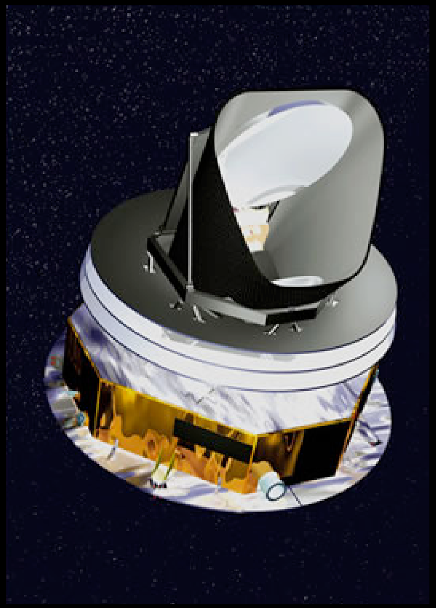
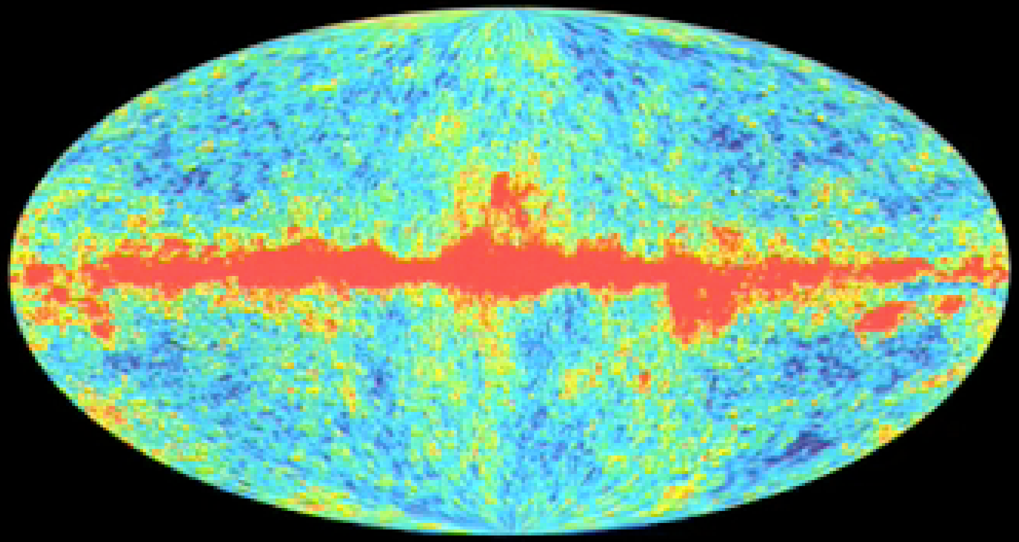
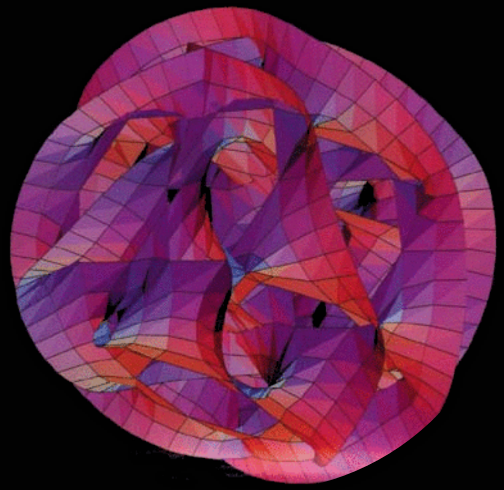
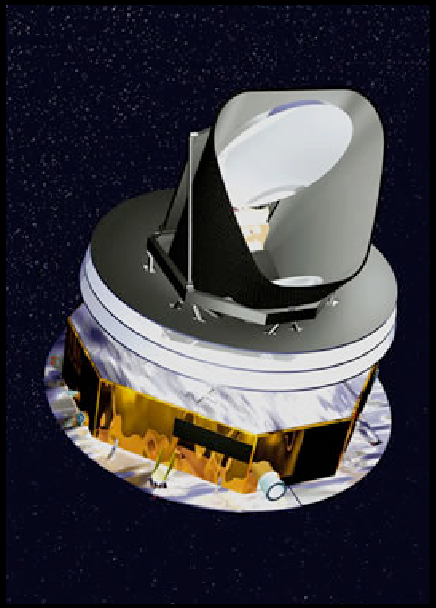


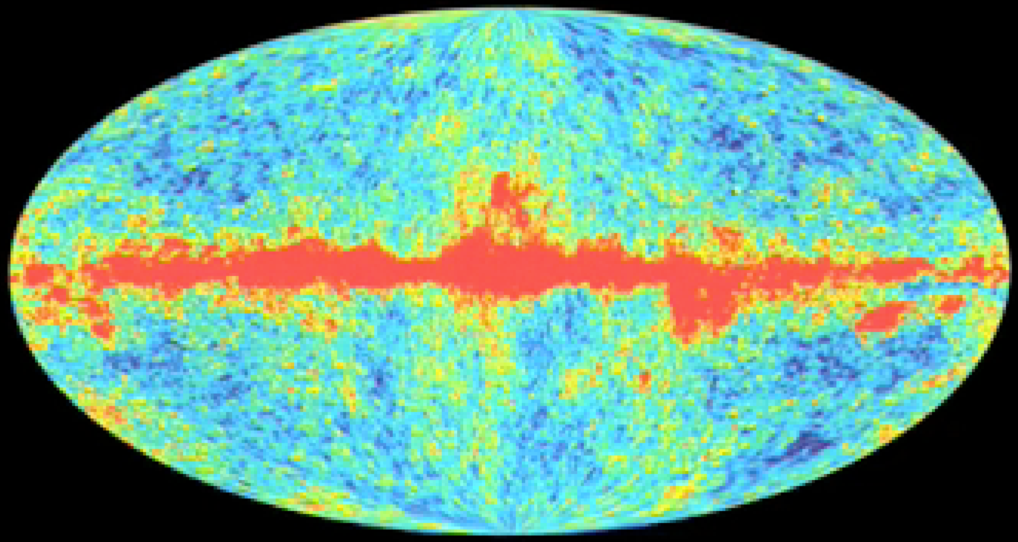


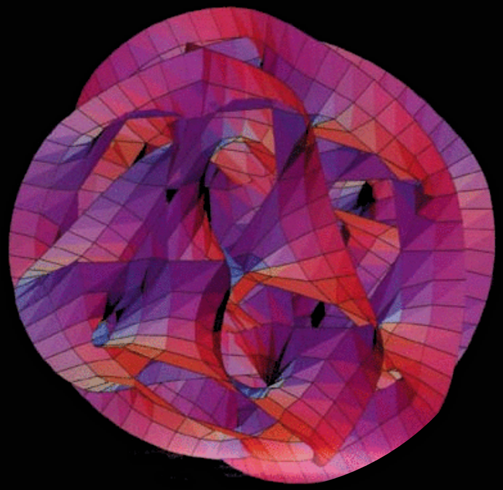


Ultra-light particles & the cosmic microwave background

Daniel Grin
Haverford College
Copernicus Webinar
3/3/2023







Ultra-light particles & the cosmic microwave background

Daniel Grin
Haverford College
Copernicus Webinar
3/3/2023

COLLABORATORS

R.Hložek, D.J. E. Marsh, P.Ferreira, J. Dunkley, E. Calabrese, R.Allison, A. Jaffe, G. Farren








T. L. Smith, V. Poulin, M. Kamionkowski

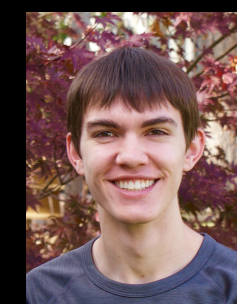
H. Tohfa, J. Crump, E. Baker

E. Trott. D. Zegeye, T. Cookmeyer









S. Singh, D. Wilson, J. Manley, J. Betz, M. Chowdhury

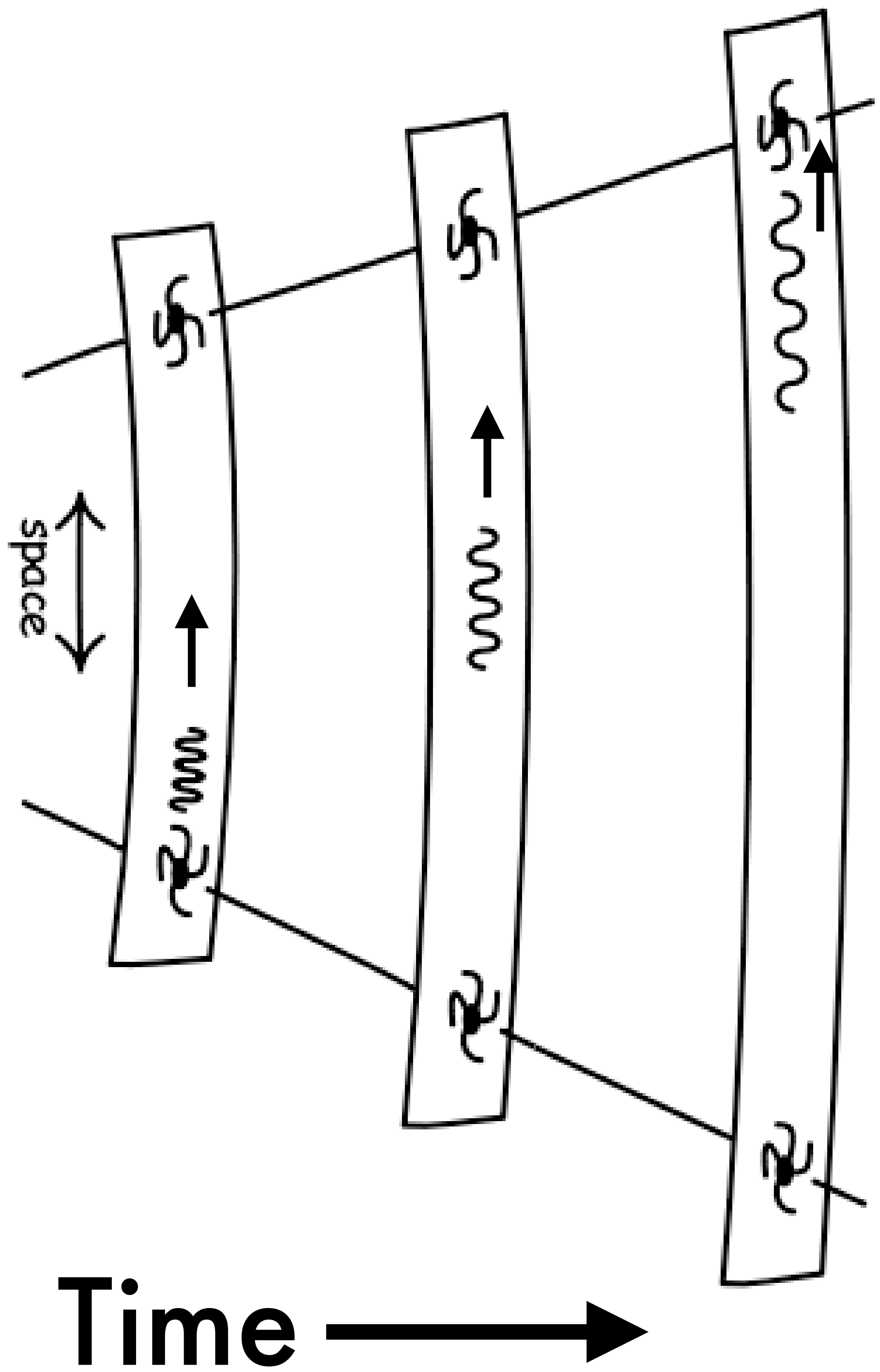


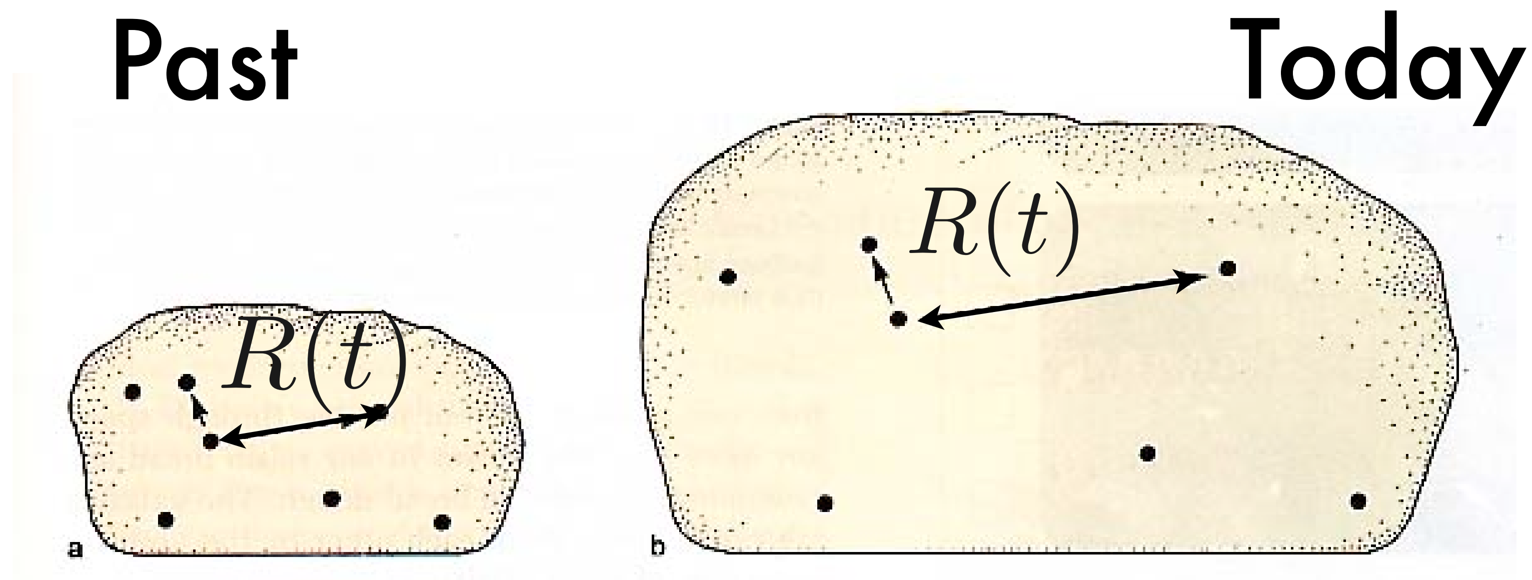


Outline

- ✳ Quick intro to CMB, ULA, etc review
- ✳ Microwave tests of ultra-light axion dark matter
    - ✳ Primary CMB anisotropies
    - ✳ Lensing & Large-scale structure
    - ✳ Bulk flows
- ✳ Light scalars and varying fundamental constants

The expanding universe



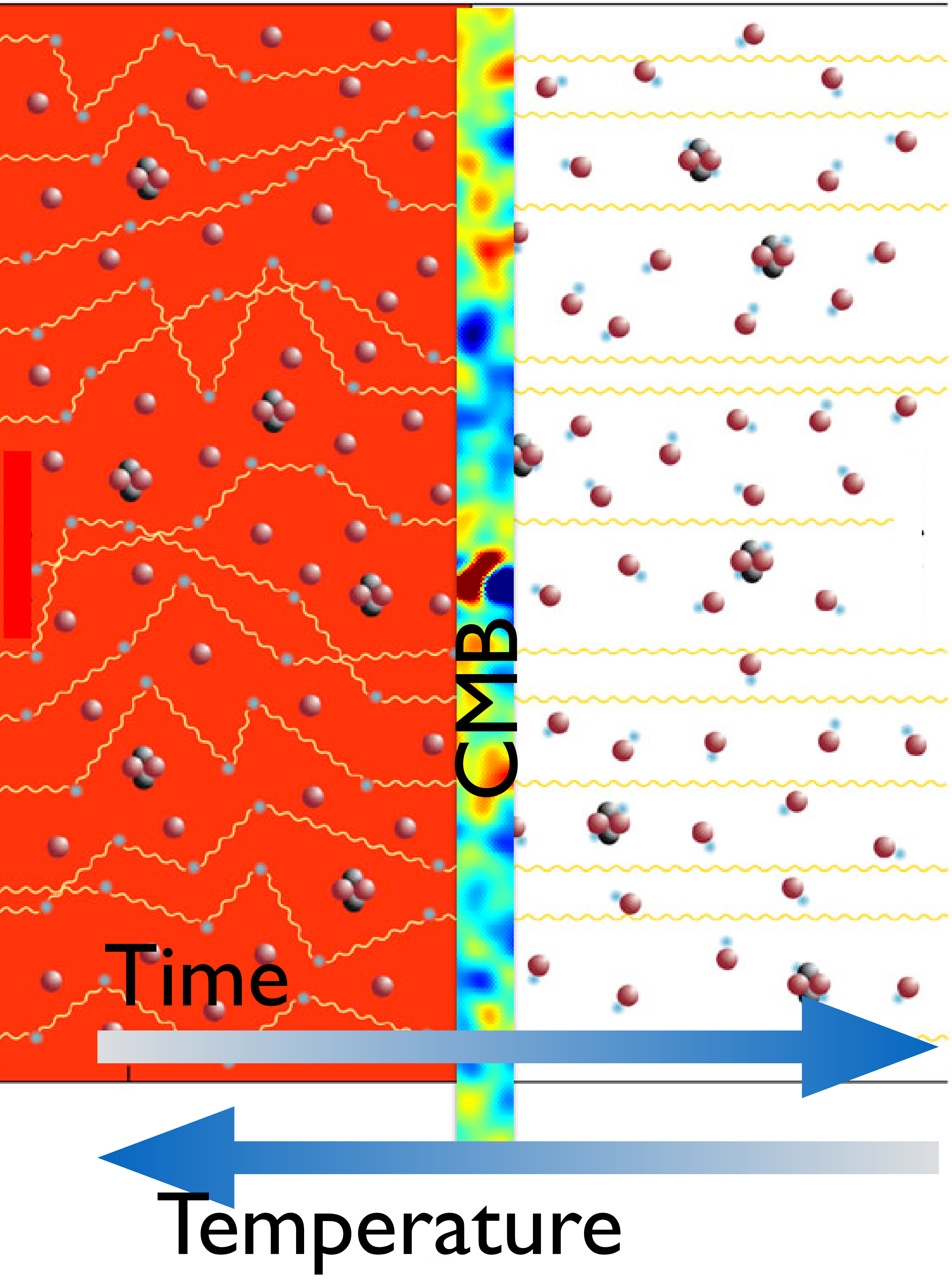


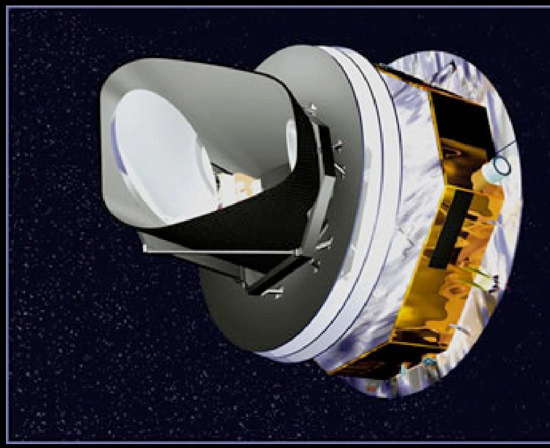
With expansion

$$z = \frac{\lambda_{\text{observed}}}{\lambda_{\text{emitted}}} - 1$$

What are we looking at?

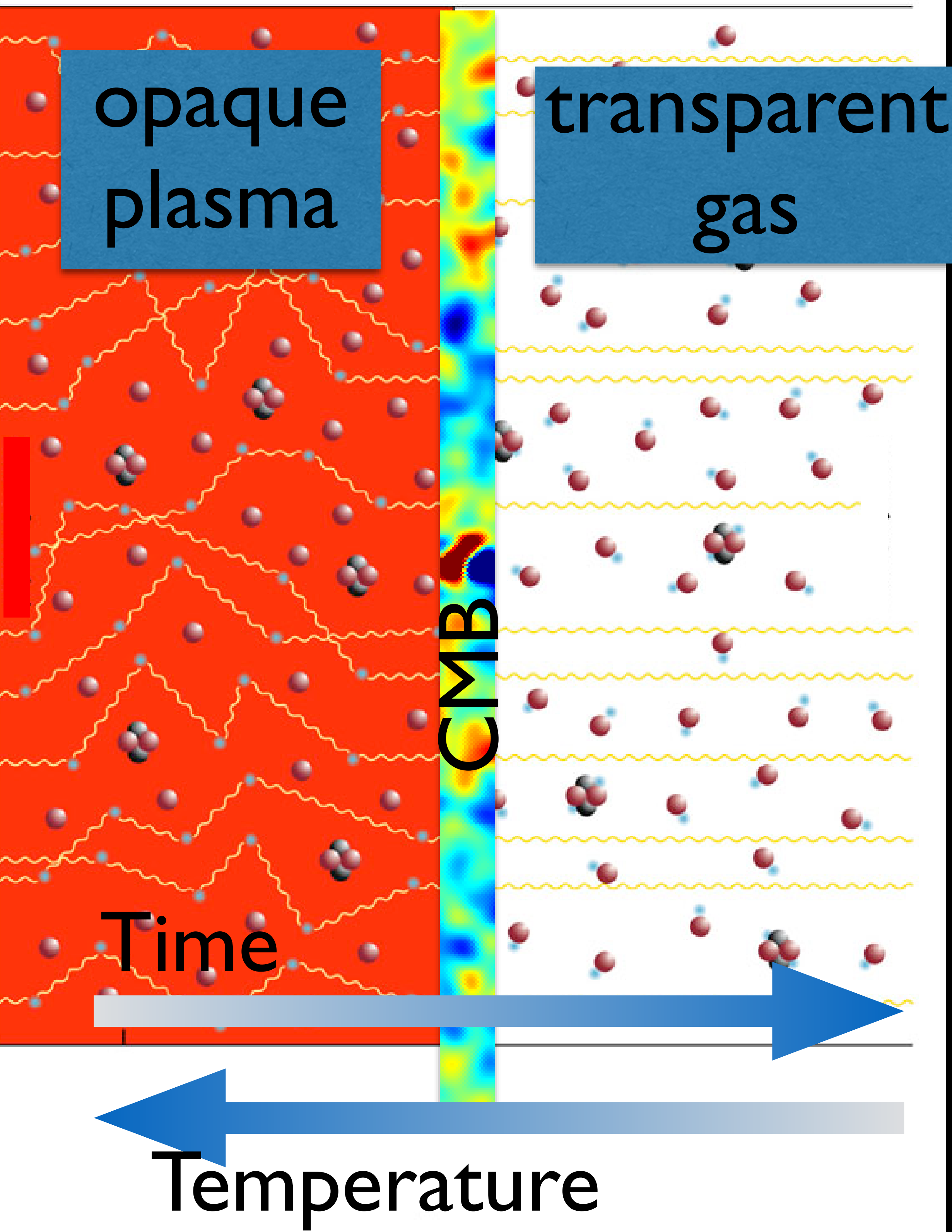
Image credit (Addison Wesley 2004)





What are we looking at?

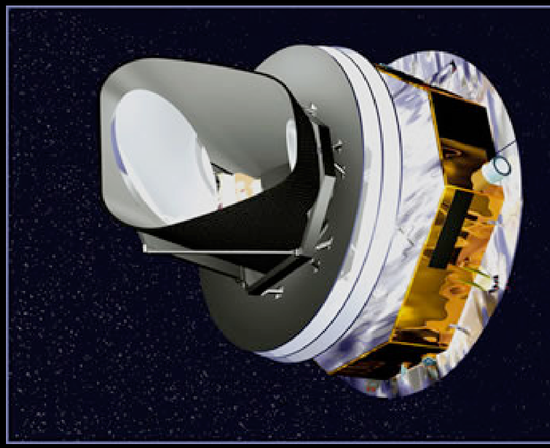
Image credit (Addison Wesley 2004)



`RECOMBINATION':

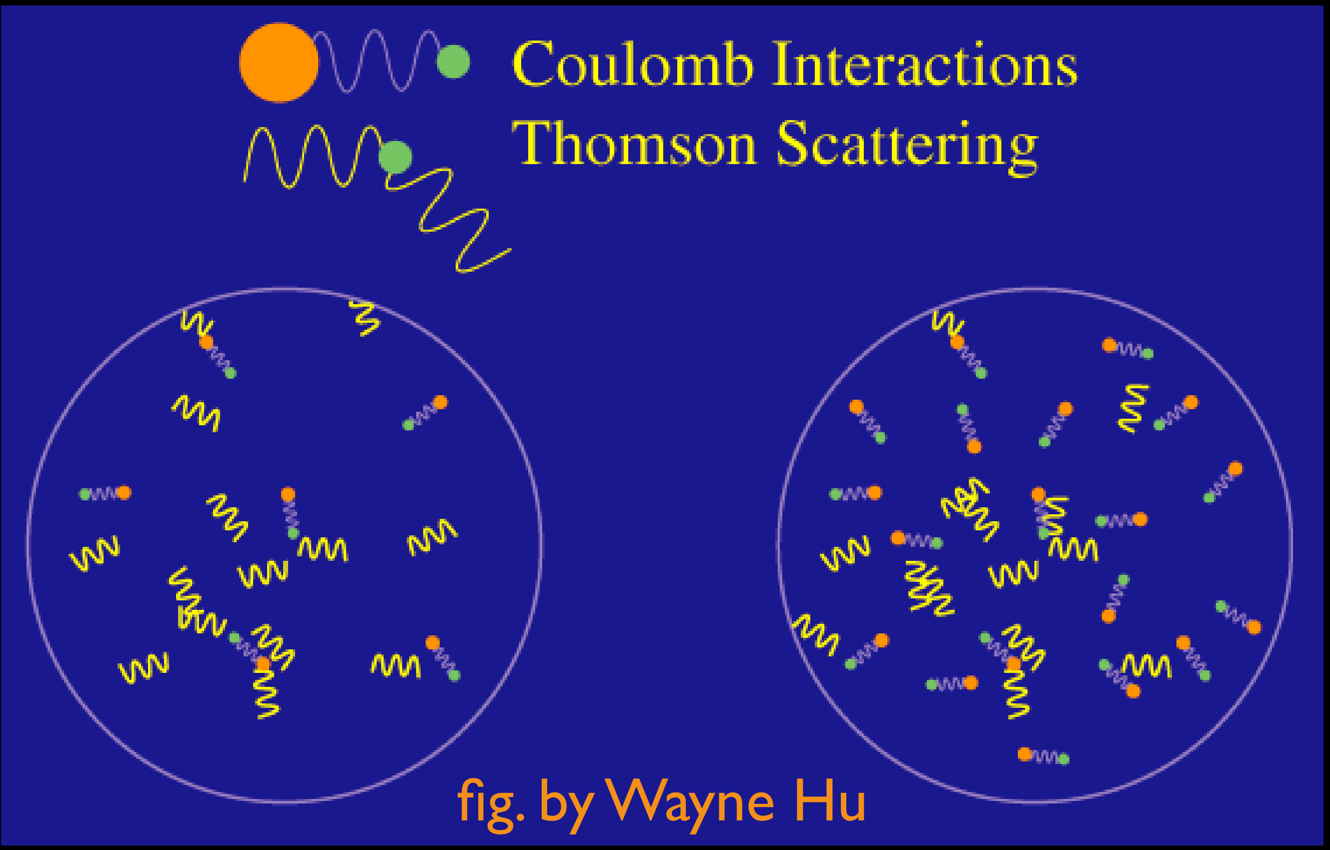
FIRST H ATOMS

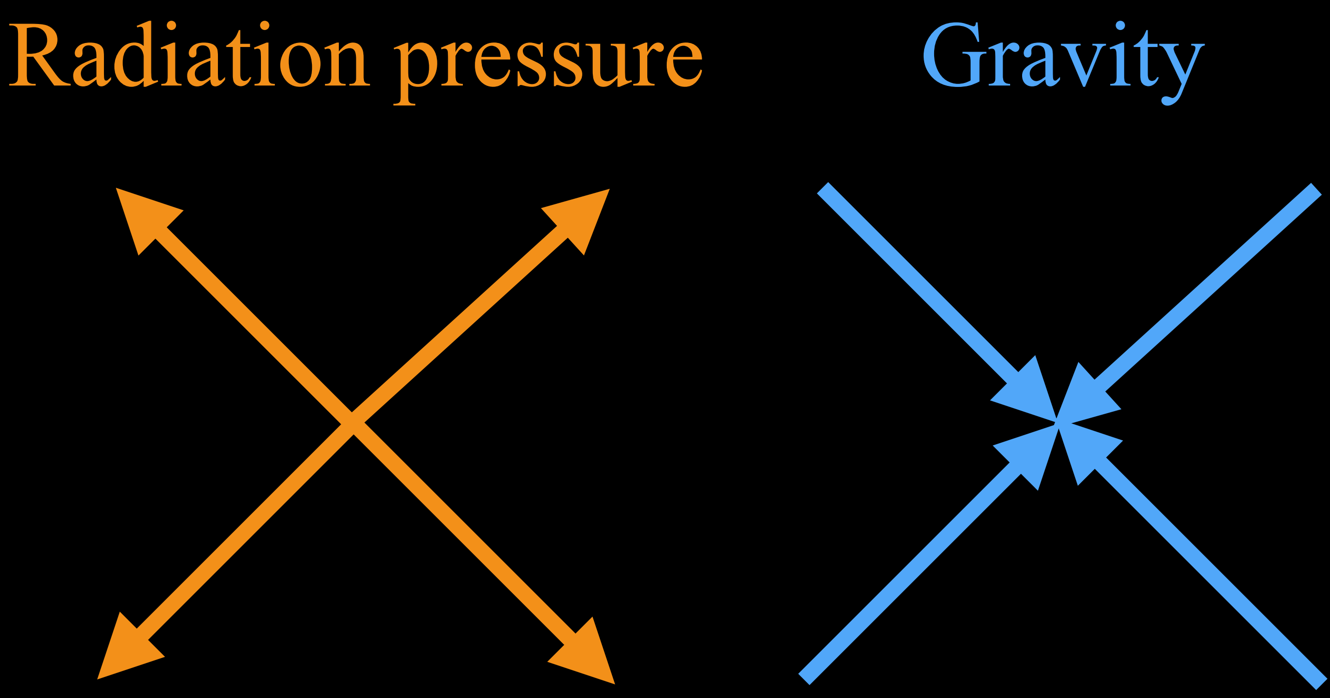
z~1100, t~380,000 years



Sound waves!

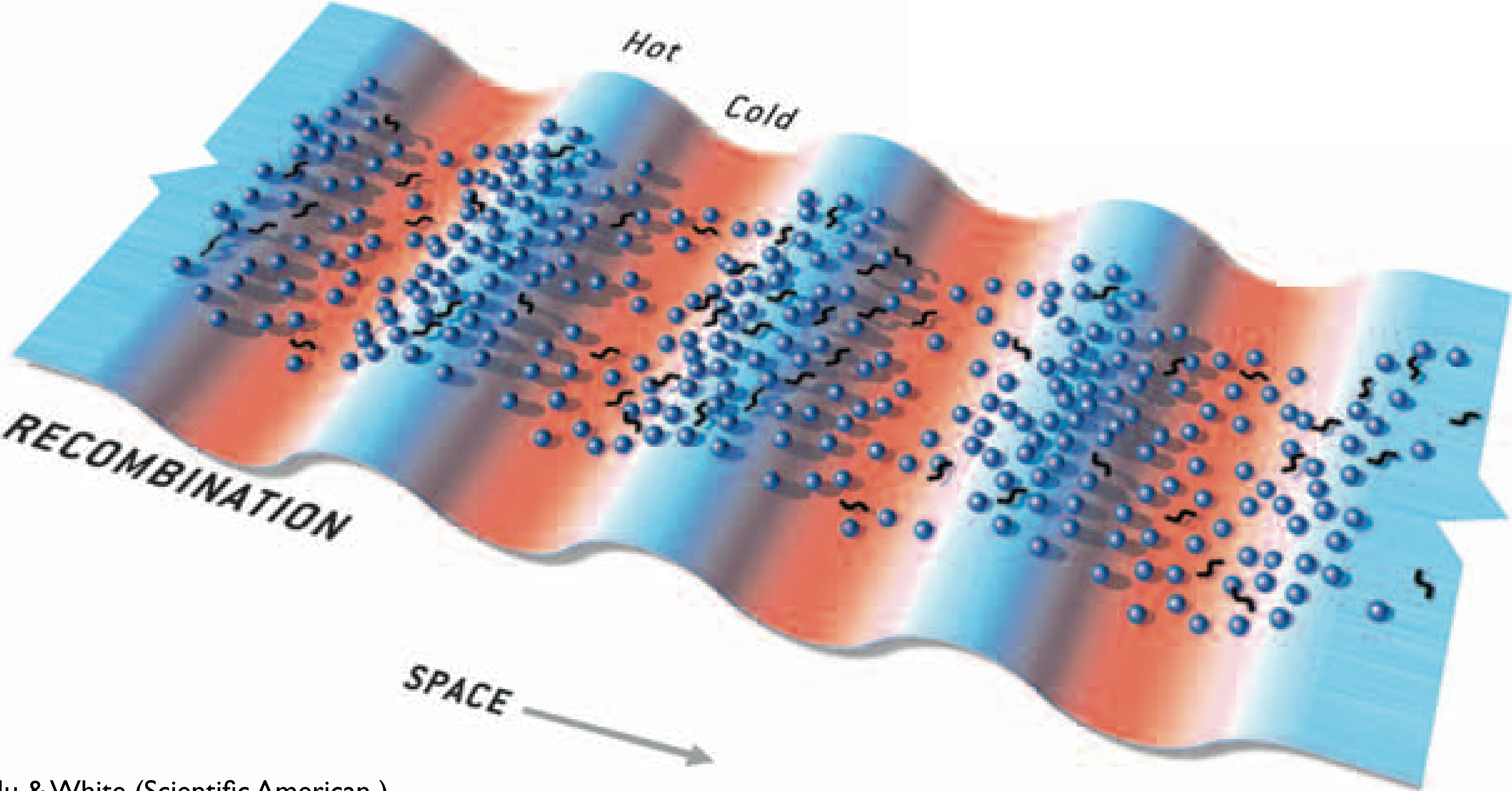
✳ Photons, protons, electrons move together





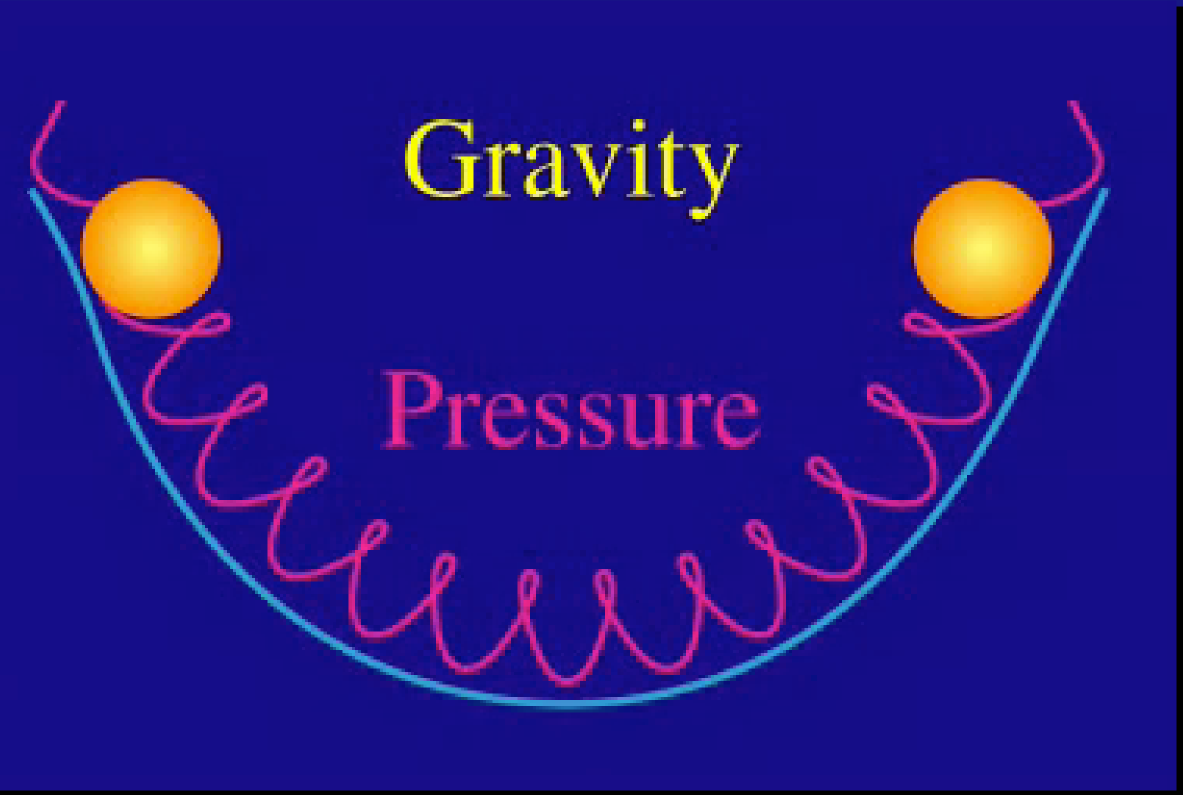
Sound waves!

- Photons, protons, electrons move together

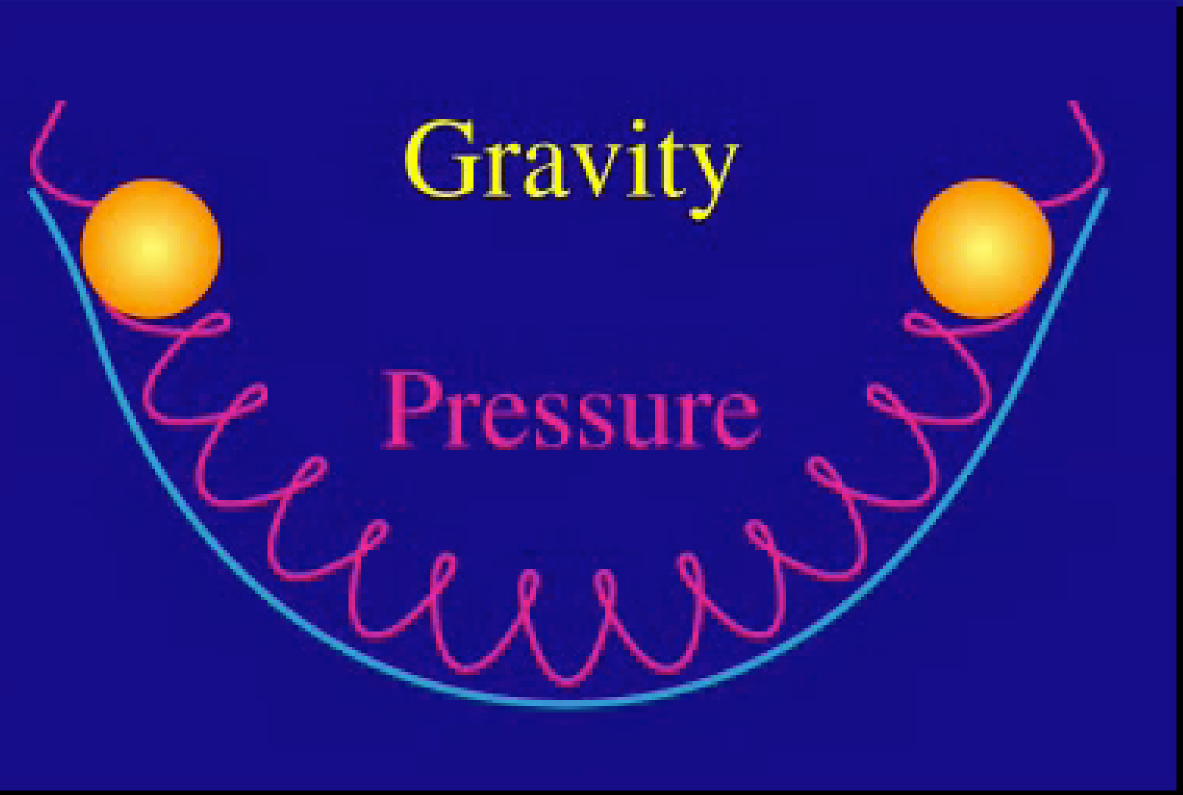


Hu & White (Scientific American)

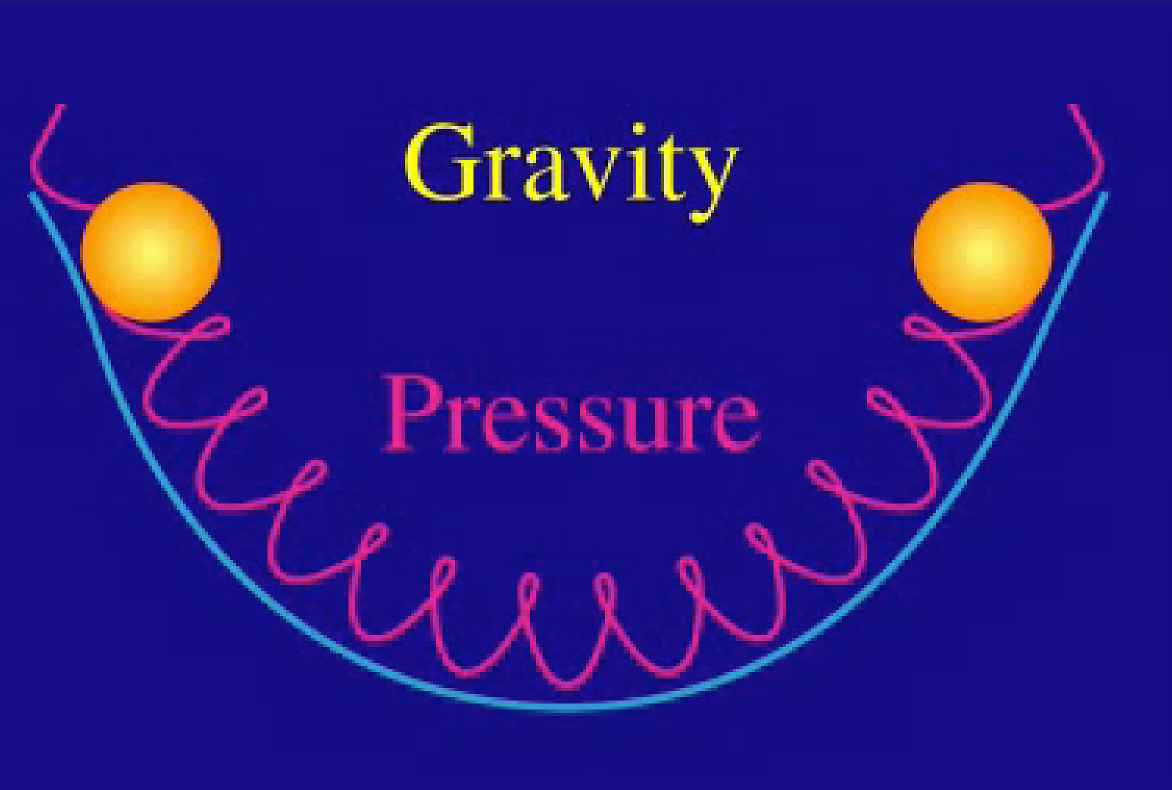
Snapshot and geometry

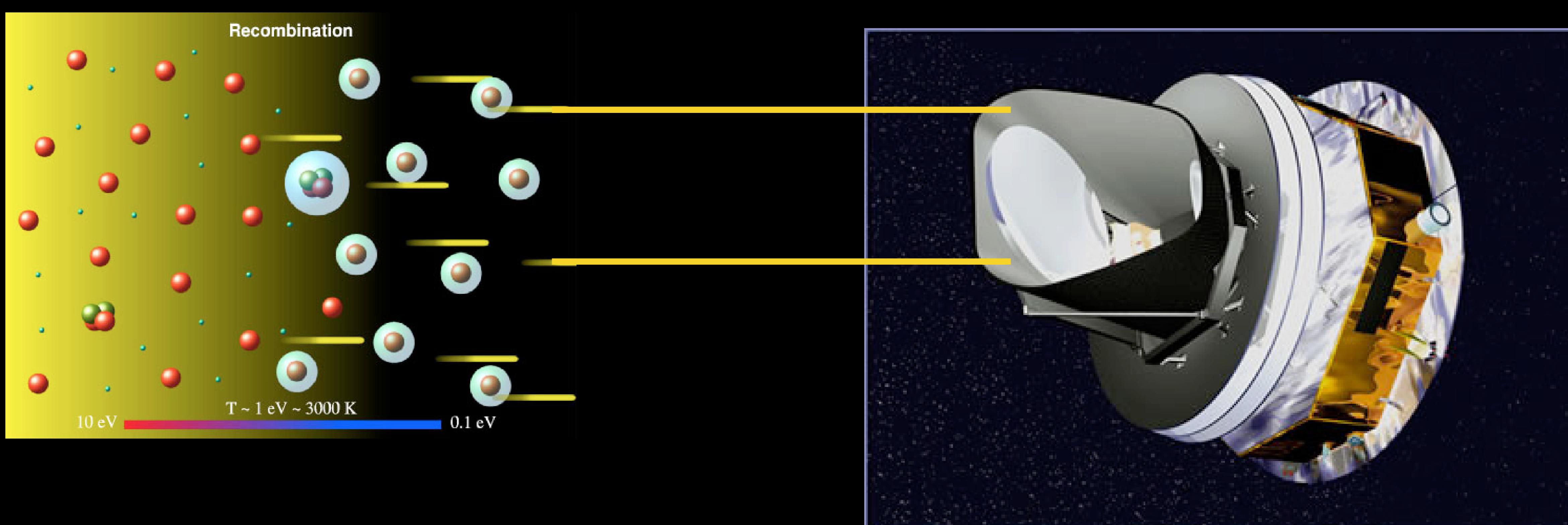


Snapshot and geometry

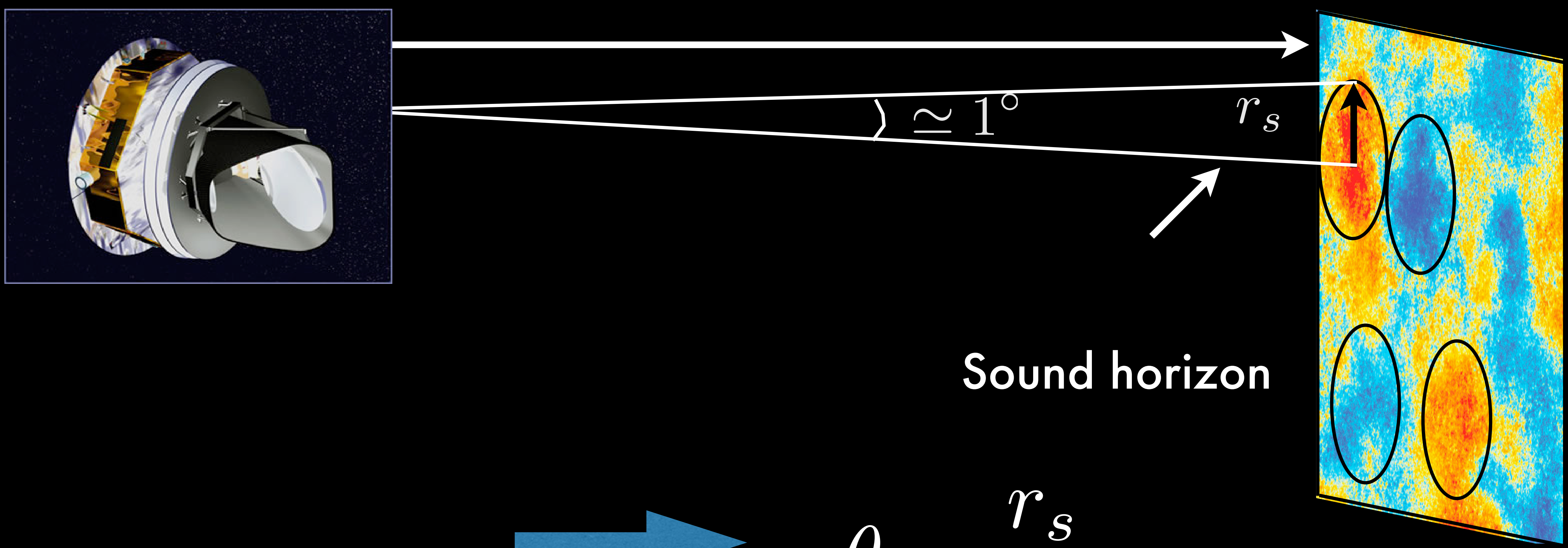


Snapshot and geometry





D (sensitive to any energy source)

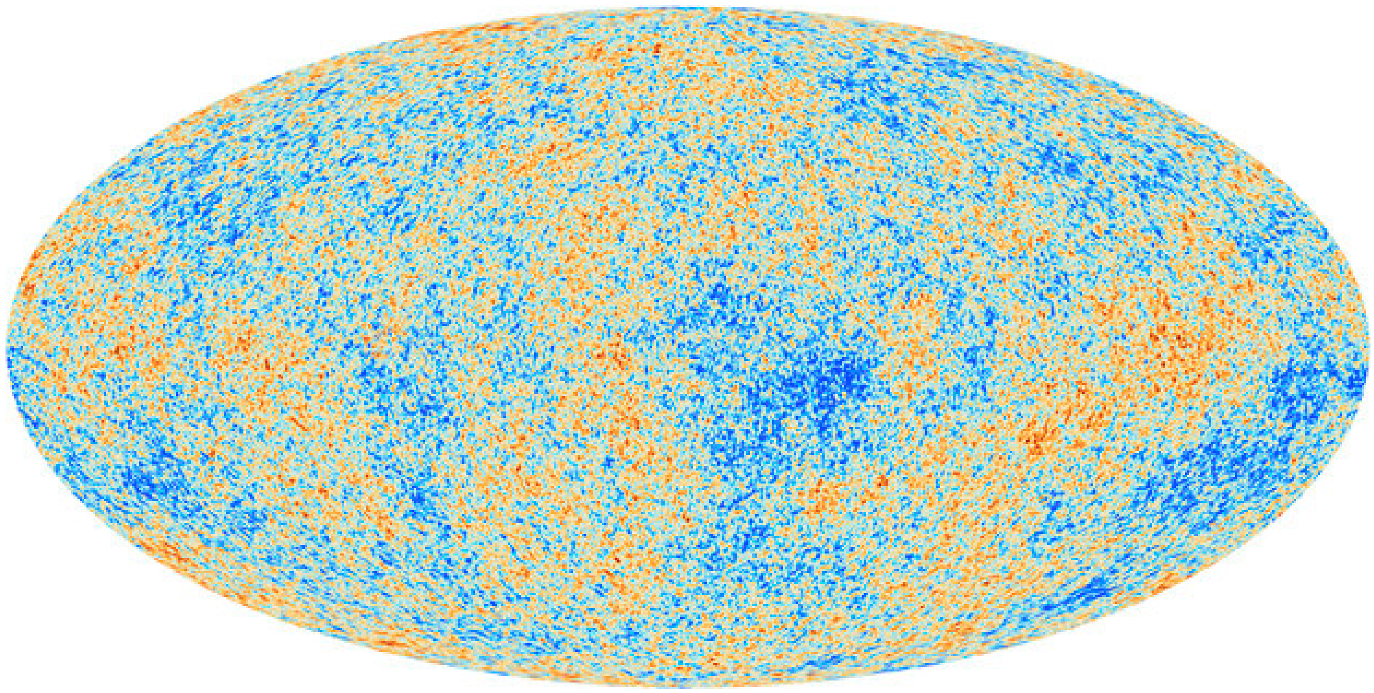


$$\theta = \frac{r_s}{D}$$

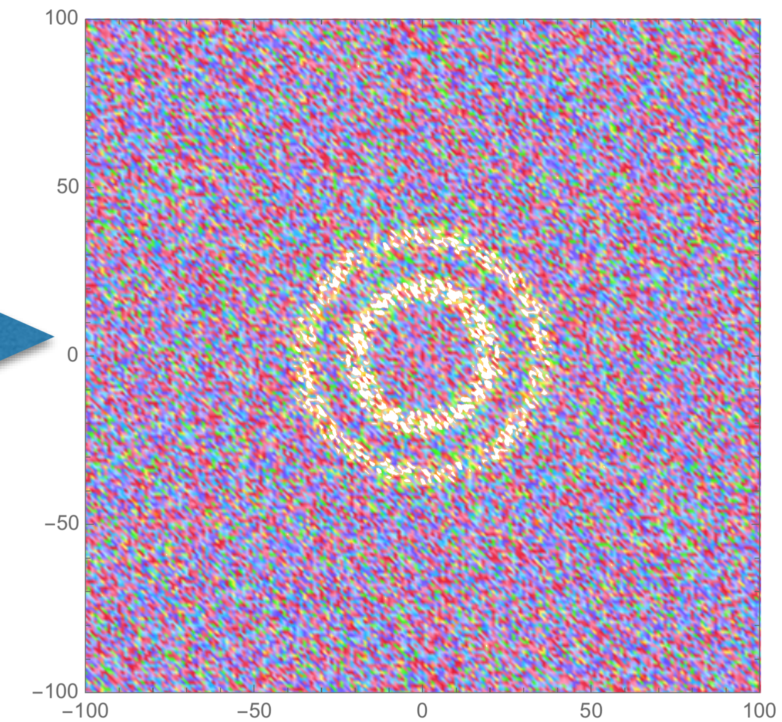
Modified figure from T. Smith used with permission

Fourier analysis of primordial sound

$$T(\vec{\theta})$$



$$a(\vec{k}) = \int T(\vec{\theta}) e^{i\vec{\theta}\cdot\vec{k}} d^2\theta$$



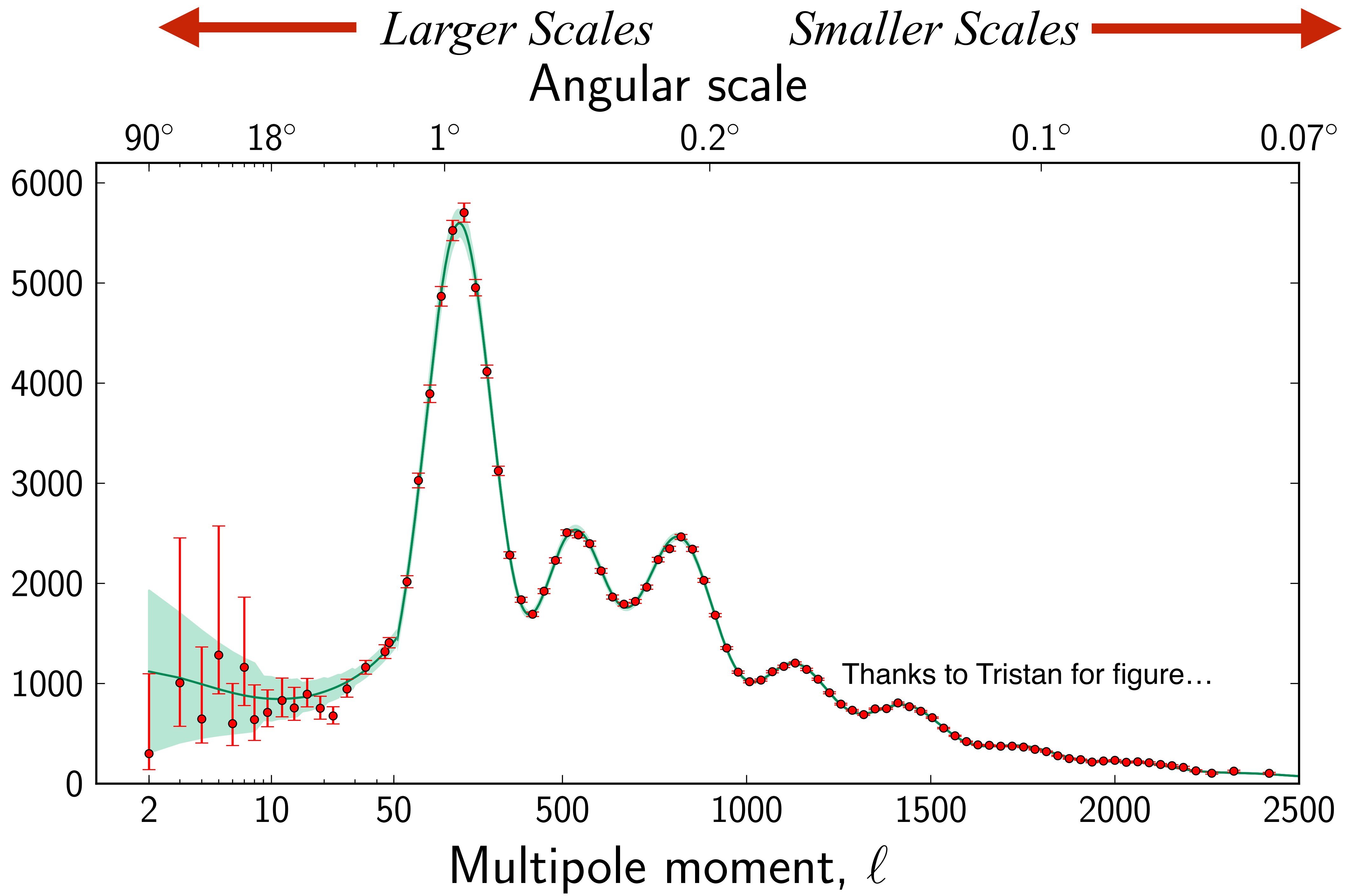
Thanks to Tristan for figure…

Fourier analysis of primordial sound

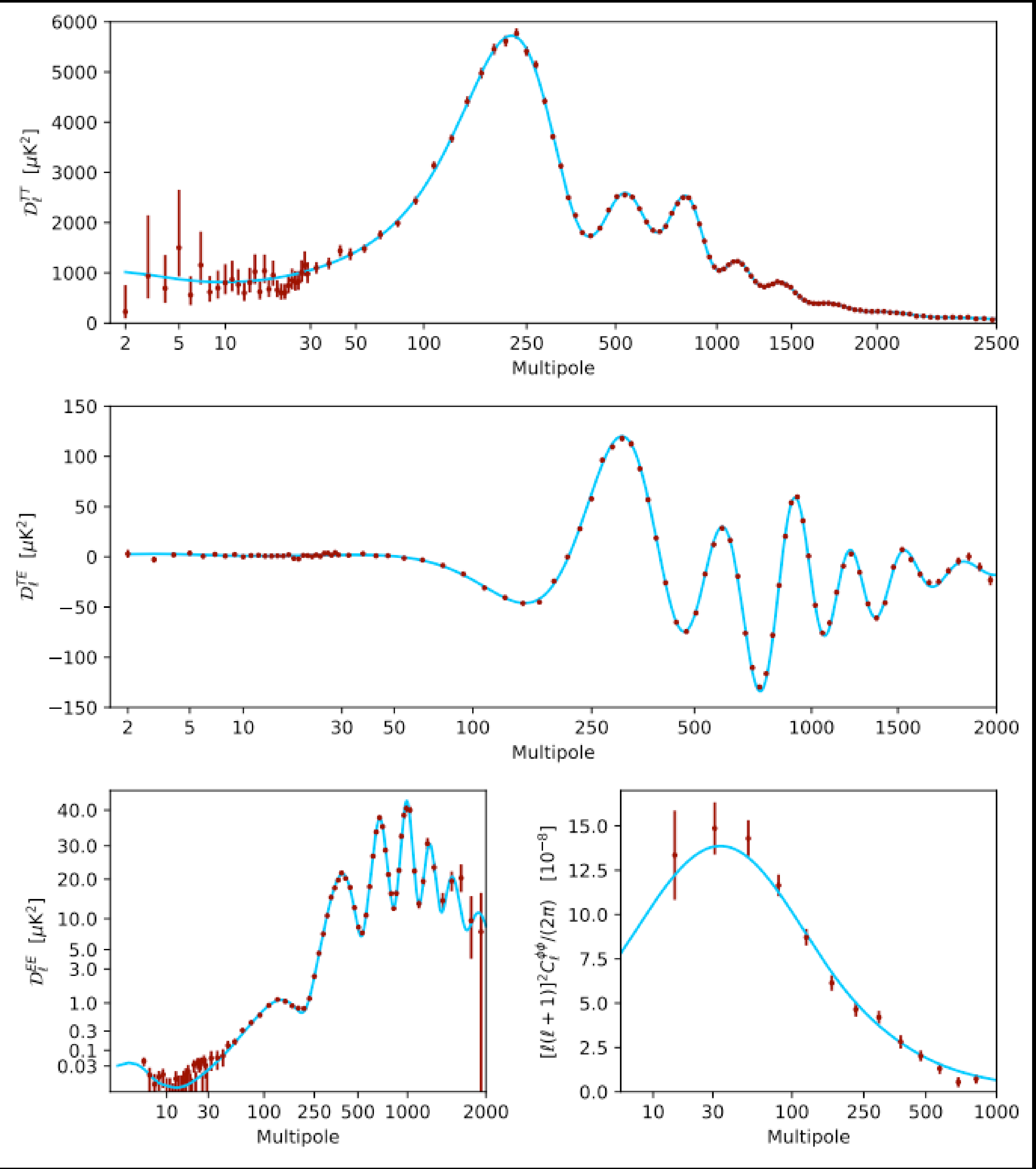
Temperature variance

μK^2

$$\frac{l(l+1)C_l}{2\pi}$$

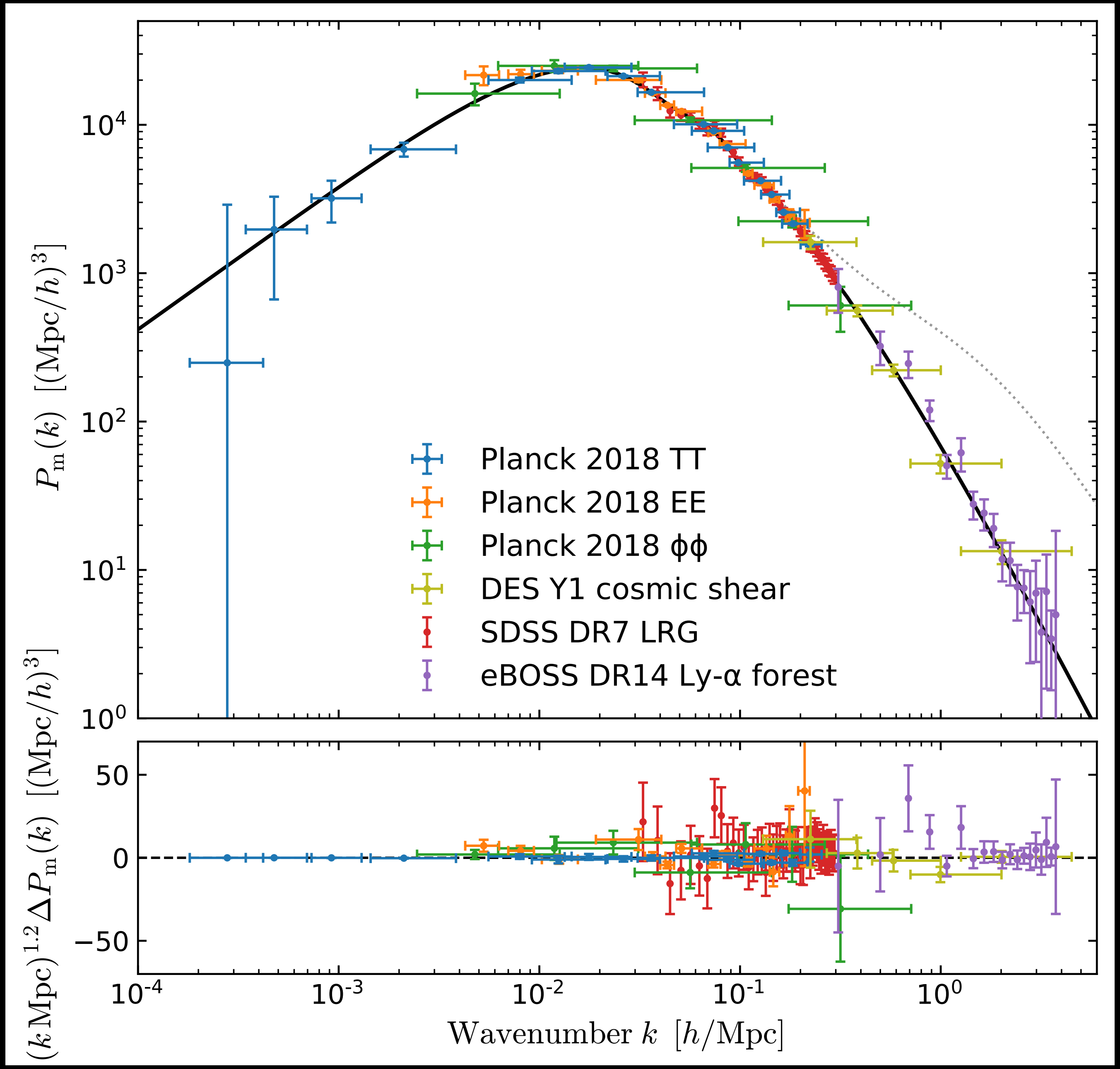


Era of precision cosmology!



A&A 641, A1 (2020), Planck 2018 data

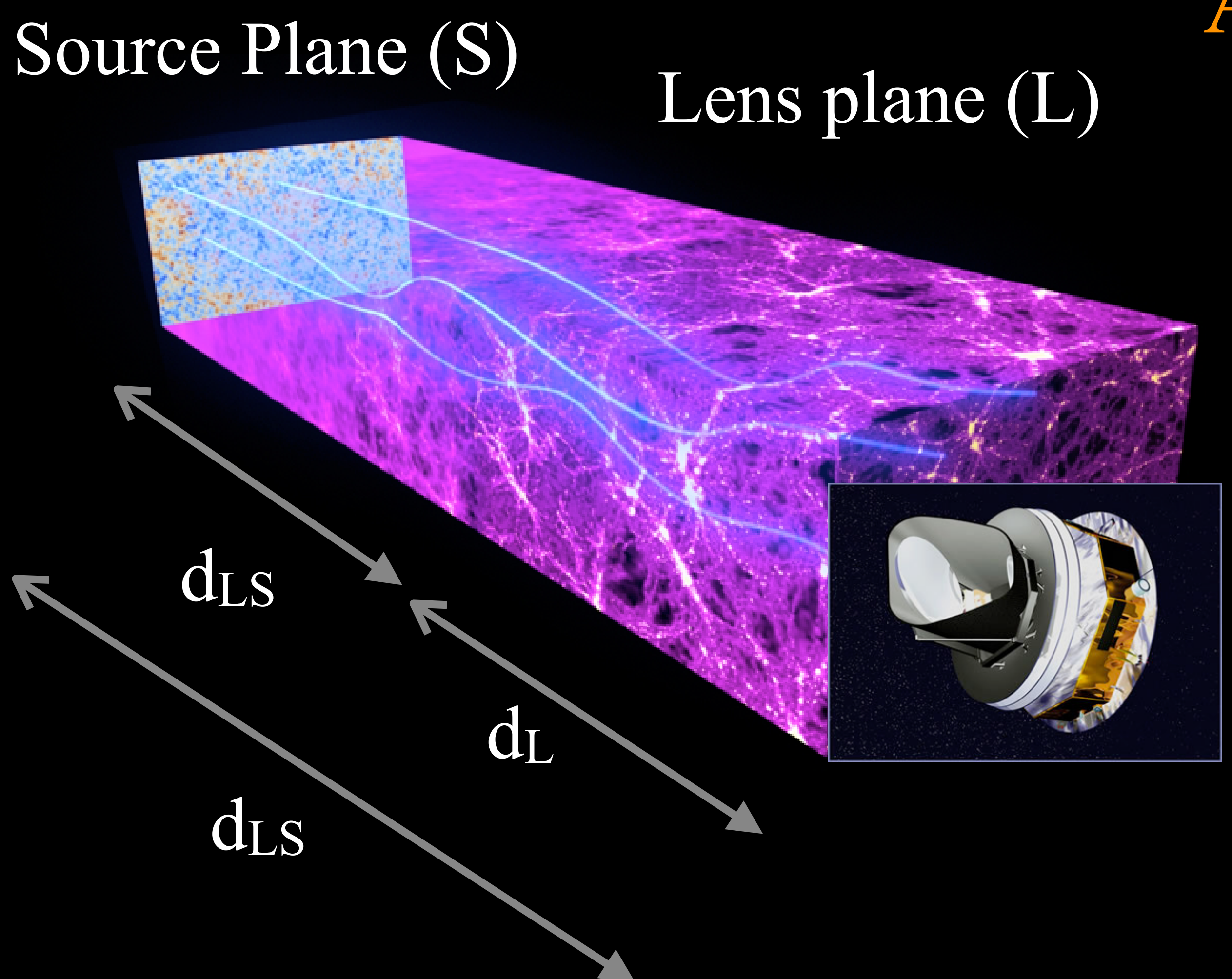
Galaxy clustering observations

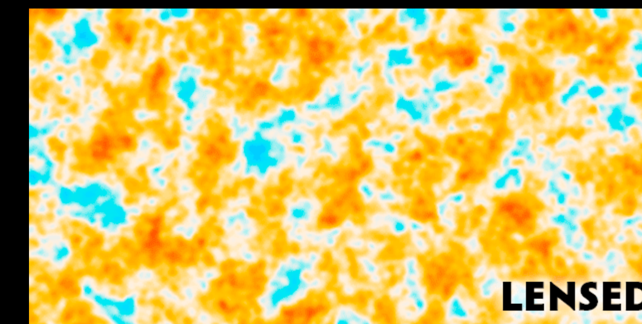


Chabanier et al. 2019, MNRAS 489, p2247

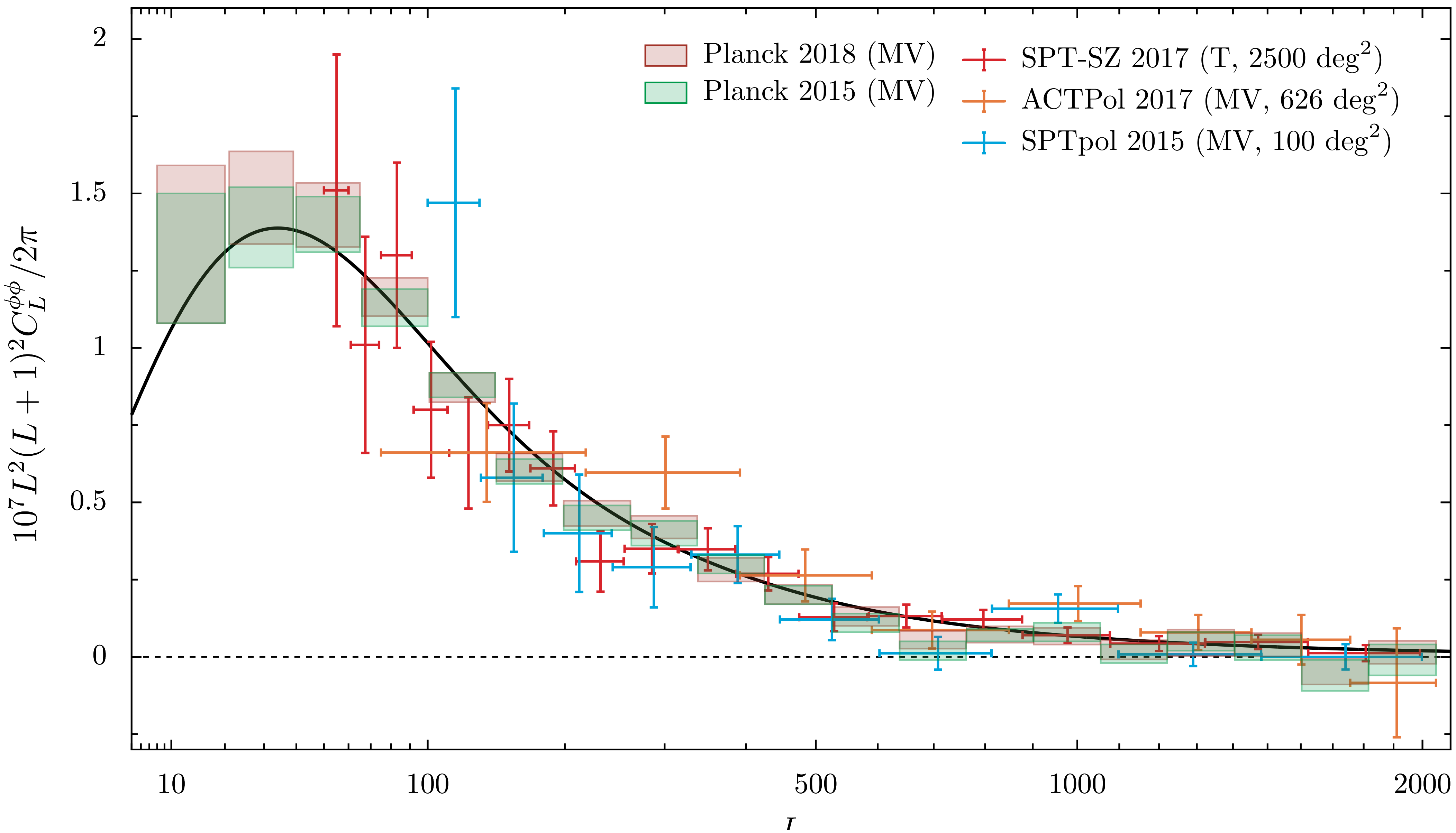
LENSING

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





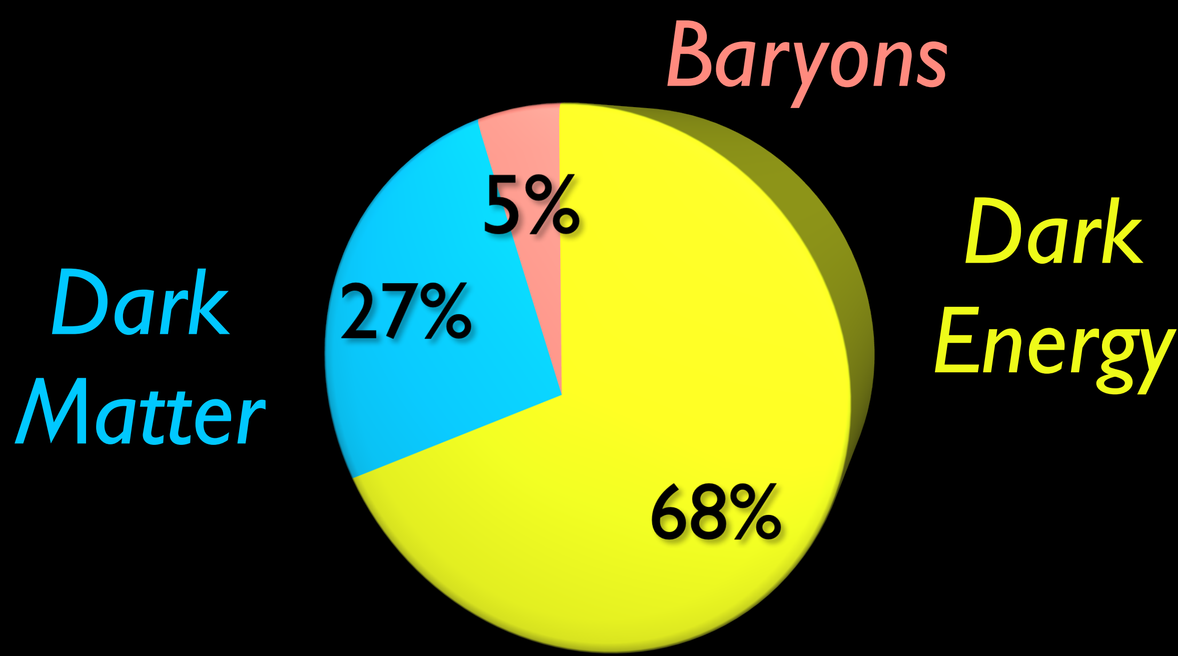
LENSING



arXiv: 1807.06210

40σ detection!

Cosmic energy budget



$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
Ω_Λ	0.6847 ± 0.0073

5% baryonic matter: protons, electrons, atoms

- ✳"stuff we know"

27% cold dark matter (CDM)

- ✳Primordially non-relativistic non-interacting `gas'
- ✳Assume no scattering/interaction with standard model particles

68% dark energy

Cosmic energy budget

$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
Ω_Λ	0.6847 ± 0.0073

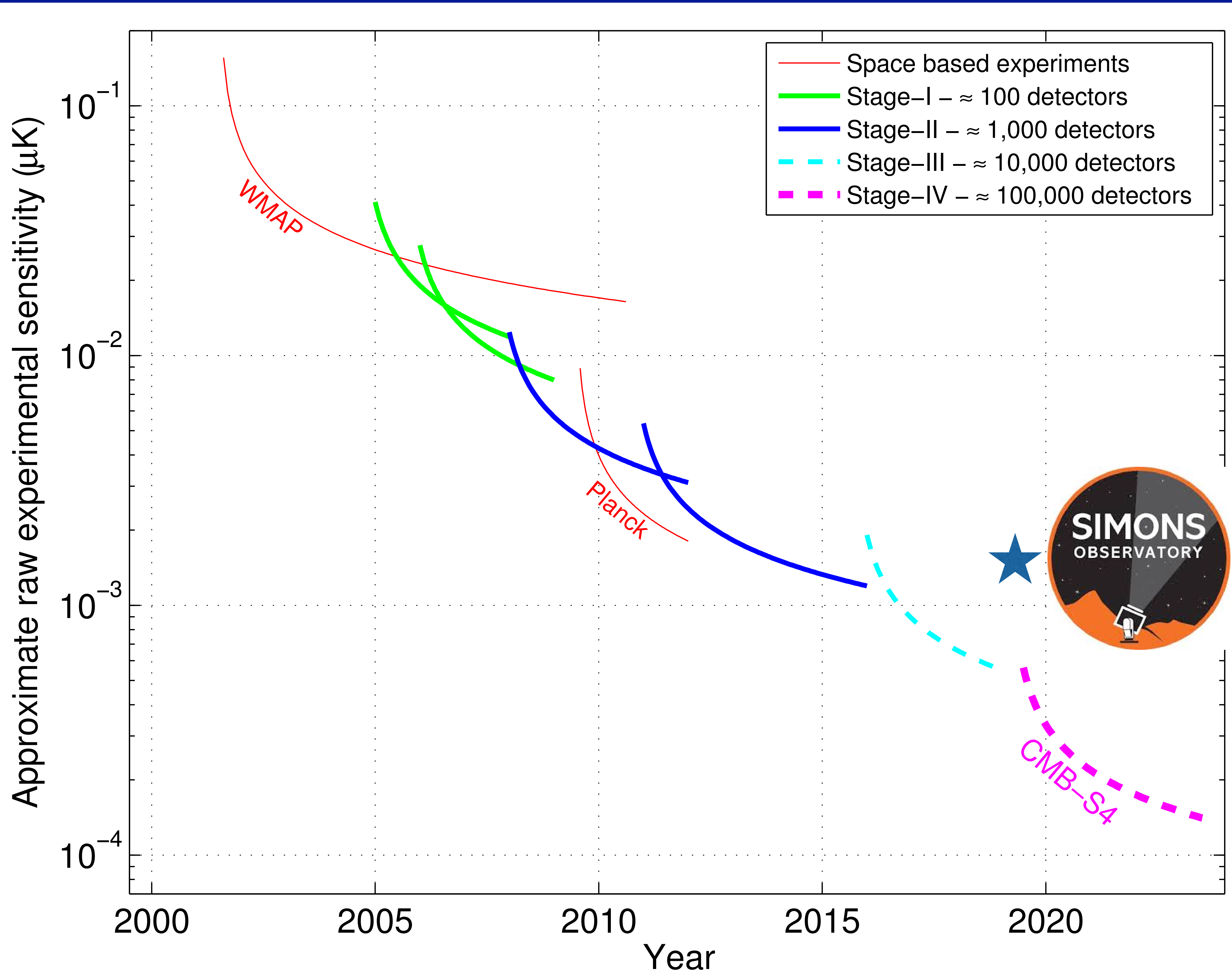
Future CMB experiments

CMB-S4
Next Generation CMB Experiment

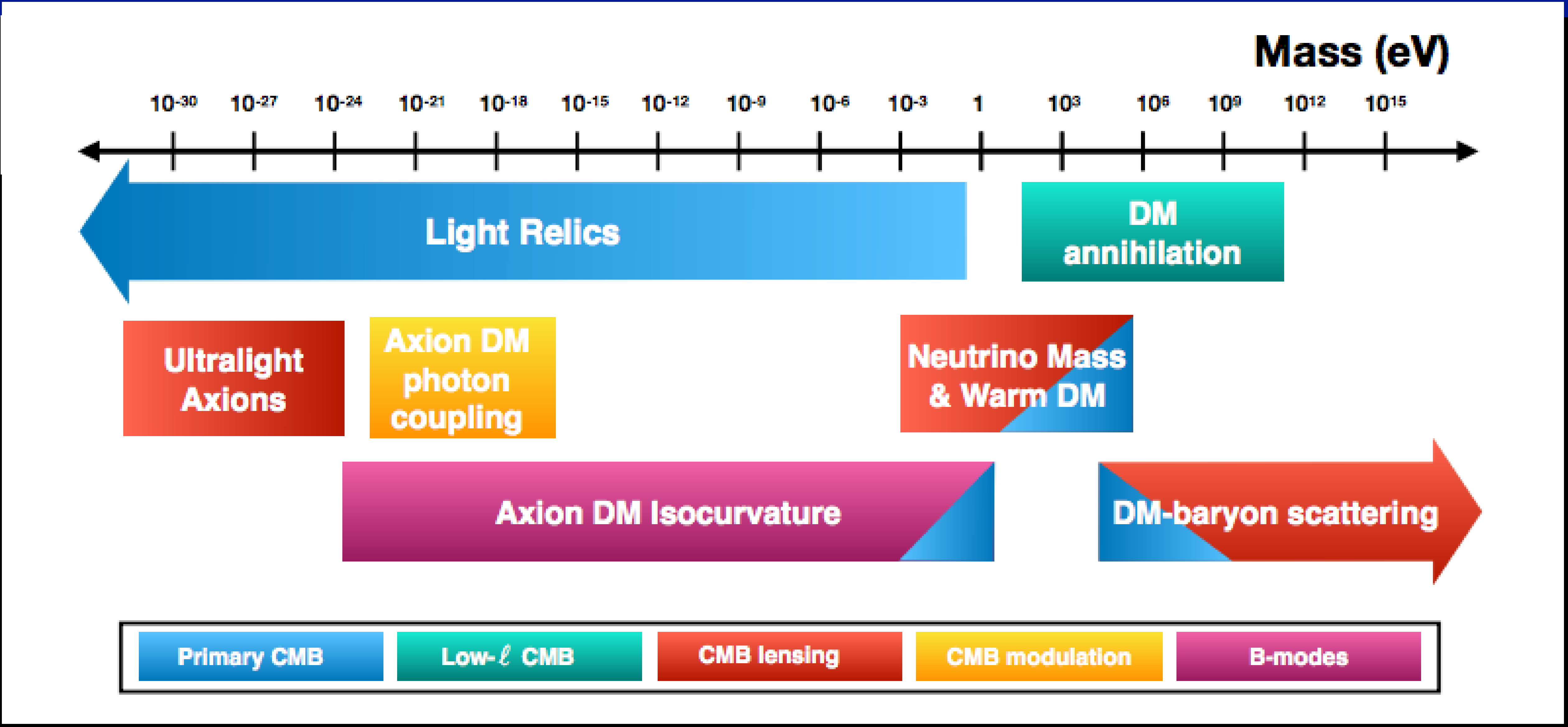
- Next gen. CMB ground-based expt. concept
  - ~1 arcmin beam
  - 1 μK arcmin noise level
  - ~500,000 detectors
  - Location, sky coverage TBD

From CMB-S4 Science book…. arXiv: 1610.02743

Future CMB experiments

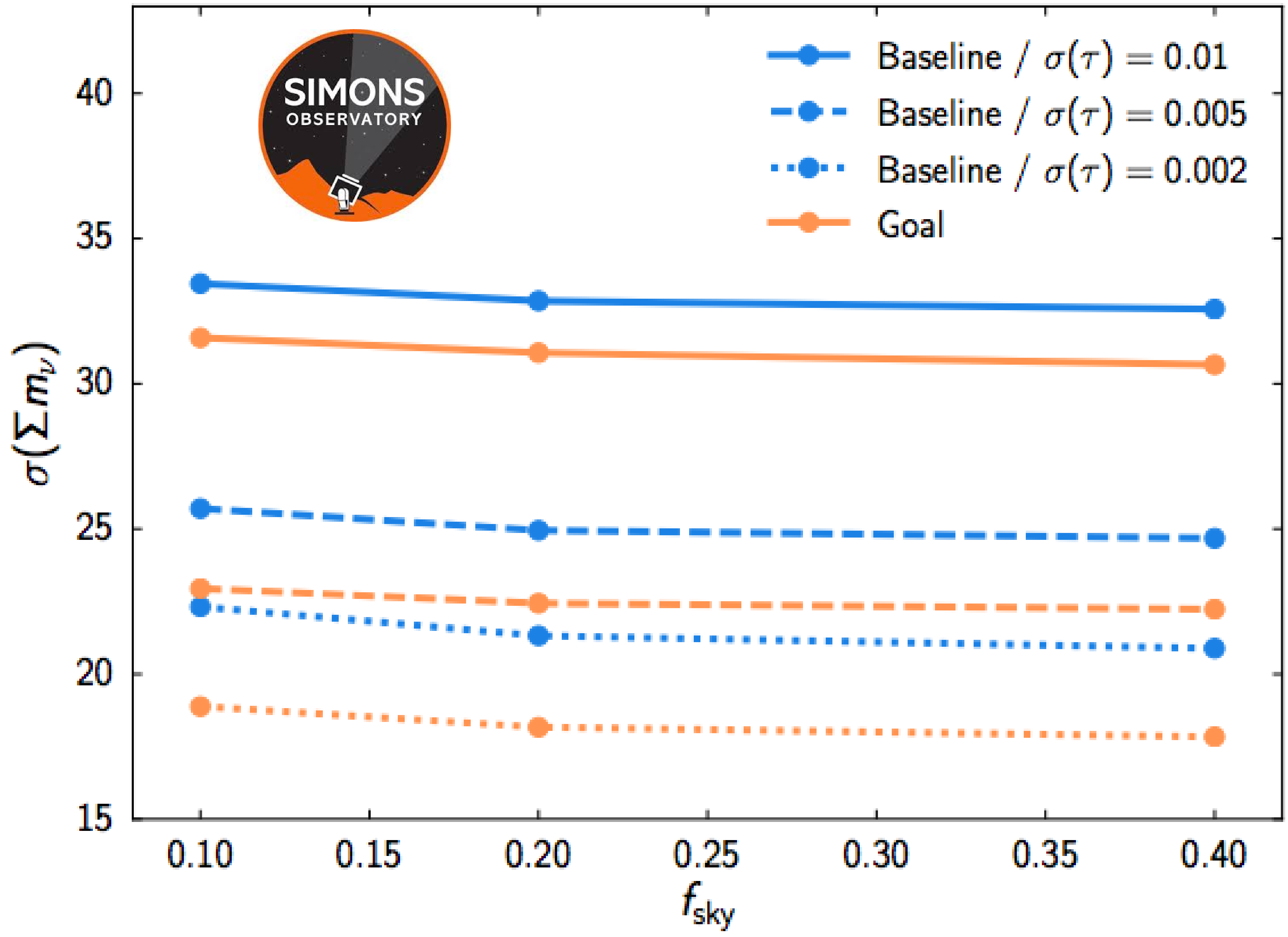


Future CMB experiments



From CMB-S4 Science book…. arXiv: 1610.02743

FUTURE CMB EXPERIMENTS



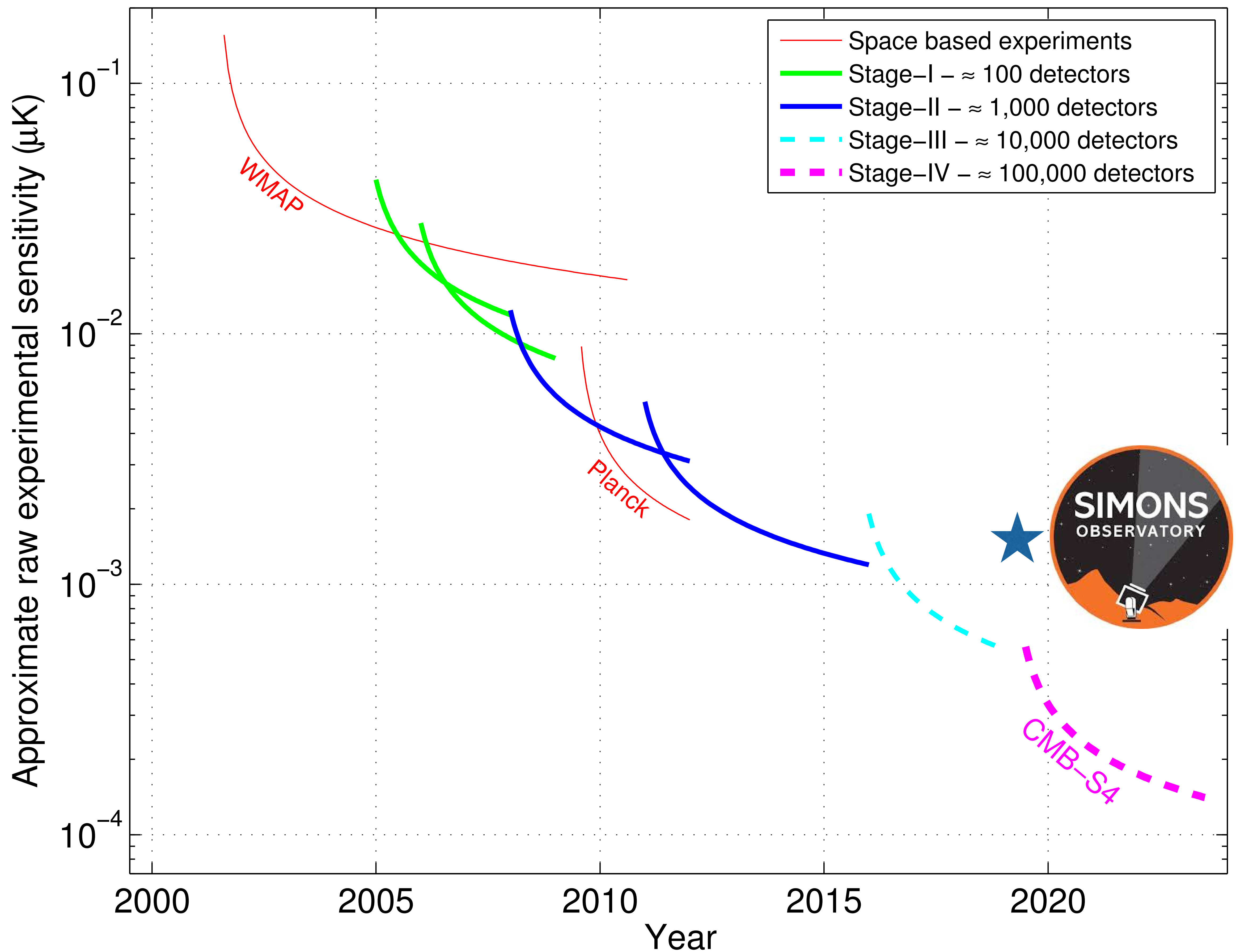
CMB-S4

Next Generation CMB Experiment

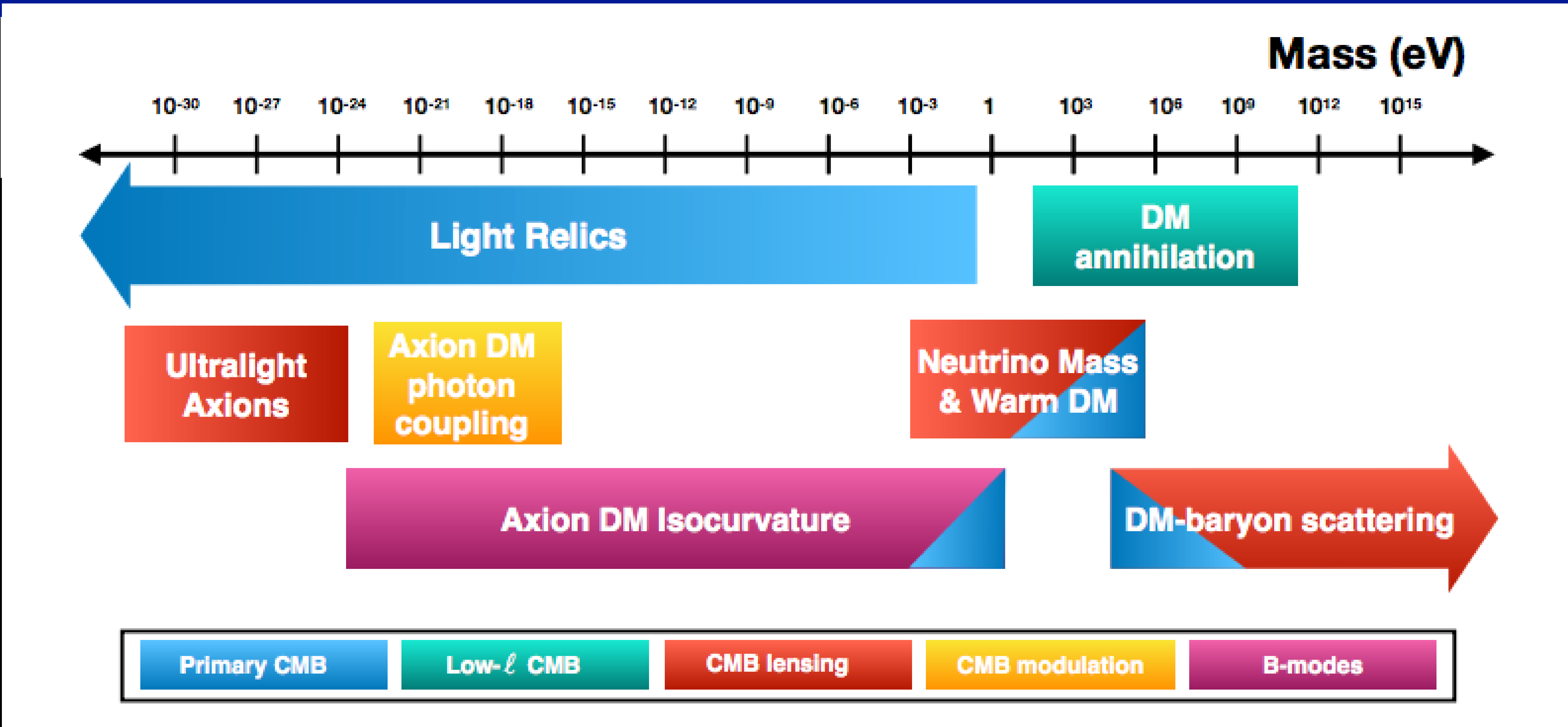
- Next gen. CMB ground-based expt. concept
  - ~1 arcmin beam
  - 1 μK arcmin noise level
  - ~500,000 detectors
  - Location, sky coverage TBD

From CMB-S4 Science book…. arXiv: 1610.02743

FUTURE CMB EXPERIMENTS

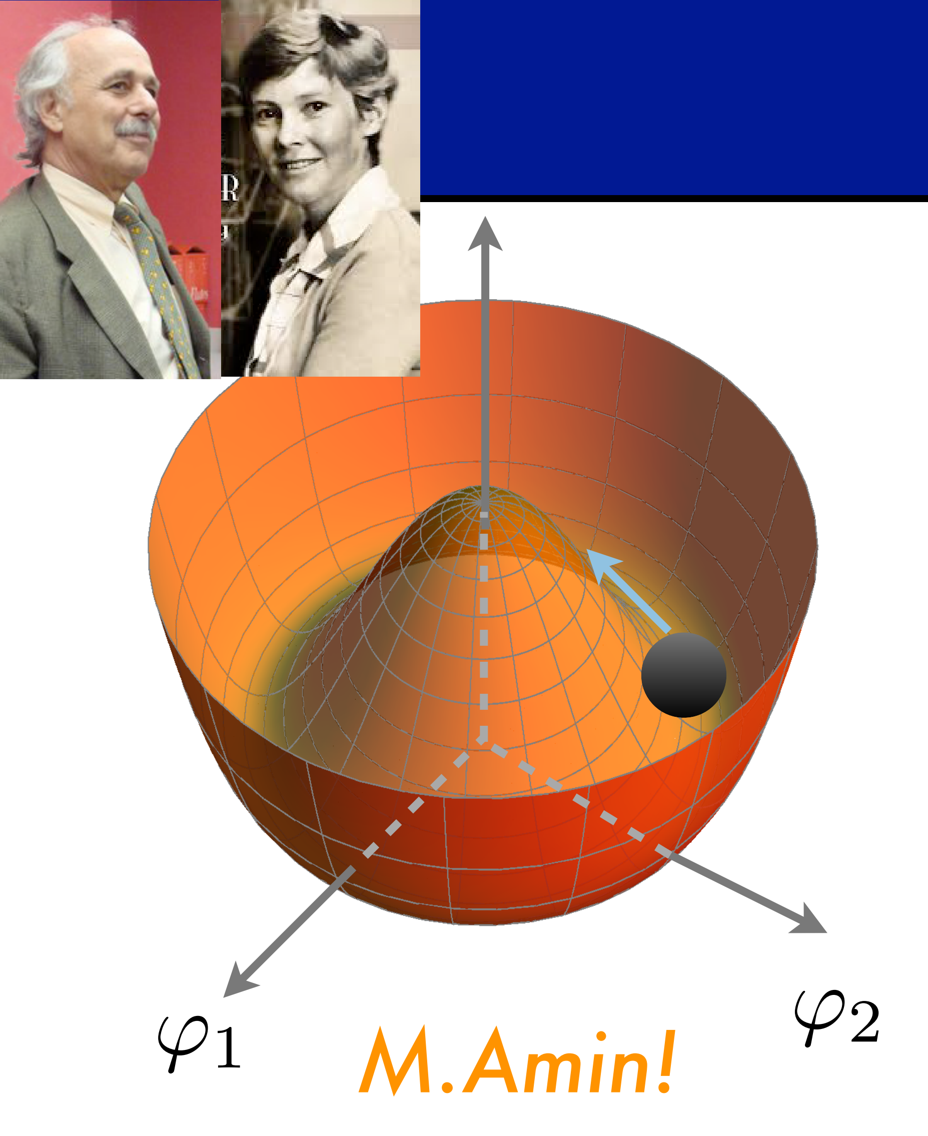


FUTURE CMB EXPERIMENTS



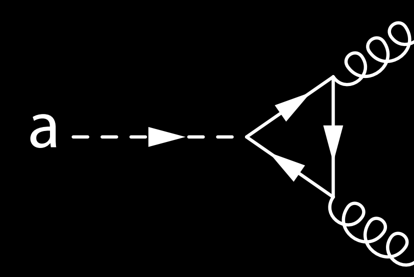
From CMB-S4 Science book…. arXiv: 1610.02743

What are axions?



New scalar field with global U(1) symmetry!

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



✳ Weakly couples to SM gauge fields (via fermions)

$$\mathcal{L} \propto \frac{1}{f_{\rm a}} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

✳ Axion gets mass through non-perturbative QCD effects

$$m_a \sim \frac{\Lambda^2_{\rm QCD}}{f_a}$$

Peccei + Quinn (1977), Weinberg +Wilczek (1978), Kim (1979), Shifman et. al (1980), Zhitnitsky (1980), Dine et al. (1981), D.B. Kaplan (1985), A.E Nelson (1985,1990)

Axions

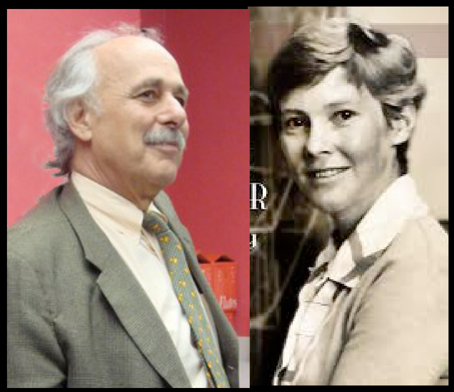
- Maxwell's equations

$$\nabla \cdot \vec{E} = 4\pi\rho_e$$ Gauss's Law

$$\vec{\nabla} \times \vec{B} - \partial_t \vec{E} = 4\pi \vec{J}_e$$ Ampere's Law

Axions

✳Maxwell's equations +New physics (Peccei/Quinn 1977)



$$\nabla \cdot \vec{E} = 4\pi\rho_e + \frac{\vec{\nabla} a(\vec{x}) \cdot \vec{B}(\vec{x})}{f_a}$$

$$\vec{\nabla} \times \vec{B} - \partial_t \vec{E} = 4\pi \vec{J}_e - \frac{1}{f_a}\left(\vec{B}\partial_t a(\vec{x}) + \vec{\nabla} a(\vec{x}) \times \vec{E}\right)$$

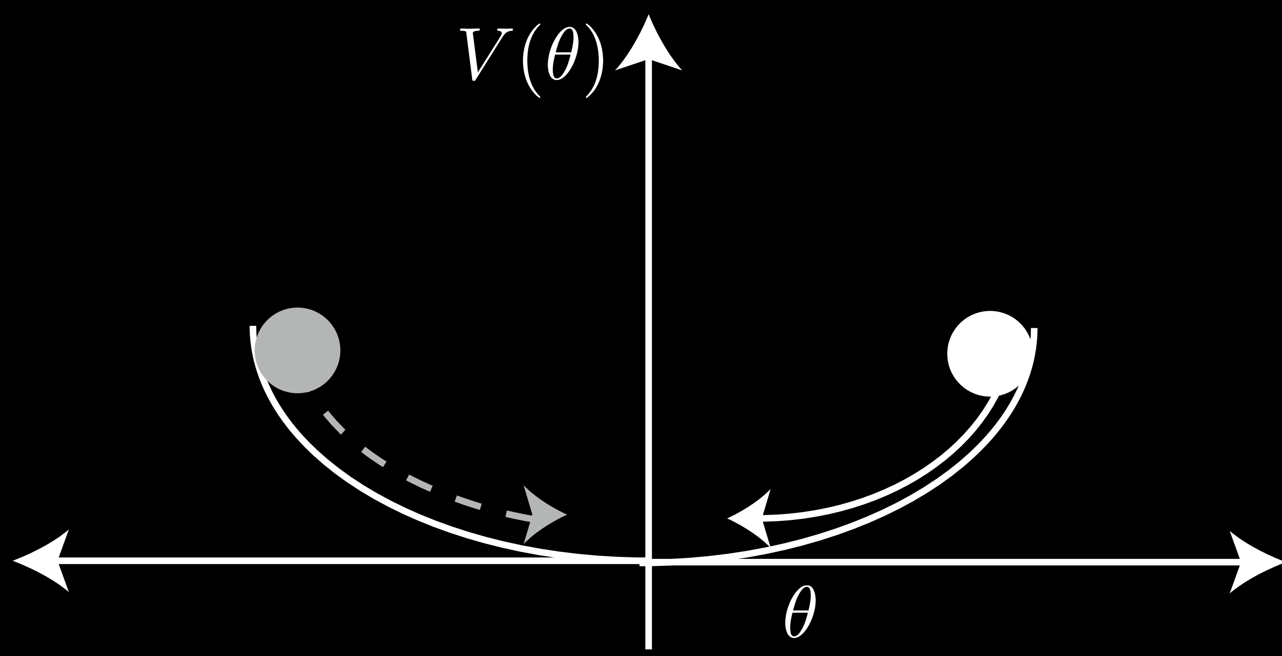
✳A new fundamental field $a(\vec{x})$

$$\partial_t^2 a(\vec{x}) - \nabla^2 a(\vec{x}) = -\frac{1}{f_a}\vec{E}\cdot\vec{B} - m^2 a(\vec{x})$$

✳Shields neutron dipole moment

relic abundance

$$m_a < 10^{-2}\ \mathrm{eV}$$

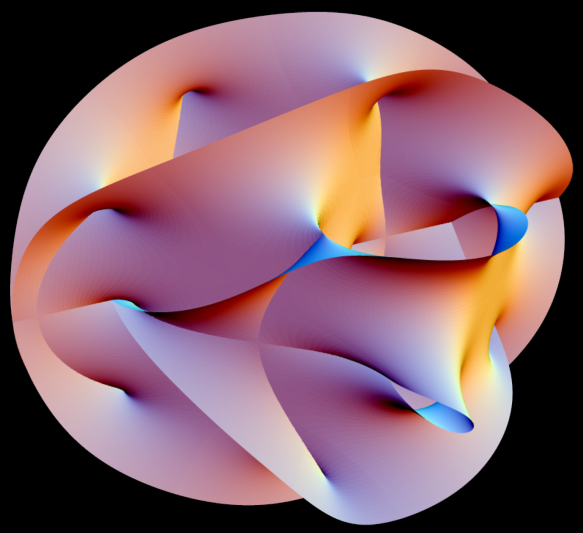


- Before PQ symmetry breaking, θ is generically displaced from vacuum value
- EOM: $\ddot{\bar{\theta}} + 3H\dot{\bar{\theta}} + m_{\mathrm{a}}^2(T)\,\bar{\theta} = 0$
- After $m_{\mathrm{a}}(T) \gtrsim 3H(T)$, coherent oscillations begin, leading to $n_{\mathrm{a}} \propto a^{-3}$

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

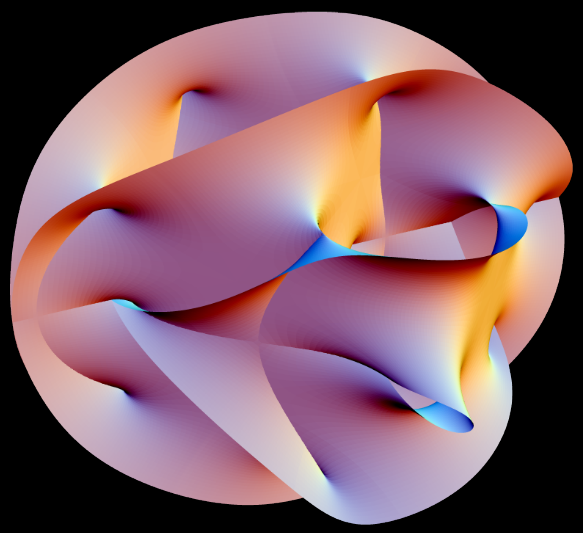
Ultra-light axions (ULAS) in string theory

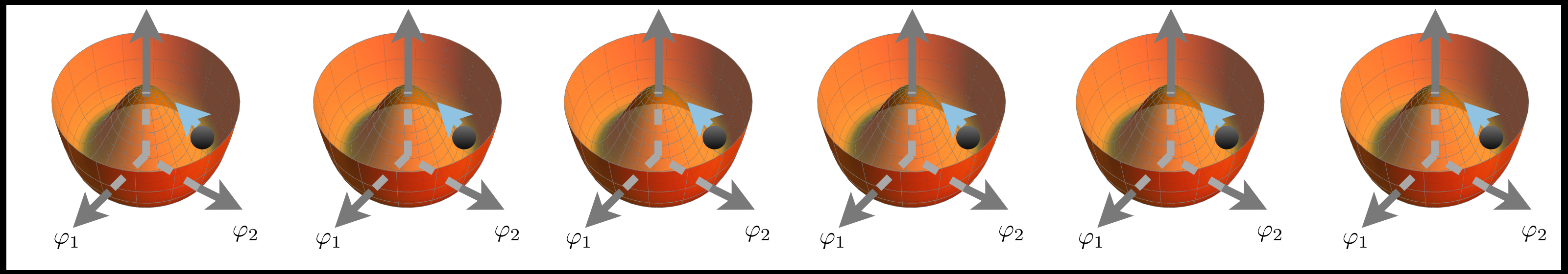
- In string theory, extra dimensions compactified: Calabi-Yau manifolds



Ultra-light axions (ULAS) in string theory

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



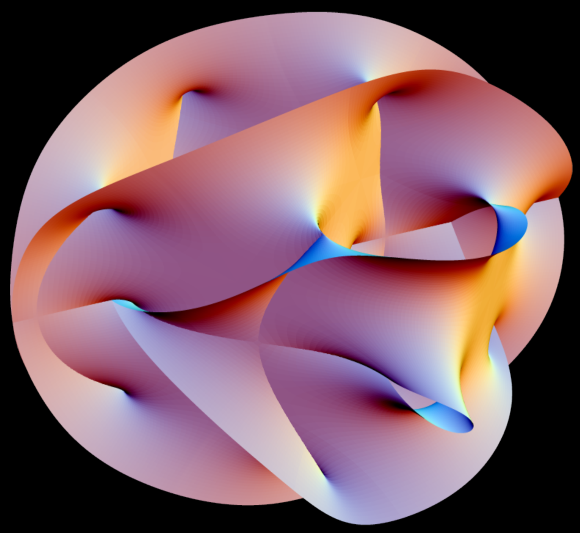


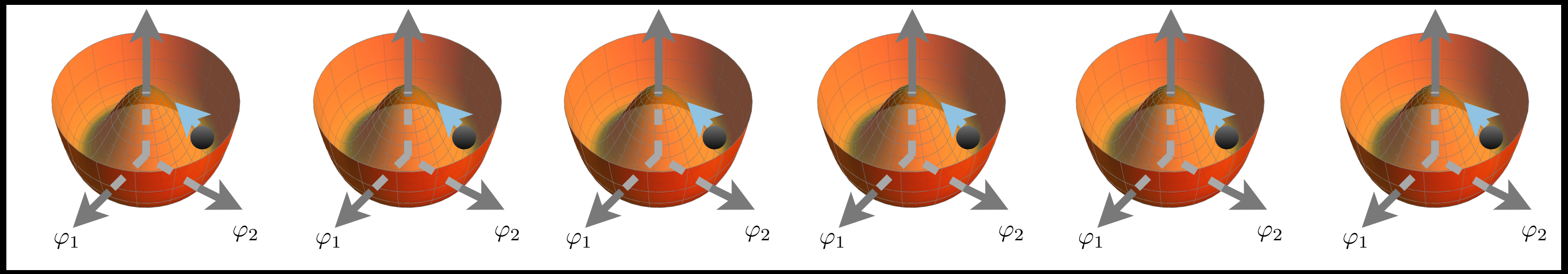
+....

Hundreds of scalars with approx shift symmetry

Ultra-light axions (ULAS) in string theory

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





+....

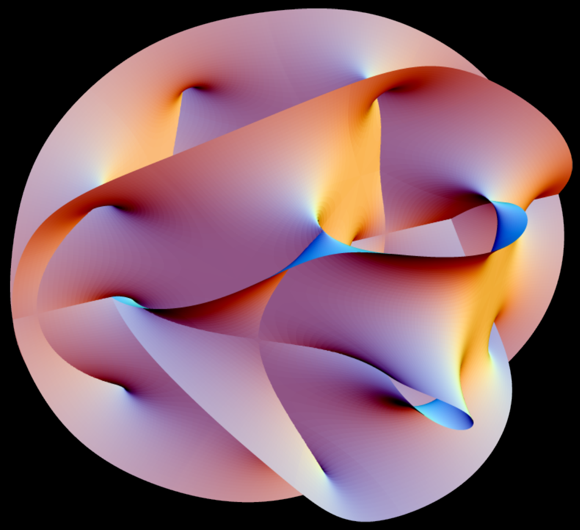
Hundreds of scalars
with approx shift symmetry

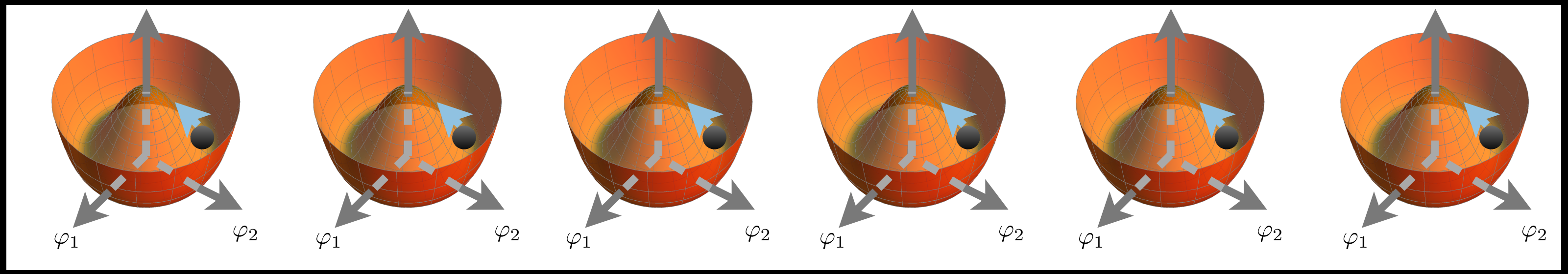
↓

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

↓

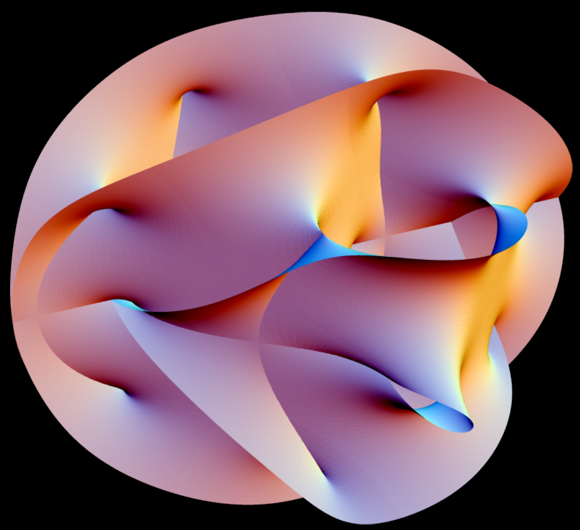
Many axions

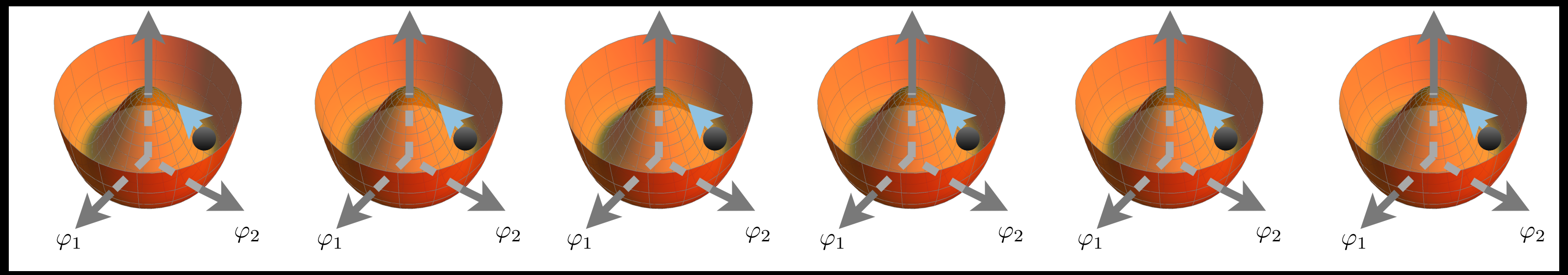
✳ Mass acquired non-perturbatively (instantons, D-Branes)

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

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

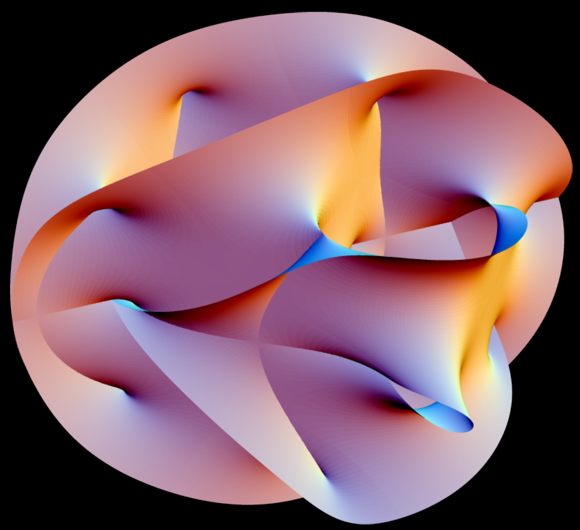
- ✳ Mass acquired non-perturbatively (instantons, D-Branes)

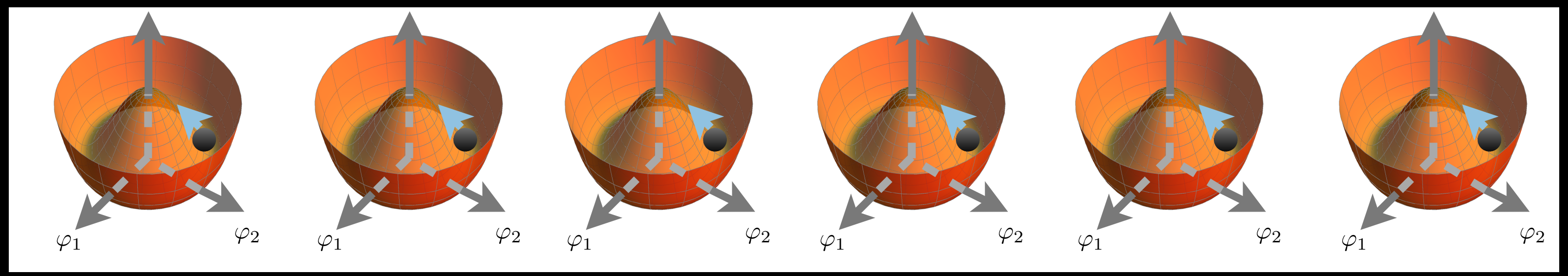
Scale of new
ultra-violet physics ← μ

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

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

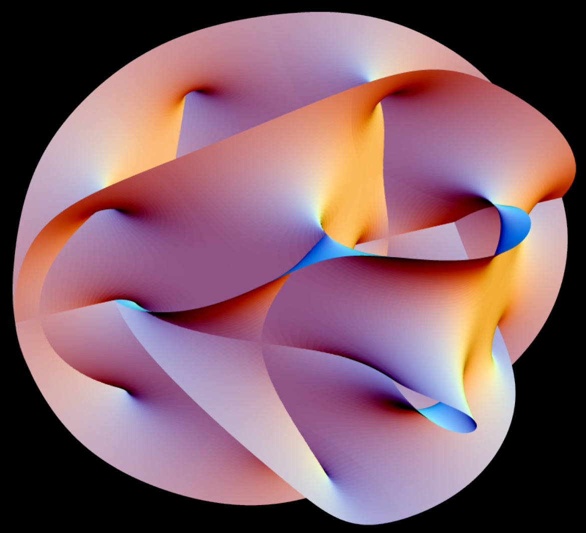
✳ Mass acquired non-perturbatively (instantons, D-Branes)

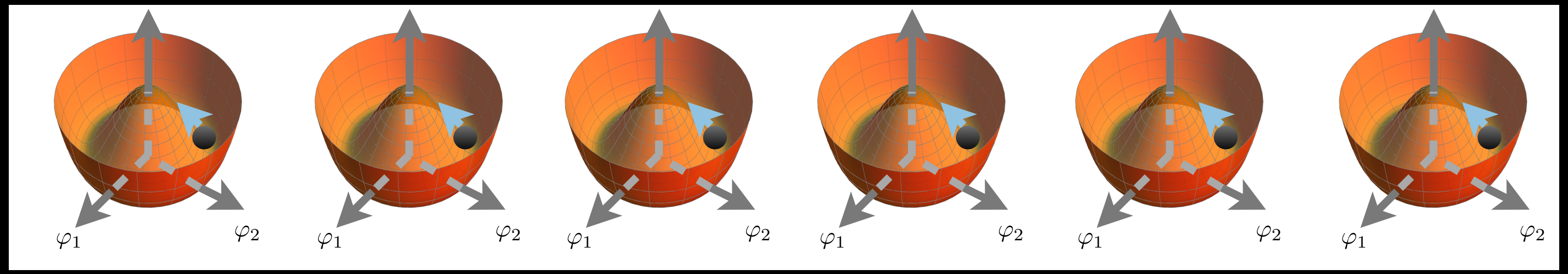
$$m_a^2 = \frac{\mu^4}{f_a^2} e^{-\text{Volume}}$$

Scale of extra dimensions in Planck units

Ultra-light axions (ULAS) in string theory

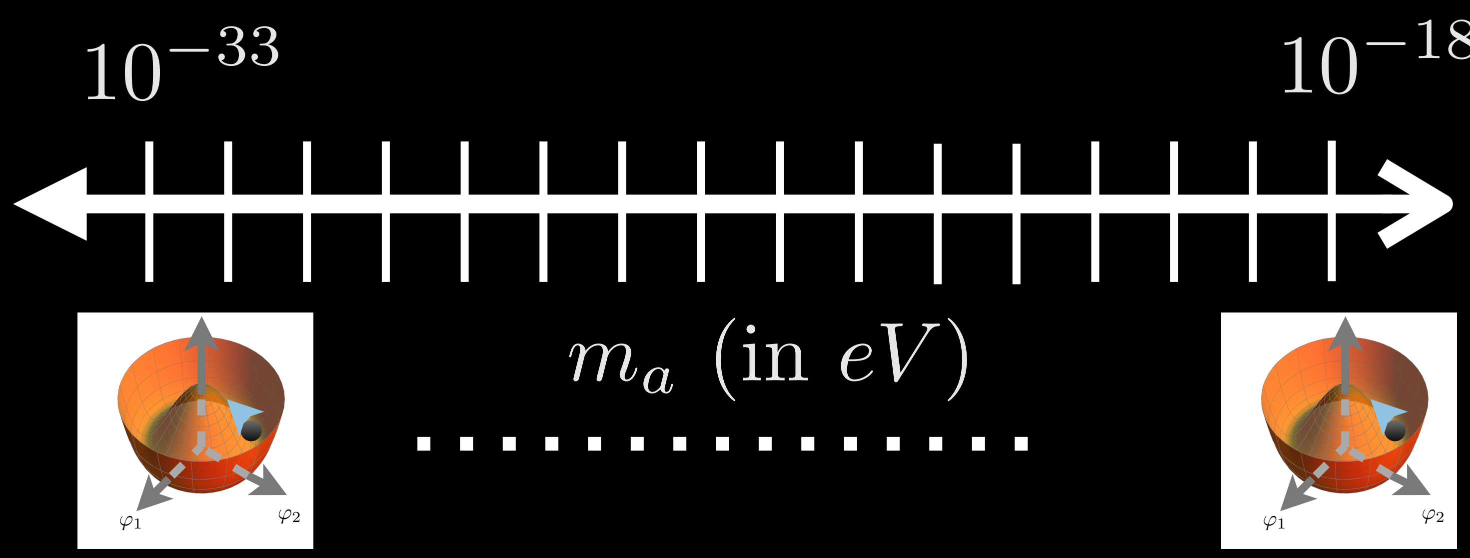
* In string theory, extra dimensions compactified: Calabi-Yau manifolds





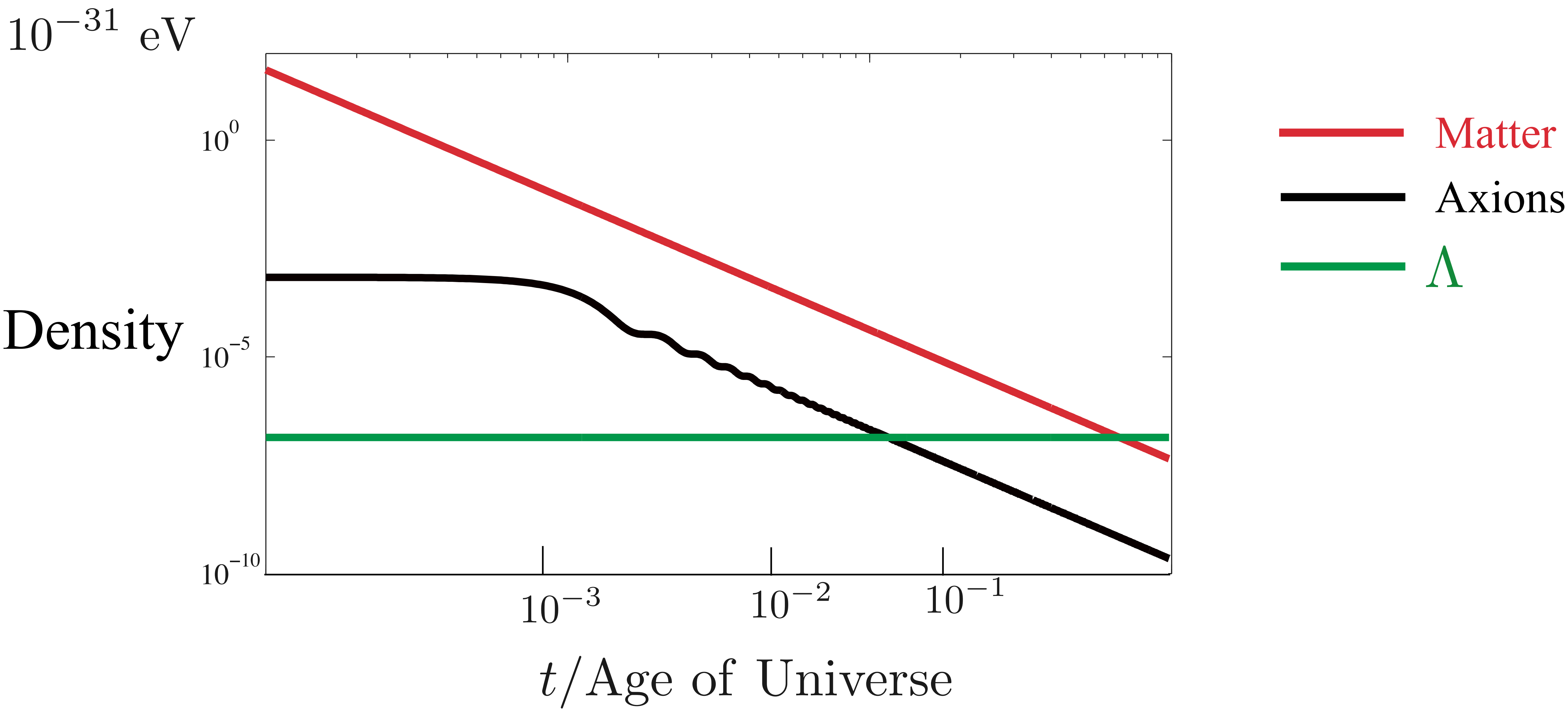
+....

Axiverse! *Arvanitaki+ 2009*
Witten and Srvcek (2006), Acharya et al. (2010),
Cicoli (2012), Hui (+ Witten, Ostriker, Tremaine) 2016



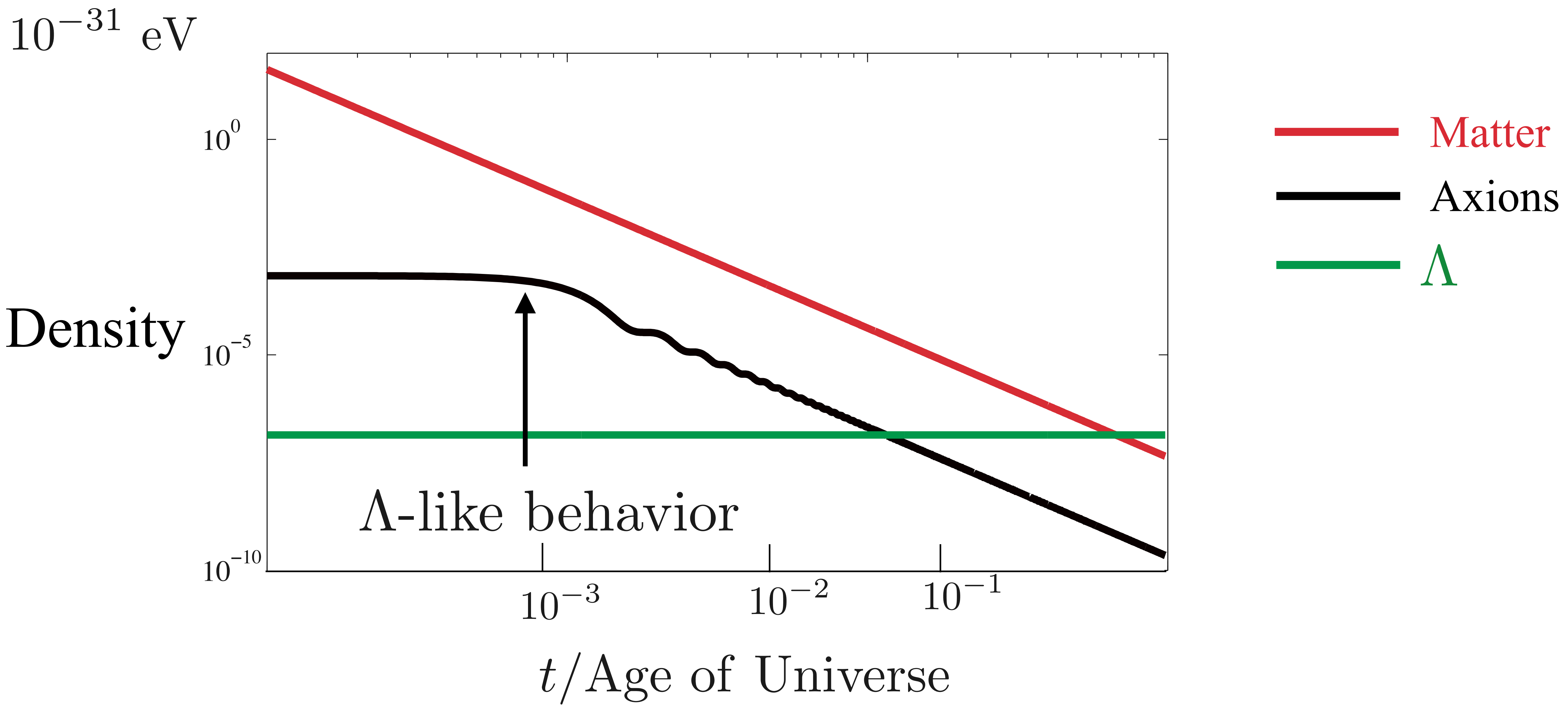
ULA cosmology

Cosmology of axions: dark matter and dark energy candidates



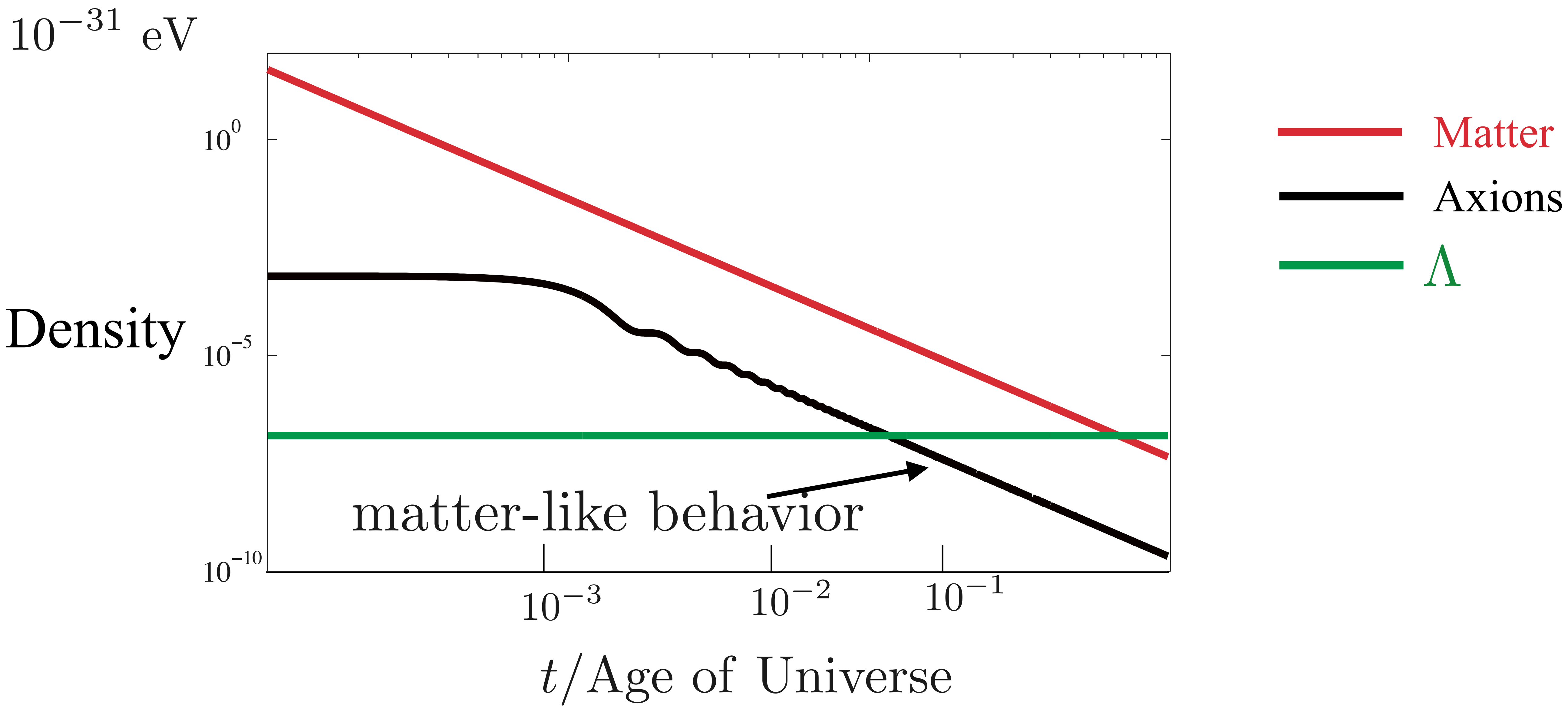
[redacted]

Cosmology of axions: dark matter and dark energy candidates



Time

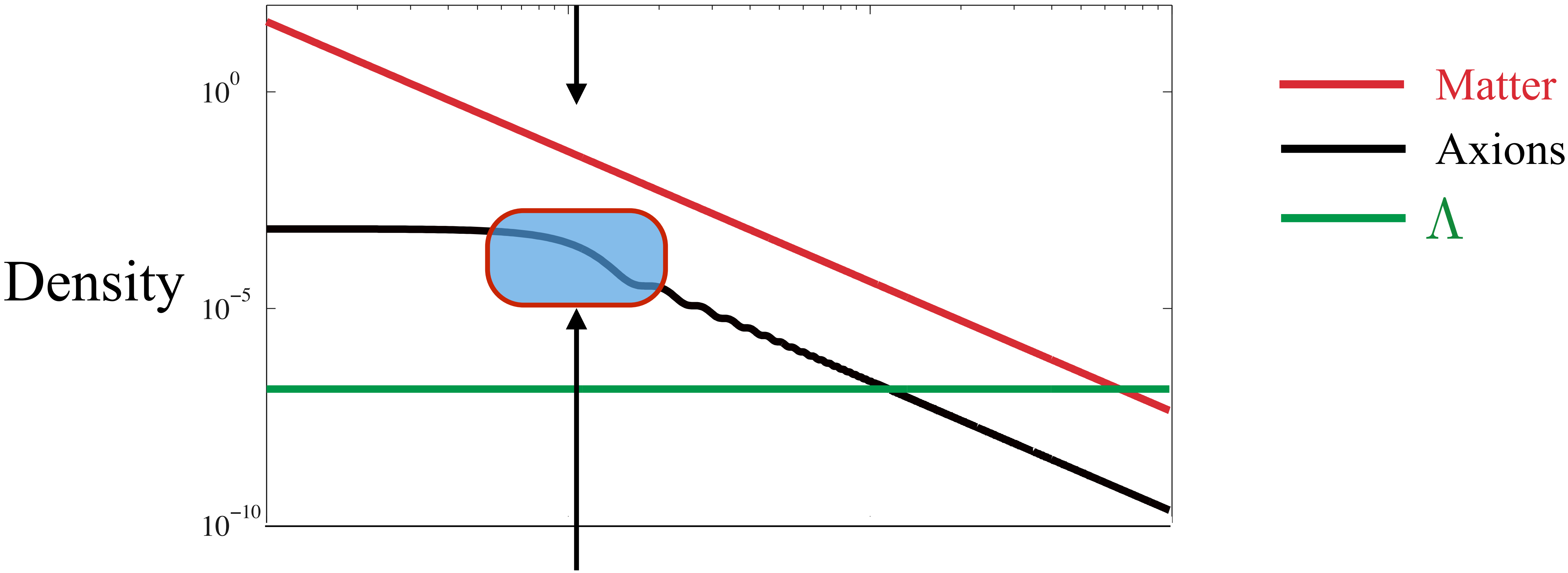
Cosmology of axions:
dark matter and dark energy candidates



[redacted]

Cosmology of axions: dark matter and dark energy candidates

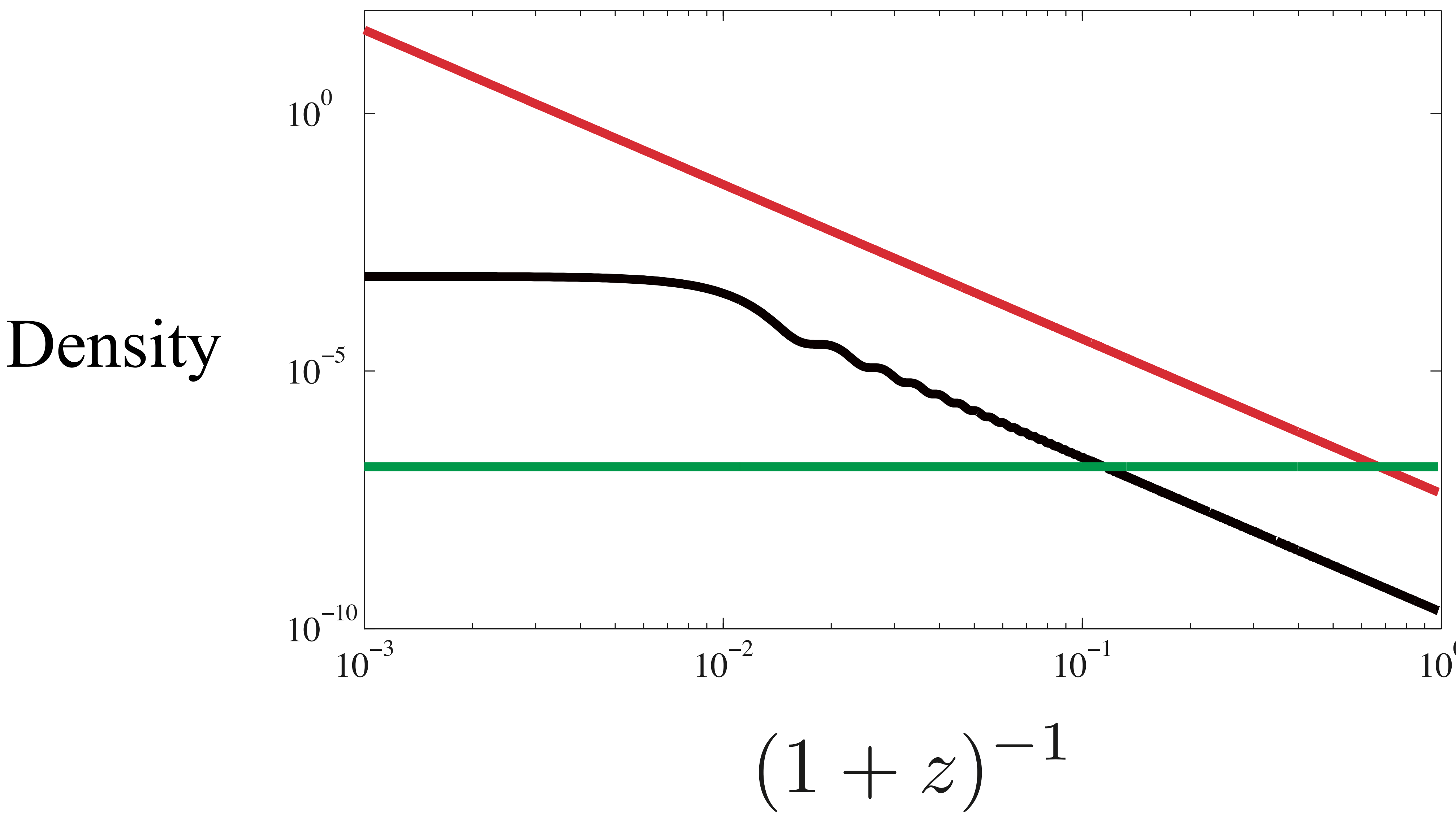
Axion mass m_a sets time of this transition



Depending on time of this transition — axions can be dark matter or dark energy

Time

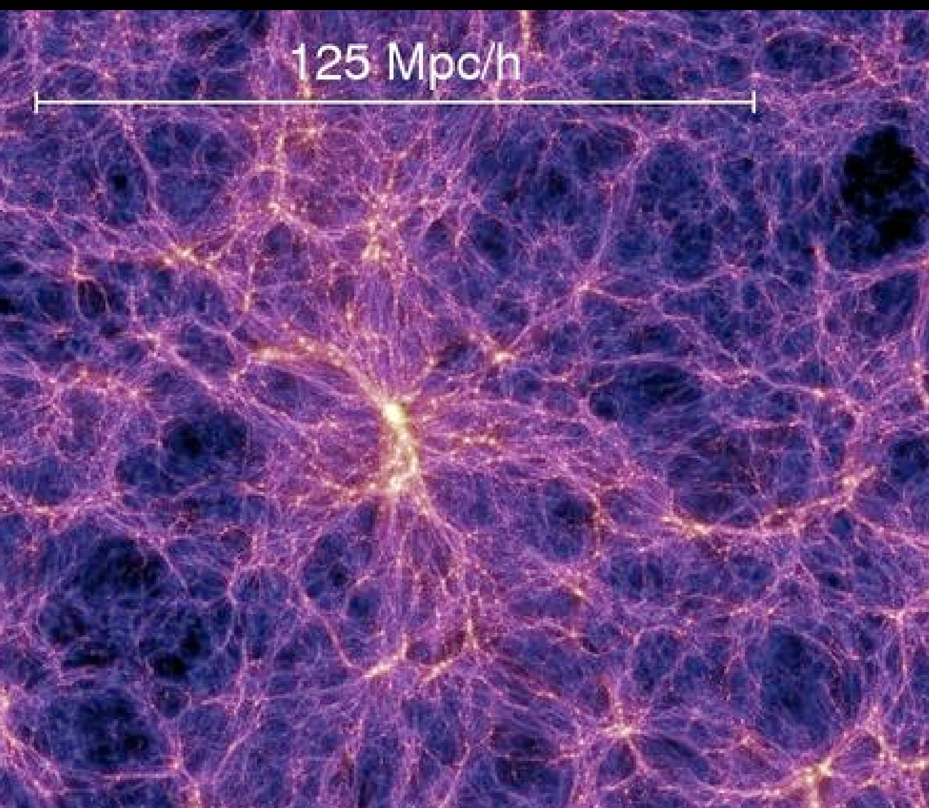
Cosmology of ultra-light axions:
dark matter and dark energy candidates

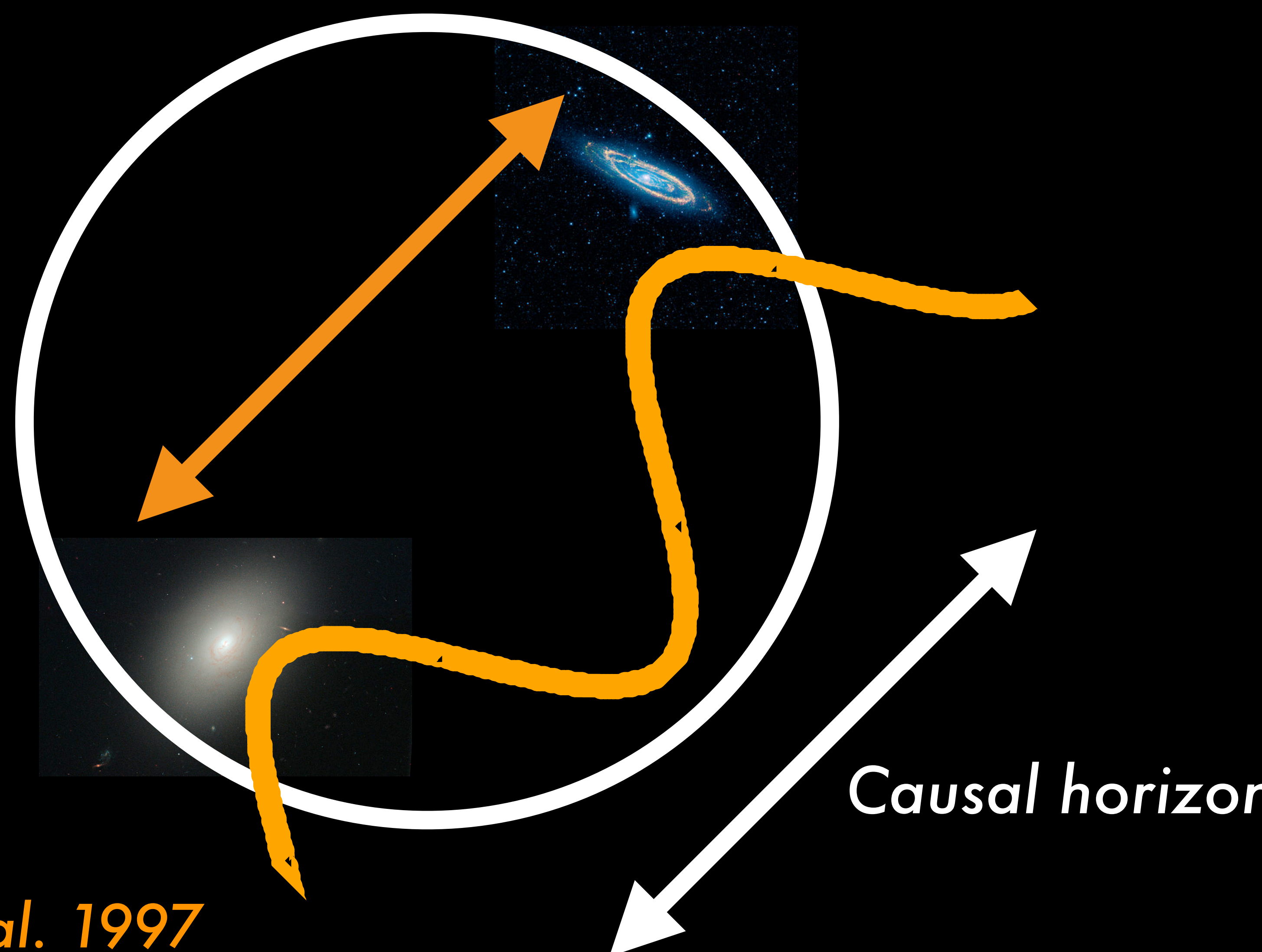


Time

Cosmology of ultra-light axions: dark matter and dark energy candidates

Scale corresponding to typical galaxy separation today





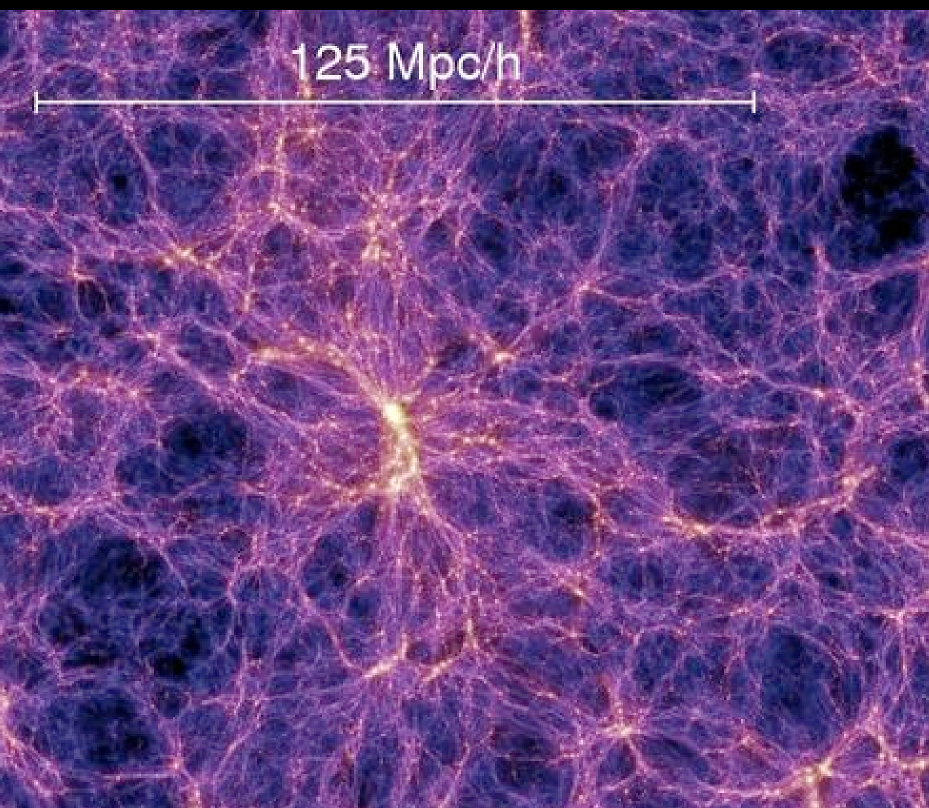
Frieman et al 1995, Coble et al. 1997

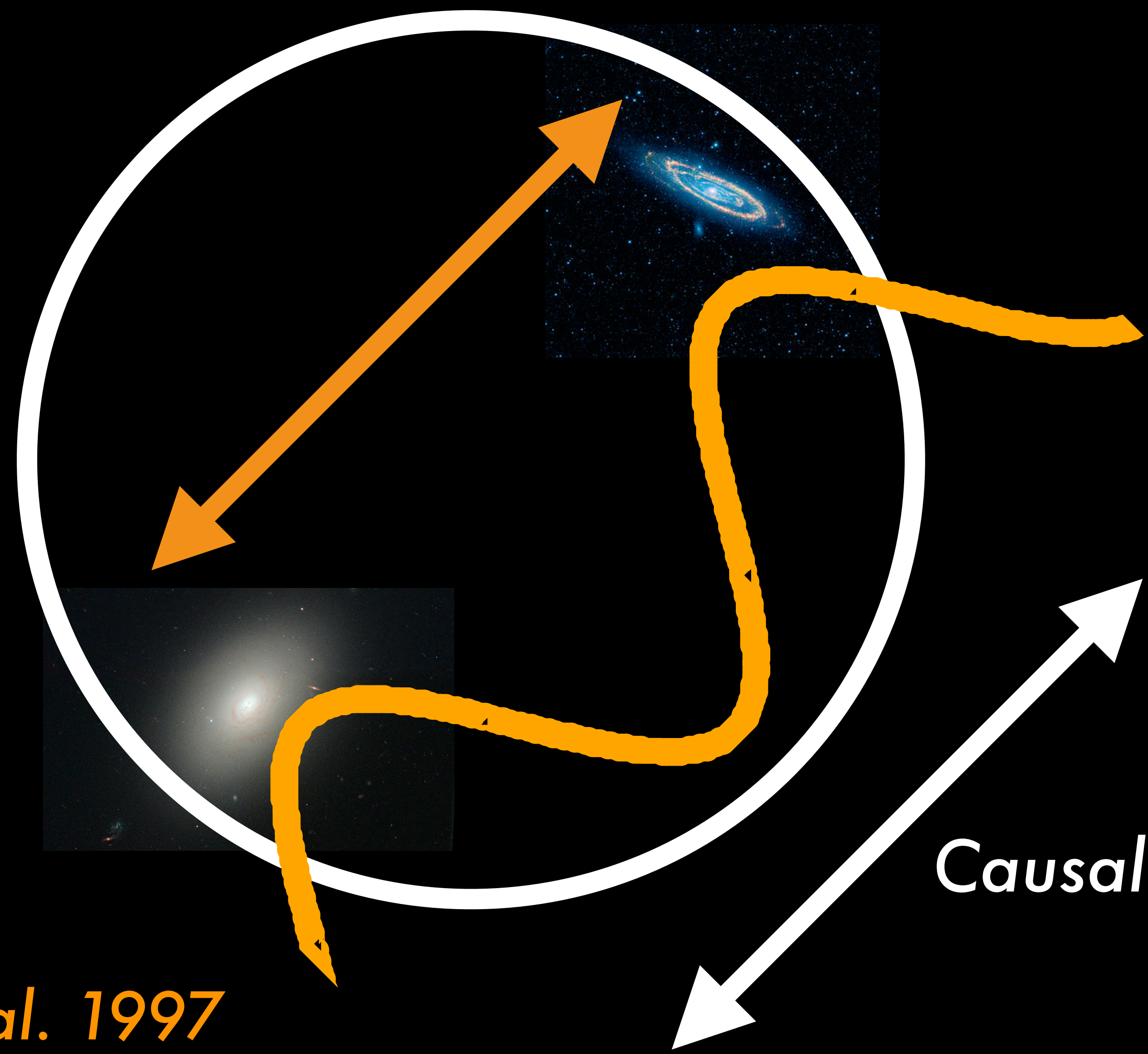
ULA as dark energy with specific w(z)

$m_a \lesssim 10^{-27}$ eV *ULA matter behavior starts too late for struct. formation*

Cosmology of ultra-light axions: dark matter and dark energy candidates

Scale corresponding to typical galaxy separation today





Causal horizon

Frieman et al 1995, Coble et al. 1997

ULA as dark matter

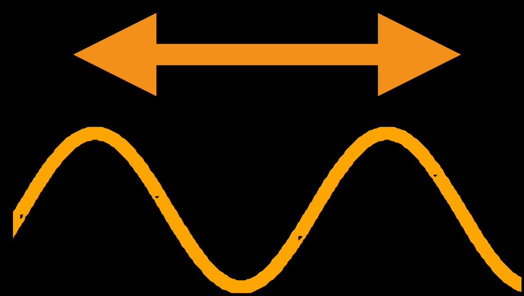
$$m_a \gtrsim 10^{-27}\ \mathrm{eV}$$

ULA matter behavior starts in time for struct. formation

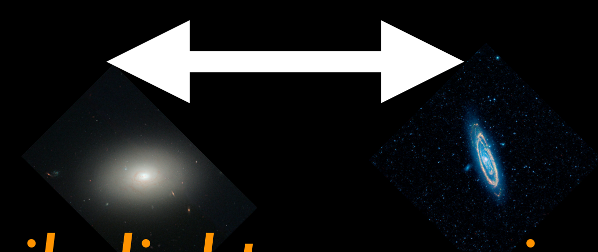
structure growth suppressed on small scales

✳Perturbed KG equation $\delta\ddot{\phi} + 3H\delta\dot{\phi} + \left[m^2 + \frac{k^2}{R^2}\right]\delta\phi \propto \Psi$

Axion deBroglie



Astronomical length



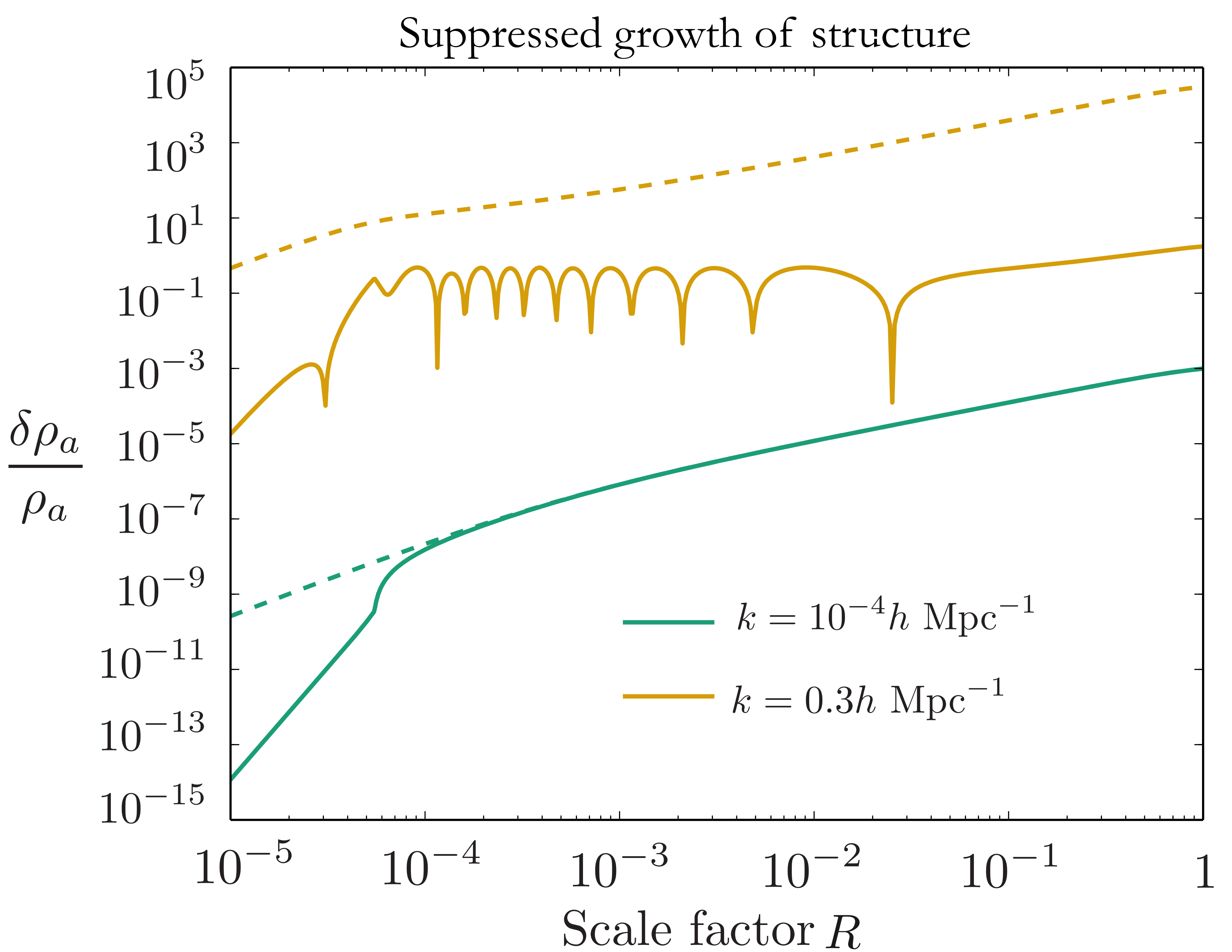
kilo-lightyear— giga-lightyear

✳WKB fluid description $c_s^2 \propto k^2/(4m_a^2 R^2)$ *Hu, Barkana, Gruzinov 2000, Hwang & Noh 2009*

✳Small-scale suppression

$$\lambda_J \sim 3 \left(\frac{m_a}{10^{-25}\ \mathrm{eV}}\right)^{-1/2} \mathrm{Mpc} \ \ (1+z)^{1/4}$$

structure growth suppressed on small scales

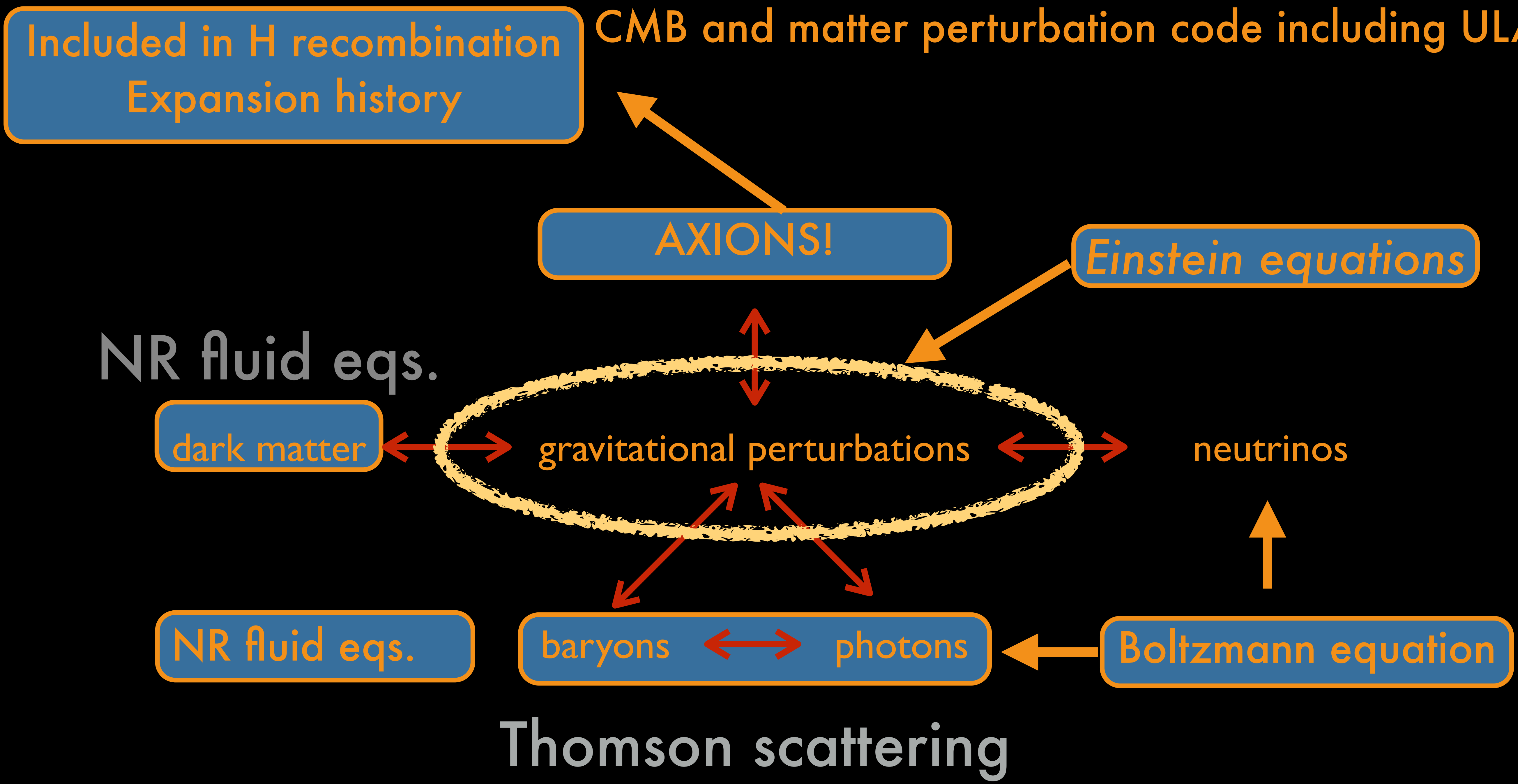


AxionCAMB

Code by Grin et al. 2013, based on CAMB (A. Lewis)

http://github.com/dgrin1/axionCAMB

CMB and matter perturbation code including ULAs!



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

Effective Fluid approximation (EFA)

	Background	Perturbations
early times	$\ddot{\phi}_0 + 2\mathcal{H}\dot{\phi}_0 + m_{\rm ax}^2 a^2 \phi_0 = 0$	$\delta\ddot{\phi} + 2\mathcal{H}\delta\dot{\phi} + \left(m_{\rm ax}^2 a^2 + k^2\right)\delta\phi = (\Psi, \Phi) \times \mathcal{O}\left(\dot{\phi}_0\right) + \left(\dot{\Psi}, \dot{\Phi}\right)\phi_0$
late times	$\rho_{\rm ax} = \rho_{\rm osc}\left(\frac{a_{\rm osc}}{a}\right)^3$	$\dot{\delta}_{\rm ax} = -k u_{\rm ax} - \frac{\dot{h}}{2},\ \dot{u}_{\rm ax} = -\frac{\dot{a}}{a}u_{\rm ax} + k c_s^2 \delta_{\rm ax}$

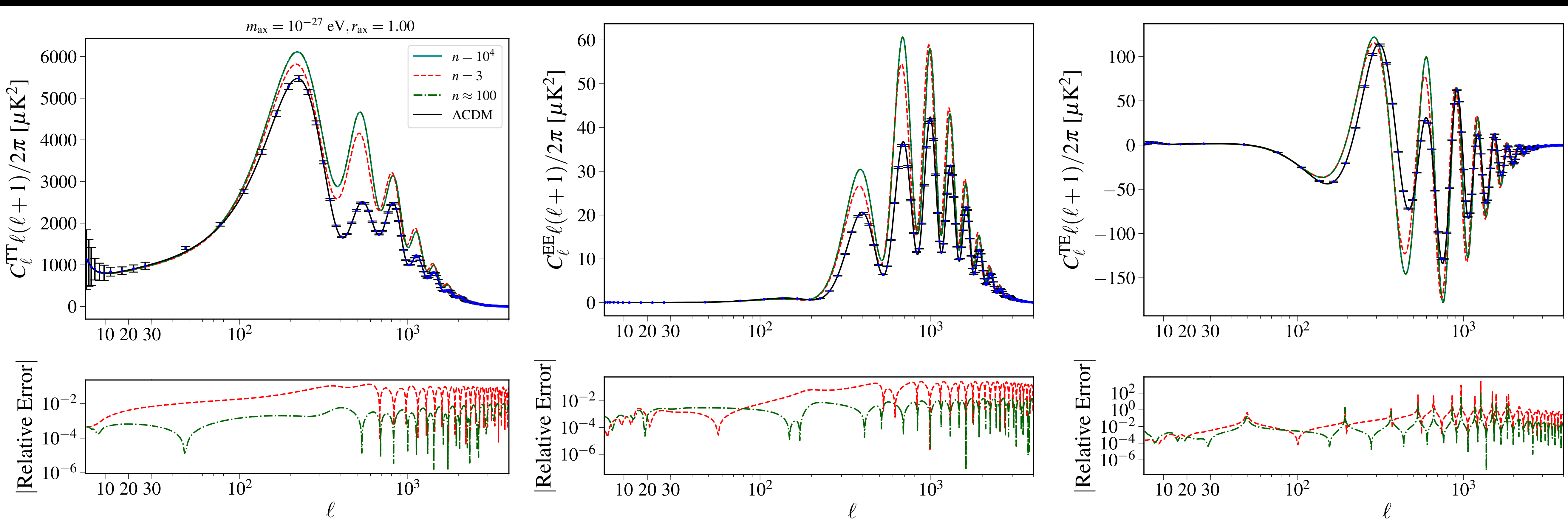
$$c_s^2 \equiv \frac{\frac{k^2}{4m_{\rm ax}^2 a^2}}{1 + \frac{k^2}{4m_{\rm ax}^2 a^2}}$$

Particle number and momentum conserved at transition $m = n\mathcal{H}/a$

$$a = a_{\rm osc}$$

CMB power spectra

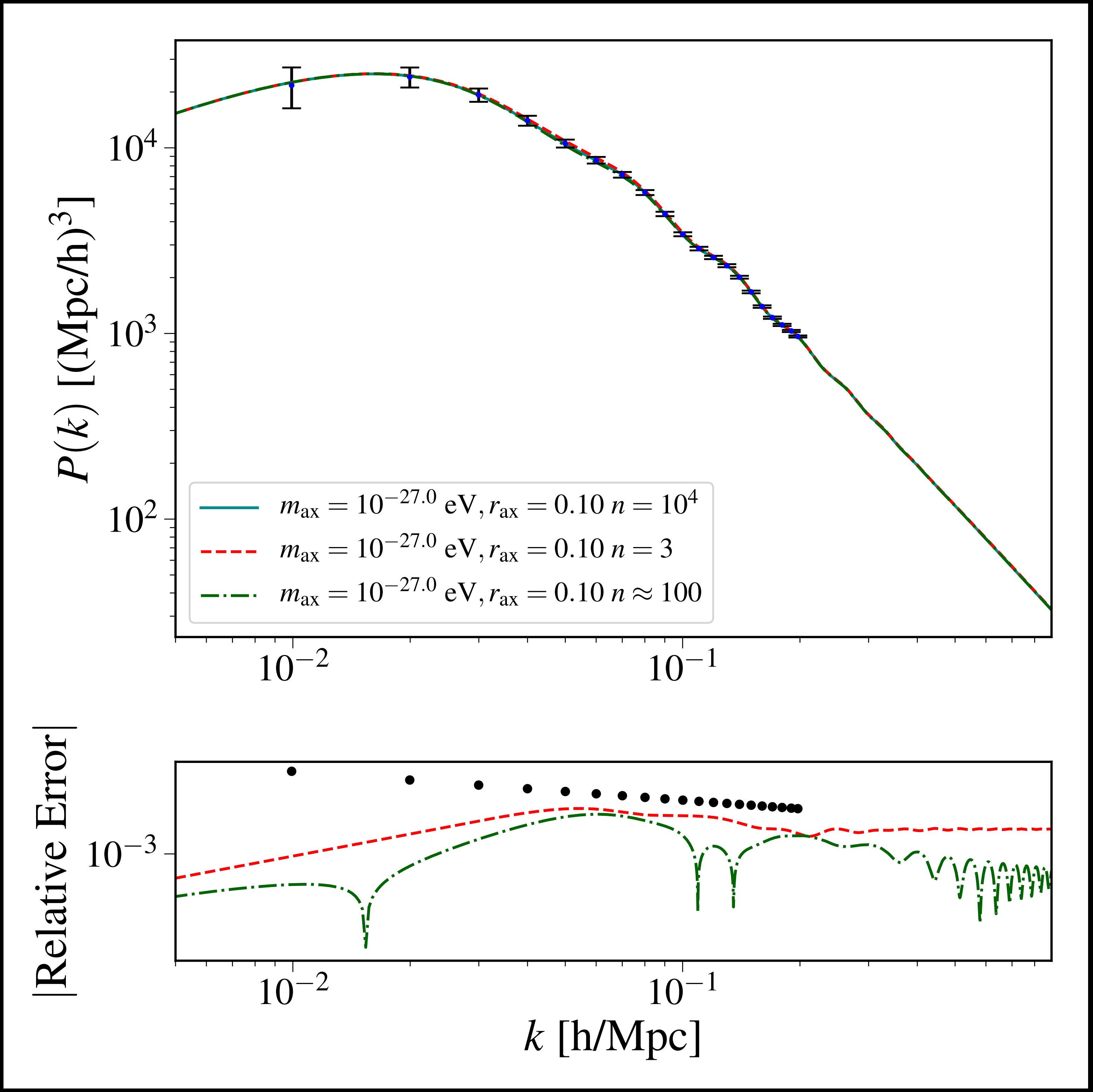
Worst-case scenario, from Cookmeyer, Grin, Smith, Phys. Rev. D 101, 023501 (2020), arXiv: 1909.11094
Uses separate Boltzmann code



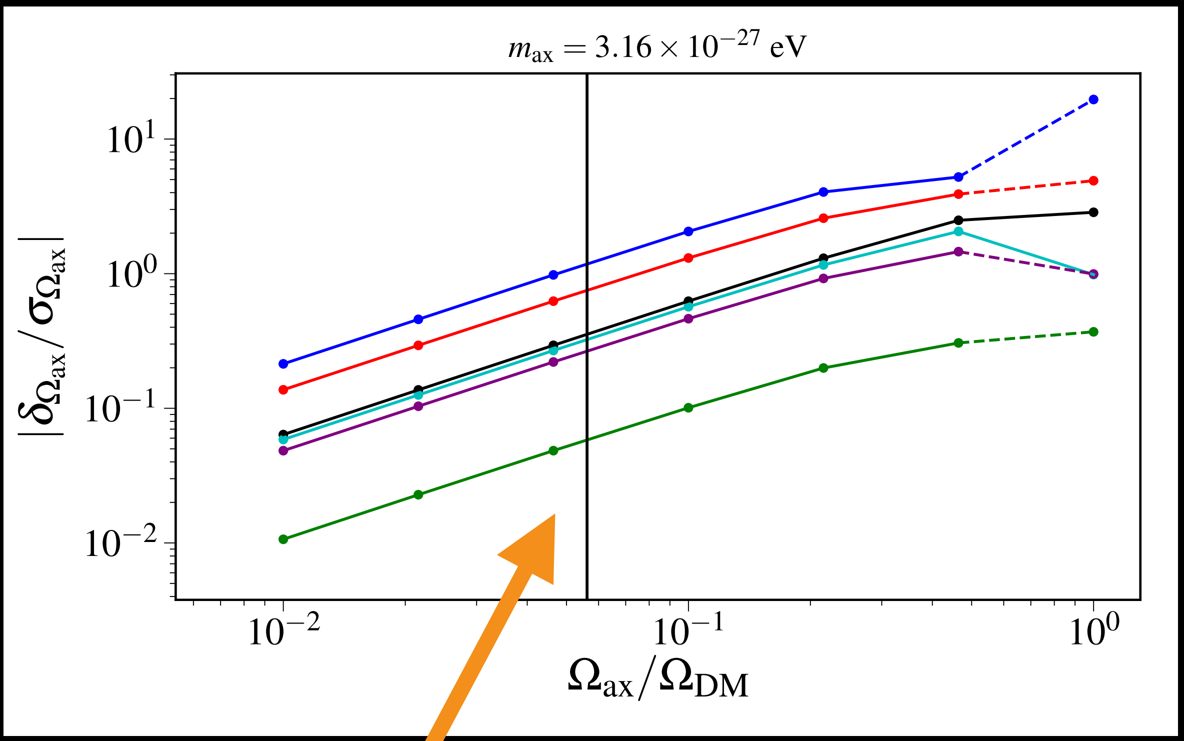
- ✳ Error ordering of prescription depends on axion mass
- ✳ Rough benchmark (Seljak Phys.Rev.D68:083507,2003) for CV-limited parameter estimates violated in some cases:

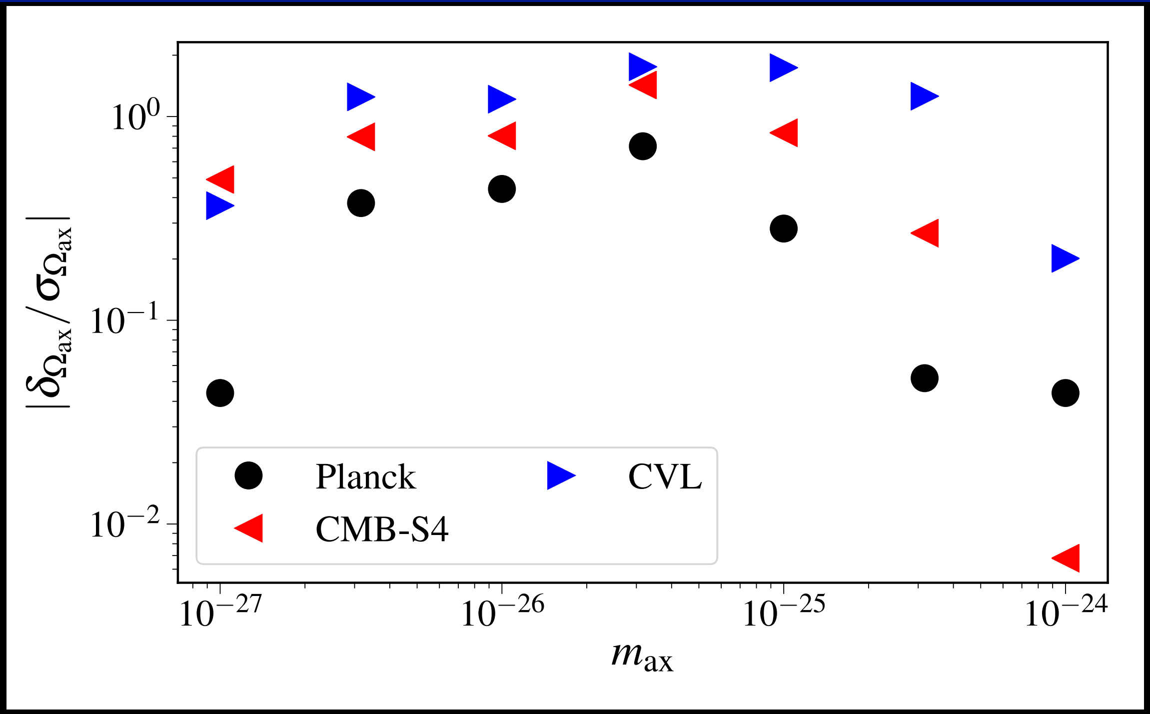
$$\frac{\Delta C_\ell}{C_l} \gtrsim \frac{3}{l} \text{ if } \ell \gtrsim \mathcal{O}(10^2) \quad \text{for } r_{\rm ax} \sim 10^{-1} \text{ and } m_{\rm ax} = 10^{-27}\ \text{eV}$$

Matter power spectrum (safe WiggleZ)



Bias results





Saturate old limits

3σ limit from Planck 2013

- Negligible bias for Planck and S4 (usually)
- Modest bias for S4 (some cases) and CVL (but likely only need to worry if claiming detection)

Improving the Effective Fluid approximation (EFA)

$$c^2_{s,\mathrm{efa}} = c^2_{s\phi} + \frac{5}{4}\frac{H^2}{m^2}$$

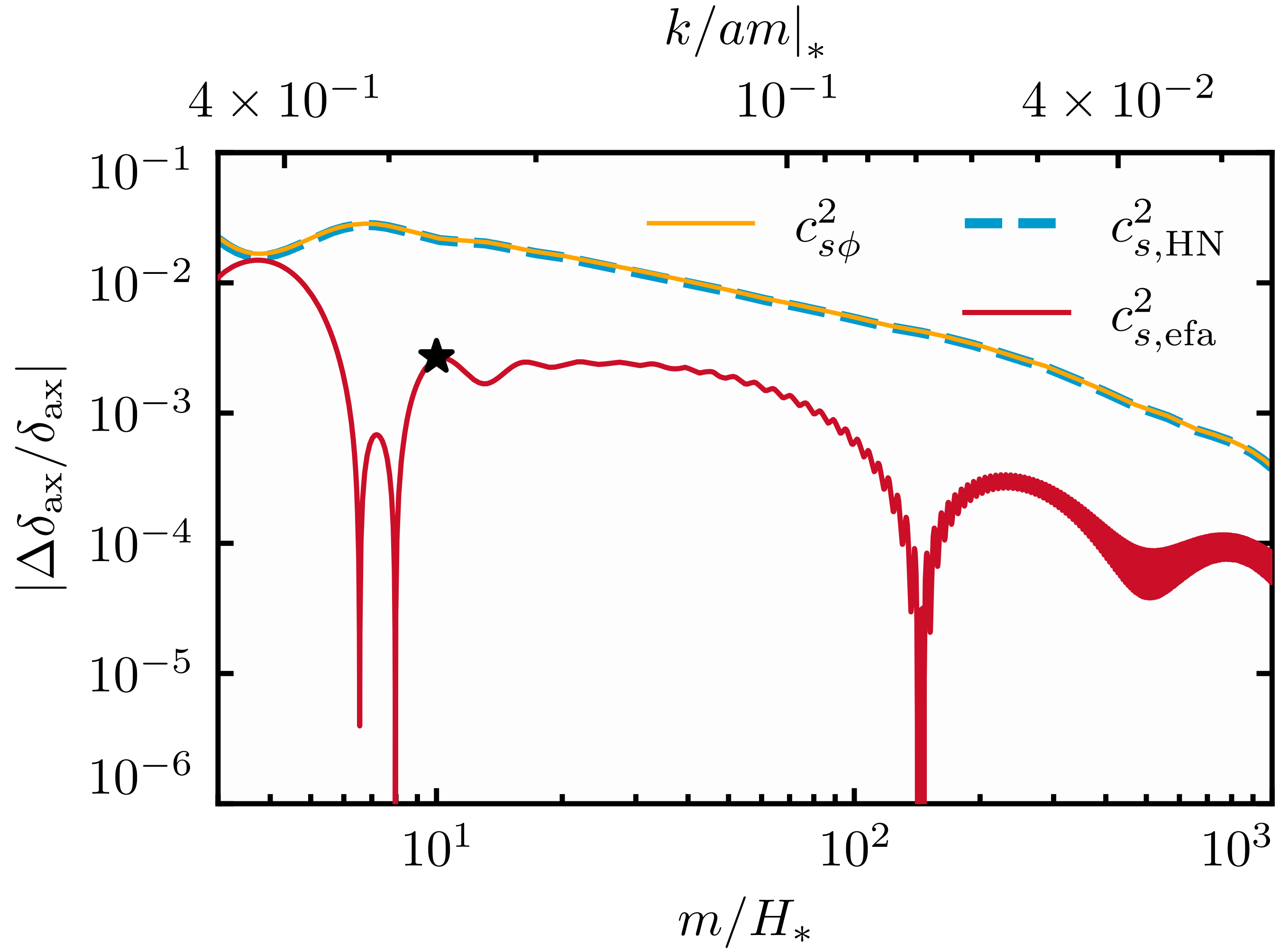
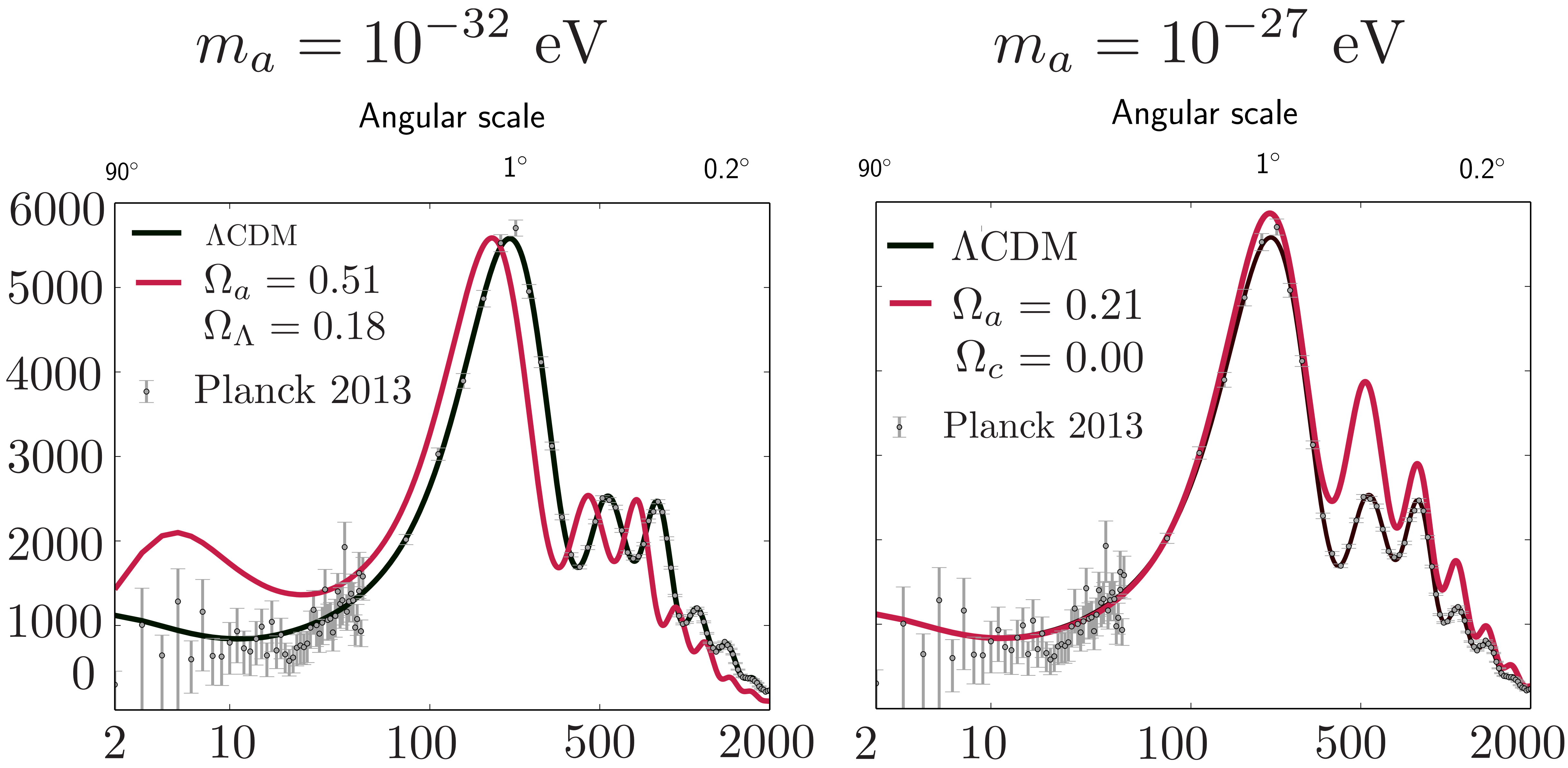


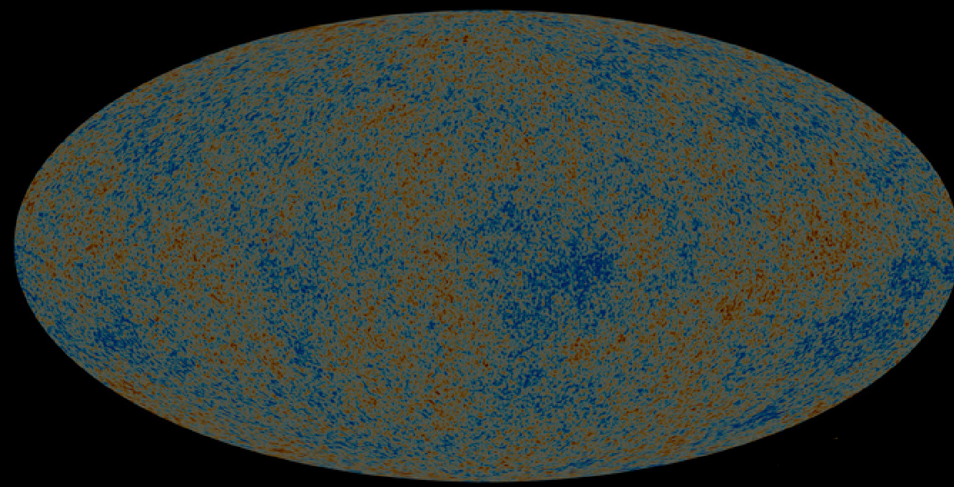
FIG. 9. For a mode $k_{1/2}$ where the matter power spectrum yields half its CDM value, we show our technique's total error as a function of our switch time parameter m/H_* for various choices of the EFA equation of state c_s^2, computed by comparing to a late switch time $m/H_* = 2 \times 10^3$. Using the field sound speed $c_{s\phi}$

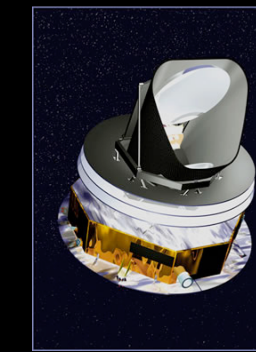
✴ From Hu/Passaglia 2022



Dramatic changes to observables can result

Data + Analysis



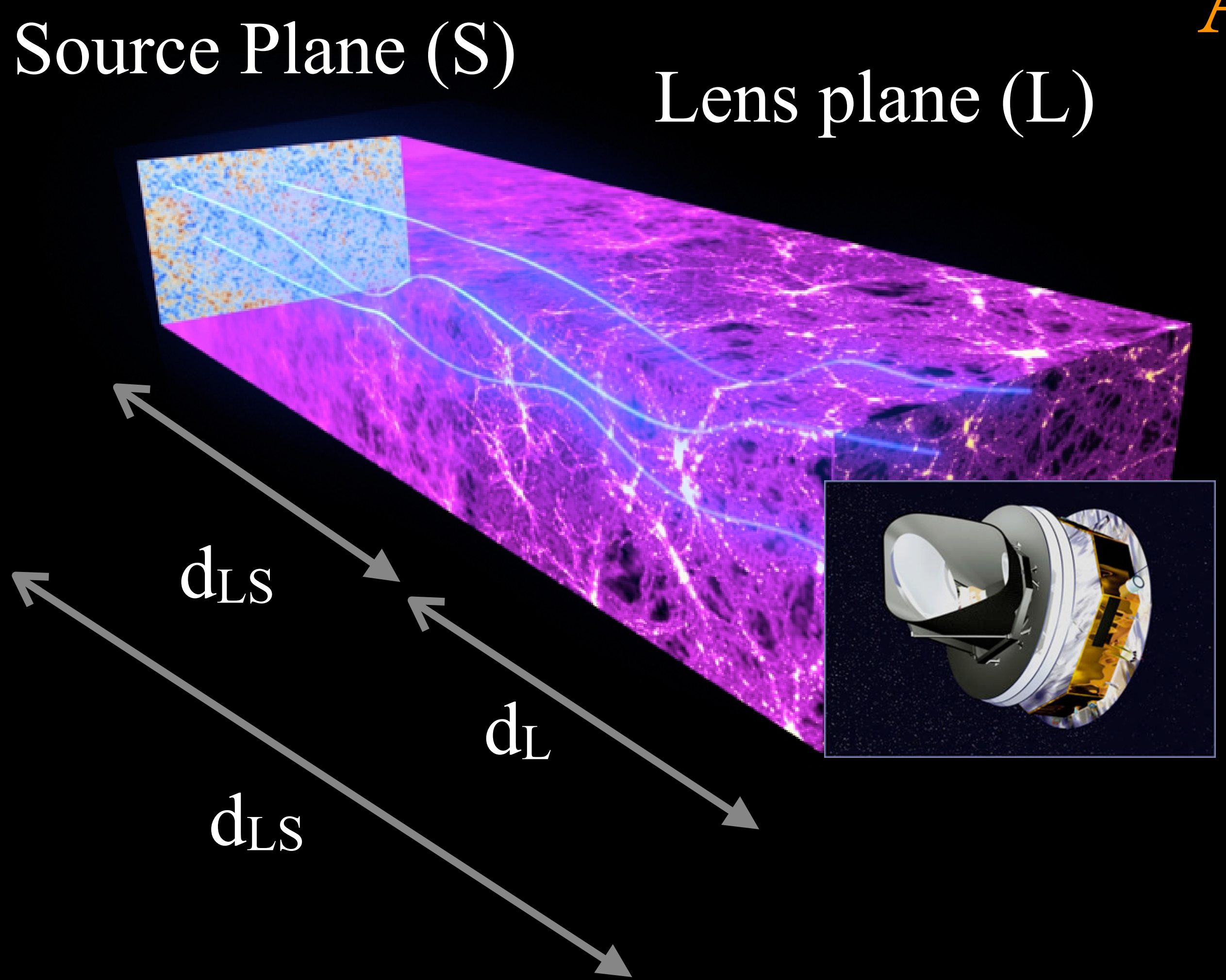


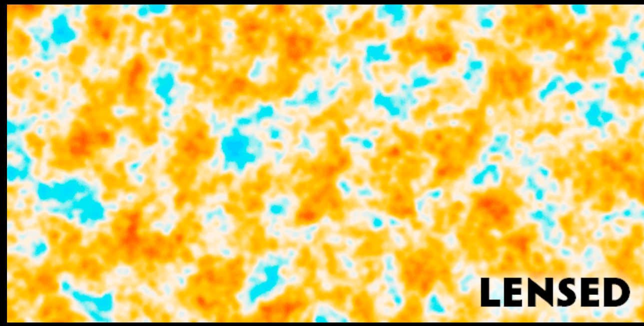
- Planck 2013 temperature anisotropy power spectra (+SPT+ACT)
    - Cosmic variance limited to $\ell \sim 1500$

- 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 $m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\mathrm{reion}}$

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

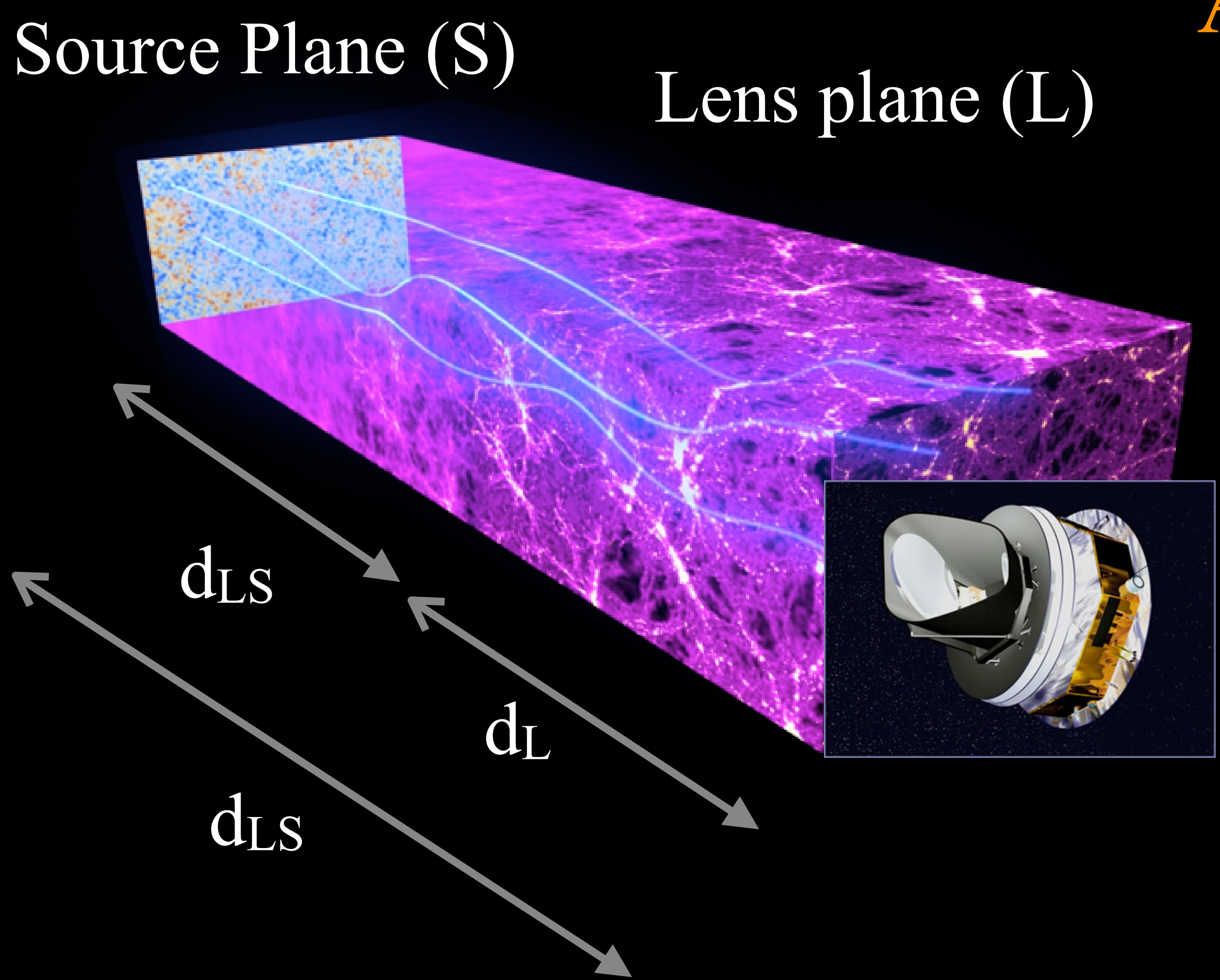


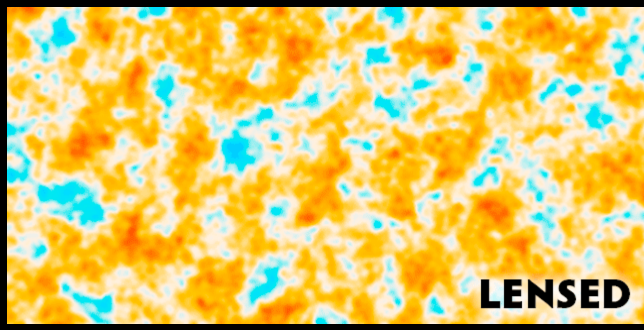


$$\vec{\alpha} = \nabla_{\vec{\theta}} \left\{ \int \left(\frac{d_{\rm LS}}{d_{\rm L} d_{\rm S}} \right) \Phi \left[d(\eta)\vec{\theta}, \eta \right] d\eta \right\}$$

CMB LENSING

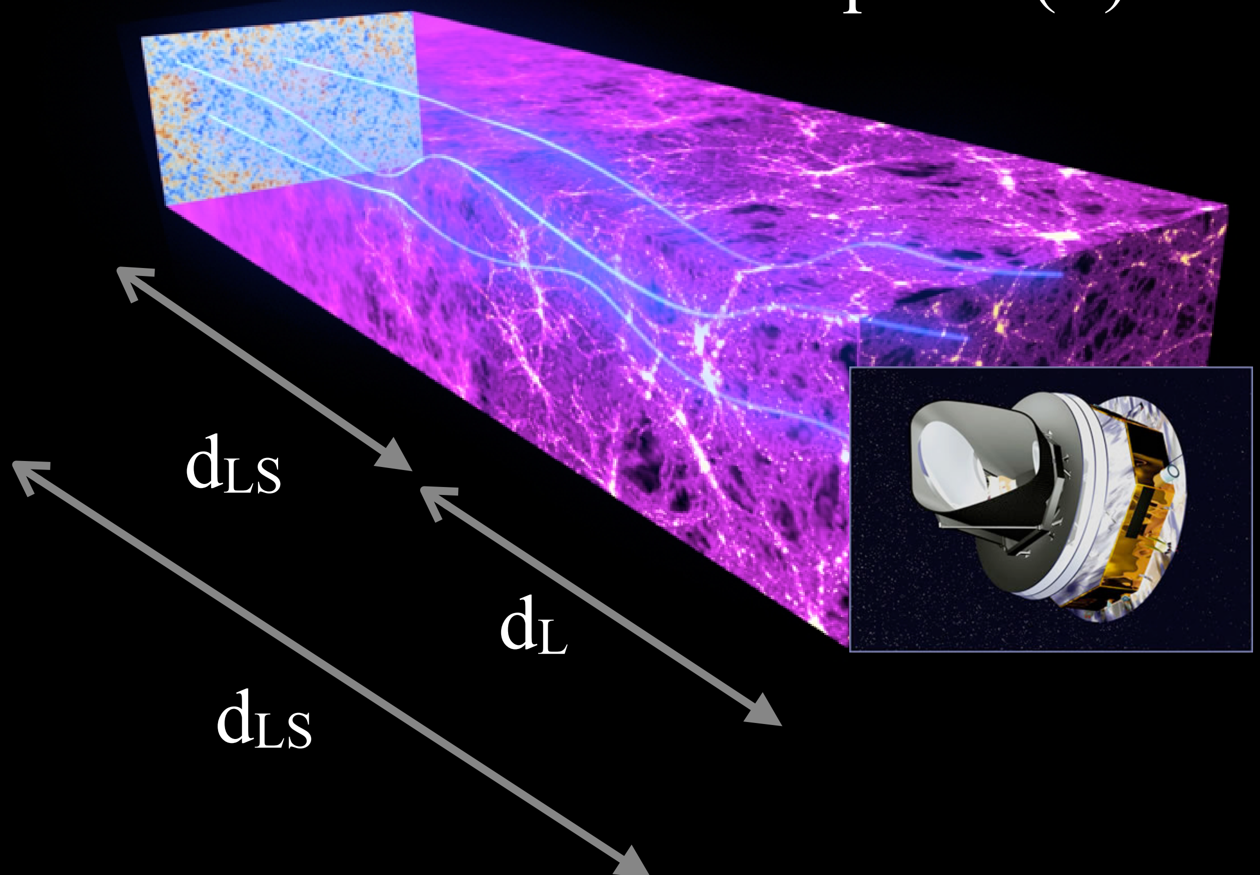
A slice of (dark matter) life at z~1



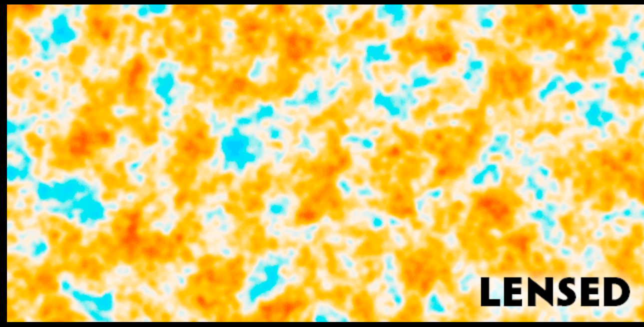


$$\vec{\alpha} = \nabla_{\vec{\theta}} \left\{ \int \left(\frac{d_{\rm LS}}{d_{\rm L} d_{\rm S}} \right) \Phi \left[d(\eta)\vec{\theta}, \eta \right] d\eta \right\}$$

CMB LENSING



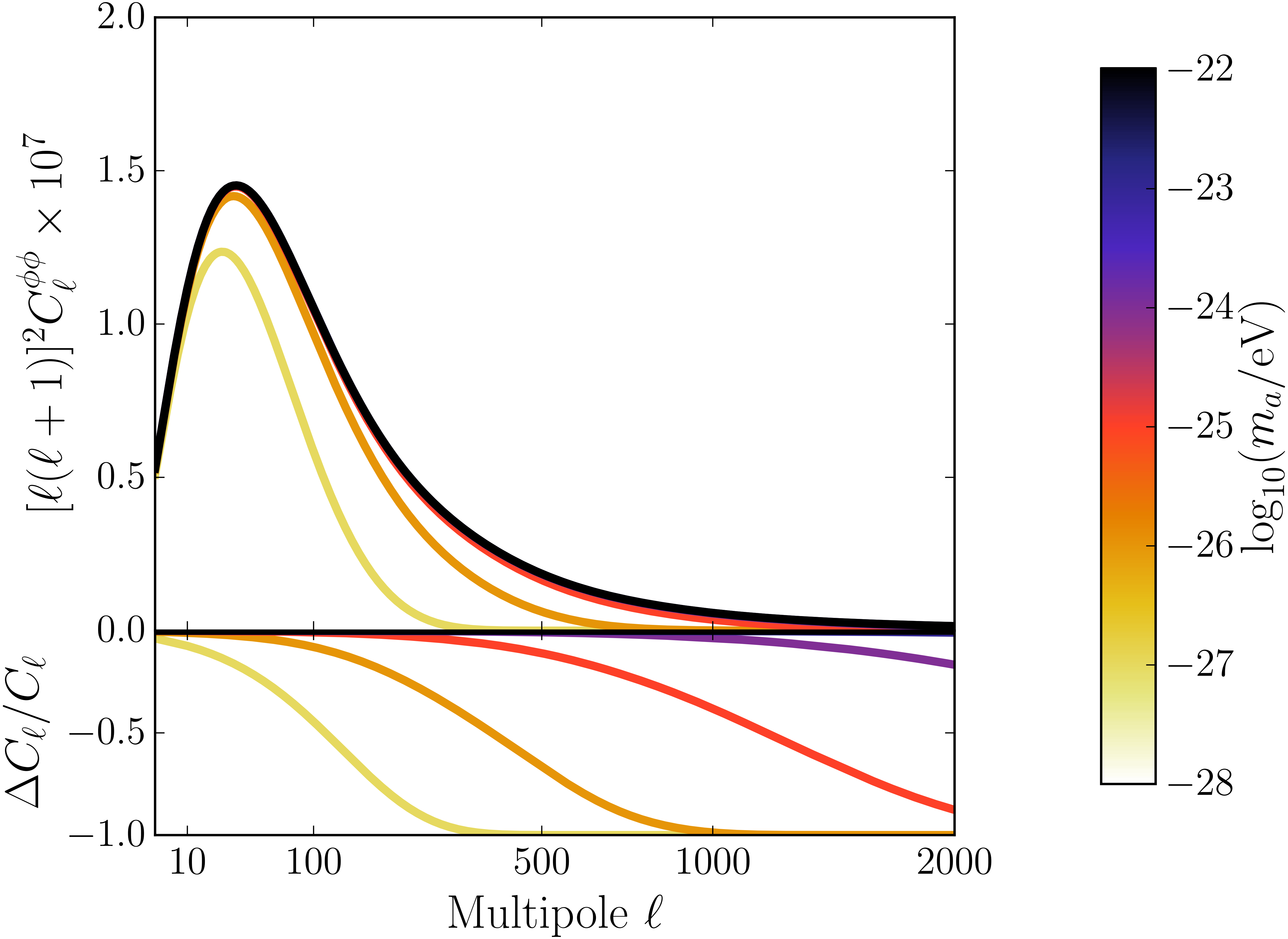
A slice of (dark matter) life at z~1



$$\vec{\alpha} = \nabla_{\vec{\theta}} \left\{ \int \left(\frac{d_{\rm LS}}{d_{\rm L} d_{\rm S}} \right) \Phi \left[d(\eta)\vec{\theta}, \eta \right] d\eta \right\}$$

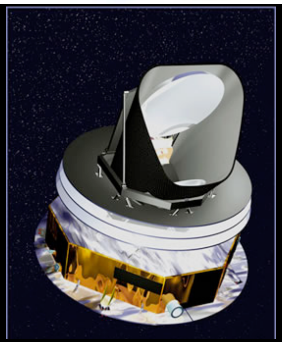
ULAs change

CMB LENSING



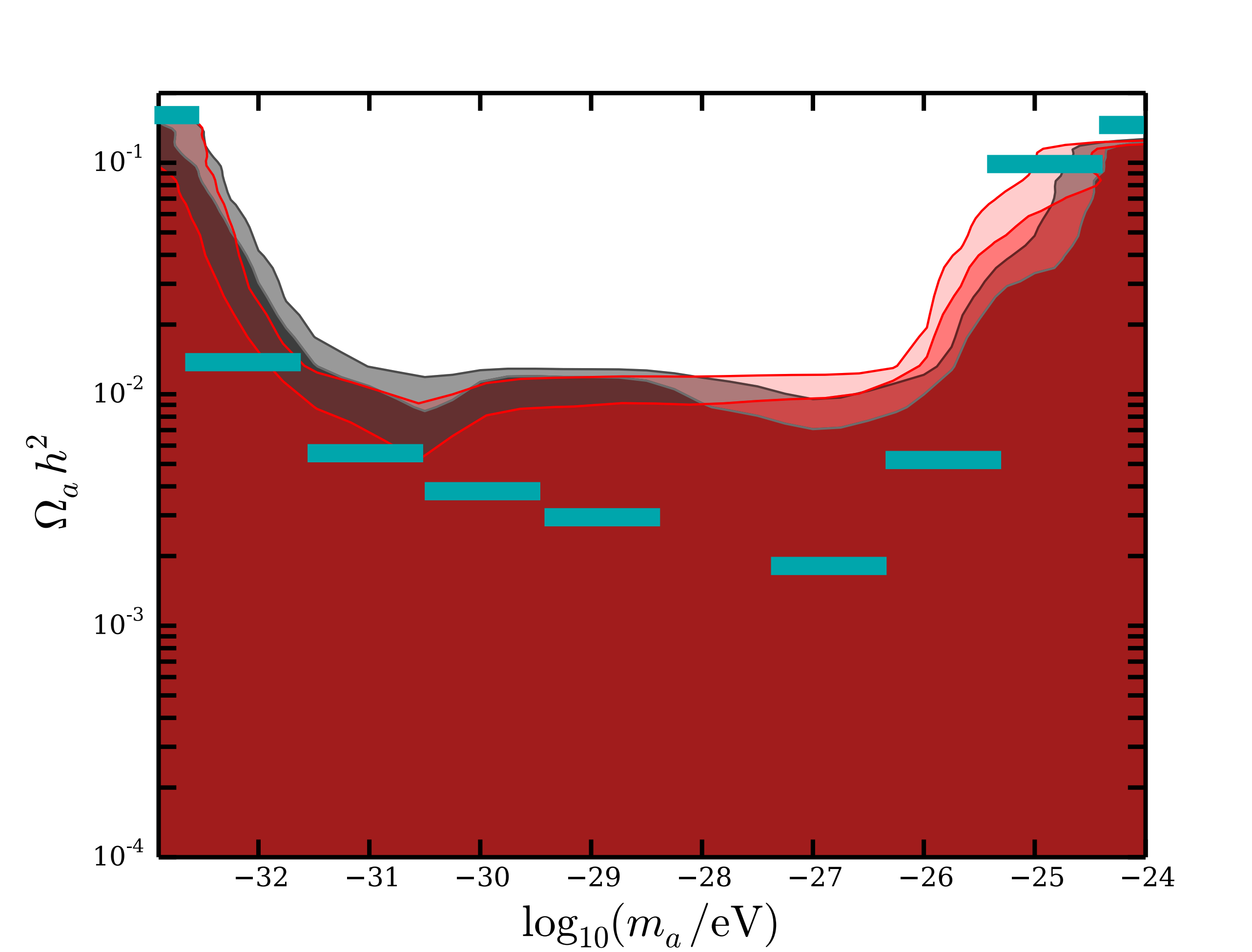
$[\ell(\ell+1)]^2 C_\ell^{\phi\phi} \times 10^7$
2.0
1.5
1.0
0.5
0.0
$\Delta C_\ell / C_\ell$
−0.5
−1.0
10
100
500
1000
2000
Multipole ℓ
−22
−23
−24
−25
−26
−27
−28
$\log_{10}(m_a/\mathrm{eV})$

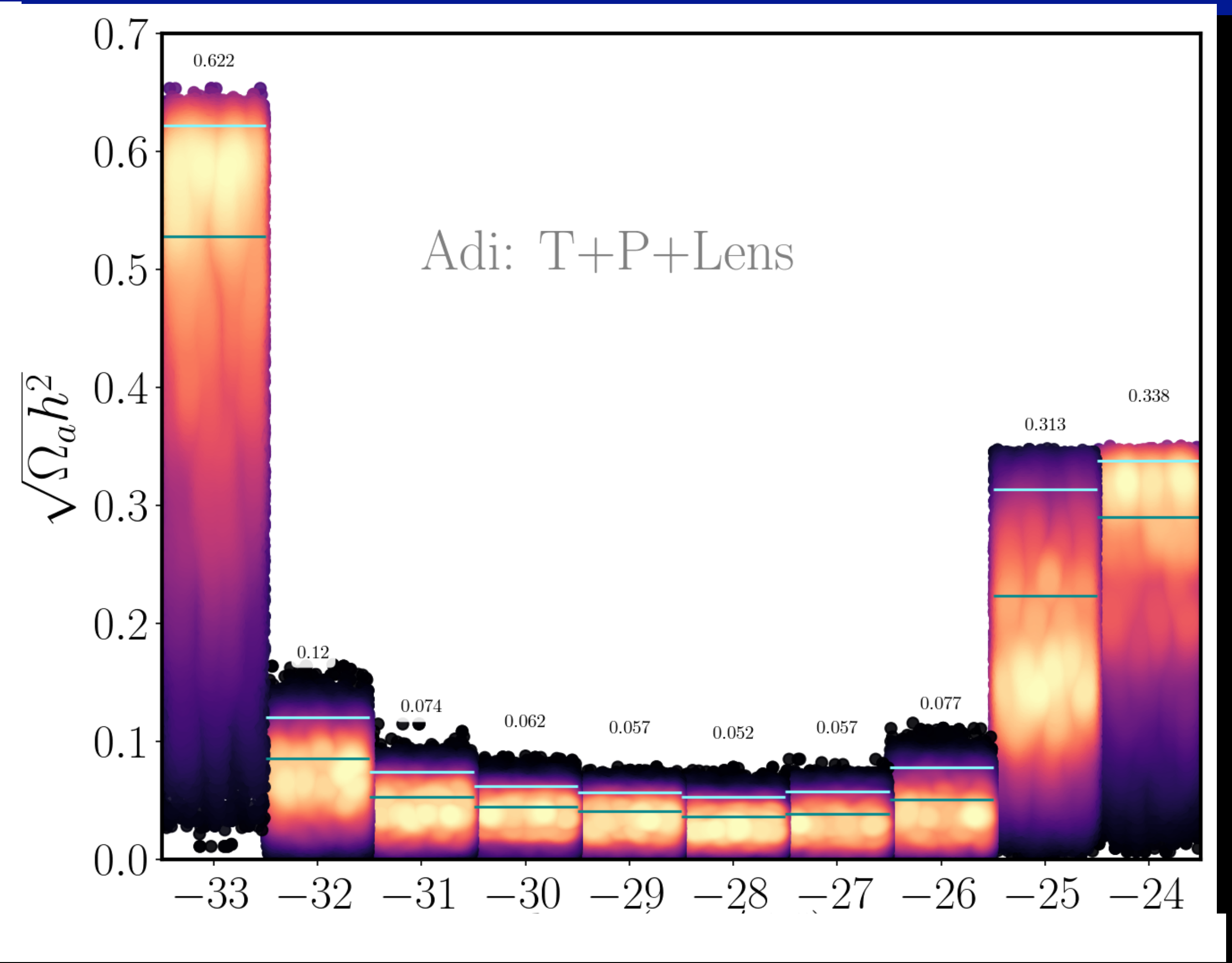
Constraints



arXiv: 1708.05681, MNRAS 476, Volume 3
arXiv: 1607.08208, Phys. Rev. D 95, 123511 (2017).
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)

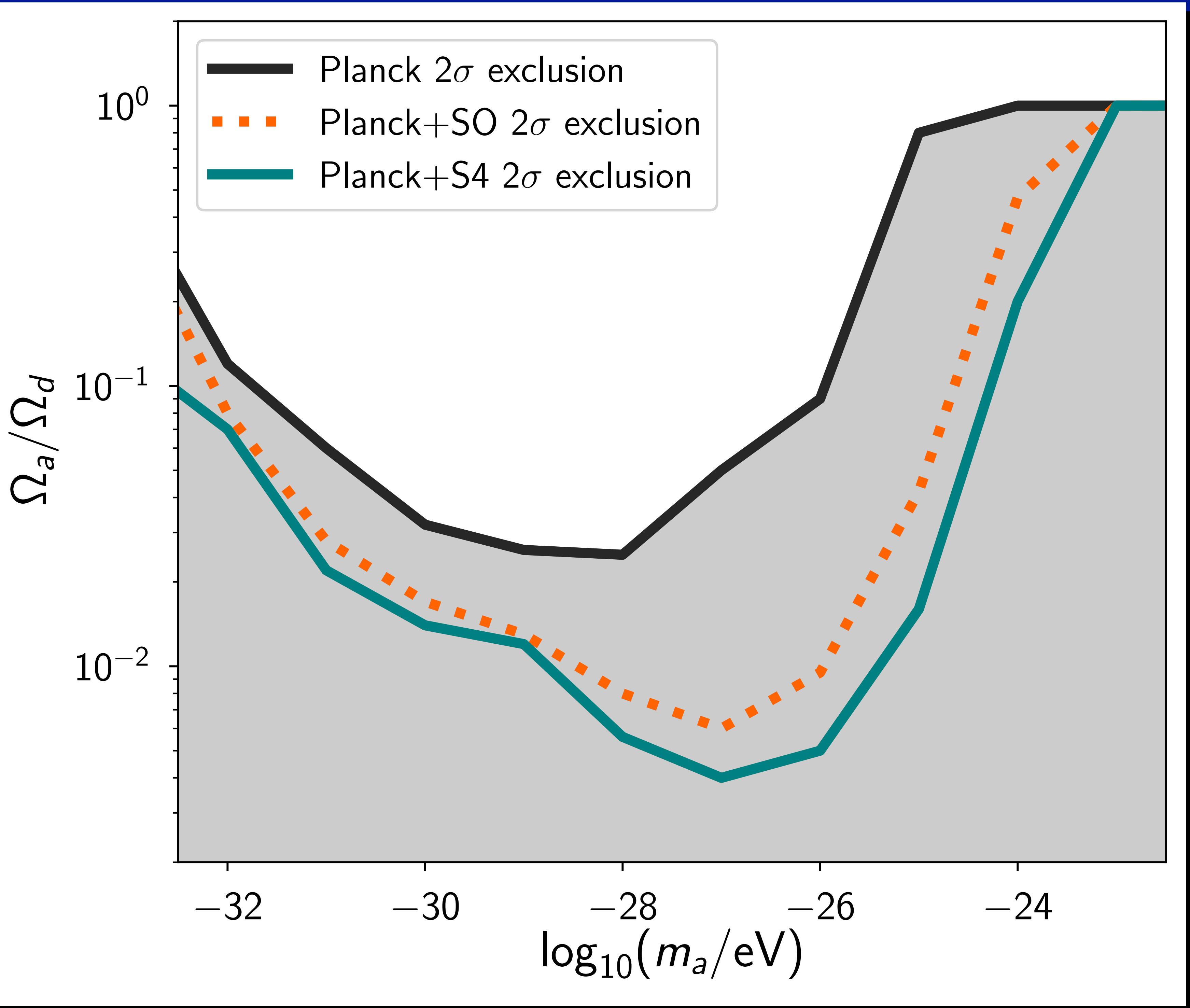
Constraints





arXiv: 1708.05681, MNRAS 476, Volume 3
arXiv: 1607.08208, Phys. Rev. D 95, 123511 (2017).
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)

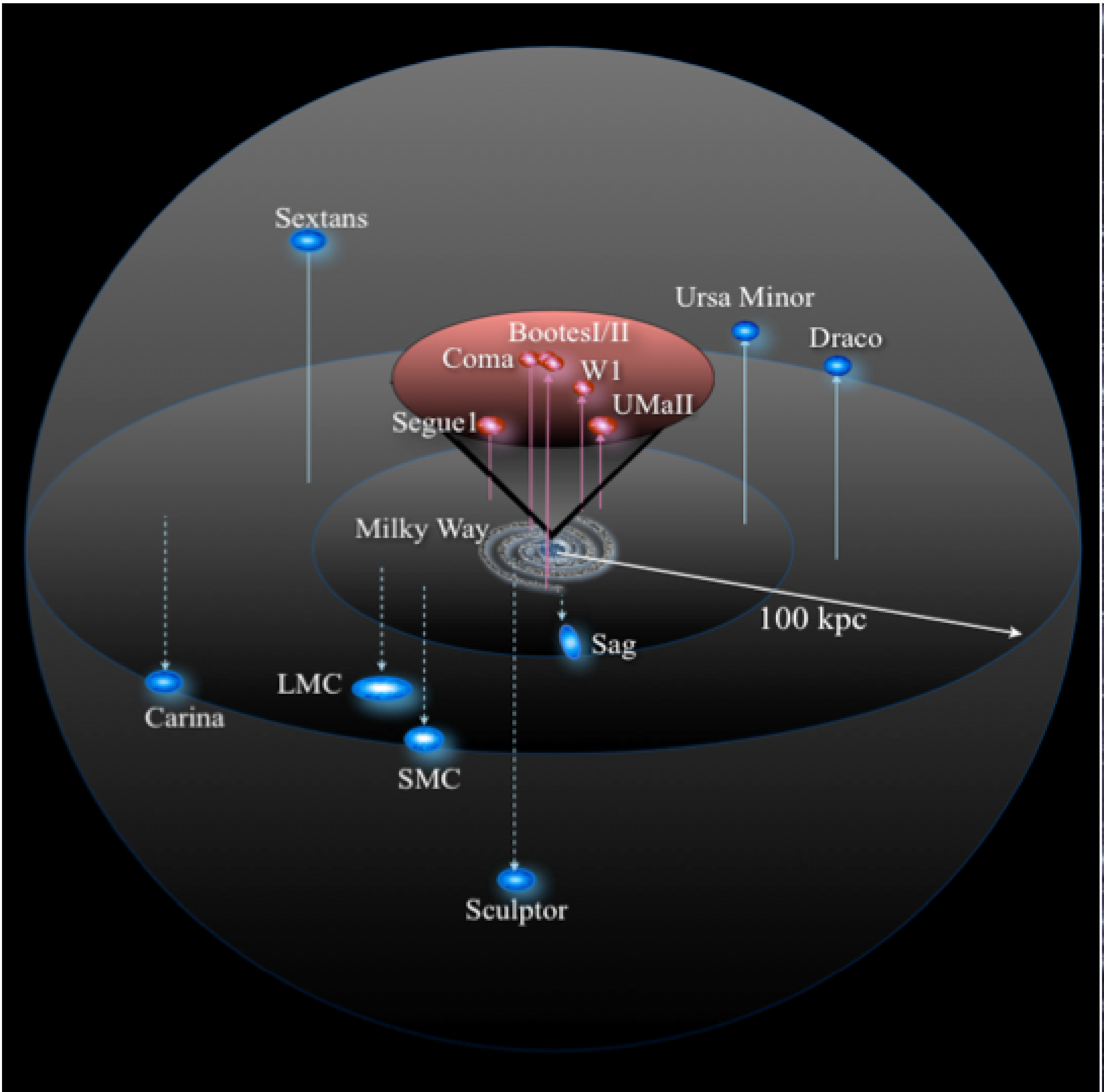
Constraints

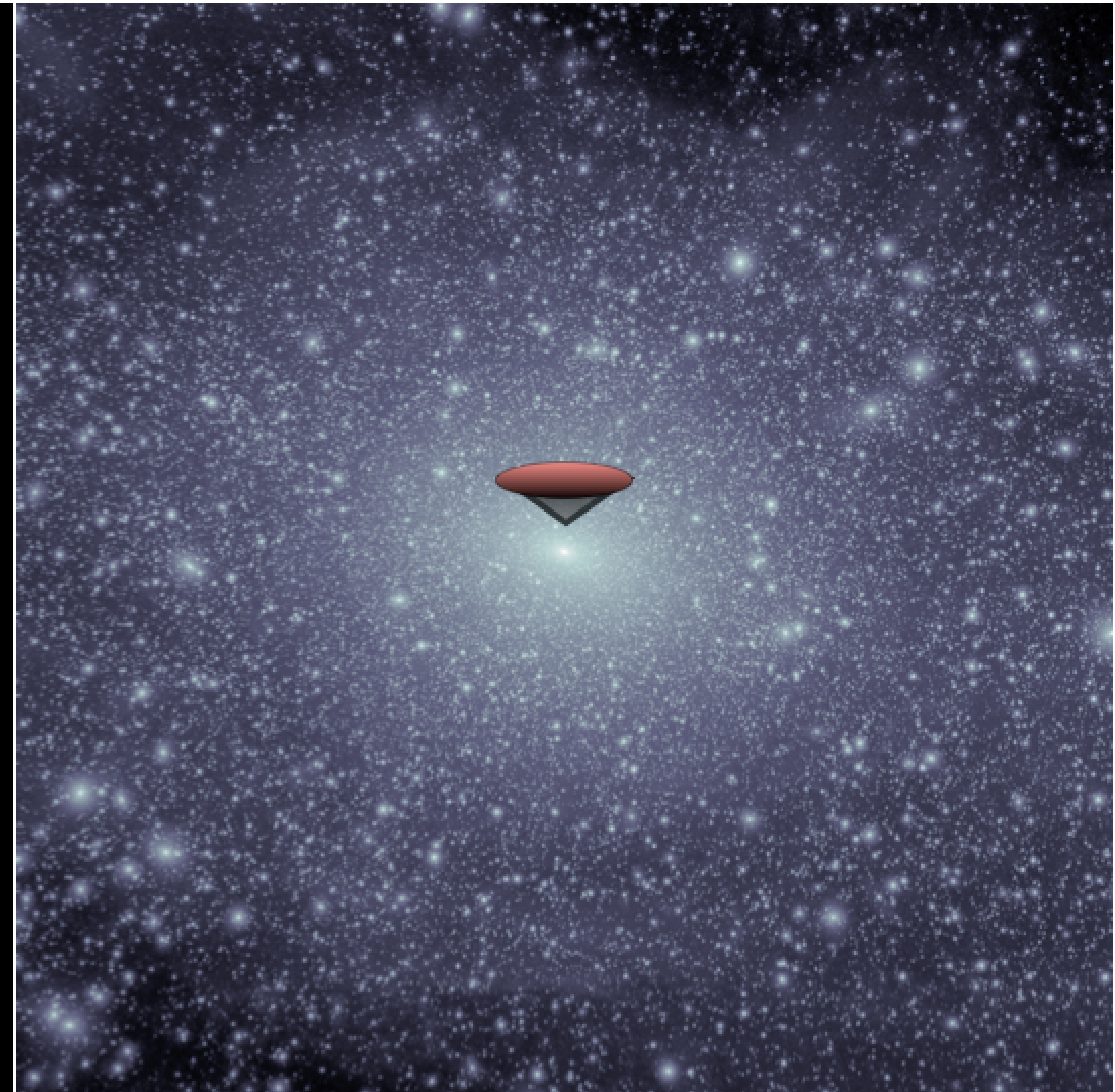


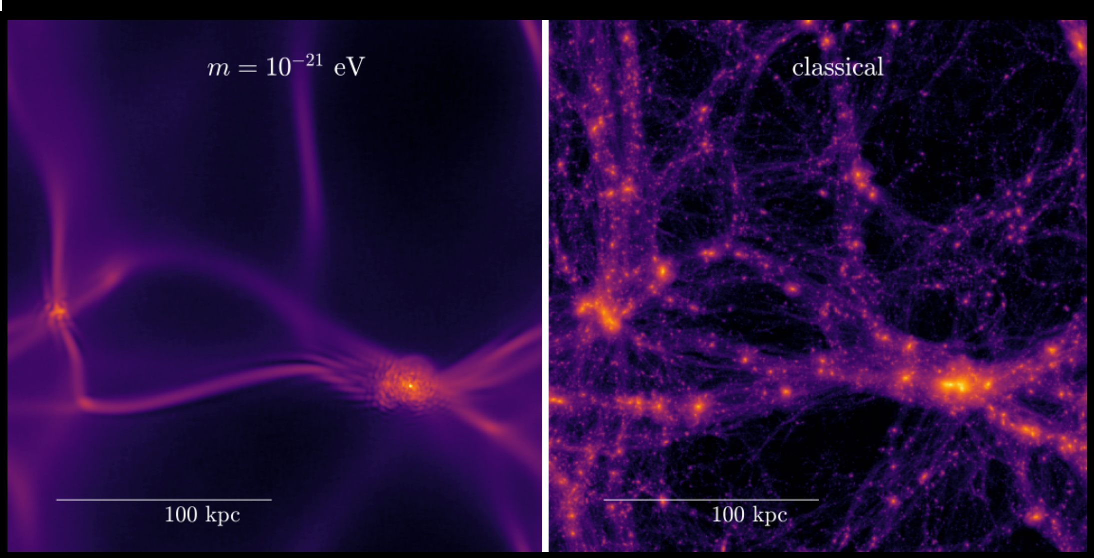
https://arxiv.org/abs/1708.05681

From CMB-S4 Science book/DSR report…. arXiv: 1610.02743, 1907.04473

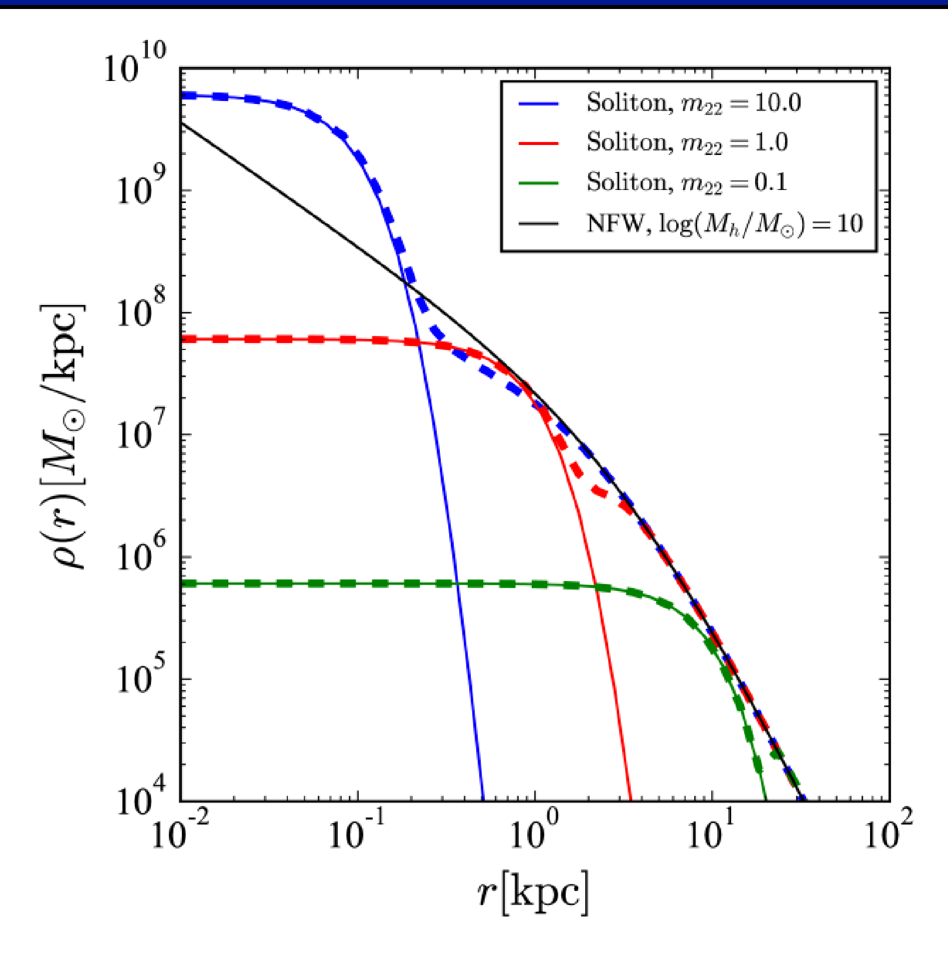
ASTROPHYSICAL ATTRACTION (SMALL-SCALE CHALLENGES TO ΛCDM)

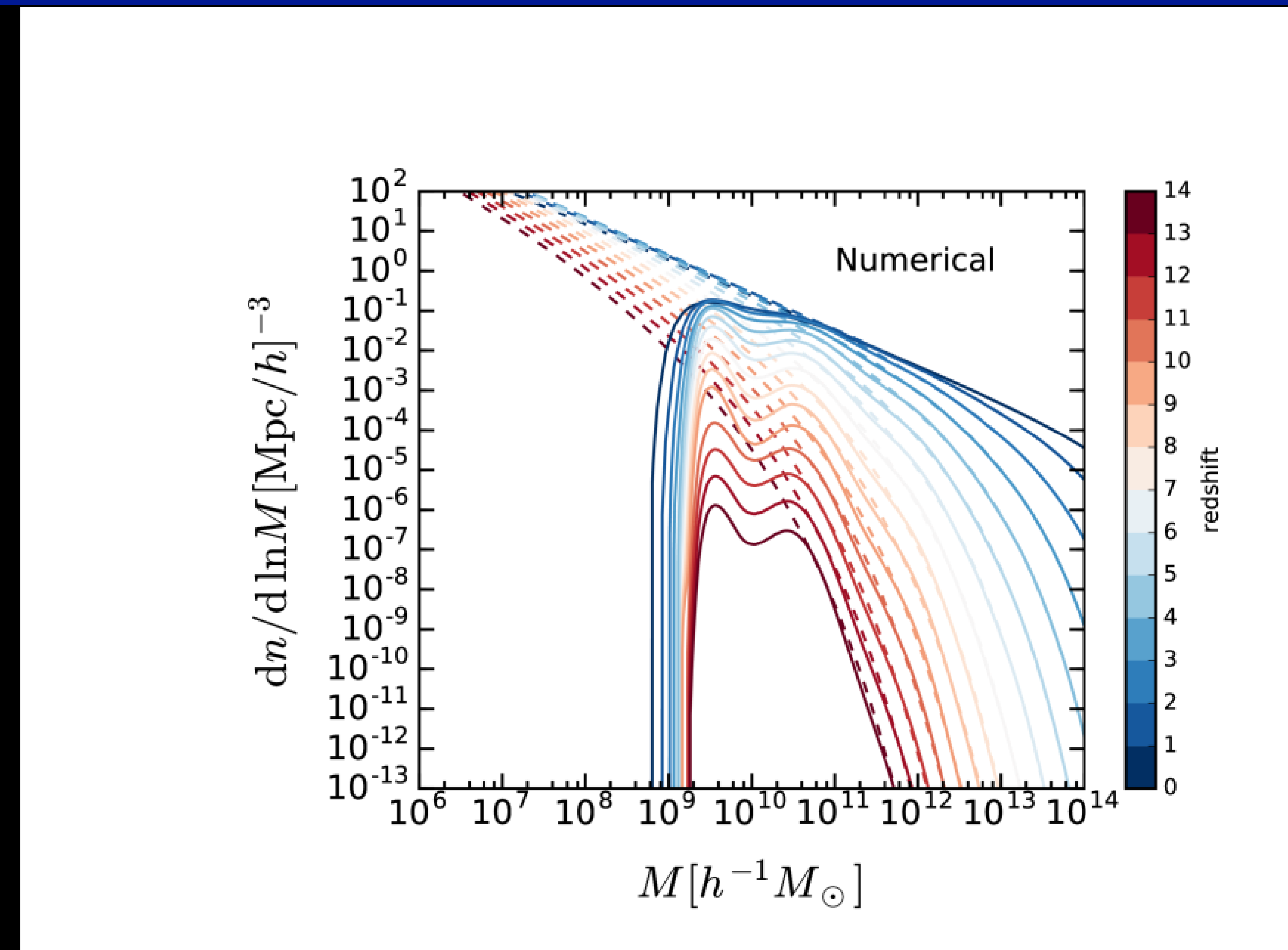






Astrophysical attraction (small-scale challenges to ΛCDM)

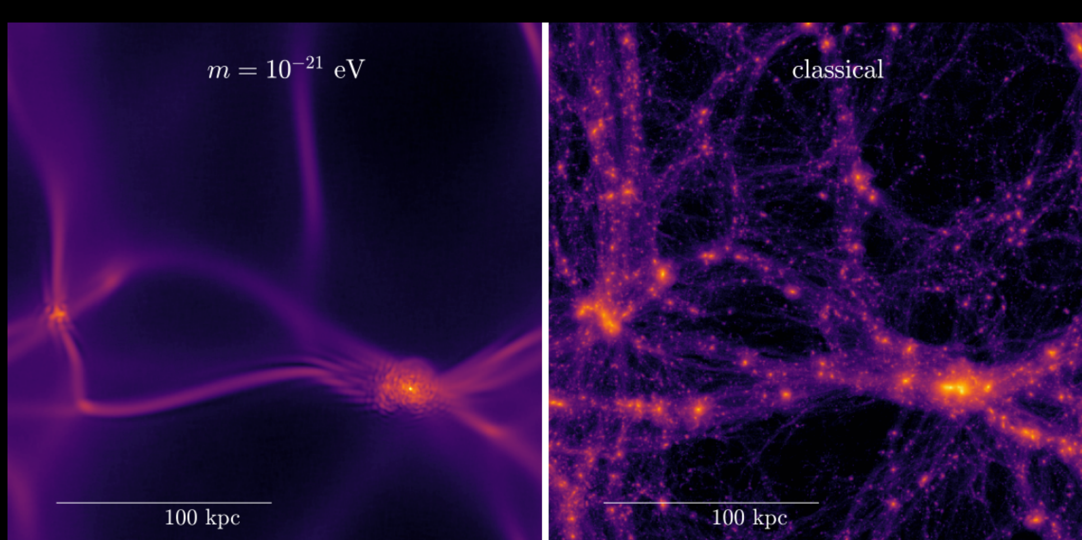




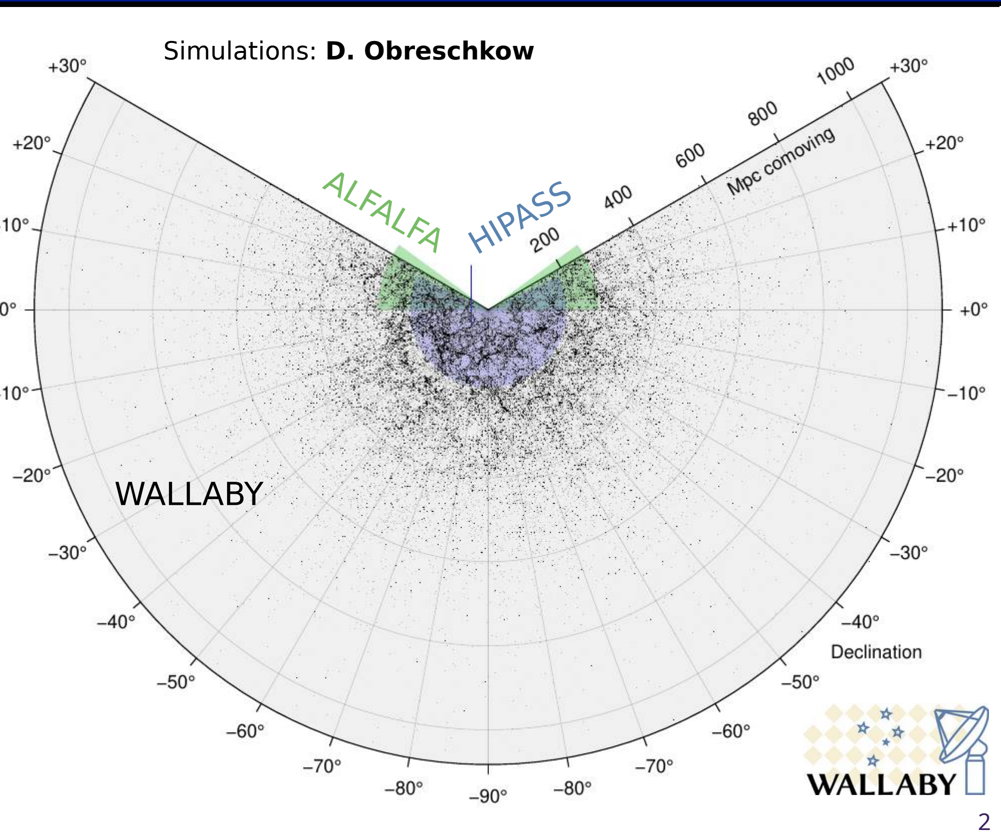
Safarzadeh & Spergel:
The Astrophysical Journal, Volume 893, Number 1

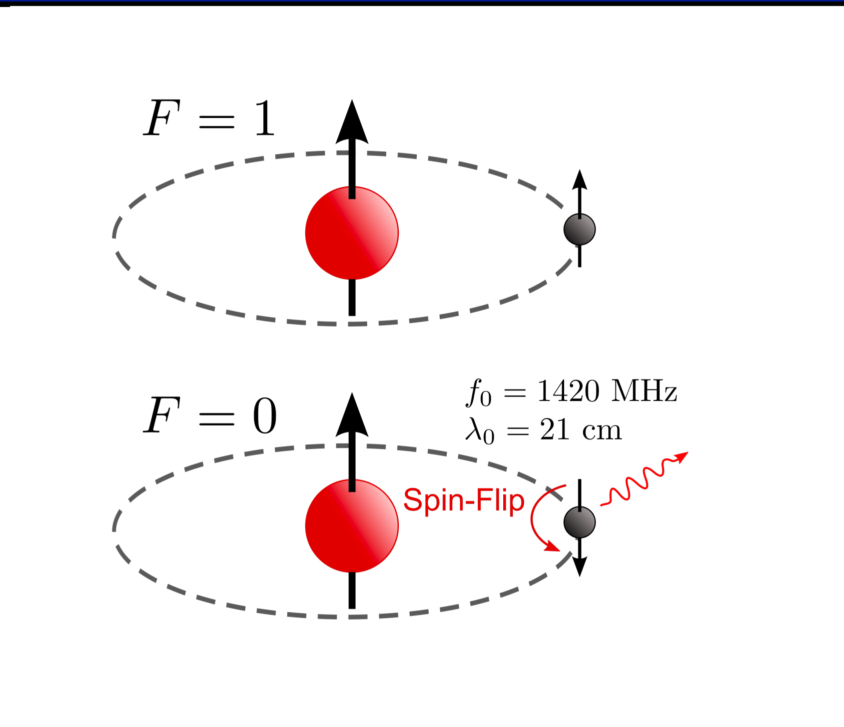
Marsh, Physics Reports
Volume 643, 1 July 2016, Pages 1-79

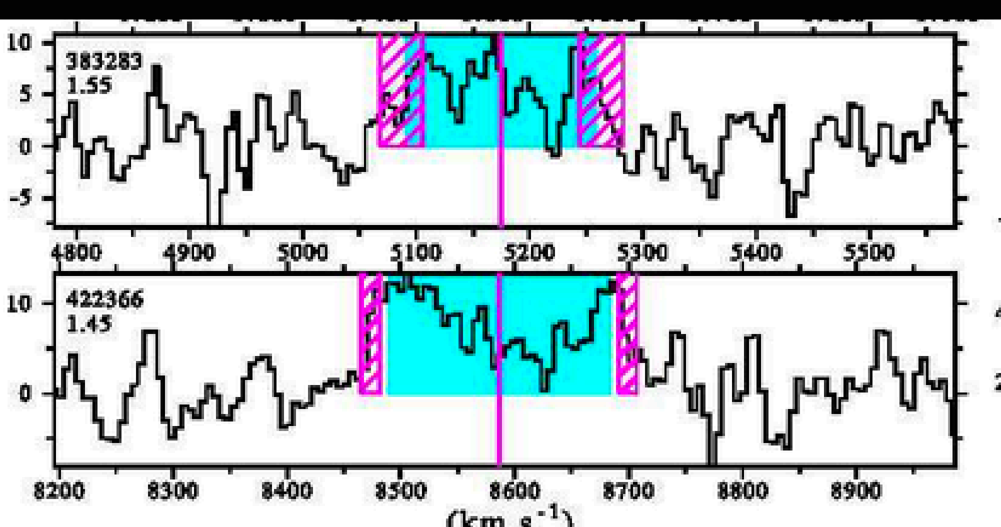
Mocz et al 2019.



Extra-galactic HI surveys: $10^6 M_\odot \rightarrow 10^{11} M_\odot$







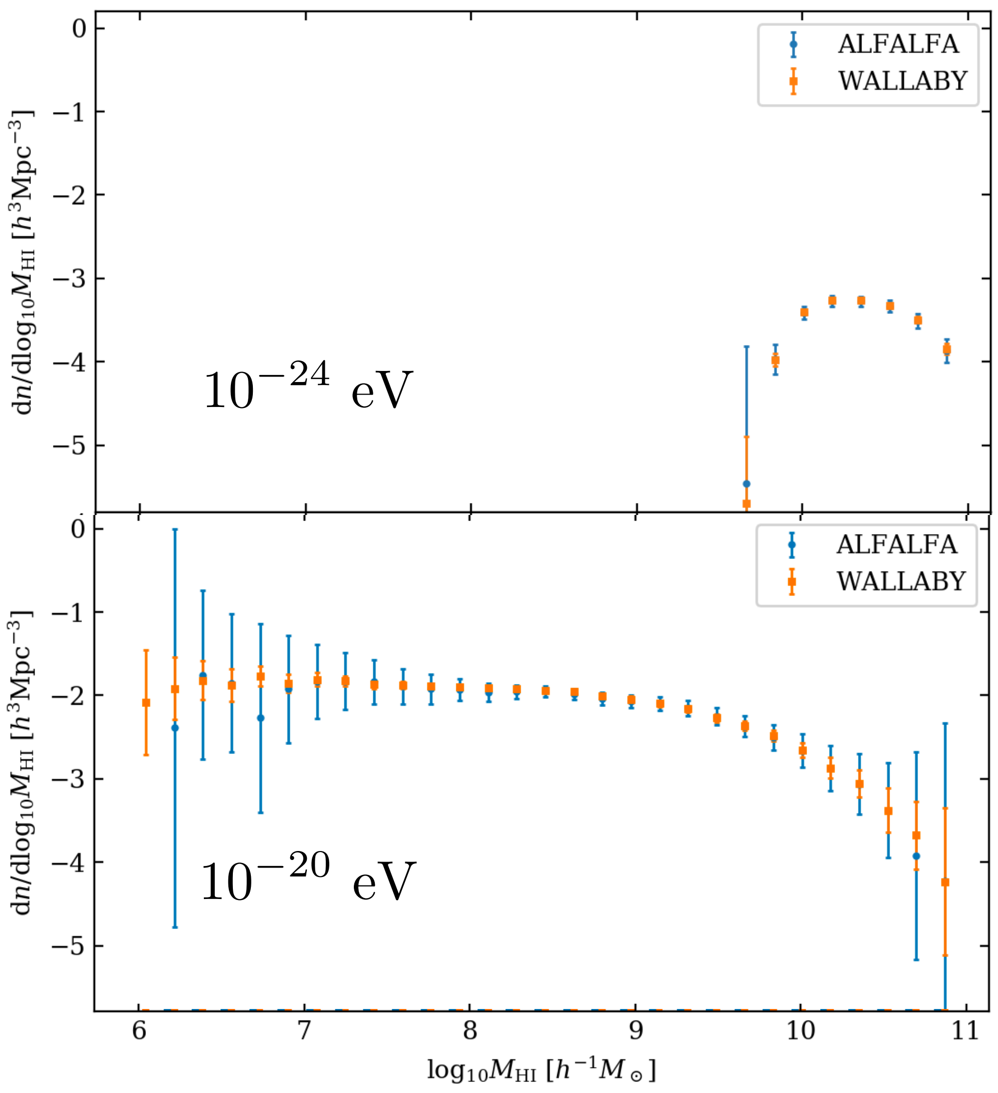
Figure/survey params from T. Westmeier

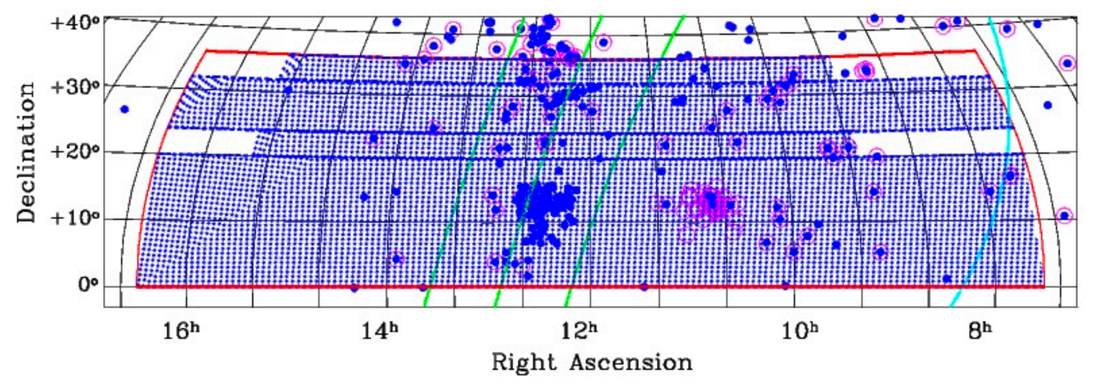
1. ALFALFA (Arecibo), done—
   - ✳ 30,000 extragalactic HI line sources out to z~0.06,
2. Wallaby (SKA pathfinder, 36 X 12 m)
   - ✳ 500,000 sources expected

Simulations:

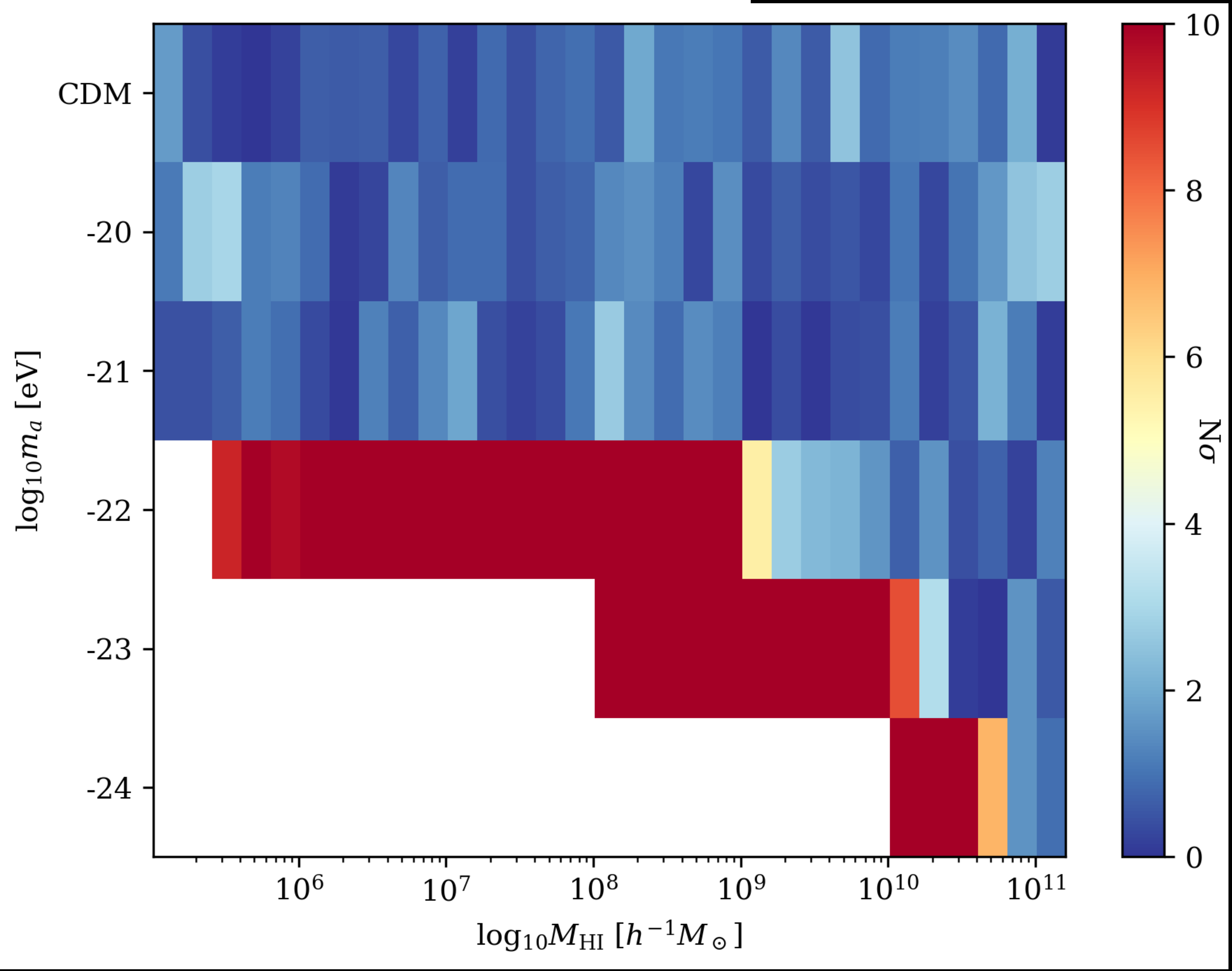
1) Specify survey volume — draw from mass function
2) Use semi-analytic $M_{\rm halo} \rightarrow M_{\rm HI}$ conversion
3) Random LOS, geometric, realization
4) Mock observation

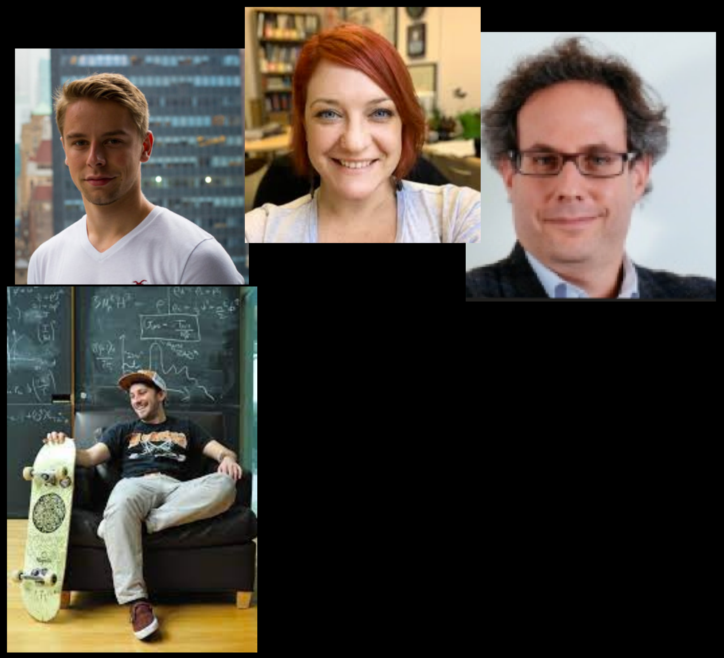
Extra-galactic HI surveys

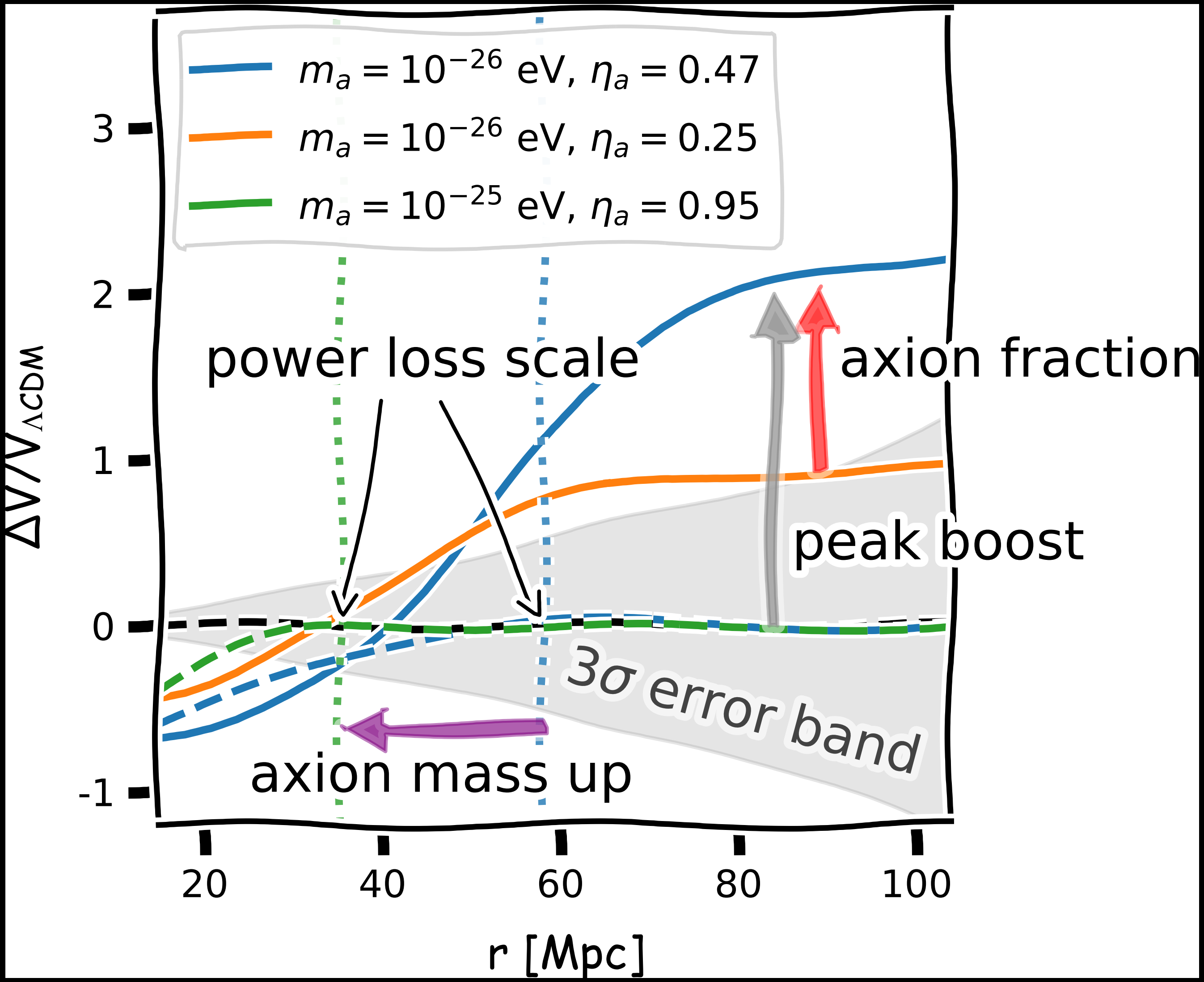




Extra-galactic HI surveys





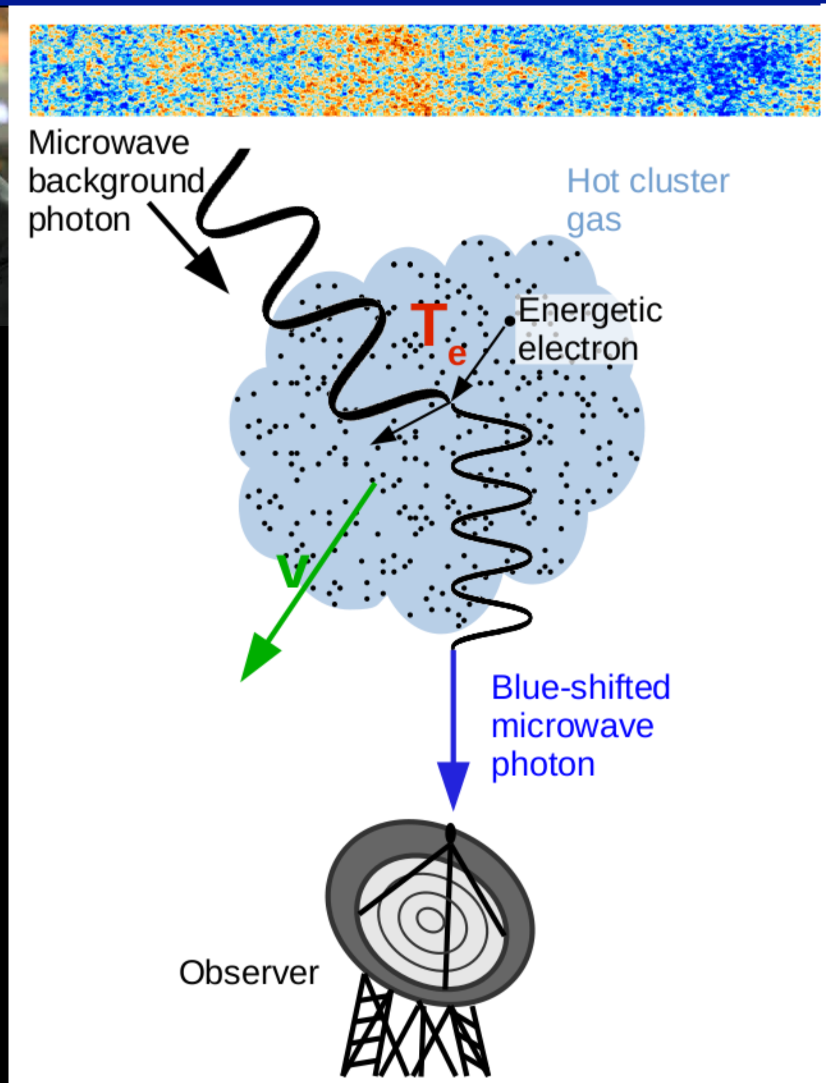


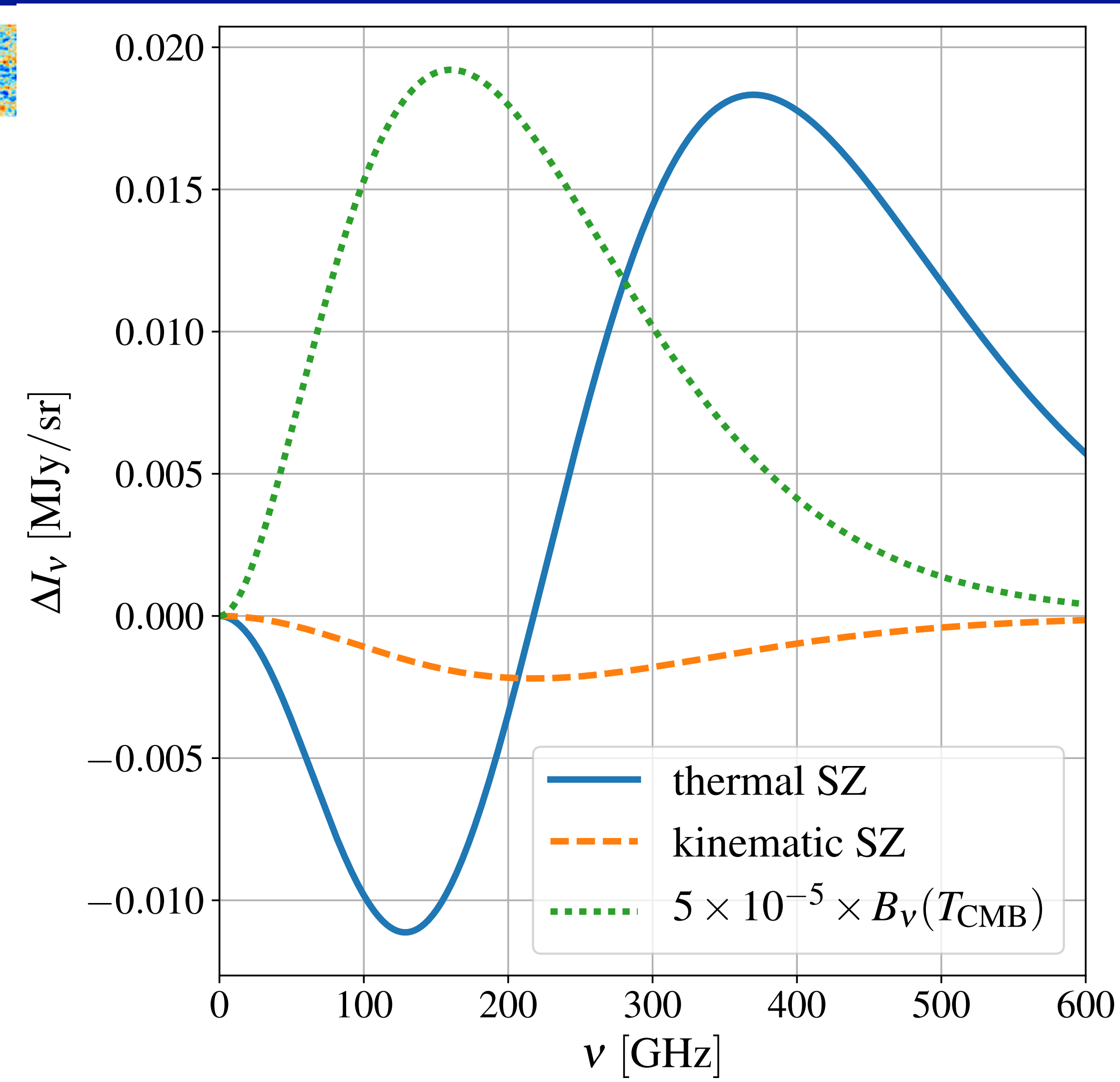
ULAs and the kinetic SZ effect

arXiv:2109.13268

G. Farren, D. Grin, et al…..

SUNYAEV ZEL'DOVICH EFFECT





Soergel (2017)

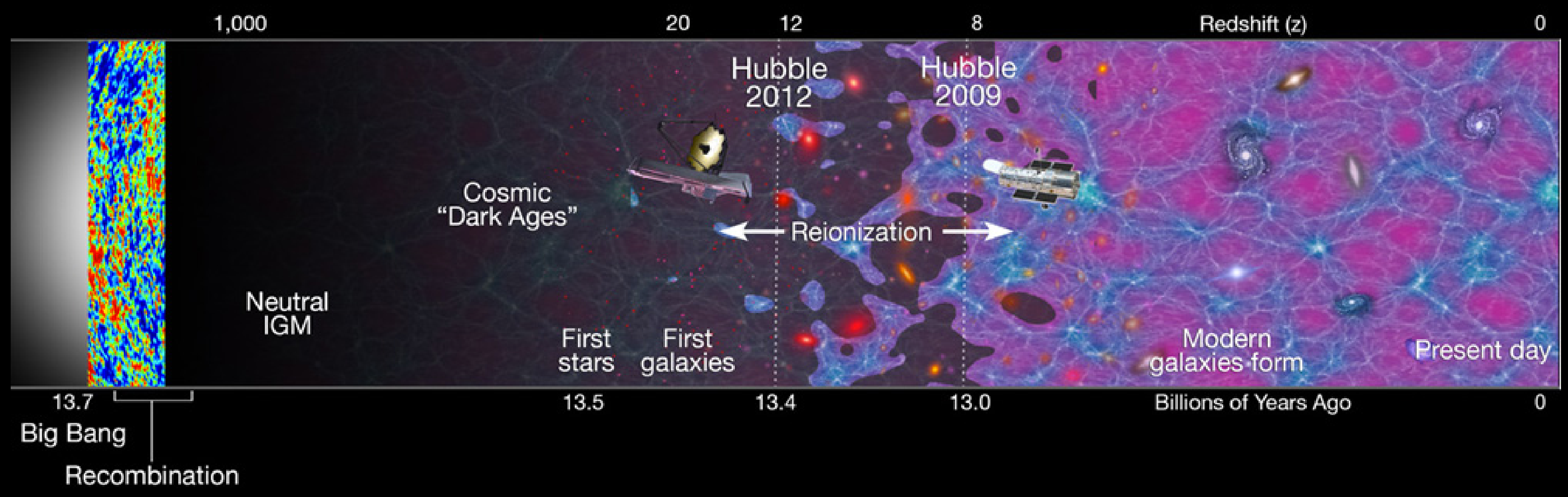
- Bulk flow contribution is kinetic (or kinematic) SZ effect:

$$\frac{\Delta T_{\mathrm{kSZ}}}{T_{\mathrm{CMB}}} = -\sigma_T \int dl\, n_e \frac{\hat{\mathbf{r}} \cdot \mathbf{v}_e}{c} \simeq -\tau \frac{\mathrm{v}_{\mathrm{los}}}{c}$$

$$\Delta T_{\mathrm{kSZ}} \approx 10\ \mu\mathrm{K}$$

Sunyaev ++ (1980)

OSTRIKER-VISHNIAC EFFECT (SPECIAL CASE OF KSZ)



- Second-order contributions to power spectra from reionization

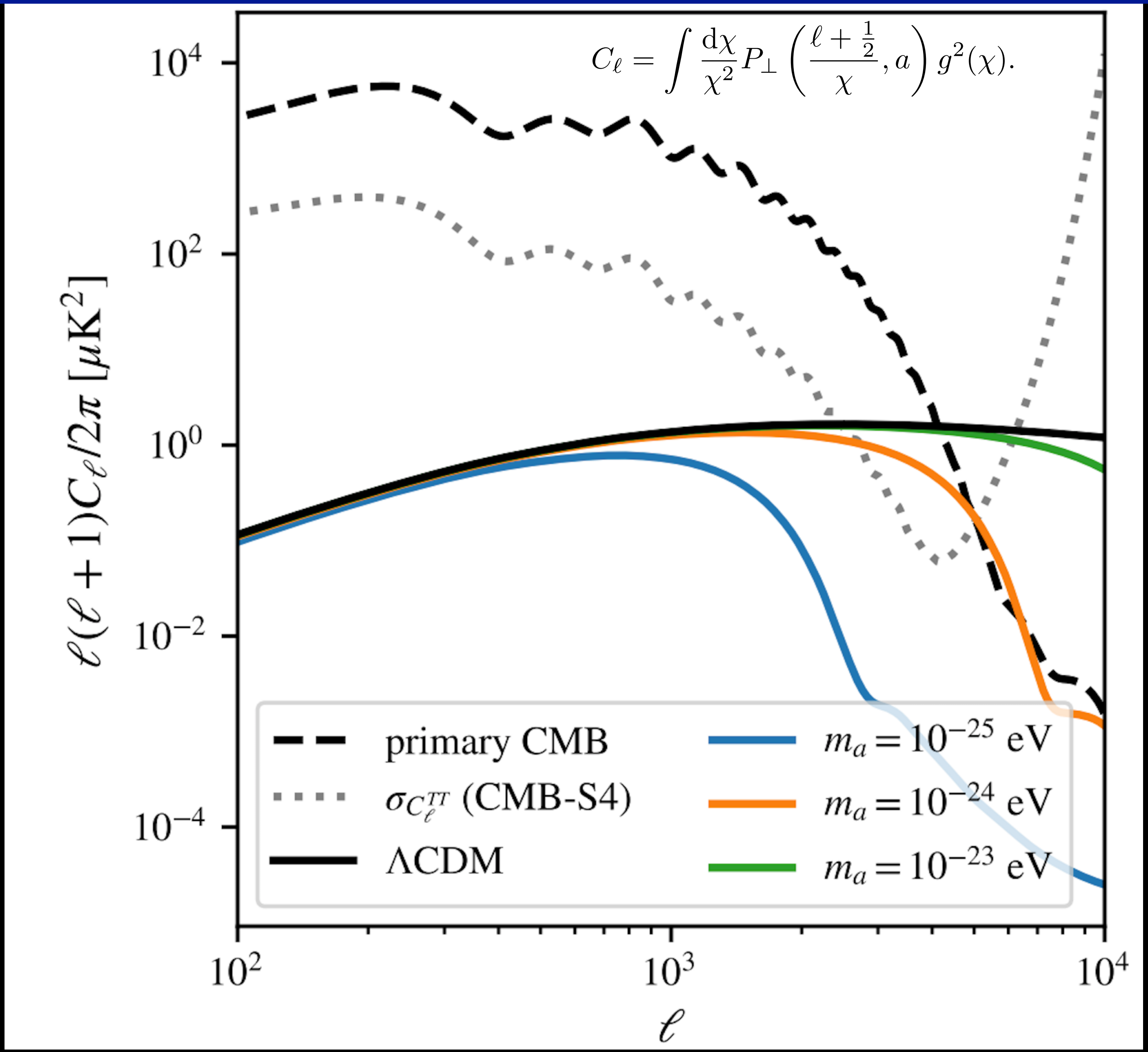
$$T \propto \overline{n}_e v \delta$$

$$\frac{dv}{dt} \propto -\nabla\Phi \propto \delta \rightarrow v \propto \delta$$

$$T \propto \overline{n}_e \delta^2$$

$$C_l^{\mathrm{TT}} \propto P^2(k)$$

OSTRIKER-VISHNIAC EFFECT (SPECIAL CASE OF KSZ)

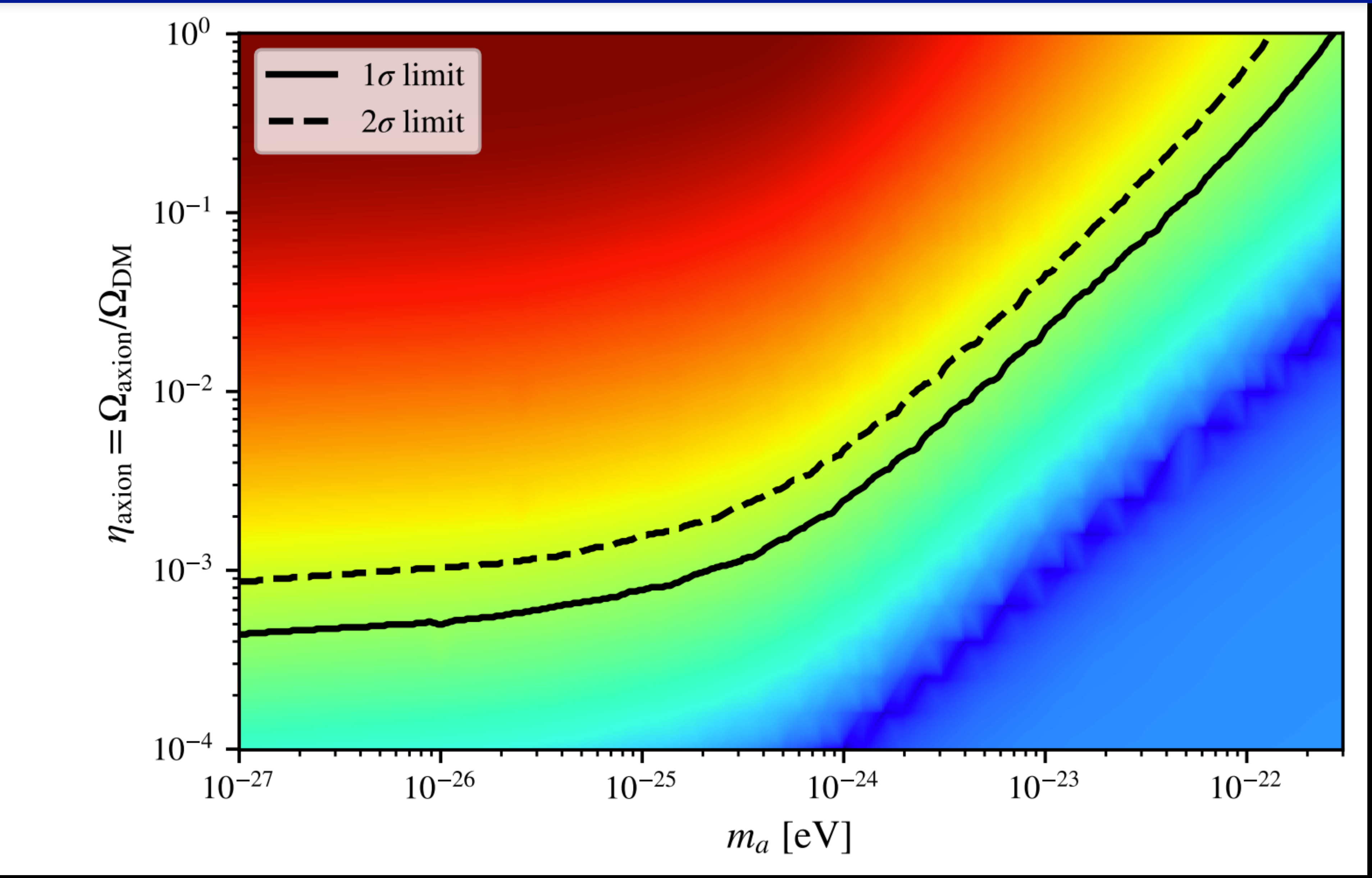


Ostriker+ (1986), Jaffe+ (1997)

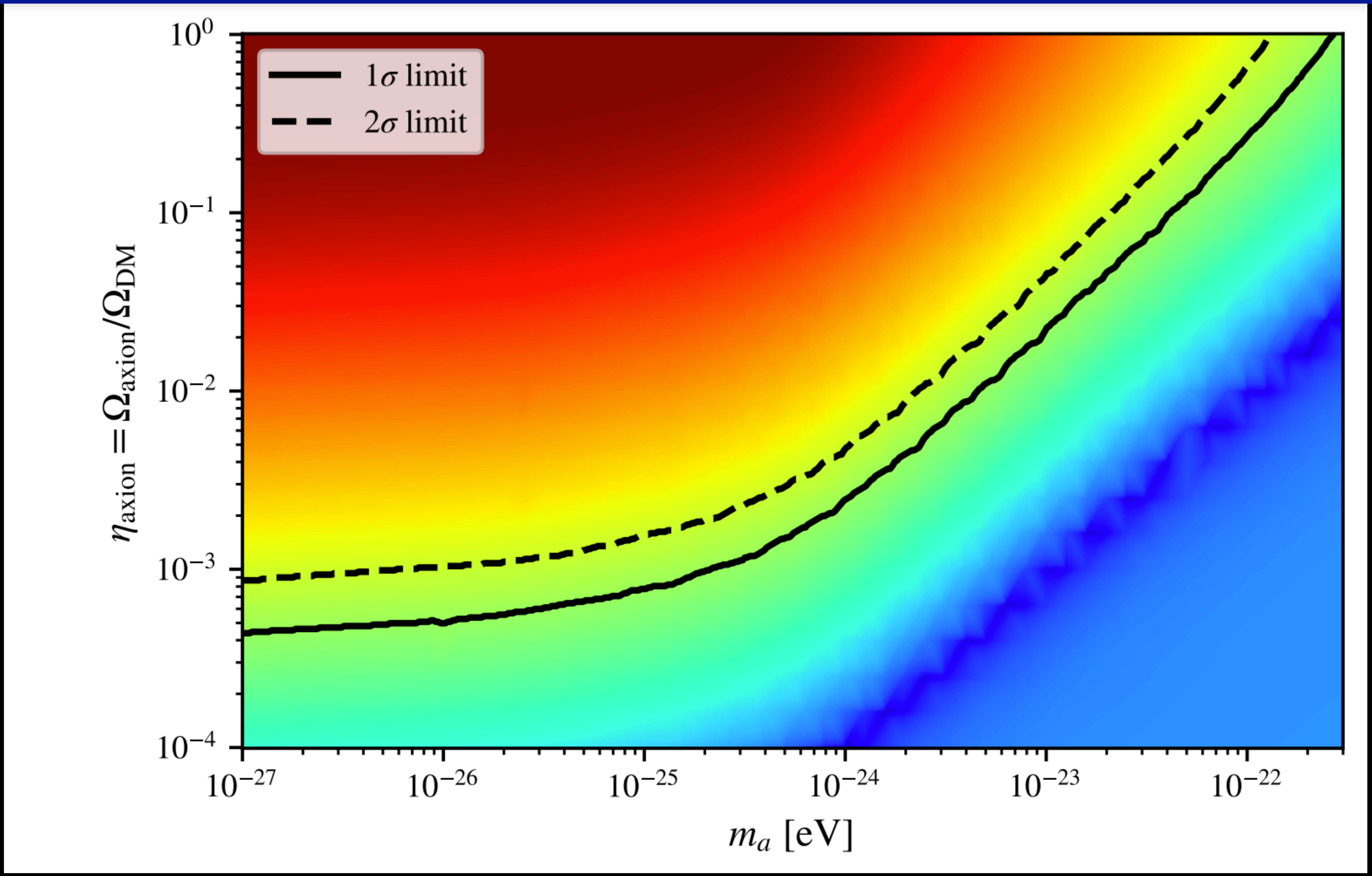
$$P_\perp(k,a) = \frac{a^2H^2(a)}{8\pi^2}\int_0^\infty \mathrm{d}y \int_{-1}^{1} \mathrm{d}x P_0(k\sqrt{1-2xy+y^2})P_0(ky)\frac{\mathcal{G}^2(k\sqrt{1-2xy+y^2},a)}{\mathcal{G}_0^2(k\sqrt{1-2xy+y^2})}\frac{\mathcal{G}^2(ky,a)}{\mathcal{G}_0^2(ky)}$$

$$\mathcal{G} = \frac{\delta_m(k,a)}{\delta_m(k,a=1)}$$

OSTRIKER-VISHNIAC EFFECT (SPECIAL CASE OF KSZ)



Ostriker-Vishniac effect (special case of kSZ)



- Challenging to robustly detect ULA effect, even with future generation experiments
- SOLUTION —**LOOK NEAR HEAVIEST COSMIC STRUCTURES**

kSZ — Cluster pairwise velocity dispersions

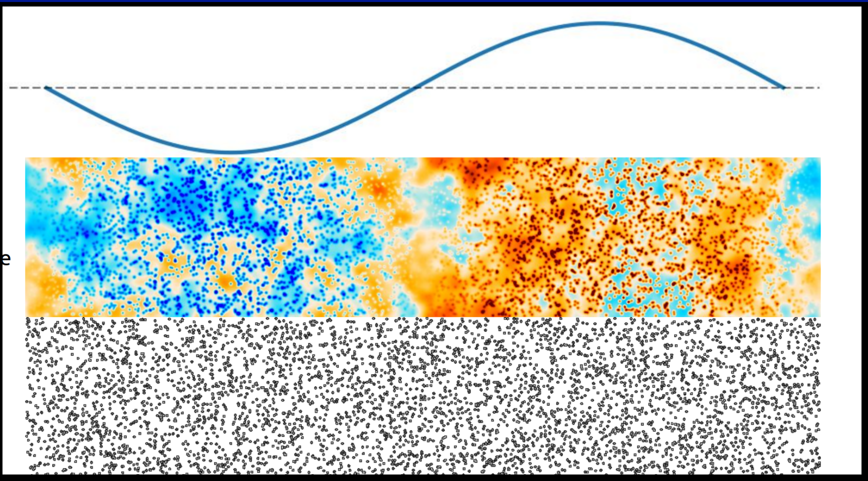
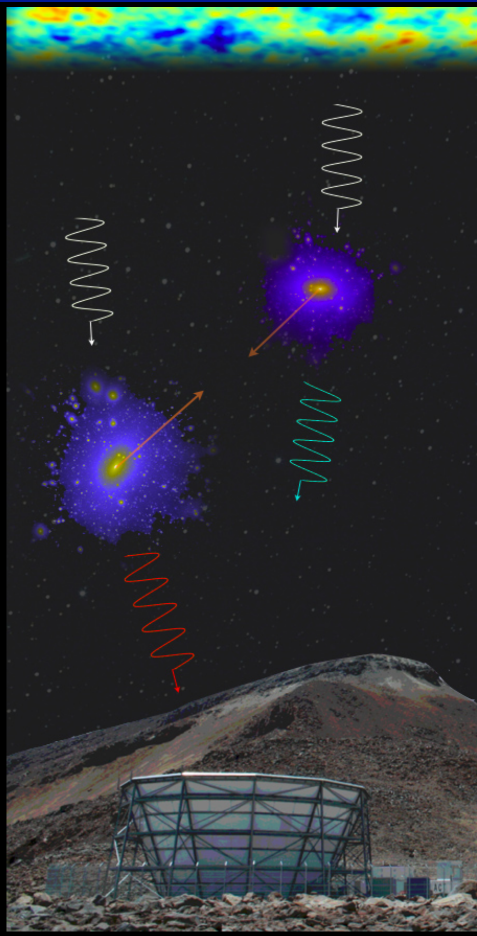


Figure from Madhavacheril…

Sunyaev ++ (1980)
Ostriker+ (1986), Jaffe+ (1997), Sheth ++ (2001), Bhattacharya ++ (2007), Hand ++ (2012), Mueller + (2014)



- Temperature change towards cluster due to local flow:

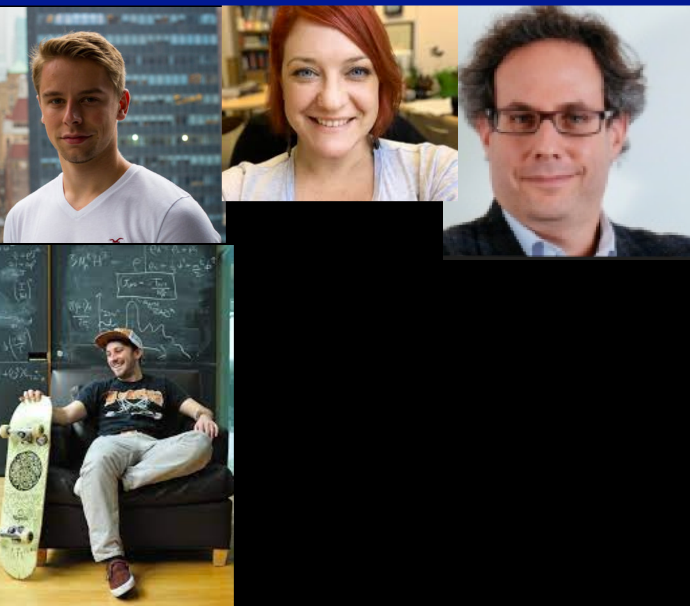
$$\frac{\Delta T}{T_{\rm CMB}}(\hat{\mathbf{n}}_i) = -\tau_{e,i}\frac{\hat{\mathbf{r}}_i \cdot \mathbf{v}_i}{c}\,.$$

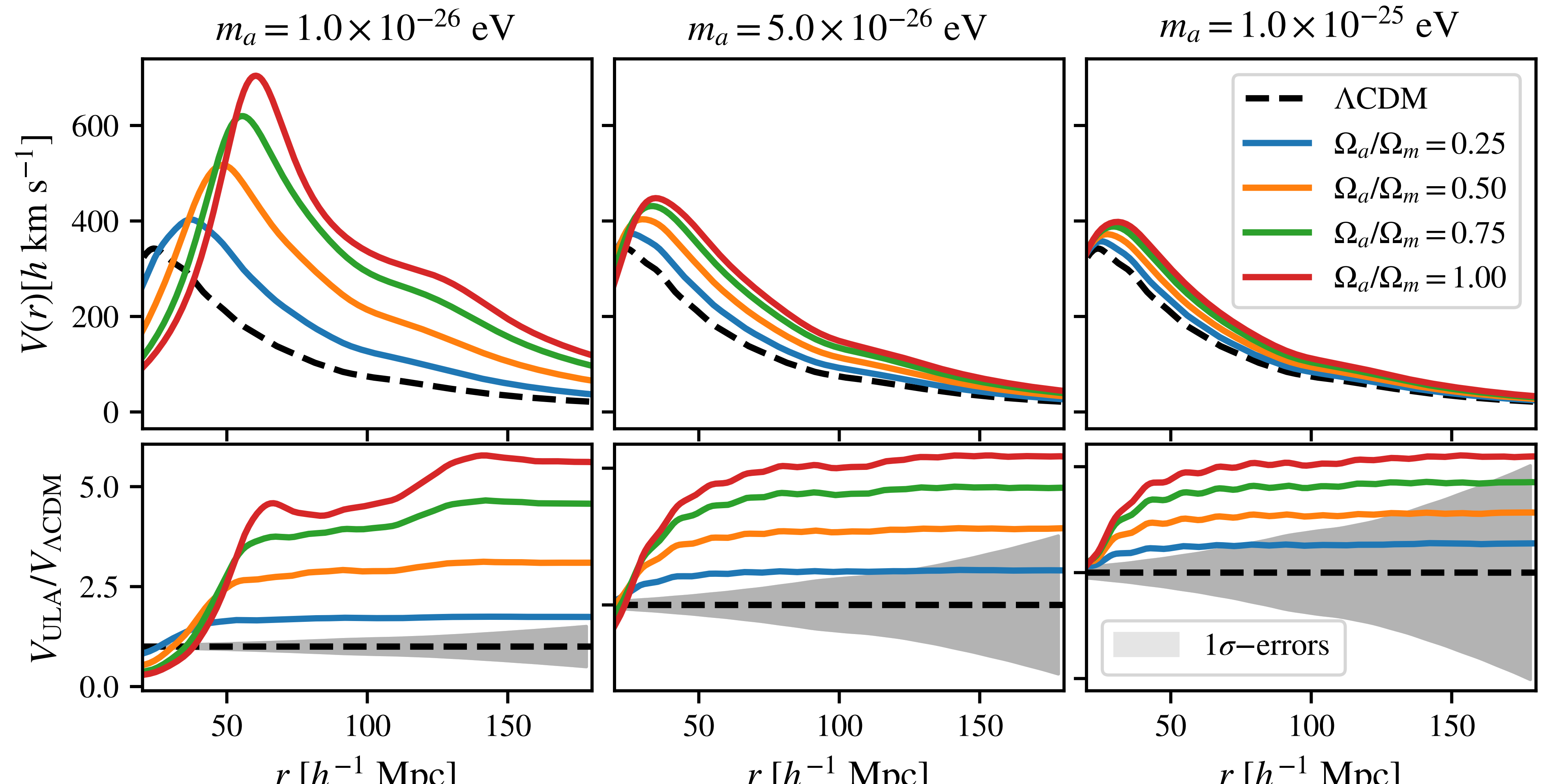
$$\Delta T_{\rm kSZ} \approx 10\ \mu{\rm K}$$

- Estimate assuming homogeneous optical depth:

$$\hat{T}_{\rm pkSZ}(r) = -\frac{\sum_{i<j,r}\left[T(\hat{\mathbf{n}}_i) - T(\hat{\mathbf{n}}_j)\right]c_{ij}}{\sum_{i<j,r} c_{ij}^2} = \bar{\tau}_e\frac{v_{12}(r)}{c}T_{\rm CMB}$$

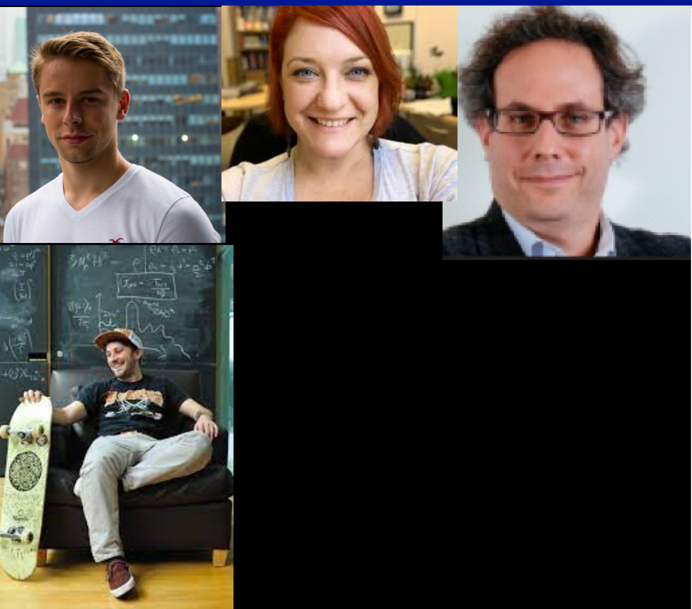
kSZ — effect of ULAs

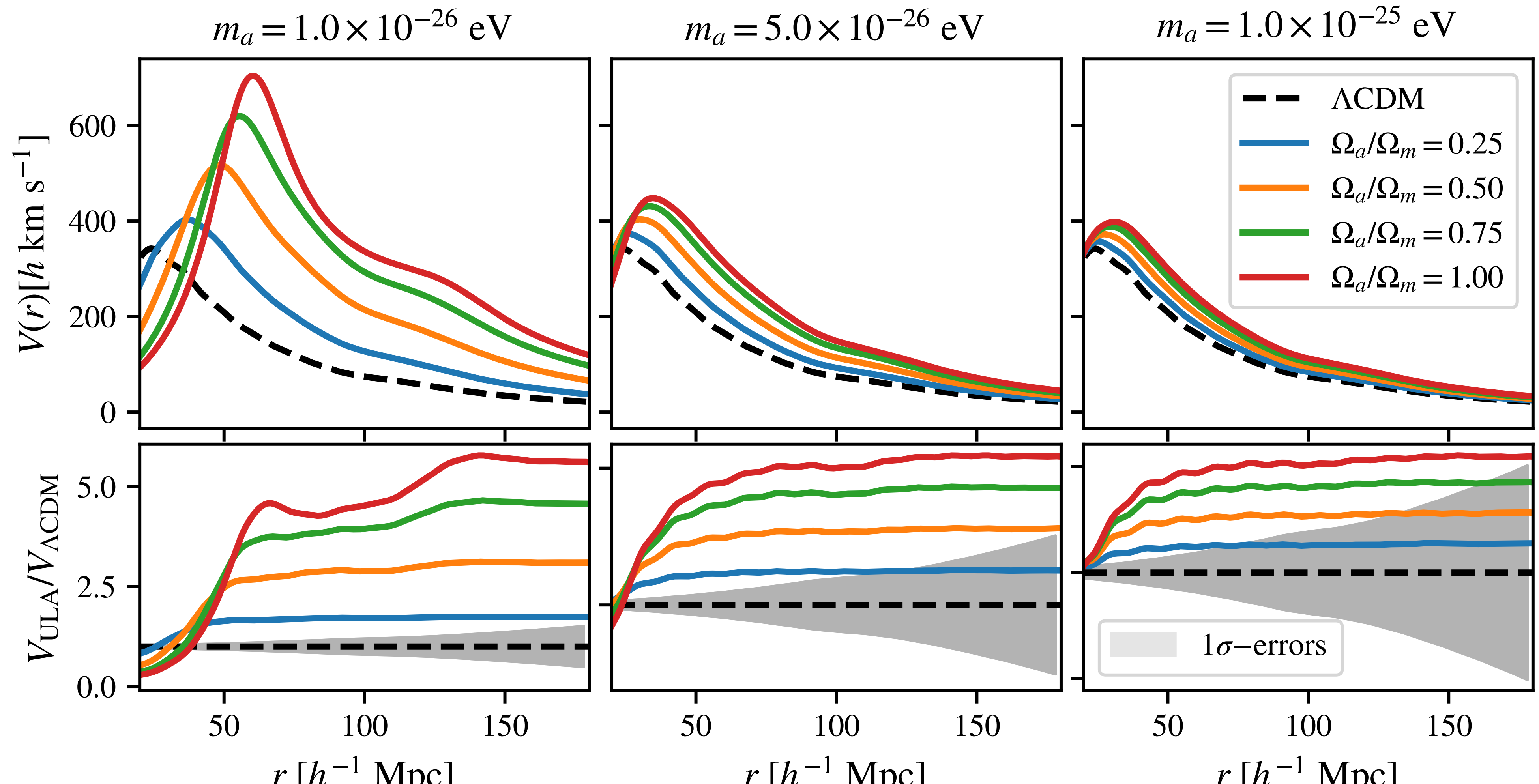




$$v_{12}(r) \propto \int d\ln k \, \langle b(k, M, a) \rangle \, \Delta^2(k, a) \frac{d \ln \delta(k, a)}{dt} W(kr)$$

kSZ — effect of ULAs

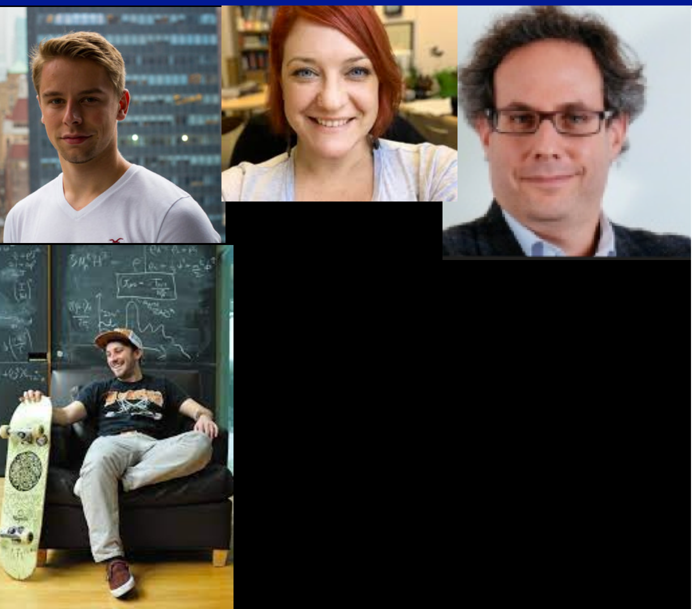


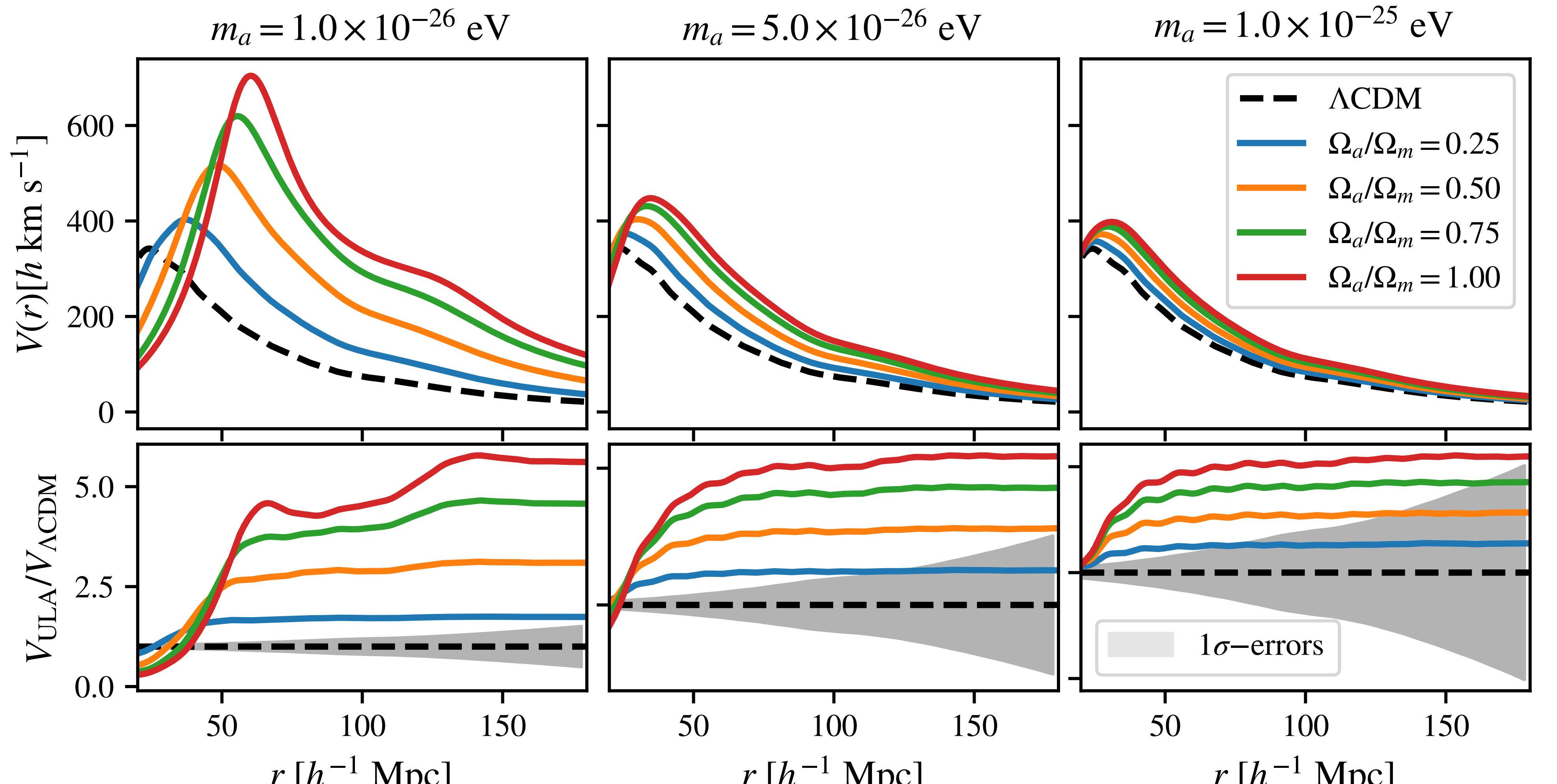


Halo bias

$$v_{12}(r) \propto \int d\ln k \, \langle b(k, M, a) \rangle \, \Delta^2(k, a) \frac{d \ln \delta(k, a)}{dt} W(kr)$$

kSZ — effect of ULAs

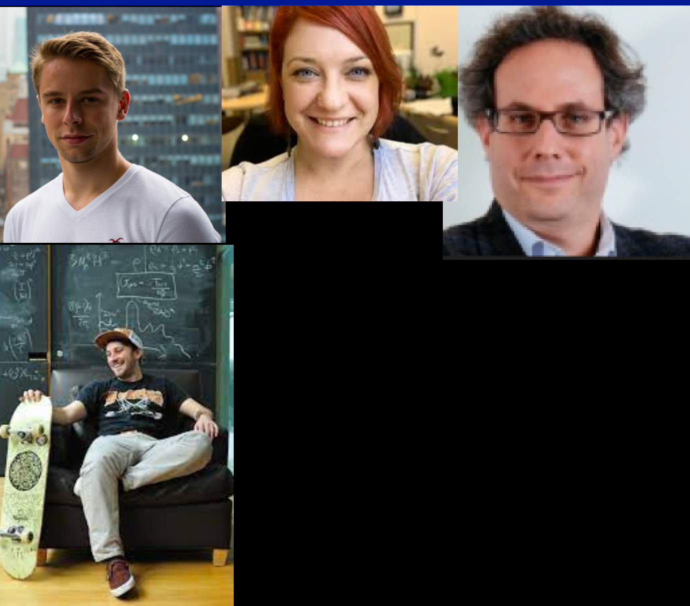


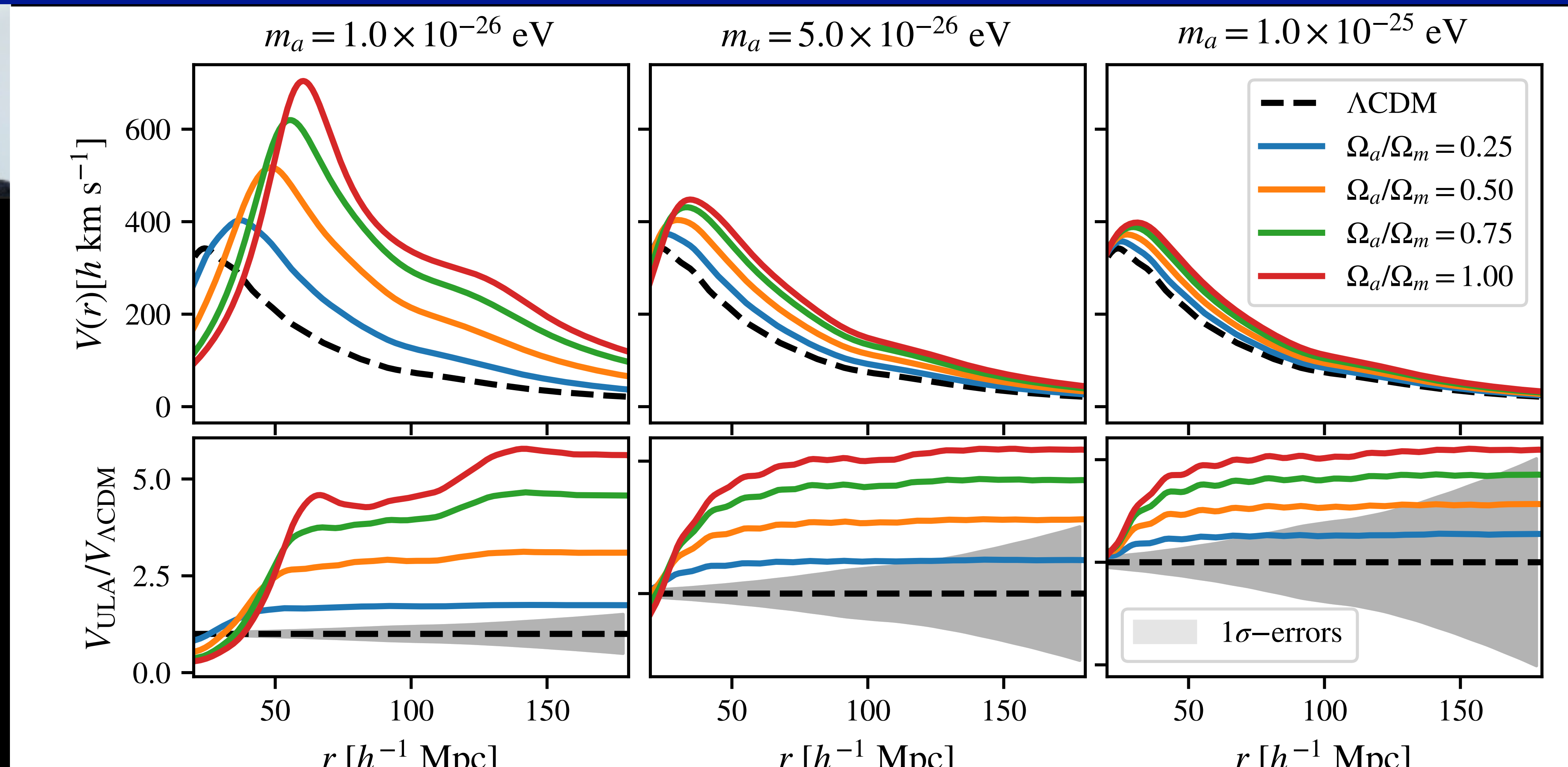


Typical fluct. on scale k

$$v_{12}(r) \propto \int d\ln k \,\langle b(k,M,a)\rangle\, \Delta^2(k,a)\, \frac{d\ln\delta(k,a)}{dt} W(kr)$$

kSZ — effect of ULAs





Geometric window

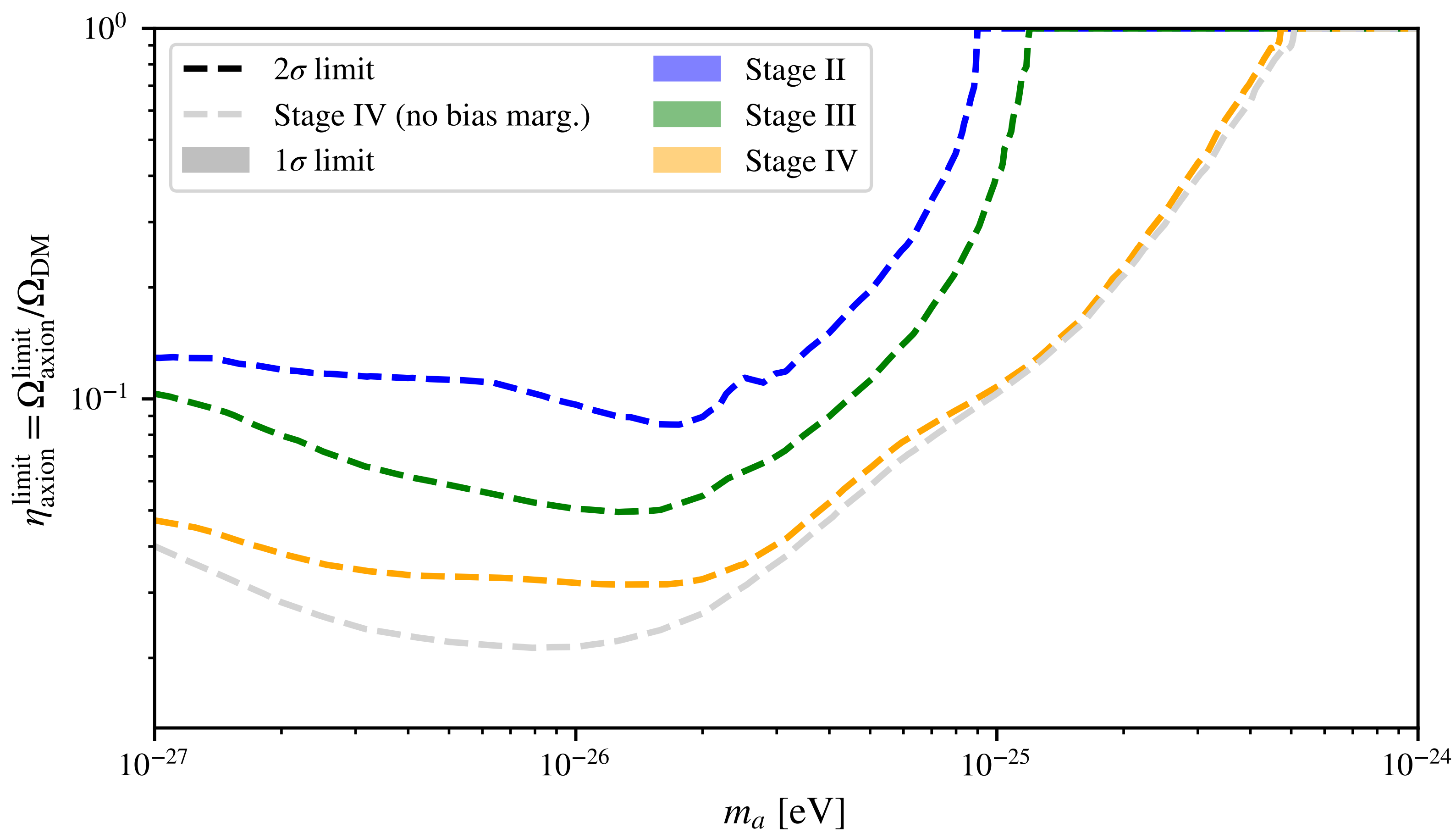
$$v_{12}(r) \propto \int d\ln k\, \langle b(k,M,a)\rangle\, \Delta^2(k,a)\, \frac{d\ln\delta(k,a)}{dt} W(kr)$$

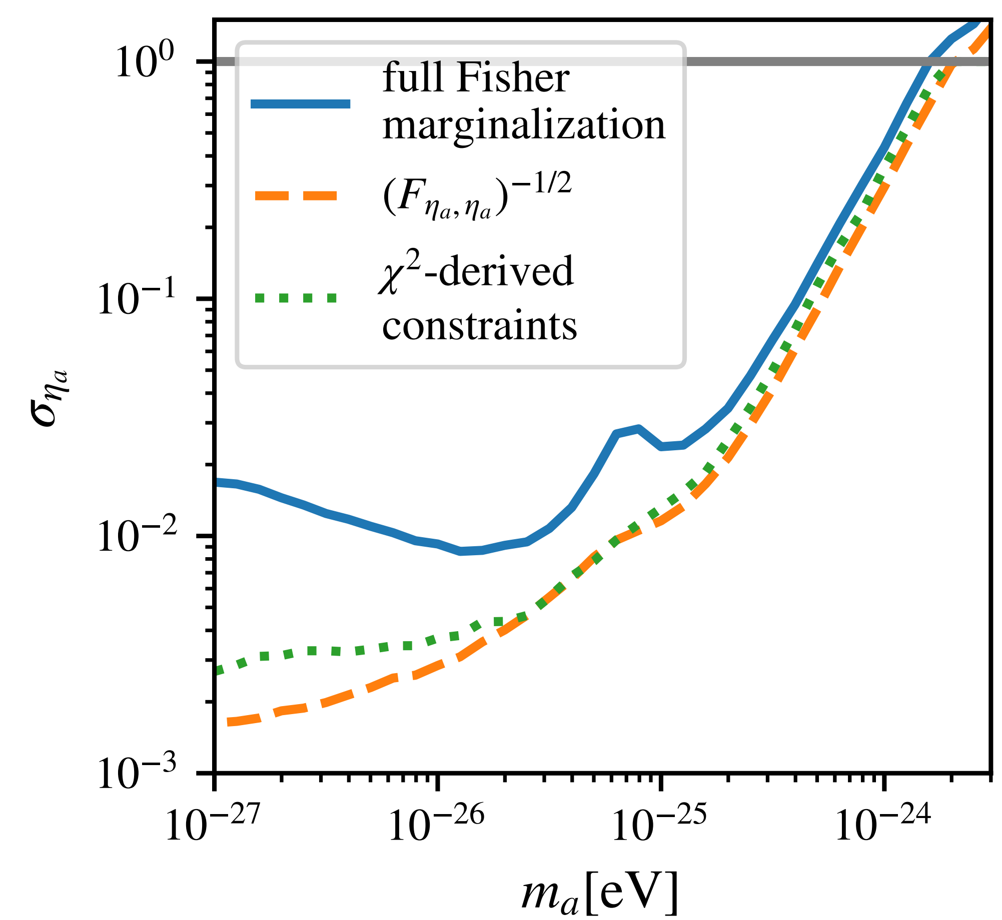
COVARIANCE, NOISE, AND FORECASTING

CMB-S4
Next Generation CMB Experiment

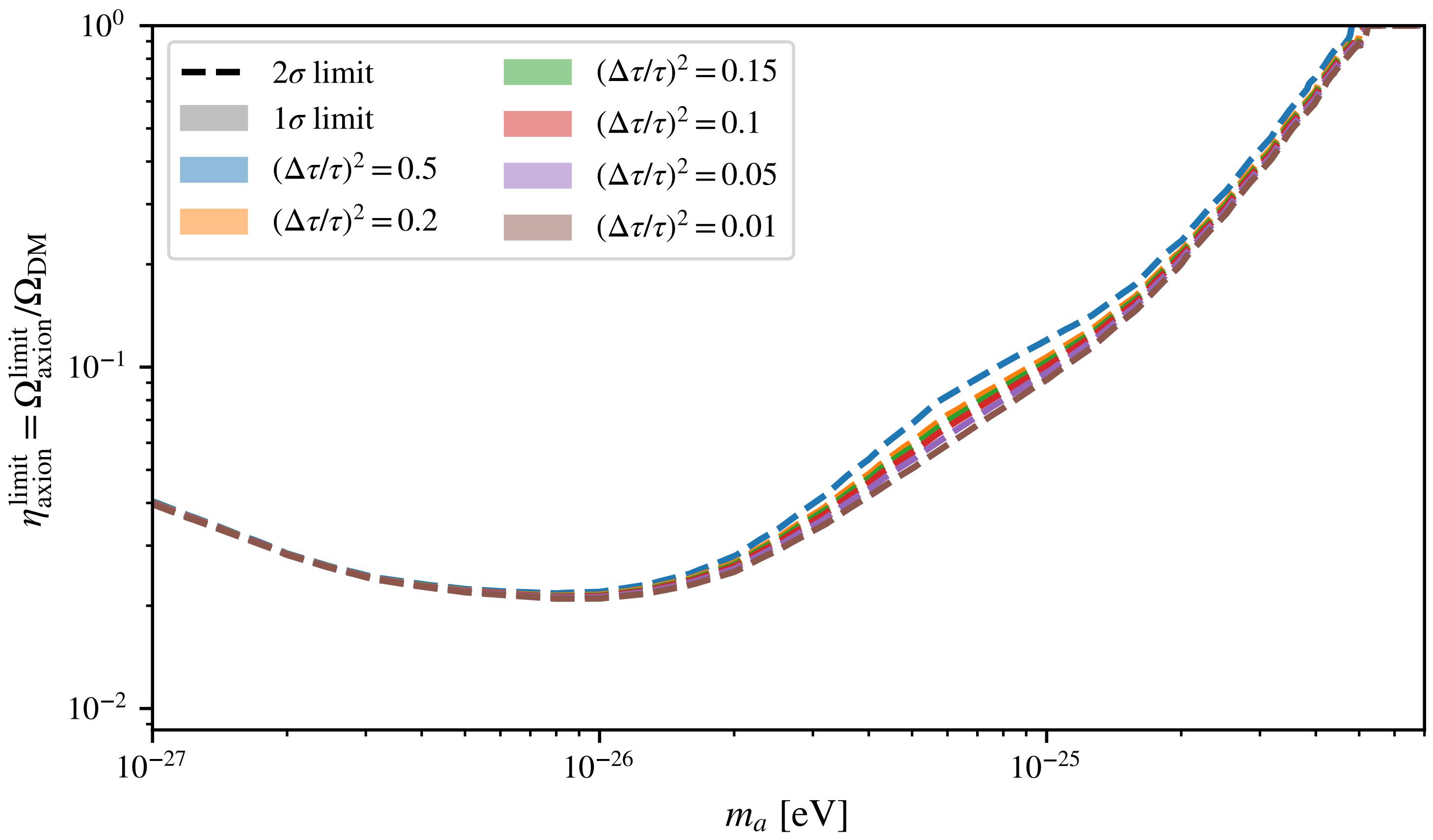
$$F_{\mu\nu} = \sum_i^{N_z} \sum_{j,k}^{N_r} \frac{\partial v(r_j, z_i)}{\partial p_\mu} C^{-1}(r_j, r_k, z_i) \frac{\partial v(r_k, z_i)}{\partial p_\nu}$$

		Survey Stage		
Survey	Parameters	II	III	IV
CMB	$\Delta T_{\rm instr}$ (μKarcmin)	20	7	1
Galaxy	$z_{\rm min}$	0.1	0.1	0.1
	$z_{\rm max}$	0.4	0.4	0.6
	No. of z bins, N_z	3	3	5
	$M_{\rm min}$ ($10^{14} M_\odot$)	1	1	0.6
Overlap	Area (1000 sq. deg.)	4	6	10





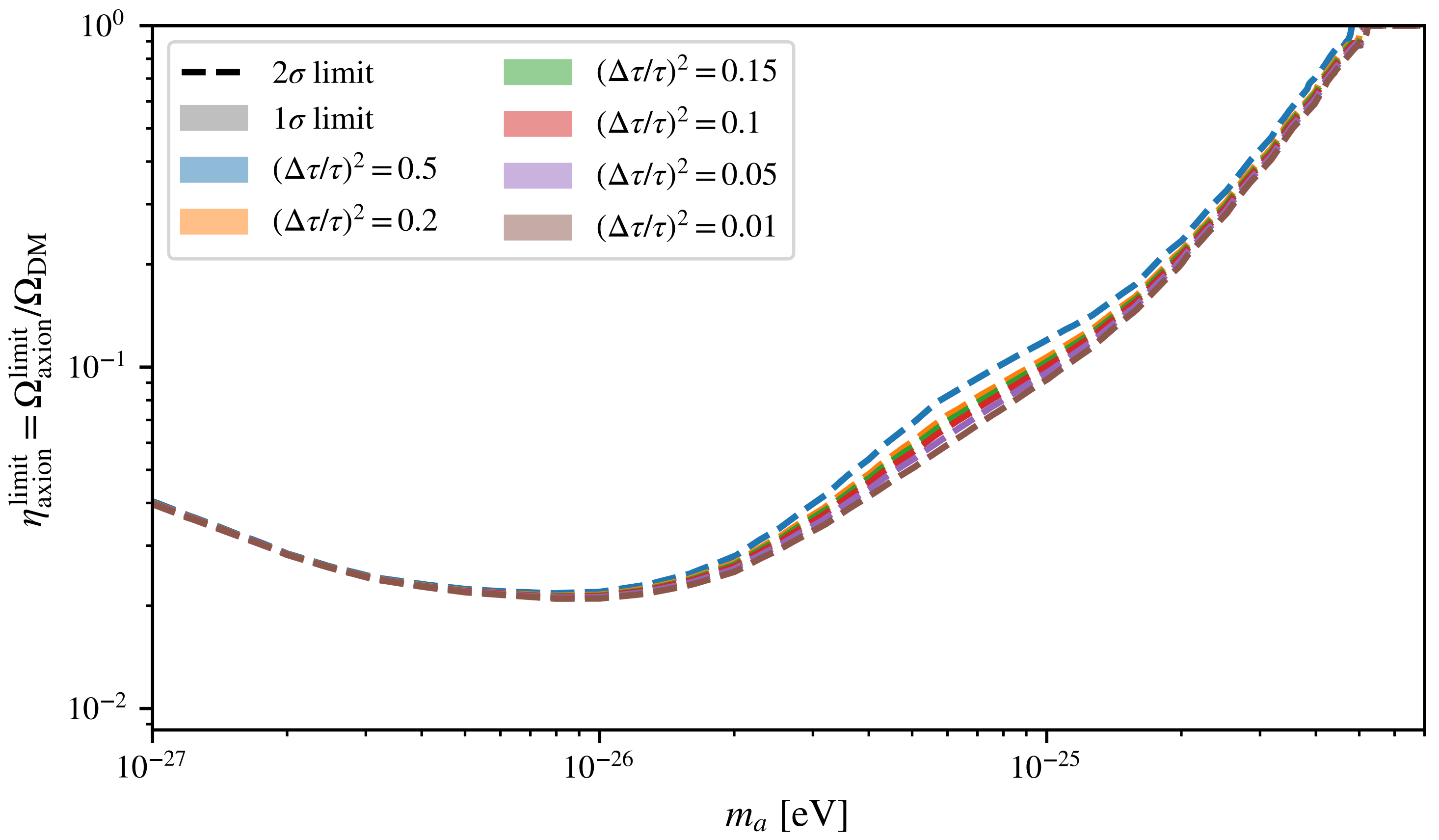
SYSTEMATIC UNCERTAINTIES



$$\frac{\Delta T}{T_{\rm CMB}}(\hat{\mathbf{n}}_i) = -\tau_{e,i}\frac{\hat{\mathbf{r}}_i \cdot \mathbf{v}_i}{c}\,.$$

$$\mathcal{B} \to b(z)\mathcal{B}$$

SYSTEMATIC UNCERTAINTIES

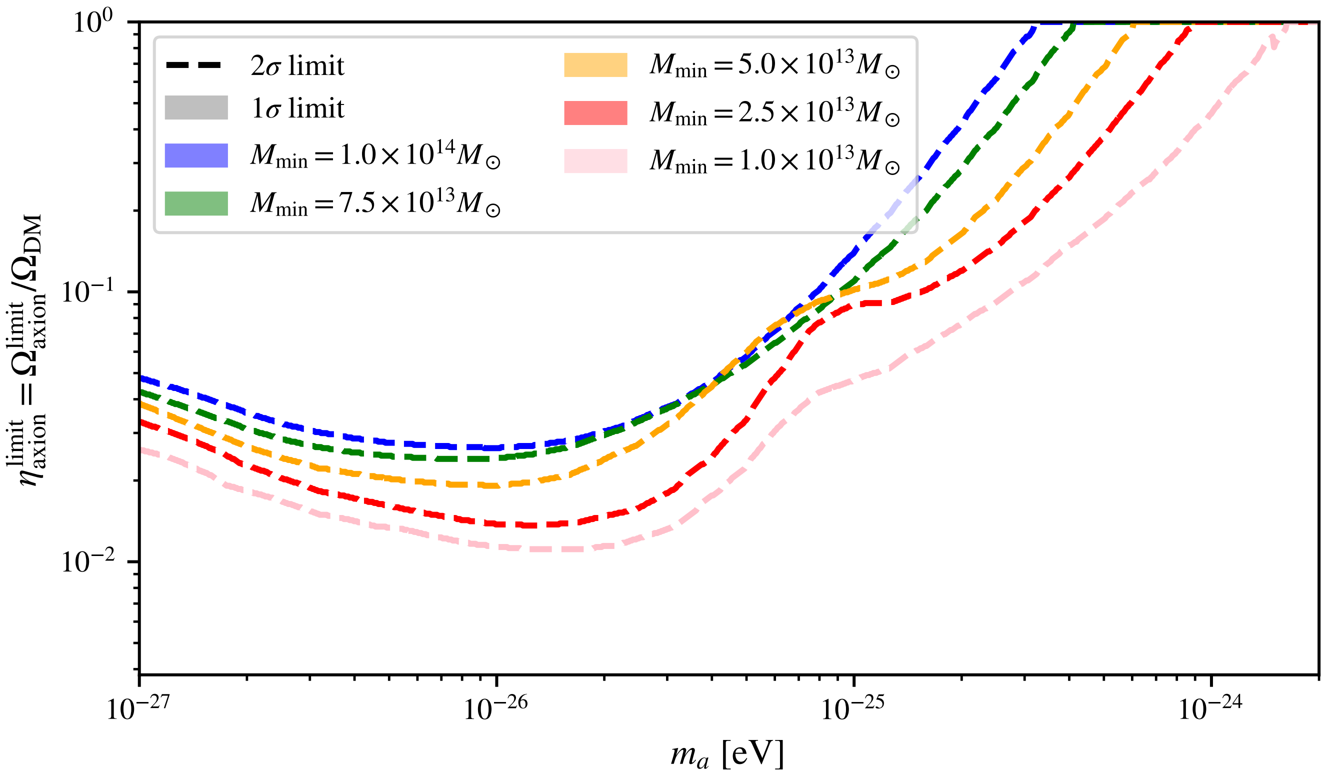


Cluster astrophysics

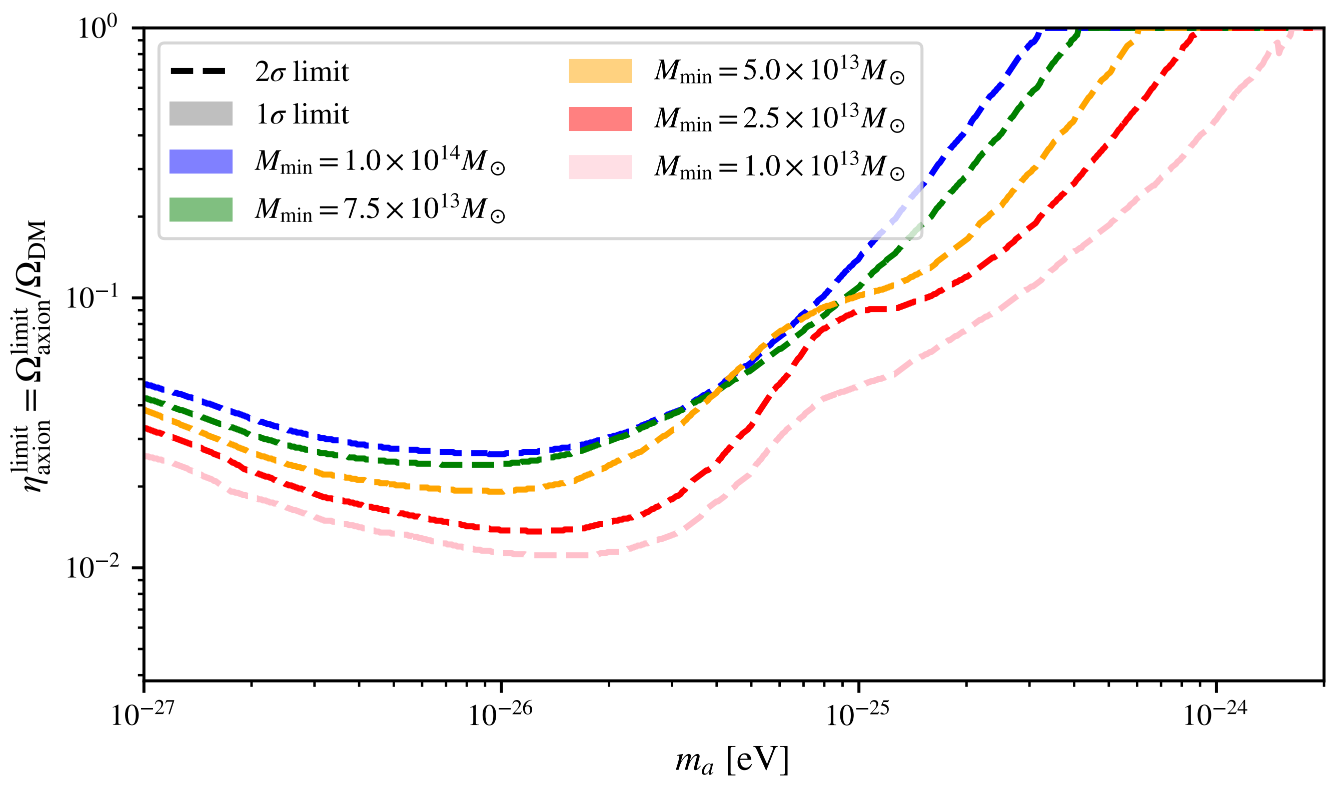
$$\frac{\Delta T}{T_{\rm CMB}}(\hat{\mathbf{n}}_i) = -\tau_{e,i}\frac{\hat{\mathbf{r}}_i \cdot \mathbf{v}_i}{c}\,.$$

Galaxy bias: $\mathcal{B} \to b(z)\mathcal{B}$

SYSTEMATIC UNCERTAINTIES



SYSTEMATIC UNCERTAINTIES



Halo Mass

Take-home ULA cosmology message

0.5% level fractional ULA abundances accessible to next generation of observations, maybe better!

Numerology of fundamental constants

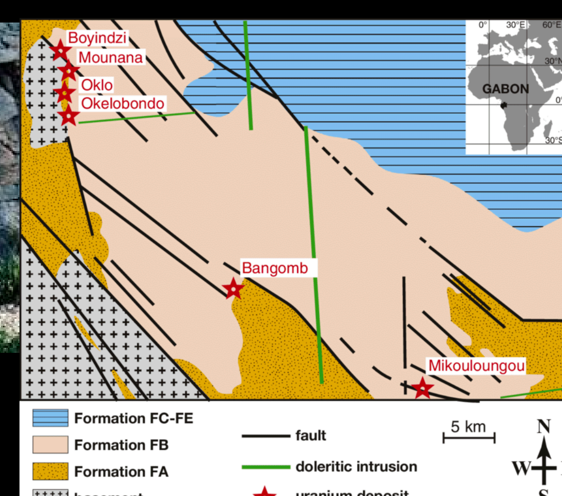
Dirac, Teller, Gamow, Dicke, and others ….

$$\frac{3e^4}{G m_p m_e^2 c^3} = T_{\mathrm{universe}}$$

What if always true?

$$G \propto 1/t \text{ or } e \propto t^{1/4} \text{ or } c \propto t^{-1/3} \text{ or } m_e \propto t^{-1/2} \text{ or } m_p \propto t^{-1}$$

Plants seed of interesting idea….



The simplest theory of varying α

- Simplest theory with varying $\alpha = \dfrac{e^2}{\hbar c} \simeq \dfrac{1}{137}$ but otherwise behaves like EM, charge conserved

ζ is a plasma fudge factor, M, energy scale of new physics

$$\ddot{\varphi} + K\dot{\varphi} + m^2\varphi = \frac{e^{-\varphi}\left(\left|\vec{E}\right|^2 - \left|\vec{B}\right|^2\right)}{8\pi\omega} = \frac{e^{-\varphi}\zeta\rho_{\mathrm{m}}}{8\pi\omega}$$

$$\omega \equiv \frac{M^2}{M_{\mathrm{pl}}^2}$$

Modified Maxwell Equations

$$\nabla \cdot \left(e^{-2\varphi}\vec{E}\right) = 4\pi e_0 n_e(\vec{x}) \qquad \nabla \cdot \left(e^{-2\varphi}\vec{E}\right) = 4\pi e_0 n_e(\vec{x}) \qquad \nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{d\mathbf{B}}{dt} \qquad \nabla \times \left(e^{-2\varphi}\mathbf{B}\right) + \frac{1}{c}\frac{d}{dt}\left(e^{-2\varphi}\mathbf{E}\right) = \frac{4\pi\vec{J}}{c}$$

- Bekenstein, Sandvik, Barrow, Magueijio, and much followup by Mota, Martins, Vucetich, Kraiselburd, Livio, and others….

The simplest theory of varying α

- Simplest theory with varying $\alpha = \frac{e^2}{\hbar c} \simeq \frac{1}{137}$ but otherwise behaves like EM, charge conserved

ζ is a plasma fudge factor, M, energy scale of new physics

$$\ddot{\varphi} + K\dot{\varphi} + m^2\varphi = \frac{e^{-\varphi}\left(\left|\vec{E}\right|^2 - \left|\vec{B}\right|^2\right)}{8\pi\omega} = \frac{e^{-\varphi}\zeta\rho_{\mathrm{m}}}{8\pi\omega}$$

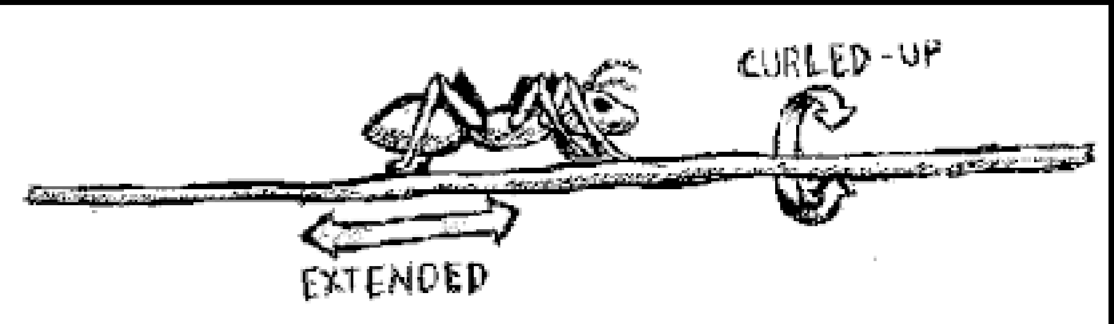
$$\omega \equiv \frac{M^2}{M_{\mathrm{pl}}^2}$$

Modified Maxwell Equations

$$\nabla \cdot \left(e^{-2\varphi}\vec{E}\right) = 4\pi e_0 n_e(\vec{x}) \qquad \nabla \cdot \left(e^{-2\varphi}\vec{E}\right) = 4\pi e_0 n_e(\vec{x}) \qquad \nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{d\mathbf{B}}{dt} \qquad \nabla \times \left(e^{-2\varphi}\mathbf{B}\right) + \frac{1}{c}\frac{d}{dt}\left(e^{-2\varphi}\mathbf{E}\right) = \frac{4\pi\vec{J}}{c}$$

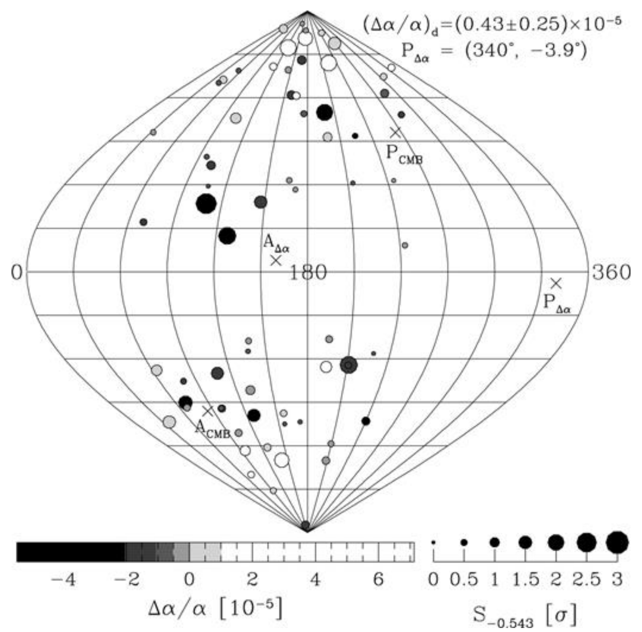
String-inspired models (runaway dilation)



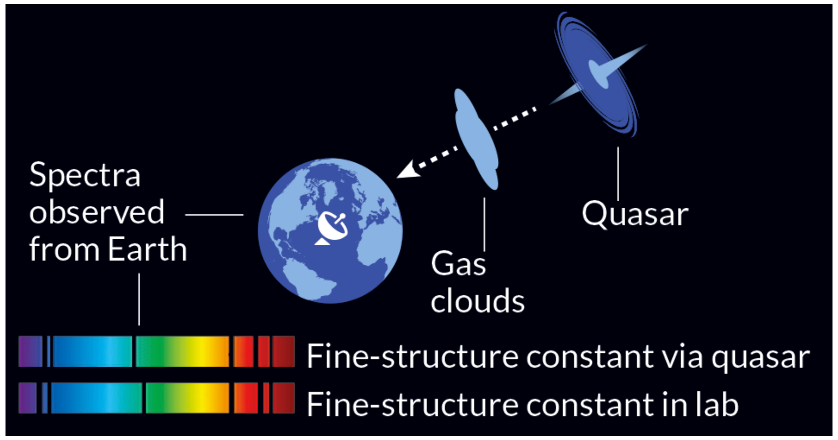
Extra-dimensions (Kaluza-Klein theories)

$$\ddot{\psi} + 3H\dot{\psi} + \frac{dV}{d\psi} + \frac{\omega'(\psi)\dot{\psi}^2}{2\omega(\psi)} = -\frac{B_f'(\psi)}{\omega(\psi)} e^{-B_f(\psi)} \zeta_m G \rho_m,$$

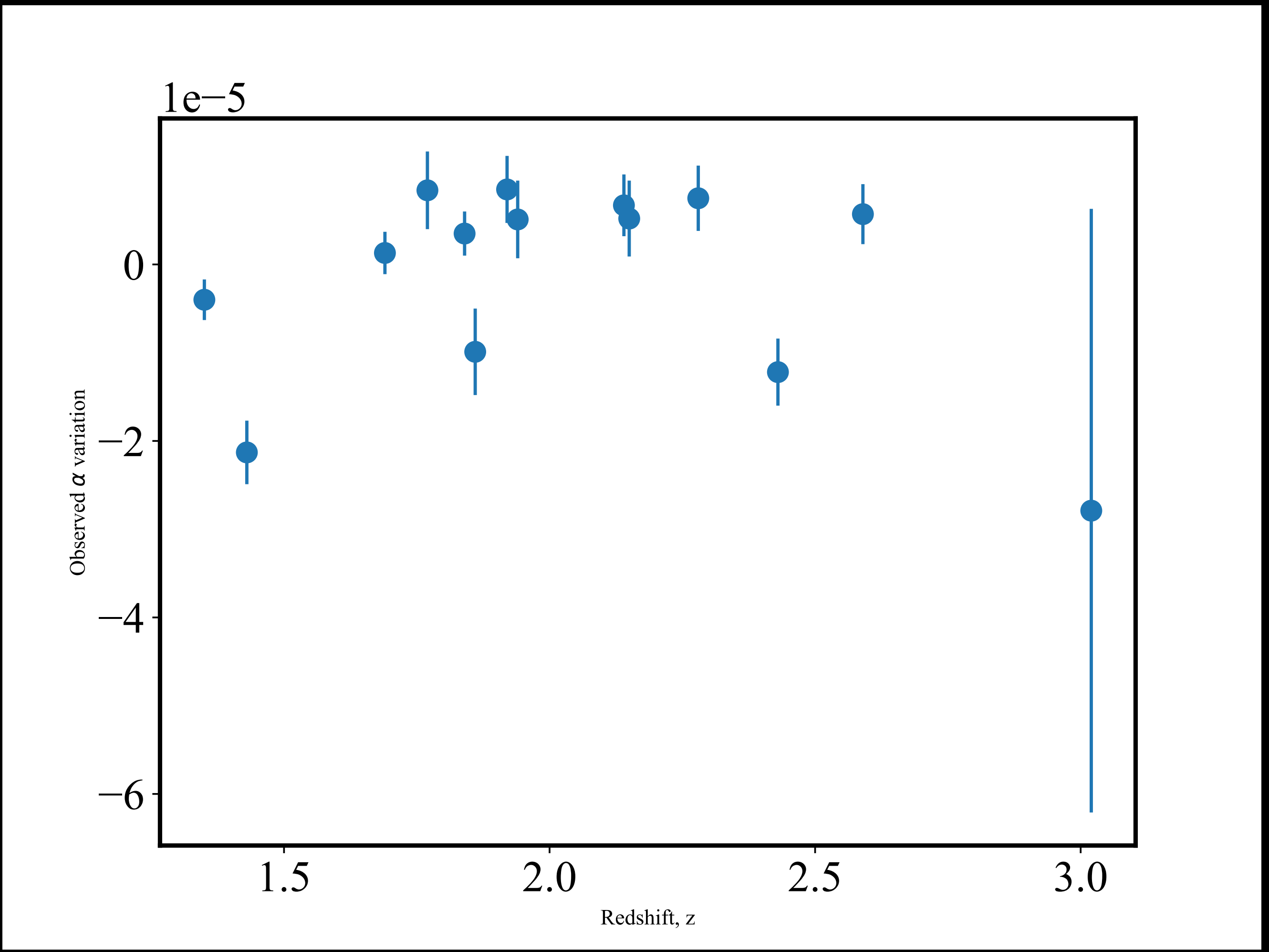
QSO hints and constraints



$$\Delta\lambda \propto \Delta\alpha^2$$



- ✴Webb, Martins, Murphy, Flambaum, Barrow, and others….



- ✴Hints of α variation from distant accreting black holes in galaxies

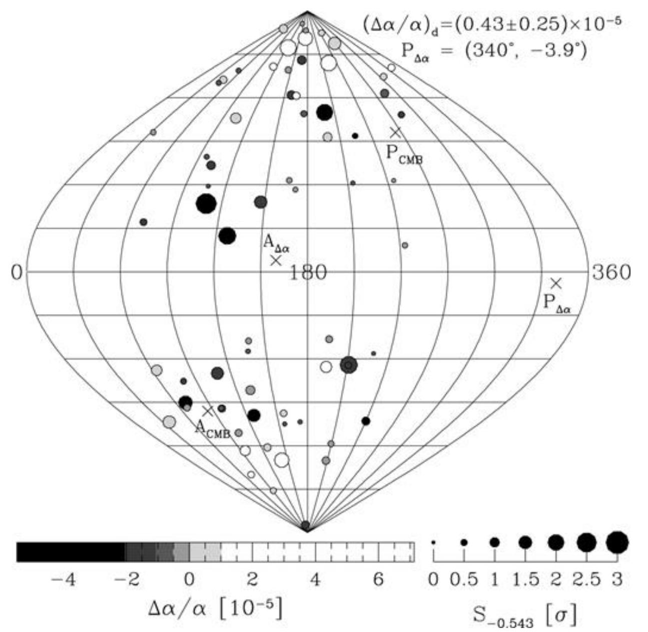
Mon.Not.Roy.Astron.Soc. 327 (2001) 1223. astro-ph/0012420

Mon.Not.Roy.Astron.Soc. 461 (2016) 3, 2461-2479 1606.06293

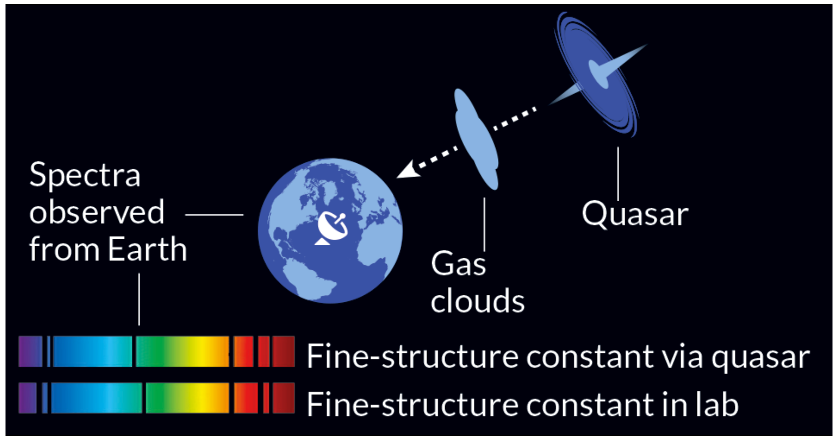
Reports on Progress in Physics, arXiv: 1709.02923

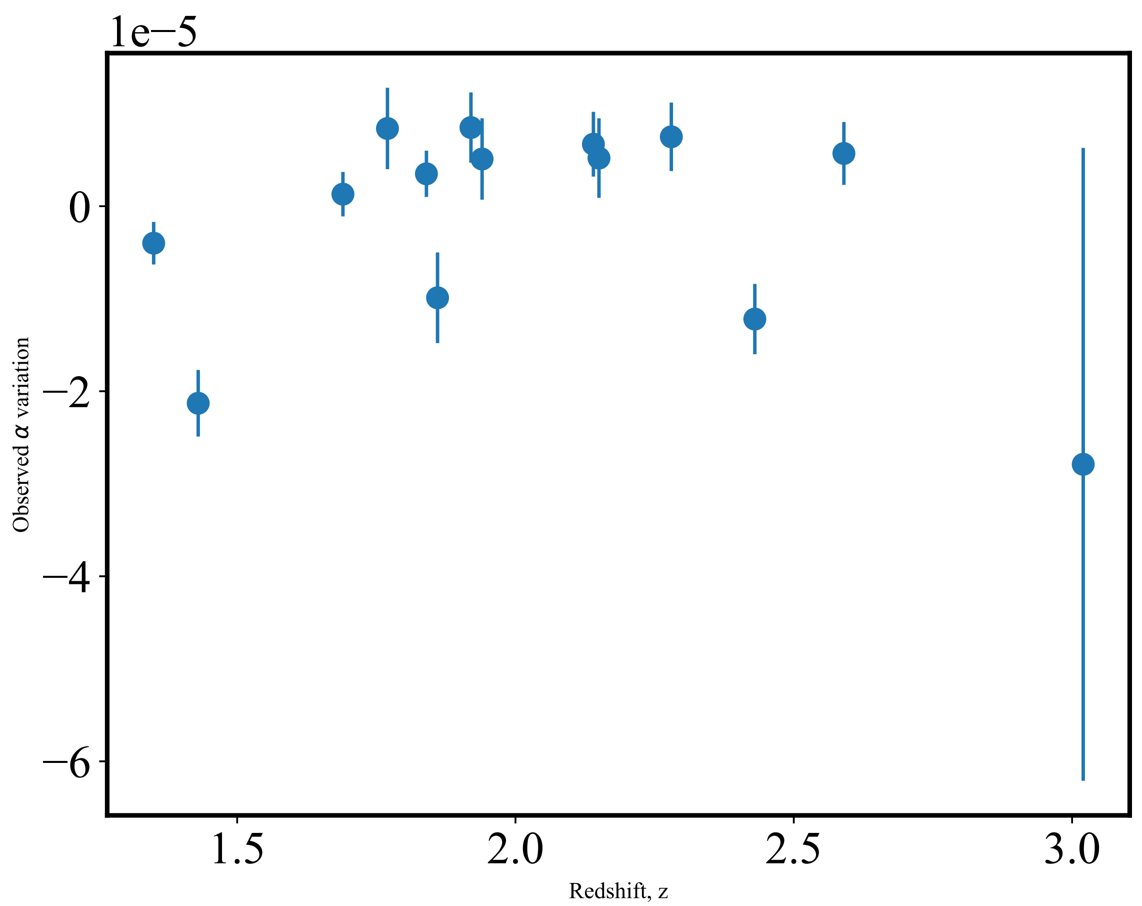
Phys.Rev.Lett. 107 (2011) 191101, *arXiv: 1008.3907*

QSO hints and constraints



$$\Delta\lambda \propto \Delta\alpha^2$$





Mon.Not.Roy.Astron.Soc. 327 (2001) 1223. astro-ph/0012420

Mon.Not.Roy.Astron.Soc. 461 (2016) 3, 2461-2479 1606.06293

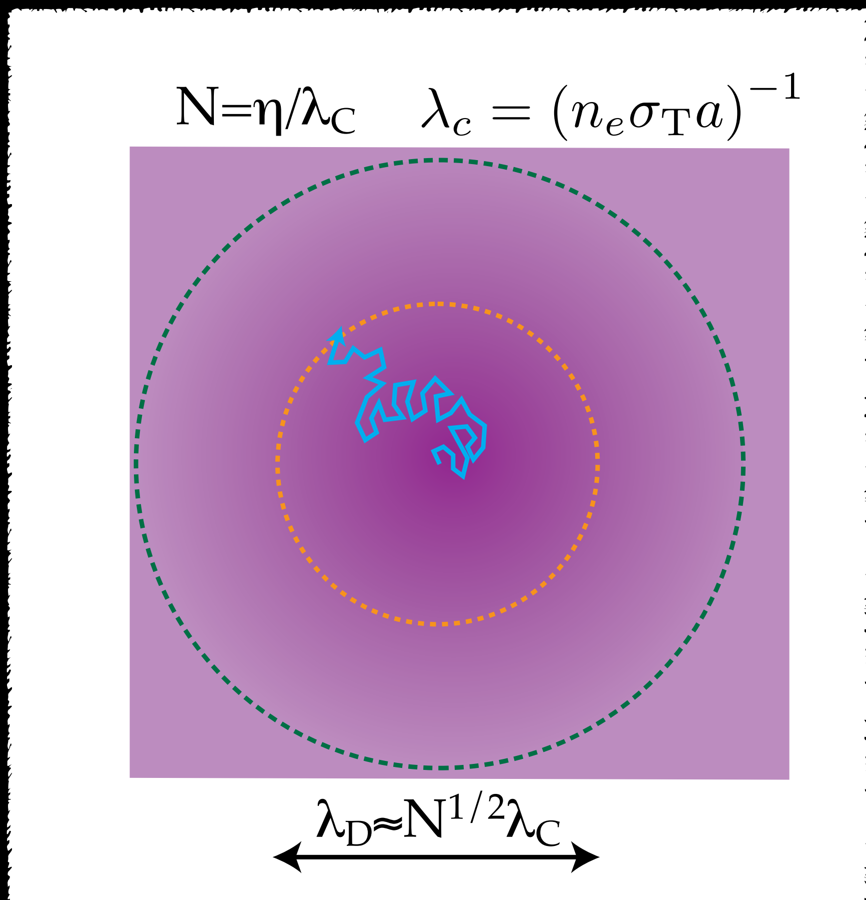
Reports on Progress in Physics, arXiv: 1709.02923

Phys.Rev.Lett. 107 (2011) 191101, *arXiv: 1008.3907*

Effects on CMB

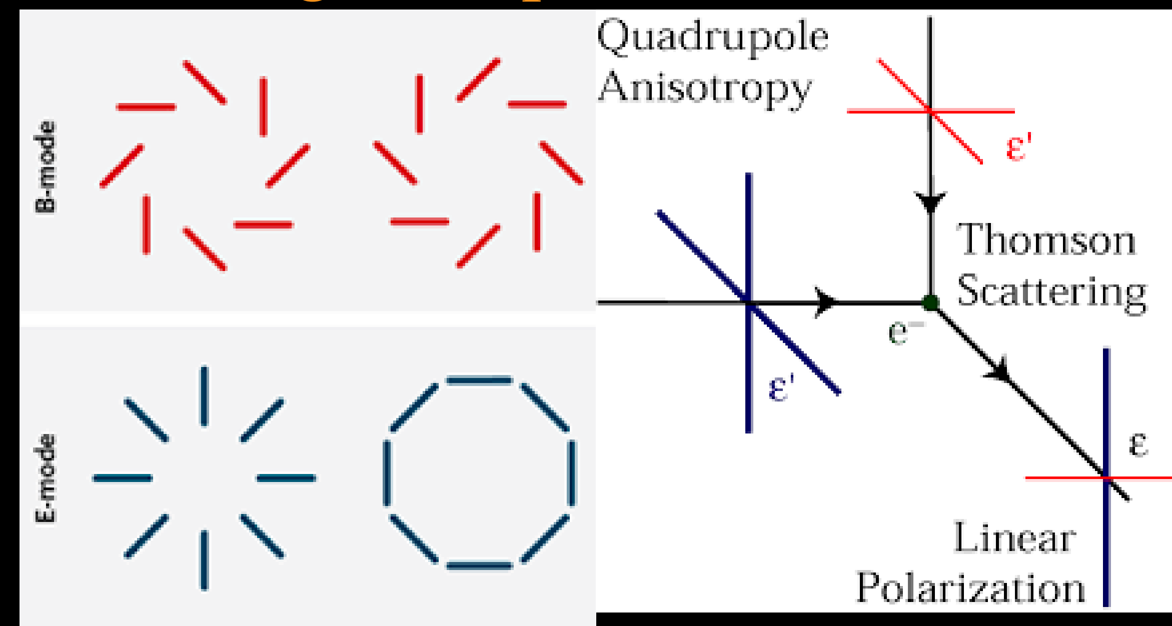
Images courtesy of Wayne Hu's website and Yacine Ali-Haïmoud

Diffusion



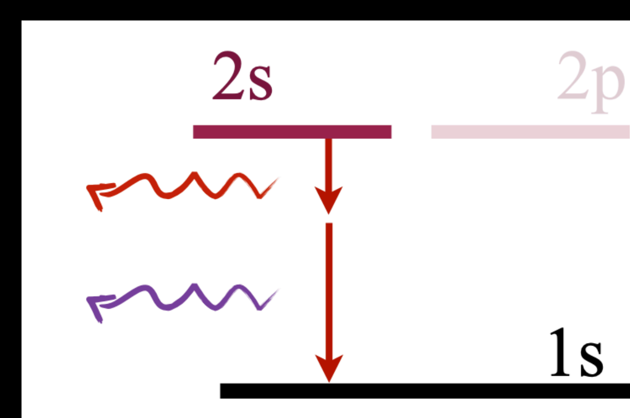
$$\sigma_T \propto \frac{8\pi}{3}\left(\frac{\alpha \hbar c}{mc^2}\right)^2$$

Scattering from polarization modulated



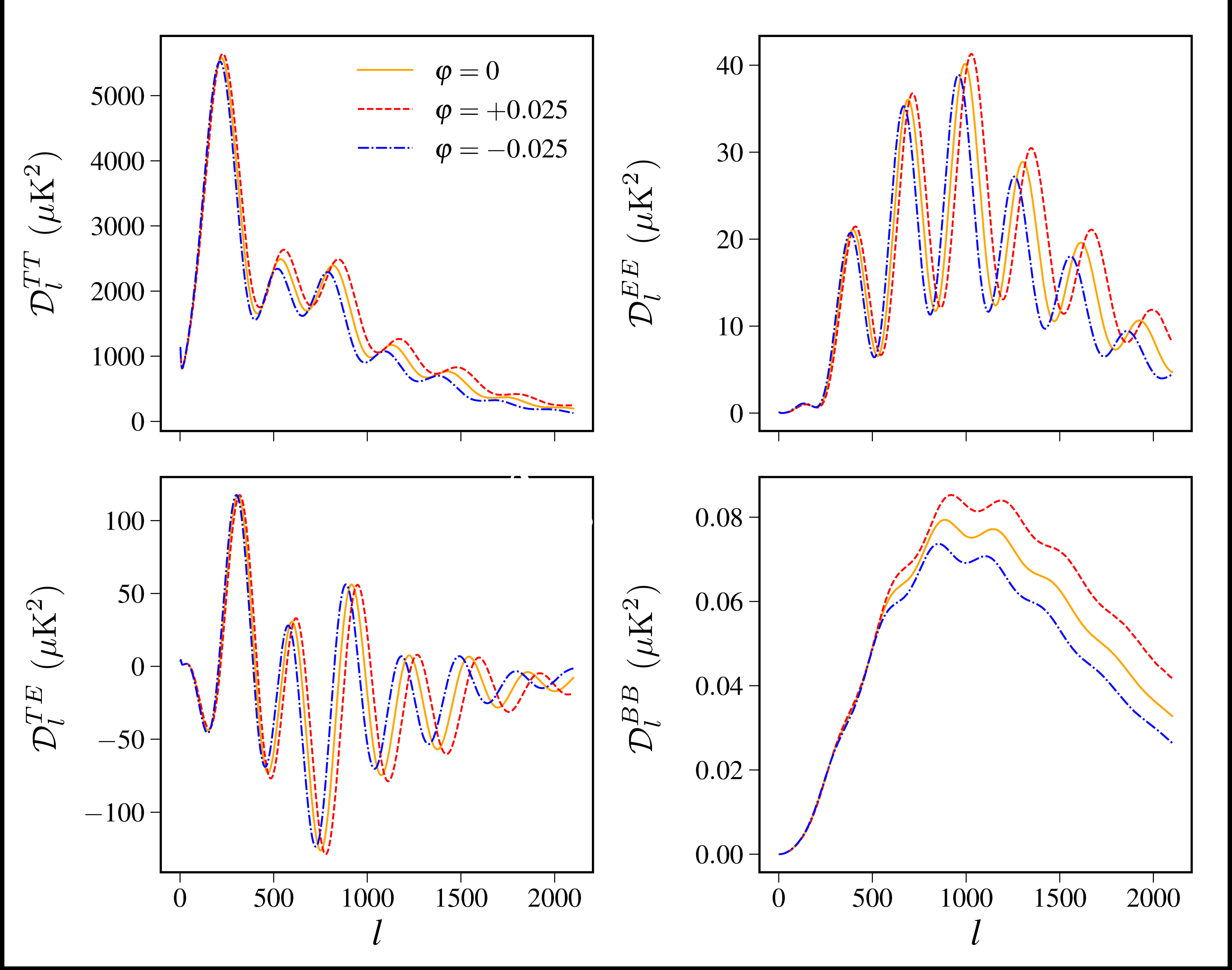
Recombination modulated

$$\Lambda_{2s\rightarrow 1s} \propto \alpha^8$$



Effects on CMB

Image from Phys. Rev. D 99, 043531 (2019)



$$\alpha = \alpha_0 \left(1 + \varphi\right)$$

Constraints so far

$\alpha_{\rm rec} \neq \alpha_0$ SingleValues **OR**

$\frac{\Delta\alpha}{\alpha_0} = A\,(1+z)^p$ very simple models

Menegoni, Galli, Chluba, Hart, Martins, Rocha, and others— Planck 2018 data

$$\frac{\Delta\alpha}{\alpha} \leq 0.005 \quad \text{at } 1\sigma$$

$$\Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}, \omega$$

Constraints so far

$\alpha_{\rm rec} \neq \alpha_0$ SingleValues **OR**

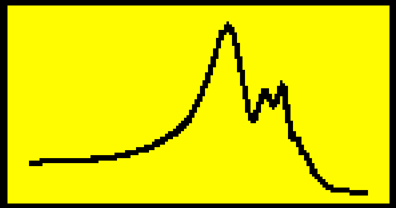
$$\frac{\Delta\alpha}{\alpha_0} = A\,(1+z)^p \;\; \text{very simple models}$$

Menegoni, Galli, Chluba, Hart, Martins, Rocha, and others— Planck 2018 data

$$\frac{\Delta\alpha}{\alpha} \leq 0.005 \quad \text{at } 1\sigma$$

$$\Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}, \omega$$

CAMB OR OTHER BOLTZMAN CODE



Compare with data
Explore posterior using Monte Carlo Markov Chain (MCMC)

Constraints so far

$\alpha_{\rm rec} \neq \alpha_0$ SingleValues **OR**

$\frac{\Delta\alpha}{\alpha_0} = A\,(1+z)^p$ very simple models

Menegoni, Galli, Chluba, Hart, Martins, Rocha, and others— Planck 2018 data

$$\frac{\Delta\alpha}{\alpha} \leq 0.005 \quad \text{at } 1\sigma$$

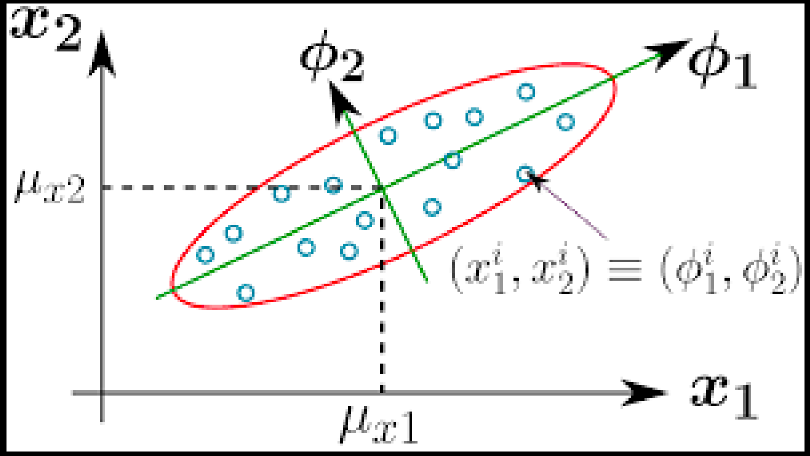
$$\Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}, \omega$$

PCA — Principal Component analysis

✳Expand fine-structure parameter in some basis to discretize

$$\alpha = \sum_i a_i f_i(z)$$

✳Find principal aces of iso-likelihood contours in parameters space



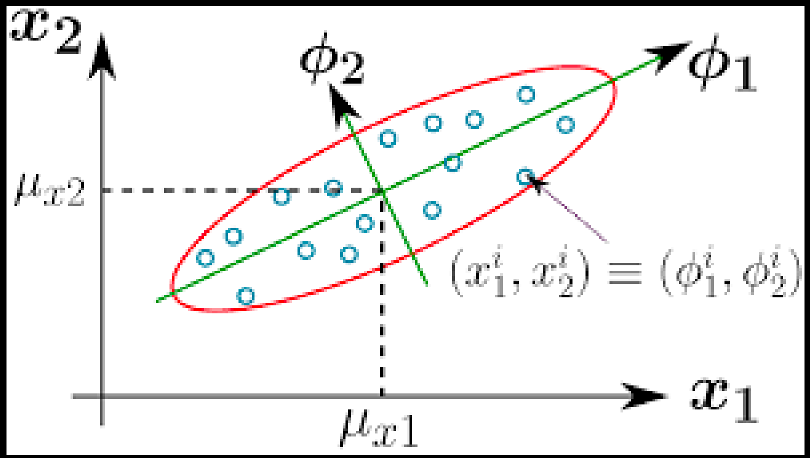
$$\mathcal{L} \propto \exp[-\sum_{ij} a_i \mathbf{F}_{ij} a_j]$$

$$\mathbf{F}_{ij} = \sum_{\ell} \frac{f_{\rm sky} \times (2\ell+1)}{2} \left(\frac{dC_\ell}{da_i}\right)^2$$

✳These "vectors" are the best constrained models $\alpha(z)$

PCA — Principal Component analysis

$$\alpha = \sum_i a_i f_i(z)$$

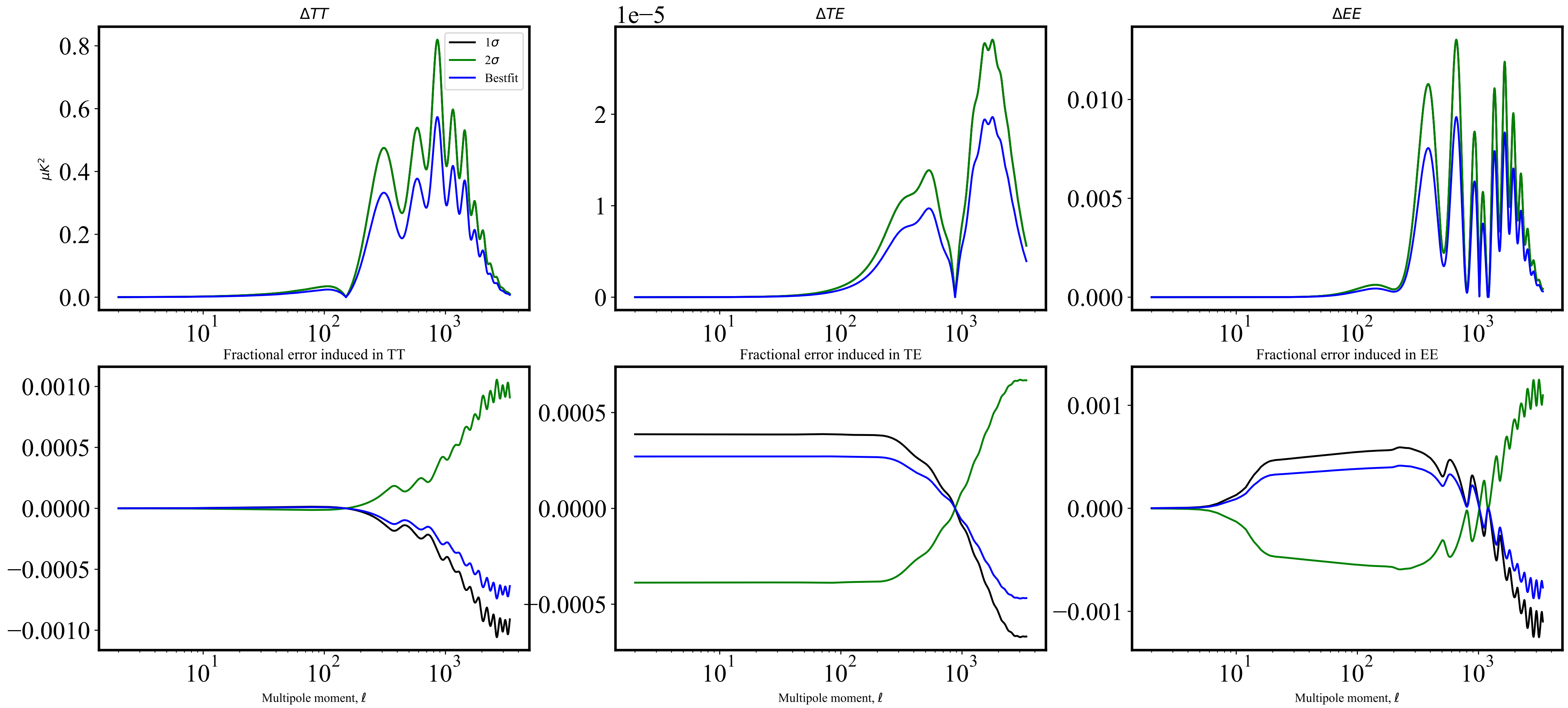


$$\mathcal{L} \propto \exp[-\sum_{ij} a_i \mathbf{F}_{ij} a_j]$$

$$\mathbf{F}_{ij} = \sum_\ell \frac{f_{\rm sky} \times (2\ell + 1)}{2} \left(\frac{dC_\ell}{da_i} \right)^2$$

Projecting BSBM onto PCs — observables

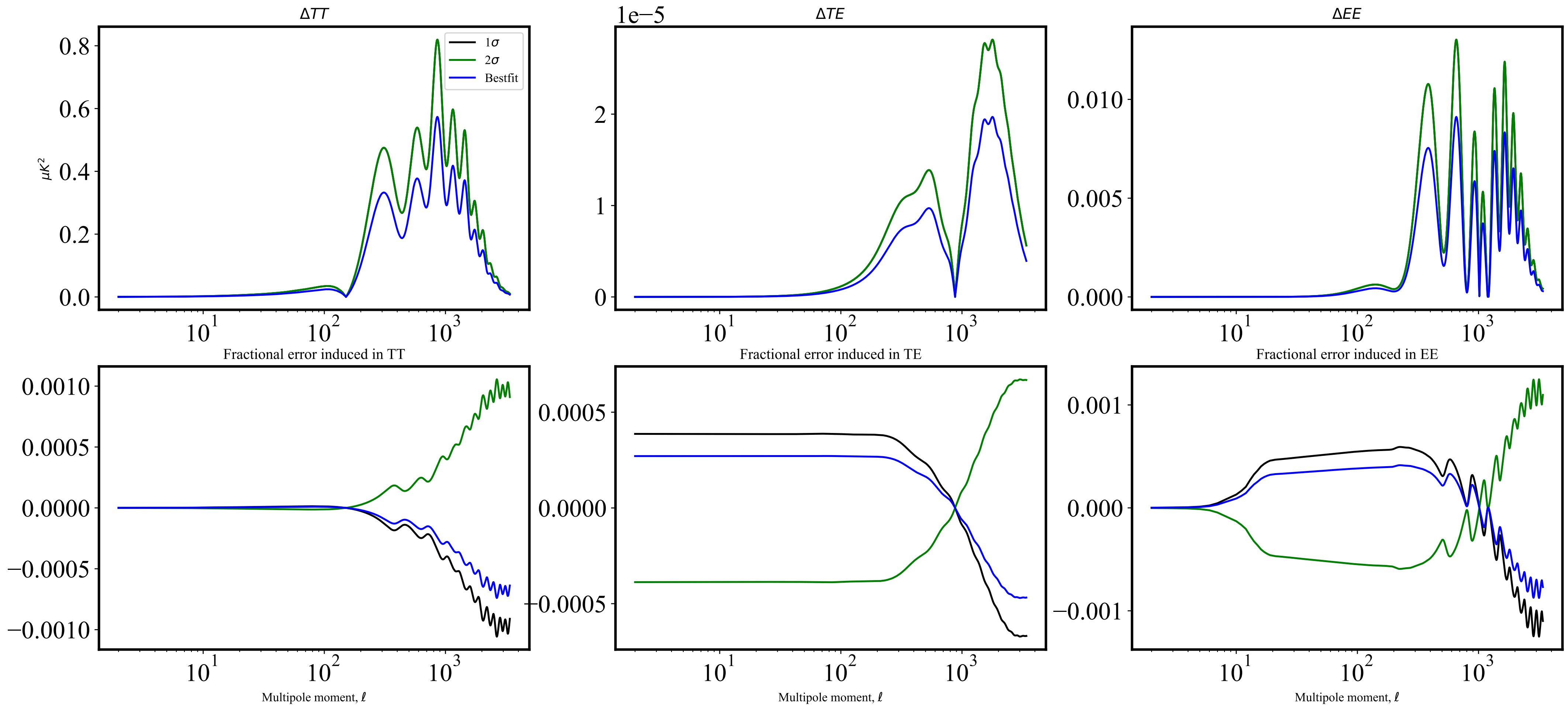
H. Tohfa



$$\frac{\Delta C}{C}(z) = \sum_i \rho_i E_i(z)\,, \qquad \rho_i = \int \frac{\Delta C}{C}(z) \cdot E_i(z)\, \mathrm{d}z$$

Projecting BSBM onto PCs — observables

H. Tohfa

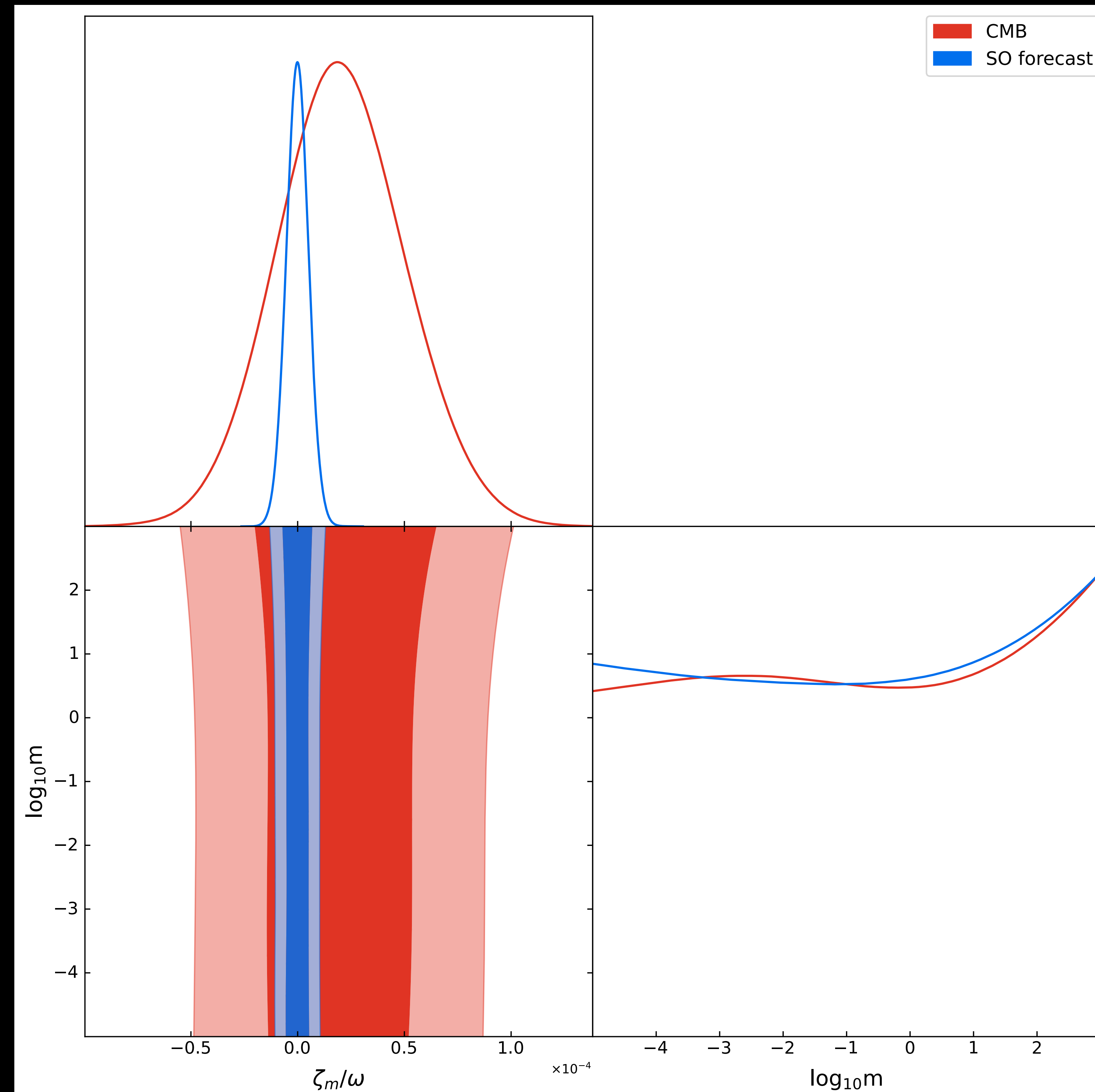


$$\frac{\Delta C}{C}(z) = \sum_i \rho_i \, E_i(z) \, , \qquad \rho_i = \int \frac{\Delta C}{C}(z) \cdot E_i(z) \; \mathrm{d}z$$

Projecting BSBM onto PCs — constraints and forecasts

Constraints from Planck 2018 data analysis

H. Tohfa (UCR, U. Washington)



Future work

- Spatial variation in BSBM models + effect on CMB
- Full set of model family (e.g. dilaton models)
- Full covariance analysis with other cosmological parameters
- Understood poorly understand plasma physics of this work