Nano-eV Axions Beyond the Horizon

"Axion cosmology beyond the horizon"
DBK, A.E. Nelson, arXiv:0809.1206 (2008)

Axion dark matter?

1982: Abbott, Sikivie; Dine, Fischler; Preskill, Wilczek, Wise

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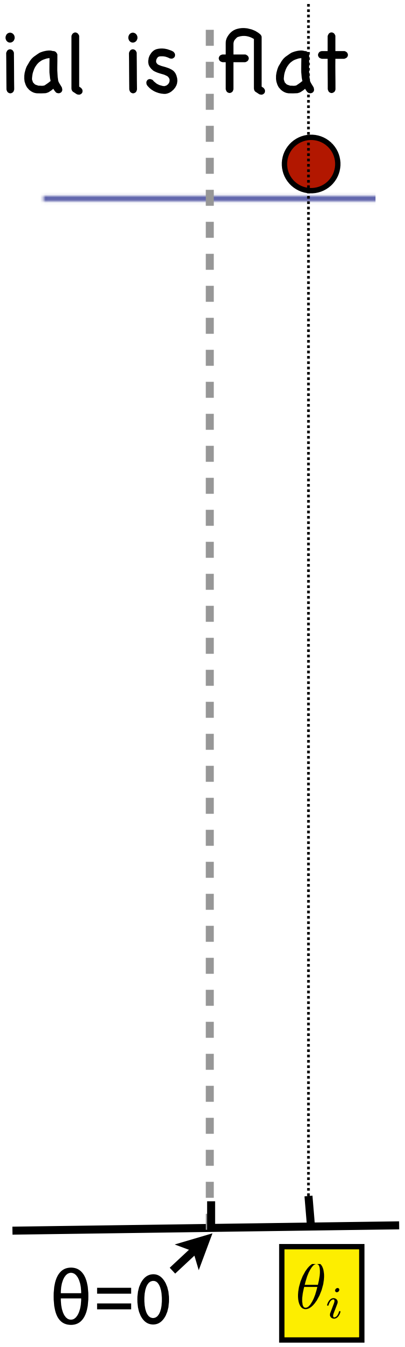

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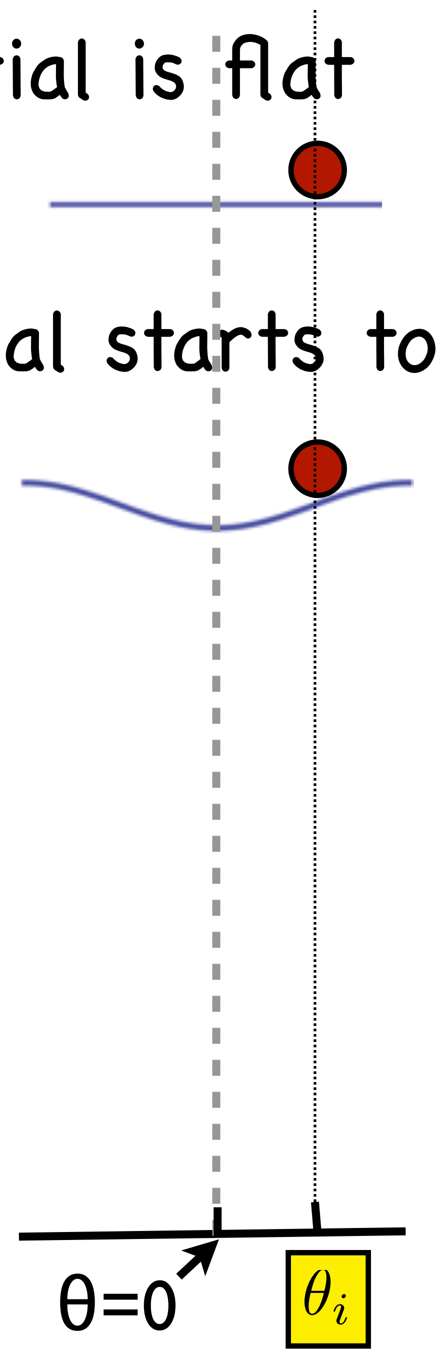

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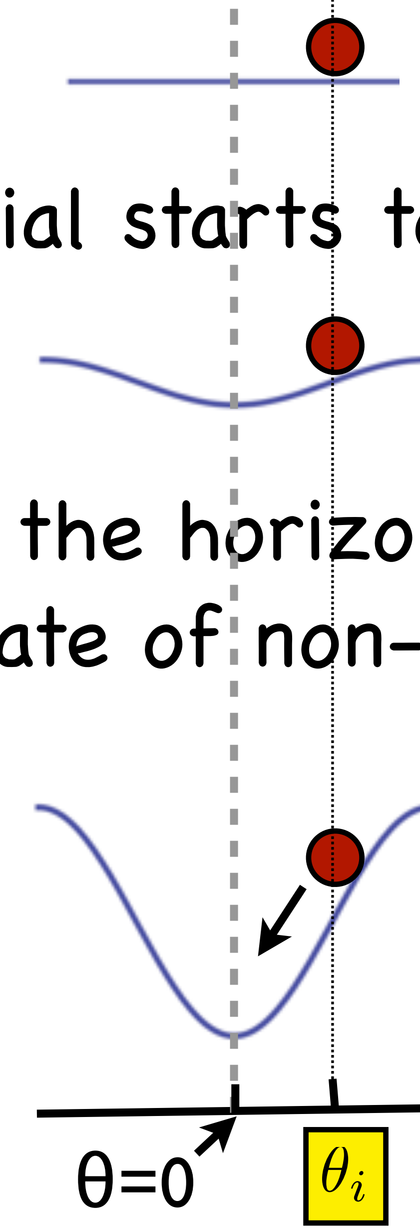
- When the axion Compton wavelength crosses the horizon, axion field begins to oscillate, = Bose condensate of non-interacting particles = CDM

$$m_a(t_{\rm osc}) = H(t_{\rm osc})$$



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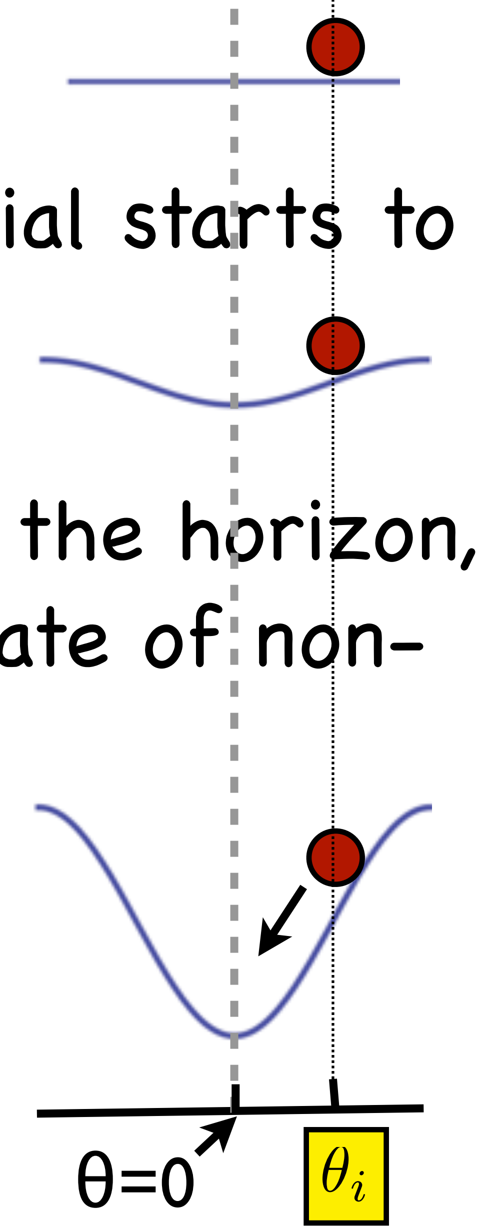

- Axions can eventually dominate the universe

$$\rho_{\rm CDM} \propto R^{-3}\ , \quad \rho_{\rm rad} \propto R^{-4}$$

a/f_a is an angle

How does the axion dark matter depend on f_a?

DARK MATTER DENSITY IN AXIONS

AXION DECAY CONSTANT

$$\frac{\rho_a}{\rho_{\rm dm}} \simeq \theta_i^2 \left(\frac{f_a}{\text{few} \times 10^{11}\ \text{GeV}} \right)$$

OBSERVED DARK MATTER DENSITY

INITIAL MISALIGNMENT ANGLE
(if small - otherwise ~ $\sin^2\theta_i$)

Axion dark matter today:

$$\rho_a(t_0) \simeq \rho_{\rm dm}\, \theta_i^2 \left(\frac{f_a}{\text{few} \times 10^{11}\ \text{GeV}} \right)$$

observed dark matter density

Upper bound on f_a...

...*Assuming* initial misalignment angle is O(1)

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- upper bound: $f_a \lesssim 10^{12}\ \text{GeV}$
- axions make good dark matter candidate for $f_a \simeq 10^{12}\ \text{GeV}$ $\left(m_a \simeq 10^{-5} - 10^{-6}\ \text{eV}\right)$

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assumes: PQ symmetry breaks after inflation/reheating

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Axions with PQ symmetry breaking *before* inflation:

- initial misalignment angle θ_i random
- today our horizon comes from a single causally connected patch from before inflation with one particular value for θ_i

So the initial misalignment angle can assume any value, is a constant across our horizon, and there is no bound on f_a (but *small* θ_i required for large f_a! Fine-tuned!)

[S.Y. Pi]

Inflation:

- Epoch of expansion much faster than speed of light
- Causal patch stretched to far outside the horizon
- Followed by reheating epoch & conventional Big Bang evolution
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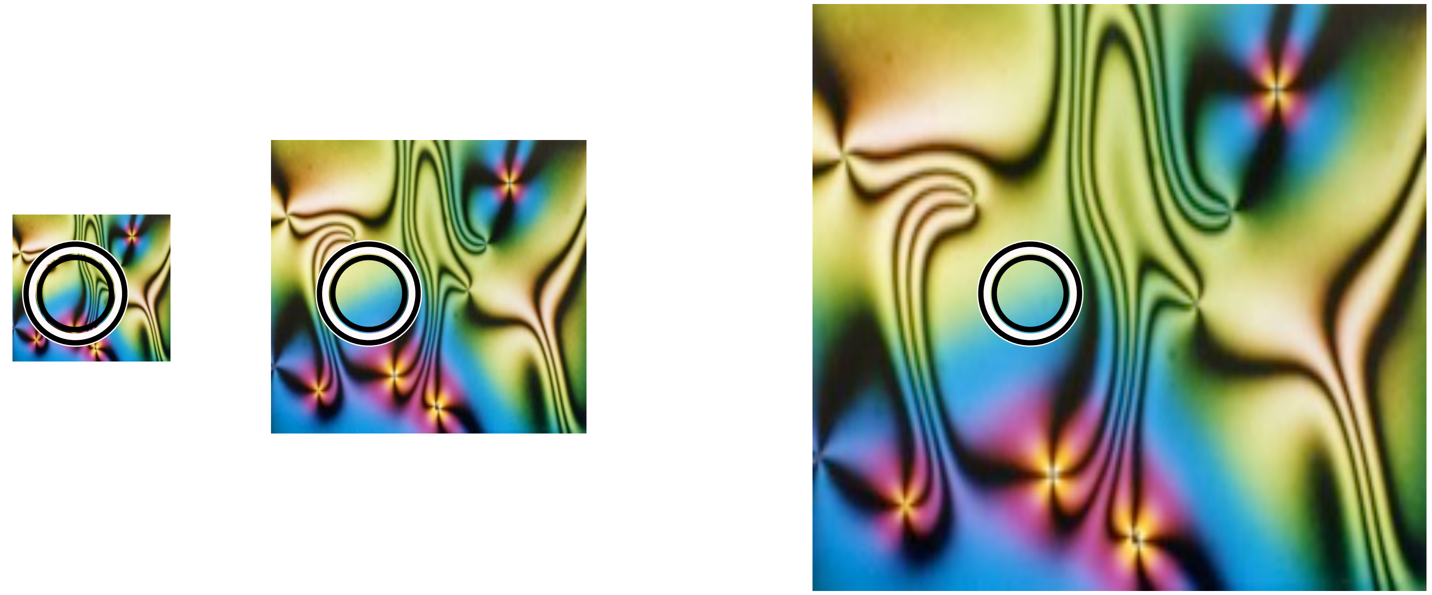

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- Fine tuning of initial axion misalignment angle
  - *Can be fixed by anthropic principle*
- Generation of isocurvature fluctuations (as opposed to adiabatic)
  - *Can be fixed with sufficiently low inflation scale*

Isocurvature axion fluctuations (Turner & Wilczek):

Inflation gives rise to fluctuations in massless fields

$$\langle \phi_{\mathbf{k}} \phi^*_{\mathbf{k}'} \rangle = \frac{2\pi^2}{k^3} \left(\frac{H_i}{2\pi} \right)^2 (2\pi)^3 \delta^3(\mathbf{k} - \mathbf{k}')$$

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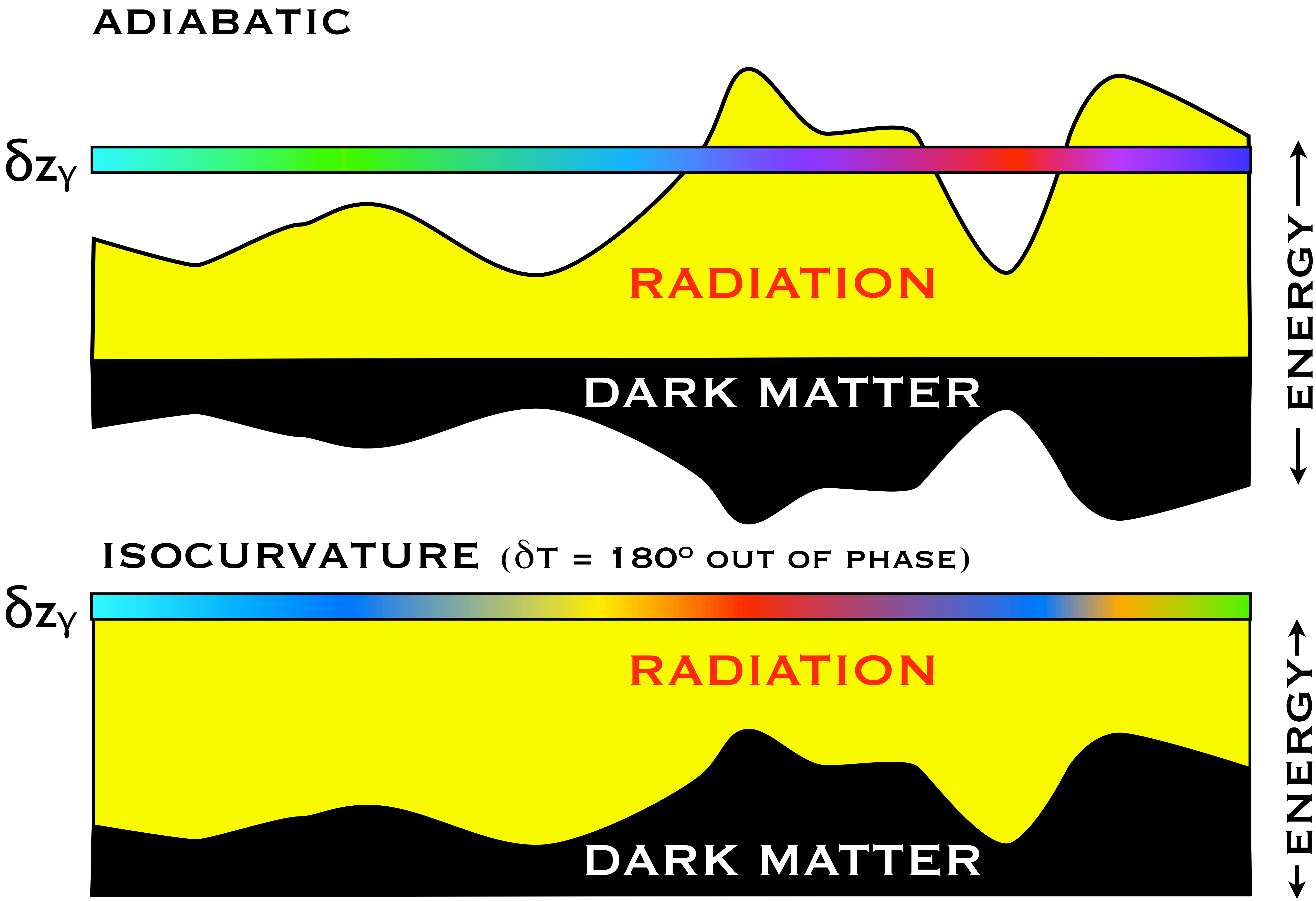
Isocurvature perturbations:

- Fluctuations in energy density of matter & radiation
- **NO** fluctuations in total energy (matter + radiation)


ADIABATIC
δzγ
RADIATION
DARK MATTER
ENERGY
ISOCURVATURE (δT = 180° OUT OF PHASE)
δzγ
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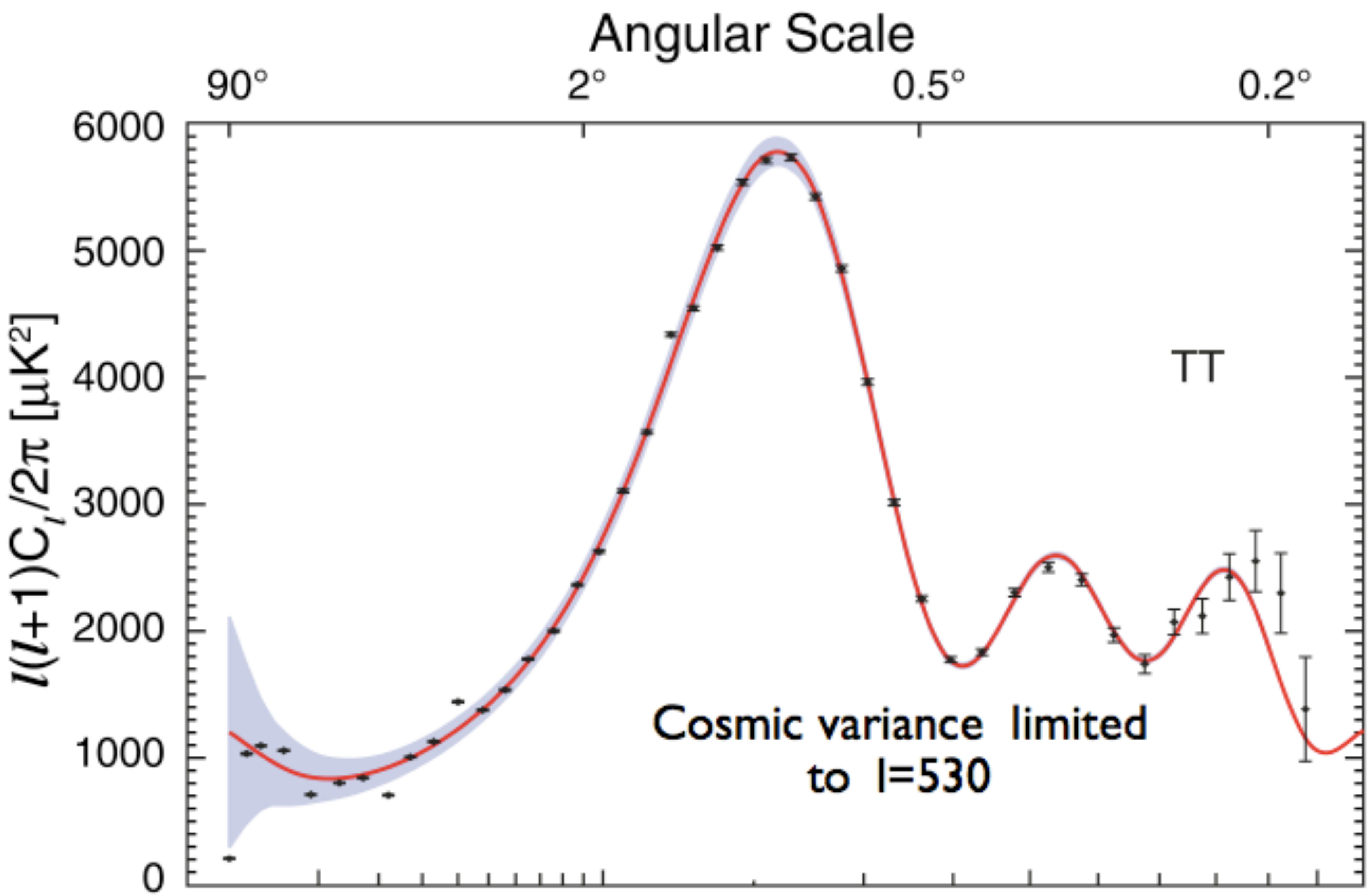
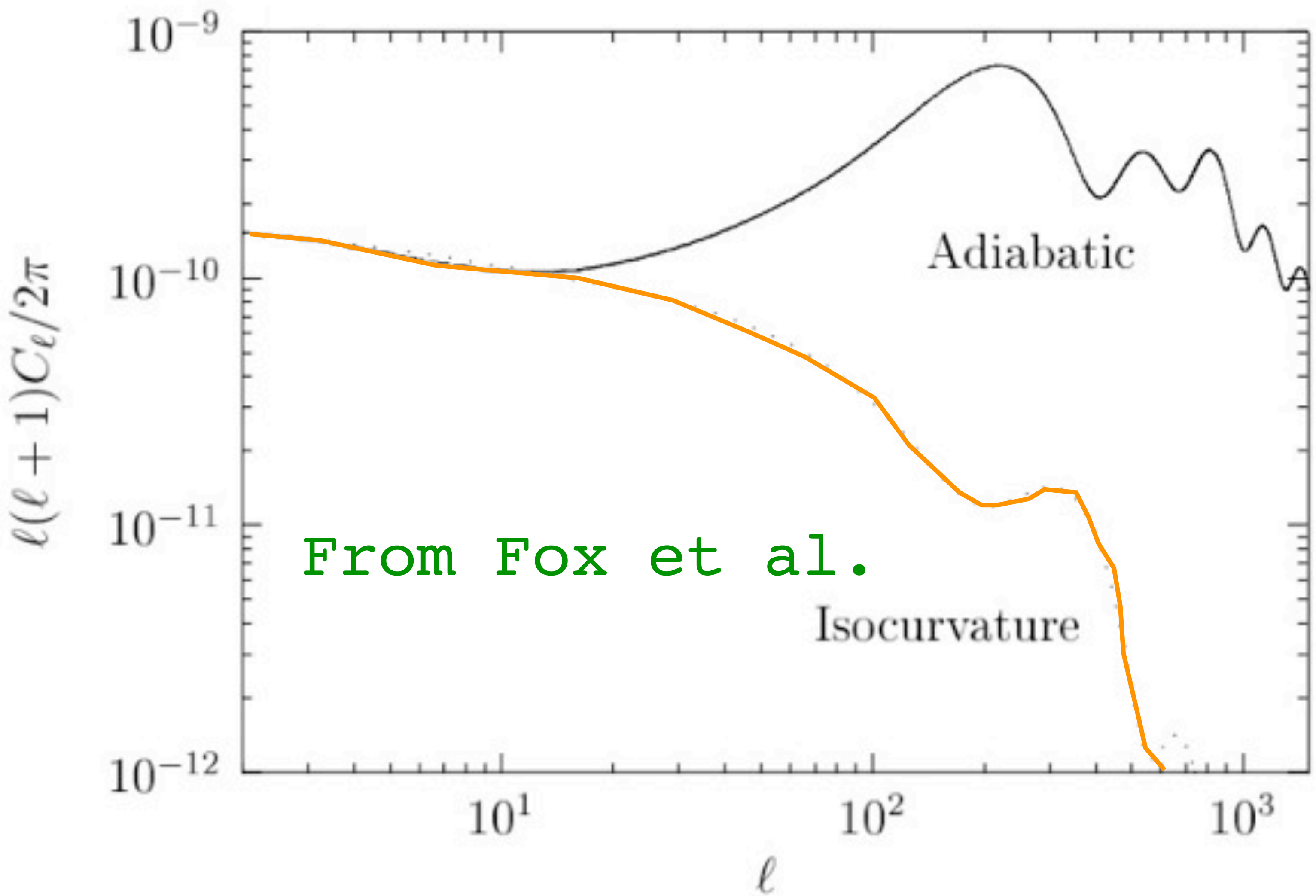
DARK MATTER
ENERGY

Initial **adiabatic** perturbation spectrum agrees well with CMB observation



WMAP 5-yr results

Initial isocurvature perturbation spectrum disagrees with CMB observation at small angles



Can tolerate small isocurvature perturbations

Limit: (isocurvature)/(adiabatic) < 0.1

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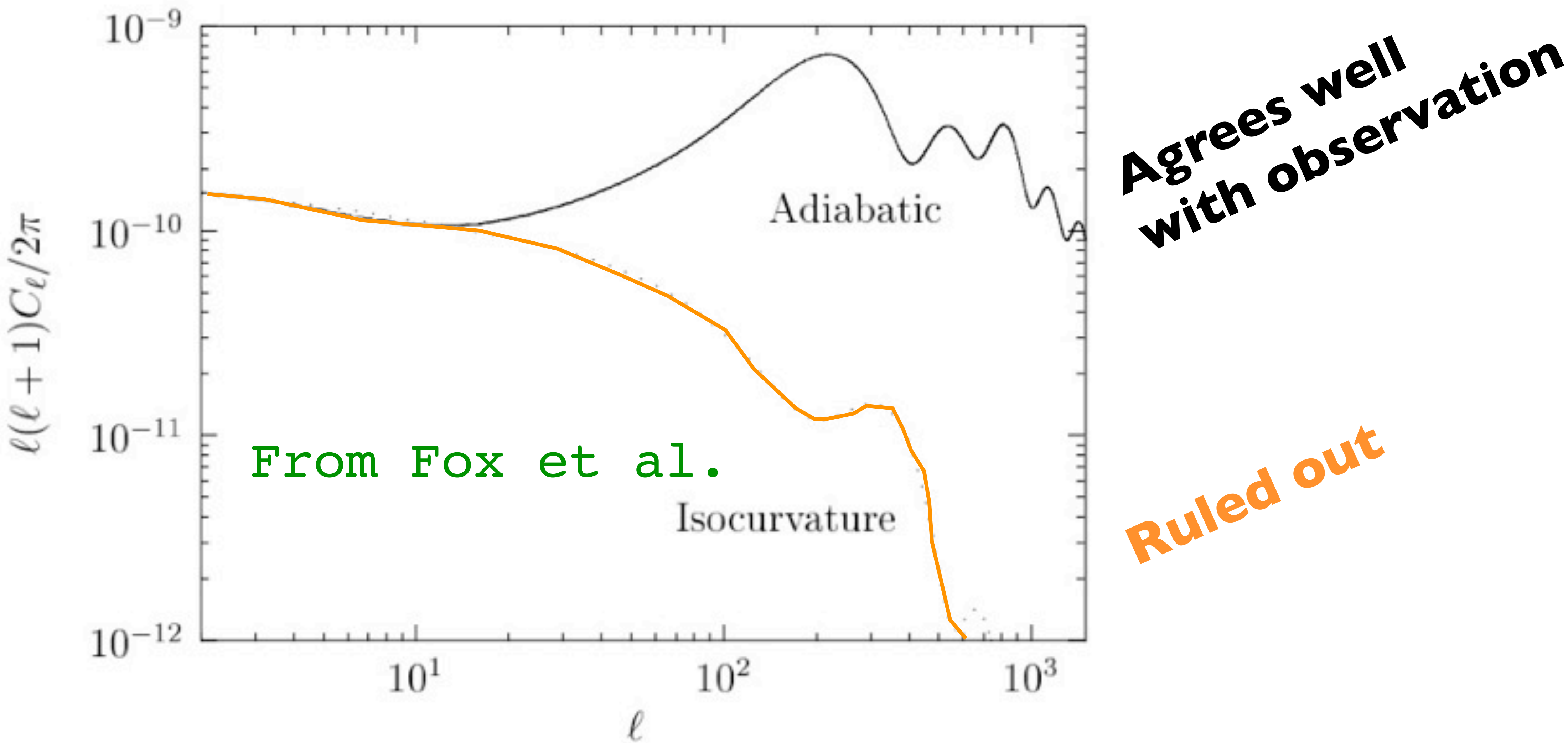

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Inflation induced fluctuations in axions:

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If axions are the dark matter:

$$\theta_i \simeq \left(\frac{10^{12}\ \text{GeV}}{f_a}\right)^{1/2}$$

and one gets an **upper** bound on H_I for a given f_a.

E.g: $f_a = 10^{16}$ GeV -> $H_I < 10^8$ GeV

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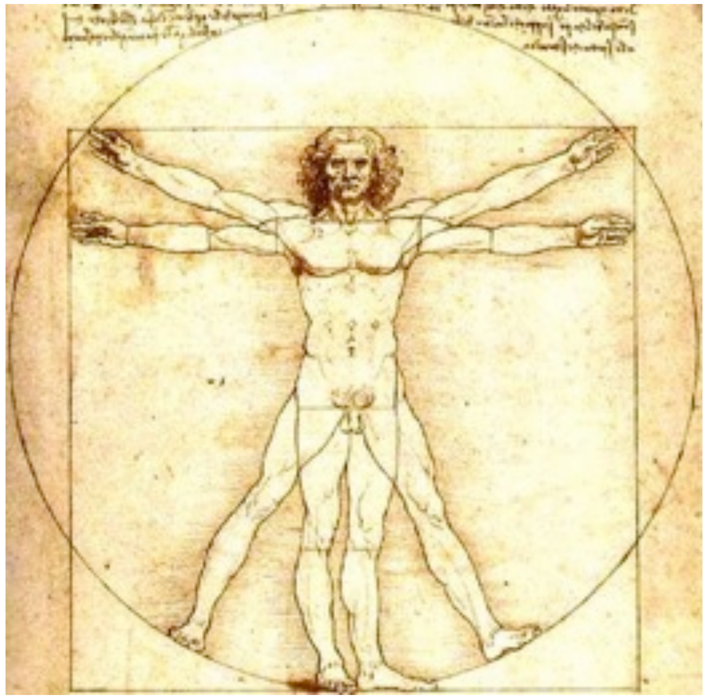
Small H_I implies small tensor perturbations:

Observation of tensor perturbations in CMB would **rule out** $f_a > 10^{12}$ GeV

Fine tuning of initial axion misalignment angle:

- *Can be fixed by anthropic principle*



Anthropic selection of small initial axion angle (eg, of universe not over-dominated by axion dark matter)

Easy to abuse anthropic arguments!!

Sensible argument requires:

★ensemble of physical parameters to choose from

★understanding of a priori probability distribution

★effect of evolution of cosmic structure, life...

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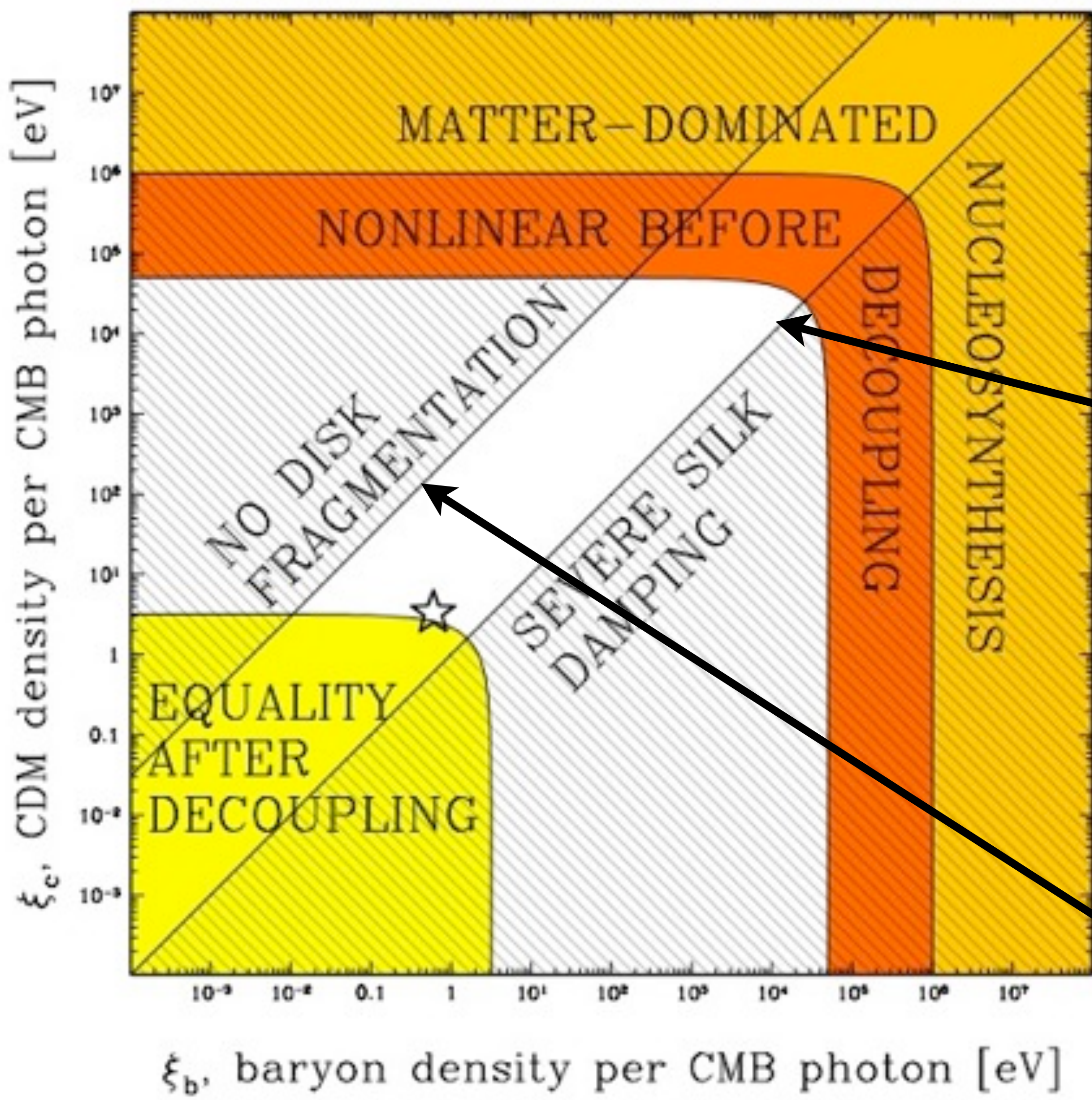
Axion case ideal (why is θ_i small with inflation?)

★different patches with different θ_i

★initial distribution flat on $[0,2\pi)$

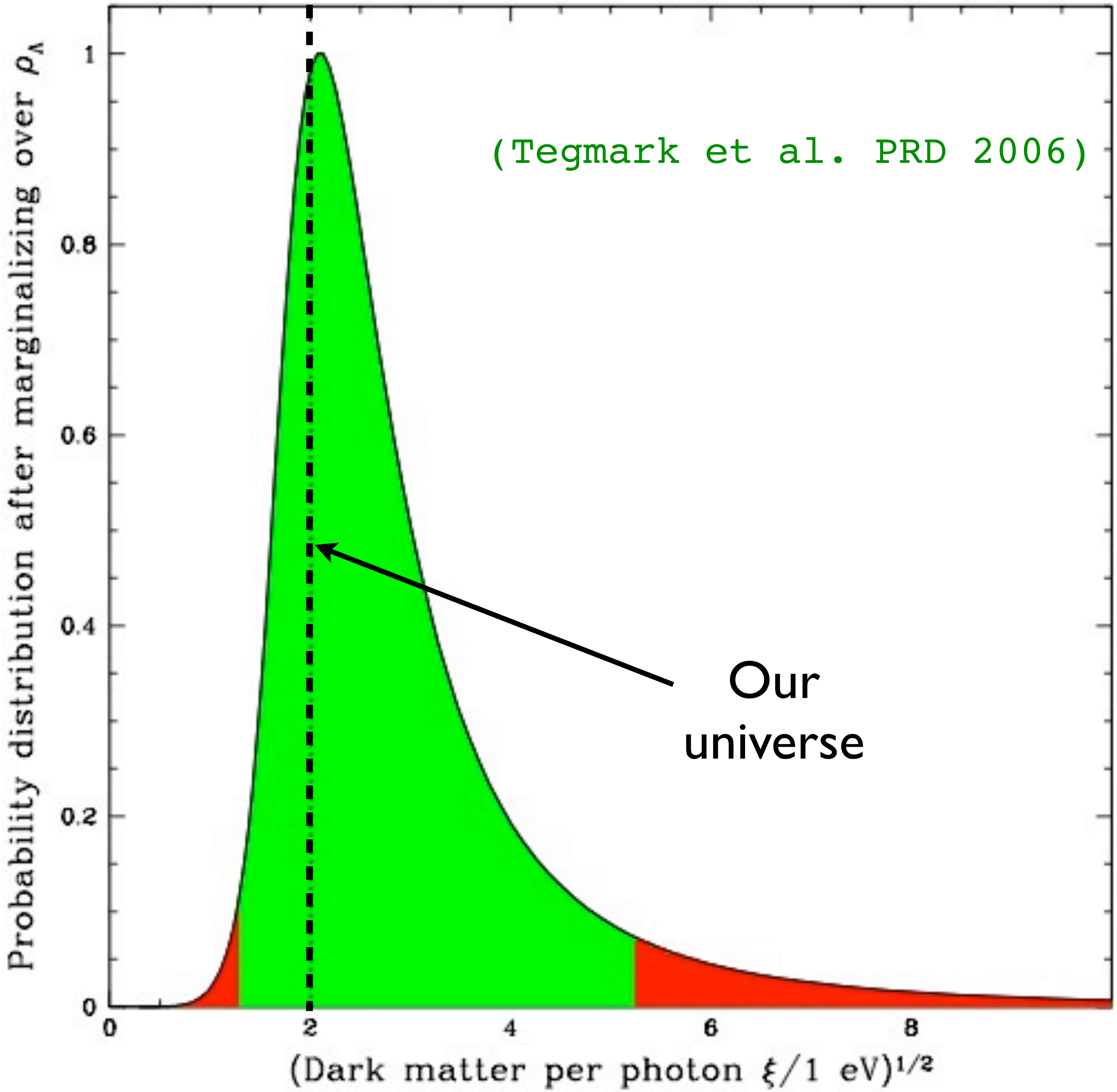
★affects evolution of cosmic structure through dark matter density Ω_{dm}



(Tegmark al.)

Need
(Dark Matter)/Baryon
ratio >1 for structure

Need enough baryons
to form fragmented
galactic disks, stars



Dark matter density

- Anthropic arguments for axions rely on a known initial probability distribution for the axion misalignment angle, and relatively simple cosmology to determine "viability"
- Inflation removes upper bound on f_a, allows for GUT/string axions
- $f_a > 10^{12}$ GeV allows anthropic solution to dark matter coincidence

Could there be observable consequences from these ultra-light pre-inflationary axions?

Direct detection of ultralight axions ($f_a > 10^{12}$ GeV) very challenging!

Do you have any ideas?

Indirect detection through cosmology looks more promising now.

DBK, A.E. Nelson: arXiv:0809.1206

Observable consequences?

Look at the Universe today

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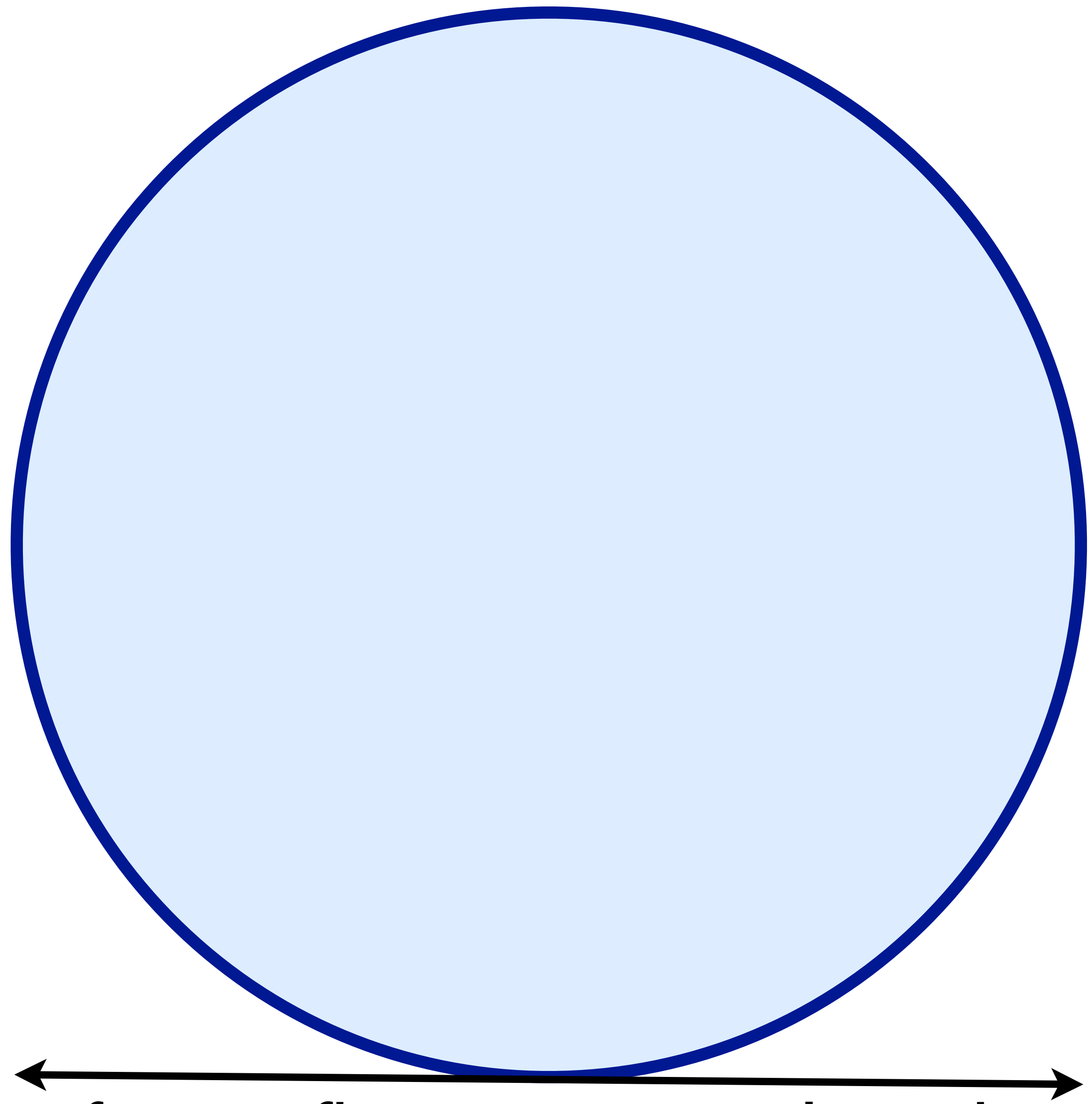

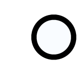

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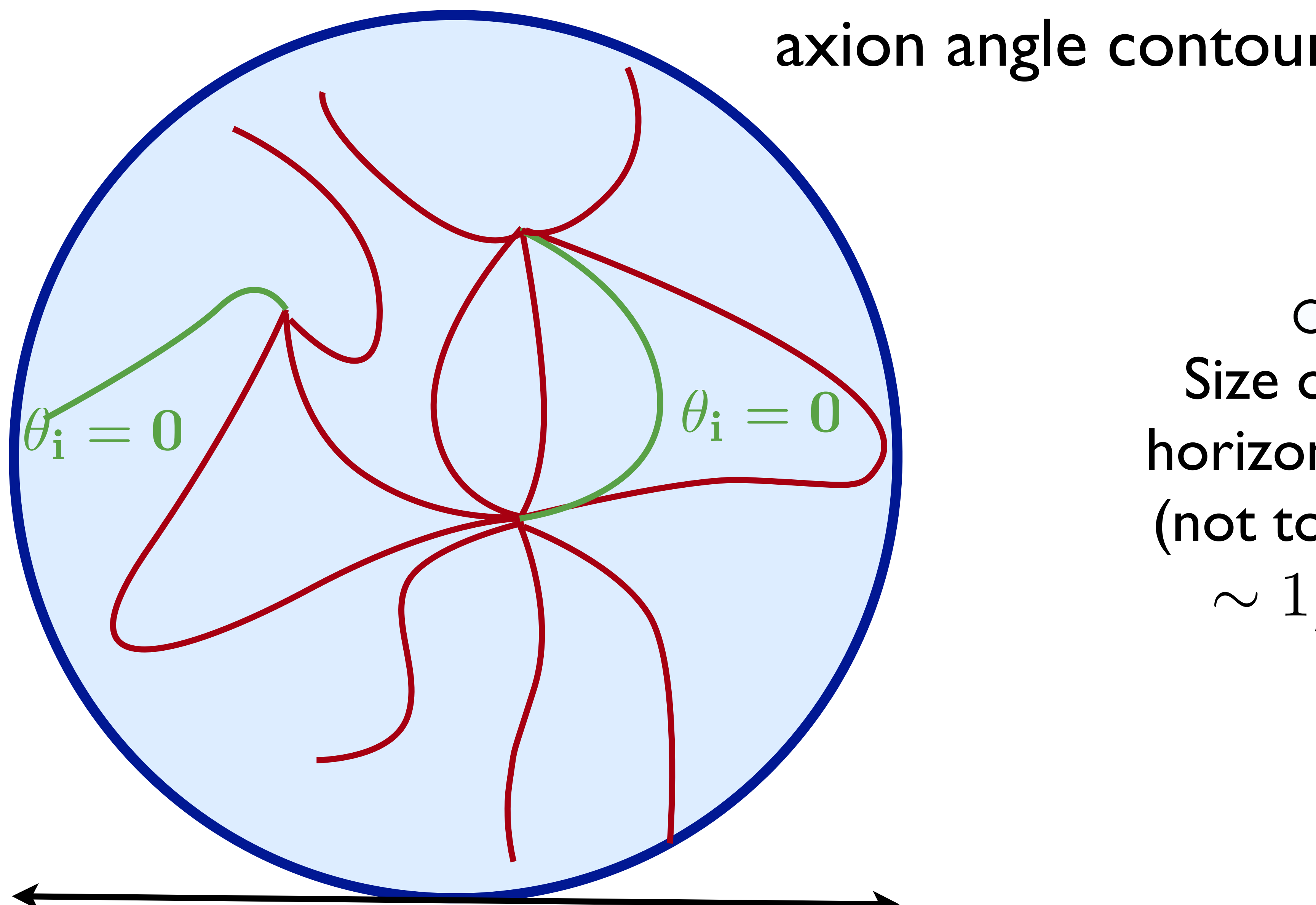

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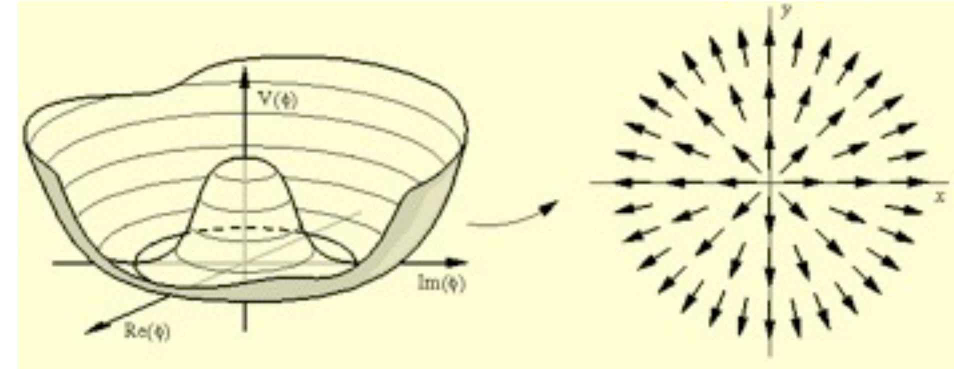
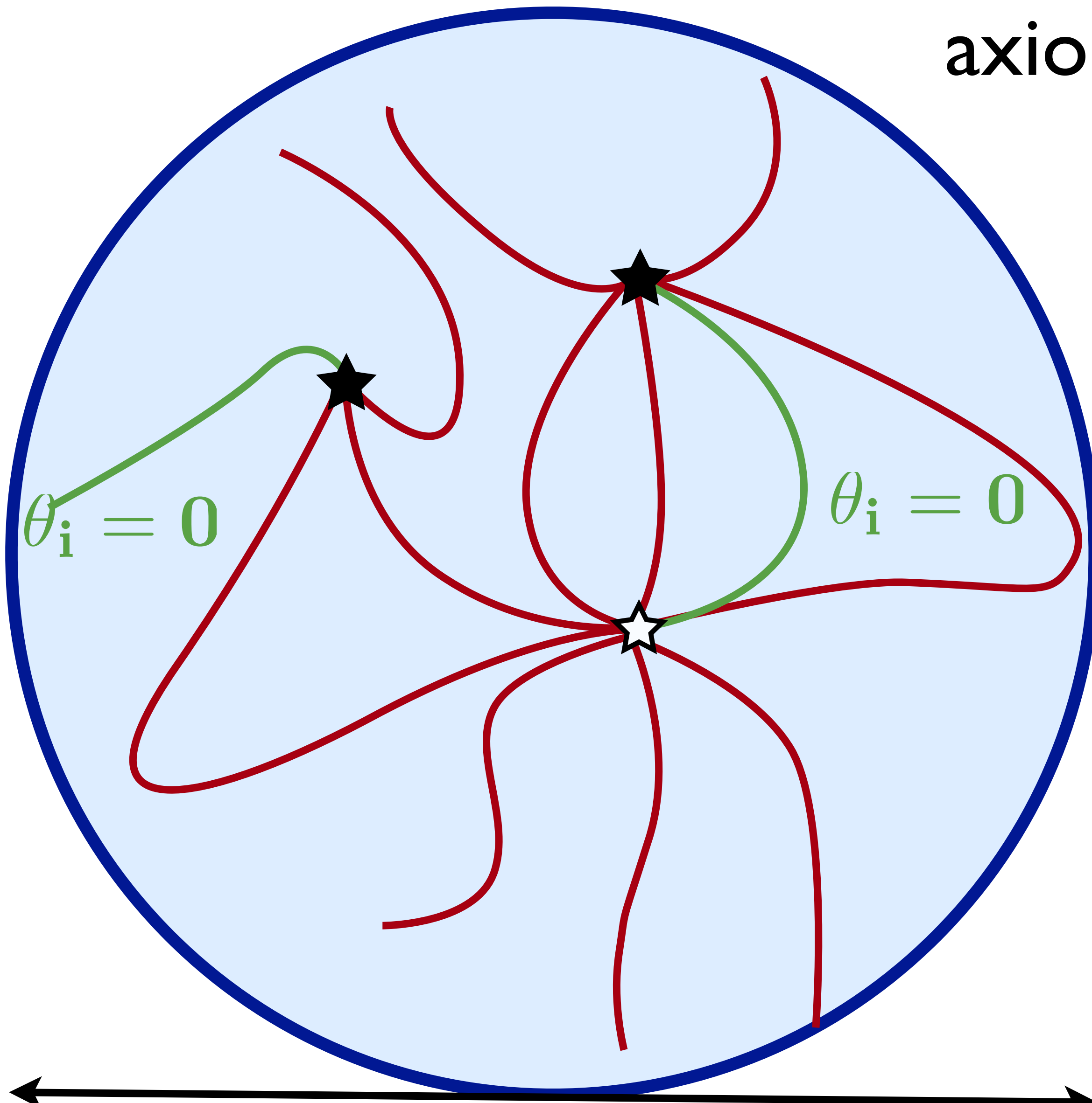


★ = axion strings

axion angle contours



○
Size of our horizon today (not to scale)
$\sim 1/H_0$

Size of pre-inflationary causal patch today
$\equiv r/H_0$

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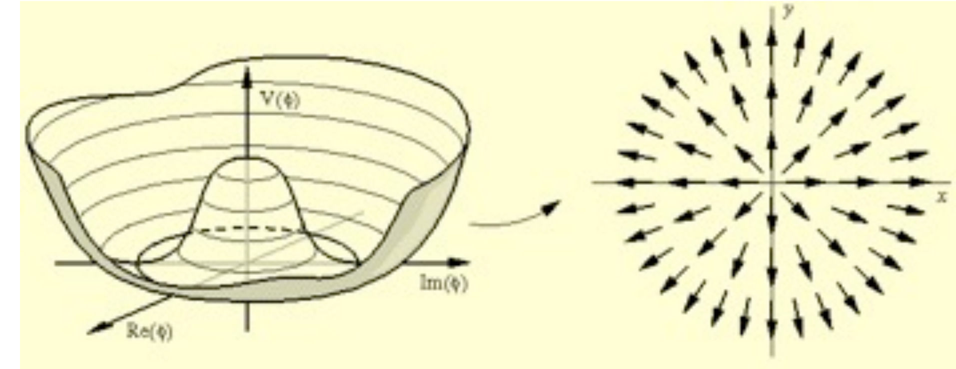

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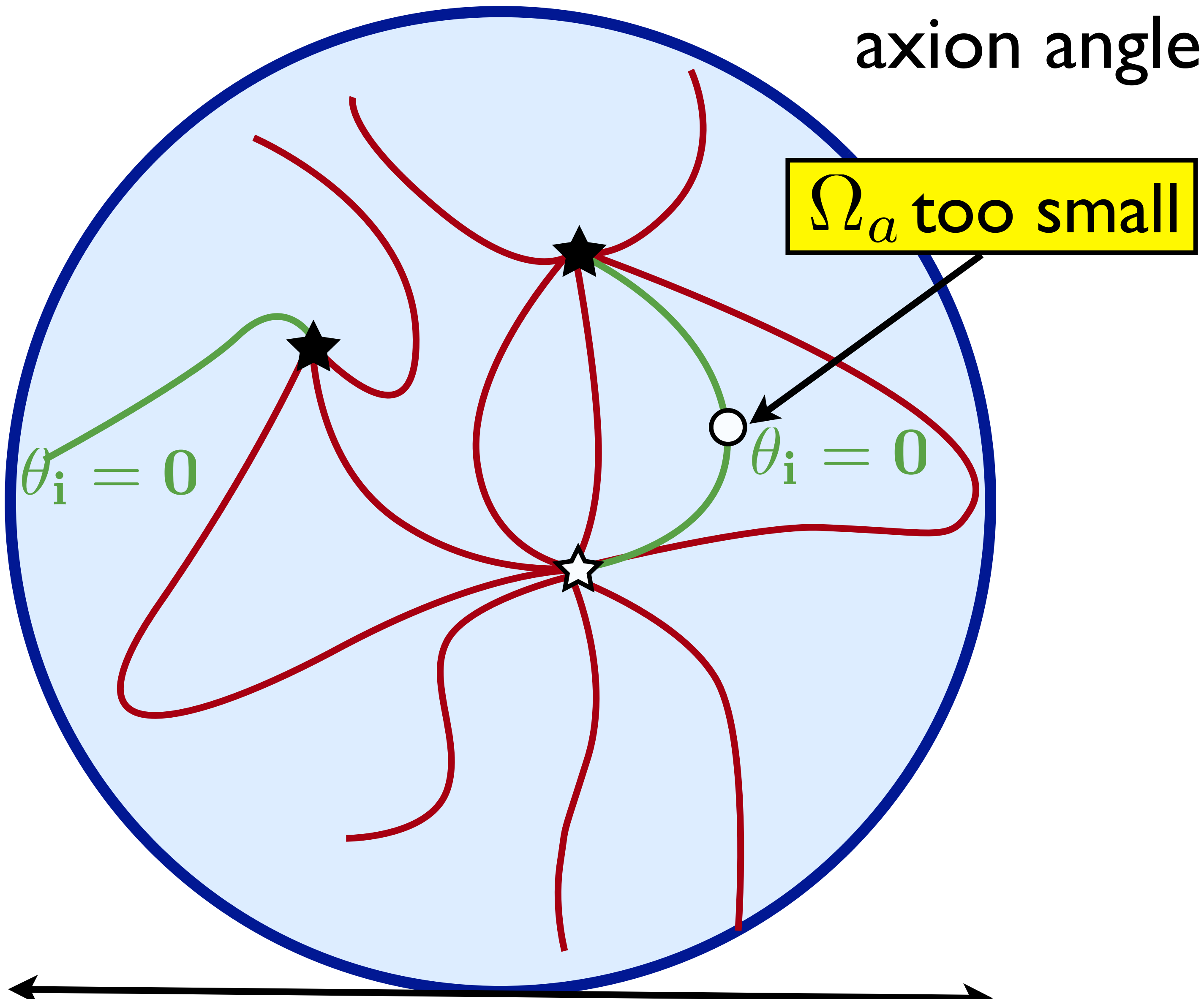

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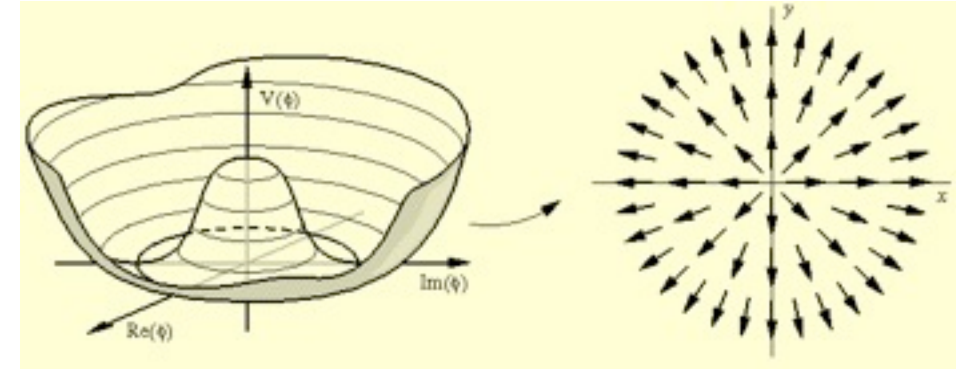

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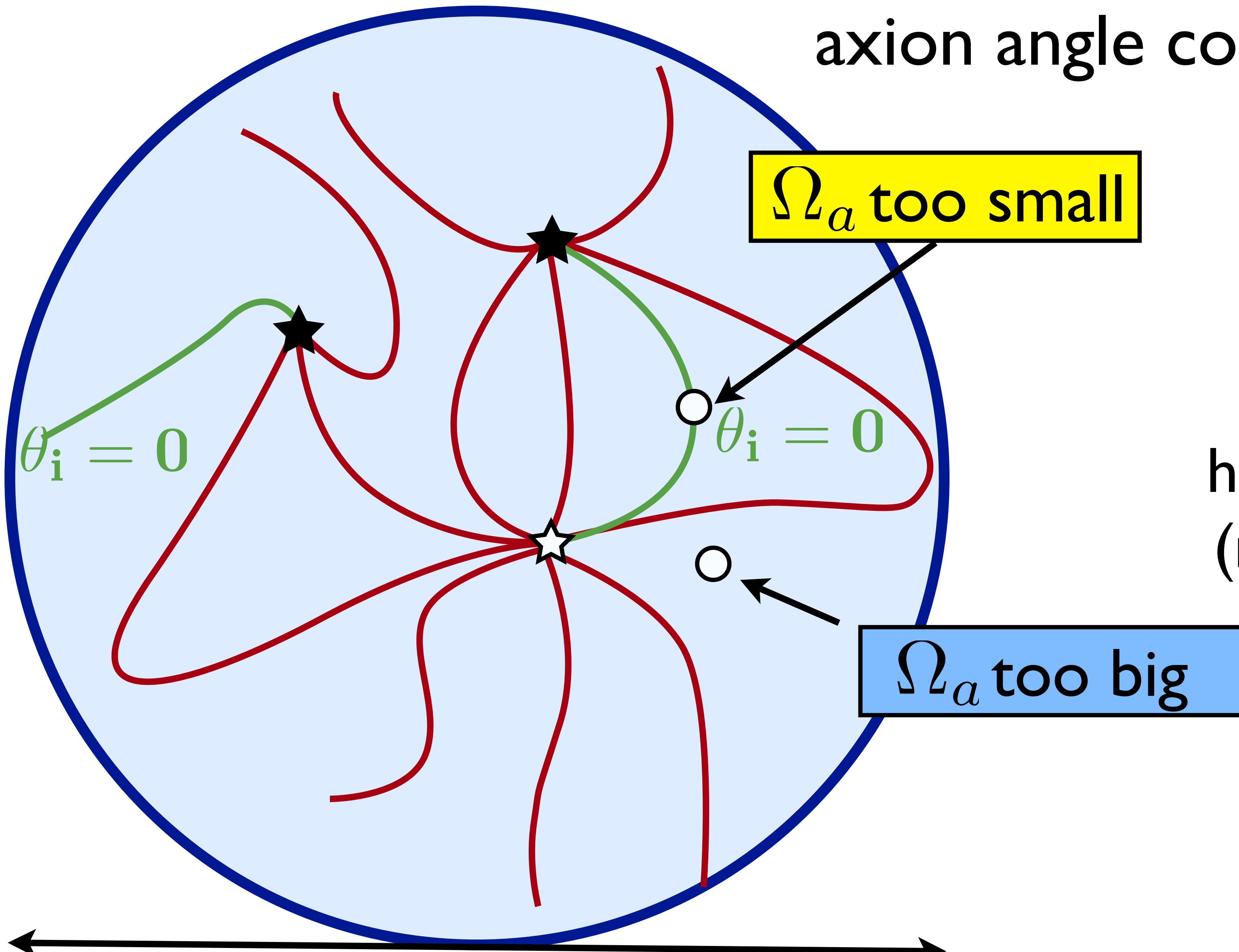

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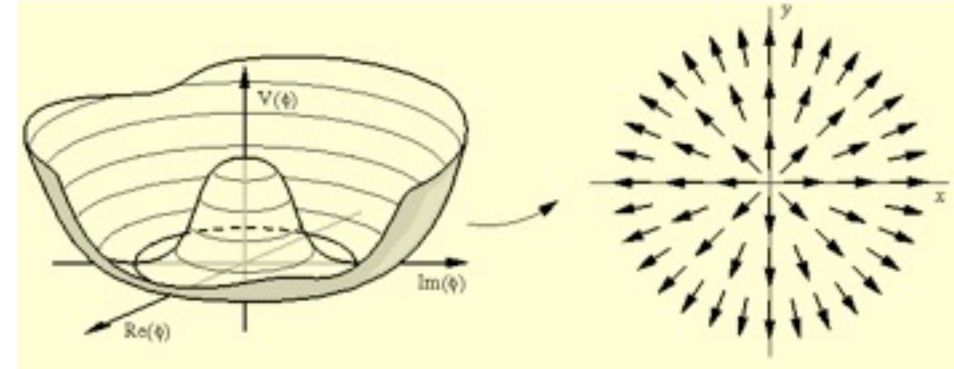

Our observed universe: Ω_a just right!

$$\theta_i \sim \sqrt{\frac{10^{12}\ \mathrm{GeV}}{f_a}}$$

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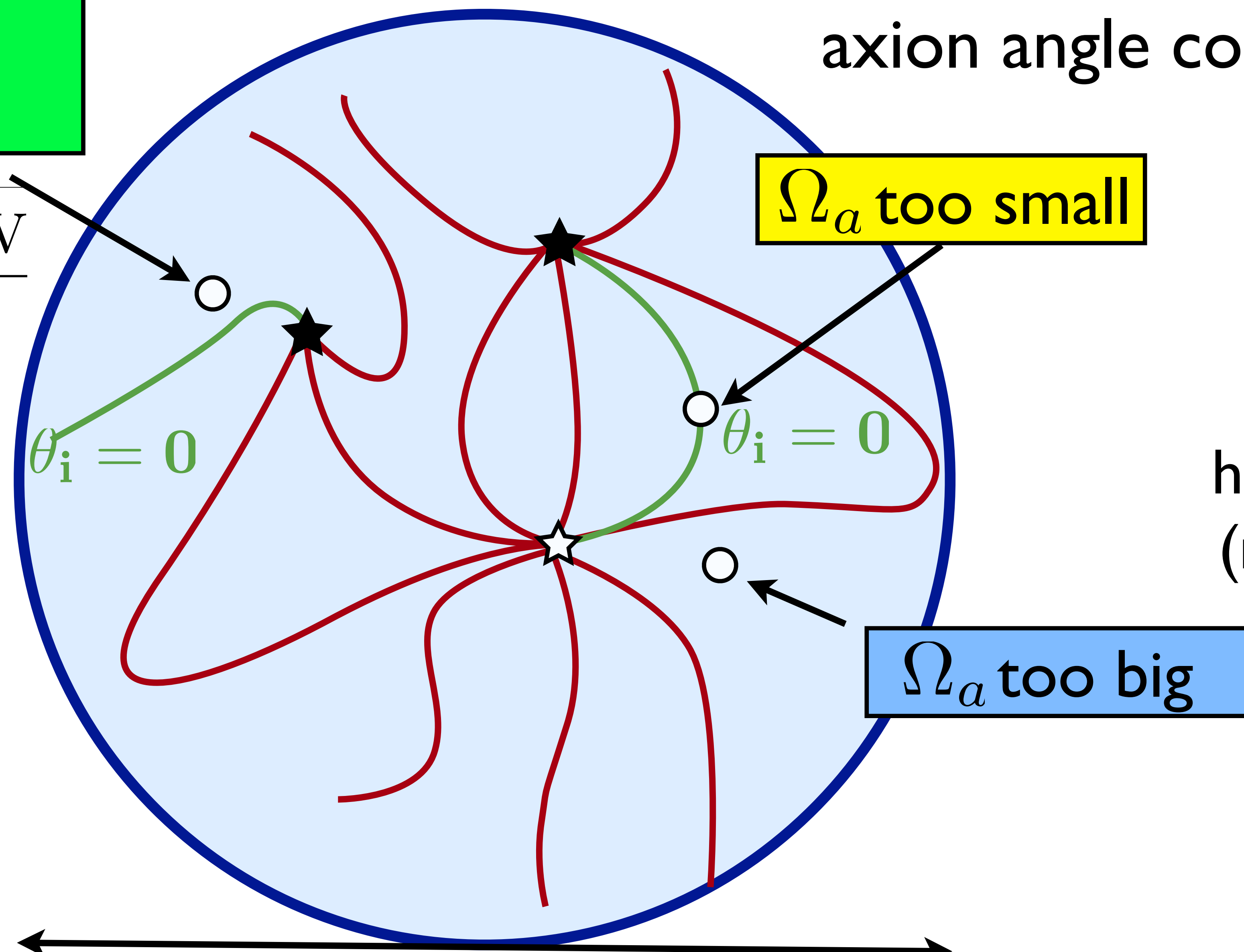

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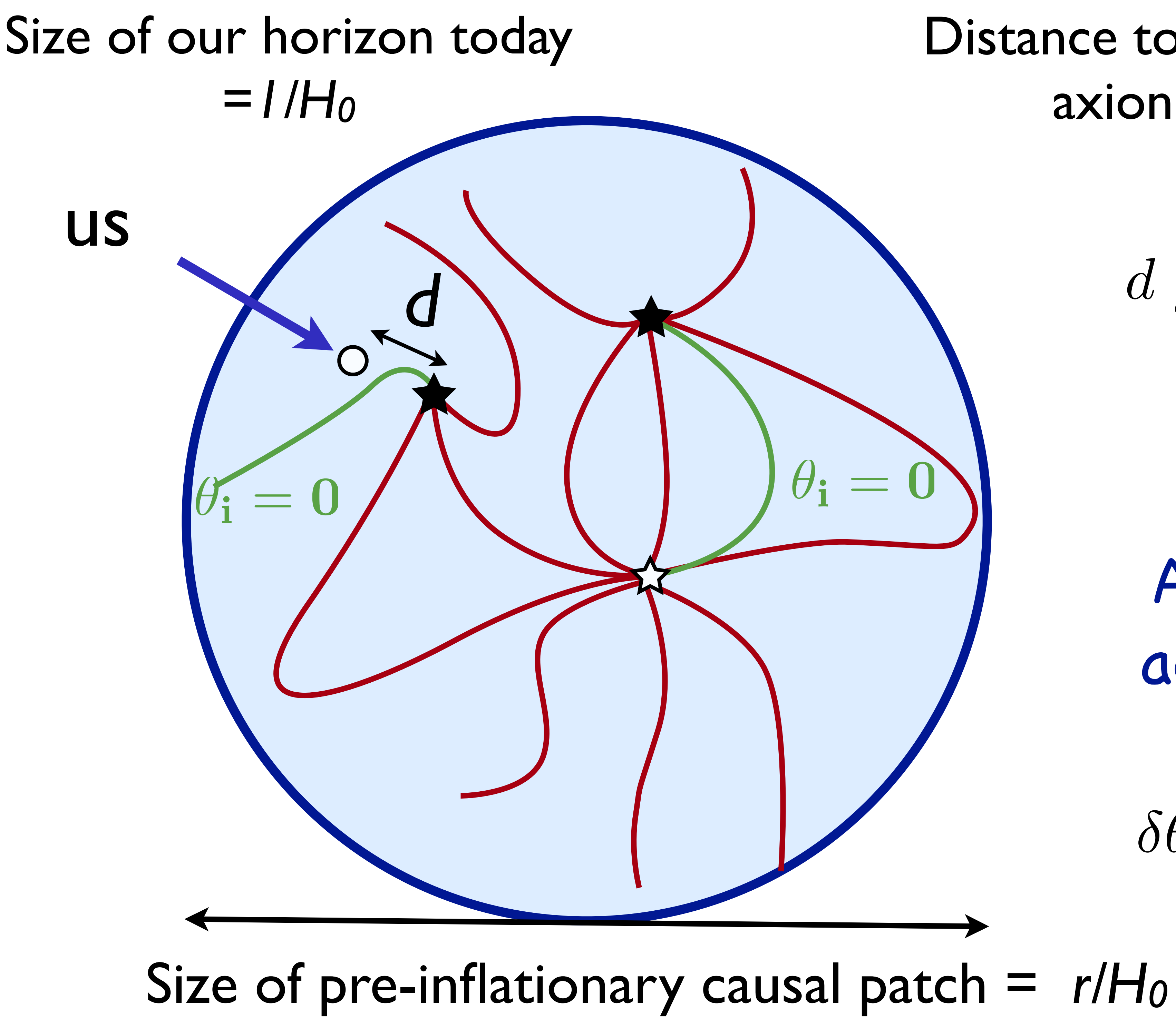
There are axion strings outside our horizon



Distance to nearest cosmic axion string = *d*

$$d \lesssim r/H_0$$

Axion angle varies across our horizon:

$$\delta\theta \sim 2\pi \frac{1/H_0}{d} = \frac{2\pi}{r}$$

Axion strings are $\leq \boldsymbol{r}$ horizon lengths away
= classical, superhorizon fluctuation
...so θ_i is not exactly constant in our horizon

$$\delta\theta_i \sim 2\pi \frac{1/H_0}{d} = \frac{2\pi}{r}$$

gives rise to dark matter gradient

$$\frac{\delta\Omega_a}{\Omega_a} \simeq 2\frac{\delta\theta_i}{\theta_i} \simeq 2\frac{(2\pi/r)}{\theta_i}$$

$$\theta_i \sim \sqrt{\frac{10^{12}\ \mathrm{GeV}}{f_a}}$$

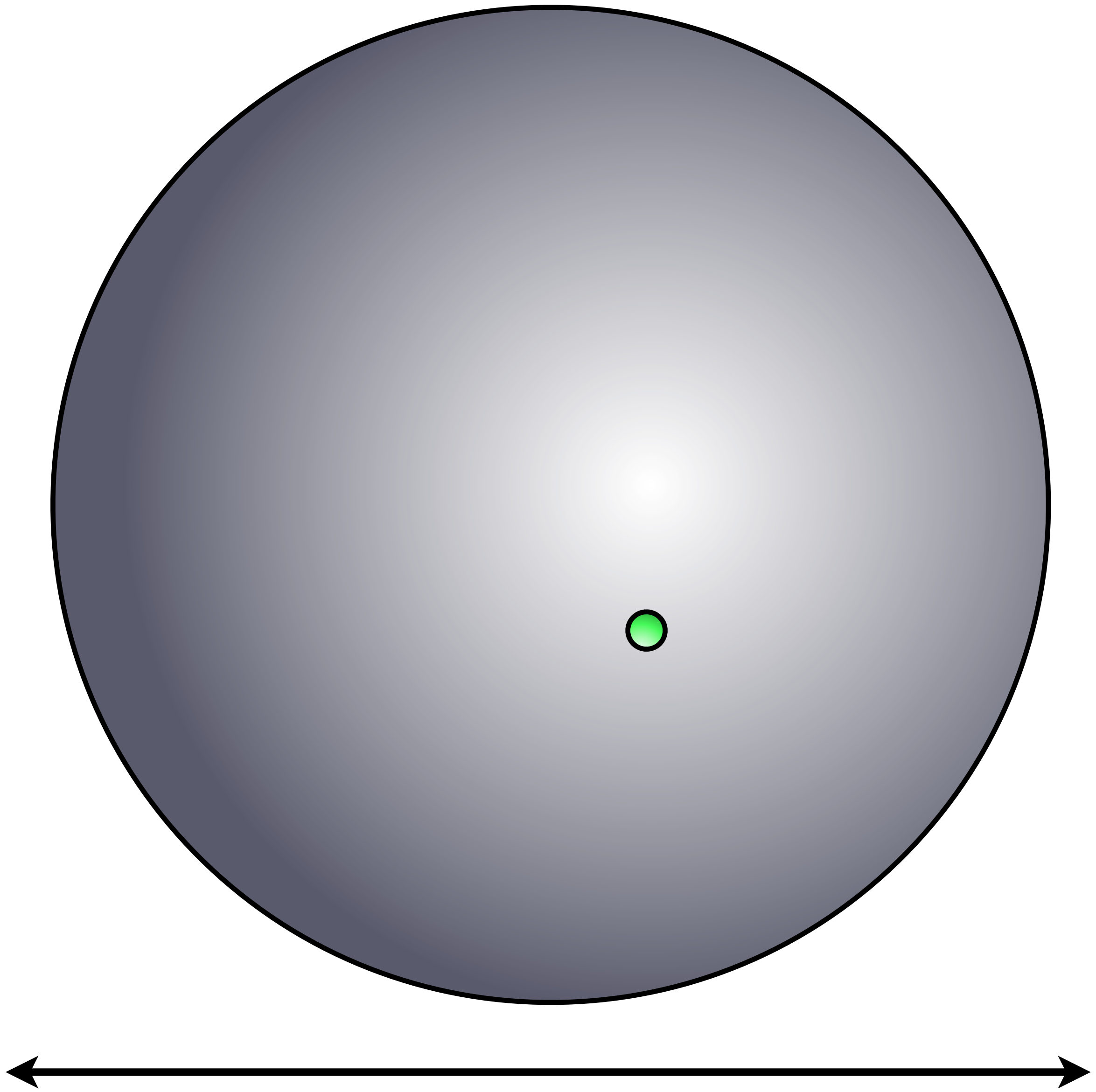
Fine tuning with **large f_a** means enhanced sensitivity to fluctuations. How do we see them? How big does r have to be?

Today's dark matter distribution is sensitive to inhomogeneities in axion angle (axion strings!) at the beginning of inflation

- There are 25-60 e-foldings of inflation **after** our horizon leaves the inflationary horizon
- Relic pre-inflationary inhomogeneities and curvature today are sensitive to the amount of inflation **r** that **precedes** horizon departure
- What are current bounds on **r**?

Inflation must solve the flatness problem:

Curvature before inflation = *O(1)*



$$r \sim \frac{\text{curvature radius}}{\text{horizon size today}} \sim \frac{1}{\sqrt{|\Omega - 1|}} \gtrsim 10$$

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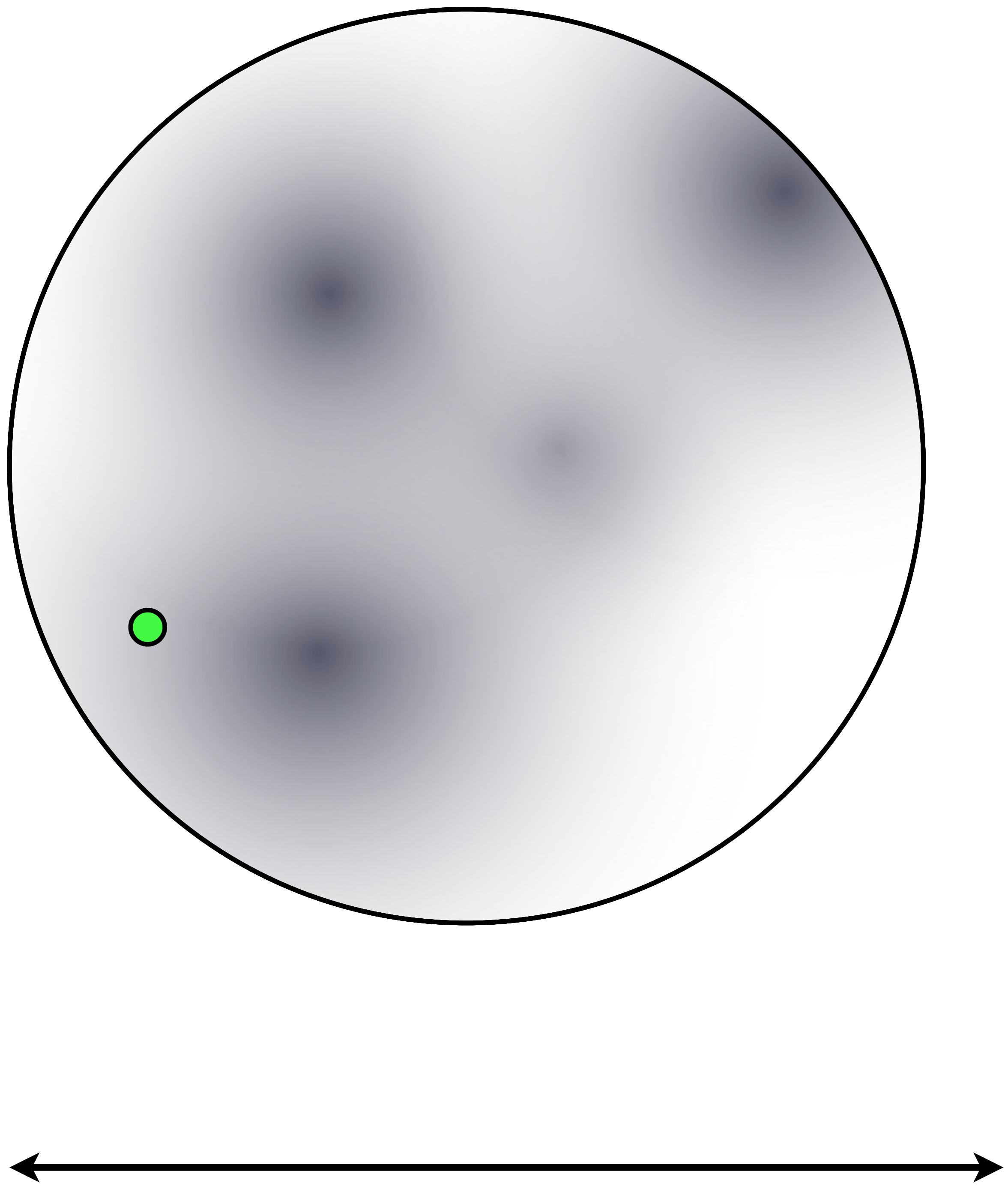
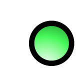


Assume: pre-inflation inhomogeneities = *O(1)* on scale of pre-inflation horizon

CMB multipoles will depend on

$$(kH_0)^\ell \sim \left(\frac{H_0}{rH_0}\right)^\ell = r^{-\ell}$$

So biggest effect of super-horizon fluctuations today are in lowest multipoles



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If you plug in super-horizon adiabatic perturbation

$$\left(\frac{\delta\rho}{\rho}\right)_k \;, \qquad k \ll \frac{1}{H_0}$$

Find for CMB $\delta T/T$:

- Monopole moment unphysical
- Dipole moment cannot be distinguished from Doppler shift from local ("peculiar") velocity; and distant matter at rest in rest frame of CMB
- Quadrupole moment puts limit:

$$1/r^2 \lesssim (3\times 10^{-5}) \qquad r \gtrsim 200$$

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Grishchuk-Zel'dovitch 1978

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Observed quadrupole

Grishchuk-Zel'dovitch 1978

Castro et al. 2003

More sophisticated: WMAP+CDMΛ $\quad r > 3900$

If you plug in super-horizon isocurvature perturbation (eg: axions!) get non Sachs-Wolfe contribution:

$$\delta\rho_{\rm rad} = -\delta\rho_a$$

Find for CMB $\delta T/T$:

- Monopole moment unphysical
- Dipole moment **can** be distinguished from Doppler shift from local "peculiar" velocity (recall: δT_γ 180° out of phase)

Intrinsic dipole in CMB ≠ dipole in gravitational potential, so no corresponding flow of matter

We will see different dipole in CMB vs redshift of distant matter (Type 1 SN)

"Tilted Universe", M. Turner, 1990

Present and future bounds on tilted universe

- Tilted universe: gradient on matter density⇒photon rest frame ≠ matter rest frame
- CMB dipole gives our proper motion in photon rest frame
- SNI surveys give our proper motion in matter rest frame (currently rough agreement with CMB, Gordon, Land, Slozar, arXiv:0711.4196)

Gordon, Land, Slozar present and forecast for future peculiar velocity relative to matter measurements:

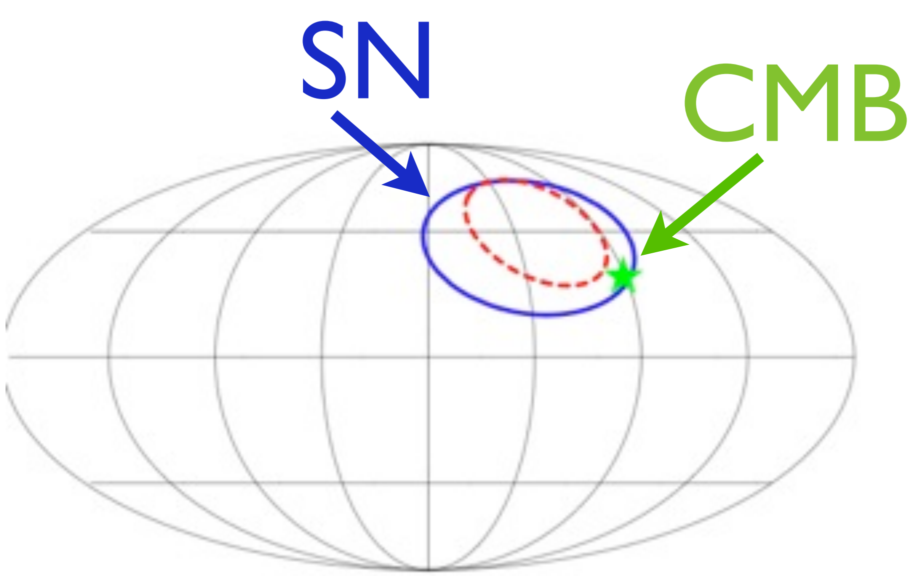

Figure 5. One sigma contours for the direction of the solar system velocity. The cases plotted are when correlated (solid) and uncorrelated (dashed) SNe peculiar velocities are used. The star shows the direction as determined by the CMB.

current

	l	b	v_O (km/s)
Solar System uncorrelated	$238 \pm 26°$	$45 \pm 14°$	475 ± 134
Solar System correlated	$234 \pm 44°$	$39 \pm 21°$	468 ± 186
Local Group uncorrelated	$260 \pm 14°$	$32 \pm 11°$	697 ± 137
Local Group correlated	$257 \pm 24°$	$29 \pm 16°$	690 ± 201

Table 1. The mean and standard deviation for the estimate of the solar system and local group velocity from current SNe data. The results for both the correlated and uncorrelated peculiar velocities are shown.

future

	l	b	v_O (km/s)
GAIA Uncorrelated PVs	8°	5°	36
LSST Uncorrelated PVs	7°	5°	32
GAIA Correlated PVS	10°	6°	42
LSST Correlated PVS	8°	5°	34

Table 2. The forecasted marginalised standard deviation for the estimate of the solar system peculiar velocity from the future SNe surveys GAIA and LSST, where SNe peculiar velocities (PVs) are treated as uncorrelated and correlated.

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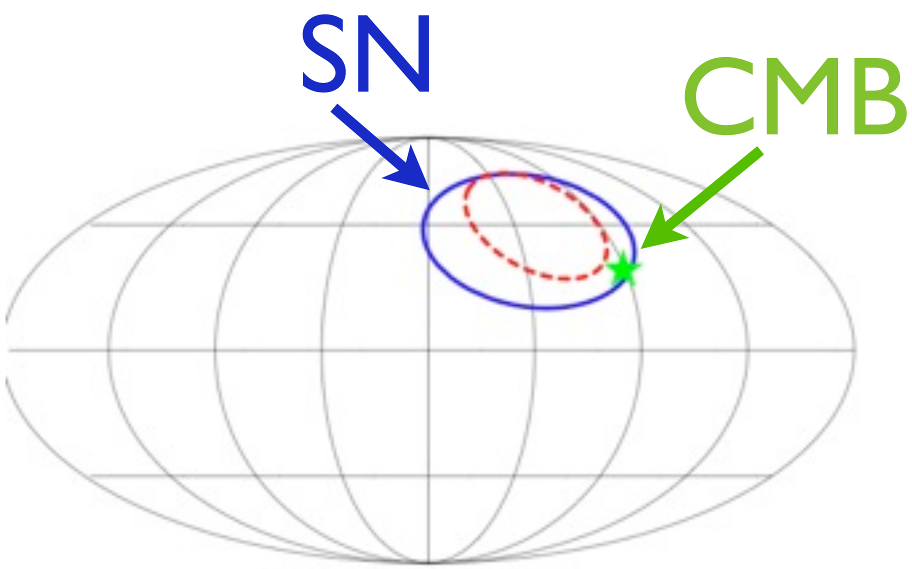

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Currently agree at ≈ 1 σ

σ will be reduced by factor of ~ 4 with GAIA, LSST

Many more recent papers indicating bulk flow of ~ 100 km/sec

e.g.:

Cosmic flows in the nearby universe from Type Ia Supernovae

Stephen Turnbull et al., 7 Nov 2011

bulk flow = 150 ± 43 km/sec

Measuring the cosmological bulk flow using the peculiar velocities of supernovae

De Chang Dai et al., 14 April 2011

bulk flow = 188 +119/-103 km/sec

Now: peculiar velocity measurements agree to $\delta v \sim 0.5 \times 10^{-3}$
Future: detect $\delta v \sim 1 \times 10^{-4}$

Fined tuned axion enhances isocurvature dipole moment

From axion strings:

$$\frac{\delta\Omega_a}{\Omega_a} \simeq 2\frac{\delta\theta_i}{\theta_i} \simeq 2\frac{(2\pi/r)}{\theta_i}$$
$$\simeq \delta v$$

small θ_i enhances dipole anisotropy of dark matter

Detectable if $\gtrsim 10^{-4}$

For $f_a \sim 10^{17}$ GeV: $\theta_i \simeq 10^{-3} \Longrightarrow$

$\delta v = 10^{-4}$ sensitive to $r = 10^7$!

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For $f_a \sim 10^{17}$ GeV: $\theta_i \simeq 10^{-3} \implies$ $\delta v = 10^{-4}$ sensitive to $r = 10^7$!

We could detect an axion string 10,000,000 times horizon lengths away (6×10^{16} light-years)

Conclusions:

- Ultralight axions (f_a ~ GUT scale, $m_a \sim 10^{-9}$ eV) remain a viable possibility for the dark matter

- Requires low scale inflation: they can be ruled out by observation of tensor perturbations in the CMB

- They may be indirectly detectable in large scale flow (Turner's Tilted Universe scenario)

  if lucky, $r \leq 10^7$

- Black hole super-radiance another possible way to detect? (Arvanitaki, Dubovsky, 2010)