (1+z)^3$ [as cold dark matter should]

Peccei + Quinn (1977), Weinberg +Wilczek (1978), Kim (1979), Zhitnitsky (1980), Dine et al. (1981), Sikivie (1982, 1983, 1985,1986, and many others!)

WHAT ARE AXIONS?

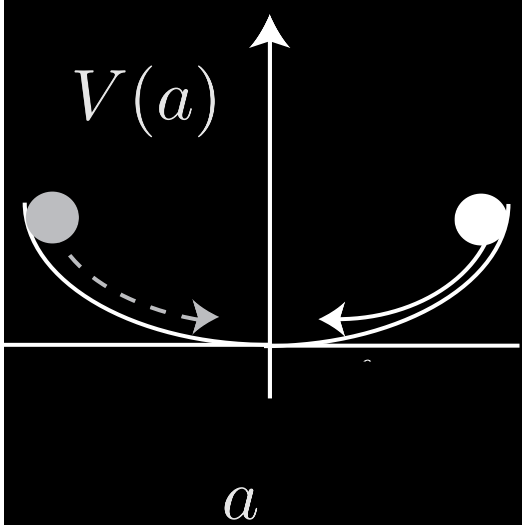


New scalar field with global U(1) symmetry!

Broken at scale f_a

$$\mathcal{L}_{\mathrm{CPV}} = \frac{\theta g^2}{32\pi^2} G\tilde{G} - \boxed{\frac{a}{f_{\mathrm{a}}} g^2 G\tilde{G}}$$

$$m_a \sim \frac{\Lambda_{\mathrm{QCD}}^2}{f_a}$$

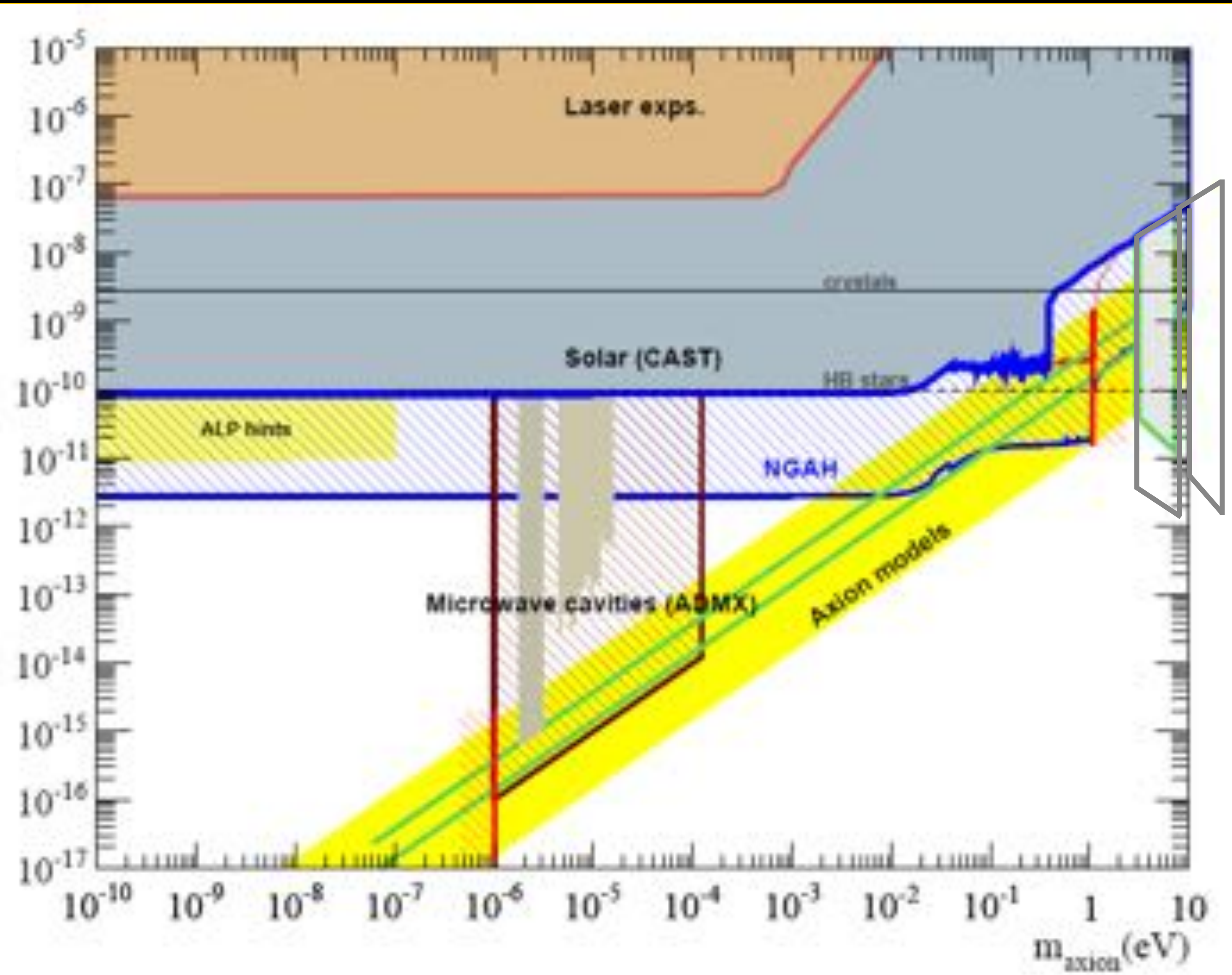


$$\boxed{\Omega_{\mathrm{mis}} h^2 = 0.236 \left\langle \theta_i^2 f(\theta_i) \right\rangle \left(\frac{m_a}{6.2\mu\mathrm{eV}} \right)^{-7/6}}$$

Peccei + Quinn (1977), Weinberg +Wilczek (1978), Kim (1979), Zhitnitsky (1980), Dine et al. (1981), Sikivie (1982, 1983, 1985,1986, and many others!)

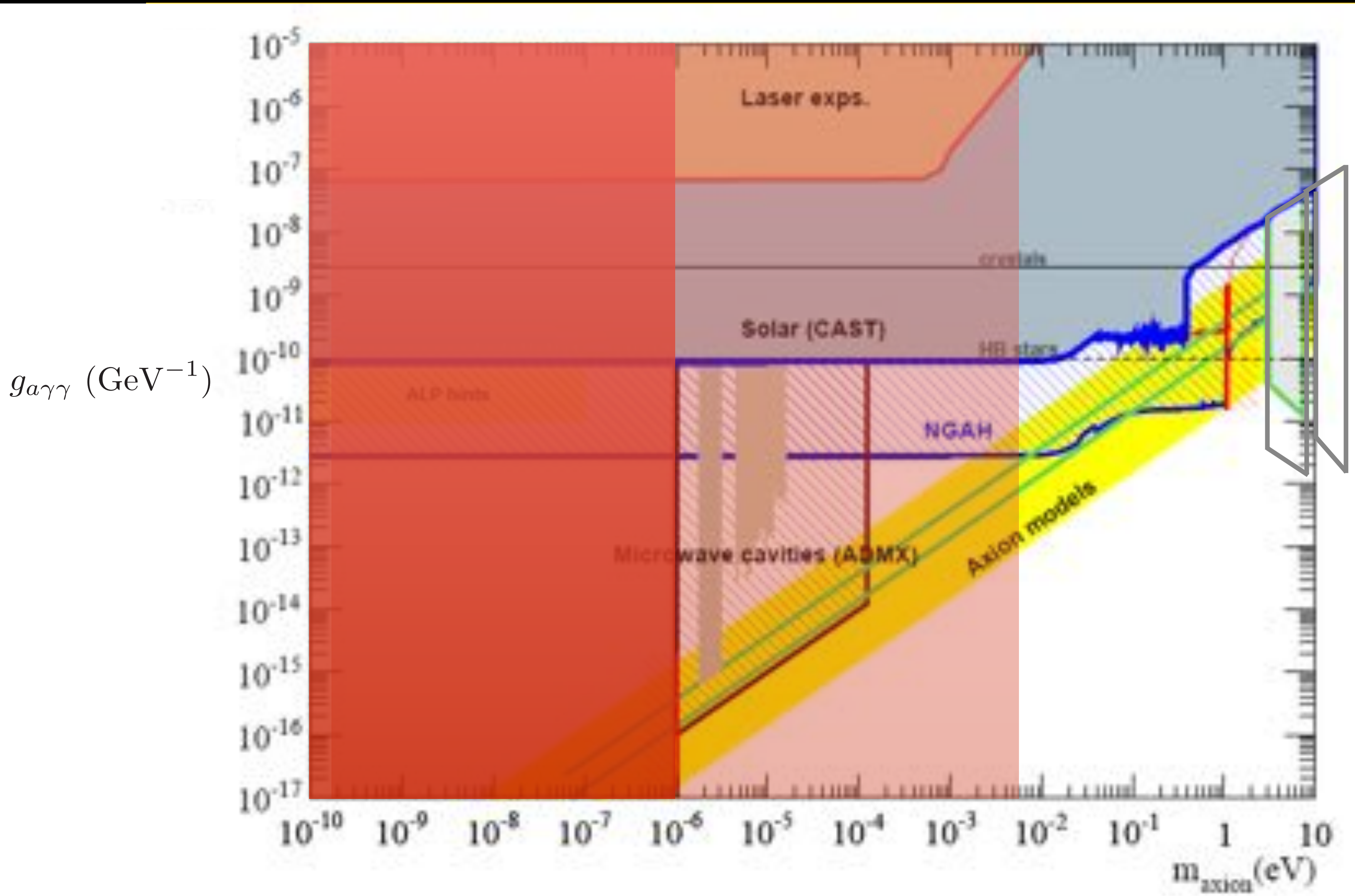
LIMITS

$g_{a\gamma\gamma}$ (GeV^{-1})



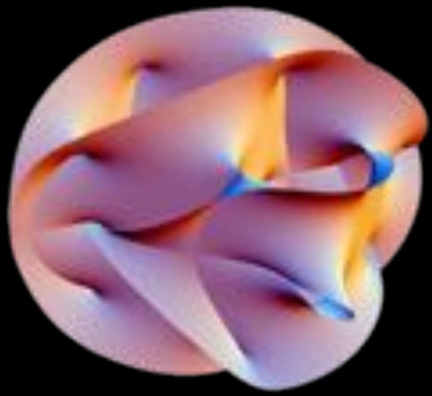
LIMITS

Cosmological dark matter



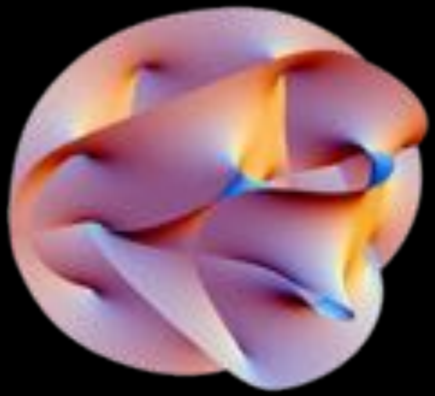
Ultra-light axions (ULAs) in string theory

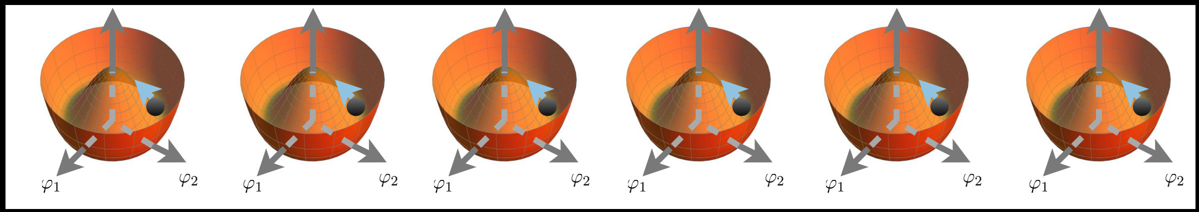
- In string theory, extra dimensions compactified: Calabi-Yau manifolds



Ultra-light axions (ULAs) in string theory

- In string theory, extra dimensions compactified: Calabi-Yau manifolds



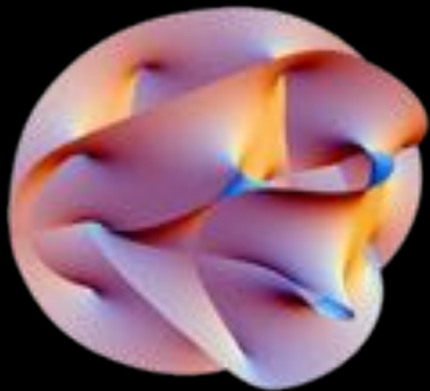


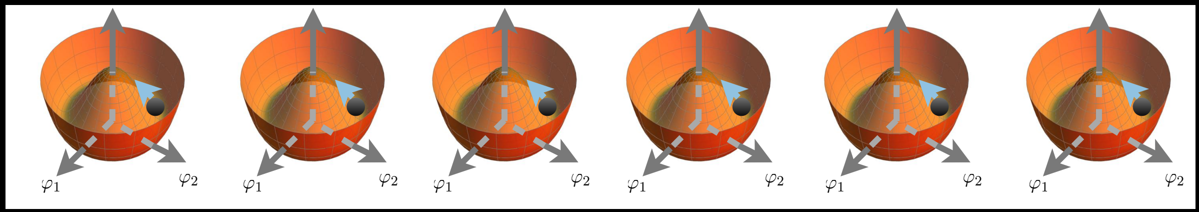
+....

Hundreds of scalars with approx shift symmetry

Ultra-light axions (ULAs) in string theory

✴ In string theory, extra dimensions compactified: Calabi-Yau manifolds





+....

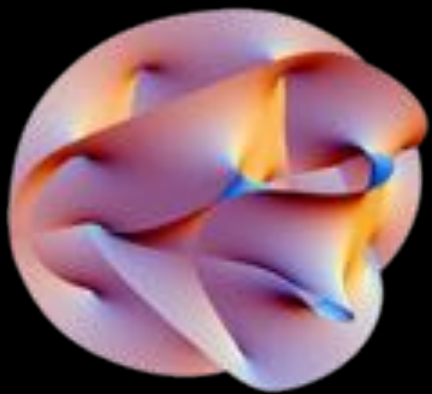
Hundreds of scalars with approx shift symmetry

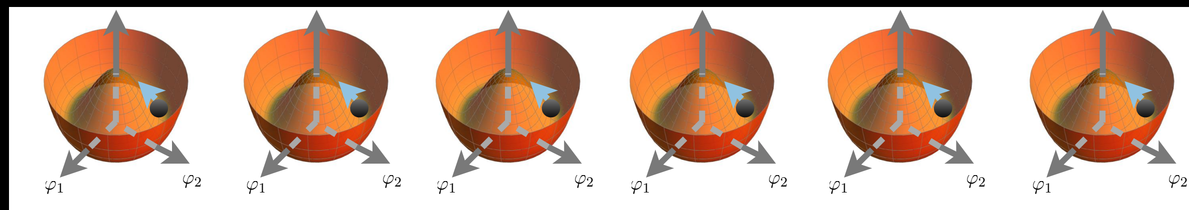
↓

Many axions

Ultra-light axions (ULAs) in string theory

- In string theory, extra dimensions compactified: Calabi-Yau manifolds





+....

Hundreds of scalars with approx shift symmetry

↓

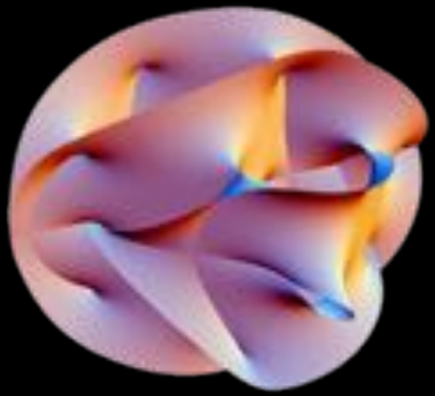
Many axions

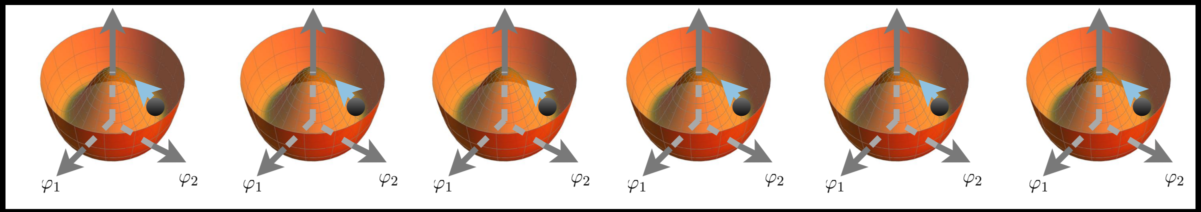
- Mass acquired non-perturbatively (instantons, D-Branes)

$$\boxed{m_a^2 = \frac{\mu^4}{f_a^2} e^{-\mathrm{Volume}}}$$

ULTRA-LIGHT AXIONS (ULAS) IN STRING THEORY

- In string theory, extra dimensions compactified: Calabi-Yau manifolds





+....

Hundreds of scalars with approx shift symmetry

Many axions

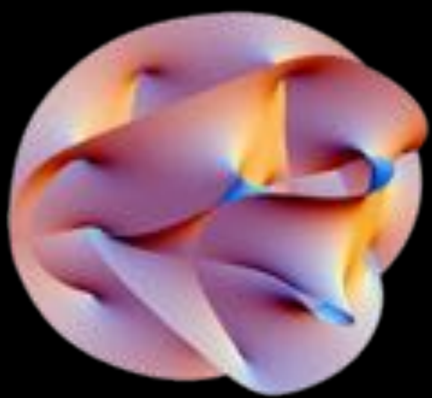
- Mass acquired non-perturbatively (instantons, D-Branes)

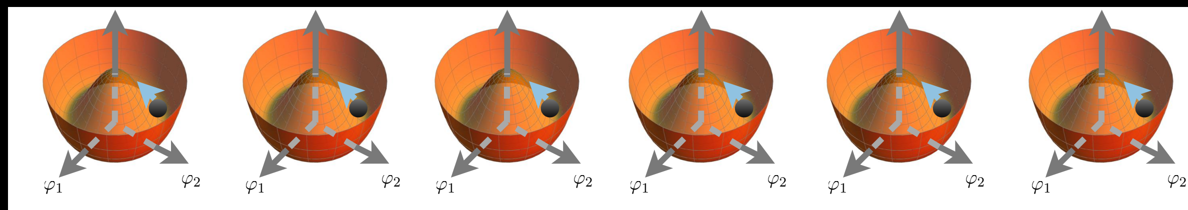
Scale of new ultra-violet physics

$$m_a^2 = \frac{\mu^4}{f_a^2} e^{-\mathrm{Volume}}$$

ULTRA-LIGHT AXIONS (ULAS) IN STRING THEORY

- In string theory, extra dimensions compactified: Calabi-Yau manifolds





+....

Hundreds of scalars with approx shift symmetry

Many axions

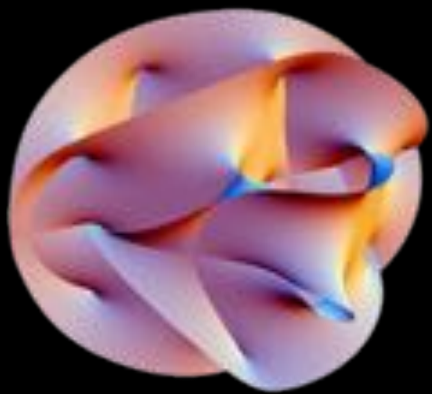
- Mass acquired non-perturbatively (instantons, D-Branes)

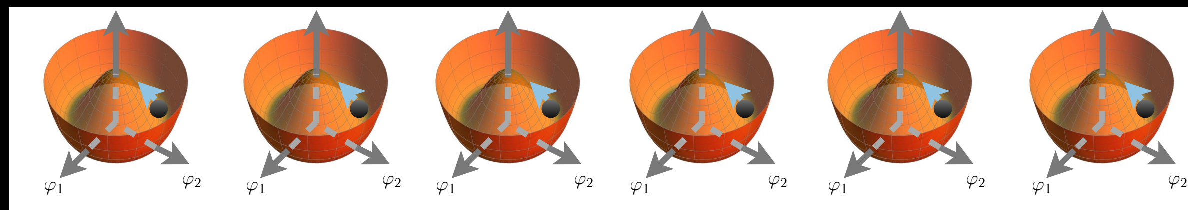
$$m_a^2 = \frac{\mu^4}{f_a^2} e^{-\text{Volume}}$$

Scale of extra dimensions in Planck units

Ultra-light axions (ULAs) in string theory

✴ In string theory, extra dimensions compactified: Calabi-Yau manifolds

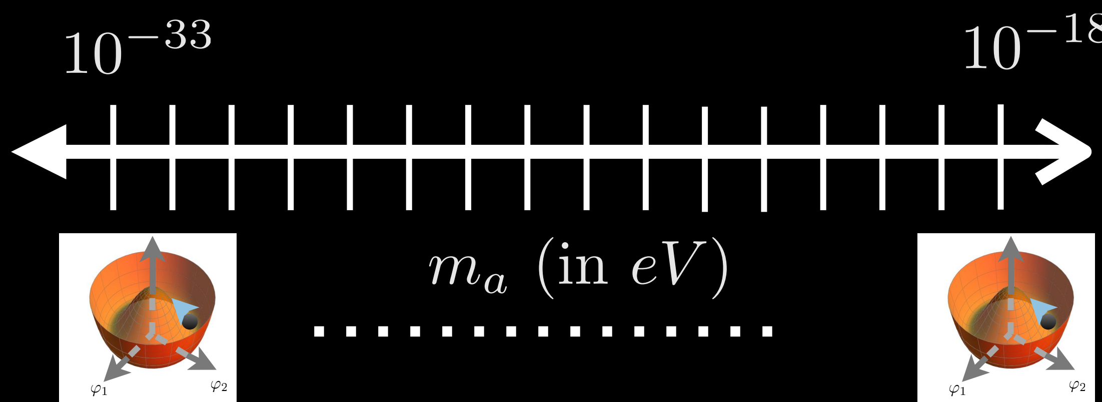




+....

Axiverse! *Arvanitaki+ 2009*

Witten and Srvcek (2006), Acharya et al. (2010), Cicoli (2012)



Testing ultra-light axions with cosmology

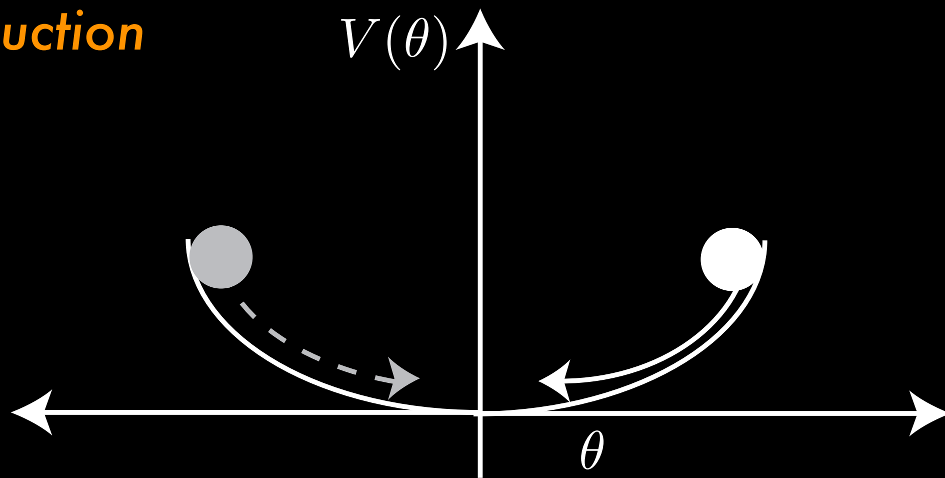
$$\boxed{10^{-33}\ \mathrm{eV} < m_a < 10^{-18}\ \mathrm{eV}}$$



R.Hlozek, DG, D.J.E. Marsh, P.Ferreira

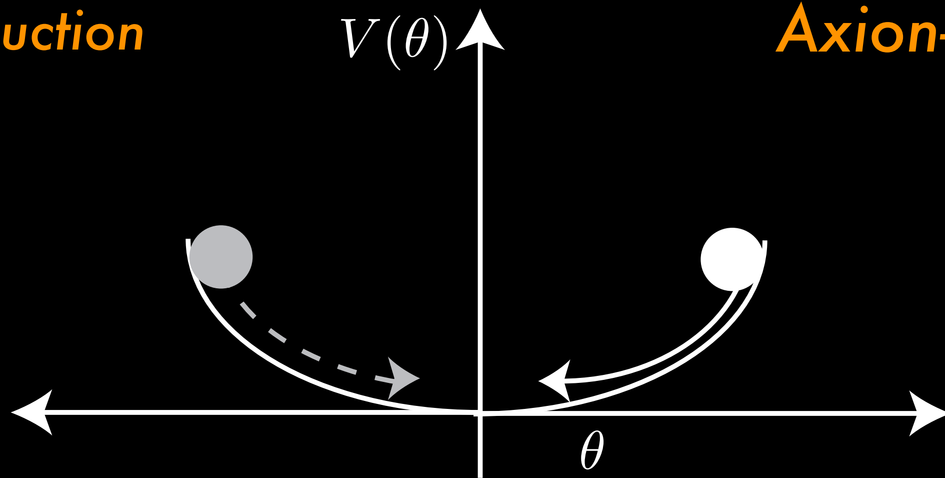
Cosmological axion evolution

Misalignment production



Cosmological axion evolution

Misalignment production | *Axion-driven acceleration*

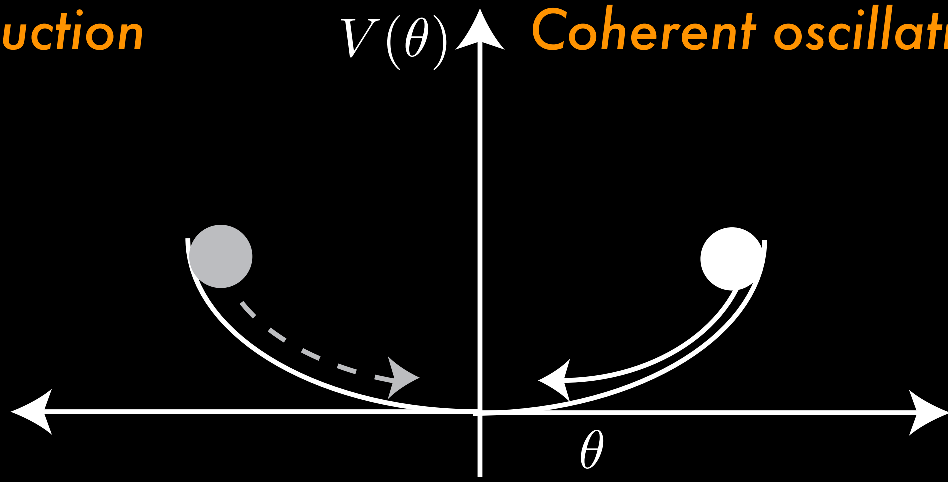


$$\boxed{m \ll 3H \to n_a \propto \ \mathrm{const}, w_a \equiv \frac{P_a}{\rho_a}, w_a \simeq -1}$$

$$m \gg 3H \to n_a \propto a^{-3}, \langle w_a \rangle_{T=2\pi/m_a} = 0$$

Cosmological axion evolution

Misalignment production *Coherent oscillation, Axions act like CDM*

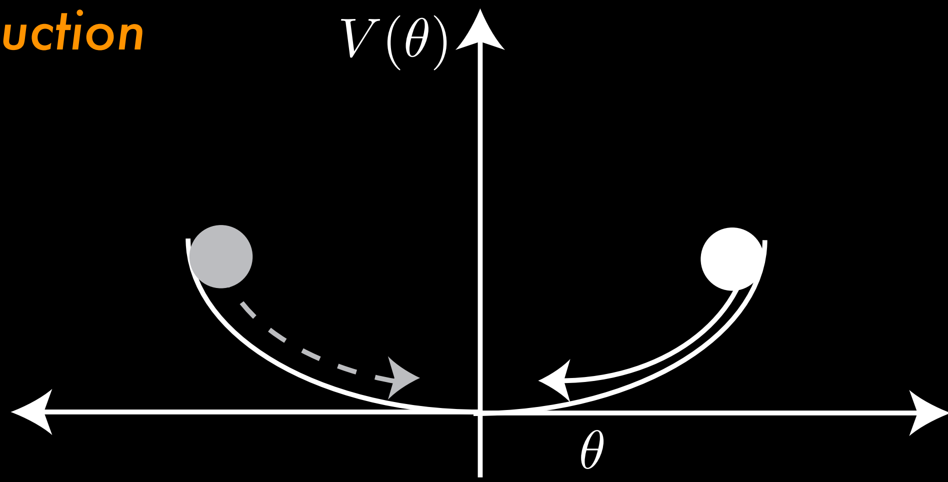


$$m \ll 3H \to n_a \propto \ \mathrm{const}, w_a \equiv \frac{P_a}{\rho_a}, w_a \simeq -1$$

$$\boxed{m \gg 3H \to n_a \propto a^{-3}, \langle w_a \rangle_{T=2\pi/m_a} = 0}$$

Cosmological axion evolution

Misalignment production

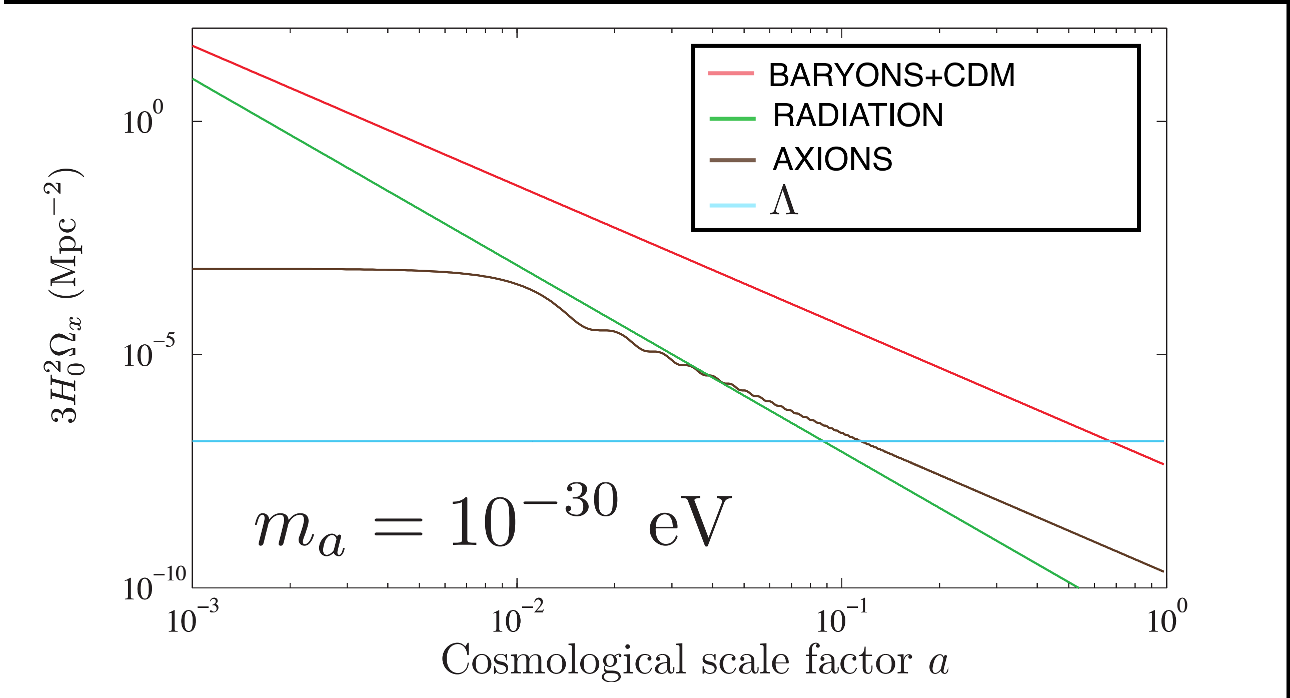


For QCD axion, we have a CDM candidate!

$$\Omega_{\text{mis}} h^2 = 0.236 \left\langle \theta_i^2 f(\theta_i) \right\rangle \left(\frac{m_a}{6.2 \mu\text{eV}} \right)^{-7/6}$$

Cosmological axion evolution

Different parameter space for non-QCD axion(Frieman et al 1995, Coble et al. 2007)



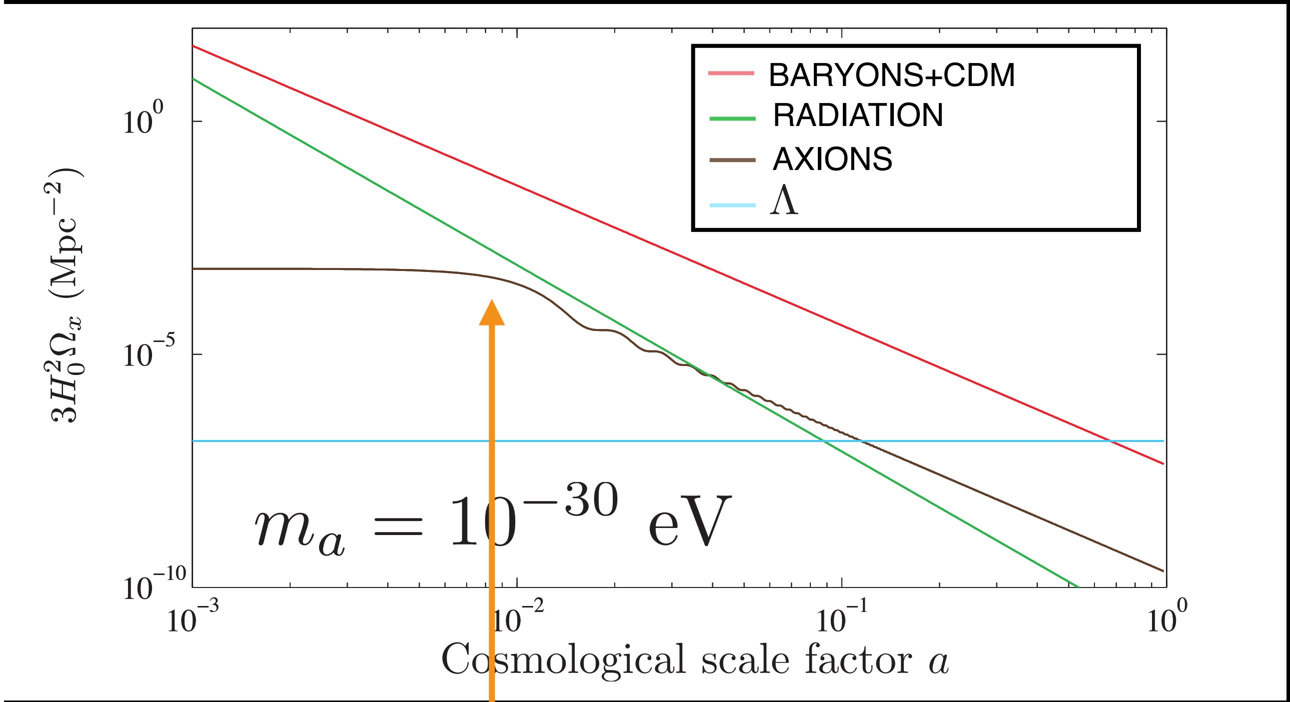
10^{-33} eV $< m_a < 10^{-18}$ eV

$$\Omega_a \propto \left(f_a \overline{\theta}\right)^2 \sqrt{m_a}$$

Cosmological axion evolution

Different parameter space for non-QCD axion(Frieman et al 1995, Coble et al. 2007)

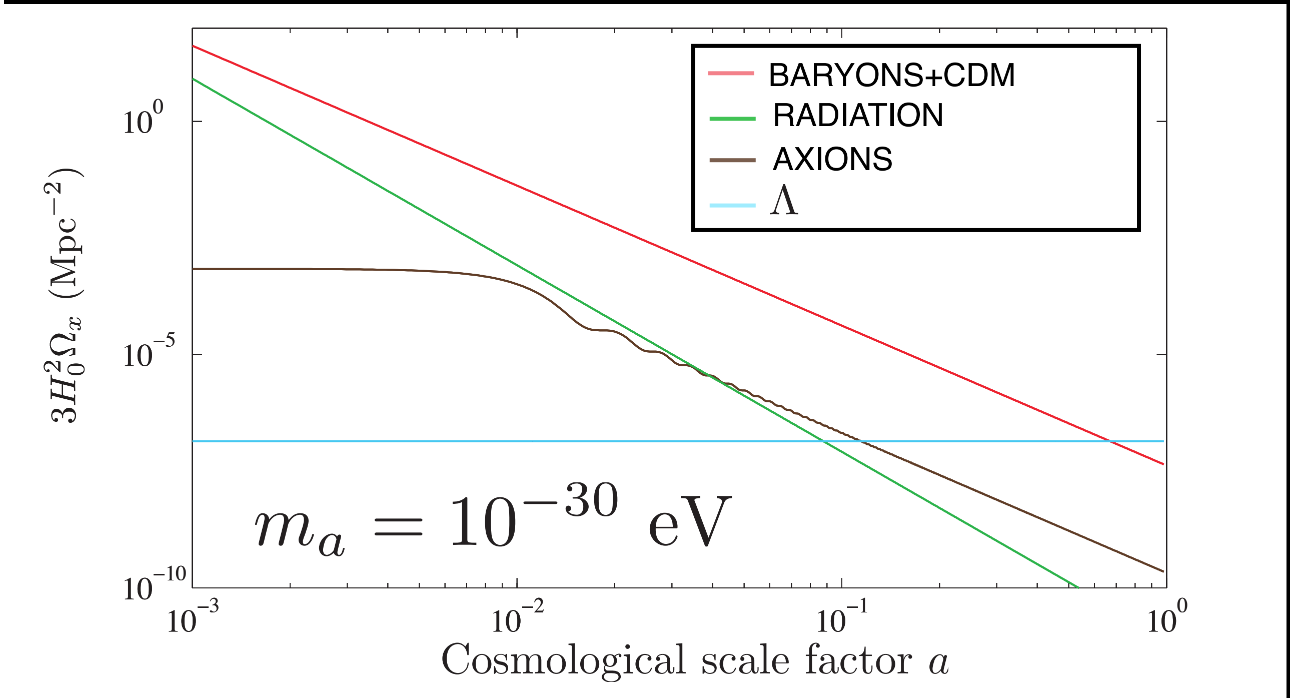
$$10^{-33}\ \text{eV} < m_a < 10^{-18}\ \text{eV}$$



$$a \equiv a_{\rm osc} \quad m_a = 3H(a)$$

Cosmological axion evolution

Different parameter space for non-QCD axion(Frieman et al 1995, Coble et al. 2007)



10^{-33} eV $< m_a < 10^{-18}$ eV

'DM' axions $a_{\rm osc} < a_{\rm eq}$ *Oscillation starts in time for struct. formation*

$m_a > 10^{-27}$ eV

DE axions $a_{\rm osc} > a_{\rm eq}$ *Oscillation starts too late for struct. formation*

$m_a < 10^{-27}$ eV

Growth of ULA perturbations

- Perturbed Klein-Gordon + Gravity

$$\ddot{\delta\phi} + 2\mathcal{H}\dot{\delta\phi} + (k^2 + m_a^2 a^2)\delta\phi = 4\dot{\Psi}\dot{\phi}_0 - \Psi a^2 m_a^2 \phi_0$$

- Axionic Jeans Scale is macroscopic [in contrast to QCD axion]:

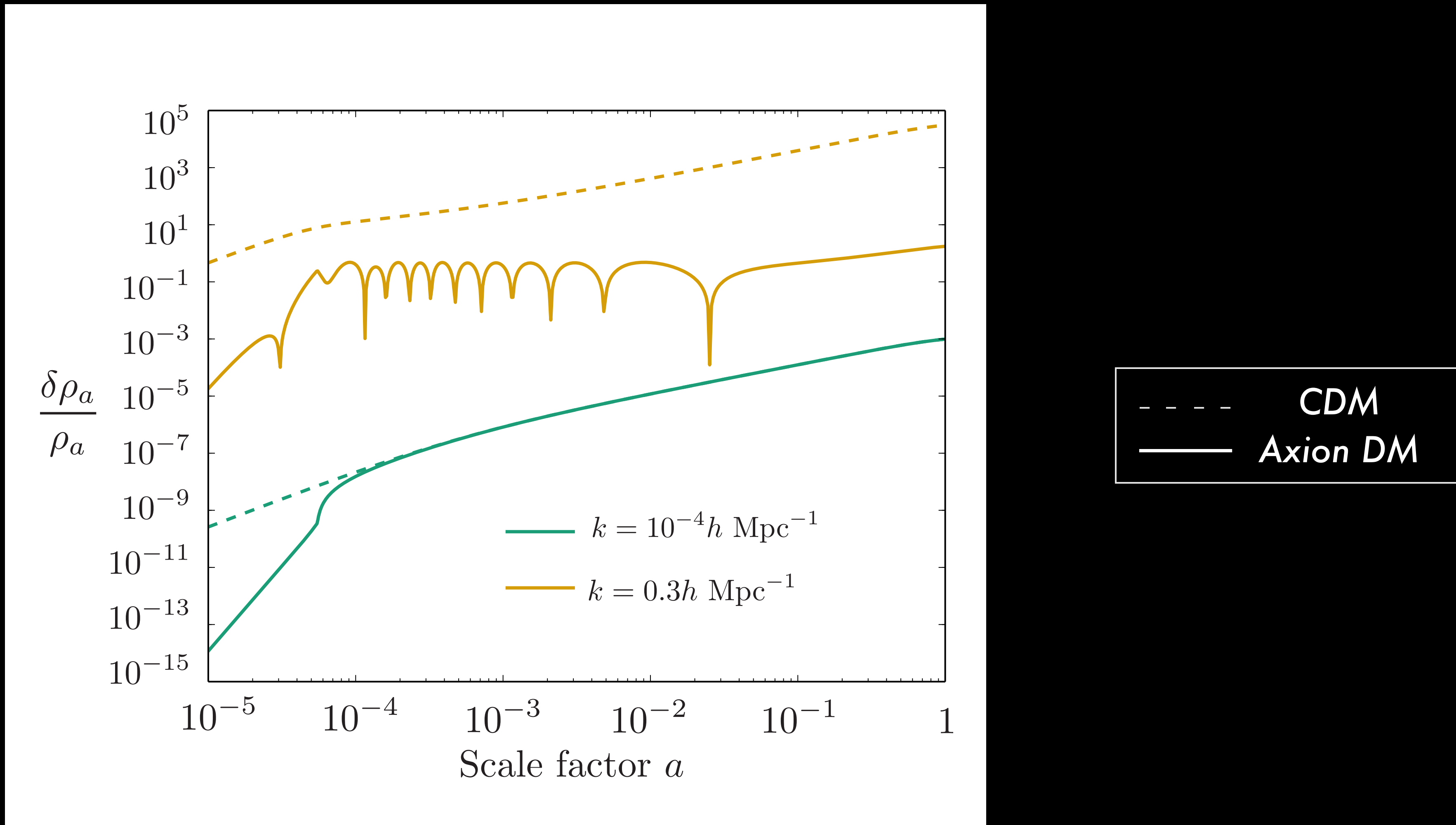
$$\boxed{\lambda_J = 2.4 h^{-1/2}\left(\frac{m}{10^{-25}\ \mathrm{eV}}\right)^{-1/2}\ \mathrm{Mpc}}$$

- Computing observables is expensive for $m \gg 3\mathcal{H}$:
  - Coherent oscillation time scale $\Delta\eta \sim (ma)^{-1} \ll \Delta\eta_{\mathrm{CAMB}}$
  - WKB approximation

$$\delta\phi = A_c\Delta_c(k,\eta)\cos(m\eta) + A_s\Delta(k,\eta)\sin(m\eta)$$

$$\boxed{c_a^2 = \frac{\delta P}{\delta\rho} = \frac{k^2/(4m^2a^2)}{1 + k^2/(4m^2a^2)}}$$

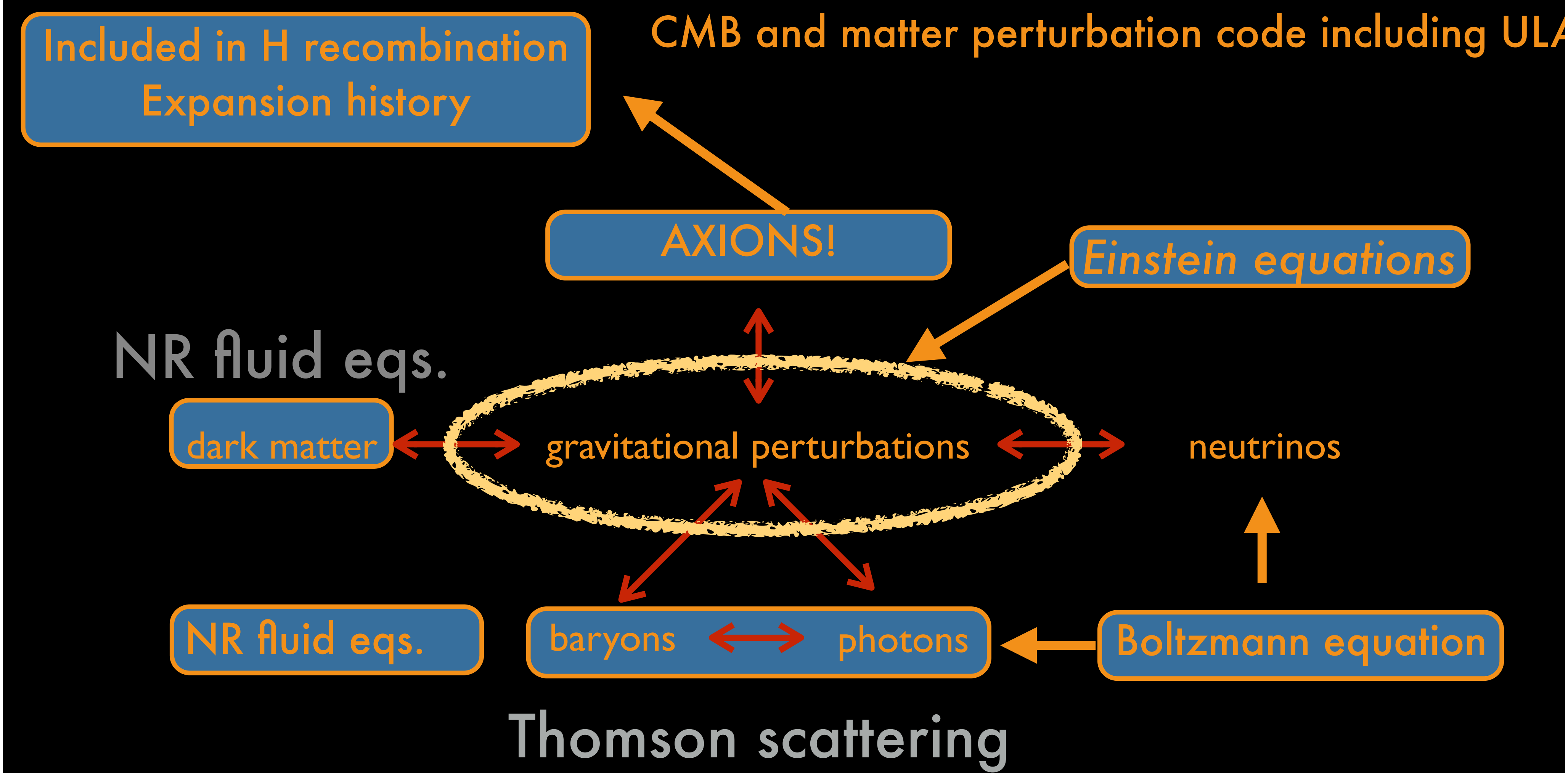
Growth of ULA perturbations



✳Modes with $k \gg k_{\rm J} \sim \sqrt{m\mathcal{H}}$ oscillate instead of growing

AXIONCAMB

CMB and matter perturbation code including ULAs!



ULA of any mass is self-consistently followed from DE to DM regime

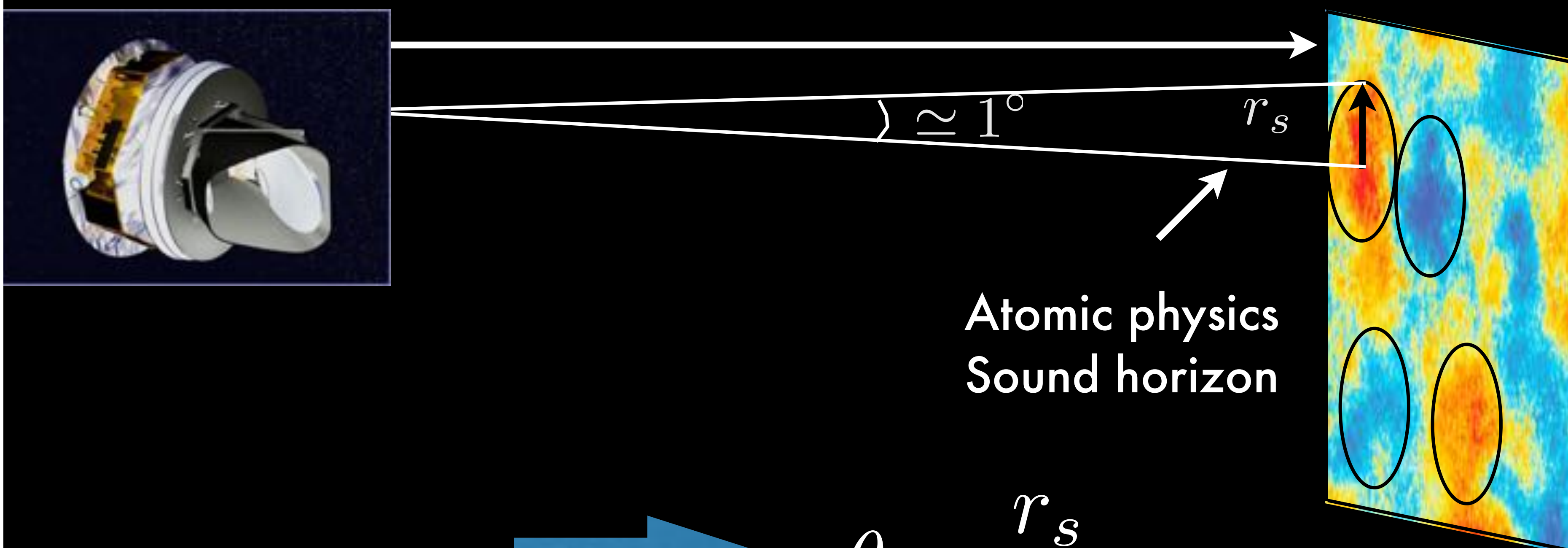
AxionCAMB

Code by Grin et al. 2013, based on CAMB (A. Lewis)
http://github.com/dgrin1/axionCAMB

Please download, comment, test, poke, and improve it!

ULAs as dark energy and the angular sound horizon

D (sensitive to any energy source)



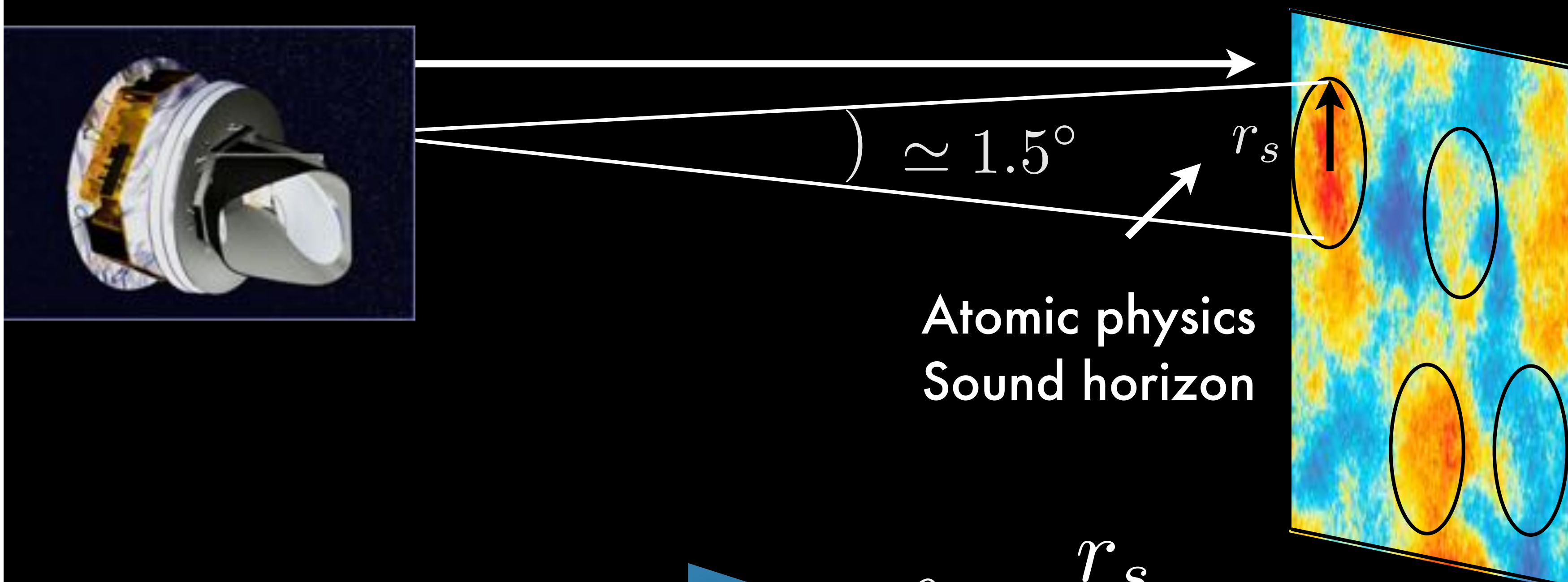
$$\theta = \frac{r_s}{D}$$

Fig. modified from T. Smith with permission

Faster early expansion brings LSS closer

ULAs as dark energy and the angular sound horizon

D (sensitive to any energy source)



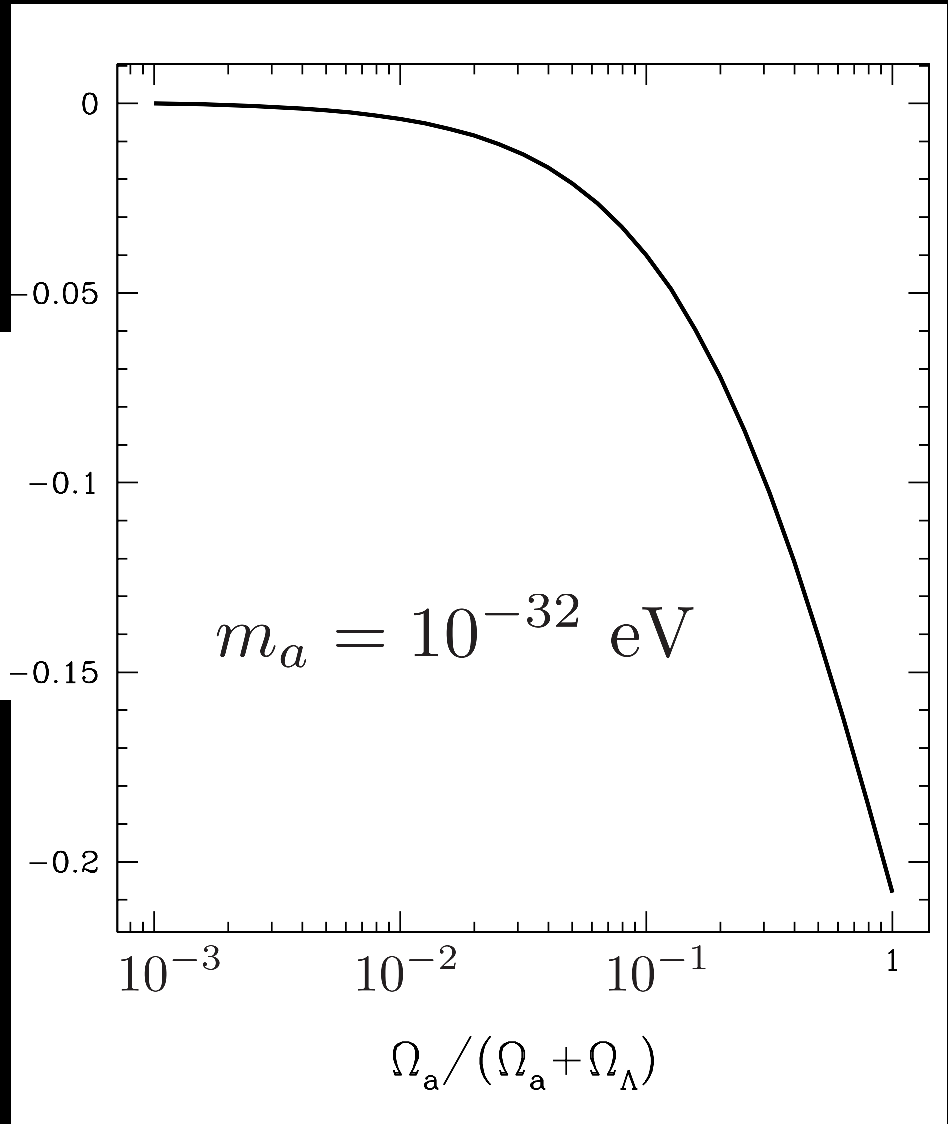
$$\rightarrow \quad \theta = \frac{r_s}{D}$$

Fig. modified from T. Smith with permission

Faster early expansion brings LSS closer

ULAs as dark energy and the angular sound horizon

$$\frac{D(z_{\mathrm{decoupling}}) - D^{\mathrm{axion}}(z^{\mathrm{axion}}_{\mathrm{decoupling}})}{D(z_{\mathrm{decoupling}})}$$



Faster early expansion brings LSS closer

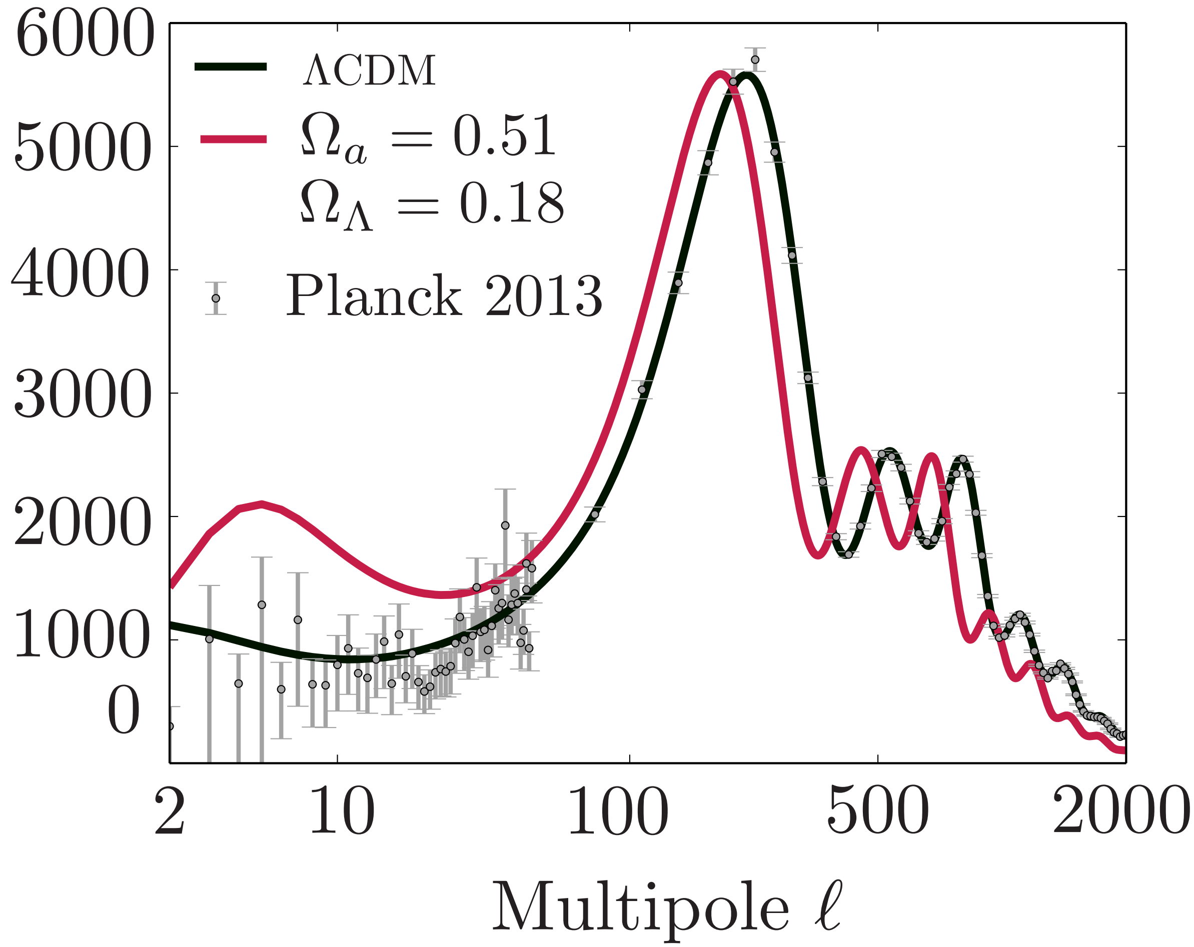
ULAs as dark energy

$$m_a = 10^{-32}\ \text{eV}$$

Temperature Variance

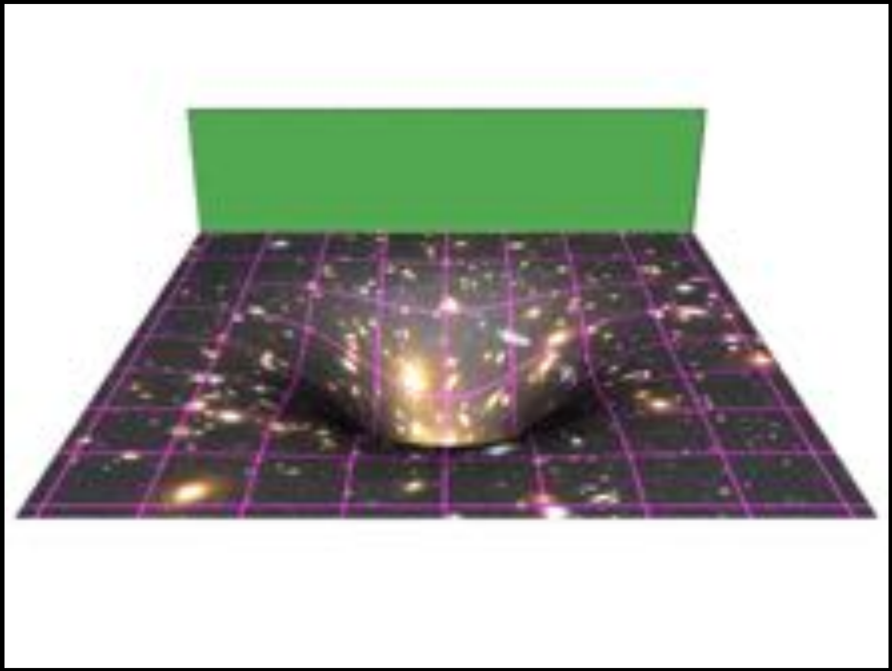
$$\mu\text{K}^2$$

$$\frac{\ell(\ell+1)C_\ell^{\mathrm{TT}}}{2\pi}$$



ULAs and the CMB: high mass and early ISW

Higher mass (DM-like) case: high-l ISW

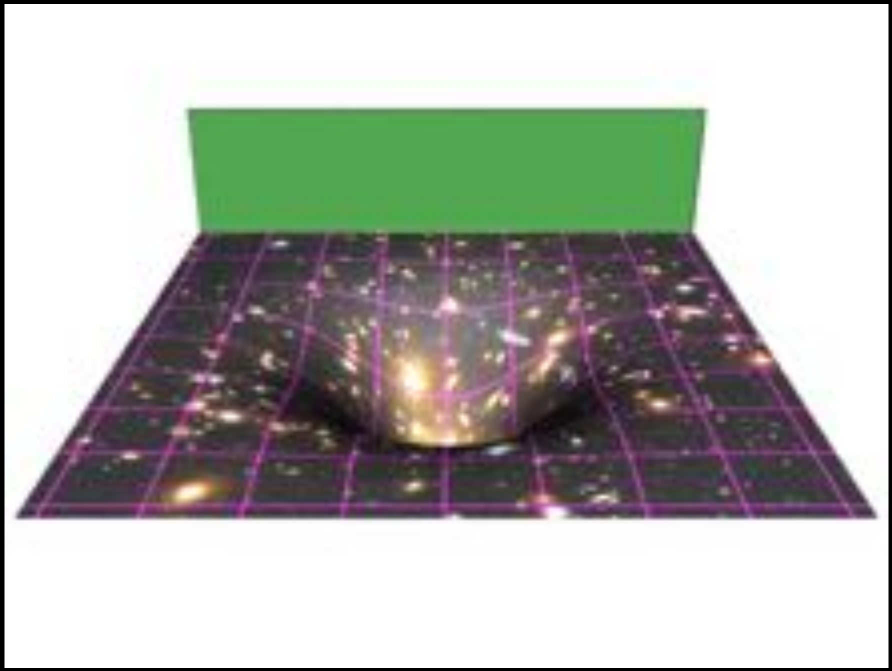


CMB temperature anisotropies from potential decay

$$\Delta T_{\mathrm{ISW}} = -2\int_0^{\eta_{\mathrm{dec}}} d\eta \dot{\Phi}(\eta, \hat{n}\eta)$$

ULAs and the CMB: high mass and early ISW

Higher mass (DM-like) case: high-l ISW

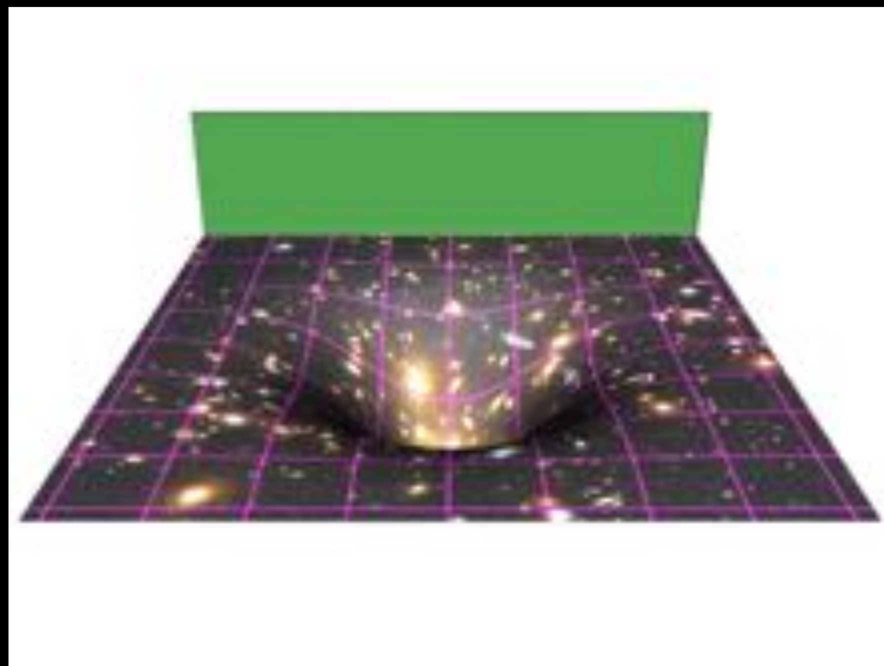


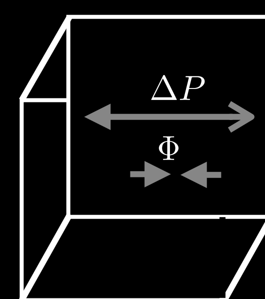
CMB temperature anisotropies from potential decay

$$\Delta T_{\rm ISW} = -2\int_0^{\eta_{\rm dec}} d\eta\dot{\Phi}(\eta,\hat{n}\eta)$$

ULAs and the CMB: high mass and early ISW

Higher mass (DM-like) case: high-l ISW



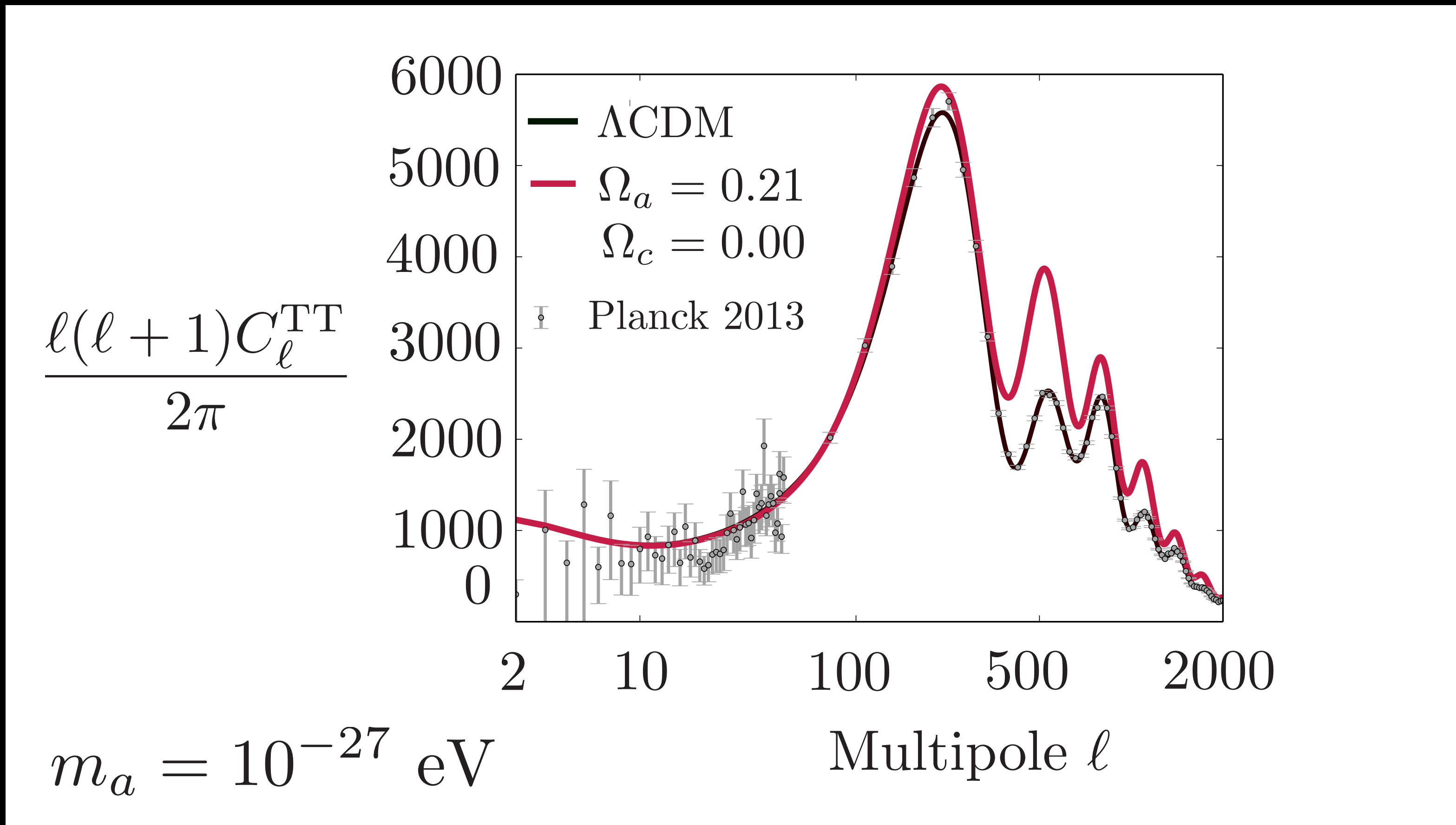


Radiation pressure causes potential decay

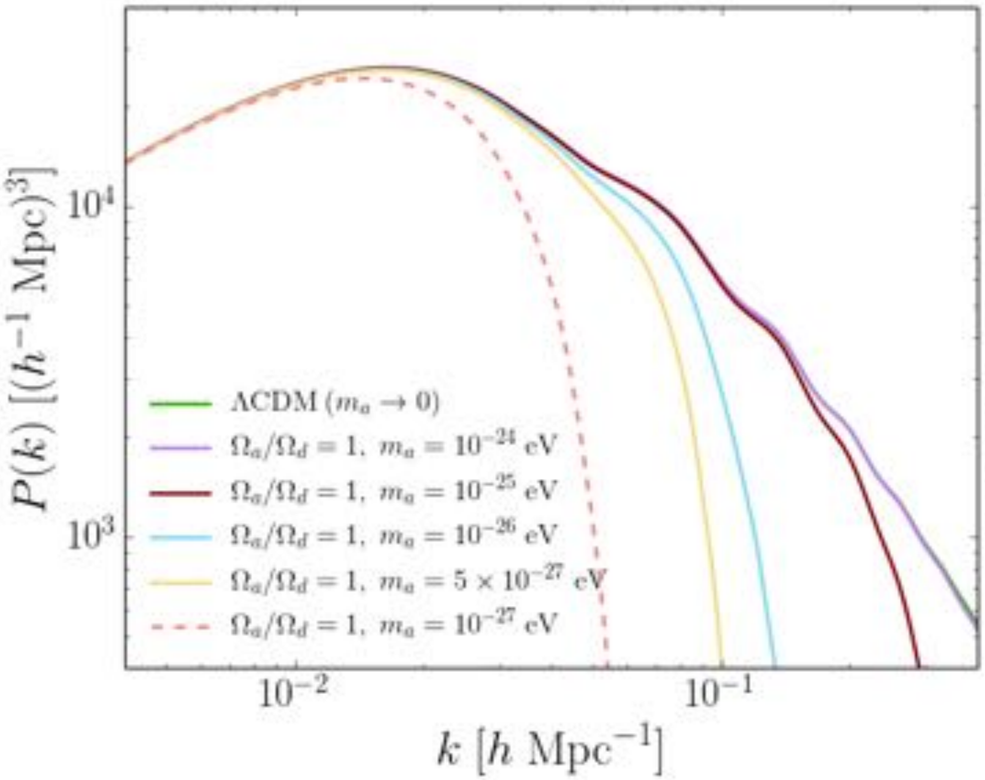
$$\Delta P \Delta A > \rho \delta V \nabla \Phi$$

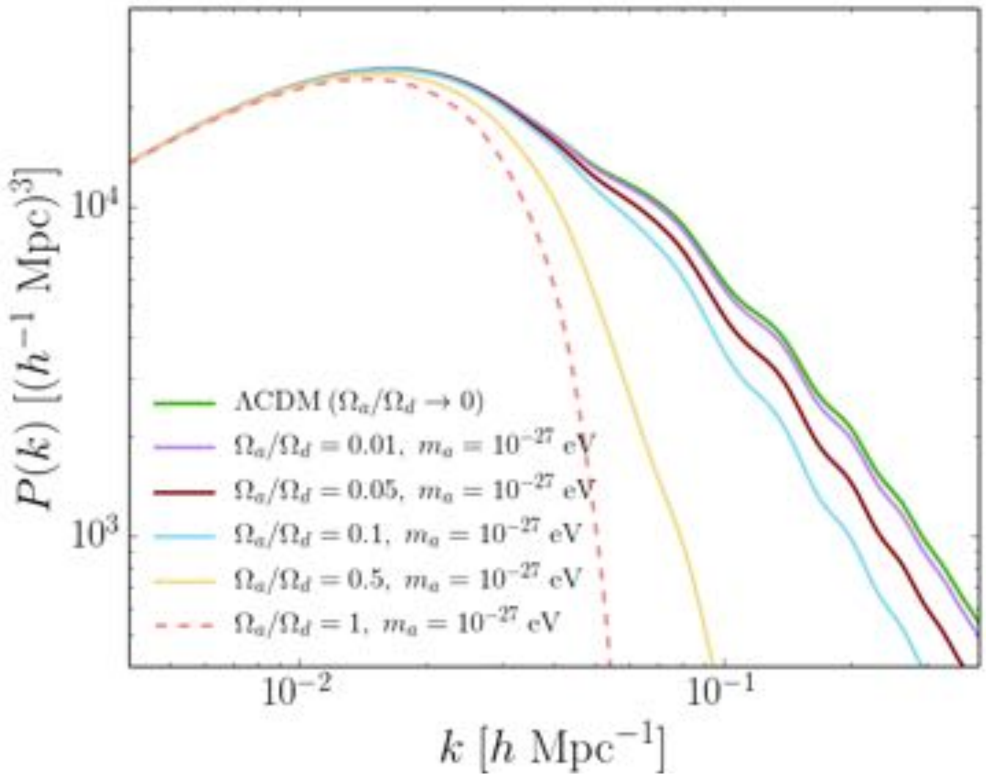
ULAs and the CMB: high mass and early ISW

Higher mass (DM-like) case: high-l ISW



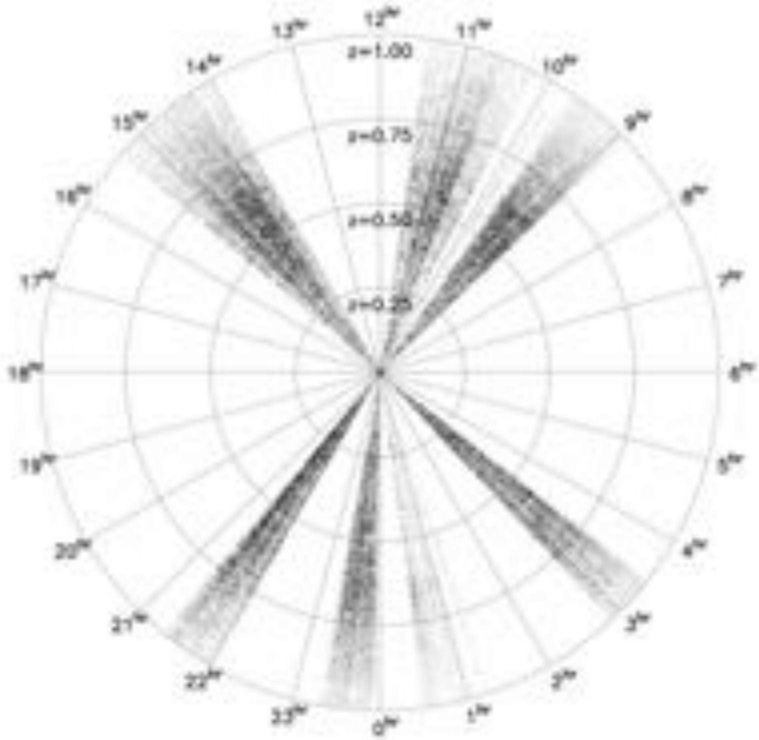
Matter power spectrum for ULA (in DM regime)

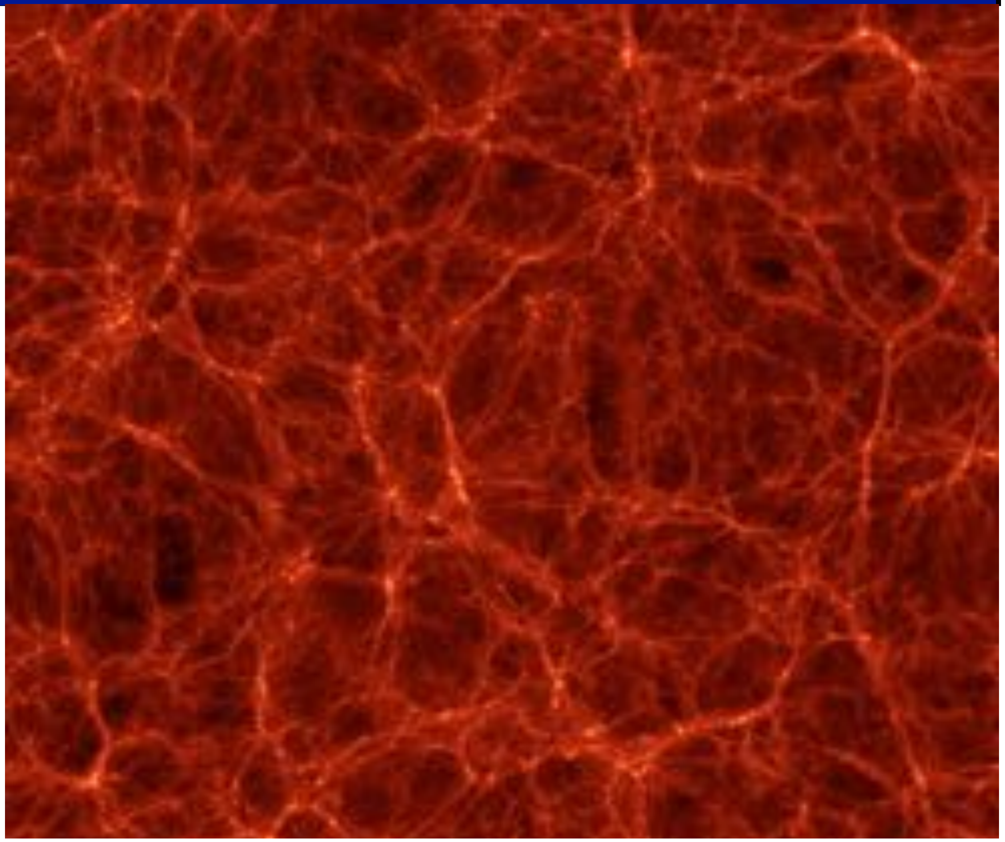




- ✳DM perturbation growth severely suppressed if $k > k_J \simeq \sqrt{m\mathcal{H}}$
- ✳Suppression $\propto -\dfrac{\Omega_a}{\Omega_a + \Omega_c}$
- ✳Analogous to effect of neutrinos

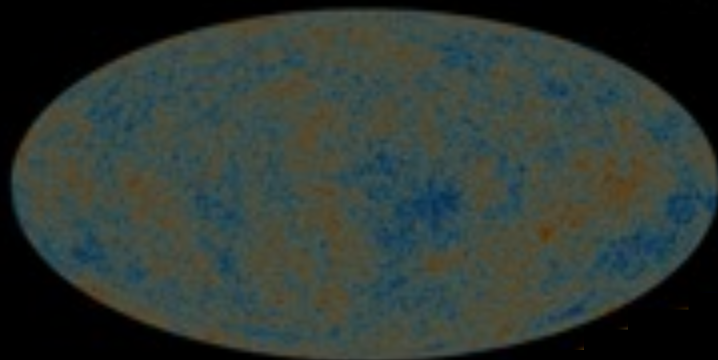
Matter power spectrum for ULA (in DM regime)





- DM perturbation growth severely suppressed if $k > k_J \simeq \sqrt{m\mathcal{H}}$
- Suppression $\propto -\dfrac{\Omega_a}{\Omega_a + \Omega_c}$
- Analogous to effect of neutrinos

DATA + ANALYSIS

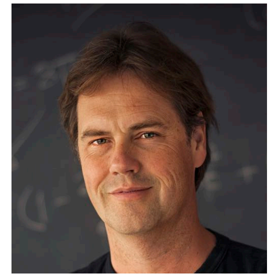


- ✳Planck 2013 temperature anisotropy power spectra (+SPT+ACT)
  - ✳Cosmic variance limited to $\ell \sim 1500$
- ✳WiggleZ galaxy survey (linear scales only $k \lesssim 0.2h\ \mathrm{Mpc}^{-1}$)
  - ✳240,000 emission line galaxies at z<1
  - ✳3.9 m Anglo-Australian Telescope (AAT)
- ✳Nested sampling, MCMC, vary $m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$

CONSTRAINTS

Comparison with data

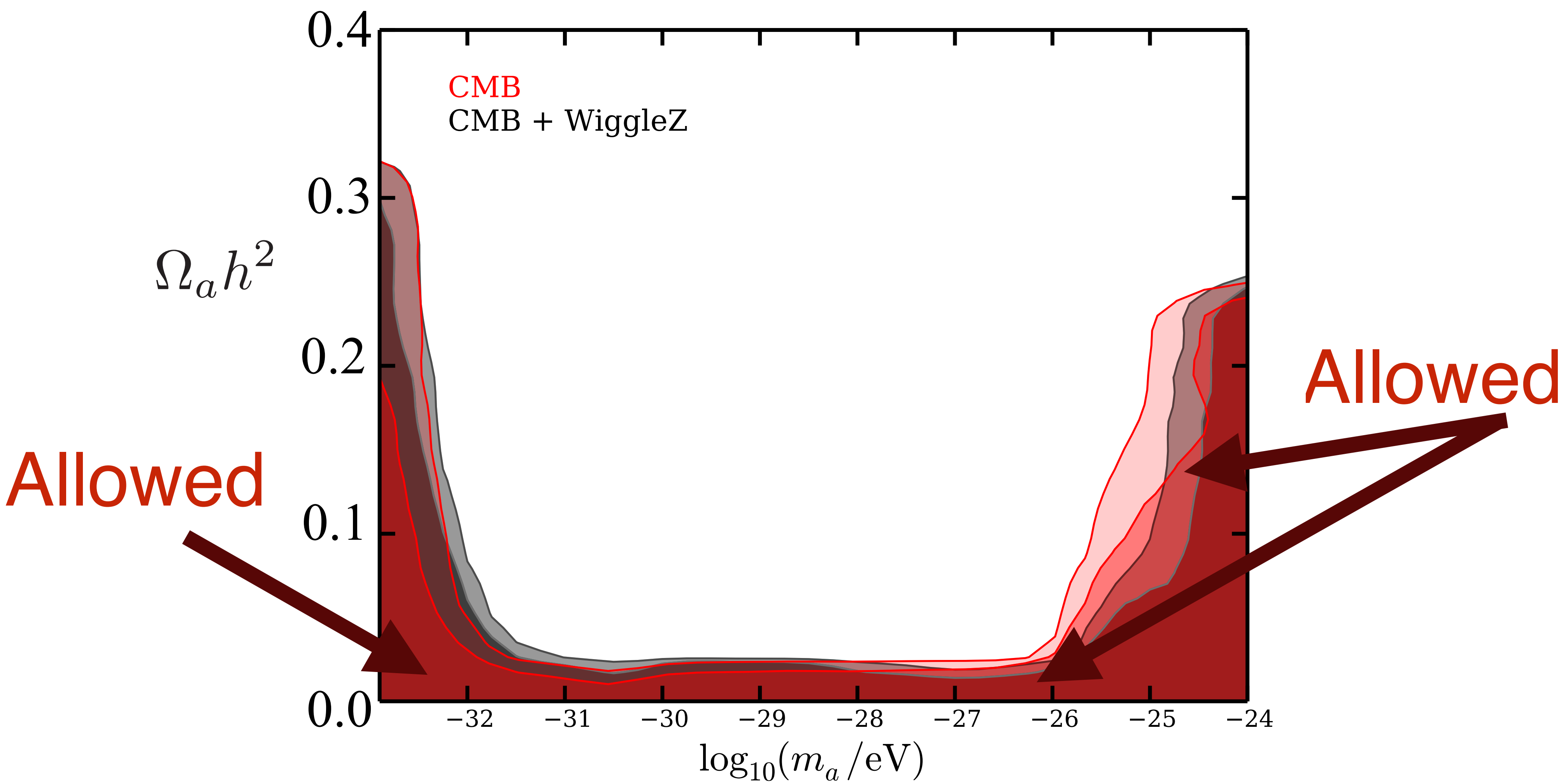


R.Hlozek, DG, D.J. E. Marsh, P.Ferreira

arXiv:1410.2896, Phys. Rev. D 91, 103512 (2015)
arXiv:1403.4216, Phys. Rev. Lett. 113, 011801 (2014)
arXiv:1303.3008, Phys. Rev. D 87, 121701(R) (2013)

CONSTRAINTS



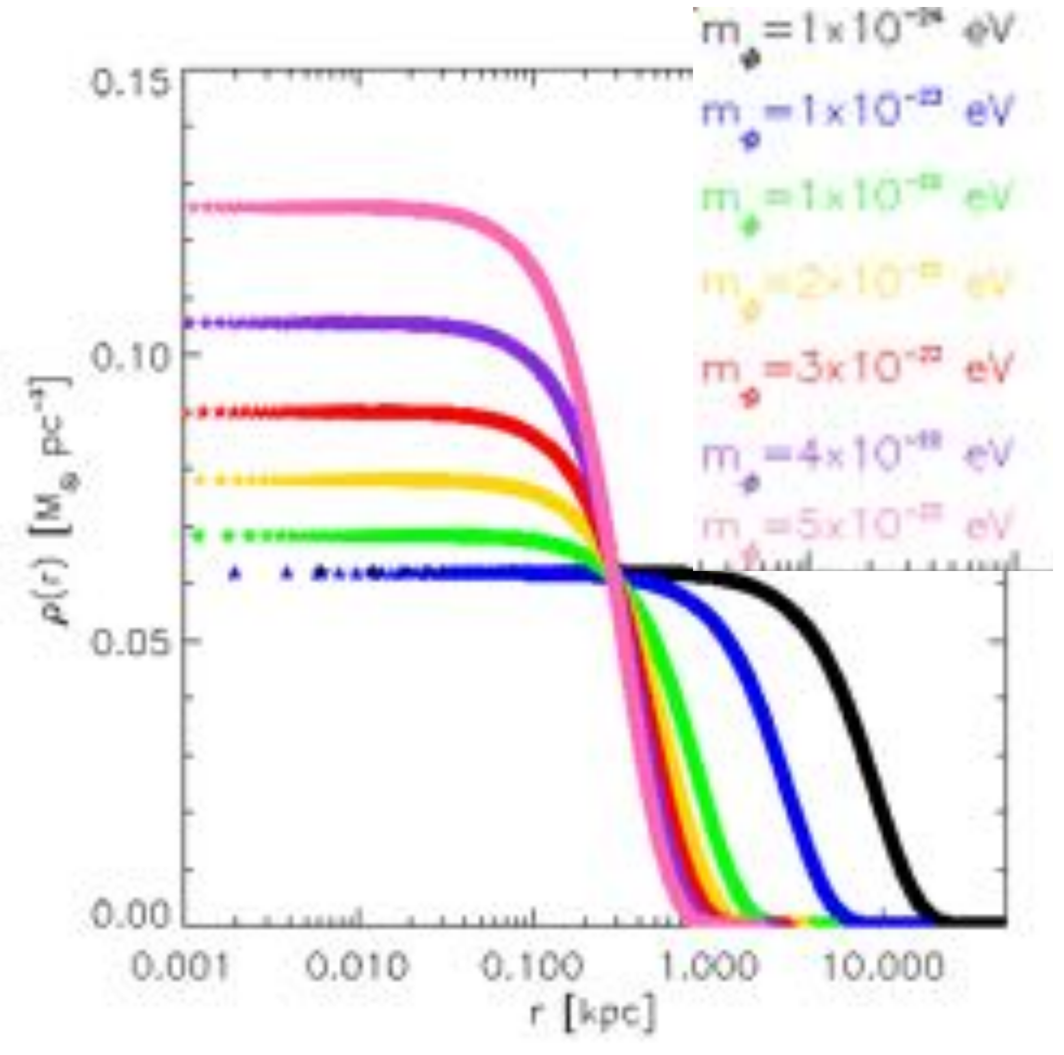
✴Tight constraints over 7 orders of magnitude in mass:

Thanks to AxiCamb and Planck

✴ULAs are viable DM/DE candidates in linear theory outside ``belly”

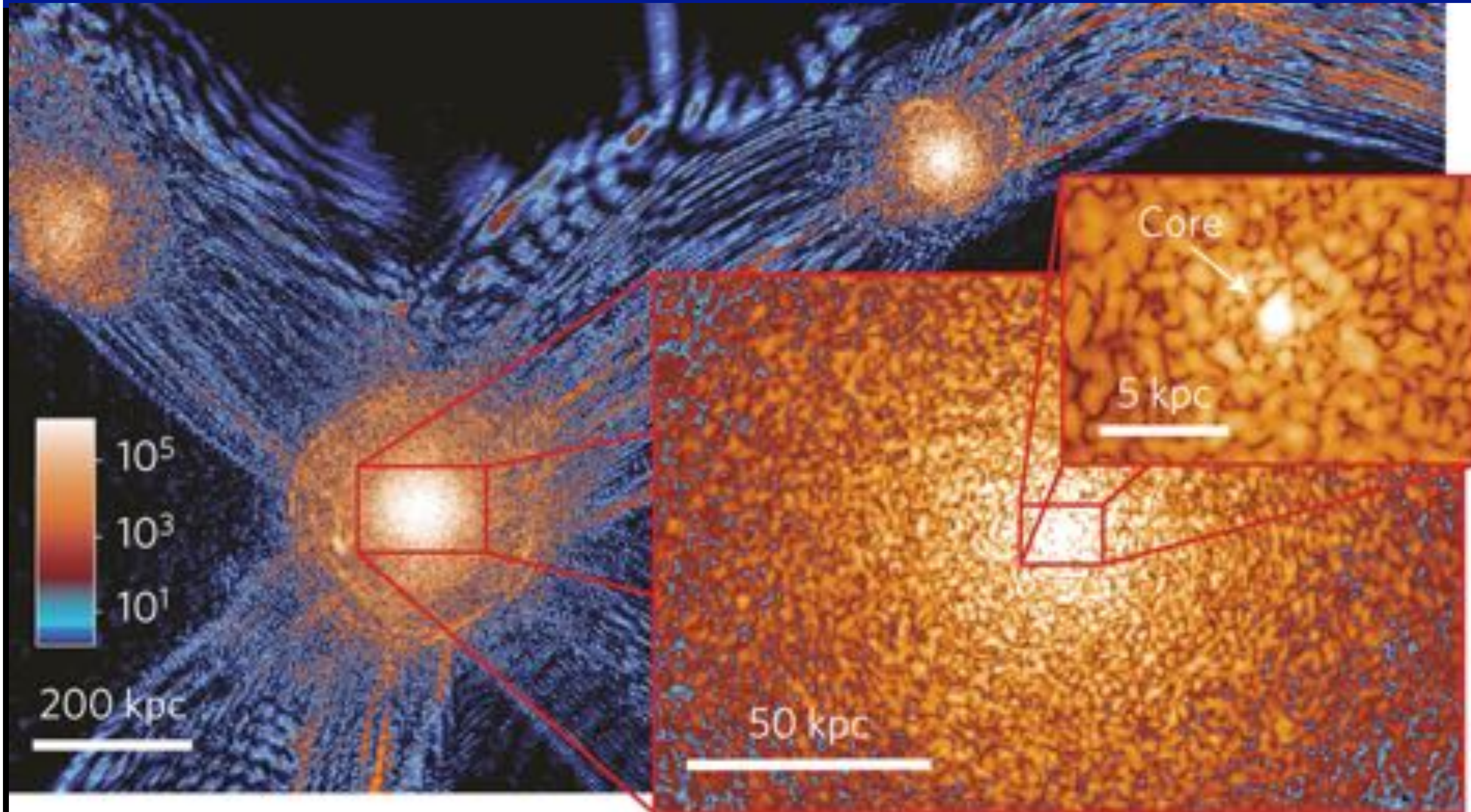
What's next?

FUTURE WORK: ULAS CORES + CUSPS?



Cores! (Hu/Gruzinov/Barkana 2001, see also Marsh and Silk 2013, Marsh and Pop 2015, Matos 2012, Schive 2014, and others)

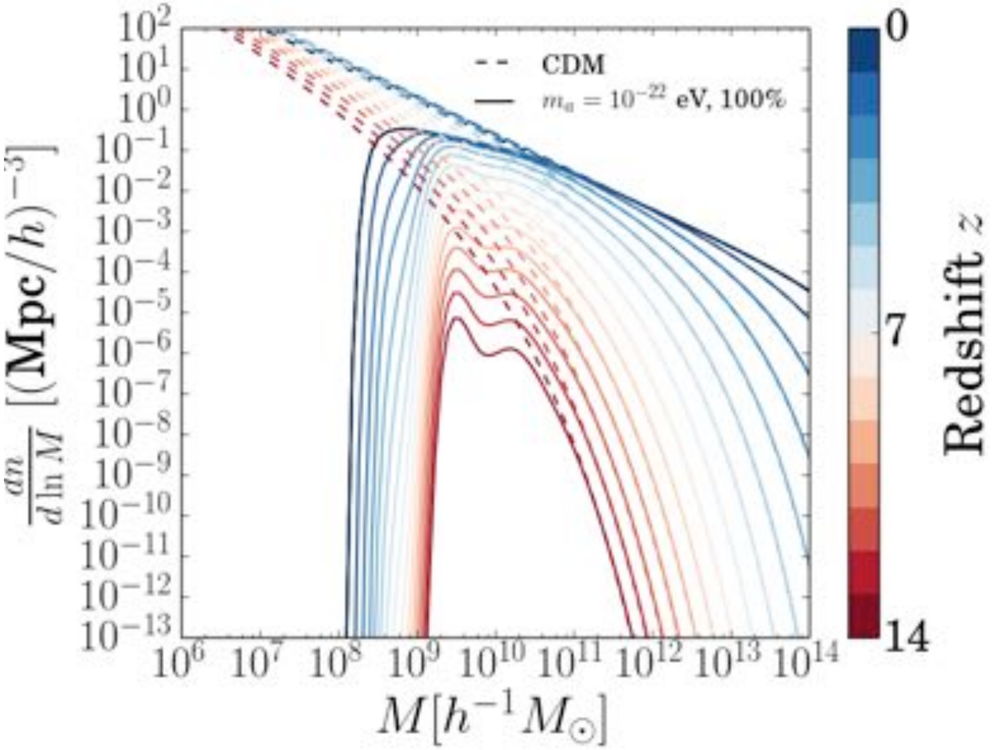
Future work: ULAs cores + cusps?

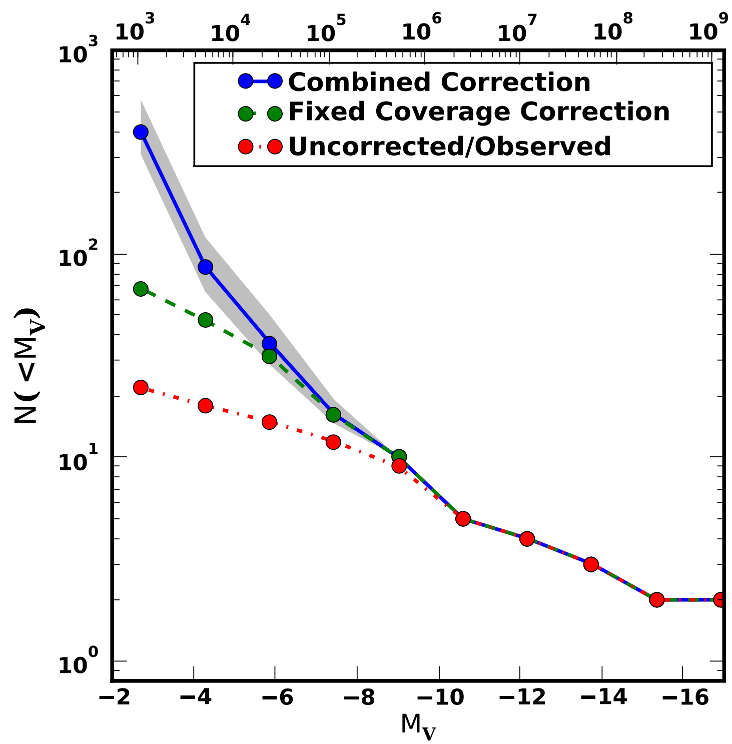


From Schive et al., more cosmological volume needed for statistics, baryons, etc...

Future work: ULAs and galaxies

Missing satellite problem?





Hui, Ostriker, Tremaine and Witten 2016

Marsh et al 2014, Klypin 1999, Bullock 2010

Dynamical friction, tidal disruption, substructure, FDM disks?, globular cluster orbits in Fornax dwarf, halo model, spherical collapse, better simulations (much work to be done!)

IMPROVING THEORETICAL PREDICTIONS

- Hard switch from scalar-field evolution (KG equation) to 0th-order WKB (fluid) description

$m \gg 3\mathcal{H}$ $\delta\phi = A_c \Delta_c(k,\eta)\cos(m\eta) + A_s \Delta(k,\eta)\sin(m\eta)$

$$\boxed{c_a^2 = \frac{\delta P}{\delta \rho} = \frac{k^2/(4m^2a^2)}{1+k^2/(4m^2a^2)}}$$

- Real mode functions not sines and cosines!
- Corrections to WKB near match-point

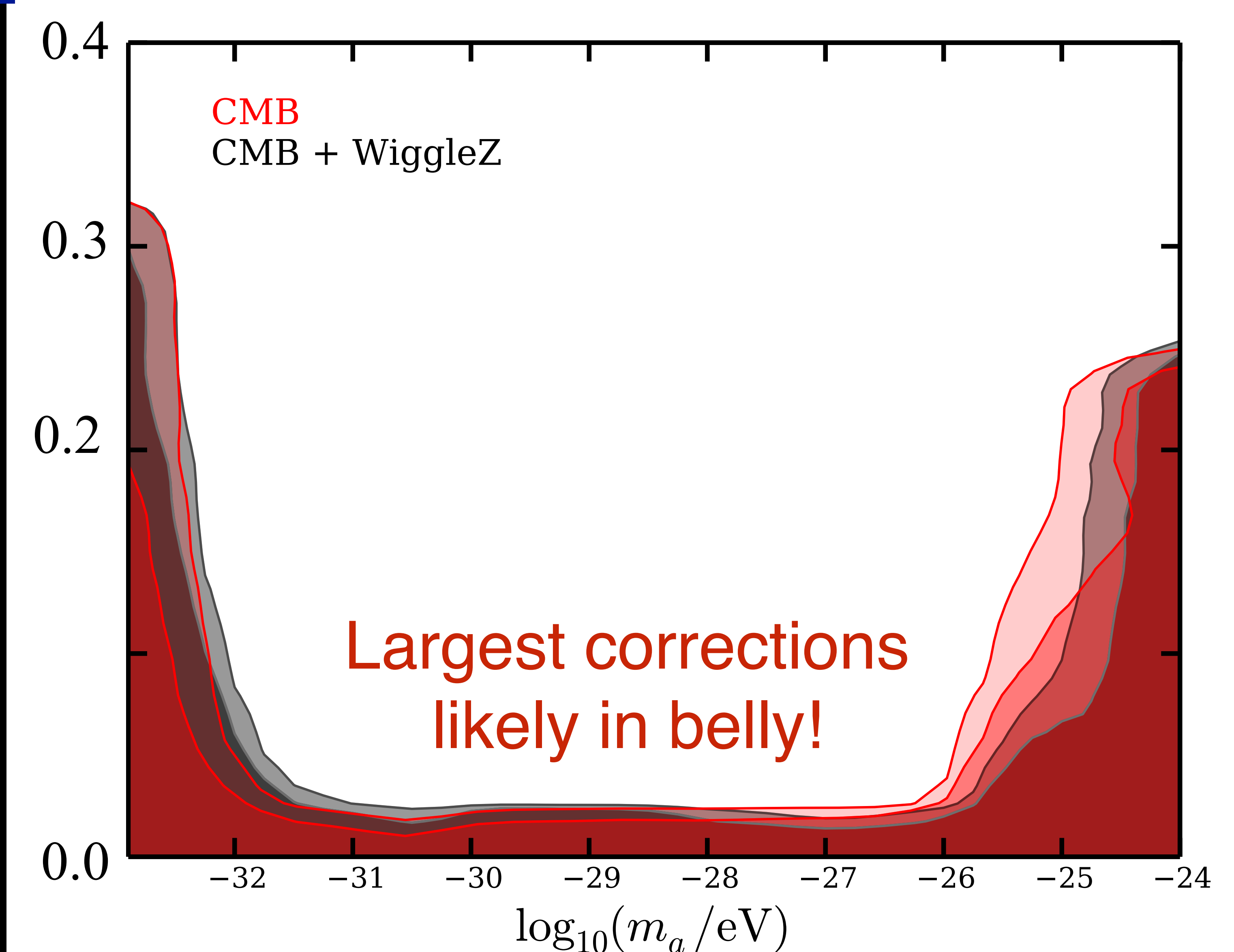
IMPROVING THEORETICAL PREDICTIONS

Work in progress,
J. Cookmeyer
HC 2017

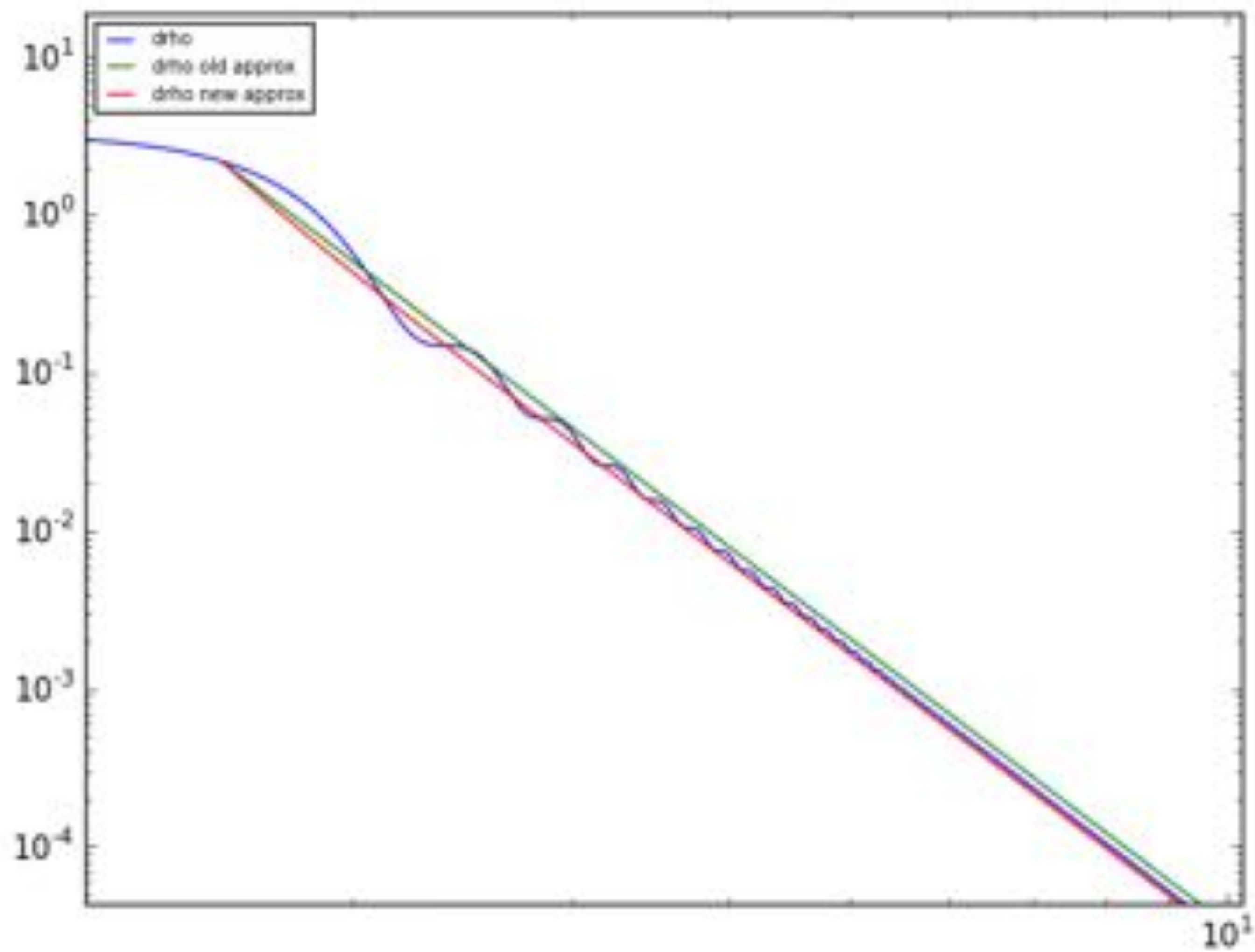
$$c_s^2 = \frac{k^2/(4m_a^2a^2)}{1+k^2/(4m_a^2a^2)} + \left(\frac{\mathcal{H}}{m_a}\right)^2 g(k,\eta,m_a)$$

IMPROVING THEORETICAL PREDICTIONS

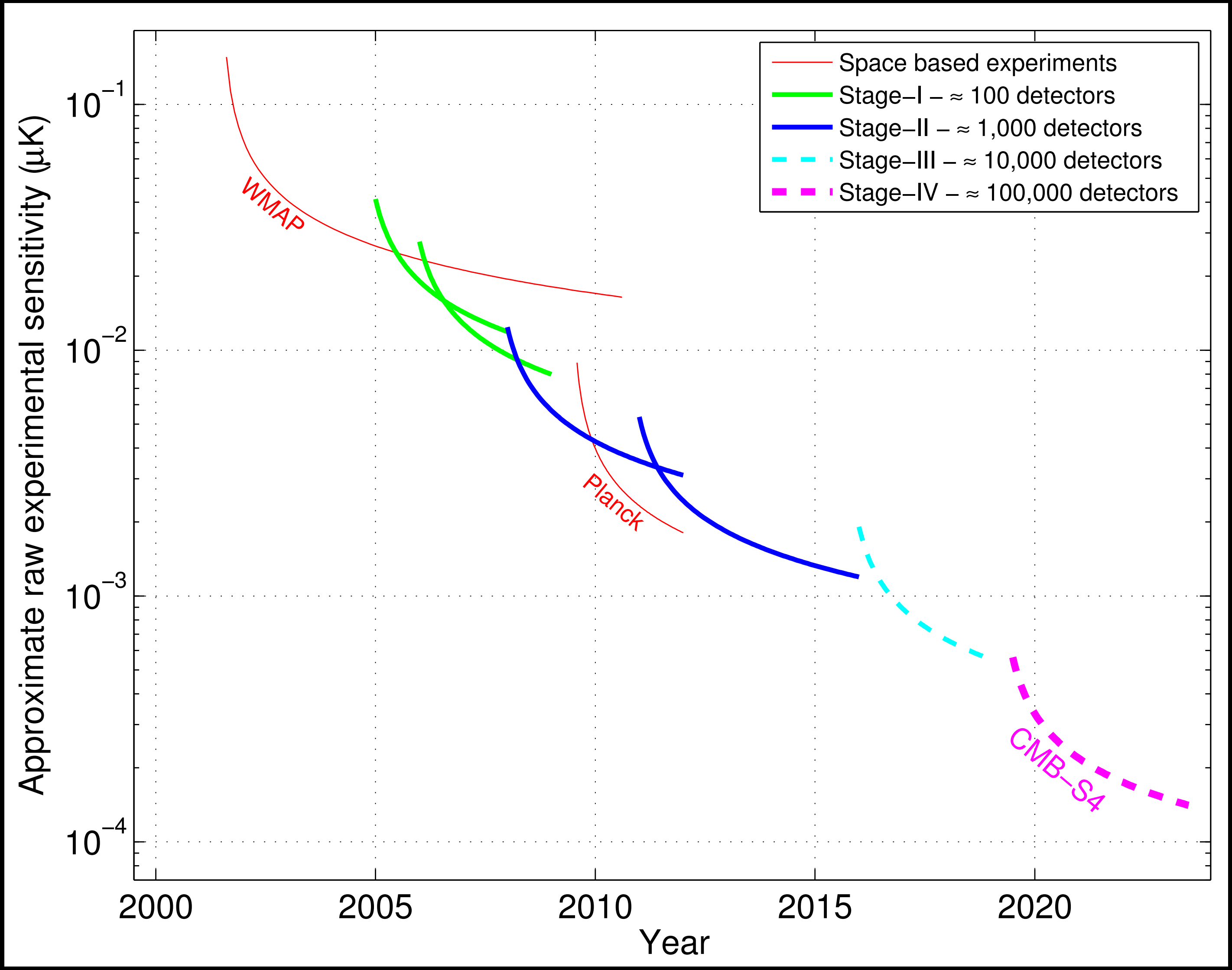
Work in progress, J. Cookmeyer HC 2017



Work in progress,
J. Cookmeyer
HC 2017



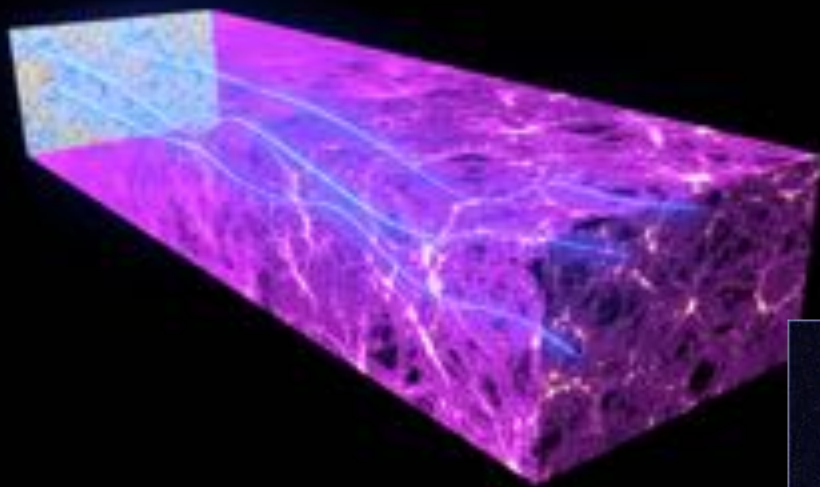
CMB-S4

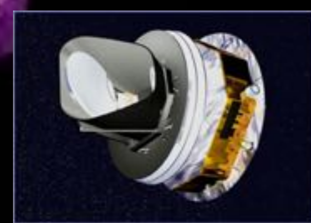


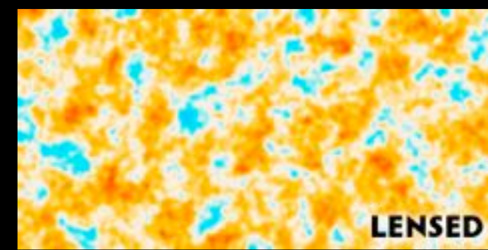
From CMB-S4 Science book…. arXiv: 1610.02743

FUTURE WORK: CMB LENSING

A slice of (dark matter) life at z~1

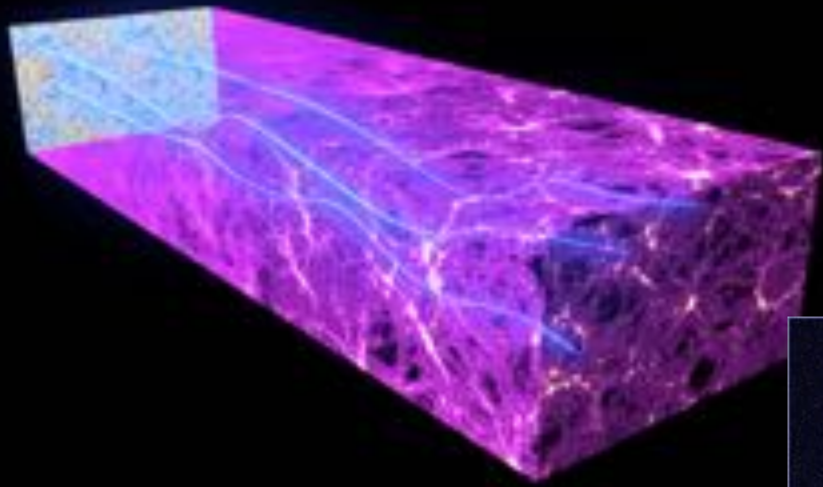


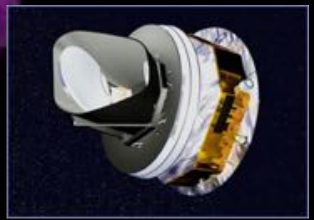


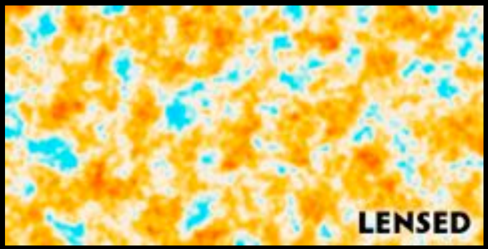


FUTURE WORK: CMB LENSING

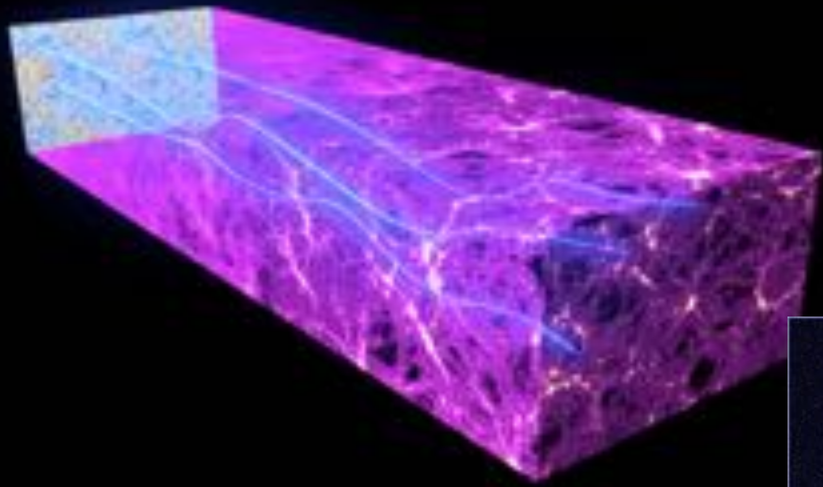
A slice of (dark matter) life at z~1



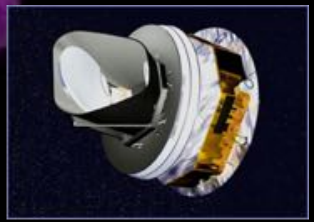


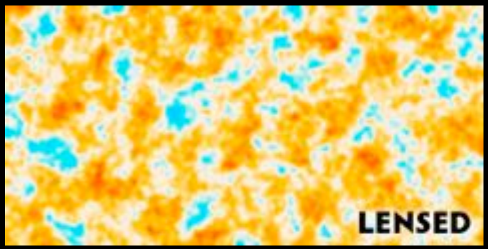


Future work: CMB lensing



A slice of (dark matter) life at z~1



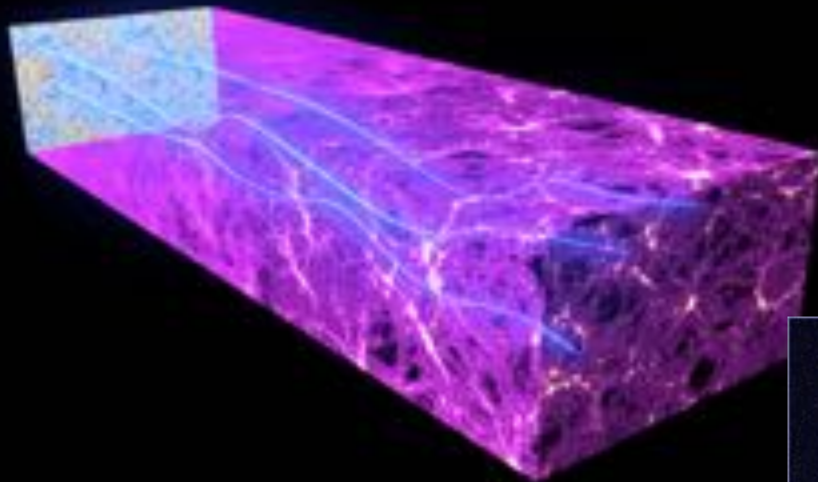


$$\kappa(\vec{\theta}) = \frac{1}{2}\nabla^2_{\vec{\theta}}\psi(\vec{\theta}) = \frac{1}{2}\vec{\nabla}\cdot\vec{\alpha}$$

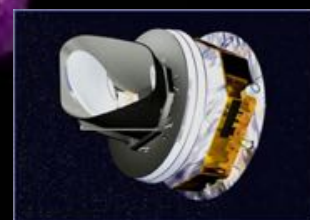
Deflection angle

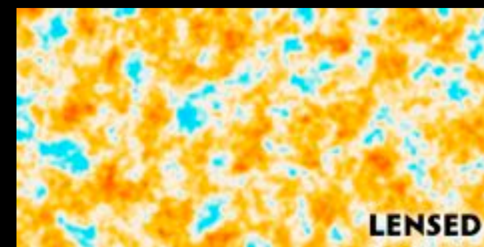
$$\psi(\vec{\theta}) = \frac{2d_c(\eta_{ls})}{d_c(\eta_l)d_c(\eta_s)}\int \Phi(d_c(\eta)\theta,\eta)d\eta$$

Future work: CMB lensing



A slice of (dark matter) life at z~1





$$\kappa(\vec{\theta}) = \frac{1}{2}\nabla^2_{\vec{\theta}}\psi(\vec{\theta}) = \frac{1}{2}\vec{\nabla}\cdot\boxed{\vec{\alpha}}$$

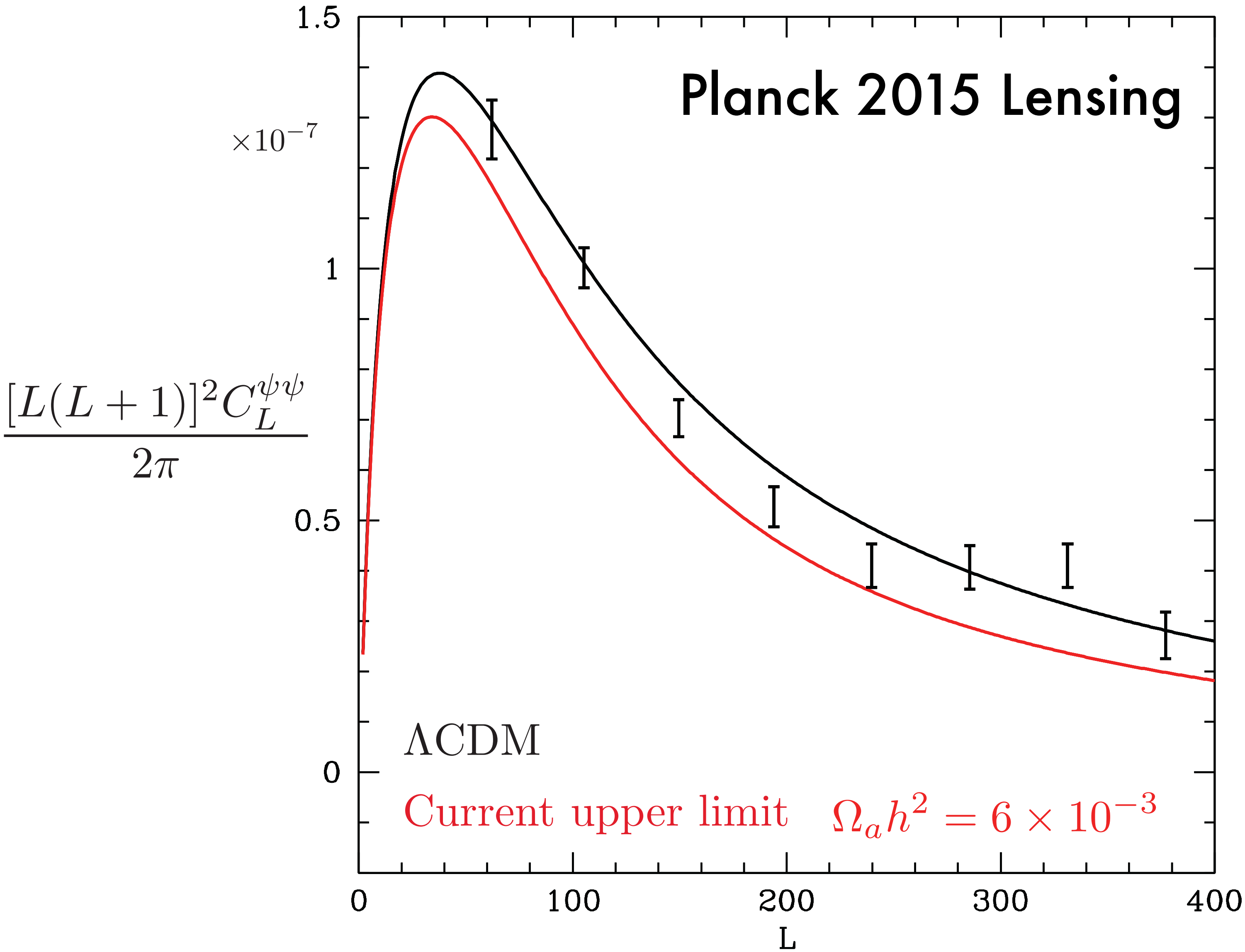
Deflection angle

$$\psi(\vec{\theta}) = \frac{2d_c(\eta_{ls})}{d_c(\eta_l)d_c(\eta_s)}\int\Phi(d_c(\eta)\theta,\eta)d\eta$$

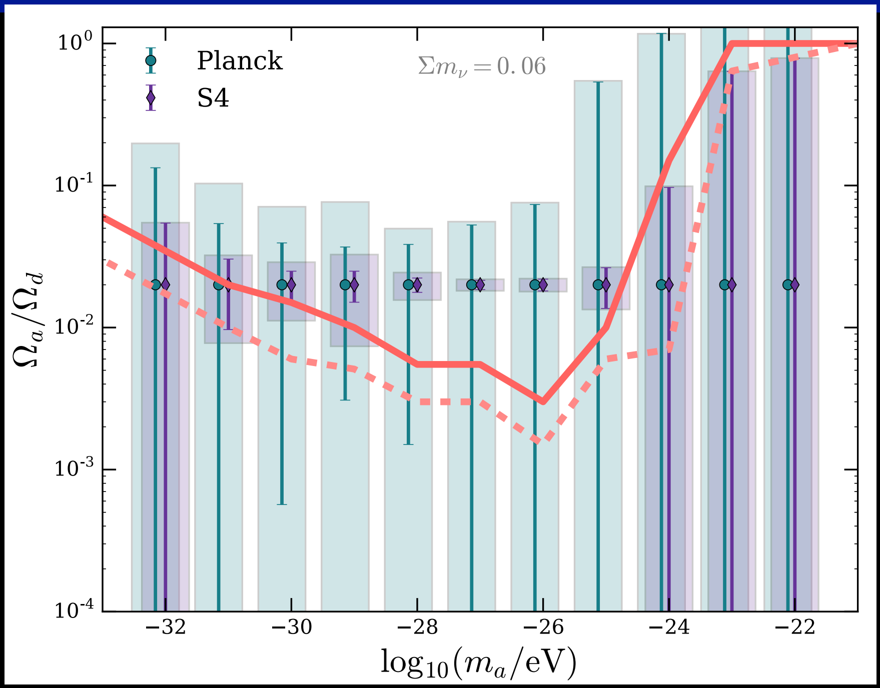
ULAs change

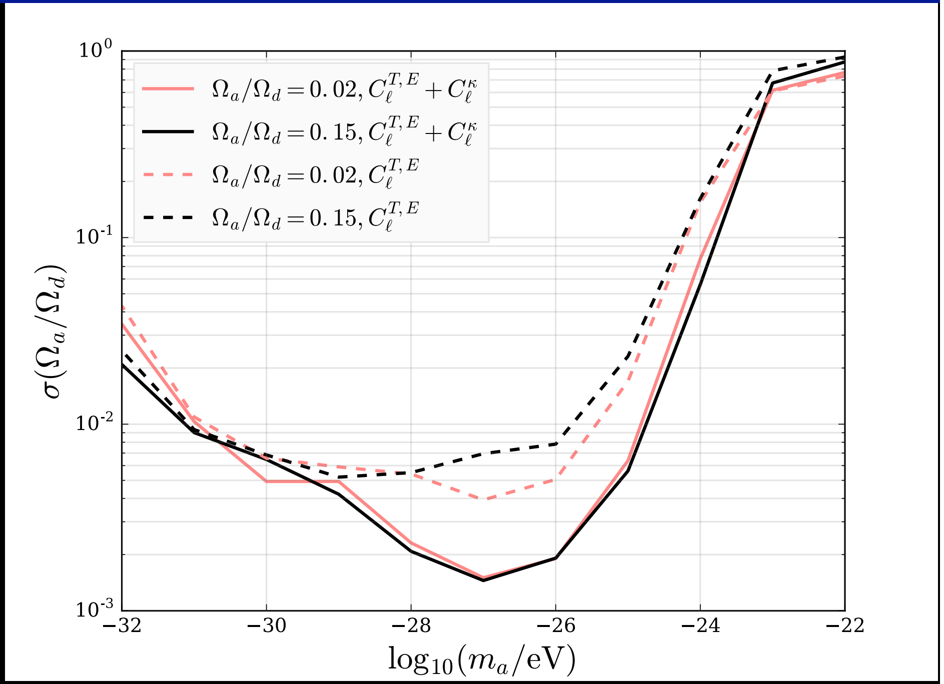
FUTURE WORK: CMB LENSING

ULA saturating TT-only limits falsifiable at 4.5σ



S4-cast for lensing and ULAs





Fisher forecast using OxFish code— OOM improvement drive by lensing

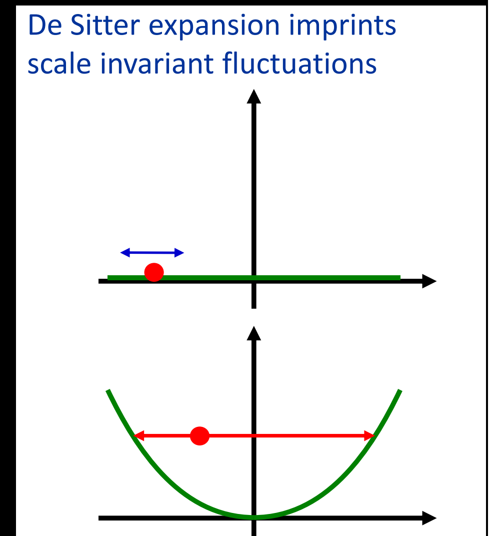
arXiv: 1607.08208

R.Hlozek, D.J.E. Marsh, D.G., J. Dunkley, R. Allison, E. Calabrese

Axions and isocurvature

- If PQ symmetry broken during/before inflation

$$\boxed{\sqrt{\langle a^2\rangle} = \frac{H_\mathrm{I}}{2\pi}} \qquad f_a > H_I$$



Quantum zero-point fluctuations!

- Subdominant species seed isocurvature fluctuations

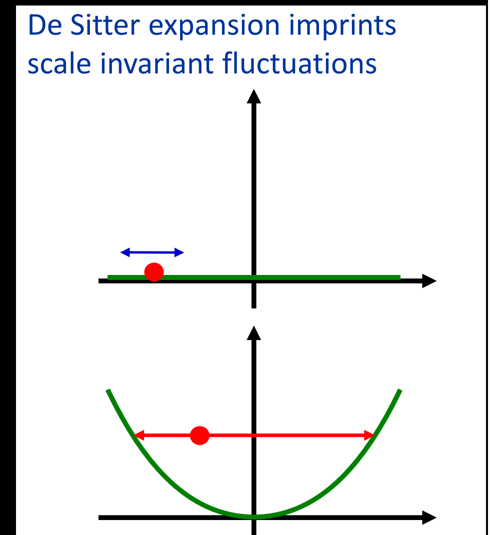
$$\boxed{\zeta \propto \frac{\rho_a}{\rho_\mathrm{tot}}\frac{\delta\rho_a}{\rho_a} \ll 10^{-5}}$$

$$\boxed{S_{a\gamma} = \frac{\delta n_a}{n_a} - \frac{\delta n_\gamma}{n_\gamma} = \frac{\delta\rho_a}{\rho_a} - \frac{3}{4}\frac{\delta\rho_\gamma}{\rho_\gamma} = 2\frac{\delta a}{a} \sim 10^{-5}}$$

Axions and isocurvature

- If PQ symmetry broken during/before inflation

$$\boxed{\sqrt{\langle a^2\rangle} = \frac{H_{\rm I}}{2\pi}} \qquad f_a > H_I$$



Quantum zero-point fluctuations!

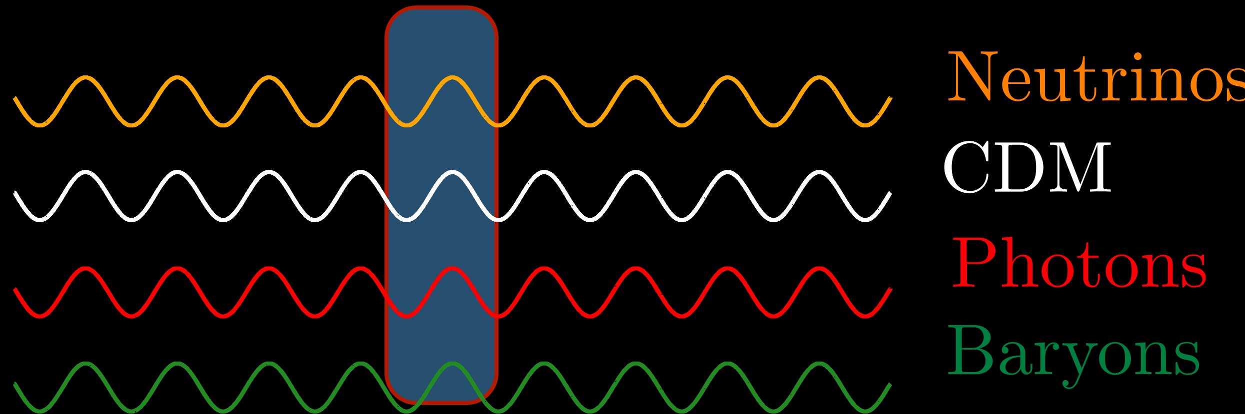
- Subdominant species seed isocurvature fluctuations

$$\boxed{\zeta \propto \frac{\rho_a}{\rho_{\rm tot}}\frac{\delta\rho_a}{\rho_a} \ll 10^{-5}}$$

Related to axion abundance

$$\boxed{S_{a\gamma} = \frac{\delta n_a}{n_a} - \frac{\delta n_\gamma}{n_\gamma} = \frac{\delta\rho_a}{\rho_a} - \frac{3}{4}\frac{\delta\rho_\gamma}{\rho_\gamma} = 2\frac{\delta a}{a} \sim 10^{-5}}$$

Adiabatic



$$S_i = 0$$

$$\boxed{S_i = \frac{\delta n_i}{n_i} - \frac{\delta n_\gamma}{n_\gamma}}$$

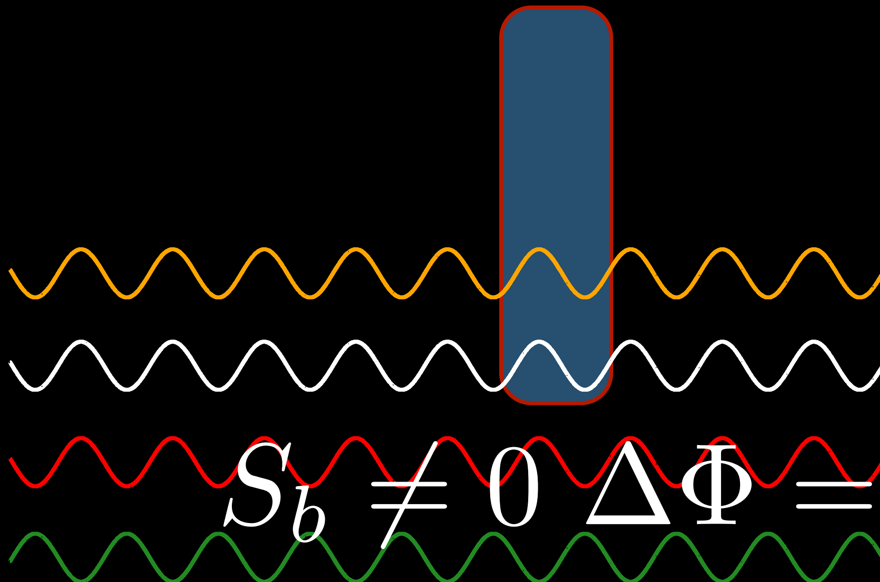
$$\boxed{\nabla^2 \Phi = 4\pi G \delta\rho}$$

$$ds^2 = a^2(\eta)\left\{-(1+2\Phi)\,d\eta^2 + (1-2\Phi)\,dx^i dx_j\right\}$$

Zoology of initial conditions

Neutrinos
CDM
Photons
Baryons

Baryon isocurvature



$$S_b \neq 0 \quad \Delta\Phi = 0$$

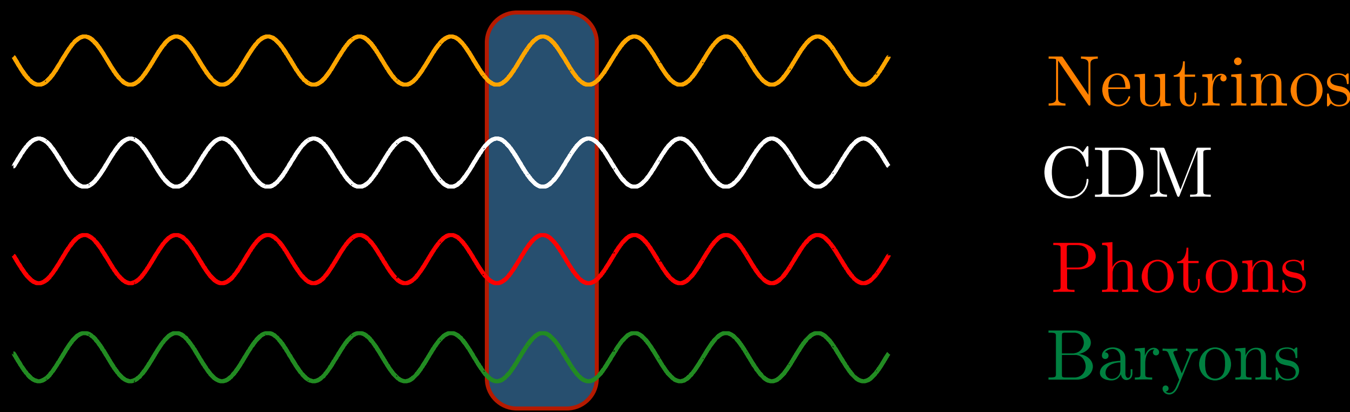
$$S_i = \frac{\delta n_i}{n_i} - \frac{\delta n_\gamma}{n_\gamma}$$

$$\nabla^2\Phi = 4\pi G\delta\rho$$

$$ds^2 = a^2(\eta)\left\{-(1+2\Phi)\,d\eta^2 + (1-2\Phi)\,dx^i dx_j\right\}$$

ZOOLOGY OF INITIAL CONDITIONS

CDM isocurvature



$$S_c \neq 0 \quad \Delta\Phi = 0$$

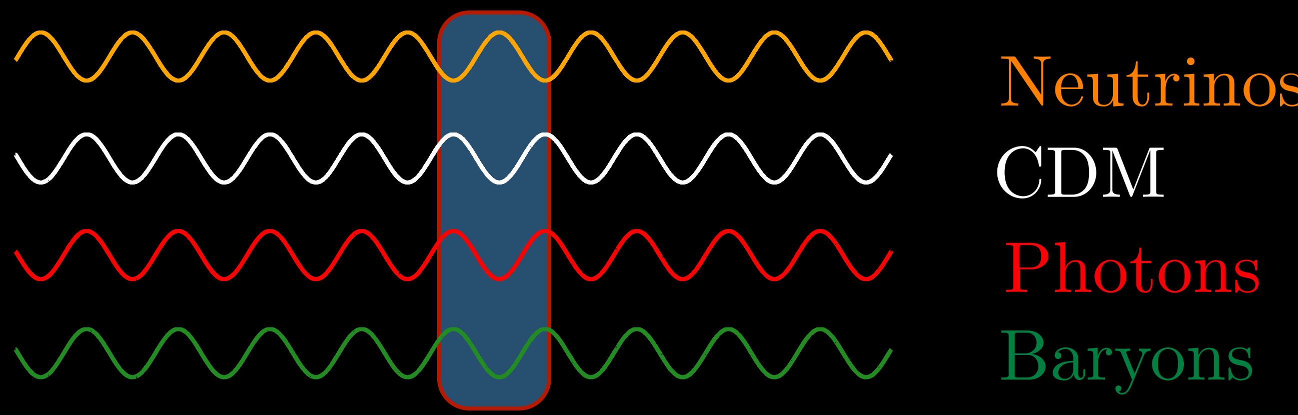
$$S_i = \frac{\delta n_i}{n_i} - \frac{\delta n_\gamma}{n_\gamma}$$

$$\nabla^2\Phi = 4\pi G\delta\rho$$

$$ds^2 = a^2(\eta)\left\{-(1+2\Phi)\,d\eta^2 + (1-2\Phi)\,dx^i dx_j\right\}$$

ZOOLOGY OF INITIAL CONDITIONS

ν
isocurvature



$$S_\nu \neq 0 \quad \Delta\Phi = 0$$

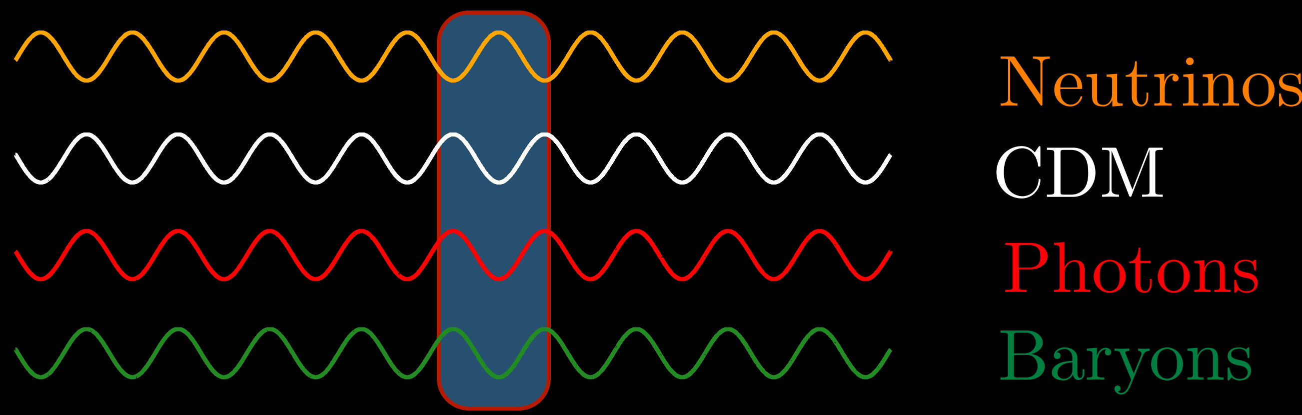
$$S_i = \frac{\delta n_i}{n_i} - \frac{\delta n_\gamma}{n_\gamma}$$

$$\nabla^2\Phi = 4\pi G\delta\rho$$

$$ds^2 = a^2(\eta)\left\{-(1+2\Phi)\,d\eta^2 + (1-2\Phi)\,dx^i dx_j\right\}$$

ZOOLOGY OF INITIAL CONDITIONS

ν
isocurvature

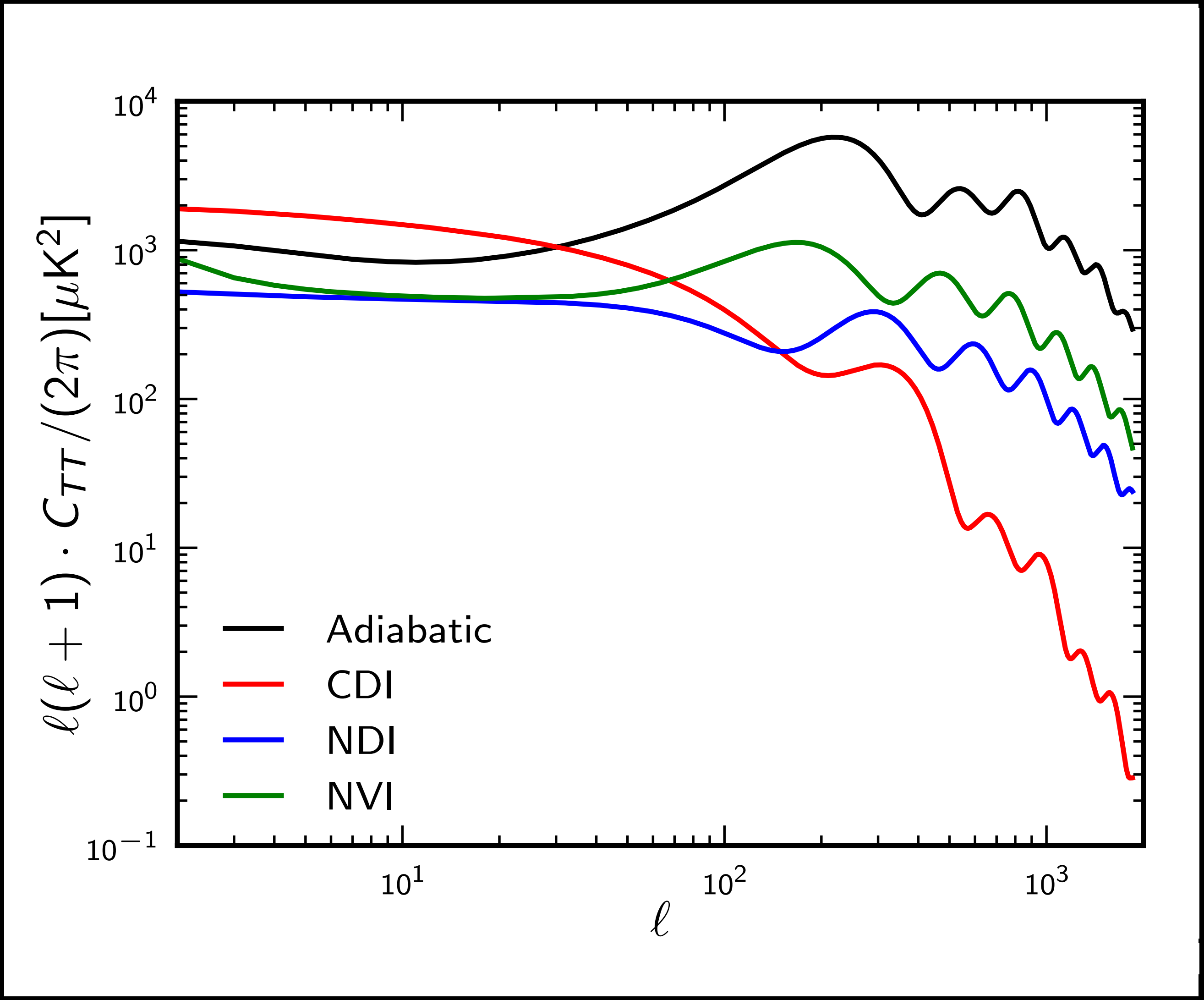


$$S_\nu \neq 0 \quad \Delta\Phi = 0$$

All density initial conditions can be expressed in terms of these!
These conditions are not conserved under fluid evolution

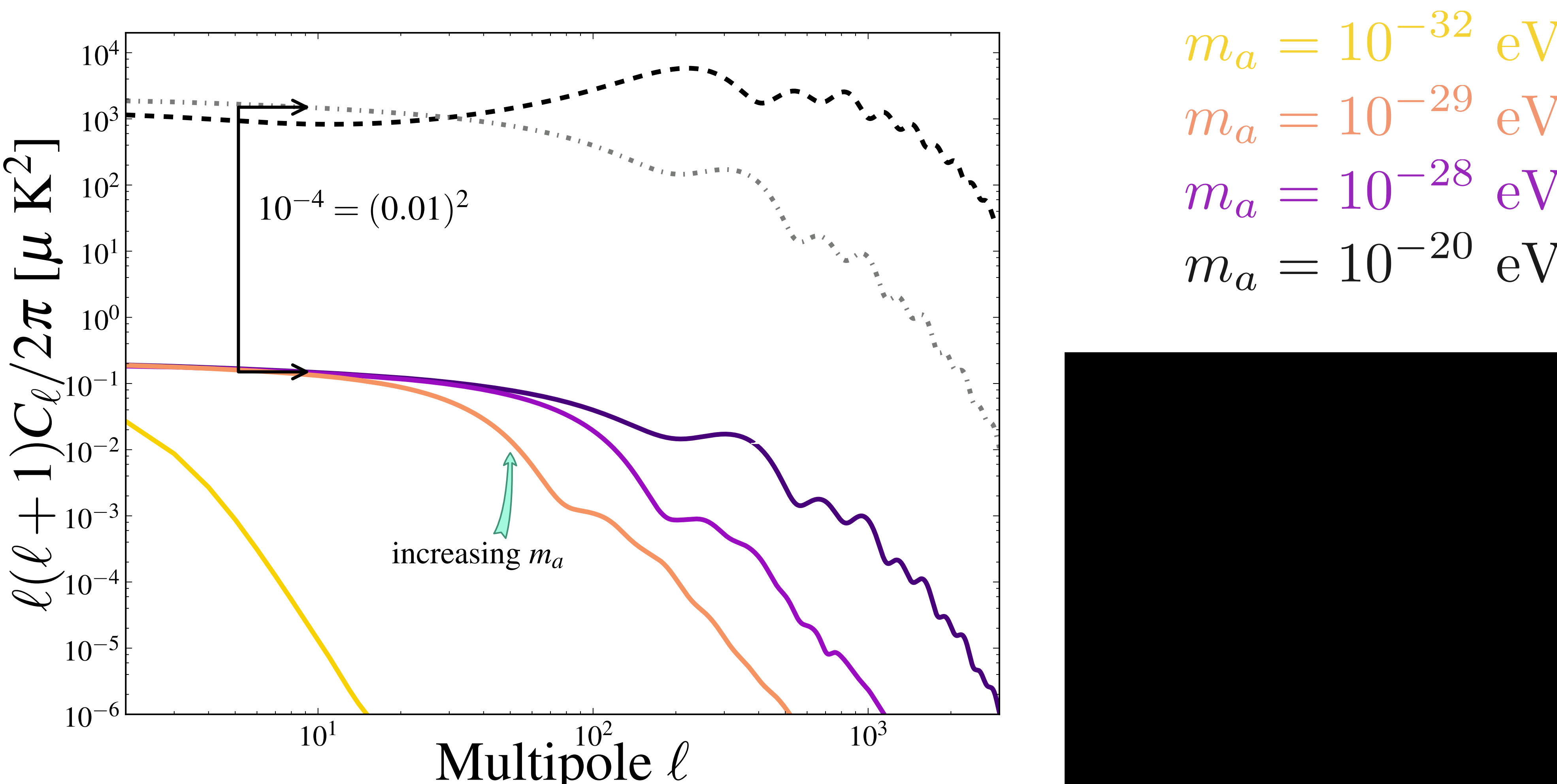
Initial conditions determine dynamics for a linear system

CMB POWER SPECTRA



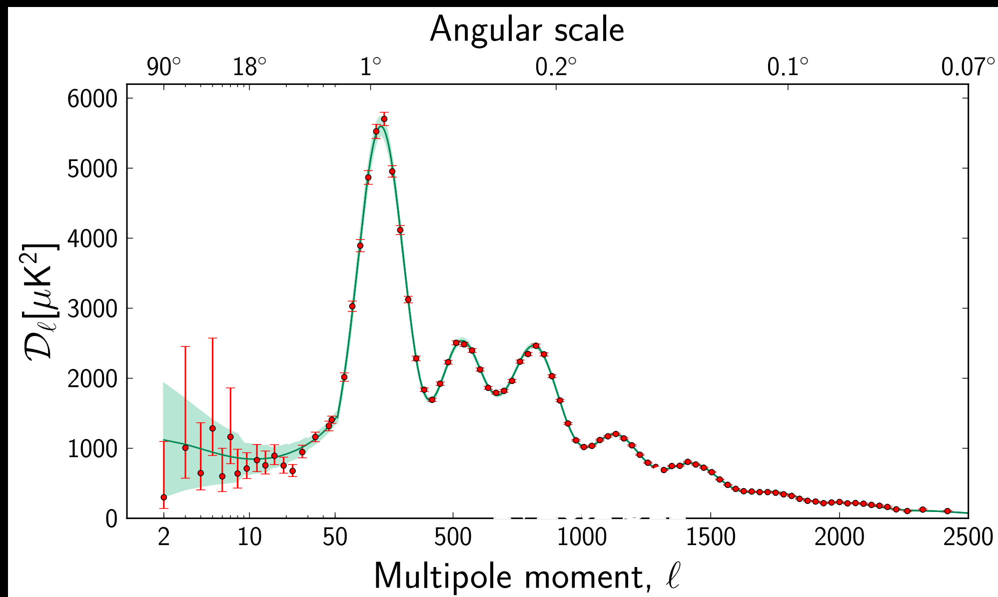
From arXiv: 1303.5082 (Planck inflation paper)

ULAS AND ISOCURVATURE FLUCTUATIONS



Spectra from AXIONCAMB using initial conditions obtained in DG+ (2015 in prep)

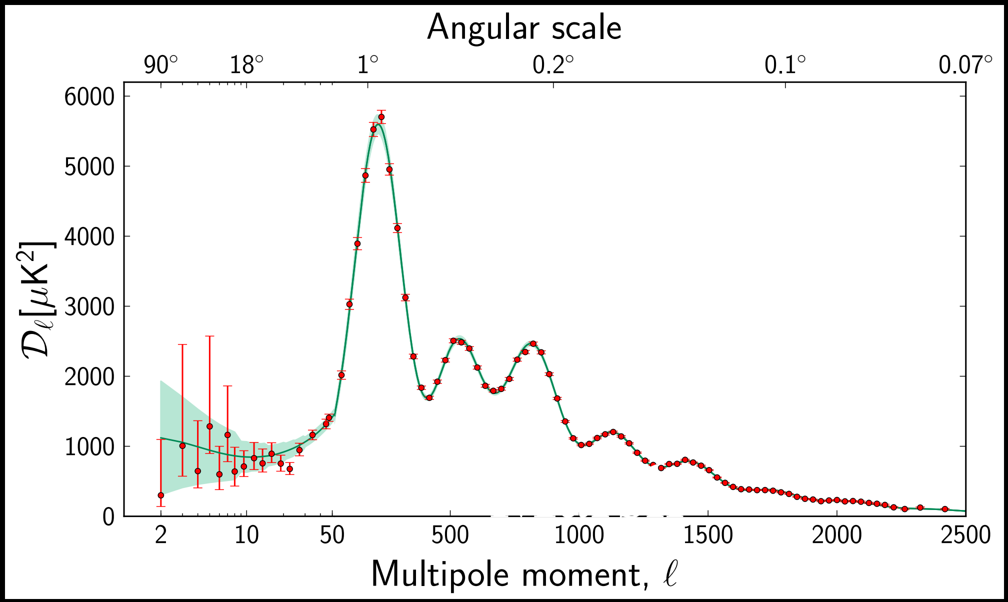
Planck 2015 TT



$$\alpha \equiv \frac{P_{S_{c\gamma}}(k)}{P_{S_{c\gamma}(k)} + P_{\mathcal{R}}(k)} \leq 0.039$$

$$\alpha \propto \left(\frac{H_I}{f_a \overline{\theta}}\right)^2 \qquad \Omega_a \propto \left(f_a \overline{\theta}\right)^2 \sqrt{m_a}$$

Planck 2015 TT



QCD axion

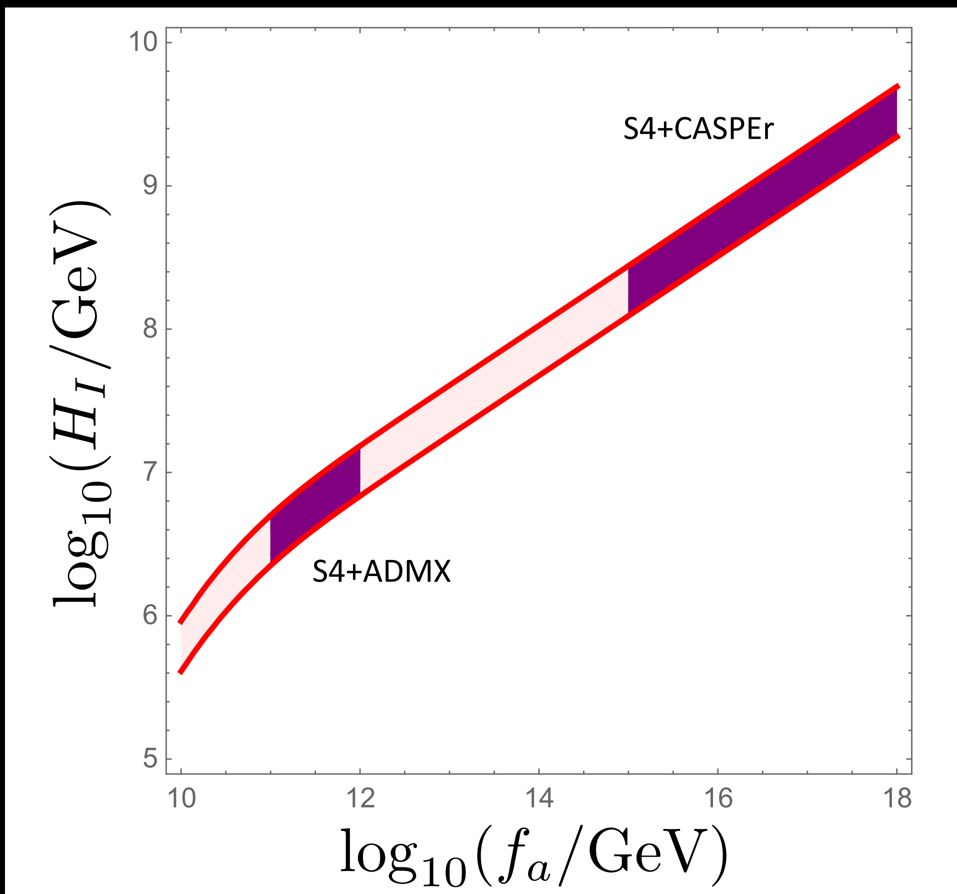
$$\frac{\Omega_a}{\Omega_a + \Omega_c} \lesssim 10^{-12} \left(\frac{10^{14}\mathrm{GeV}}{H_I} \right)^{7/2}$$

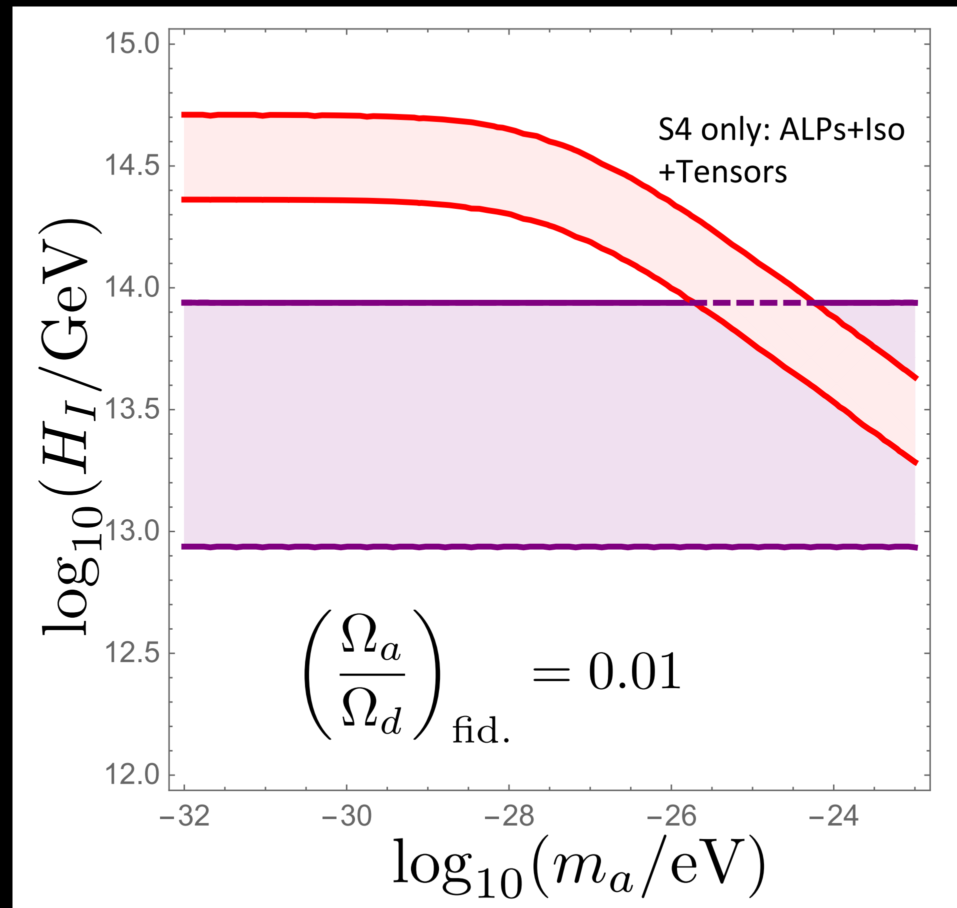
ULAs

$$\frac{\Omega_a}{\Omega_a + \Omega_c} \lesssim 10^{-3} \left(\frac{10^{14}\mathrm{GeV}}{H_I} \right)$$

D.J.E. Marsh, DG +, arXiv:1403.4216, Phys. Rev. Lett. 113, 011801
D.J.E. Marsh, DG +, arXiv:1303.3008, Phys. Rev. D 87, 121701(R)

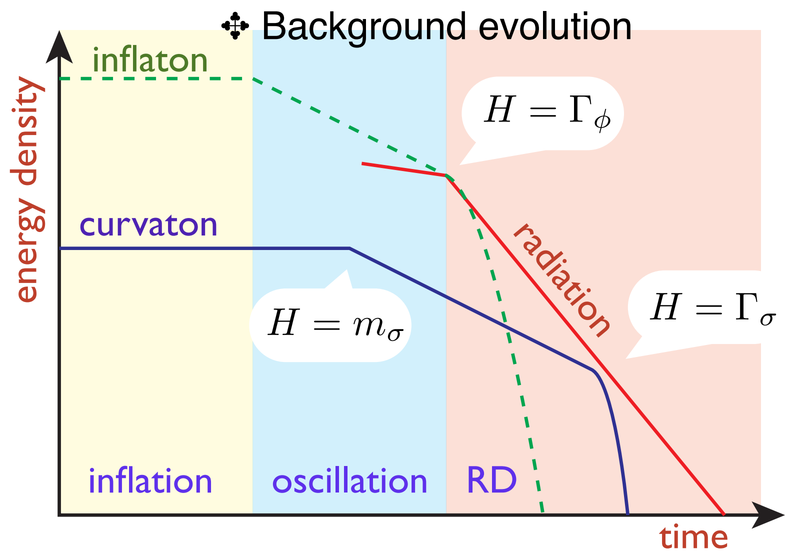
HIGH-ENERGY COSMOLOGY WITH AXION ISOCURVATURE

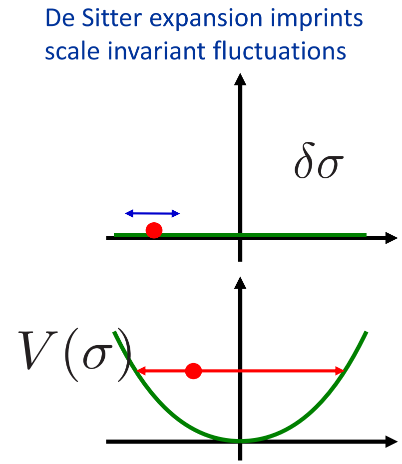




From CMB-S4 Science book…. arXiv: 1610.02743

CURVATON MODEL





some schematics from Wands, Enqvist, Lyth, Takahashi (2012-2015)

✳ Hard for an inflationary model to do everything you want

$$\frac{k^3 P_{\mathcal{R}}(k)}{2\pi^2} = \frac{H_k^2}{8\pi^2 M_{\rm pl}^2 \epsilon} \qquad \epsilon = \frac{M_{\rm pl}^2}{2}\left(\frac{V'}{V}\right)^2$$

✳ \`Curvaton' σ is a spectator (sub-dominant) during inflation

✳ After reheating, σ decays with

$$r_{\rm D} \equiv \frac{\rho_\sigma}{\rho_\sigma + (4/3)\,\rho_{\rm RAD}}$$

Many curvaton candidates (e.g. sneutrino from MSSM, axion, generic modulus)

Curvature perturbations in curvaton model

- Curvaton becomes more important once $m_\sigma \gg H, \;\; \rho_\sigma \propto a^{-3}$
- Inflationary curvature perts assumed negligible

$$\zeta = \frac{r_{\mathrm{D}} \delta_{\rho_\sigma}}{3}$$

- 3 possibilities for curvaton decay products

$$\delta_x = \begin{cases} 0 & \text{if } x \text{ produced before curvaton decay} \\ \frac{3}{r_{\mathrm{D}}}\zeta & \text{if } x \text{ produced by curvaton decay} \\ 3\zeta & \text{if } x \text{ produced after curvaton decay} \end{cases}$$

Mismatch for species produced before, by curvaton decay

Isocurvature!

Totally (or anti) correlated with density field

Lyth,Wands, Ungarelli (2002-2003) 2002, Malik and Lyth 2006
Mollerach 1990, Moroi and Takahashi 2001

NEUTRINO ISOCURVATURE IN THE CURVATON MODEL

- Weak interactions convert lepton number to neutrino density
- There could be lepton asymmetry (carries to neutrinos)

$$f^{\pm}_{i \in \{\nu_e, \nu_\tau, \nu_\mu\}} = \left[e^{E/T_i} + 1 \right]^{-1}$$

- Neutrino isocurvature generated if lepton number produced by curvaton decay

$$\delta_\nu \neq \delta_\gamma \qquad S_{\nu\gamma} \neq 0$$

- Modified relationship between relativistic species and total curvature

$$\zeta = (1 - R_\nu)\frac{\delta_\gamma}{4} + R_\nu \frac{\delta_\nu}{4}$$

NEUTRINO ISOCURVATURE IN THE CURVATON MODEL

- Variety of lepton number generation scenarios
  - Affleck/Dine leptogenesis (L-generation by curvaton decay)

σ

$$S_{\nu\gamma} = \frac{135}{7}\left(\frac{\xi_{\rm lep}}{\pi}\right)^2\left(\frac{1}{r_{\rm D}} - 1\right)\zeta$$

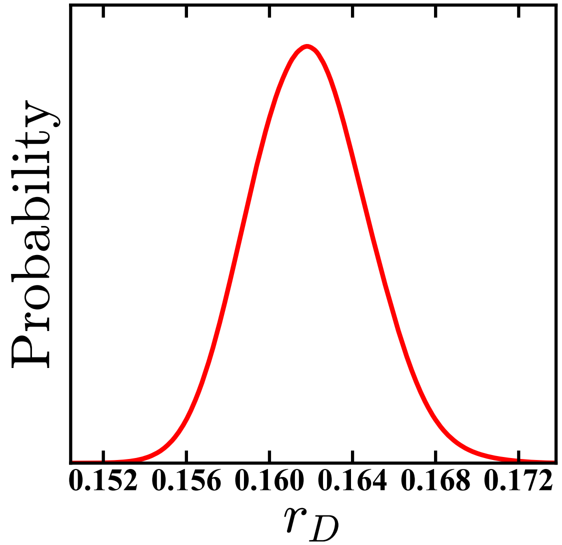
PANOPLY OF DECAY SCENARIOS

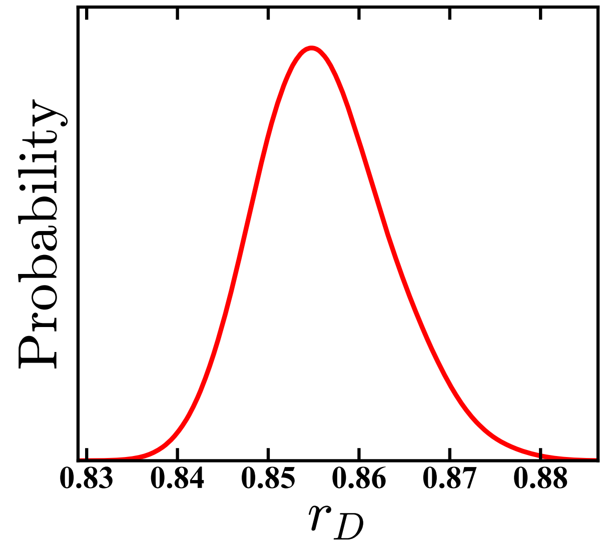
✳ Project: T.L. Smith + DG, systematically explore all 27 decay scenarios

arXiv: 1511.07431, Phys. Rev. D 94 103517

scenario	$\frac{S_{b\gamma}}{\zeta}$	$\frac{S_{c\gamma}}{\zeta}$	$\frac{S_{m\gamma}}{\zeta}$
$(b_{\rm by}, c_{\rm before}, L_{y_L})$	$3\left(\frac{1}{r_D}-1\right)+R_\nu\frac{S_{\nu\gamma}}{\zeta}$	$-3+R_\nu\frac{S_{\nu\gamma}}{\zeta}$	$3\left(\frac{\Omega_b}{\Omega_m r_D}-1\right)+R_\nu\frac{S_{\nu\gamma}}{\zeta}$
$(b_{\rm before}, c_{\rm by}, L_{y_L})$	$-3+R_\nu\frac{S_{\nu\gamma}}{\zeta}$	$3\left(\frac{1}{r_D}-1\right)+R_\nu\frac{S_{\nu\gamma}}{\zeta}$	$3\left(\frac{\Omega_c}{\Omega_m r_D}-1\right)+R_\nu\frac{S_{\nu\gamma}}{\zeta}$
$(b_{\rm by}, c_{\rm after}, L_{y_L})$	$3\left(\frac{1}{r_D}-1\right)+R_\nu\frac{S_{\nu\gamma}}{\zeta}$	$R_\nu\frac{S_{\nu\gamma}}{\zeta}$	$3\frac{\Omega_b}{\Omega_m}\left(\frac{1}{r_D}-1\right)+R_\nu\frac{S_{\nu\gamma}}{\zeta}$
$(b_{\rm after}, c_{\rm by}, L_{y_L})$	$R_\nu\frac{S_{\nu\gamma}}{\zeta}$	$3\left(\frac{1}{r_{\rm D}}-1\right)+\frac{S_{b\gamma}}{\zeta}$	$3\frac{\Omega_c}{\Omega_m}\left(\frac{1}{r_D}-1\right)+R_\nu\frac{S_{\nu\gamma}}{\zeta}$
$(b_{\rm before}, c_{\rm after}, L_{y_L})$	$-3+R_\nu\frac{S_{\nu\gamma}}{\zeta}$	$R_\nu\frac{S_{\nu\gamma}}{\zeta}$	$-3\frac{\Omega_b}{\Omega_m}+R_\nu\frac{S_{\nu\gamma}}{\zeta}$
$(b_{\rm after}, c_{\rm before}, L_{y_L})$	$R_\nu\frac{S_{\nu\gamma}}{\zeta}$	$-3+\frac{S_{b\gamma}}{\zeta}$	$-3\frac{\Omega_c}{\Omega_m}+R_\nu\frac{S_{\nu\gamma}}{\zeta}$
$(b_{\rm before}, c_{\rm before}, L_{y_L})$	$-3+R_\nu\frac{S_{\nu\gamma}}{\zeta}$	$\frac{S_{b\gamma}}{\zeta}$	$\frac{S_{b\gamma}}{\zeta}$
$(b_{\rm by}, c_{\rm by}, L_{y_L})$	$3\left(\frac{1}{r_D}-1\right)+R_\nu\frac{S_{\nu\gamma}}{\zeta}$	$\frac{S_{b\gamma}}{\zeta}$	$\frac{S_{b\gamma}}{\zeta}$
$(b_{\rm after}, c_{\rm after}, L_{y_L})$	$R_\nu\frac{S_{\nu\gamma}}{\zeta}$	$R_\nu\frac{S_{\nu\gamma}}{\zeta}$	$R_\nu\frac{S_{\nu\gamma}}{\zeta}$

Compensated scenarios





$(b_{\rm by}, c_{\rm before})$ $\qquad$ $(b_{\rm before}, c_{\rm by})$

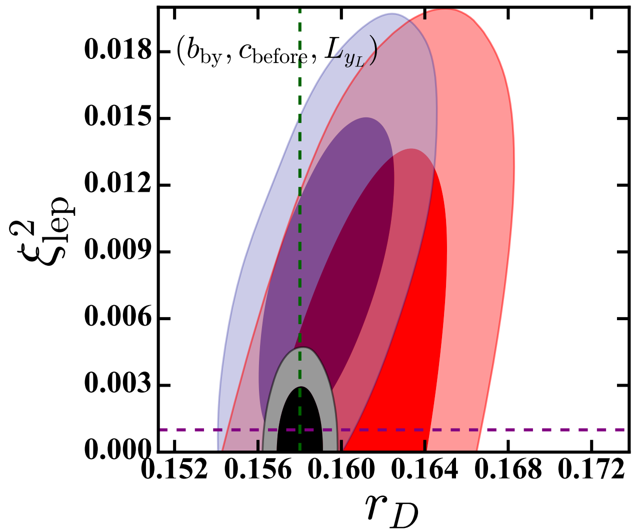
- Total non-relativistic isocurvature nearly vanishes for allowed values

$$S_{m\gamma} = 3\zeta\left(\frac{\Omega_b}{\Omega_m r_{\rm D}} - 1\right) \qquad S_{m\gamma} = 3\zeta\left(\frac{\Omega_c}{\Omega_m r_{\rm D}} - 1\right)$$

- Allowed parameter space for compensated scenarios:
  - baryon/CDM entropy fluctuations $S_{bc} \propto \zeta \neq 0$

More on this soon.... stay tuned!

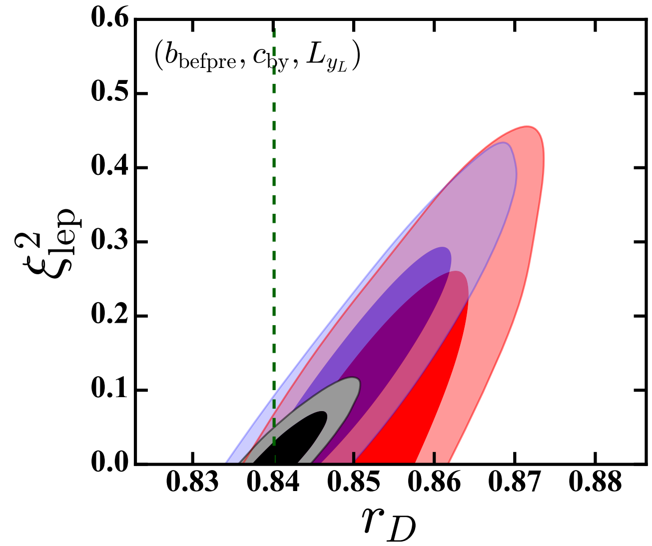
Compensated scenarios: enhanced lepton constraints



Planck: TT + allP + BAO

Planck: TT + lowP + BAO

S4 sensitivity



- Compare with $\xi^2_{\rm lep} \leq 0.3$ from $N_{\rm eff}$ only

- Unavoidable neutrino isocurvature when matter isocurvature nearly vanishes

$$S_{\nu\gamma} = \frac{135}{7}\left(\frac{\xi_{\rm lep}}{\pi}\right)^2\left(\frac{1}{r_{\rm D}} - 1\right)\zeta$$

- “Nuisance” mode identified (Lewis 2002)

Compensated Isocurvature Perturbation (CIP)

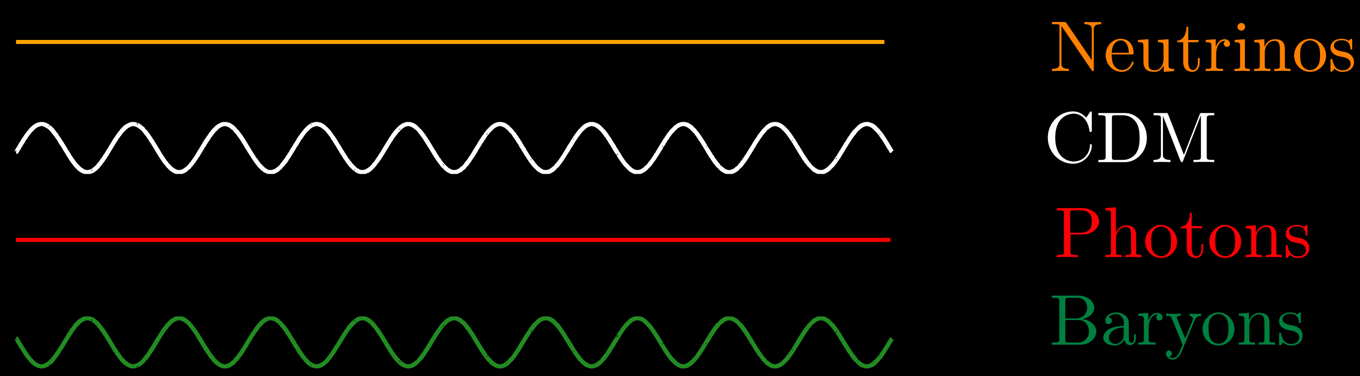
$$\delta_{\rm b}^{\rm CIP} = \Delta(\hat{n},\eta) \quad \delta_{\rm c}^{\rm CIP} = -\frac{\Omega_c}{\Omega_{\rm b}}\Delta(\hat{n},\eta), \quad \delta\rho_{\rm b}^{\rm CIP} + \delta\rho_{\rm c}^{\rm CIP} = 0$$

Baryon-dark matter ‘entropy’

$$\boxed{\mathcal{S}_{\rm bc} = \frac{\delta n_{\rm b}}{n_{\rm b}} - \frac{\delta n_{\rm c}}{n_{\rm c}} \neq 0}$$

- Subdominant fluctuations: Adiabatic modes dominate, but do the relative number densities of DM and baryons fluctuate?

- “Nuisance” mode identified (Lewis 2002)

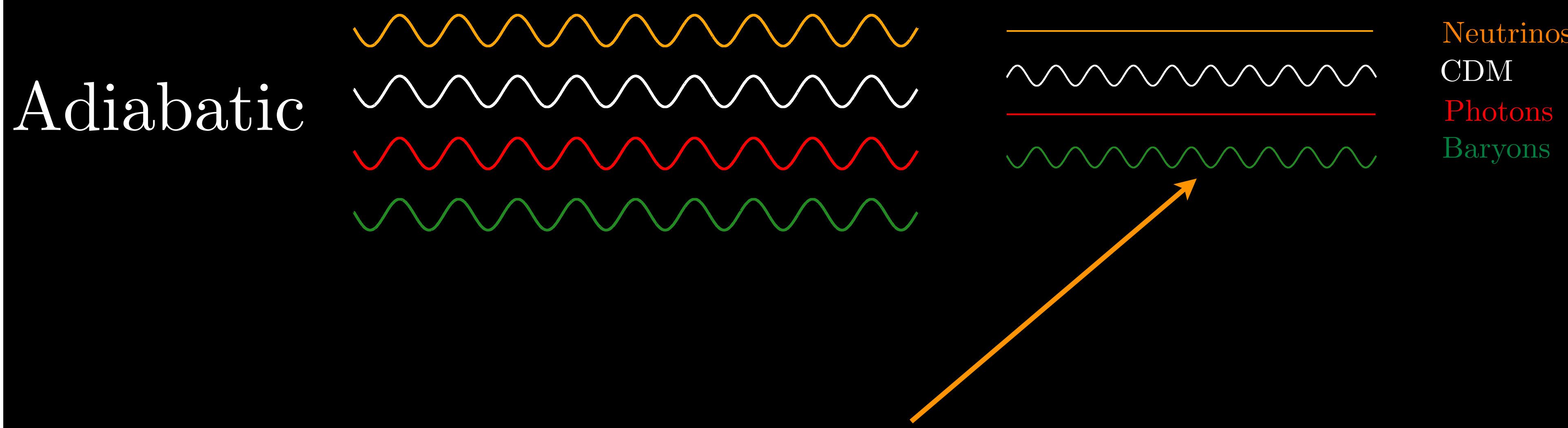


Compensated Isocurvature Perturbation (CIP)

- Subdominant fluctuations: Adiabatic modes dominate, but do the relative number densities of DM and baryons fluctuate?

BARYON-DM ISOCURVATURE

✳ "Nuisance" mode identified (Lewis 2002)



Compensated Isocurvature Perturbation (CIP)

✳ Subdominant fluctuations: Adiabatic modes dominate, but do the relative number densities of DM and baryons fluctuate?

WHY DIDN'T ANYONE NOTICE?

✳ *Observationally null in the CMB! (*surprising but true, only at linear order!*)*

$$\Delta P = 0 \text{ if}$$

$$\lambda > \lambda_J \sim \frac{c_{s,b}}{H} \sim \frac{c}{H}\sqrt{\frac{k_B T_b}{m_p}} \rightarrow \ell \gtrsim 10^5$$

✳ Baryon terms in photon equations …

$$\propto \overline{n}_e \sigma_T (1+\delta_b)\nabla \cdot \vec{v}_b$$

WHY DIDN'T ANYONE NOTICE?

- *Observationally null in the CMB! (*surprising but true, only at linear order!*)*

$$\Delta P = 0 \text{ if}$$

$$\lambda > \lambda_J \sim \frac{c_{s,b}}{H} \sim \frac{c}{H}\sqrt{\frac{k_B T_b}{m_p}} \rightarrow \ell \gtrsim 10^5$$

- Baryon terms in photon equations …

$$\propto \overline{n}_e \sigma_T (1+\delta_b)\nabla\cdot\vec{v}_b$$

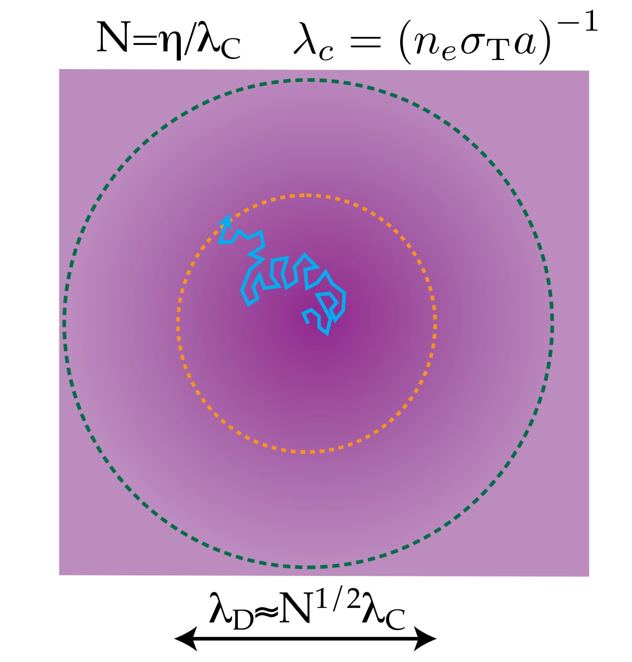
higher order effect … neglected in first-order Boltzmann codes

COMPENSATED ISOCURVATURE AND THE CMB: *z~1100 EFFECTS*

- ✳ Acoustic horizon scale modulated by CIPs
- ✳ Baryon-photon sound speed depends on electron density

$$c_s^2 = \frac{1}{3}\left[1 + 3\rho_{\mathrm{b}}/4\rho_\gamma\right]^{-1}$$

- ✳ Damping scale modulated by CIPs



COMPENSATED ISOCURVATURE AND THE CMB: *z~1100* EFFECTS

COMPENSATED ISOCURVATURE AND THE CMB: *z~1100 EFFECTS*

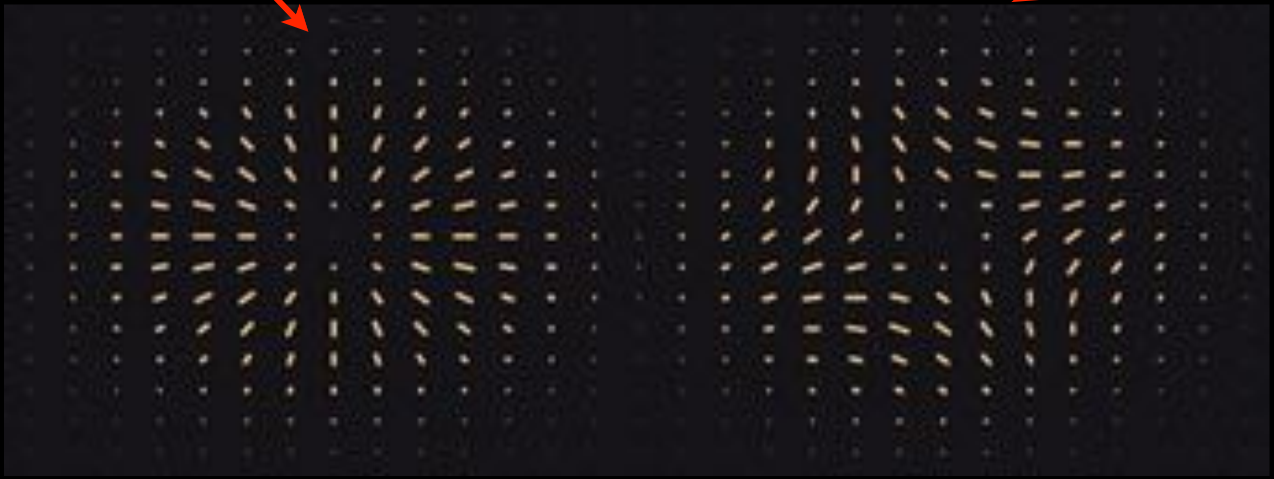
- Polarization : $\Delta(\hat{n})$ affects T_{2i} generation and n_e

$$Q,U \propto \int \boxed{n_e}(\eta)\left[1+\boxed{\Delta\left(\hat{n}\right)\right]T_{2i}\left(\eta,\hat{n}\right)}d\eta$$

COMPENSATED ISOCURVATURE AND THE CMB: *z~1100 EFFECTS*

- Funnels E modes to B modes

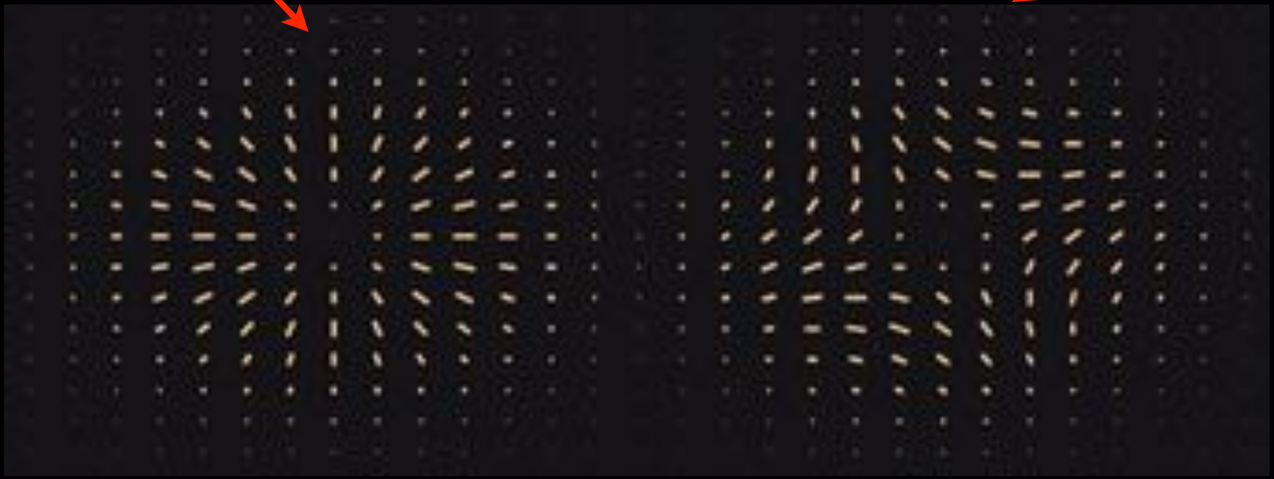
(μK^2)



COMPENSATED ISOCURVATURE AND THE CMB: *z~1100 EFFECTS*

- Funnels E modes to B modes

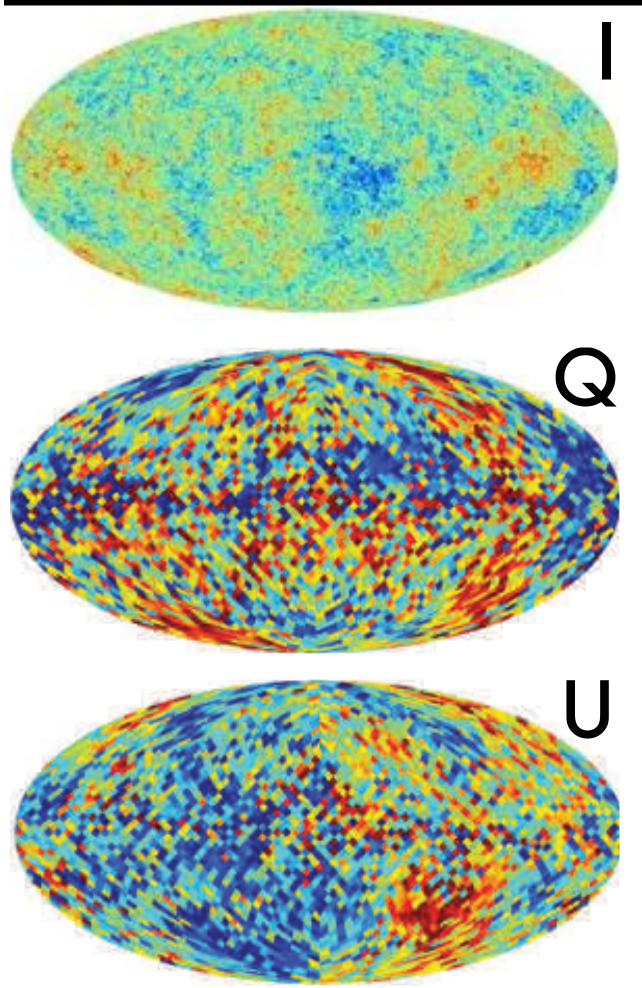
(μK^2)



CMB detectability of CIPs shown in
arXiv: 1107.1716- Phys. Rev. Lett. 107 261301, DG+
arXiv: 1107.5047- Phys. Rev. D. 84 123003, DG+

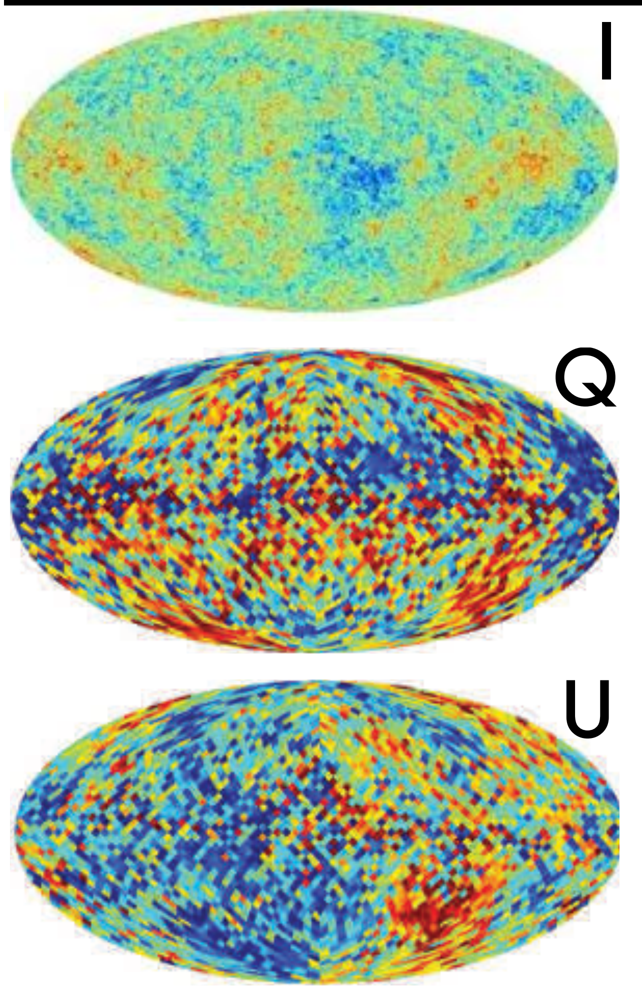
COMPENSATED ISOCURVATURE AND THE CMB: *RECOVERING THE REALIZATION*

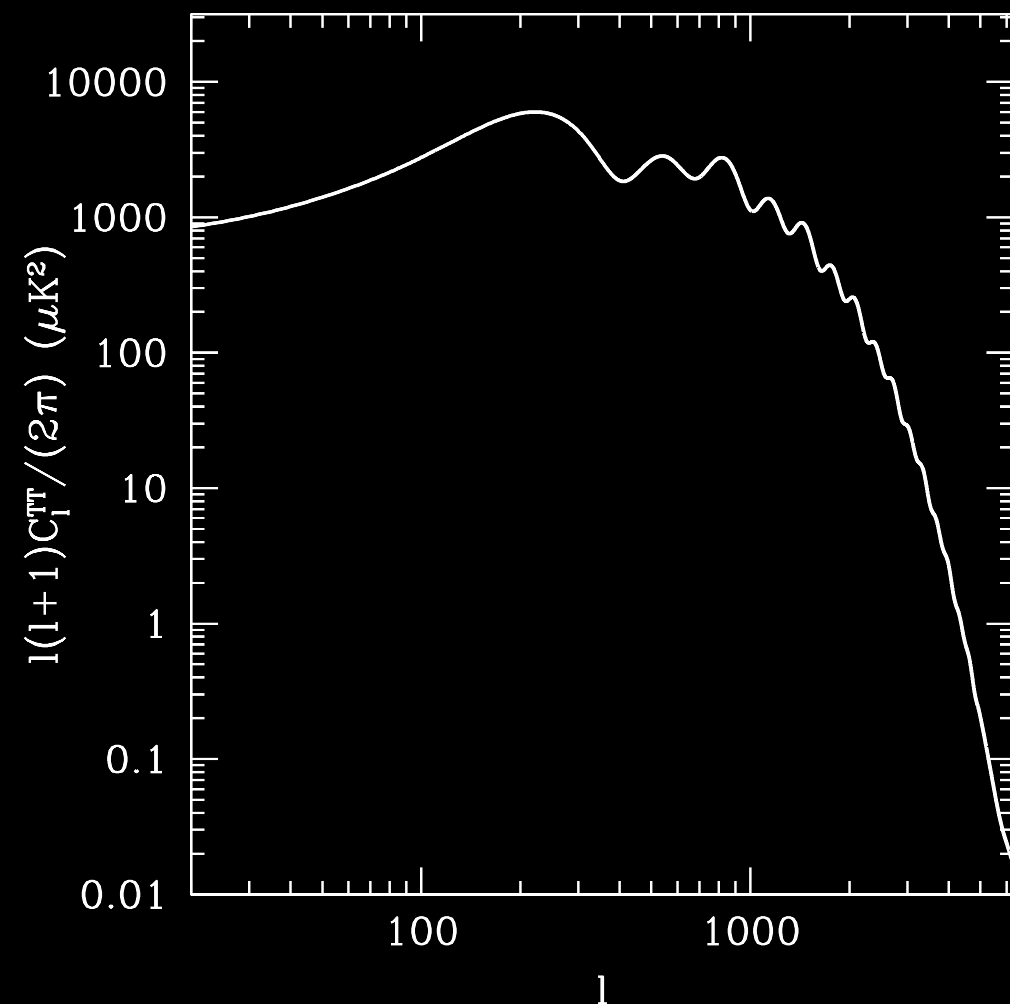
- Power spec. results were true, averaging over realizations of primordial $\Phi(\hat{n})$ and CIP amplitude $\Delta(\hat{n})$



COMPENSATED ISOCURVATURE AND THE CMB: *RECOVERING THE REALIZATION*

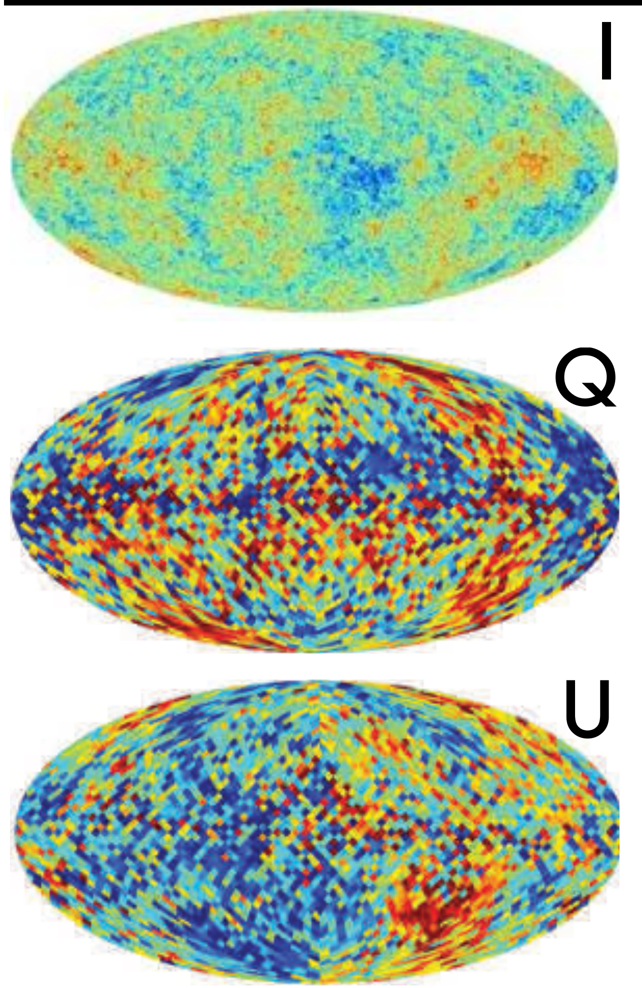
- Power spec. results were true, averaging over realizations of primordial $\Phi(\hat{n})$ and CIP amplitude $\Delta(\hat{n})$

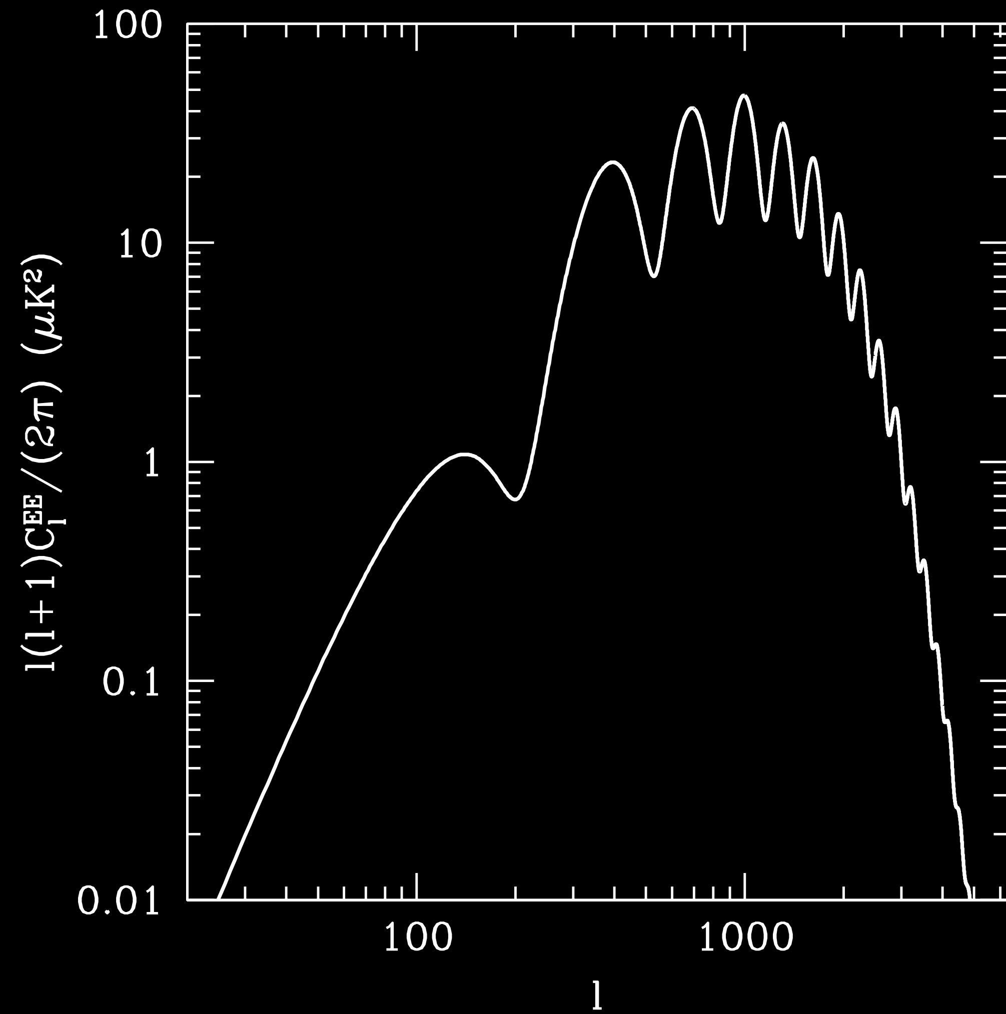




COMPENSATED ISOCURVATURE AND THE CMB: *RECOVERING THE REALIZATION*

- Power spec. results were true, averaging over realizations of primordial $\Phi(\hat{n})$ and CIP amplitude $\Delta(\hat{n})$

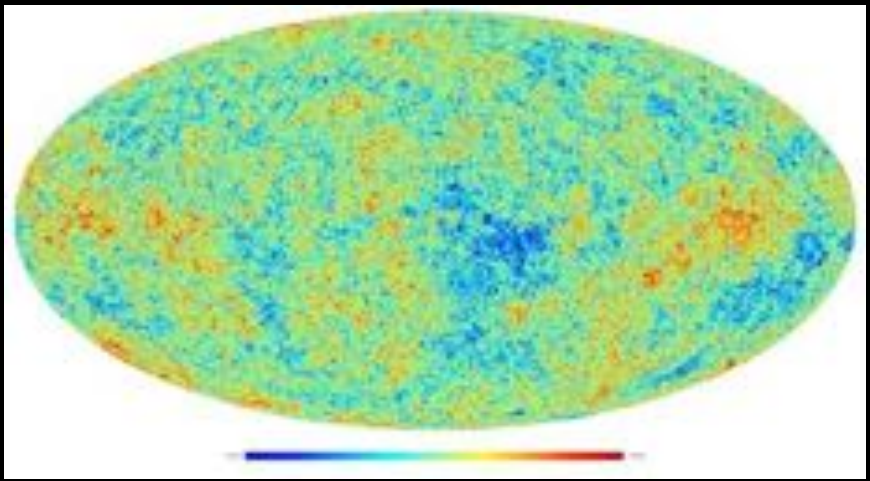




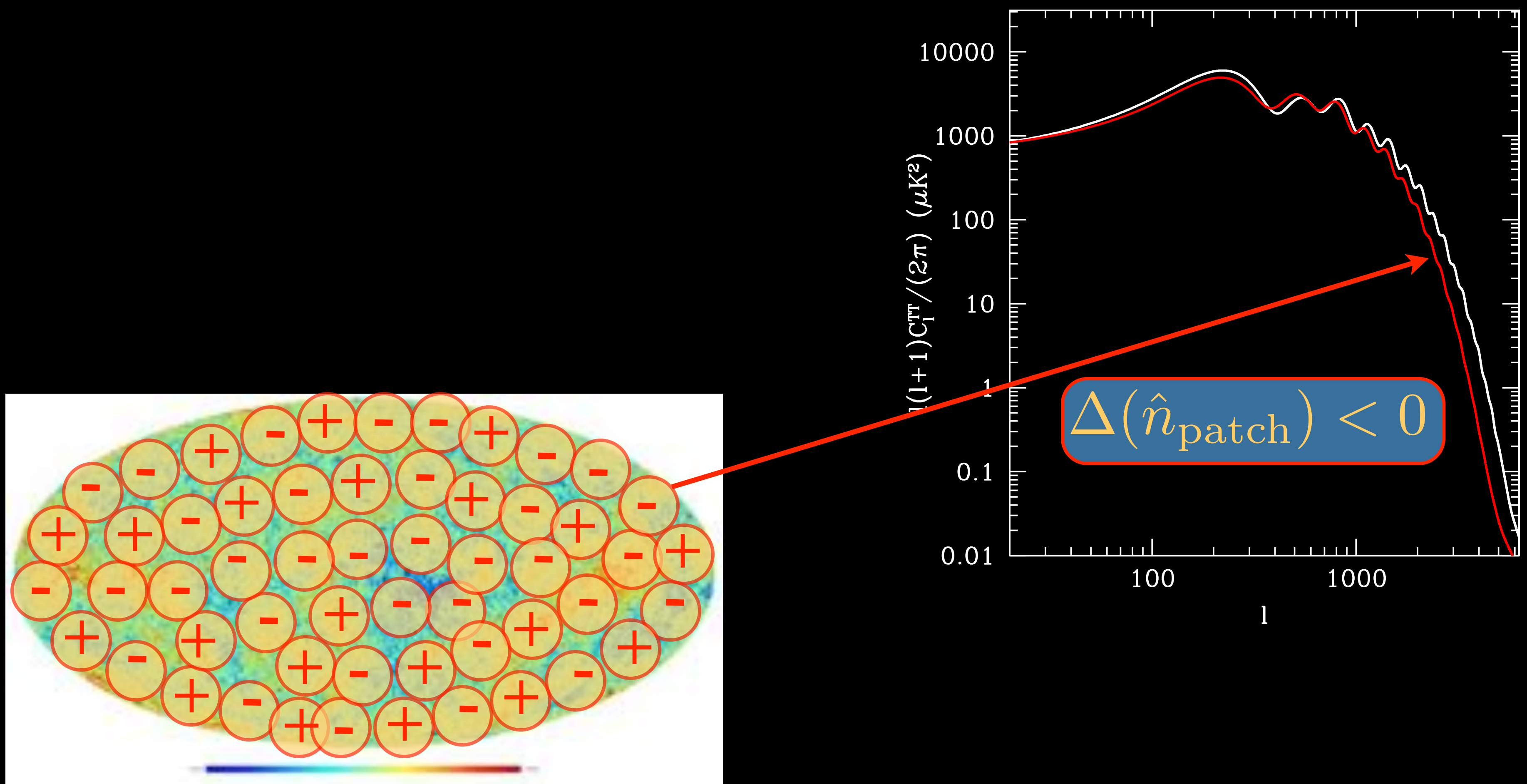
COMPENSATED ISOCURVATURE AND THE CMB: *RECOVERING THE REALIZATION*

- Power spec. results were true, averaging over realizations of primordial $\Phi(\hat{n})$ and CIP amplitude $\Delta(\hat{n})$

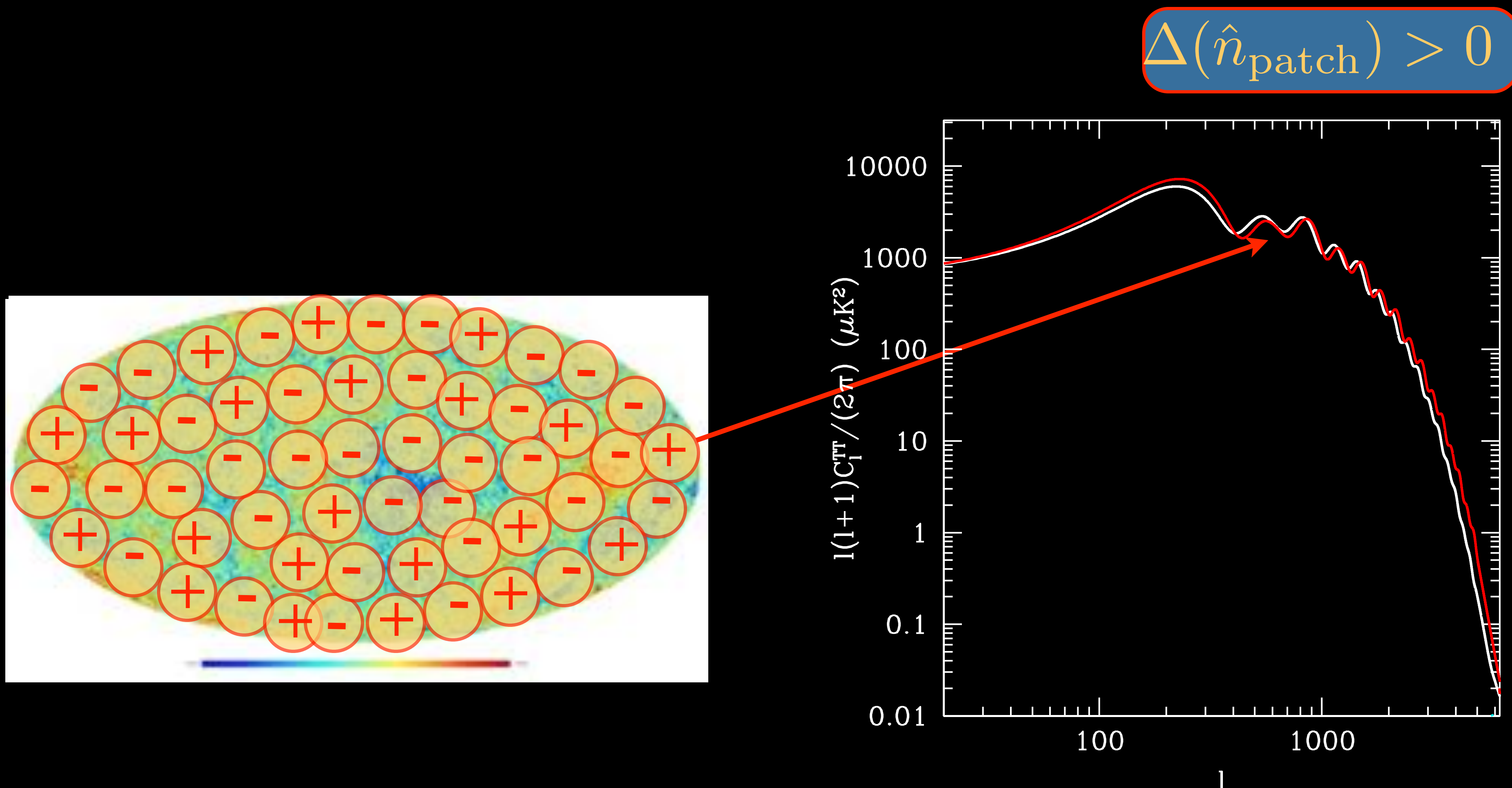
- In single realization of CIP spec., a long wavelength CIP w/ amp Δ_{LM} modulates the power spectrum across the sky



COMPENSATED ISOCURVATURE AND THE CMB:
RECOVERING THE REALIZATION



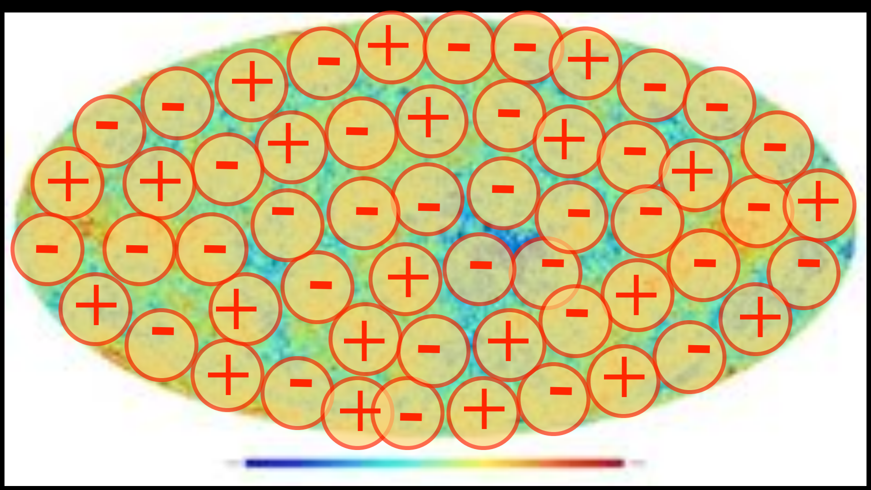
COMPENSATED ISOCURVATURE AND THE CMB: *RECOVERING THE REALIZATION*



COMPENSATED ISOCURVATURE AND THE CMB:
RECOVERING THE REALIZATION

- ✳ Power spec. results were true, averaging over realizations of primordial $\Phi(\hat{n})$ and CIP amplitude $\Delta(\hat{n})$

- ✳ In single realization of CIP spec., a long wavelength CIP w/ amp Δ_{LM} modulates the power spectrum across the sky



✳Heuristically:
1. Tile all-sky map with patches
2. Measure power spec in each patch
3. Reconstruct $\Delta(\hat{n})$

OFF-DIAGONAL CORRELATIONS: TOY MODEL

$$T(\vec{\theta})_{\rm CIP} = T(\vec{\theta})_{\rm no\ CIP} + \left.\frac{dT(\vec{\theta})_{\rm no\ CIP}}{d\Omega_b}\right|_{\Omega_m} \Delta(\vec{\theta})$$

OFF-DIAGONAL CORRELATIONS: TOY MODEL

$$T(\vec{\theta})_{\rm CIP} = T(\vec{\theta})_{\rm no\ CIP} + \left.\frac{dT(\vec{\theta})_{\rm no\ CIP}}{d\Omega_b}\right|_{\Omega_m} \boxed{\Delta(\vec{\theta})}$$

CIP modulation

OFF-DIAGONAL CORRELATIONS: TOY MODEL

$$T(\vec{\theta})_{\mathrm{CIP}} = T(\vec{\theta})_{\text{no CIP}} + \left.\frac{dT(\vec{\theta})_{\text{no CIP}}}{d\Omega_b}\right|_{\Omega_m} \Delta(\vec{\theta})$$

$$T(\vec{l})_{\mathrm{CIP}} = T(\vec{l})_{\text{no CIP}} + \int d\vec{L}\, \left.\frac{dT(\vec{L}-\vec{l})_{\text{no CIP}}}{d\Omega_b}\right|_{\Omega_m} \Delta(\vec{L})$$

Mode coupling in Fourier space

OFF-DIAGONAL CORRELATIONS: TOY MODEL

$$T(\vec{\theta})_{\rm CIP} = T(\vec{\theta})_{\rm no\ CIP} + \left.\frac{dT(\vec{\theta})_{\rm no\ CIP}}{d\Omega_b}\right|_{\Omega_m} \Delta(\vec{\theta})$$

$$T(\vec{l})_{\rm CIP} = T(\vec{l})_{\rm no\ CIP} + \int d\vec{L}\, \left.\frac{dT(\vec{L}-\vec{l})_{\rm no\ CIP}}{d\Omega_b}\right|_{\Omega_m} \Delta(\vec{L})$$

$$\left\langle T\left(\vec{l}\right)_{\rm CIP} T^{*}\left(\vec{l'}\right)_{\rm CIP}\right\rangle = (2\pi)^2\, C_l^{TT} \delta^{(2)}(\vec{l}-\vec{l'}) + (2\pi)^2\, \Delta(\vec{l}+\vec{l'}) \left.\frac{dC_{l'}^{TT}}{d\Omega_b}\right|_{\Omega_m}$$

There in standard cosmology

OFF-DIAGONAL CORRELATIONS: TOY MODEL

$$T(\vec{\theta})_{\rm CIP} = T(\vec{\theta})_{\rm no\ CIP} + \left.\frac{dT(\vec{\theta})_{\rm no\ CIP}}{d\Omega_b}\right|_{\Omega_m} \Delta(\vec{\theta})$$

$$T(\vec{l})_{\rm CIP} = T(\vec{l})_{\rm no\ CIP} + \int d\vec{L}\, \left.\frac{dT(\vec{L}-\vec{l})_{\rm no\ CIP}}{d\Omega_b}\right|_{\Omega_m} \Delta(\vec{L})$$

$$\left\langle T\left(\vec{l}\right)_{\rm CIP} T^{*}\left(\vec{l'}\right)_{\rm CIP}\right\rangle = (2\pi)^2\, C_l^{TT}\delta^{(2)}(\vec{l}-\vec{l'}) + (2\pi)^2\, \Delta(\vec{l}+\vec{l'}) \left.\frac{dC_{l'}^{TT}}{d\Omega_b}\right|_{\Omega_m}$$

Isotropy-breaking term in fixed CIP realization

OFF-DIAGONAL CORRELATIONS: TOY MODEL

$$T(\vec{\theta})_{\rm CIP} = T(\vec{\theta})_{\rm no\ CIP} + \left.\frac{dT(\vec{\theta})_{\rm no\ CIP}}{d\Omega_b}\right|_{\Omega_m} \Delta(\vec{\theta})$$

$$T(\vec{l})_{\rm CIP} = T(\vec{l})_{\rm no\ CIP} + \int d\vec{L}\, \left.\frac{dT(\vec{L}-\vec{l})_{\rm no\ CIP}}{d\Omega_b}\right|_{\Omega_m} \Delta(\vec{L})$$

$$\left\langle T\left(\vec{l}\right)_{\rm CIP} T^{*}\left(\vec{l'}\right)_{\rm CIP}\right\rangle = (2\pi)^2\, C_l^{TT}\delta^{(2)}(\vec{l}-\vec{l'}) + (2\pi)^2\,\Delta(\vec{l}+\vec{l'})\left.\frac{dC_{l'}^{TT}}{d\Omega_b}\right|_{\Omega_m}$$

Can be used to reconstruct CIP from CMB map!

Isotropy-breaking term in fixed CIP realization

Filtering the map: real space response

✴ Generate CIP map (reconstruction)

$$\hat{\Delta}_{LM} = \left(N_L^{\Delta\Delta}\right)^{-1} \int d\hat{n} Y^*_{LM}(\hat{n})\overline{T}(\hat{n})S(\hat{n}) + (1 \leftrightarrow 2)$$

$$\bar{T}(\hat{n}) = \sum_{lm} Y_{lm}(\hat{n})\bar{T}^{(a)}_{lm},$$

$$S(\hat{n}) = \sum_{lm} Y_{lm}(\hat{n})C_l^{\mathrm{T,dT}}\bar{T}_{lm},$$




Filtering the map: real space response

✴ Generate CIP map (reconstruction)

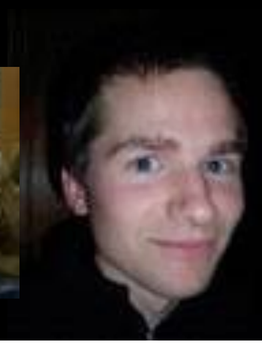
$$\hat{\Delta}_{LM} = \left(N_L^{\Delta\Delta}\right)^{-1} \int d\hat{n} Y_{LM}^*(\hat{n}) \overline{T}(\hat{n}) S(\hat{n}) + (1 \leftrightarrow 2)$$

$$\bar{T}(\hat{n}) = \sum_{lm} Y_{lm}(\hat{n}) \bar{T}_{lm}^{(a)},$$

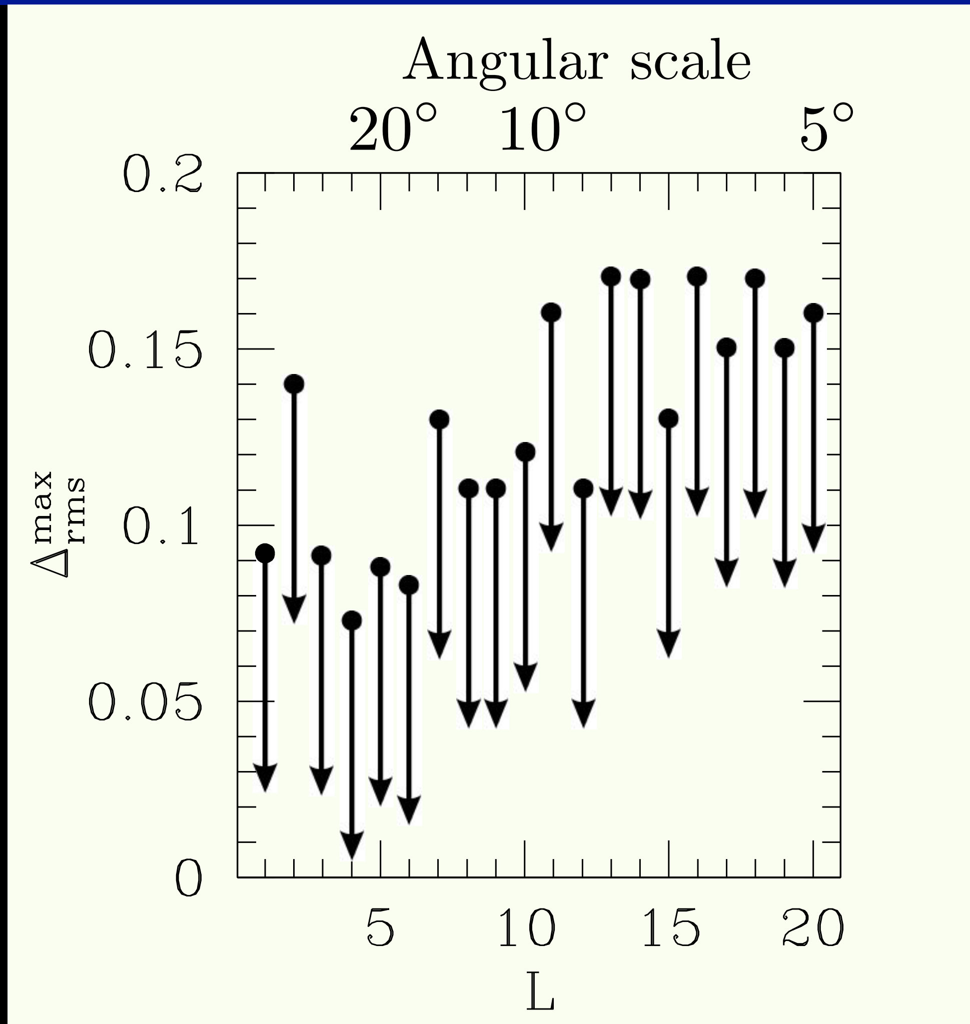
$$S(\hat{n}) = \sum_{lm} Y_{lm}(\hat{n}) C_l^{\mathrm{T,dT}} \bar{T}_{lm},$$

arXiv: 1306.4319 (DG, Duncan Hanson + …)-Phys. Rev. D 89, 023006 (2014)

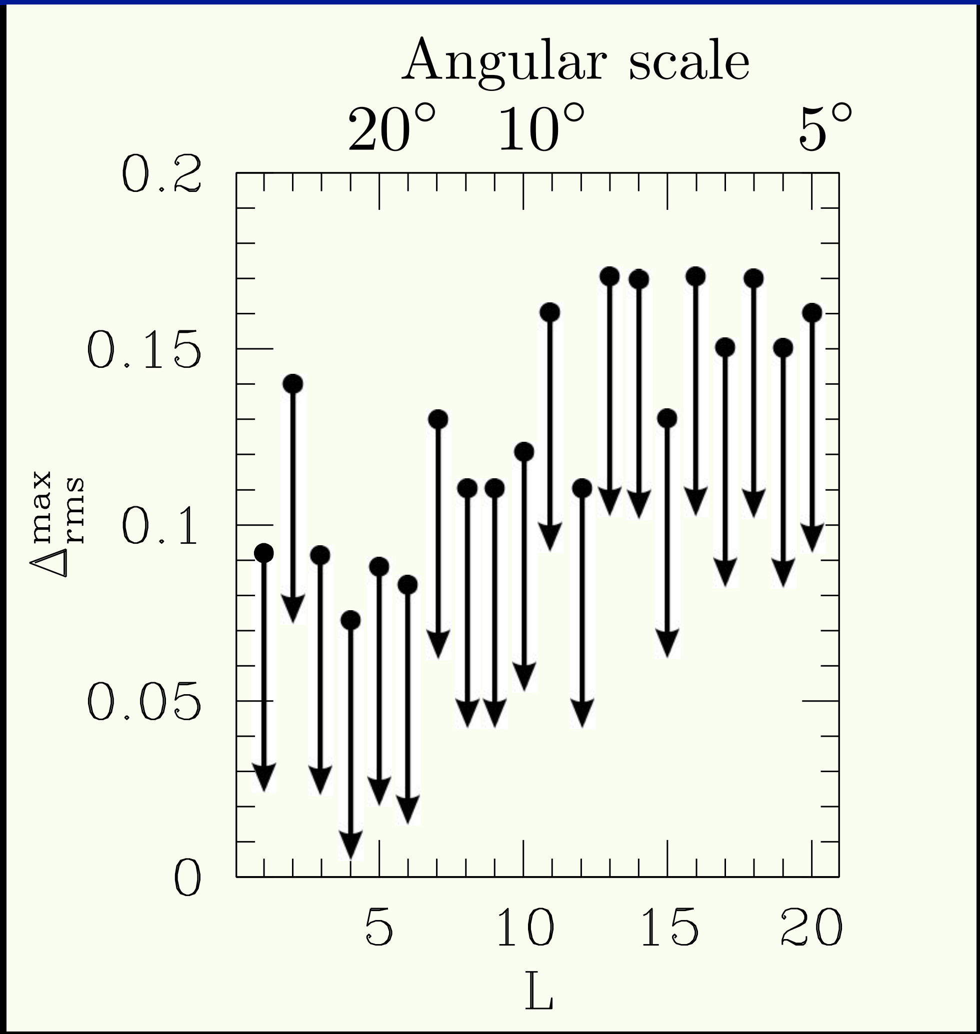


Upper limit to CIP spectrum at a variety of scales

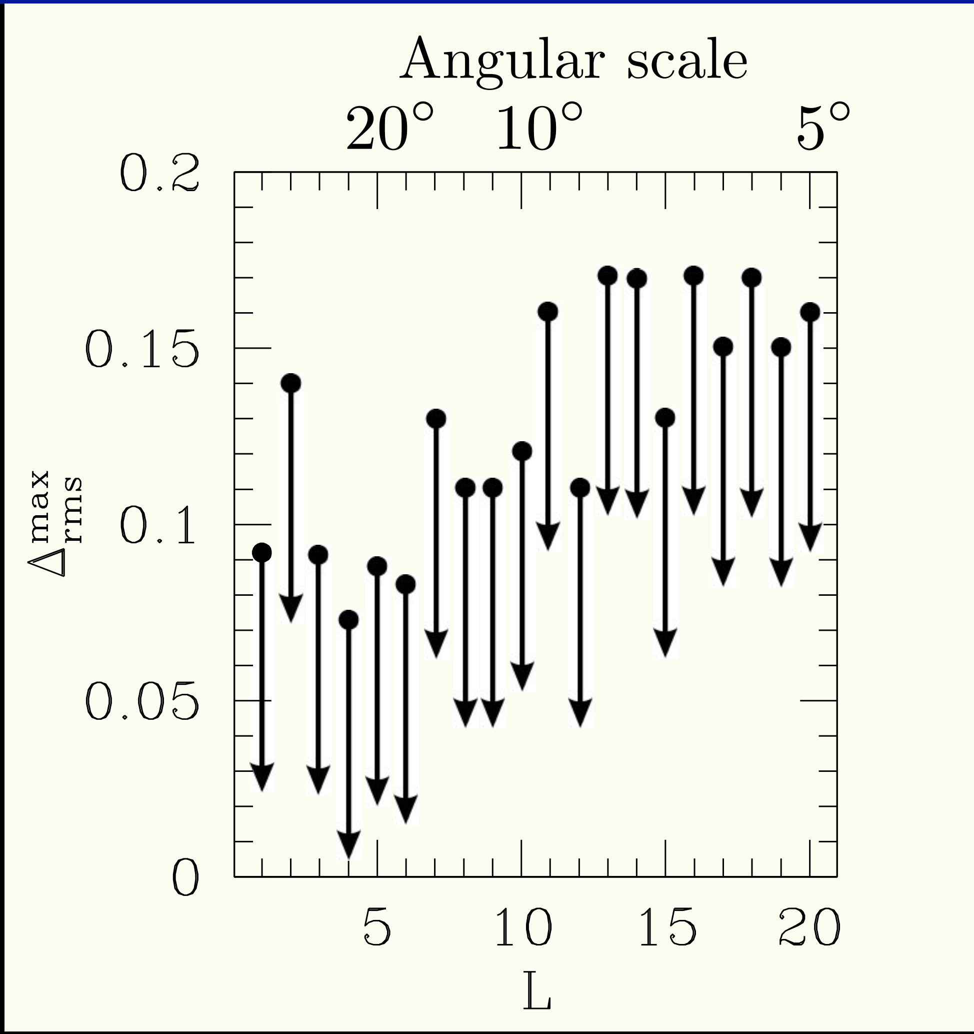


Upper limit to CIP spectrum at a variety of scales



Cosmic baryon fraction is homogeneous at 10-20% level at 5-100˚ scales at z=1100!

Upper limit to CIP spectrum at a variety of scales



$$A_L = 1.14 \pm 0.08$$

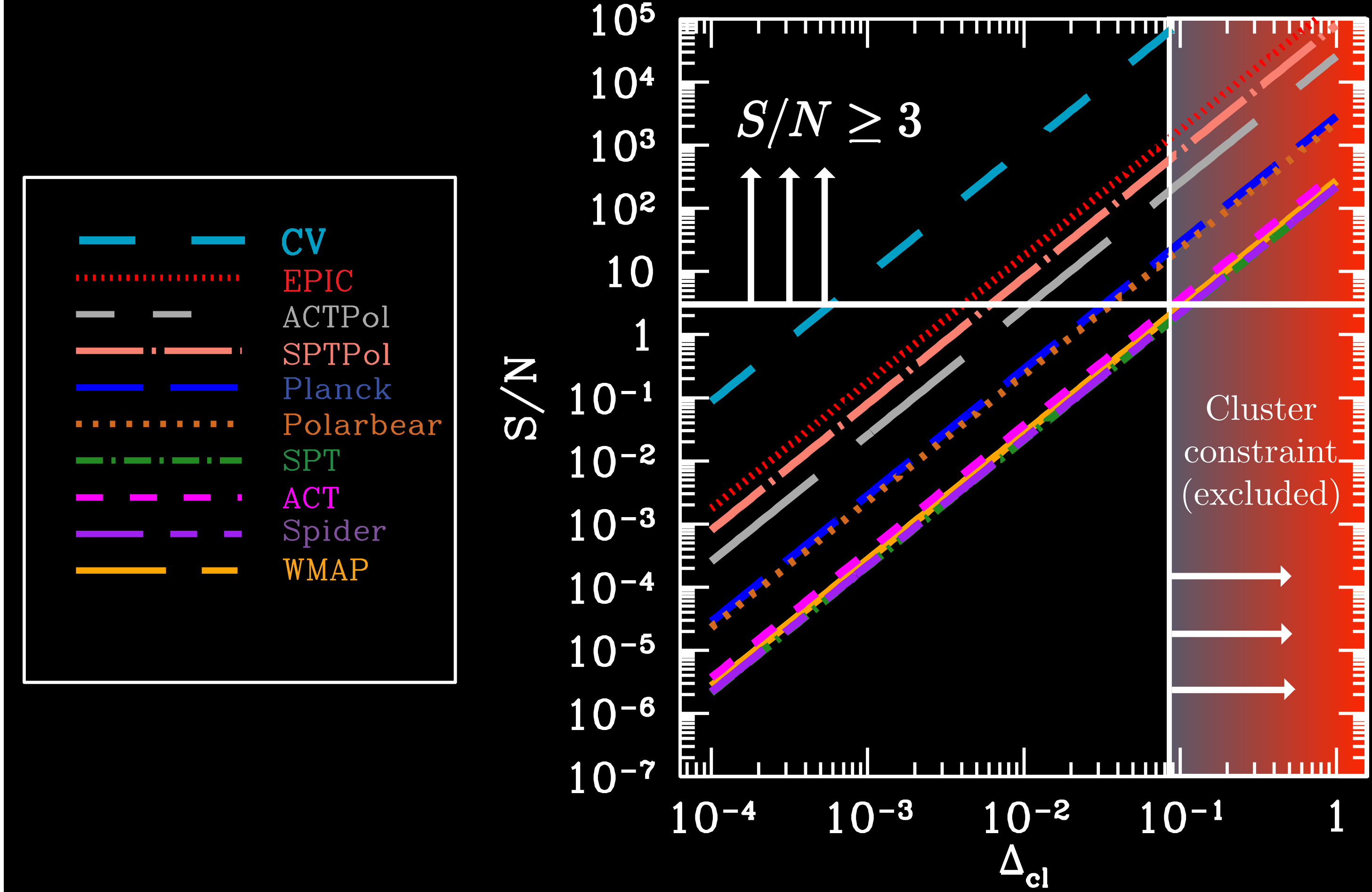
$$\Delta^2_{\rm rms} \leq 0.01$$

Comparable limit from Planck power spectra (lower order statistic)

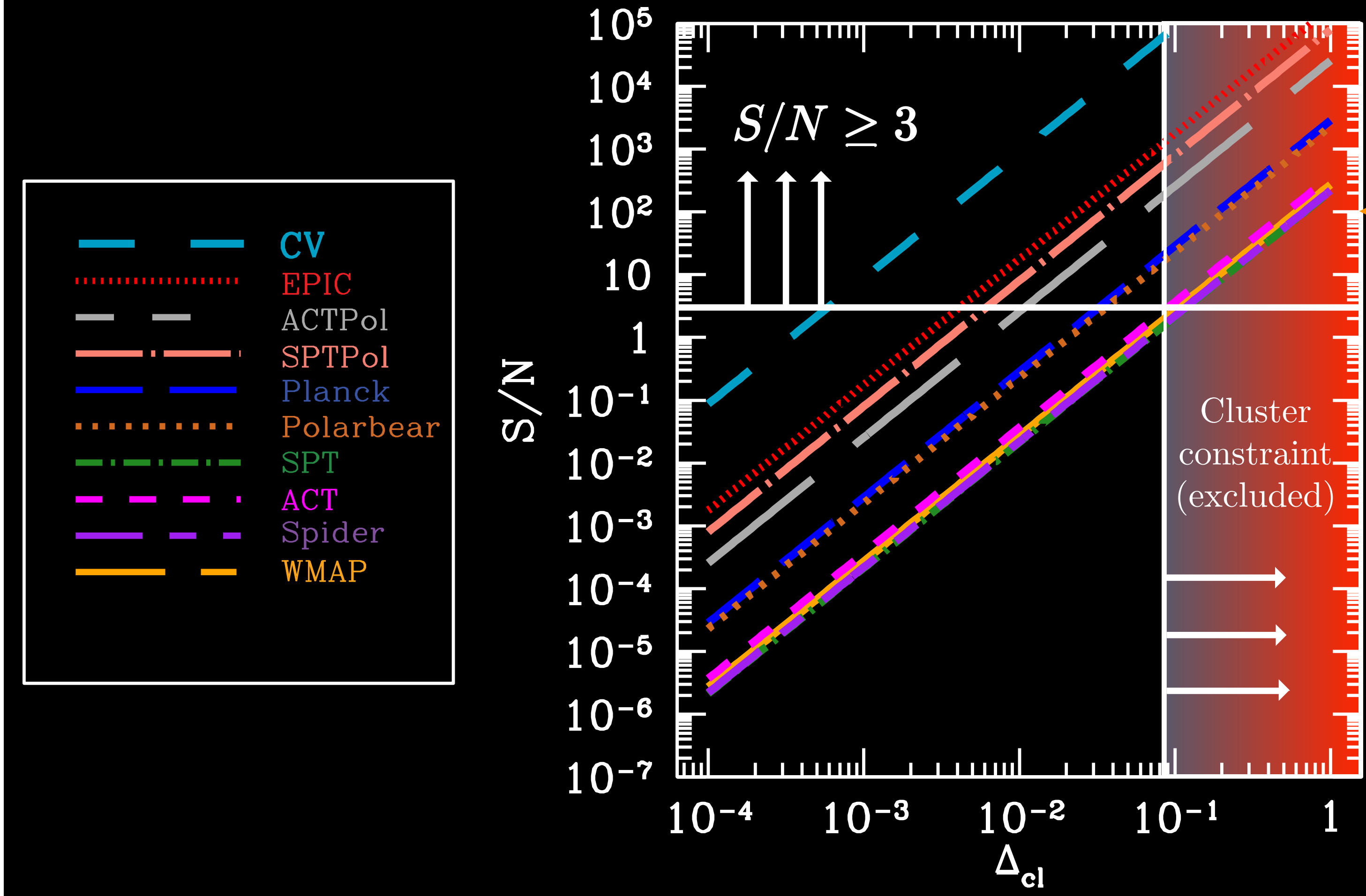
Julian B. Muñoz, DG, Liang Dai, Ely Kovetz, Marc Kamionkowski

arXiv: 1511.04441 , Phys. Rev. D 93, 043008

COMPENSATED ISOCURVATURE AND THE CMB: FORECAST WITH RECONSTRUCTION



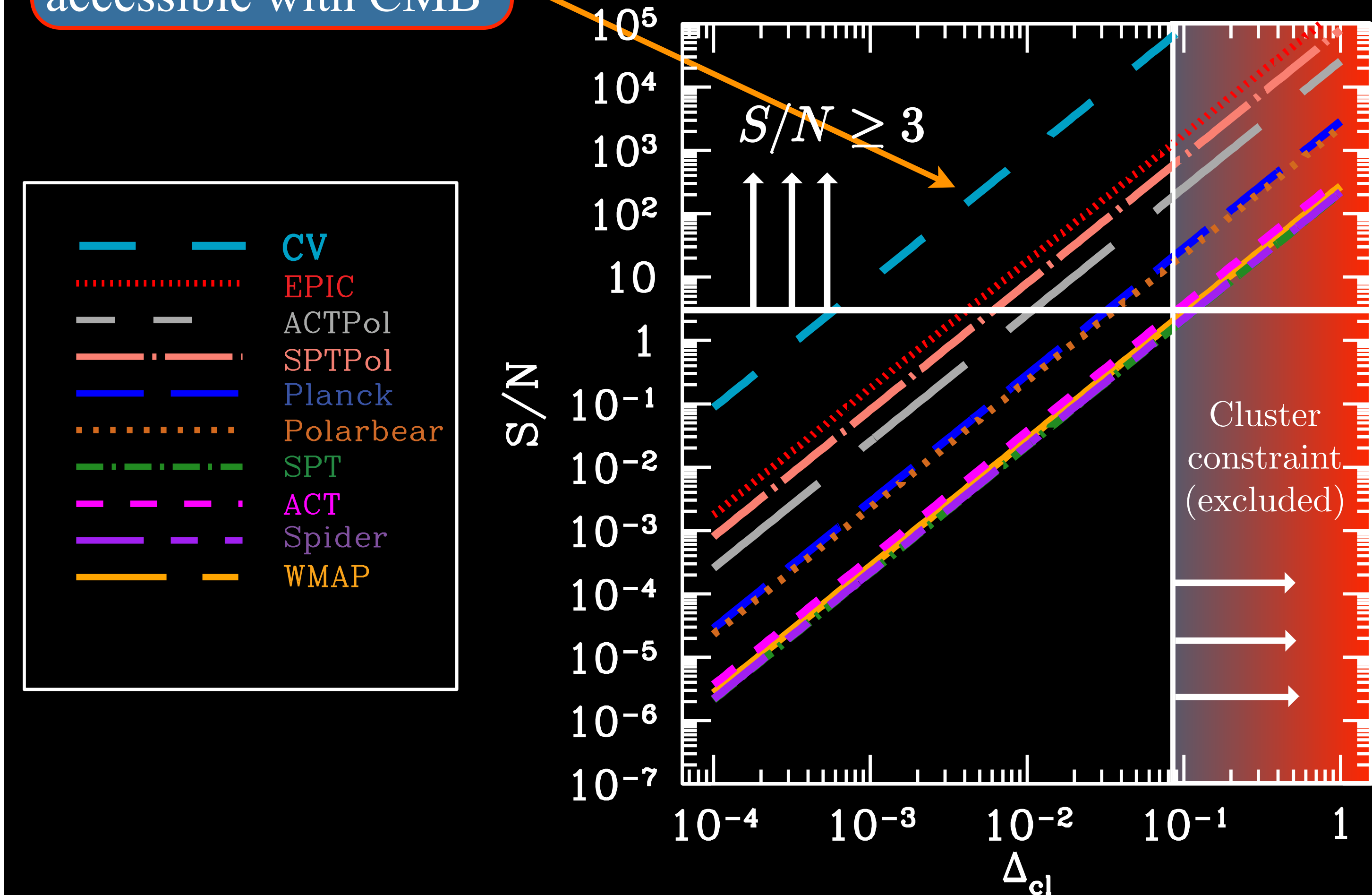
COMPENSATED ISOCURVATURE AND THE CMB: FORECAST WITH RECONSTRUCTION



Excluded by galaxy cluster measurements of baryon fraction

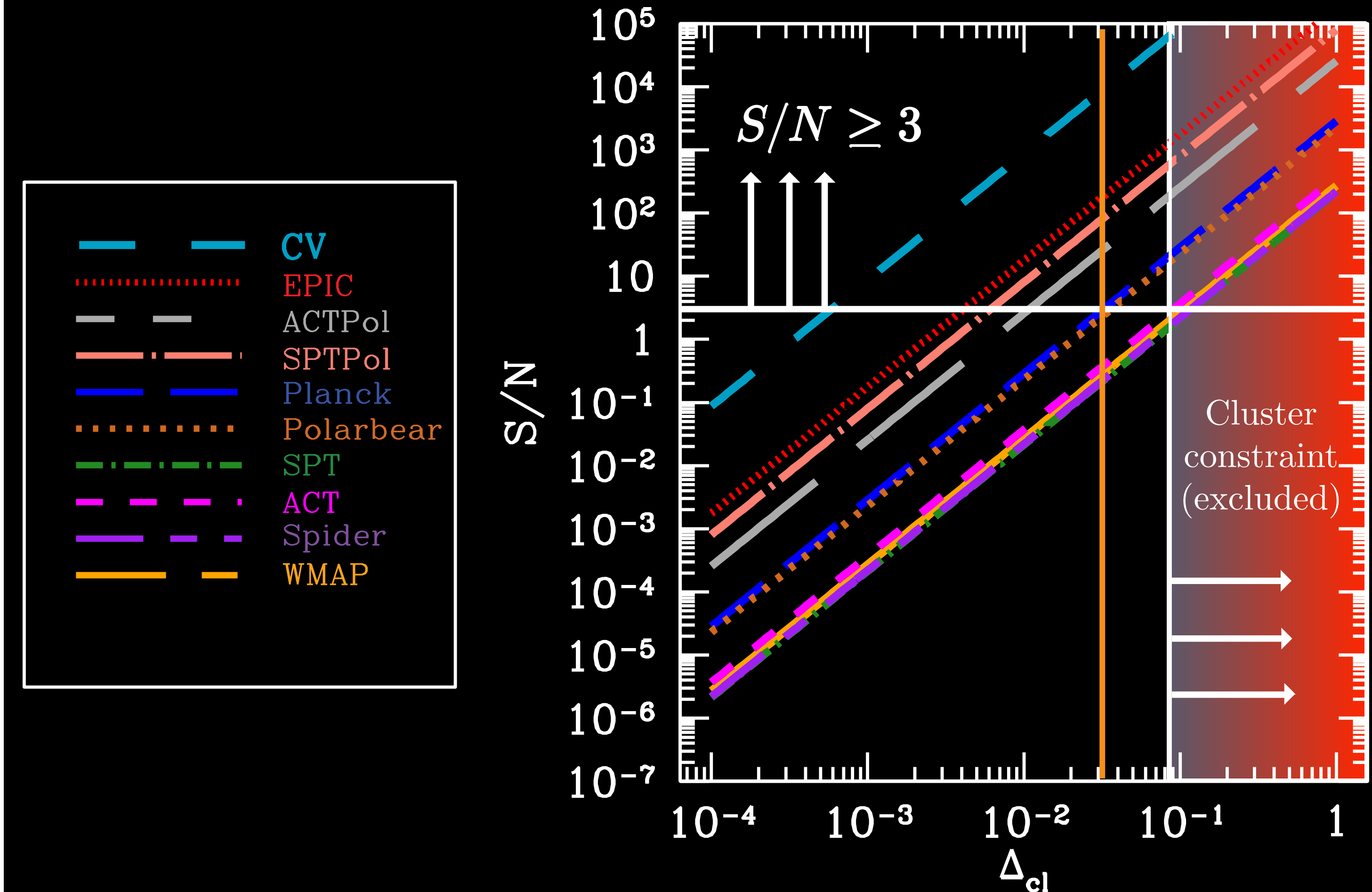
COMPENSATED ISOCURVATURE AND THE CMB: FORECAST WITH RECONSTRUCTION

Parameter space accessible with CMB



Two orders of magnitude improvement: conservatively

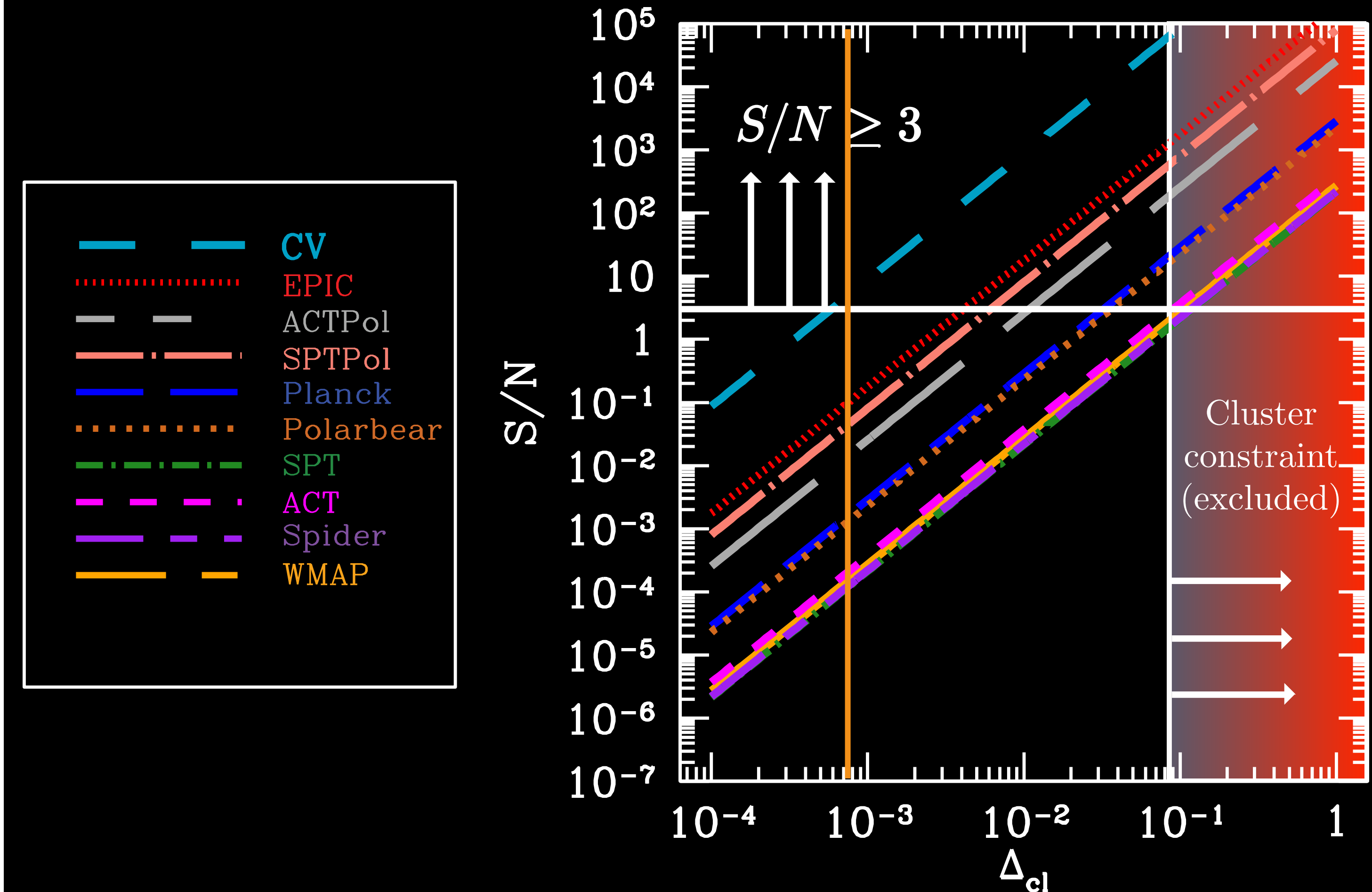
COMPENSATED ISOCURVATURE AND THE CMB: FORECAST WITH RECONSTRUCTION



Ultimate reach of power-spectrum only (Gaussian) method

Two orders of magnitude improvement: conservatively

COMPENSATED ISOCURVATURE AND THE CMB: FORECAST WITH RECONSTRUCTION



Naive curvaton target

Two orders of magnitude improvement: conservatively

CIPS IN THE CURVATON MODEL

- Most interesting curvaton scenario if baryon number generated by curvaton decay, CDM after

$$S^{\text{eff}}_{m\gamma} = S_{c\gamma} + \frac{\Omega_b}{\Omega_c} S_{b\gamma} \propto \left(r_{\rm D} - \frac{\Omega_b}{\Omega_m} \right) \zeta$$

- Linear CMB isocurvature limits then require

$$r_{\rm D} = 0.160 \pm 0.005$$

- Predicting …

$$S_{bc} = A\zeta; \;\; A \simeq 19$$

CIPS IN THE CURVATON MODEL

- Most interesting curvaton scenario if baryon number generated by curvaton decay, CDM after

$$S_{m\gamma}^{\rm eff} = S_{c\gamma} + \frac{\Omega_b}{\Omega_c} S_{b\gamma} \propto \left(r_{\rm D} - \frac{\Omega_b}{\Omega_m} \right) \zeta$$

- Linear CMB isocurvature limits then require

$$r_{\rm D} = 0.160 \pm 0.005$$

- Predicting …

$$S_{bc} = A\zeta;\ \ A \simeq 19$$

Large, possibly detectable CIPs, correlated with adiabatic fluctuations

CIPS IN THE CURVATON MODEL

- Correlation of CIP and temperature fields

$$\left\langle \Delta^*(\vec{k}) \left[\frac{\Delta T(\vec{k}')}{T}\right]\right\rangle = -\frac{1}{5}\left\langle \Delta^*(\vec{k})\zeta\right\rangle = -\frac{A}{5}\left\langle \zeta^*(\vec{k})\zeta(\vec{k}')\right\rangle = -(2\pi)^3\frac{A}{5}\delta^3(\vec{k}-\vec{k}')P_{\zeta\zeta}(k)$$

- Correlate two maps to estimate A

$$\hat{A} \propto \sum_{LM} \frac{\hat{\Delta}^*_{LM} T_{LM}}{2L+1} \propto \sum_{LMlml'm'} T_{LM} T^*_{lm} T_{l'm'} V^{LM}_{lml'm'}$$

C. He Heinrich, DG, and Wayne Hu
arXiv:1505.00369
PRD92, 063018


CIPS IN THE CURVATON MODEL

- Correlation of CIP and temperature fields

$$\left\langle \Delta^*(\vec{k}) \left[\frac{\Delta T(\vec{k}')}{T} \right] \right\rangle = -\frac{1}{5} \left\langle \Delta^*(\vec{k}) \zeta \right\rangle = -\frac{A}{5} \left\langle \zeta^*(\vec{k}) \zeta(\vec{k}') \right\rangle = -(2\pi)^3 \frac{A}{5} \delta^3(\vec{k} - \vec{k}') P_{\zeta\zeta}(k)$$

Sachs-Wolfe (large-scale) CMB transfer function

- Correlate two maps to estimate A

$$\hat{A} \propto \sum_{LM} \frac{\hat{\Delta}^*_{LM} T_{LM}}{2L+1} \propto \sum_{LMlml'm'} T_{LM} T^*_{lm} T_{l'm'} V^{LM}_{lml'm'}$$

C. He Heinrich, DG, and Wayne Hu
arXiv:1505.00369
PRD92, 063018


CIPS IN THE CURVATON MODEL

- Correlation of CIP and temperature fields

$$\left\langle \Delta^*(\vec{k}) \left[\frac{\Delta T(\vec{k}')}{T}\right] \right\rangle = -\frac{1}{5}\left\langle \Delta^*(\vec{k})\zeta \right\rangle = -\frac{A}{5}\left\langle \zeta^*(\vec{k})\zeta(\vec{k}') \right\rangle = -(2\pi)^3 \frac{A}{5}\delta^3(\vec{k}-\vec{k}')P_{\zeta\zeta}(k)$$

- Correlate two maps to estimate A

$$\hat{A} \propto \sum_{LM} \frac{\hat{\Delta}^*_{LM} T_{LM}}{2L+1} \propto \sum_{LMlml'm'} T_{LM} T^*_{lm} T_{l'm'} \underbrace{V^{LM}_{lml'm'}}_{\text{Weighting}}$$

C. He Heinrich, DG, and Wayne Hu
arXiv:1505.00369
PRD92, 063018

CIPS IN THE CURVATON MODEL

✳ Correlation of CIP and temperature fields

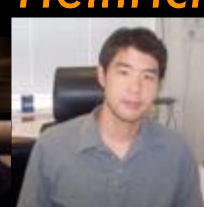
$$\left\langle \Delta^*(\vec{k}) \left[\frac{\Delta T(\vec{k}')}{T} \right] \right\rangle = -\frac{1}{5} \left\langle \Delta^*(\vec{k}) \zeta \right\rangle = -\frac{A}{5} \left\langle \zeta^*(\vec{k}) \zeta(\vec{k}') \right\rangle = -(2\pi)^3 \frac{A}{5} \delta^3(\vec{k} - \vec{k}') P_{\zeta\zeta}(k)$$

✳ Correlate two maps to estimate A

$$\hat{A} \propto \sum_{LM} \frac{\hat{\Delta}^*_{LM} T_{LM}}{2L+1} \propto \sum_{LMlml'm'} T_{LM} T^*_{lm} T_{l'm'} V^{LM}_{lml'm'}$$

3-pt function!

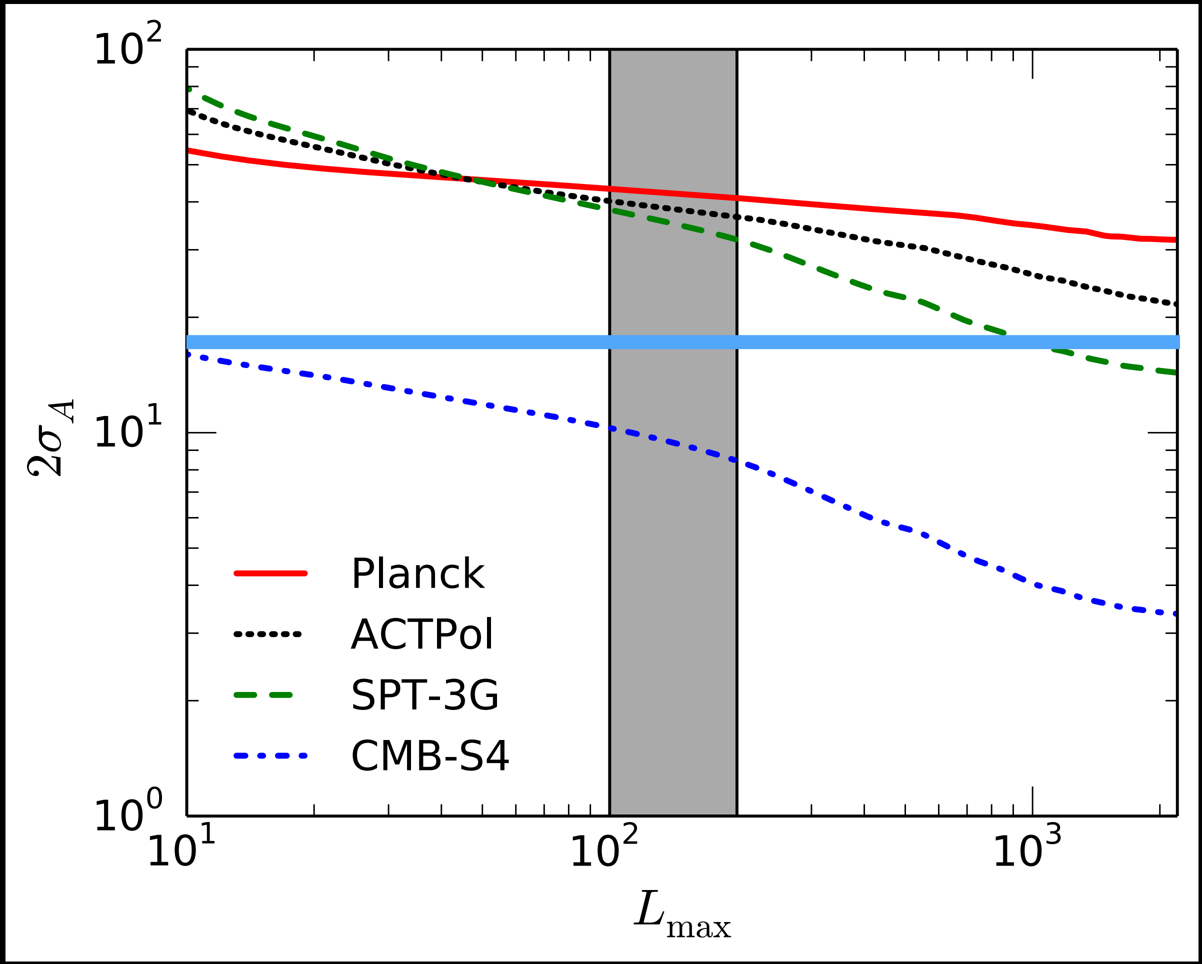
C. He Heinrich, DG, and Wayne Hu



arXiv:1505.00369

PRD92, 063018

OBSERVABILITY OF CURVATON-GENERATED CHIPS

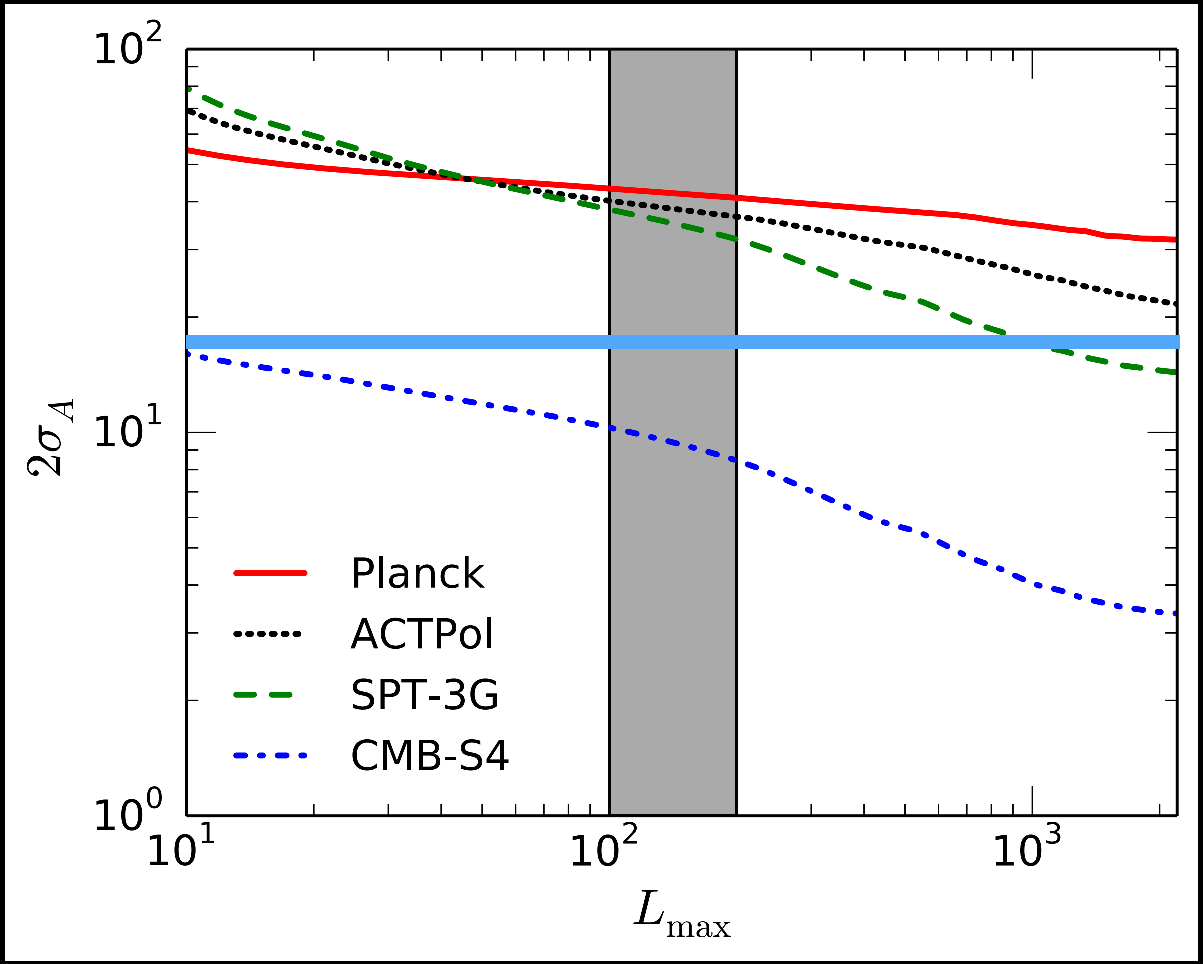


Curvaton CIP amplitude is detectable

C. He Heinrich, DG, and Wayne Hu

arXiv:1505.00369
PRD92, 063018

OBSERVABILITY OF CURVATON-GENERATED CHIPS



Curvaton CIP amplitude is detectable

Conclusions

- Ultra-light axions
  - ~1% level constraints on horizon
  - Lensing is very promising, as is tensor + iso combo
  - Work to be done improving theory
- Curvaton-sourced isocurvature perturbations
  - Existing constraints require fine tuning curvaton-decay scenario
  - Some scenarios will be strongly probed by CIP measurements