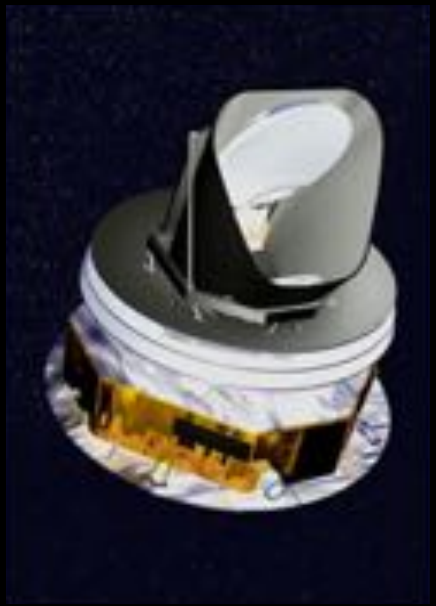
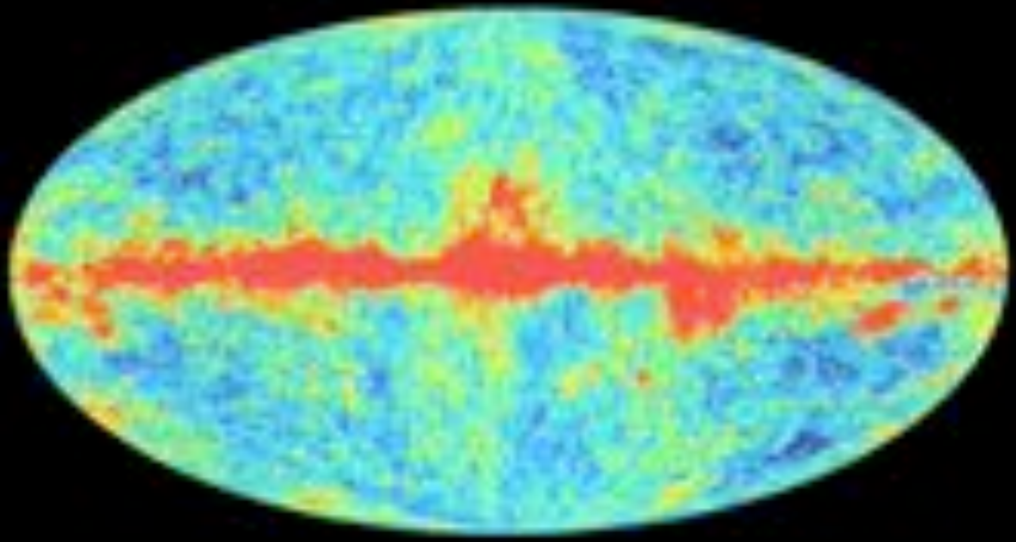
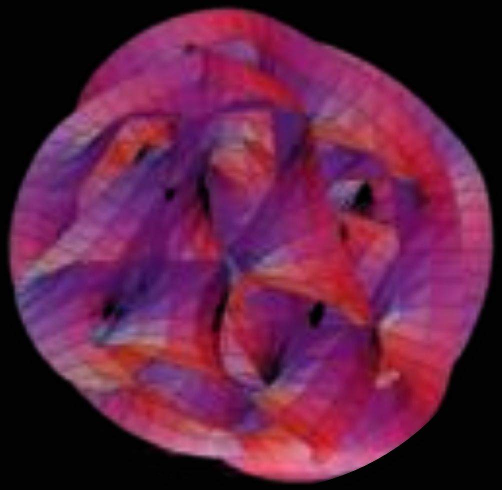






Searching for axions using the cosmic microwave background

Daniel Grin
Haverford College

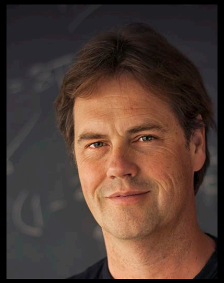
Physics Colloquium
Villanova University
2/10/2017

Outline

- ✳ The cosmic microwave background — a high-energy physics laboratory
- ✳ Beyond the standard model
- ✳ Testing axion dark matter and dark energy using the CMB
- ✳ Future work

Collabs: R.Hložek, D.J. E. Marsh, P.Ferreira, J. Dunkley, E. Calabrese, R.Allison






Standard model (SM) of particle physics

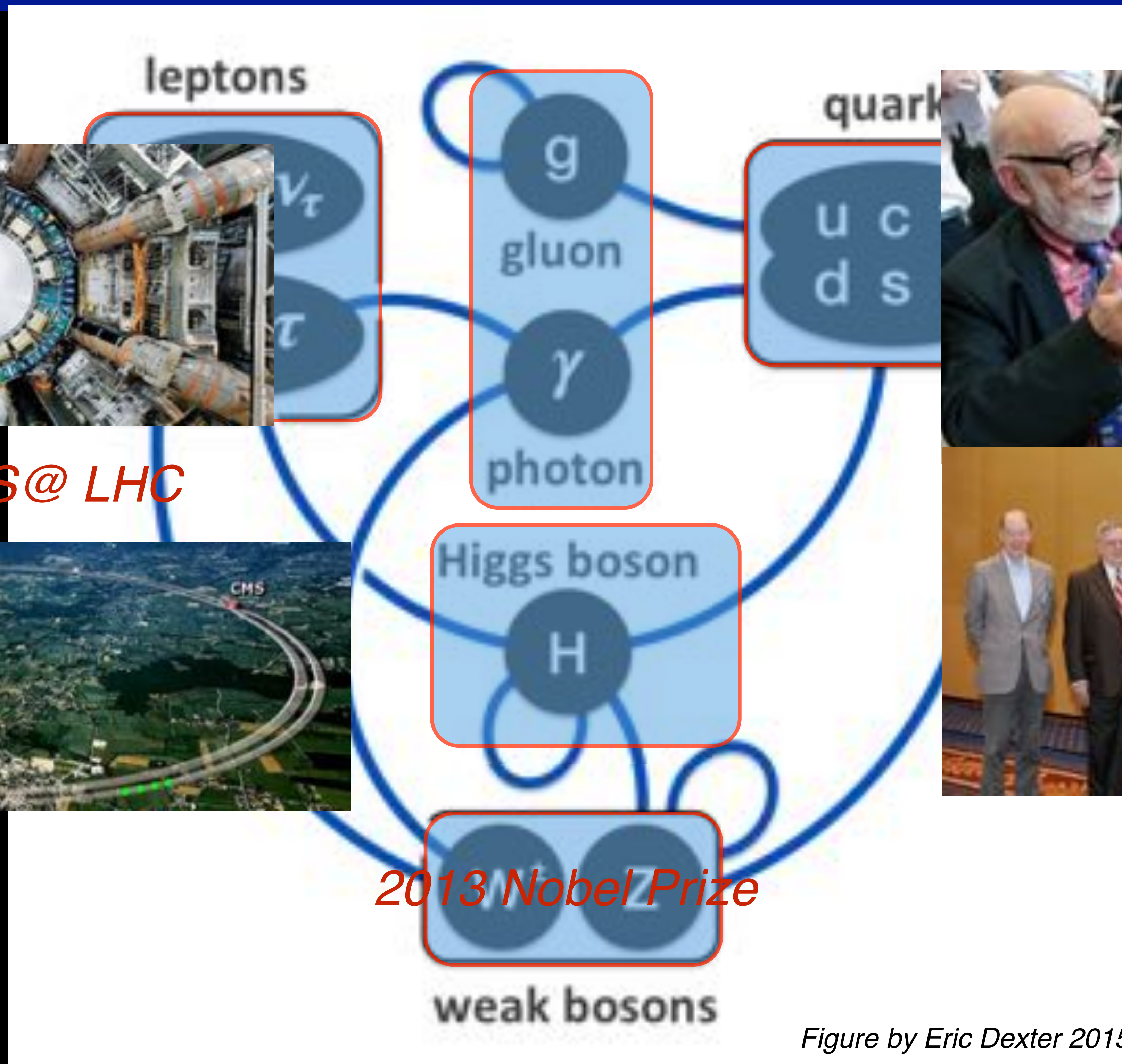


Figure by Eric Dexter 2015

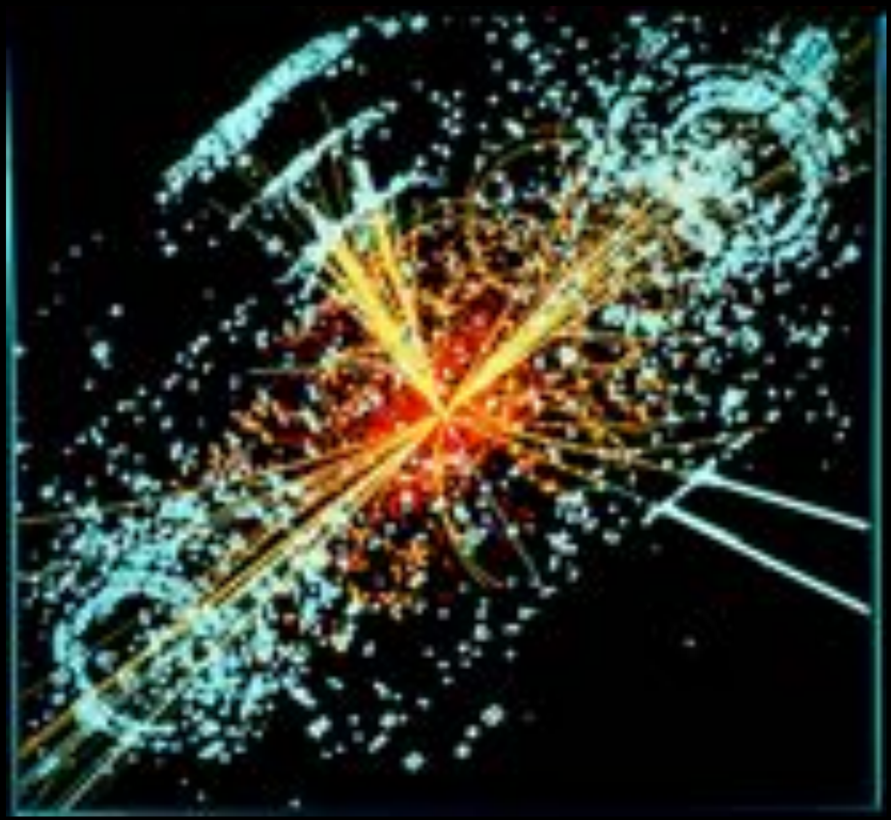
ATLAS@ LHC

2013 Nobel Prize

Force carriers

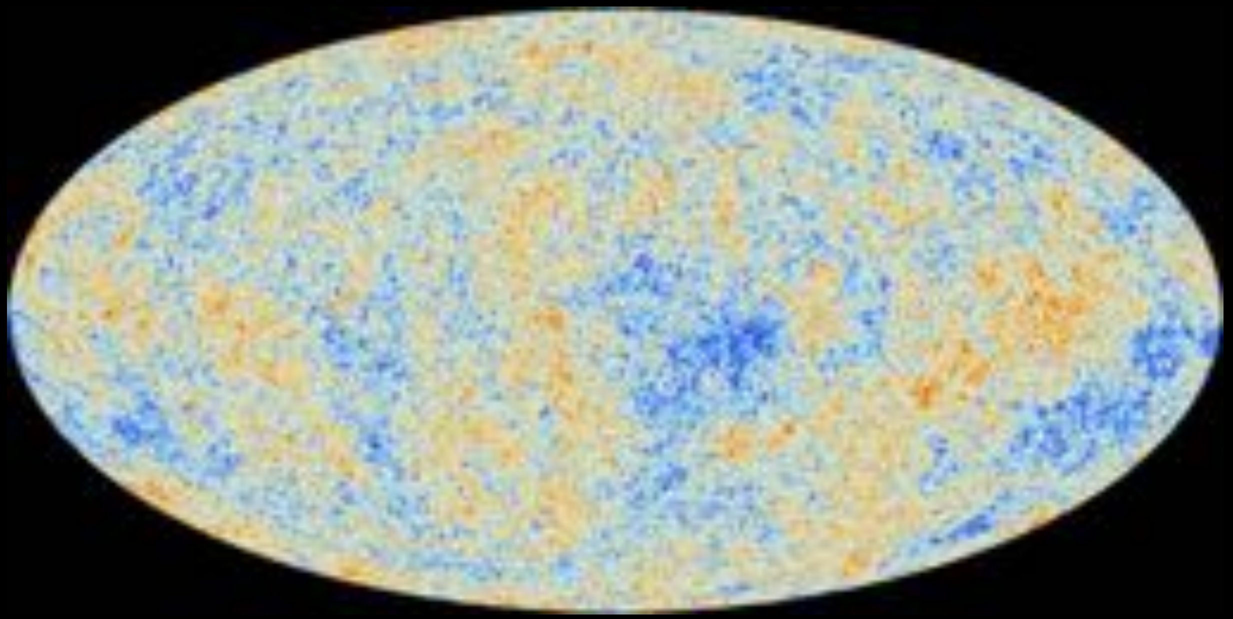
The cosmic microwave background (CMB)

Large Hadron Collider



$13\ \mathrm{TeV}$

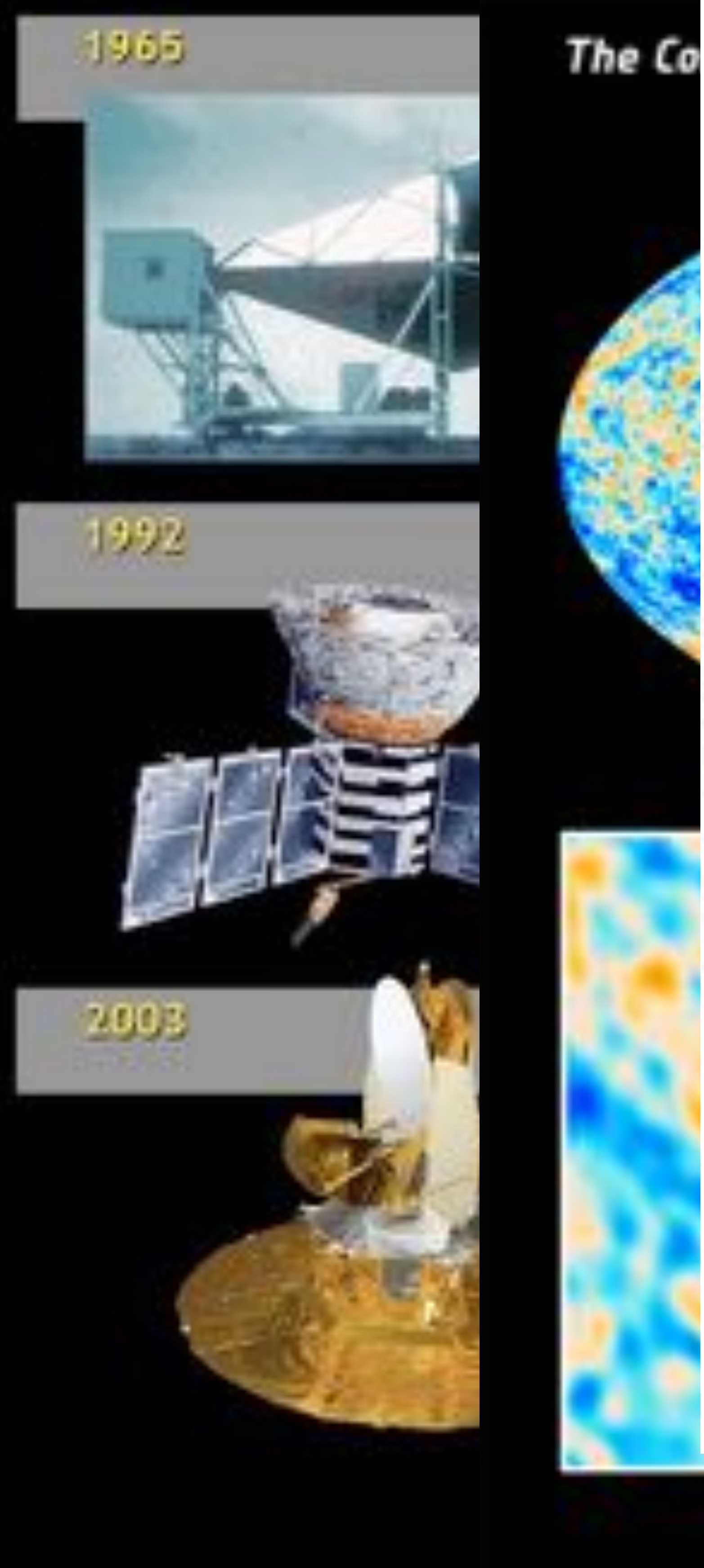
Cosmic microwave background

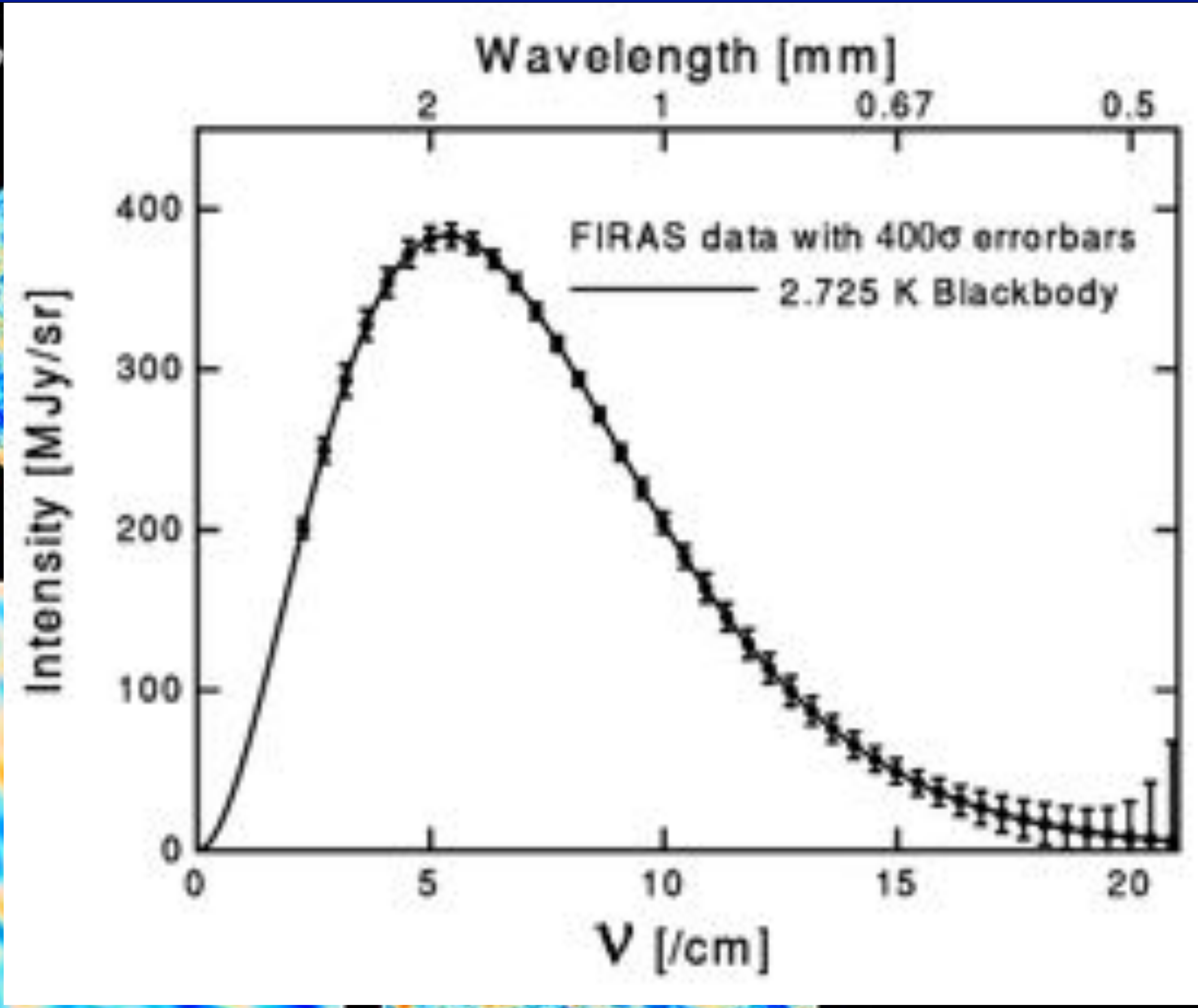


$10^{16}\ \mathrm{GeV}$

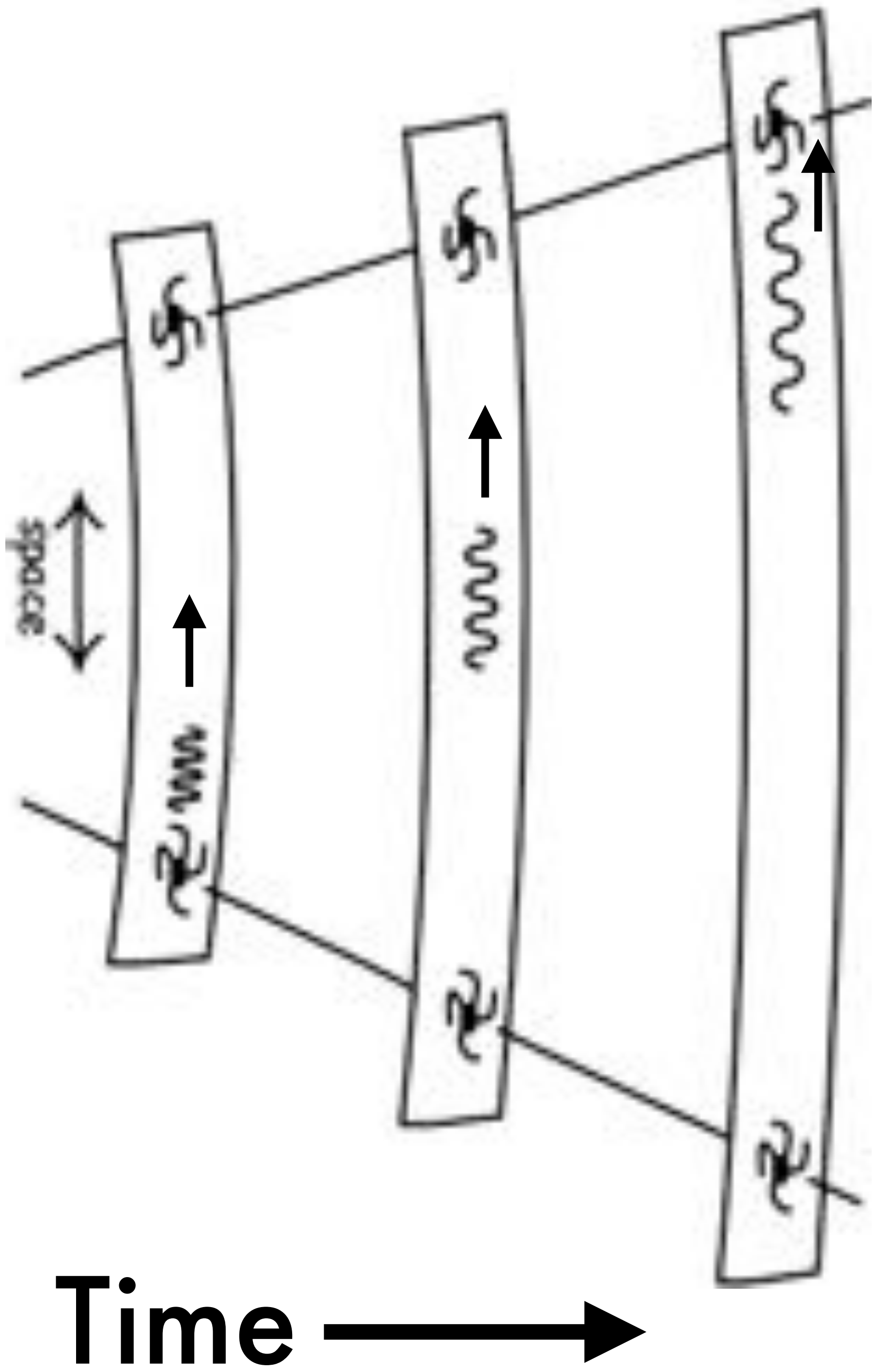
$t \sim 10^{-36}\mathrm{s} \to \sim 10^{-32}\ \mathrm{s}$

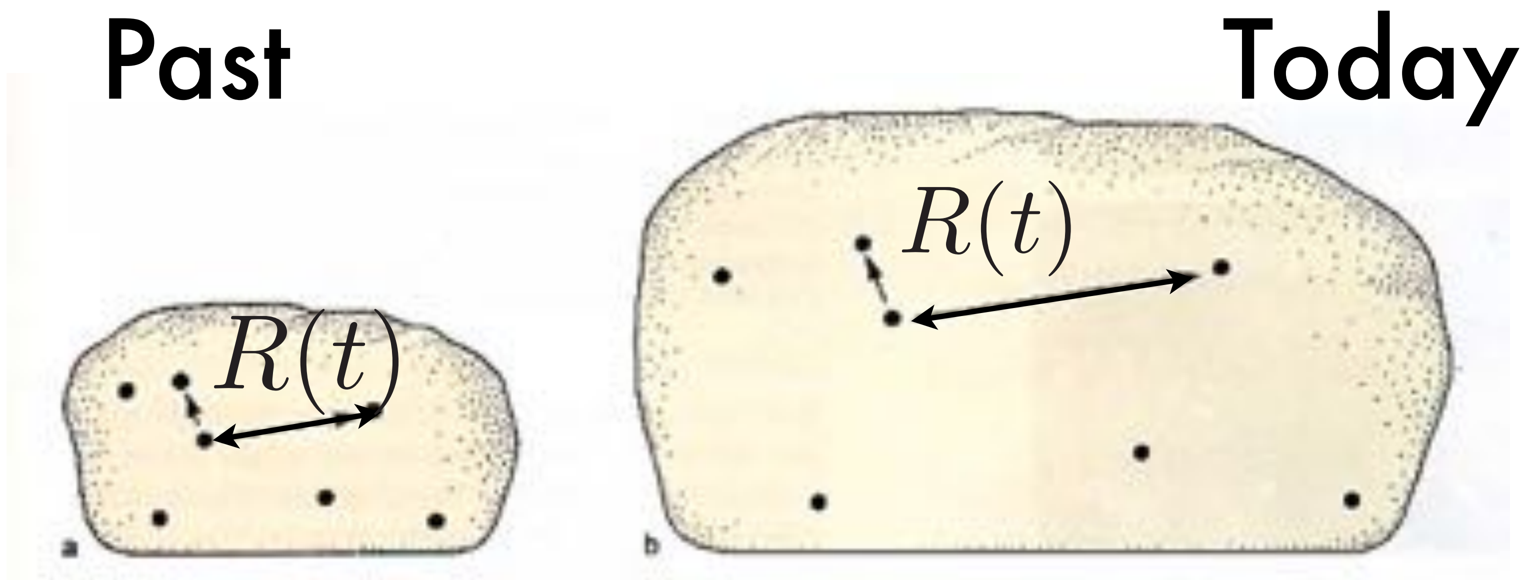
COSMIC MICROWAVE BACKGROUND (CMB): EXPERIMENTAL PROGRESS





The expanding universe

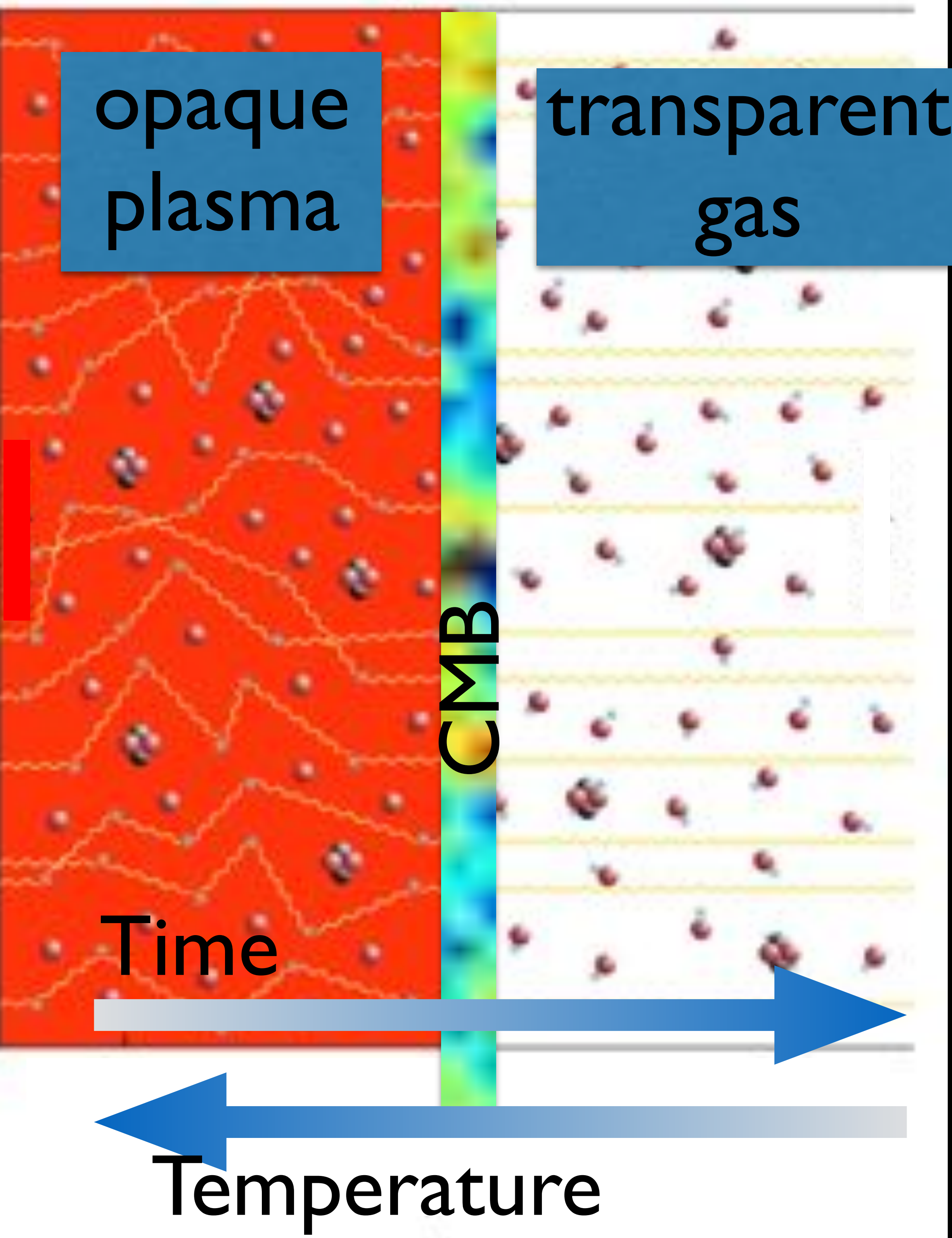




With expansion

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

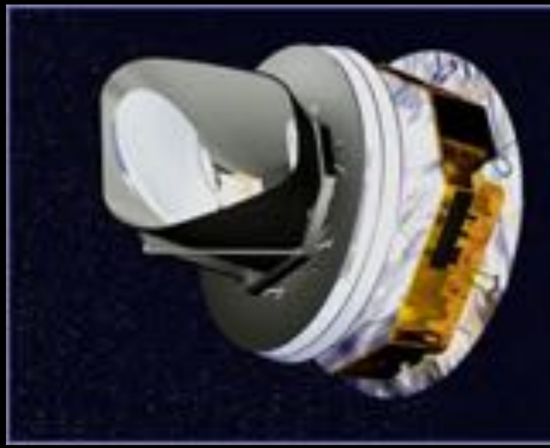
Image credit (Addison Wesley 2004)



`RECOMBINATION':

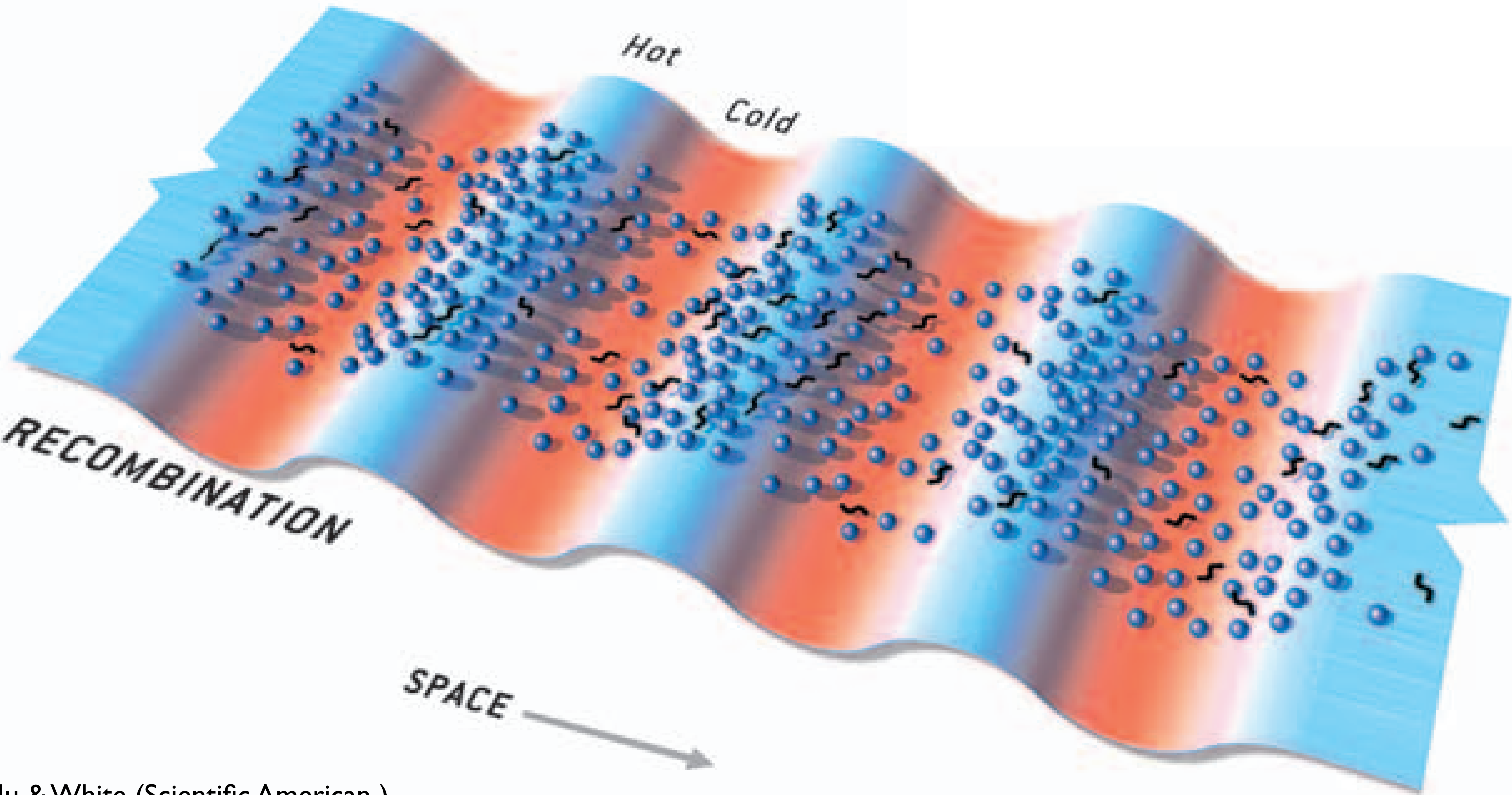
FIRST H ATOMS

z~1100, t~380,000 years



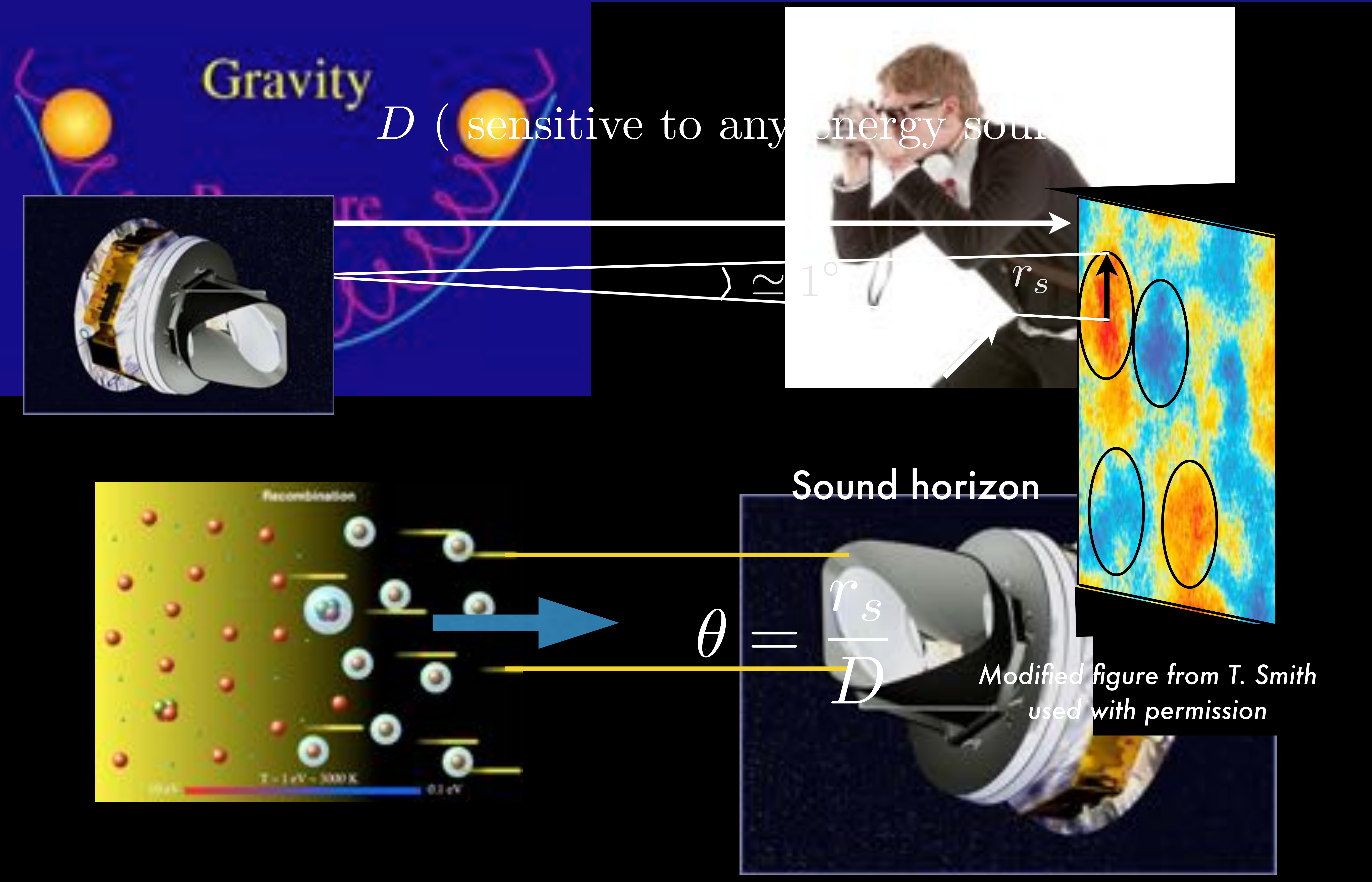
SOUND WAVES!

- Photons, protons, electrons move together

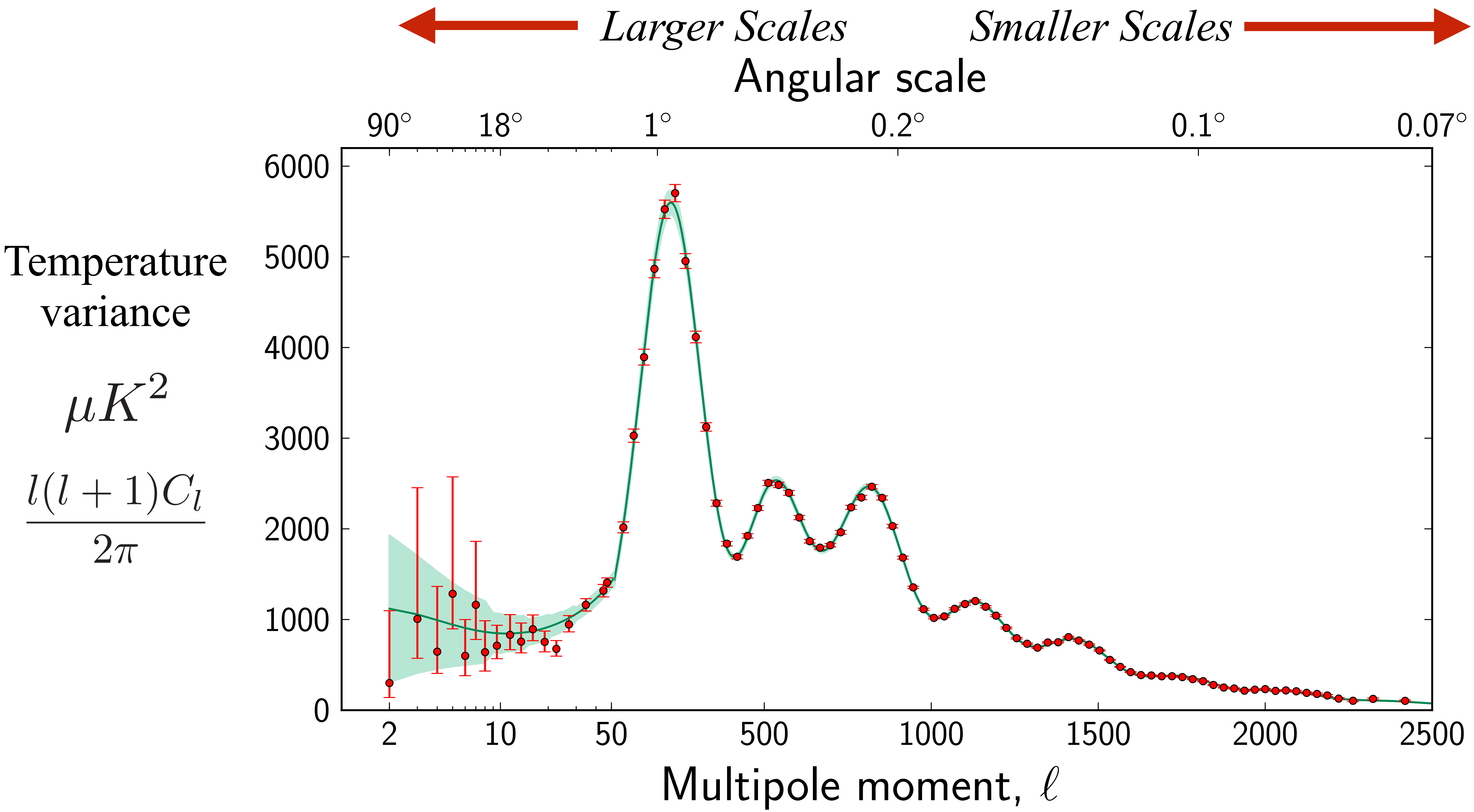


Hu & White (Scientific American)

Snapshot and geometry



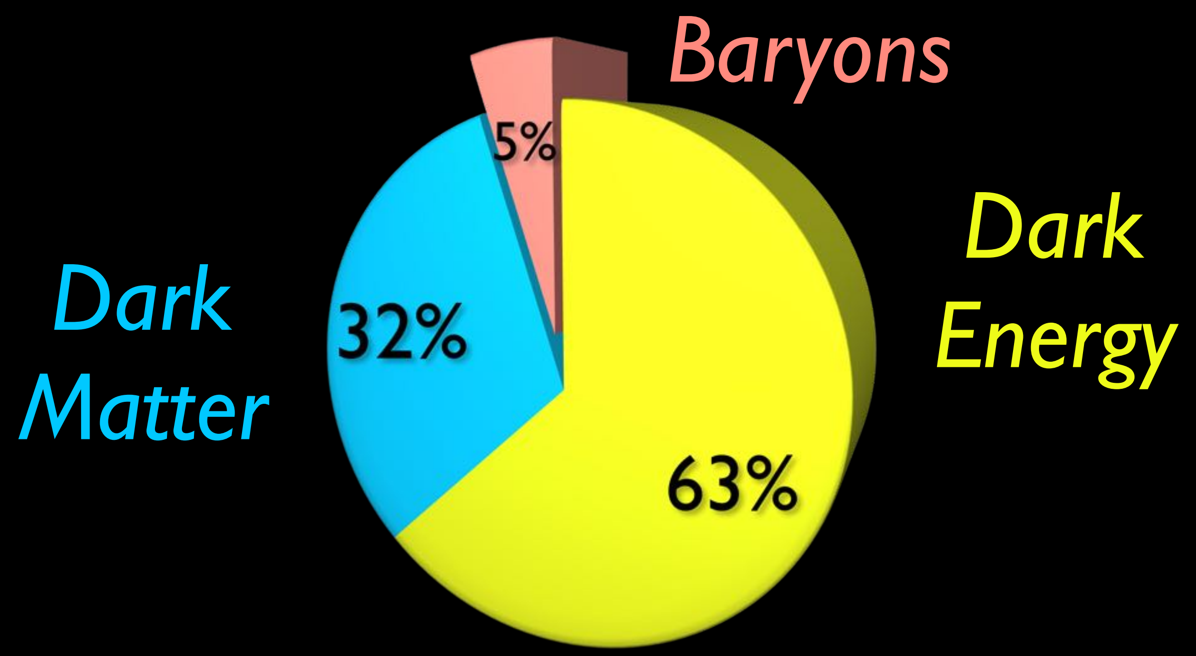
Fourier analysis of primordial sound



Fourier analysis of primordial sound

- Power spectrum is sensitive to
  - Expansion history after first atoms form
  - Dynamics of sound waves at this epoch
  - Properties of gravitational field
  - Total matter density, radiation density, electron/proton density

Cosmic energy budget



Ω_{DE}

5% baryonic matter: protons, electrons, atoms

- "stuff we know"

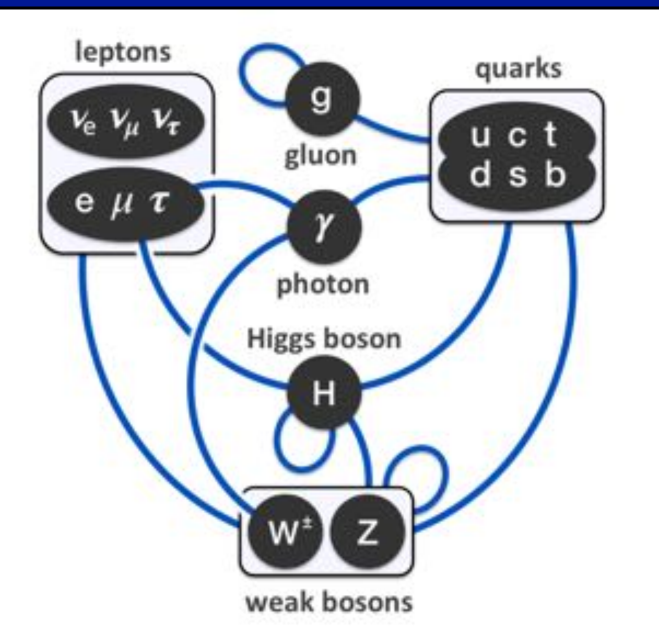
32% cold dark matter (CDM)

- Stable, neutral, non-relativistic particle
- Weak interactions with standard model

63% dark energy

Stuff we don't know!

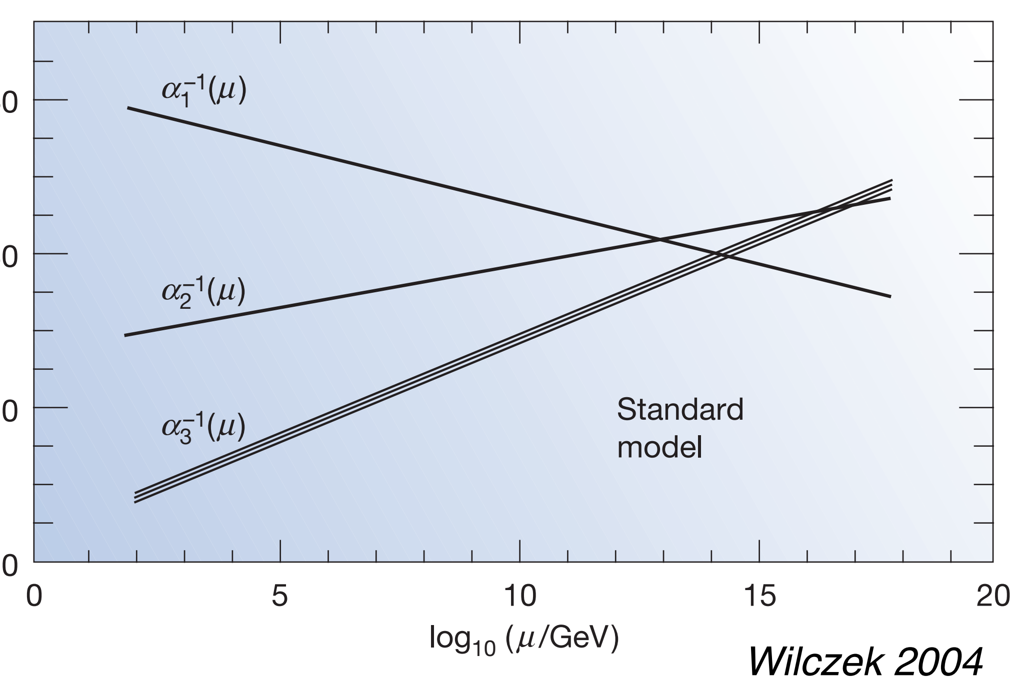
Theoretical shortcomings of SM



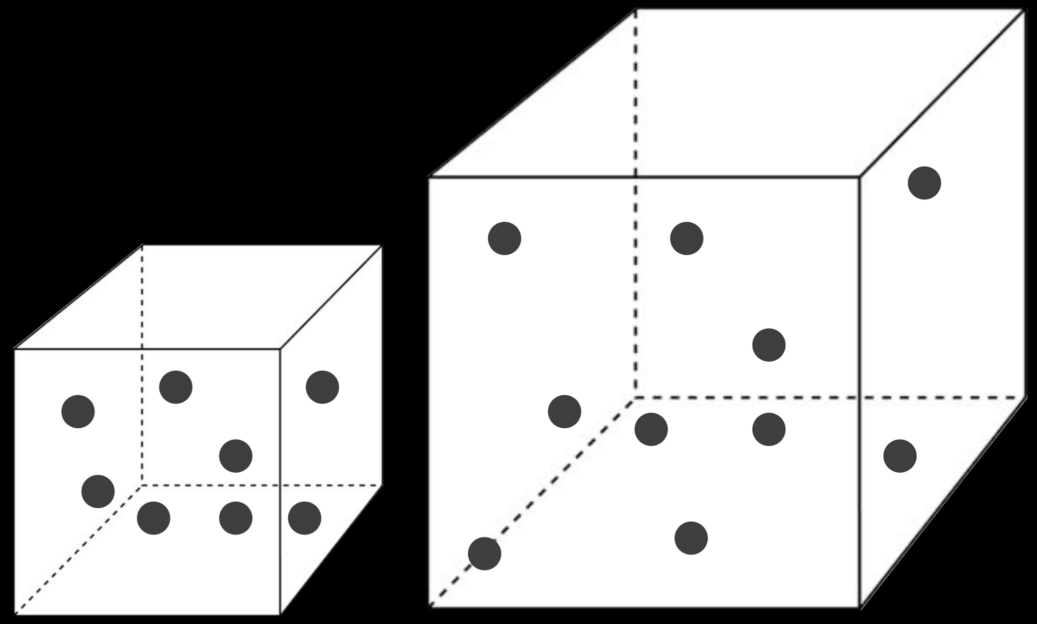
Such a mess!

Gravity is different!

Forces narrowly miss unification!



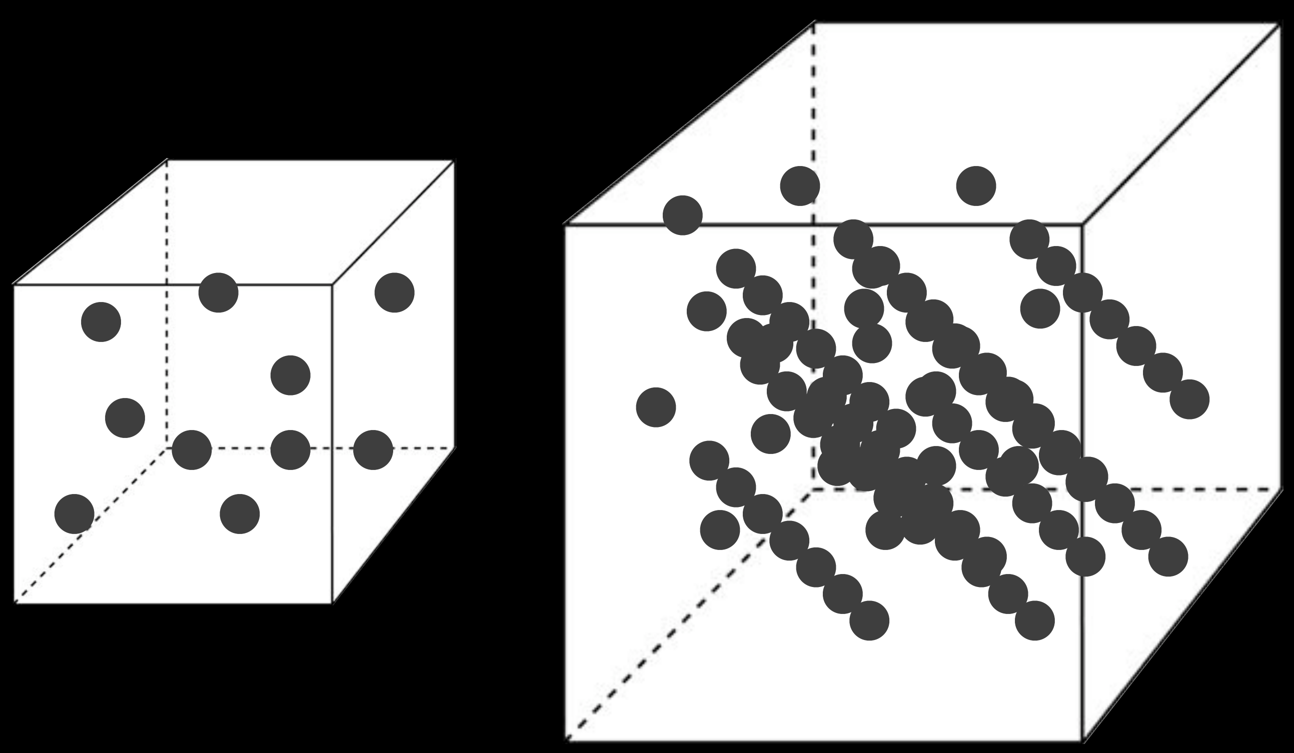
DARK ENERGY?



$$\rho_{\text{matter}} = \frac{\text{mass} \times \text{number}}{\text{volume}} \sim \frac{1}{R^3}$$

energy density in matter particles

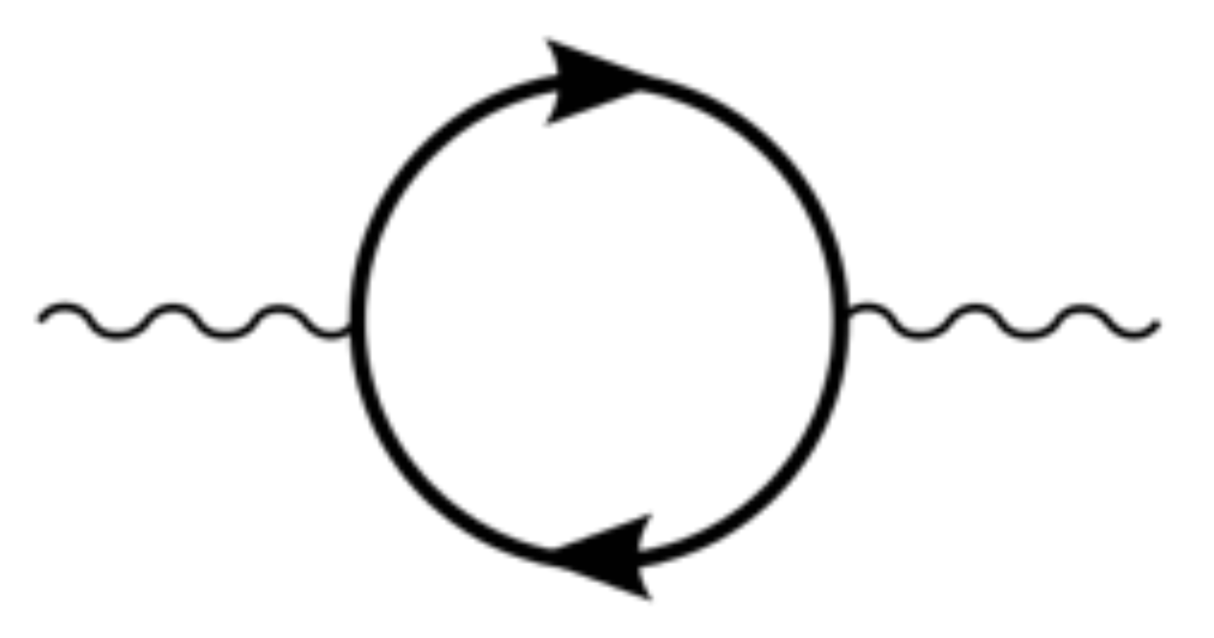
$\ddot{R}(t) > 0$ Cosmic acceleration requires very unusual substance



Cosmological Constant Λ

$$\rho_\Lambda \sim \text{const}$$

DARK ENERGY: SM VACUUM ENERGY?



Crudely:

$$\Delta E \sim \frac{\hbar}{\Delta t}$$

Full standard model vacuum energy predicts….

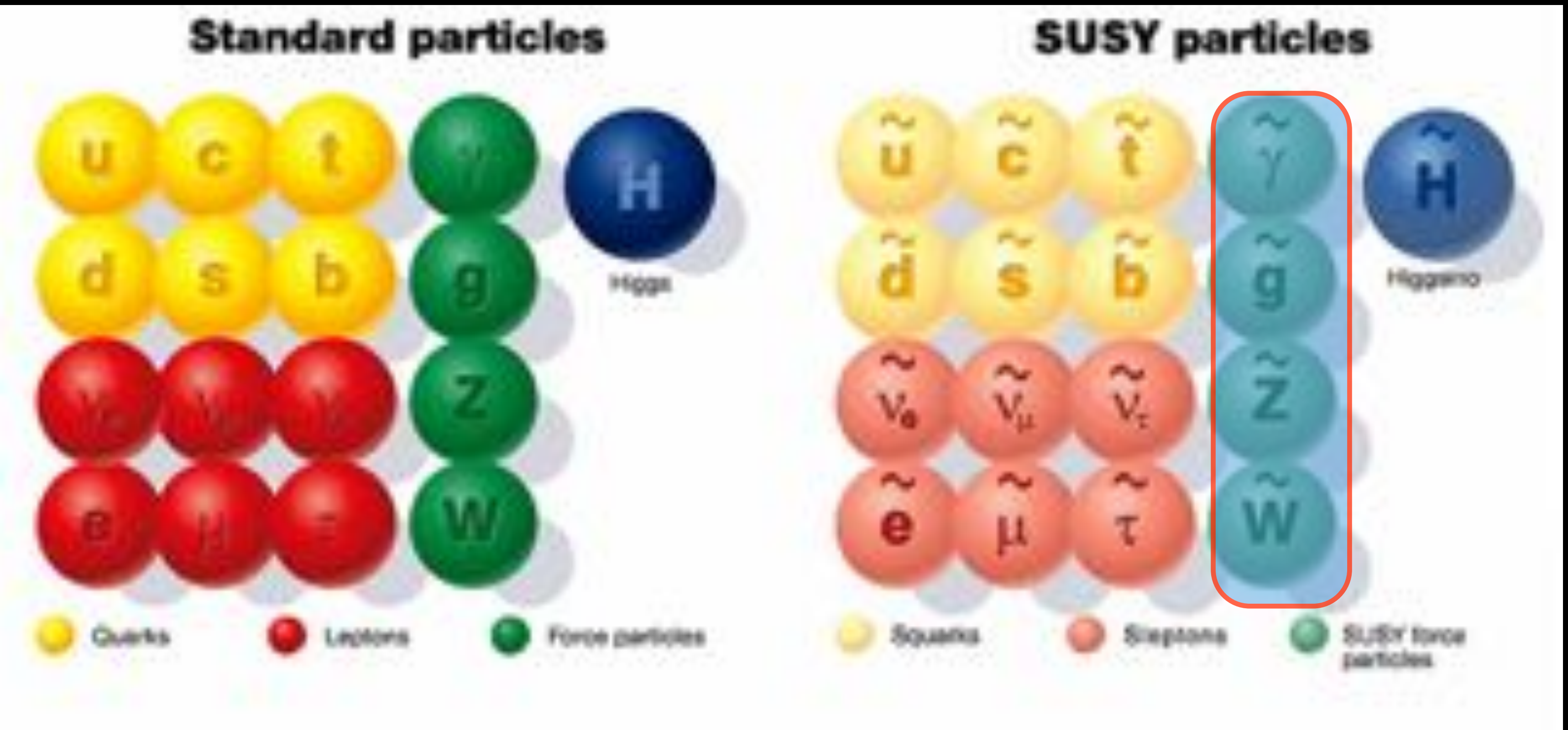
$$\Omega_\Lambda \sim 10^{120} \quad \text{vs } \Omega_\Lambda \simeq 0.63$$

This is what you call a colossal failure

Supersymmetry theory

Dark matter?

* Solves many of SM's problems!

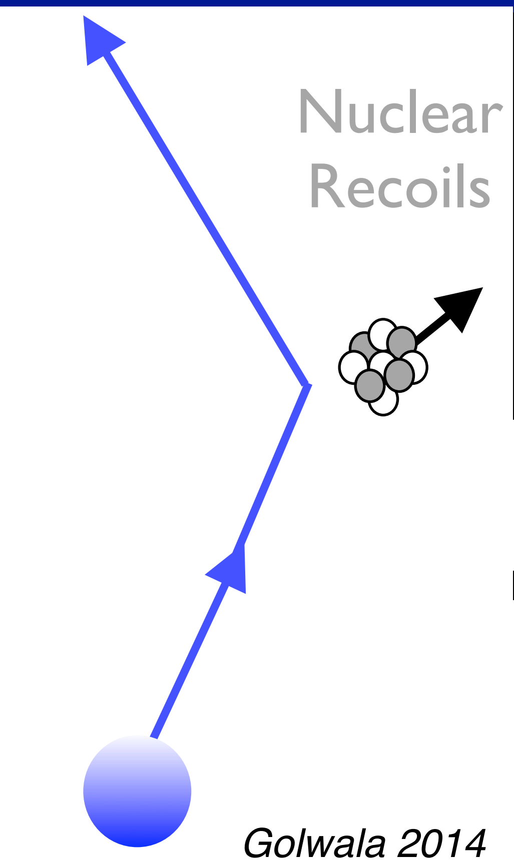


* Heavy! $m_{\text{dark matter}} \sim 10^2$ GeV vs $m_{\text{proton}} \sim 1$ GeV
* Correct dark-matter abundance! 32% of cosmic mean density

Recurring theme:

Filling in the holes of the standard model can also furnish candidates for dark matter (or dark energy)!

Dark matter: terrestrial experiment



So far, no dice!

Time to consider alternative dark matter & dark energy candidates!

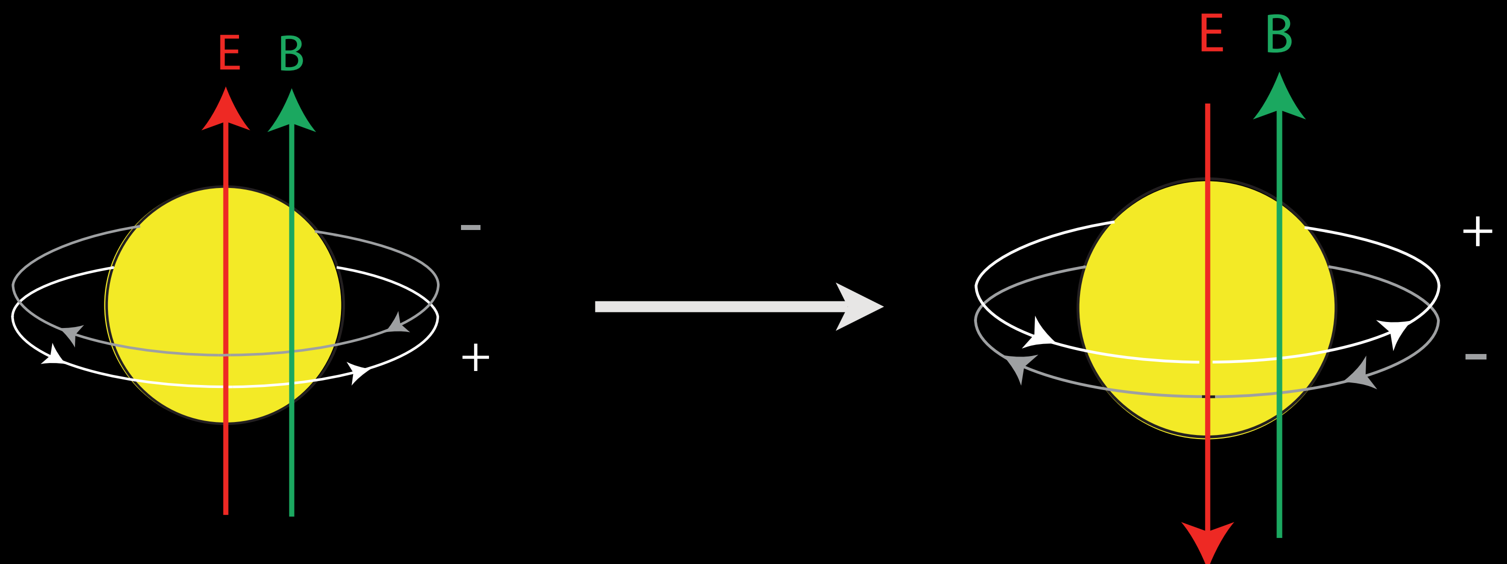
Axions

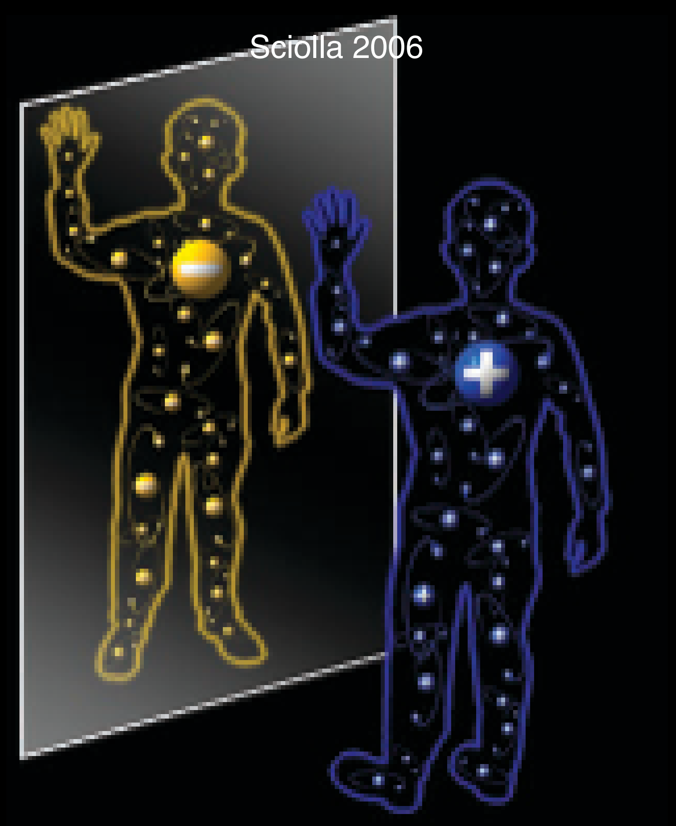
The theory of the strong interaction has a problem ….

THE STRONG CP PROBLEM

✳ The theory of the strong interaction predicts an electric dipole moment for the neutron!

Violates charge-parity (CP) symmetry!





$$d_n \simeq 10^{-16}\ \theta\ \mathrm{e\ cm}$$

$$\theta \lesssim 10^{-10},$$

We (physicists) don't like small numbers that don't have a dynamical explanation!

Axions

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

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

Gauss's Law

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

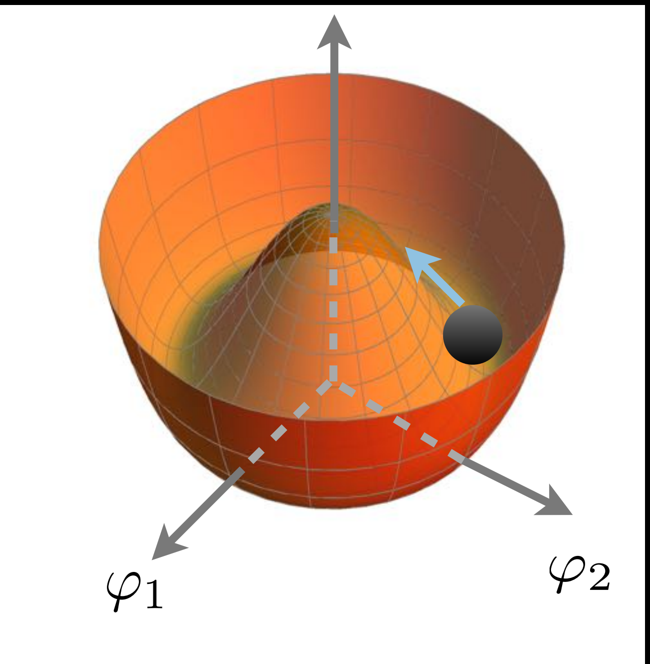
Ampère's Law

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

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

✳Shields neutron dipole moment

What are axions?

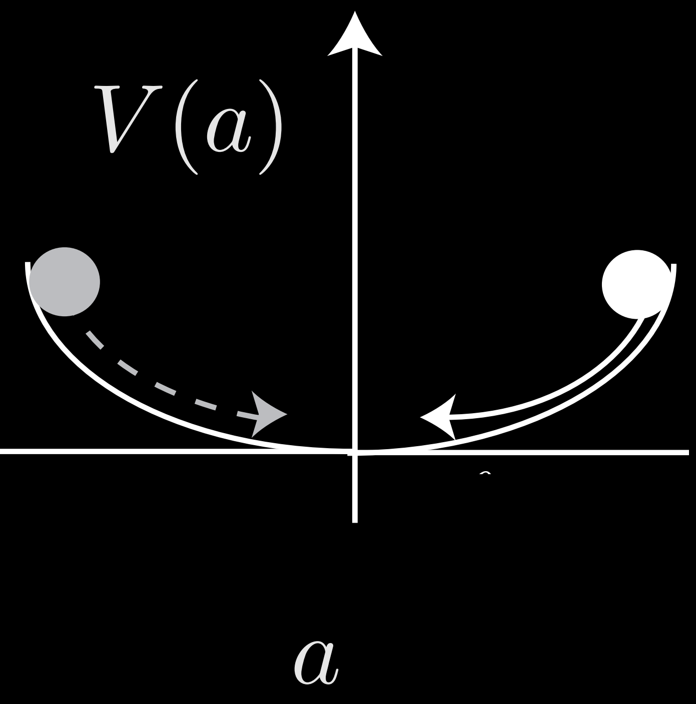


New scalar field with global U(1) symmetry!

Broken at scale f_a

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

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



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

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

Similar story to super-symmetry: Axions solve a problem with the standard model, and furnish dark matter/dark-energy candidates!

$$10^{12}\ \mathrm{GeV} < f_a < 10^{19}\ \mathrm{GeV}$$

vs

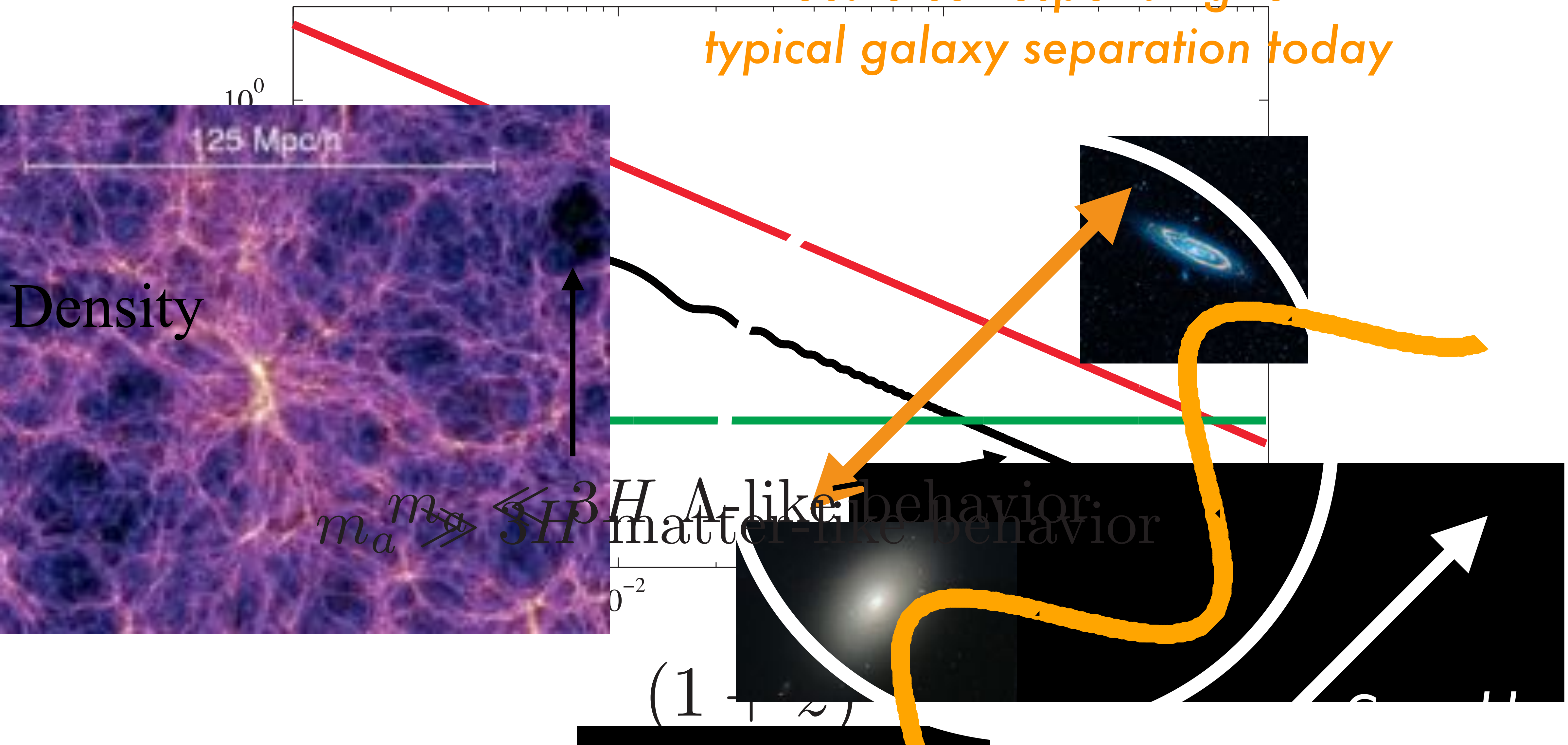
$$13\ \mathrm{TeV}$$

at terrestrial coliders

What about *VERY* low mass axions?

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)

ULA as dark matter

$m_a \lesssim 10^{-27}$ eV

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

ULA matter behavior starts too late for struct. formation

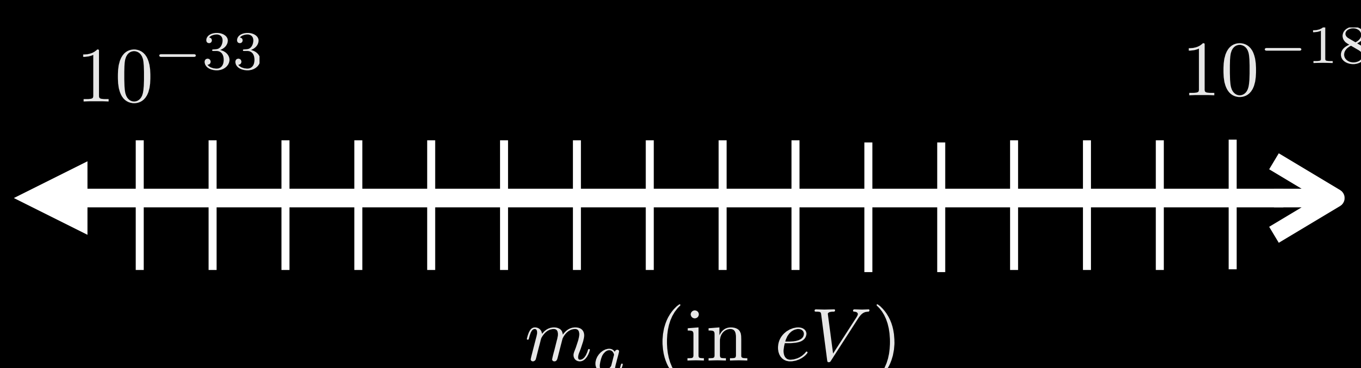
- One framework that solves SM problems is string theory
  Particles are vibrational excitations of an extended object (a ‘string’)

Figure by Matthew Herndon

- String theory may require *many* axions.

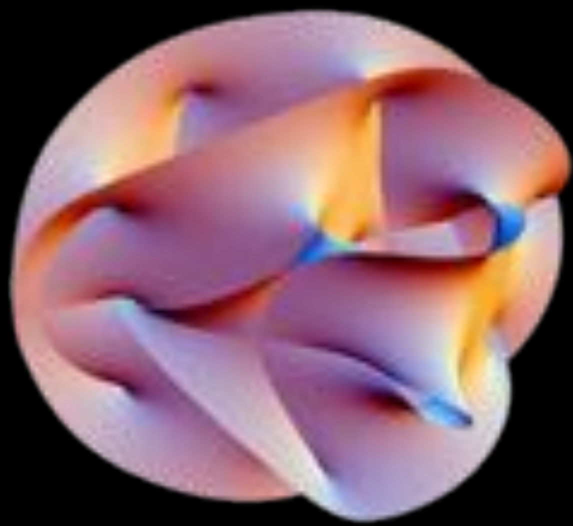
- Wide range of masses have correct dark matter/dark energy abundance

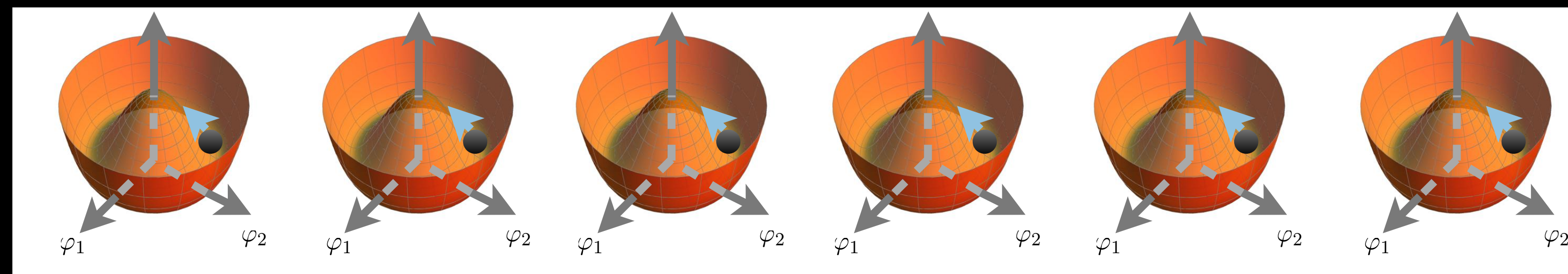
Axiverse! Witten and Srvcek (2006), *Arvanitaki+ 2009*
Acharya et al. (2010), Cicoli (2012)



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

Axiverse! *Arvanitaki+ 2009*

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

Ultra-light axions

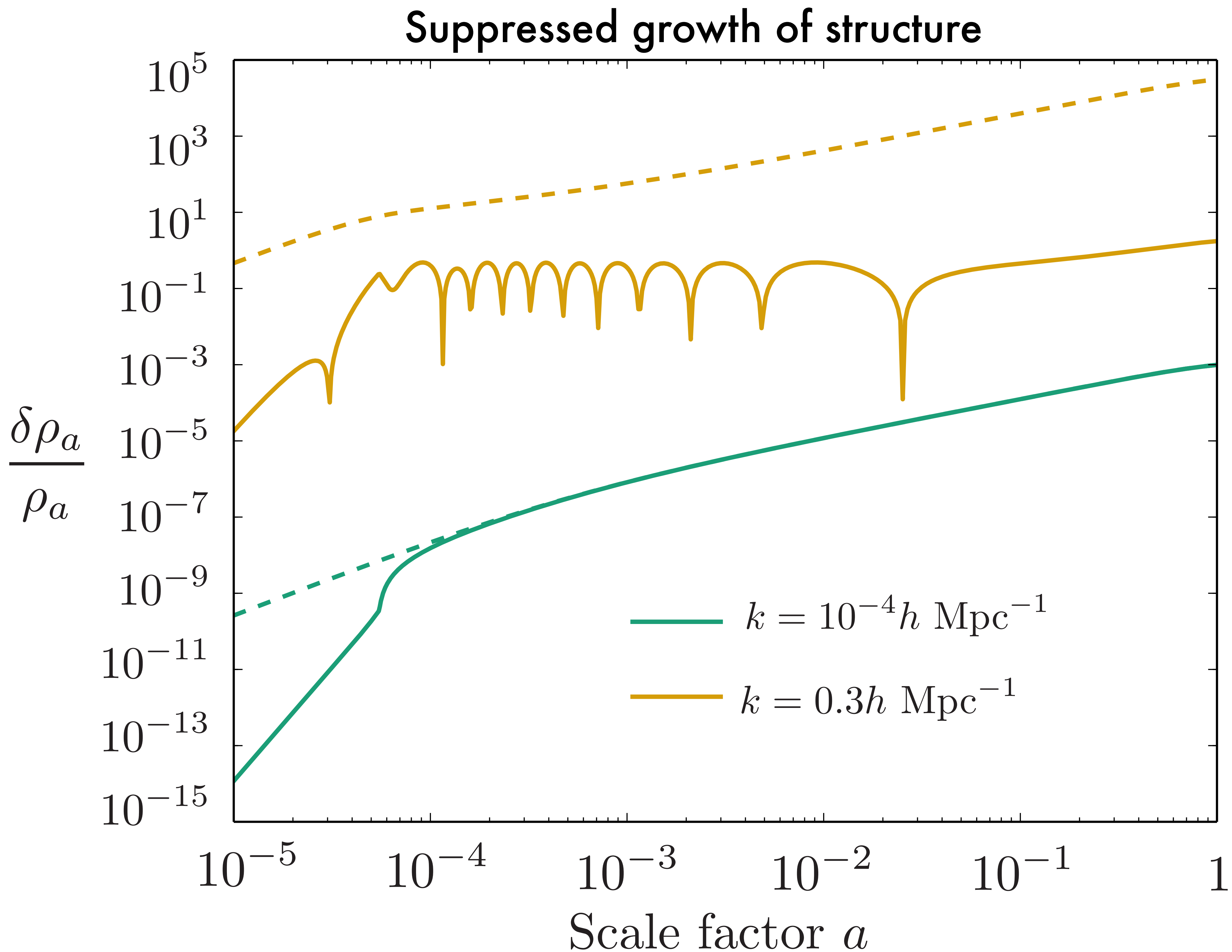
- Interactions with standard model are very small!

$$g_{a\gamma\gamma} \propto m_a$$

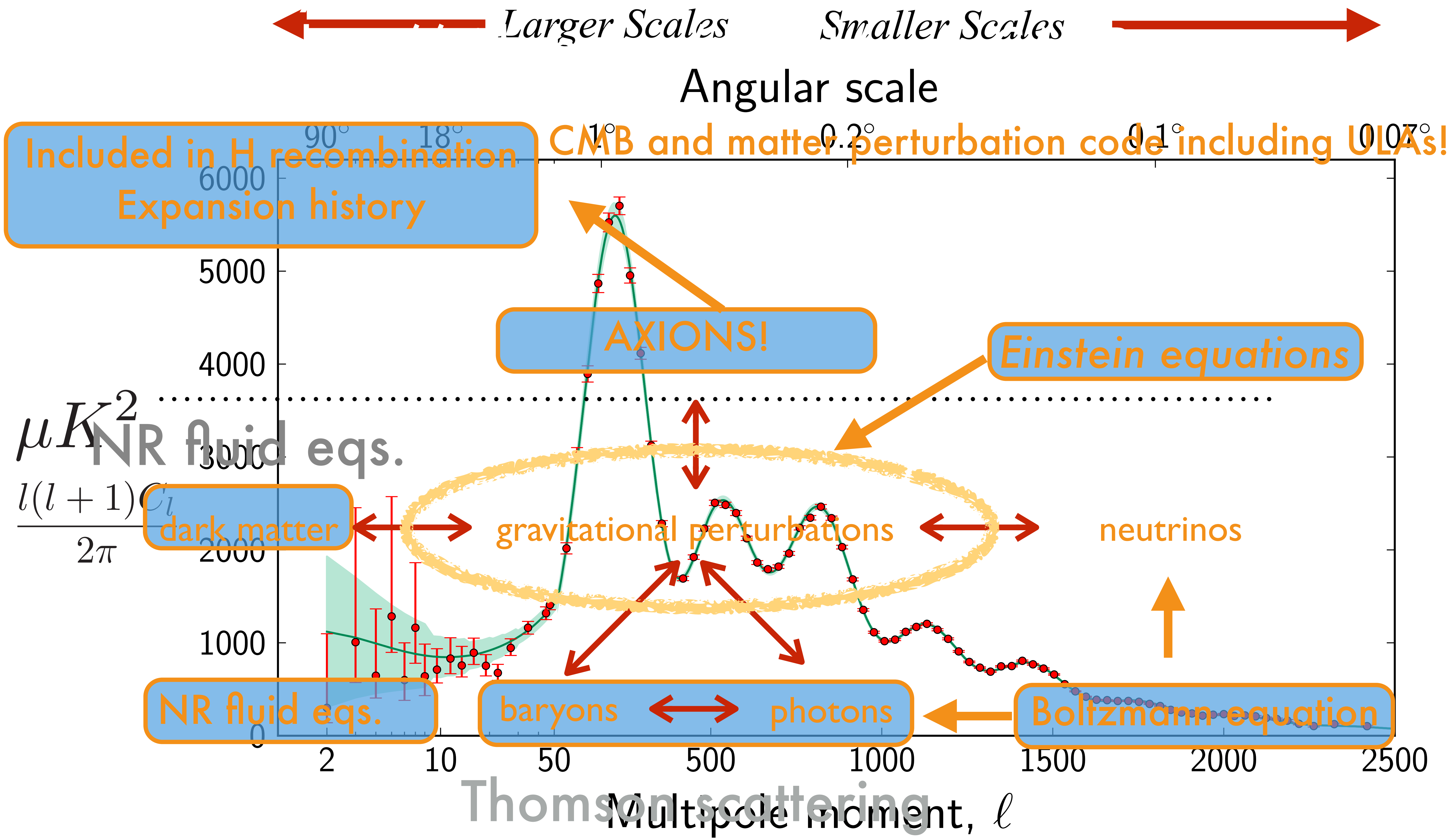
- Inaccessible to terrestrial experimentation

Ultra-light axions still gravitate!

Axions imprint on cosmology

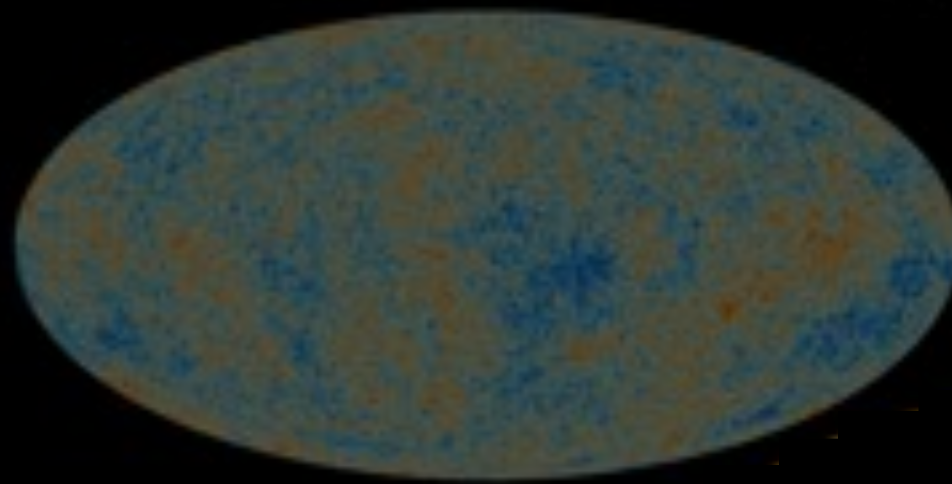


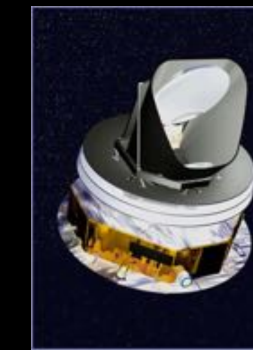
AXIONCAMB



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

Data + Analysis



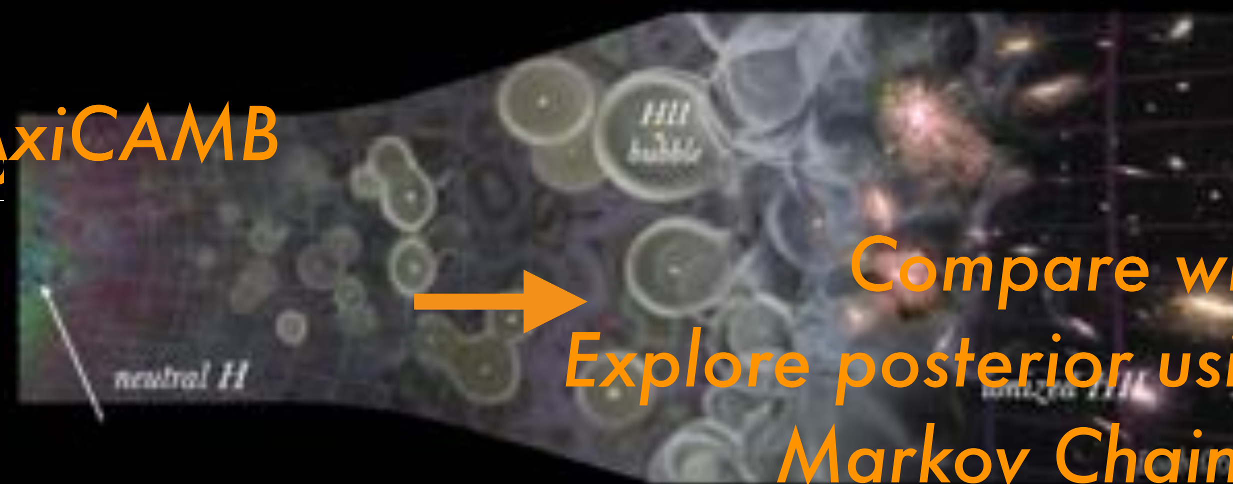


- Planck 2013 temperature anisotropy power spectra (+SPT+ACT)
  - Cosmic variance limited to $\ell \sim 1500$
- WiggleZ galaxy survey (linear scales only $k \lesssim 0.2h\ \mathrm{Mpc}^{-1}$)
  - 240,000 emission line galaxies at z<1
  - 3.9 m Anglo-Australian Telescope (AAT)
- Nested sampling, MCMC,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

Difficult parameter space

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

$\Delta^2_{\mathcal{R}}(k$ AxiCAMB ditions

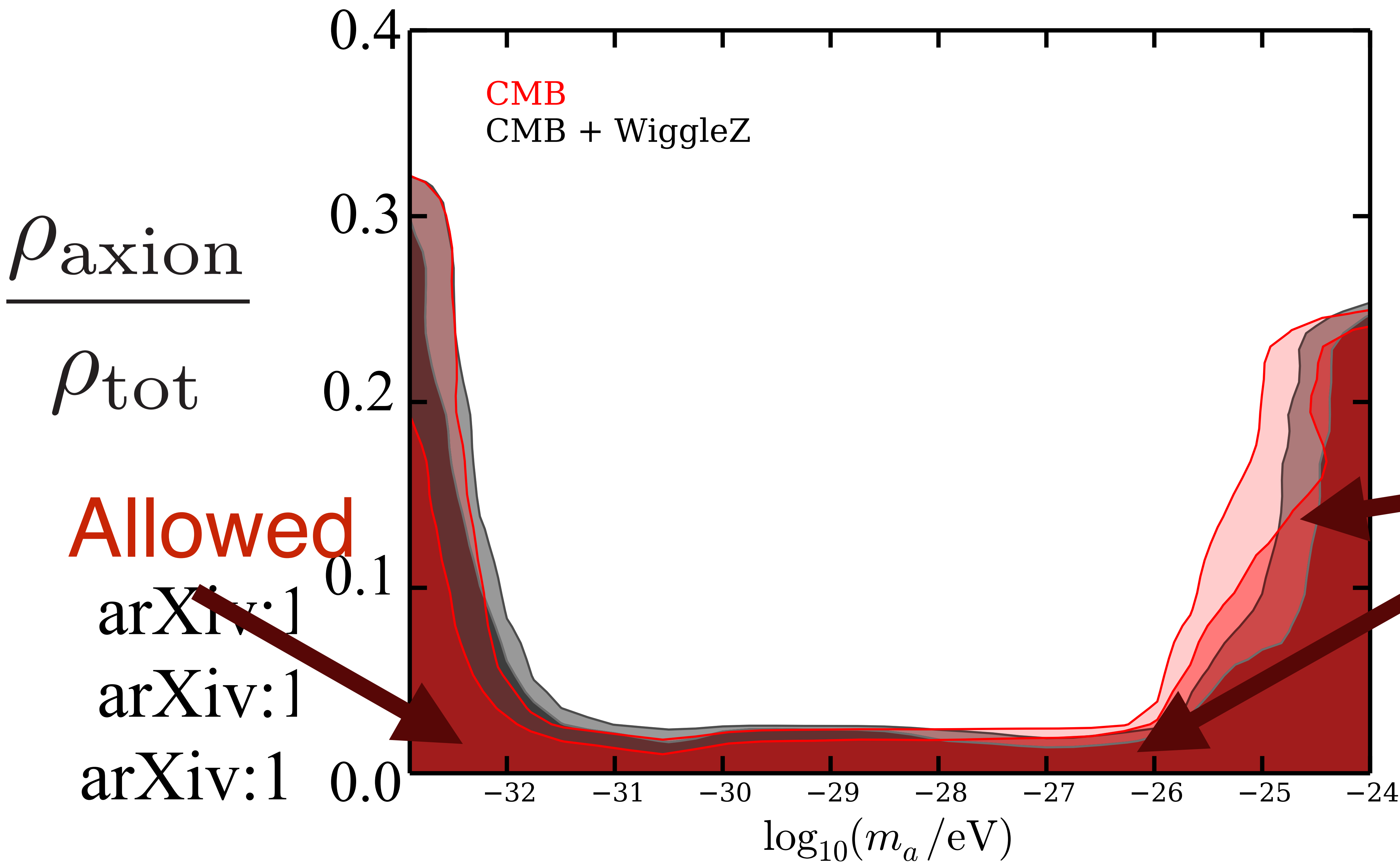


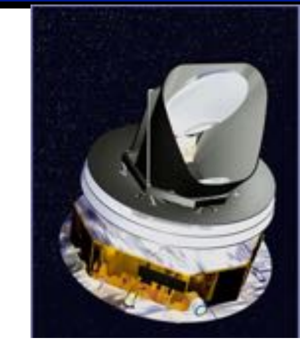
Compare with data

Explore posterior using Monte Carlo Markov Chain (MCMC)

Degeneracies addressed using nested sampling MultiNest (Hobson, Feroz, others 2008)

CONSTRAINTS





arXiv:1 ... 15)

arXiv:1 ... (2014)

arXiv:1 ... 2013)

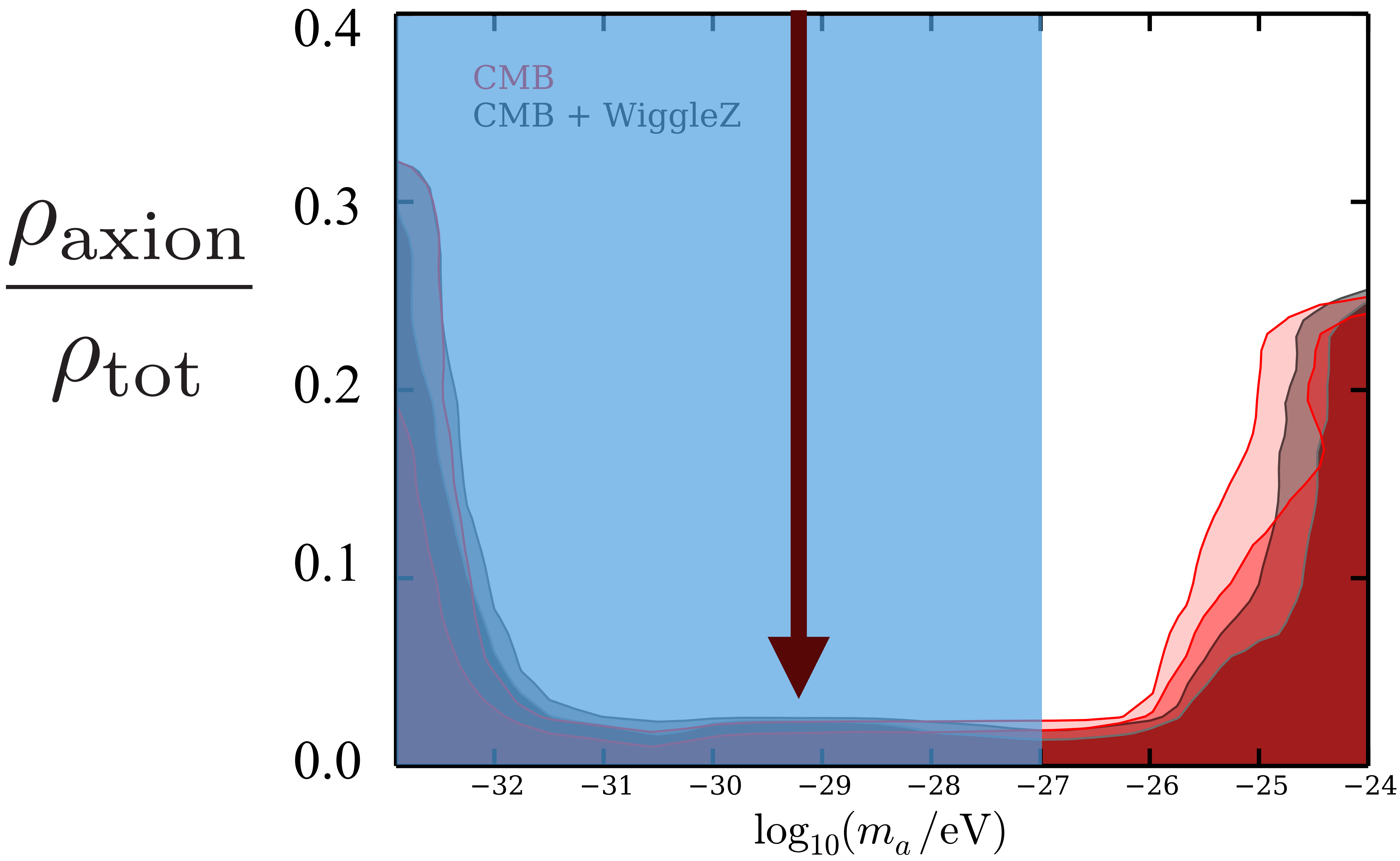
✳Tight constraints over 7 orders of magnitude in mass:

Thanks to AxionCAMB and Planck

✳ULAs are viable DM/DE candidates in linear theory outside ``belly''

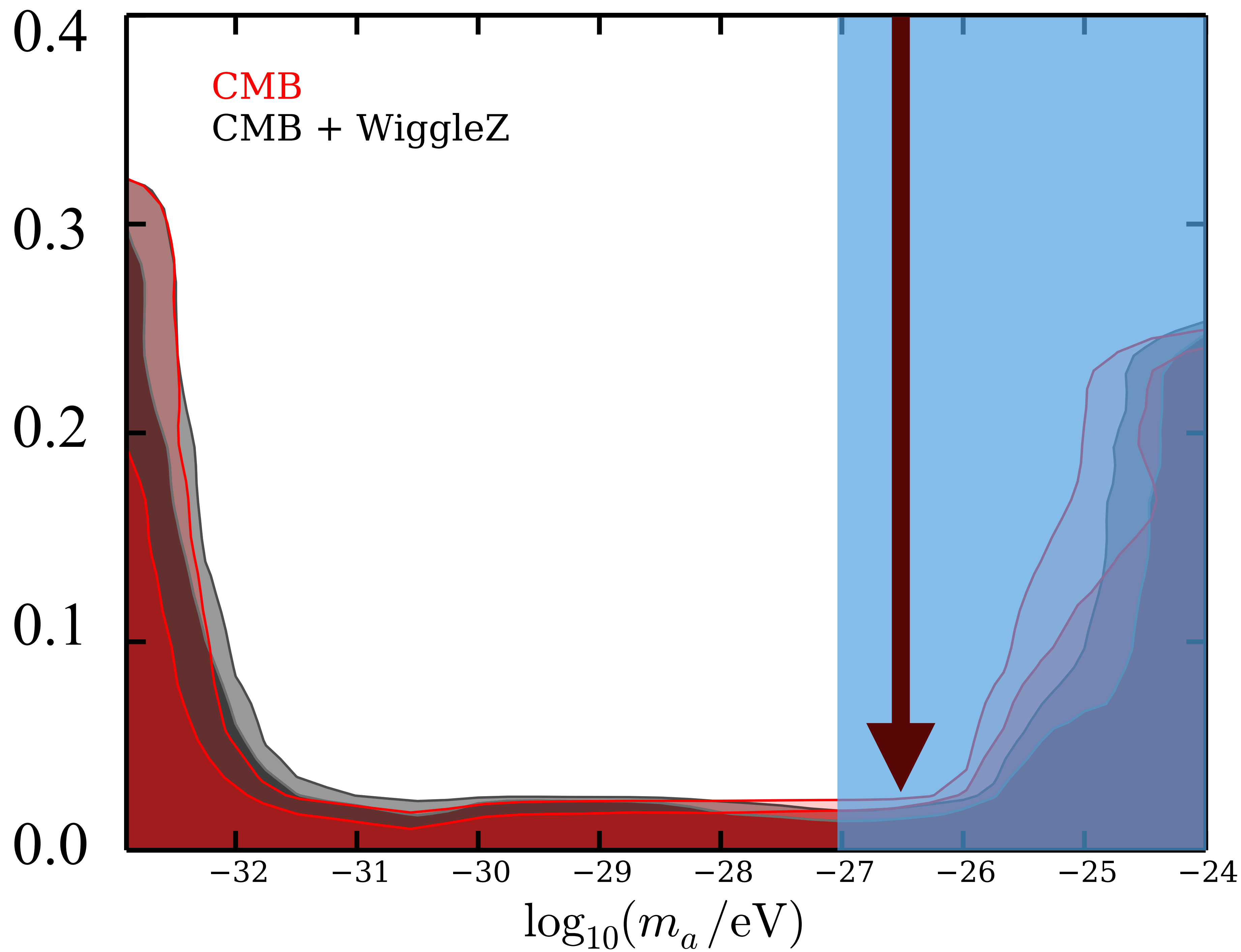
CONSTRAINTS

Dark-energy type axions

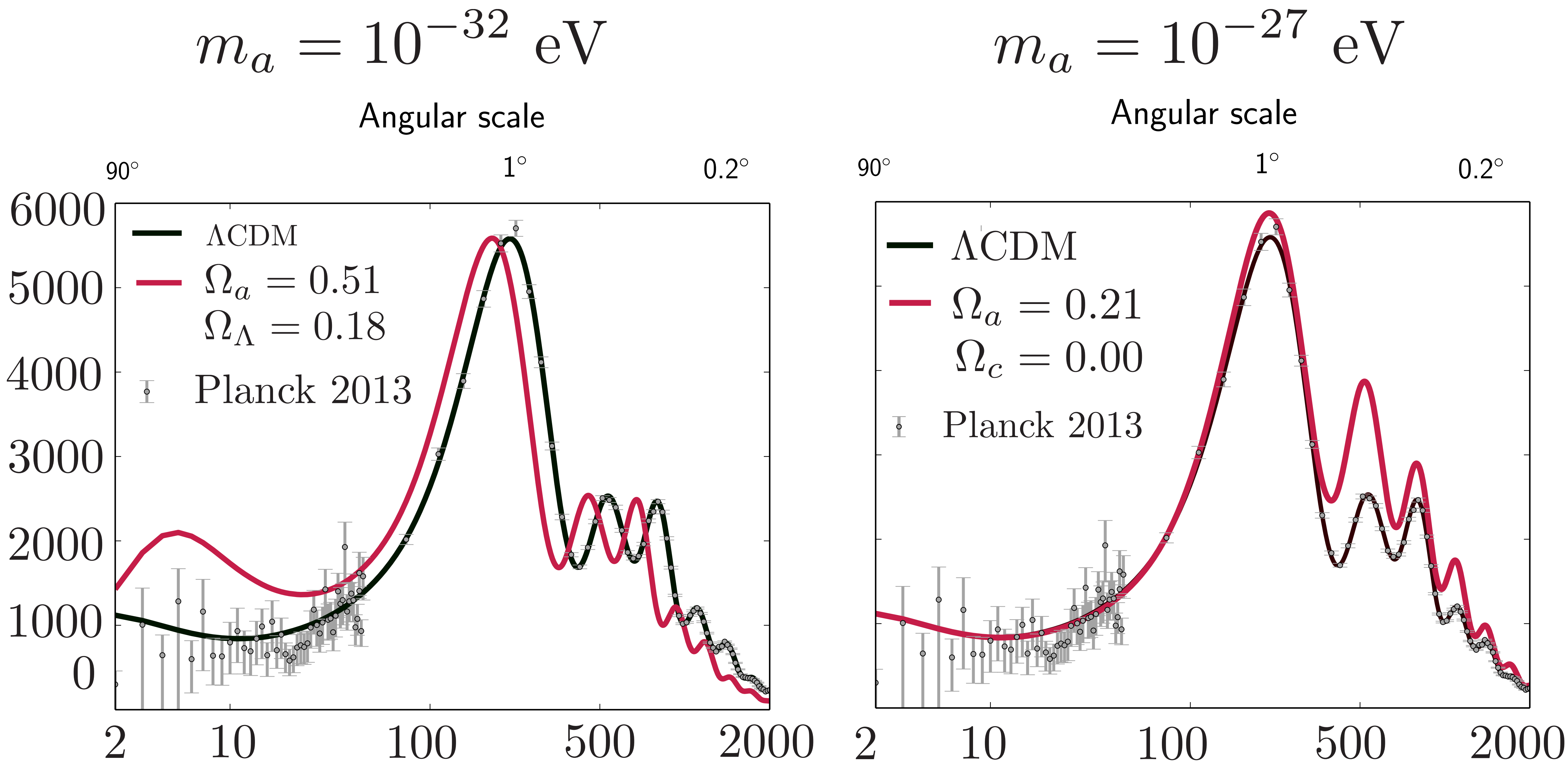


Dark-matter type axions

$$\frac{\rho_{\rm axion}}{\rho_{\rm tot}}$$

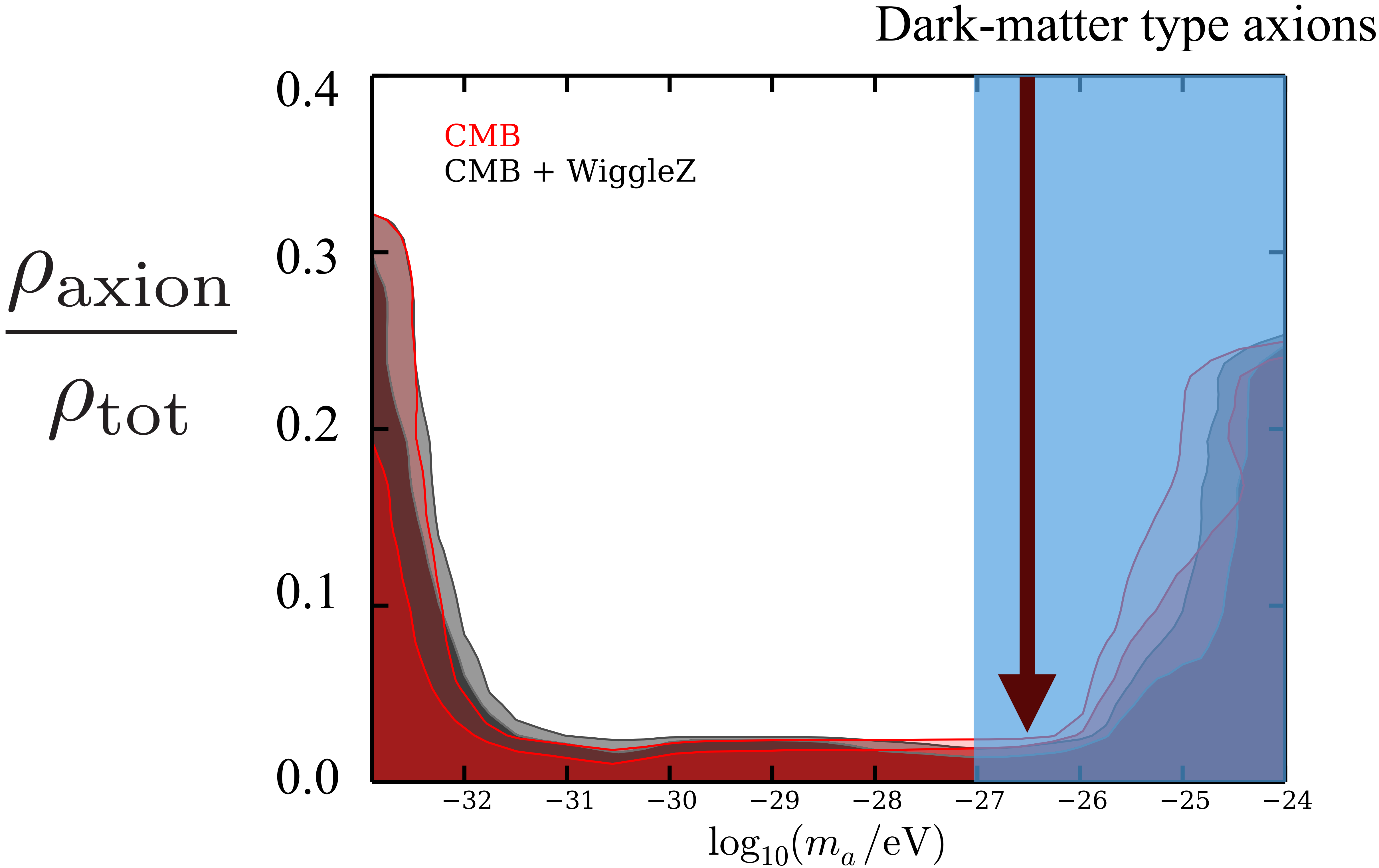


CONSTRAINTS



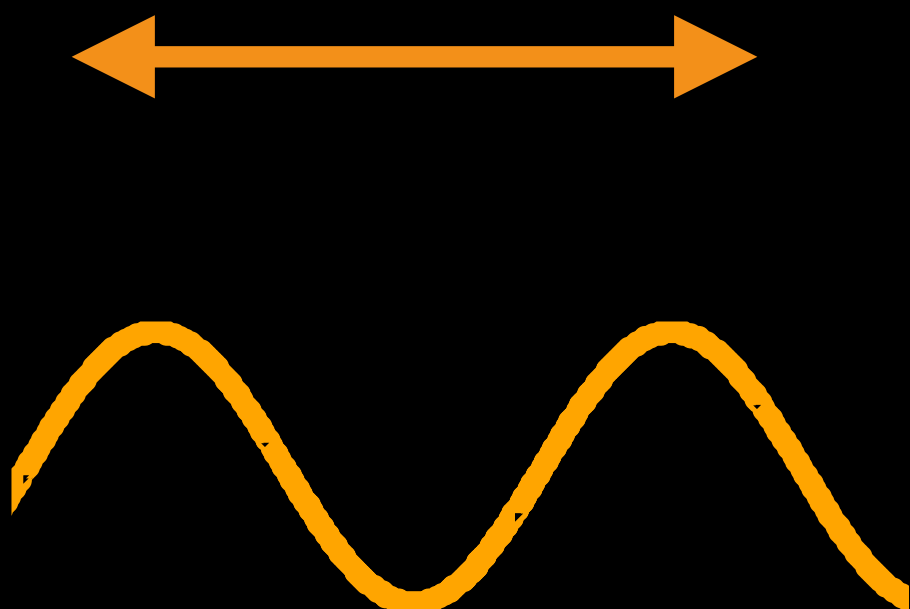
Dramatic changes to observables can result

CONSTRAINTS

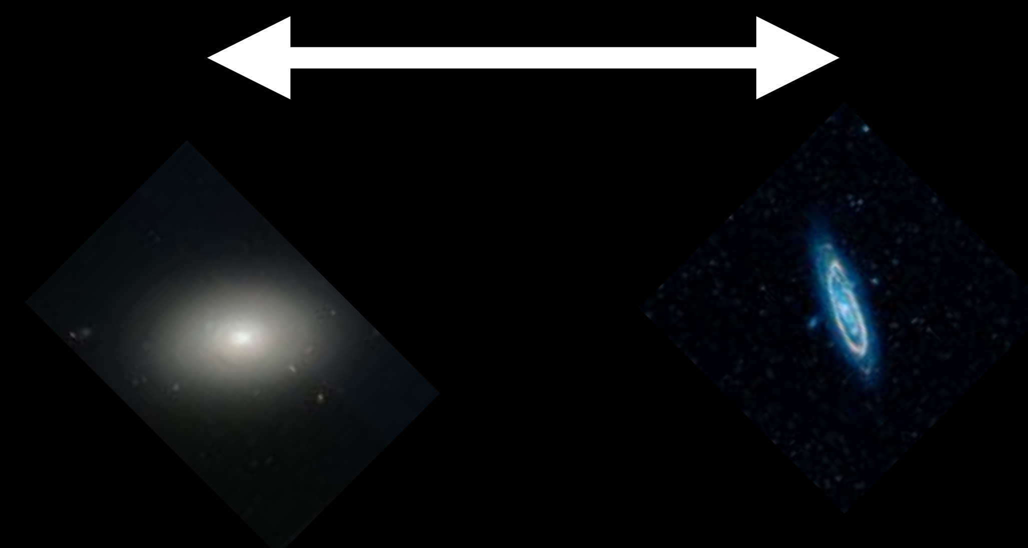


Look for ultra-light axions in the cosmos

Axion deBroglie wavelength

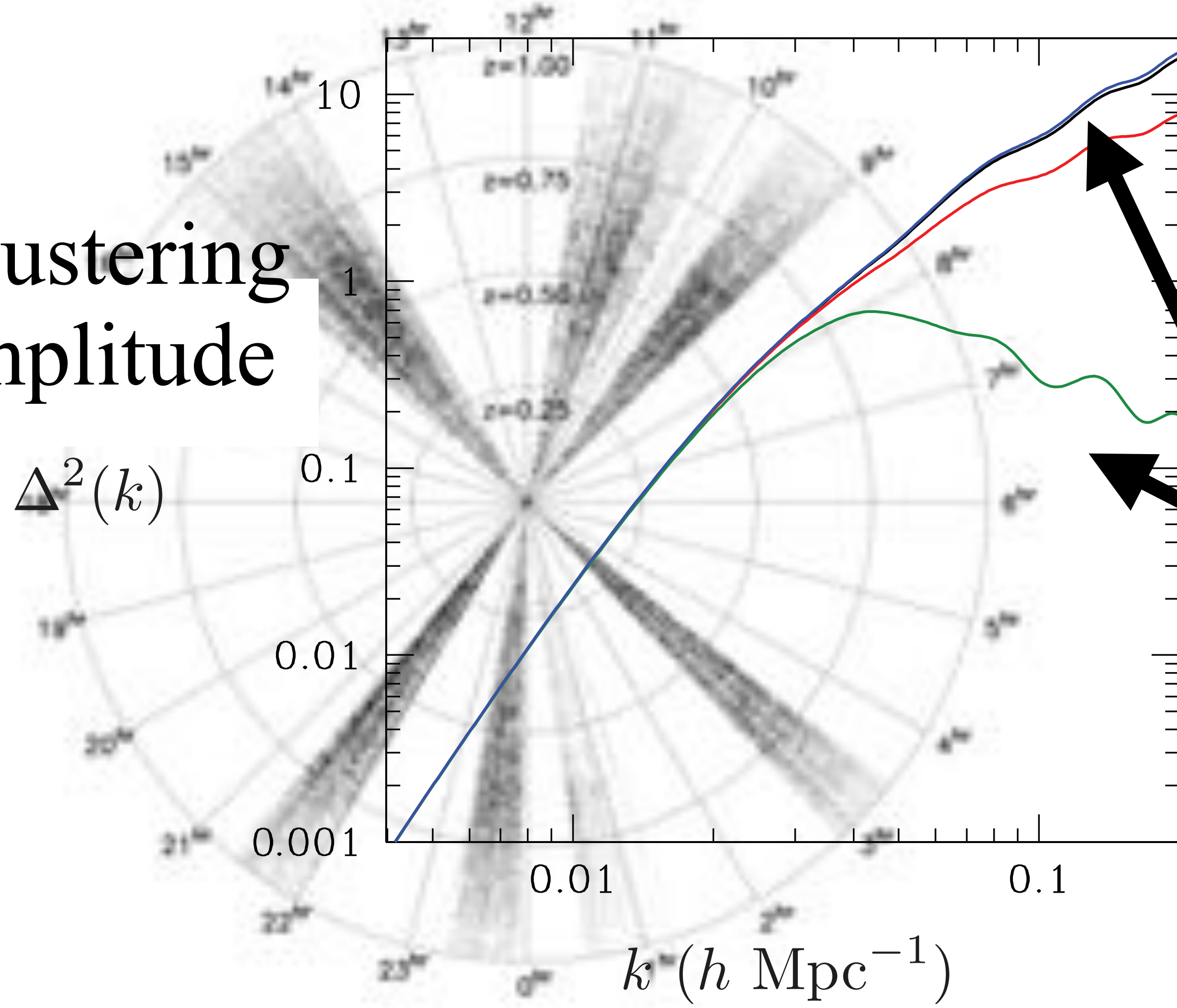


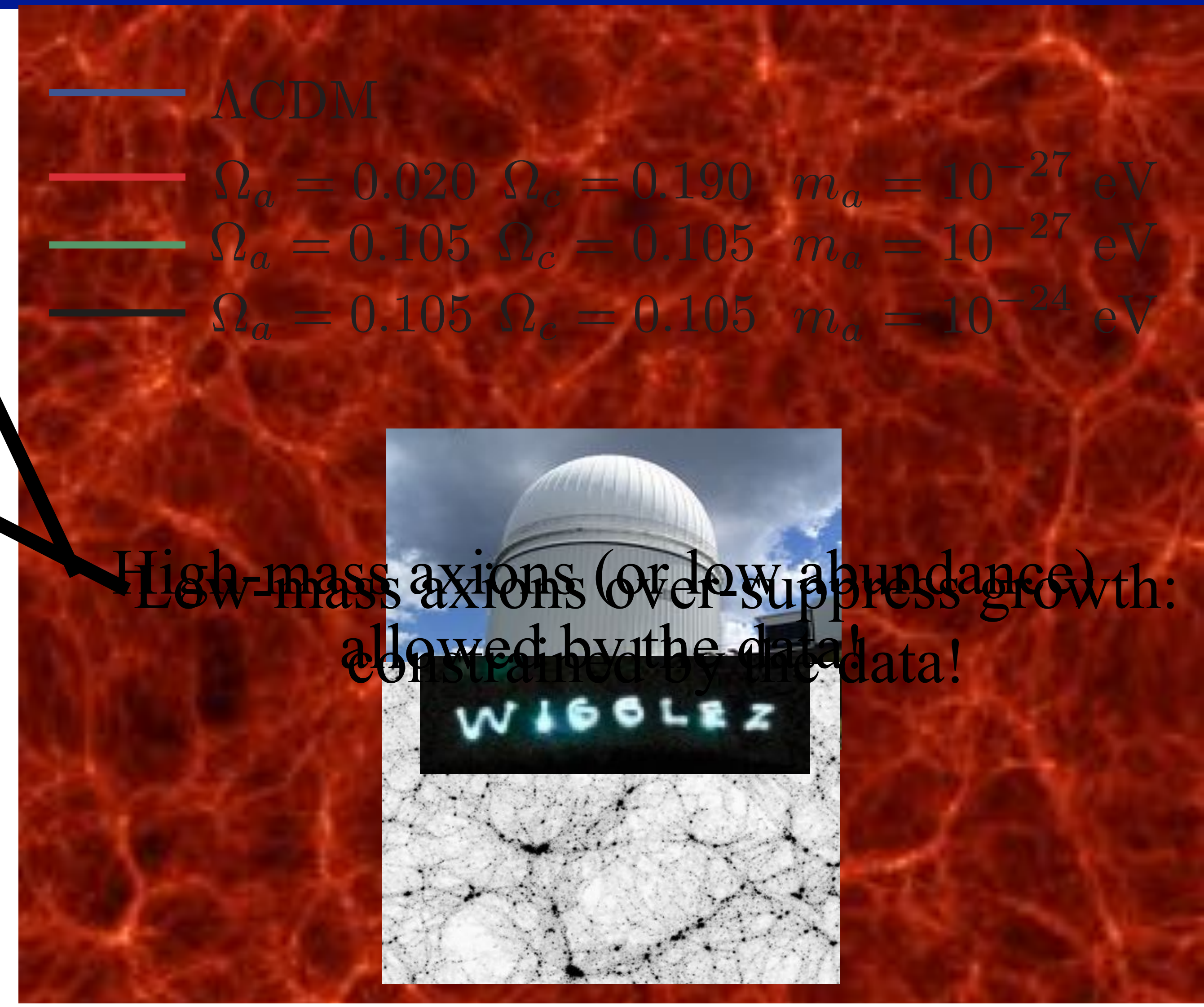
Astronomical length scale
kilo-lightyear – giga-lightyear!



Matter clustering for ULA (in dark matter regime)

Clustering amplitude





Larger length scales

✴DM structure growth severely suppressed on sca $\overline{m\mathcal{H}}$

✴Galaxies trace the matter in the universe

✴Suppression grows $\propto -\dfrac{\Omega_a}{\Omega_a+\Omega_c}$

CMB-S4

CMB-S4
Next Generation CMB Experiment

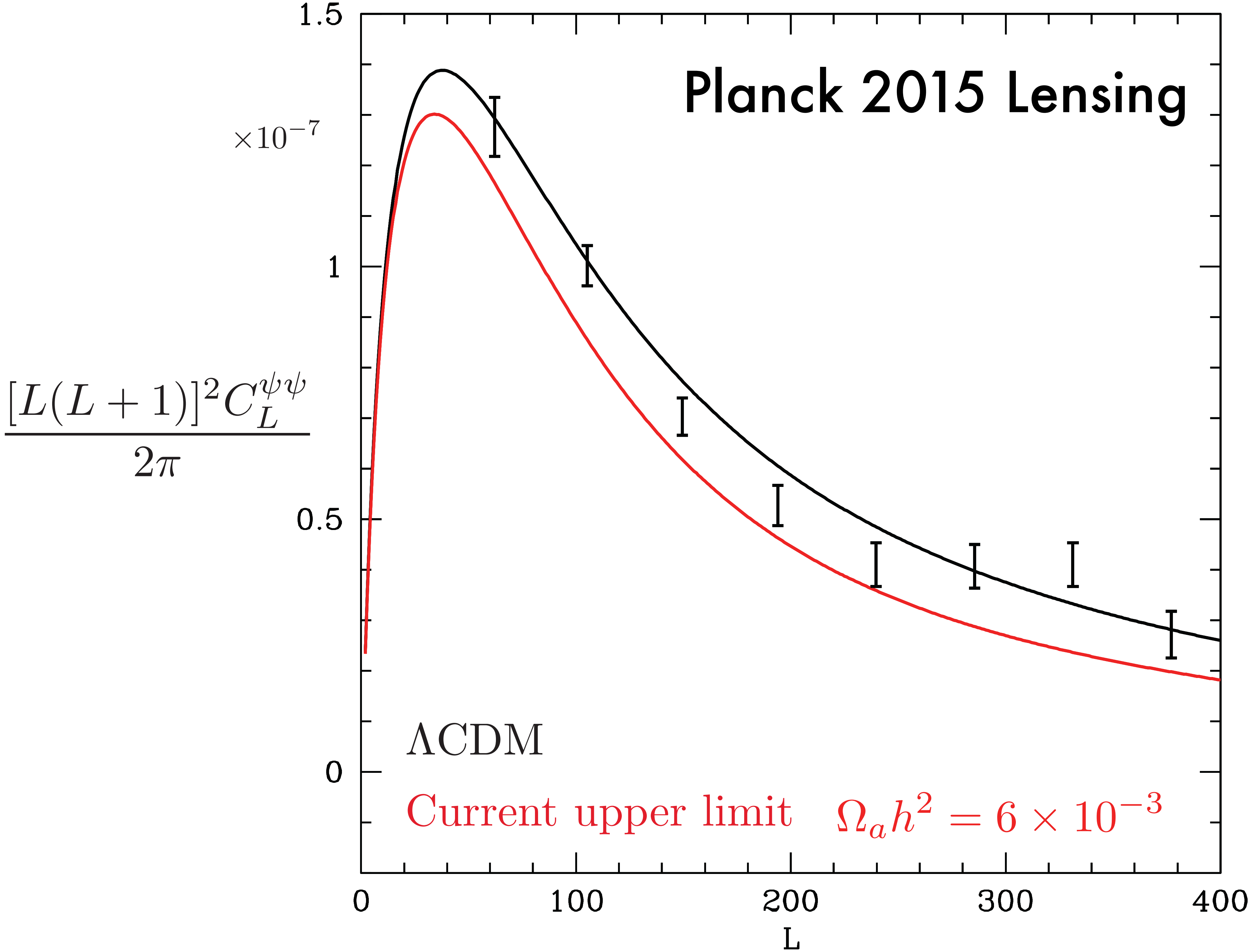
- Next gen. CMB ground-based expt. concept
  - ~1 arcmin beam
  - $1\ \mu$K arcmin noise level
  - ~500,000 detectors
  - Location, sky coverage TBD

From CMB-S4 Science book…. arXiv: 1610.02743

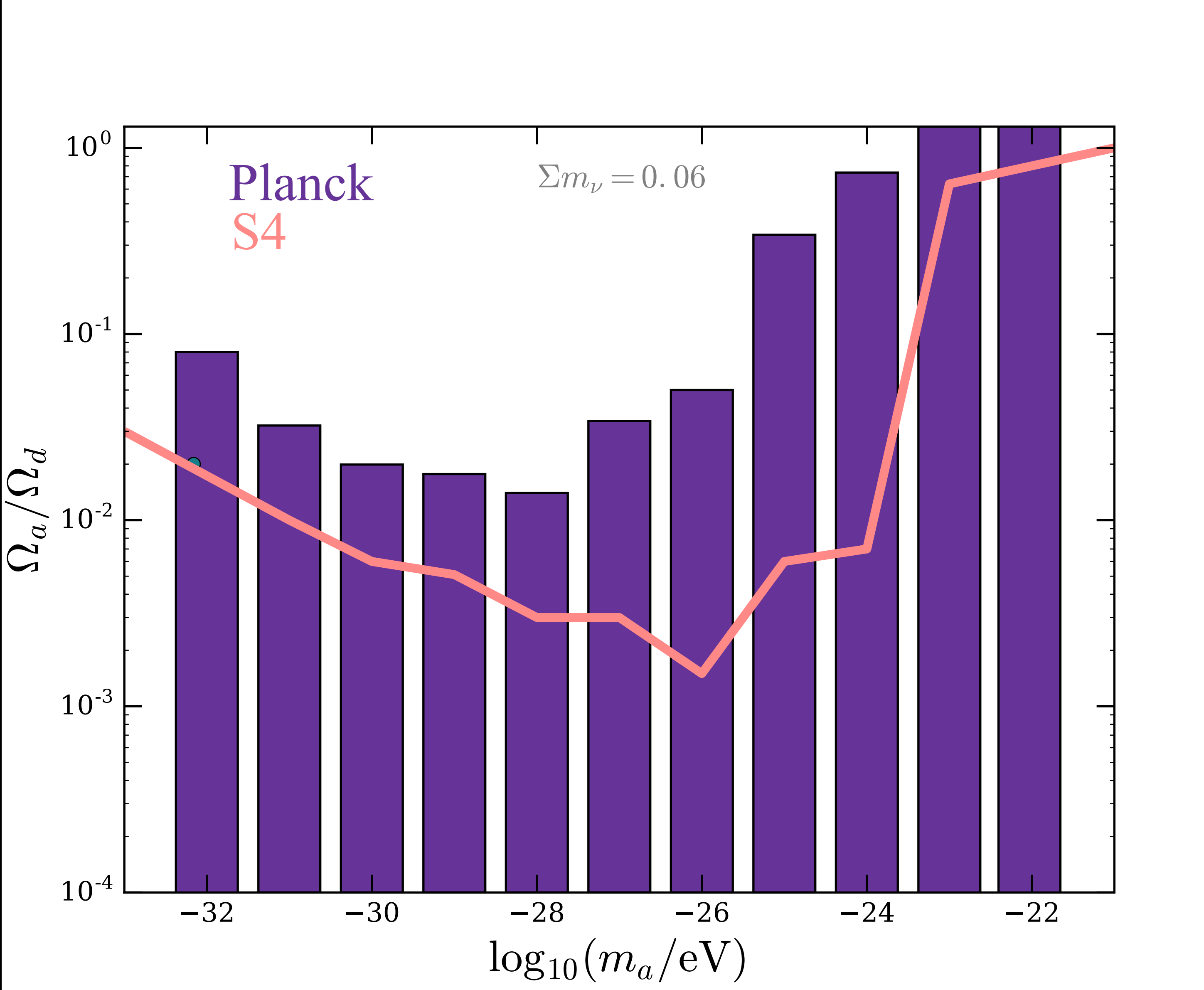
CMB LENSING

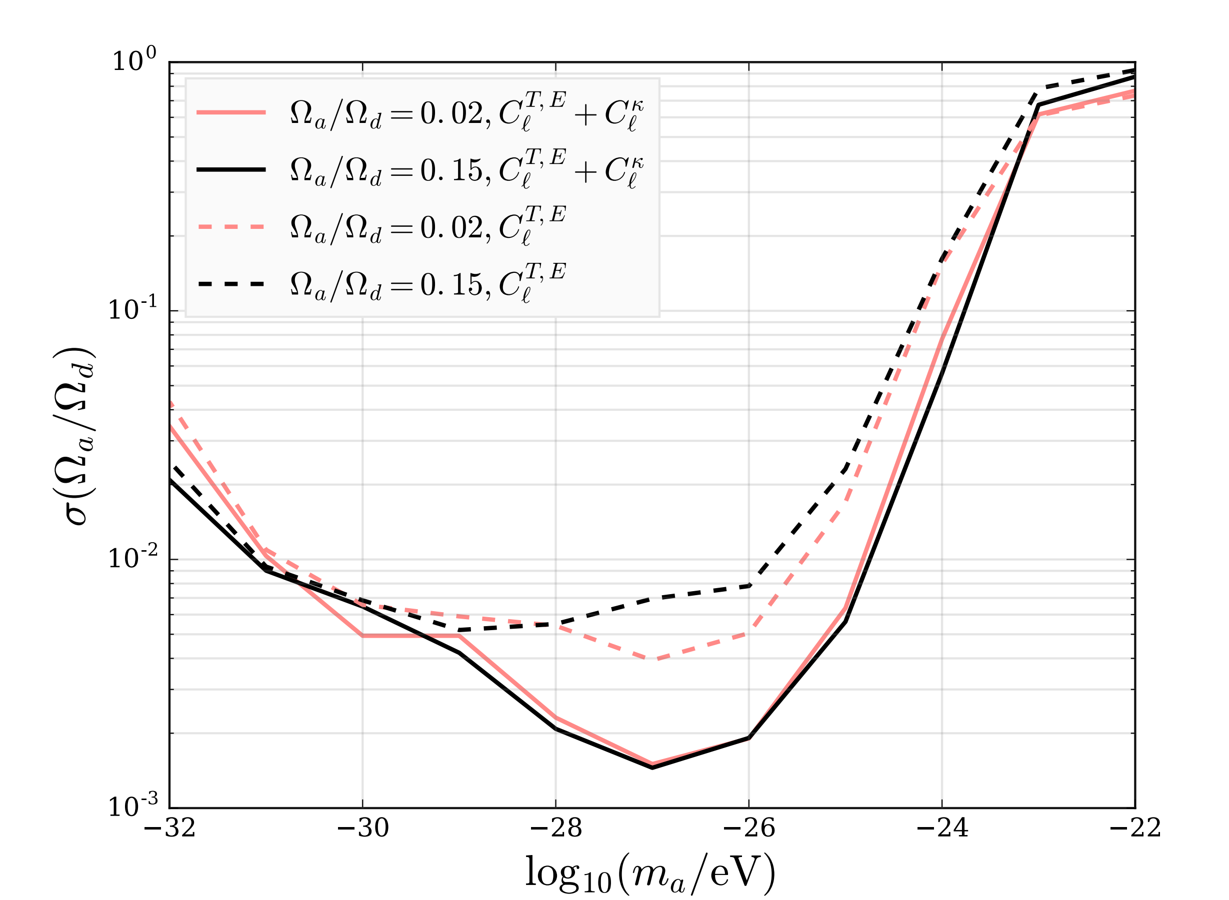
Source [partially hidden] z~1

ULA saturating TT-only limits falsifiable at 4.5σ



S4-cast for lensing and ULAs





Fisher forecast using OxFish code— OOM improvement driven by lensing

INITIAL CONDITIONS— INFLATION

INFLATION

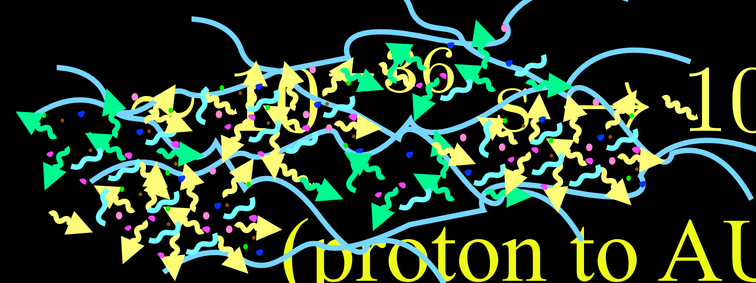
Quantum fluctuations set initial conditions for CMB and all resulting inhomogeneity (galaxies etc)

Alan Guth 1981

$\Delta E \sim \frac{\hbar}{\Delta t}$

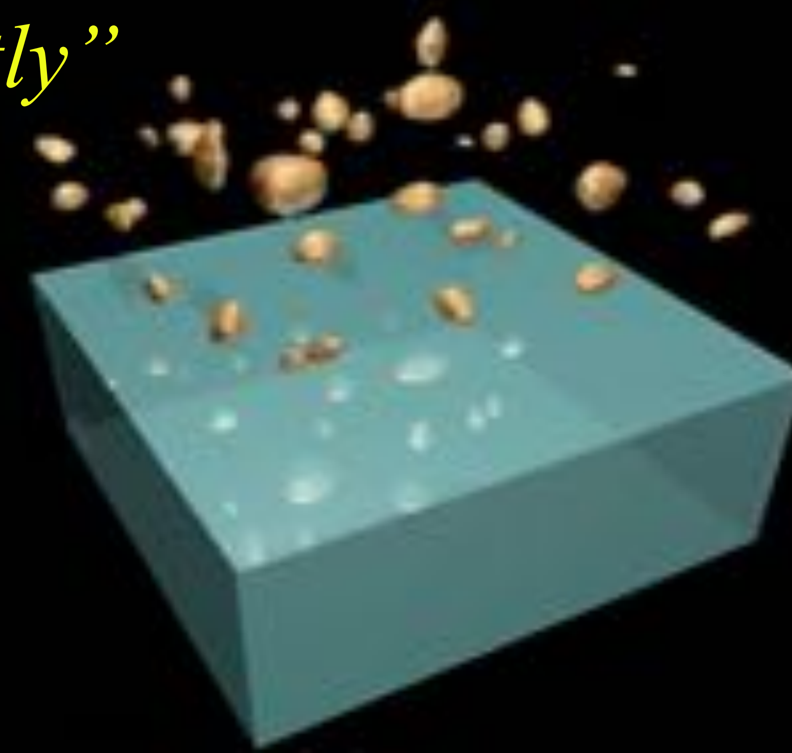
The Universe expanded exponentially in time

Scale doubled 260 times "*instantly*"



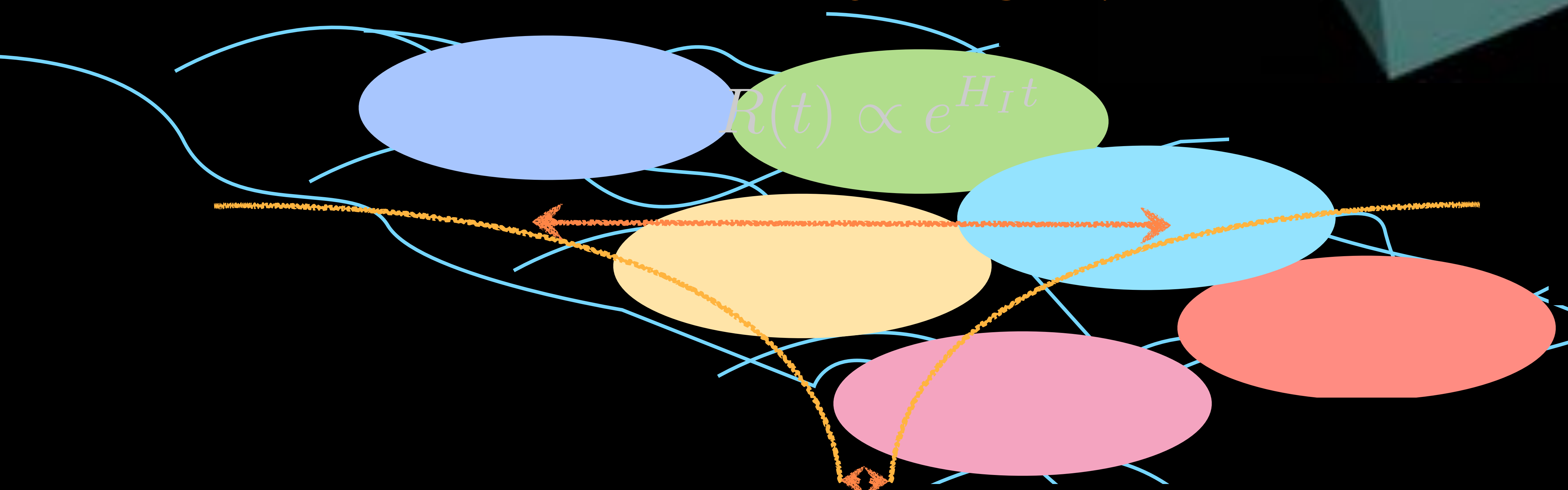
10^{-36} s $\to 10^{-32}$ s

(proton to AU).



$E \sim 10^{16}$ GeV

$R(t) \propto e^{H_I t}$



Implications for measuring the scale of primordial inflation

$m_a \gtrsim 10^{-26}\ \mathrm{eV}$

$H_I \lesssim 10^{13.5}\ \mathrm{GeV}$

$4\times 10^{-8}\ \mathrm{eV} \gtrsim m_a \gtrsim 4\times 10^{-11}\ \mathrm{eV}$

$10^{8}\ \mathrm{GeV} \lesssim H_I \lesssim 10^{10}\ \mathrm{GeV}$

$$\Phi \propto \left(\frac{\delta\rho_a}{\rho_a}\right)\left(\frac{\rho_a}{\rho_{\rm total}}\right) \ll 10^{-5}$$

$4\times 10^{-4}\ \mathrm{eV} \gtrsim m_a \gtrsim 4\times 10^{-5}\ \mathrm{eV}$

$10^{6}\ \mathrm{GeV} \lesssim H_I \lesssim 10^{7}\ \mathrm{GeV}$

Neutrinos

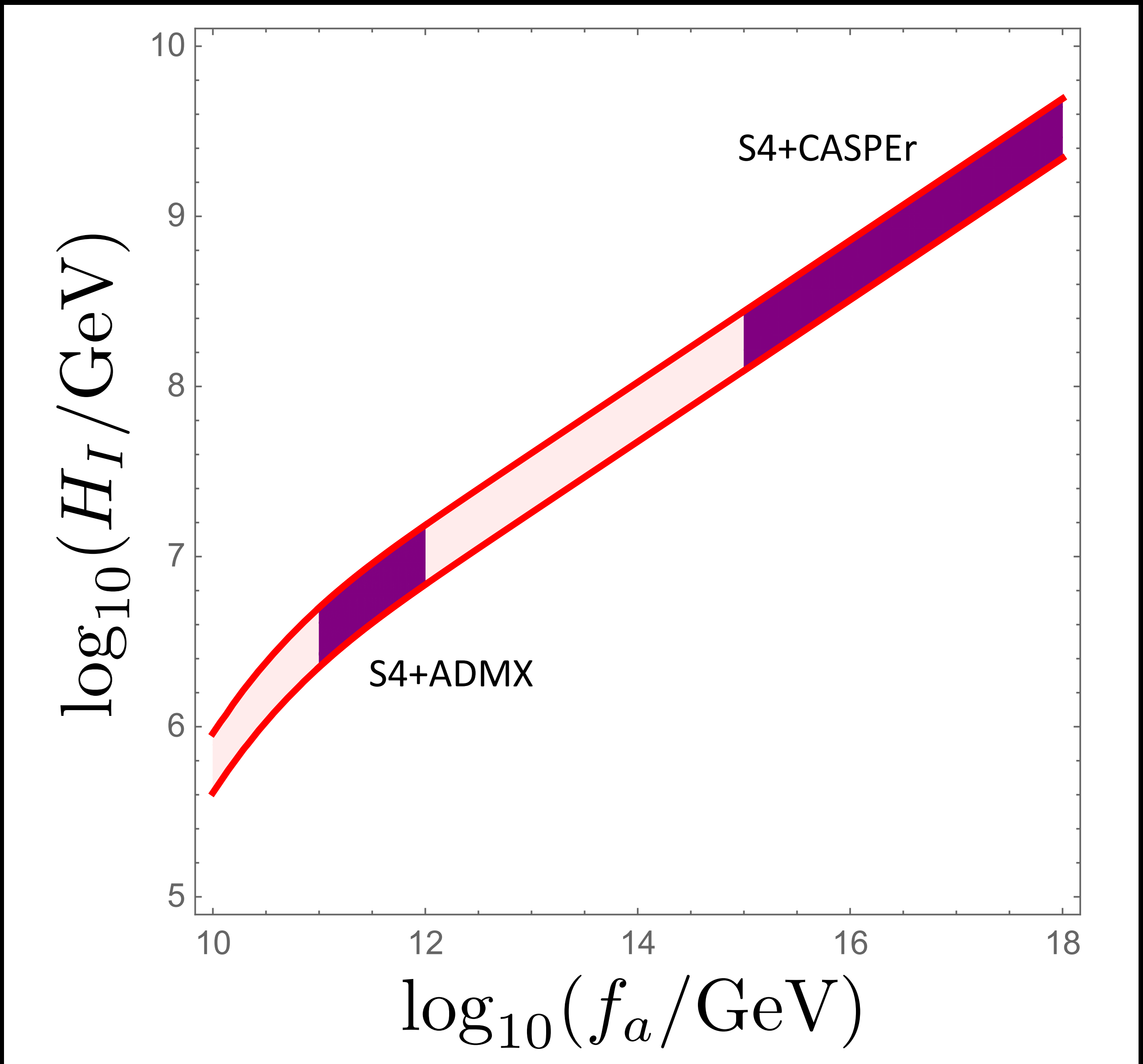
CDM

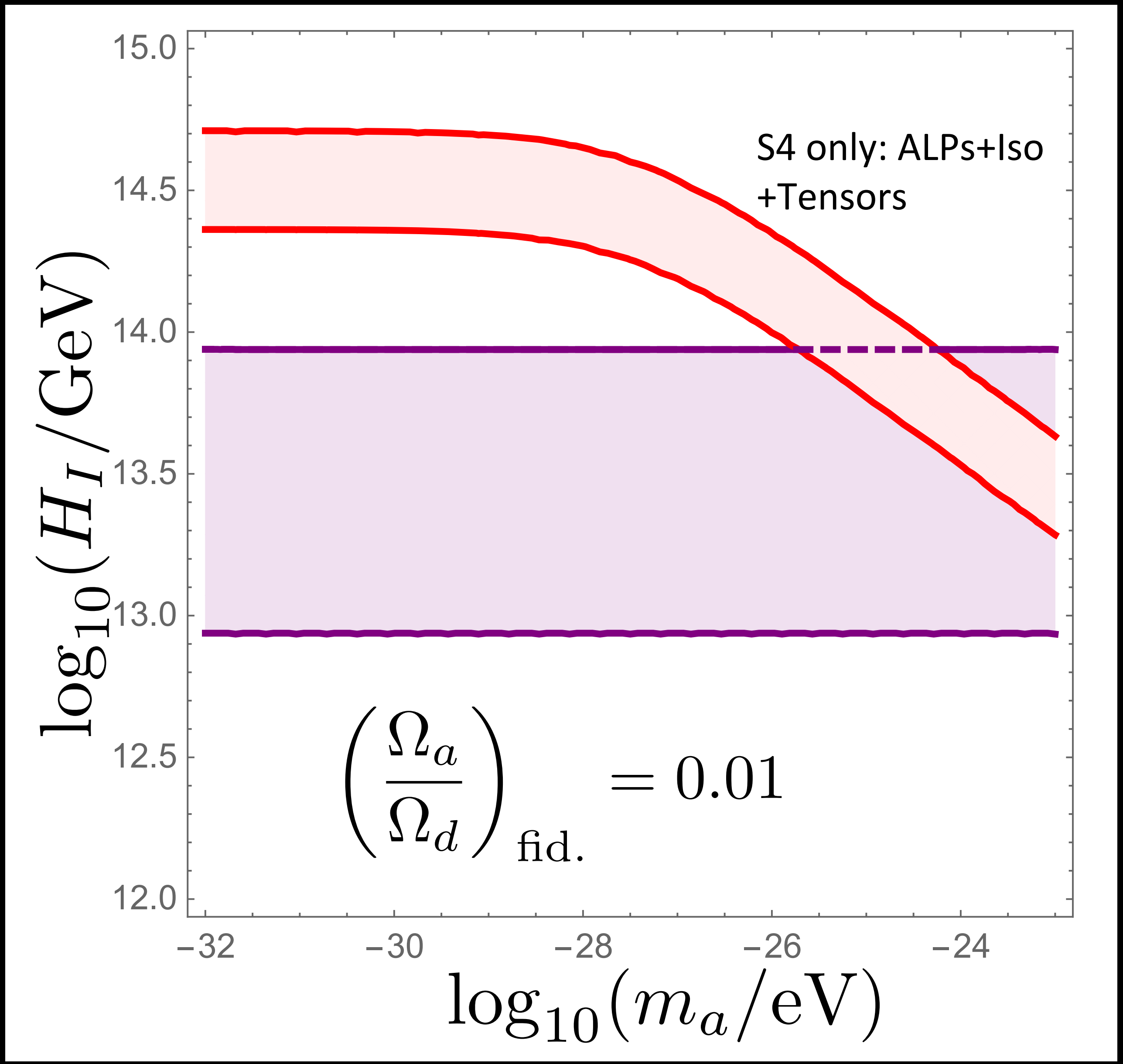
Photons

Baryons

Could be probed by ADMX/CASPER (ongoing/upcoming axion search experiments)

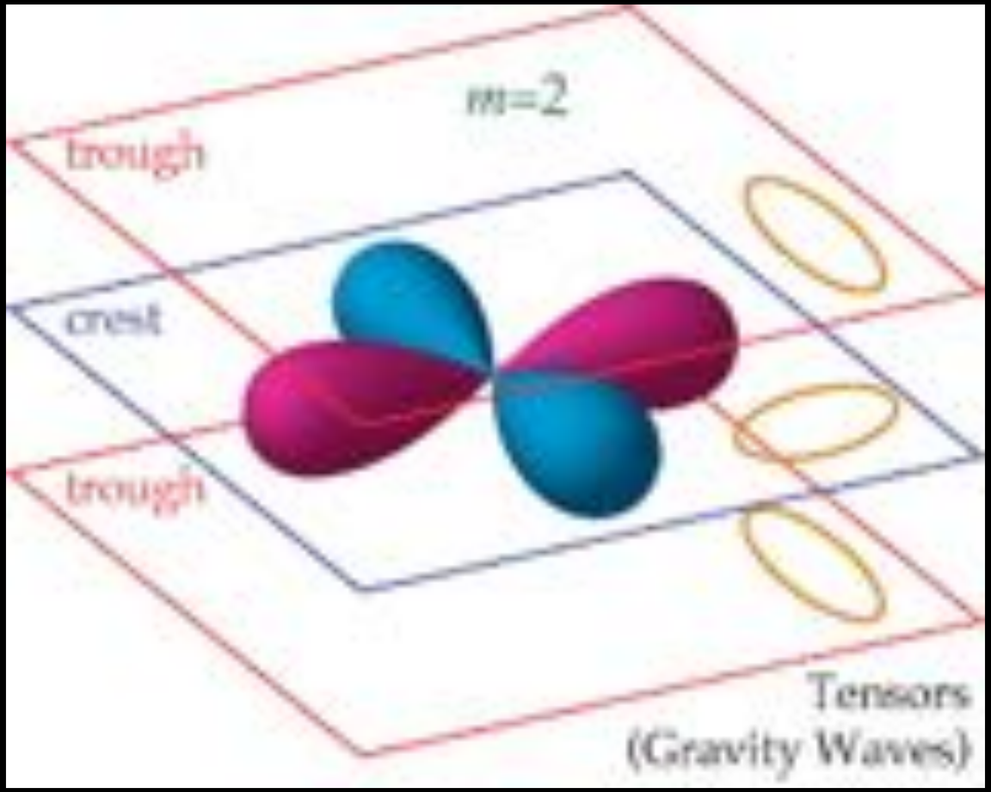
HIGH-ENERGY COSMOLOGY WITH AXION ISOCURVATURE

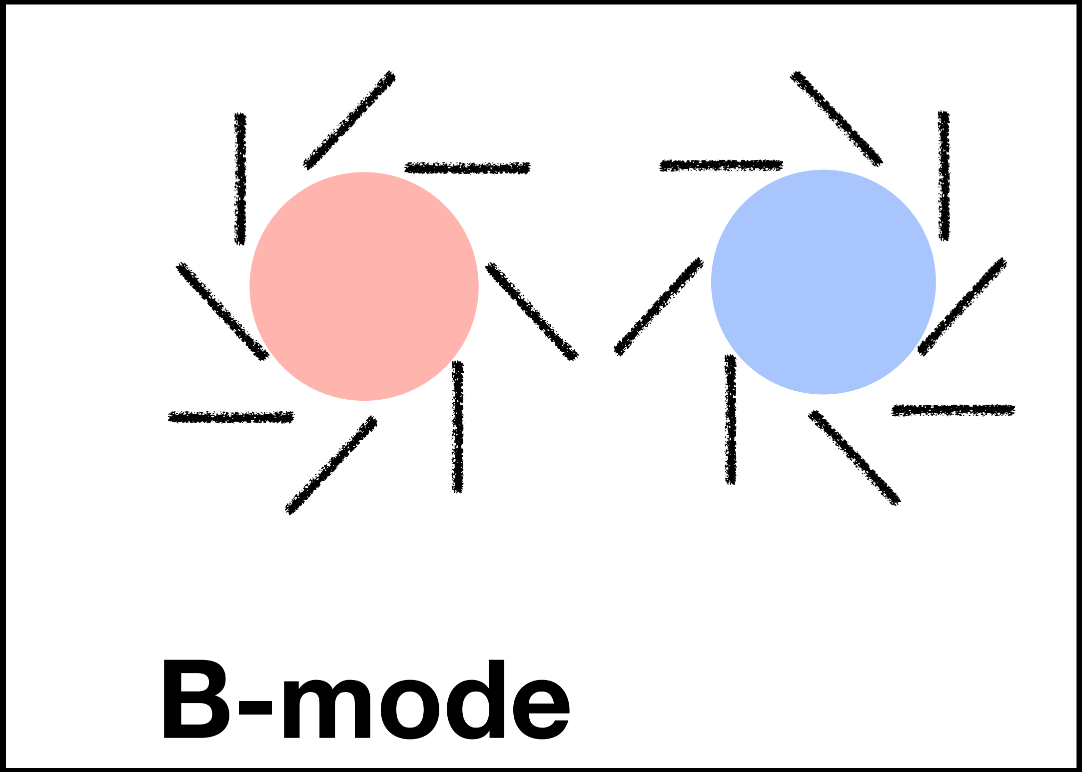


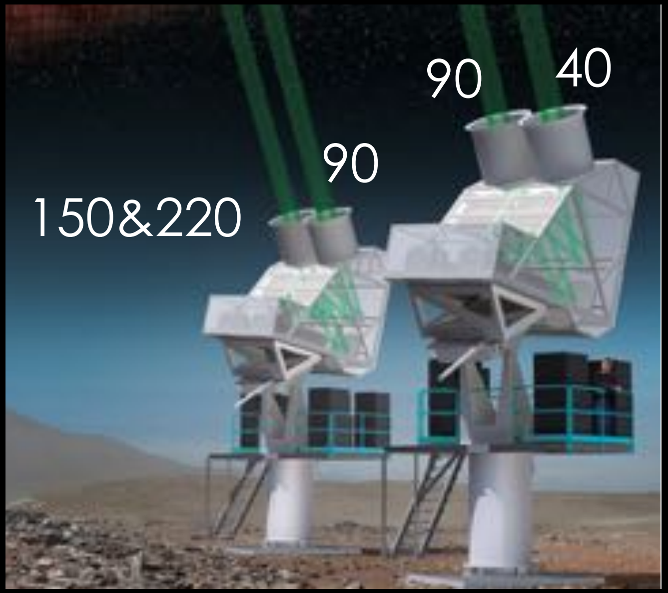


The observational/experimental horizon for axion
dark matter/dark energy tests is bright!
Potential trouble for GUT-scale inflation

ULAs as an inflationary probe



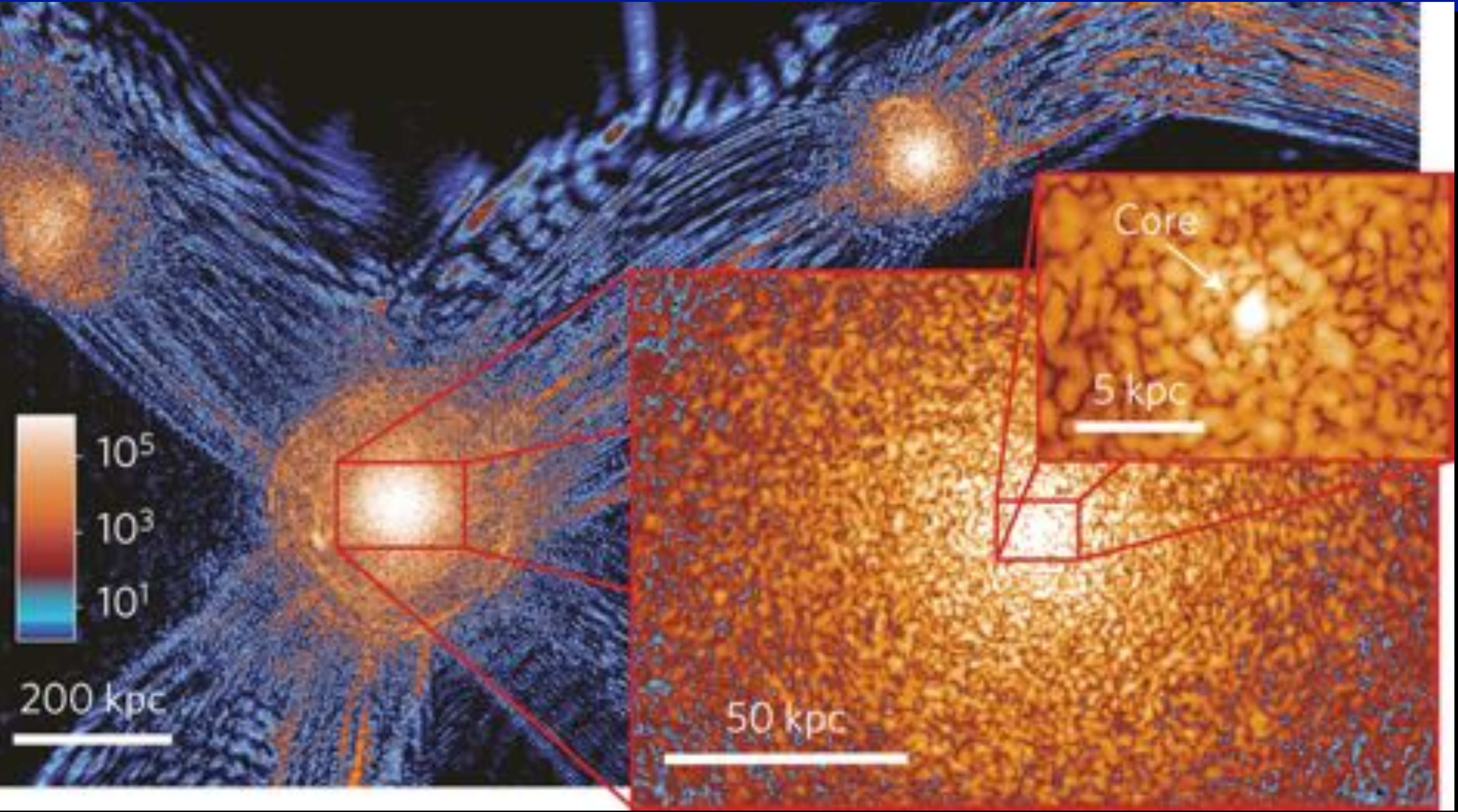




Spider SPT/BICEP2-3/KECK

CLASS

Future work: ULAs cores + cusps?

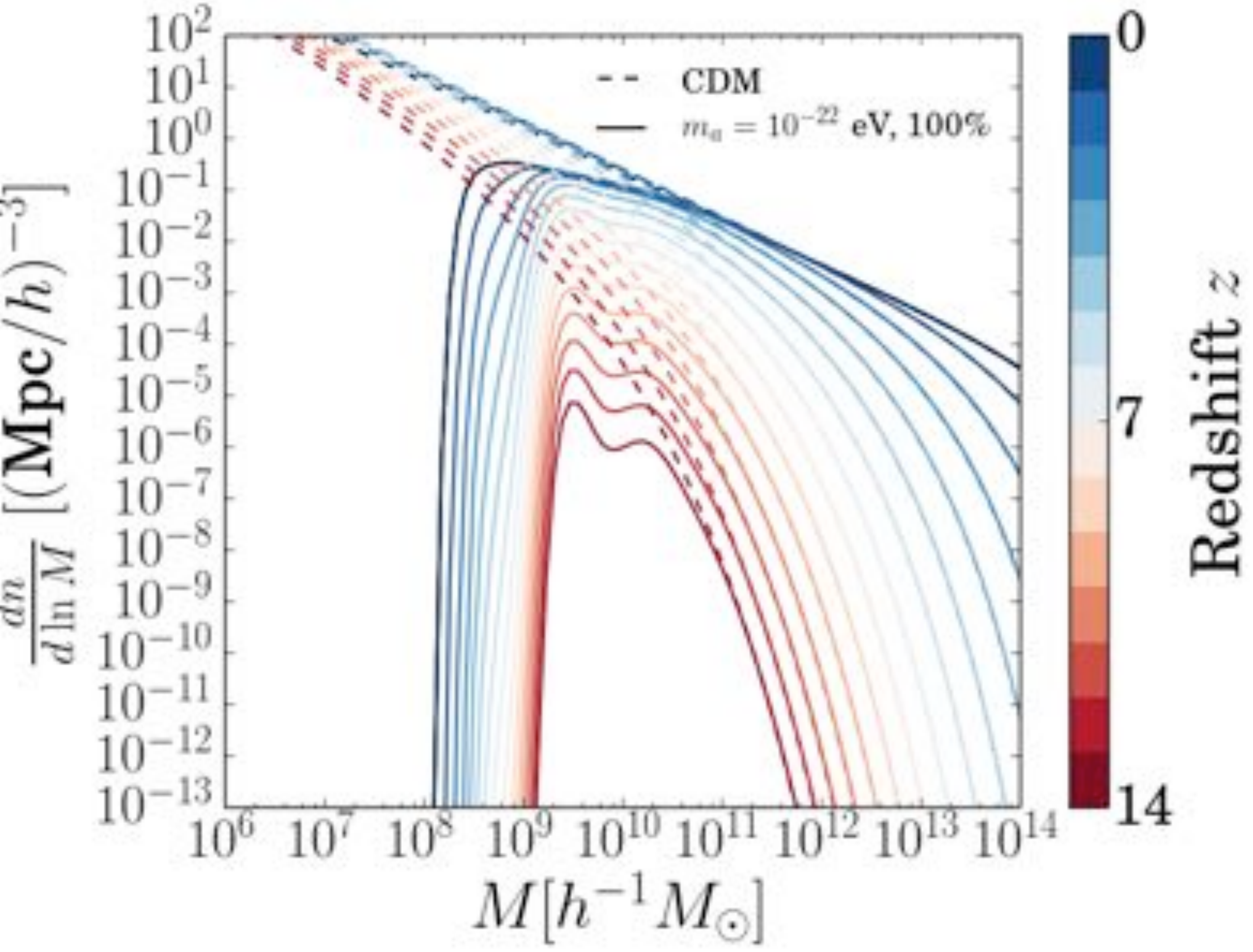


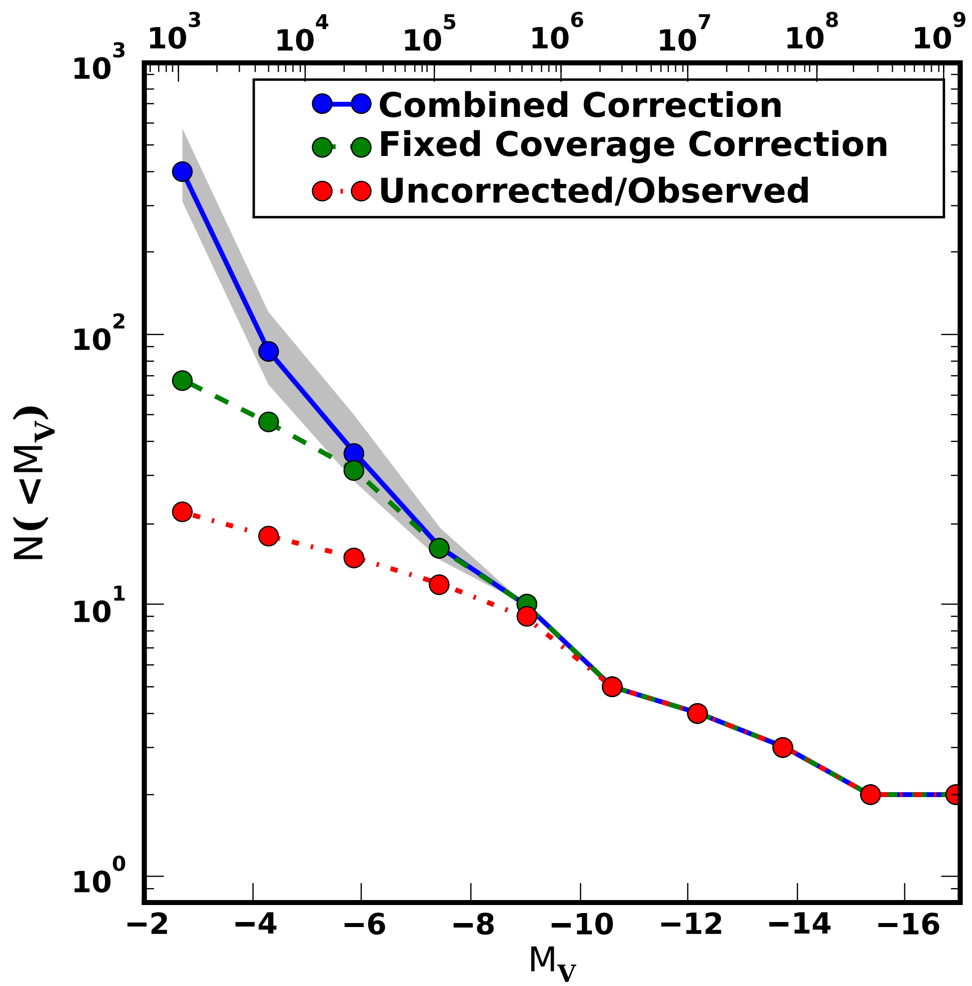
Cores! (Hu/Gruzinov/Barkana 2001, see also Marsh and Silk 2013; Marsh and Pop 2015, Matos 2012, Schive 2014, and others)

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

Future work: ULAs and galaxies

Missing satellite problem?





Marsh et al 2014, Klypin 1999, Bullock 2010

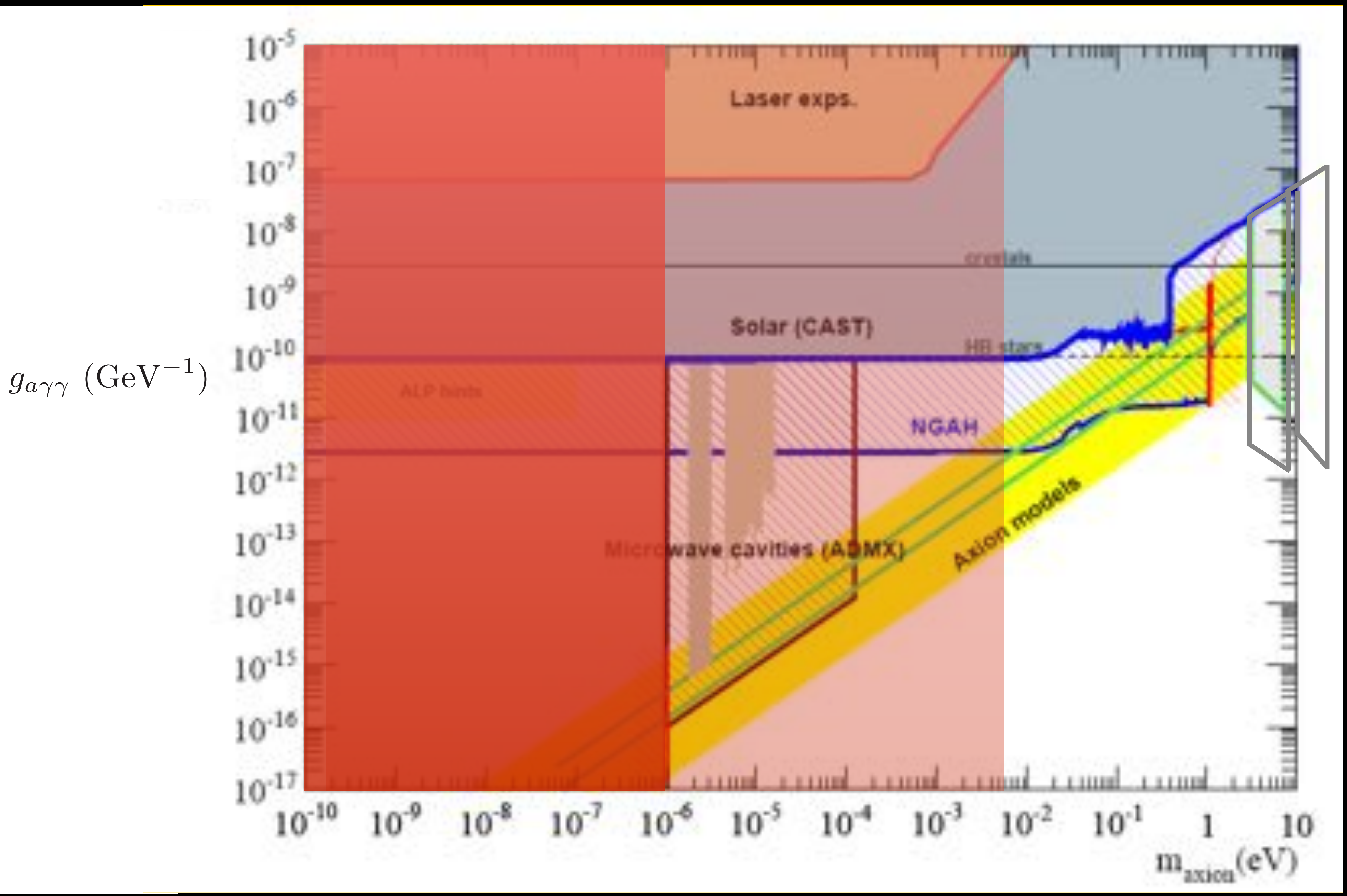
Conclusions

- ~1% level constraints on horizon for ultra-light axions
- Lensing is very promising, as is tensor + iso combo
- Work to be done improving theory on galactic scales

Backup slides

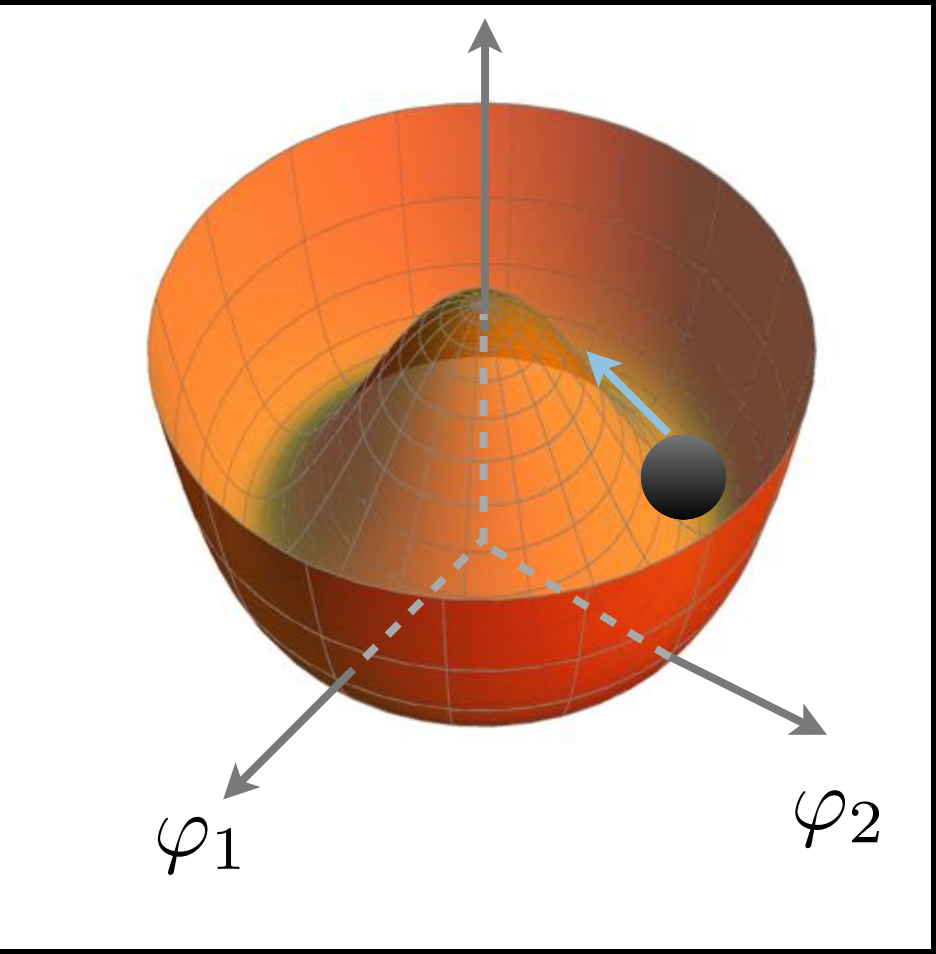
Limits

Cosmological dark matter



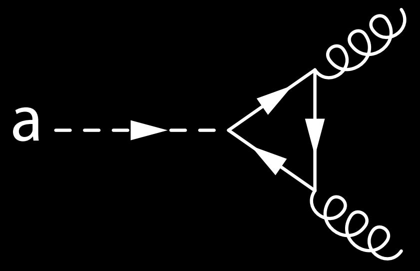
Axion Fundamentals

What are axions?



New scalar field with global U(1) symmetry!

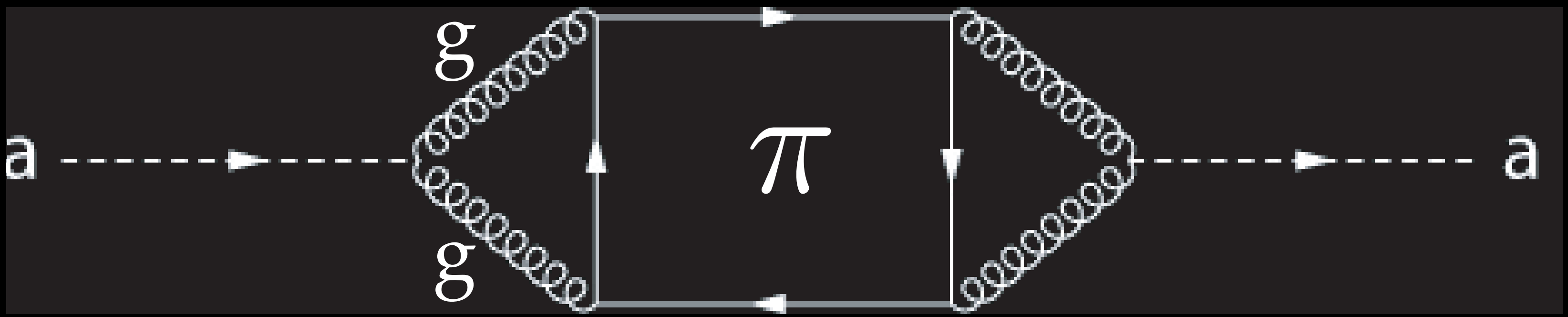
$$\mathcal{L}_{\rm CPV} = \frac{\theta g^2}{32\pi^2} G\tilde{G} - \boxed{\frac{a}{f_{\rm a}} g^2 G\tilde{G}}$$



✳ Couples to SM gauge fields (via fermions)

✳ Dynamically erases QCD CP-violation

✳ Mass through pion mixing



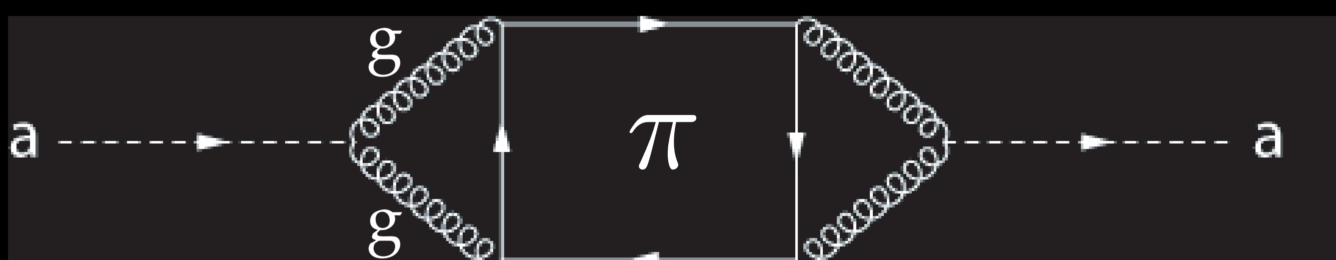
Peccei + Quinn (1977), Weinberg +Wilczek (1978), Kim (1979), Shifman et. al (1980), Zhitnitsky (1980), Dine et al. (1981), D.B. Kaplan (1985), A.E Nelson (1985,1990)

Axions solve the strong CP problem

- New field (axion) and U(1) symmetry dynamically drive net CP-violating term to 0

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

- Through coupling to pions, axions pick up a mass



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

$$m_a = 6.2\mu \text{ eV} \left(\frac{10^{12} \text{ GeV}}{f_a} \right)$$

$$\Lambda_{\mathrm{QCD}} \simeq 200 \text{ MeV}$$

Strong CP problem

- Strong interaction violates CP through θ -vacuum term

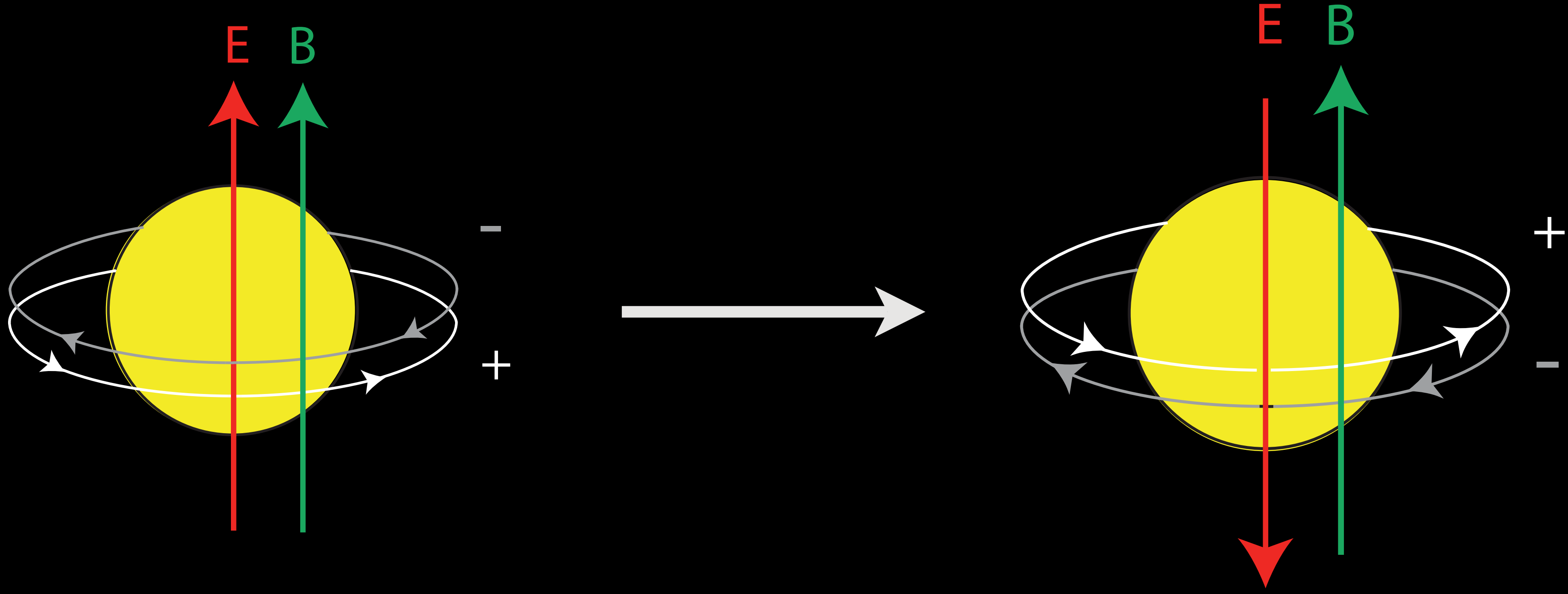
QCD strong-CP problem

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

- Limits on the neutron electric dipole moment are strong. Fine tuning?

$$d_n \simeq 10^{-16}\ \theta \text{ e cm}$$

$$\theta \lesssim 10^{-10},$$



KEY QUESTIONS:

* ***Can the dark matter or dark energy be an ultra-light boson, like an axion?***
* Strong interaction violates CP through θ-vacuum term

QCD strong-CP problem

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

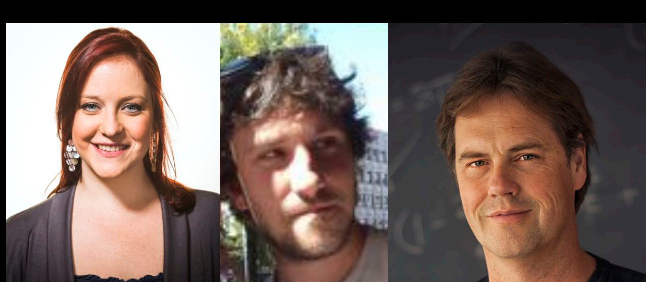
* What is the connection between the physics of inflation and the physics of the dark sector? Are initial fluctuations in different species spatially locked?
* Limits on the neutron electric dipole moment are strong. Fine tuning?

$$d_n \simeq 10^{-16}\ \theta \text{ e cm}$$

* What new probes of the dark sector could we soon have at our disposal?

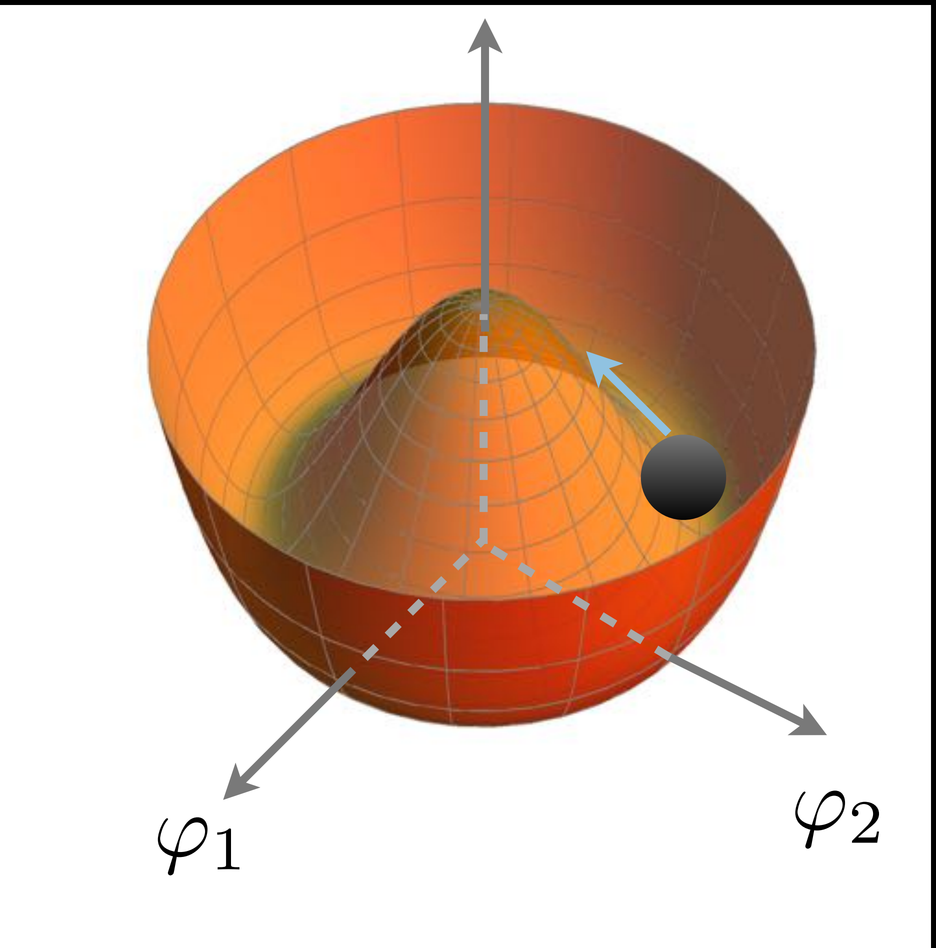
$$\theta \lesssim 10^{-10},$$

in collaboration with R. Hložek (Princeton), D. J. E. Marsh (Perimeter Institute), P. Ferreira (Oxford):



arXiv:1303.3008, Phys. Rev. D 87, 121701 (2013)
arXiv:1403.4216, Phys. Rev. Lett. 113, 011801 (2014)
arXiv:1410.2896, submitted to Phys, Rev. D

WHAT ARE AXIONS?



New scalar field with global U(1) symmetry!

Broken at scale f_a

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- Mass acquired non-perturbatively
- Small coupling to SM gauge fields
- Solves strong CP problem

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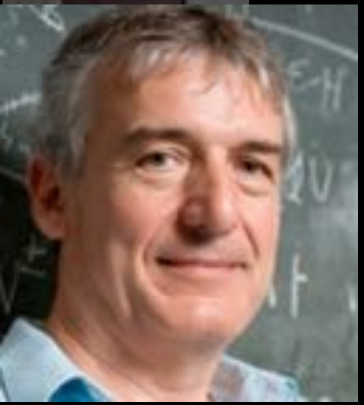
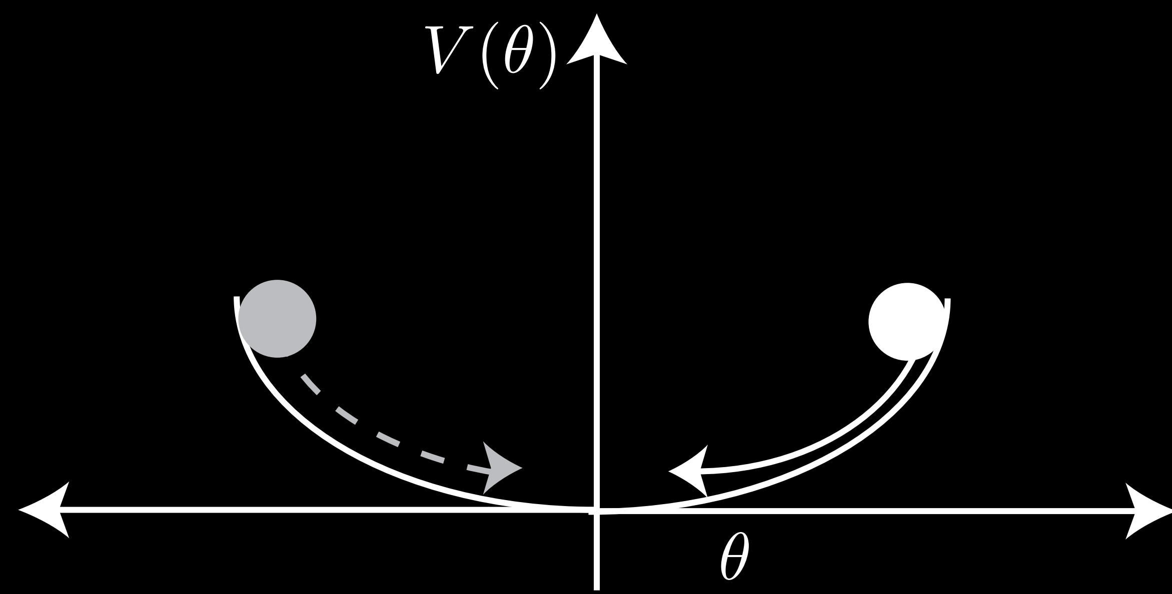
Cleaning up the dark matter mess?



QCD axions are DM candidates

$m_a \lesssim 10^{-2}$ eV



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

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

→ axion is a cold dark matter candidate

✳ Axions **ARE** cold

$v_a/c \lesssim 10^{-13}$ at CMB decoupling timescales

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

Solves a problem in particle physics:
Gives us a dark matter candidate for free!

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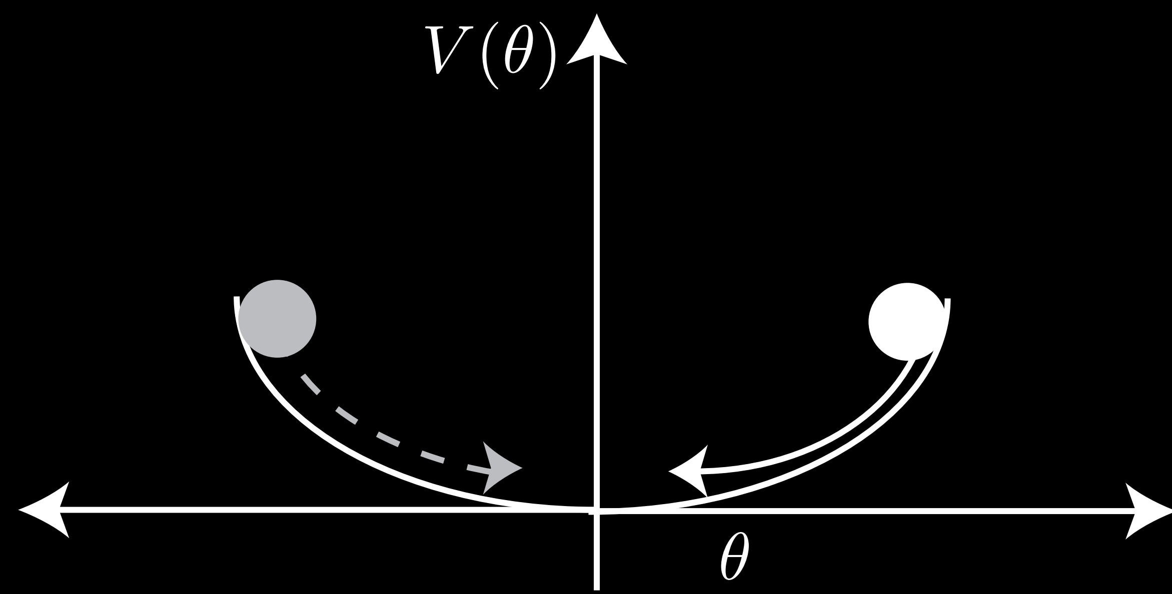

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Solves a problem in particle physics:
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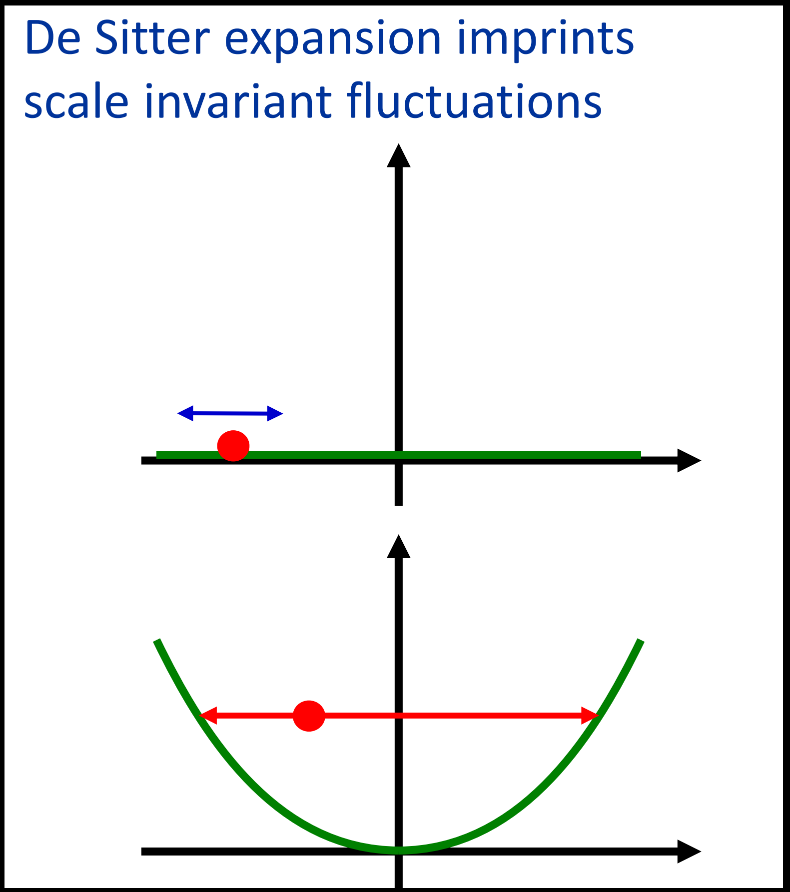
Anthropic axion window: $f_a > \max\{T_{\rm RH}, H_{\rm I}\}$

- Axion field is relatively homogeneous

$$\langle \theta^2 \rangle = \bar{\theta}^2 + \left(\frac{H_I}{2\pi f_a}\right)^2$$

Vacuum fluctuations from inflation

Misalignment in our Hubble Patch



From Raffelt 2012

- Abundance

$$\Omega_a h^2 \simeq 0.43 \left(\frac{f_a}{10^{12}\ \text{GeV}}\right)^{7/6} \theta_i^2$$

$$\Omega_a h^2 \simeq 0.005 \left(\frac{f_a}{10^{12}\ \text{GeV}}\right)^{3/2} \theta_i^2$$

- $\overline{\theta}$ can be tuned to get DM abundance for many axion masses

Classic axion window: $f_a < \max\{T_{\rm RH}, H_{\rm I}\}$

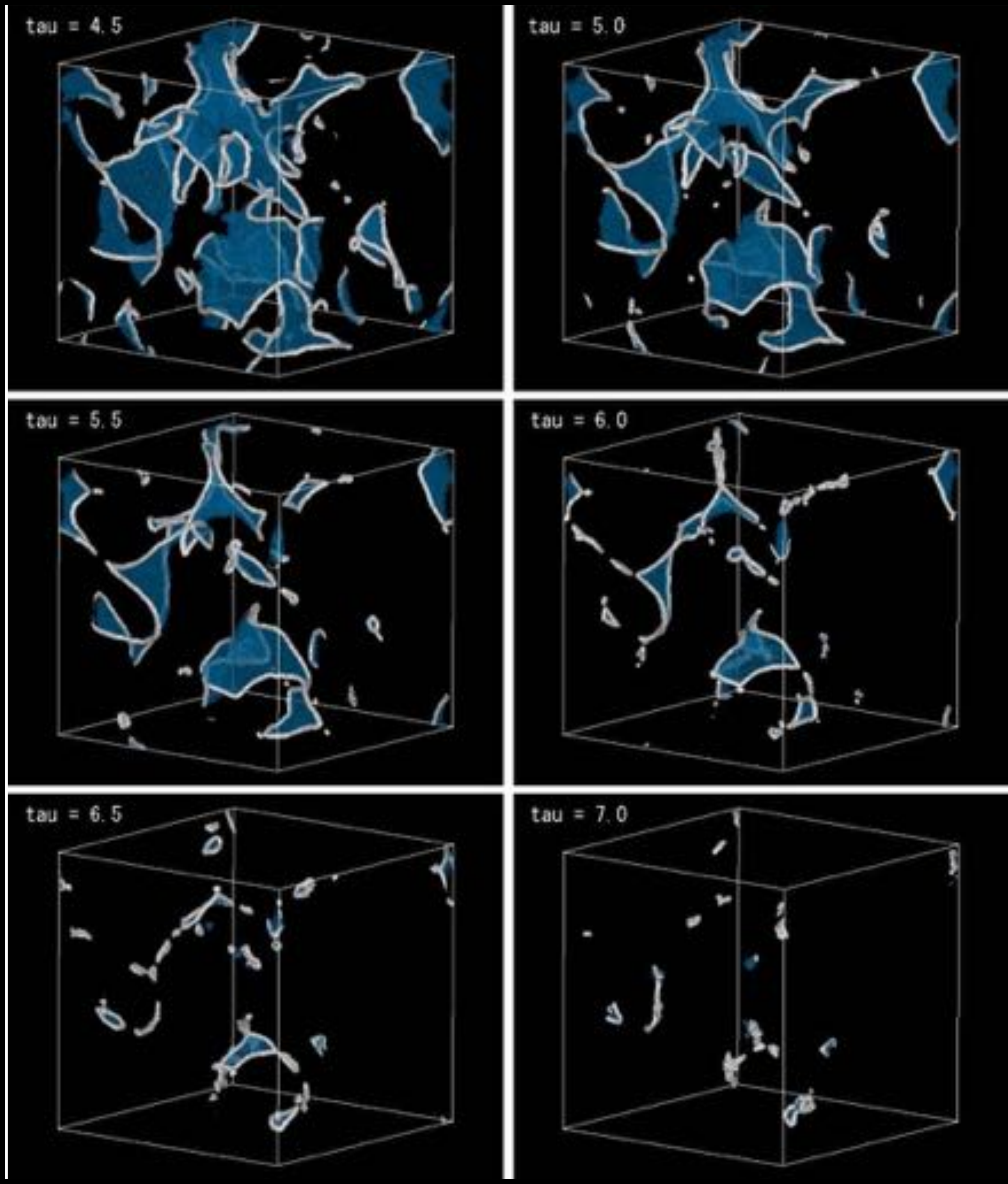
- Axion field is very inhomogeneous

$$\left\langle \overline{\theta}_i^2 \right\rangle = \frac{\pi^2}{6}$$

- Defects [domain walls, strings, etc..]

$$\mathcal{O}(1) \lesssim \alpha_{\rm defect} \lesssim \mathcal{O}(10^2)$$

CONTROVERSY!



From Hiramatsu 2012

- Abundance

$$\Omega_a h^2 \simeq 2.0\,\{1 + f_{\rm defect}\}\left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6}$$

Dark matter axion abundance

- QCD axion couples to quarks/pions, temp-dependent mass
  - High-temp regime

$$m_{\rm a} = 0.02 m_{\rm a}^{(T=0)} \left(\frac{\Lambda_{\rm QCD}}{T}\right)^4 \text{ if } T \gg \Lambda_{\rm QCD}$$

  - Low-temp regime $m_{\rm a} = m_{\rm a}^{(T=0)}$ if $T \lesssim \Lambda_{\rm QCD}$

$$\boxed{\Omega_{\rm mis} h^2 = 0.236 \left\langle \theta_i^2 f(\theta_i) \right\rangle \left(\frac{f_a}{10^{12}\ \text{GeV}}\right)^{7/6}} \quad \text{if } f_a \lesssim 10^{18}\ \text{GeV}$$

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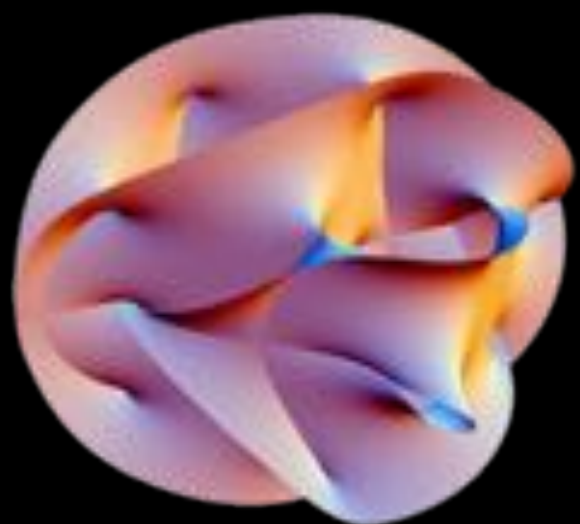
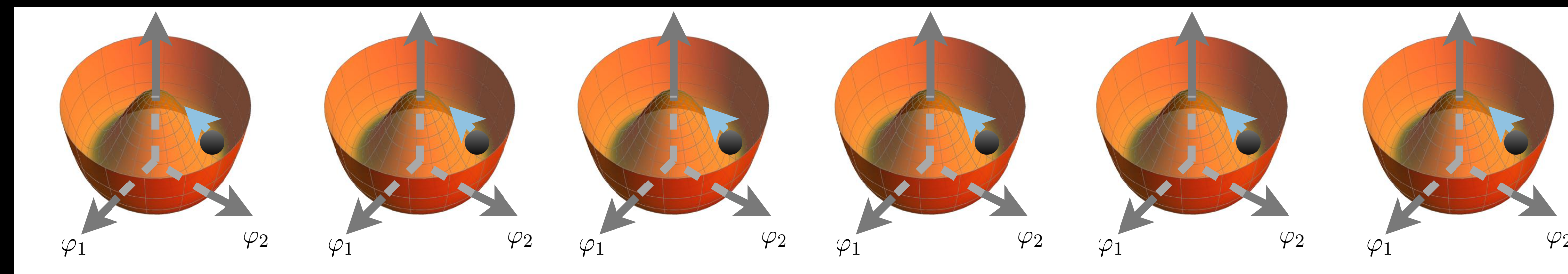
ULTRA-LIGHT AXIONS (ULAS) IN STRING THEORY

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





+....

Hundreds of scalars with approx shift symmetry

Many axions

Axiverse! *Arvanitaki+ 2009*

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

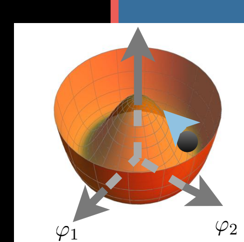
* Mass acquired non-perturbatively (instantons, D-Branes)

Scale of new ultra-violet physics

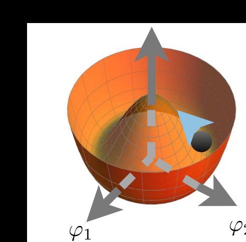
Scale of extra dimensions in Planck units

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

10^{-33} m_a (in eV) 10^{-18}

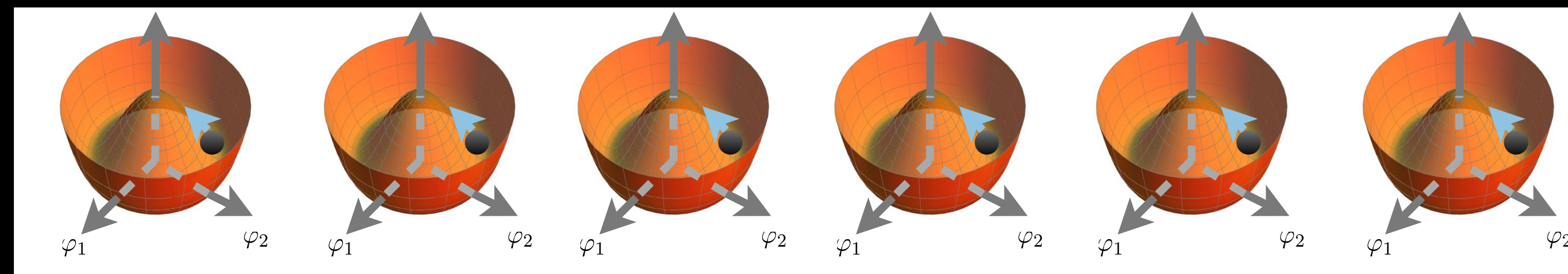


....



Ultra-light axions (ULAs) in string theory

✳ Bosons moving in extra dimensions are axions in 4D!



+....

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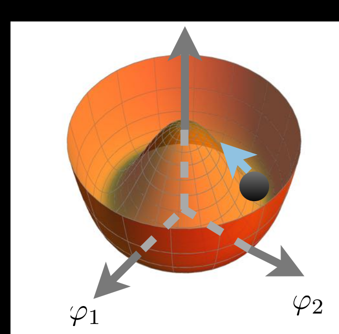
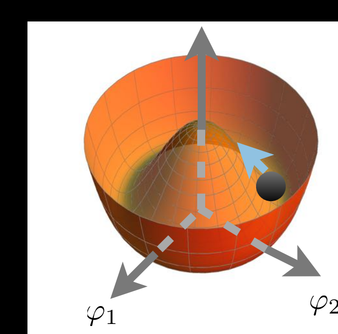
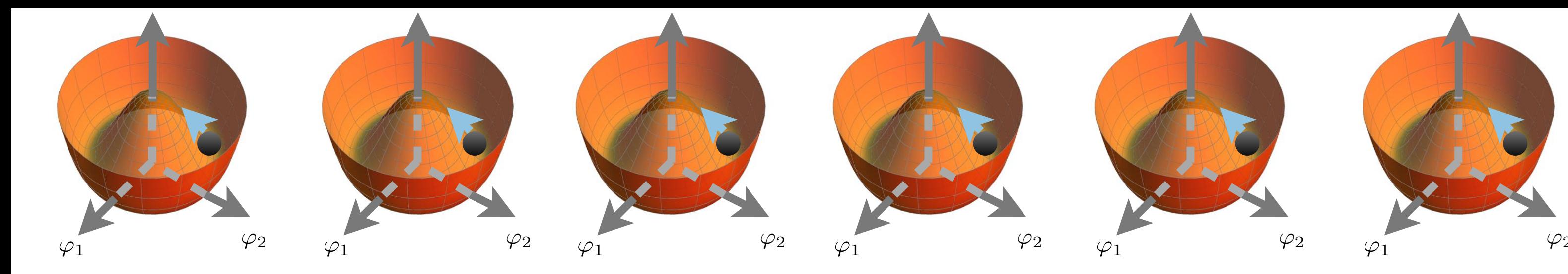


m_a (in eV)



Ultra-light axions (ULAs) in string theory

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



+....

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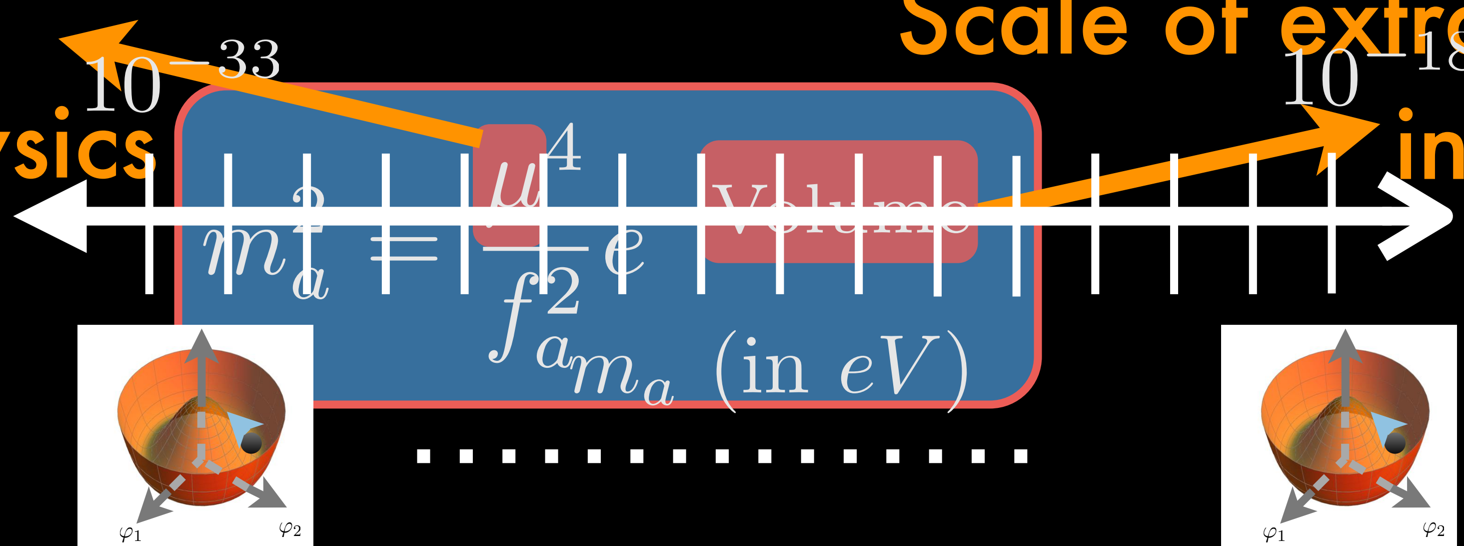
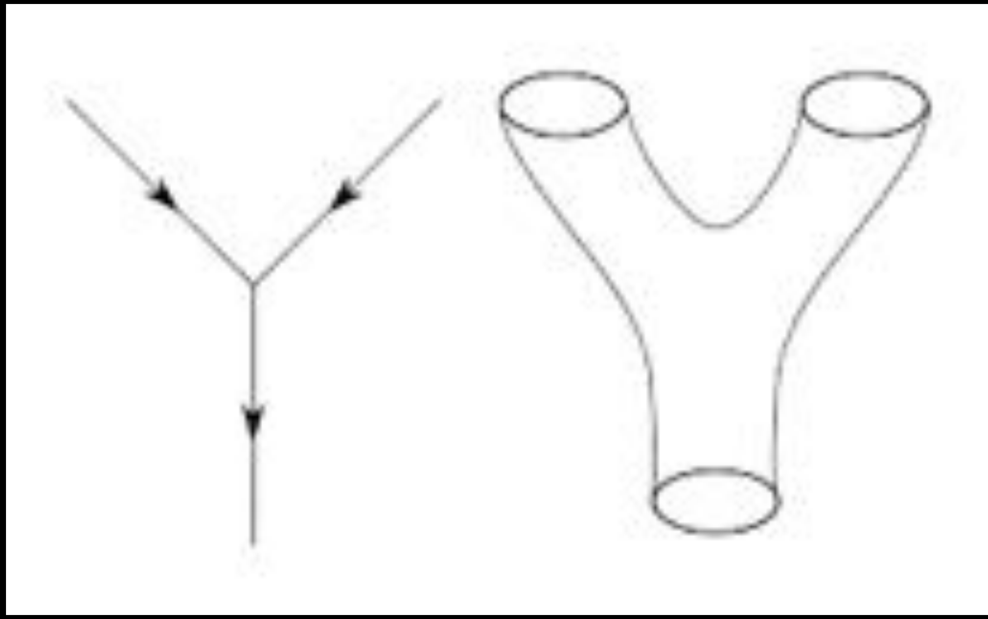


String theory

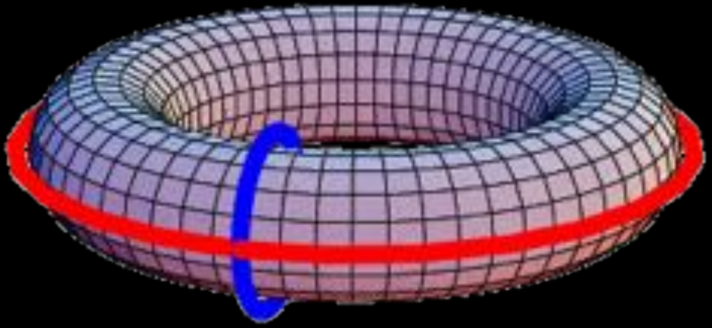
* One framework that solves SM problems is string theory

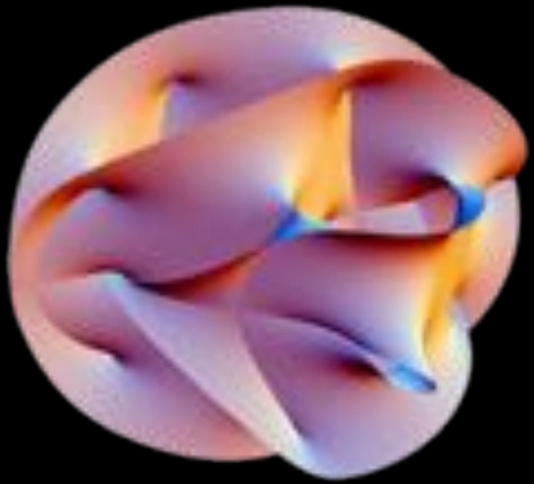


Replace point particles with extended objects

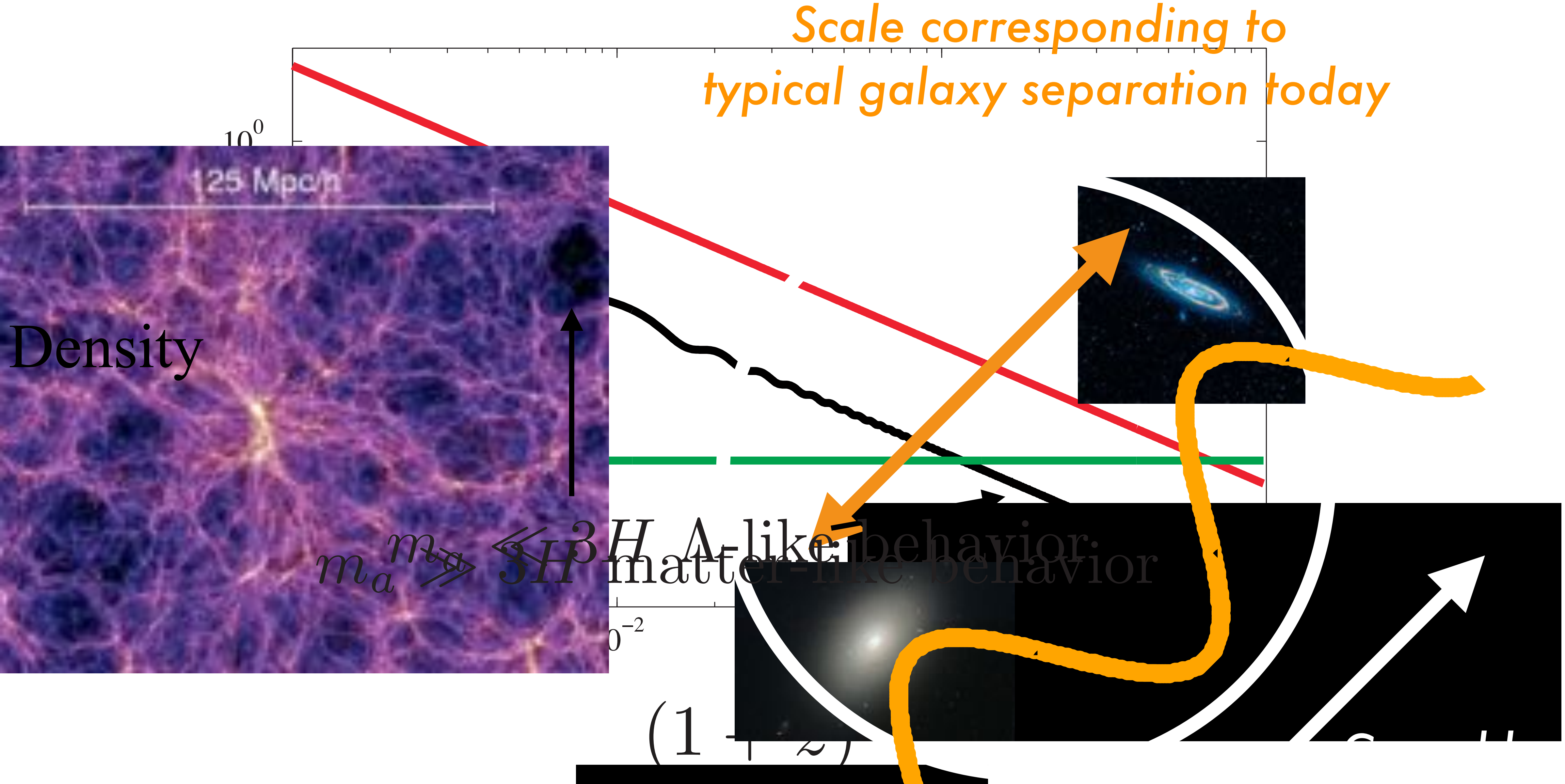
* String theory requires 6 extra dimensions that we don’t see!

  Must be curled up/compactified





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



Frieman et al 1995, Coble et al. 1997

ULA as dark energy with specific w(z)

ULA as dark matter

Corresponds to time of matter/radiation equality, when $\rho_m = \rho_\gamma + \rho_\nu$

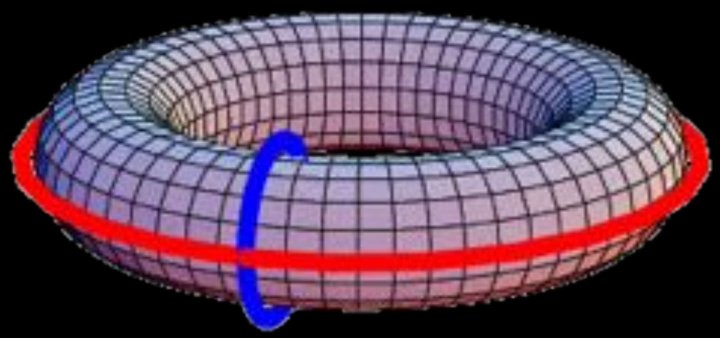
Simple relic density constraints: $m_a \gtrsim 10^{-27}$ eV

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

ULA matter behavior starts too late for struct. formation

Light axions and string theory

- String theory has extra dimensions: *compactify (6)!*
- Form fields and gauge fields: `Axion' is KK zero-mode of form field



$$\mathcal{L} \propto \frac{aG\tilde{G}}{f_{\mathrm{a}}}$$

ULAs: gravitational constraints

Independent of axion SM couplings: uncertainties astrophysical!

DUST!

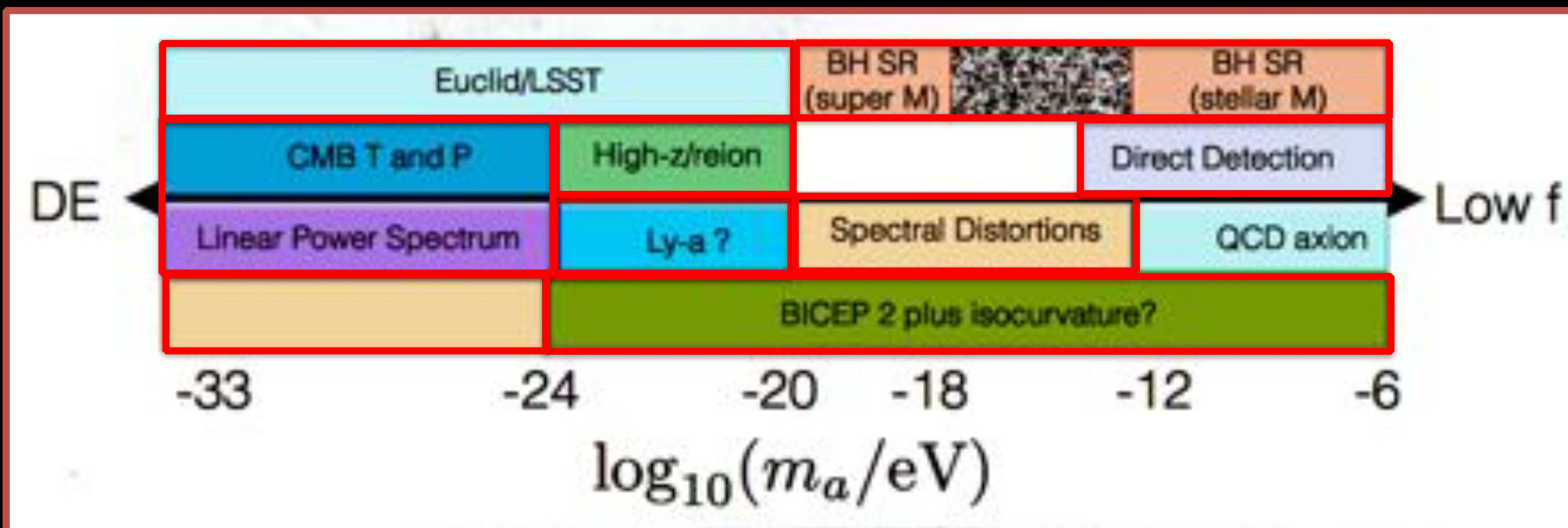
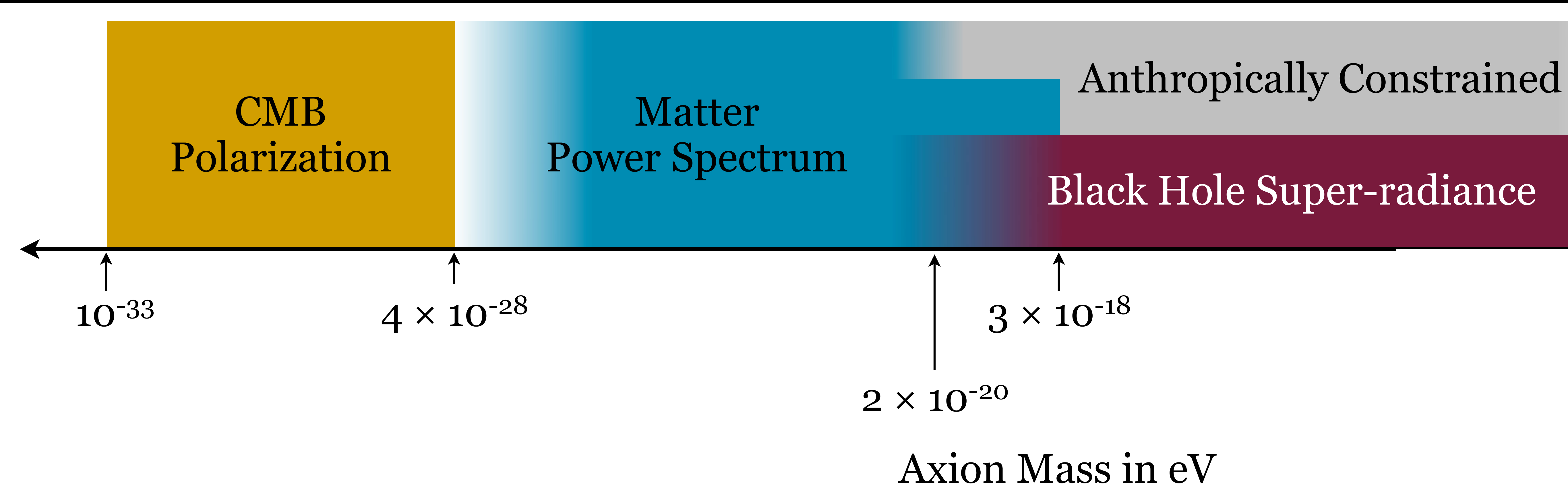


figure adapted from DJEM 2014

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

Flat logarithmic mass distribution:
Very low axion masses natural!

THE AXIVERSE: ULTRA-LIGHT AXIONS (ULAS)



(instantons, D-branes)

New UV scale: not QCD scale

Scalars with approximate shift symmetry → "Axion"

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

$$f_a \propto \frac{M_{\text{pl}}}{\text{Volume}}$$

$$\mathcal{L} \propto g_{a\gamma\gamma} \vec{E}_{\text{gauge}} \vec{B}_{\text{gauge}}$$

$$g_{a\gamma\gamma} \propto \frac{1}{f_a}$$

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

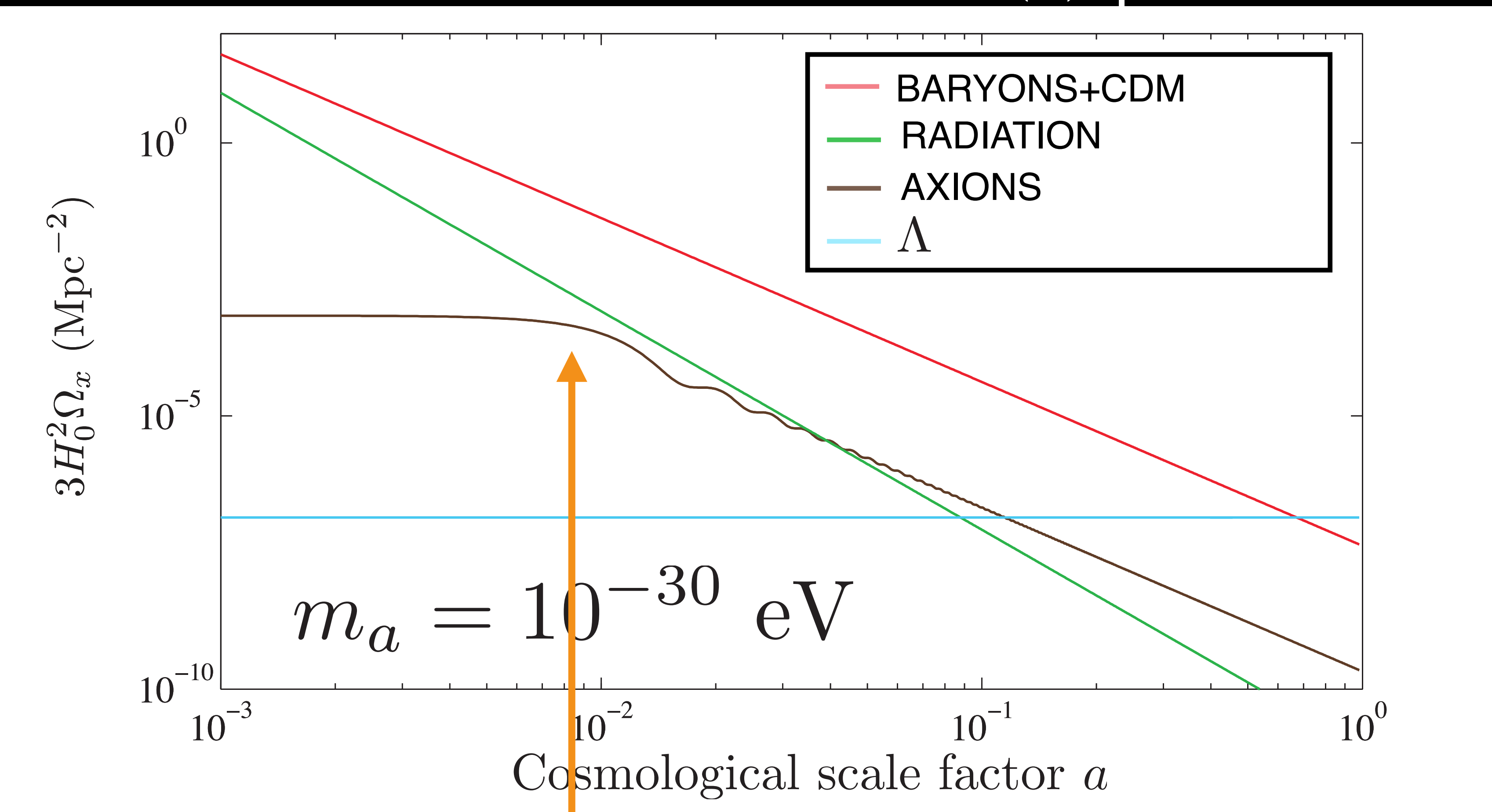
Cosmological axion evolution

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

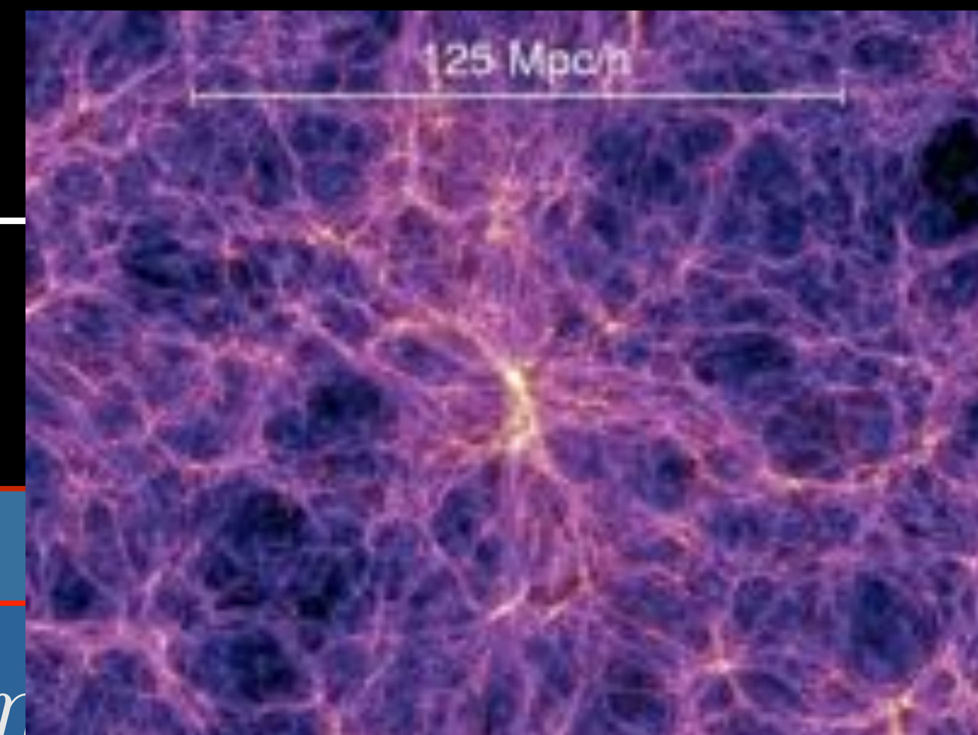
Misalignment production $V(\theta)$ Coherent

Axion-driven acceleration

Axions are like CDM



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



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

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

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

$$m_a \gg 10^{-27}\ \mathrm{eV} \qquad 3H \to m_a \qquad \rho \propto a^{-3}, \langle w_a \rangle_{T=2\pi/m_a} = 0$$

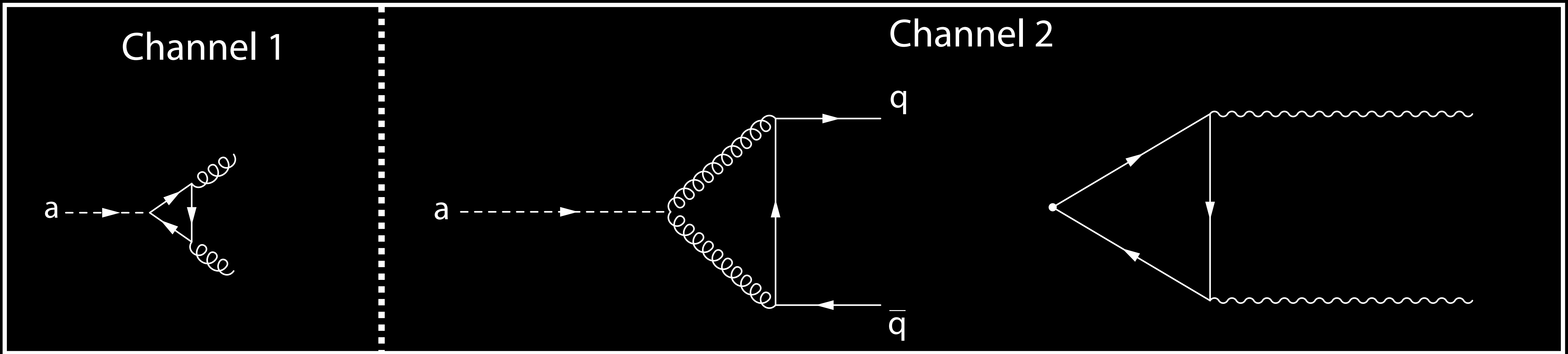
DE axions

$$a_{\rm osc} > a_{\rm eq}$$

Oscillation starts too late for struct. formation

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

Two-photon coupling of axion



- Axions interact weakly with SM particles $\Gamma, \sigma \sim \alpha^2$

- Axions have a two-photon coupling

$$g_{a\gamma\gamma} = -\frac{3\alpha}{8\pi f_a}\xi \qquad \mathcal{L} \propto g_{a\gamma\gamma}\vec{E}\cdot\vec{B}$$

- Very little freedom once f_a specified

Axion Experiments/ Constraints

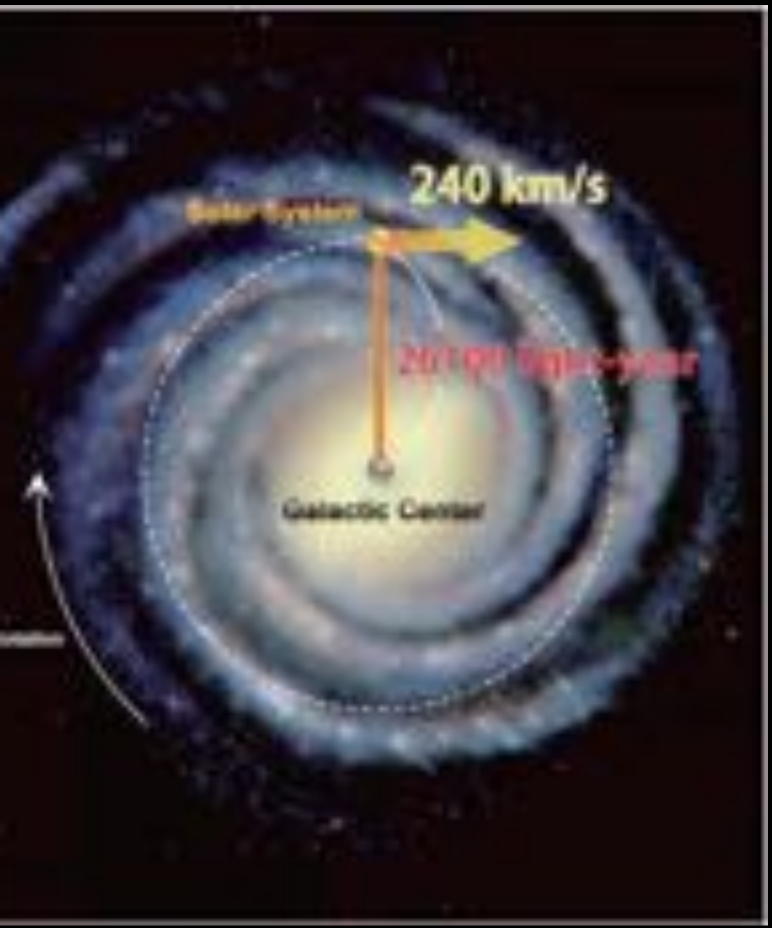
✳ ADMX: Use the DM axions the universe gives you

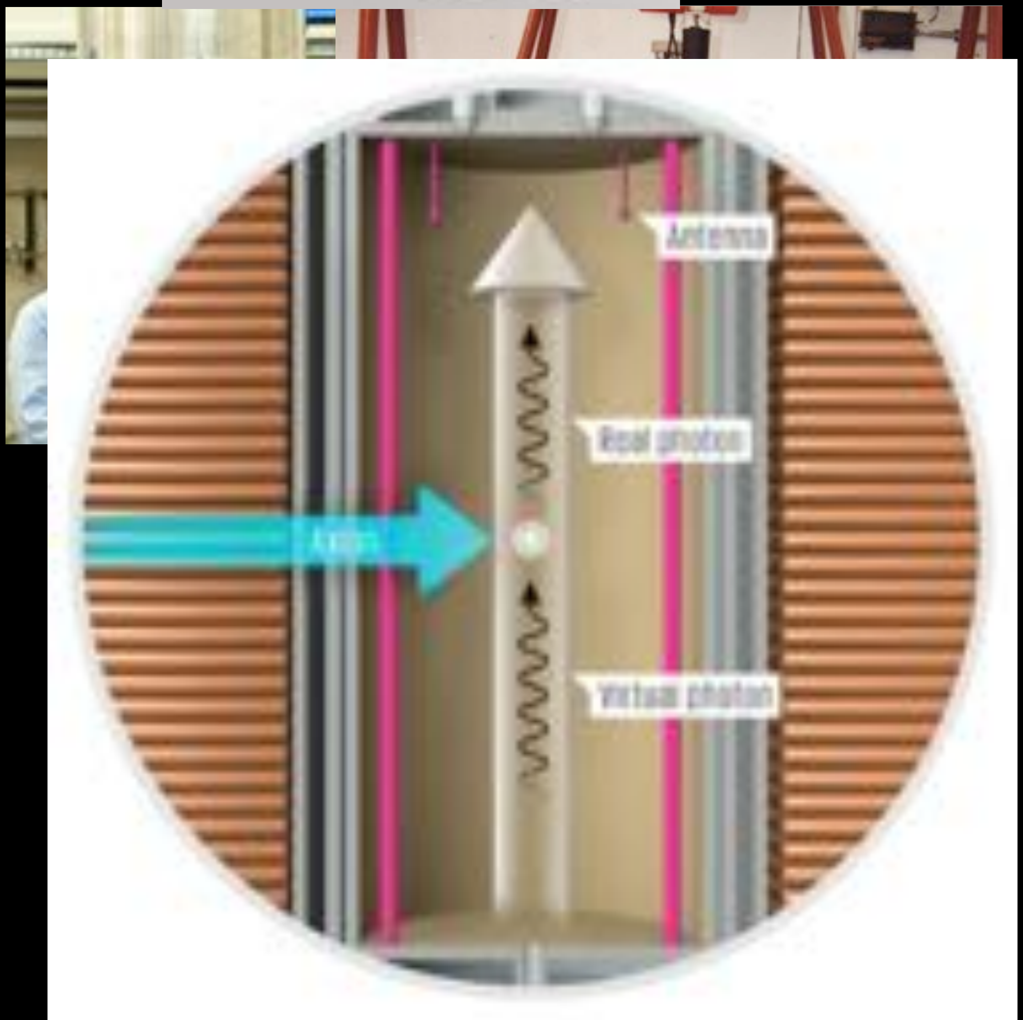
$$\mathcal{L} \propto g_{a\gamma\gamma} a \vec{E} \cdot \vec{B} \quad g_{a\gamma\gamma} \propto 1/f_a$$

P. Sikivie 1983

L. Rosenberg and G. Rybka +....

$E_\gamma = m_a c^2$ → *Excite cavity TEM modes*



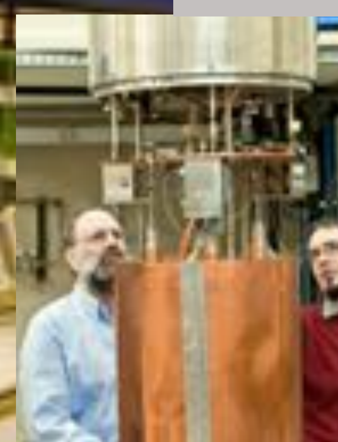


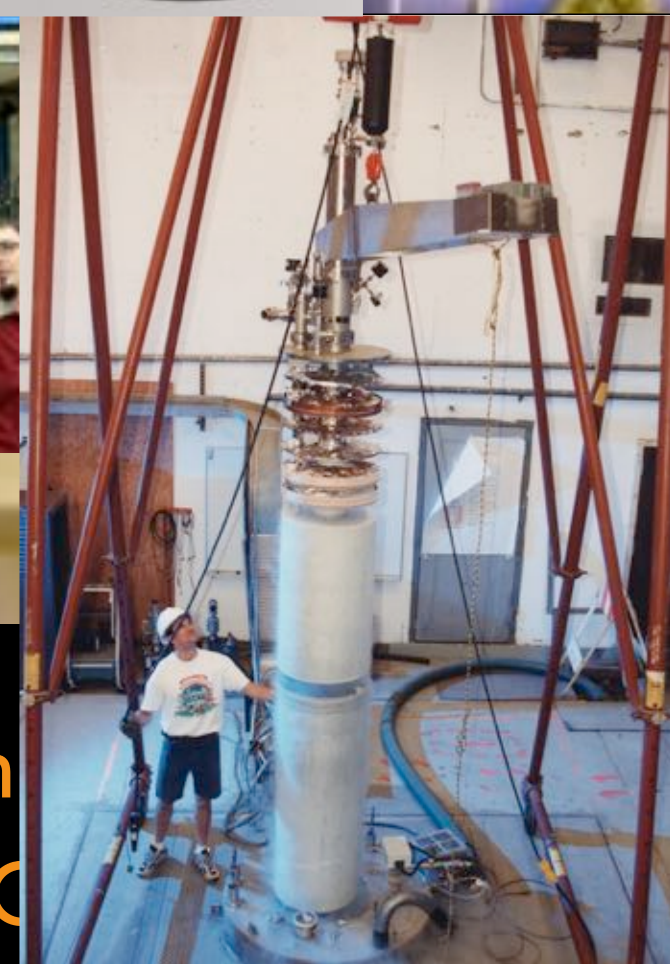
How to look for axions

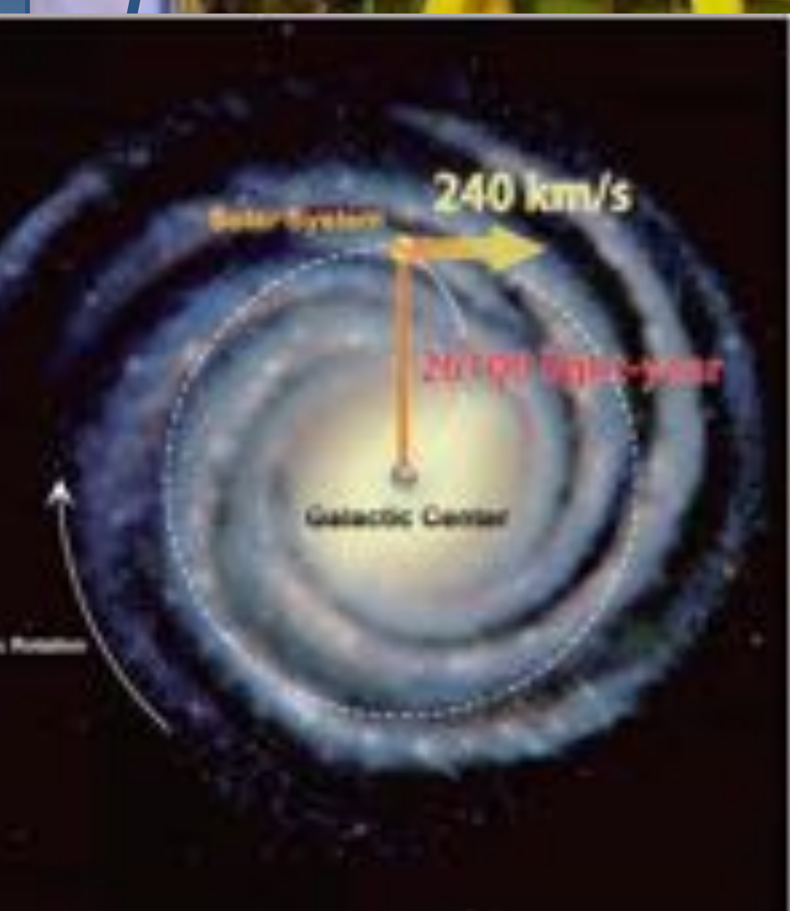
* By construction, axions interact with photons $g_{a\gamma\gamma} = -\frac{3\alpha\xi}{2\pi f_a}$

Pierre Sikivie

Use the dark matter in the universe!





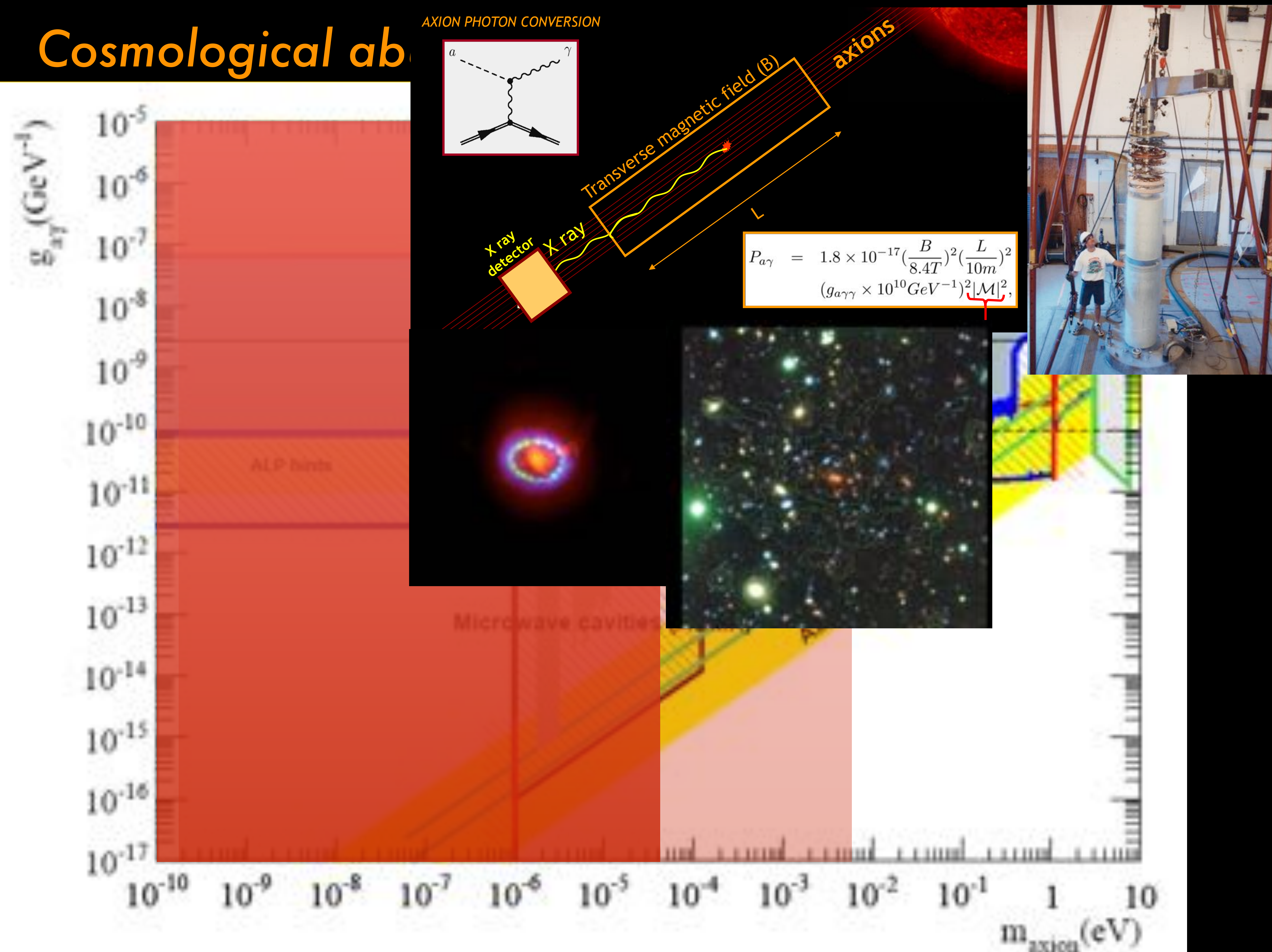


stars— Turn th tons on Earth!

CAST/IAXO

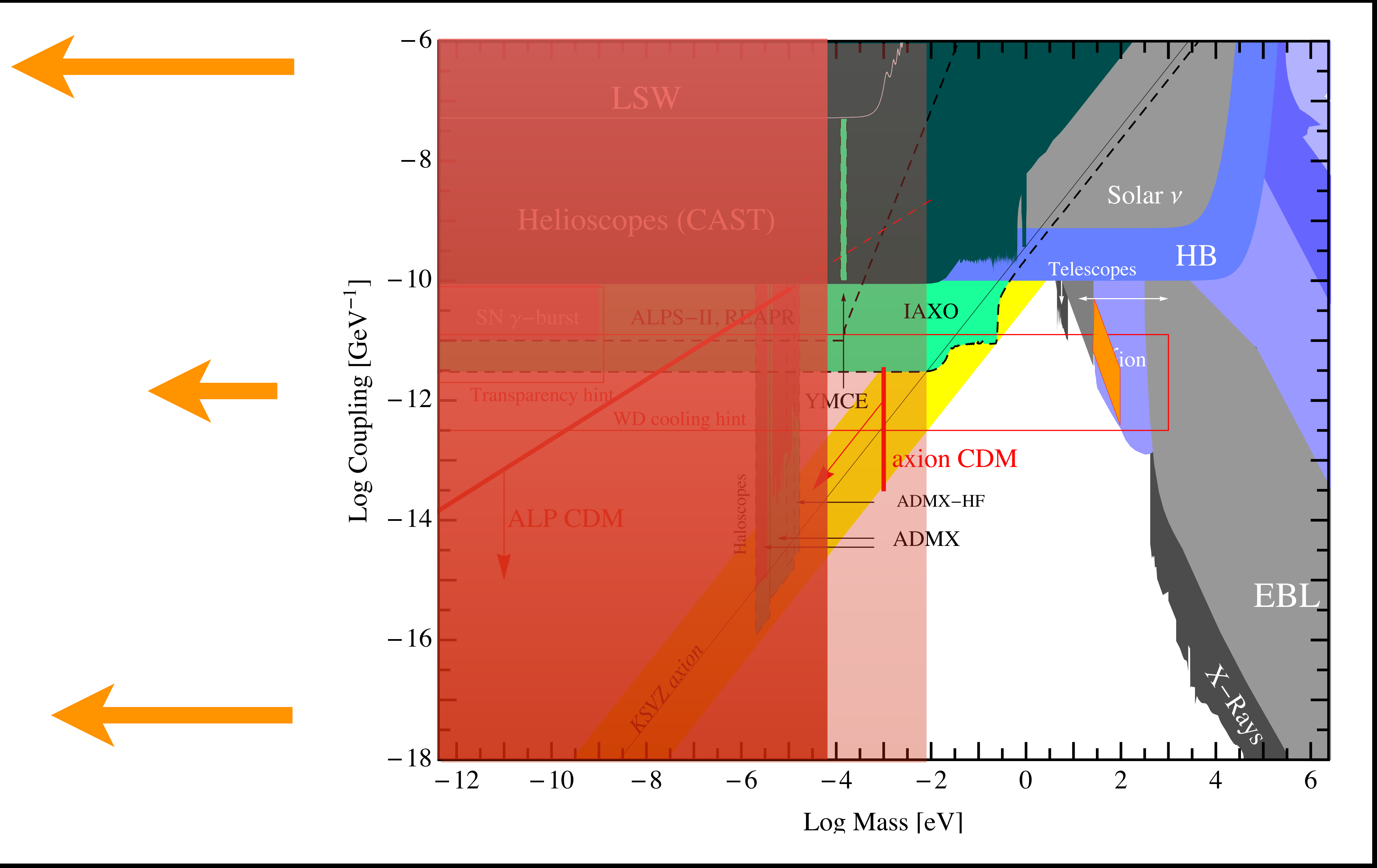
Limits and horizon

Cosmological ab



Experimental constraints
ULA and axion-like particles (ALPs)

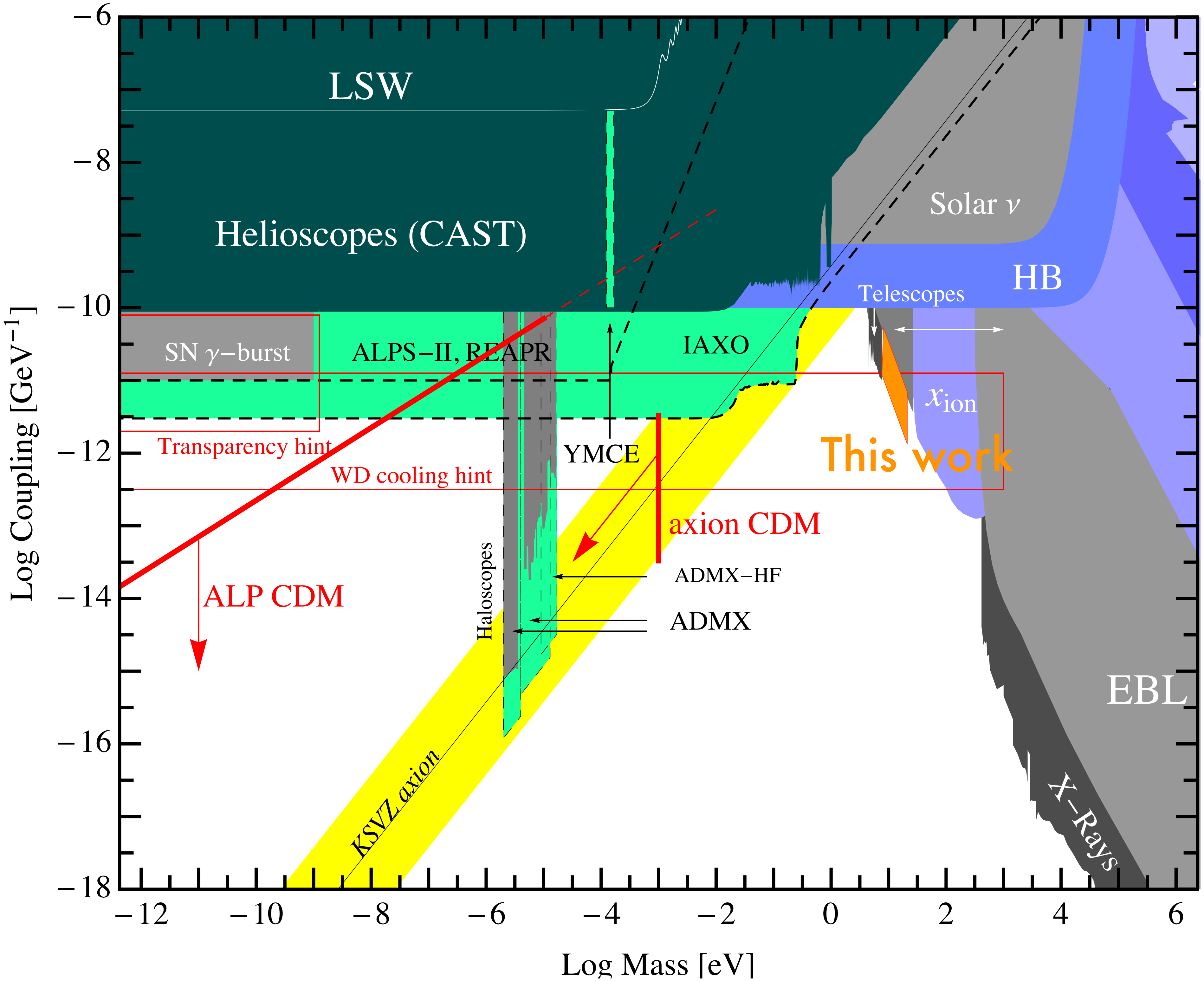
Experimental lab constraints essential
Cosmological abundance
Gravitational limits (microlensing)



$$\mathcal{L} \propto g_{a\gamma\gamma} \vec{E} \cdot \vec{B}$$

From arXiv: 1205.2671

Lay of the land

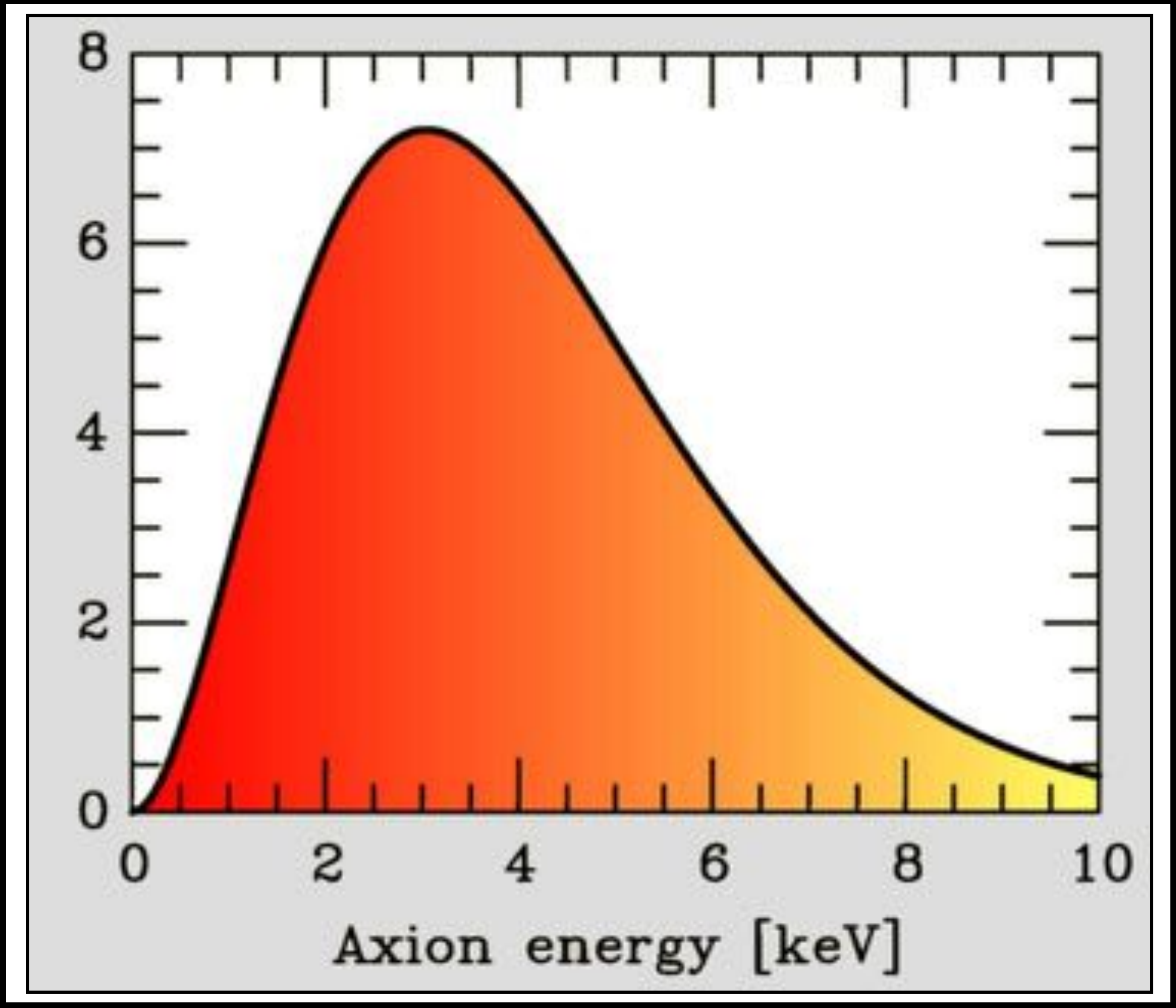


Axion helioscopes

- Resonance condition

$$qL < \pi \quad \Rightarrow \quad \sqrt{m_\gamma^2 - \frac{2\pi E_a}{L}} < m_a < \sqrt{m_\gamma^2 + \frac{2\pi E_a}{L}}$$

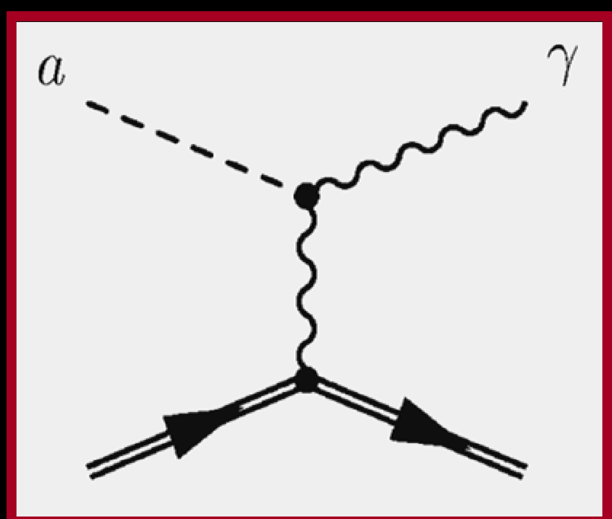
- Broad axion energy spectrum

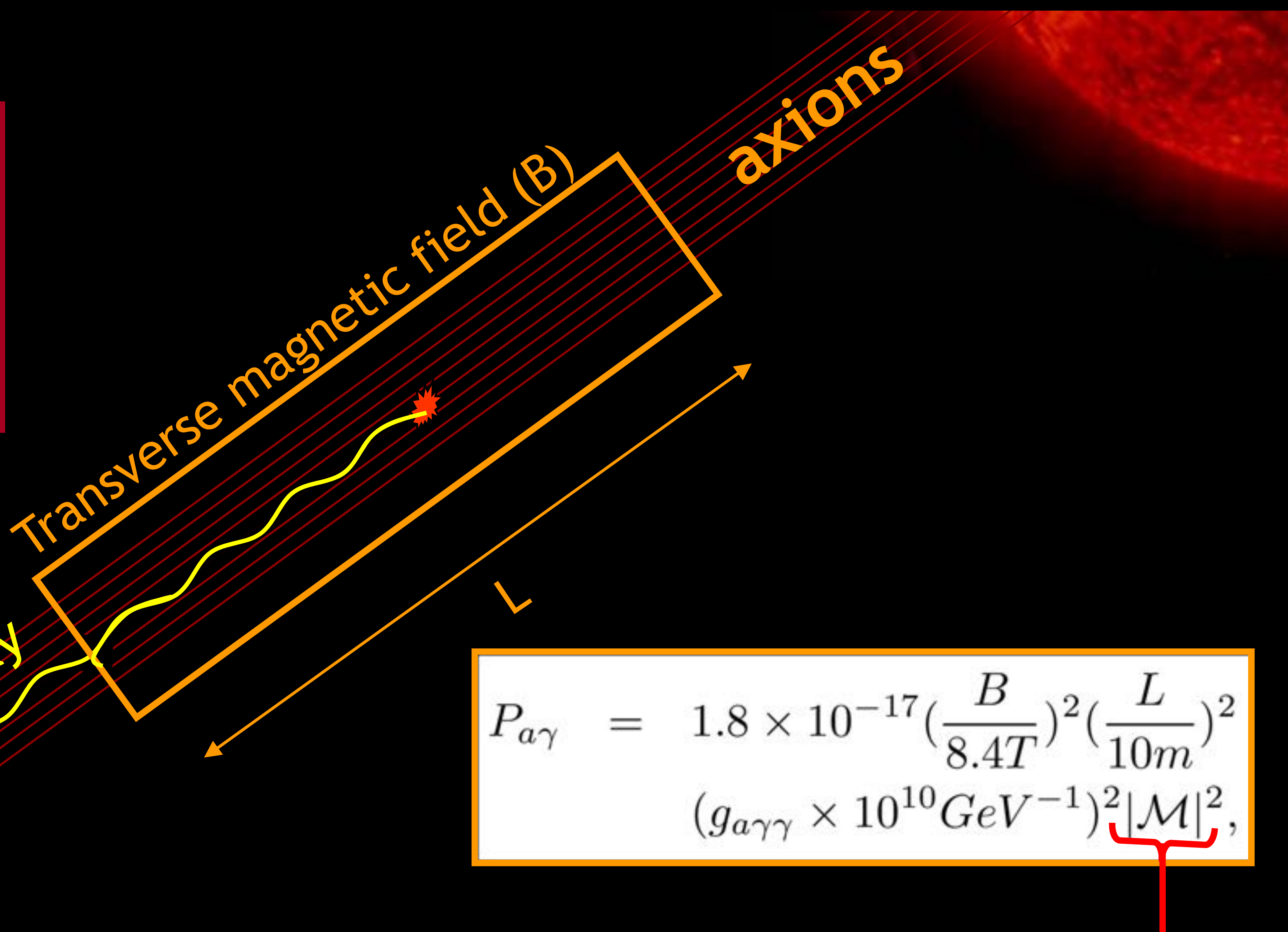


Axion helioscopes

- Backwards Primakoff process (Sikivie, Zioutas, and many others)

From Irastorza 2013





$$P_{a\gamma} = 1.8 \times 10^{-17}\left(\frac{B}{8.4T}\right)^2\left(\frac{L}{10m}\right)^2 (g_{a\gamma\gamma} \times 10^{10} GeV^{-1})^2 \underbrace{|\mathcal{M}|^2}_{},$$

CAST/IAXO

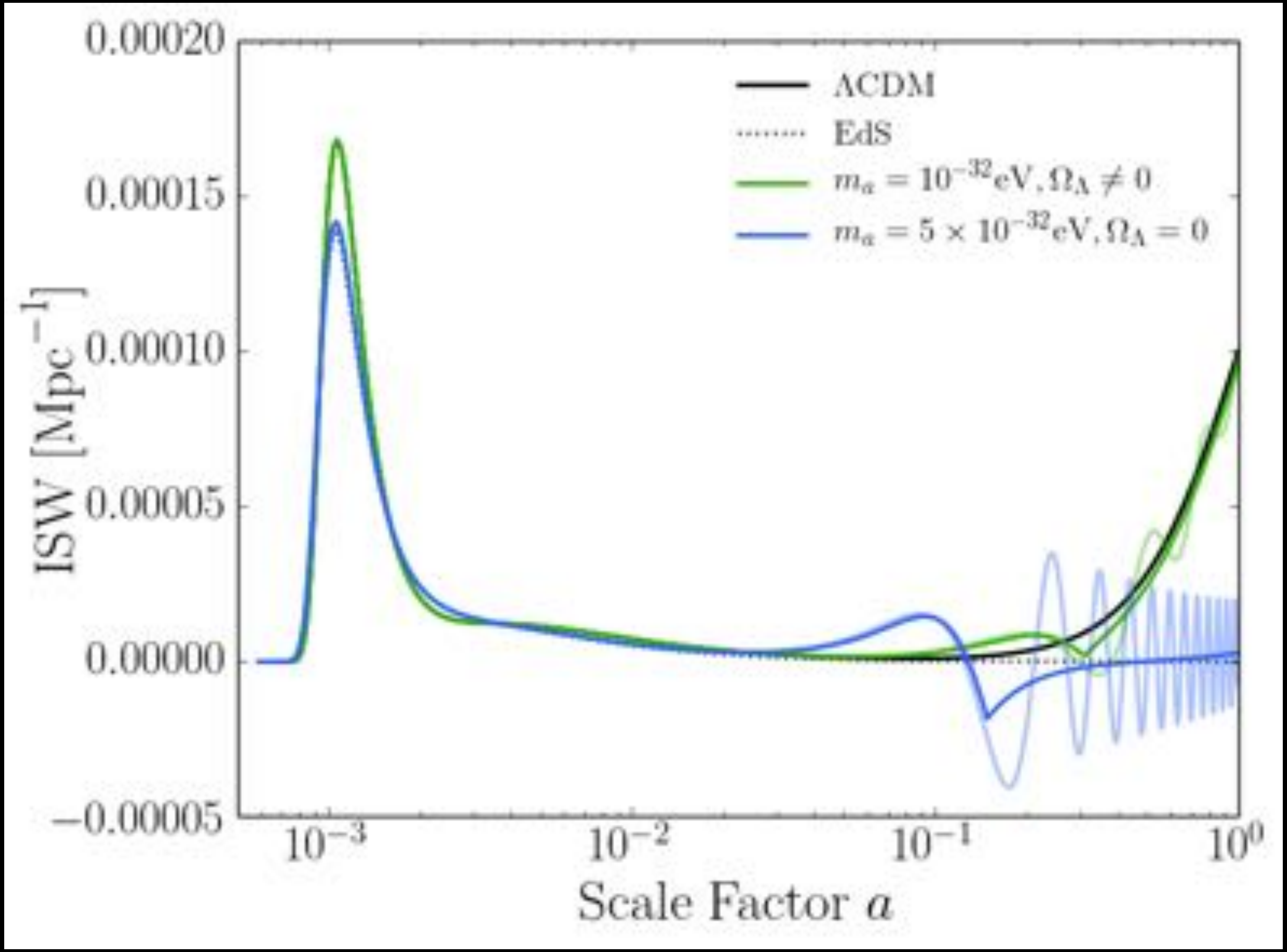
- CAST
  - LHC test magnet (B=9 T, L=9.26 m)

Lakic 2012

- IAXO proposal: 15-20m length magnet, optimized shape [not LHC DUD]

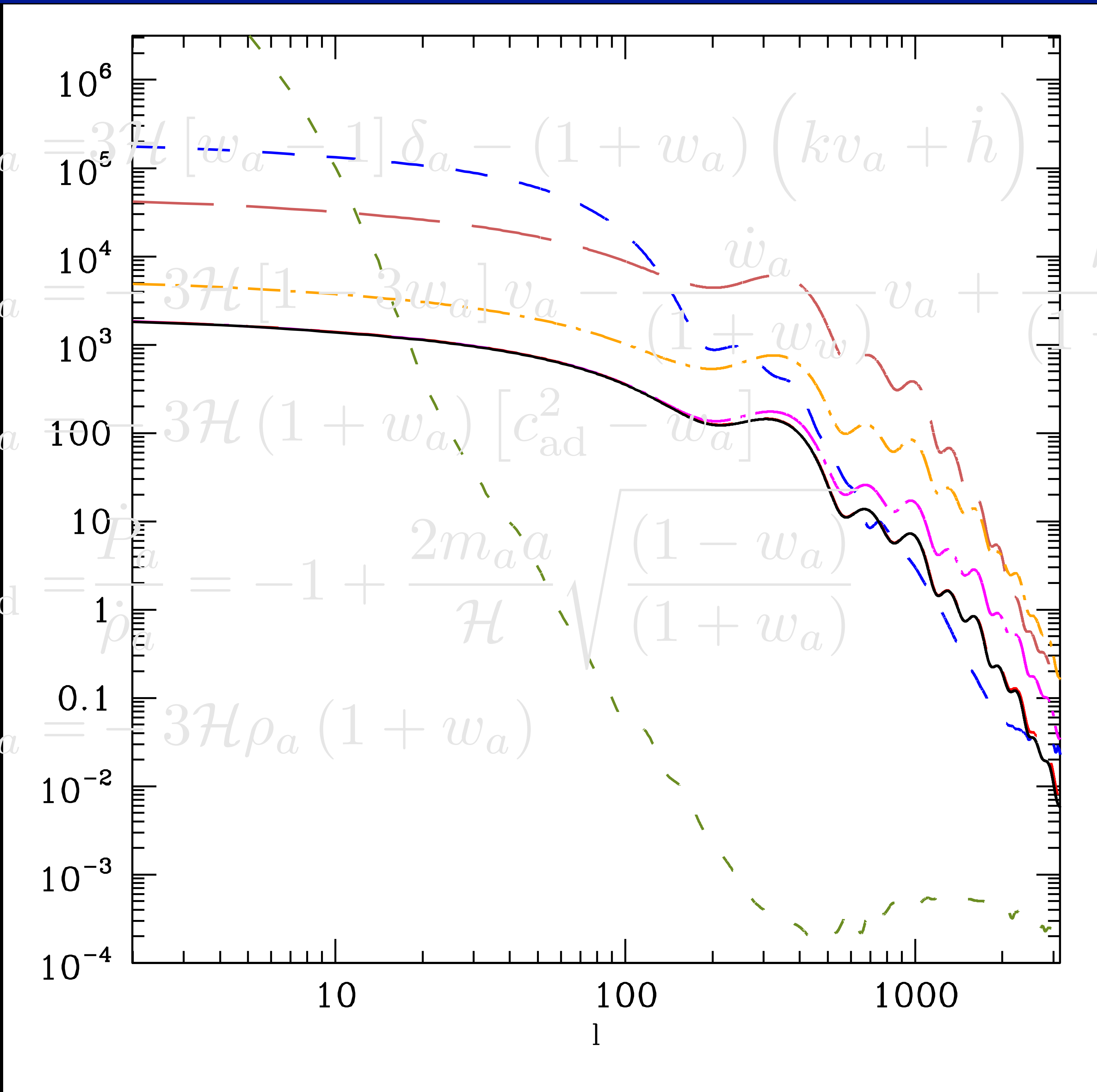
ULA Search Technical Details

ISW TEST



0.00020
0.00015
0.00010
0.00005
0.00000
−0.00005
ISW [Mpc^{-1}]
ΛCDM
EdS
$m_a = 10^{-32}\mathrm{eV}, \Omega_\Lambda \neq 0$
$m_a = 5 \times 10^{-32}\mathrm{eV}, \Omega_\Lambda = 0$
10^{-3}
10^{-2}
10^{-1}
10^{0}
Scale Factor a

Getting under the hood: The need for numerical care



$$\dot{\delta}_a = 3\mathcal{H}\left[w_a - 1\right]\delta_a - (1 + w_a)\left(kv_a + \dot{h}\right)$$

$$\dot{v}_a = -3\mathcal{H}\left[1 - 3w_a\right]v_a - \frac{\dot{w}_a}{(1 + w_a)}v_a + \frac{k\delta_a}{(1 + w_a)}$$

$$\dot{w}_a = -3\mathcal{H}\left(1 + w_a\right)\left[c^2_{\mathrm{ad}} - w_a\right]$$

$$c^2_{\mathrm{ad}} = \frac{\dot{P}_a}{\dot{\rho}_a} = -1 + \frac{2m_a a}{\mathcal{H}}\sqrt{\frac{(1 - w_a)}{(1 + w_a)}}$$

$$\dot{\rho}_a = -3\mathcal{H}\rho_a\left(1 + w_a\right)$$

Getting under the hood: The need for correct (super-horizon) initial conditions

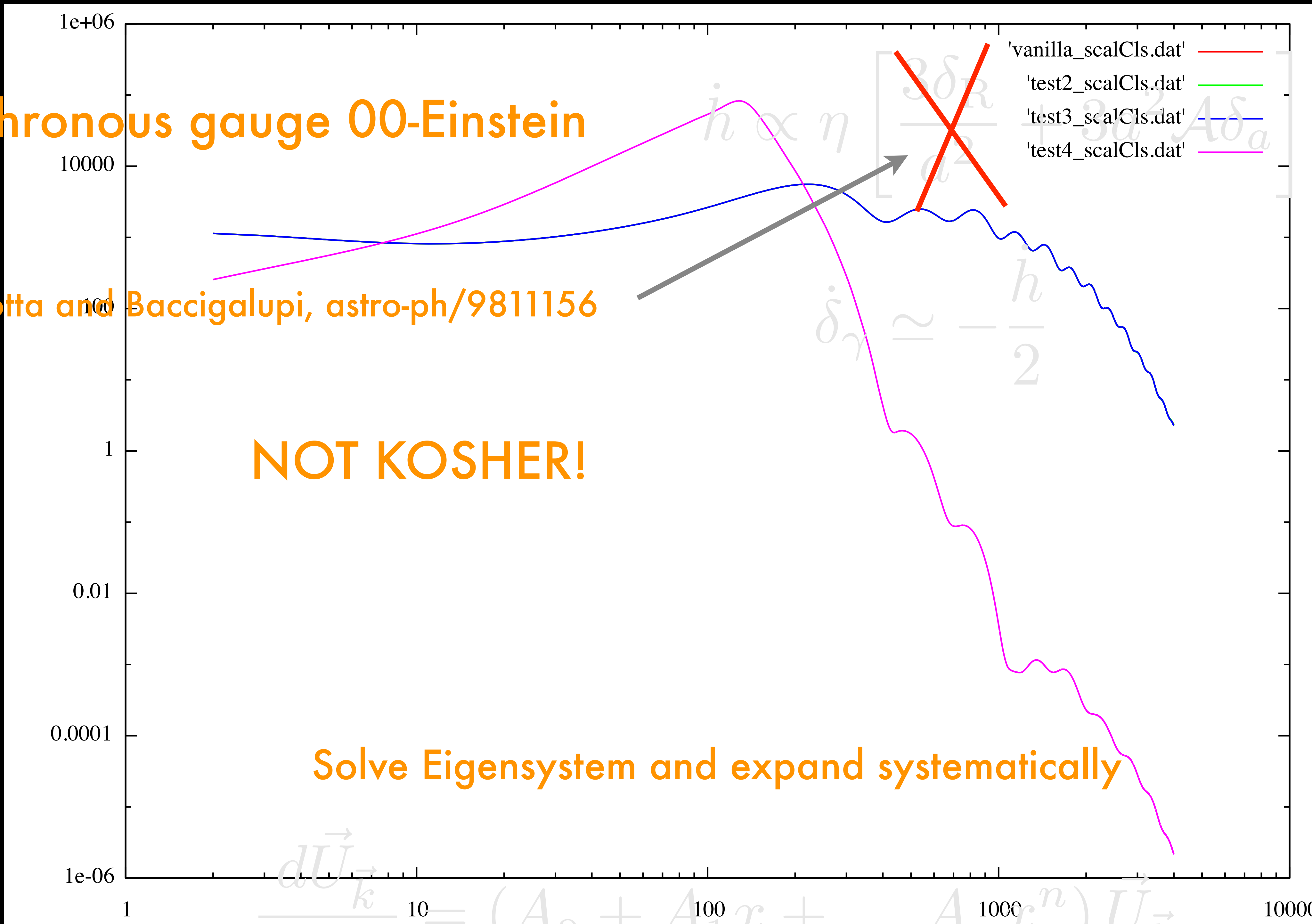
Synchronous gauge 00-Einstein

$$\dot{h} \propto \eta \left[\frac{3\delta_R}{a^2} + 3a^2 A\delta_a \right]$$

Perrotta and Baccigalupi, astro-ph/9811156

$$\dot{\delta}_\gamma \simeq -\frac{\dot{h}}{2}$$

NOT KOSHER!

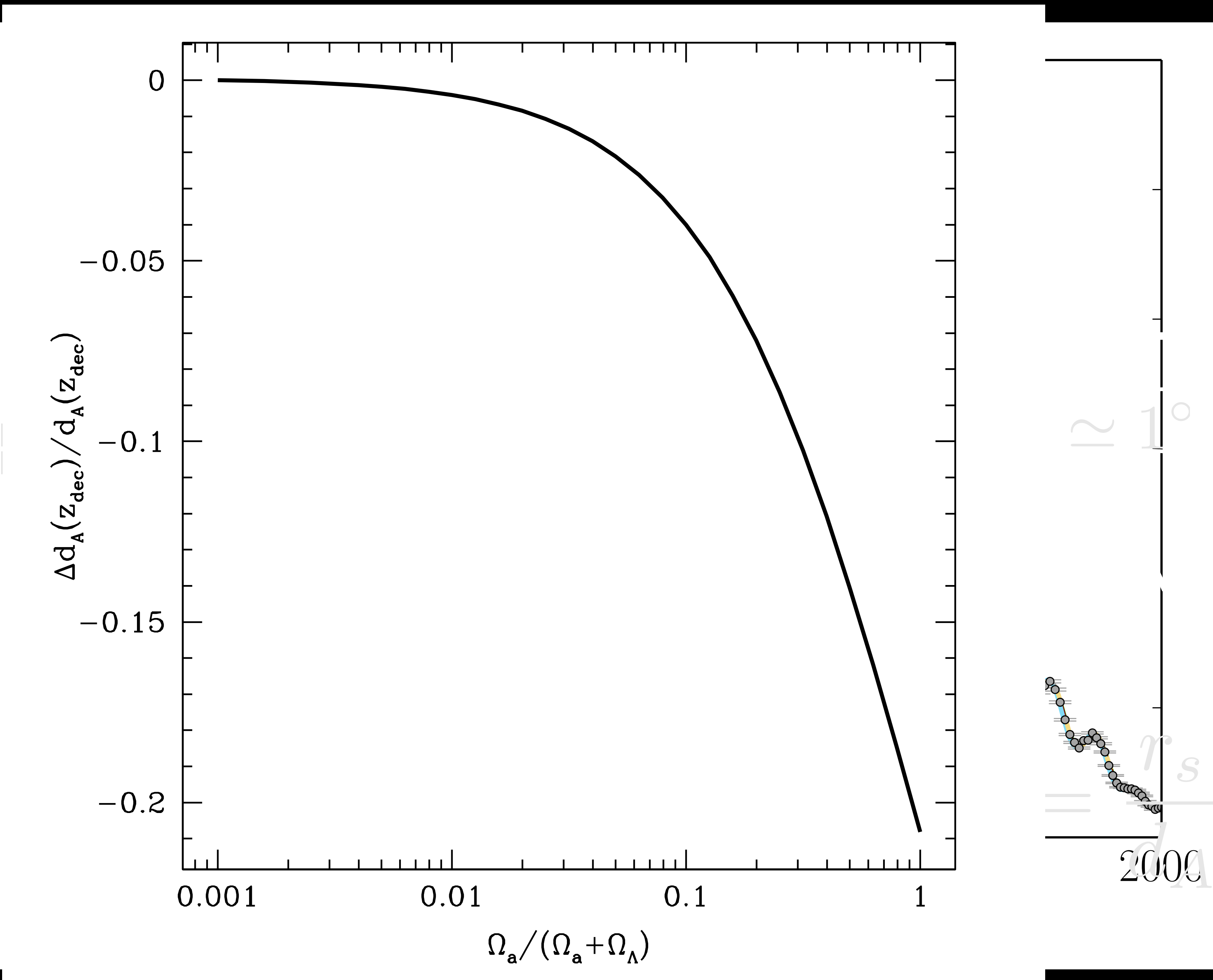


Solve Eigensystem and expand systematically

$$\frac{d\vec{U}_{\vec{k}}}{d\ln x} = (A_0 + A_1 x + \dots A_n x^n)\,\vec{U}_{\vec{k}}$$

Bucher, Moodley, and Turok, PRD62, 083508, sol'ns can be obtained using this technique, outlined in Doran et al. , astro-ph/0304212

ULAs and the angular sound horizon



$$\theta_s \equiv \frac{r_s}{d_A(z=1100)} = \left(l_{\rm CMB}^{\rm peak}\right)^{-1}$$

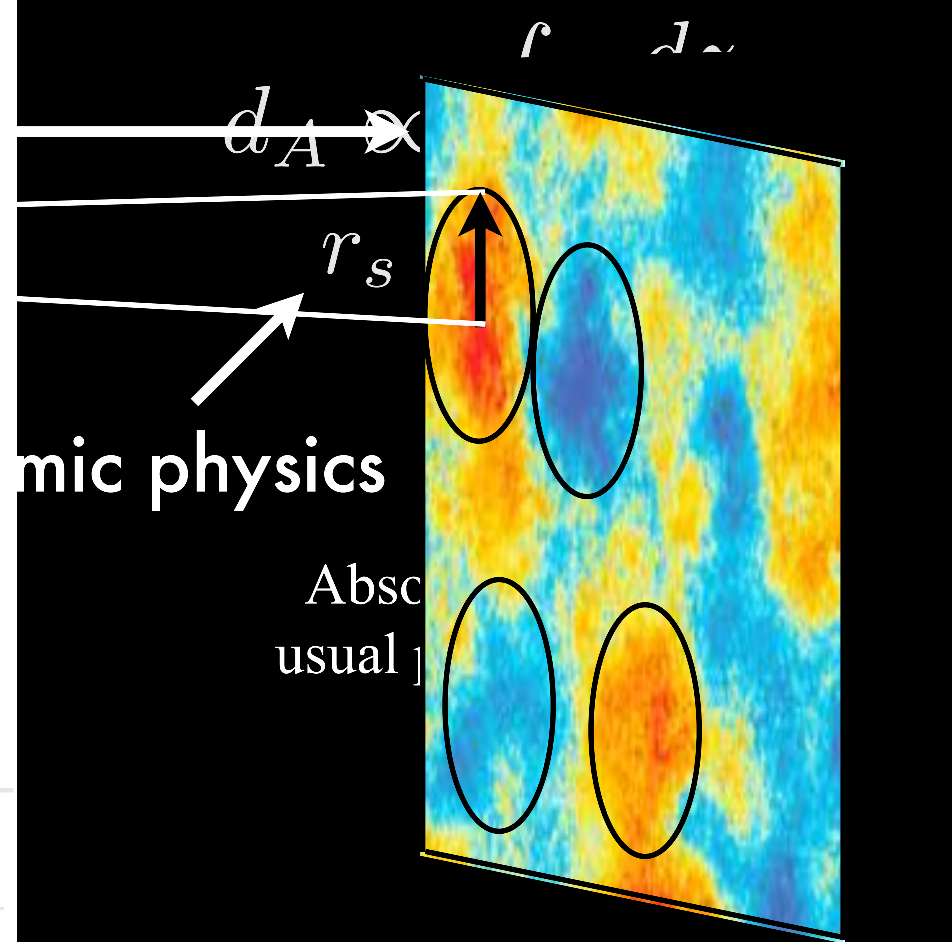


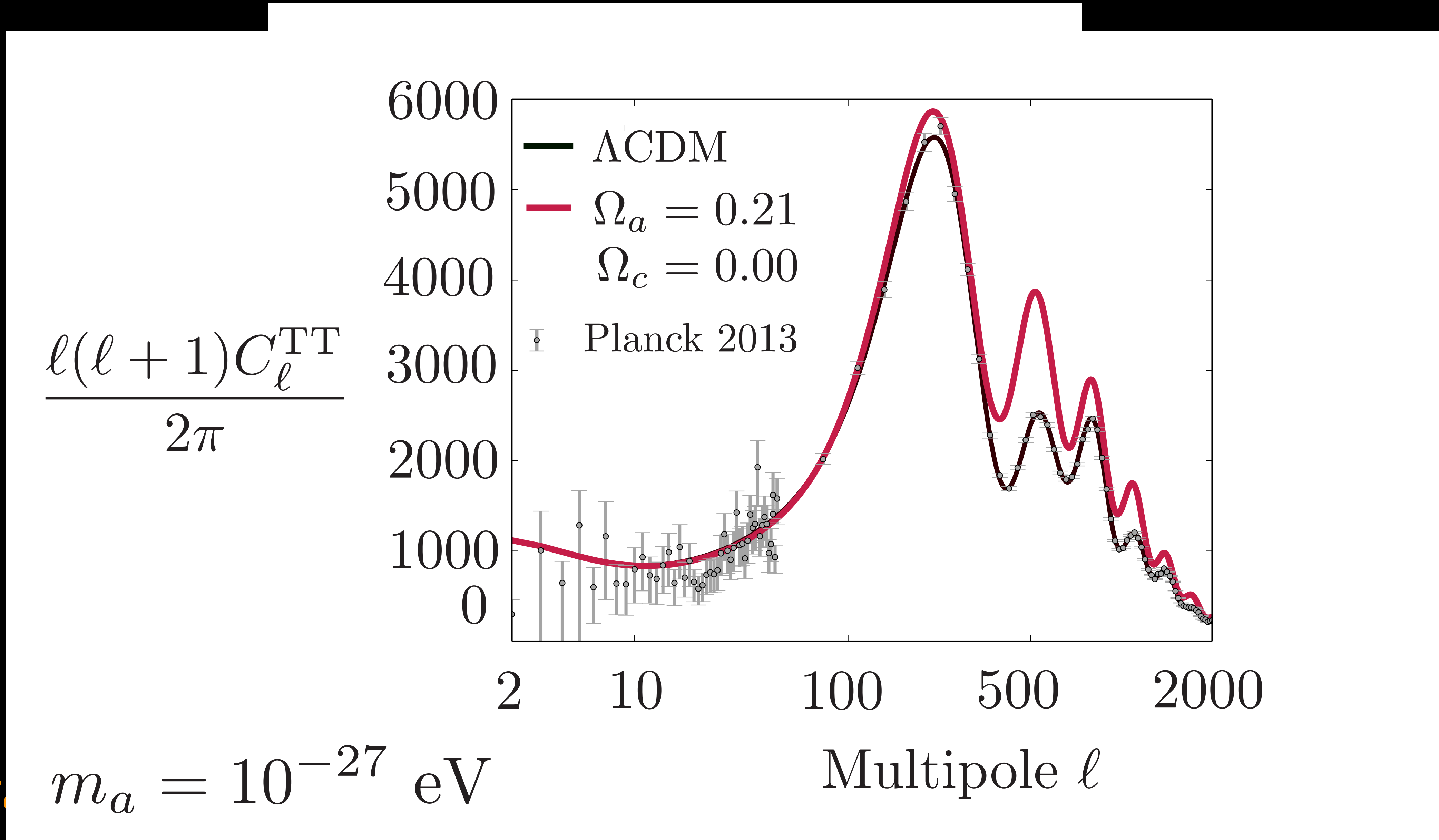
Diagram by T. Smith (used with permission)

$$H(z) = H_0 \left\{ \frac{\Omega_m}{a^3} + \frac{\Omega_{\rm axion}}{a^{3\int[1+w(\eta)]d\eta}} \right\}^{1/2}$$

Faster early expansion brings LSS closer

ULAs and the CMB: high mass and early ISW

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

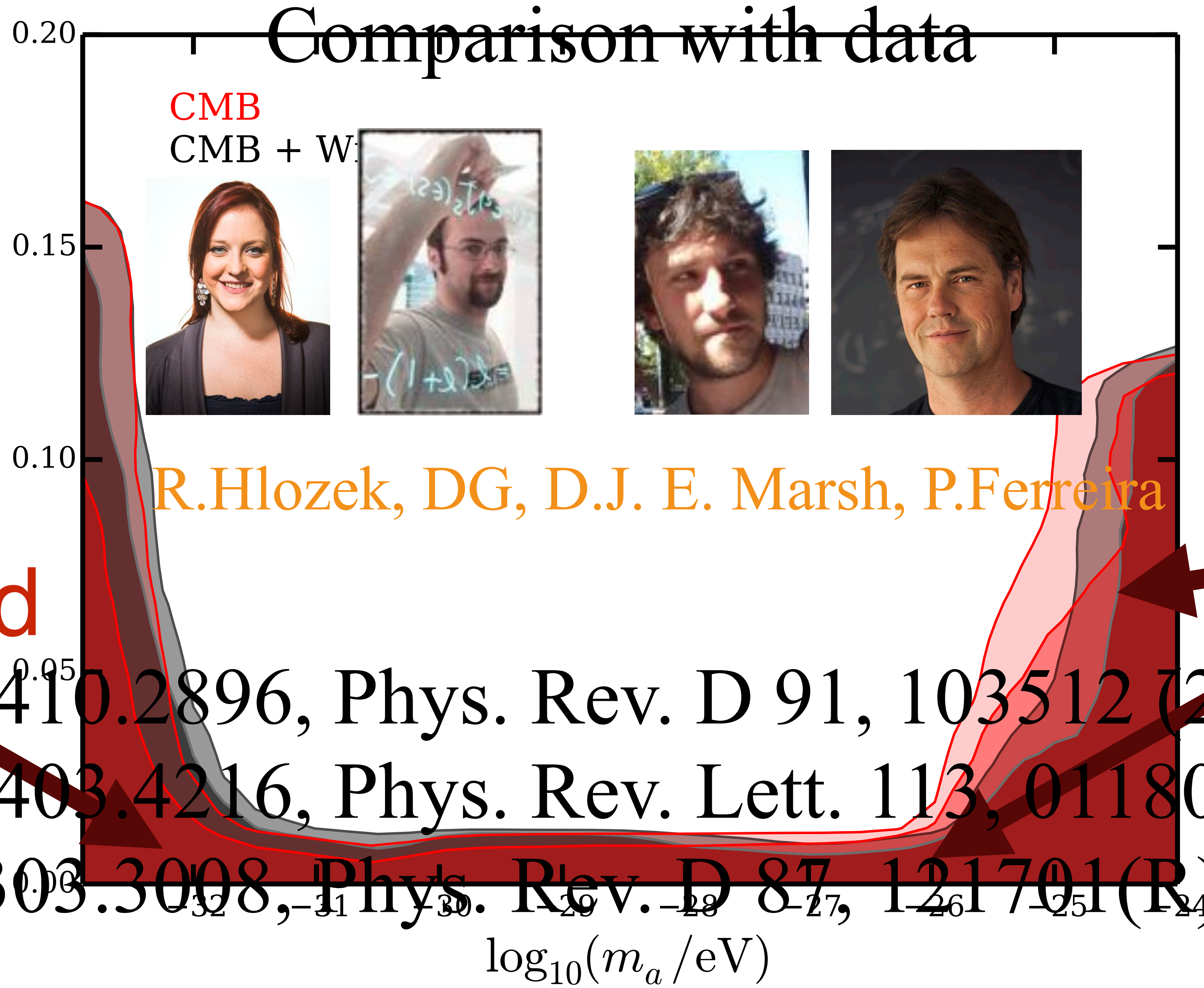


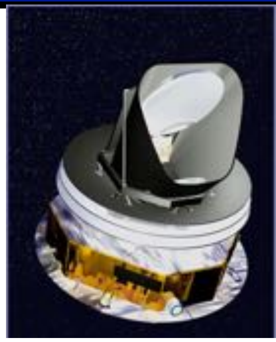
Radi

$$\Phi \propto \frac{1}{k^2}\left\{\frac{\Omega_m\delta_m\left(1-\frac{\Omega_a}{\Omega_m}\right)}{a^3}+\frac{\delta_R\Omega_R}{a^4}\right\}$$

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

CONSTRAINTS





$$\frac{\rho_{\rm axion}}{\rho_{\rm tot}}$$

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

Allowed

Allowed

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)

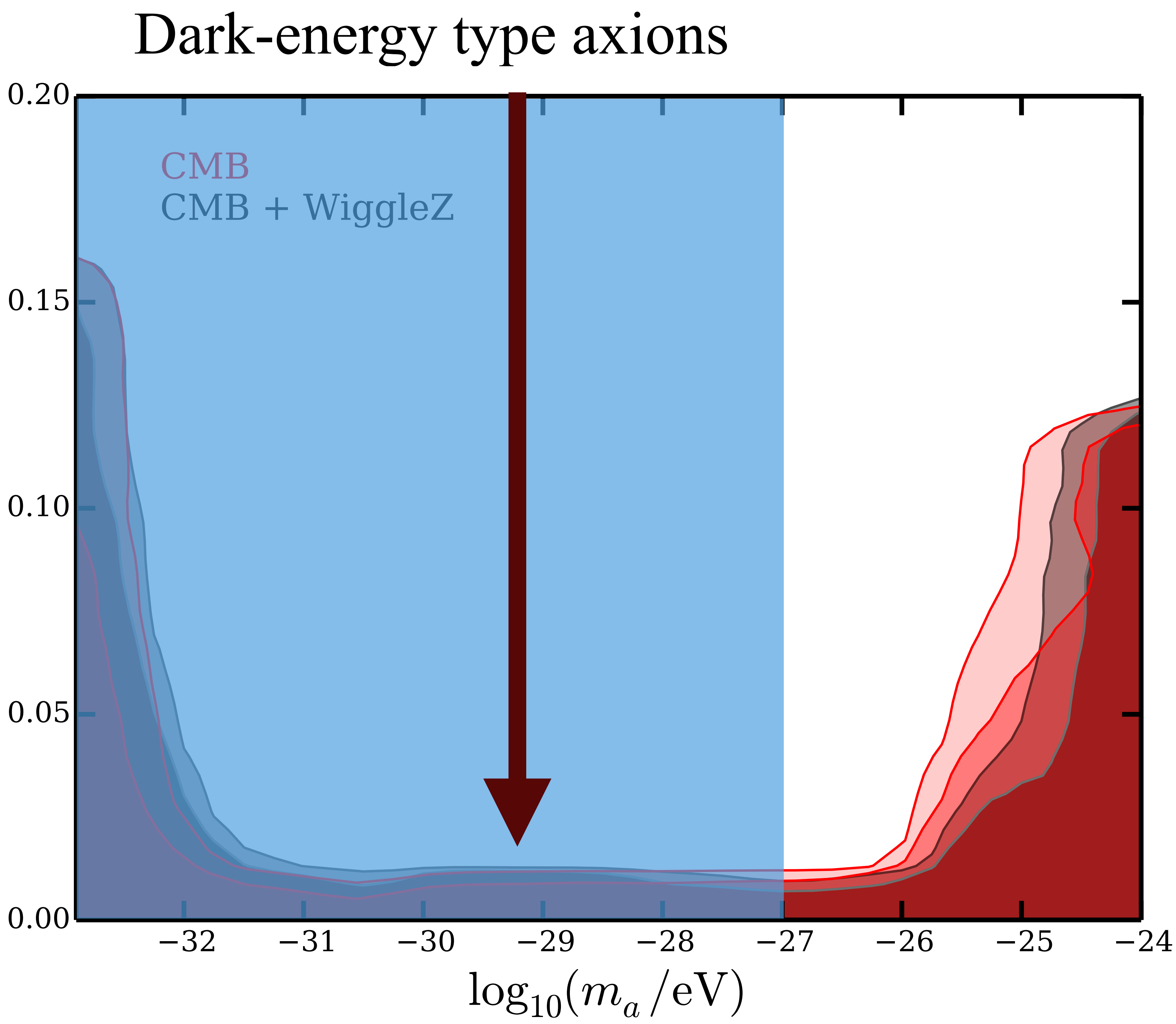
✴Tight constraints over 7 orders of magnitude in mass:

Thanks to AxiCamb and Planck

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

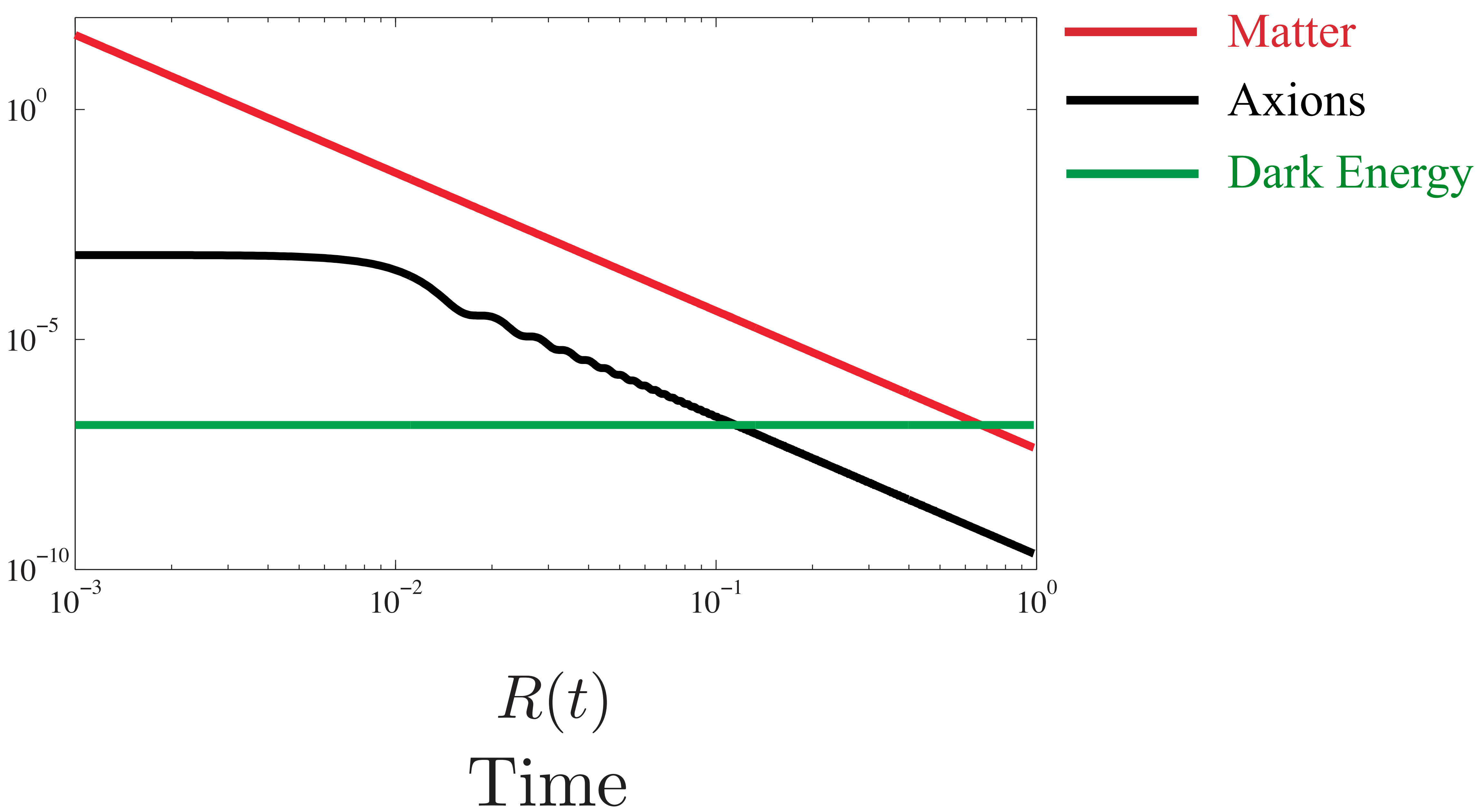
Physics behind the constraints

$$\frac{\rho_{\rm axion}}{\rho_{\rm tot}}$$



CMB Constraints at low masses

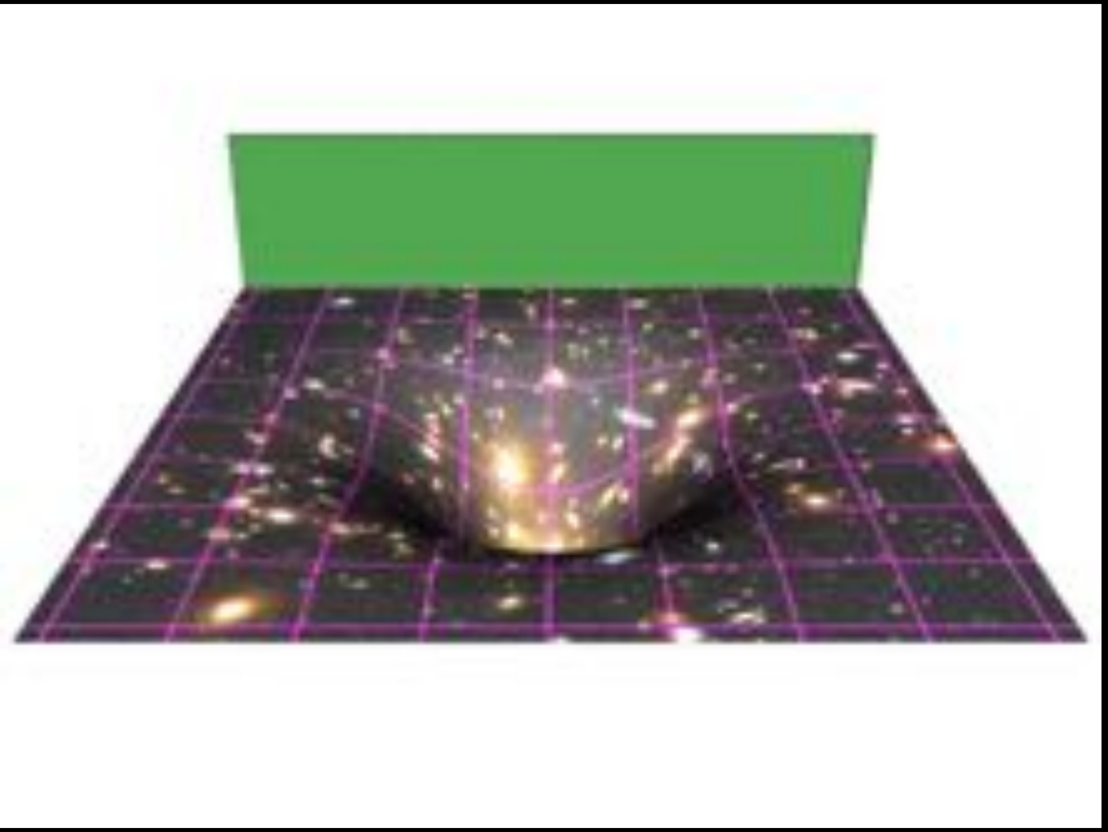
- Axion energy density behaves unusually



What about this bump?

Faster early expansion brings CMB emission surface closer

Low mass (DE-like) case: late Integrated Sachs-Wolfe Effect

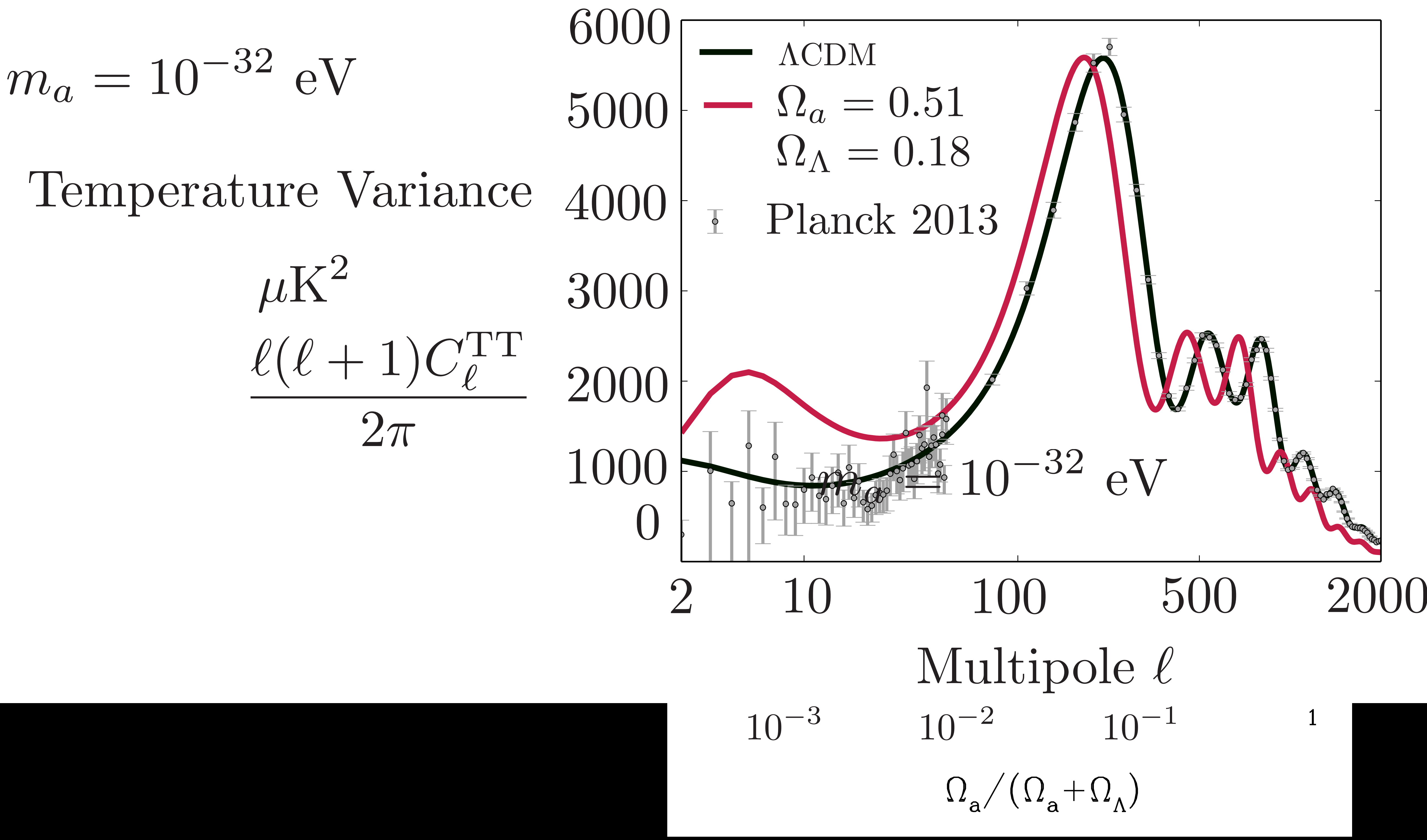


CMB temperature anisotropies from potential decay

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

ULAs as dark energy

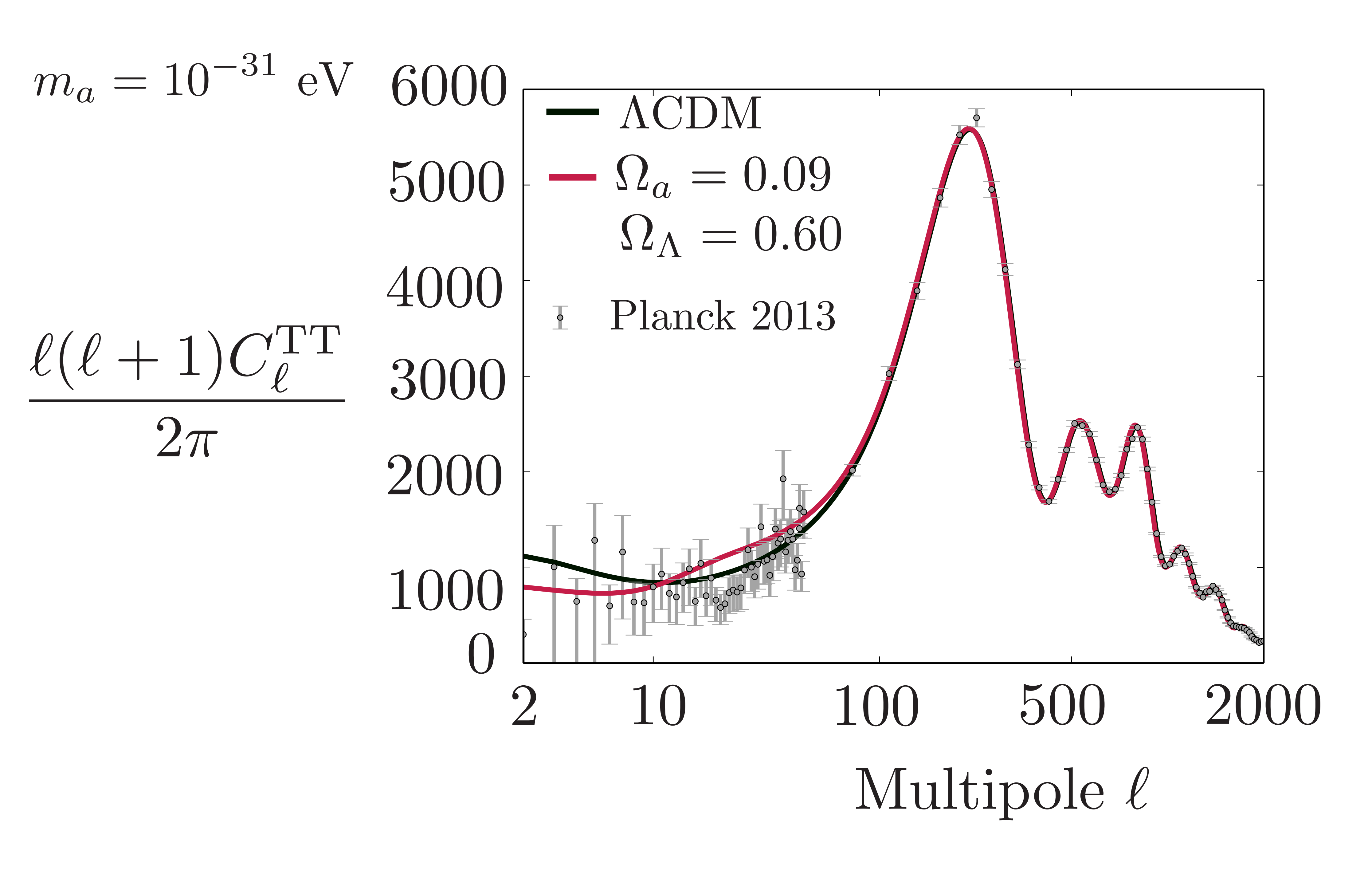
$m_a = 10^{-32}$ eV



Faster early expansion brings LSS closer

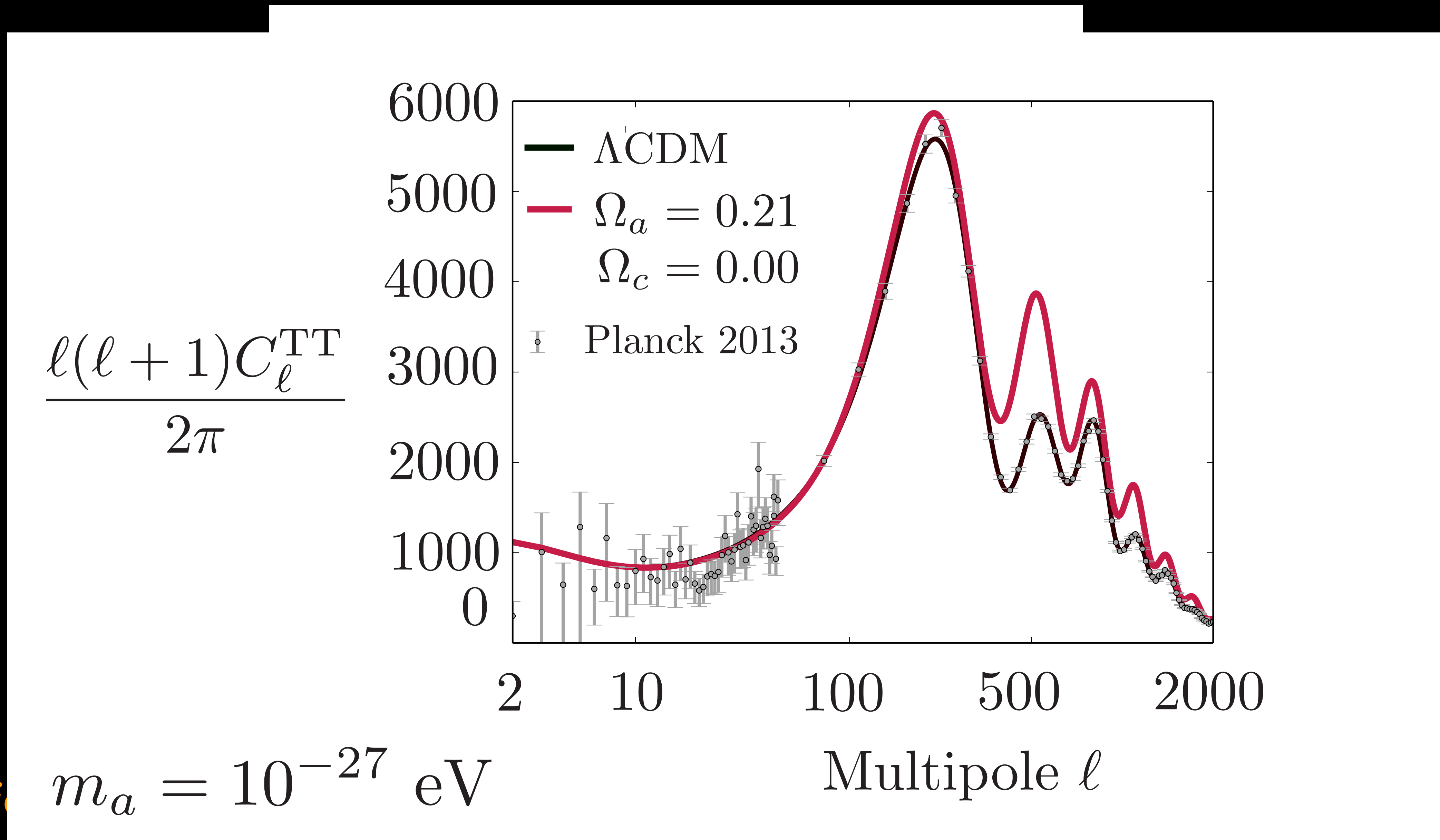
ULAs as dark energy and perturbations in other fluids

Low mass (DE-like) case: late Integrated Sachs-Wolfe Effect



ULAs and the CMB: high mass and early ISW

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



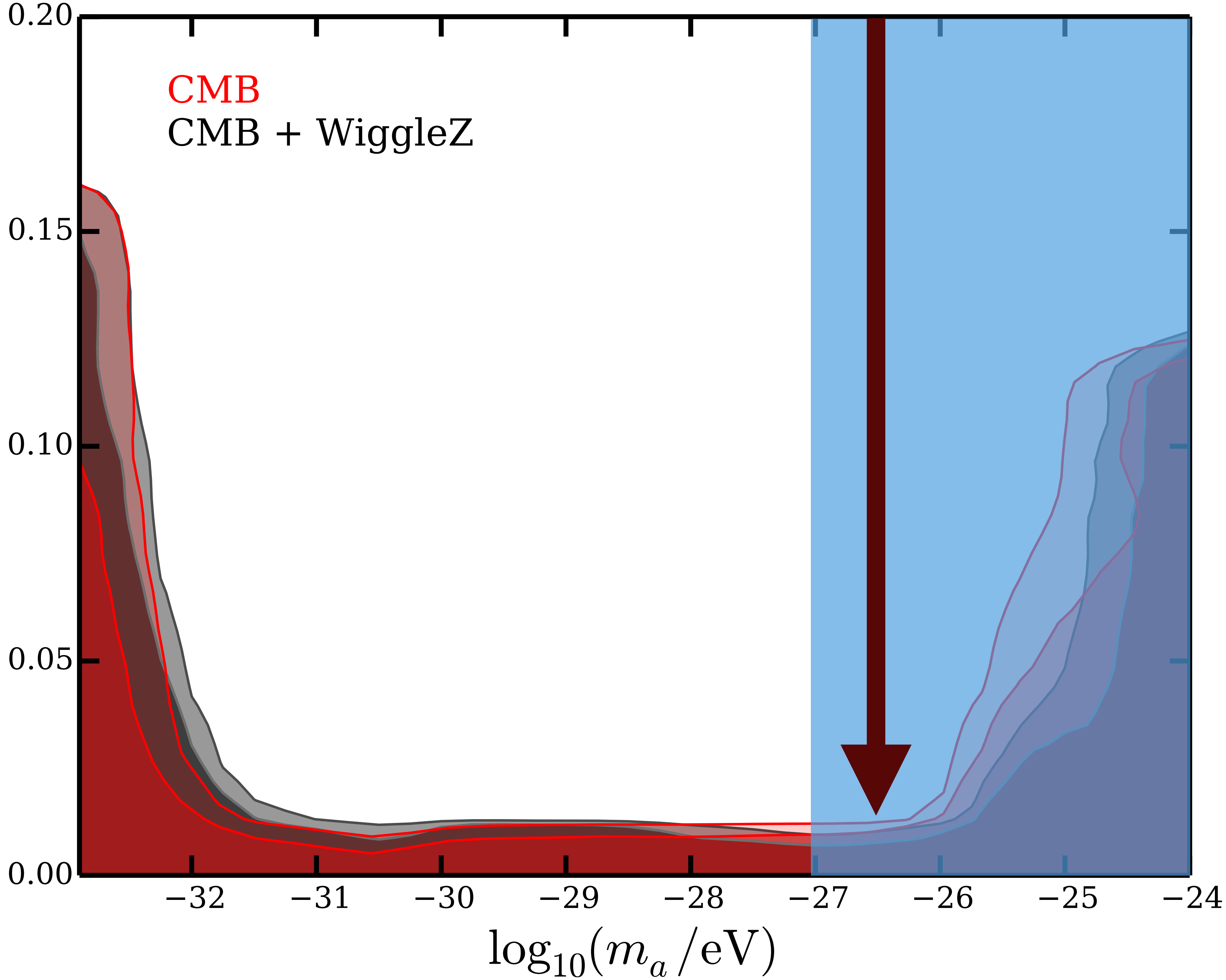
Radi

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

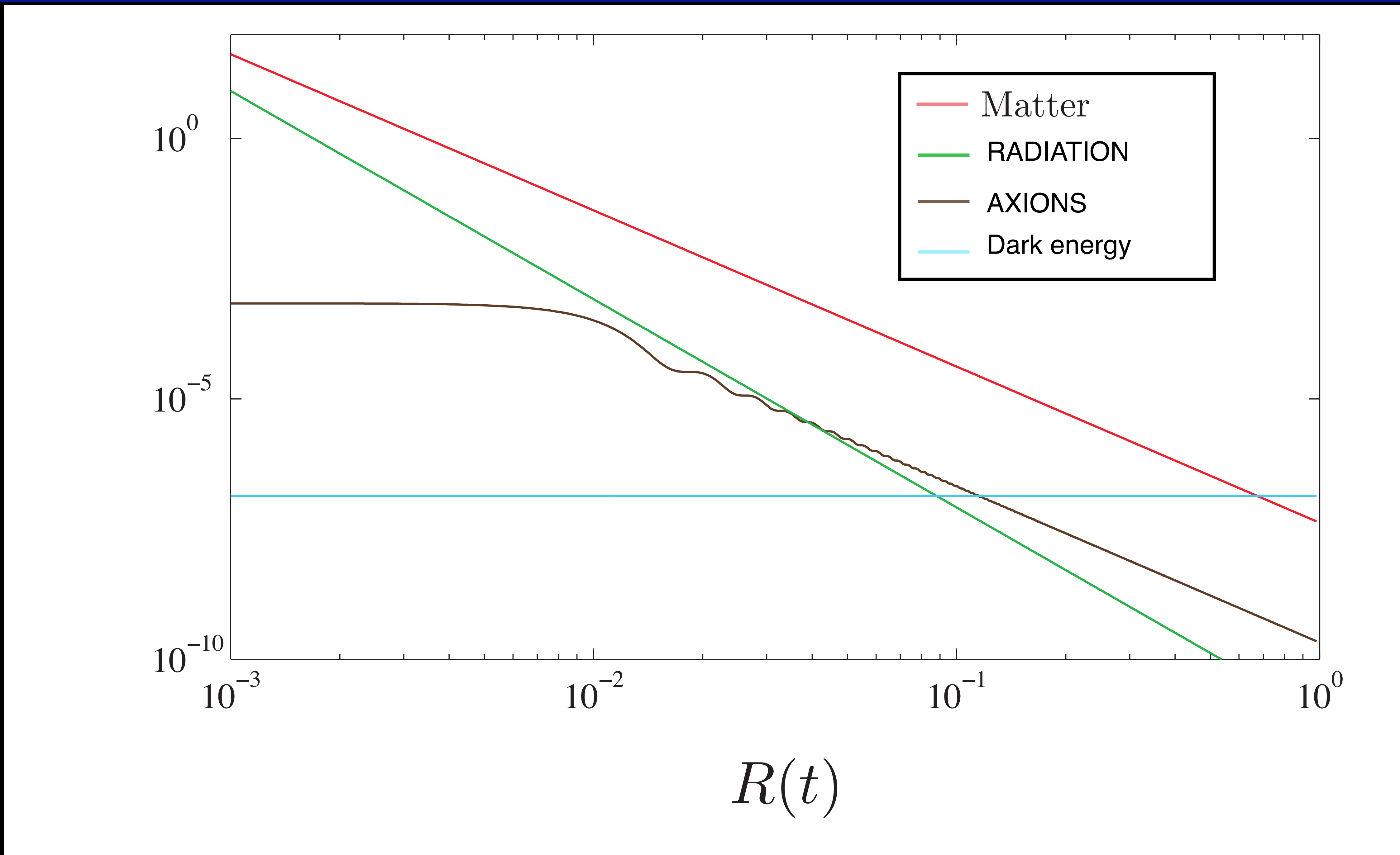
Physics behind the constraints

Dark-matter type axions

$$\frac{\rho_{\rm axion}}{\rho_{\rm tot}}$$



ULAs and the CMB: high mass and early ISW



CMB temperature anisotropies from potential decay

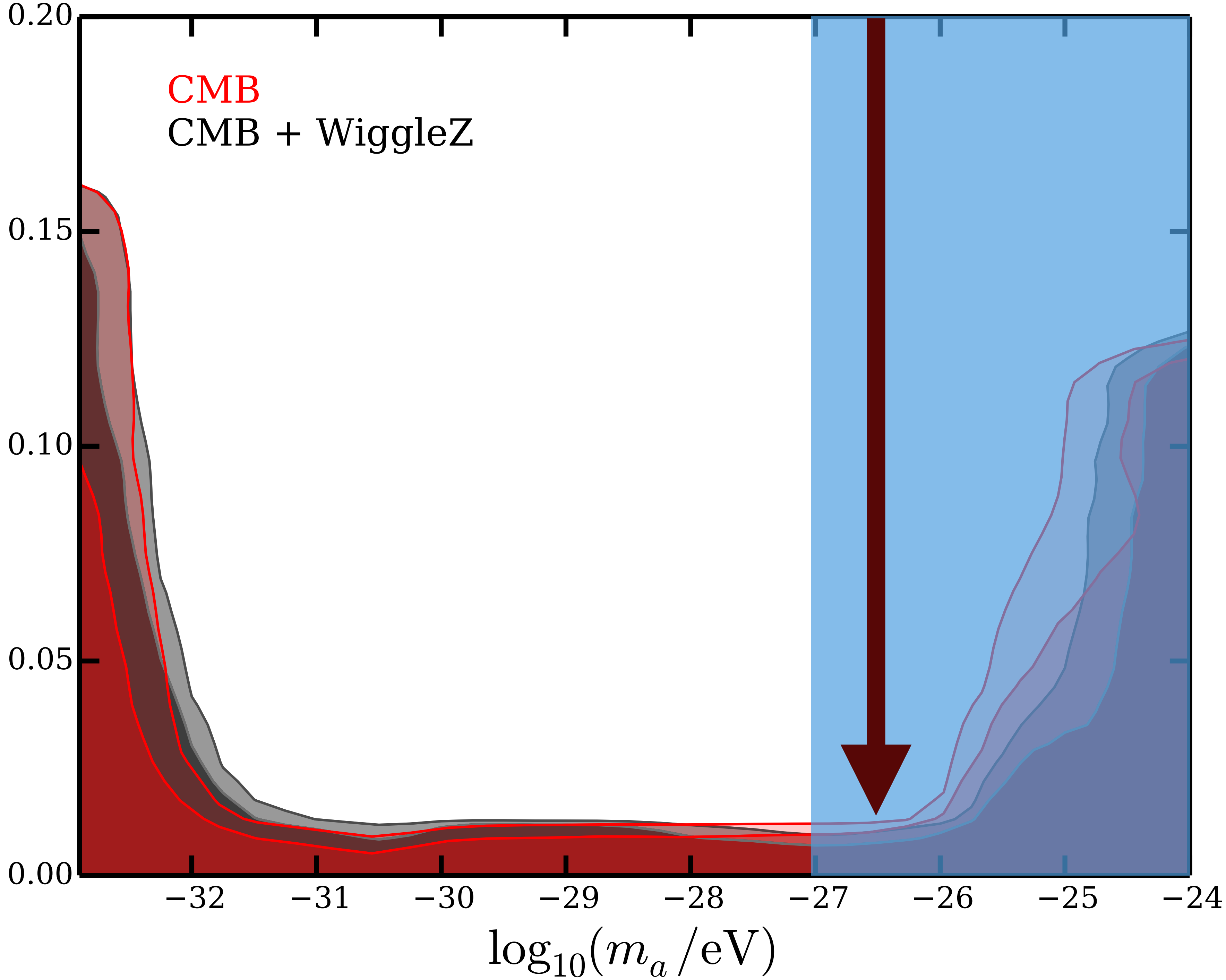
Matter radiation balance changed at z~3400

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

PHYSICS BEHIND THE CONSTRAINTS

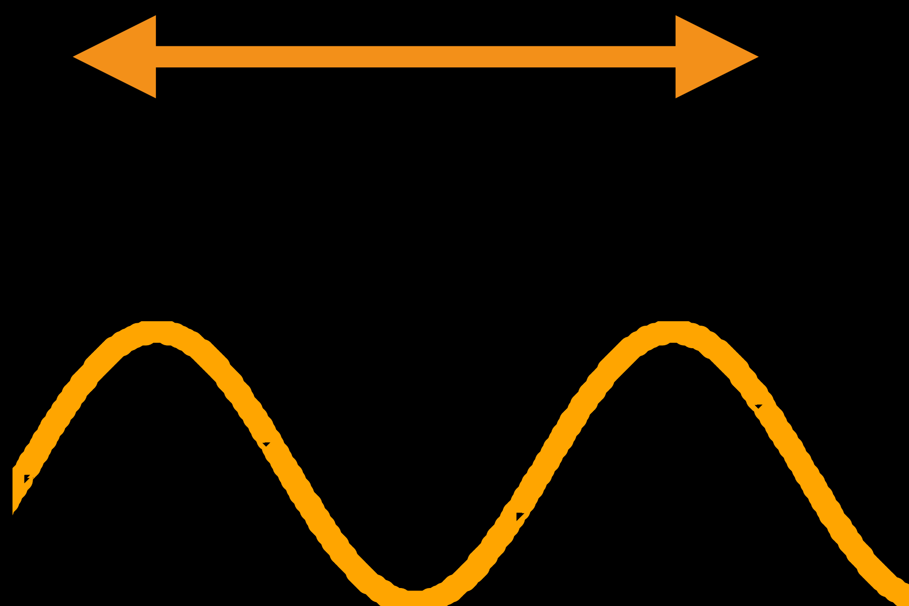
Dark-matter type axions

$$\frac{\rho_{\rm axion}}{\rho_{\rm tot}}$$

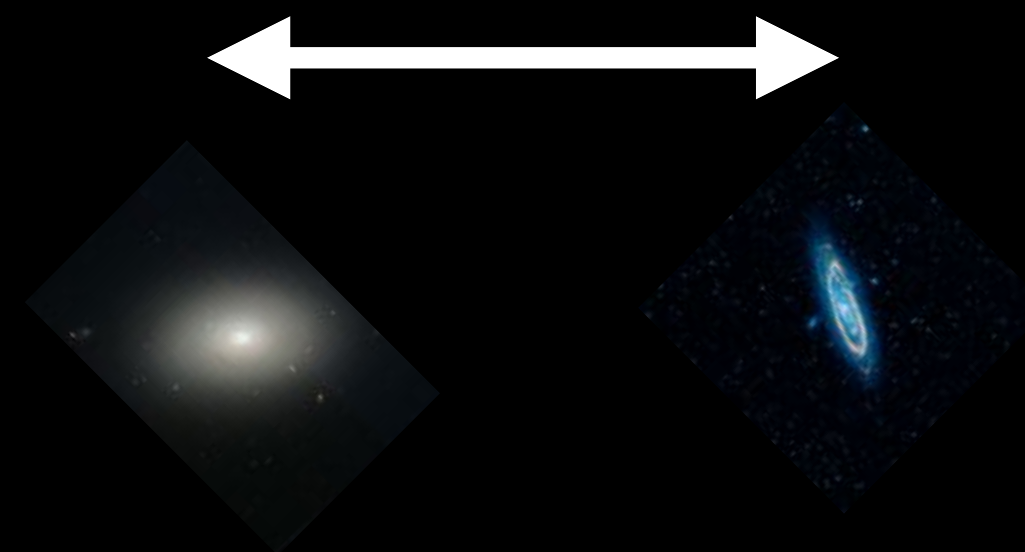


Look for ultra-light axions in the cosmos

Axion deBroglie wavelength



Astronomical length scale
kilo-lightyear – giga-lightyear!

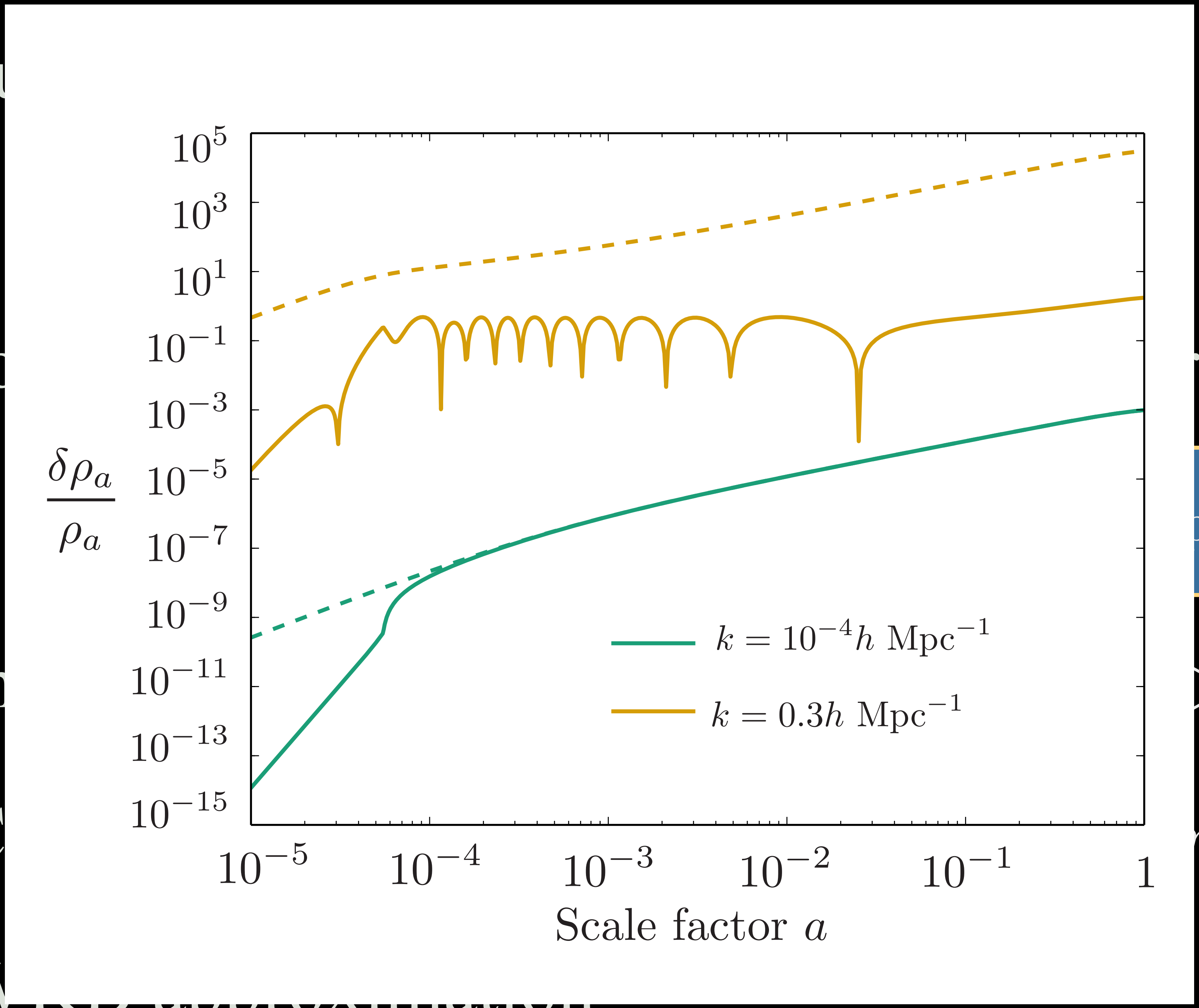


GROWTH OF ULA PERTURBATIONS

✳Pertu

$- \Psi a^2 m_a^2 \phi_0$

✳Axio … rast to QCD axion]:



pc

CDM

Axion DM

✳Com … $\gg 3\mathcal{H}$:

✳ C … $na)^{-1} \ll \Delta\eta_{\mathrm{CAMB}}$

✳ WKB approximation

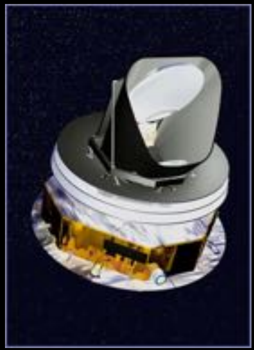
$$\delta\phi = A_c \Delta_c(k,\eta)\cos(m\eta) + A_s \Delta(k,\eta)\sin(m\eta)$$

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

✳"Pressure" stabilization

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

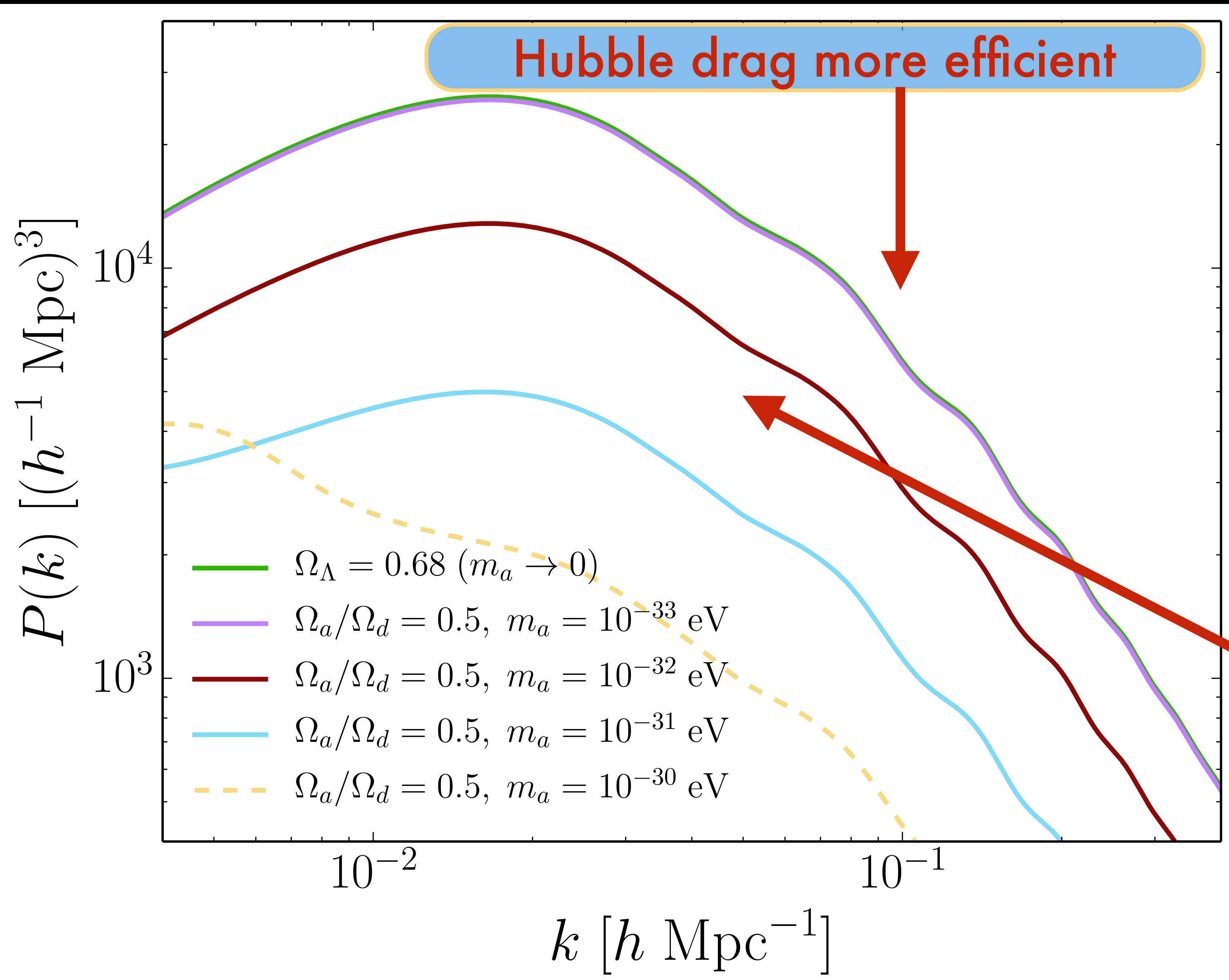
DATA



- ✳Planck 2013 temperature anisotropy power spectra (+SPT+ACT+BAO)
  - ✳Cosmic variance limited to $\ell \sim 1500$
  - ✳Power spectrum already shown

- ✳WiggleZ galaxy survey (linear scales only $k \lesssim 0.2h\ \mathrm{Mpc}^{-1}$)
  - ✳Galaxy bias marginalized over
  - ✳Theory P(k) convolved with survey window function
  - ✳240,000 emission line galaxies at z<1
  - ✳3.9 m Anglo-Australian Telescope (AAT)

Matter power spectrum for ULA (in DE regime)



θ_s fixed to lock CMB

$H_0 \downarrow$

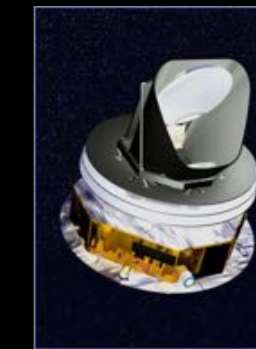
$k_{eq} = \lambda^{-1}_{\mathrm{horizon,eq}} \downarrow$

Peak of P(k) to lower k

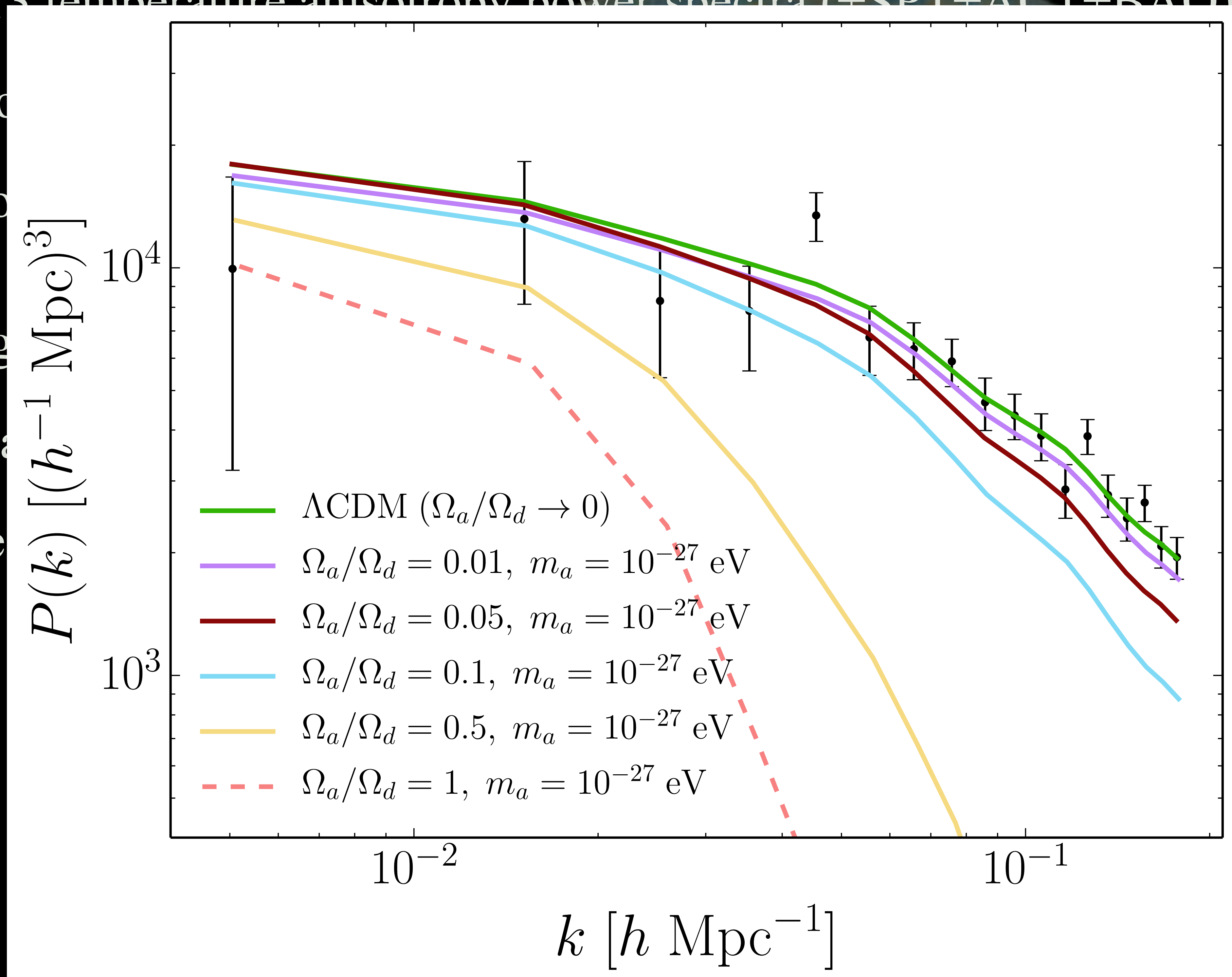
$$1 + z_{eq} = \frac{\Omega_m h^2}{\rho_{\mathrm{rad}}}$$

Matter-radiation equality delayed

Data



- Planck 2013 temperature anisotropy power spectra (+SPT+ACT+BAO)
  - Co
  - Po
- WiggleZ g
  - Gal
  - The

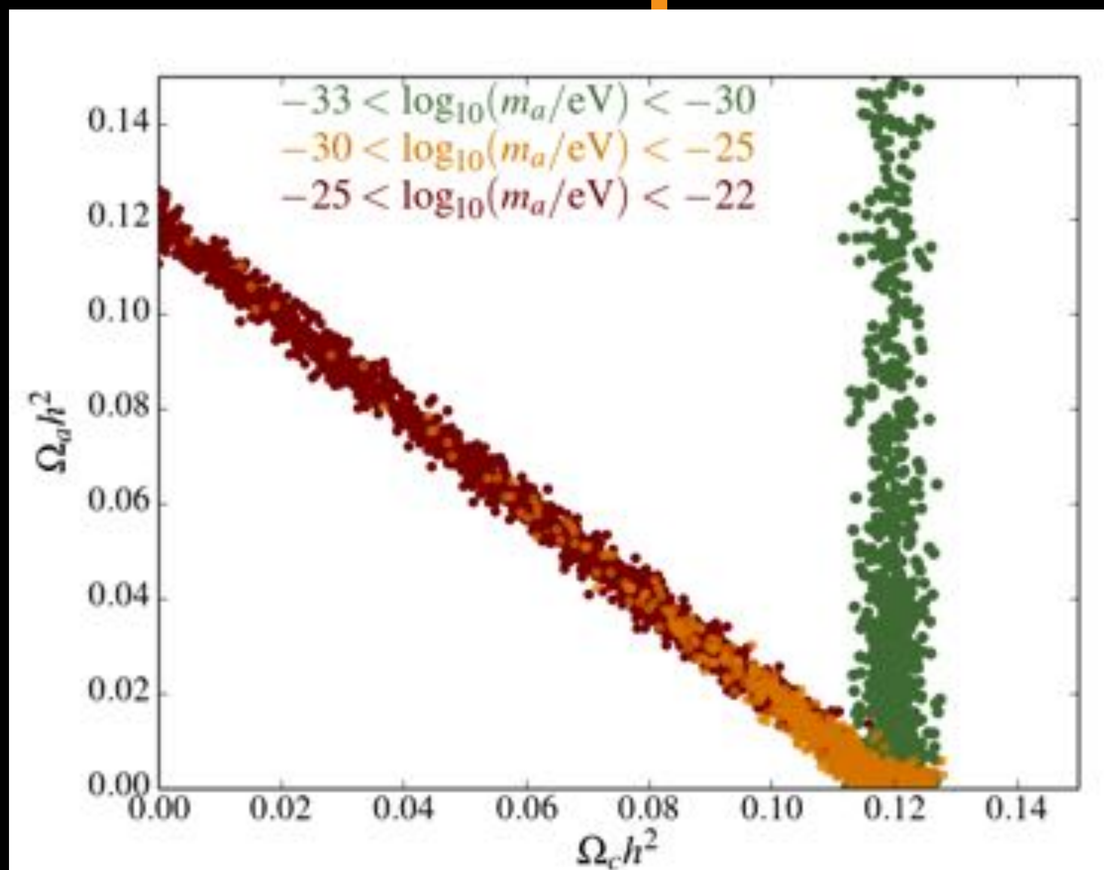


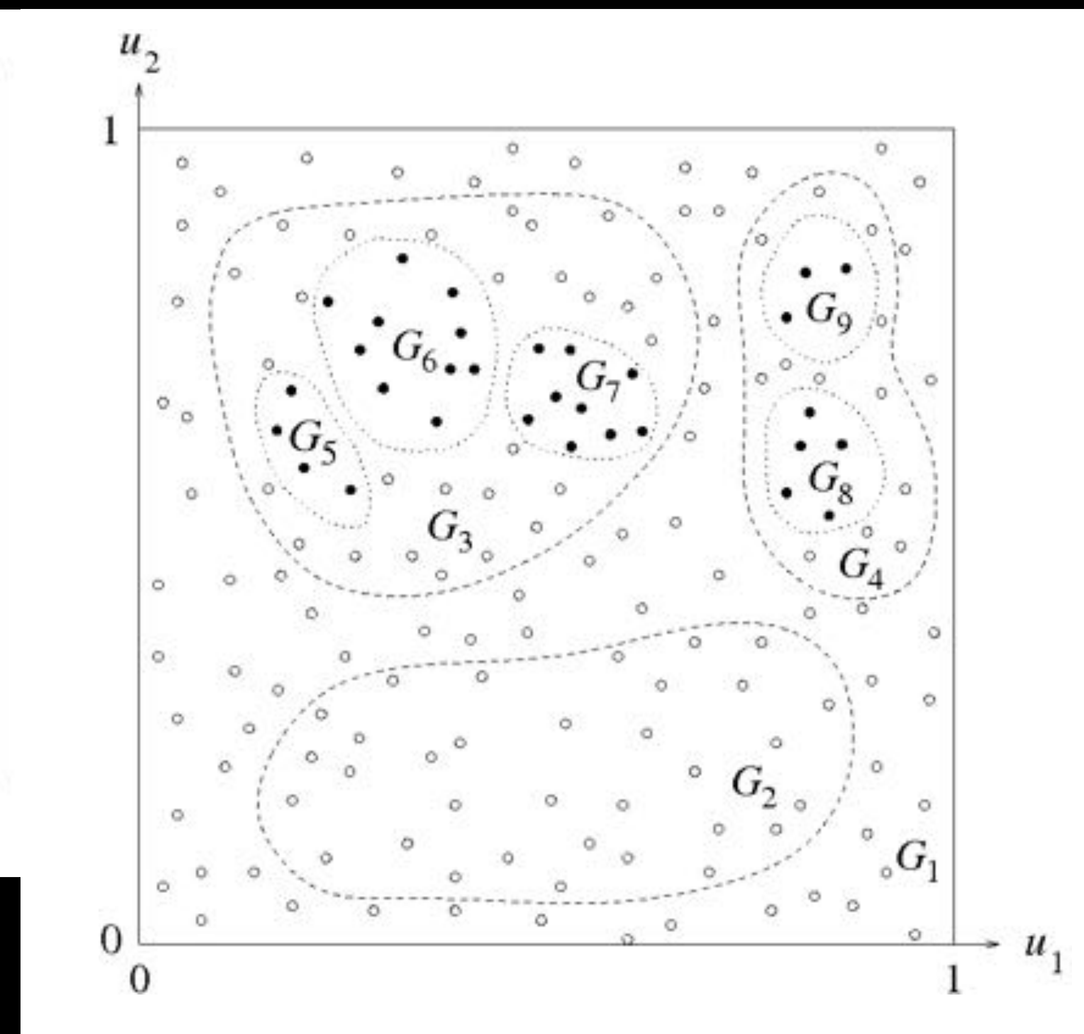
<1

(AAT)

Difficult parameter space

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



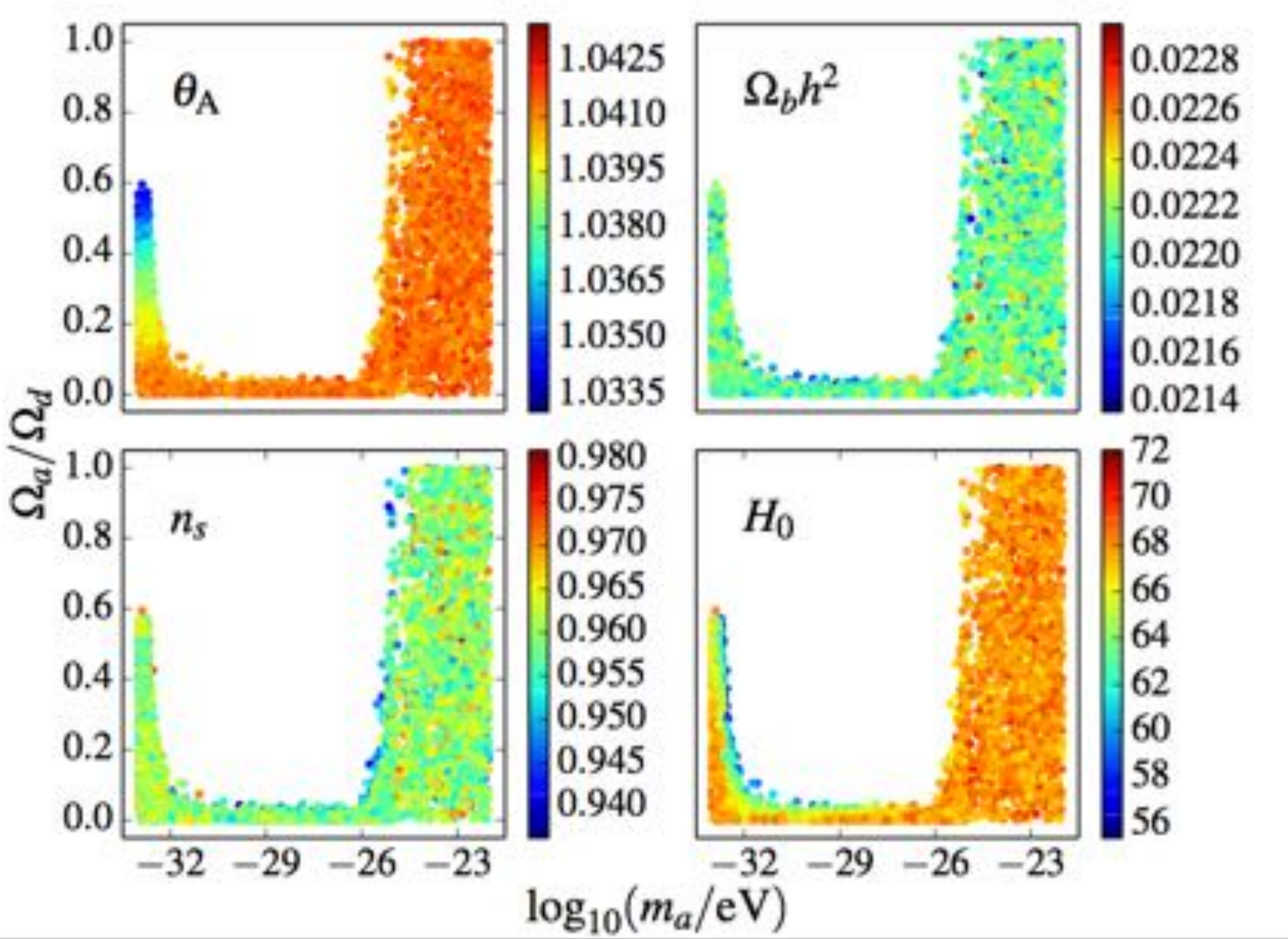


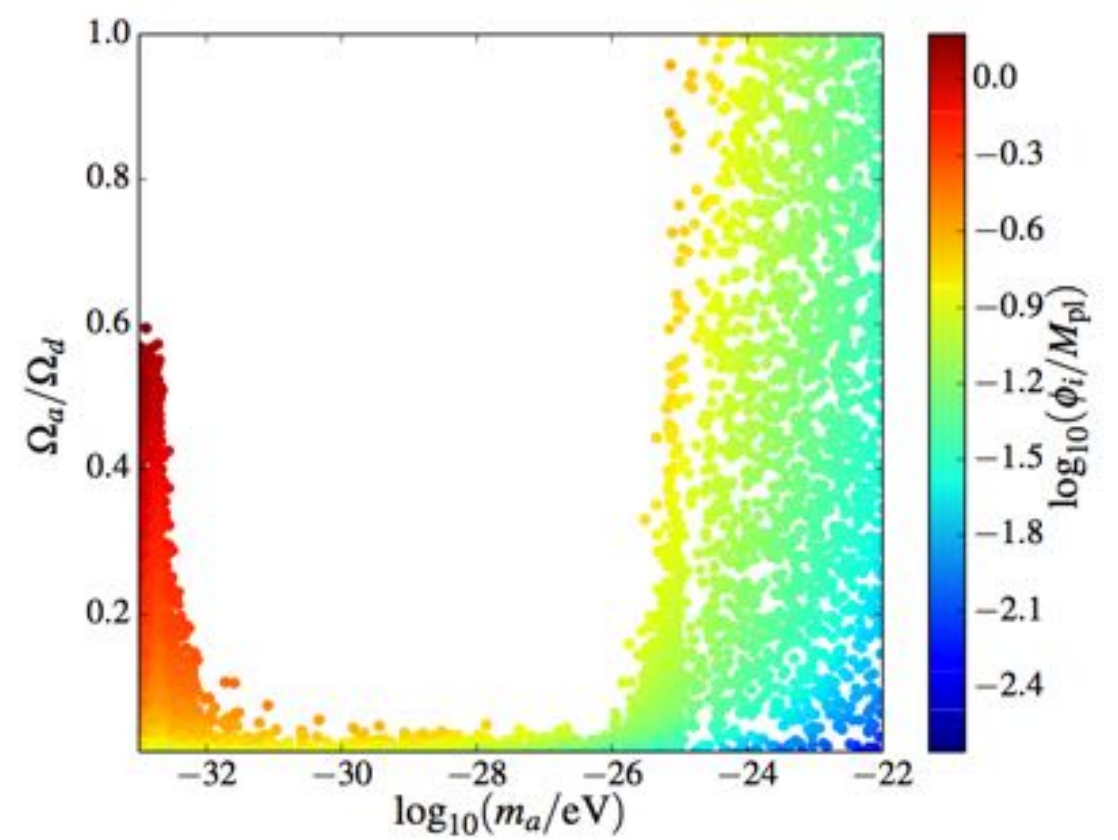
rlo

Addressed using nested sampling

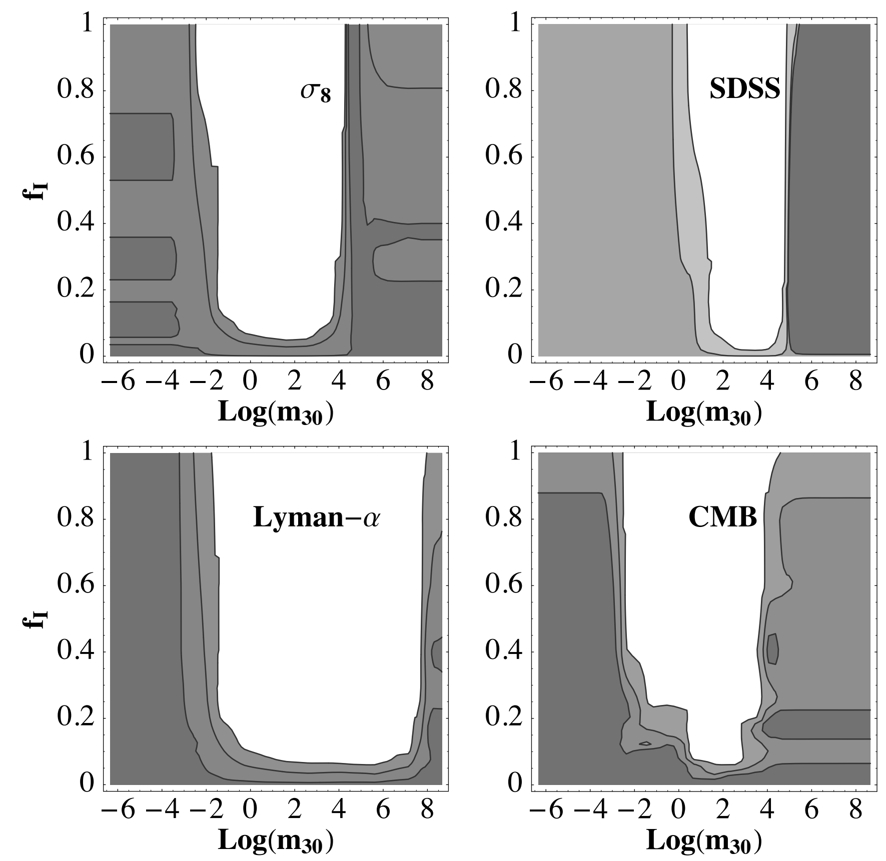
MULTINEST (Hobson, Feroz, others 2008)

Degeneracies/Weak gravity conjecture





Amendola and Barbieri



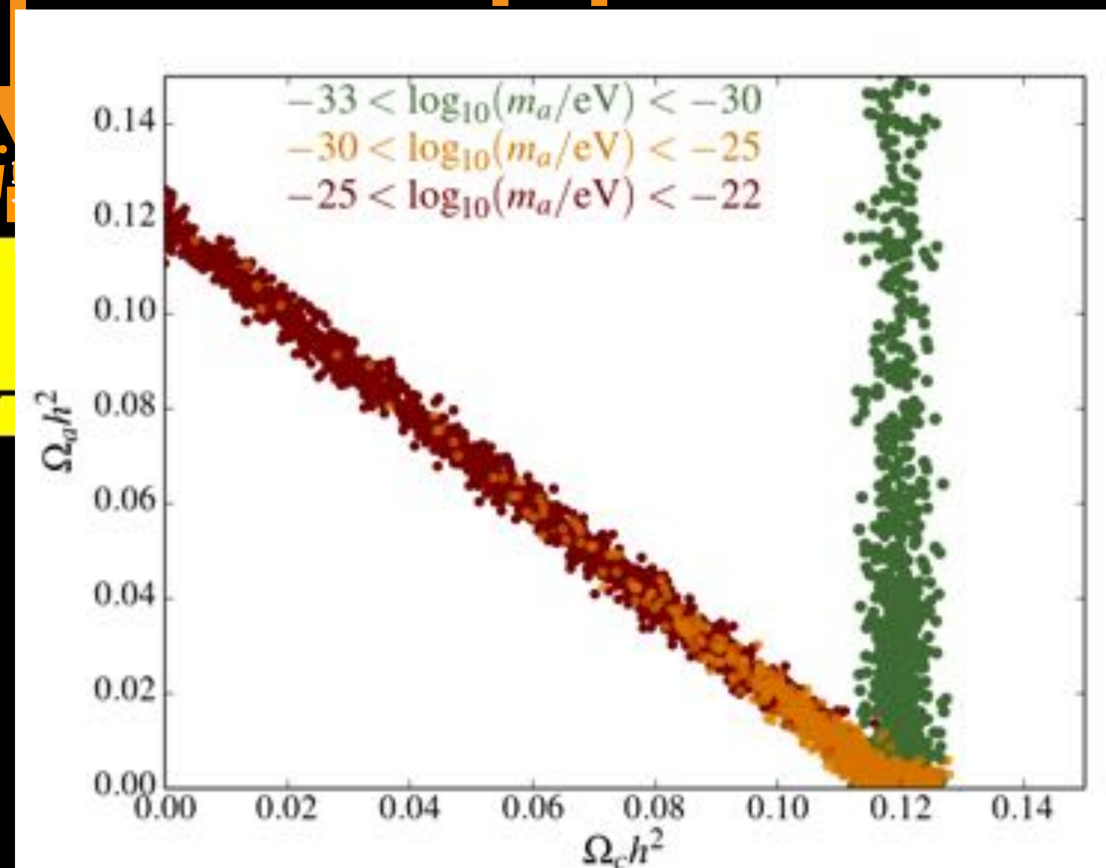
Old power spectrum constraints from Amendola and Barbieri, arXiv:hep-ph/0509257

1) Grid search
2) No isocurvature
3) No marginalization over foregrounds
4) No lensing, no polarization
5) No real Boltzmann code [step in power spectrum, or unclustered DE at low m]

Difficult parameter space

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

$\tau_{\rm reion} = \int$



with data

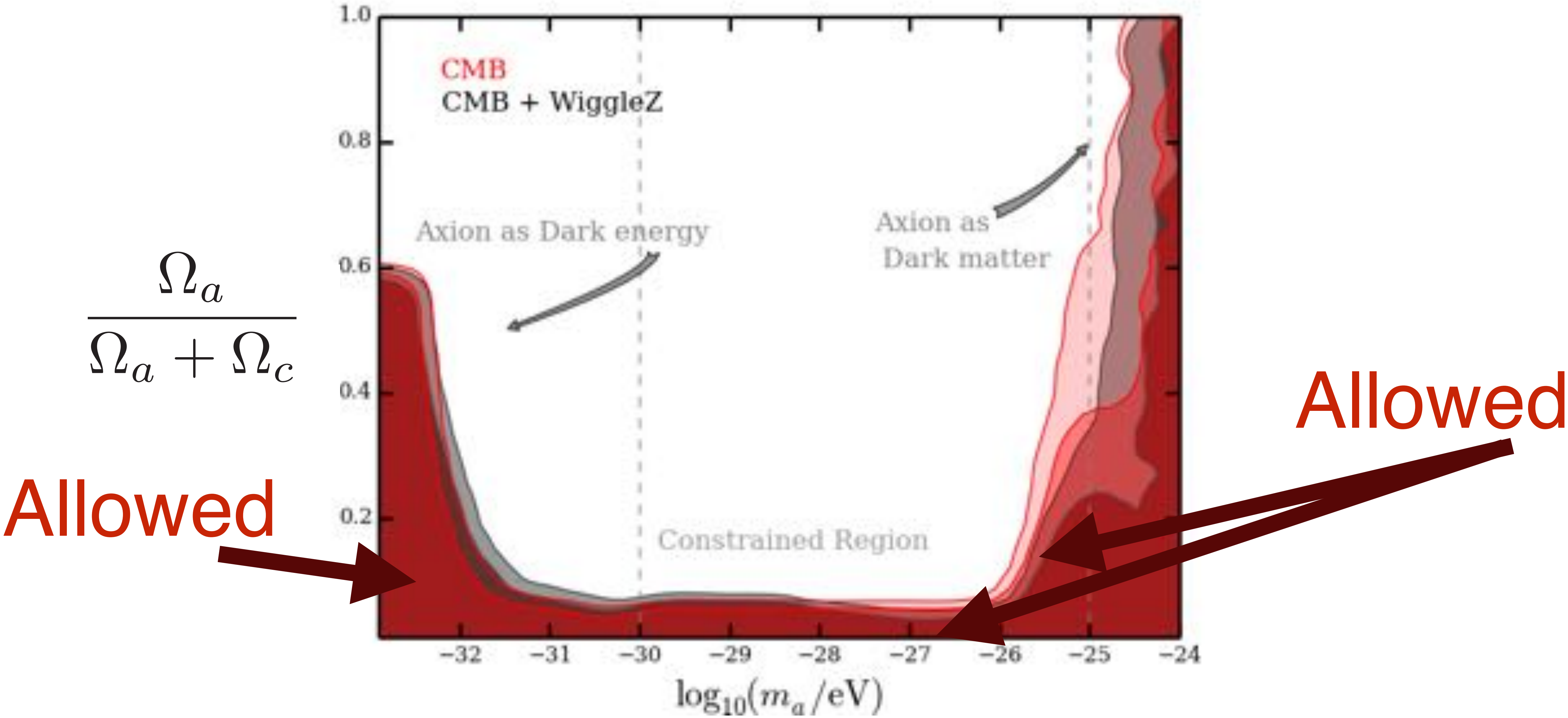
using Monte Carlo

in (MCMC)

Addressed using nested sampling

MULTINEST (Hobson, Feroz, others 2008)

CONSTRAINTS



- ✳Interesting constraints over 7 orders of magnitude in mass:

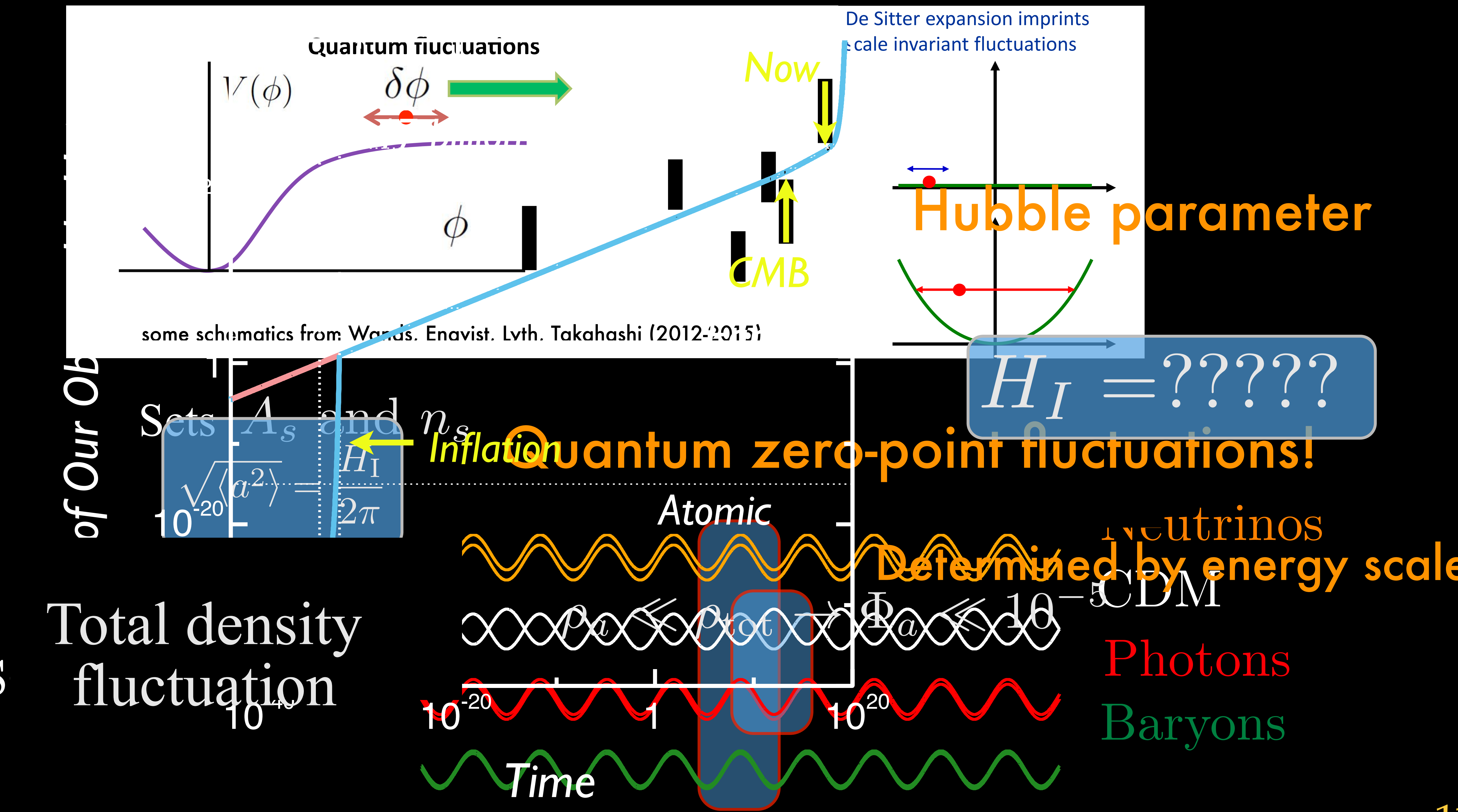
  Thanks to AXICAMB and MULTINEST

- ✳ULAs highly constrained if $10^{-32}\ \mathrm{eV} \lesssim m_a \lesssim 10^{-25.5}\ \mathrm{eV}$
- ✳ULAs are viable DM/DE candidates in linear theory outside ``belly''

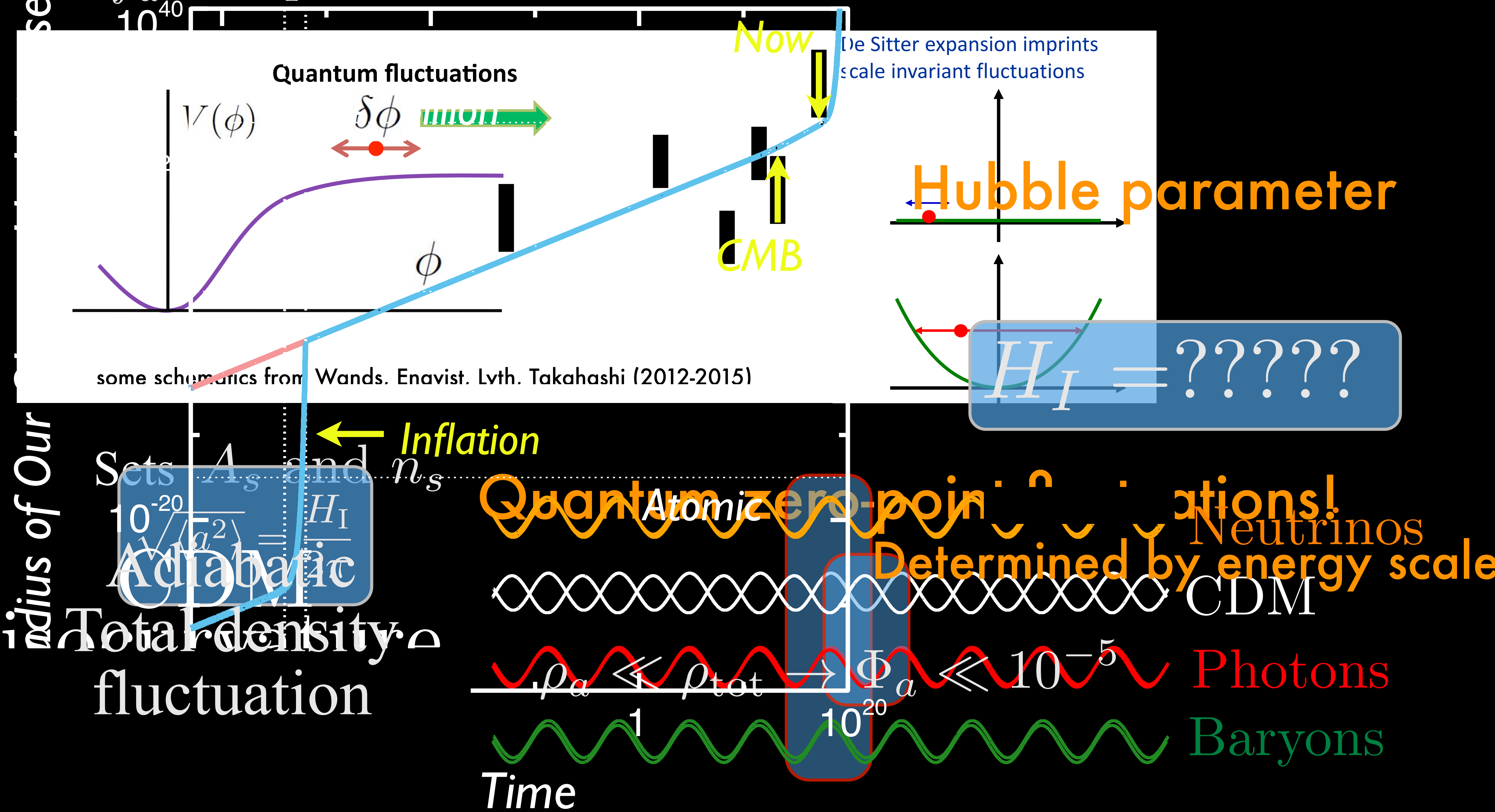
Axions and isocurvature fluctuations

✳ Inflation is an early epoch of accelerated expansion

$f_a > H_I$

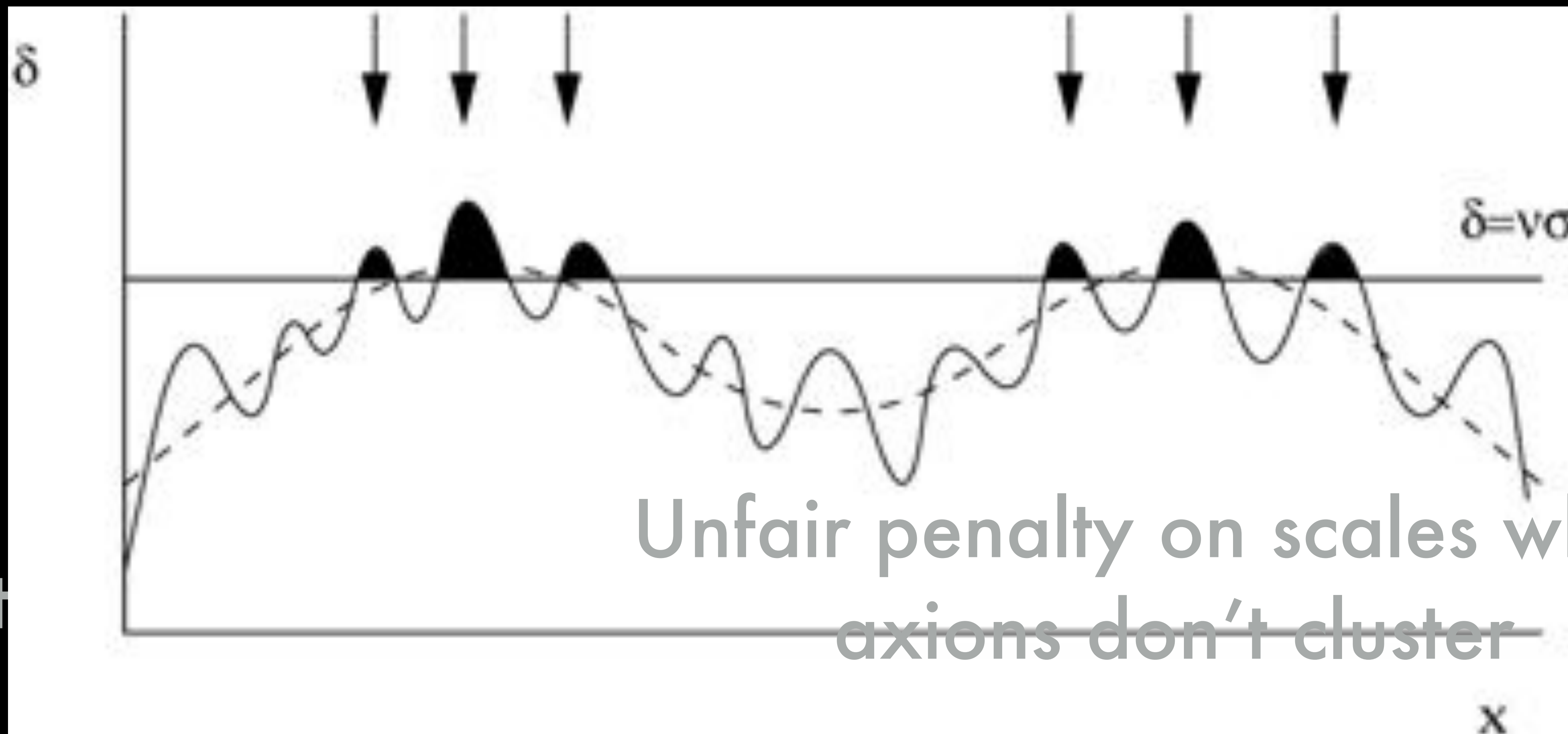


- Inflation is an early epoch of accelerated expansion
- If $f_a > H_I$



Additional slides:
ULAs and galaxies

* Galaxies are biased tracers

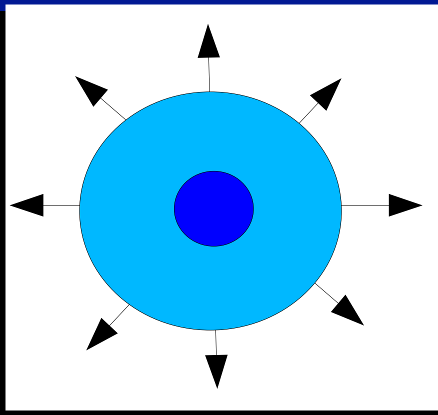


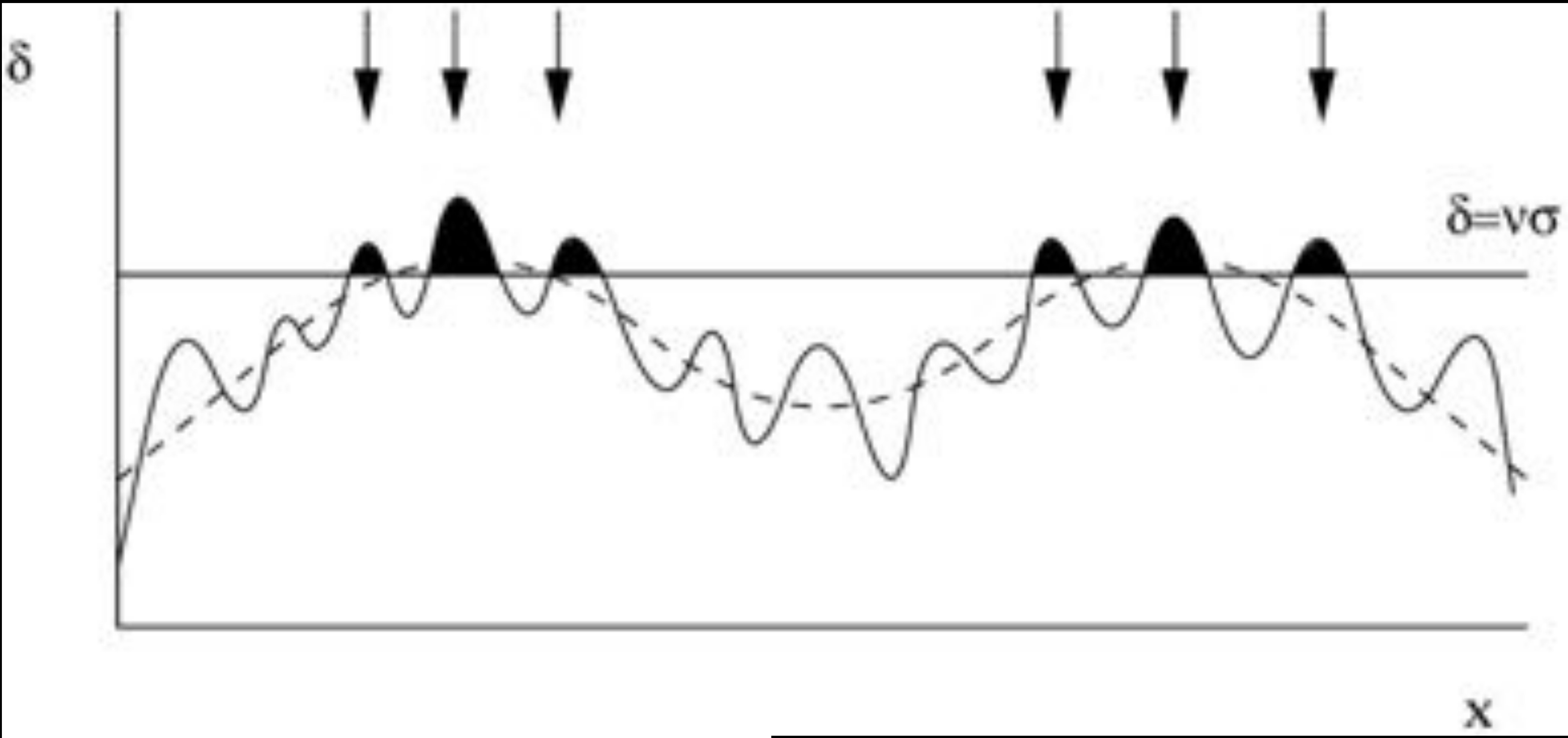
Unfair penalty on scales where axions don't cluster

Doesn't t

Future work: ULAs and galaxies

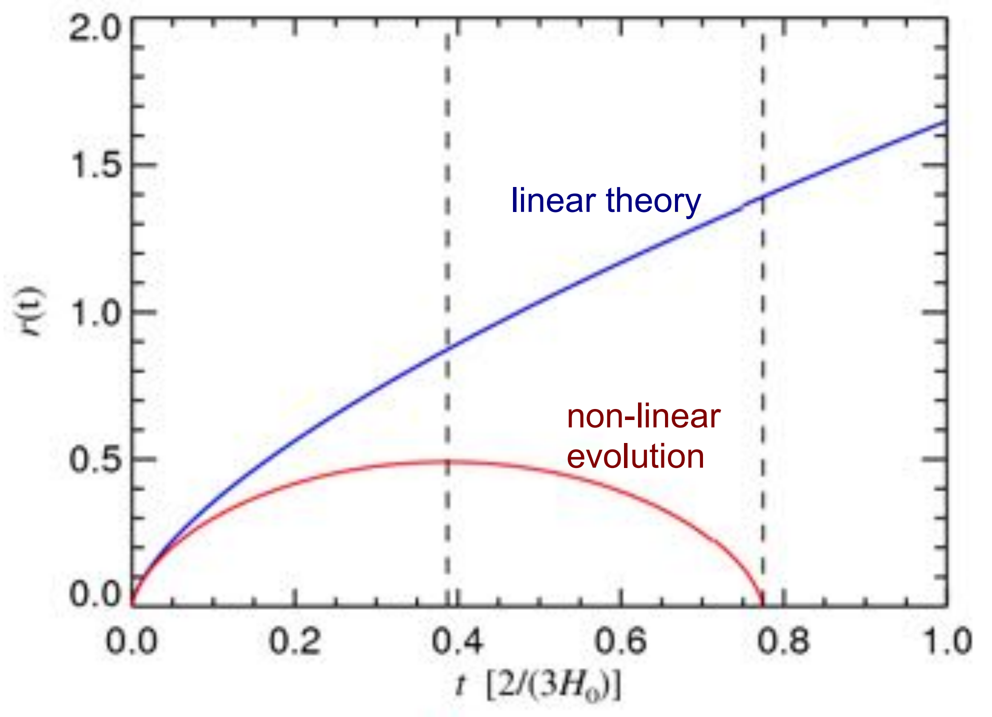
Collapse threshold for ULA DM unknown



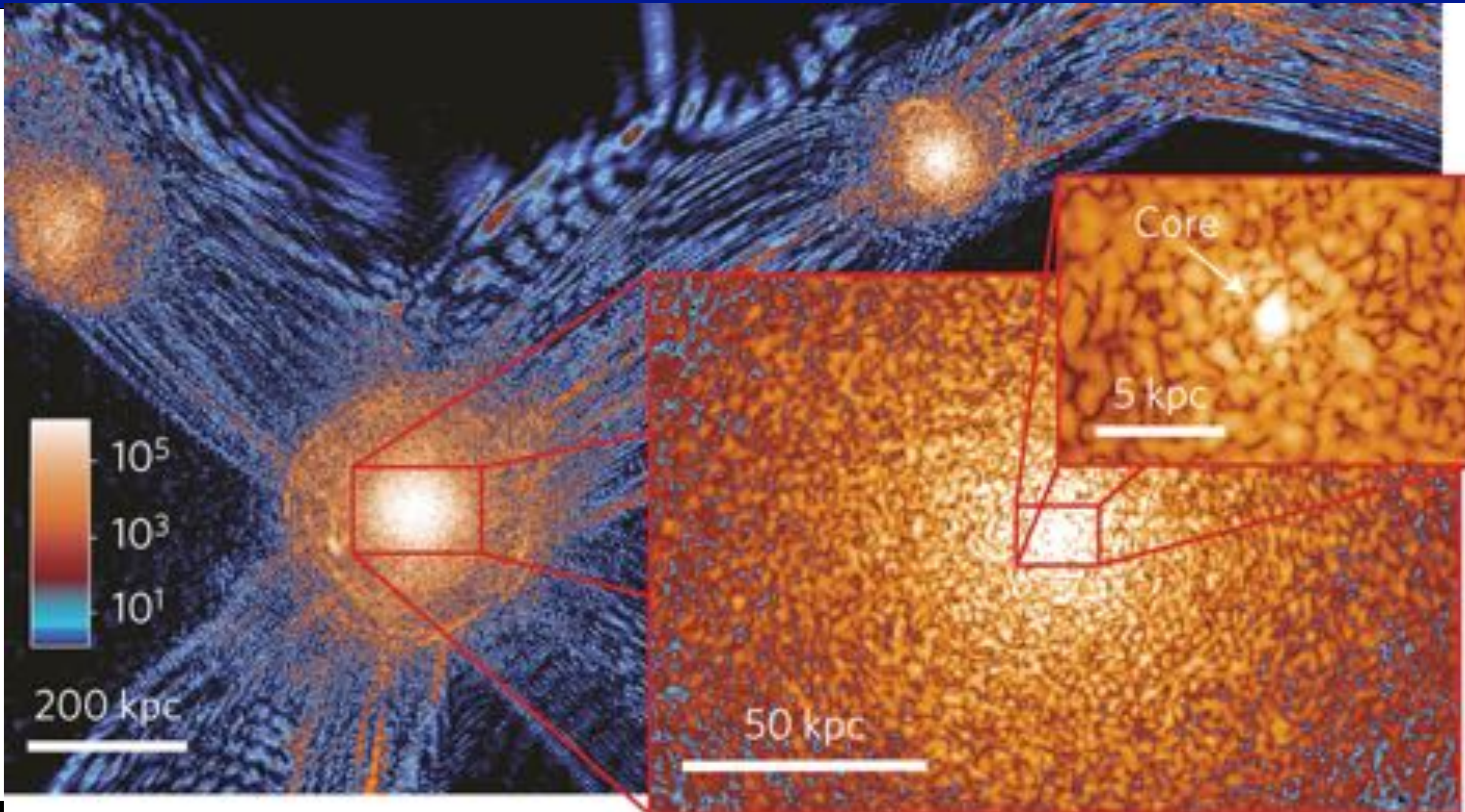


$$\delta_c^{\Lambda \mathrm{CDM}} = 1.686$$

$$\delta_c^{\Lambda \mathrm{ULA}} = ????$$



Future work: ULAs cores + cusps?

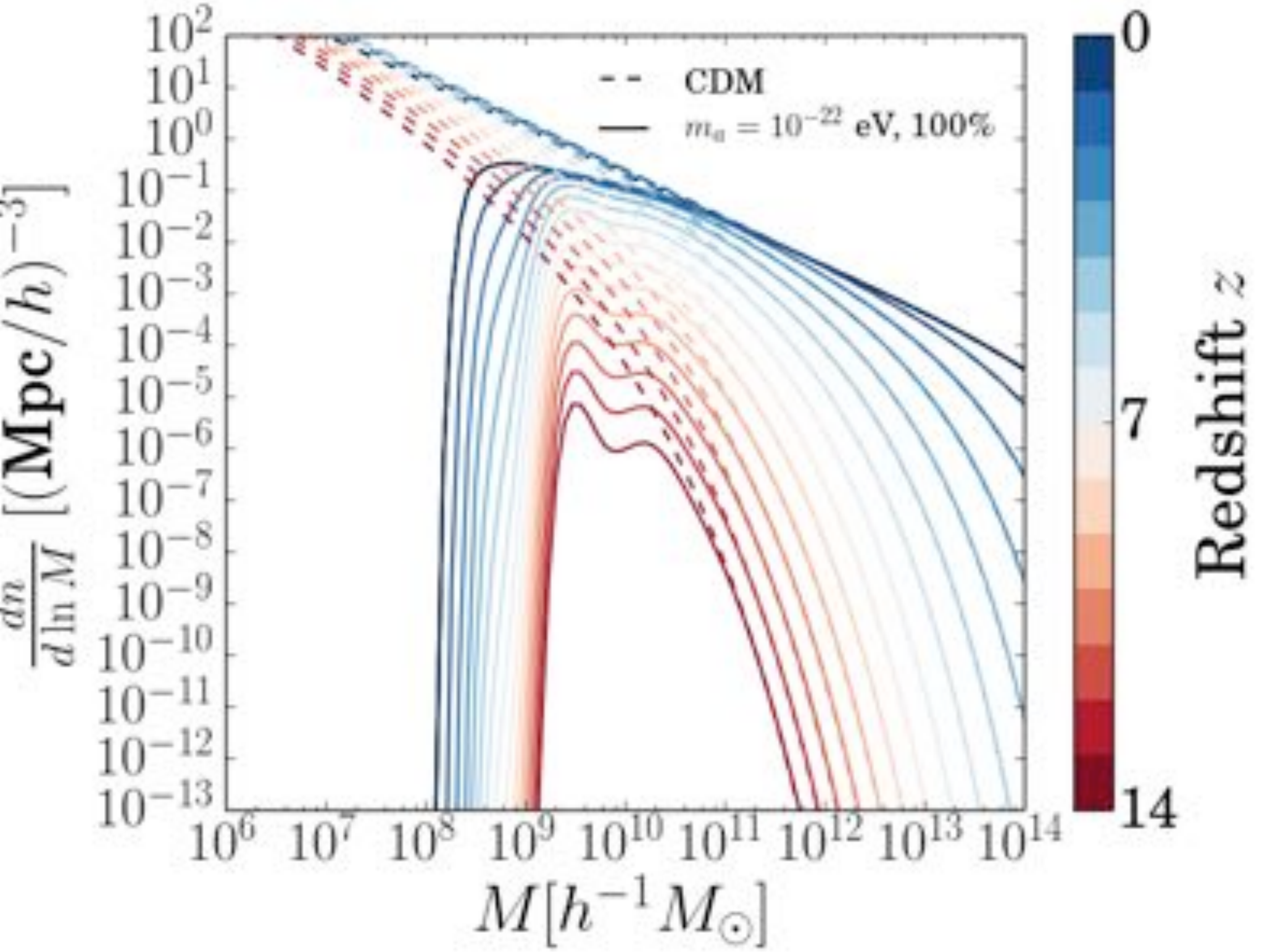


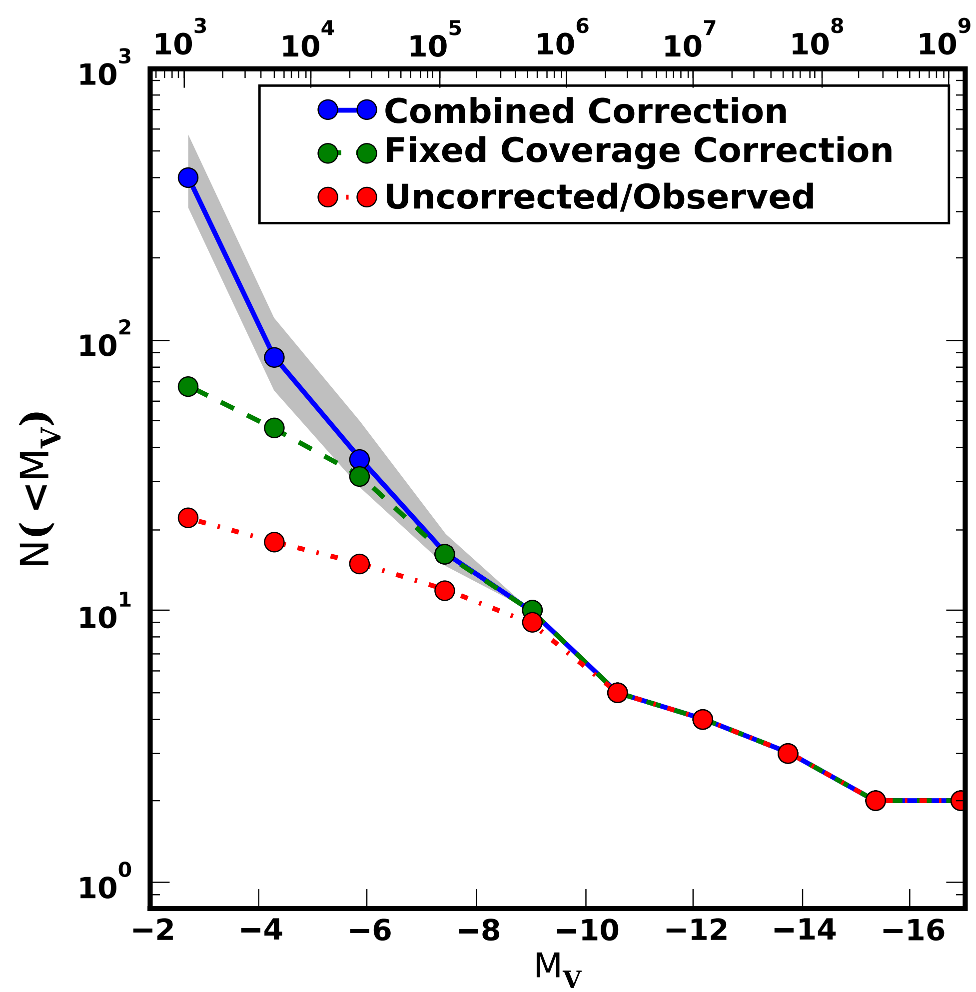
Cores! (Hu/Gruzinov/Barkana 2001, see also Marsh and Silk 2013; Marsh and Pop 2015, Matos 2012, Schive 2014, and others)

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

FUTURE WORK: ULAS AND GALAXIES

Missing satellite problem?





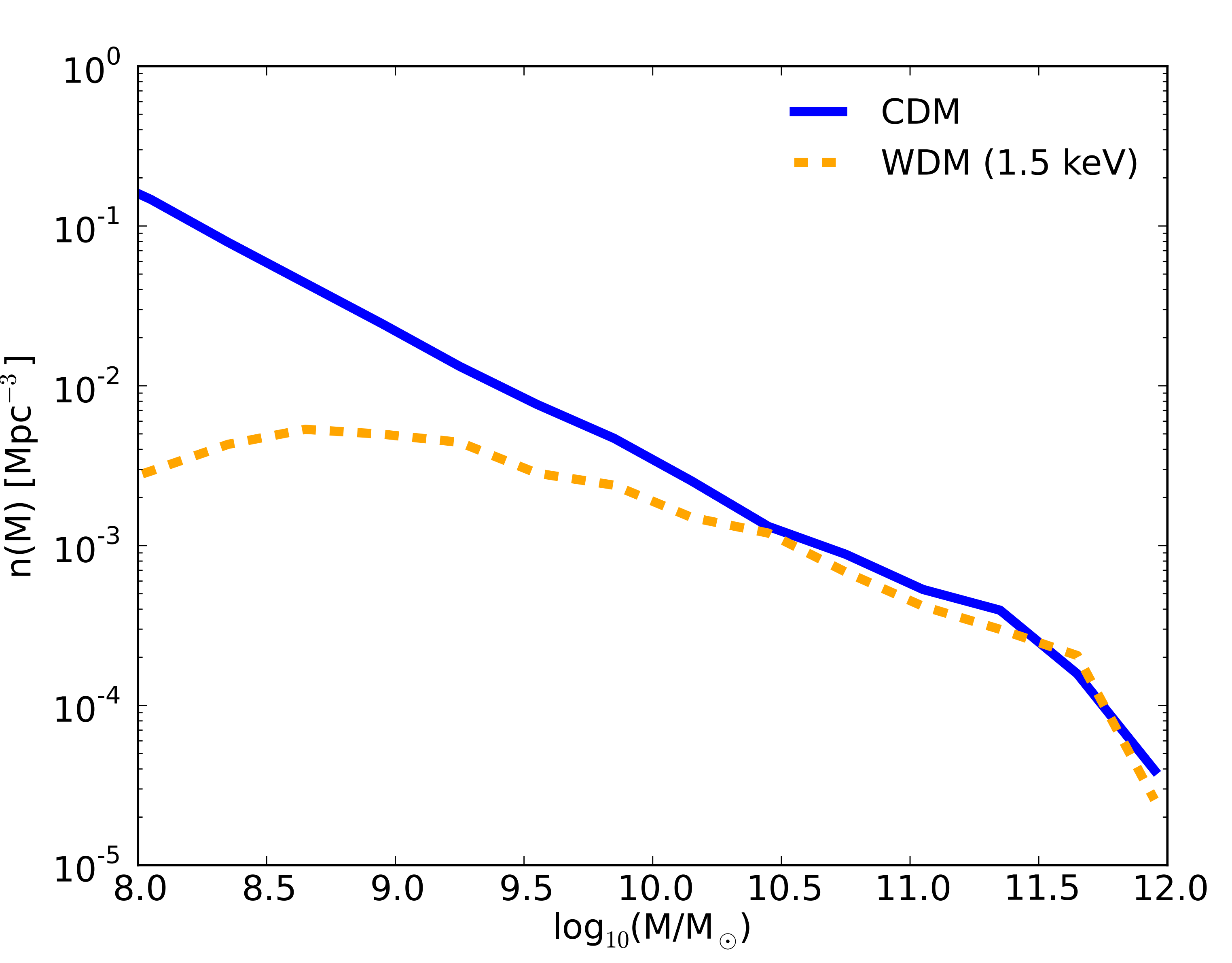
Marsh et al 2014, Klypin 1999, Bullock 2010

Dynamical friction, tidal distruption, substructure, halo model, spherical collapse, better simulations (much work to be done!)

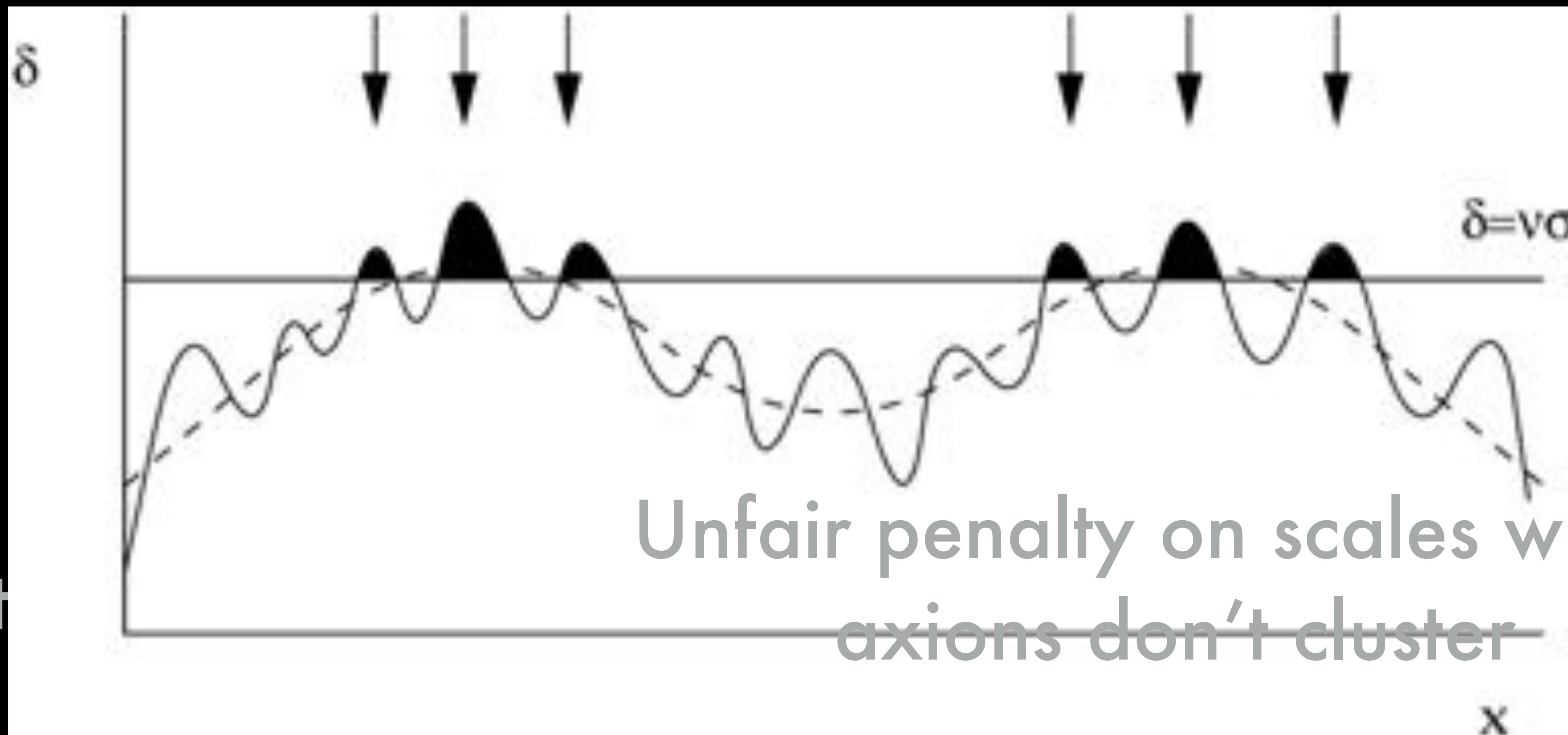
FUTURE WORK: ULAS AND GALAXIES

- Galaxy correlation function (counts, bias)
- Galaxy lensing
- Substructure in halos [flux ratio anomalies in multiply lensed]

ULA substructure?



- Galaxies are biased tracers



Doesn’t

Unfair penalty on scales where axions don’t cluster

- We use hard switch at $k_{osc}=k_{eq}; k_{\rm osc}\equiv a_{\rm osc}H_{\rm osc}$
- Realistic [smooth] treatment of scale-dependent bias needed (incorporating physics of ULA formation in halos)
  - Often neglected (but shouldn’t be) for neutrinos (LoVerde 2013)