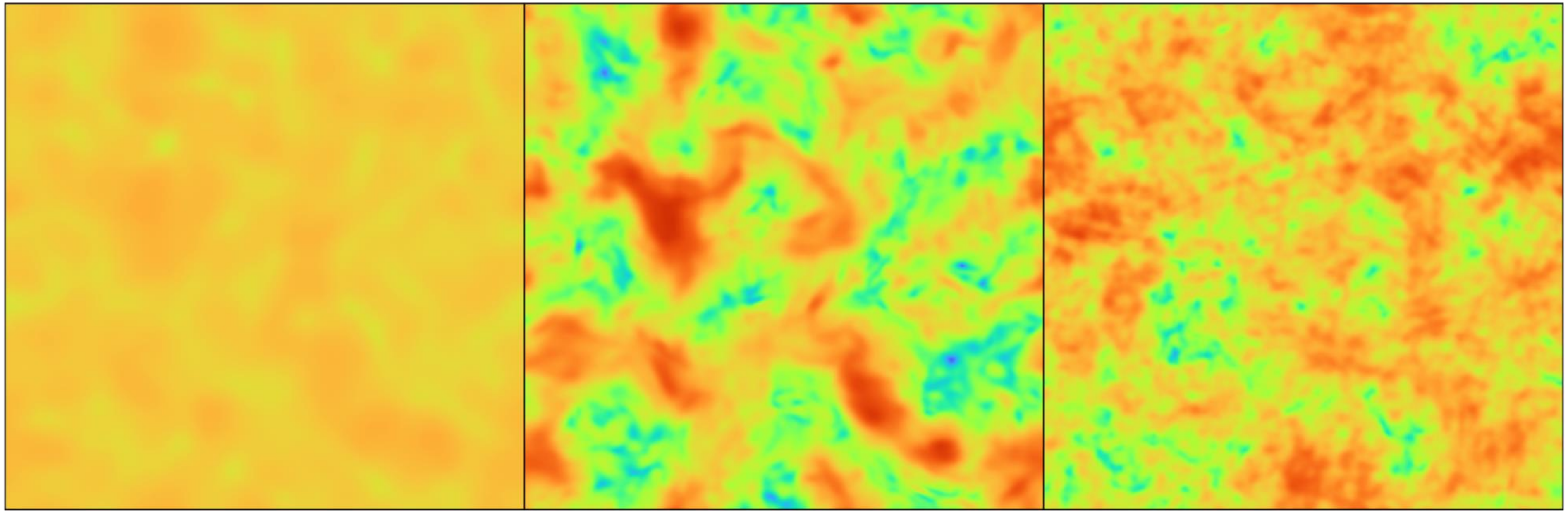
Seeing the dark: Gravitational relics of dark photon production



Zach Weiner • University of Illinois at Urbana-Champaign

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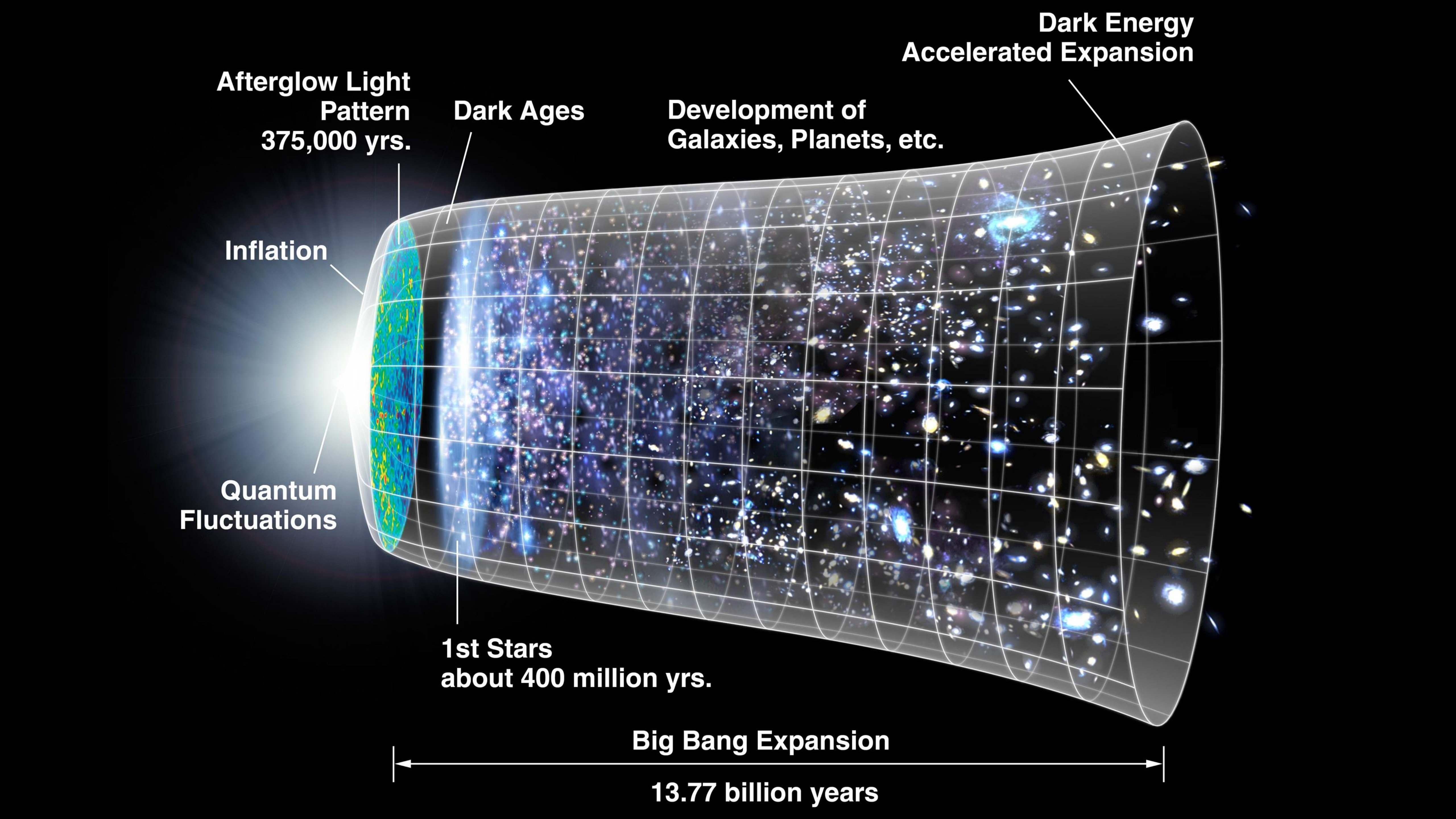
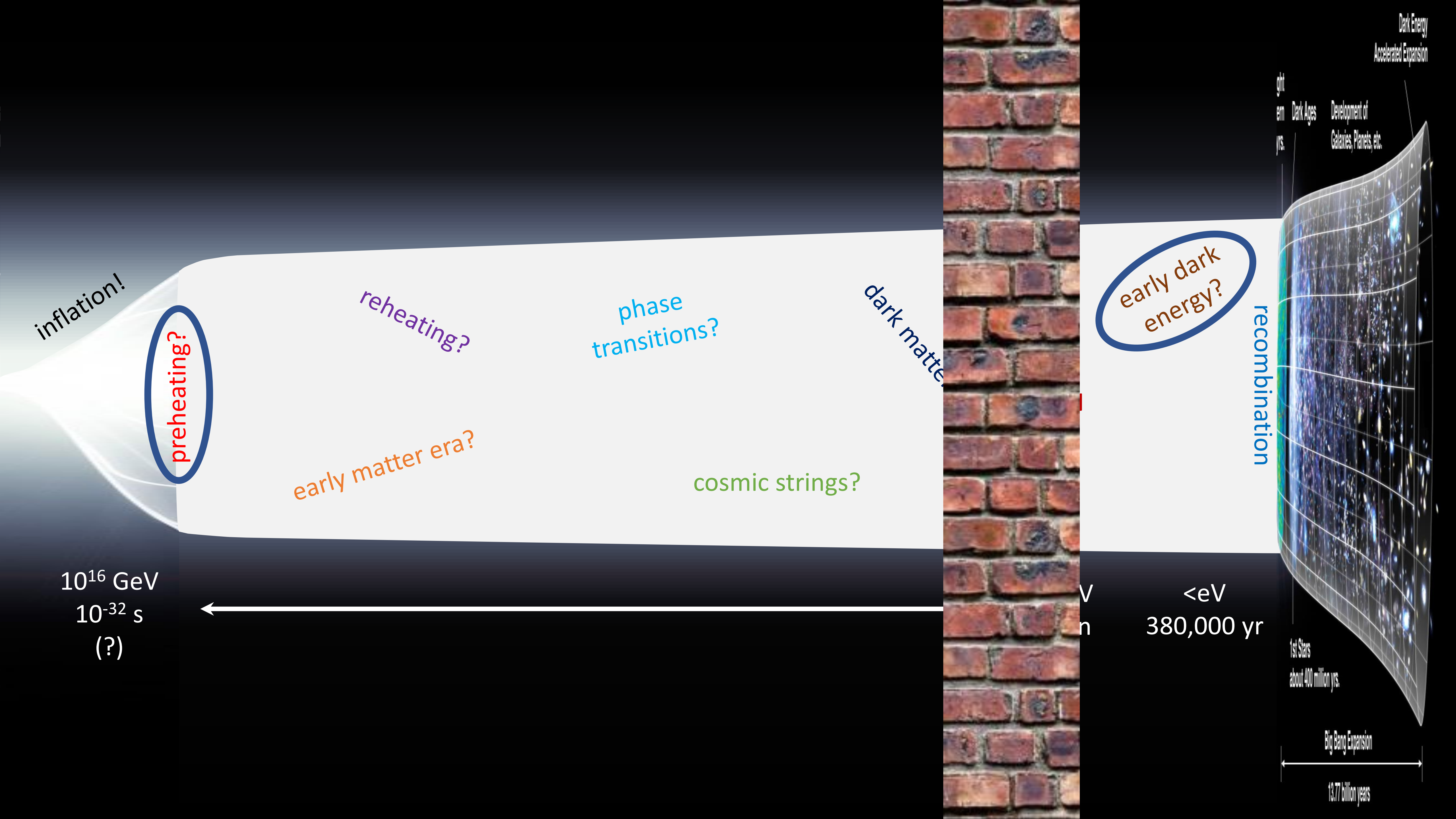
BSM PANDEMIC Seminars

October 20, 2020

DOE CSGF


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years



inflation!
preheating?
reheating?
phase transitions?
dark matte
early matter era?
cosmic strings?
early dark energy?
recombination
10^{16} GeV
10^{-32} s
(?)
<eV
380,000 yr
Dark Energy Accelerated Expansion
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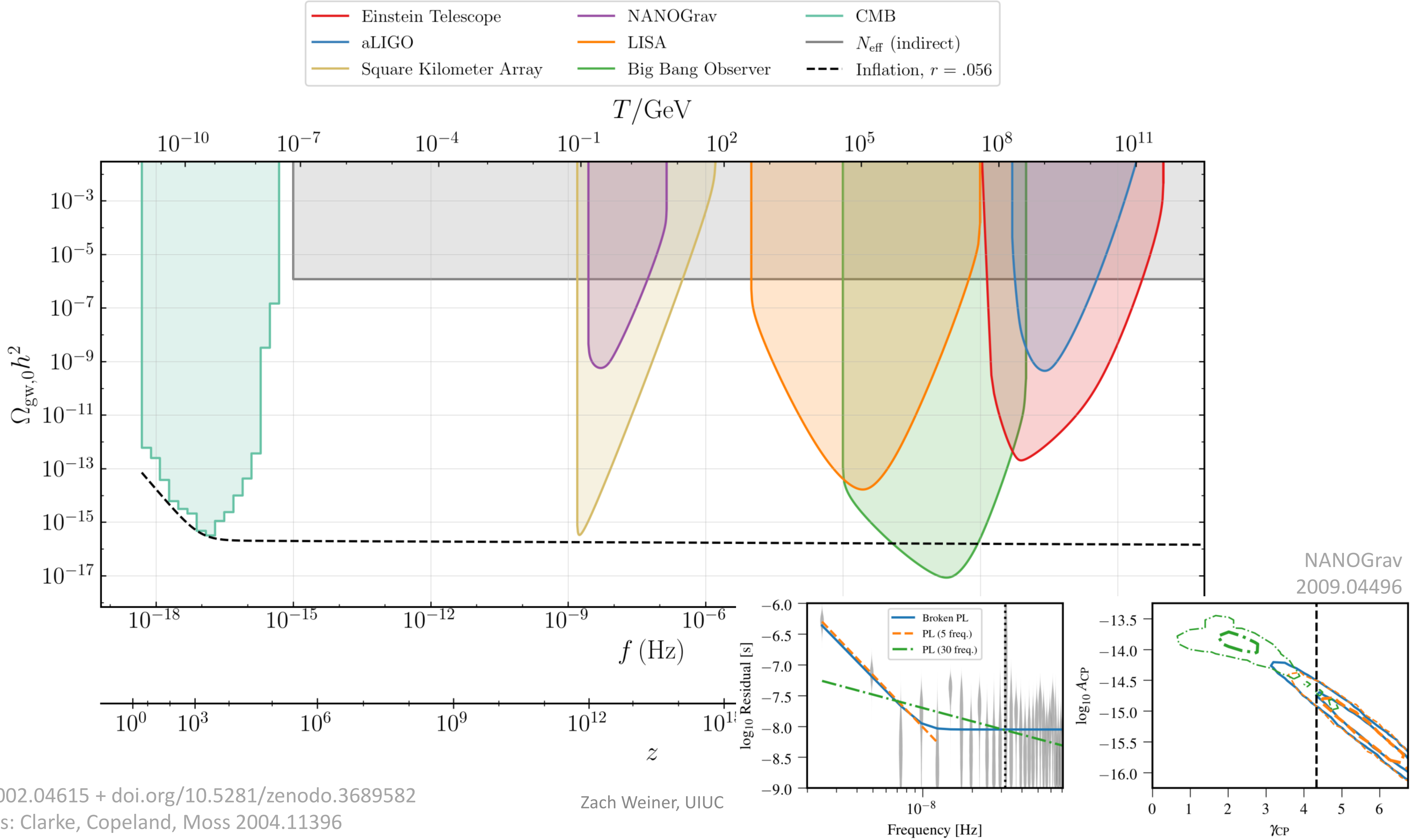

NANOGrav
2009.04496

Schmitz, 2002.04615 + doi.org/10.5281/zenodo.3689582
CMB curves: Clarke, Copeland, Moss 2004.11396

Zach Weiner, UIUC

Gravitational waves constrain resonant dark photon production from axions

reheating after inflation

early dark energy for the Hubble tension

PHYSICAL REVIEW LETTERS **124,** 171301 (2020)

Constraining Axion Inflation with Gravitational Waves across 29 Decades in Frequency

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(Received 4 October 2019; revised manuscript received 17 February 2020; accepted 11 March 2020; published 27 April 2020)

We demonstrate that gravitational waves generated by efficient gauge preheating after axion inflation generically contribute significantly to the effective number of relativistic degrees of freedom $N_{\rm eff}$. We show that, with existing Planck limits, gravitational waves from preheating already place the strongest constraints on the inflaton's possible axial coupling to Abelian gauge fields. We demonstrate that gauge preheating can completely reheat the Universe regardless of the inflationary potential. Further, we quantify the variation of the efficiency of gravitational wave production from model to model and show that it is correlated with the tensor-to-scalar ratio. In particular, when combined with constraints on models whose tensor-to-scalar ratios would be detected by next-generation cosmic microwave background experiments, $r \gtrsim 10^{-3}$, constraints from $N_{\rm eff}$ will probe or rule out the entire coupling regime for which

DOI: 10.1103/PhysRevLett.124.171301

Constraining early dark energy with gravitational waves before recombination

Zachary J. Weiner,[1,*] Peter Adshead,[1,†] and John T. Giblin, Jr.[2,3,‡]

[1] *Illinois Center for Advanced Studies of the Universe & Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*
[2] *Department of Physics, Kenyon College, Gambier, Ohio 43022, USA*
[3] *CERCA/ISO, Department of Physics, Case Western Reserve University, Cleveland, Ohio 44106, USA*

We show that the nonperturbative decay of ultralight scalars into Abelian gauge bosons, recently proposed as a possible solution to the Hubble tension, produces a stochastic background of gravitational waves which is constrained by the cosmic microwave background. We simulate the full nonlinear dynamics of resonant dark photon production and the associated gravitational wave production, finding the signals to exceed constraints for the entire parameter space we consider. Our findings suggest that gravitational wave production from the decay of early dark energy may provide a unique probe of these models.

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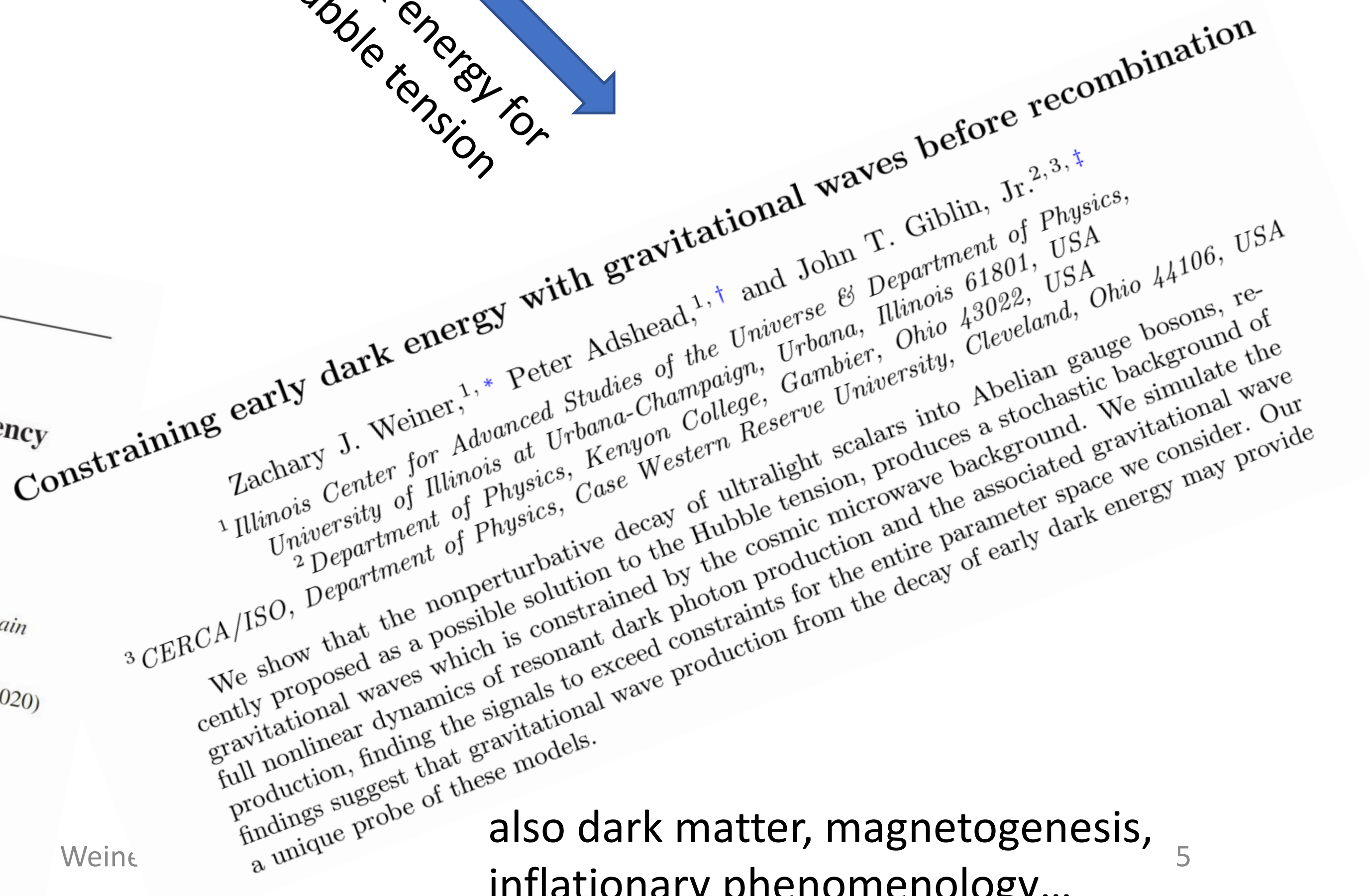

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also dark matter, magnetogenesis, inflationary phenomenology…

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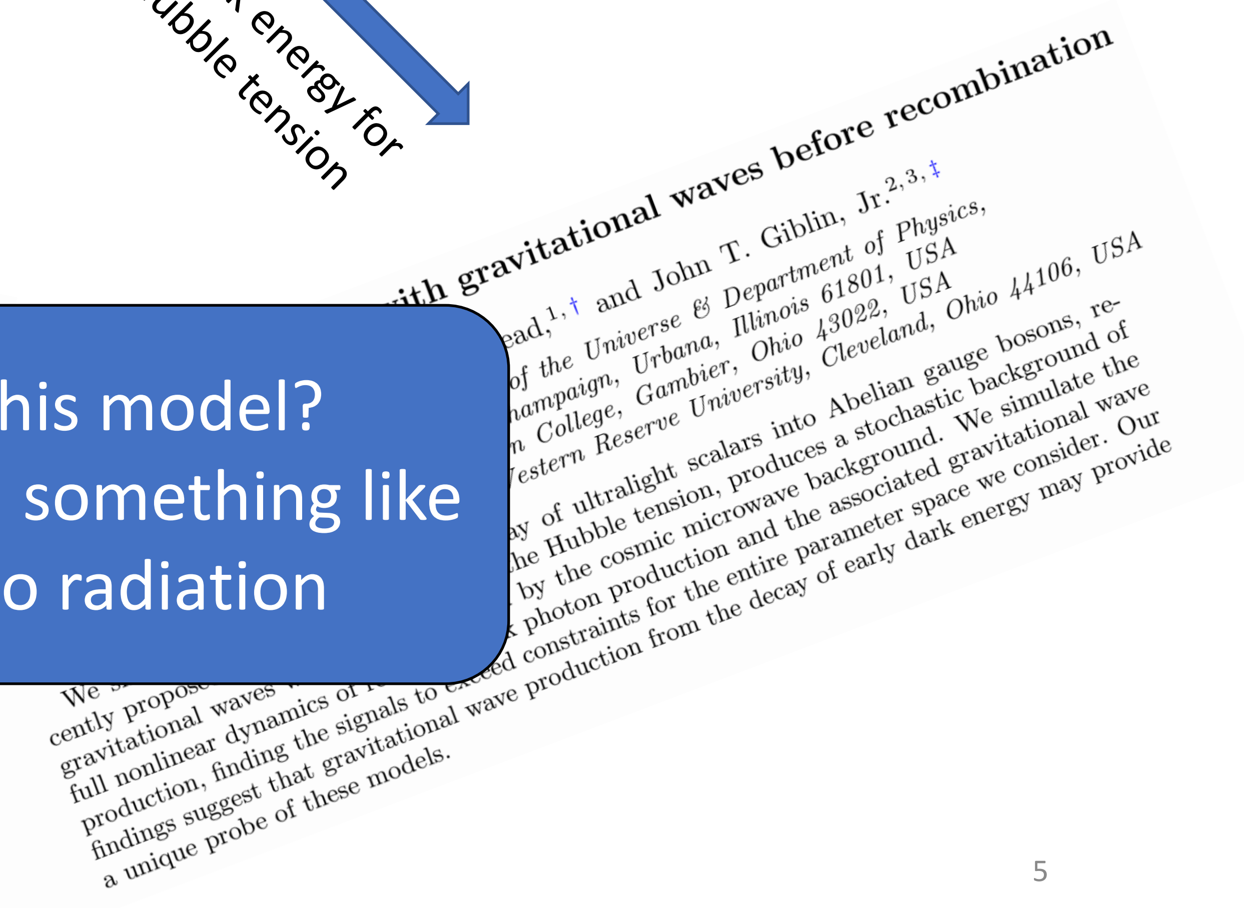
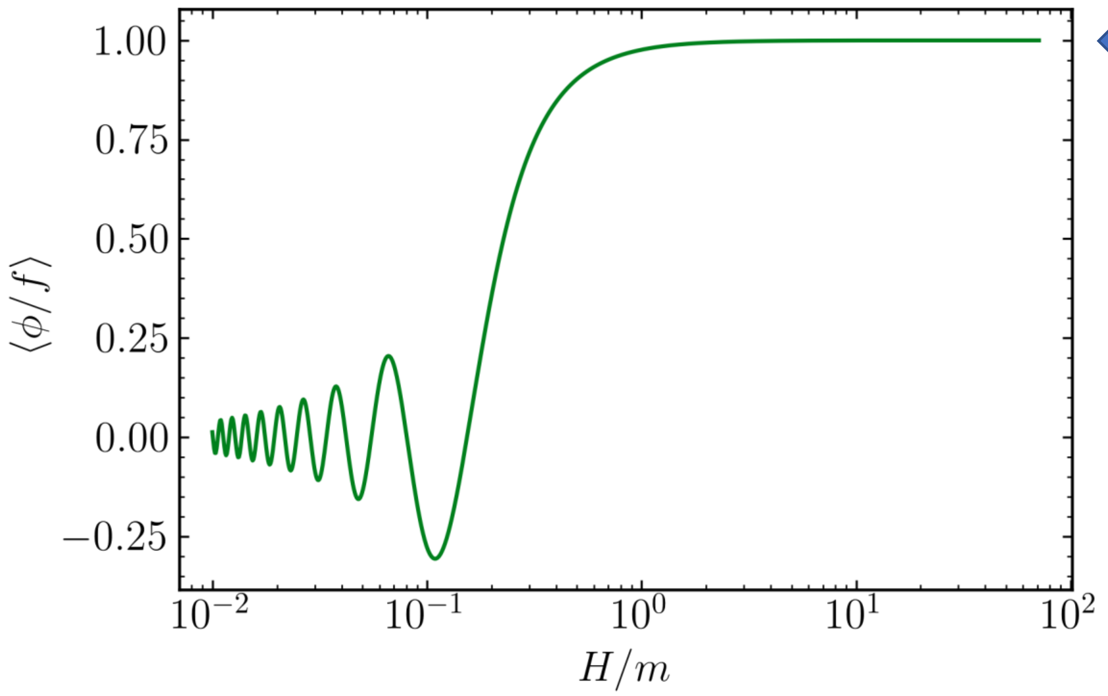


Why invoke this model?
To transition from something like dark energy to radiation

Cosmological scalar fields

$$\phi'' + 2aH\phi' + a^2m^2\phi = 0$$



some initial homogeneous configuration

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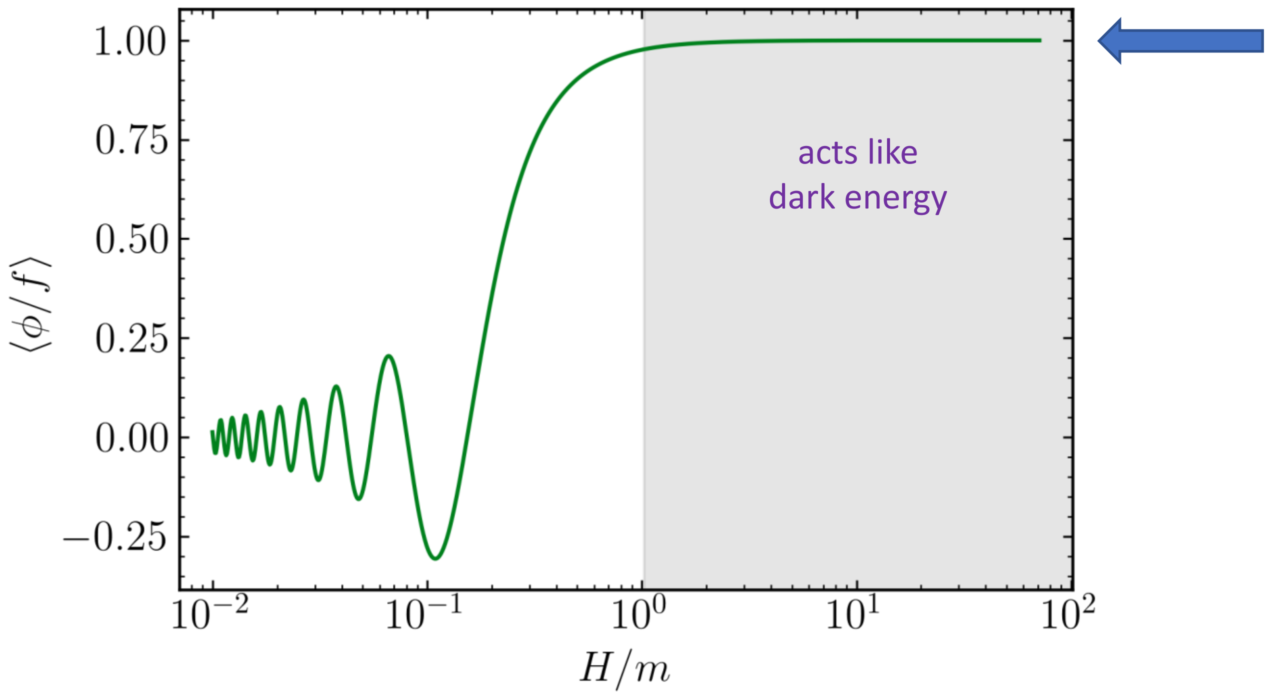

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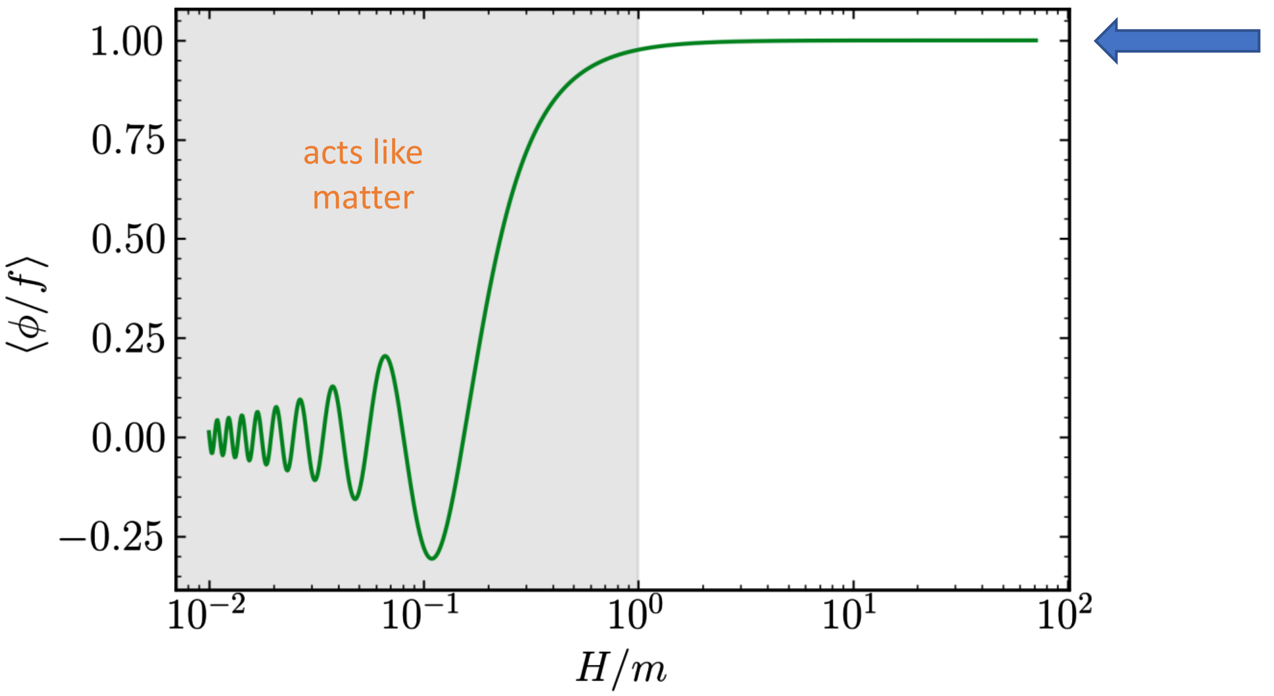


some initial
homogeneous
configuration

Tachyonic production of gauge bosons

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha}{4f}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\sim \mathbf{E}^2 - \mathbf{B}^2 \qquad \frac{\alpha}{f}\phi\mathbf{E}\cdot\mathbf{B}$$

linearized EOM of polarizations

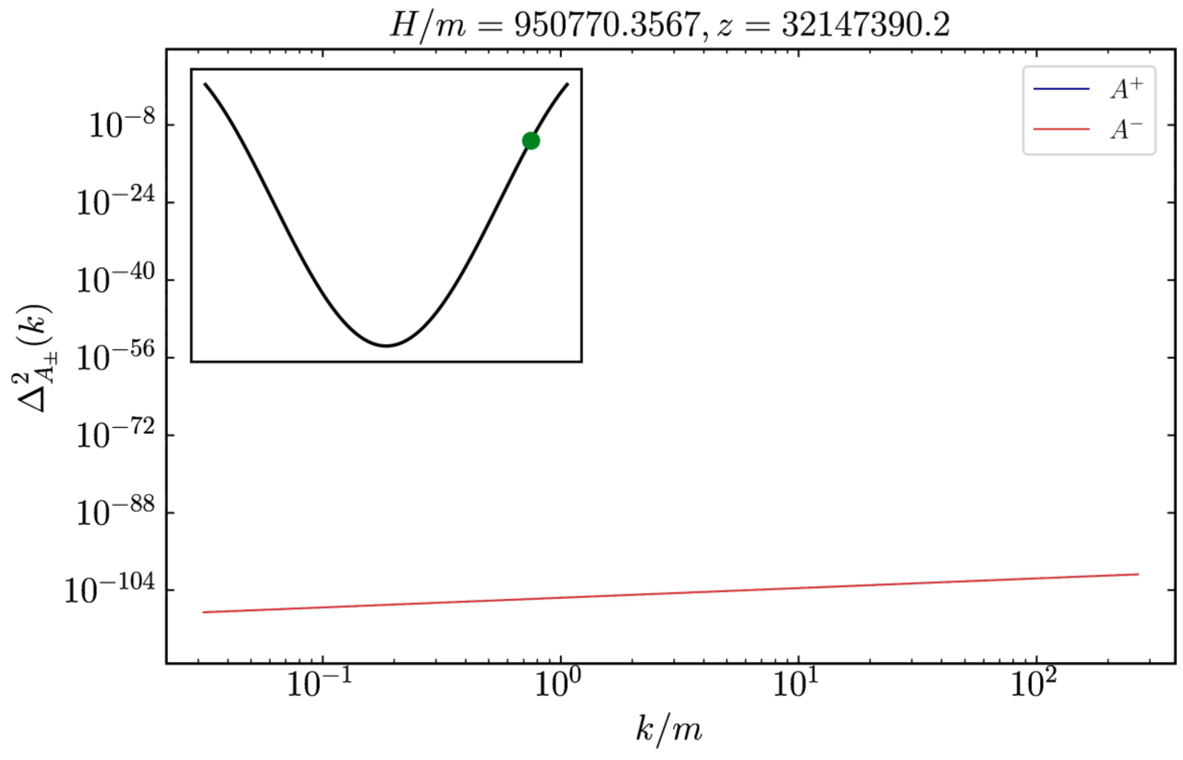
$$A''_\pm + \left(k^2 \mp \frac{\alpha}{f}k\phi'\right)A_\pm = 0$$

one polarization: negative effective frequency[2]

→ exponential growth for $k < \frac{\alpha}{f}|\phi'|$

$$A_-(k) \sim e^{|\xi|}$$

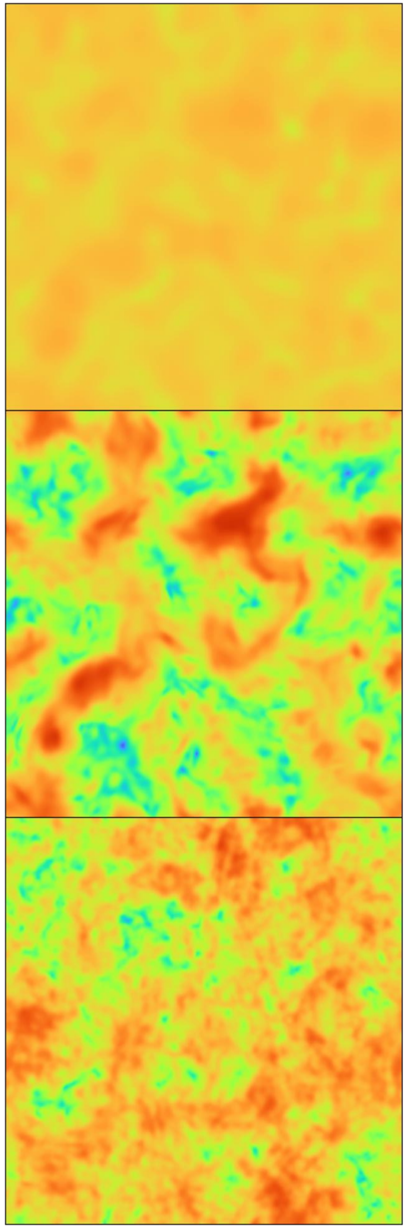
instability parameter $\xi \equiv \frac{\alpha}{f}\frac{\phi'}{2aH}$



solution of linearized system

Beyond the linear regime

- Mode amplitudes quickly grow
  - System becomes nonlinear
- Gauge fields will backreact onto the axion
  - Exert friction on the axion's homogeneous motion
  - The axion itself will fragment
- Highly inhomogeneous field configurations
  - Source gravitational perturbations!
- Must employ numerical simulations to capture the physics

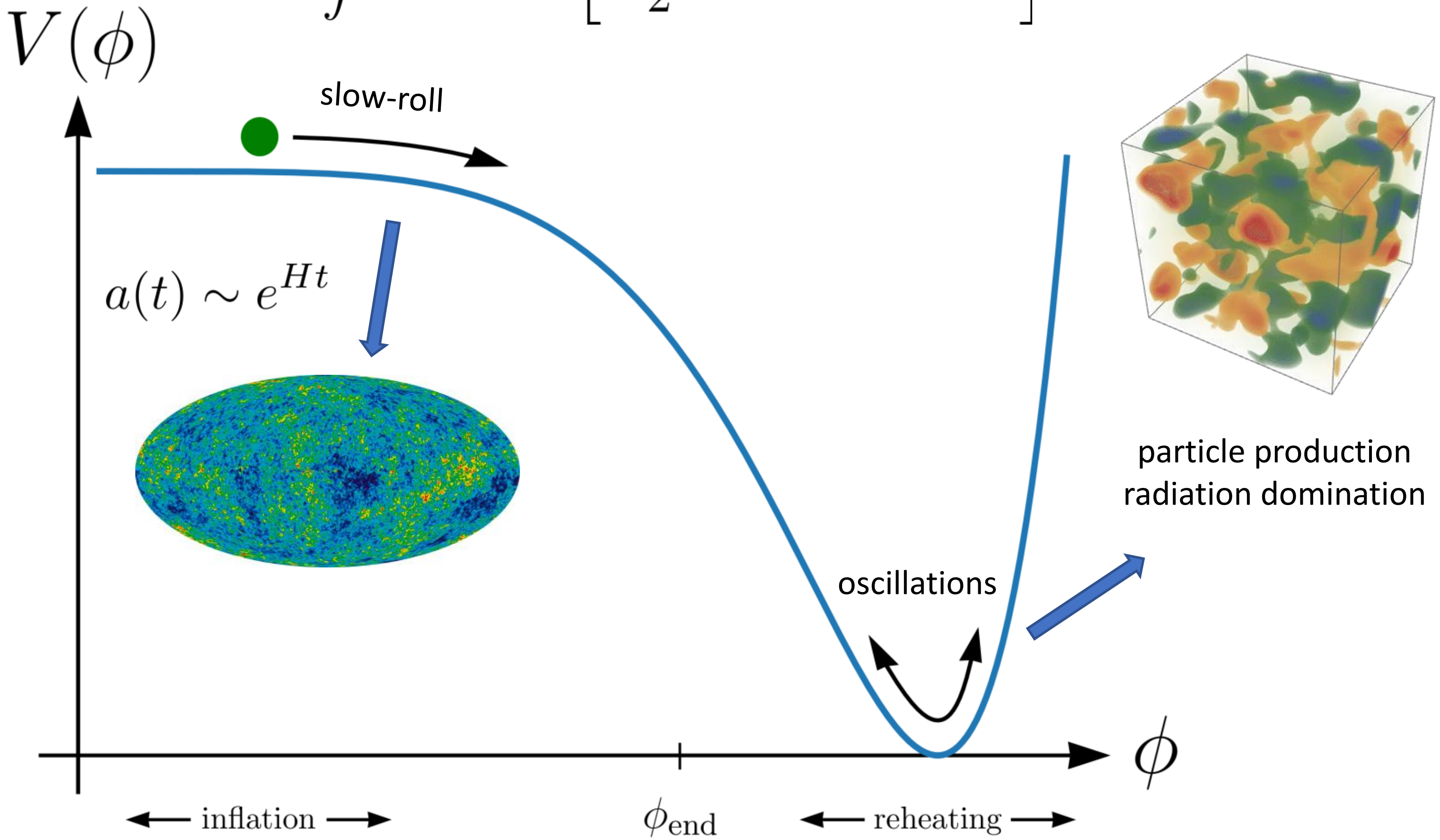


Application I: reheating after inflation

Why (p)reheating?

the "inflaton"

$$S = \int \mathrm{d}^4x \sqrt{-g} \left[-\frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) \right]$$



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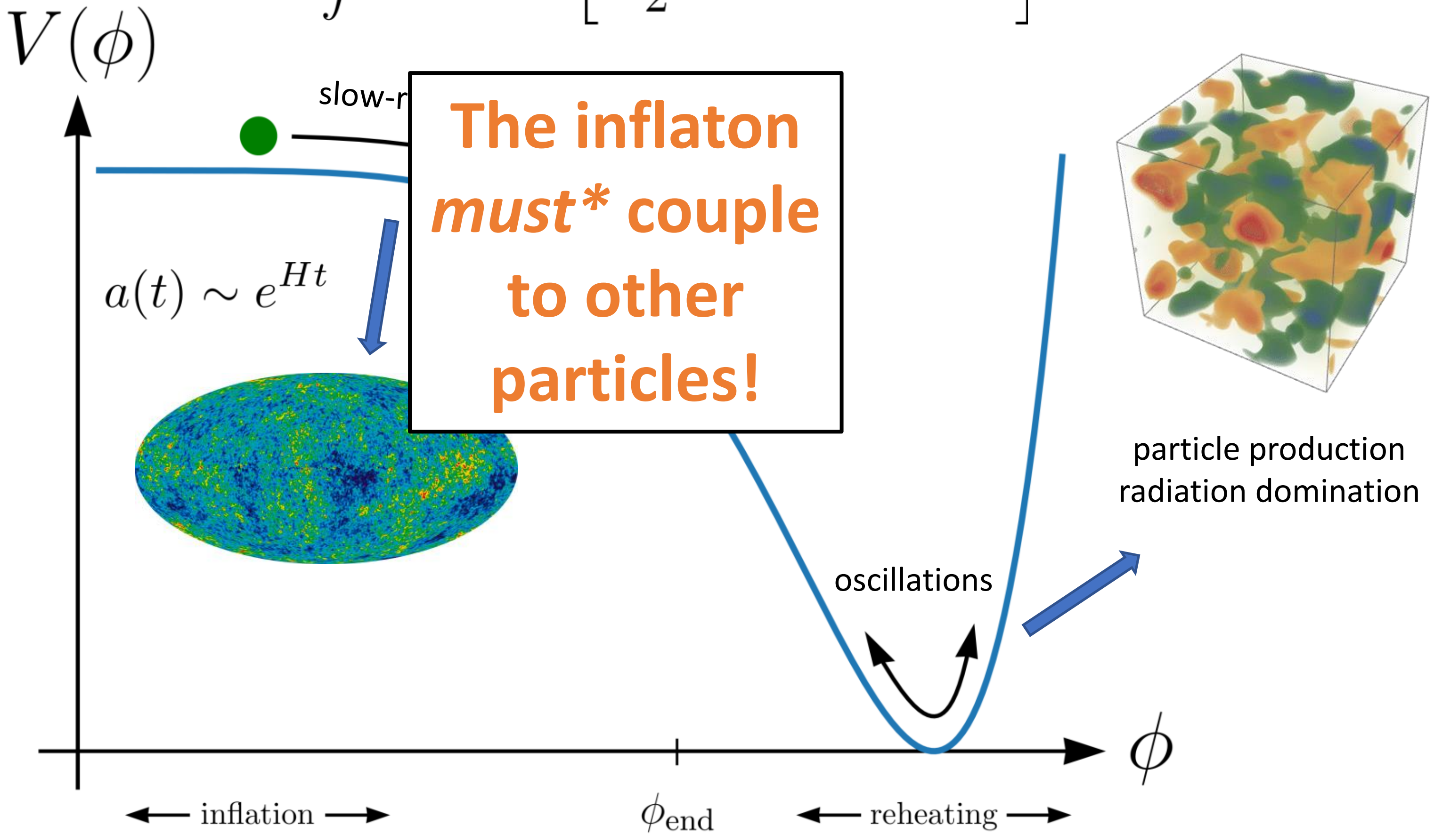
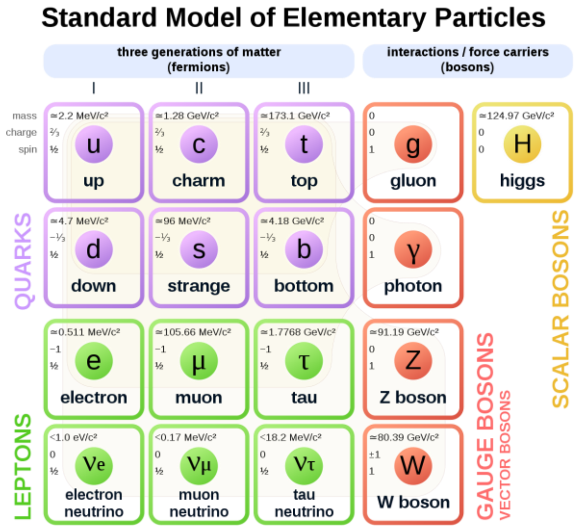


Preheating into gauge bosons

- Toy model: add another scalar field
  - Long history of study in a variety of models
- Why gauge fields?
  - Need to eventually populate Standard Model (or SM-like) degrees of freedom
  - Any dark/hidden sector's forces would likely be mediated by gauge fields
  - Naturally realizes radiation-dominated era
- More exciting phenomenology, even during inflation!

Polarized electromagnetic fields	Chiral gravitational waves
Non-Gaussianity	Primordial black holes



Lattice simulations of preheating

classical fields: PDE initial-value problem

discretize onto a 3D grid

$$\phi'' - \partial_i \partial_i \phi + 2\mathcal{H}\phi' + a^2 \frac{\mathrm{d}V}{\mathrm{d}\phi} = -a^2 \frac{\alpha}{4f} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$A_i'' - \partial_j \partial_j A_i - \frac{\alpha}{f} \epsilon^{ikl} \phi' \partial_k A_l + \frac{\alpha}{f} \epsilon^{ikl} \partial_k \phi \left(A_l' - \partial_l A_0 \right) = 0$$

+ Friedmann equations, gravitational waves…

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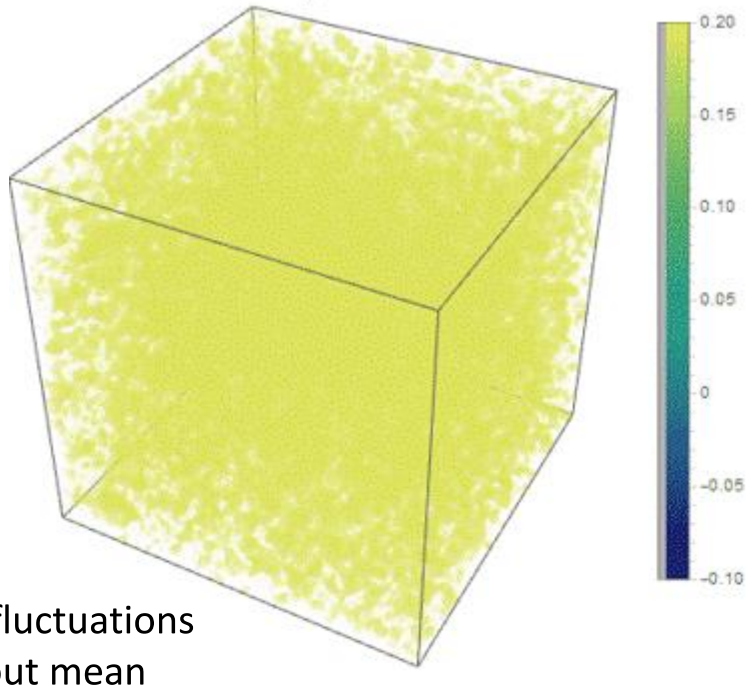
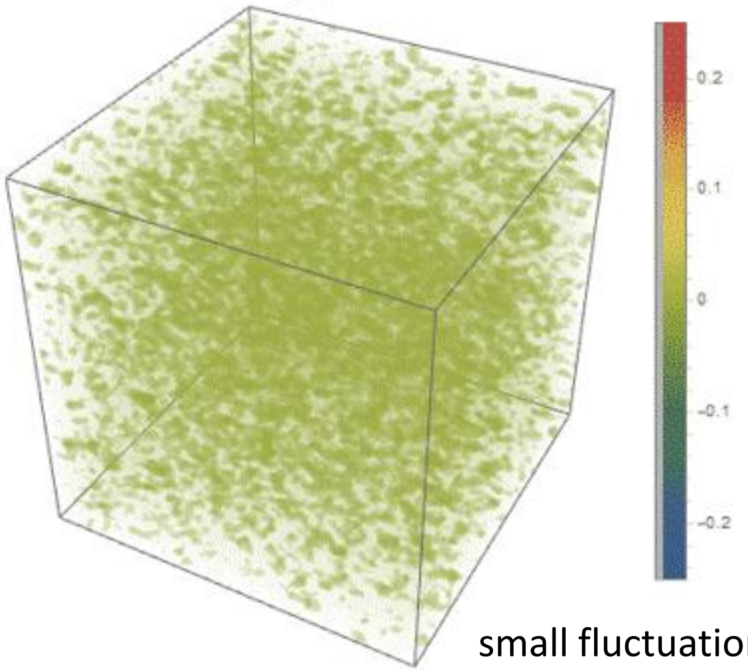


small fluctuations
about mean

coupled field



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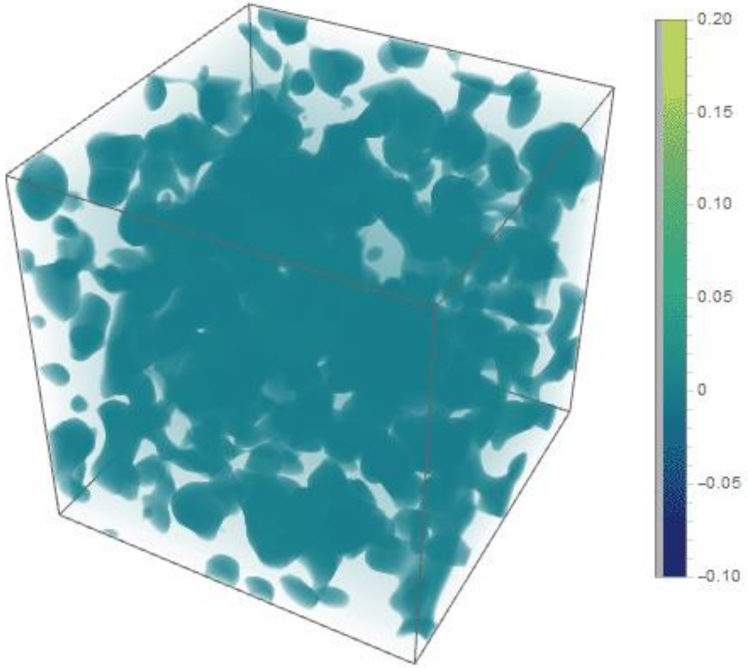

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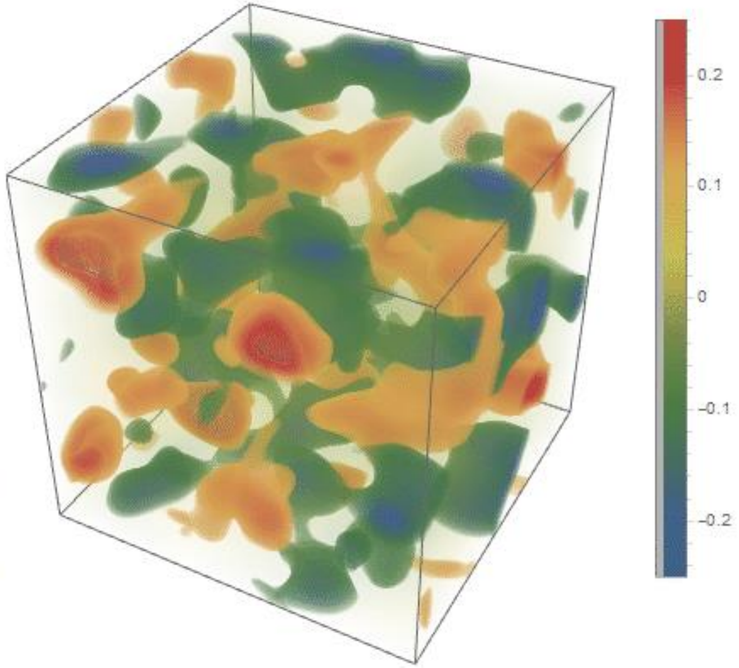
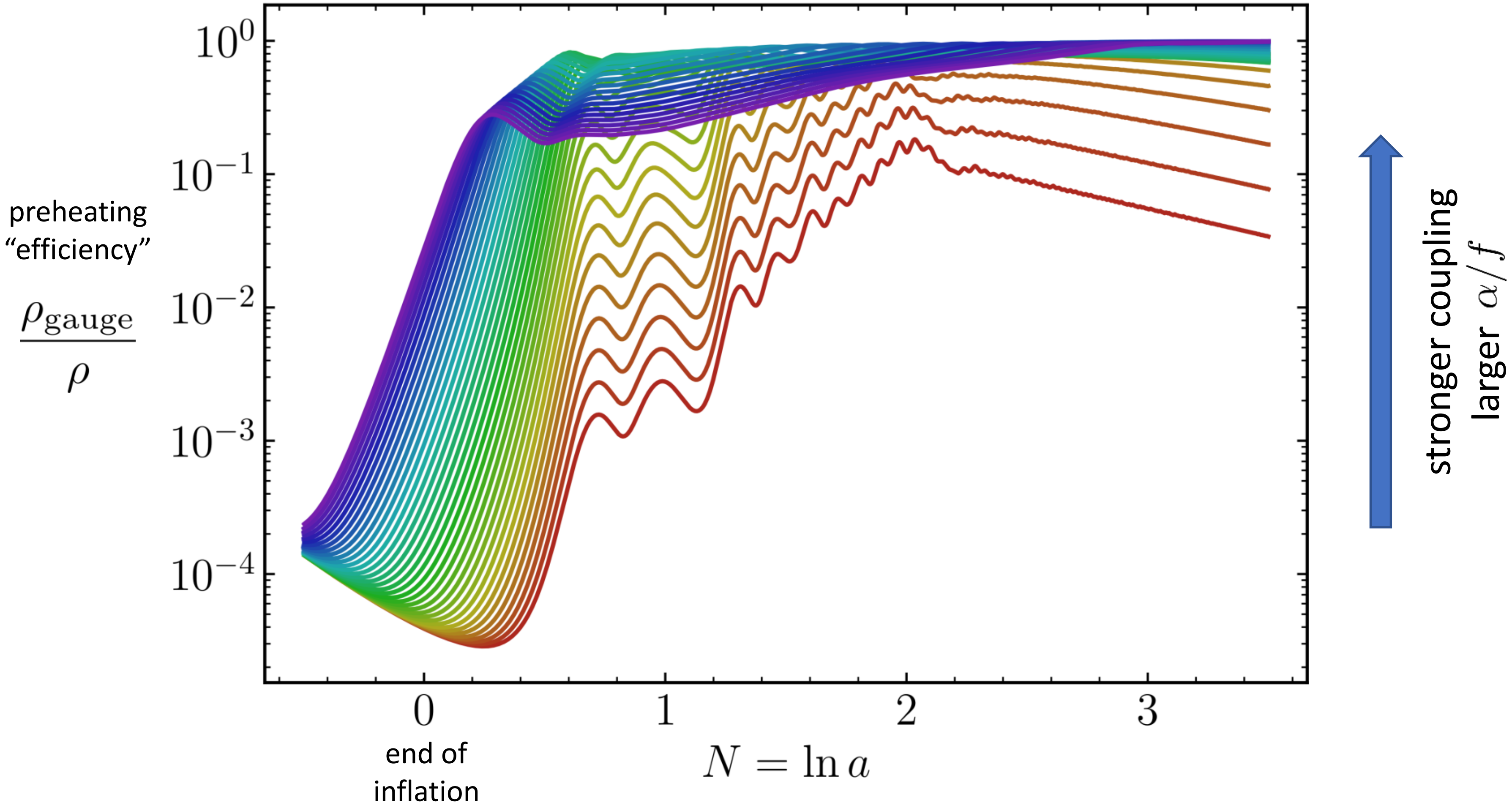


Gauge preheating after inflation



Generation of gravitational waves

Preheating generates anisotropic stress

$$T_{ij}^{A} = -\frac{1}{a^2}\left[E_i E_j + B_i B_j + \frac{\delta_{ij}}{2}\left(\mathbf{E}^2 + \mathbf{B}^2\right)\right]$$

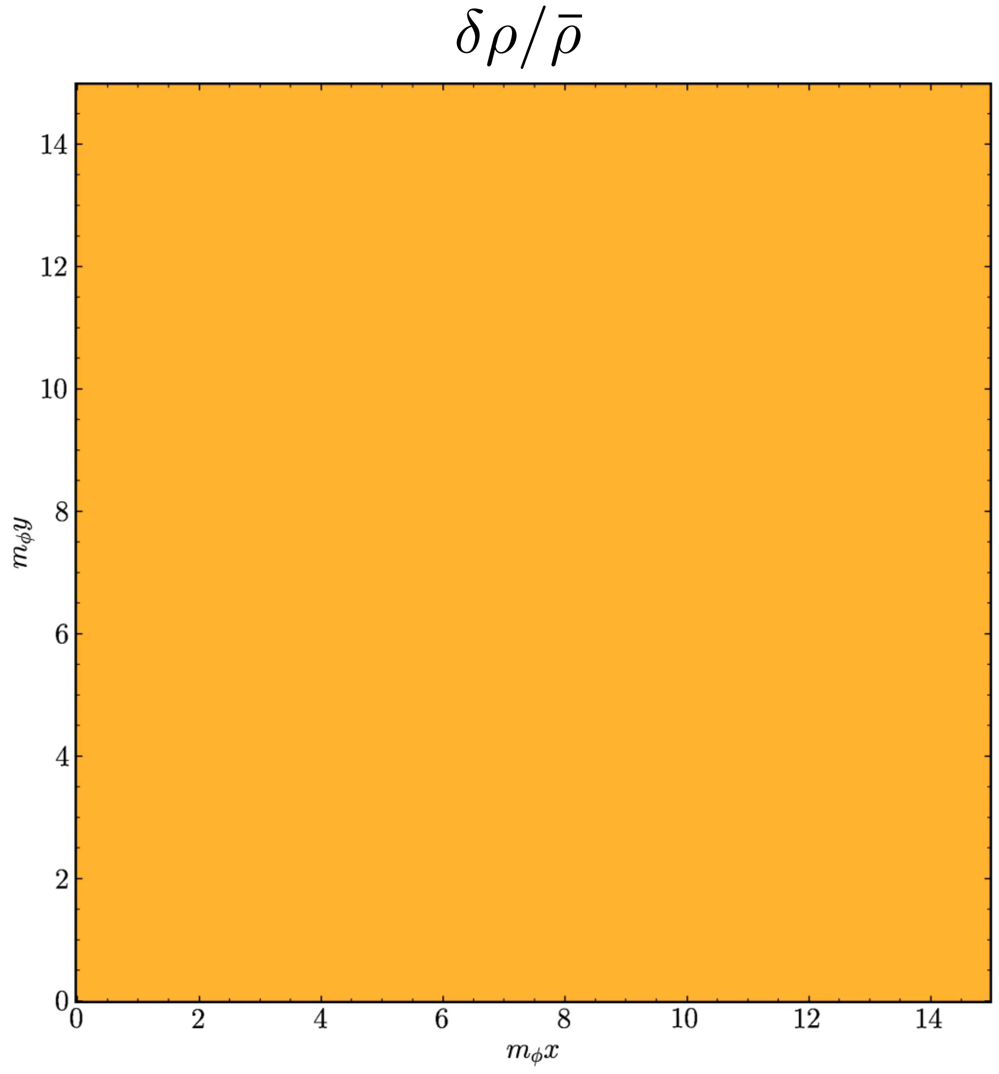
$$T_{ij}^{\phi} = \partial_i \phi \partial_j \phi - a^2 \delta_{ij}\left(\frac{1}{2}\partial_\mu \partial^\mu \phi + V(\phi)\right)$$

which sources gravitational waves

$$h_{ij}'' - \nabla^2 h_{ij} + 2\mathcal{H} h_{ij}' = \frac{2}{M_{\mathrm{pl}}^2} T_{ij}^{\mathrm{TT}}$$

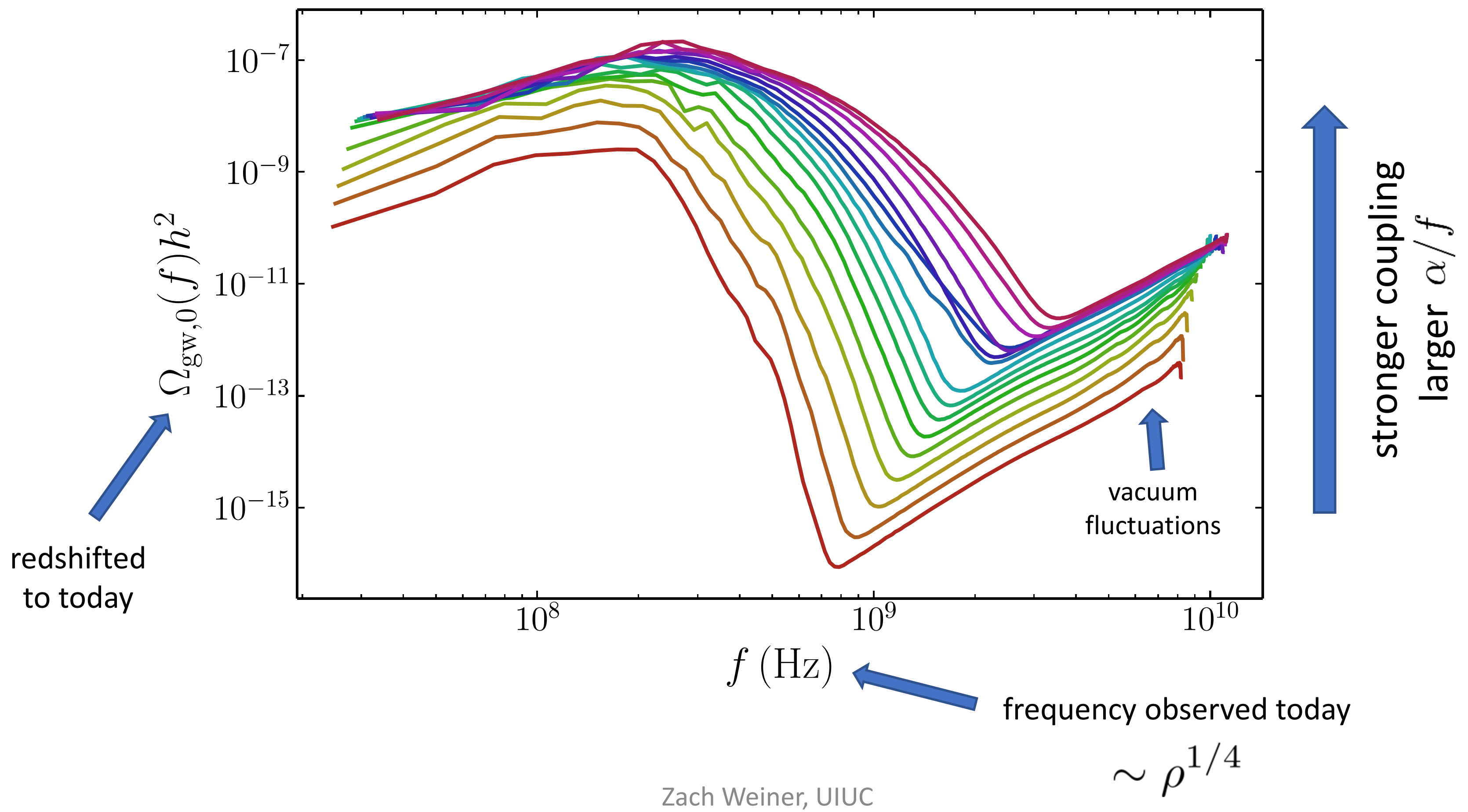
linear, inhomogeneous PDE

transverse-traceless projection of the stress tensor



Generation of gravitational waves

$$\Omega_{\rm gw}(k) \equiv \frac{1}{\rho}\frac{\mathrm{d}\rho_{\rm gw}}{\mathrm{d}\ln k} = \frac{1}{24\pi^2 L^3}\frac{k^3}{\mathcal{H}^2}\sum_\lambda \left|h_k^{\lambda\prime}(\tau)\right|^2$$



Constraints from N_{eff}

- As radiation, GWs contribute to the effective number of relativistic degrees of freedom:

$$\frac{\Omega_{\mathrm{gw},0} h^2}{\Omega_{\gamma,0} h^2} = \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} \Delta N_{\mathrm{eff}}$$

- CMB-S4 will probe ΔN_{eff} to a level that would constrain*

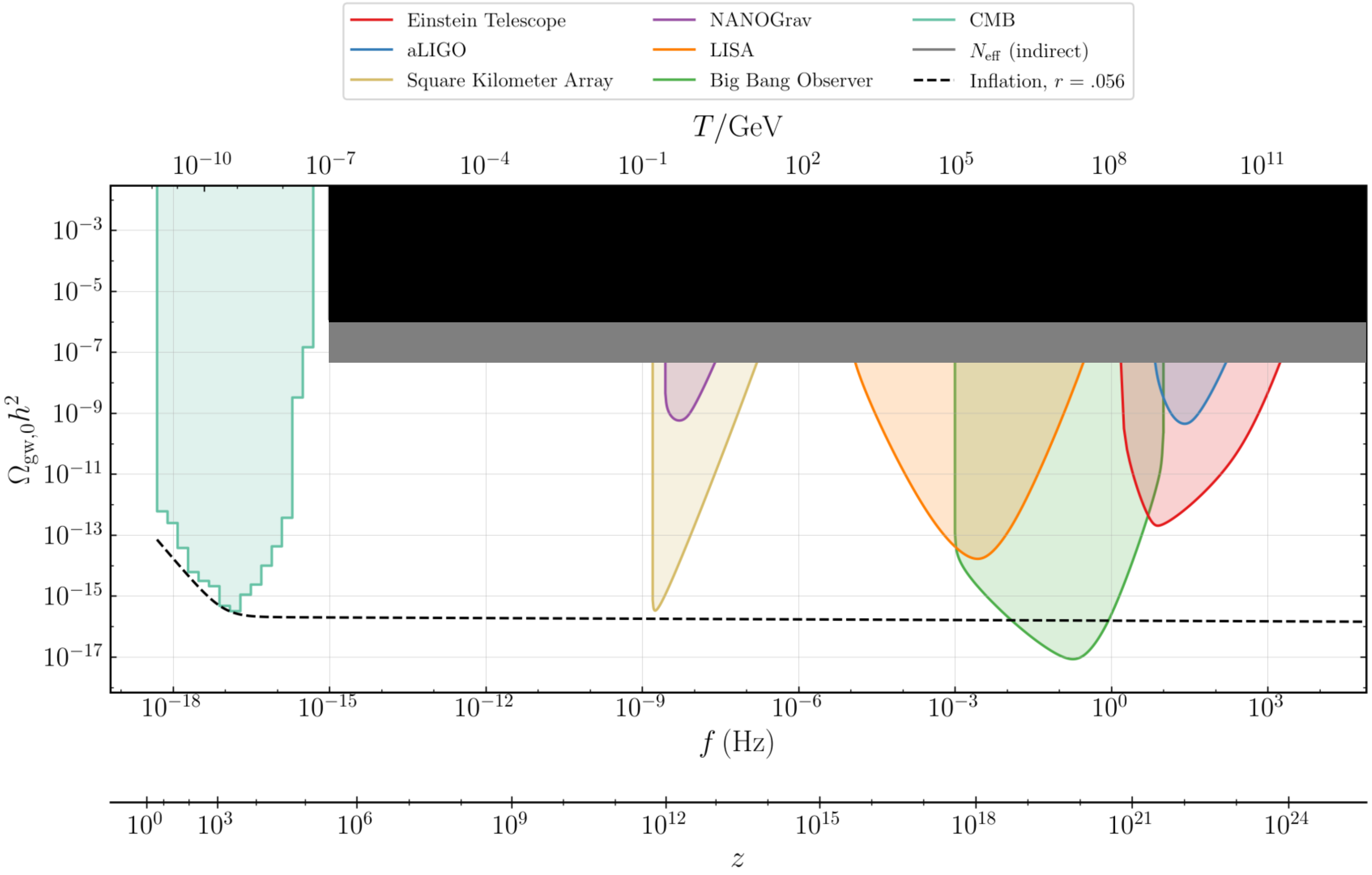
$$\Omega_{\mathrm{gw},0} h^2 \lesssim 7.6 \times 10^{-8}$$

$$\left(\Omega_{\mathrm{radiation},0} h^2 \sim 10^{-5} \right)$$

*arXiv:1508.02393

Constraints from N_{eff}

- As ra… …ativistic degre…

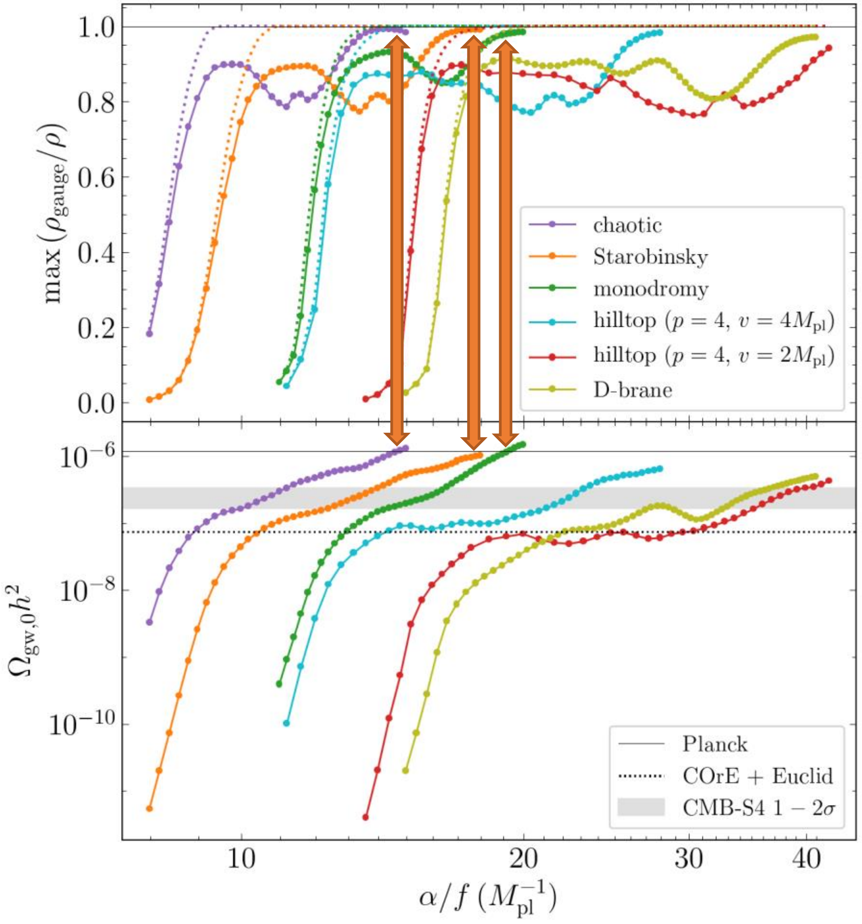


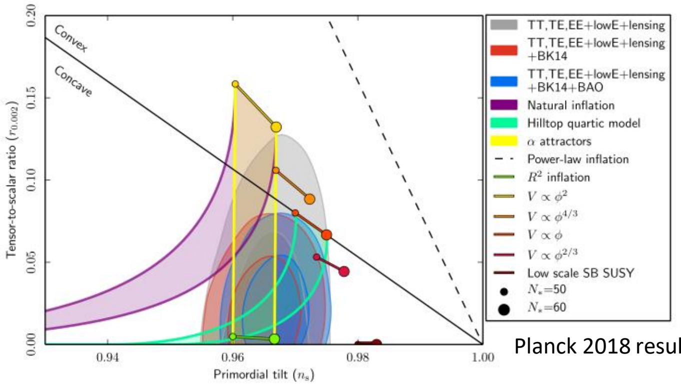
- CMB-…

*arXiv:1508.02393

Dependence on the potential

Now: constrain coupling for high-scale inflation models





Planck 2018 results X

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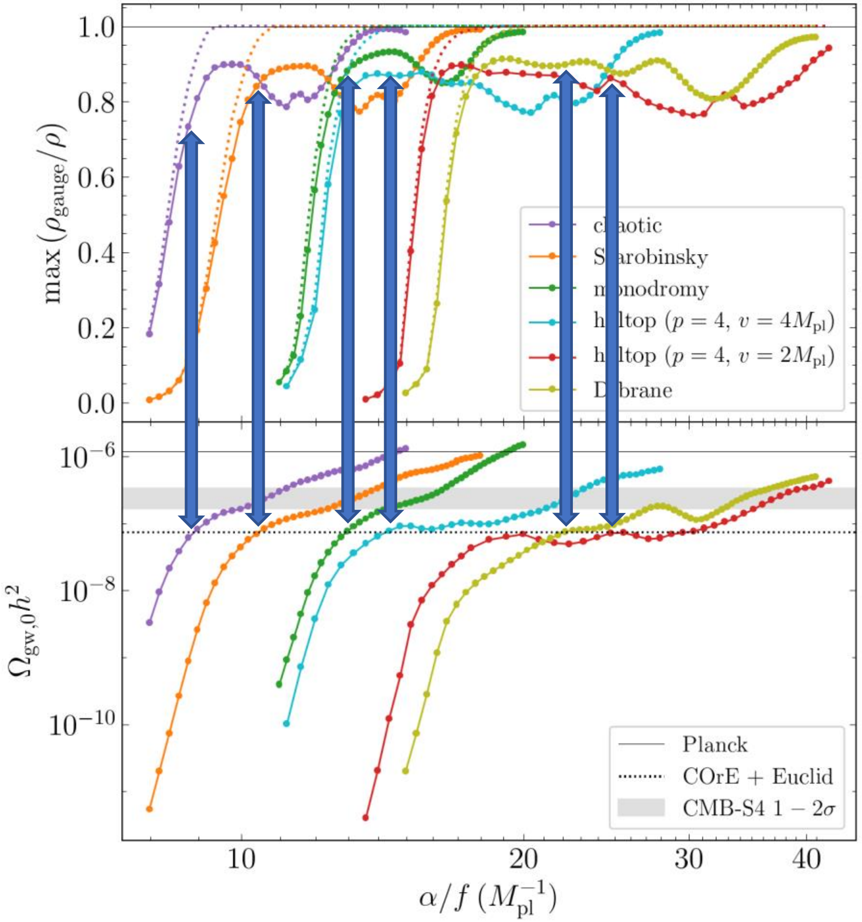
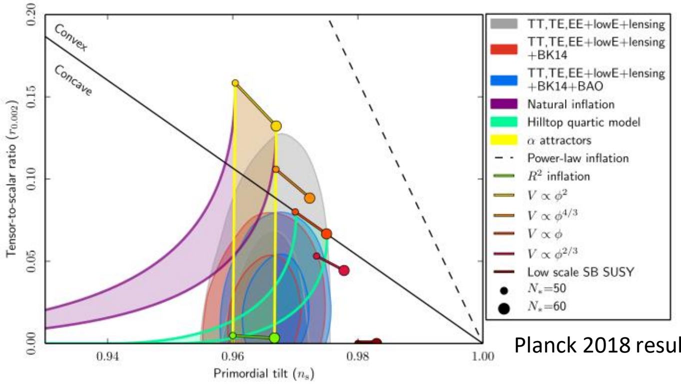


In the future: probe/rule out regime of complete preheating



Planck 2018 results X

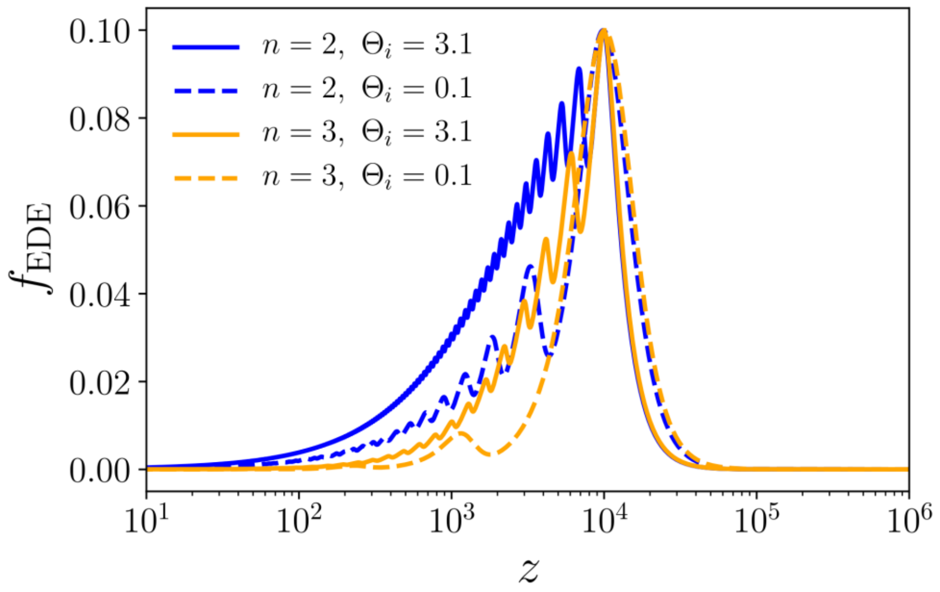
Application II: early dark energy and the Hubble tension

ZJW, Adshead, Giblin: 2008.01732

Early dark energy

- Discrepancy between local and CMB measurements of Hubble constant
- Likely calls for new physics to modify sound horizon at recombination
  - Something which transiently increases expansion rate
- First models: cosmological scalar field
  - Invoke an exotic potential → oscillations decay faster than radiation

Smith, Poulin, Amin: 1908.06995



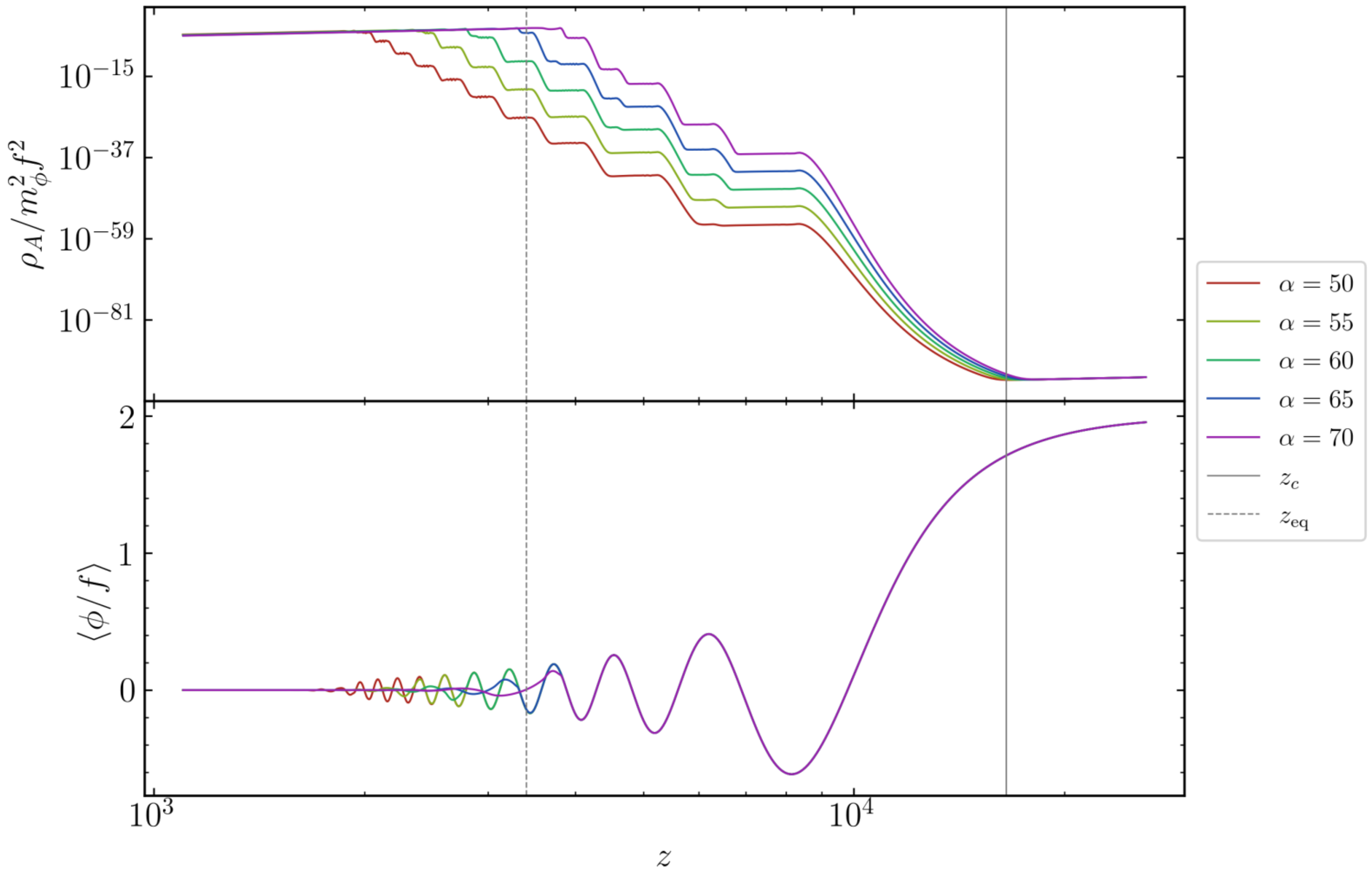
Poulin, Smith, Karwal, Kamionkowski: 1811.04083 etc.

The decaying ultralight scalar model

2006.13959: Gonzalez, Hertzberg, Rompineve

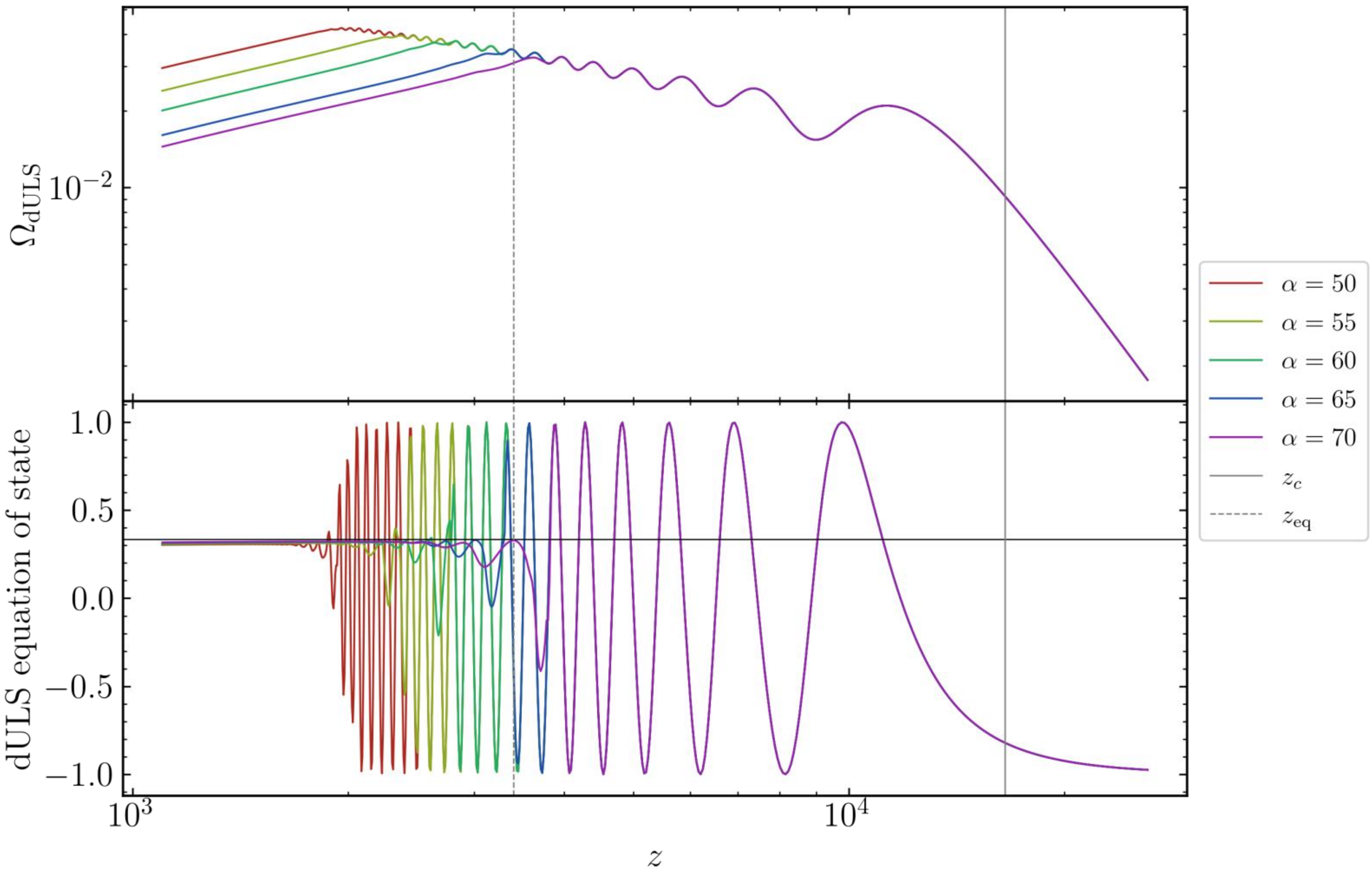
- Trade a funny potential for our favorite coupling to dark photons
- EDE still from scalar frozen up its potential
  - Resonant dark photon production → radiation
- 2006.13959: employed an effective fluid description
  - But the dynamics which deplete the axion are inherently nonlinear
  - Gravitational waves at scales entering the horizon around MR equality

Dynamics of the dULS model



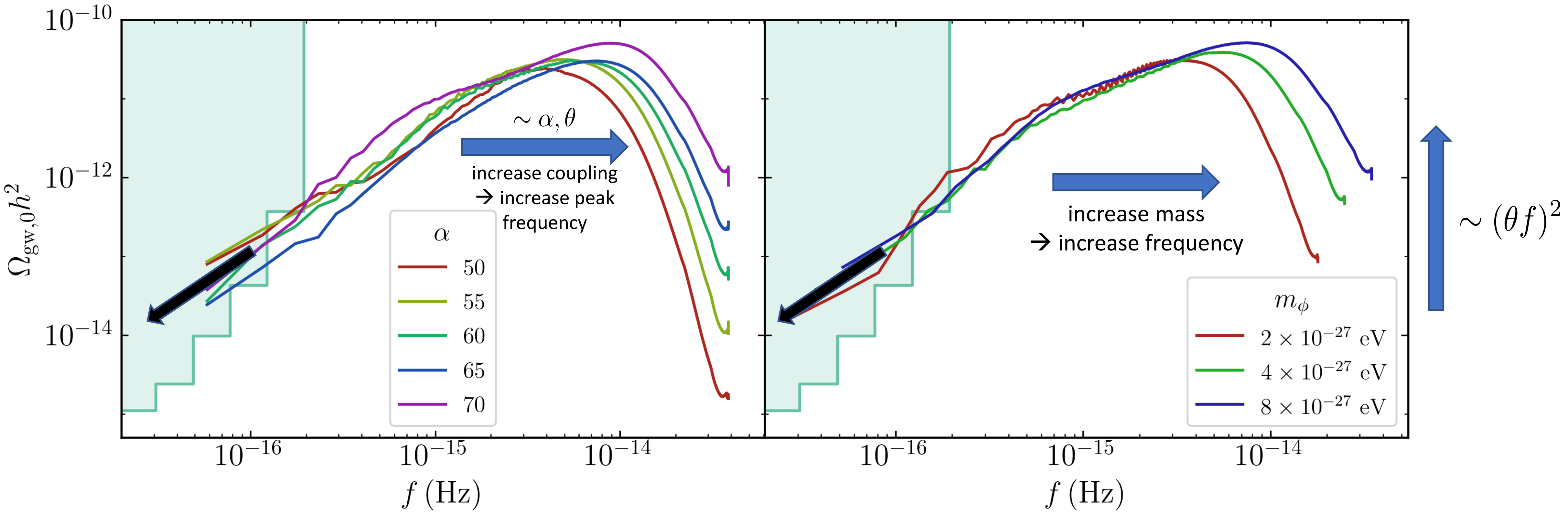
red to purple: increase coupling

Dynamics of the dULS model



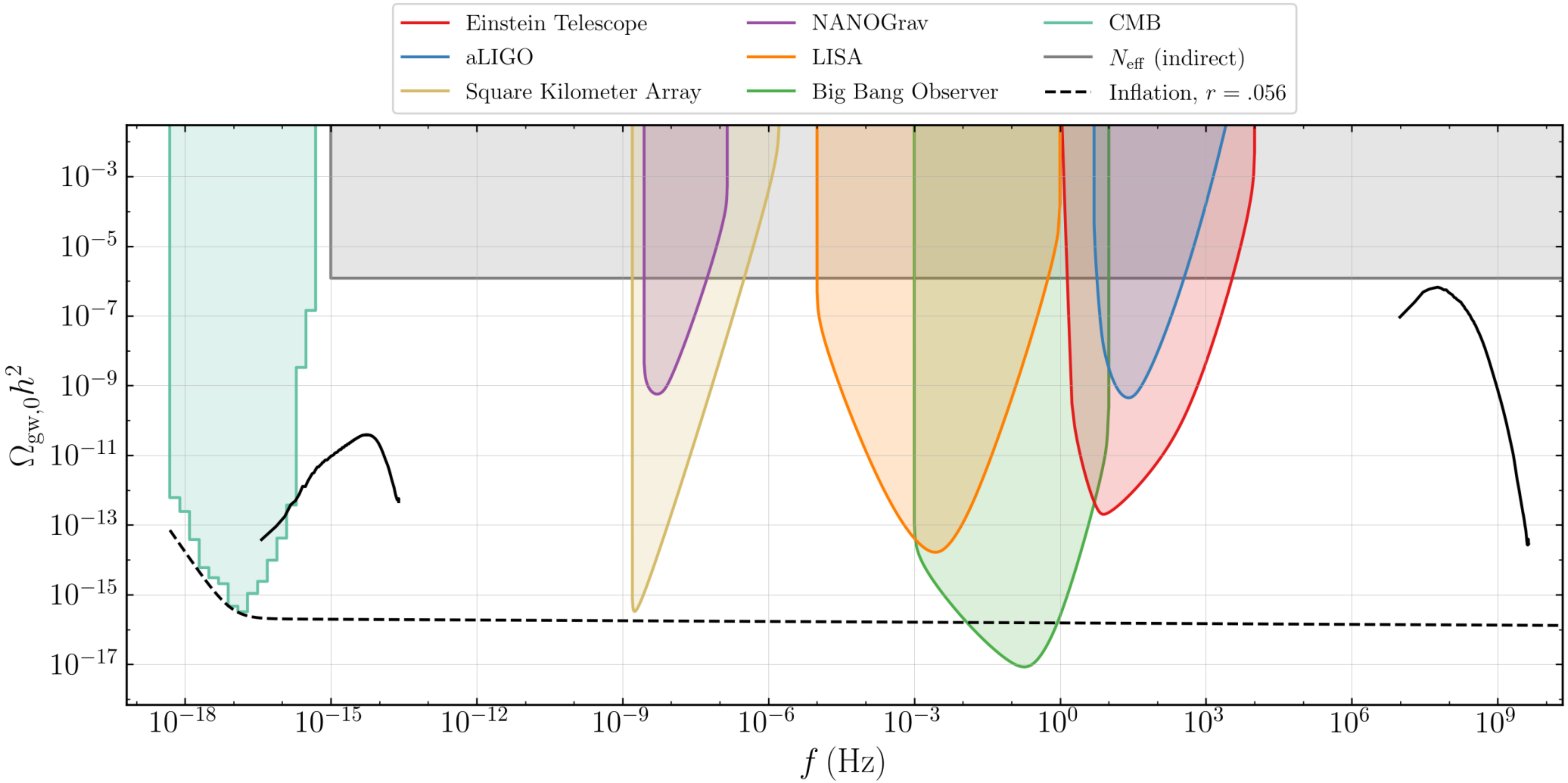
red to purple: increase coupling

Gravitational wave emission



CMB constraint: Clarke, Copeland, Moss 2004.11396

Thank you!



Einstein Telescope
aLIGO
Square Kilometer Array
NANOGrav
LISA
Big Bang Observer
CMB
$N_{\rm eff}$ (indirect)
Inflation, $r = .056$
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
$\Omega_{\rm gw,0}h^2$
10^{-18}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
f (Hz)