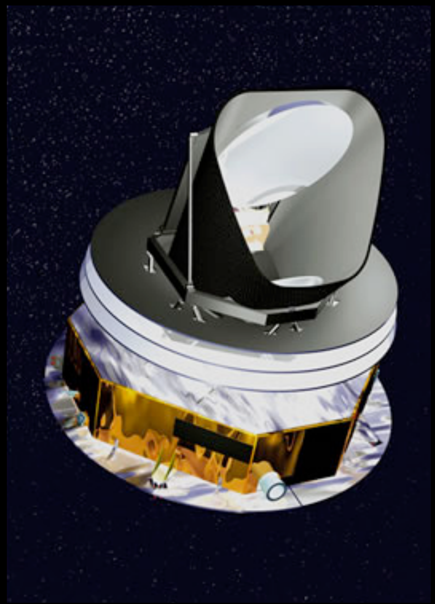
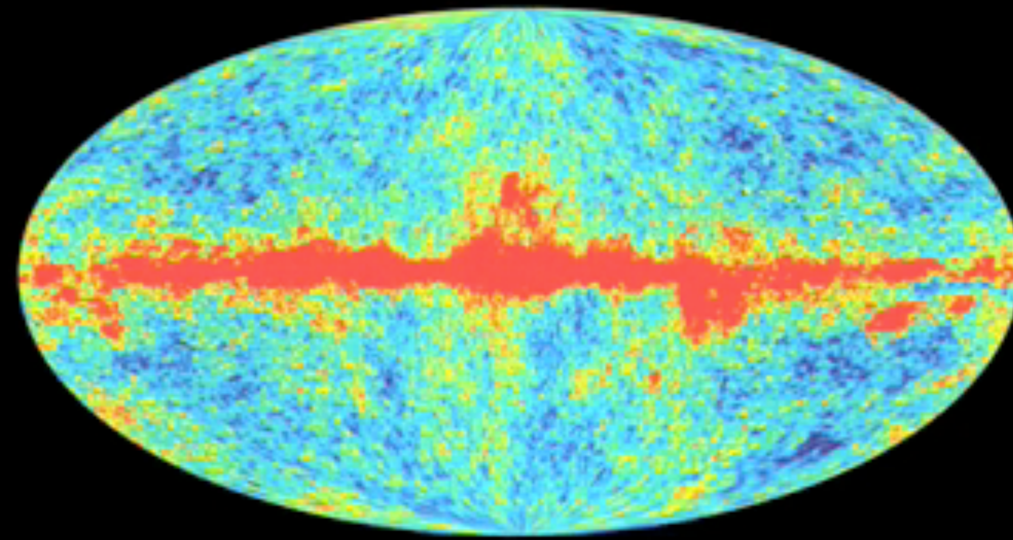
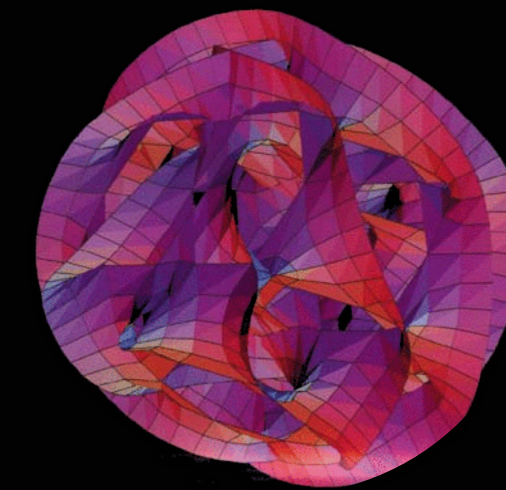


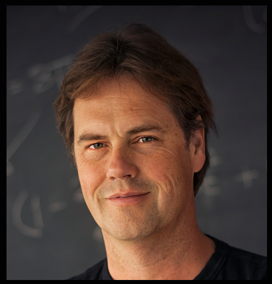




A search for ultra-light axions using CMB and large-scale structure data

Daniel Grin
University of Chicago

"Off the beaten track dark matter"



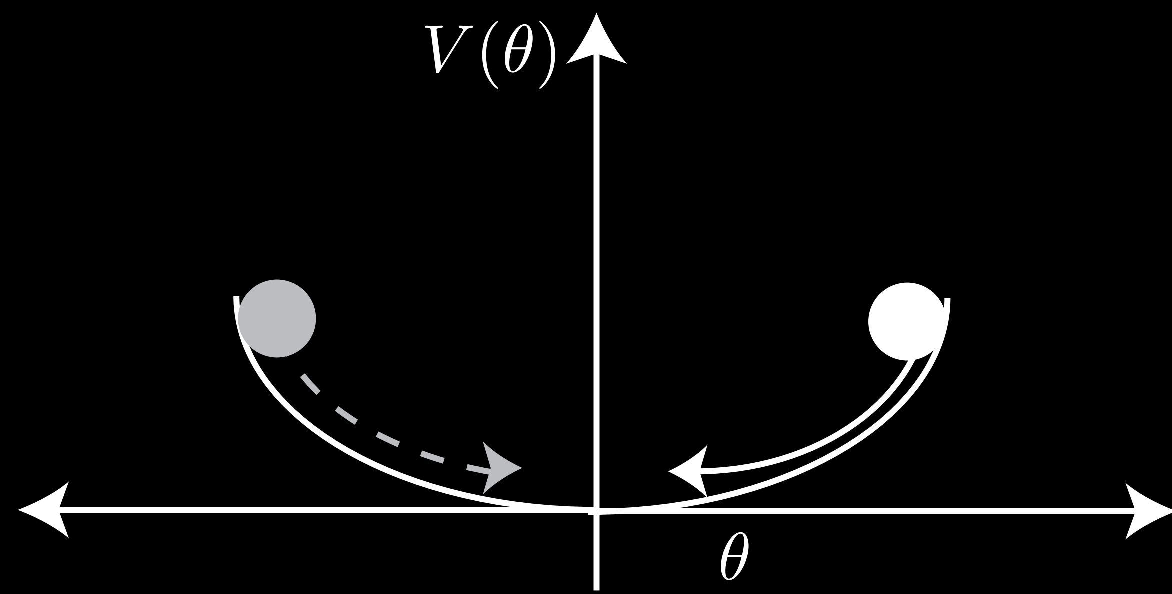
R.Hlozek, DG, D.J. E. Marsh, P.Ferreira, arXiv:1410.2896, PRD accepted

Outline

- Lightning review of QCD axions
- Motivation for ultra-light axions
- Observables (CMB and matter power spectra)
- Search for ULAs using cosmological data (Planck 2013+WiggleZ)
- Future probes
  - CMB weak lensing
  - ULA dark matter on non-linear scales
  - Isocurvature perturbations and tensor modes

QCD axions are DM candidates

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



- ✳ Field misaligned $m_a \gg 3H \to$ oscillation
- ✳ $\rho_a \propto (1+z)^3$ [as cold dark matter should]

⇒ axion is a cold dark matter candidate

- ✳ Axions **ARE** cold

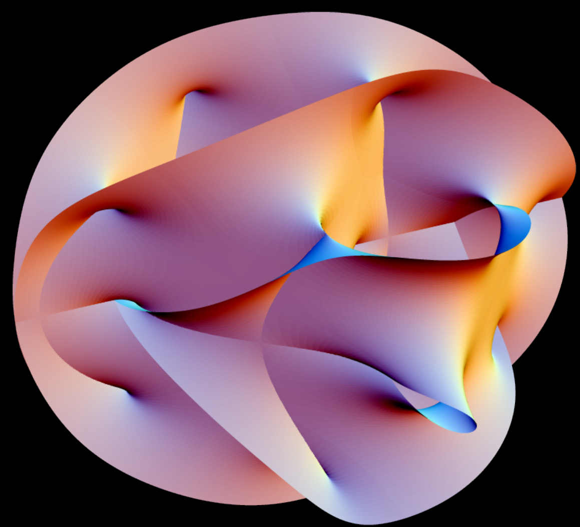
$v_a/c \lesssim 10^{-13}$ at CMB decoupling timescales

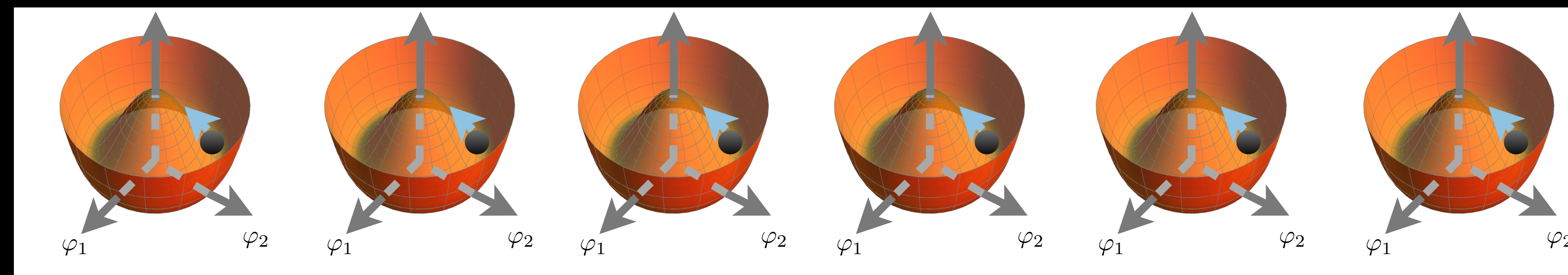
$$\Omega_{\rm mis} h^2 = 0.236 \langle \theta_i^2 f(\theta_i) \rangle \left(\frac{m_a}{6.2\,\mu\text{eV}} \right)^{-7/6}$$

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

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*

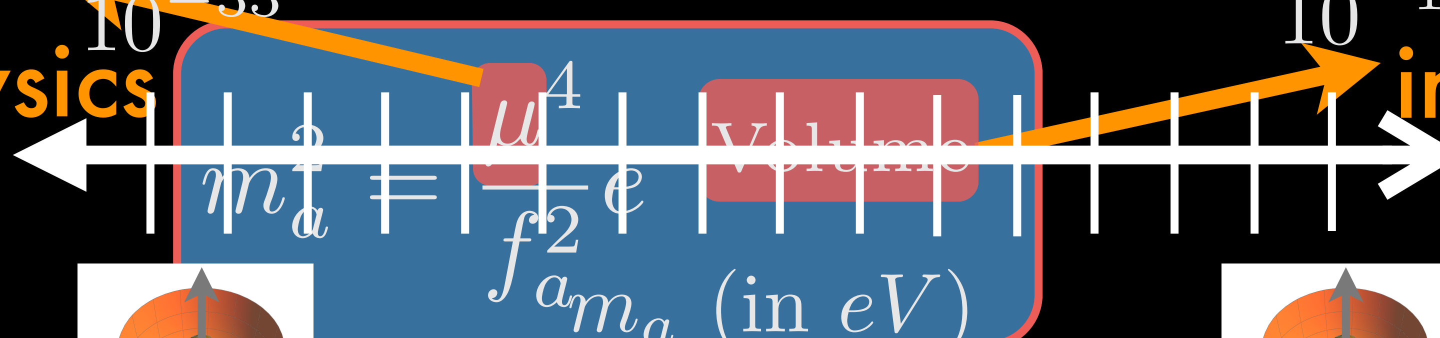
Witten and Srvcek (2006), Acharya et al. (2010), Cicoli (2012)

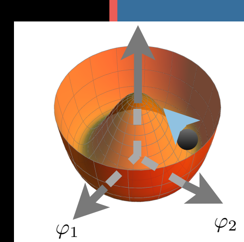
* Mass acquired non-perturbatively (instantons, D-Branes)

Scale of new ultra-violet physics

Scale of extra dimensions in Planck units

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





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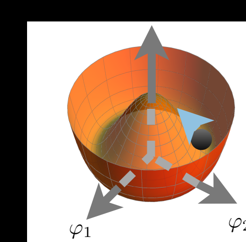
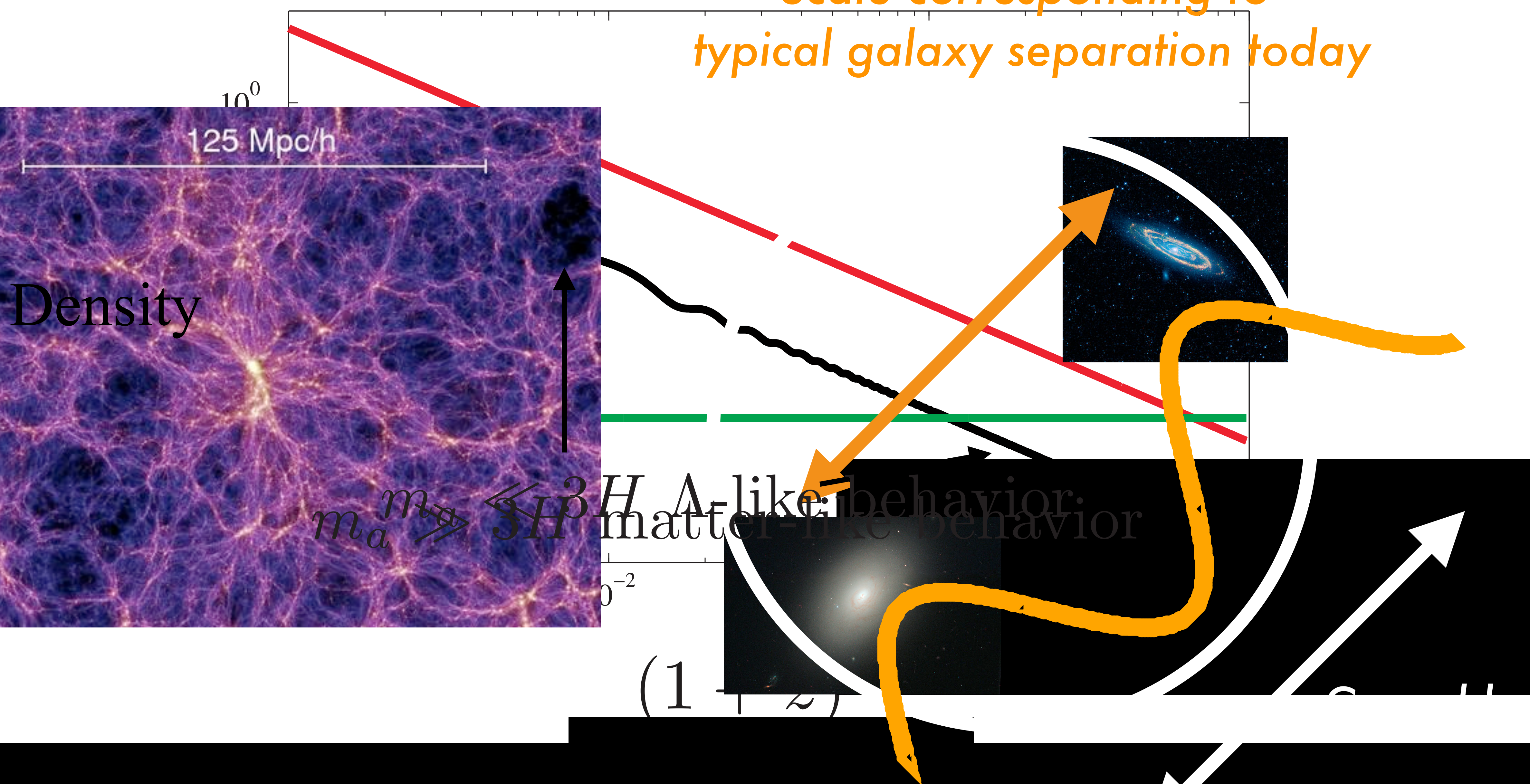


Cosmology of ultra-light axions: dark matter and dark energy candidates

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

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

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

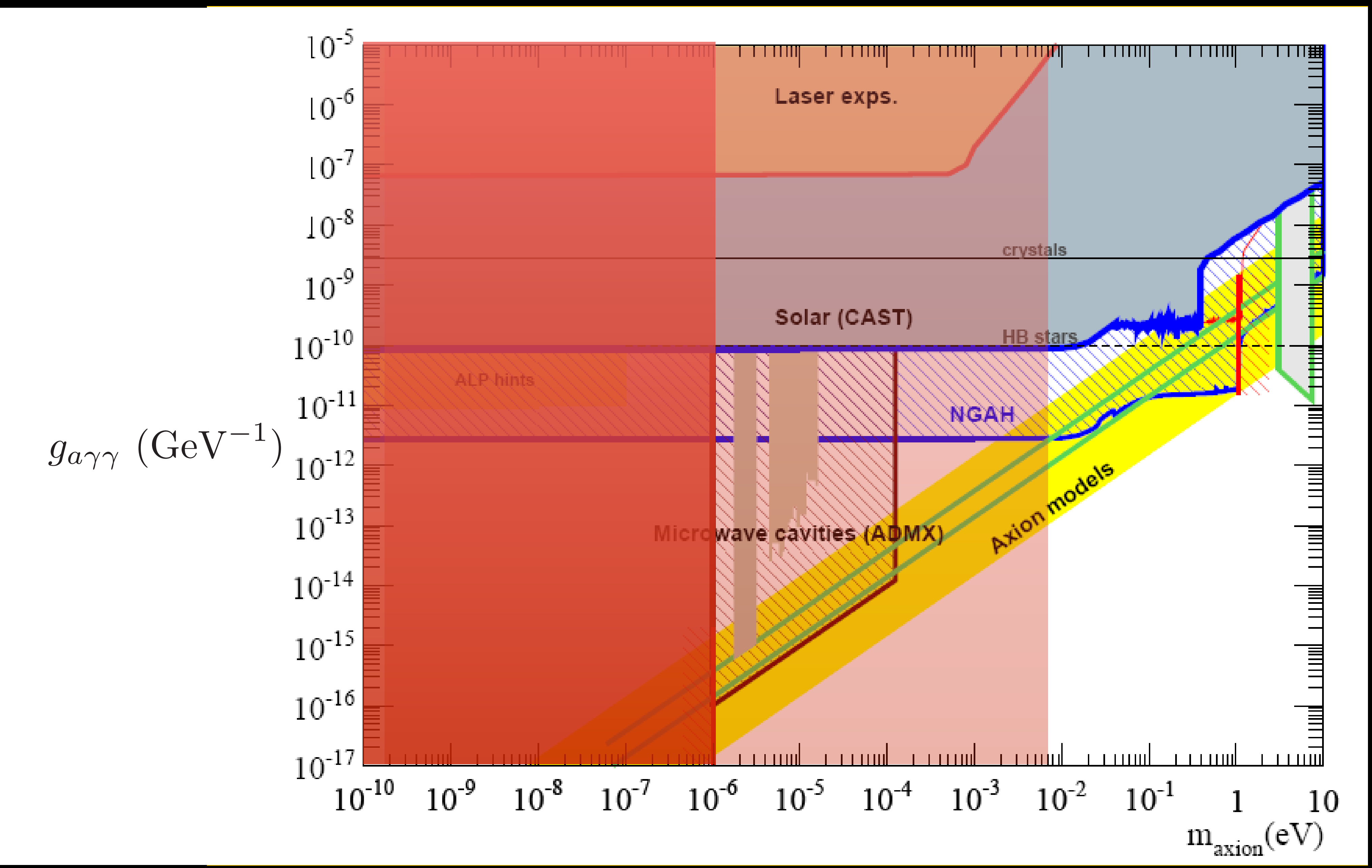
ULA matter behavior starts too late for struct. formation

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

Ultra-light axions are dark matter and dark energy candidates

Limits

Cosmological abundance



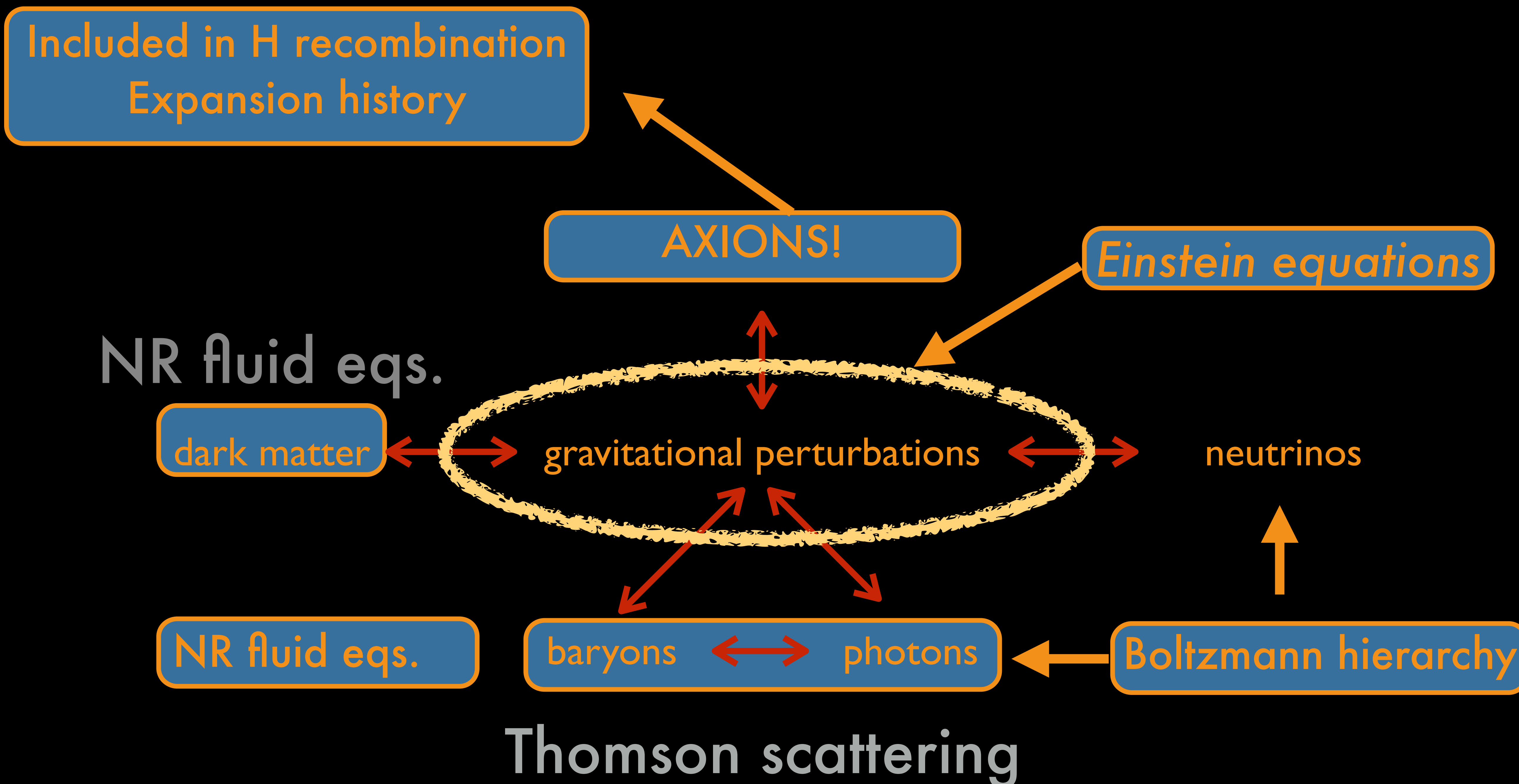
$$\mathcal{L} \propto g_{a\gamma\gamma} a \vec{E} \cdot \vec{B} \quad g_{a\gamma\gamma} \propto 1/f_a$$

What about ultra-light axions (ULAs)?
Photon couplings are model-dependent:
Use gravity and cosmological data
to test ULAs

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

AxiCAMB

CMB and matter perturbation code including ULAs!
Code in prep for public release as part of CosmoSIS package



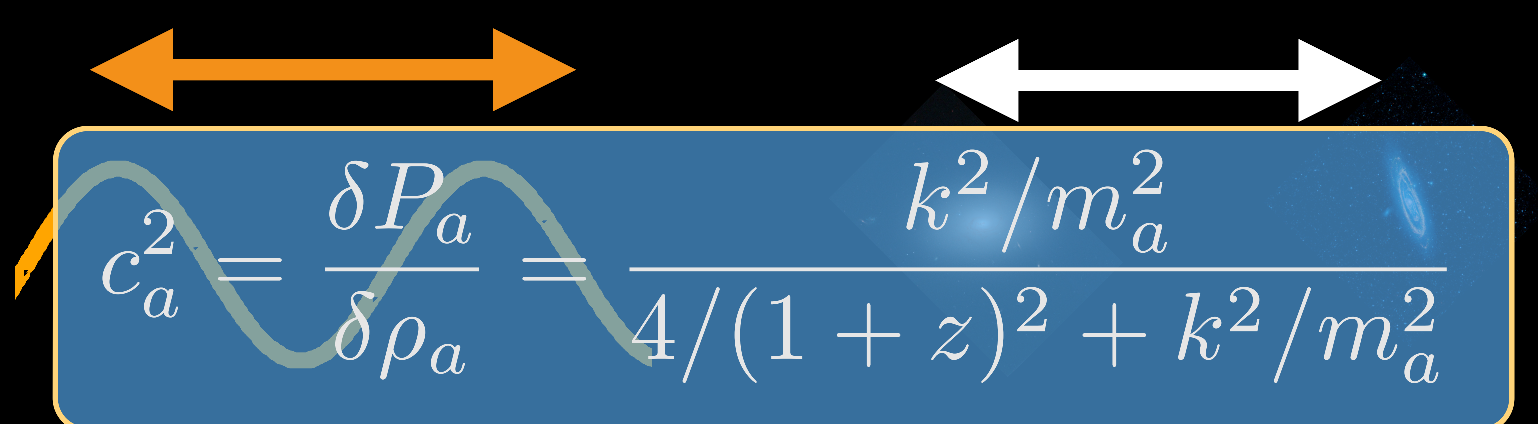
ULA of any mass is self-consistently followed from DE to DM regime

Growth of ULA perturbations

- Perturbed Klein-Gordon + Gravity $k = 2\pi/\lambda$: wavenumber

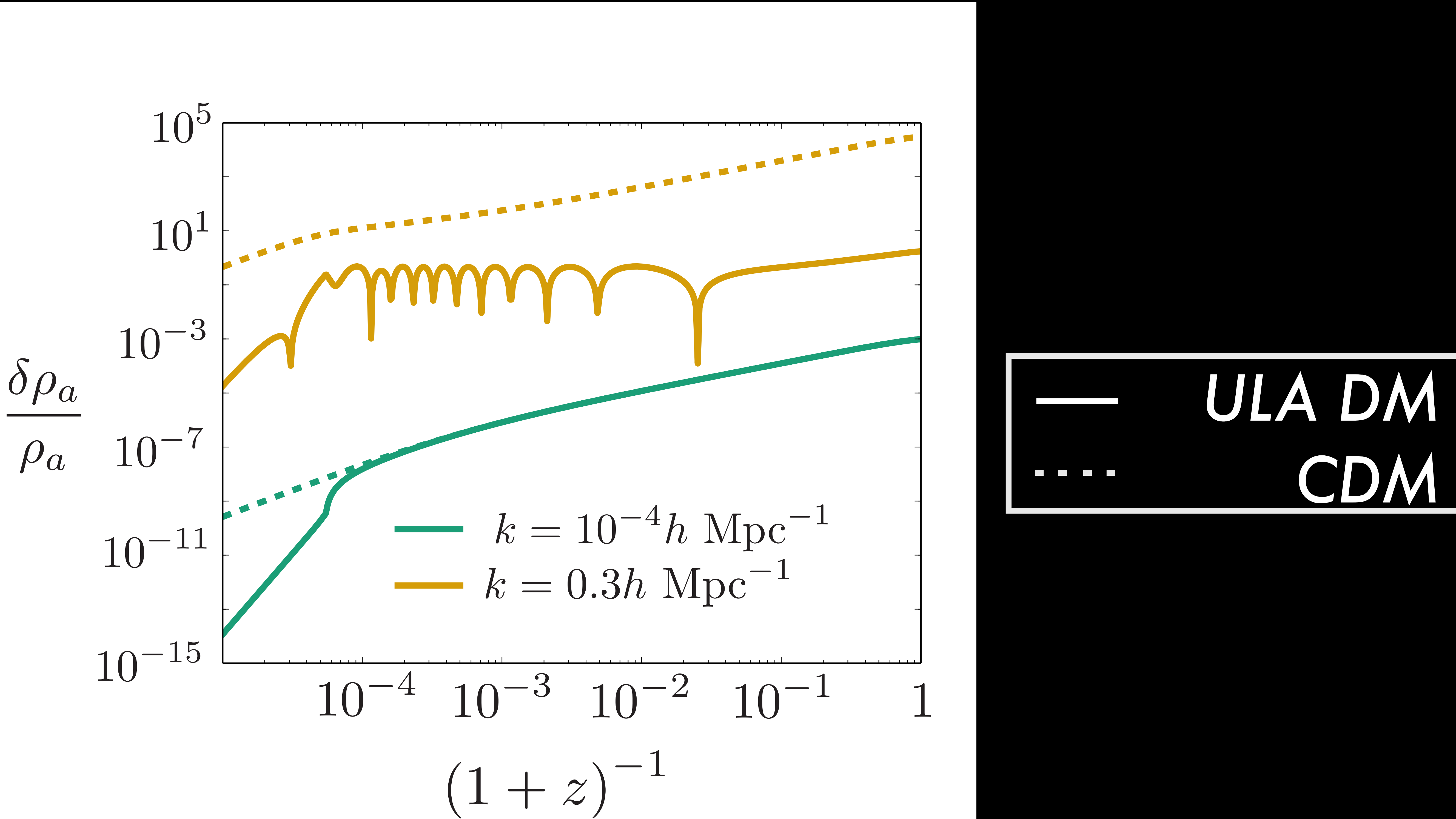
$$\ddot{\delta\phi} + 2\mathcal{H}\delta\dot{\phi} + (k^2 + m_a^2 a^2)\delta\phi = \mathcal{O}(H^2, m^2)\Psi$$

- Axionic Jeans Scale is macroscopic [in contrast to QCD axion]:
- Computing observables is expensive for $m_a \gg 3H$:
  - Coherent oscillation requires prohibitive time step
  - WKB approximation at late time, exact KG early times



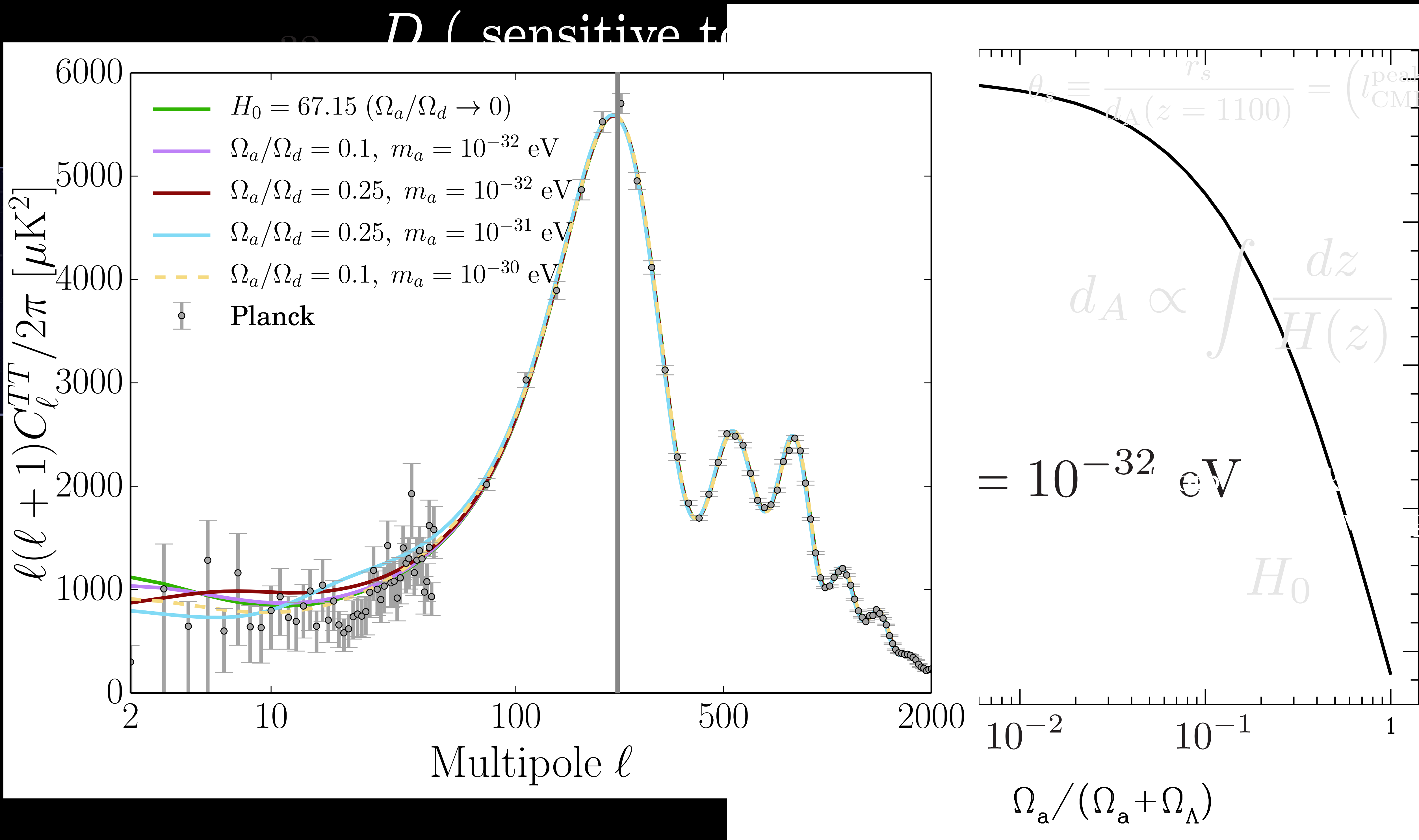
$$c_a^2 = \frac{\delta P_a}{\delta\rho_a} = \frac{k^2/m_a^2}{4/(1+z)^2 + k^2/m_a^2}$$

Growth of ULA perturbations



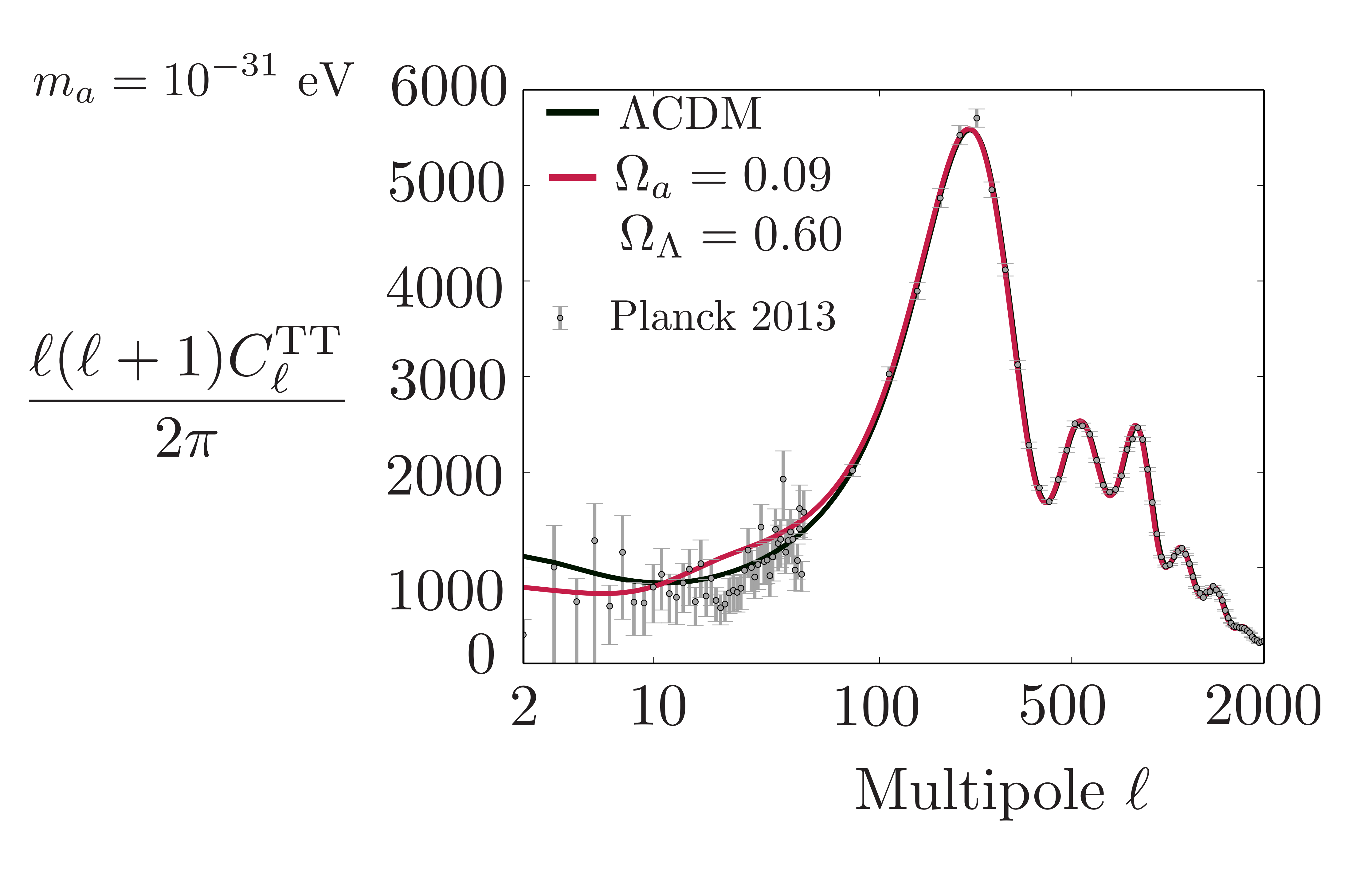
- ✴Pressure stabilization for modes with $k \gg k_{\mathrm{J}} \sim \sqrt{m\mathcal{H}}$
- ✴Otherwise ULAs behave like cold dark matter (CDM)

ULAs as dark energy and the angular sound horizon



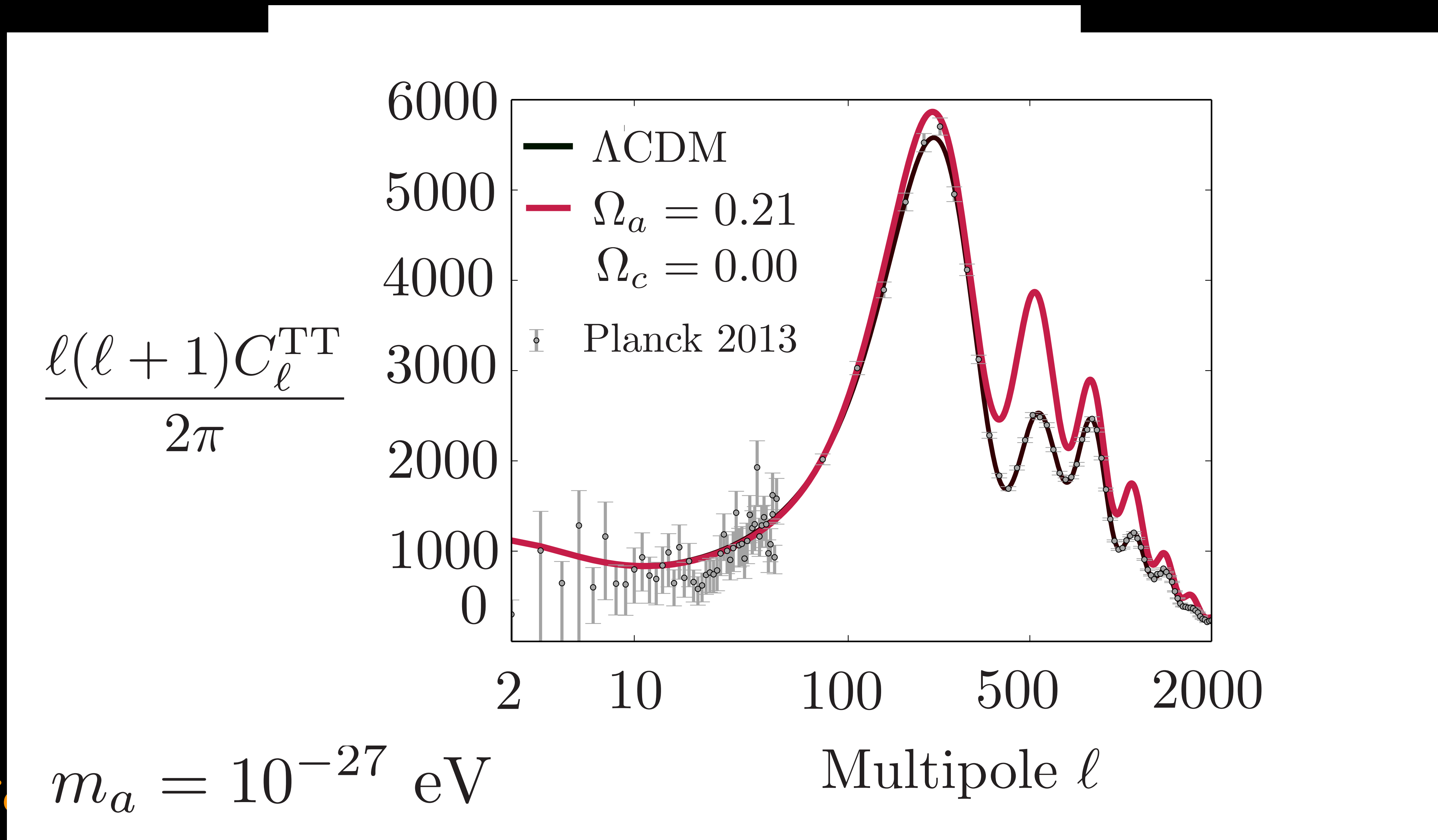
ULAs as dark energy and perturbations in other fluids

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

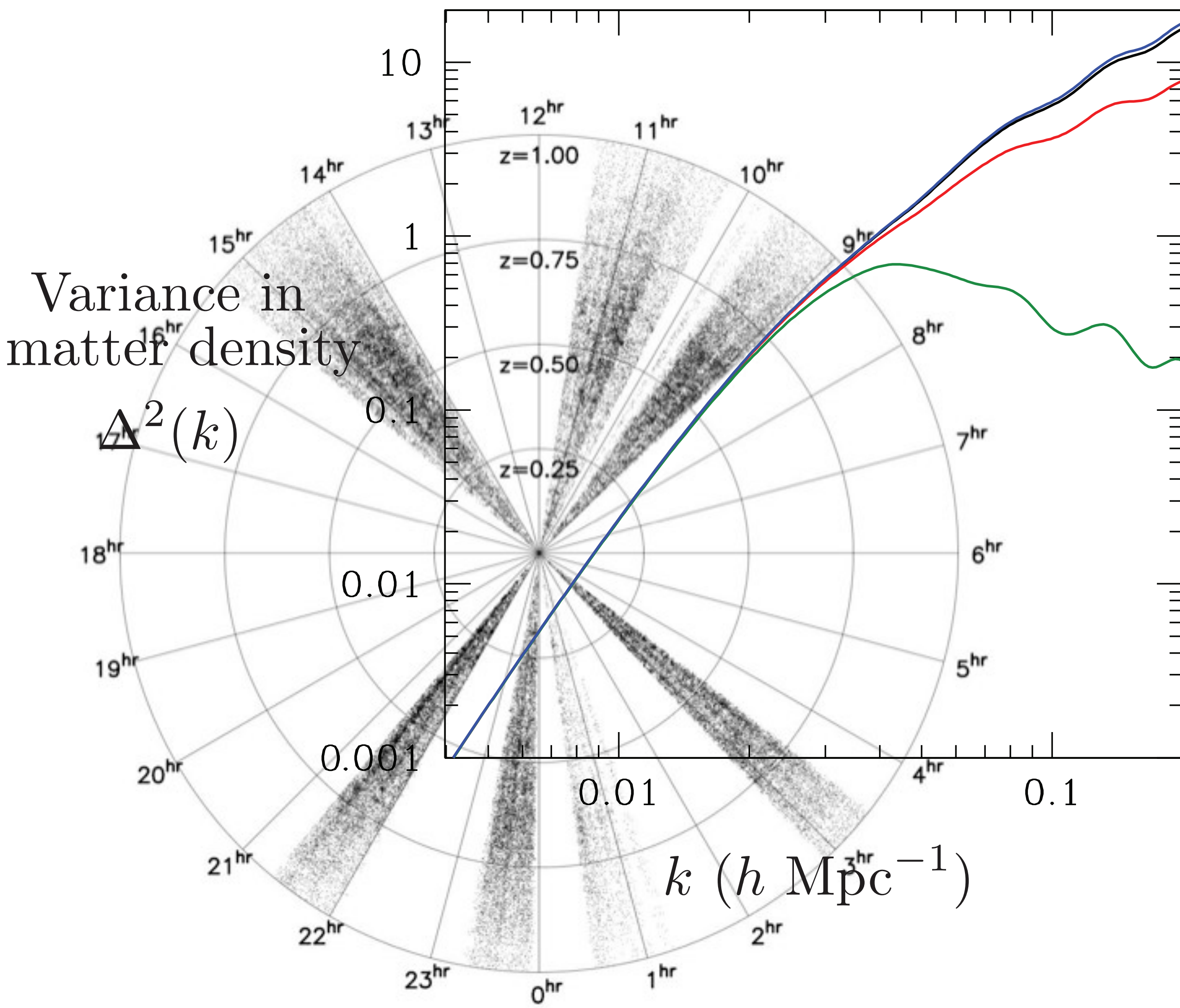


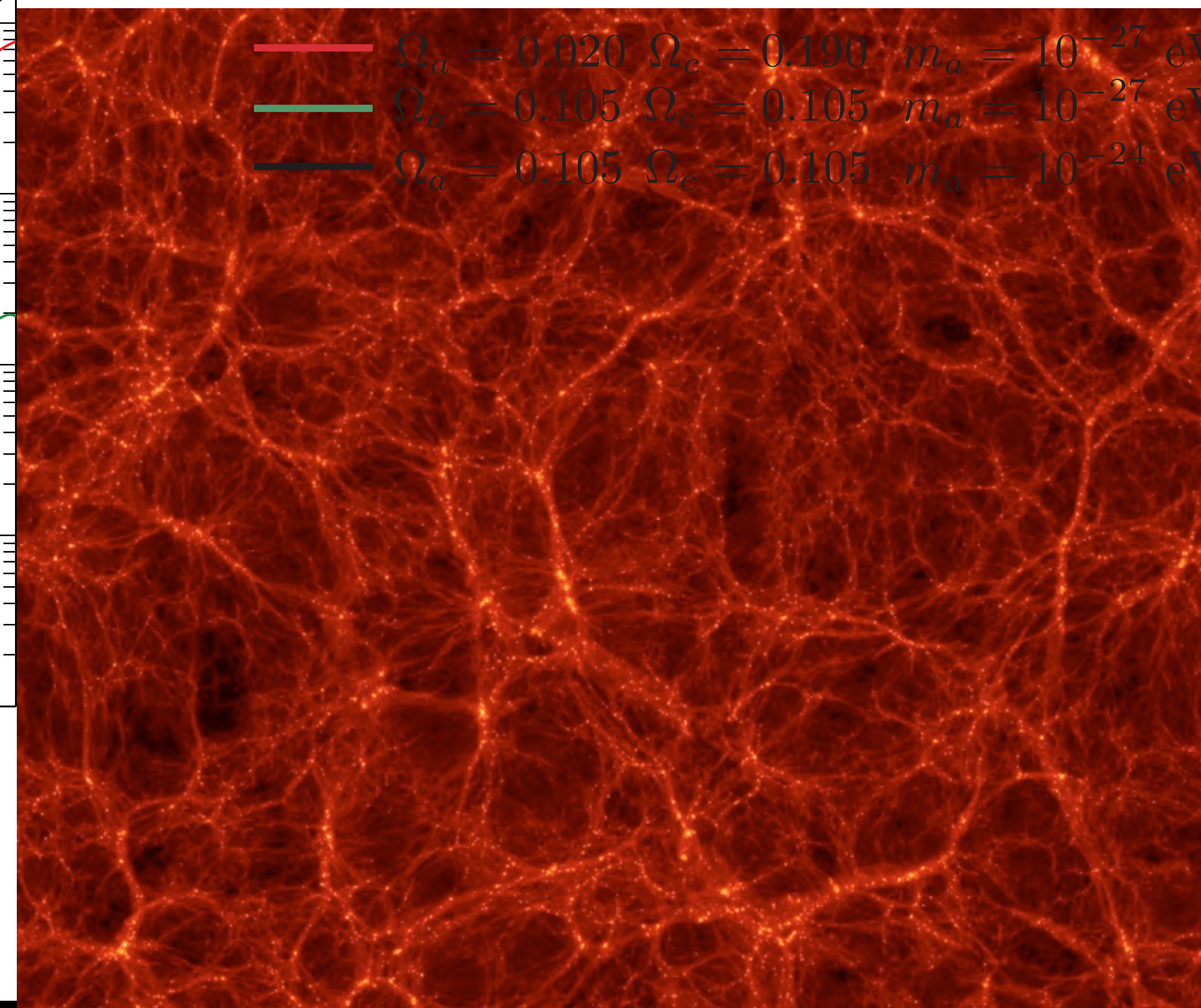
Radi

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

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

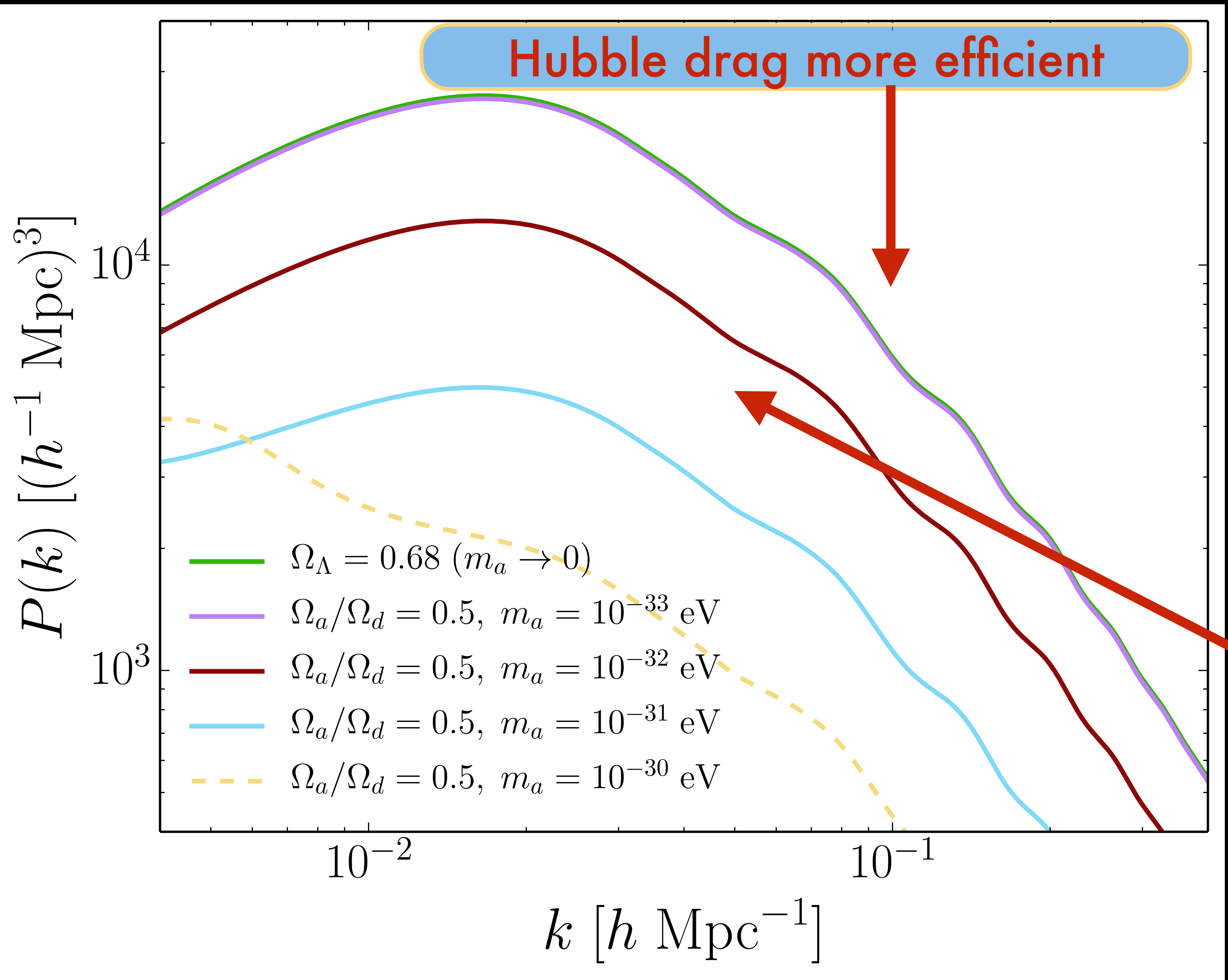
Matter power spectrum for ULA (in DM regime)





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

Matter power spectrum for ULA (in DE regime)



θ_s fixed to lock CMB

H_0 ↓

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

Peak of P(k) to lower k

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

Matter-radiation equality delayed

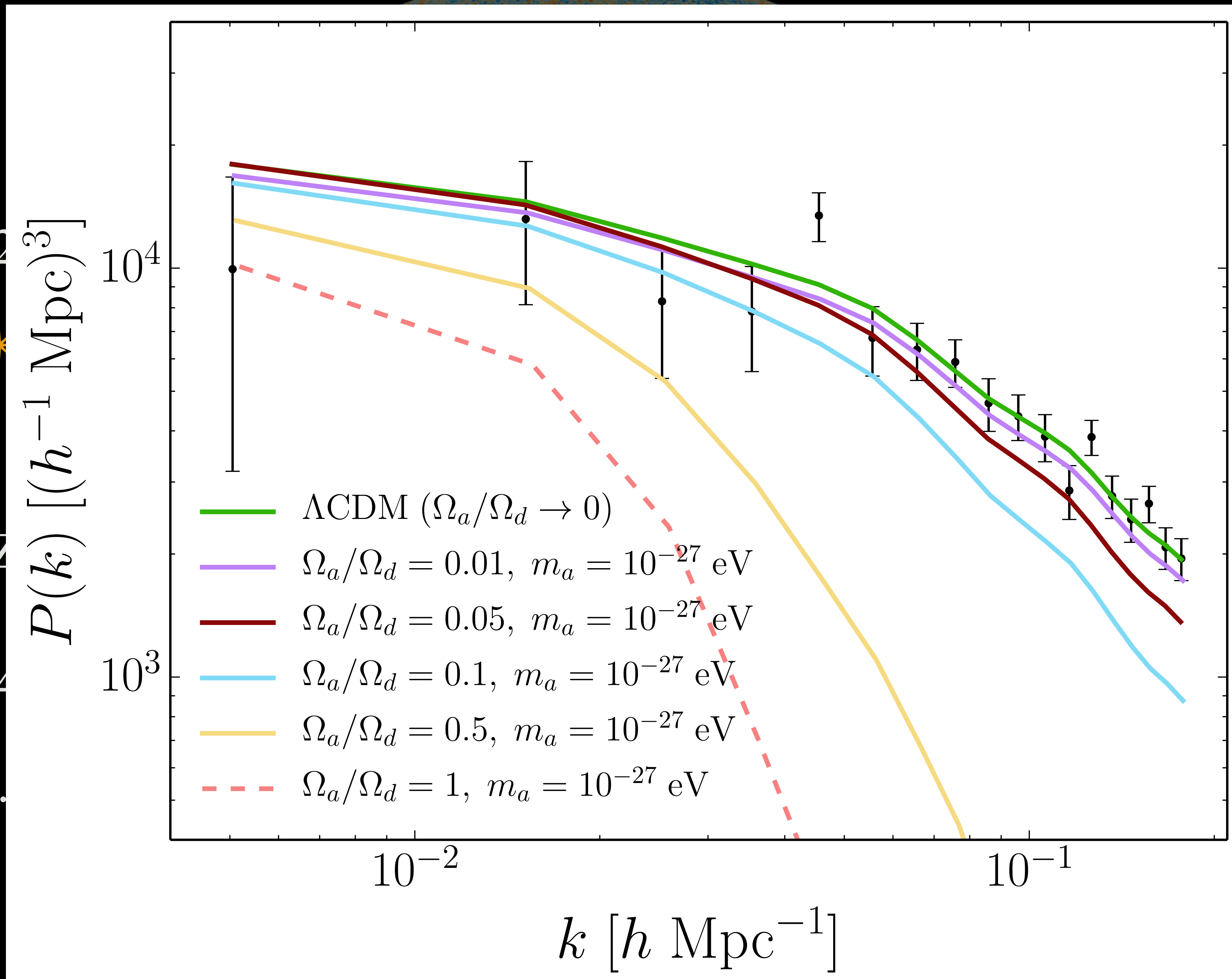
✳ Planck 2

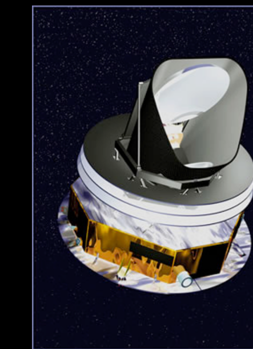
✳

✳ WiggleZ

✳ 24

✳ 3.

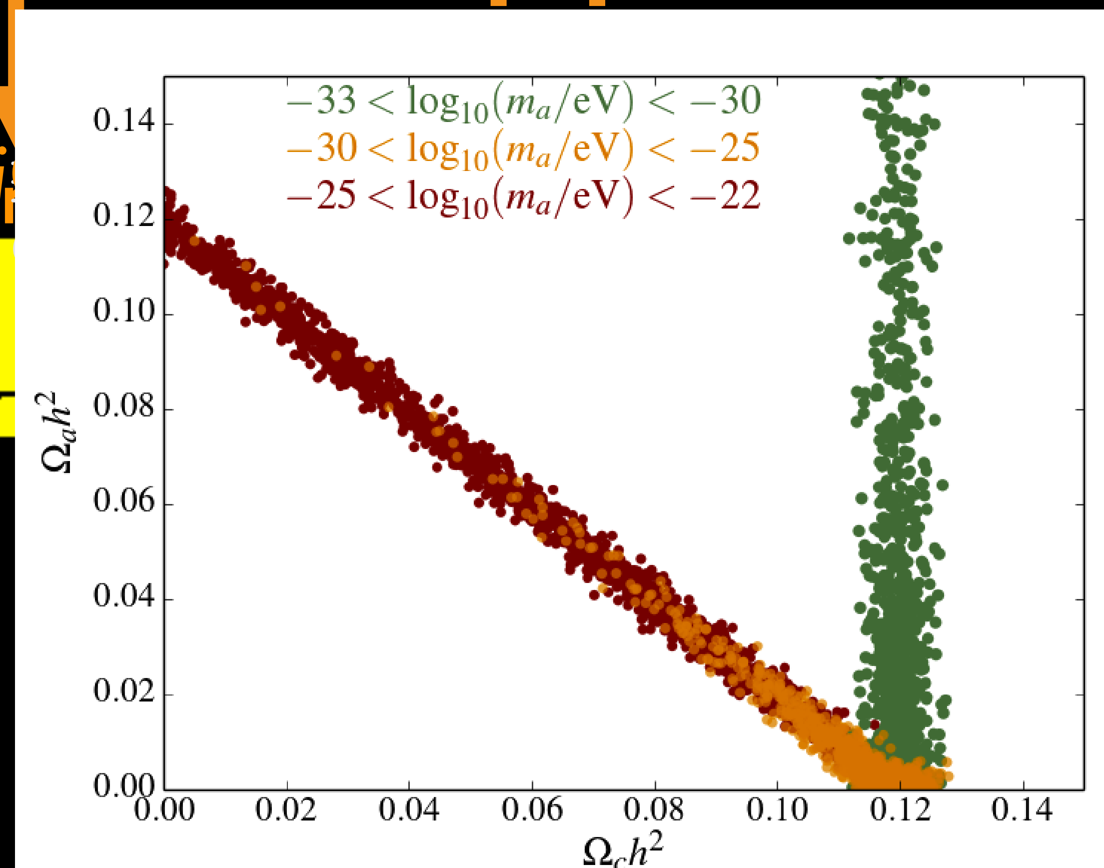




Convolve with WiggleZ window function

Difficult parameter space

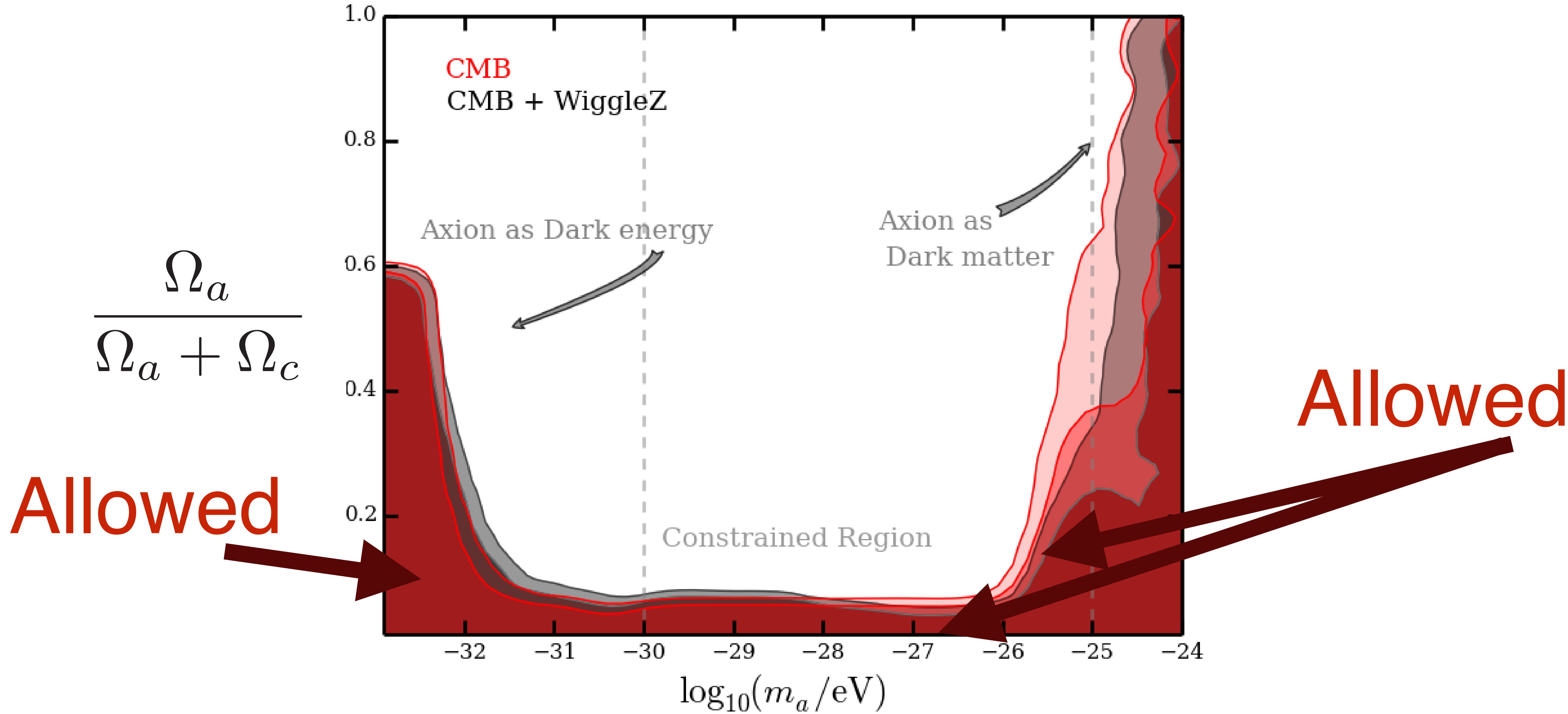
$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$$



…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:

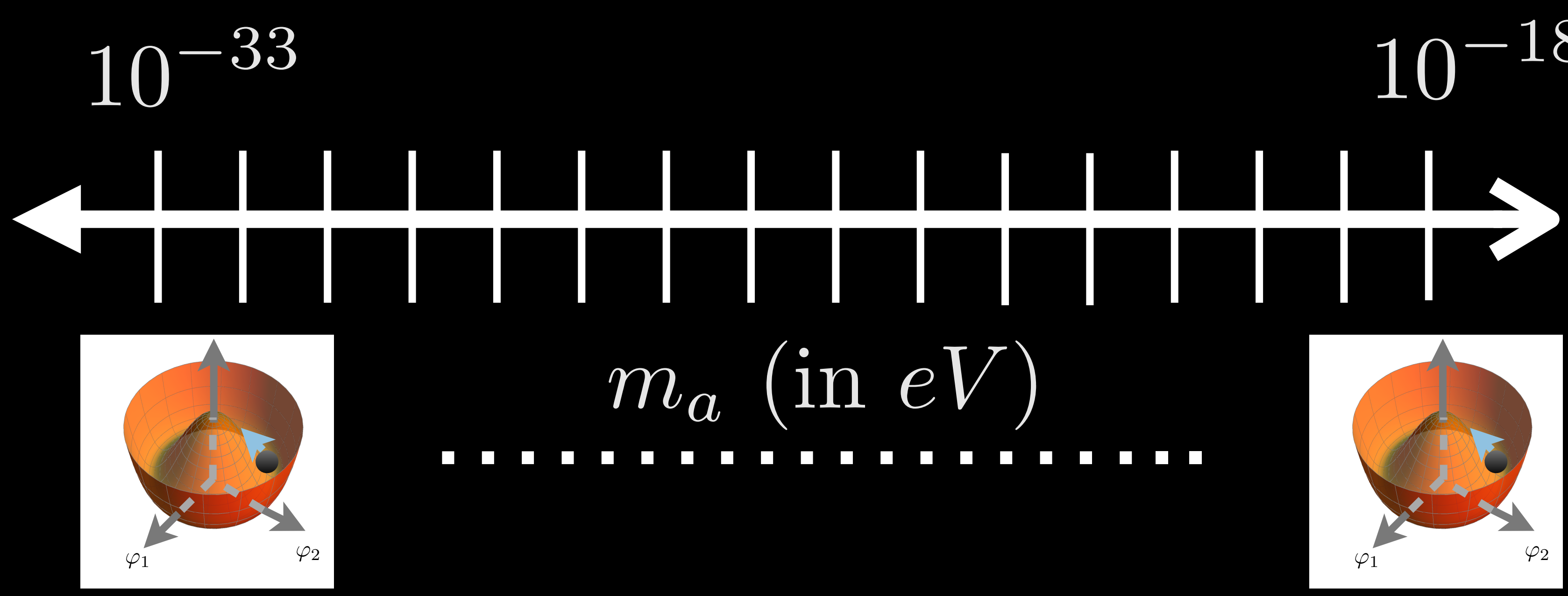
  Thanks to AXICAMB and MULTINEST

- ✶ 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”

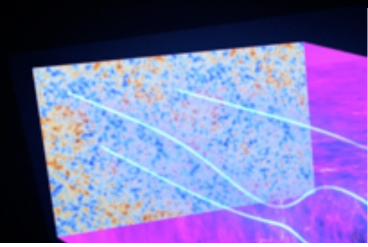
Future work: richer modeling and axiverse

✳ Include spectrum of N axions (and interactions) in axiCAMB

$$\frac{dn}{d\ln m_a} \propto \text{const}$$

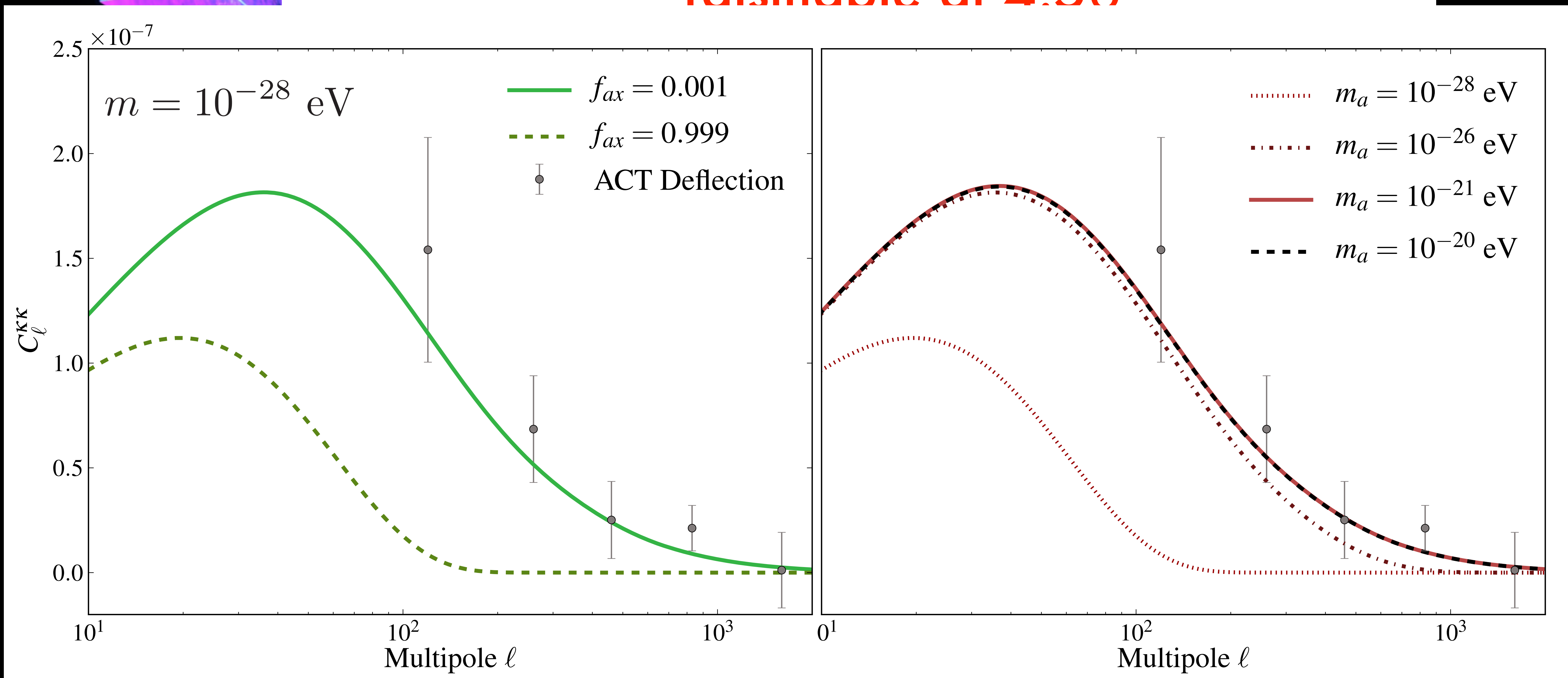


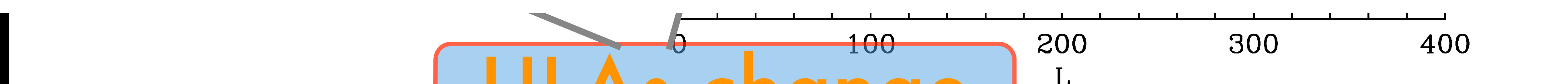
Future work: CMB lensing



ULA saturating TT-only limits
falsifiable at 4.5σ

at z~1





ULAs change

ULAs change lens geometry
and growth of structure

ULAs and galaxies

✳ ULA with $m_a \sim 10^{-22}$ eV have $\lambda_J \sim 100$ kpc

possibly helping with two challenges for ΛCDM

Cusp/core problem — Missing satellites Problem

✳ Elegant analytic arguments that ULA can help with both problems (Ma[illegible] et al. 2013 and 2014)

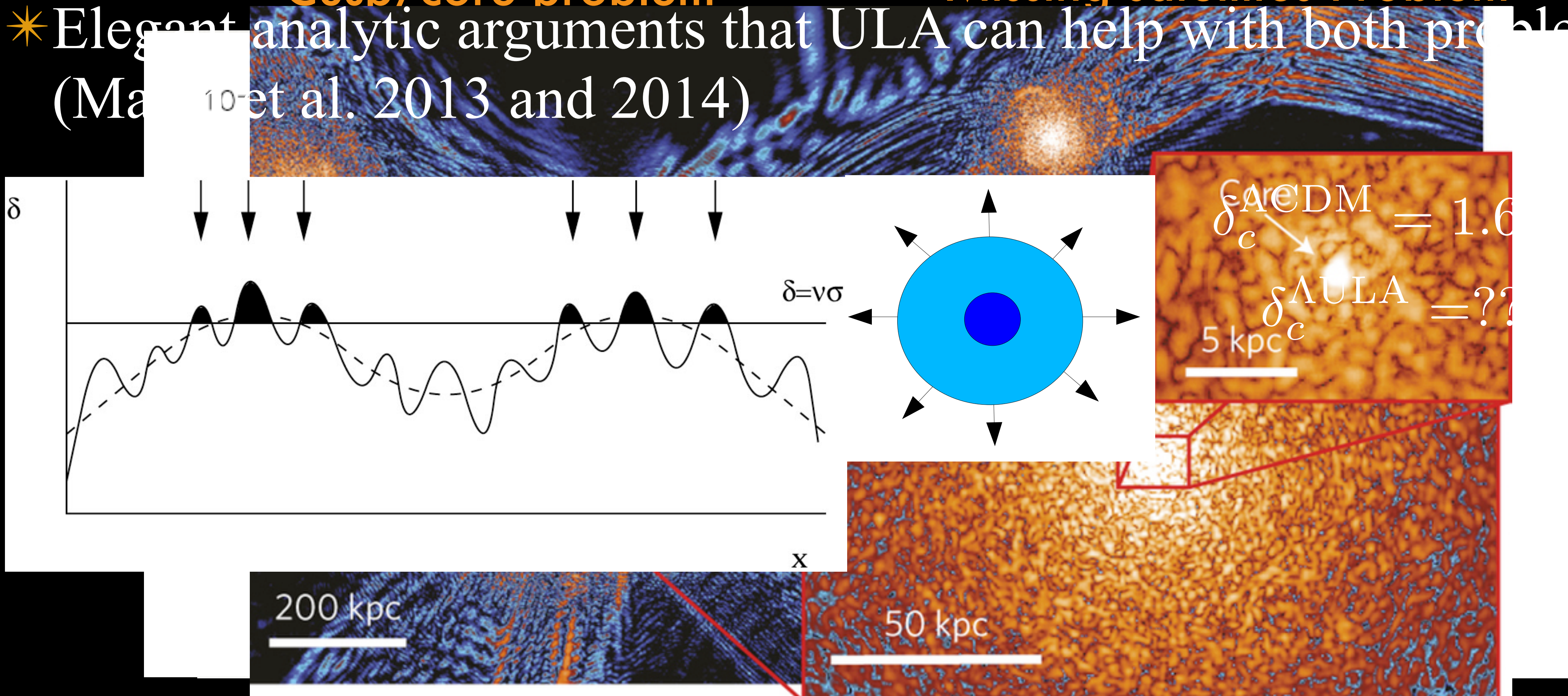
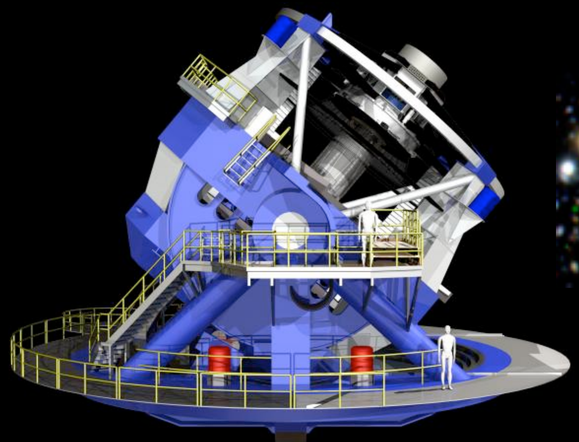


Figure from Brooks 2014/Oh 2011 — Figure from Bullock 2010

✳ Scant simulation work (N-body not appropriate for ULA) (Schive 2014)

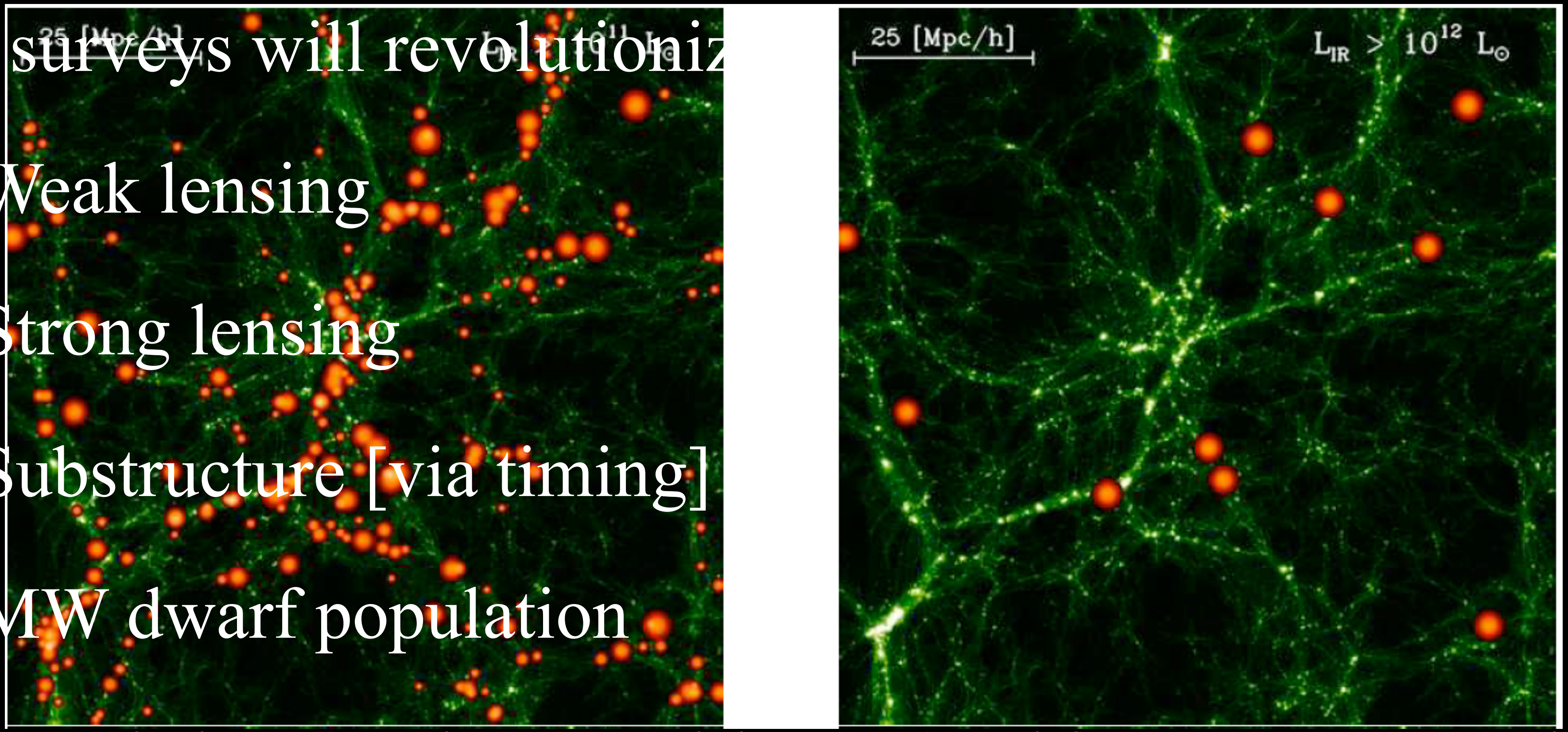
- Future growth in mode number driven by galaxy surveys



LSST

WFIRST
Wide-Field Infrared Survey Telescope

- Galaxies (and DM halos) are biased tracers of matter field (e.g. Baugh 2013)
- Future surveys will revolutioniz
  - Weak lensing
  - Strong lensing
  - Substructure [via timing]
  - MW dwarf population

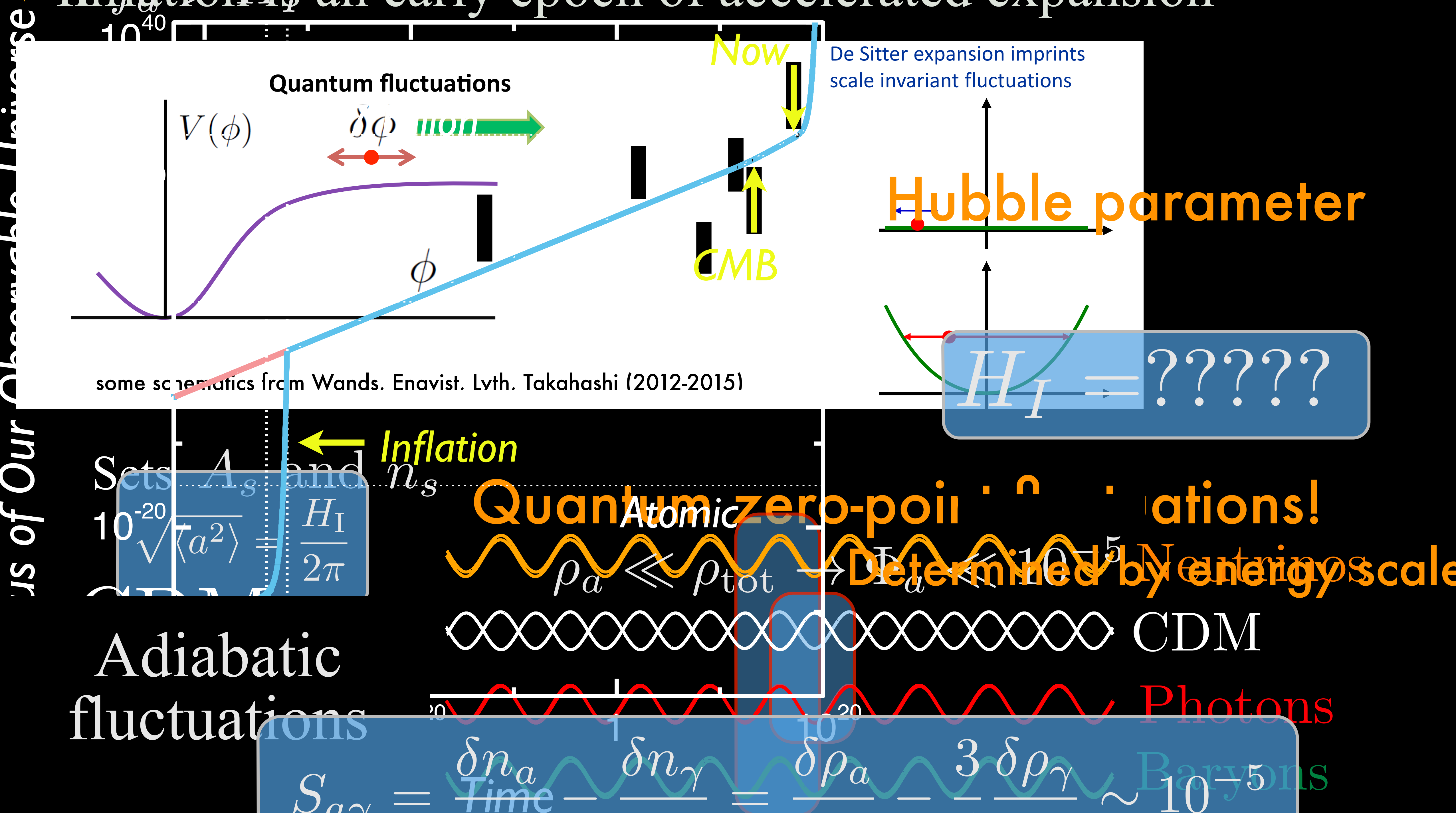


Essential to understand how (or if) ULAs populate halos

- Generally bias scale-dependent for structure suppressing species (LoVerde 2013)

Axions and isocurvature fluctuations

✳ Inflation is an early epoch of accelerated expansion



$H_I = ?????$

Sets A_s and n_s

Quantum zero-point fluctuations!

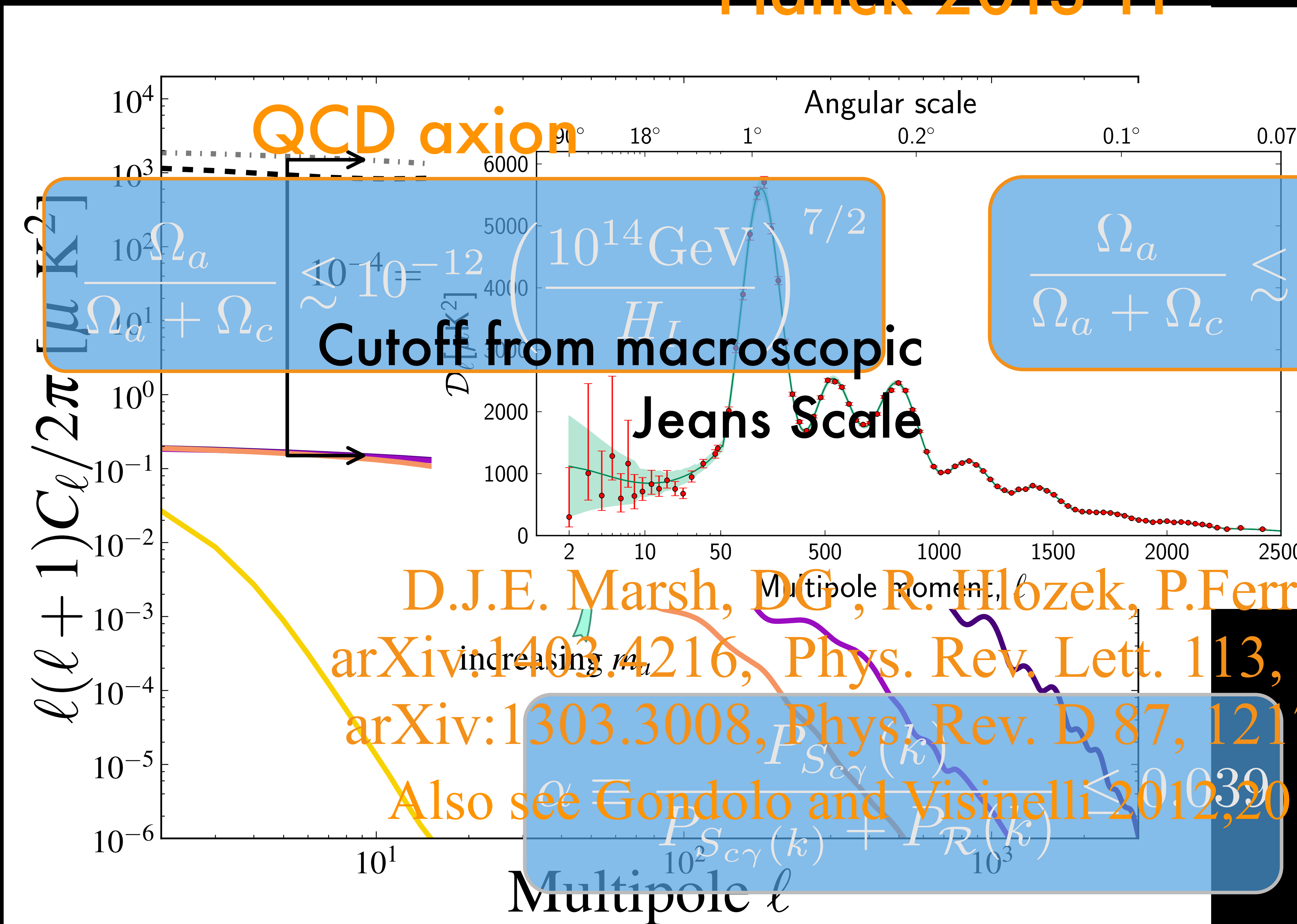
Determined by energy scale

$$\sqrt{\langle a^2\rangle} = \frac{H_I}{2\pi}$$

$$\rho_a \ll \rho_{tot} \rightarrow I_a \lesssim 10^{-5}$$

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

Planck 2013 TT



$$\frac{\Omega_a}{\Omega_a+\Omega_c} \lesssim 10^{-4}\ 10^{-12}\left(\frac{10^{14}\,\mathrm{GeV}}{H_I}\right)^{7/2}$$

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

D.J.E. Marsh, DG , R. Hlozek, P.Ferreira:
arXiv:1403.4216, Phys. Rev. Lett. 113, 011801
arXiv:1303.3008, Phys. Rev. D 87, 121701(R)
Also see Gondolo and Visinelli 2012,2013

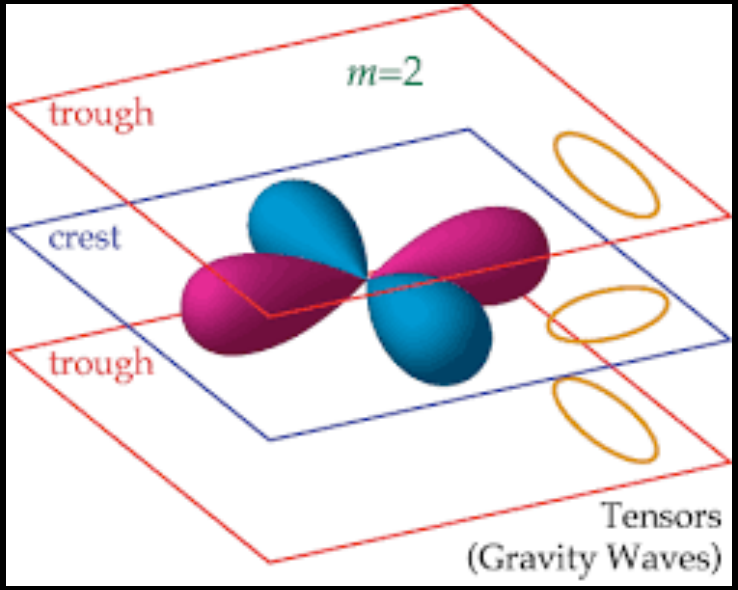
$$\alpha = \frac{P_{S_{c\gamma}}(k)}{P_{S_{c\gamma}}(k)+P_{\mathcal{R}}(k)} \lesssim 0.039$$

$$\frac{H_I}{f_a\theta}\frac{\Omega_a}{\Omega_\mathrm{d}} \lesssim 4\times 10^{-5}$$

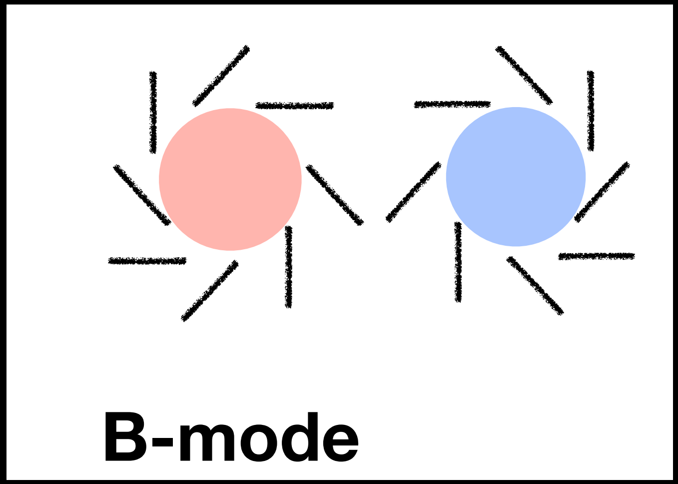
Isocurvature spectra have distinct phase structure from adiabatic fluctuations
Spectra from AxiCAMB using initial conditions obtained in DG+ (2015 in prep)

FORECAST/FUTURE WORK: TENSORS AND ULAS

✳ Primordial gravitational waves are sensitive to H_I



Potentially observable CMB polarization signature



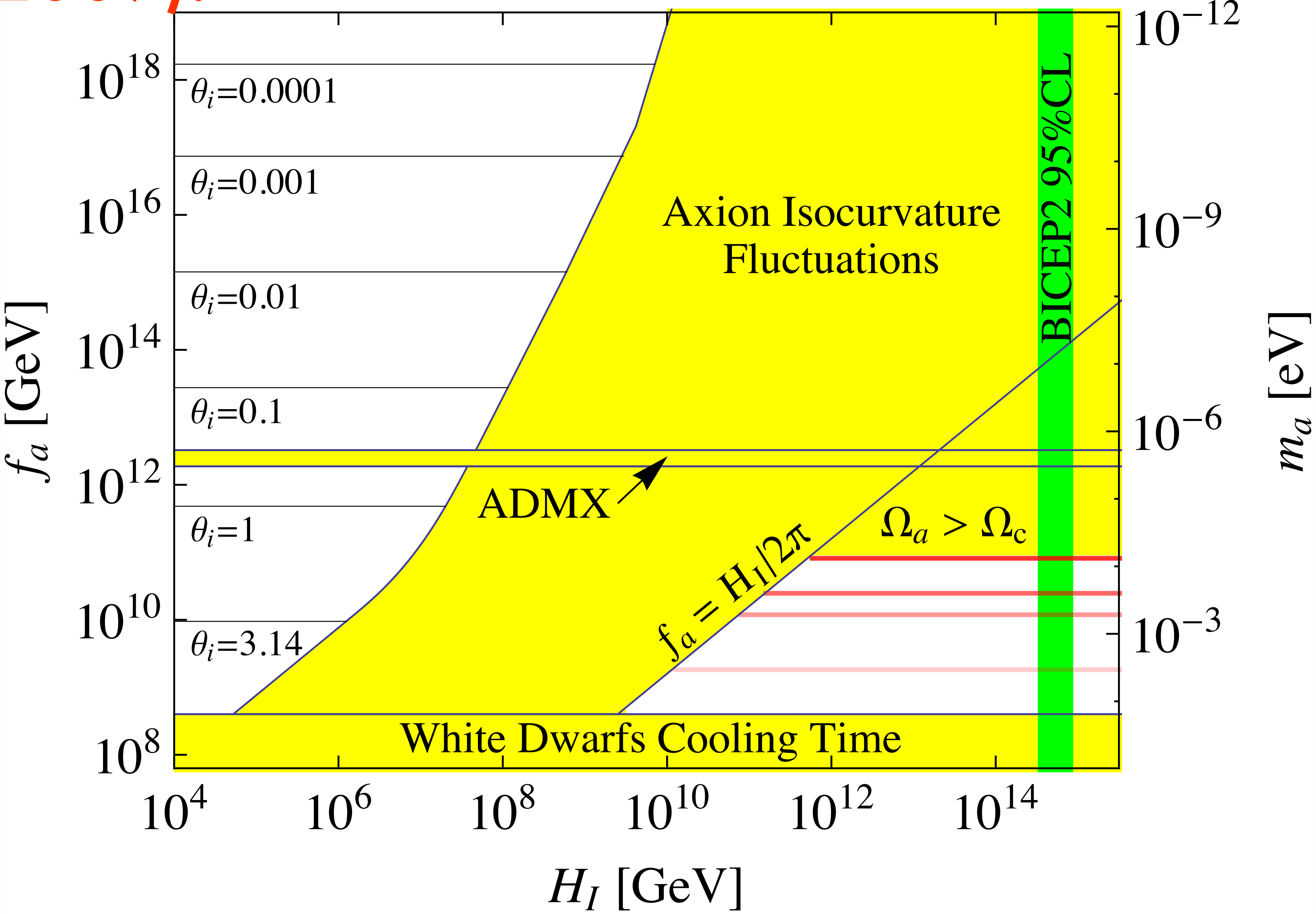
✳ Current limits are $H_I \lesssim 10^{14}\ \mathrm{GeV}$. If saturated by a detection:

QCD axion $$\frac{\Omega_a}{\Omega_a+\Omega_c} \lesssim 10^{-12}$$

ULA $$\frac{\Omega_a}{\Omega_a+\Omega_c} \lesssim 10^{-3}$$

BICEP2 [inflationary energy scale detected?]

(Gondolo 2009):



✴ Hard to accomodate QCD axion DM w/o classical window (defects)! [Marsh +yours truly+others 1403.4216 (2014), Gondolo et al. 2014 1403.4594]

$$\frac{\Omega_a}{\Omega_d} \lesssim 5 \times 10^{-12} \left(\frac{f_a}{10^{16}\ \text{GeV}} \right)^{5/6}$$

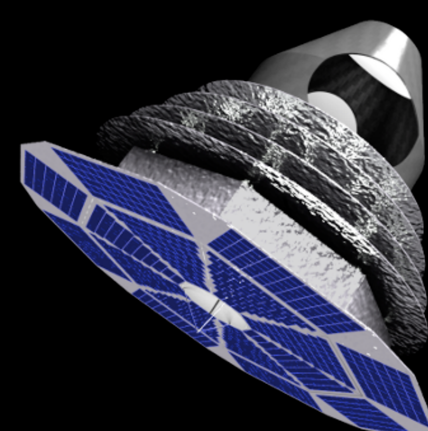
ULAs as an inflationary probe

- Discovery of QCD axion/ULA dark matter → trouble for
  - GUT-scale inflation

QCD axion $H_I \sim 10\ \mathrm{GeV}$ **ULA** $H_I \sim 10^5\ \mathrm{GeV}$

  - Null prediction for primordial B-mode searches

Spider

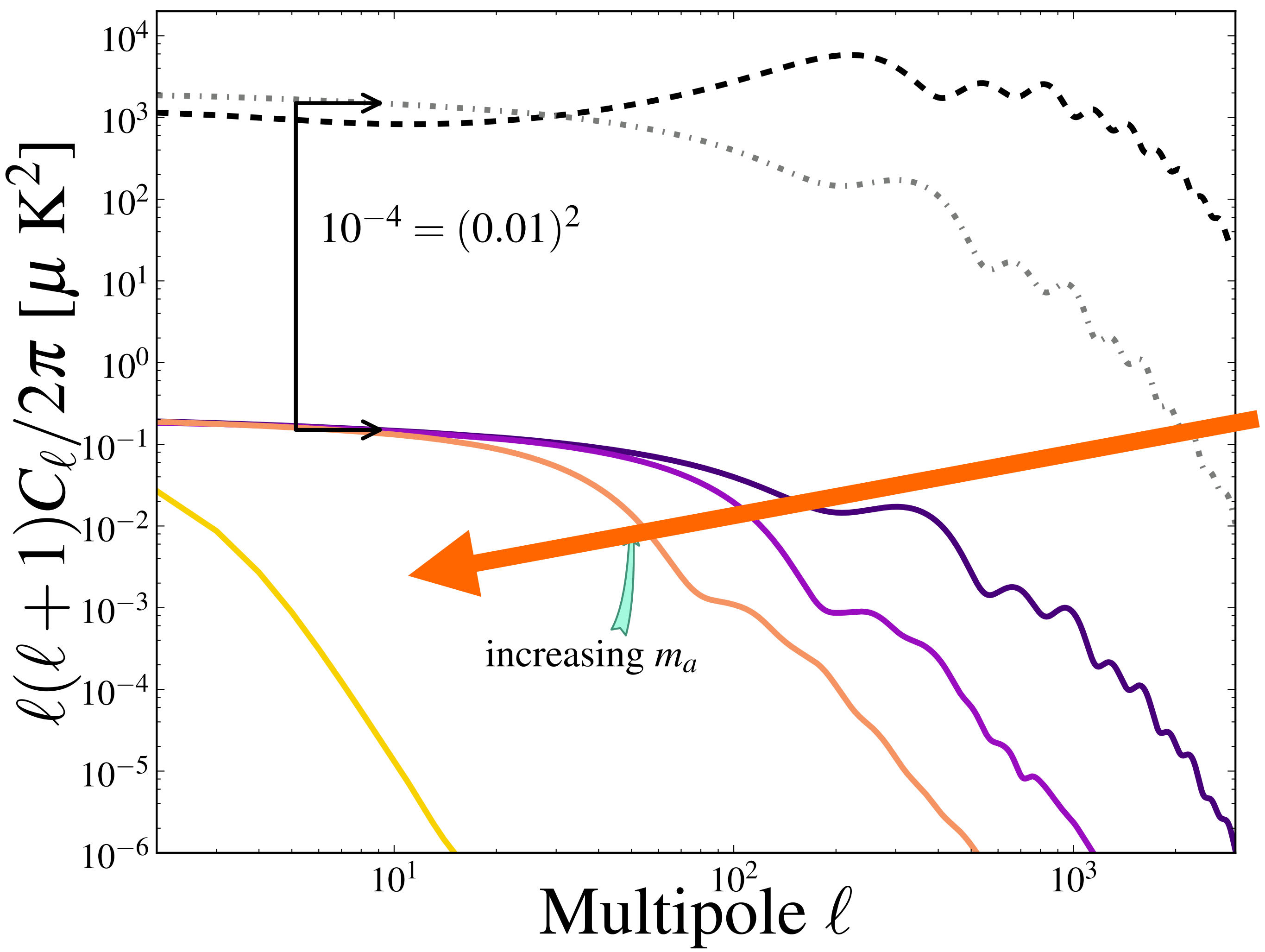


CORE

SPT/BICEP2-3/KECK

  - Avoidable with non-trivial thermal history/richer PQ symmetry breaking story

Forecast/future work: Tensors and ULAs



- ✳ Low-l plateau disappears
- ✳ Information lost
- ✳ Planck limits assume CDM isocurvature

✳ For $m_a \leq 10^{-27}$ eV, constraints cannot be simply remapped.

- ✳ MCMC in progress

CONCLUSIONS AND TAKE-AWAY

- Ultra-light axions may be probed at the 0.5% level using current cosmological data
- Opportunities/challenges exist for ULA dark matter on galactic scales
- Entropy fluctuations and tensor perturbations are a powerful ULA probe

Additional slides for question time

Additional slides:
Introduction

ACOUSTIC OSCILLATIONS IN THE CMB

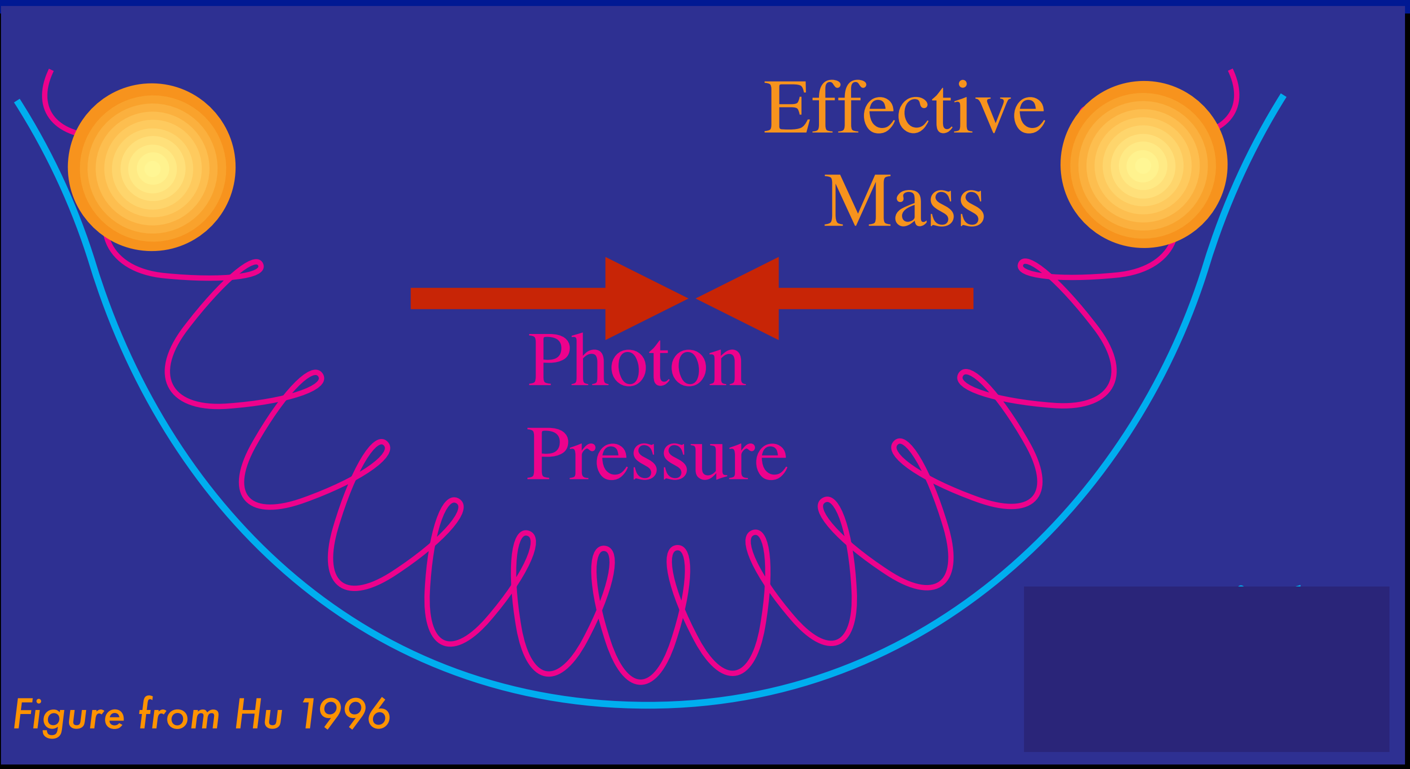


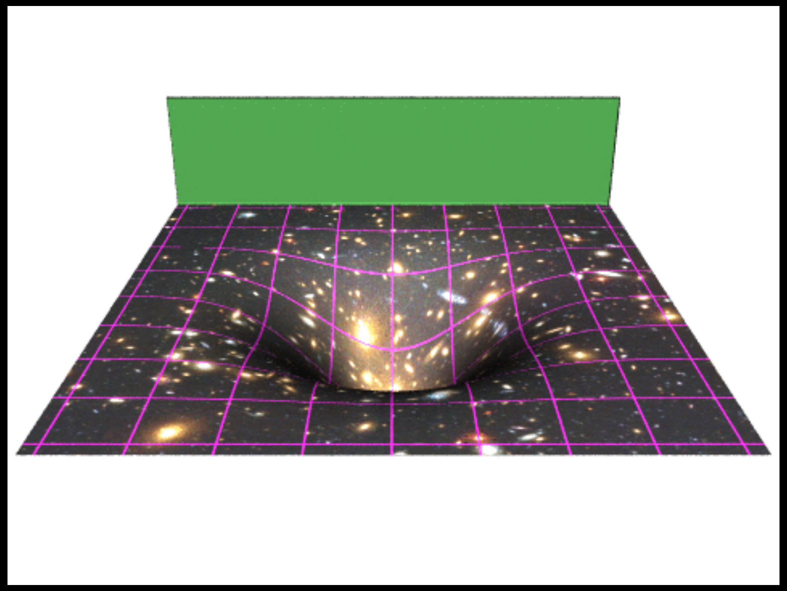
Figure from Hu 1996

Gravity compresses

Ψ

and drives

$\dot{\Psi}$

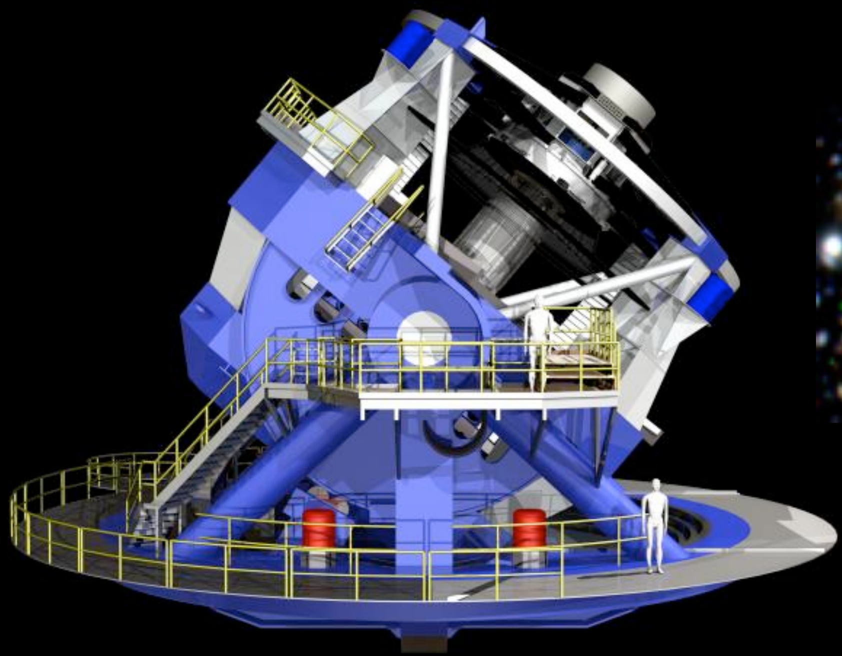


- Baryons: Inertia $p_b \propto \frac{1}{a}$
- $e^- \; \gamma$ coupled through Thomson scattering $\Gamma \propto n_e \sigma_T$
- Restoring force: Radiation Pressure

$$\delta P_\gamma = c_s^2 \delta\rho_\gamma$$

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

ONGOING/FUTURE OBSERVATIONS

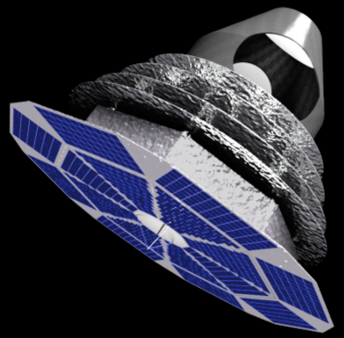


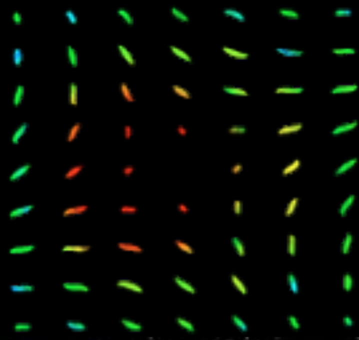
LSST

Scientific targets:
Modified Gravity
Neutrino hierarchy
Dark energy equation of state
Substructure in halos (via lensing)

SPT/BICEP2-3/KECK

SPIDER



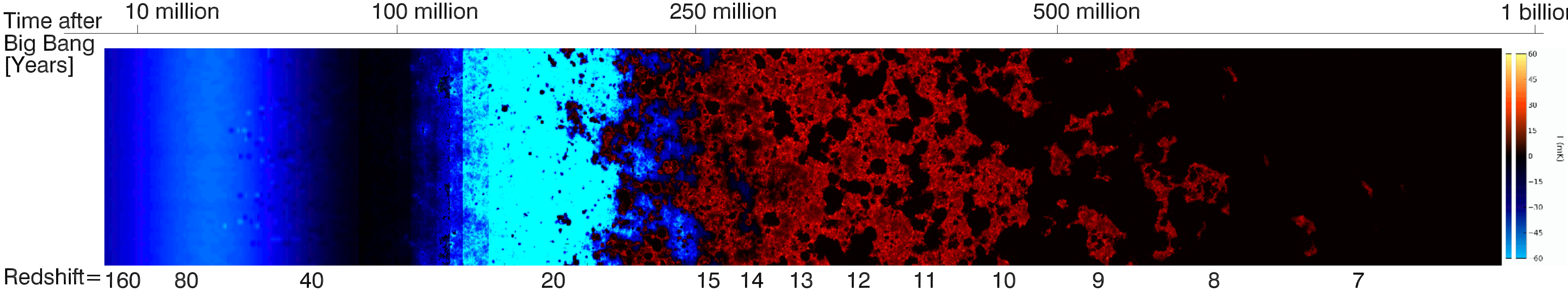


COrE
Cosmic Origins Explorer

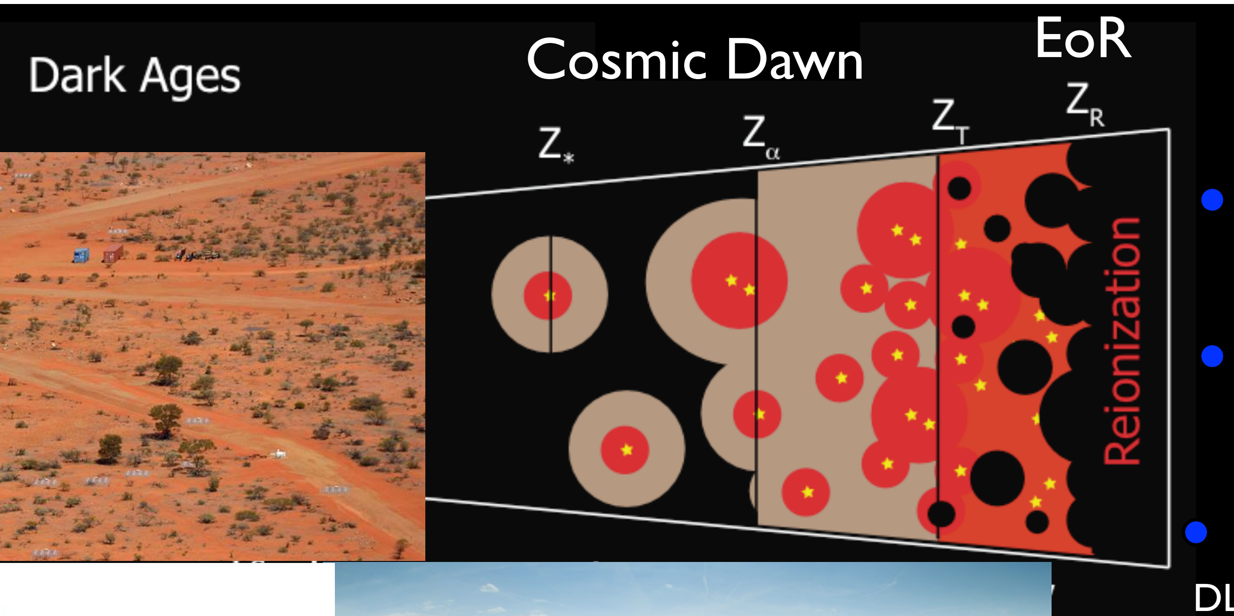
WFIRST
Wide-Field Infrared Survey Telescope

ONGOING/FUTURE OBSERVATIONS [21-CM LINE]

21-cm cosmology [probes of structure on small scales and early times]



MWA



LOFAR

SKA
SQUARE KILOMETRE ARRAY

Additional slides:
QCD Axion theory/experiment

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?

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

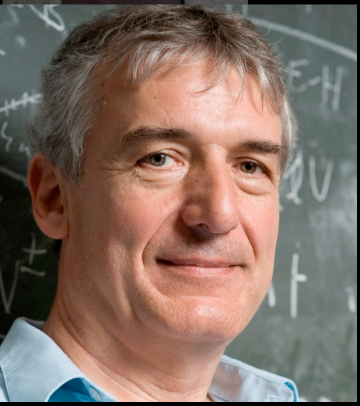
$$\theta \lesssim 10^{-10},$$

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

Cleaning up the dark matter mess?





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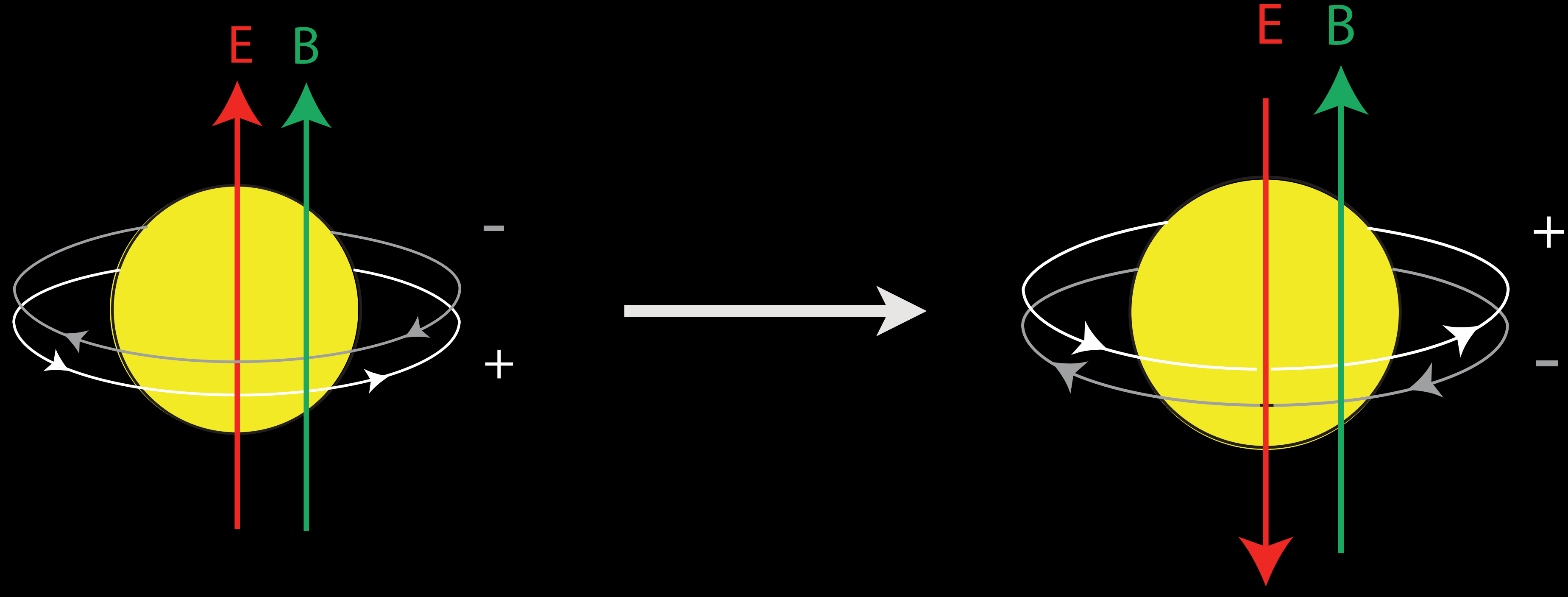

Key questions:

- ✳ **Can the *dark matter* or *dark energy* be an ultra-light boson, like an axion?**

- ✳ What is the connection between the physics of inflation and the physics of the dark sector? Are initial fluctuations in different species spatially locked?

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

Key questions:

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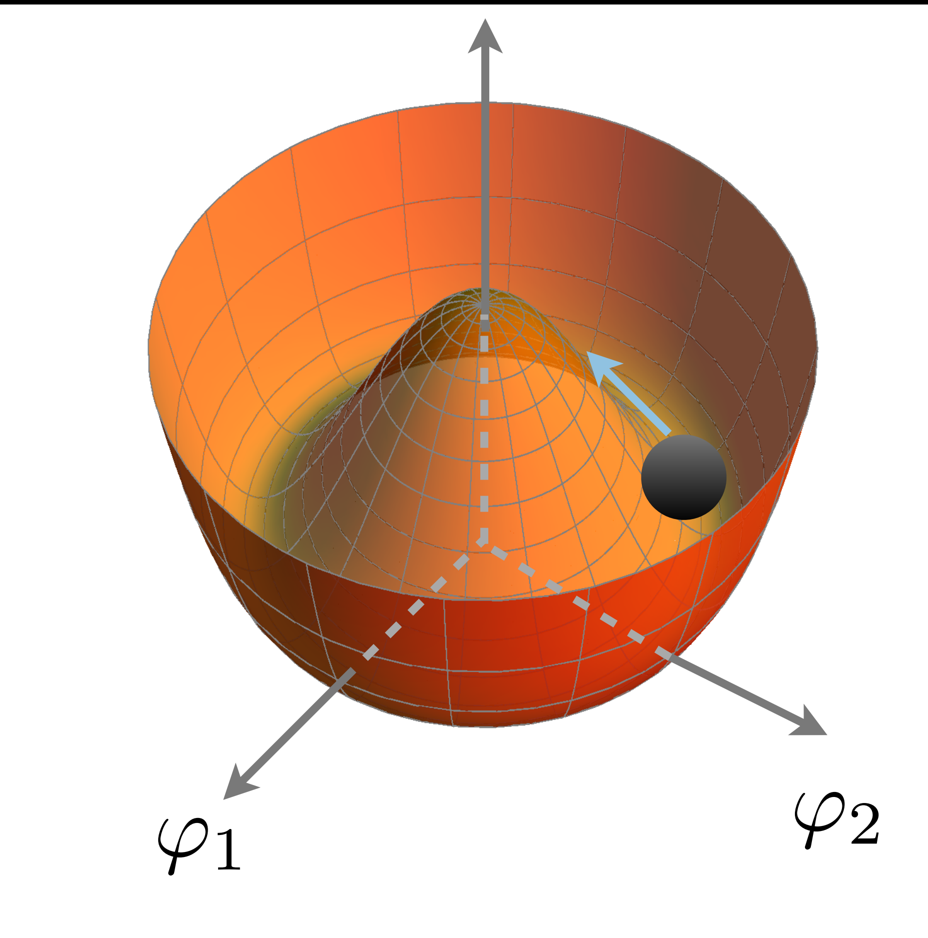
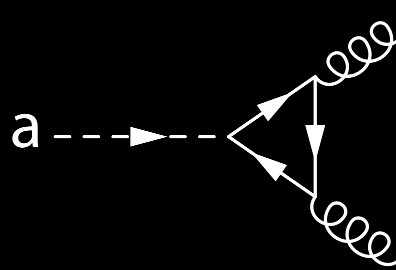
What are axions?



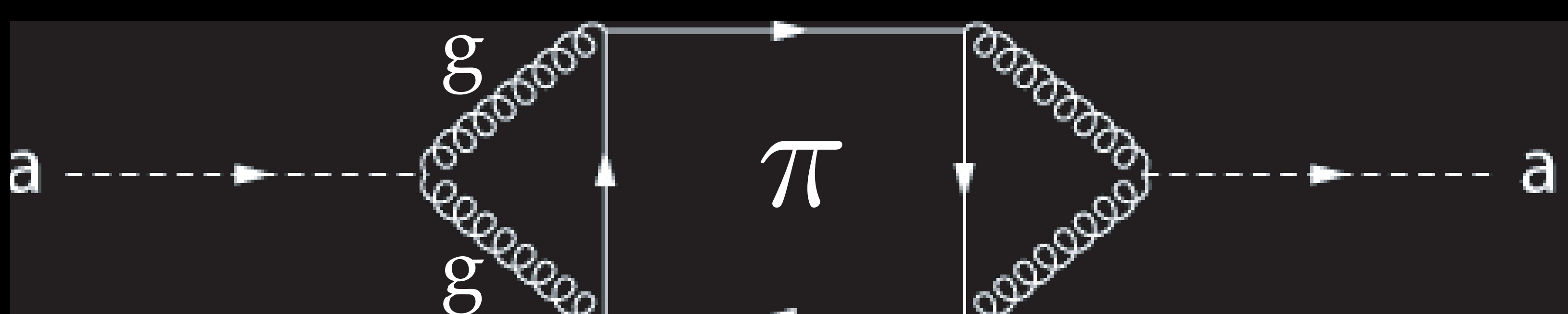
New scalar field with global U(1) symmetry!

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



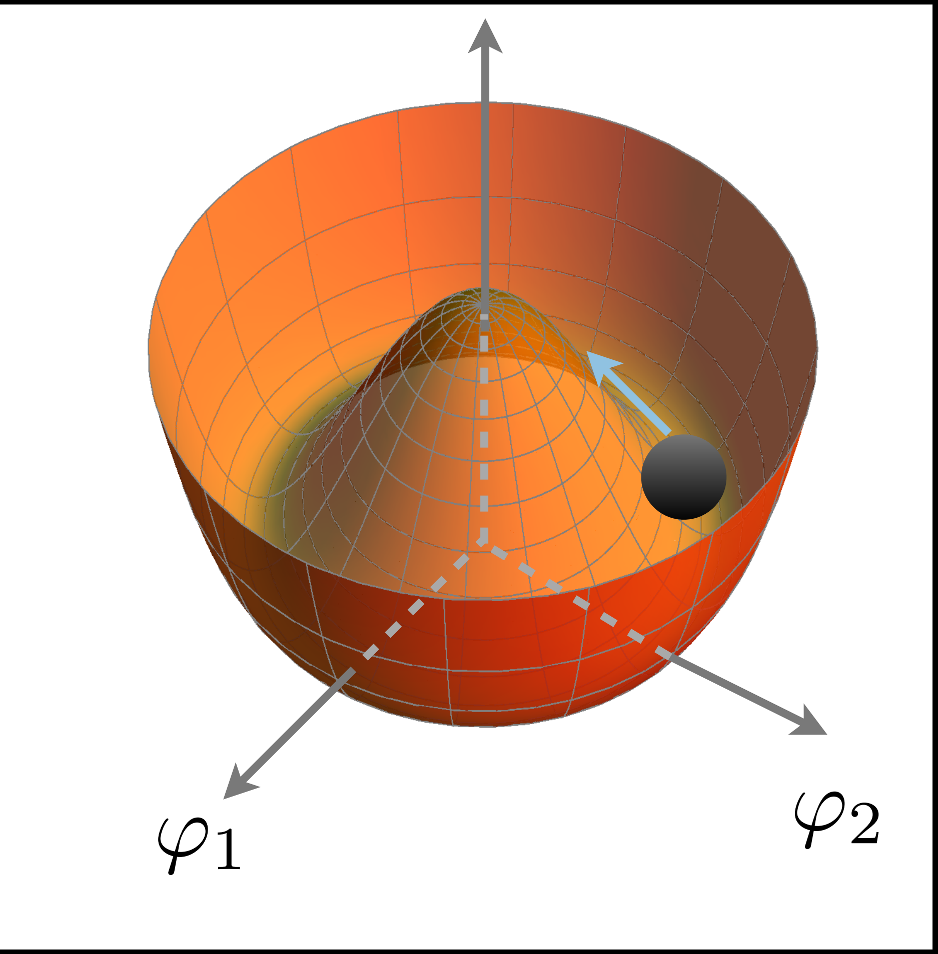
- Couples to SM gauge fields (via fermions)
- Dynamically erases QCD CP-violation

- 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)

What are axions?



New scalar field with global U(1) symmetry!

Broken at scale f_a

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

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

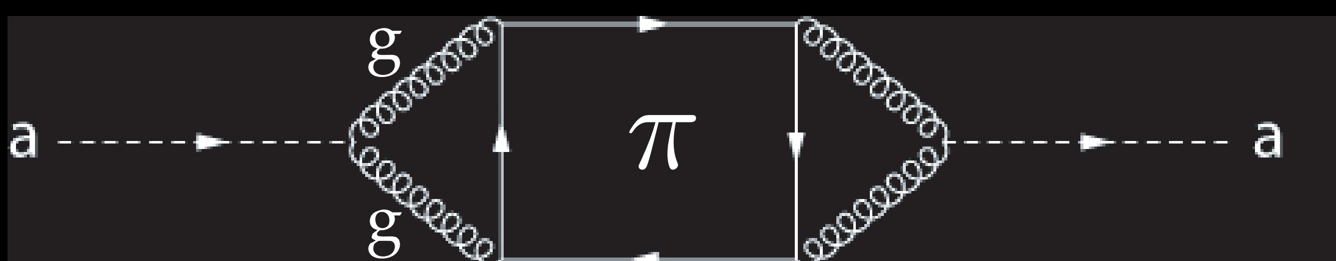
Peccei + Quinn (1977), Weinberg +Wilczek (1978), Kim (1979), Shifman et. al (1980), Zhitnitsky (1980), Dine et al. (1981), D.B. Kaplan (1985)

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

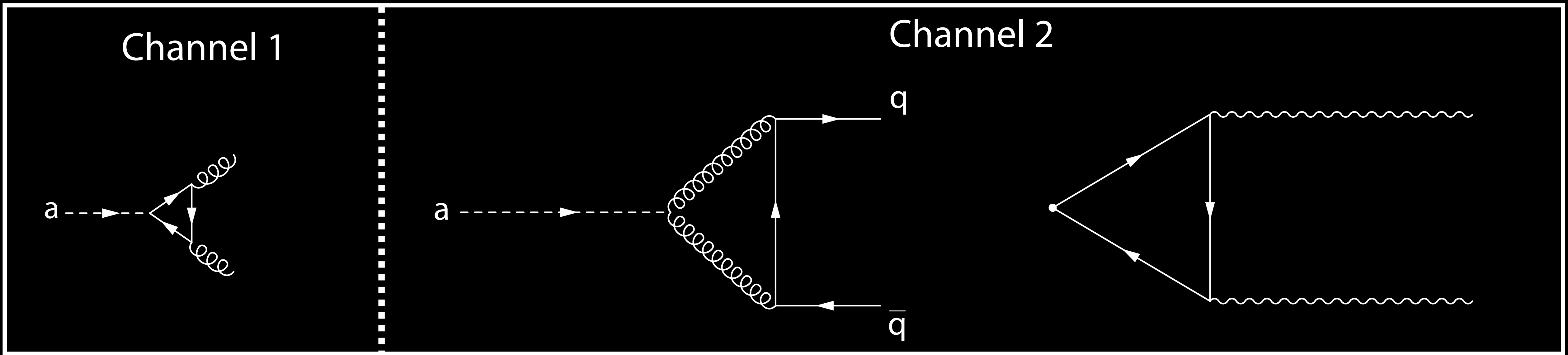


$$m_a \simeq \frac{\Lambda_{\mathrm{QCD}}^2}{f_a}$$

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

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

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

Dark matter axion abundance

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

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

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

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

$$\Omega_{\rm mis} h^2 = 0.005 \left\langle \theta_i^2 f(\theta_i) \right\rangle \left(\frac{f_a}{10^{12}\ \text{GeV}} \right)^{3/2} \quad \text{if } f_a \gtrsim 10^{18}\ \text{GeV}$$

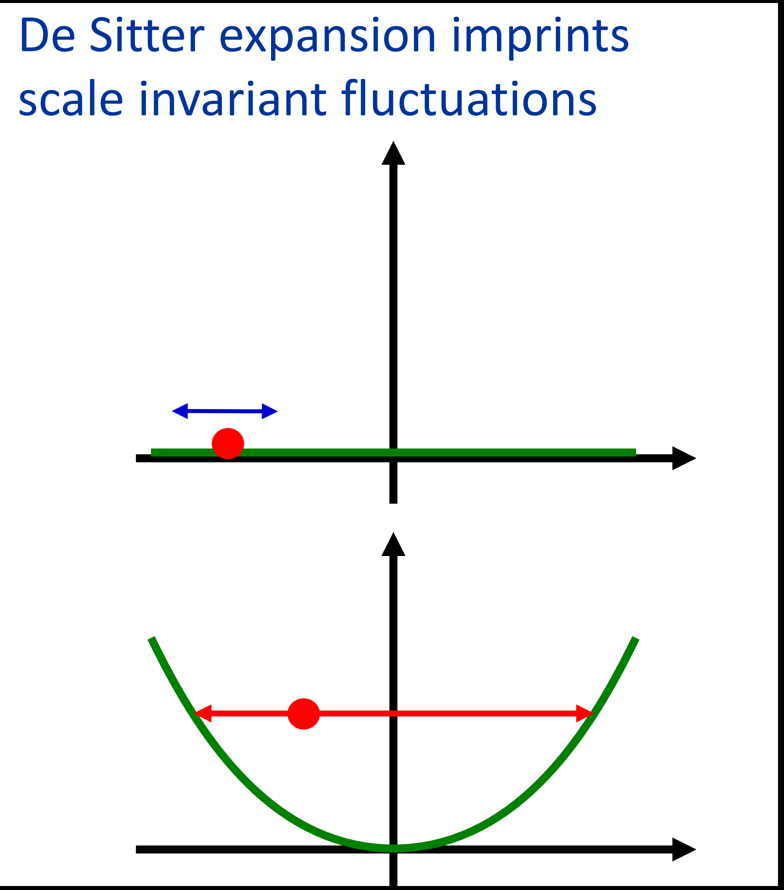
Anthropic axion window: $f_a > \max\{T_{\mathrm{RH}}, H_{\mathrm{I}}\}$

- 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

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

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

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

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

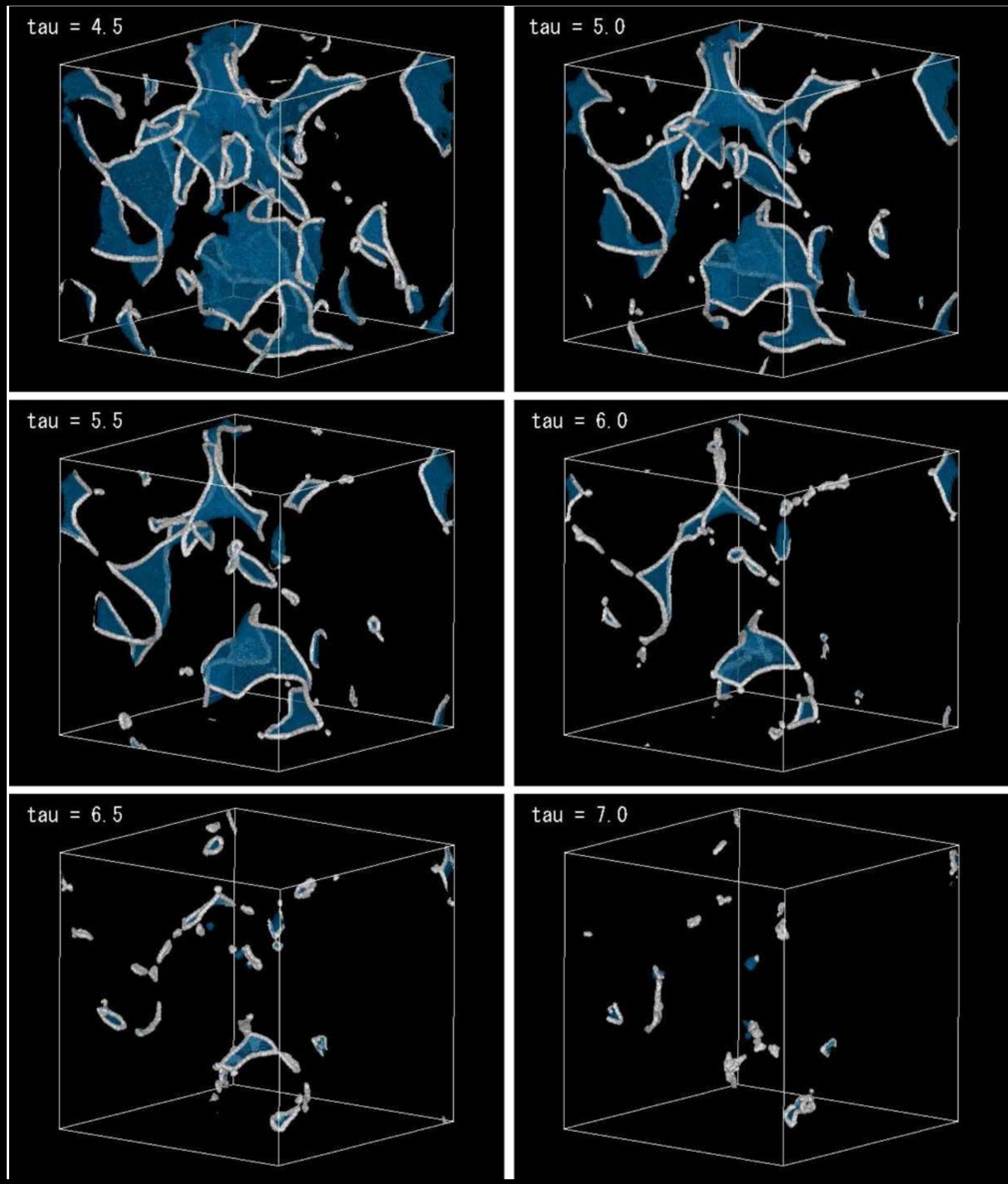
✴ Axion field is very inhomogeneous

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

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

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

CONTROVERSY!



From Hiramatsu 2012

✴ Abundance

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

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

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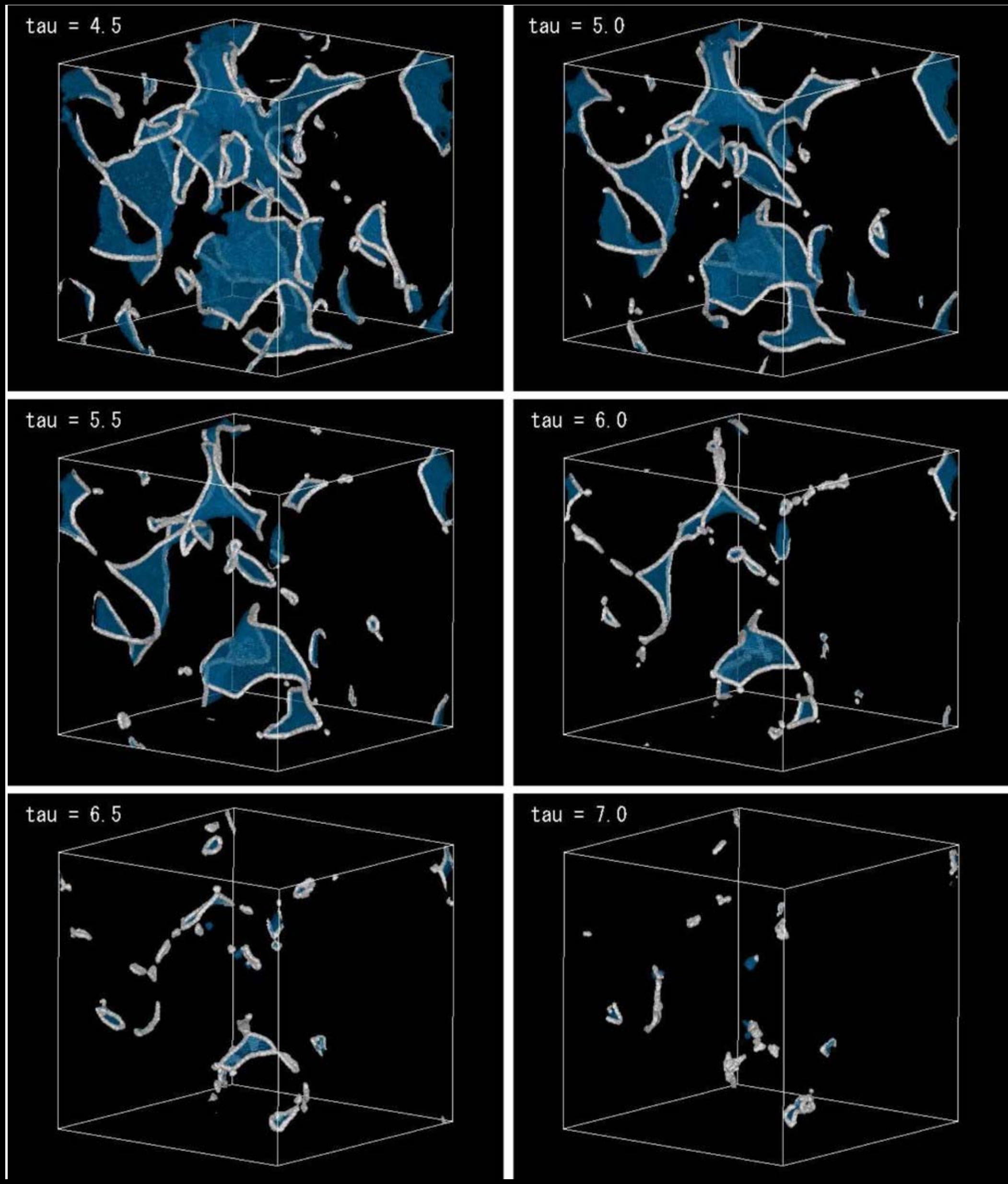
✳ Abundance



From Hiramatsu 2012

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

How to look for a QCD axion

✳ ADMX: Use the DM axions the universe gives you

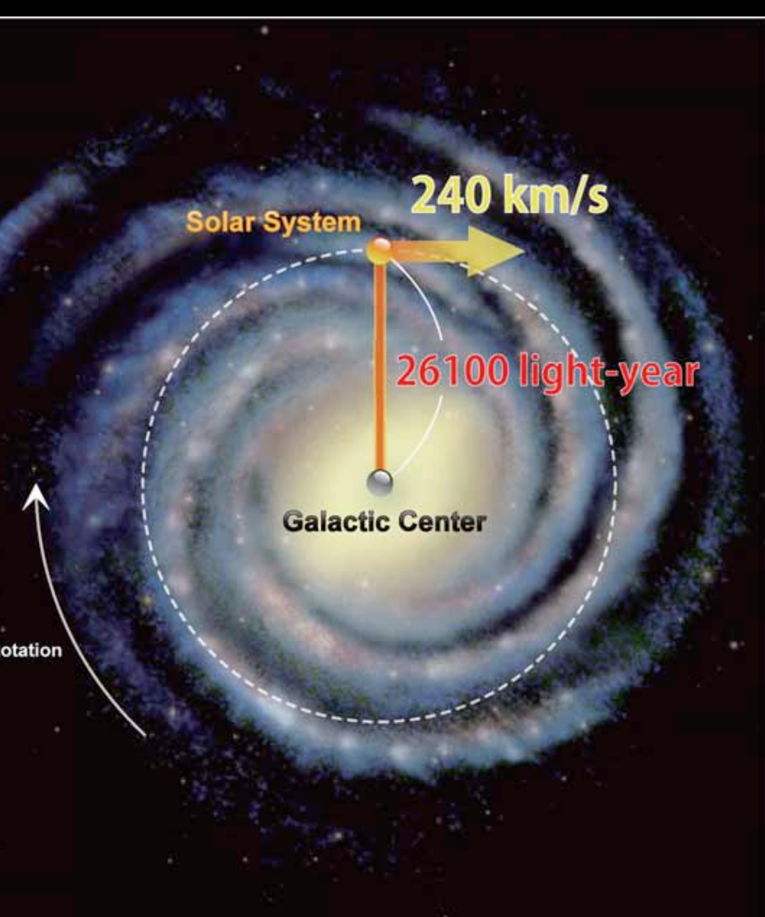
$$\mathcal{L} \propto g_{a\gamma\gamma} a \vec{E} \cdot \vec{B} \quad g_{a\gamma\gamma} \propto 1/f_a$$

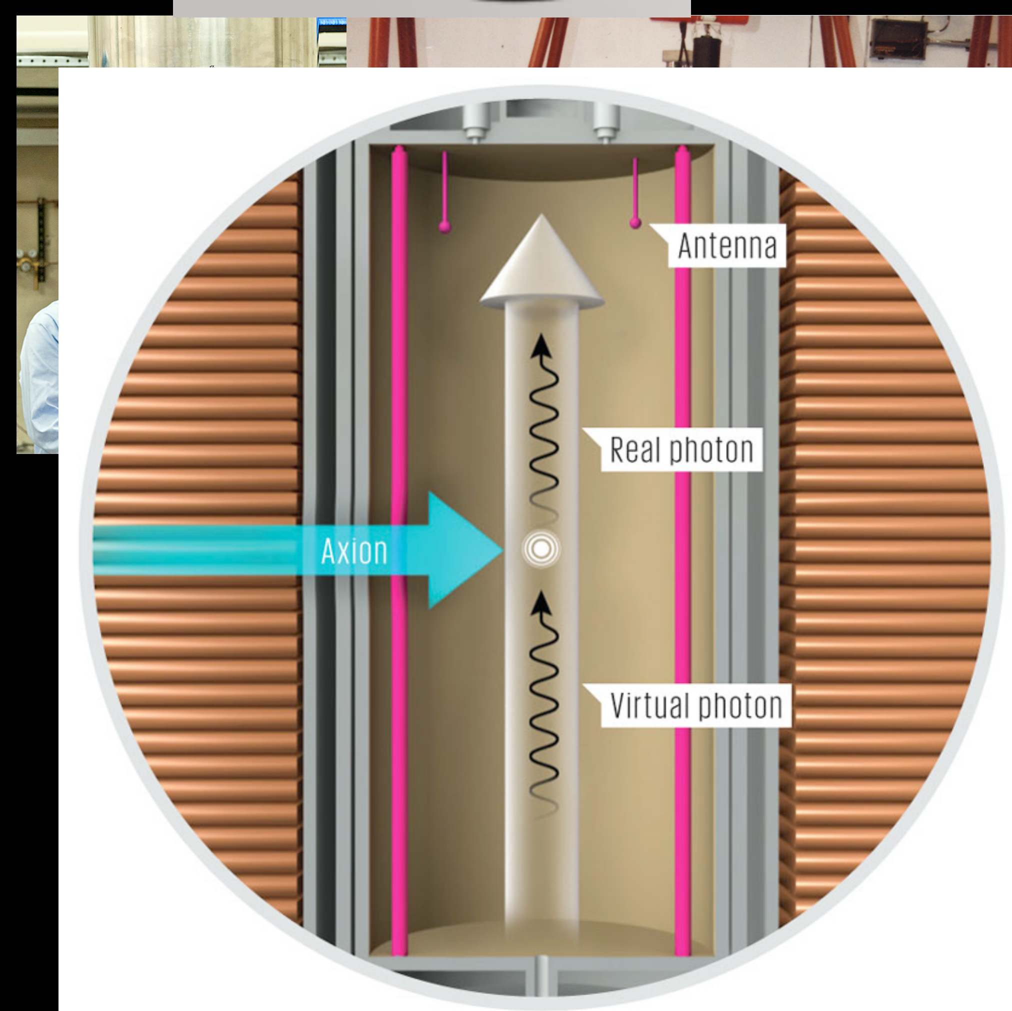
P. Sikivie 1983

$$E_\gamma = m_{\rm a} c^2$$

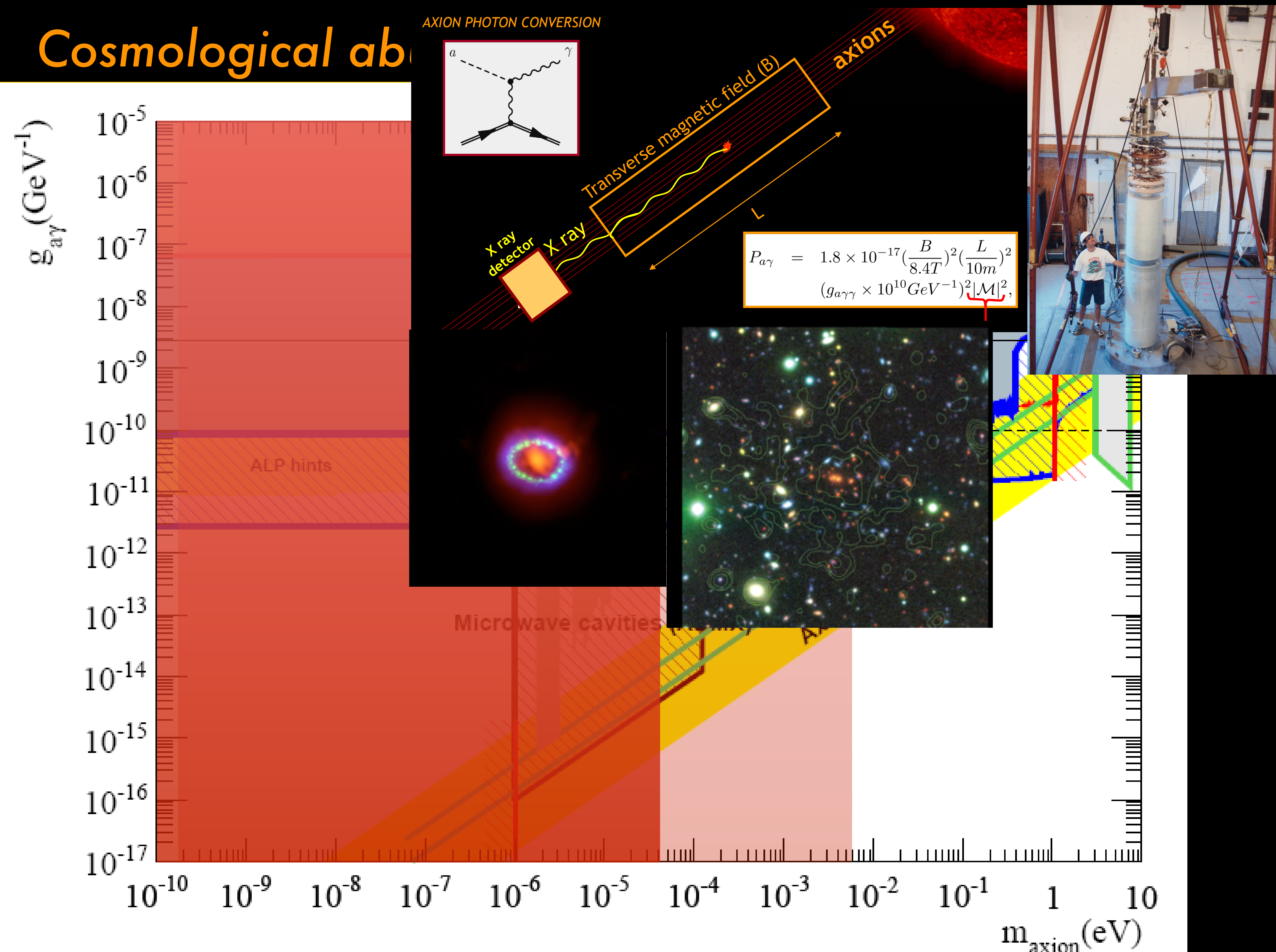
L. Rosenberg and G. Rybka +....

Excite cavity TEM modes



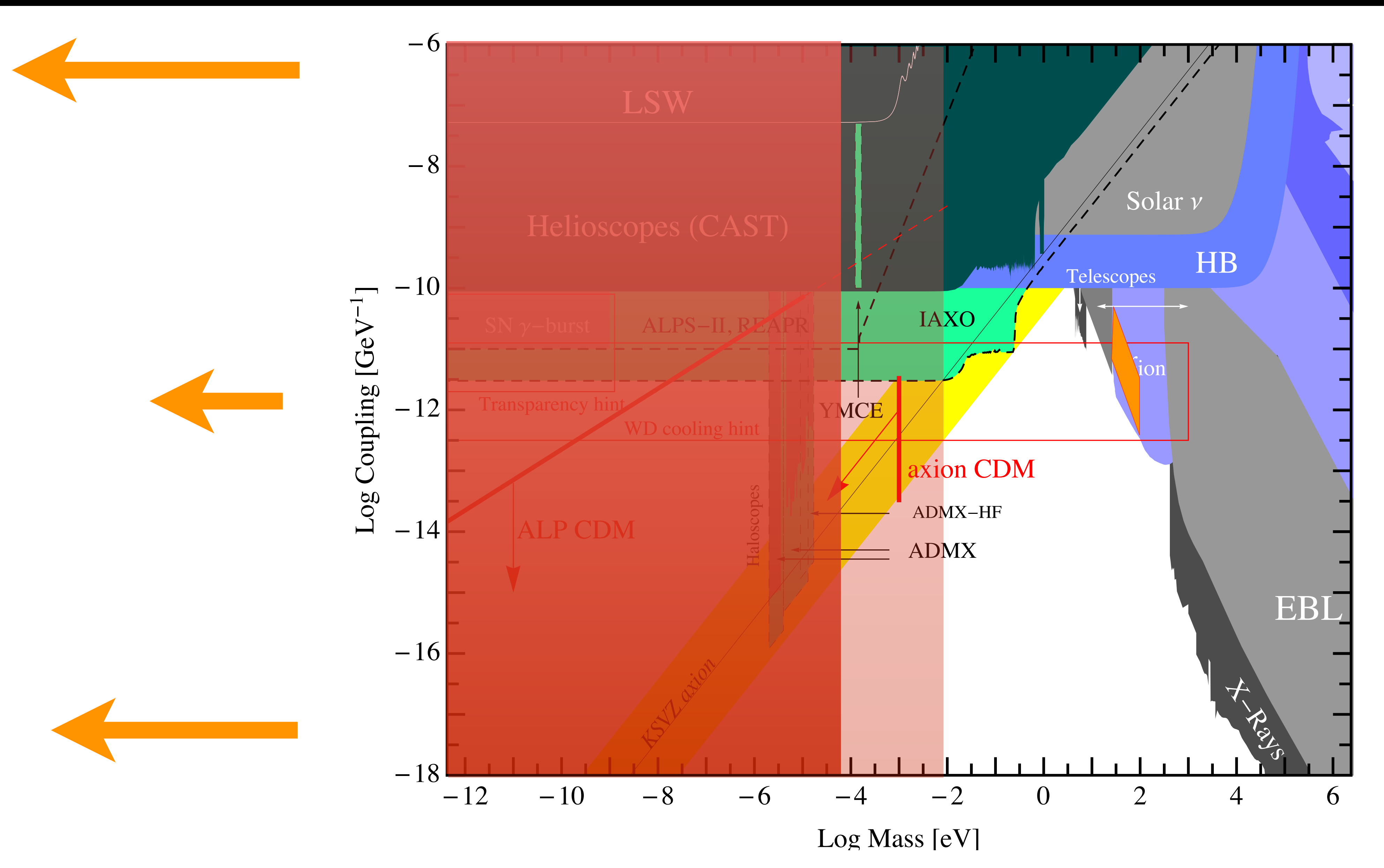


Limits and horizon



Experimental constraints
ULA and axion-like particles (ALPs)

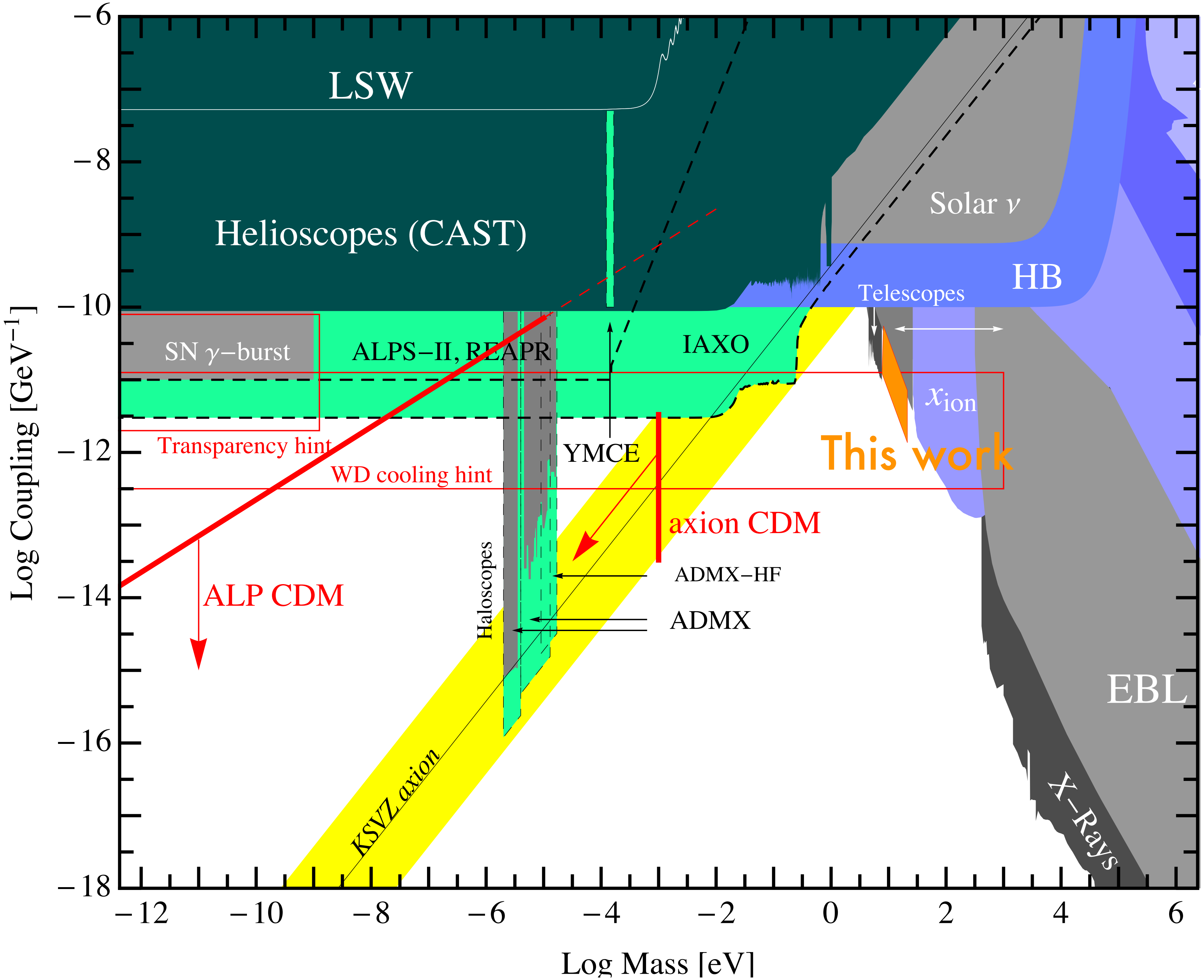
Experimental lab bounds essential
Cosmological bounds
Gravitational limits (more to come)



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

From arXiv: 1205.2671

Lay of the land

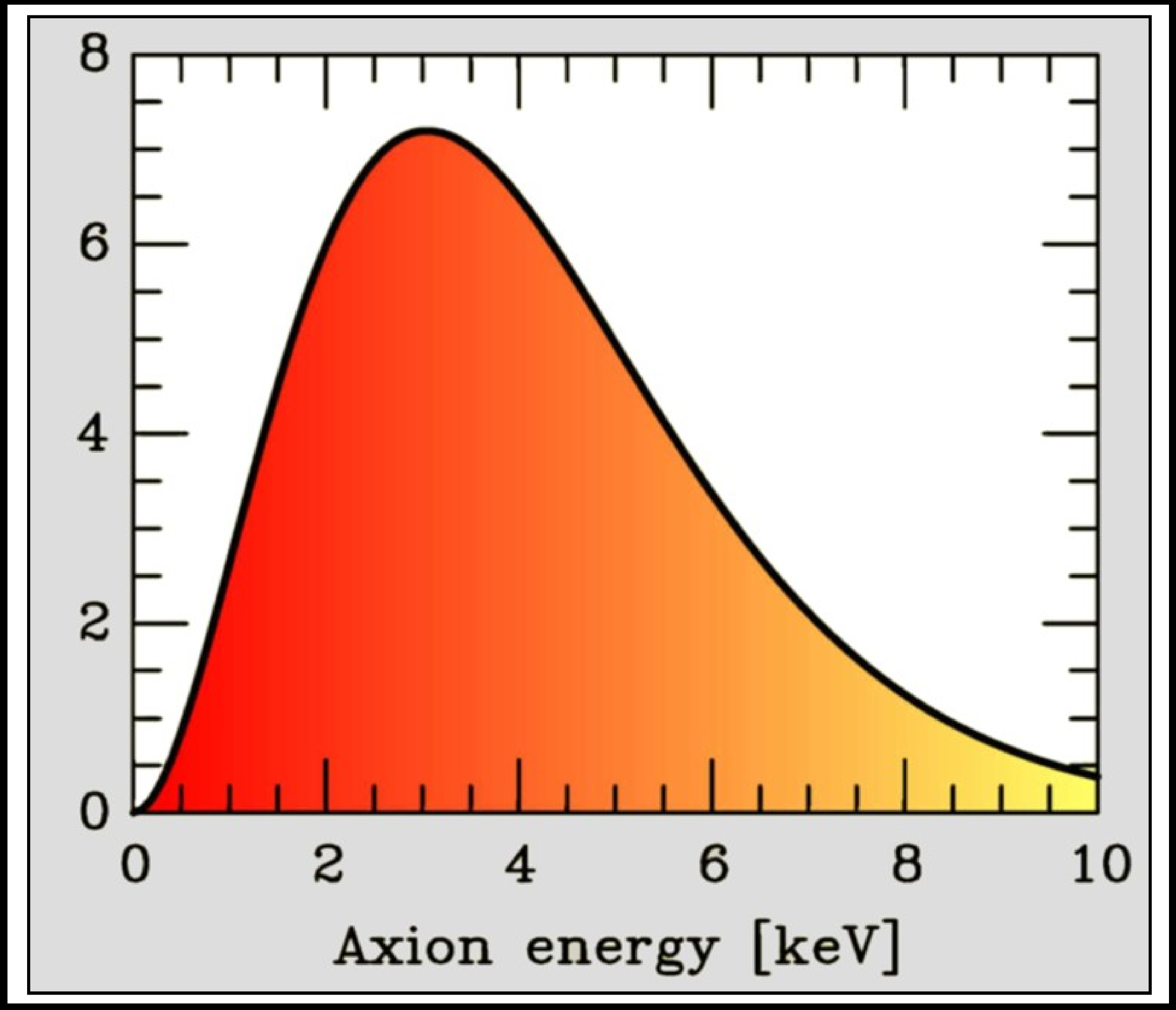


Axion helioscopes

- Resonance condition

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

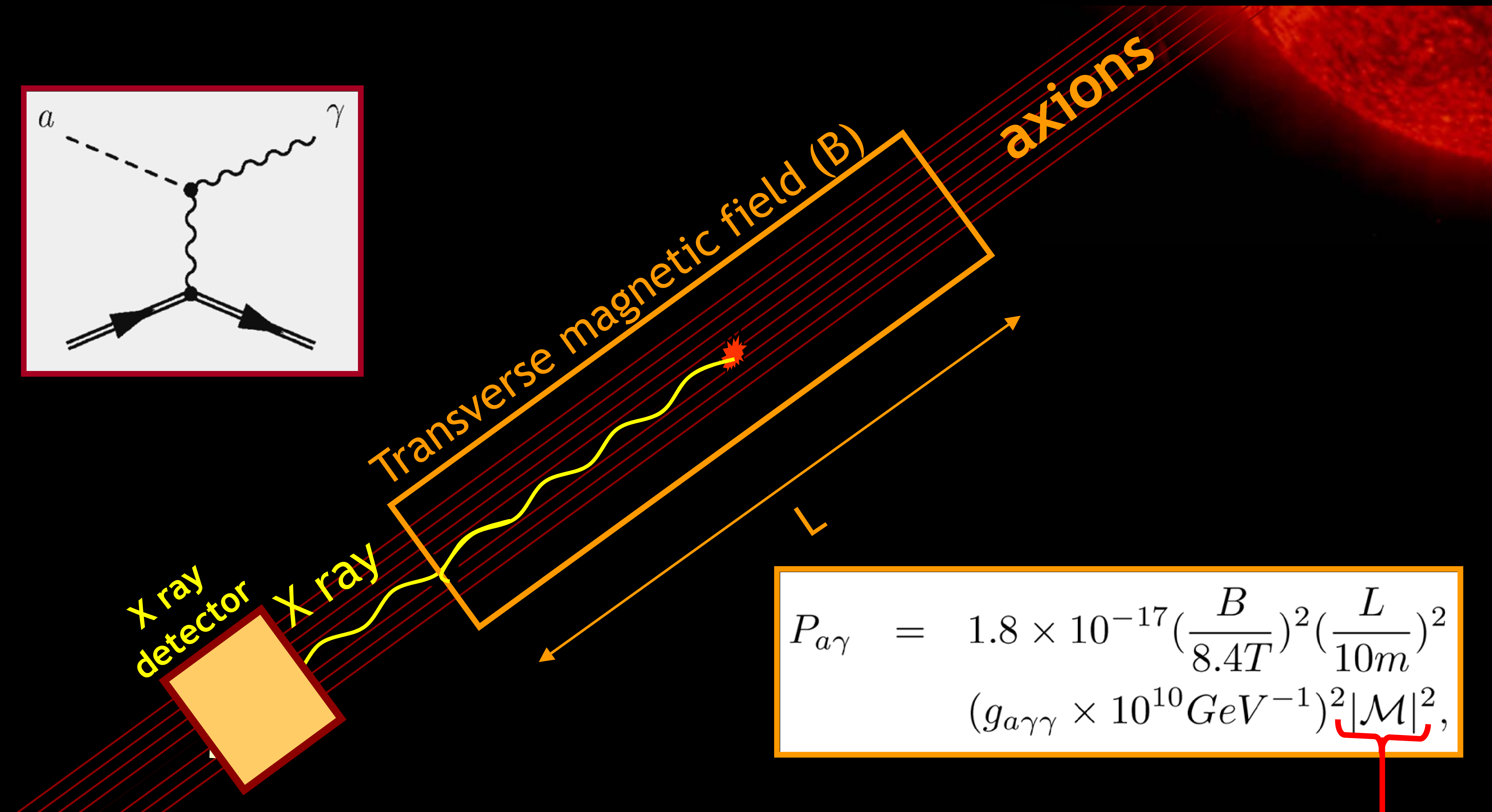
- Broad axion energy spectrum



Axion helioscopes

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

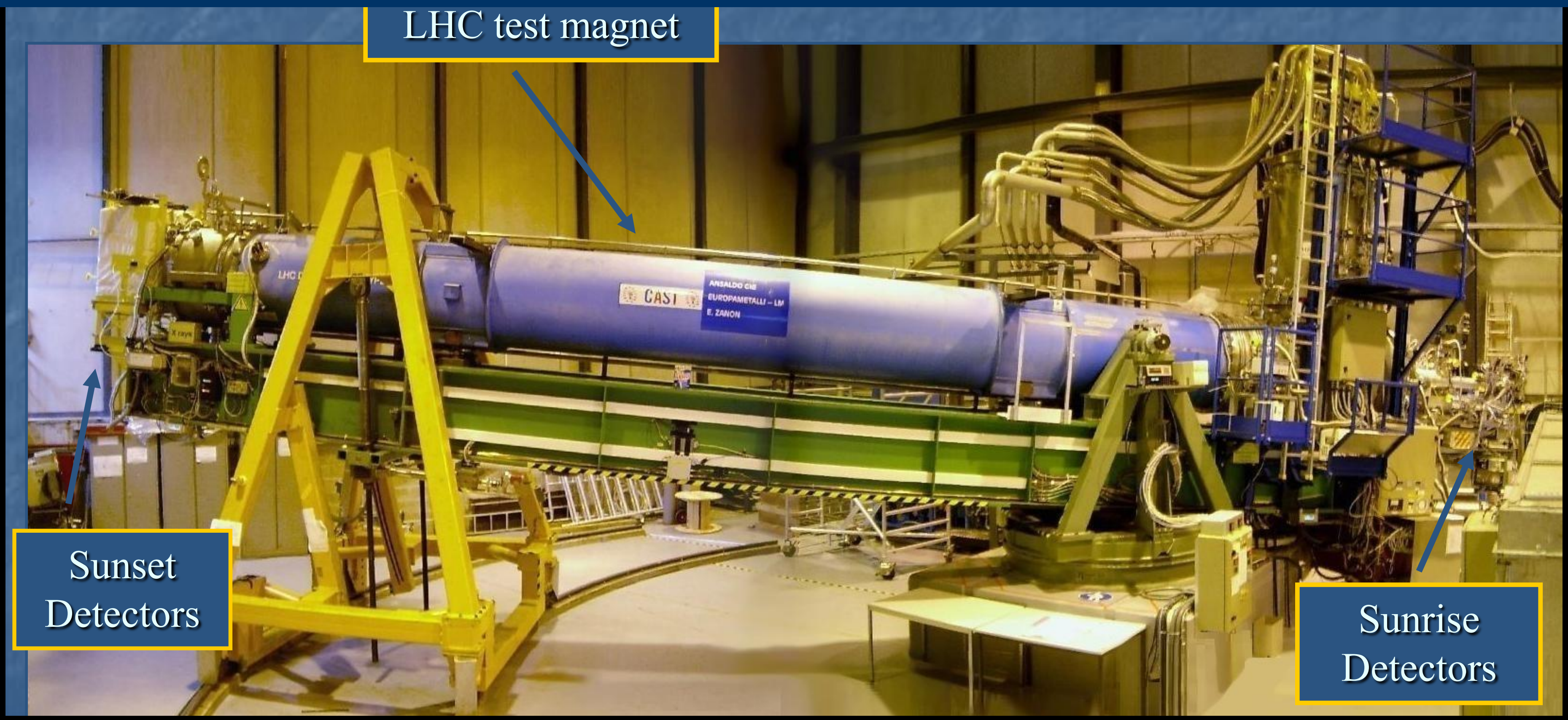
From Irastorza 2013



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

CAST/IAXO

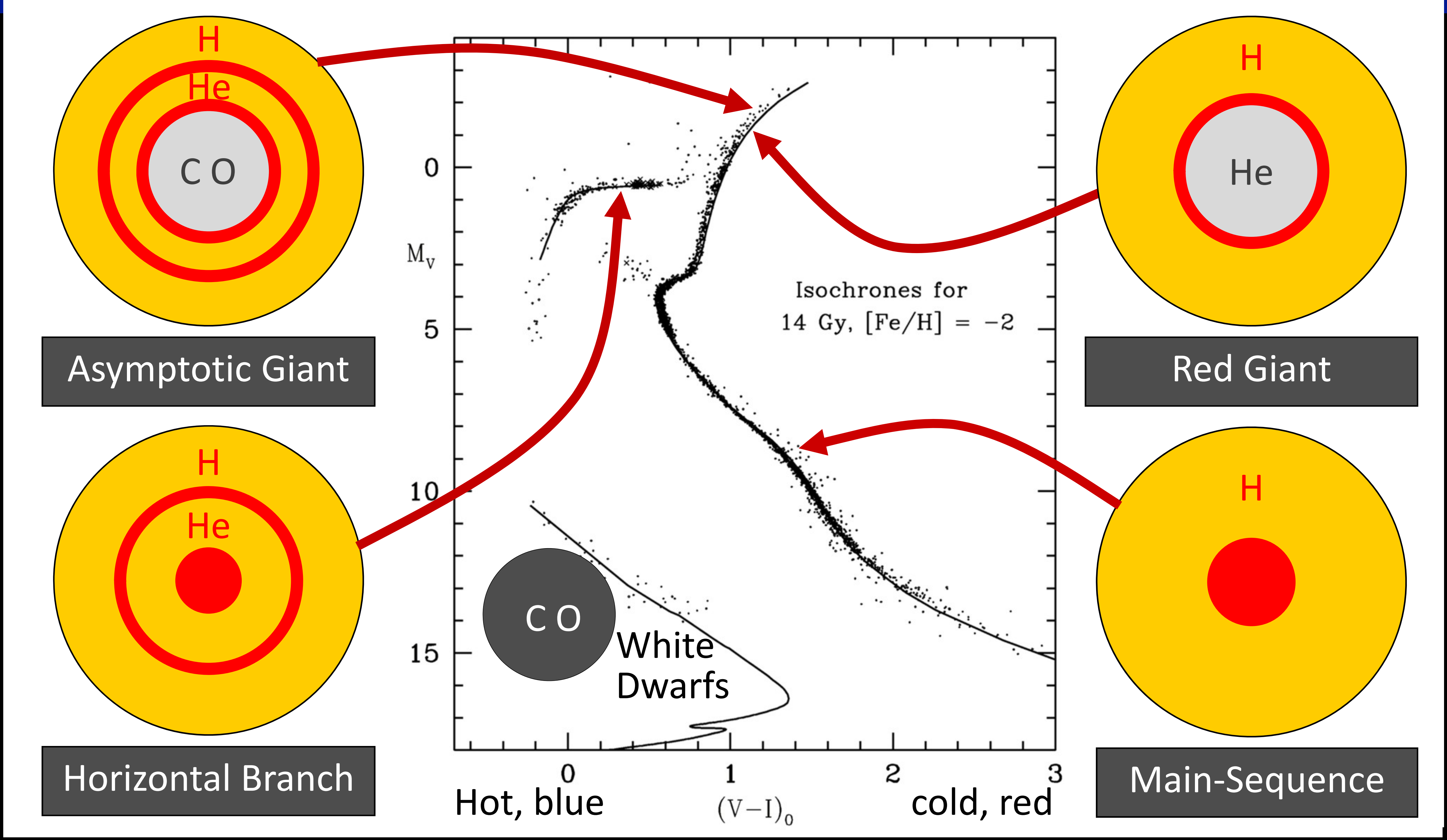
- ✳ CAST
  - ➢ LHC test magnet (B=9 T, L=9.26 m)



Lakic 2012

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

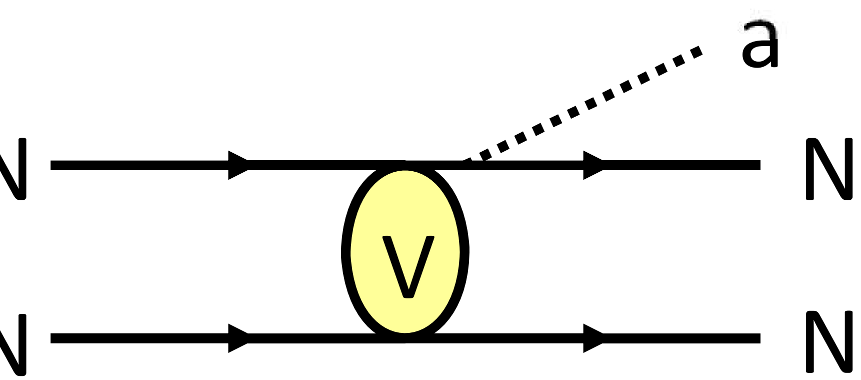
Making axions in stars, II



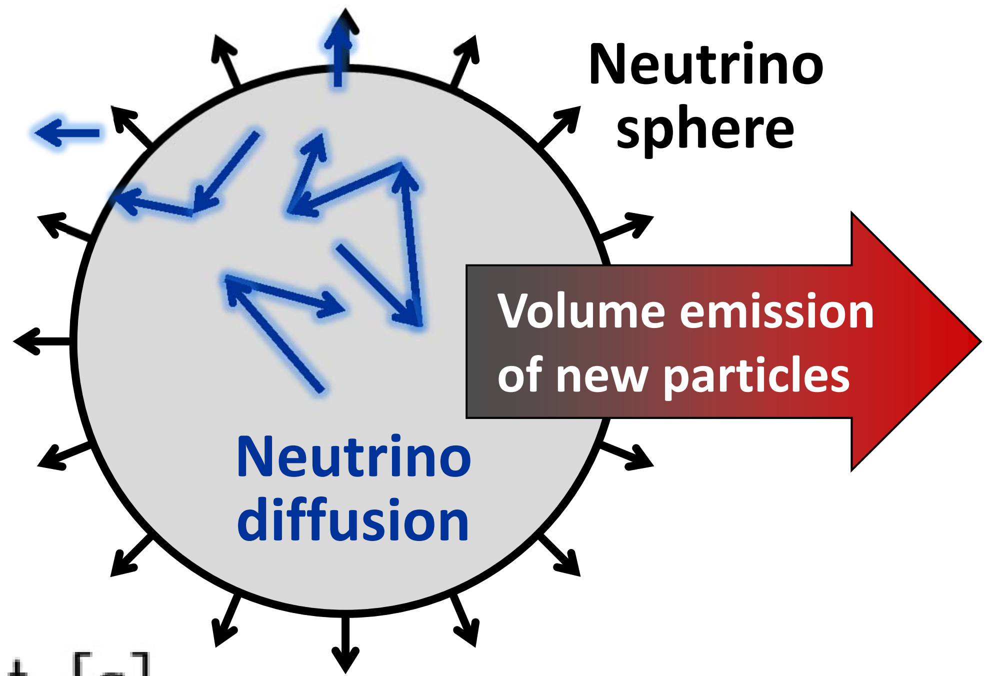
From Raffelt 2012

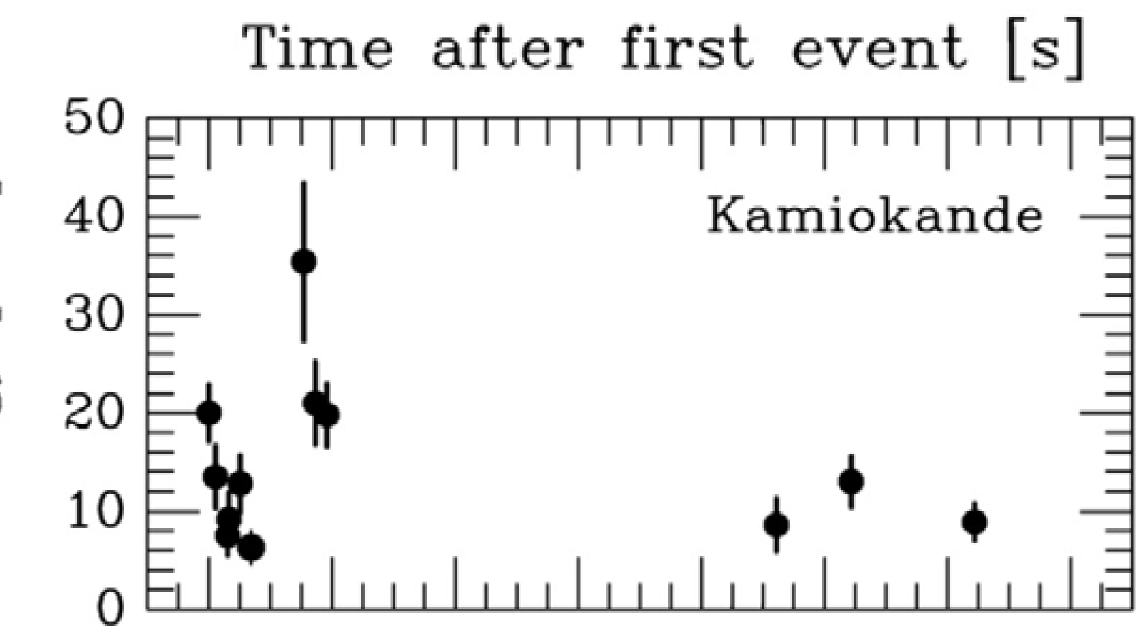
$$g_{a\gamma\gamma} \lesssim 10^{-10}\ \mathrm{GeV}^{-1}$$

Making axions in (exploding) stars, III



Nucleon-Nucleon Bremsstrahlung

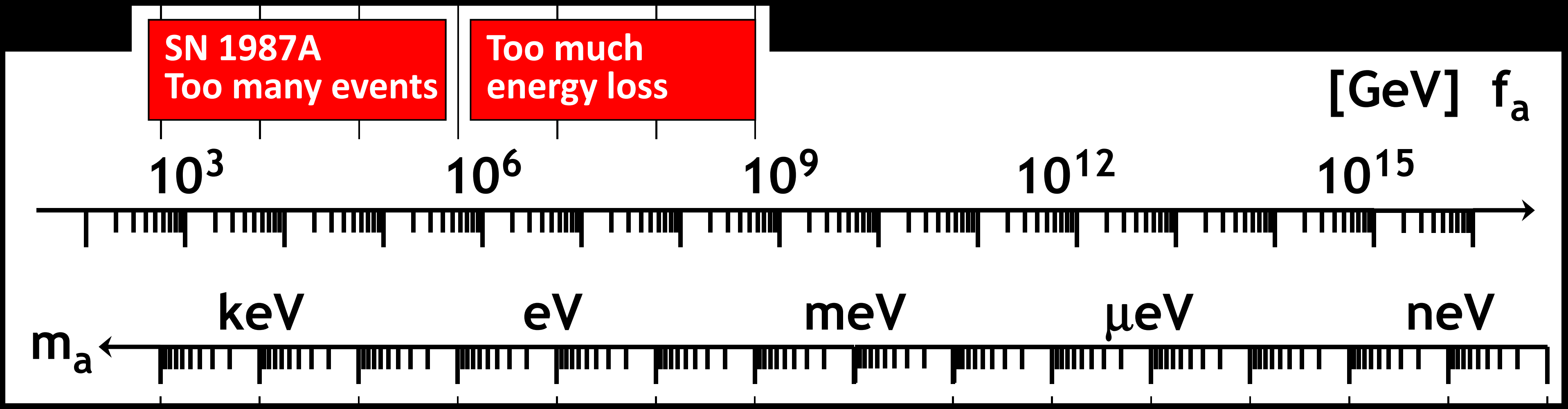




From Raffelt 2012

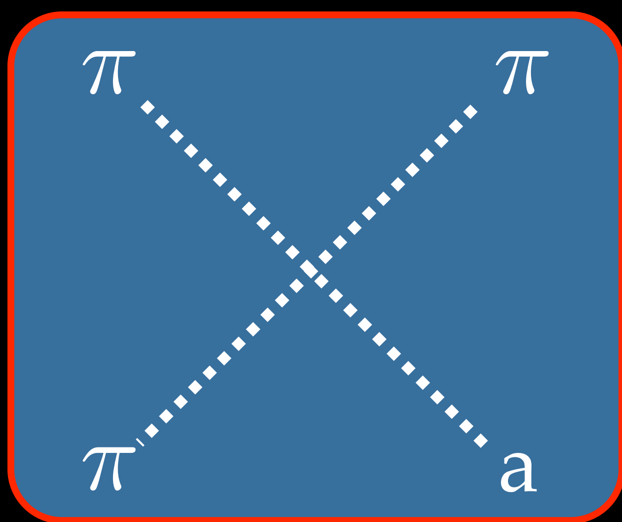
Raffelt, Seckel, and many more

Making axions in (exploding) stars, III

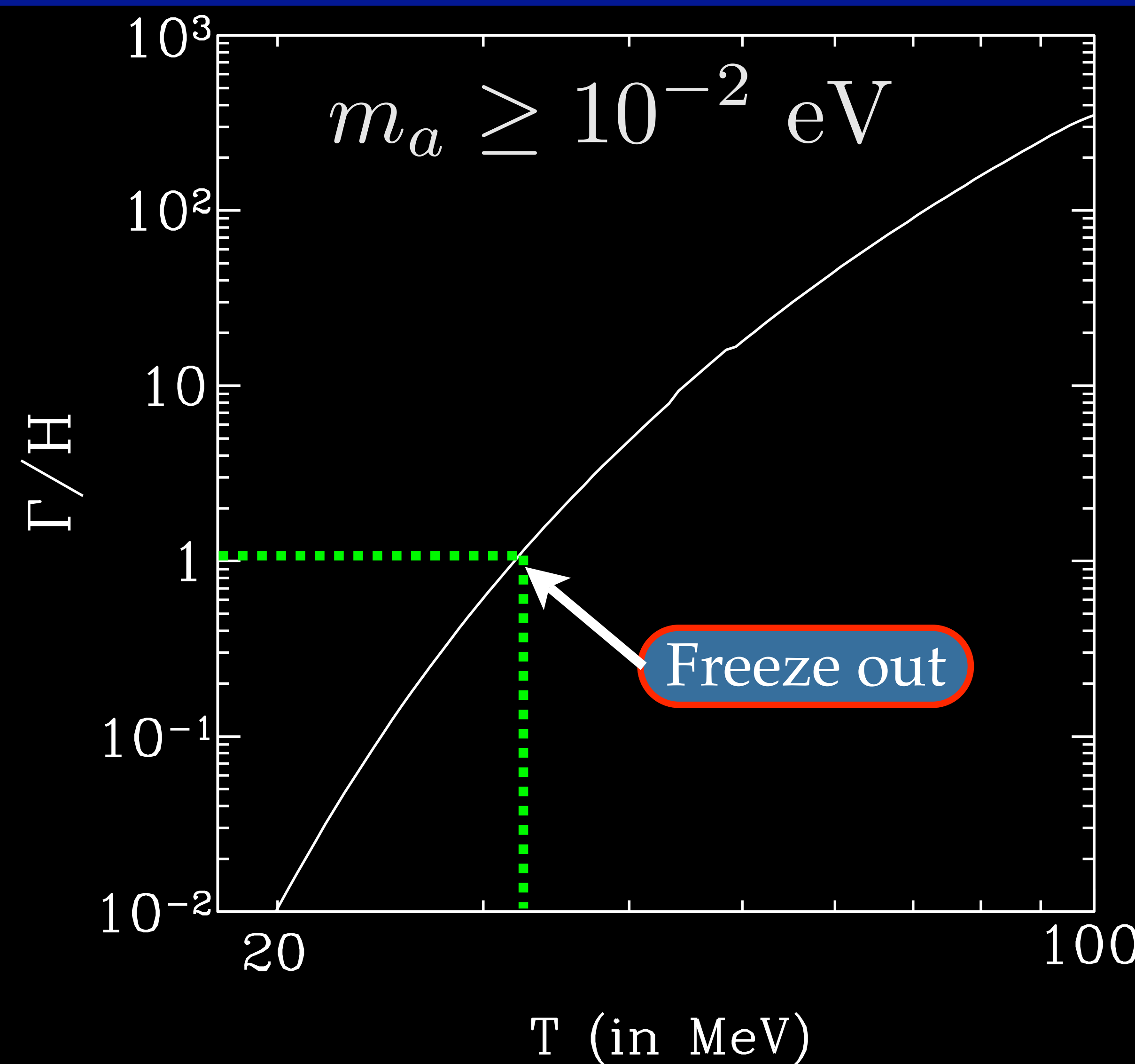


Hot axion production at early times

Axion Production:



$$\Omega_a h^2 = \frac{m_{a,\mathrm{eV}}}{130}\left(\frac{10}{g_{*,\mathrm{F}}}\right)$$



- Axions produced through interactions between non-relativistic pions in chemical equilibrium with rate

Axion hot dark matter

✳ Axion free-streaming length

$$\lambda_{\rm fs} \simeq \frac{196\ \rm Mpc}{m_{\rm a,eV}}$$

✳ Entropy generation, e.g. modulus decay

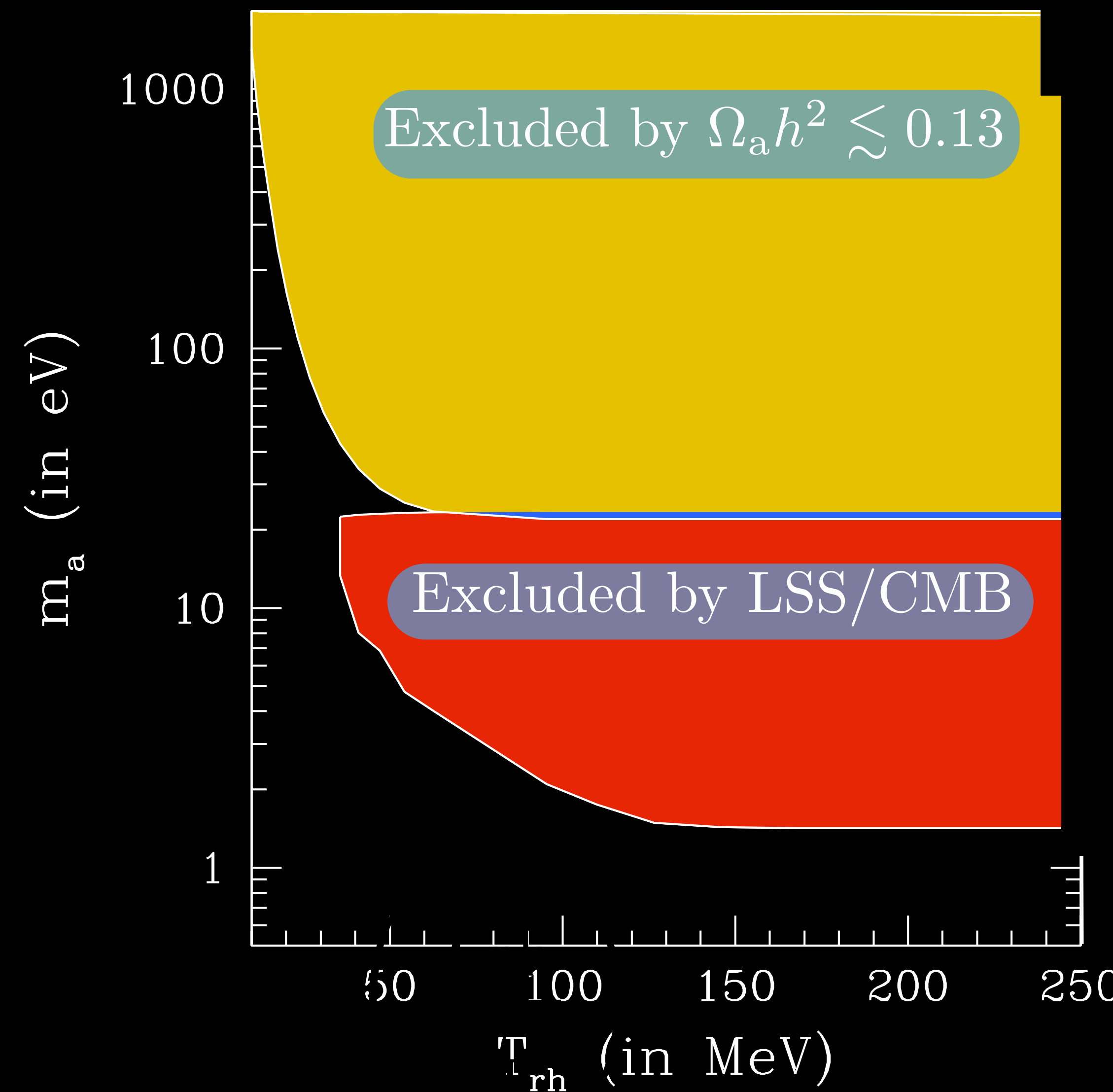
$$T_{\rm rh} \sim 10\ \rm MeV \left(\frac{m_\phi}{\rm TeV}\right)^{3/2}$$

✳ Axion temperature lowered

$$\frac{T_{\rm a}}{T_\nu} \propto \left(\frac{T_{\rm rh}}{T_{\rm F}}\right)^{5/3}$$

✳ Free streaming-length modified

$$\lambda_{\rm fs} \simeq \frac{196\ \rm Mpc}{m_{\rm a,eV}} \left(\frac{T_{\rm a}}{T_\nu}\right)$$

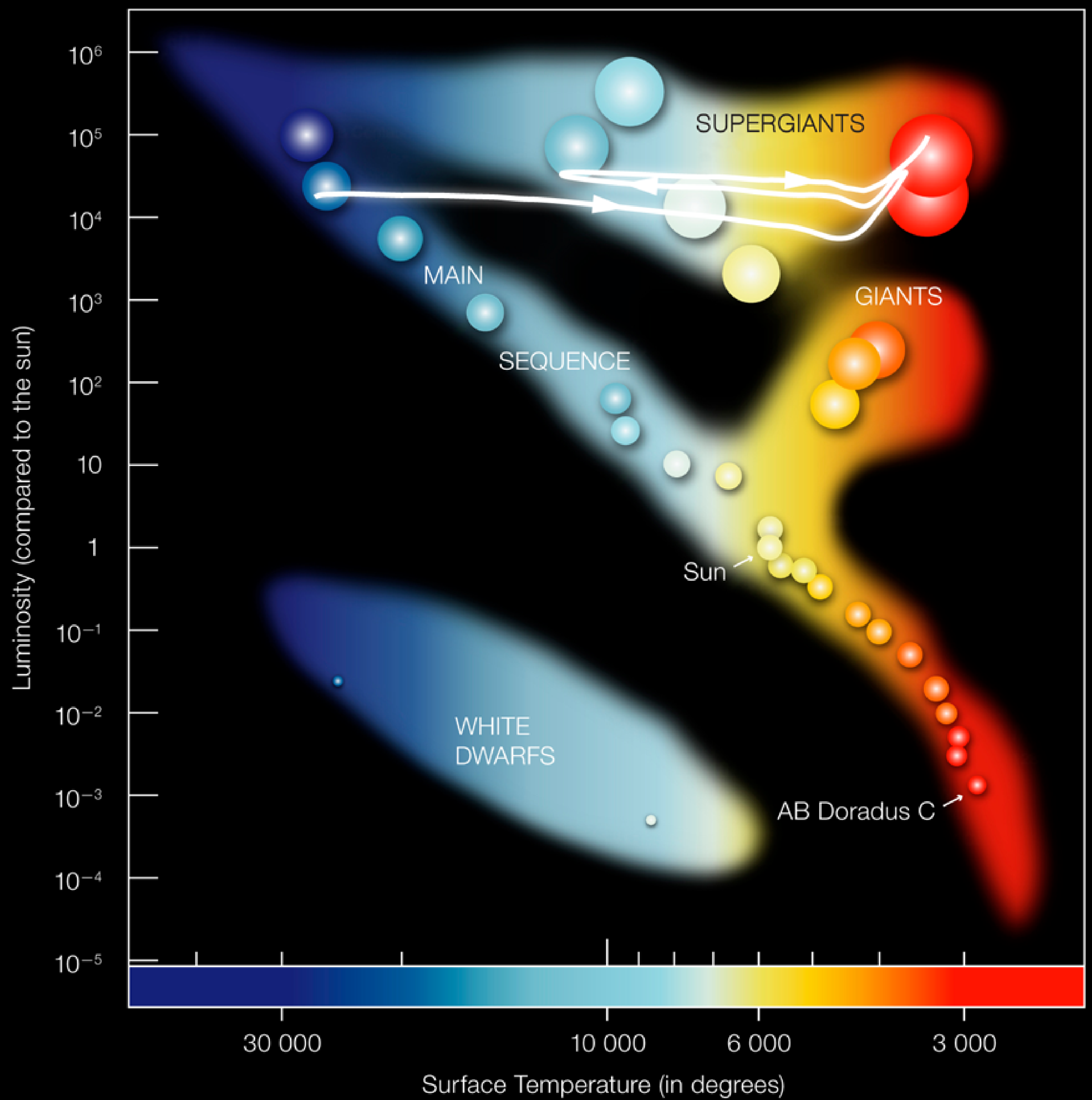


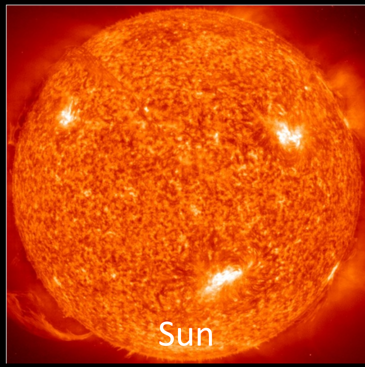
with T.L. Smith and M. Kamionkowski
Phys. Rev. D77 085020, 0711.1342

$$\Omega_a \rightarrow \Omega_a \left(\frac{T_{\rm rh}}{T_{\rm F}}\right)^5$$

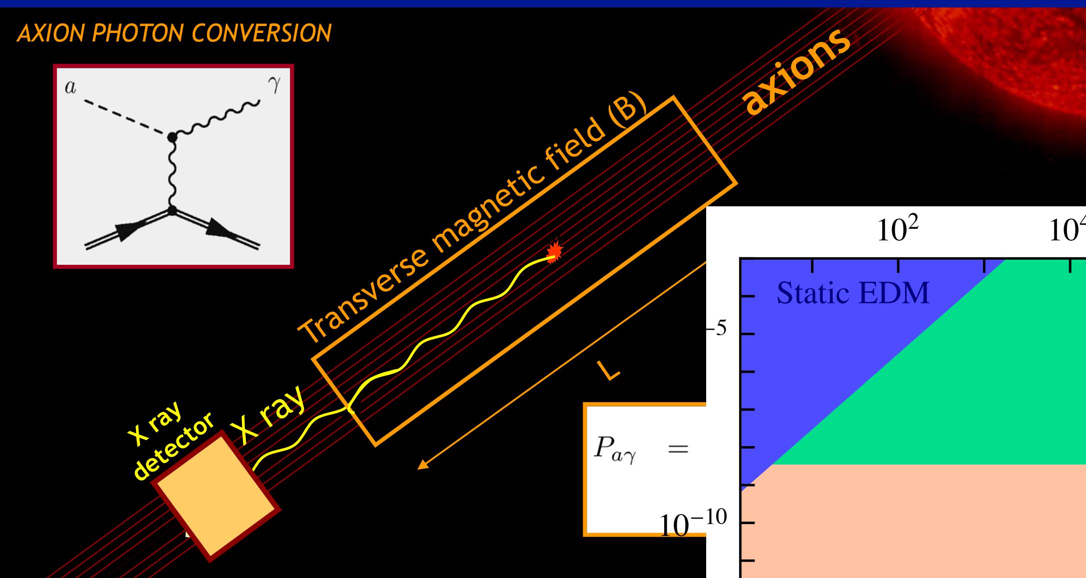
How to look for a QCD axion

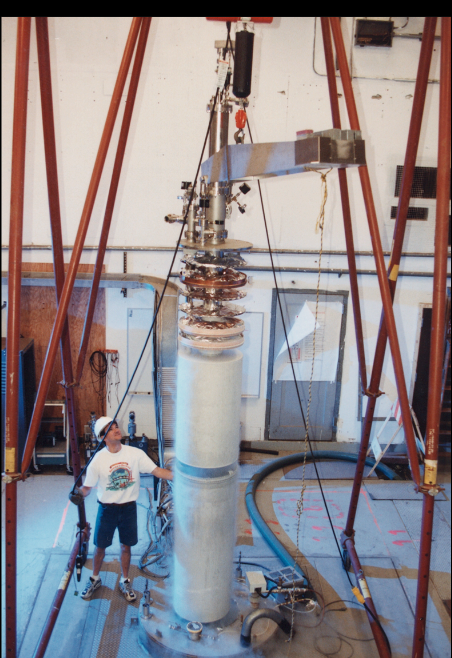
✳Helioscopes (CAST) or stellar evolution

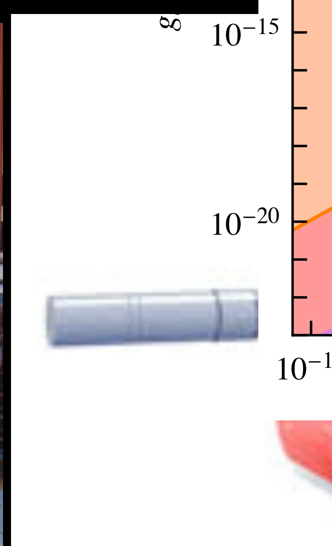




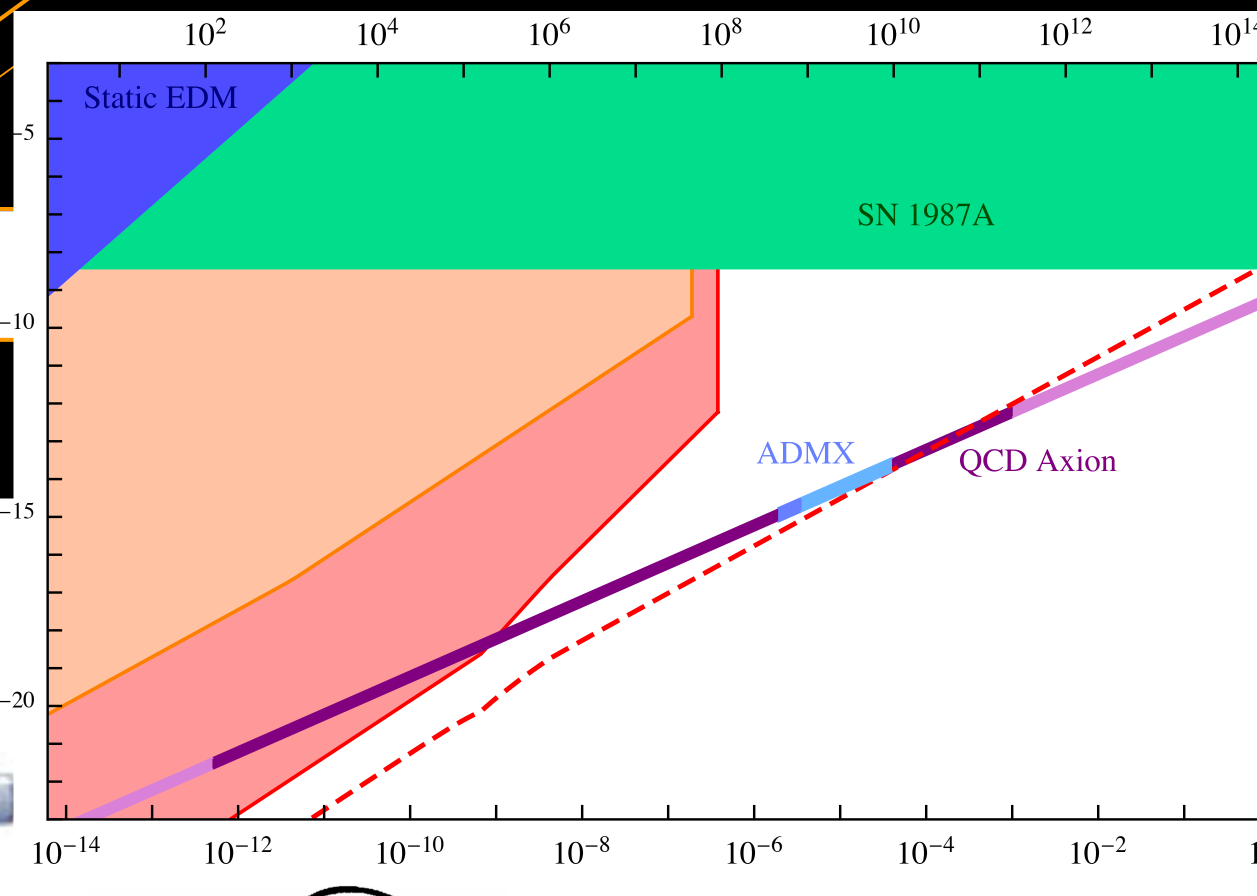
Experimental constraints
Axions and other axion-like particles (ALPS)

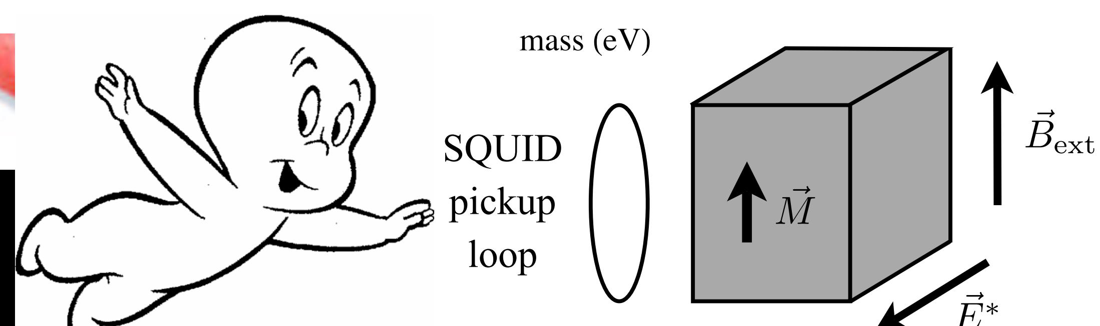


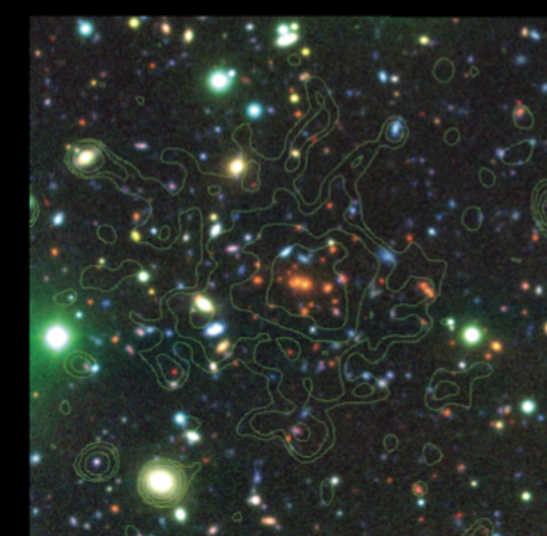




CASPer



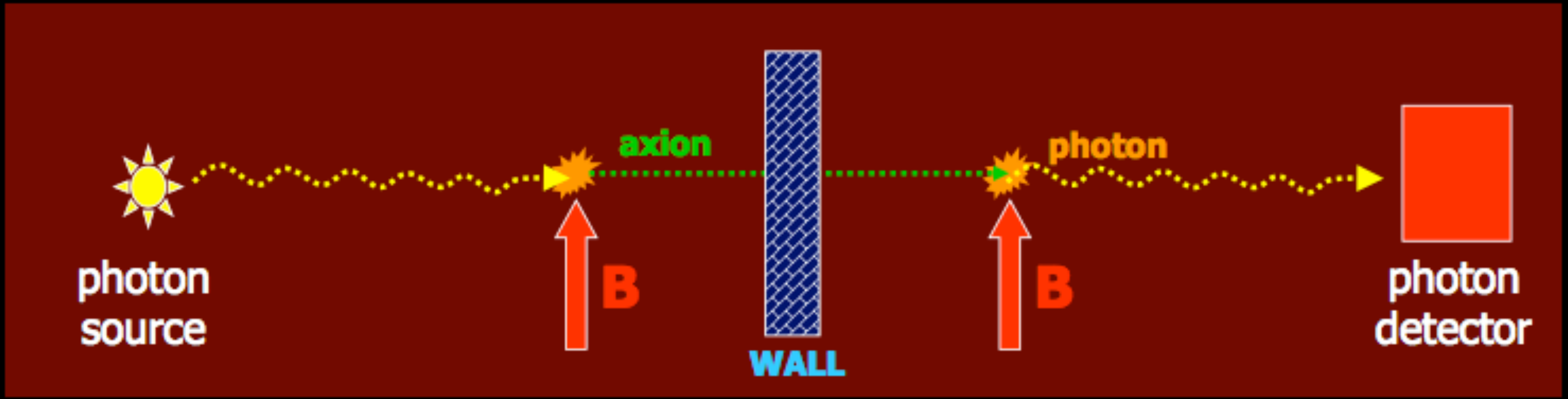




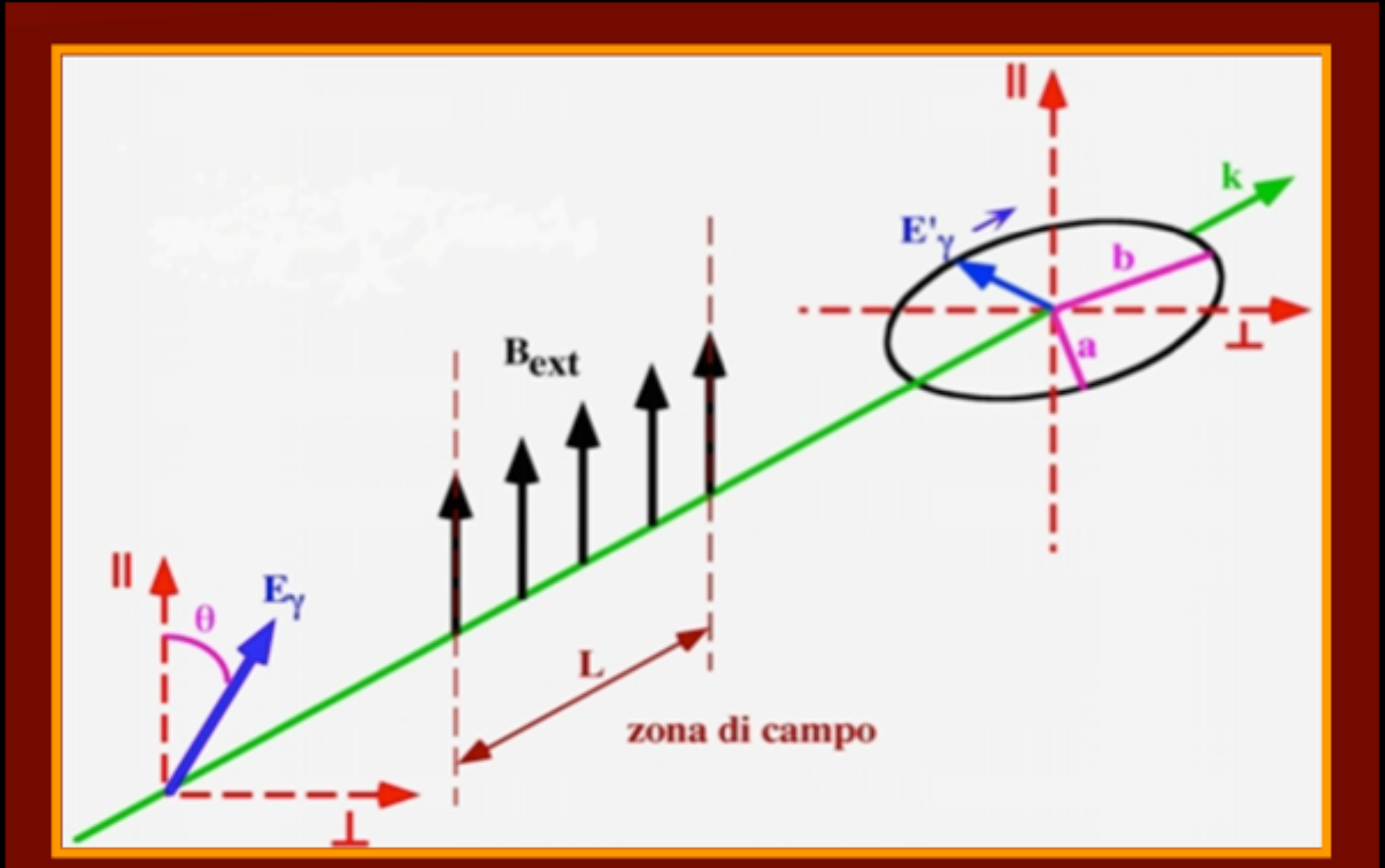
From arXiv: 1205.2671

Laser experiments

Light shining through walls (e.g. GammeV)

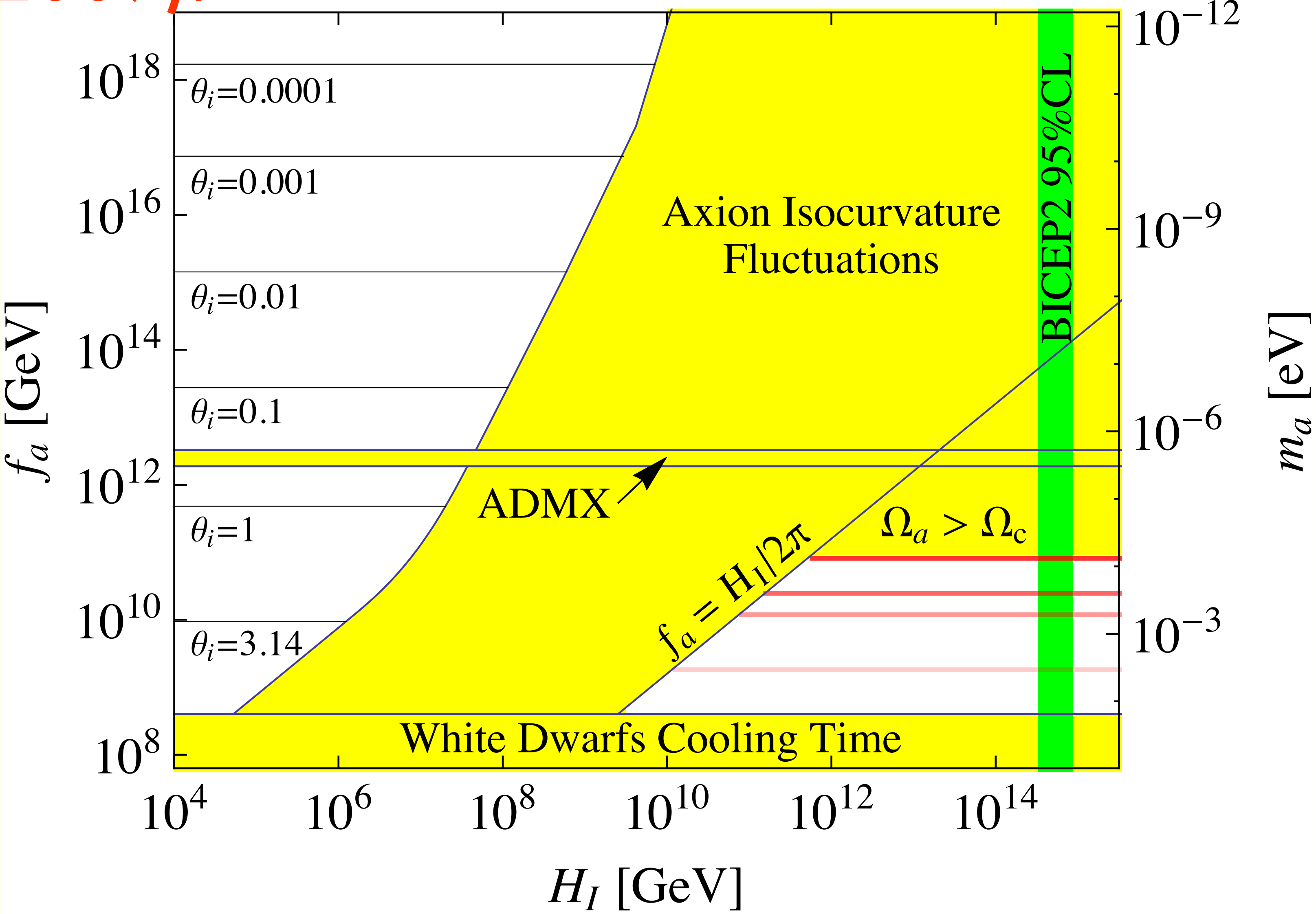


Polarization experiments (e.g. PVLAS)



BICEP2 [inflationary energy scale detected?]

(Gondolo 2009):



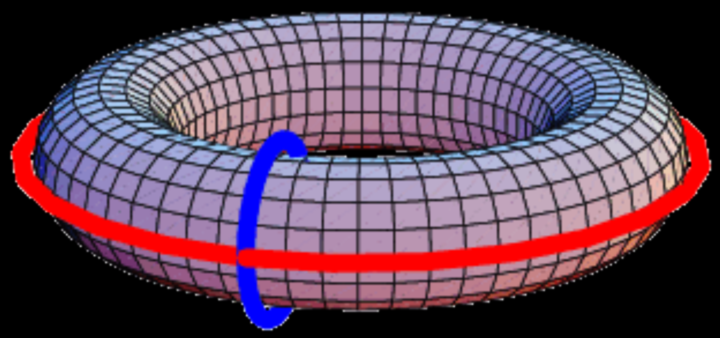
✳ Hard to accomodate QCD axion DM w/o classical window (defects)! [Marsh +yours truly+others 1403.4216 (2014), Gondolo et al. 2014 1403.4594]

$$\frac{\Omega_a}{\Omega_d} \lesssim 5 \times 10^{-12} \left(\frac{f_a}{10^{16}\ \mathrm{GeV}} \right)^{5/6}$$

More on ULA motivations

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



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

ULAs: gravitational constraints

Independent of axion SM couplings: uncertainties astrophysical!

DUST!

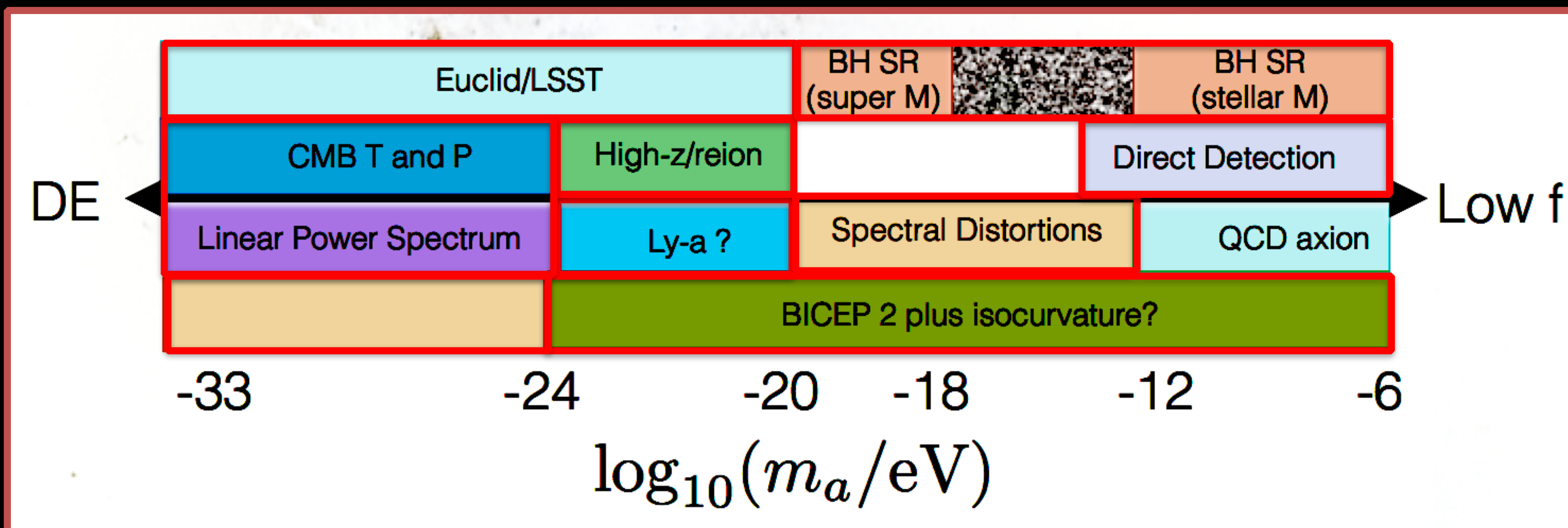
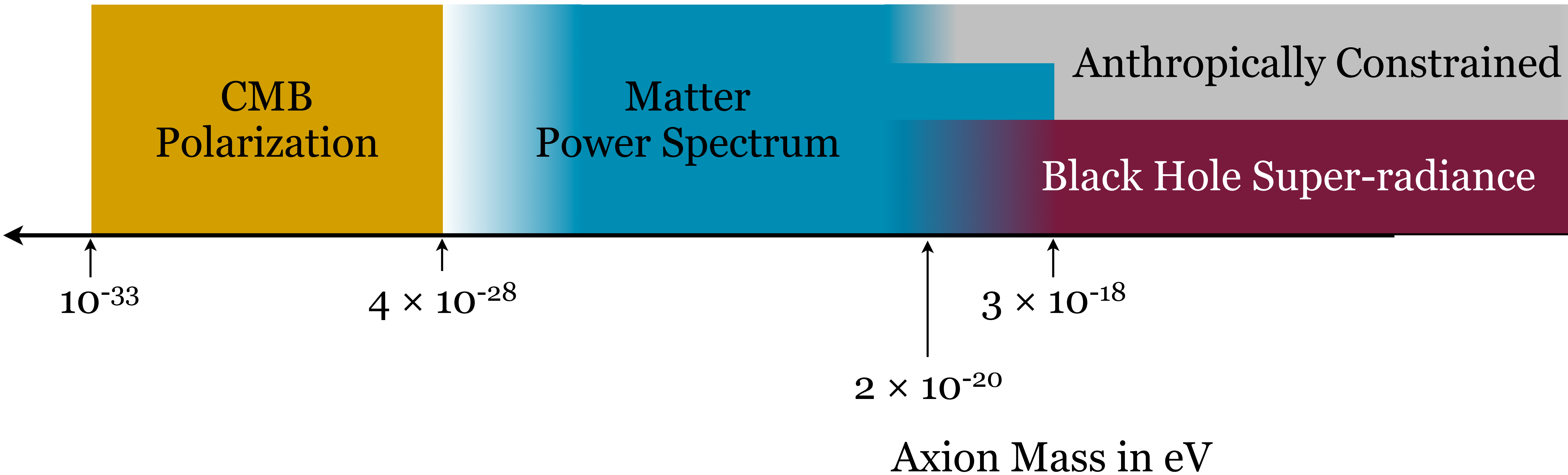


figure adapted from DJEM 2014

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

→ 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"

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

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

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

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

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

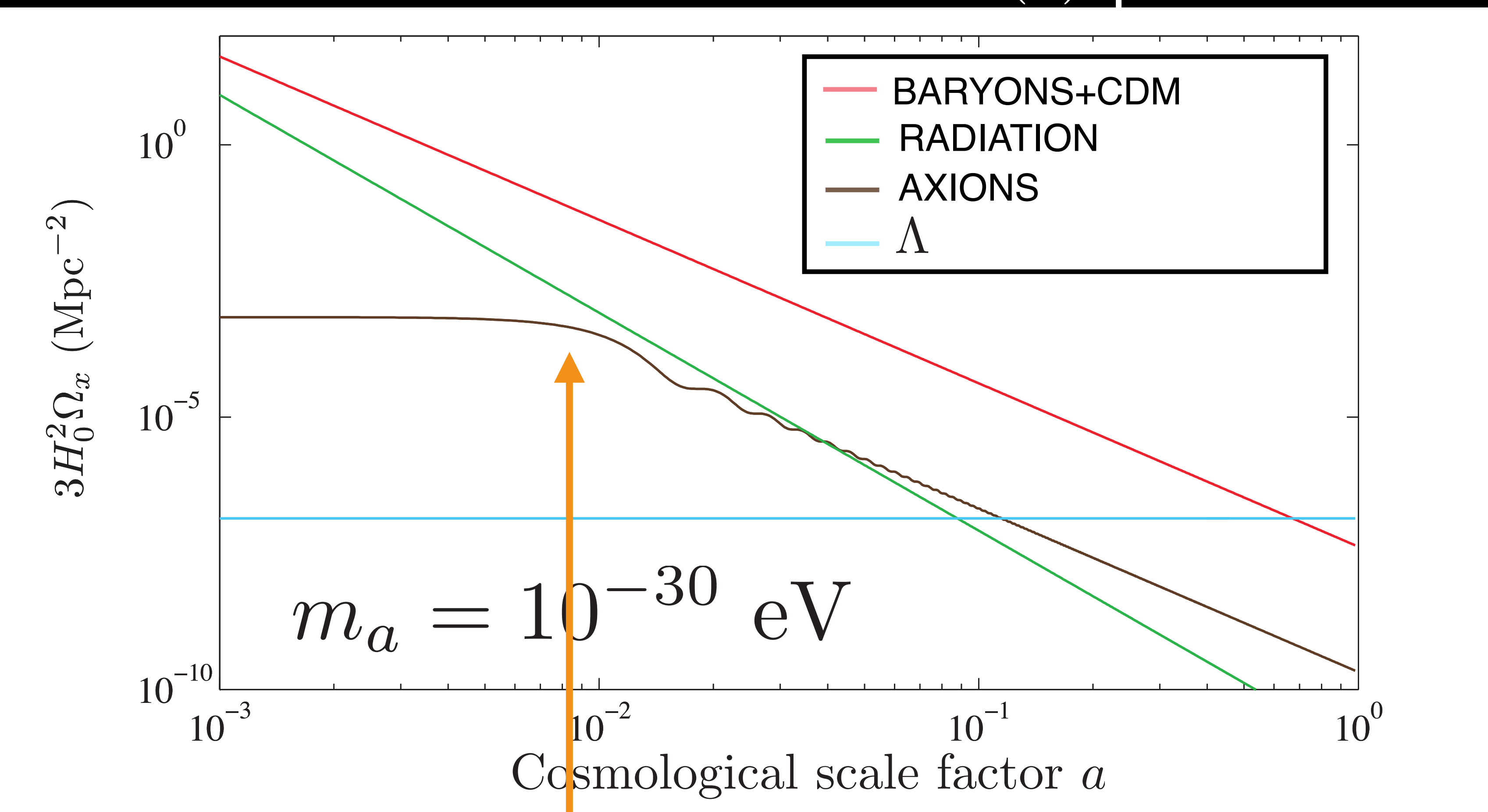
Cosmological axion evolution

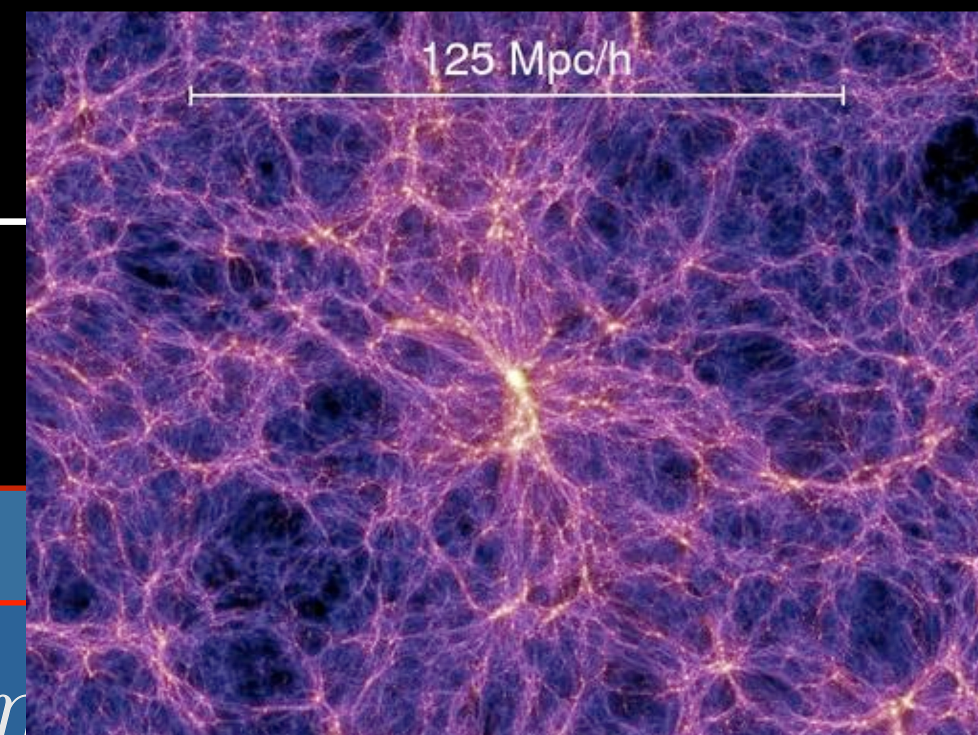
Different parameter space for non-QCD axion(Frieman et al 1995, Coble et al 2007)

Misalignment production $V(\theta)$ Coherent oscillations like CDM

Axion-driven acceleration

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





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

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

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

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

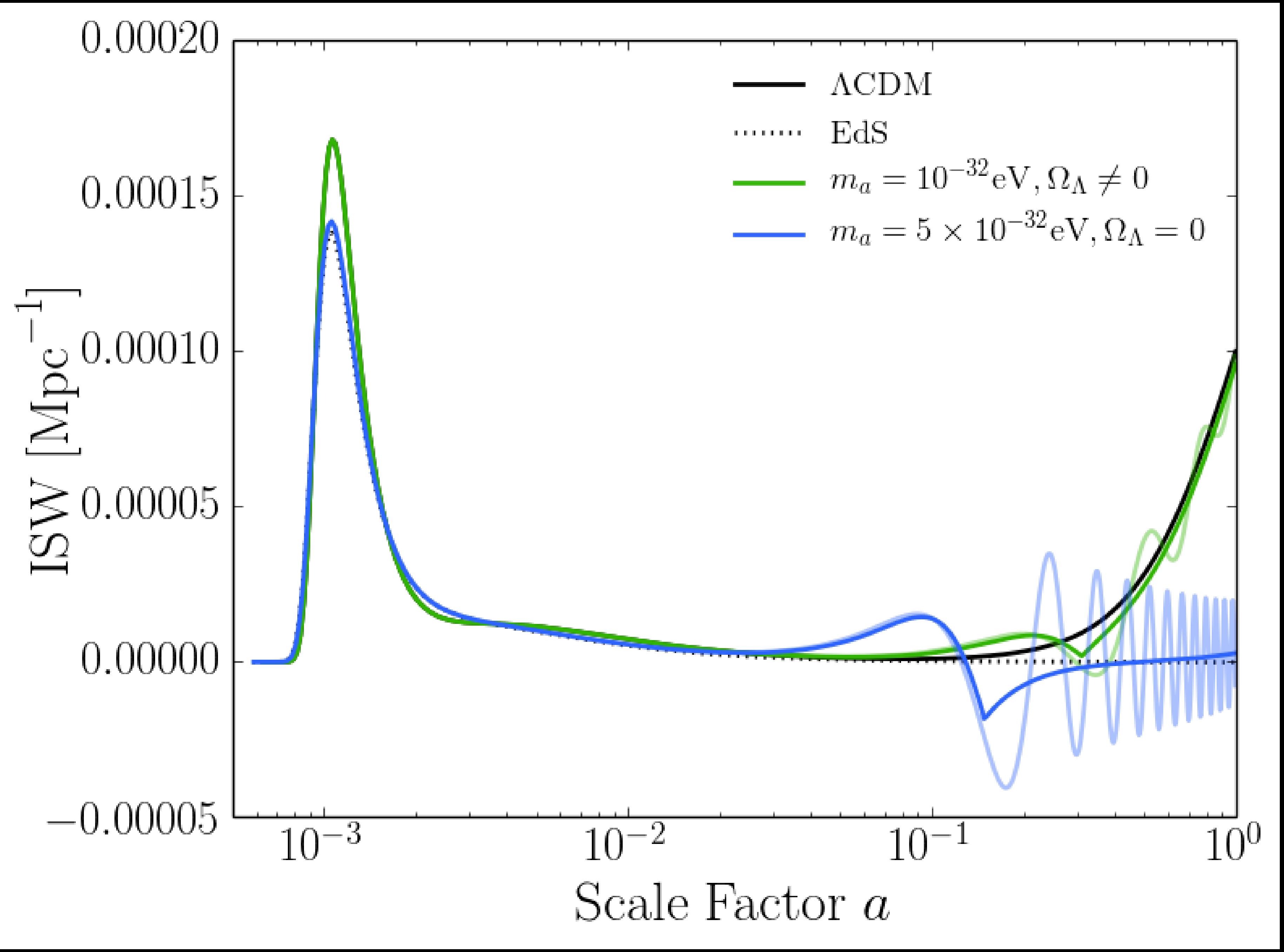
$n_a \propto a^{-3}$, $\langle w_a \rangle_{T=2\pi/m_a} = 0$

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

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

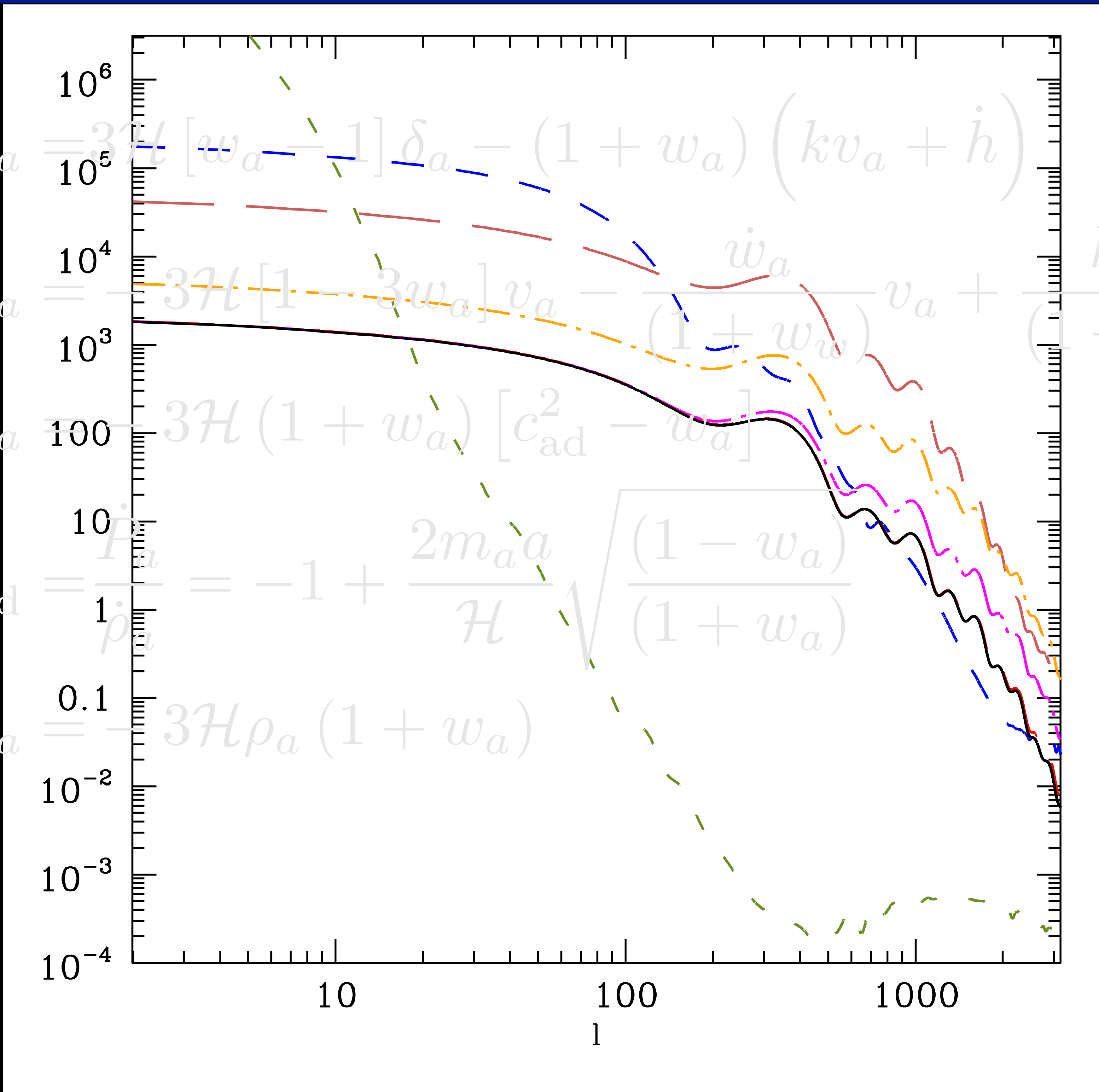
Additional slides:
ULA search details

ISW TEST



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

Getting under the hood: The need for numerical care



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

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

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

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

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

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

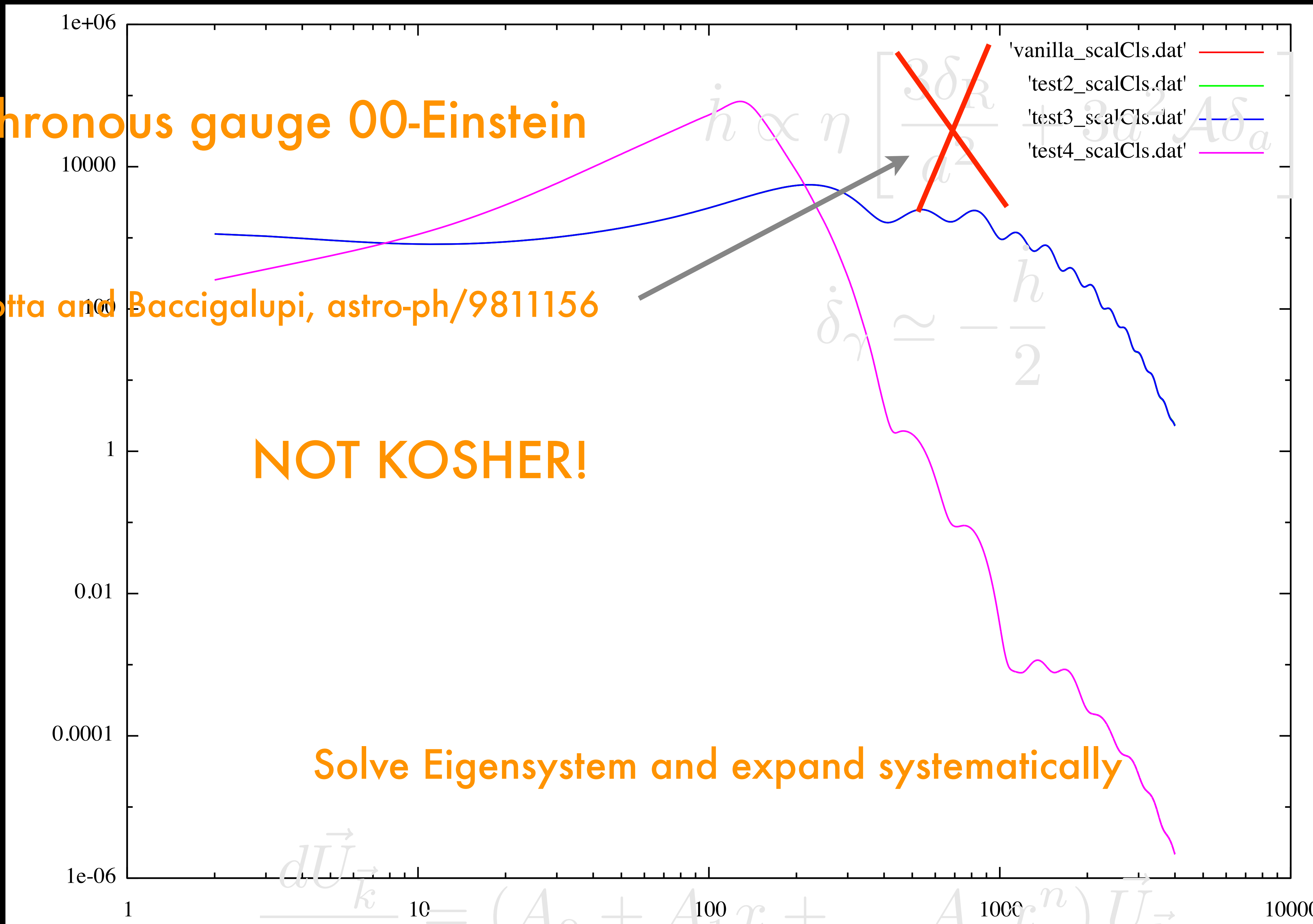
Synchronous gauge 00-Einstein

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

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

Perrotta and Baccigalupi, astro-ph/9811156

NOT KOSHER!

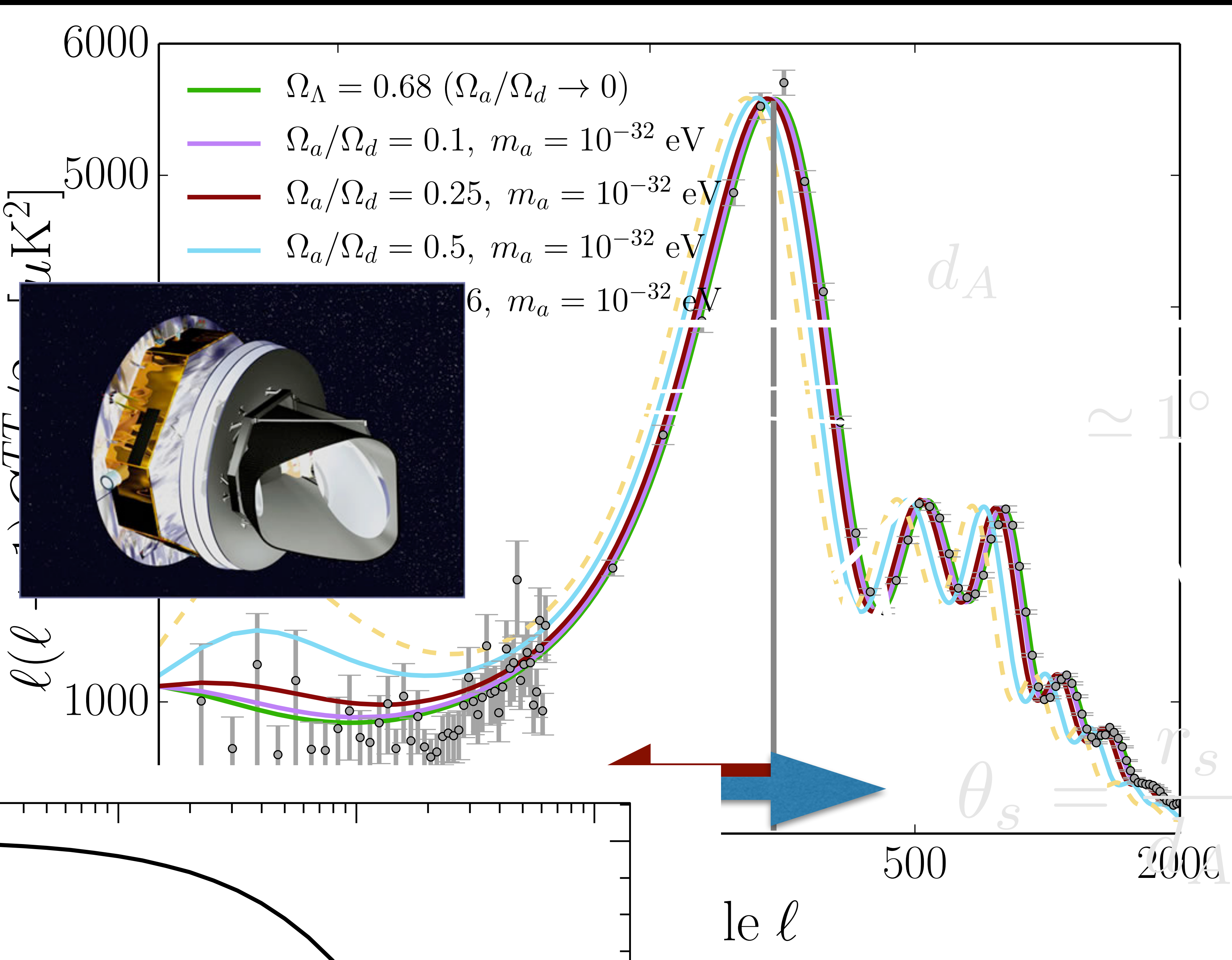


Solve Eigensystem and expand systematically

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

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



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

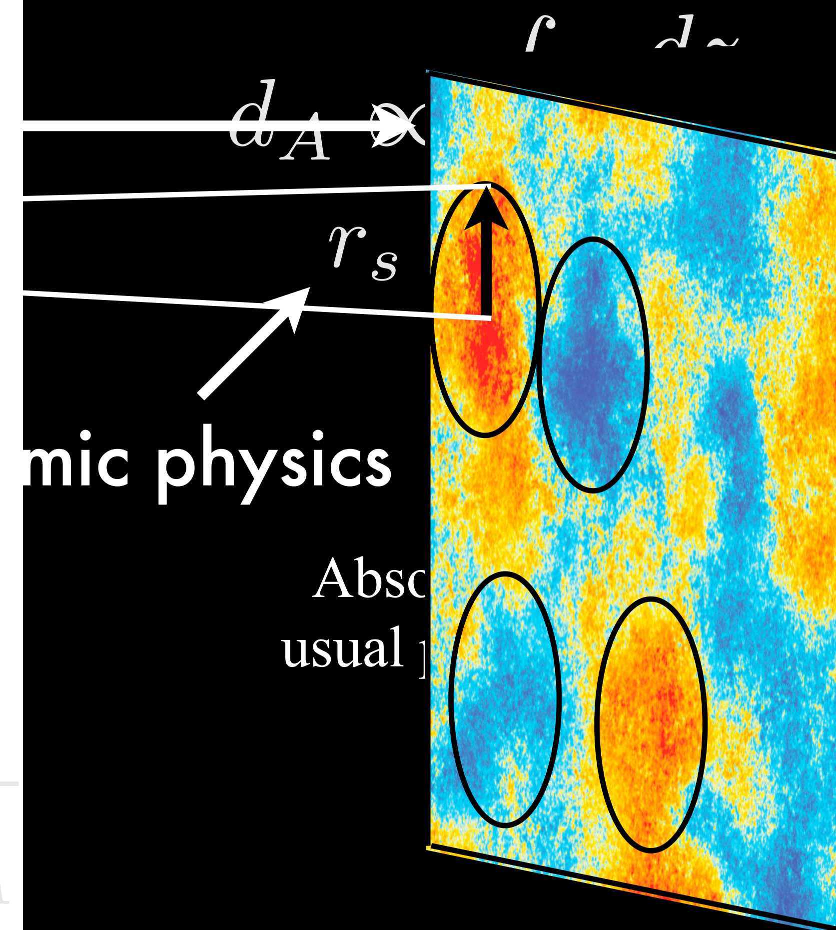
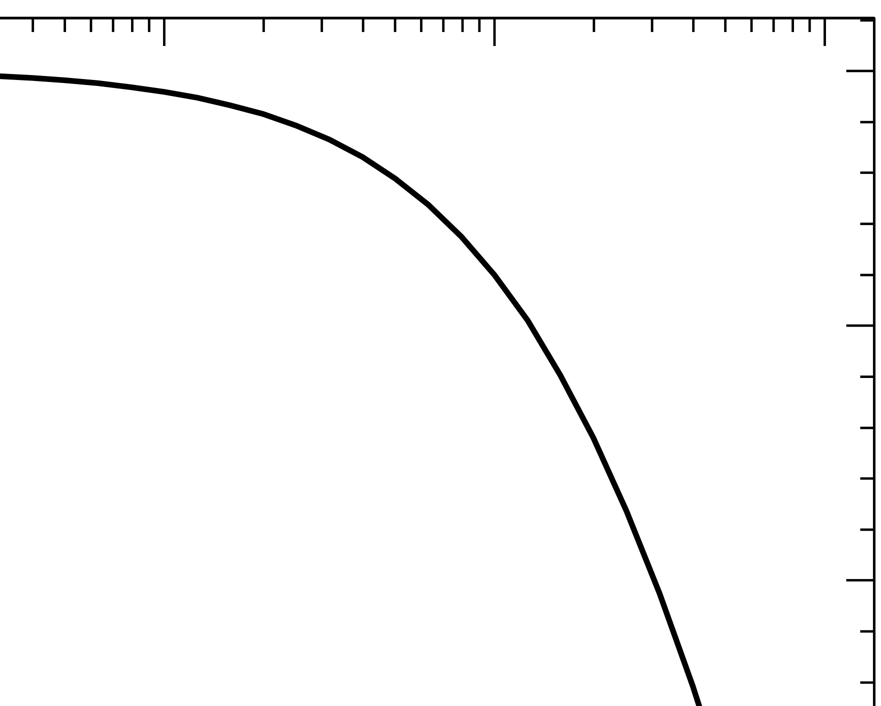


Diagram by T. Smith (used with permission)



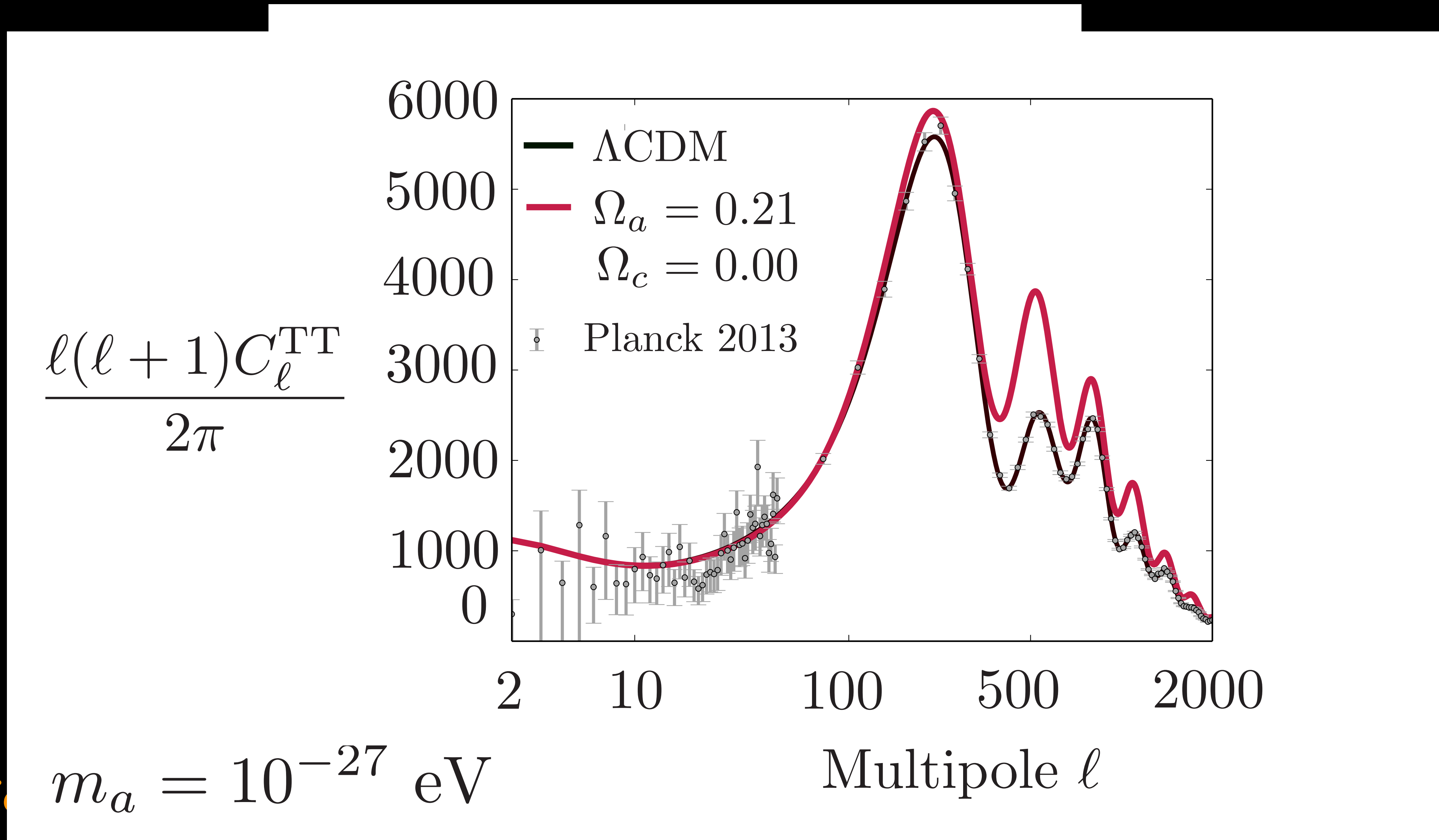
axion

$+w(\eta)]d\eta \Big\}^{1/2}$

Faster early expansion brings LSS closer

ULAs and the CMB: high mass and early ISW

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



Radi

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

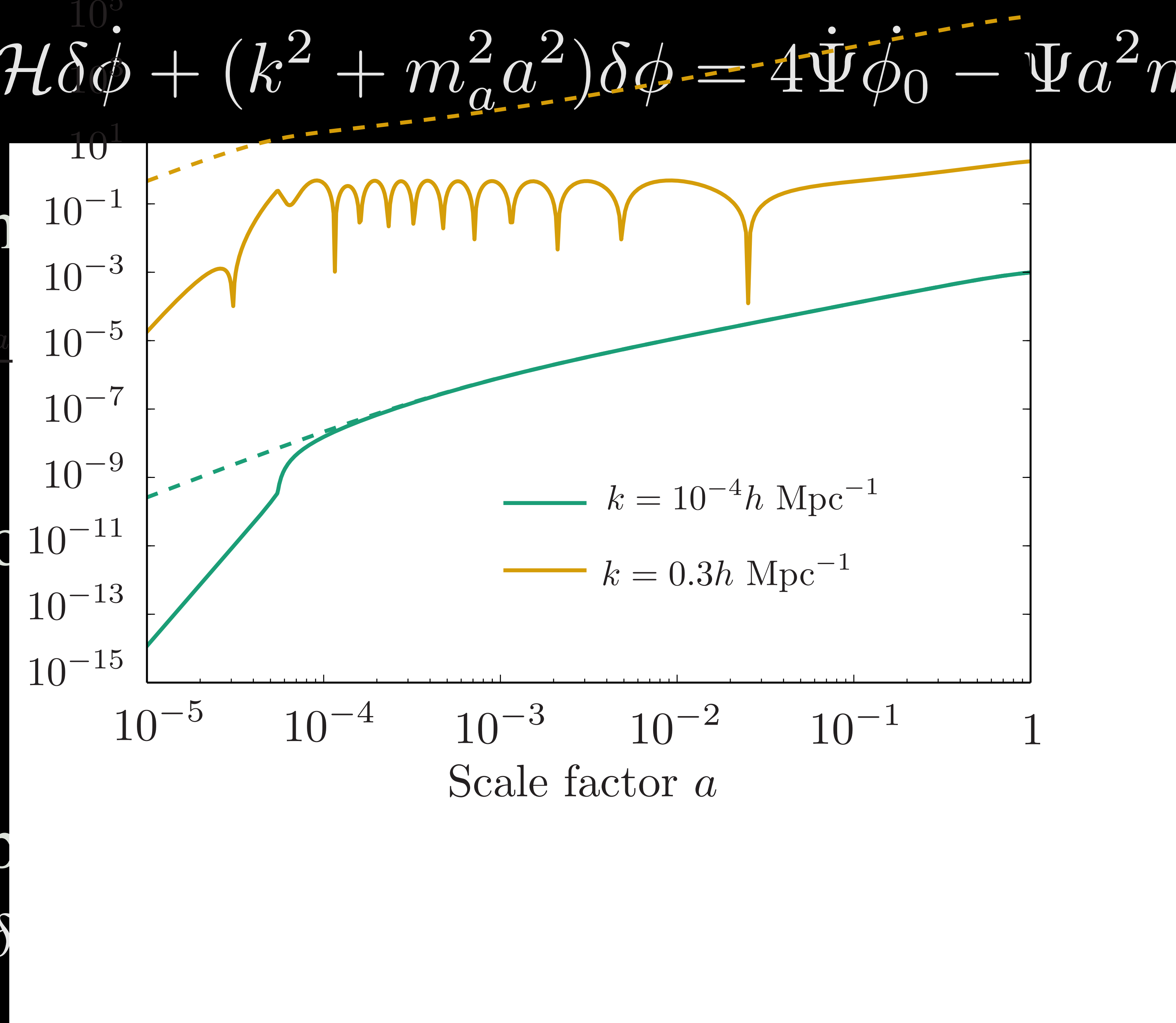
$$\Delta P \Delta A > \rho \delta V \nabla \Phi$$

GROWTH OF ULA PERTURBATIONS

- ✳ Perturbed Klein-Gordon + Gravity

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

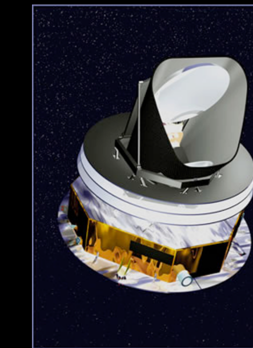
- ✳ Axionic Jean… …CD axion]:

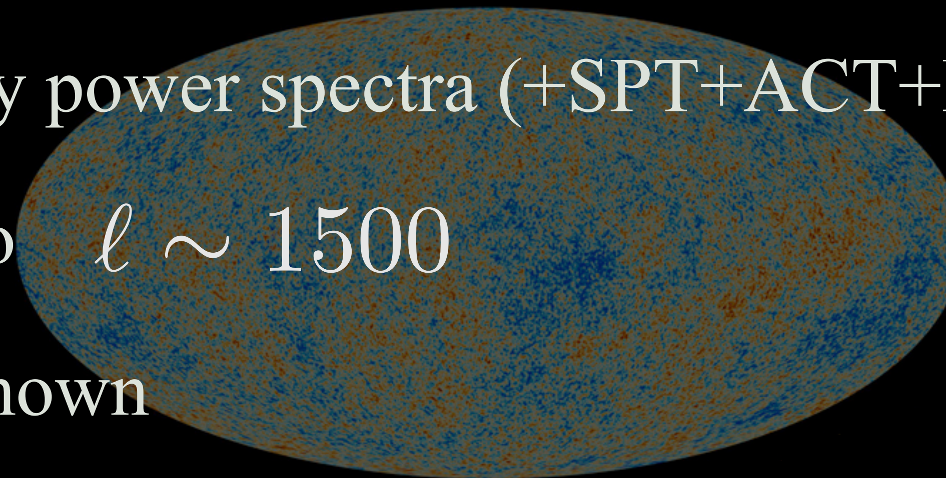


- ✳ Computing c…
  - ✳ Coherent … $\Delta\eta_{\rm CAMB}$
  - ✳ WKB app…
  - ✳ Modes with k …
  - ✳ "Pressure" stabilization

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

DATA

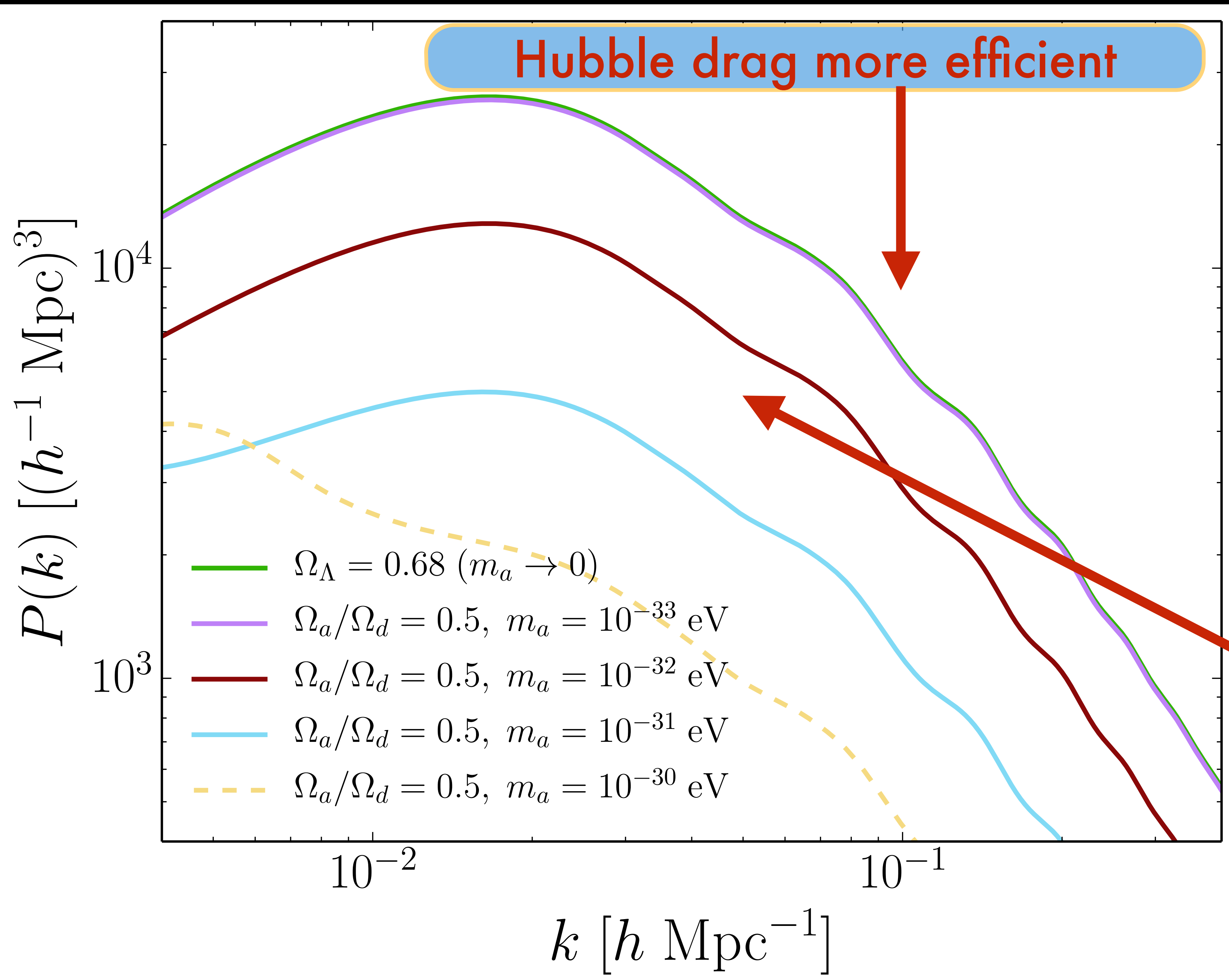




- Planck 2013 temperature anisotropy power spectra (+SPT+ACT+BAO)
  - Cosmic variance limited to $\ell \sim 1500$
  - Power spectrum already shown

- 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 ↓

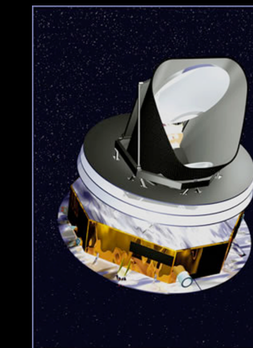
$k_{eq} = \lambda^{-1}_{\mathrm{horizon,eq}}$ ↓

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)

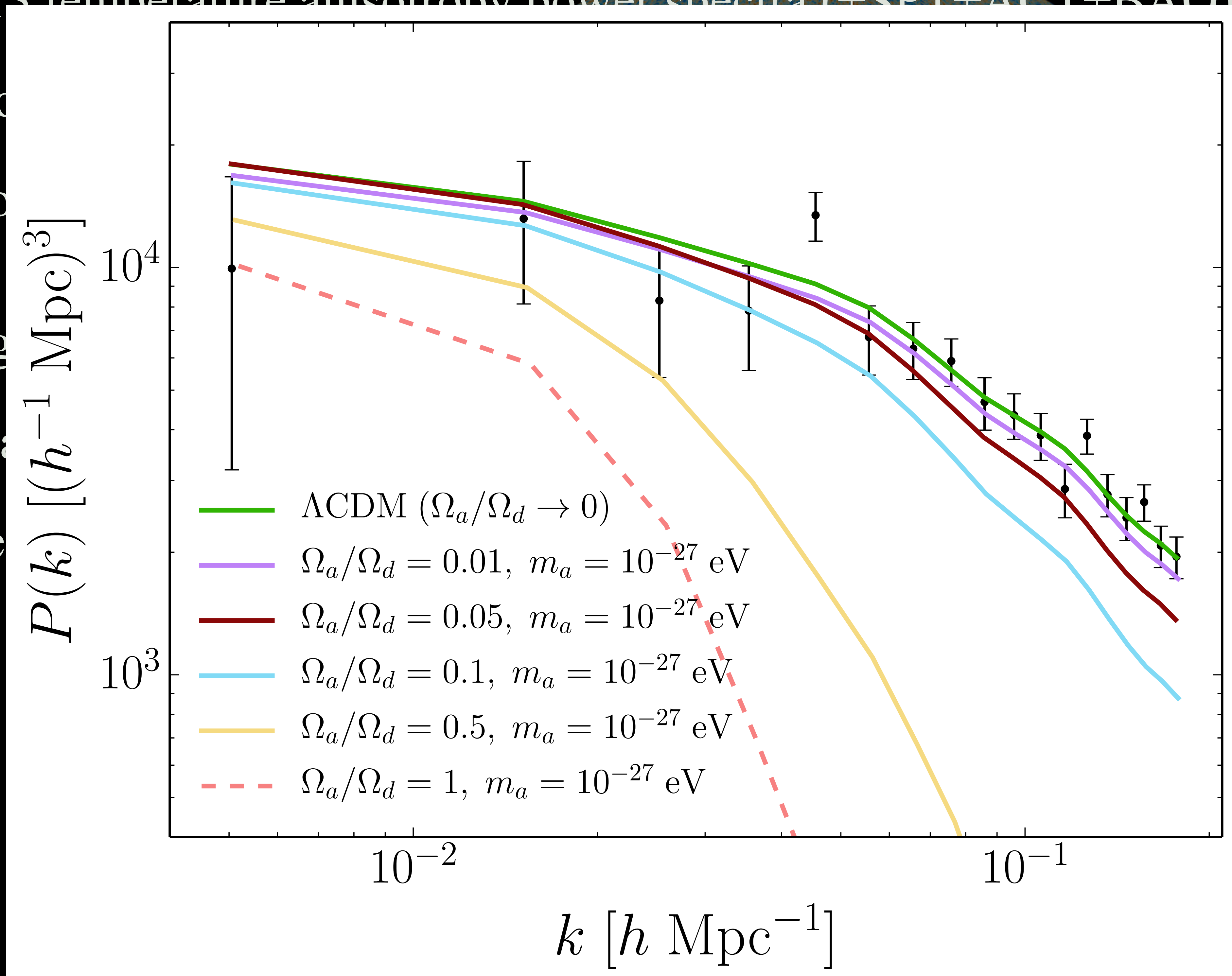
✳Co

✳Po

✳WiggleZ g

✳Gal

✳The

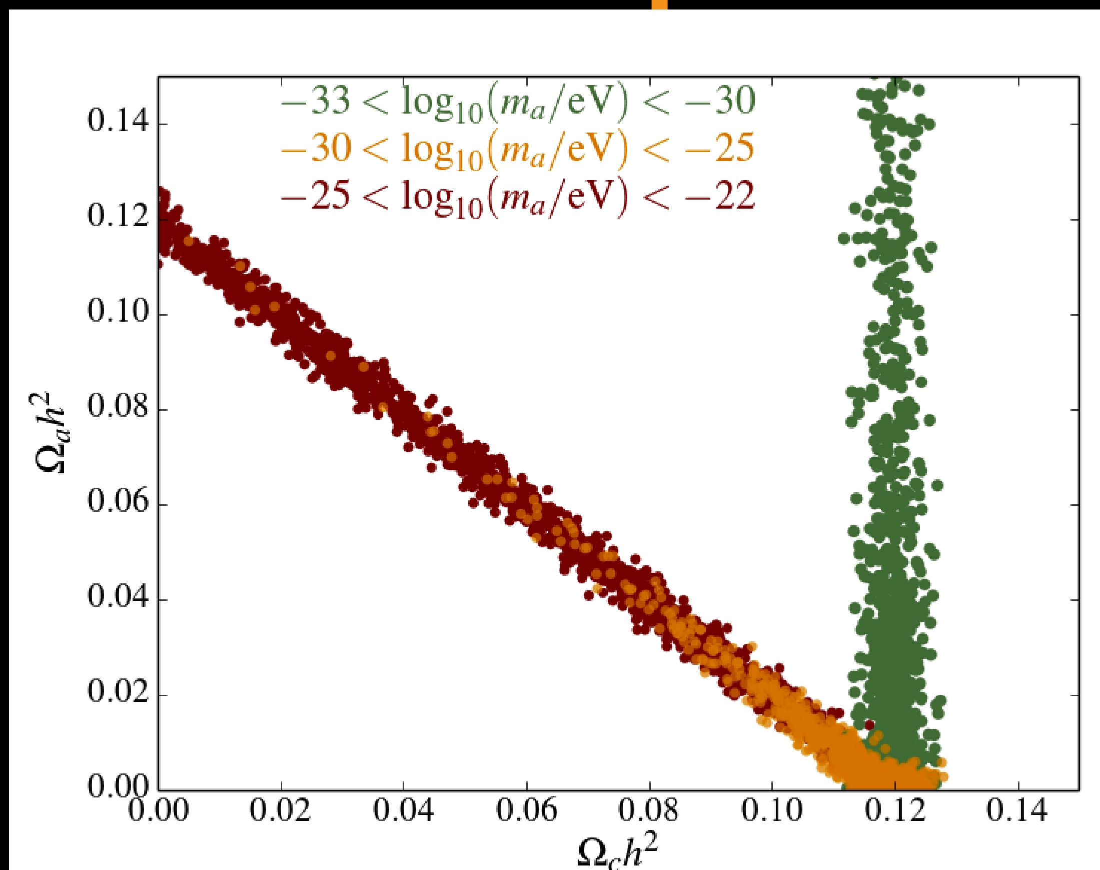


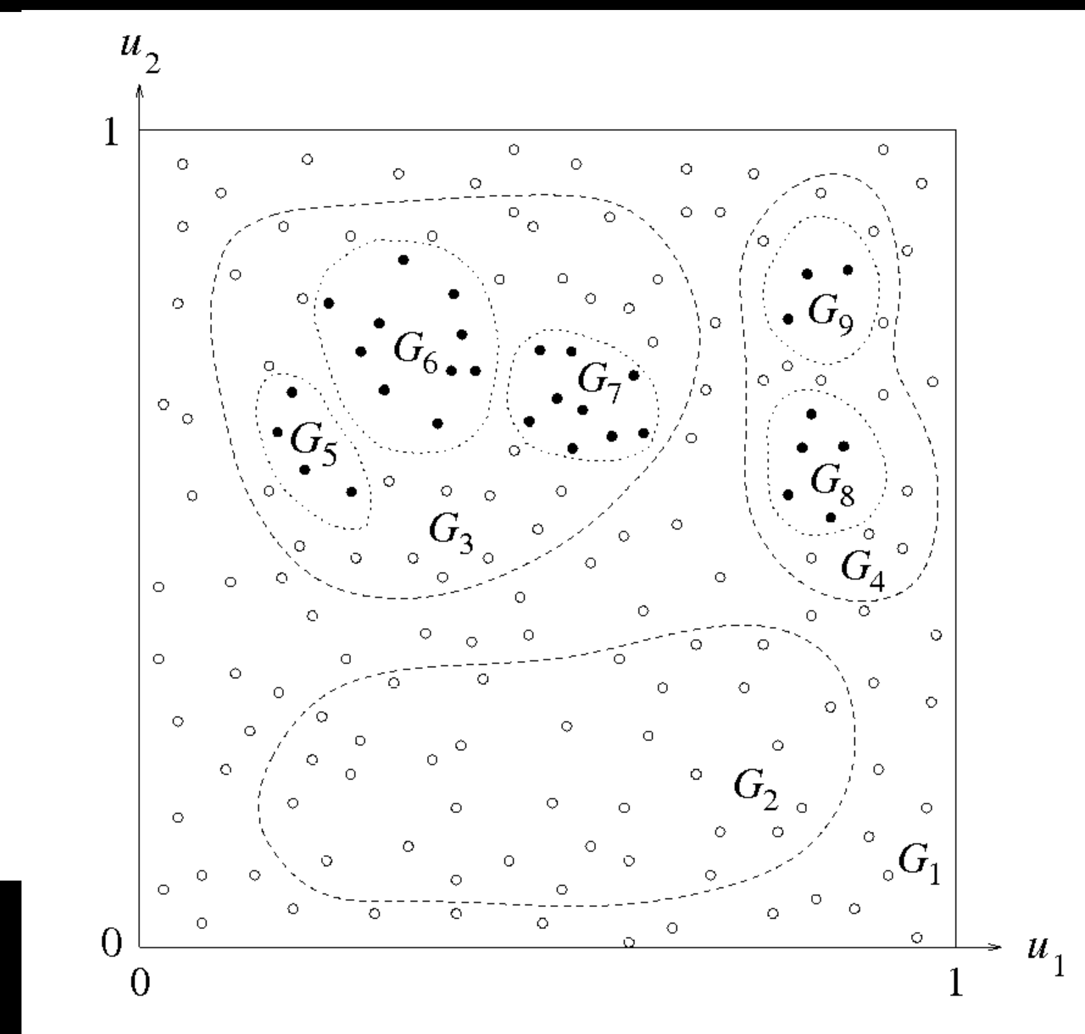
<1

(AAT)

Difficult parameter space

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





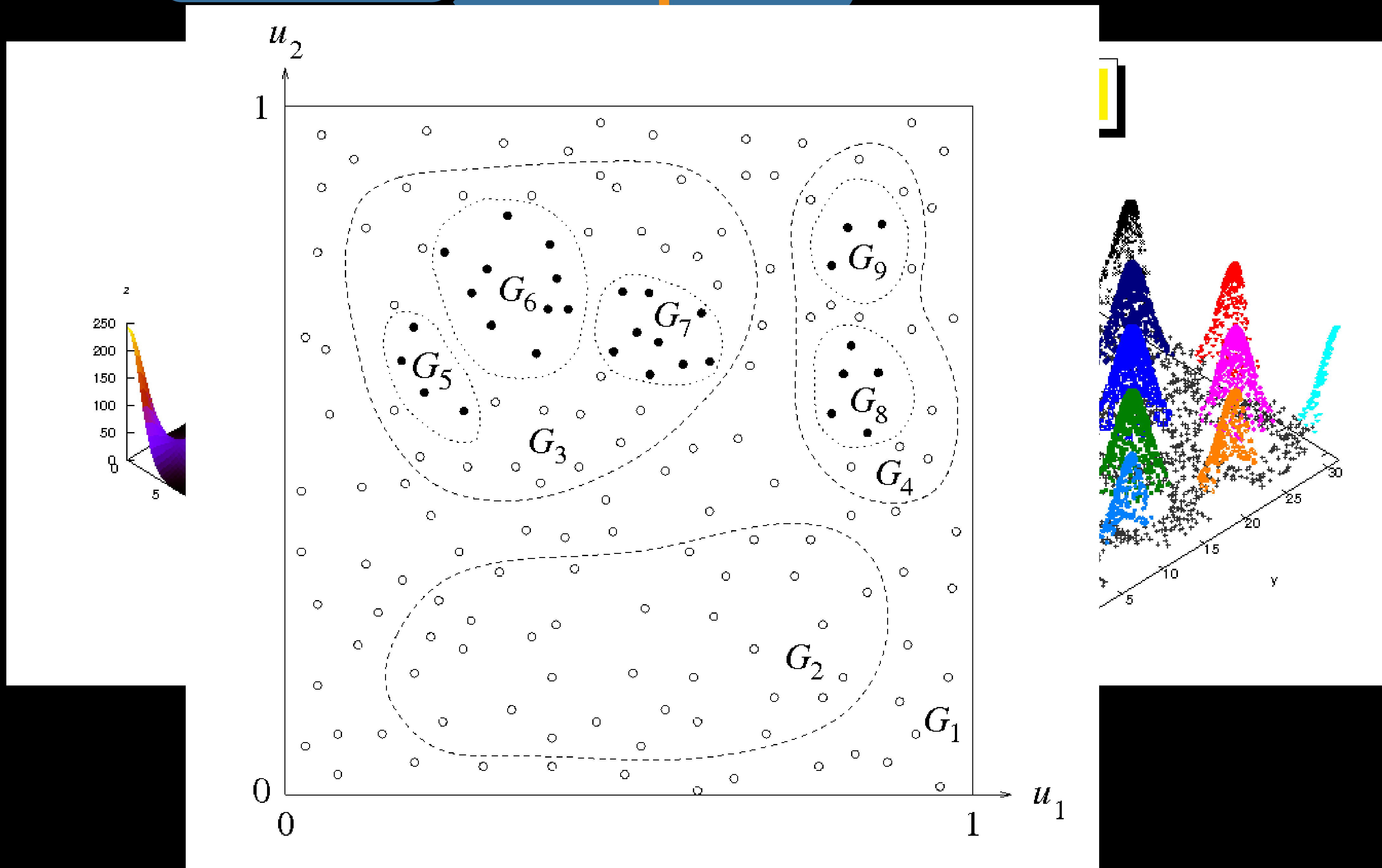
rlo

Addressed using nested sampling

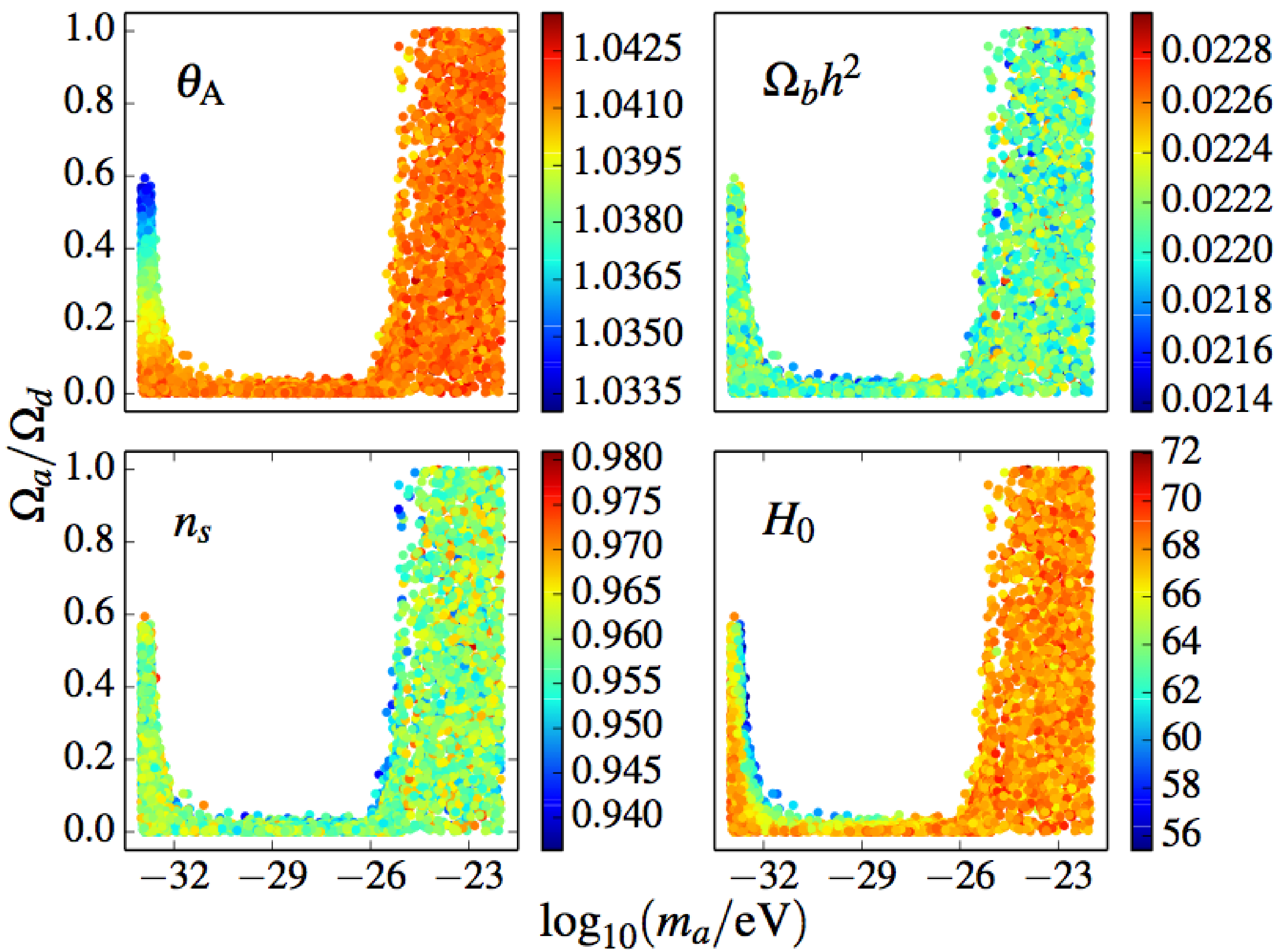
MULTINEST (Hobson, Feroz, others 2008)

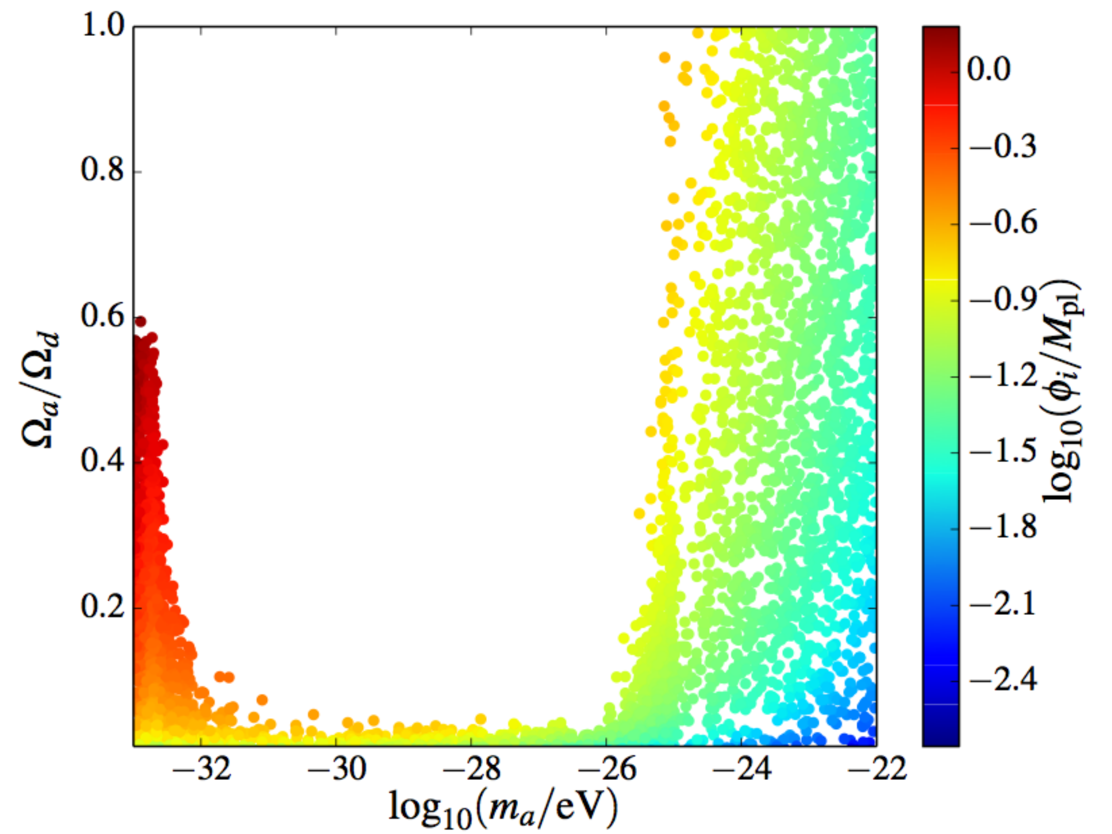
Difficult parameter space

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

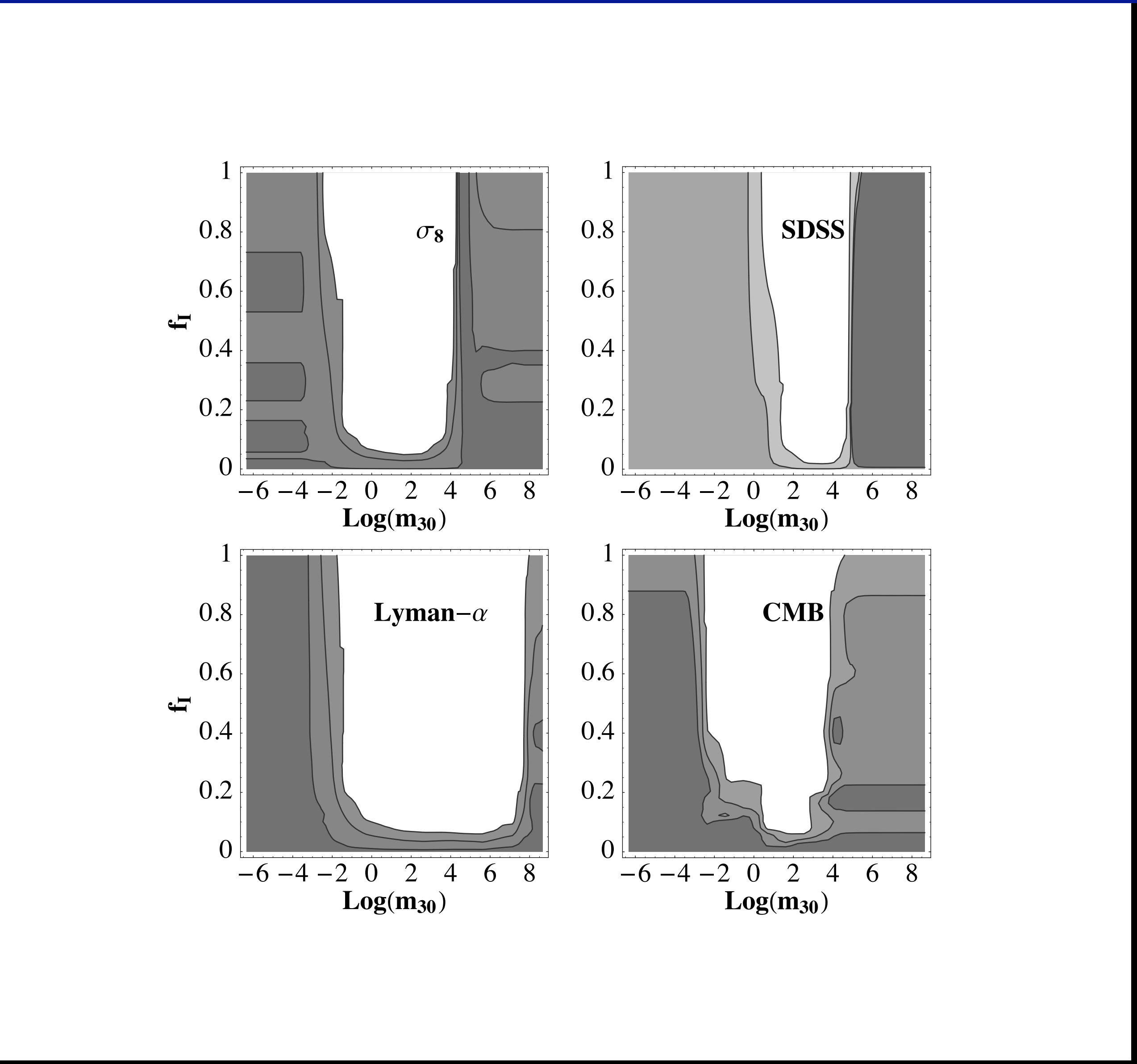


Degeneracies/Weak gravity conjecture





Amendola and Barbieri



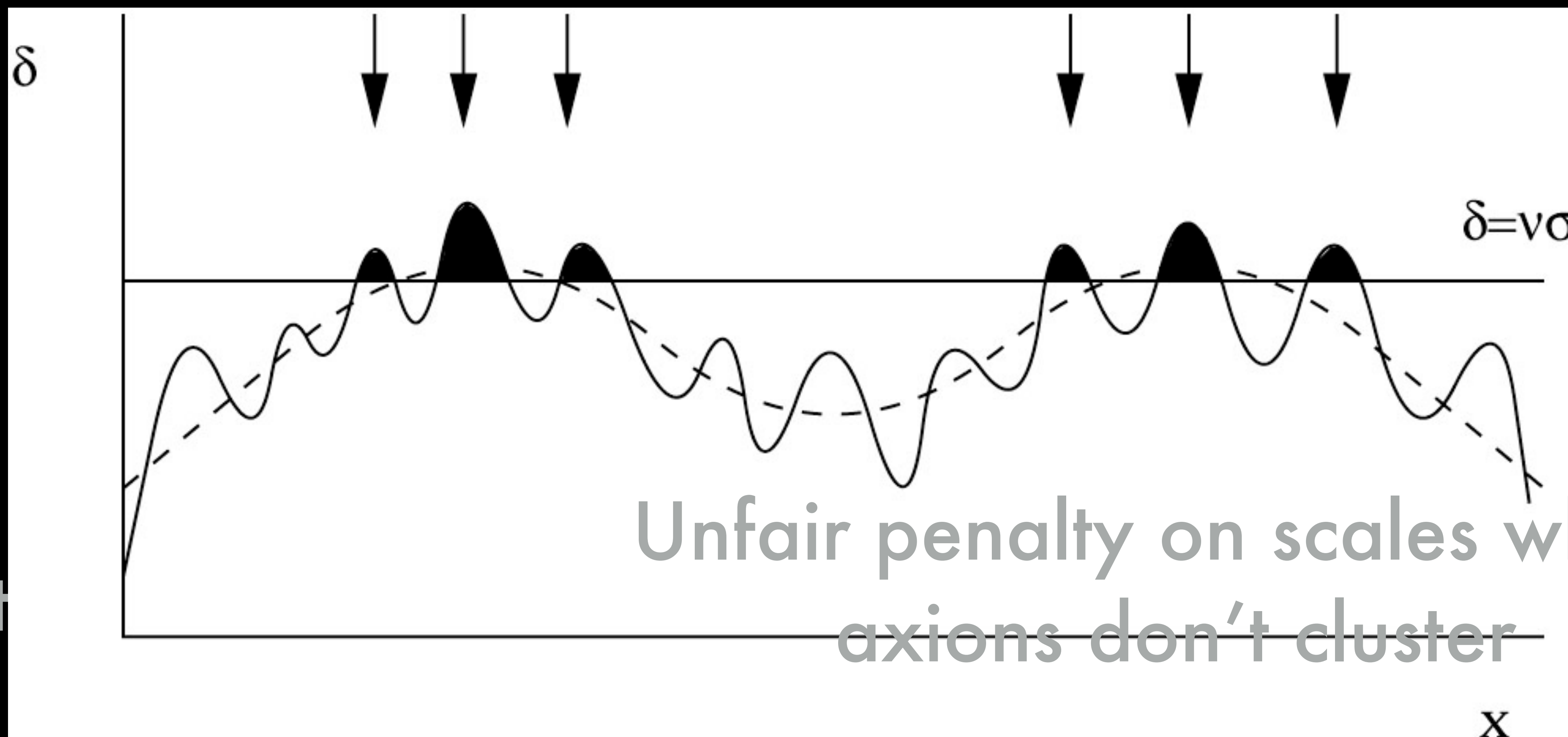
Old power spectrum constraints from Amendola and Barbieri, arXiv:hep-ph/0509257

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]

Additional slides:
ULAs and galaxies

FUTURE WORK: ULAS AND GALAXIES

- Galaxies are biased tracers

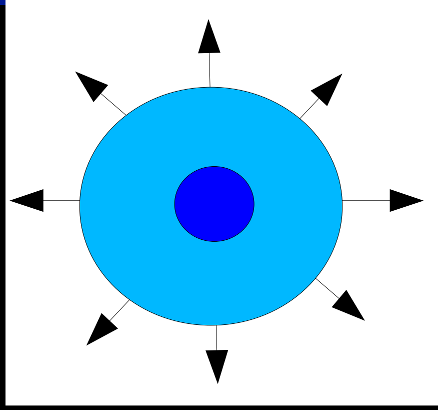


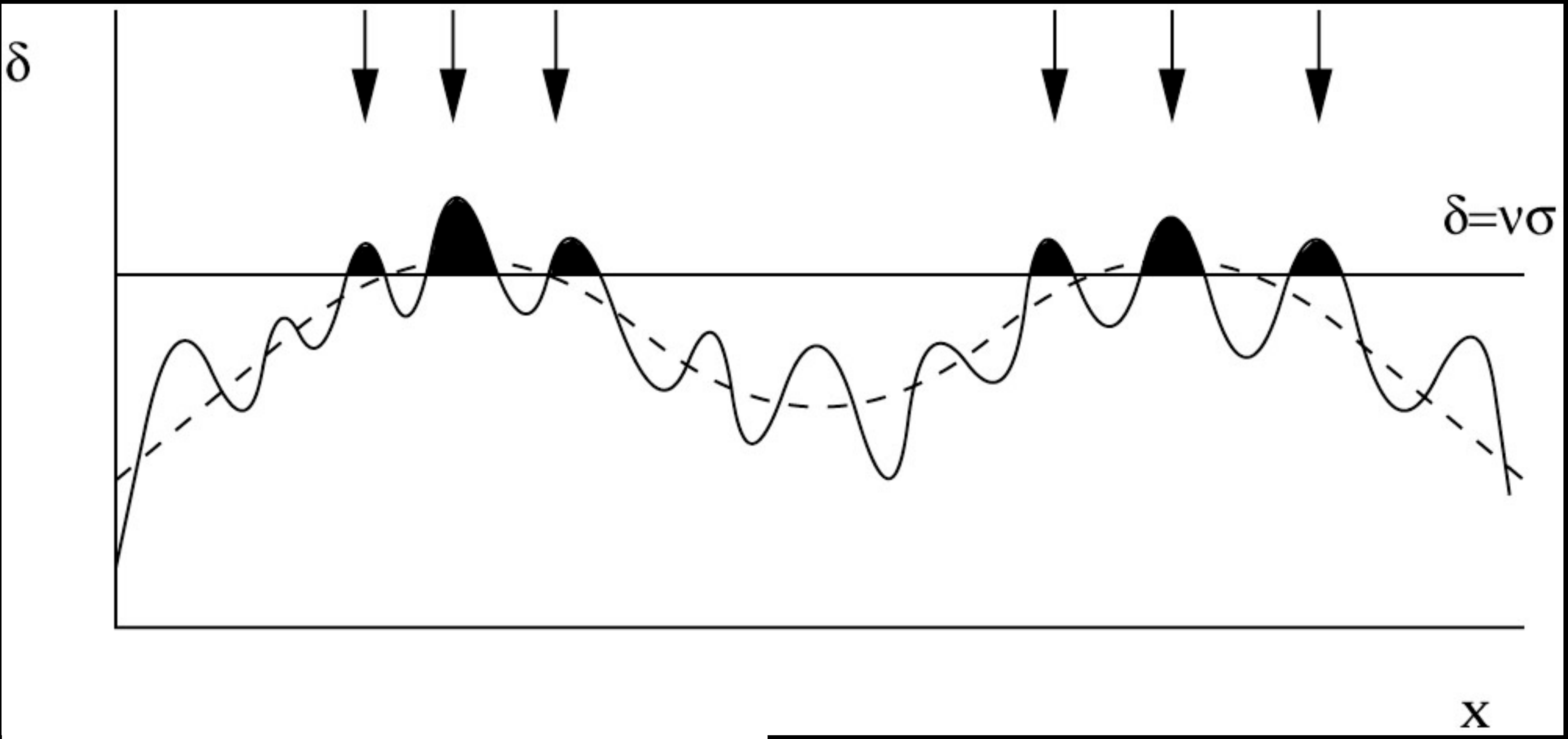
Unfair penalty on scales where axions don’t cluster

Doesn’t t

FUTURE WORK: ULAS AND GALAXIES

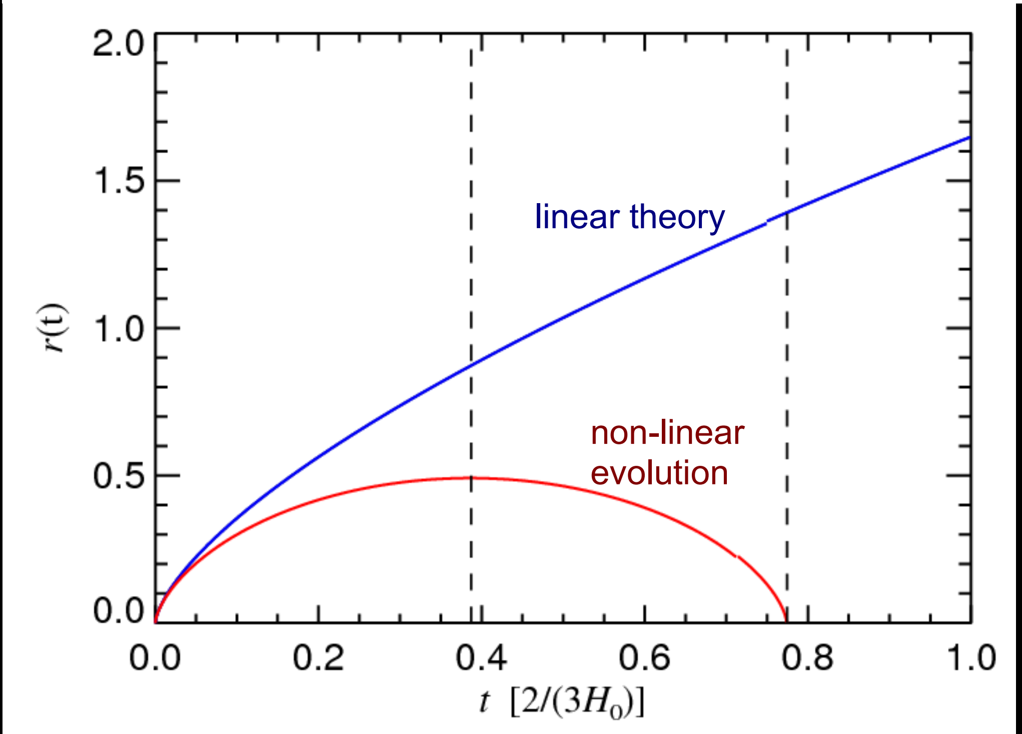
Collapse threshold for ULA DM unknown



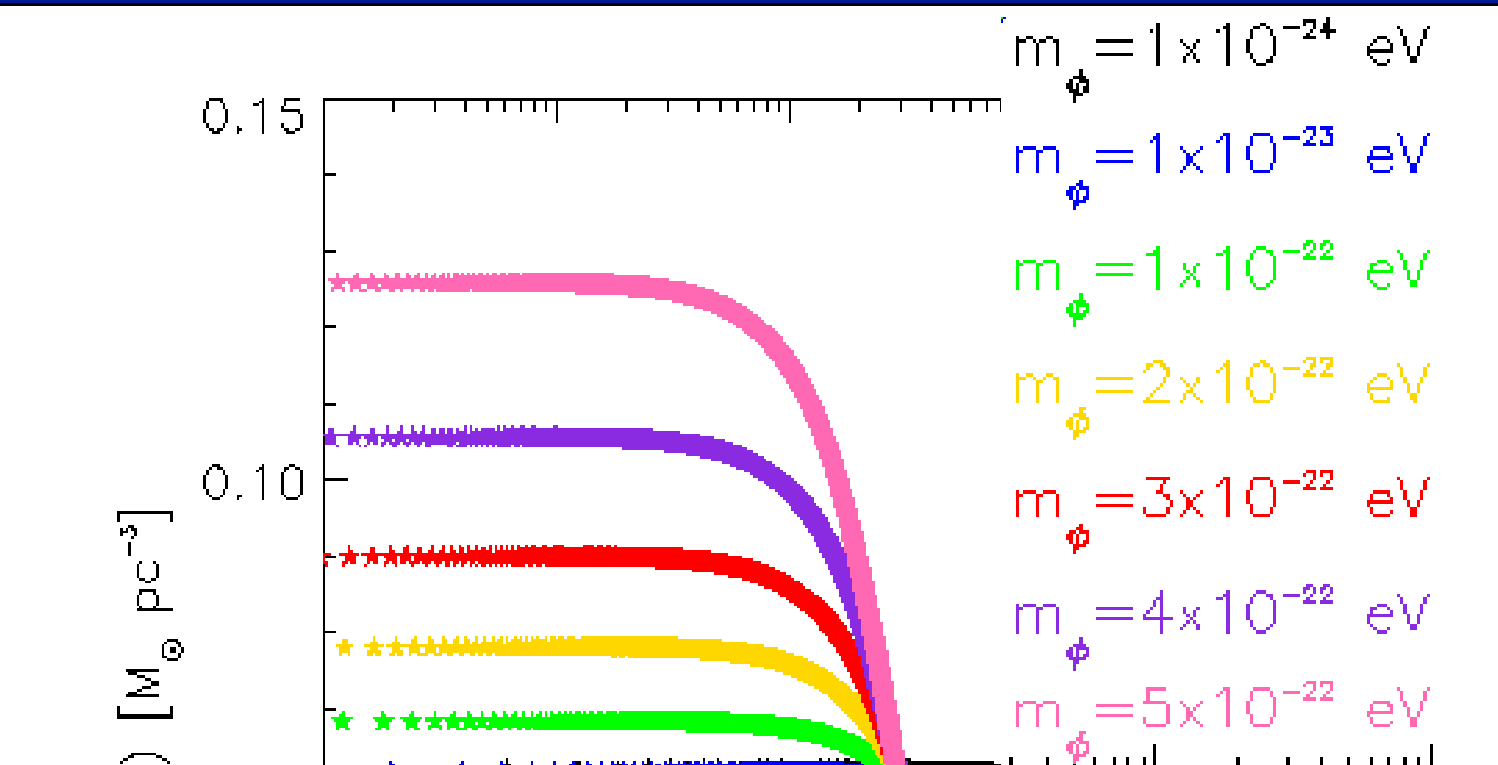


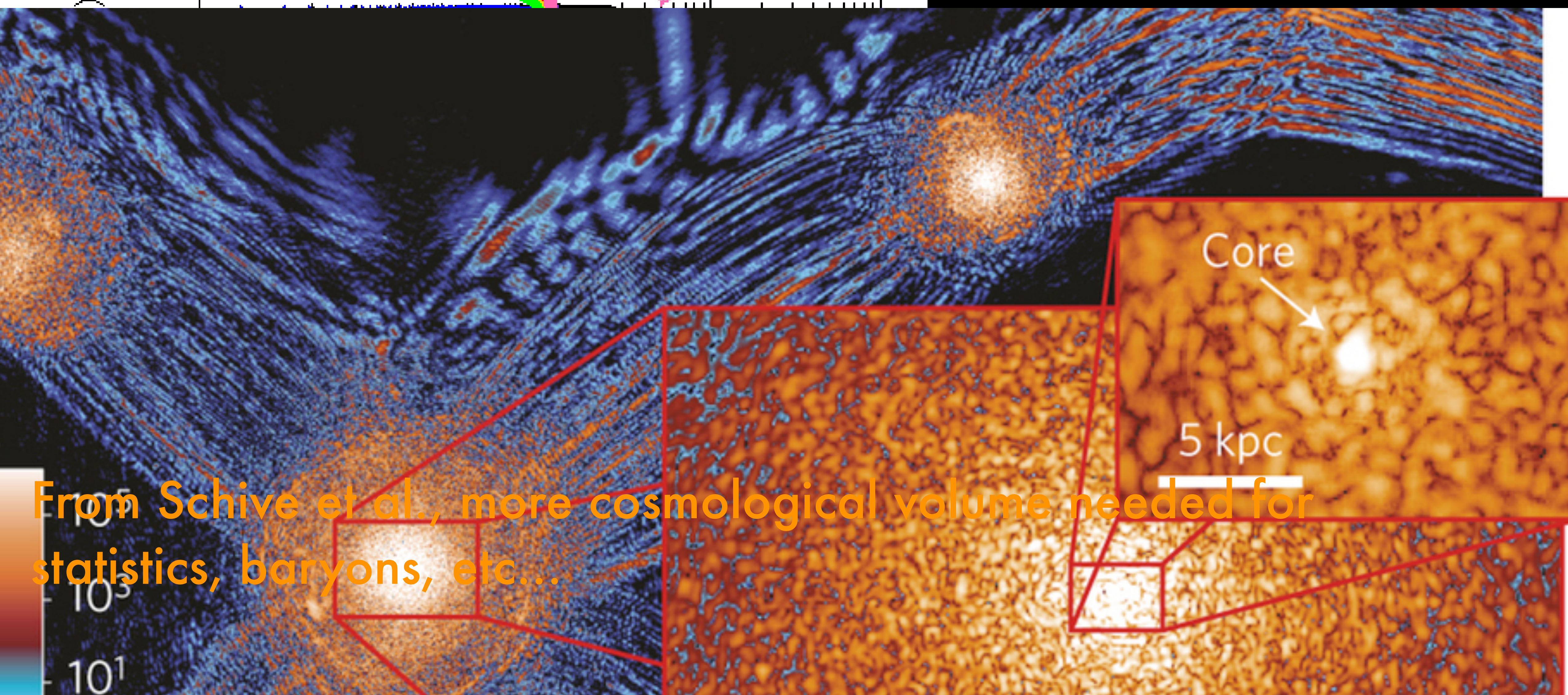
$$\delta_c^{\Lambda\mathrm{CDM}} = 1.686$$

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



Future work: ULAs cores + cusps?

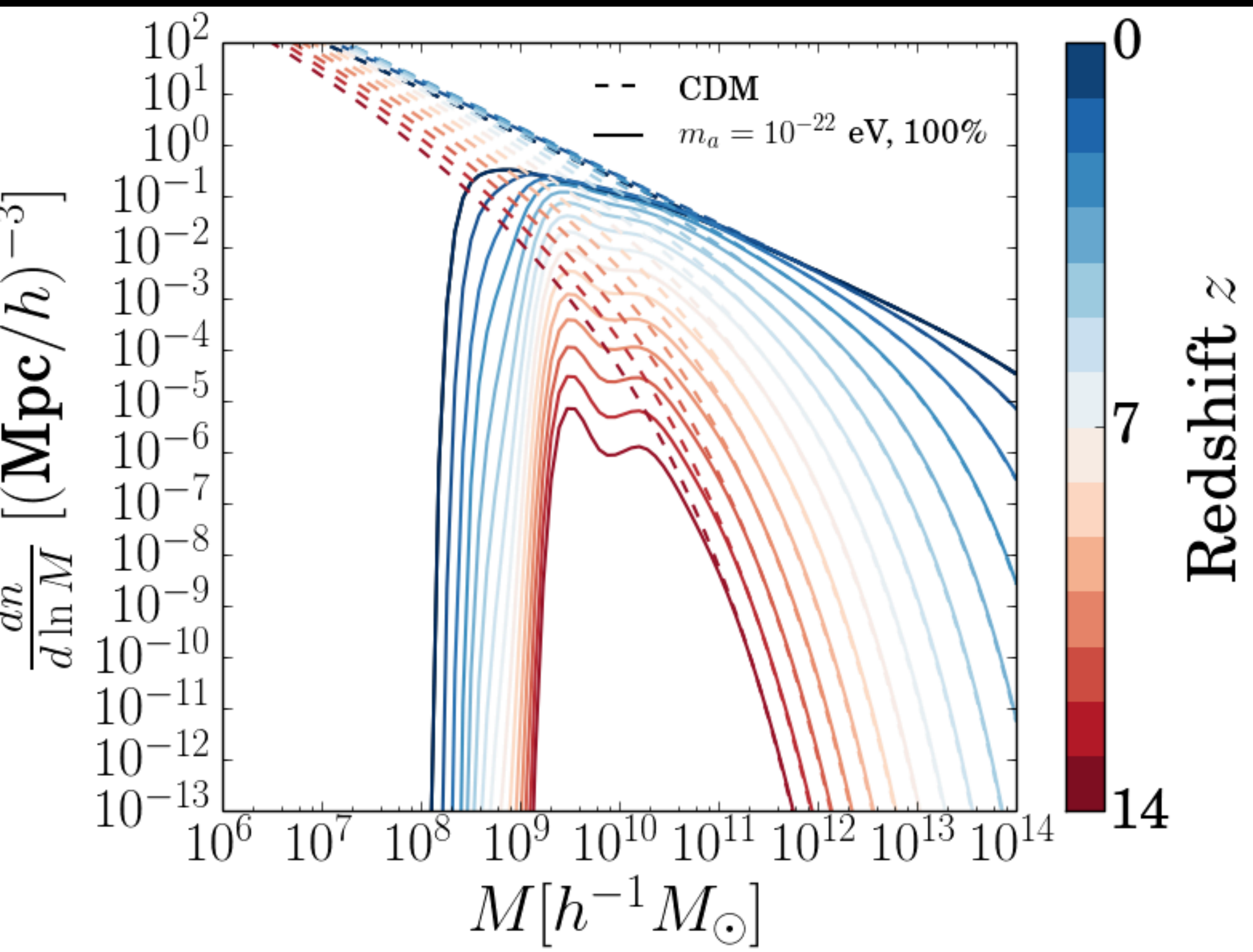


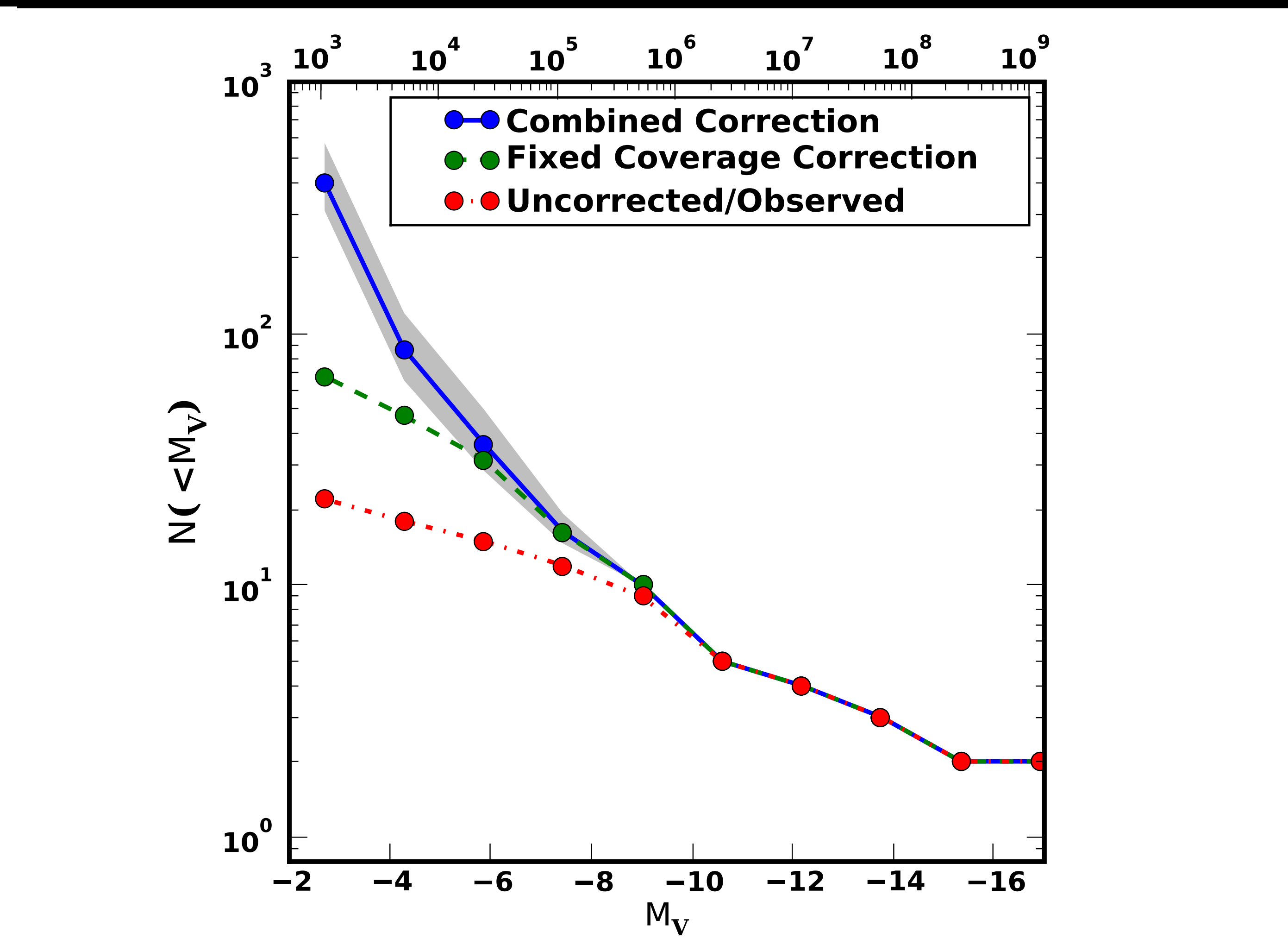


From Schive et al., more cosmological volume needed for statistics, baryons, etc…

FUTURE WORK: ULAS AND GALAXIES

Missing satellite problem?



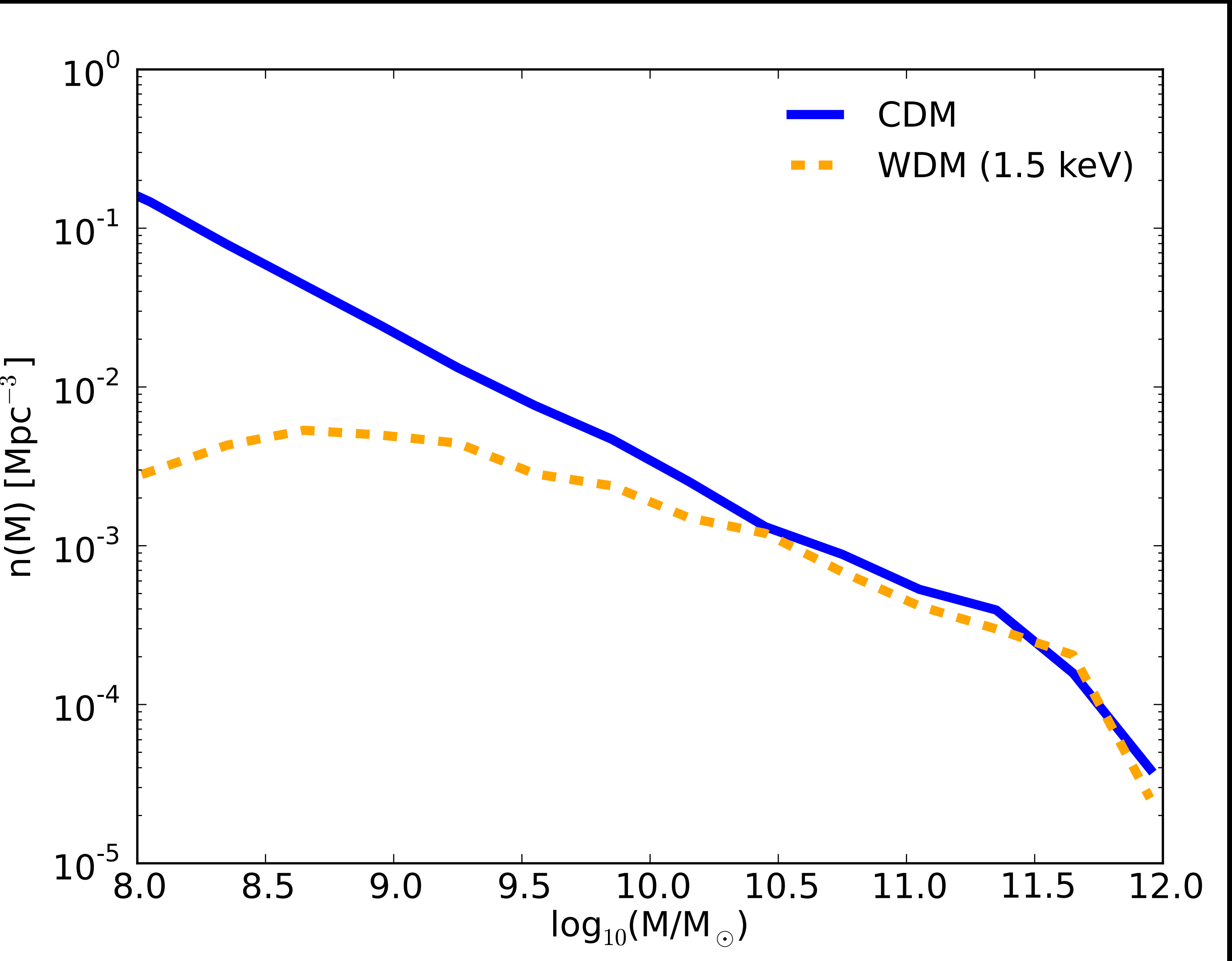


Marsh et al 2014, Klypin 1999, Bullock 2010

Future work: ULAs and galaxies

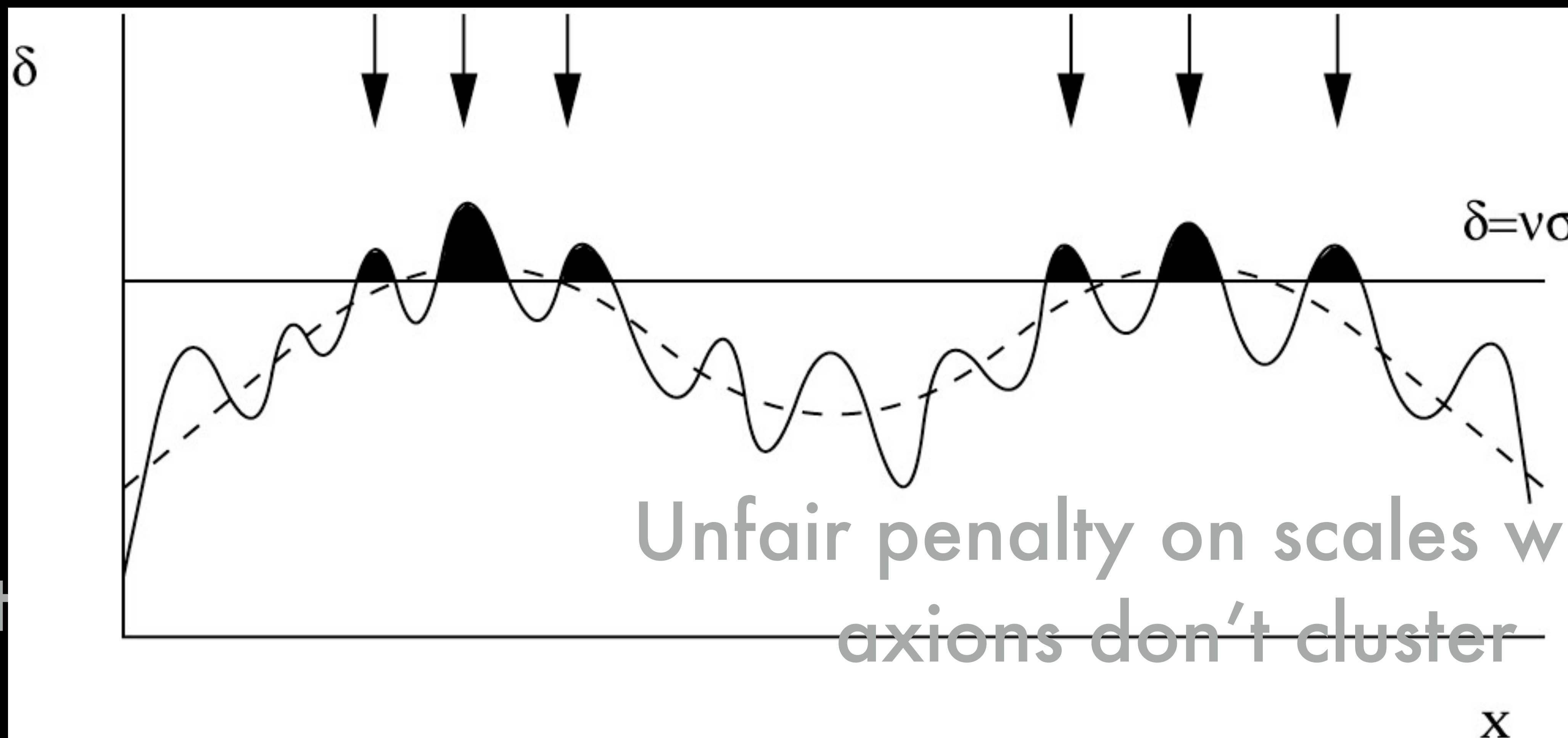
- ✳Galaxy correlation function (counts, bias)
- ✳Galaxy lensing
- ✳Substructure in halos [flux ratio anomalies in multiply lensed]

ULA substructure?



FUTURE WORK: ULAS AND GALAXIES

✳ 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)