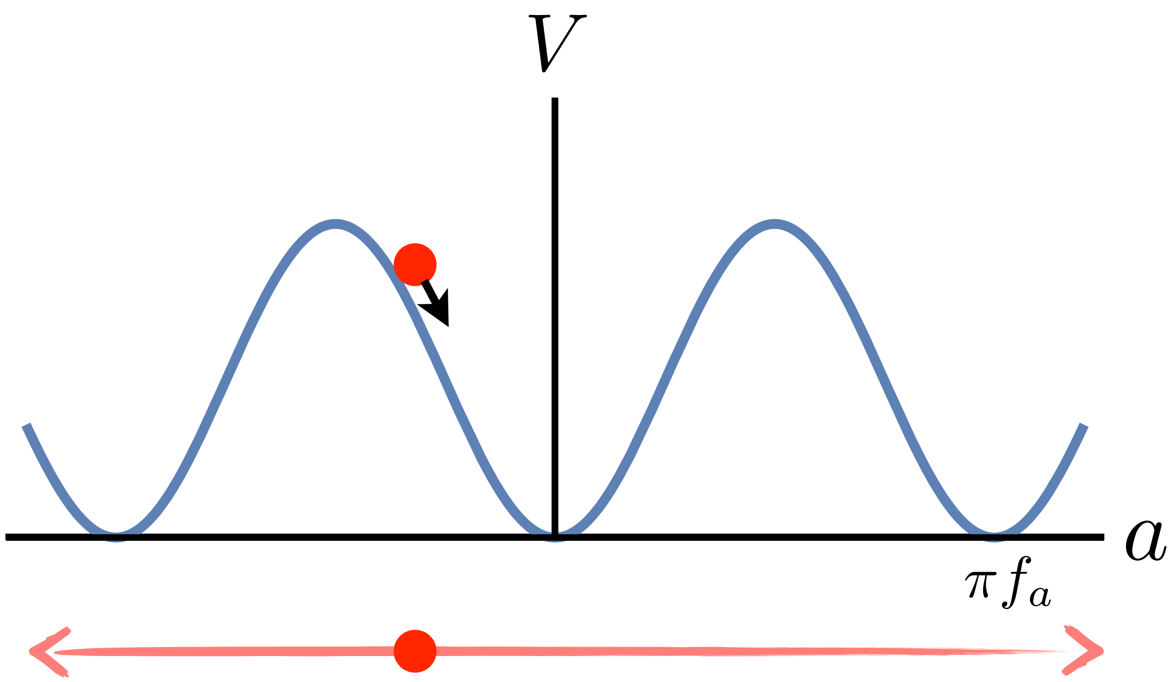
Axion and Hidden Photon Production Mechanisms

Peter W. Graham

Misalignment Production: "Pre-Inflationary Scenario"

PQ symmetry broken already during inflation (high f_a)

Nonthermal DM production mechanism:

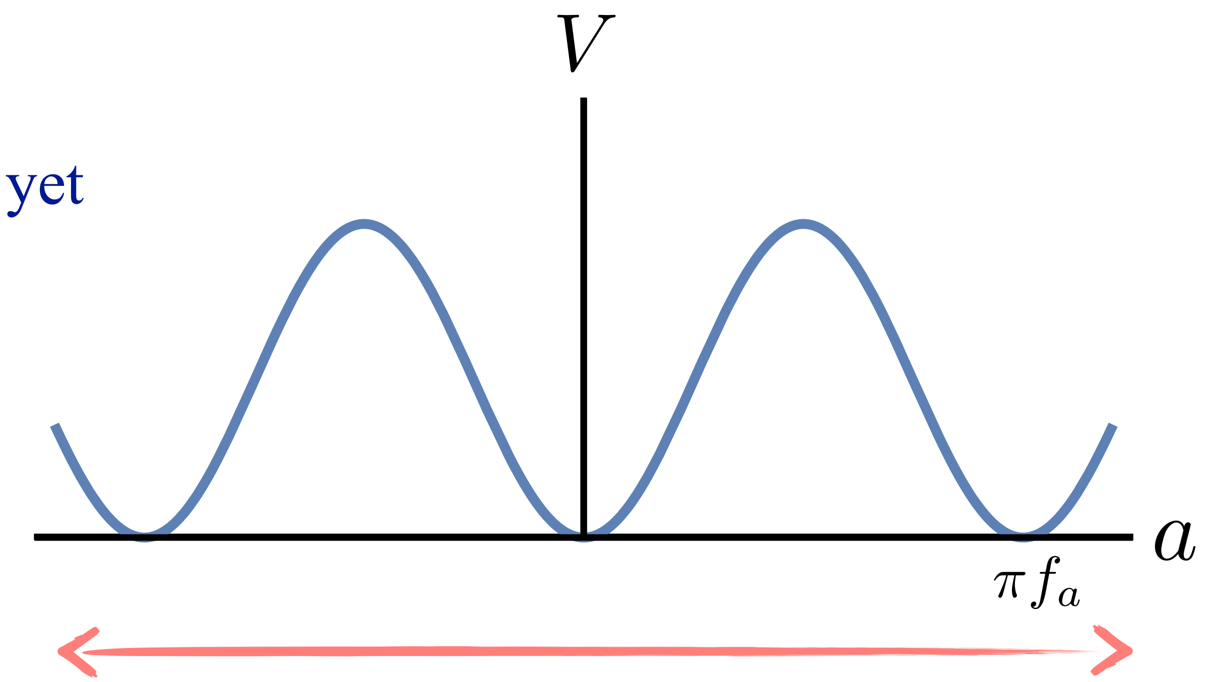


- during high-scale inflation axion potential is off
- after inflation axion field begins with some value in our Hubble patch
- around QCD phase transition axion potential turns on
- axion begins to oscillate + spatial gradients (momentum) low from inflation ➜ axion is cold DM
- abundance is right for DM if $m_a \sim 10^{-5}\,\mathrm{eV}$ and $\theta_{\rm in} \sim \frac{a_{\rm in}}{f_a} \sim 1$
- for lower masses require smaller $\theta_{\rm in}$ to avoid "overclosure", often called lower bound on axion mass, in fact only a very mild "accident": $\theta_{\rm in} \sim \sqrt{\frac{m_a}{10^{-5}\,\mathrm{eV}}}$

light fields naturally produced non-thermally in large abundance

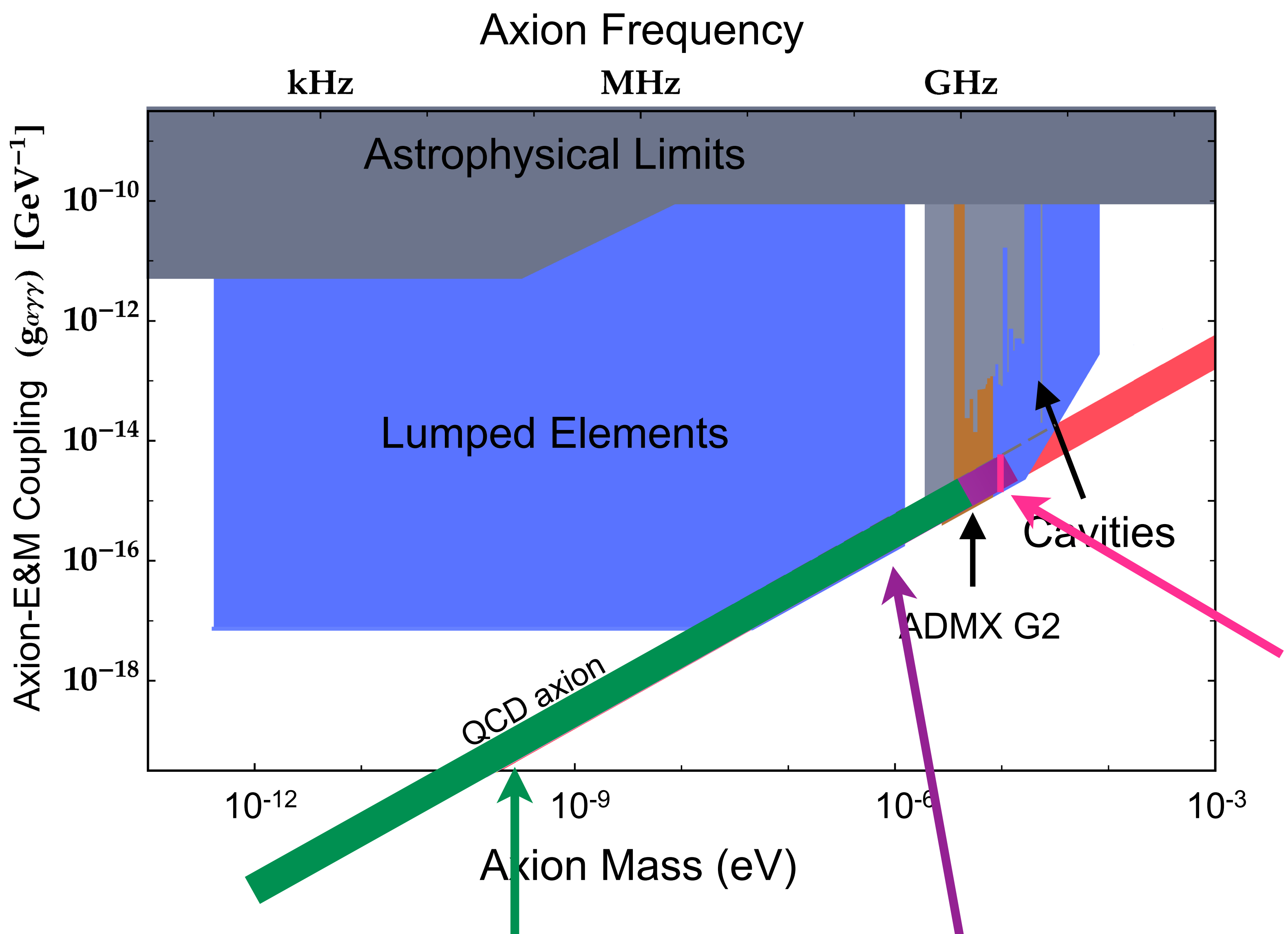
"Post-Inflationary Scenario"

PQ symmetry breaks after inflation



- before PQ breaks axion field value not determined yet
- PQ symmetry breaks after inflation
  ➜ axion field initially distributed
  over entire range
- around QCD phase transition potential turns on and axion begins to oscillate
- form axion strings, hard to calculate exact contribution to abundance
- abundance is right for DM at only a single value of axion mass ~ few GHz (large theory "error" due to QCD, strings)
- may form small-scale structure (minihalos, miniclusters, axion stars…), hard to calculate. Uncertain how much of the axion DM tied up in these from none to almost all of it
- note if almost all tied up in clumps ➜ drastic effect on direct detection experiments

Mass Ranges



post-inflation

pre-inflation misalignment

many other cosmological scenarios produce low mass axions e.g.: stochastic axion scenario, entropy generation…

Agrawal,Marques-Tavares,Xue; Nomura,Rajendran,Sanches; Dine,Fischler; Steinhardt,Turner; Lazarides,Schaefer,Seckel,Shafi; Kawasaki,Moroi,Yanagida; Dvali; Choi,Kim,Kim; Banks,Dine; Banks,Dine,Graesser

The Stochastic Axion Scenario

PWG & A. Scherlis PRD **98** (2018) arXiv:1805.07362

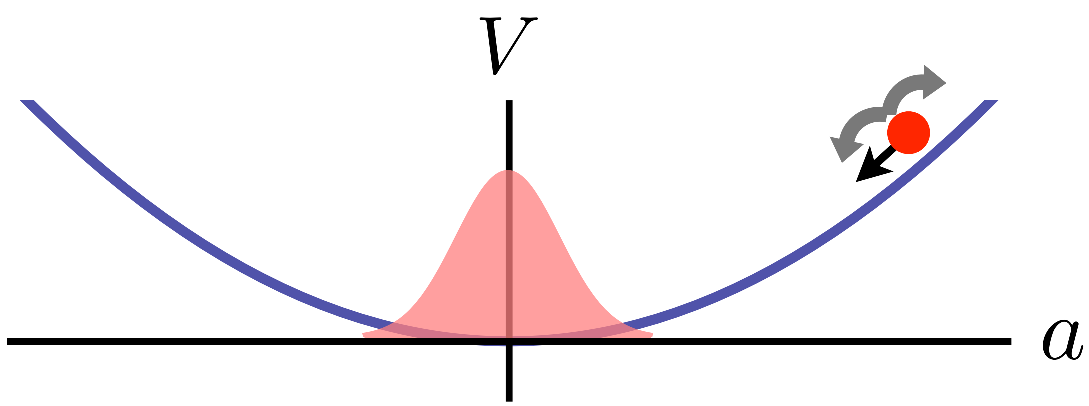
Takahashi, Yin, & Guth PRD **98** (2018) arXiv:1805.08763

A New Origin for QCD Axion Dark Matter

During high-scale inflation axion is fixed ➜ "misalignment production"

but in low-scale inflation, axion will damp

- axion potential is on
- Hubble friction is low enough



but axion also spreads ("hops") from quantum fluctuations

competition between wavepacket spreading and potential ➜

axion tends toward an equilibrium (vacuum state)

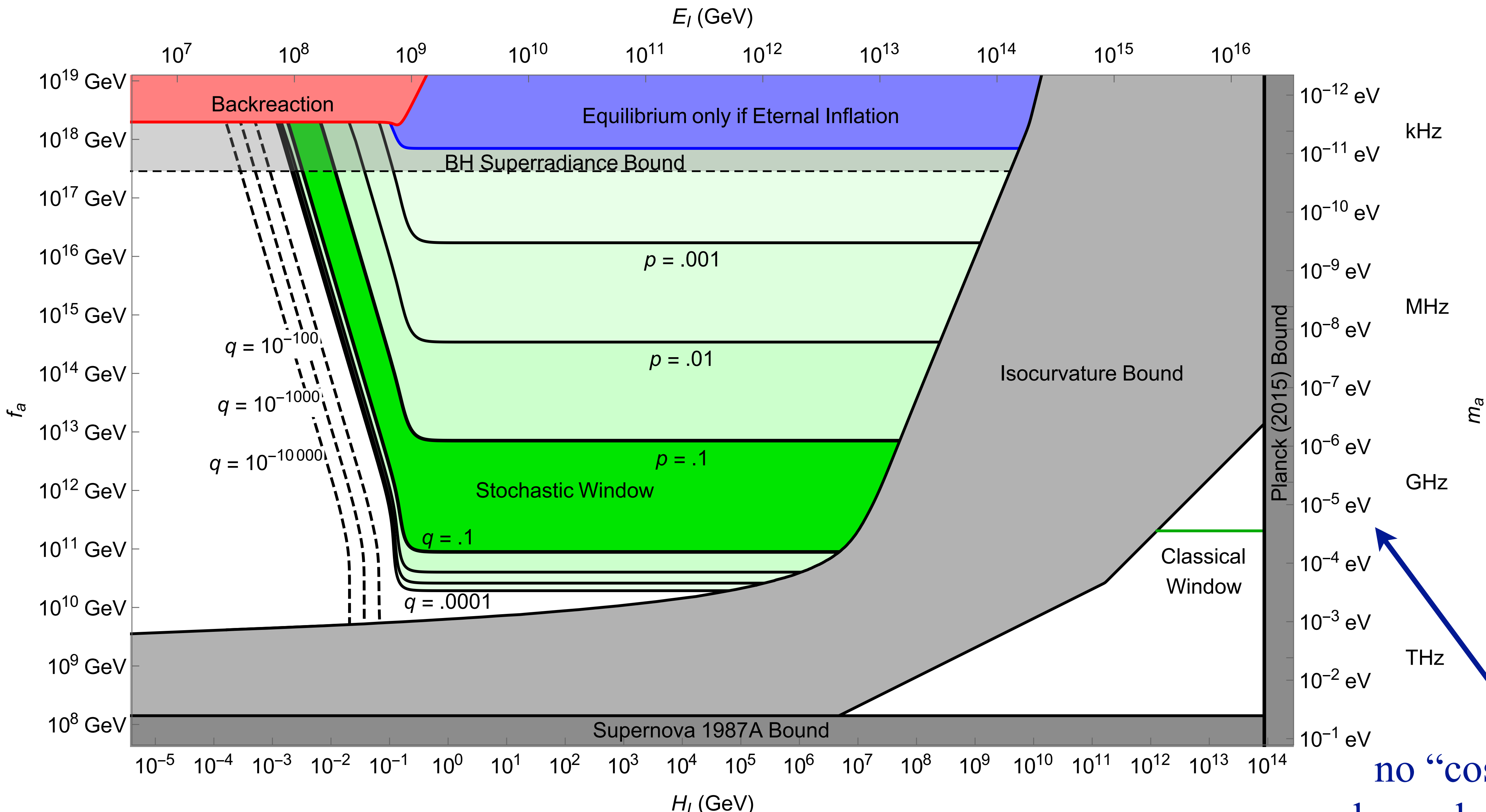
independent of initial conditions!

The Stochastic Axion Scenario

PWG & Scherlis PRD **98** (2018)
arXiv:1805.07362

a new production mechanism which strongly motivates searching entire axion mass range

avoids isocurvature bounds even though produced from quantum fluctuations



no “cosmological" lower bound on mass

many other cosmological scenarios also produce QCD axion DM of any mass

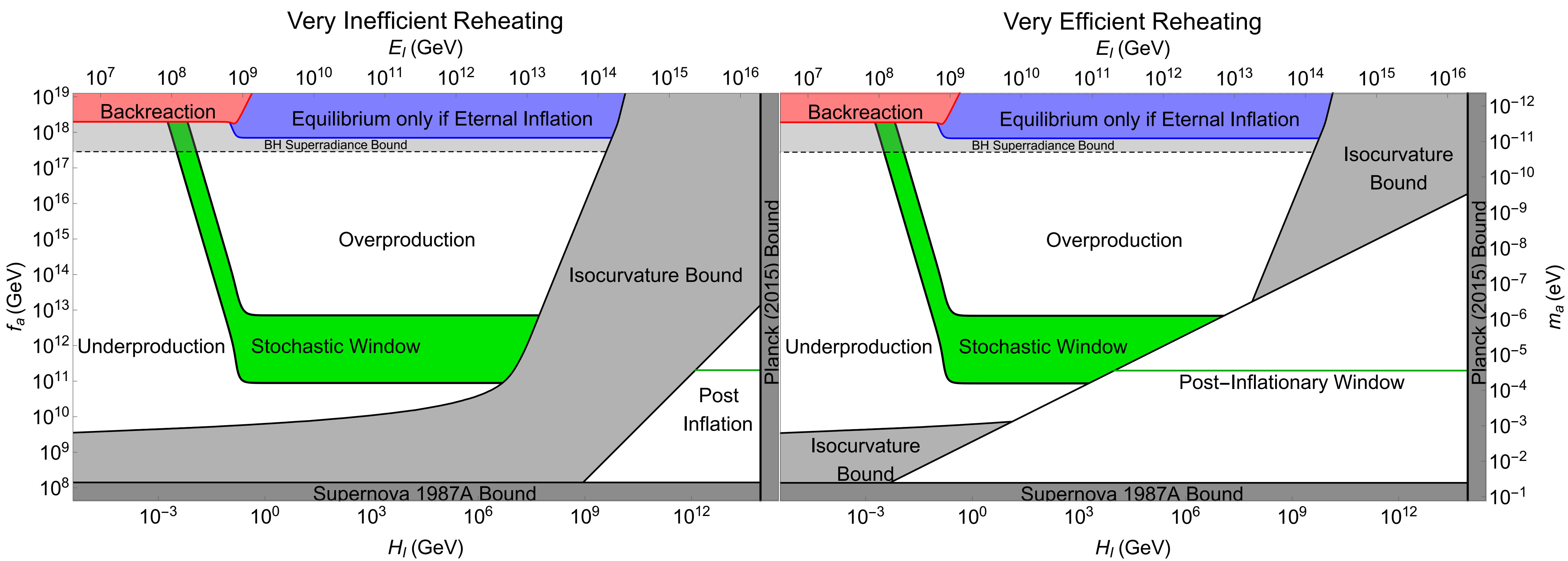
Agrawal,Marques-Tavares,Xue; Nomura,Rajendran,Sanches; Dine,Fischler; Steinhardt,Turner; Lazarides,Schaefer,Seckel,Shafi; Kawasaki,Moroi,Yanagida; Dvali; Choi,Kim,Kim; Banks,Dine; Banks,Dine,Graesser

Results: Reheating

All of this is irrelevant if temperature hits f_a during

1. Inflation: $T_{dS} \sim H_I$
2. Reheating: $T_{rh} \sim \epsilon_{eff}\sqrt{m_P H_I}$

Inefficient reheating: $T_{dS} > T_{rh}$ at high H_I



Note: $T_{rh} \gg$ TeV unless extremely inefficient.

Hidden Photons

Naturally produced during inflation: to get all of DM need a mass ~ GHz
(could be lower and some subdominant fraction of DM)

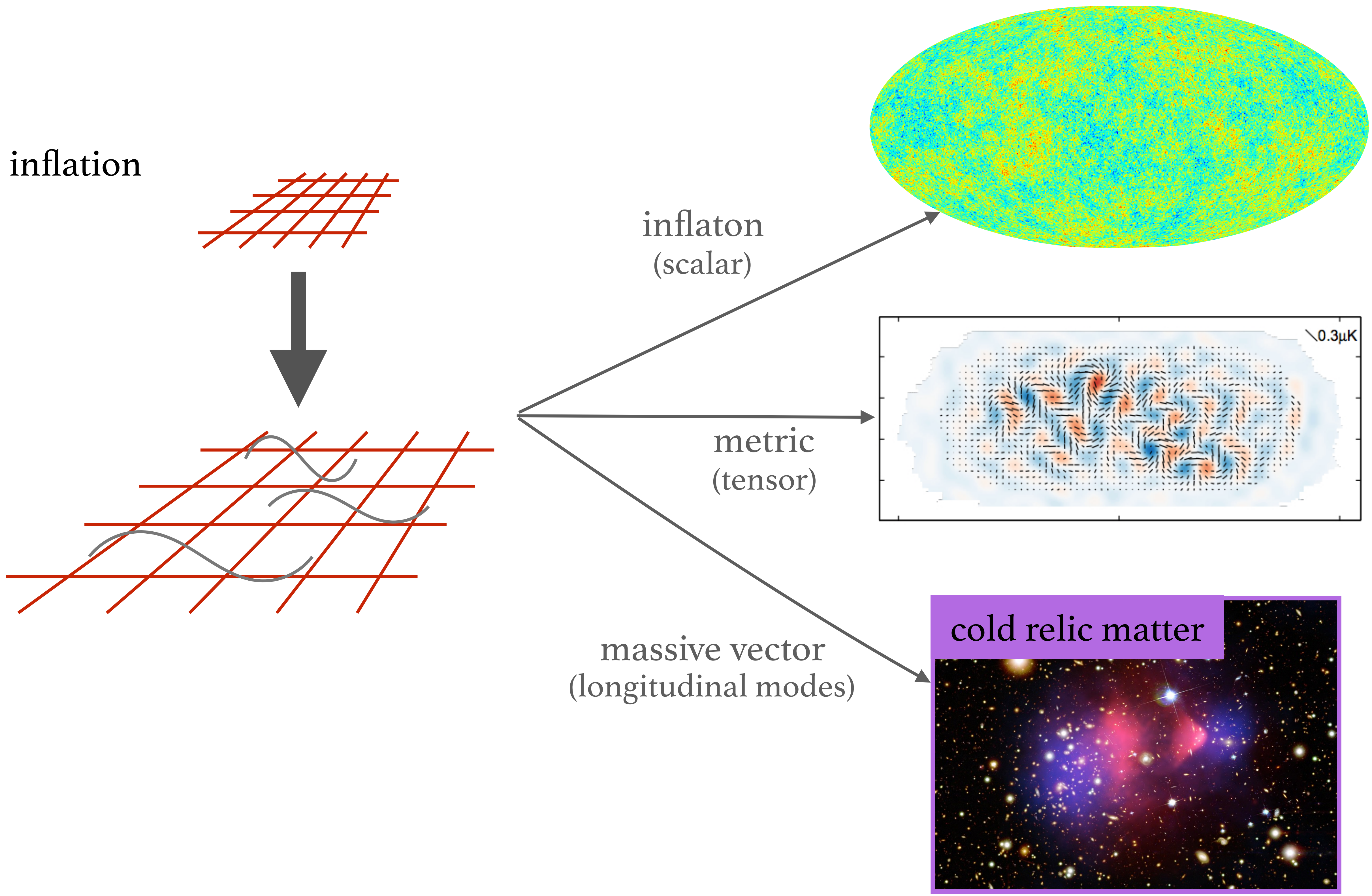
PWG, J. Mardon, & S. Rajendran 1504.02102

Production from a scalar gives any light mass

Dror, Harigaya & Narayan 1810.07195

Co, Pierce, Zhang & Zhao 1810.07196

Inflationary Production of Massive Vector



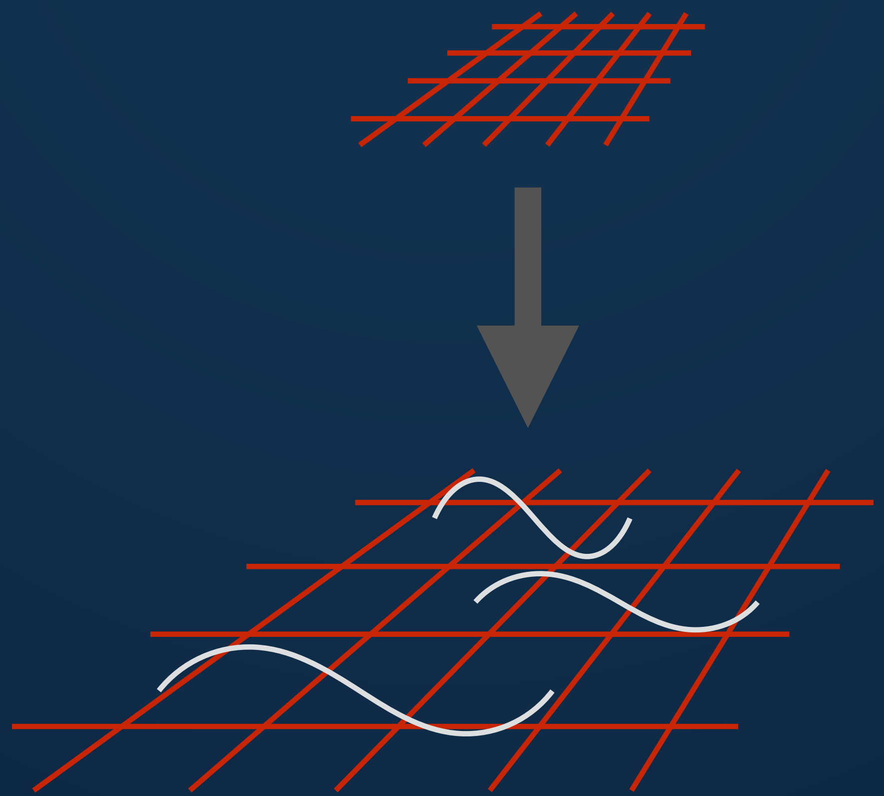
PWG, J. Mardon, & S. Rajendran 1504.02102

Inflationary Vector Production

Free massive vector field: $$\mathcal{L} \sim F'^2 + m^2 A'^2$$

Inflation $\longrightarrow$ $O(H_I)$ field fluctuations $\longrightarrow$ classical abundance

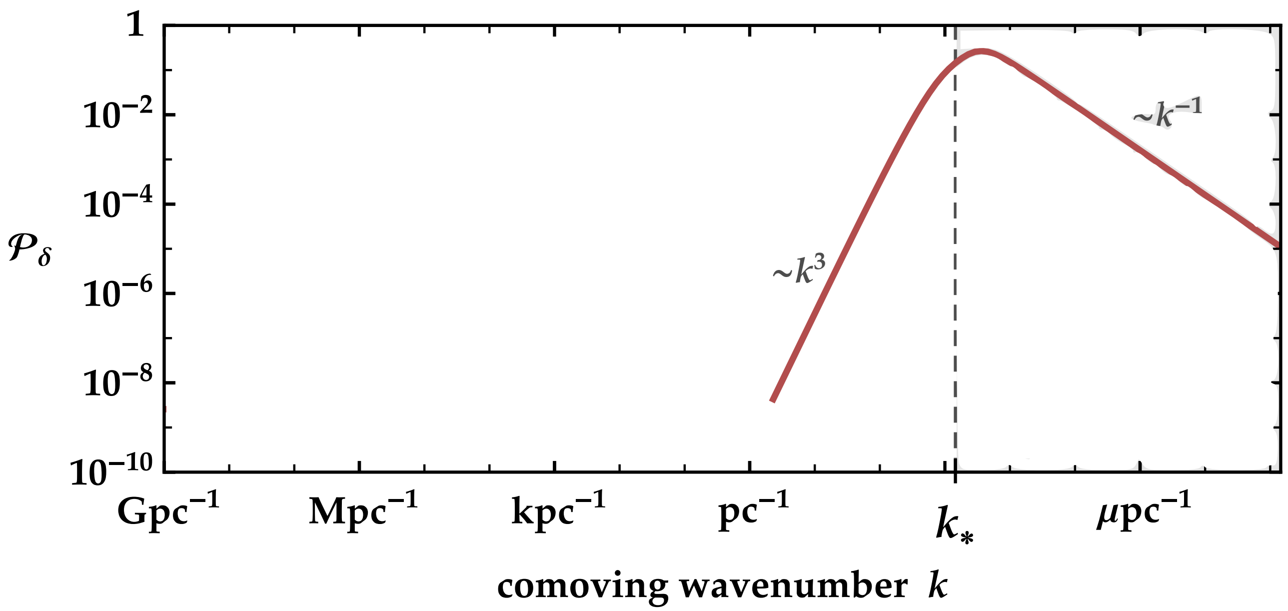
redshifting $\longrightarrow$ cold matter today



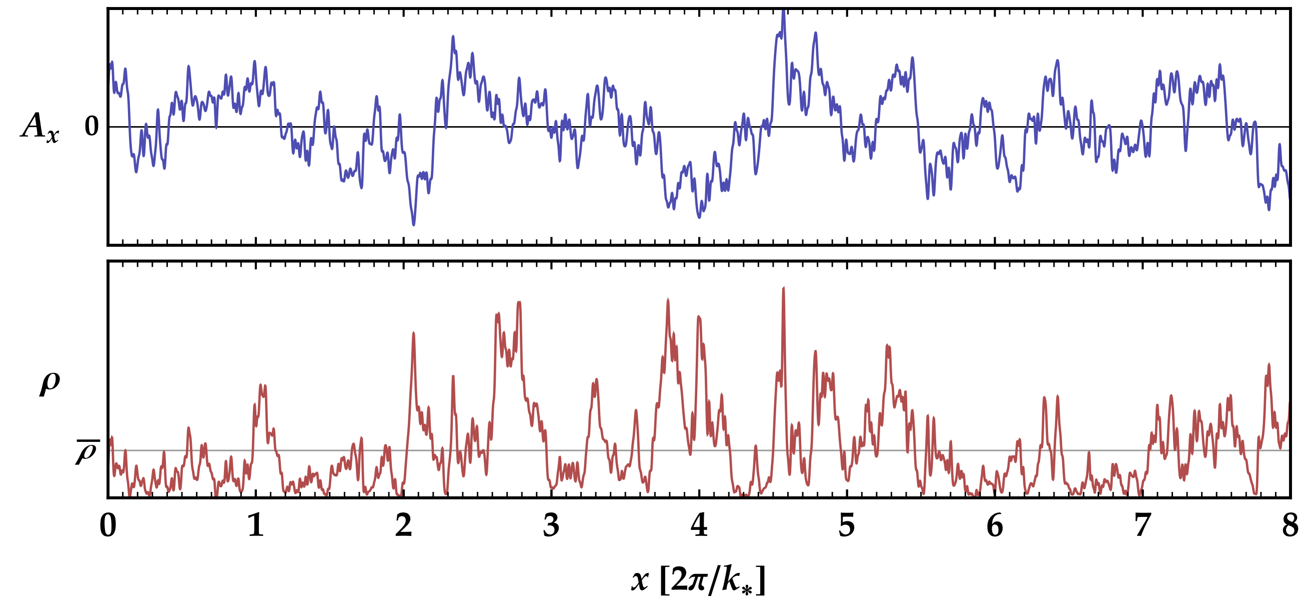
Jeremy Mardon, SITP, Stanford

Relic vector matter

Power spectrum



Large short-scale fluctuations



scalar: scale-invariant on long scales $\longrightarrow$ isocurvature problem

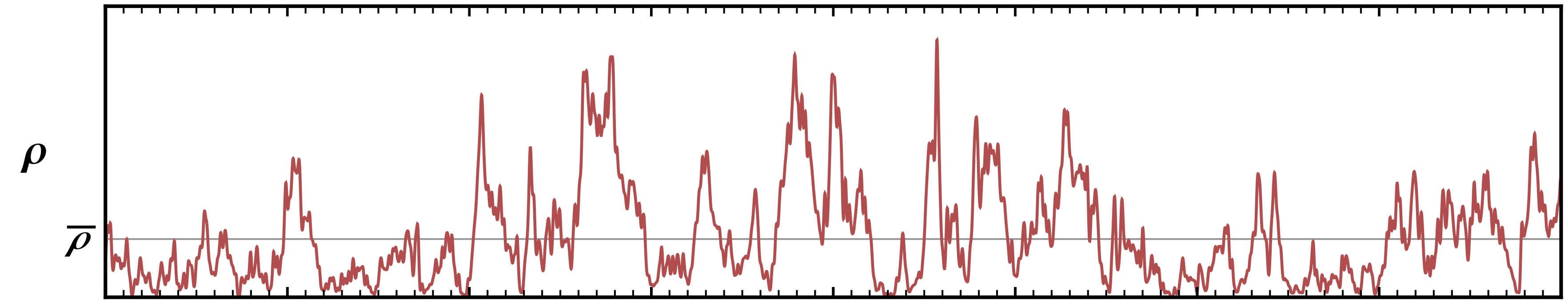
vector: suppressed power on long scales $\longrightarrow$ NO isocurvature problem

Abundance set by H_I and m:

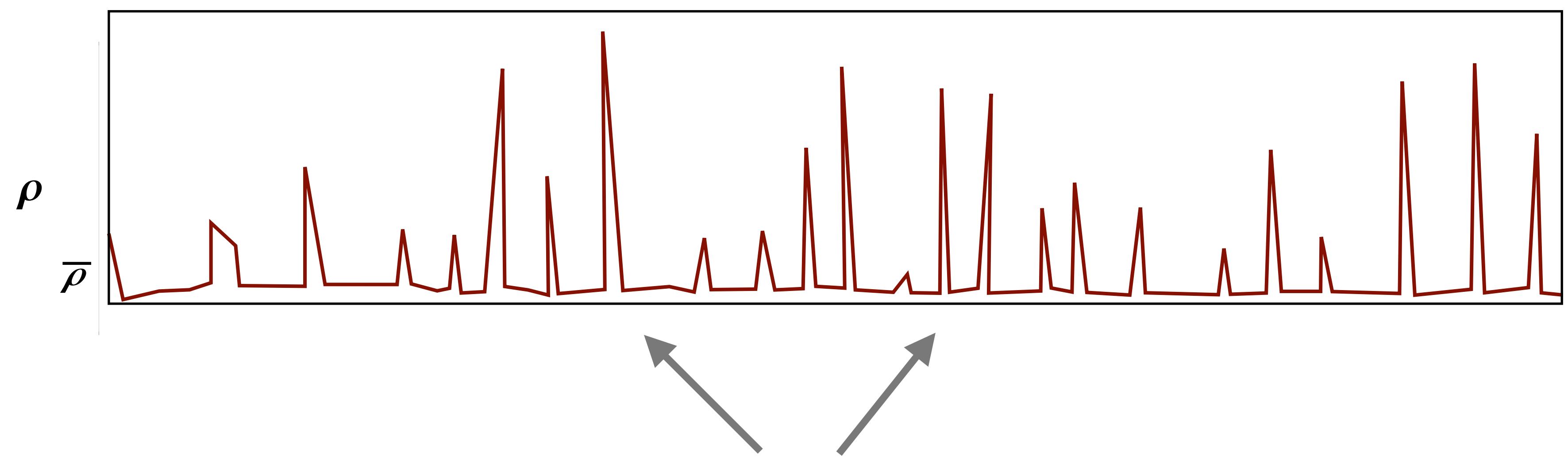
$$\frac{\Omega_A}{\Omega_{\rm cdm}} \approx \sqrt{\frac{m}{6\times 10^{-6}\,\mathrm{eV}}}\left(\frac{H_I}{10^{14}\,\mathrm{GeV}}\right)^2$$

Substructure (best guess)

Primordial fluctuations (pre m.r.e.)



Self-bound clumps (post m.r.e.)



time

small clumps

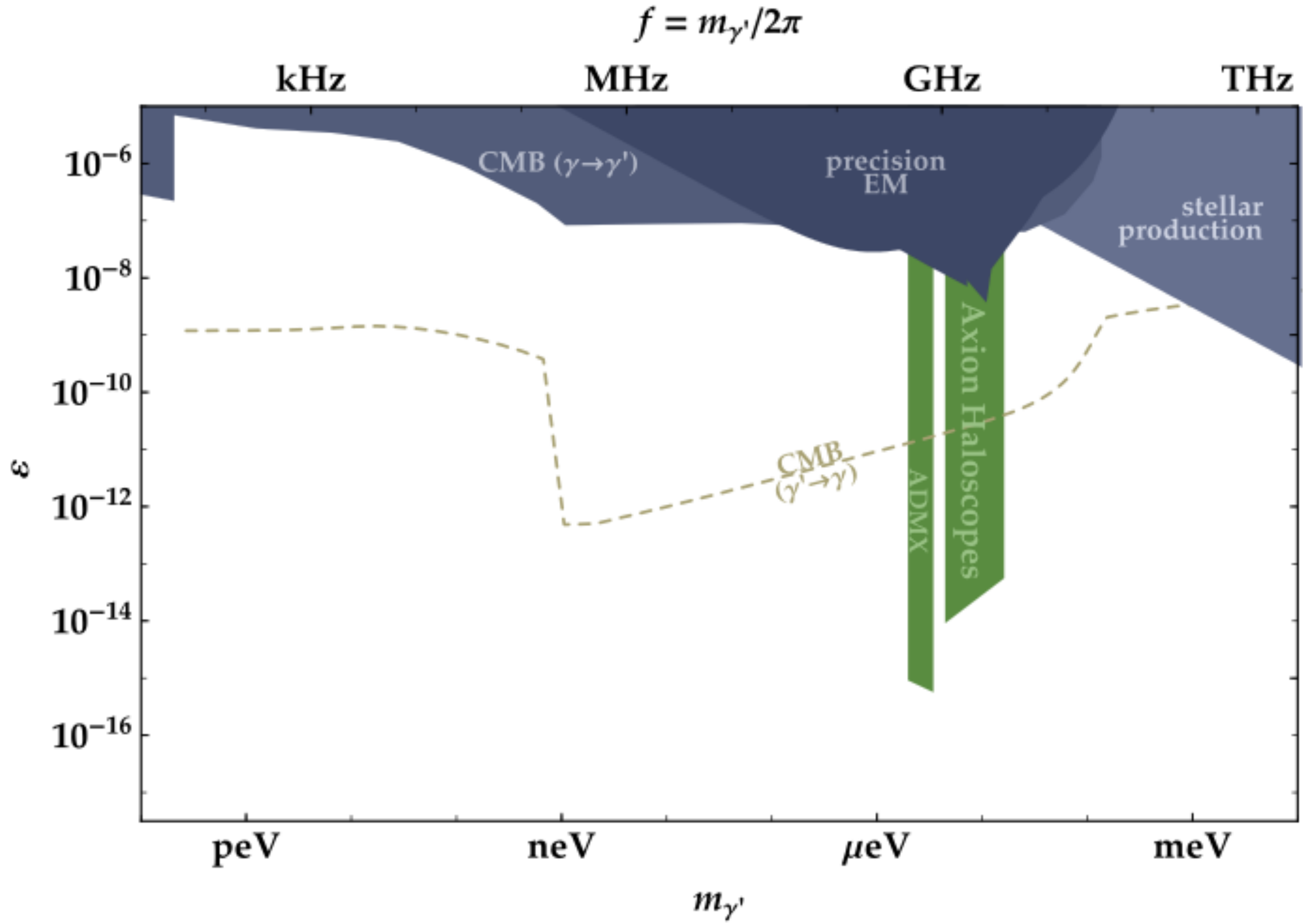
density ~ϱ_{mre} (10^6 overdense)

size ~ $L_{mre} \ll$ 1A.U.

spacing ~ $(a_0/a_{mre})L_{mre} \lesssim$ 1A.U.

Hidden Photons

coupling
to E&M



Clumping Implication for Searches?

- Large small-scale clumping is a general possibility
- ρ in lab varies over time
- $\rho \longrightarrow \sim 10^6 \rho$ when in clump (or more?)
- $\longrightarrow$ signal is HUGE and easy to see…

  …IF at right frequency
- Best strategy: scan range fast and repeat (maximizes chance of hitting frequency when in clump)?

Backup Slides

A New Origin for QCD Axion Dark Matter

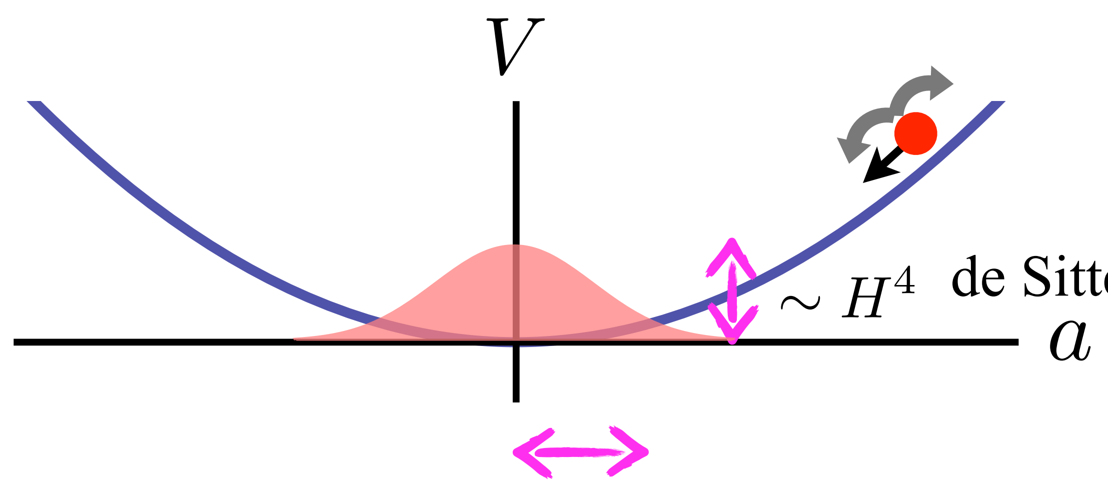
PWG & Scherlis (2018); Guth, Takahashi, Yin (2018)

But in lower scale inflation, axion potential is on during inflation

➜ zero is a preferred point for axion

biased random walk

- classical sliding
- quantum spreading "hopping"



axion tends toward an equilibrium

➜ the vacuum state (Bunch-Davies)

$m_a^2 a^2 \sim H^4$ ➜ $\sim \frac{H^2}{m_a}$ ➜ $\theta_{\rm in} \sim \frac{a_{\rm in}}{f_a} \sim \frac{H^2}{\Lambda^2_{\rm QCD}}$

Fokker-Planck: $\dot{\rho}\,(a,t) = \frac{1}{3H}\partial_a\,(V'(a)\rho(a,t)) + \frac{H^2}{8\pi^2}\partial^2_{aa}\rho(a,t)$

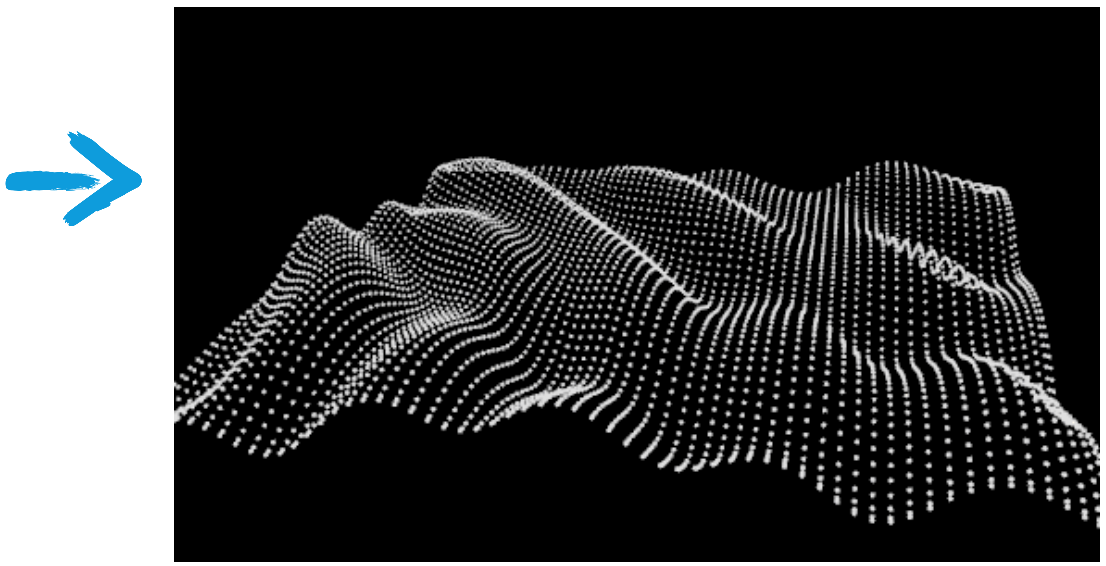
naturally gives small $\theta_{\rm in}$ ➜ easily gives correct DM abundance

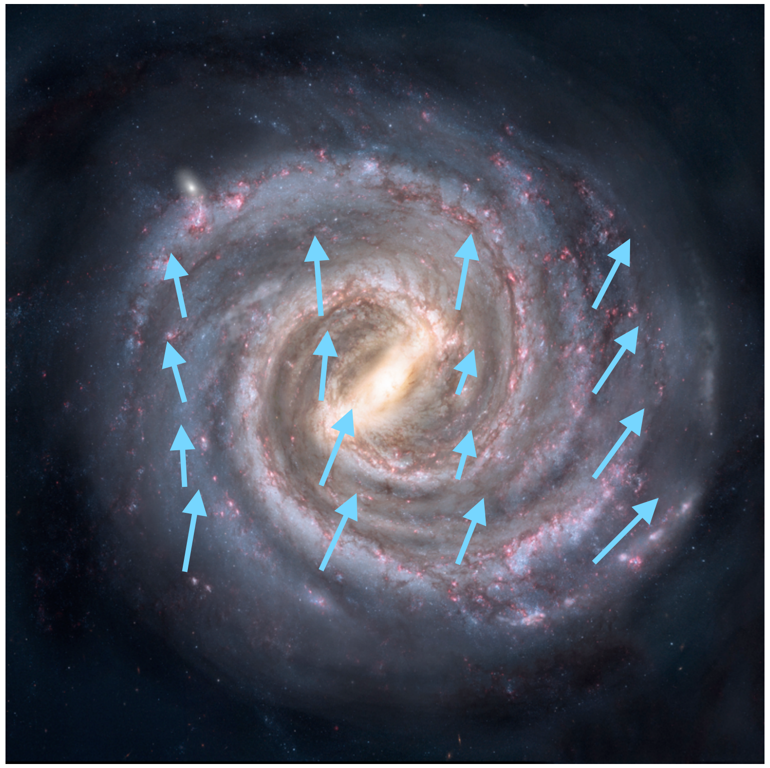
independent of initial conditions

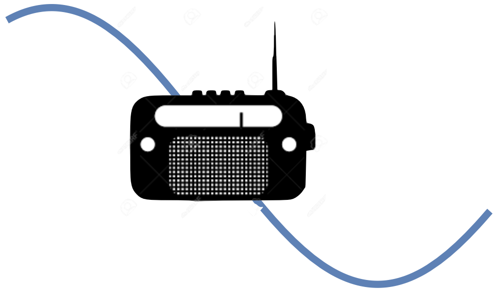
“Field” Dark Matter

particle DM

DM at long deBroglie wavelength useful to picture as a “coherent” field:







signal frequency = DM mass = m

spread by DM kinetic energy $\sim mv^2$

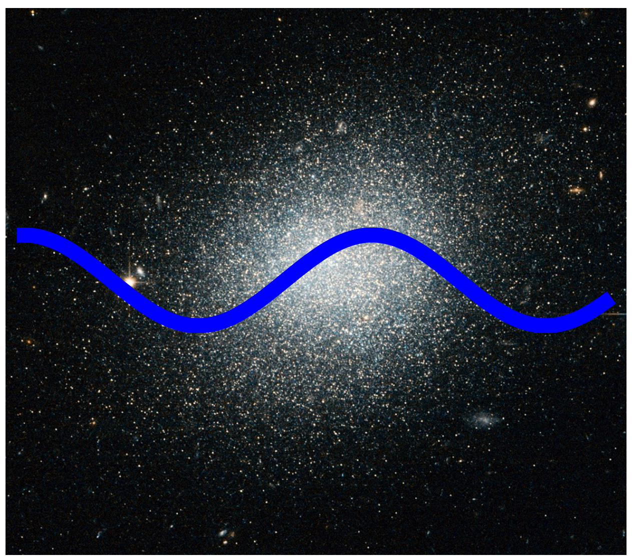
galactic virial velocity $v \sim 10^{-3}$ ➜ line width $\sim 10^{-6} m$

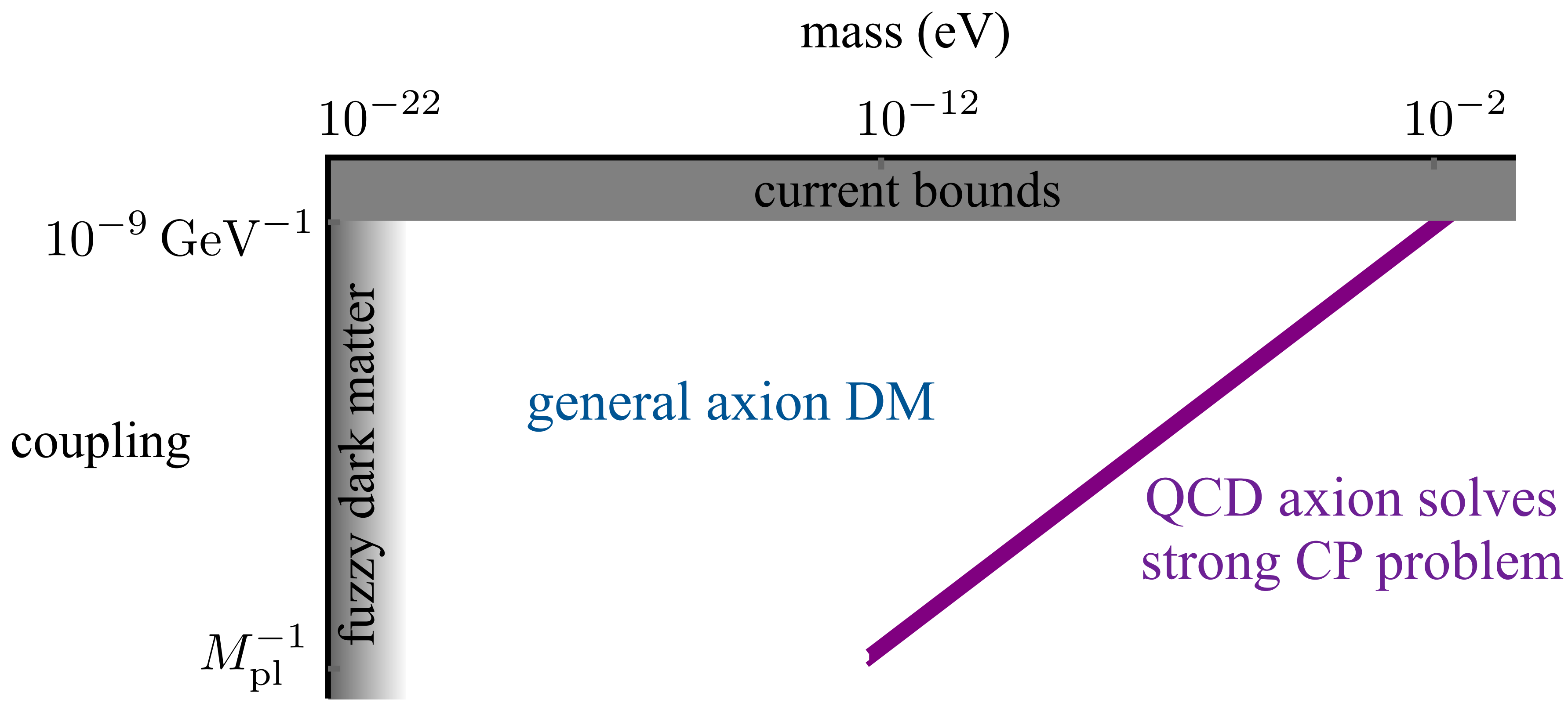
➜ coherence time, $Q \sim 10^6$ periods

The Axion

One of the best-motivated dark matter candidates ➜ how do we discover it?

Allowed parameter space:





Allowed couplings to SM:

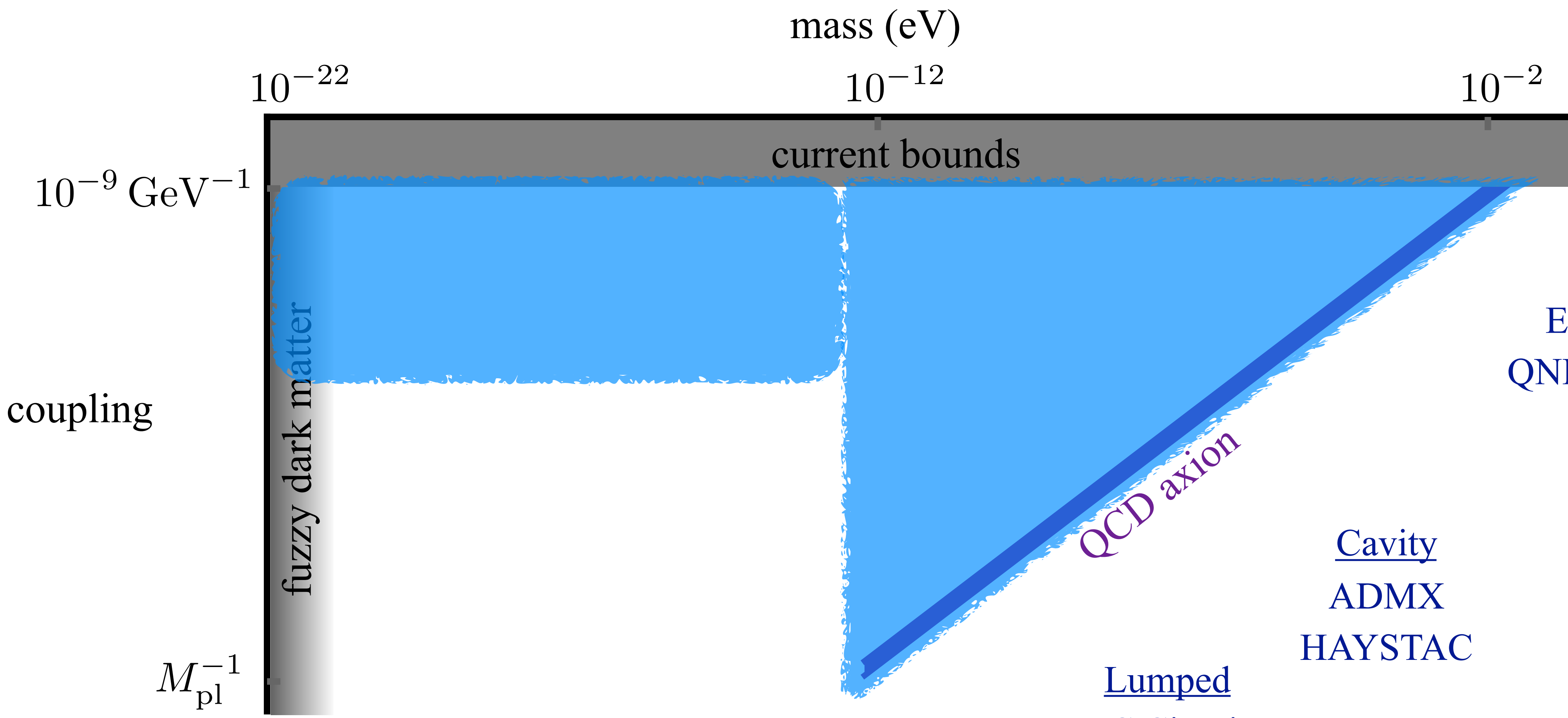
E&M - drive currents $\frac{a}{f} F\tilde{F}$

QCD - change nuclear properties $\frac{\partial_\mu a}{f} G\tilde{G}$

spin - cause precession $\frac{\partial_\mu a}{f}\bar{\psi}\gamma^\mu\gamma_5\psi$

scalar - new force/SM properties (relaxion solves hierarchy problem)

Ultralight Dark Matter Detection



Atomic interferometers + clocks
Torsion pendulums
Atomic magnetometers
CMB polarization
Pulsars
+ more!

<u>NMR</u>
CASPEr

<u>Lumped</u>
LC Circuit
ABRACADABRA
DM Radio

<u>Cavity</u>
ADMX
HAYSTAC

EM resonators &
QND photon counting
MADMAX
ORPHEUS
ARIADNE
IAXO
+ more!

and "light dark matter detectors"

Cover entire QCD axion

+ broad general axion (& dark photon) parameter space ~20 orders of magnitude in mass

likely more good ideas out there!

Axion Dark Matter Detection with the CMB

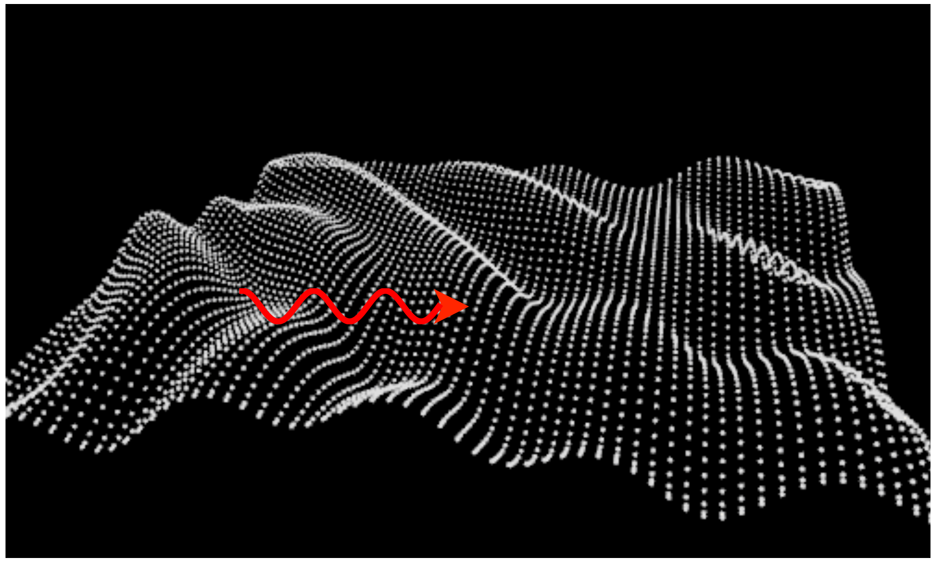
with

Michael Fedderke
Surjeet Rajendran

PRD **100** (2019)

Polarization Rotation and the CMB

a background axion field causes polarization rotation of light

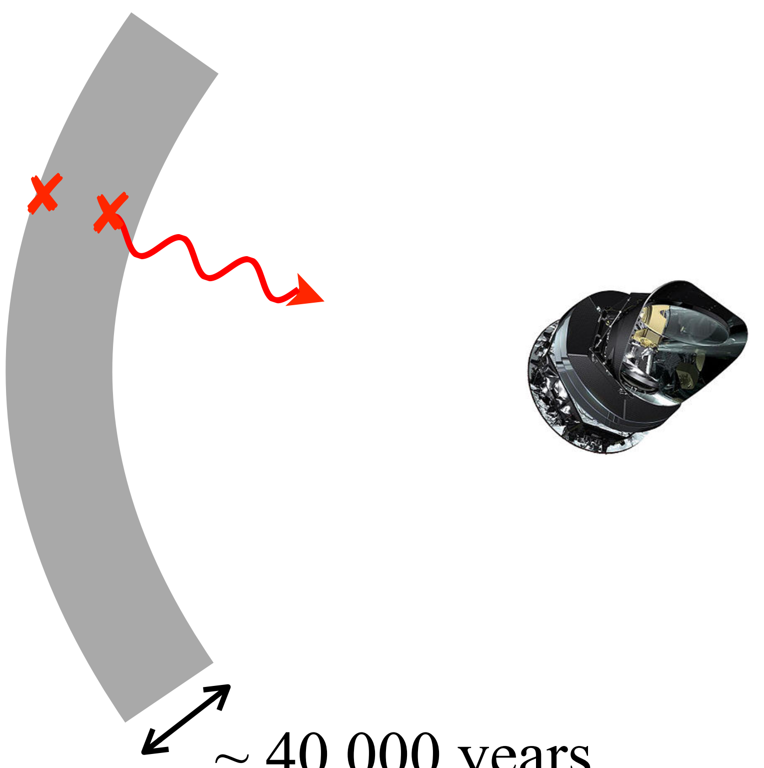


$$\Delta\theta = \frac{g_{a\gamma\gamma}}{2}\left(a_{\text{absorb}} - a_{\text{emit}}\right)$$

for axion DM: $a(t) \sim a_0 \cos\left(m_a t\right)$

potentially many observable effects, in lab and from astrophysical sources

last scattering surface



two observable effects:

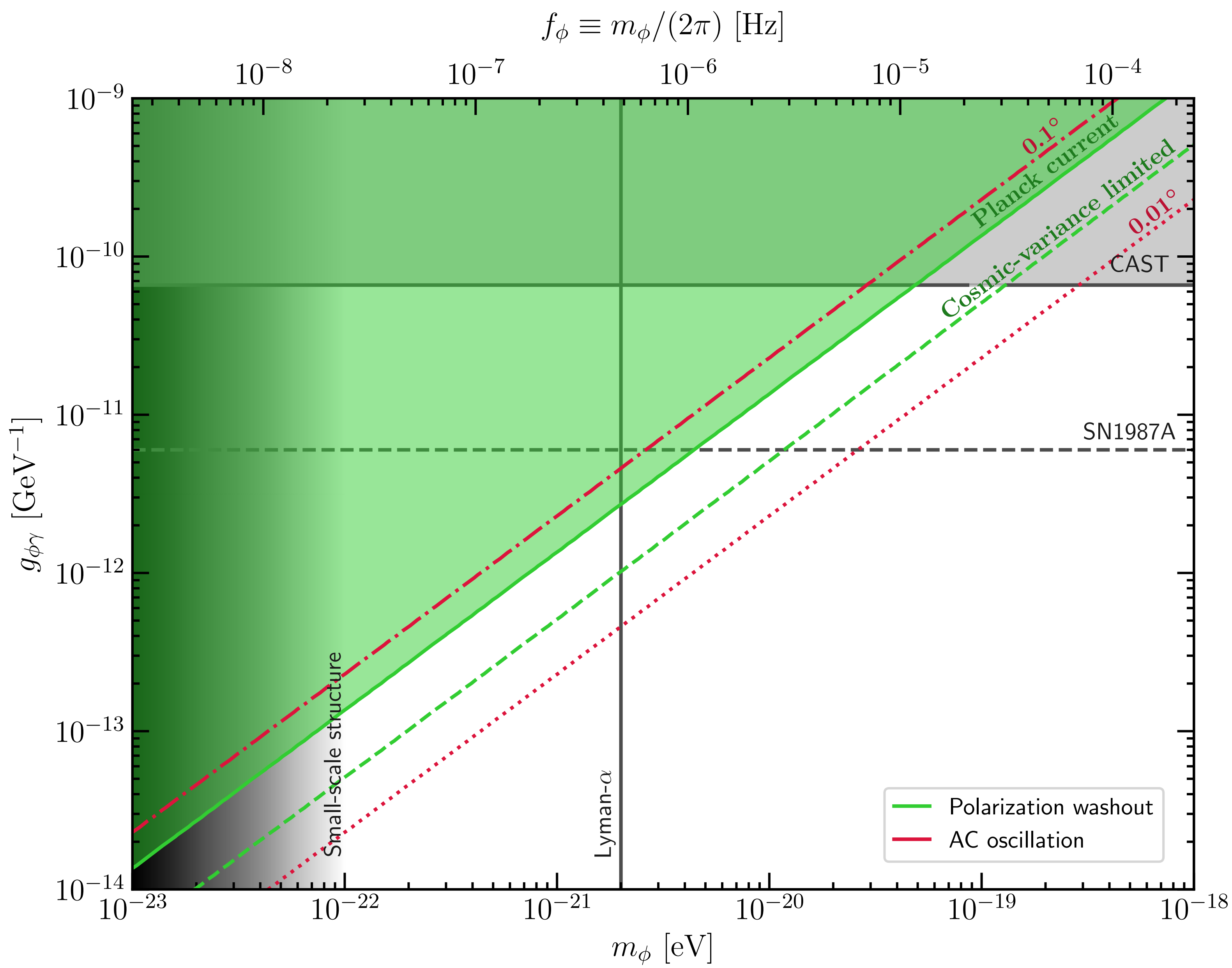
1. late time AC oscillation of polarization:

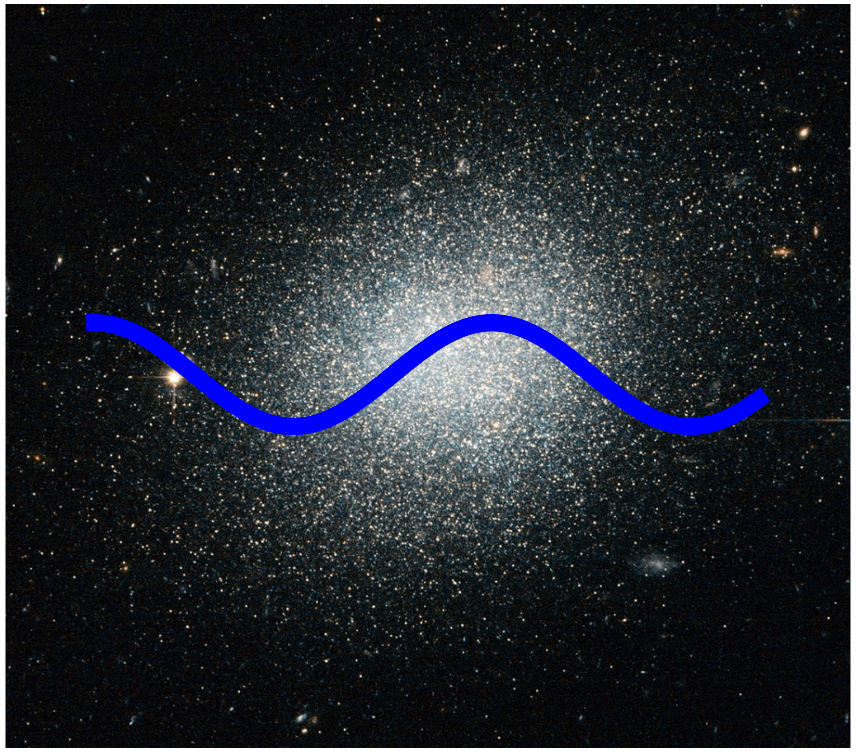
   uniformly across the sky

2. early time washout of E-modes

   uniform reduction of power in all modes $l \gtrsim 30$

CMB Sensitivity to Axion Dark Matter





probe "fuzzy dark matter" for
missing satellites problem,
core-cusp problem,…

AC oscillation most sensitive but requires dedicated analysis of existing data

if observed, easy to verify with another CMB experiment (and certainly not cosmological)