Rouzbeh Slides

Top-Down Realizations: Considerations & Constraints

HEP models of the early universe contain multiple scalar fields:

Higgs + Inflaton(s) + Others (axions, string moduli, etc)

They can lead to non-standard thermal histories $w \neq \frac{1}{3}$:

(1) Coherent oscillations

$V(\phi) \propto |\phi|^n \implies w = \frac{n-2}{n+2}$ (averaged over oscillations)

$n > 4 \implies \frac{1}{3} < w \leq 1$

A tiny radiation component will eventually dominate →

- Successful reheating without entropy generation,
- Correct DM abundance for large annihilation cross sections

$w = 1$: **Kination**

- Non-oscillatory models of inflation

- Axion rotation (Akshay, next block)

$n < 2 \Longrightarrow \; w < 0$

- Early DE (Tristan, next block)

Must be careful:

- Growth of field fluctuations for negative pressure
  → Fragmentation of coherent oscillations (Q-balls, I-balls, …)

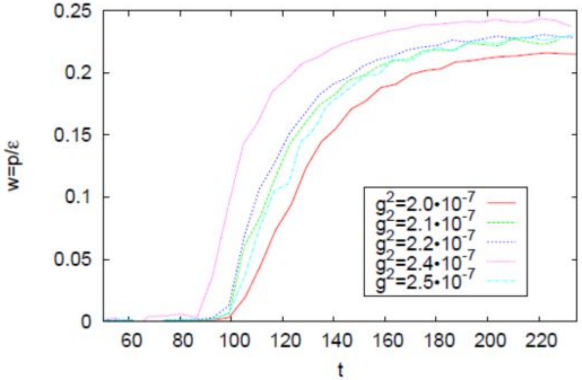
- Non-perturbative effects from self-coupling
  → Self-resonant decay of coherent oscillations

(2) Interacting scalar fields

$$V(\phi,\chi) = \frac{1}{2}m^2\phi^2 + \frac{1}{2}g^2\phi^2\chi^2 + \frac{1}{2}\sigma\phi\chi^2 + \frac{1}{4}\lambda\chi^4$$

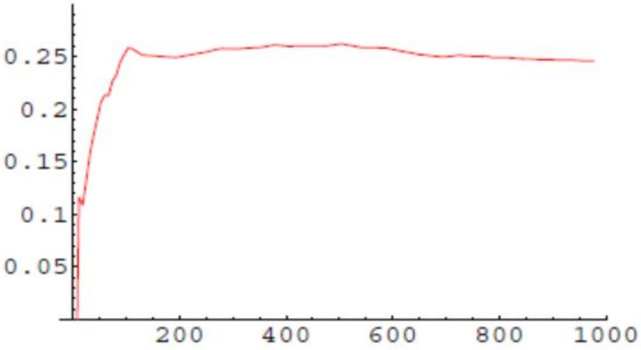
- Rapid energy transfer from ϕ oscillations to χ
- Backreaction → A plasma of ϕ, χ quanta in equilibrium with $w \simeq \frac{1}{4}$
- Reaching full equilibrium takes much longer

$\sigma = 0$



Podolsky, Felder, Kofman, Peloso (2005)

$g = 0$



Dufaux & FKPP (2006)

$$m_{eff}^2 \simeq \langle p^2 \rangle \gg m^2$$

Building explicit models is challenging.

Consider the case with $0 \leq w < \frac{1}{3}$ → Entropy generation

→ EMD a prominent example

Requirements:

(1) Obtaining the correct DM abundance.

(2) Generating the observed baryon asymmetry.

(3) Successful reheating:
- Not overproducing dangerous relics (gravitinos, DR, etc)
- Not overpopulating hidden sectors (especially multiple moduli case)

Constraints on string constructions of EMD and non-thermal DM

→ For example, LVS vs KKLT

R.A., Cicoli, Dutta, Sinha (2013, 2014)
R.A., Broeckel, Cicoli, Osinski (2020)

UV complete models should address both inflation and post-inflation.

Number of e-foldings for CMB perturbations affected:

$$N_{k_*} \approx 57.3 + \frac{1}{4}\ln(r) - \Delta N_{reh} - \Delta N_{EMD}$$

$$\Delta N_{reh} = \frac{1-3w_{reh}}{6(1+w_{reh})}\, ln\left(\frac{H_{inf}}{H_{reh}}\right) \qquad \Delta N_{EMD} = \frac{1}{6}\, ln\left(\frac{H_0}{H_R}\right) > 0$$

Two universality classes of single field inflation models: Roest (2014)

- Class I: $a = c\,, b \sim O(10)$

E.G., Starobinsky inflation and Higgs inflation $r \lesssim O(0.01)$

- Class II: $b = 8(a-1), c = 1$

E.G., axion monodromy inflation $r \sim O(0.1)$

Histories with $w < \frac{1}{3}$ restricts models of inflation & vice versa.

How long coherent oscillations of moduli last?

- Fragmentation to oscillons

Can happen for some moduli in KKLT and LVS setups

Antusch, Cefala, Krippendorf, Muia, Orani, Quevedo (2017)

- Non-perturbative decay to moduli quanta

Might happen from couplings to the Higgs

Cicoli, Hebecker, Jaeckel, Wittner (2022)

Eventually, an epoch of EMD is expected to follow.

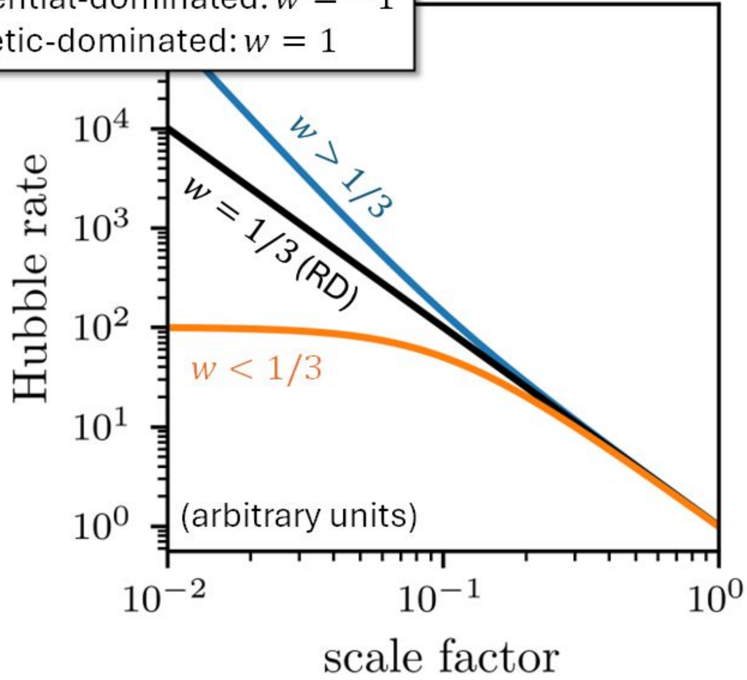
However, there could be a prolonged period with $w > 0$.

→ Affects relic abundances and number of e-foldings.

Sten Slides

Consequences of nonstandard expansion histories

$p = w\rho$
Potential-dominated: $w = -1$
Kinetic-dominated: $w = 1$



Higher/lower Hubble rate H

- Different timing of kinetic decoupling/freeze-out/…

$$\Gamma = H$$

- Different timing of horizon entry

$$k = aH$$

- More/less efficient particle drift

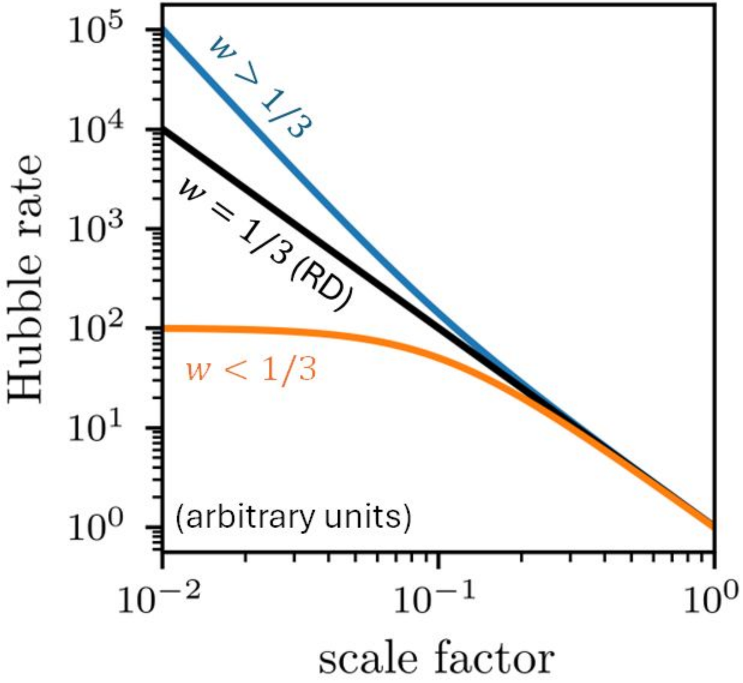
$$\boldsymbol{s} \propto \int \frac{\mathrm{d}t}{a^2} \propto \int \frac{\mathrm{d}a}{a^3 H} \propto \text{const.} + \begin{cases} a^{(3w-1)/2}, & \text{if } w \neq 1/3 \\ \ln a\,, & \text{if } w = 1/3 \end{cases}$$

  - Faster/slower growth of density perturbations
  - Faster/slower suppression of perturbations

+ gravitational waves

Chemical outcomes

e.g., thermal dark matter production

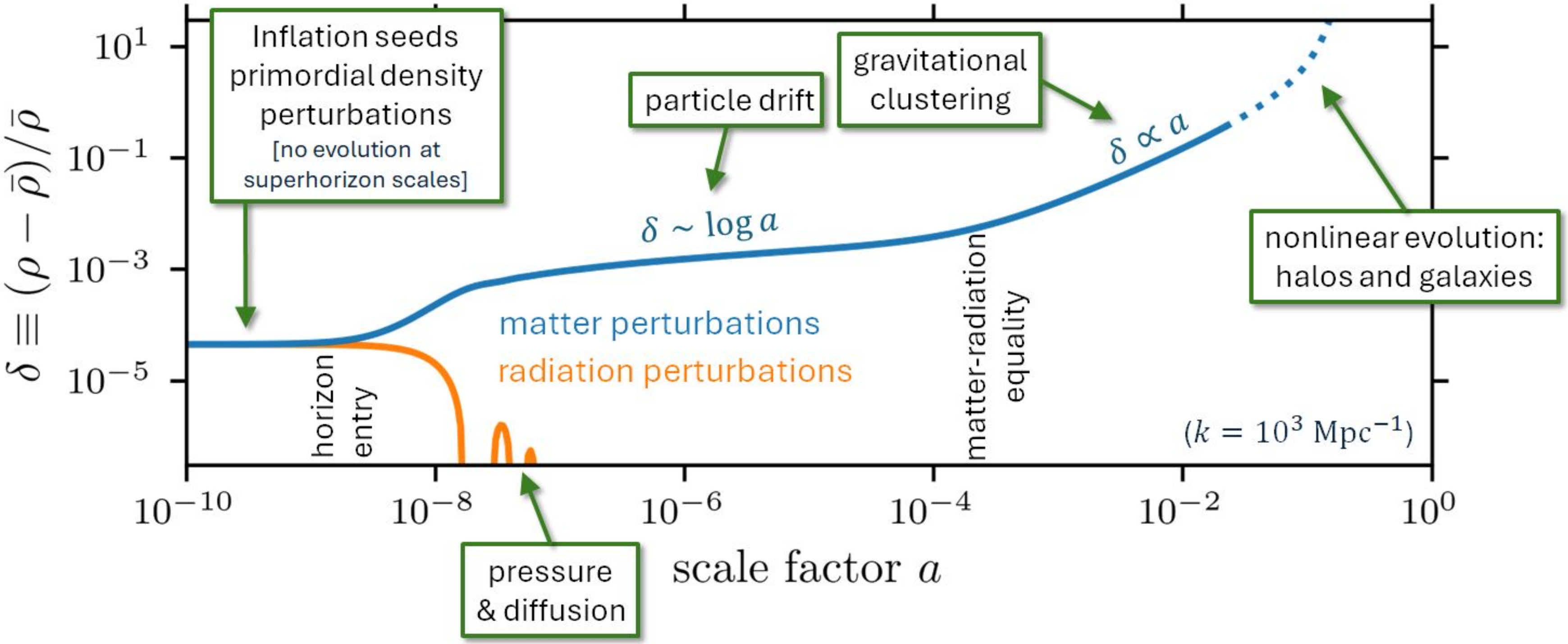


Freeze-out when $n_\chi \langle \sigma v \rangle = H$.

$w > 1/3$ → H higher
→ need higher $\langle \sigma v \rangle$ for same n_χ

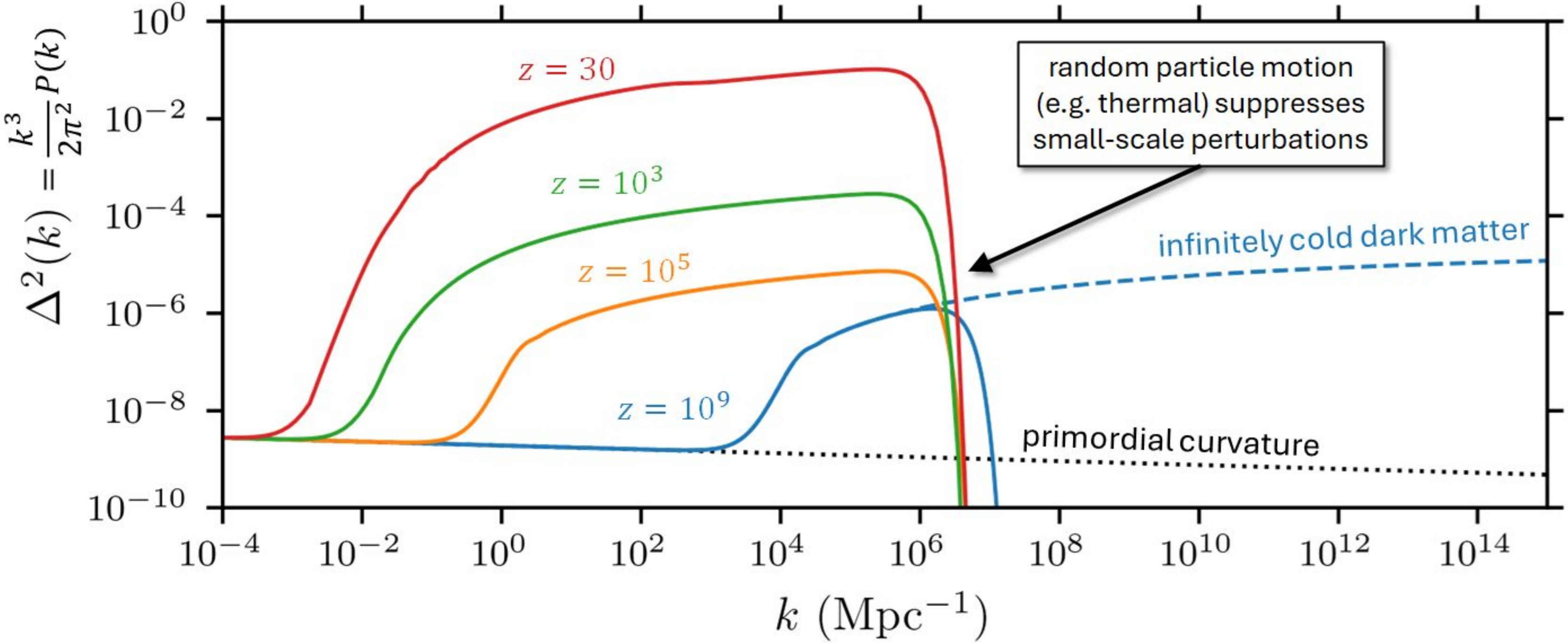
Growth of perturbations

Standard picture: radiation dominated for $a < 3 \times 10^{-4}$



Matter power spectrum

Consider a power-law primordial power spectrum that is consistent with CMB measurements

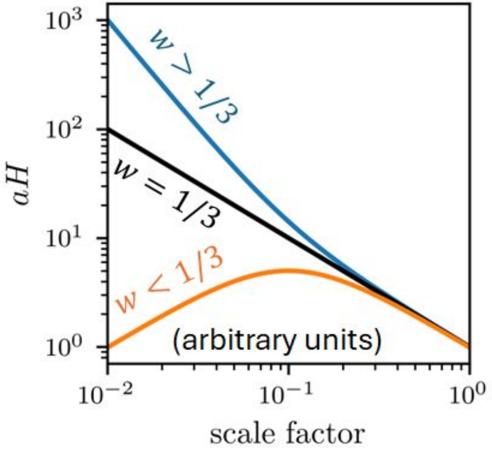


Growth of perturbations

Dominant species does not cluster, so there is no peculiar gravity.
All evolution arises only from initial motion + free particle drift.

Timing of horizon entry

$$k = aH \propto a^{-(3w+1)/2}$$



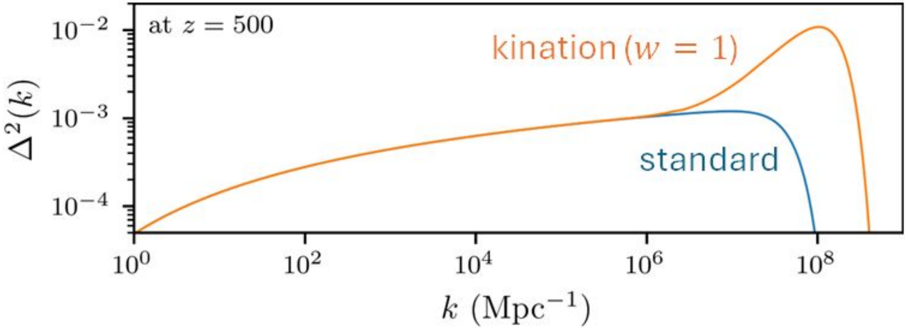
$w > 1/3$ → later horizon entry for the same k
→ less power

Efficiency of particle drift

$$\delta = -\nabla \cdot \boldsymbol{s} \propto \text{const.} + \begin{cases} a^{(3w-1)/2}, & \text{if } w \neq 1/3 \\ \ln a\,, & \text{if } w = 1/3 \end{cases}$$

$w > 1/3$ → more efficient particle drift
→ more power

Leads to power spectrum $\Delta^2(k) \propto k^{\frac{2(3w-1)}{3w+1}} \mathcal{P}_\zeta(k)$

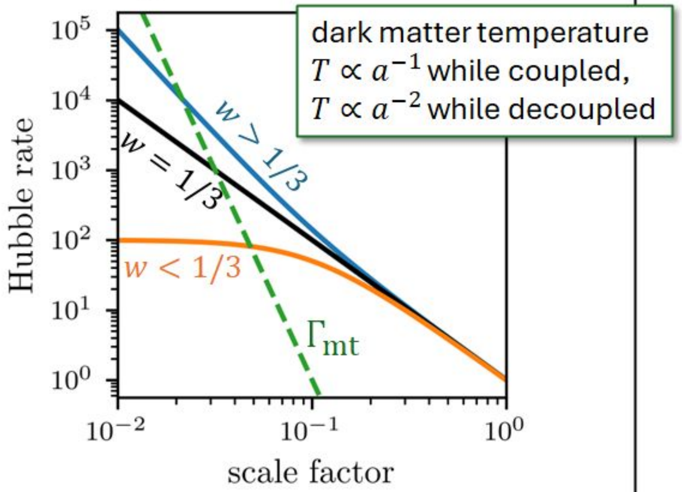


(drift won)

Suppression of perturbations

Dominant species does not cluster, so there is no peculiar gravity.
All evolution arises only from initial motion + free particle drift.

Timing of kinetic decoupling



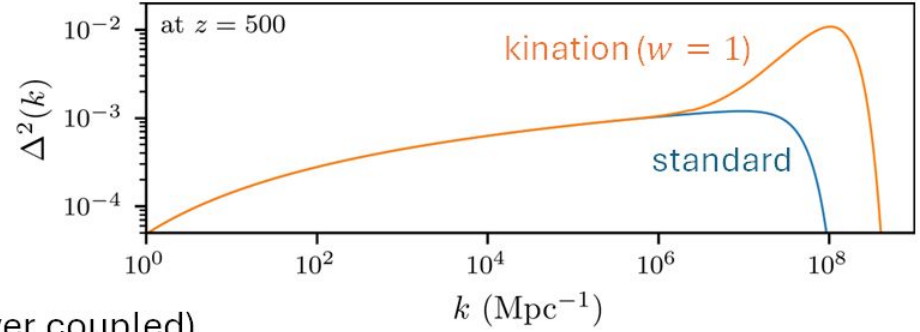
$w > 1/3$ → decoupling ($\Gamma_{\rm mt} = H$) earlier
→ smaller suppression scale

(or consider timing of DM creation, if never coupled)

Efficiency of particle drift

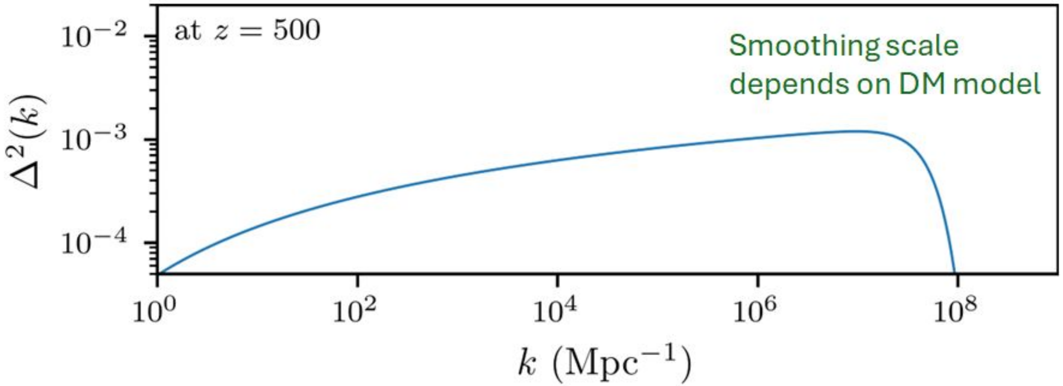
$$\delta = -\nabla \cdot \boldsymbol{s} \propto \text{const.} + \begin{cases} a^{(3w-1)/2}, & \text{if } w \neq 1/3 \\ \ln a, & \text{if } w = 1/3 \end{cases}$$

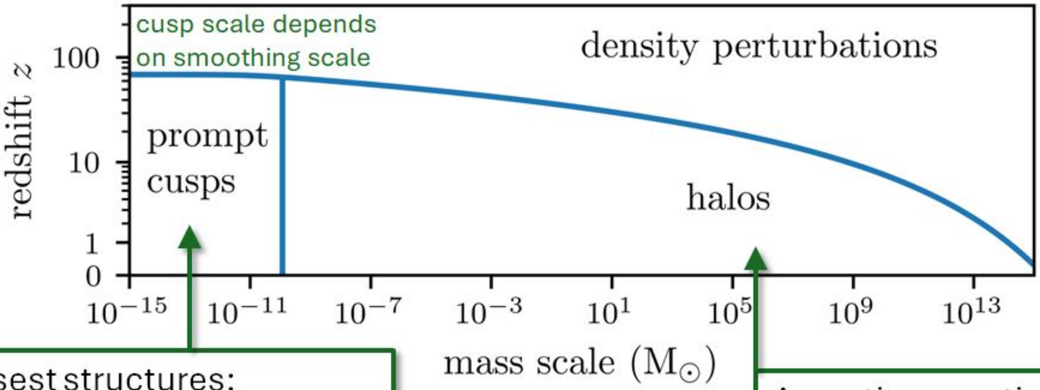
$w > 1/3$ → more efficient particle drift
→ larger suppression scale

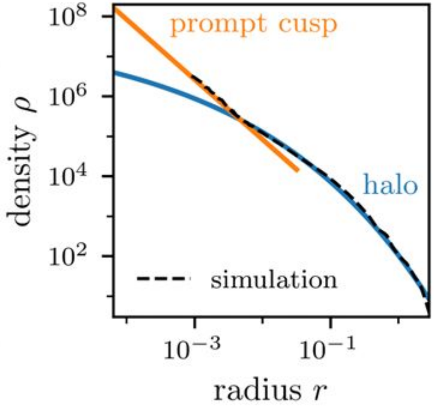


(decoupling timing won)

Matter power spectrum and nonlinear structure



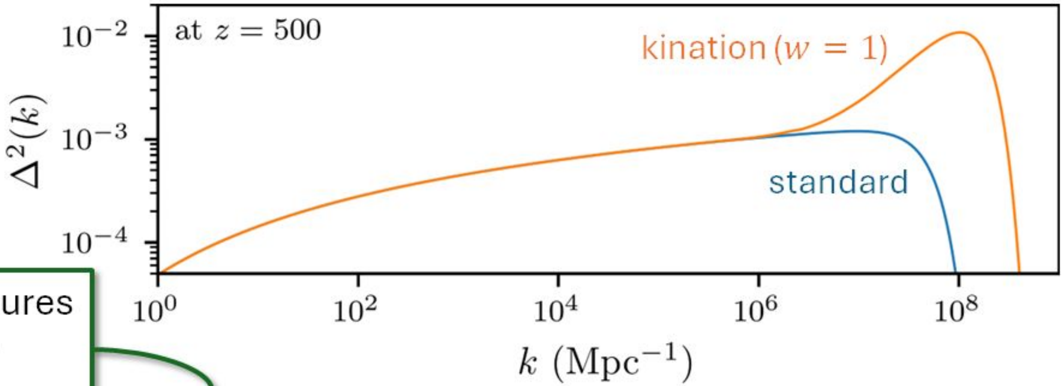




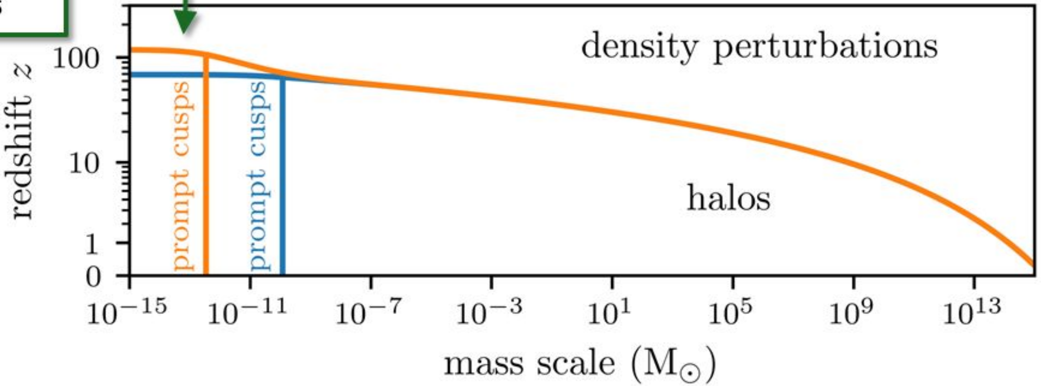
First & densest structures:
Collapse of initial peaks → $\rho \propto r^{-1.5}$ profiles

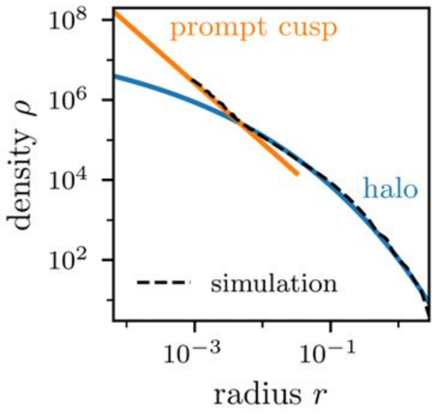
Accretion over time → NFW/Einasto profiles

Matter power spectrum and nonlinear structure



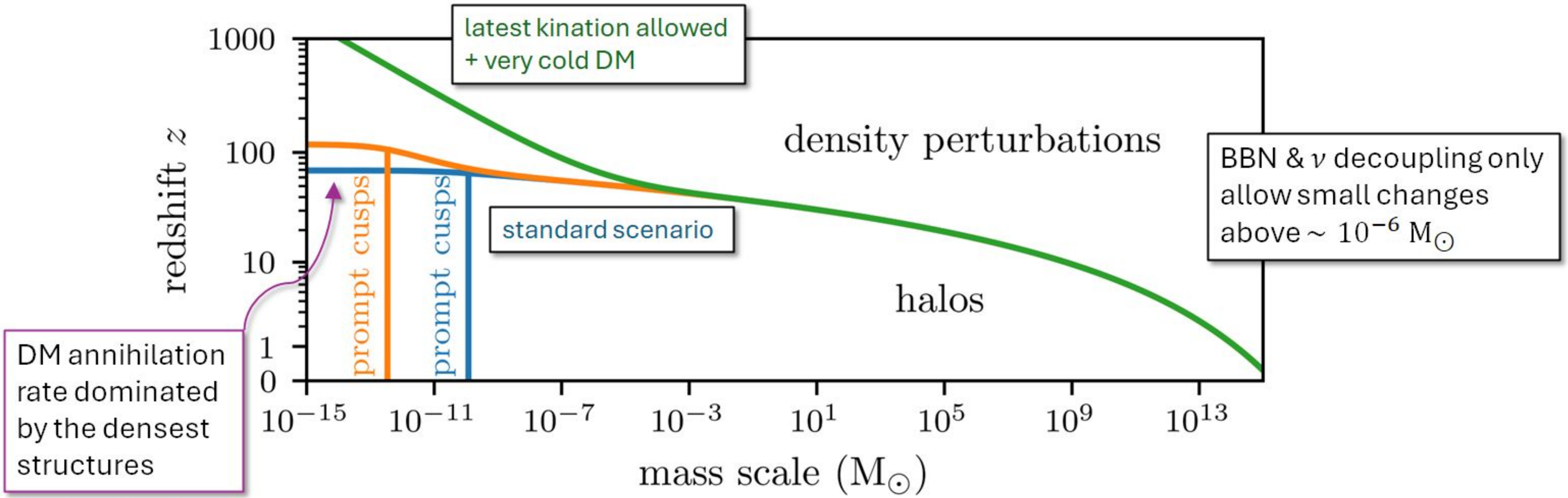
Nonlinear structures form earlier at smaller sizes





Earlier structure formation → denser structures ($\propto$ density of Universe at formation time)

Probes of structure



- solar system perturbations
- spacecraft perturbations

- microlensing
- pulsar timing

- dwarf galaxy disruption
- wide binary disruption

- Lyman α
- dwarf galaxy abundance & kinematics
- strong lensing
- stellar streams

- galaxy distribution
- CMB

(currently) only sensitive to early structure formation, i.e., if power spectrum is boosted

Tightly constrained, only small deviations allowed

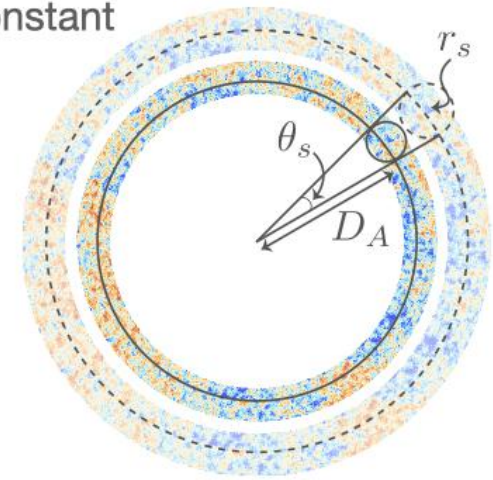
Tristan Slides

Pre-recombination resolutions to the Hubble tension

- Angular structure of the CMB must remain $\simeq$ constant

$$r_s(z_{\rm rec}) = \int_{z_{\rm rec}}^{\infty} \frac{c_s(z)}{H(z)} dz$$

$$\theta_s = \frac{r_s(z_{\rm rec})}{D_A(z_{\rm rec})} \sim \frac{c_s(z_{\rm rec})/H(z_{\rm rec})}{F(\Omega_m)/H_0} = \frac{H_0}{H(z_{\rm rec})} \frac{c_s(z_{\rm rec})}{F(\Omega_m)}$$



- If $H(z_{\rm rec})$ increases then Silk damping angular scale <u>must</u> increase

$$\theta_D \sim \frac{H_0}{\sqrt{\dot{\tau}(z_{\rm rec})H(z_{\rm rec})}} \rightarrow \delta\theta_D/\theta_D \sim \sqrt{H_0/H_0^{\Lambda\rm CDM}}$$

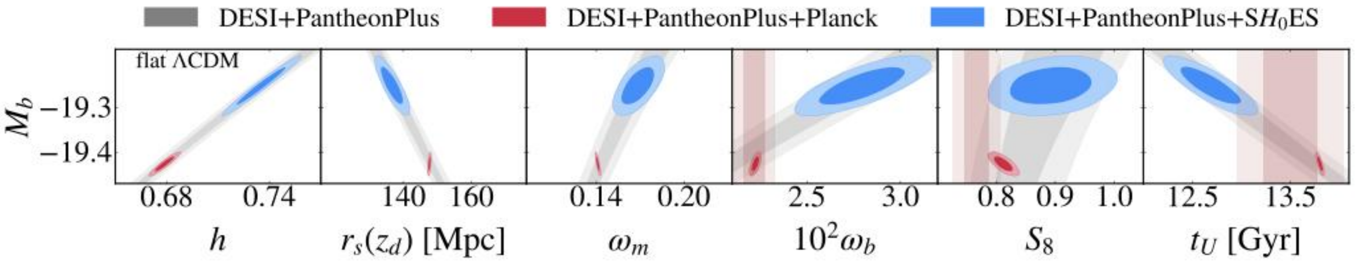
"Damping starts at larger scales" → n_s also generically increases

See Poulin, TLS, and Karwal 2302.09032

Stop calling it the Hubble tension!

Aylor++ 1811.00537
Knox and Millea 1908.03663
Bernal, Verde++ 2102.05066
Poulin, TLS++ 2407.18292
Pedrotti++ 2408.04530

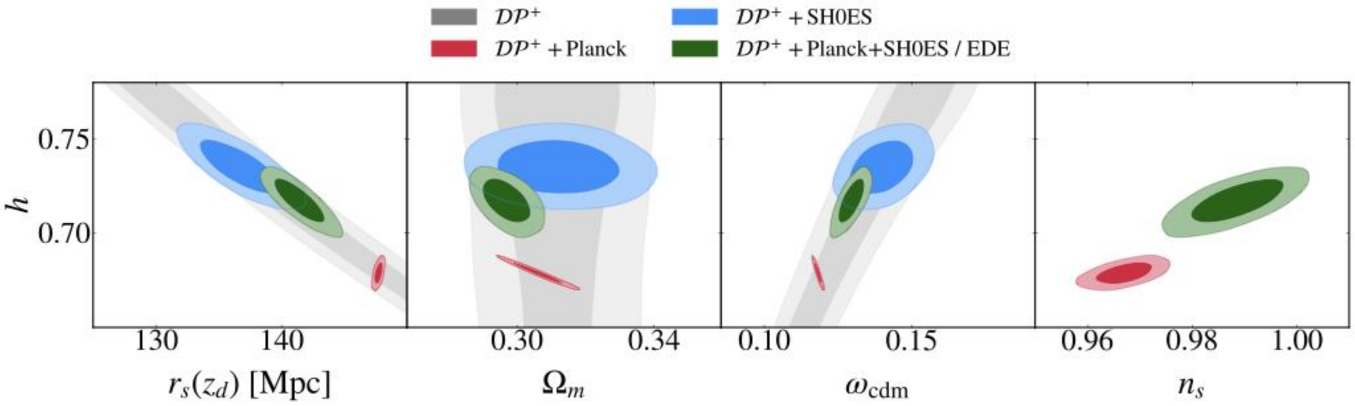
In this paper we called it the "cosmic calibration tension"



$$\omega_m = \Omega_m h^2$$

Stop calling it the Hubble tension!

See Poulin, TLS++ 2407.18292



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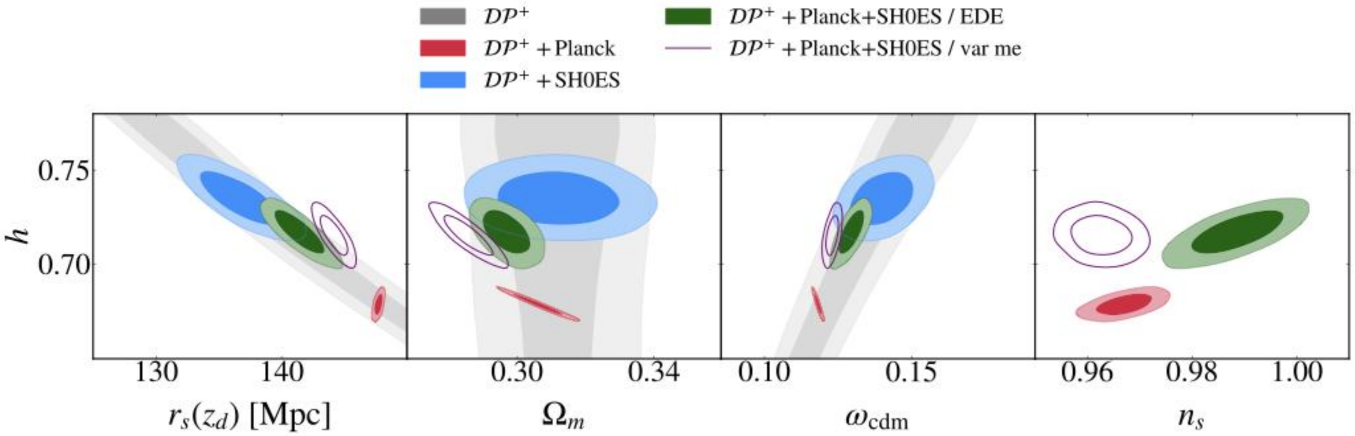
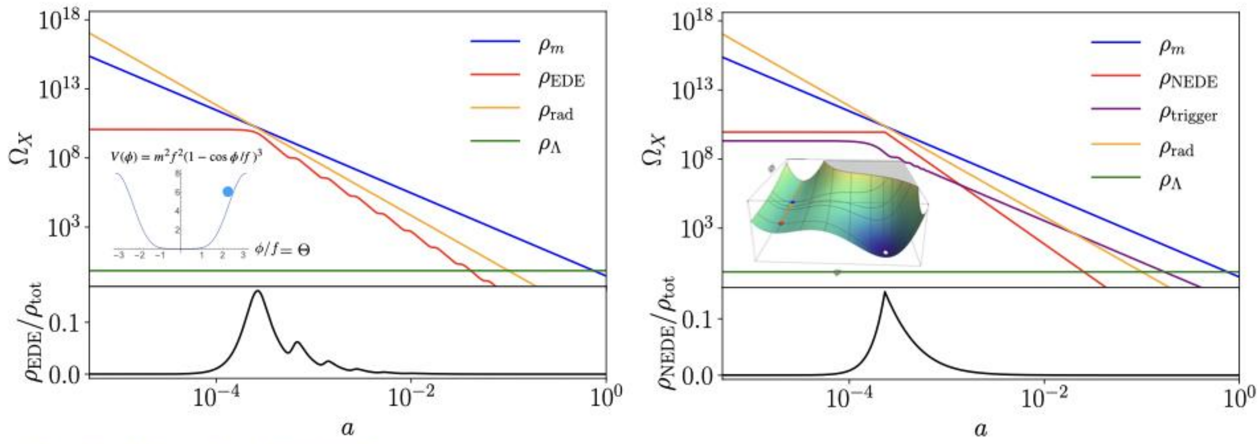


Two case studies: axion-like EDE and 'new' EDE

- Axion-like EDE is a cosmological scalar field initially fixed by Hubble friction which then oscillates
- 'New' EDE is a field in a false vacuum which undergoes a phase transition



Karwal and Kamionkowski 1608.01309
Poulin, TLS++ 1811.04083

Niedermann and Sloth 1910.10739, 2006.06686, 2009.00006

- In both cases the fields have mass parameters of order $H_{\rm eq} \simeq 10^{-27}$ eV
- Potentials of the form $V \propto \phi^n$ <u>do not work</u> *e.g., TLS, Poulin, and Amin 1908.06995*

What we learn from a fluid model

Lin++ 1905.12618

Poulin, TLS, Karwal 2302.09032

$$\rho_{\rm EDE}(a) = \rho_{\rm EDE,0} e^{3\int_a^1 [1+w_{\rm EDE}(a)] da/a}$$

$$w_{\rm EDE}(a) = \frac{1+w_f}{1+(a_c/a)^{3(1+w_f)}} - 1$$

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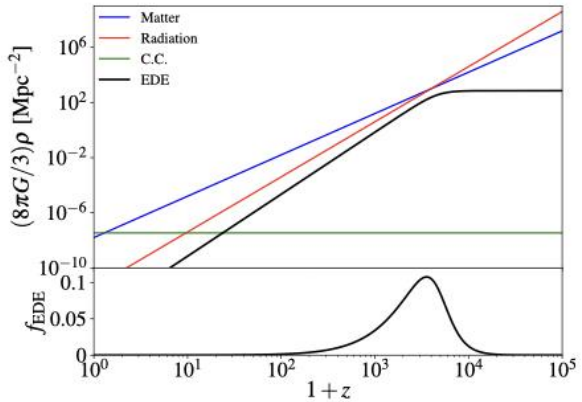

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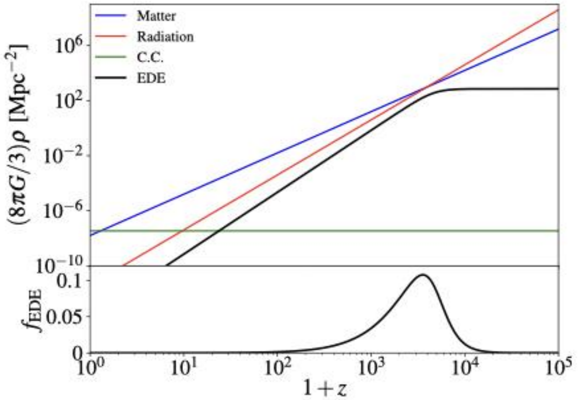

Perturbation equations:

$$\frac{d}{d\eta}\left(\frac{\delta_{\rm EDE}}{1+w_{\rm EDE}}\right) = -(\theta_{\rm EDE}+h'_\delta) - 3\frac{a'}{a}(c_s^2-c_a^2)\left(\frac{\delta_{\rm EDE}}{1+w_{\rm EDE}} + 3\frac{a'}{a}\frac{\theta_{\rm EDE}}{k^2}\right)$$

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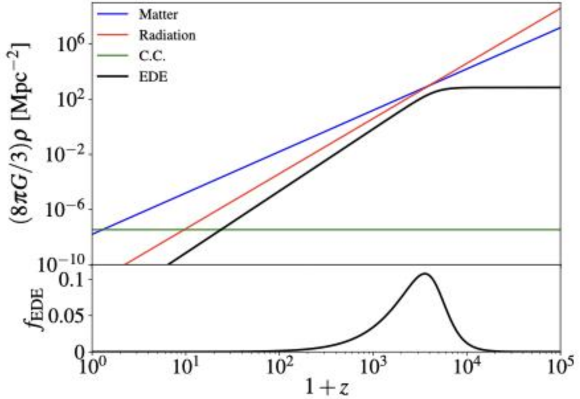

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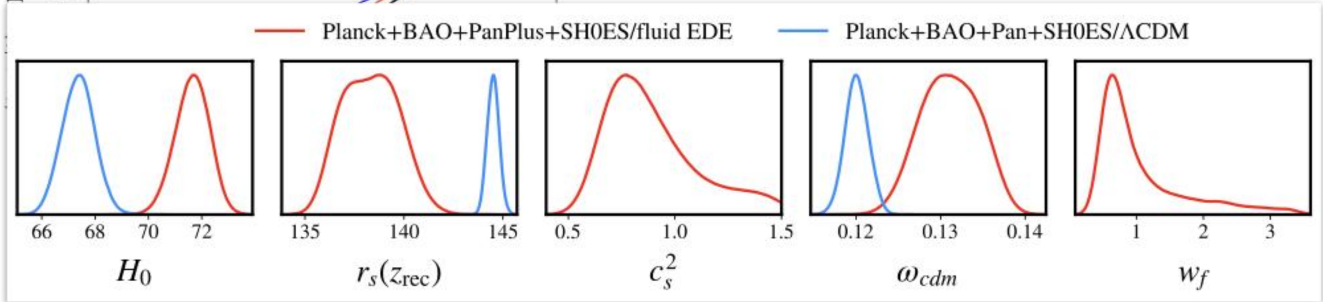

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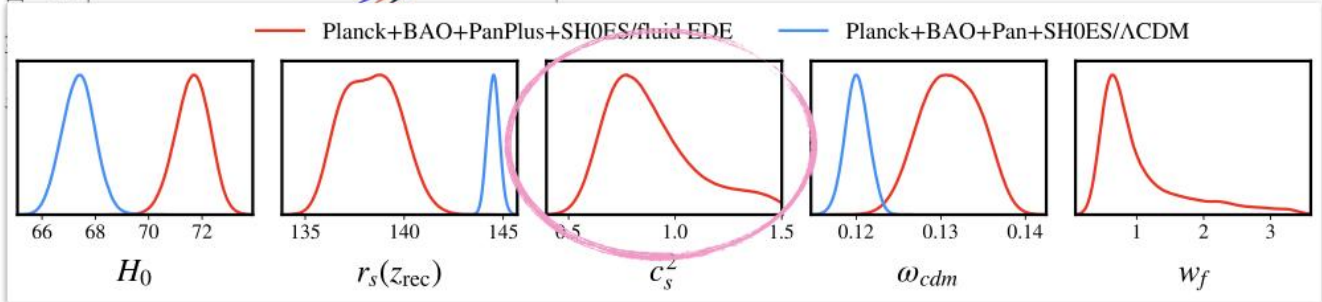
Perturbations are important!



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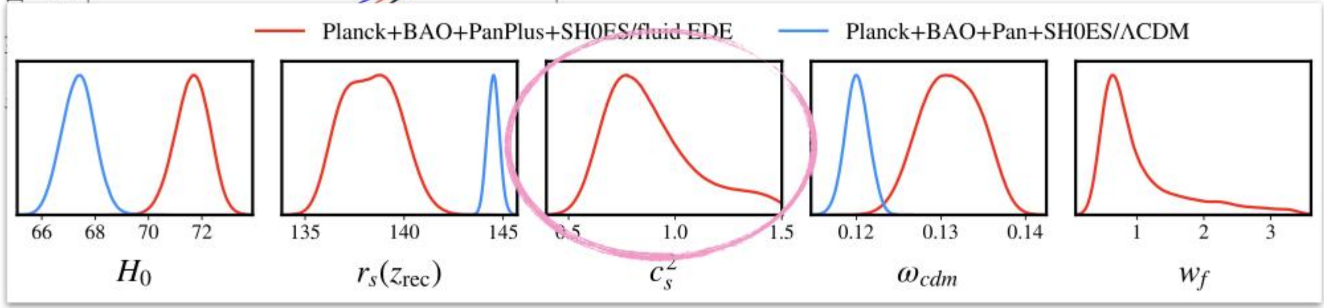

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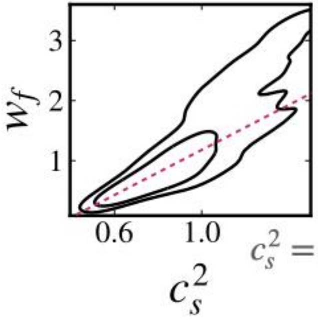


$c_s^2 = 0.54 + 0.25 \times w_f$

Extensions:

- Coupling DM & EDE to address S_8

Karwal ++ 2106.13290
McDonough ++ 1811.04083

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + i\bar{\psi}\not{D}\psi - V(\phi) - m_{\rm DM}(\phi)\bar{\psi}\psi$$

$$m_{\rm DM}(\phi) = m_0 e^{c\phi/M_{\rm pl}}$$

Leads to <u>enhanced</u> DM growth: $G_{\rm eff} = G_N\left(1 + \frac{2c^2k^2}{k^2 + a^2 d^2V/d\phi^2}\right)$ *Bean ++ 0808.1105*

- Modified gravity

Adi and Kovetz 2011.13853
Abellan, Braglia++ 2308.12345

$$S = \int d^4x\sqrt{-g}\left[\frac{F(\sigma)}{2}R - \frac{g^{\mu\nu}}{2}\partial_\mu\sigma\partial_\nu\sigma - \Lambda - V(\sigma) + \mathcal{L}_m\right]$$

$$V(\sigma) = \lambda\sigma^4/4$$

- Non-minimal coupling to address fine tuning

Sakstein and Trodden 1911.11760
Gonzalez, Liang, Sakstein and Trodden 2011.09895

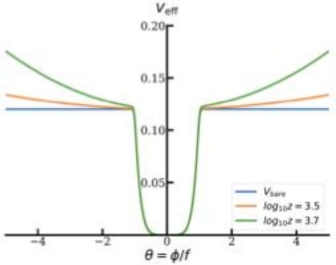
$$S = \int d^4x\sqrt{-g}\left[\frac{{M_{\rm pl}}^2 R(g)}{2} - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - V(\phi)\right] + S_\nu[\tilde{g}_{\mu\nu}],$$

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = \frac{\beta}{M_{\rm pl}}\Theta(\nu).$$

Lin, McDonough, Hill, and Hu 2212.08098

$$m_{\rm DM}(\phi) = m_0\left(1 + g\frac{\phi^2}{M_{\rm pl}^2}\right)$$

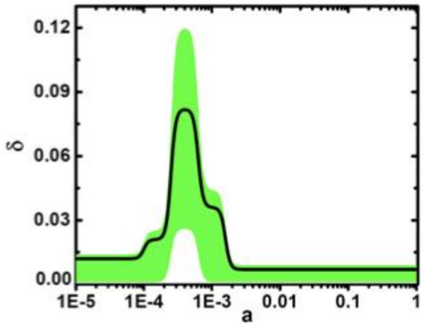
$$V_{\rm eff} \approx V(\phi) + g\frac{\phi^2}{M_{\rm pl}^2}\rho_{\rm DM}$$



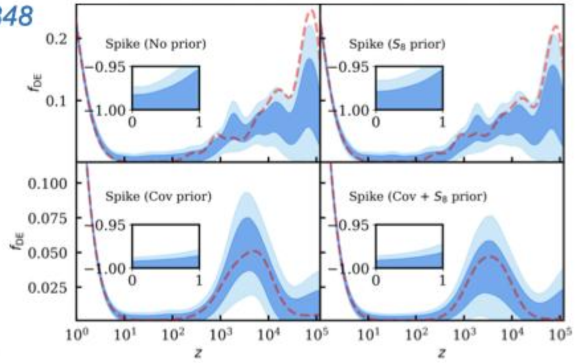
‘Model independent’ approaches?

Hojjati et al. 1304.3724

$$H^2(a) = \frac{8\pi G}{3}\left[\rho_m(a) + \rho_r(a) + \rho_\Lambda\right]\left[1 + \delta(a)\right] \qquad \delta = \sum_i \delta_i \left[\frac{1}{1 + e^{(\ln a - \ln a_{i+1})/\tau}} - \frac{1}{1 + e^{(\ln a - \ln a_i)/\tau}}\right]$$

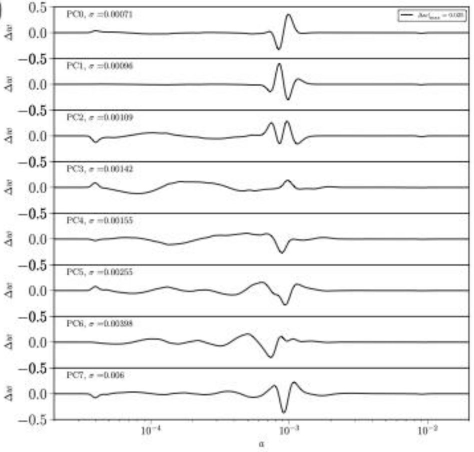


Moss et al. 2109.14848



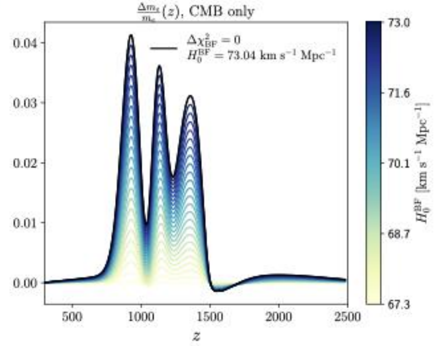
- PCA of $w(a)$

TLS and Grin, in prep.



- ‘constrained optimization’

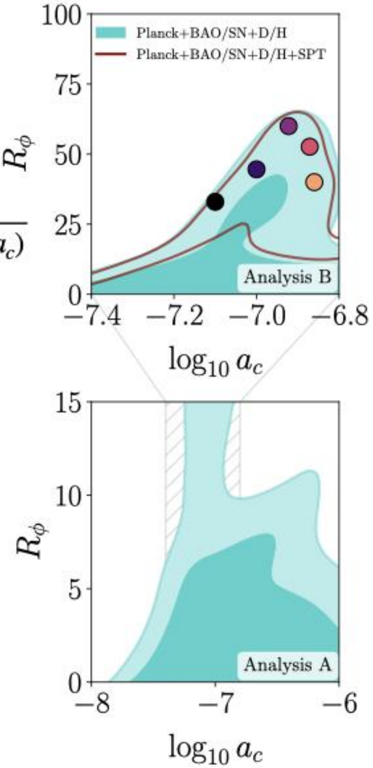
Lee++ 2212.04494

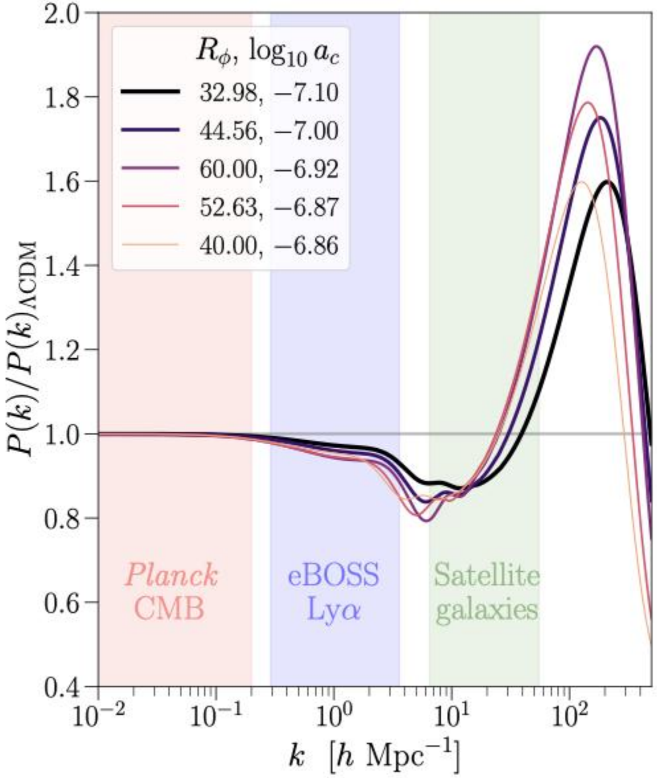


Very Early Dark Energy

Sobotka, Erickcek, and TLS, in prep.

$$R_\phi \equiv \frac{\rho_\phi(a_c)}{\rho_{\rm tot}(a_c) - \rho_\phi(a_c)}$$





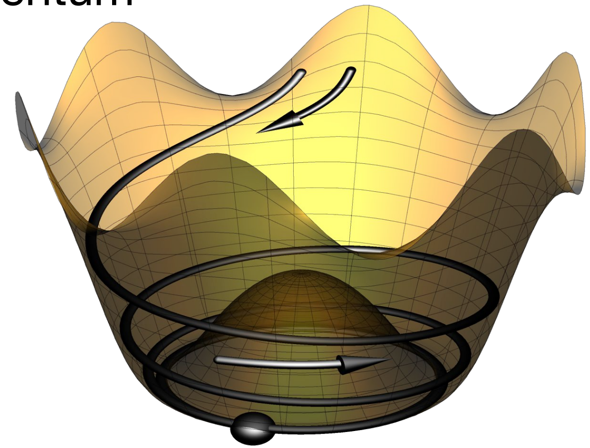
Akshay Slides

Kination (Axion Kination)

The story in Pictures

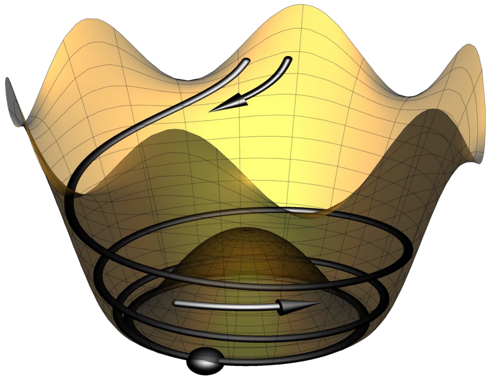
Explicit breaking of PQ symmetry sources fast axion rotation

- Complex PQ scalar field
- High-dim operators explicitly break PQ symmetry
- Induces axion rotation, giving the axion “angular momentum”



Credit: Raymond Co and Keisuke Harigaya

The story in Pictures



Conservation of charge dictates cosmology

$$V(P) = (m_S^2 - c_H H^2)|P|^2 + \left(A\frac{P^n}{M^{n-3}} + \text{h.c.}\right) + \frac{|P|^{2n-2}}{M^{2n-6}}.$$

- Rotation of PQ field corresponds to PQ charge

$$n_{PQ} = i(\dot{P}^*P - \dot{P}P^*) = \dot{\theta}\left(f_a^2 + S^2\right)$$

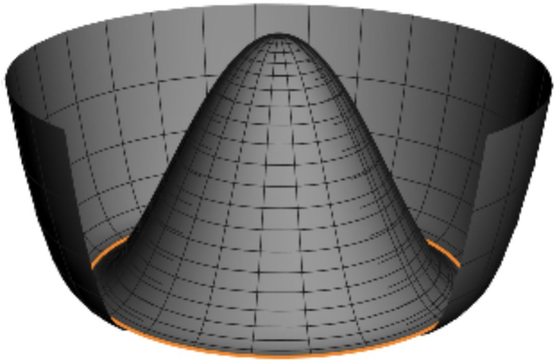
- Scaling of energy density and rotational charge fixes

$$m_S^2|P|^2 \propto a^{-3} \qquad n_{PQ} = \dot{\theta}|P^2| \propto a^{-3} \qquad \left\langle\dot{\theta}\right\rangle = const \simeq m_S$$

- Thus for P >> fa the energy density scales like matter

The story in Pictures

Conservation of charge dictates cosmology



- As P -> fa comoving charge conservation implies

$$n_{PQ} = \dot{\theta}\,|f_a^2| \propto a^{-3} \rightarrow \dot{\theta} \propto a^3$$

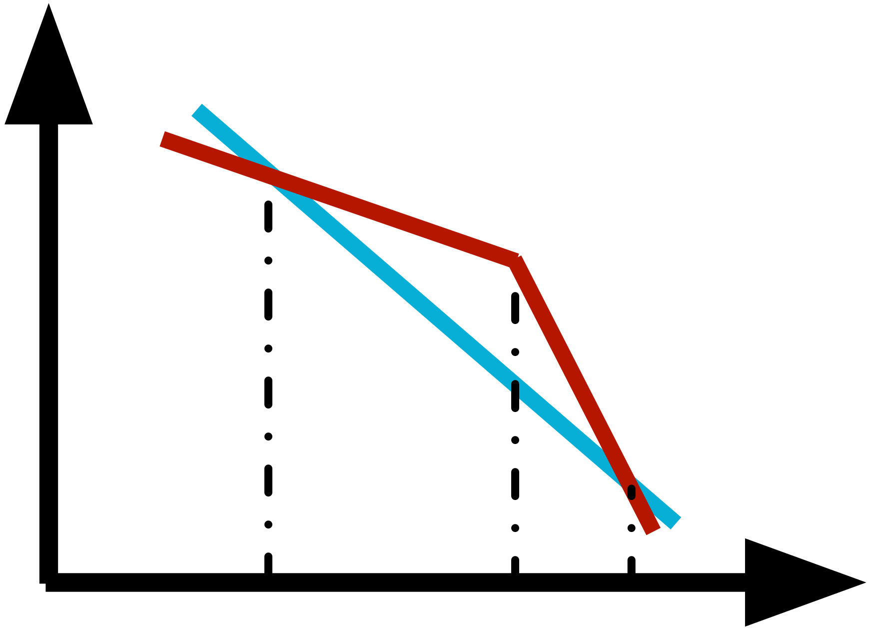
- Thus the energy density scales as

$$\rho_{PQ} = \dot{\theta}^2\,|f_a^2| \propto a^{-6}$$

- Thus once the field rotates near the minima, energy density scales as kination

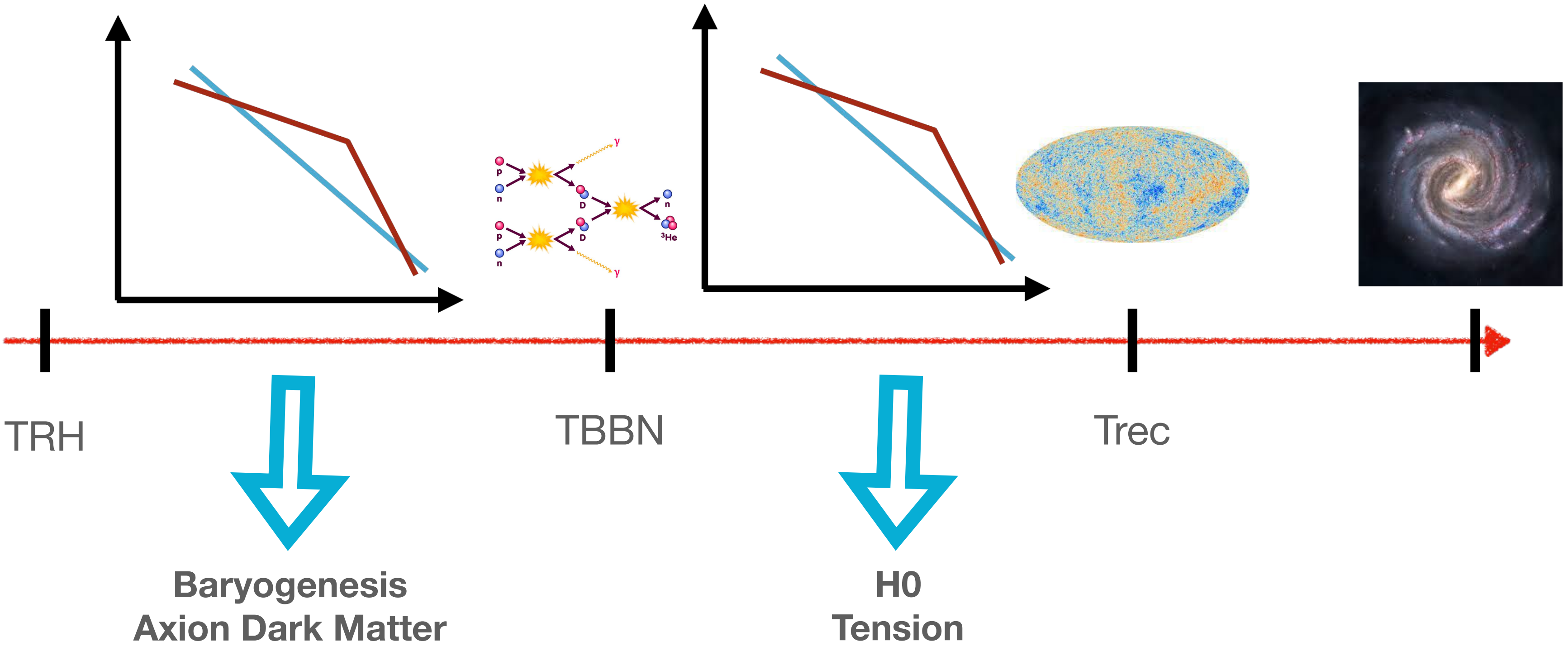
The story in pictures

Matter followed by Kination



The story in pictures

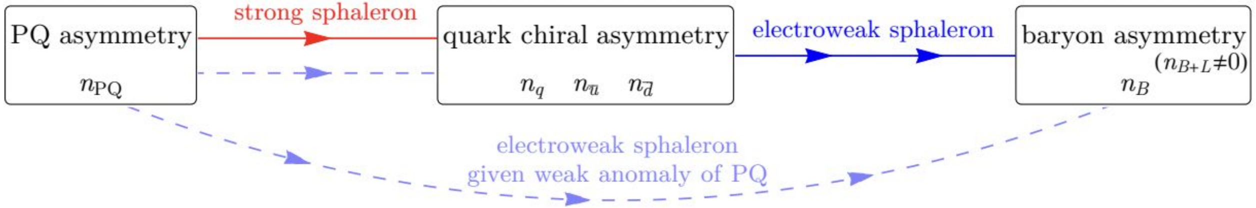
Matter followed by Kination



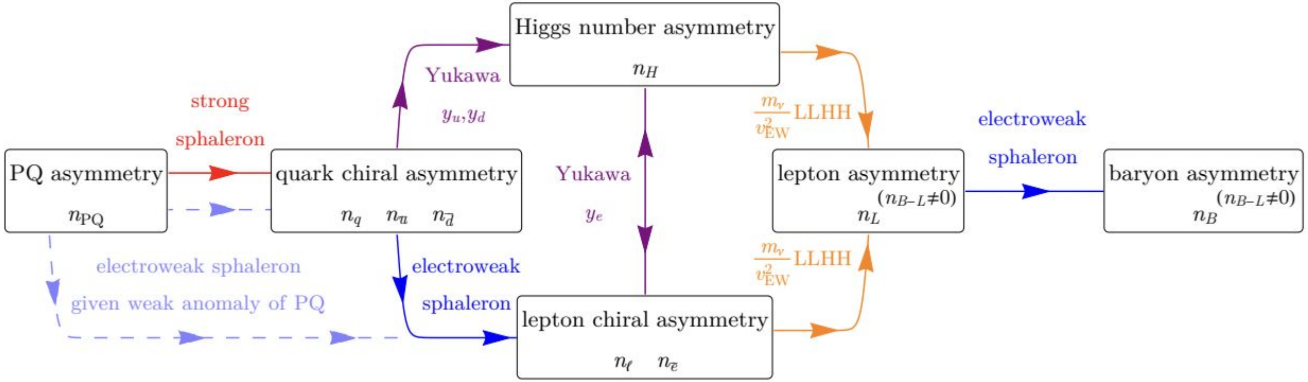
High scale axion kination - baryogenesis

- Axion rotations source chiral asymmetry which sources baryogenesis (spontaneous baryogenesis)

Axiogenesis, Co and Harigaya



Lepto-axiogenesis



High scale axion kination - DM production

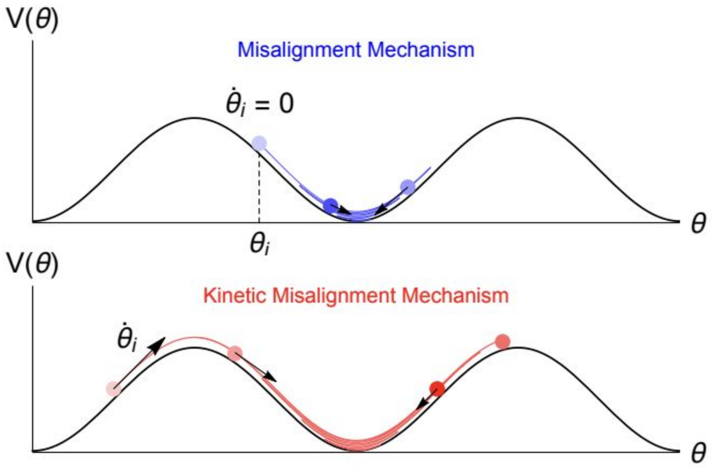
DM production comes from parametric resonance or KMM

- Parametric Resonance from saxion oscillations can produce

$$Y_a \simeq 20 \left(\frac{S_i}{10^{16}\mathrm{GeV}}\right)^2 \left(\frac{m_S}{100\mathrm{TeV}}\right)^{1/2}$$

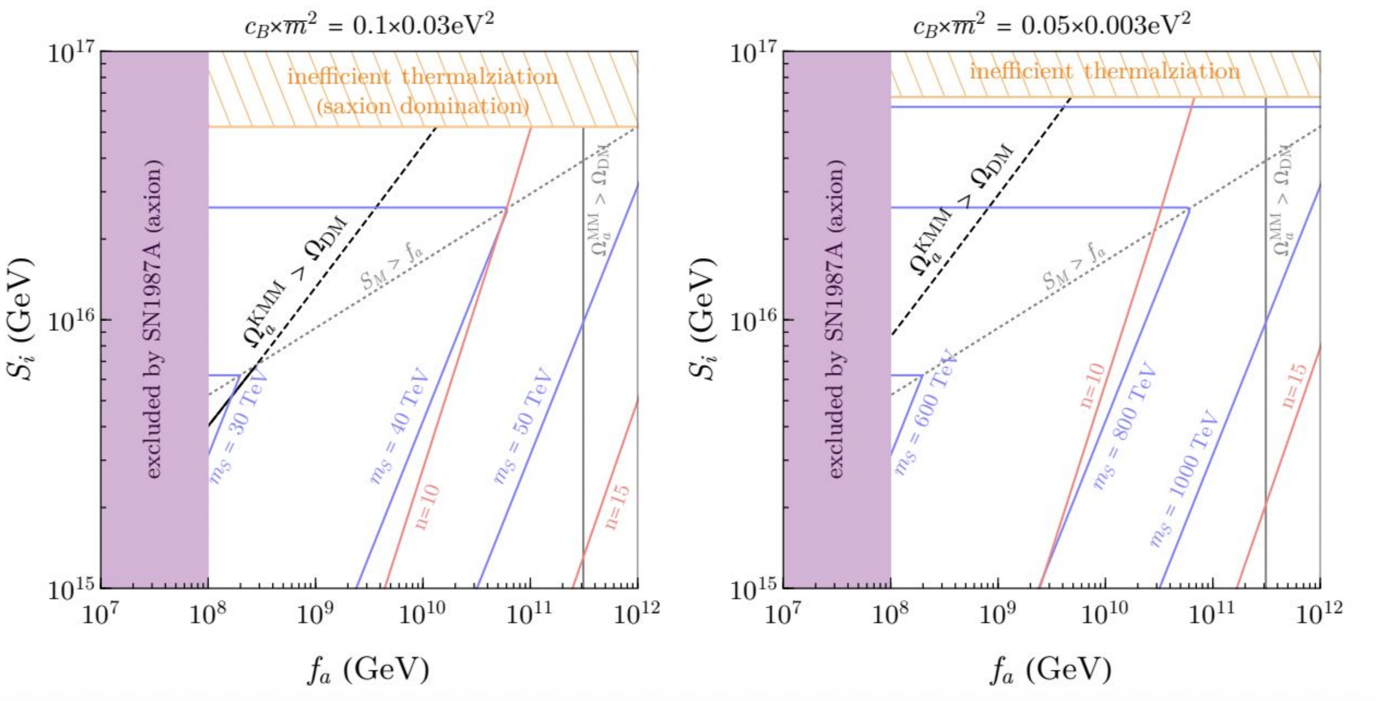
- However axions produced are warm and warmness constraints apply

- Kinetic Misalignement mechanism



Quadratic Potential

Results



Signatures of high scale kination

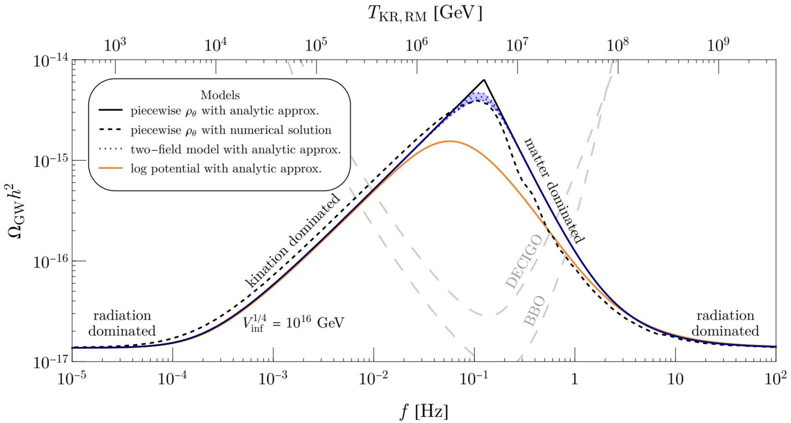
Enhancement of gravitational waves

- Gravitational waves produced from inflation have a flat spectrum.

- Modes outside horizon are frozen, behave like radiation upon horizon entry

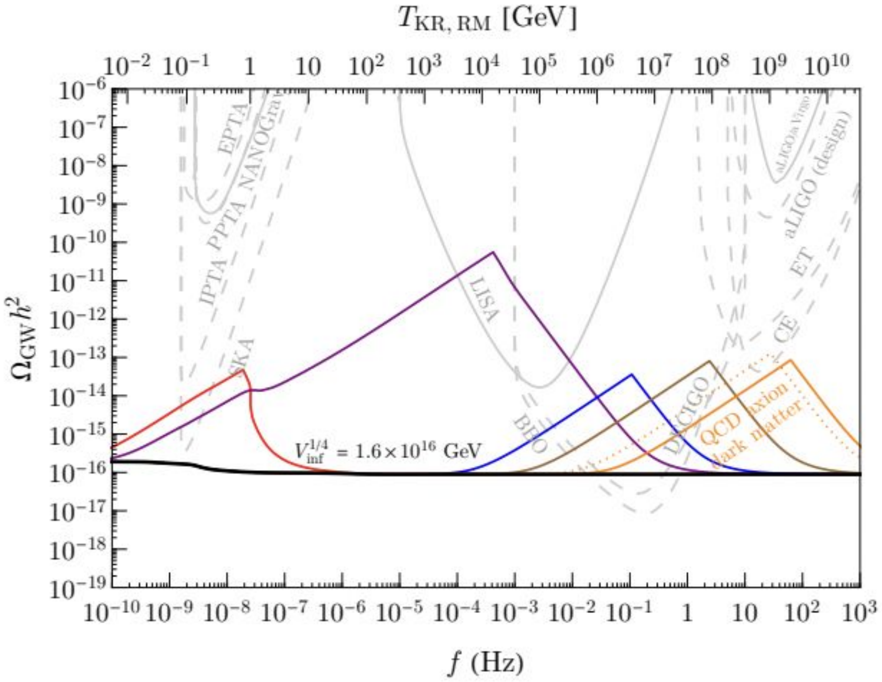
$$k \simeq H \to \rho_k \propto H^2 M_{\rm pl}^2$$

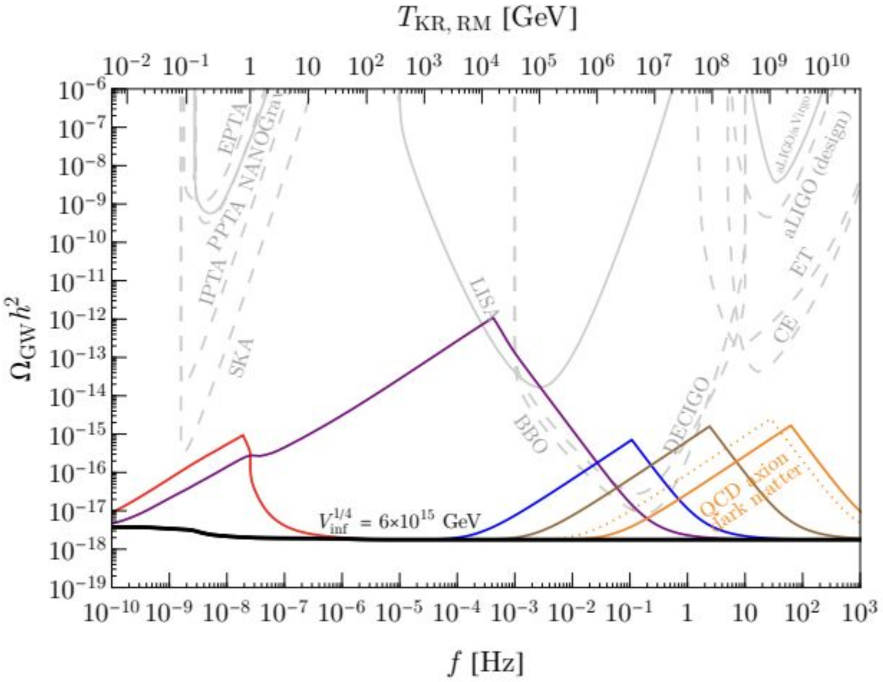
- However during matter and kination dominated era, radiation density fraction is much smaller enhancing GW spectrum



Signatures of high scale kination

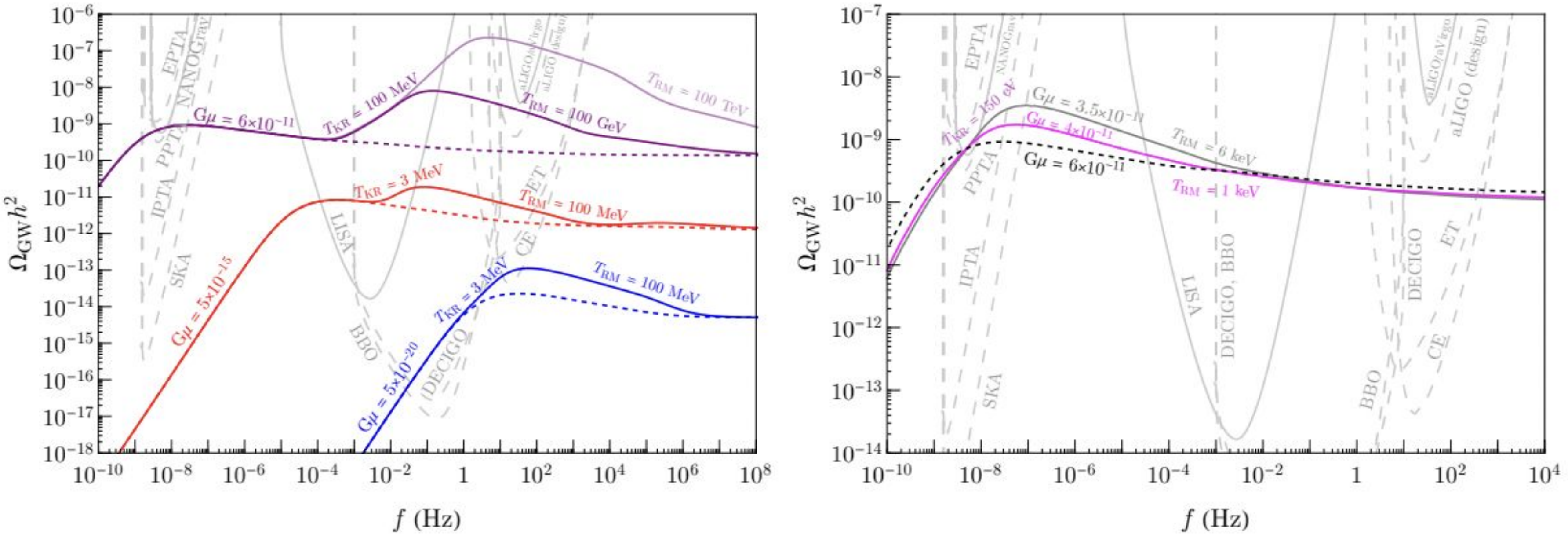
Enhancement of gravitational waves - Inflation





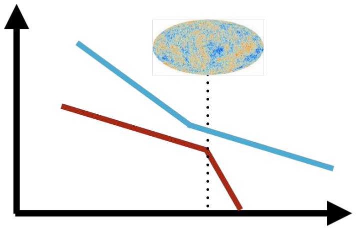
GW Waves

Enhancement of Gravitational Waves - Cosmic Strings



Low Scale Kination

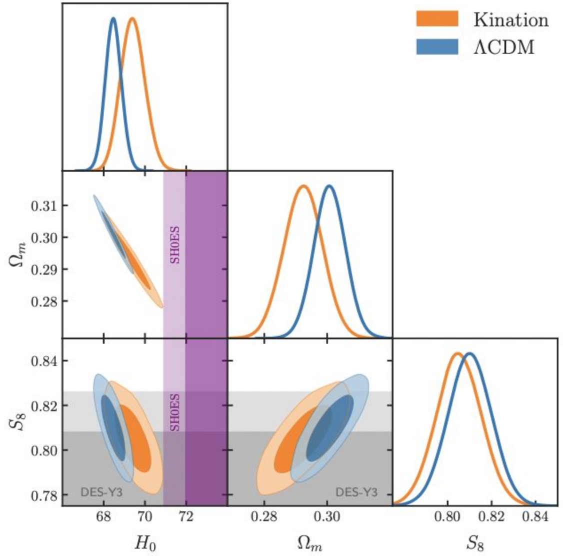
H0 tension



There is a disagreement between local measurements and CMB measurements of H0 (see Tristan's talk)

- Like EDE, a small amount of axion kination around recombination helps alleviate the Hubble tension

- Reduces H0 tension without increasing S8 tension



Conclusion

Why is Axion Kination Cool?

- Explicit breaking of PQ symmetry sources fast axion rotation.
- Can explain strong CP problem, neutrino masses, baryogenesis and dark matter
- Axion rotations can induce a modified cosmology, giving rise to early matter domination followed by kination
- Modifies matter power spectrum, gravitational waves spectrum providing a unique signature that will be probed by future experiments.
- Can reduce H0 tension without increasing S8 tension
- First “reasonable” model for Kination
- Feature of early matter domination, followed by Kination gives unique signature
- Exit from matter domination without entropy production