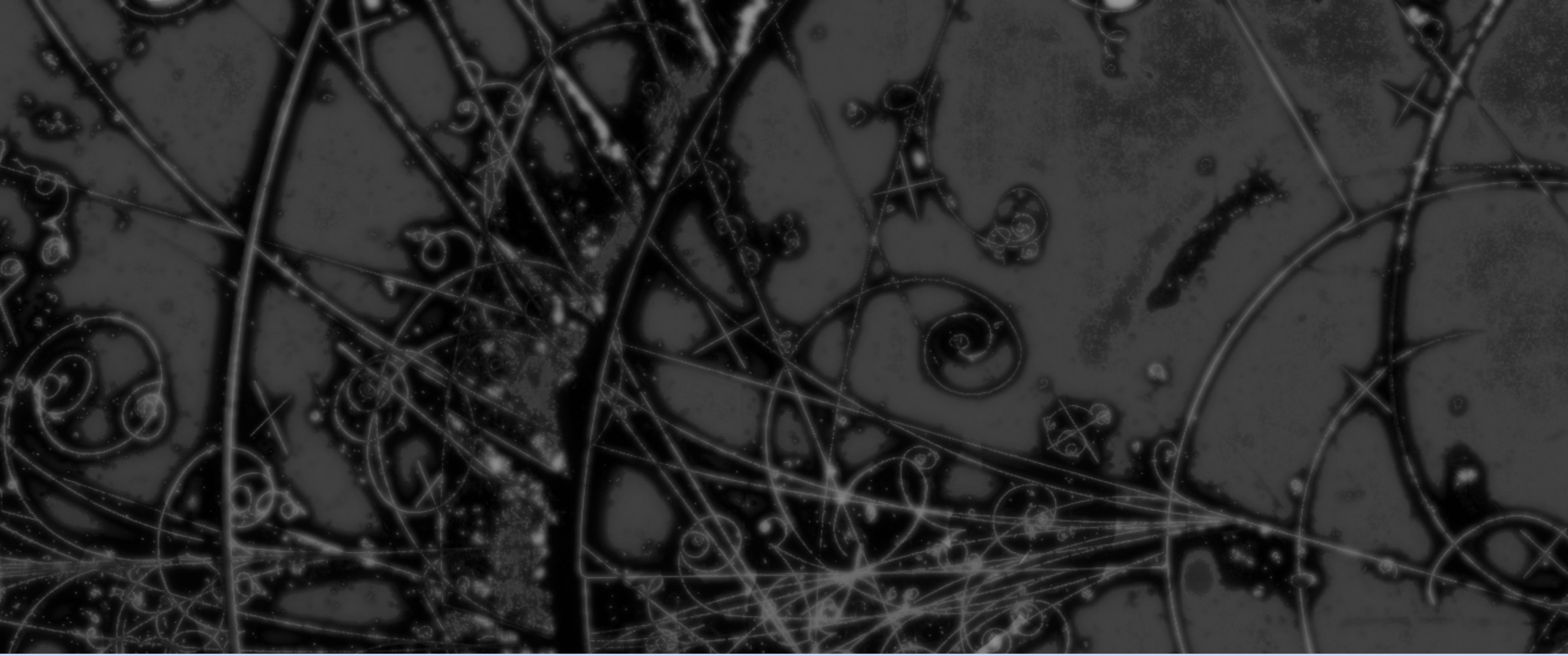
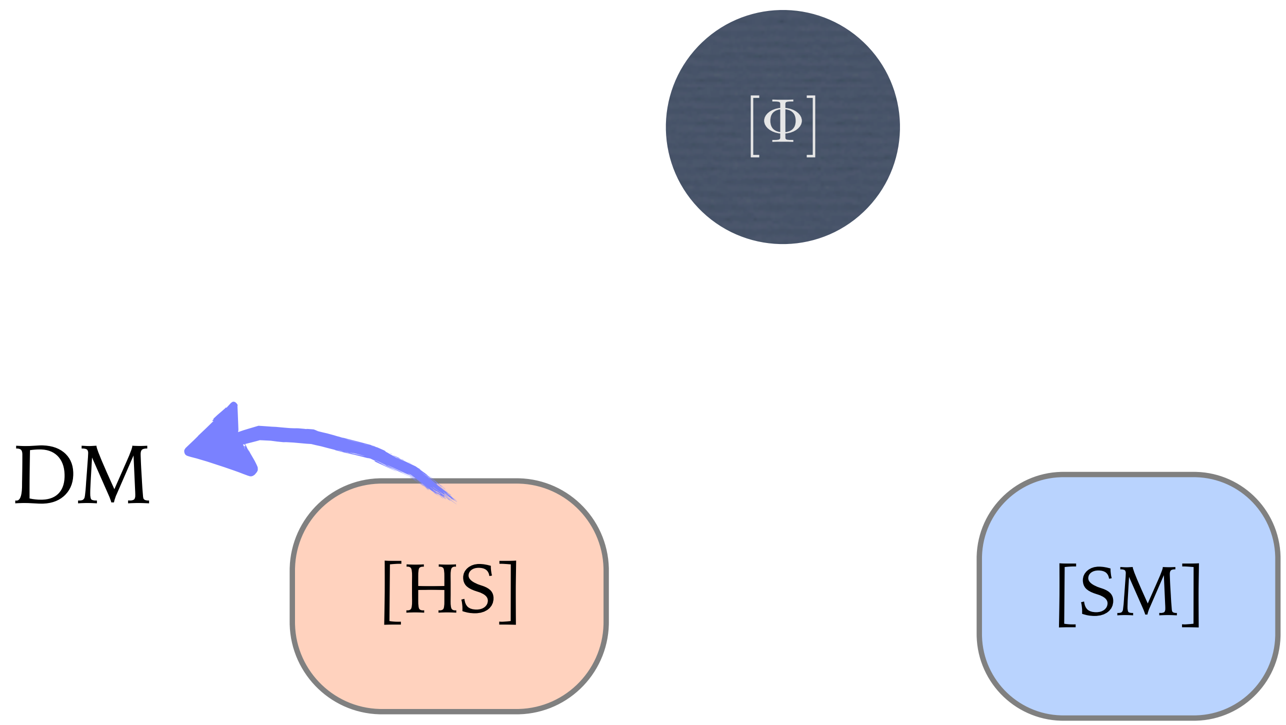


HIDDEN THERMAL HISTORIES

Jessie Shelton
UIUC

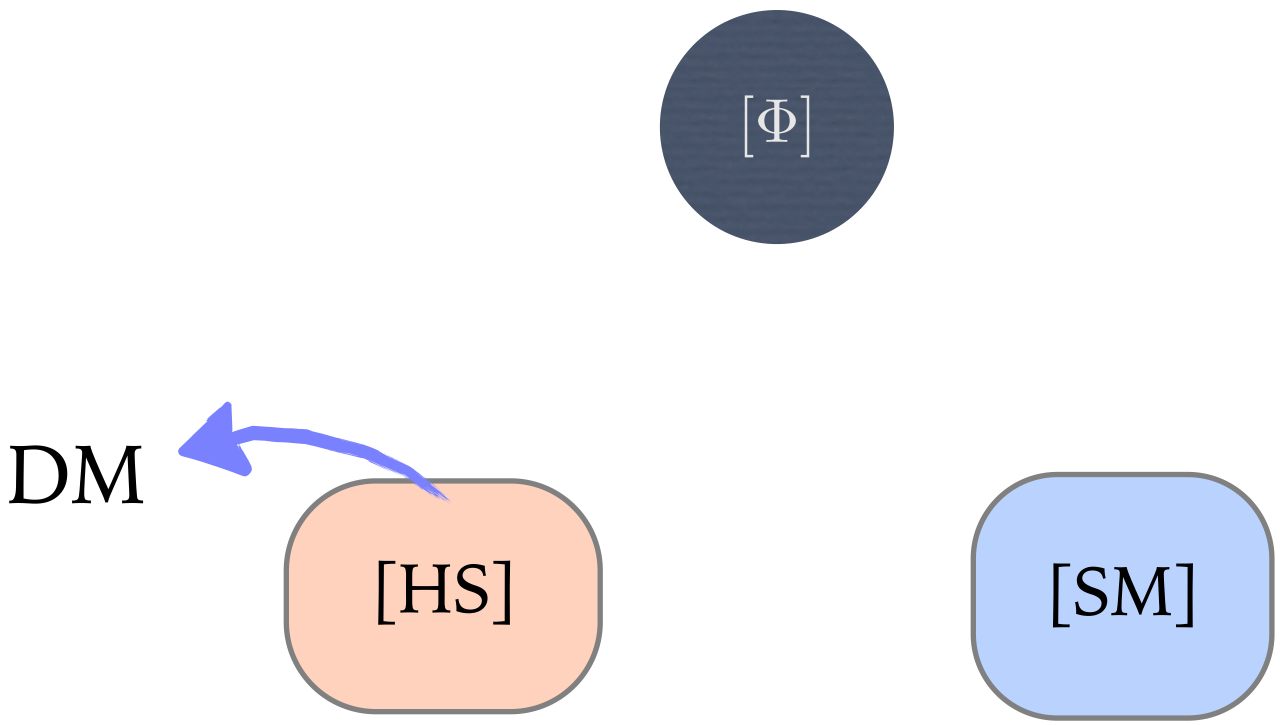
KITP Inflationary Reheating meets Particle Physics Frontier
February 4, 2020

DARK SECTORS



- Why dark sectors?
  - broad, generic class of models
  - many interesting signatures, both celestial and terrestrial

DARK SECTORS

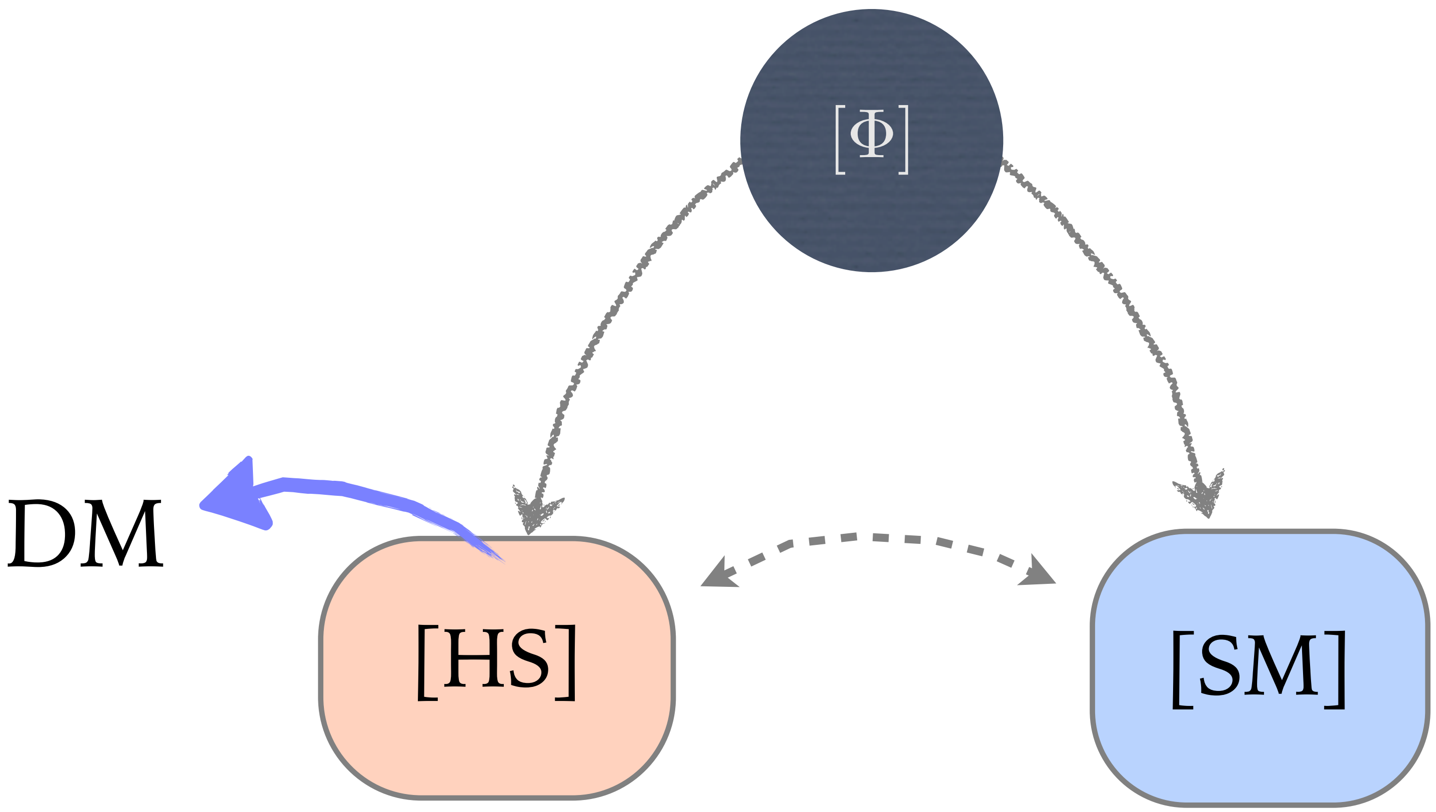


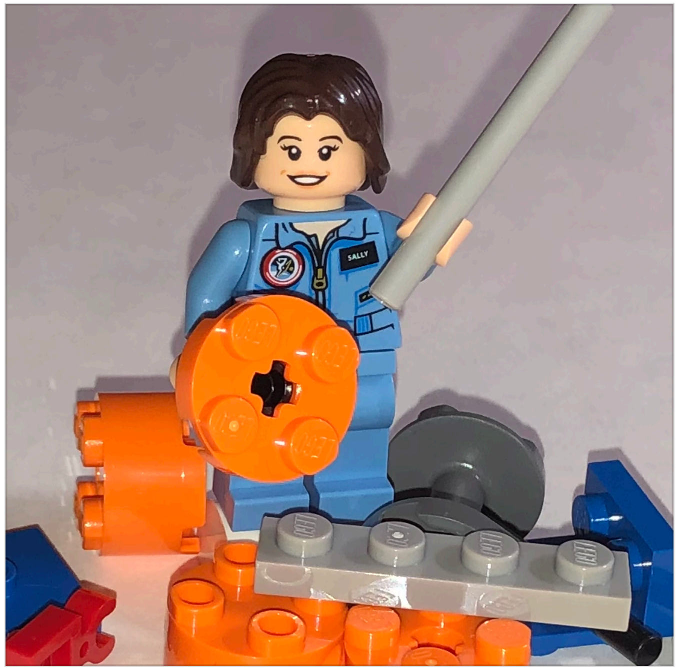
- Why dark sectors?
  - broad, generic class of models
  - many interesting signatures, both celestial and terrestrial

- Dark radiation baths contain a macroscopic amount of stuff: energy, entropy
  - must come from somewhere
  - must go somewhere

DARK SECTORS

- Minimal cosmologies for dark sectors?

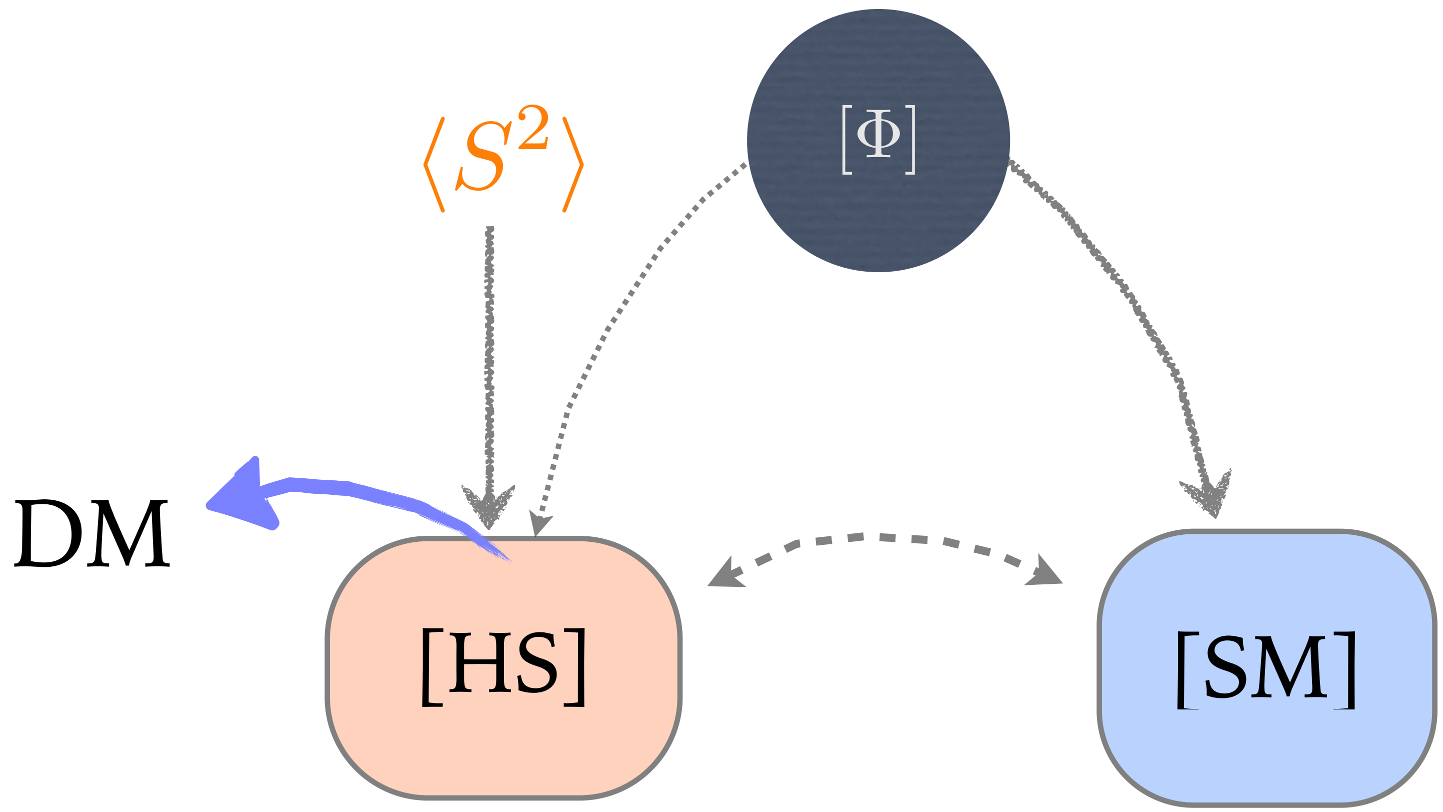


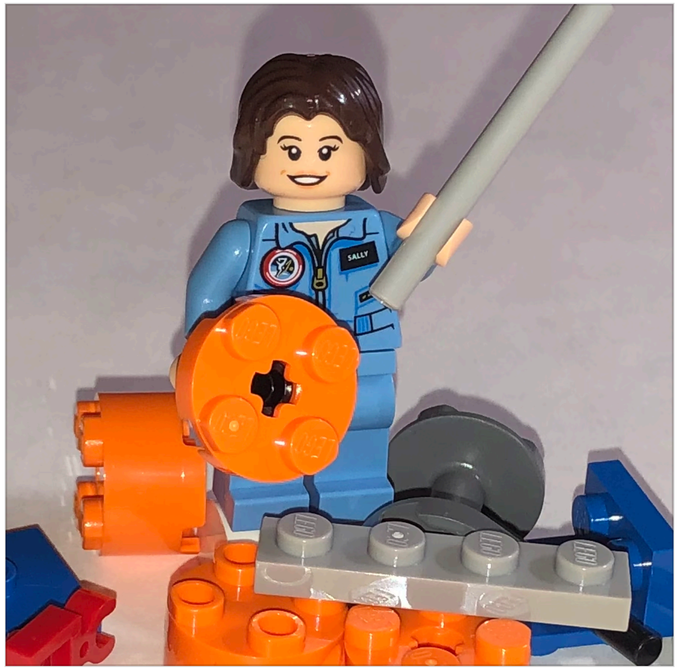


- asymmetric reheating: new signatures in decoupled sectors

DARK SECTORS

- Minimal cosmologies for dark sectors?

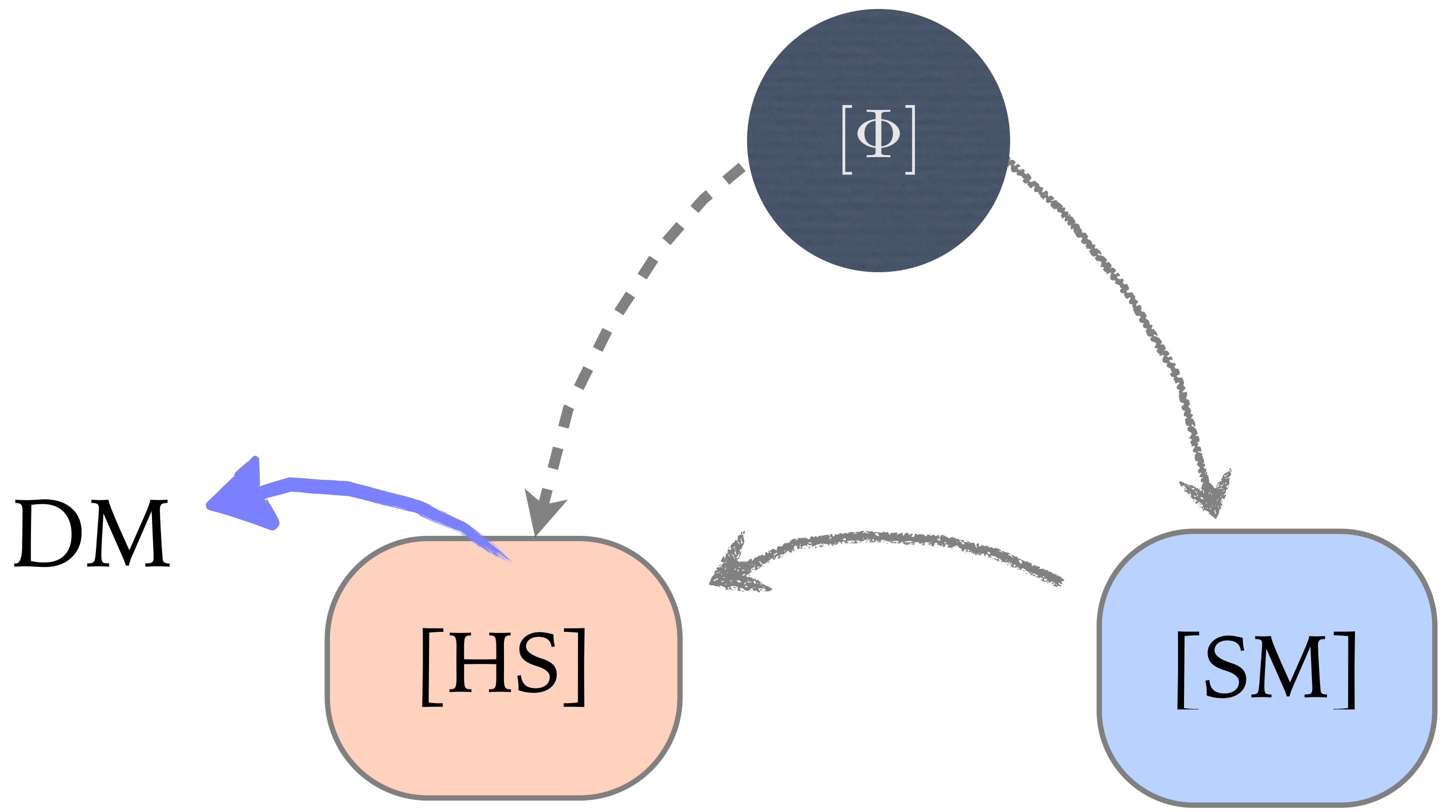


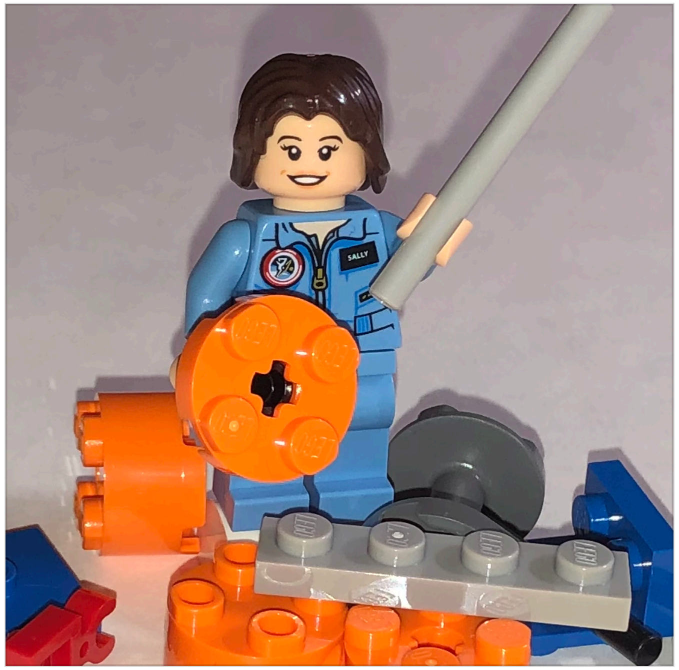


- asymmetric reheating: new signatures in decoupled sectors
- seeded by stochastic evolution: isocurvature

DARK SECTORS

- Minimal cosmologies for dark sectors?

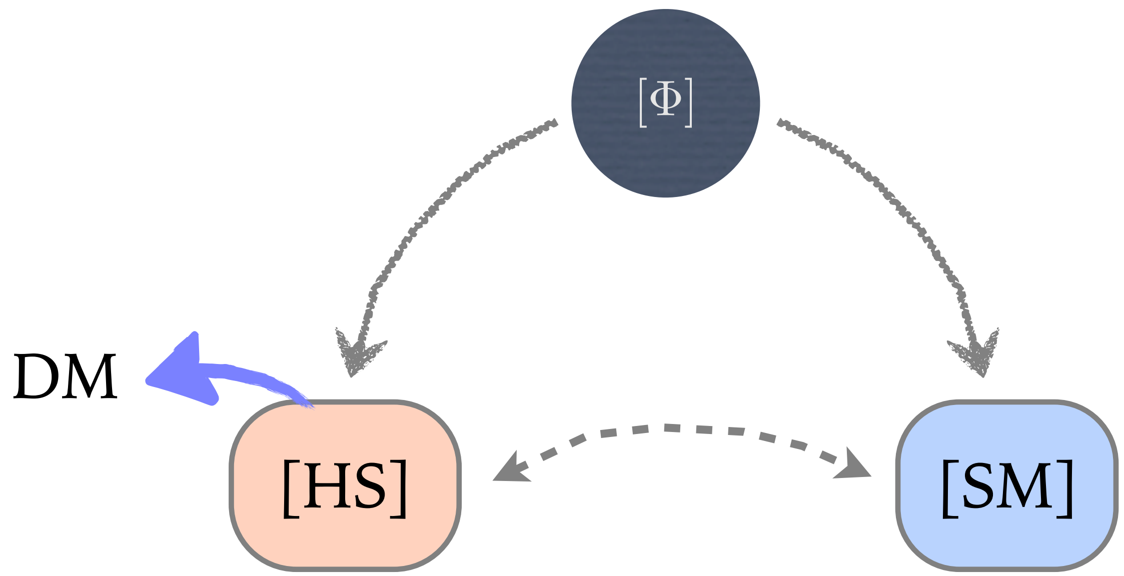




- asymmetric reheating: new signatures in decoupled sectors
- seeded by stochastic evolution: isocurvature
- from Standard Model: predictive; interesting sizes of couplings

MINIMAL COSMOLOGY I: ASYMMETRIC REHEATING

- reheating populates HS, SM directly



- generally $T_{HS} \neq T_{SM}$
- coupling sectors to same physics in UV necessarily implies interactions
- how important is scattering? Depends on whether m_ϕ is light compared to T_{RH}

[Hodges; Berezhiani, Dolgov, Mohapatra; Adshead, Cui, JS; Adshead, Ralegankar, JS; …]

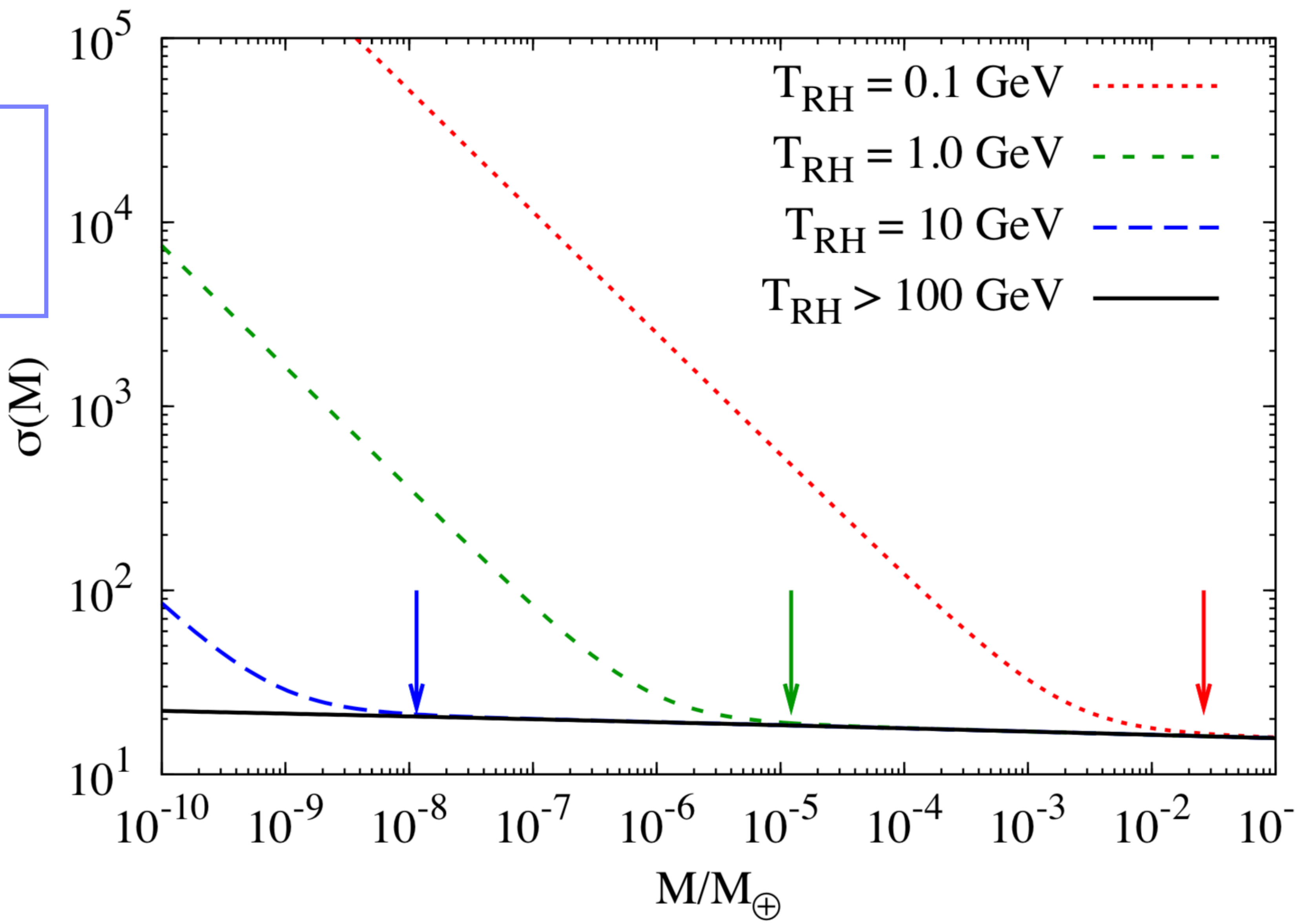
FATE OF A DECOUPLED RADIATION BATH

- What happens to the entropy in a dark radiation bath?
  - Cosmologically allowable fates depend on mass of lightest particle(s)
    - if sufficiently light, can be stable: N_{eff}
    - if too massive: must decay
      - BBN or later: signals!
      - pre-BBN? Can easily come to dominate expansion of universe: early matter-dominated era

DECOUPLED DARK SECTORS: EARLY MATTER DOMINATION

- Pre-BBN slowdown in expansion rate gives matter a head start on clustering on very small scales:

present-day RMS density fluctuation

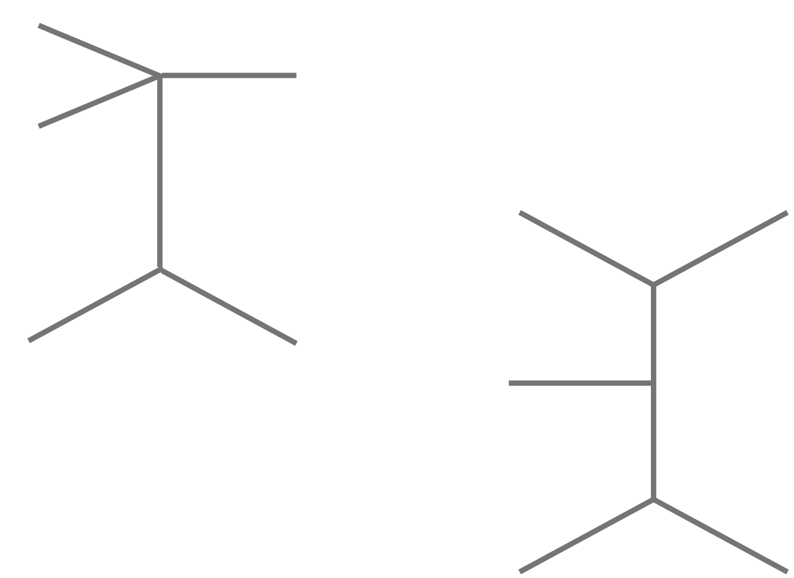


mess up nucleosynthesis

[Erickcek]

EARLY CANNIBAL DOMINATION

- But relic dark radiation bath might not act as simply matter: may have interesting self-interactions
- Cannibalism: number-changing self-interactions can keep particle in thermal equilibrium after it becomes non-relativistic
  - ϕ^4 theory exhibits cannibalism
  - hidden glueballs



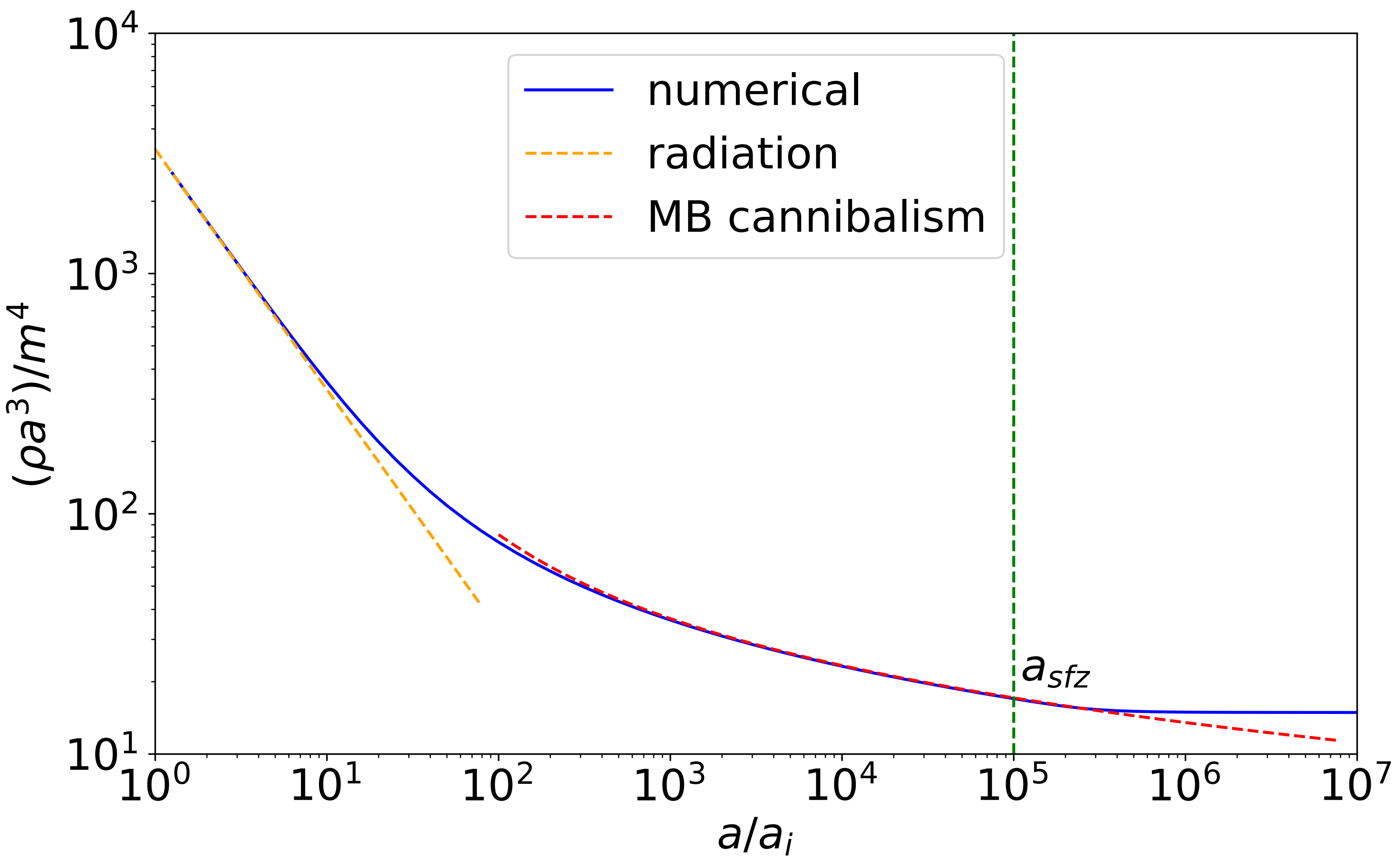
[Carlson, Hall, Machacek; Pappadopulo, Ruderman, Trevisan; Farina, Pappadopulo, Ruderman, Trevisan; …]

EARLY CANNIBAL DOMINATION

- Cannibals cool down slowly:

radiation:

$\rho \sim 1/a^4$



cannibal:

$\rho \sim 1/(a^3 \ln a)$

matter:

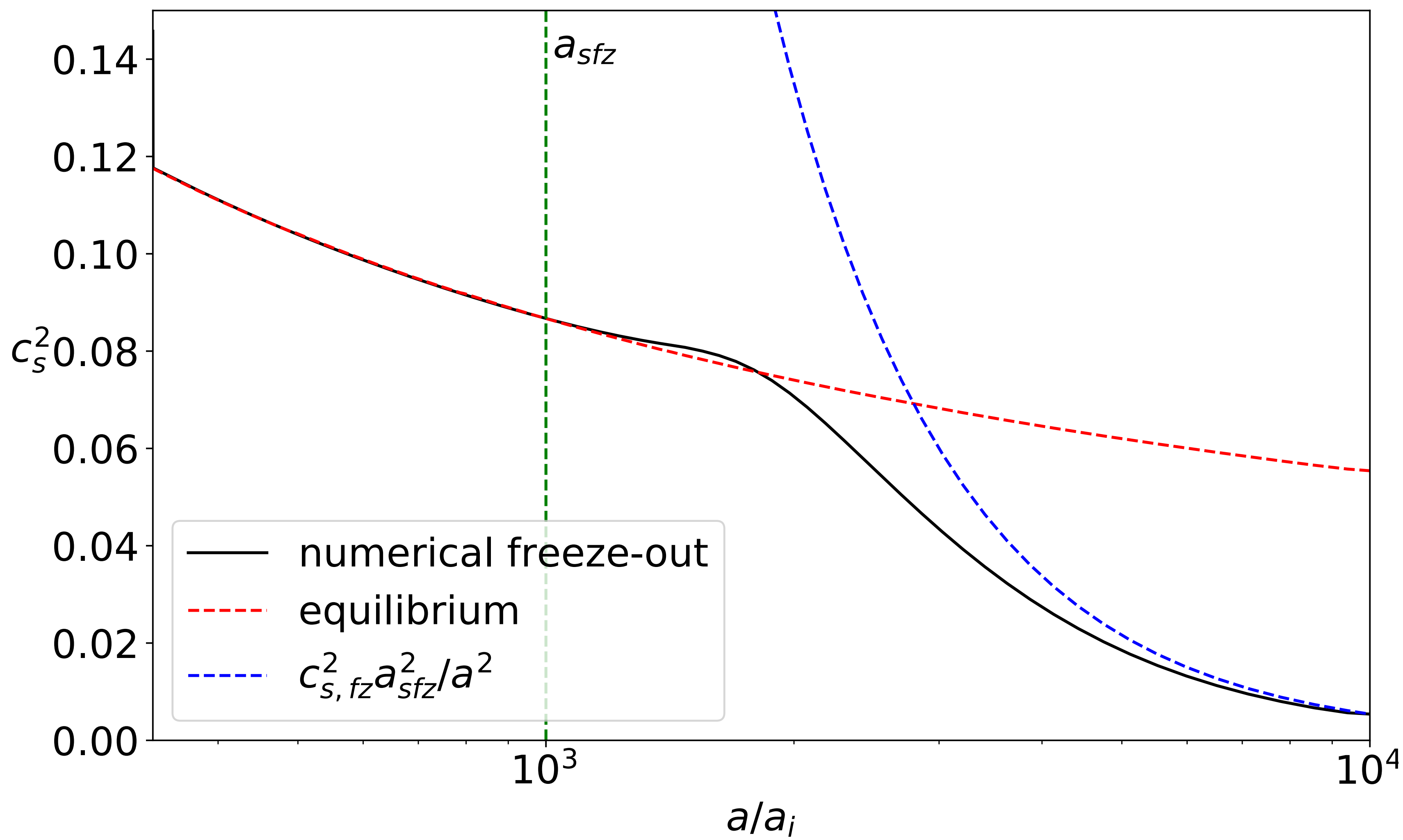
$\rho \sim 1/a^3$

$$\frac{a_{sfz}}{a_{10m}} \sim \text{few} \times 10^4 \alpha_c^{2/3} \left(\frac{\text{GeV}}{m}\right)^{2/9}$$

[Erickcek, Ralegankar, JS (to appear)]

EARLY CANNIBAL DOMINATION

- Imprint of cannibal self-interactions in the distribution of dark matter on very small scales?
- Difficulty cooling $\rightarrow$ pressure support:



[Erickcek, Ralegankar, JS (to appear)]

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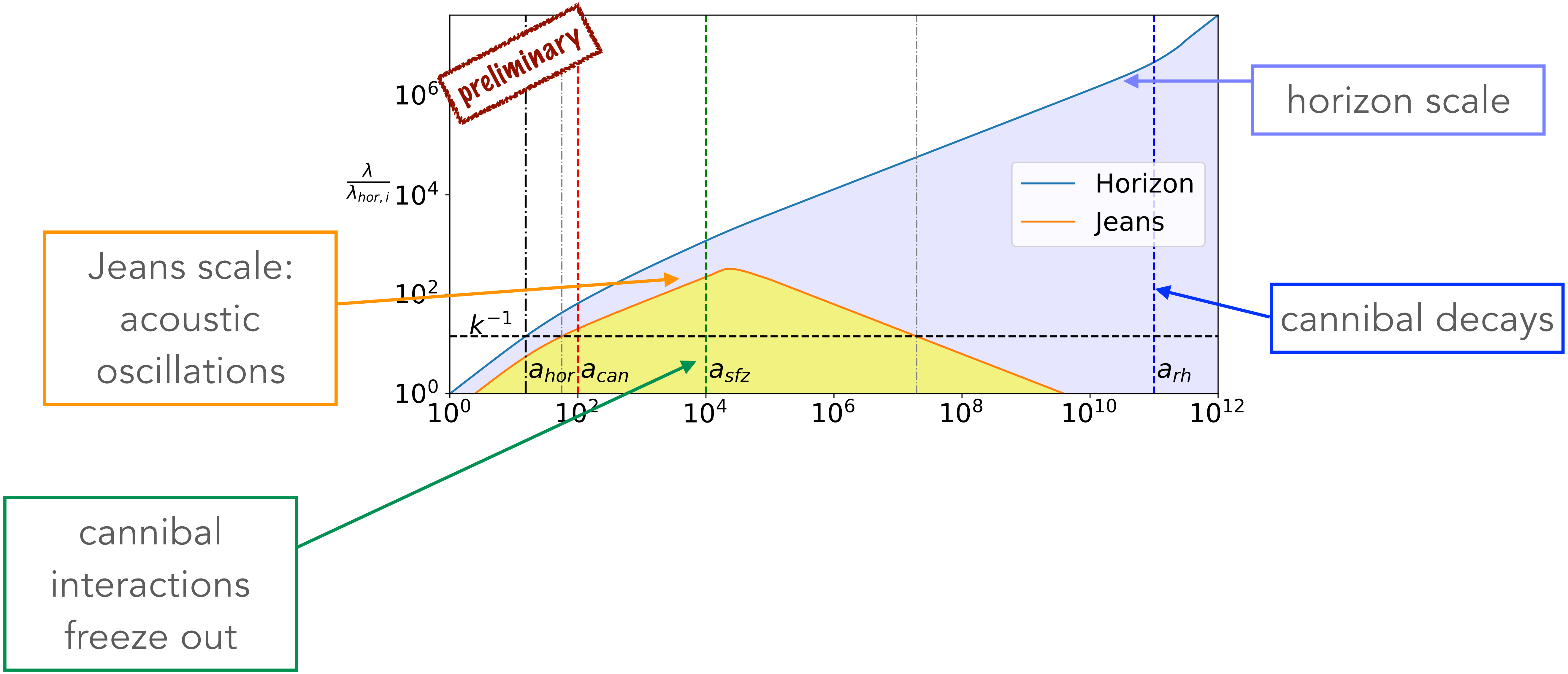

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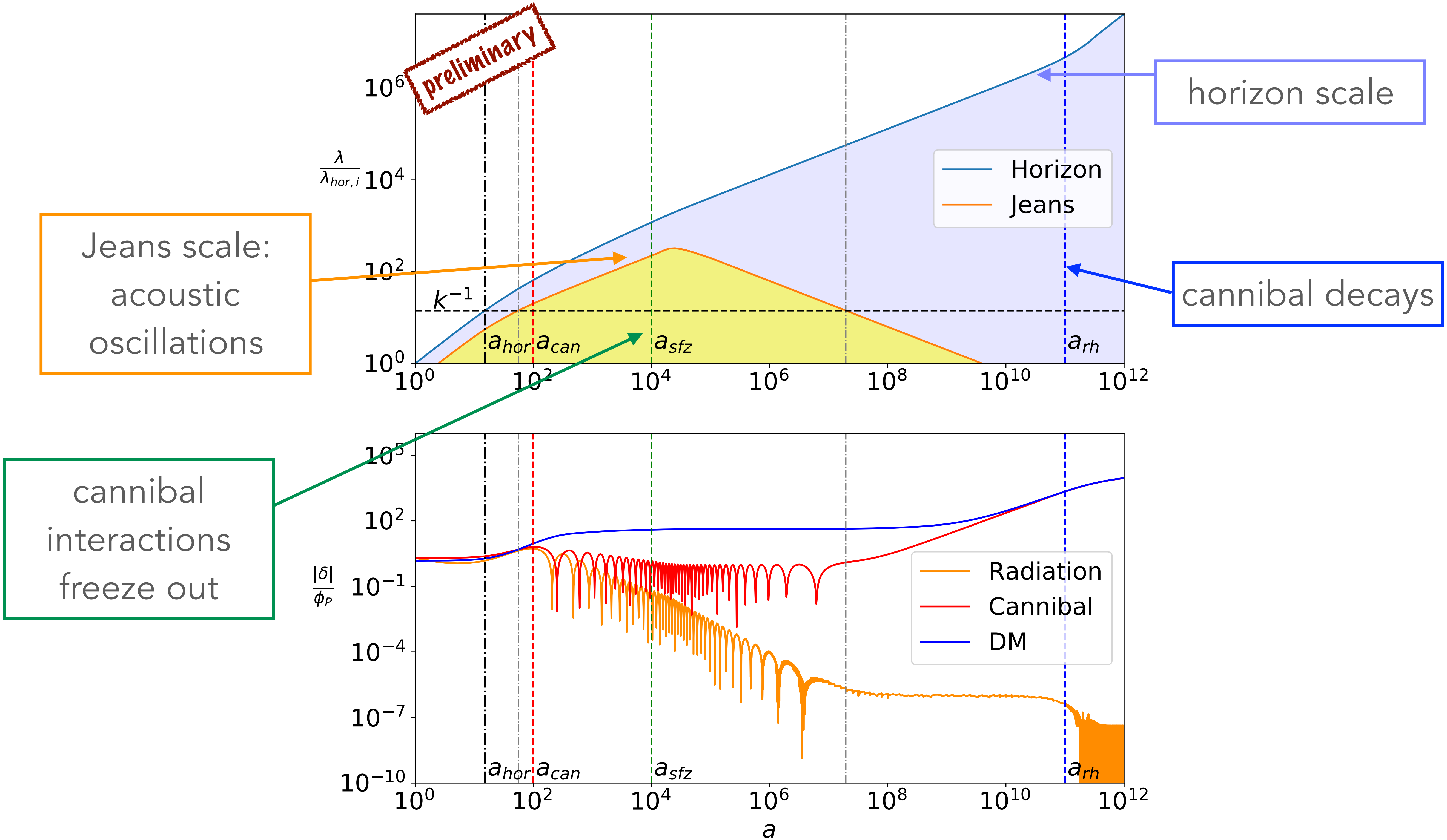

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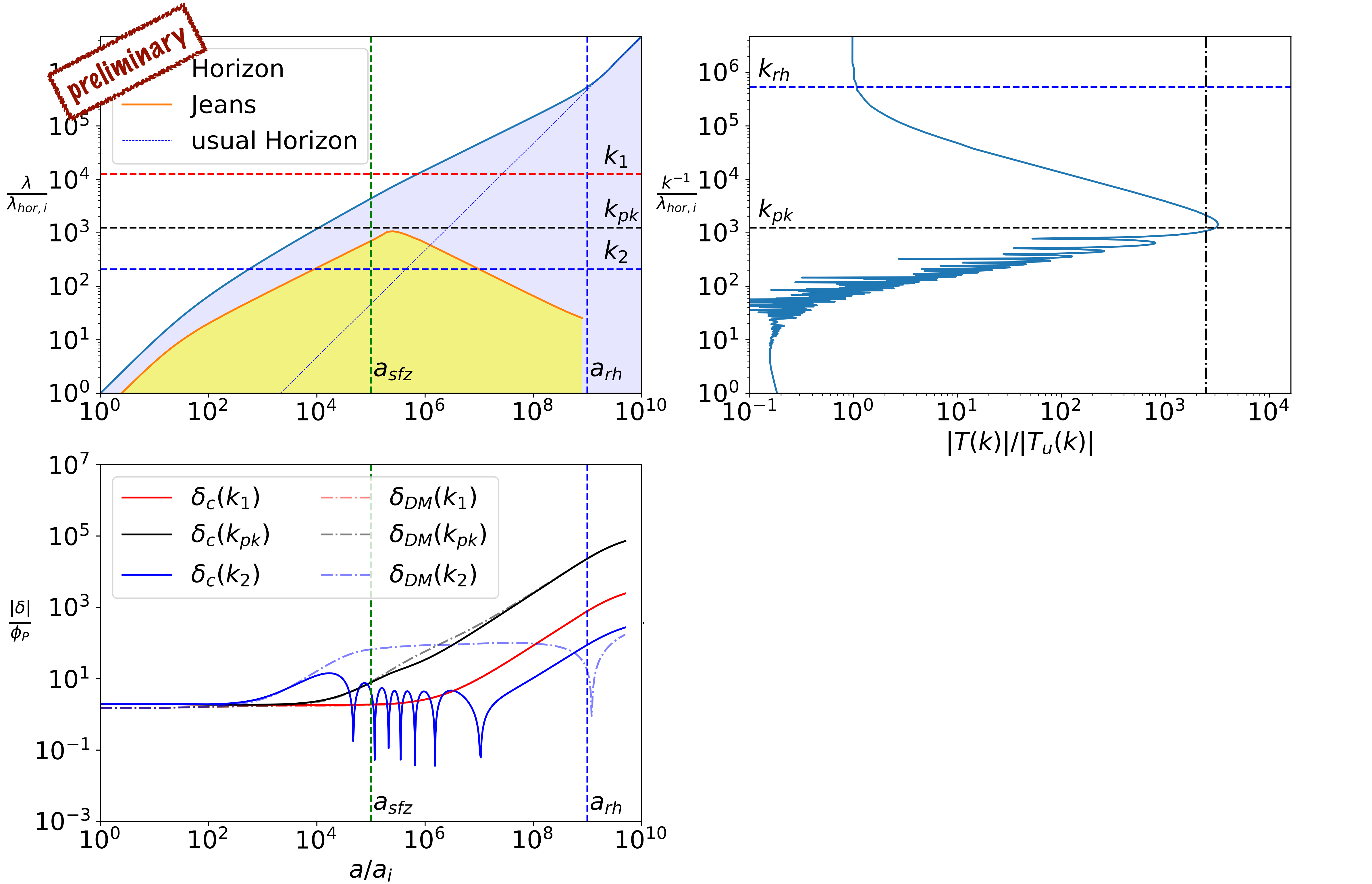

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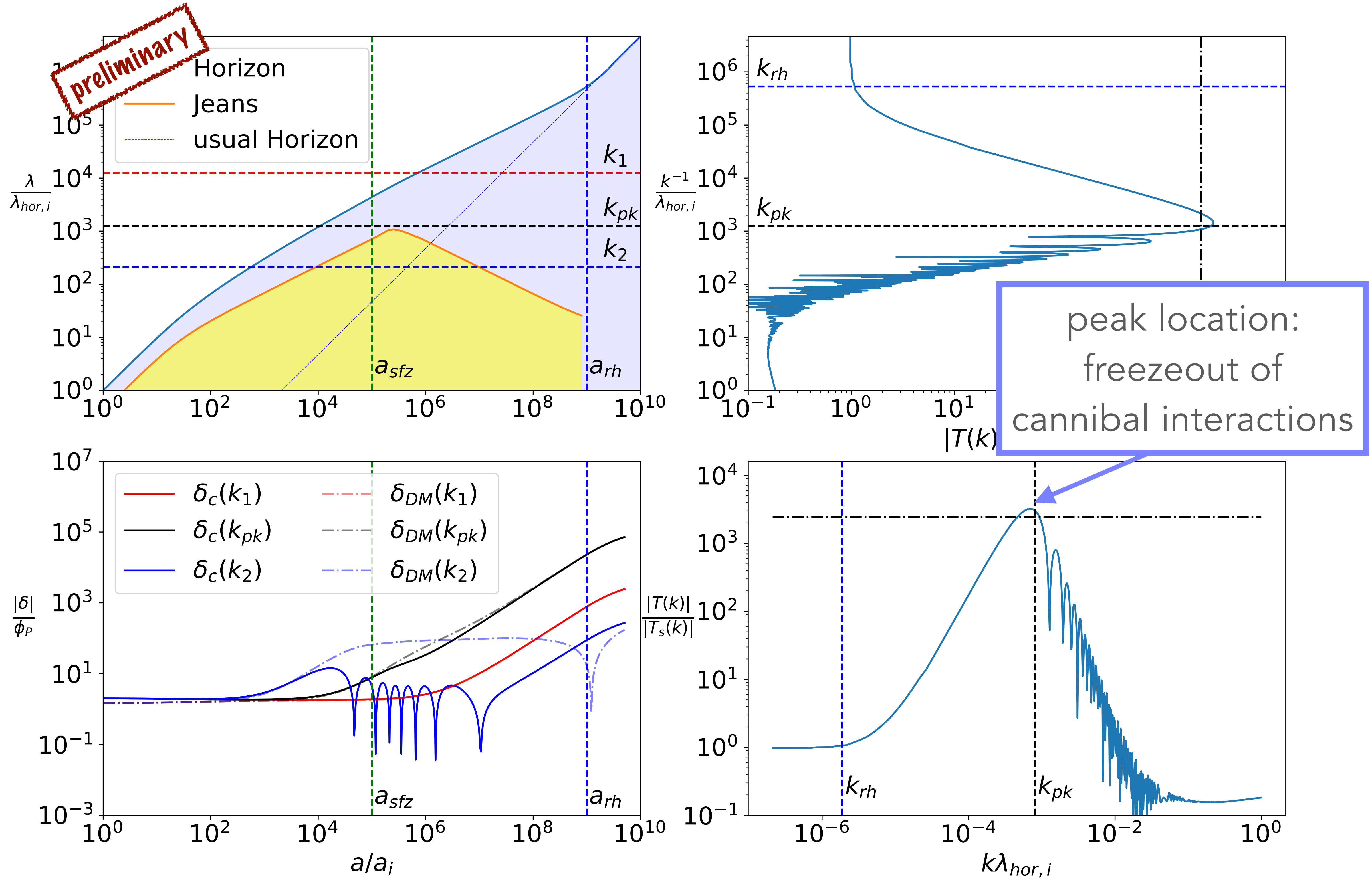

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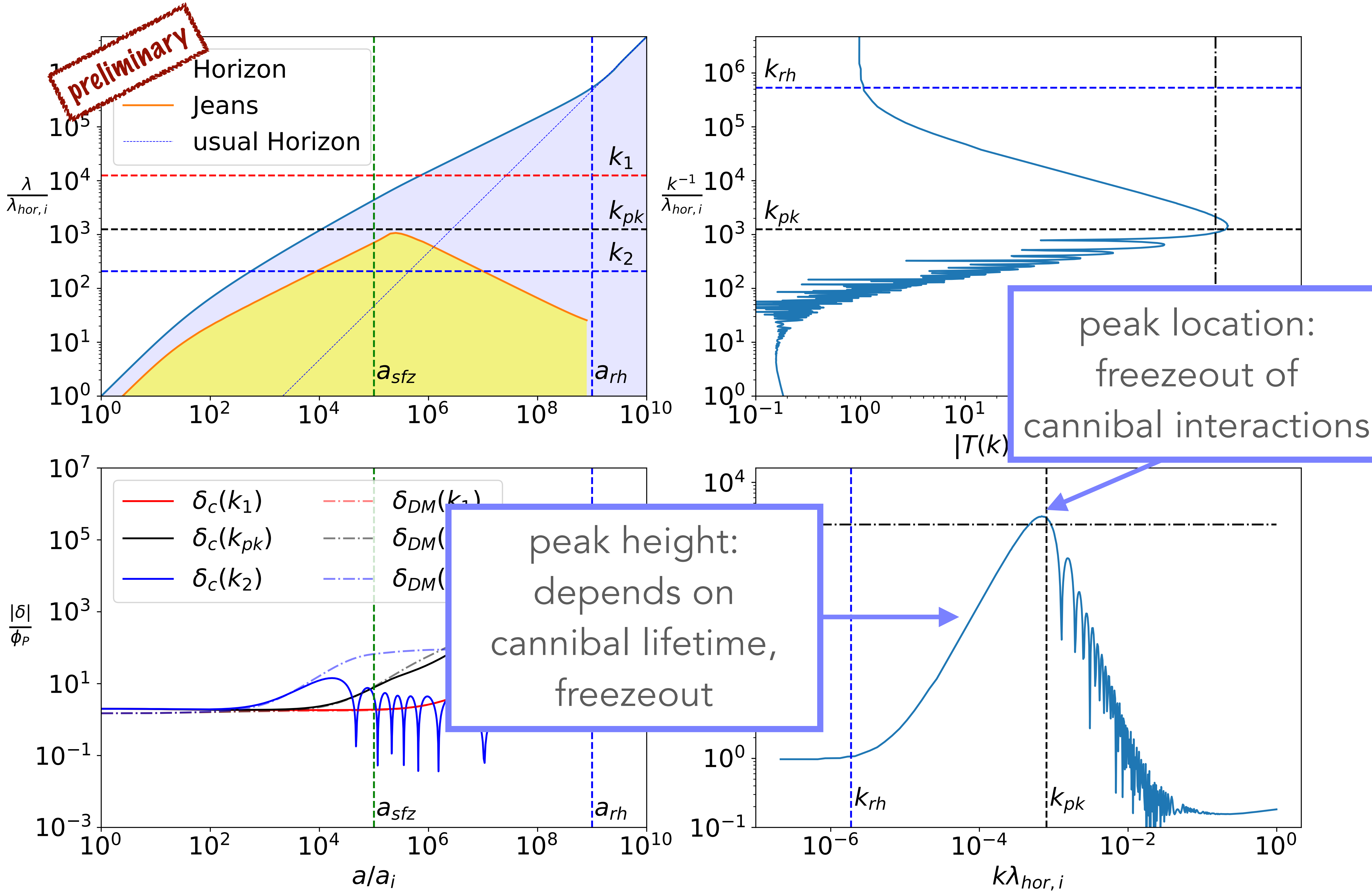
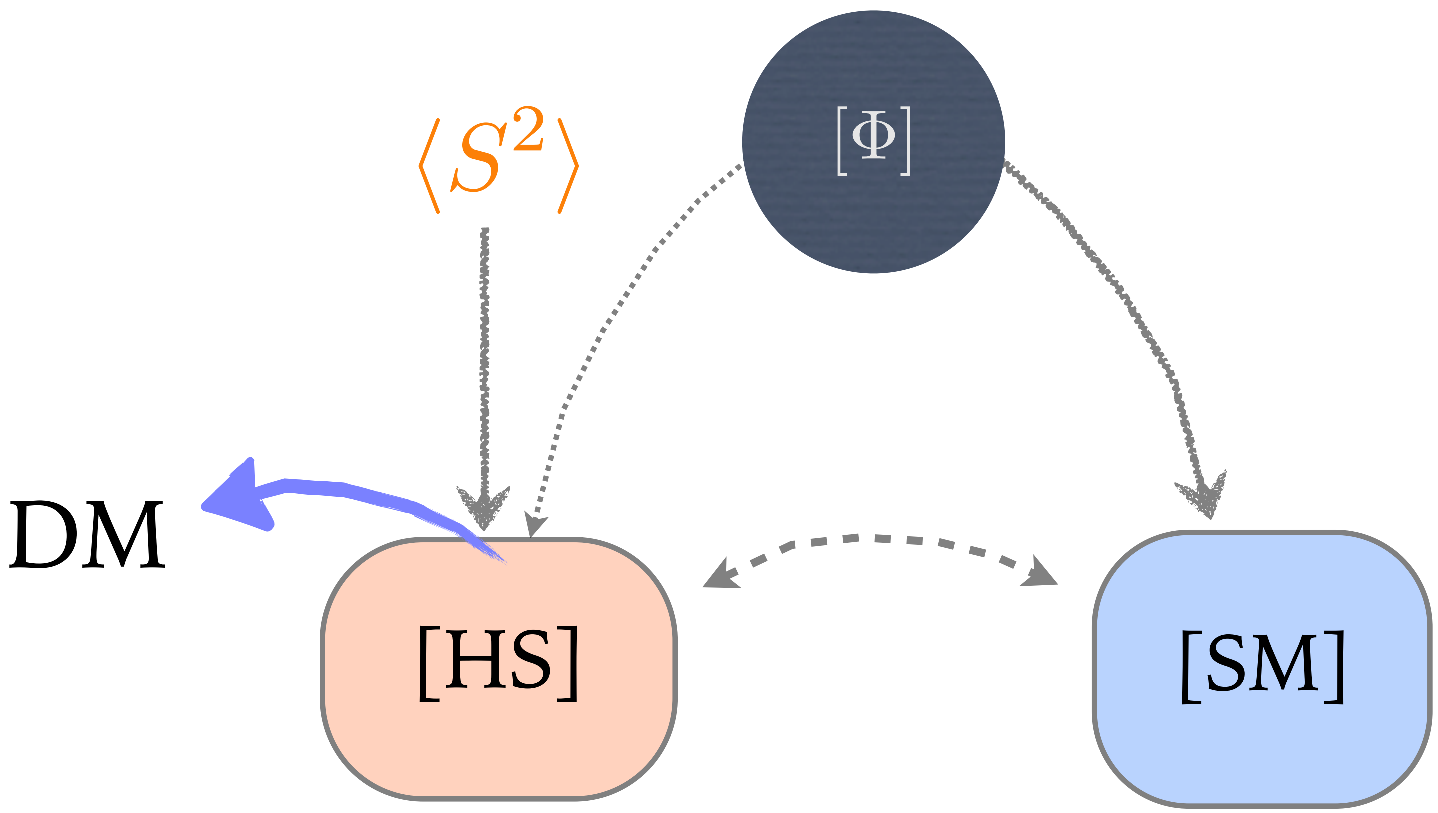


[Erickcek, Raleganker, JS (to appear)]

MINIMAL COSMOLOGY II: SPECTATOR DESCENT

➤ Radiation bath descended from stochastic vev:



➤ one major motivation for scalars in hidden sectors:
spontaneously break dark gauge groups

[Peebles, Vilenkin; Kainulainen, Nurmi, Tenkanen, Tuominen, Vaskonen; Tenkanen; …]

SPECTATORS WITH CONTINUOUS SYMMETRIES

- Evolution of scalar vev χ described by Fokker-Planck equation for probability distribution $\rho(\chi)$
- Generalize to field in linear rep of continuous symmetry:

$$\frac{\partial \rho}{\partial t} = \frac{1}{3H}\left[\rho \frac{\partial^2 V}{\partial \chi^2} + \frac{\partial V}{\partial \chi}\frac{\partial \rho}{\partial \chi}\right] + \frac{H^3}{8\pi^2}\frac{\partial^2 \rho}{\partial \chi^2}$$

[Starobinsky, Yokoyama; Adshead, Pearce, JS, Weiner (to appear)]

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- or in terms of the magnitude of the vev alone:

$$\rho_{\text{eff}}(\chi) \equiv \chi^{N-1} \rho(\chi) \Omega^{N-1}$$

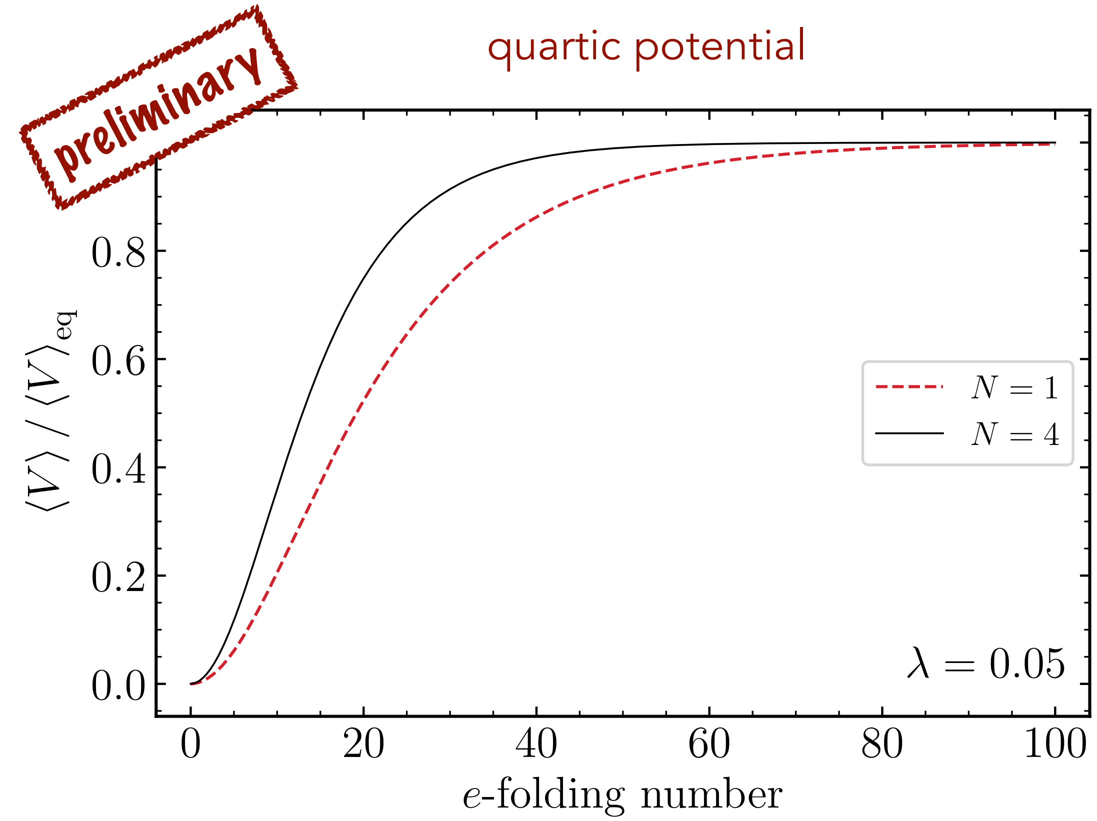
$$\frac{8\pi^2}{H^3} \frac{\partial \rho_{\text{eff}}}{\partial t} = \frac{8\pi^2}{3H^4}\left(\frac{\partial^2 V}{\partial \chi^2} + \frac{(N-1)}{\chi^2}\right)\rho_{\text{eff}} + \frac{8\pi^2}{3H^4}\left(\frac{\partial V}{\partial \chi} - \frac{(N-1)}{\chi}\right)\frac{\partial \rho_{\text{eff}}}{\partial \chi} + \frac{\partial^2 \rho_{\text{eff}}}{\partial \chi^2}$$

[Starobinsky, Yokoyama; Adshead, Pearce, JS, Weiner (to appear)]

SPECTATORS WITH CONTINUOUS SYMMETRIES

- Consequences of enlarged field space:
  - larger mean vevs, energy densities
    - quartic: $\langle \chi^2 \rangle \sim \sqrt{N} H^2$

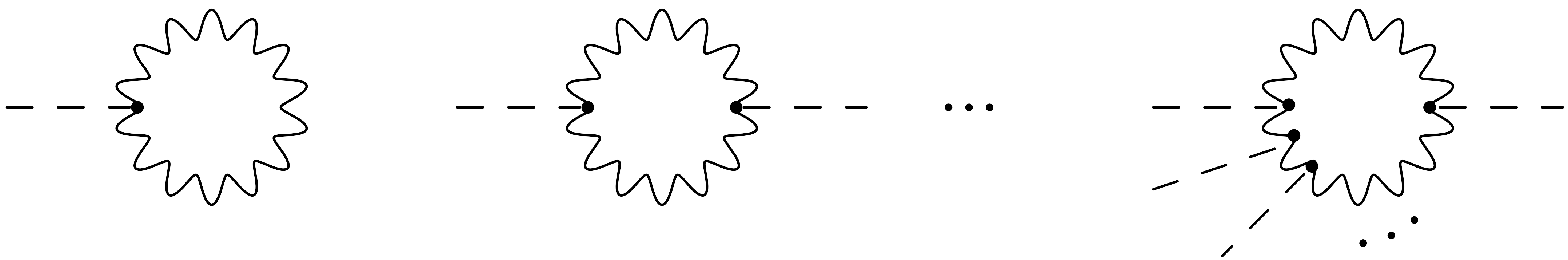
      $\langle V \rangle \sim N H^4$
  - faster approach to equilibrium distribution



[Adshead, Pearce, JS, Weiner (to appear)]

STOCHASTIC SPECTATOR FIELDS

- What about unitary gauge?
- New counter-term needed to remove spurious UV divergences:

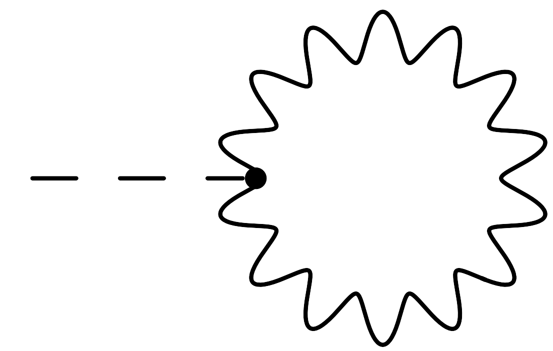


$$\int \frac{d^4k}{(2\pi)^4}\,\frac{k^2}{k^2-m^2} \sim i\Lambda_{UV}^4 \qquad \Rightarrow \qquad \mathcal{L}_{ct} = (N-1)\Lambda_{UV}^4 \ln(\chi)$$

[Lee, Zinn-Justin; Weinberg; Grosse-Knetter, Kogerler; Hertzberg, Jain]

STOCHASTIC SPECTATOR FIELDS

- What happens during inflation?
  - Stochastic approach:



$$\int \frac{d^4k}{(2\pi)^4}\,\frac{k^2}{k^2-m^2} = i\Lambda_{UV}^4 - i\Lambda_{IR}^4$$

canceled by counterterm

finite residual contribution

- with IR cutoff (subhorizon four-volume)[-1]: $\delta L_{ug} = (N-1)\frac{3H^4}{8\pi^2}\ln(\chi)$

[Adshead, Pearce, JS, Weiner (to appear)]

STOCHASTIC SPECTATOR FIELDS

- This adds new terms to the Fokker-Planck equation:

$$\frac{8\pi^2}{H^3}\frac{\partial\rho_{\rm eff}}{\partial t} = \frac{8\pi^2}{3H^4}\left(\frac{\partial^2 V}{\partial\chi^2} + \frac{(N-1)}{\chi^2}\right)\rho_{\rm eff} + \frac{8\pi^2}{3H^4}\left(\frac{\partial V}{\partial\chi} - \frac{(N-1)}{\chi}\right)\frac{\partial\rho_{\rm eff}}{\partial\chi} + \frac{\partial^2\rho_{\rm eff}}{\partial\chi^2}$$

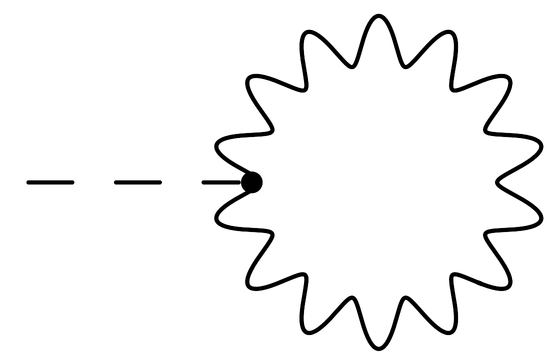
- But this is exactly the Fokker-Planck equation that governs the PDF for the radial mode of an *N*-dimensional field $\vec{\chi}$

[Adshead, Pearce, JS, Weiner (to appear)]

STOCHASTIC SPECTATOR FIELDS

- As the vev gets larger, so does the mass gap:

$$\int \frac{d^4k}{(2\pi)^4} \frac{k^2}{k^2 - m^2}$$



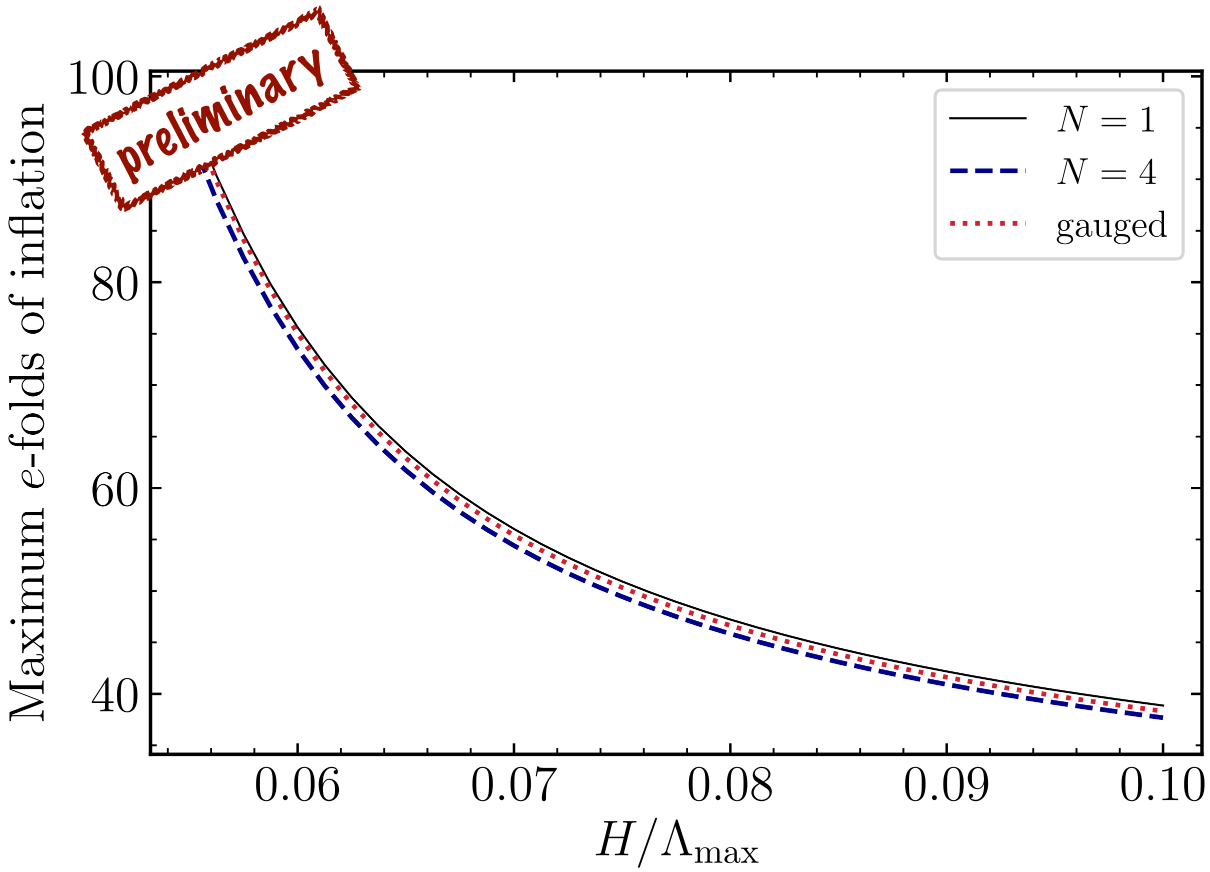
- $\Rightarrow$ expect spectators with a gauge symmetry to smoothly interpolate from *N*-d to 1-d

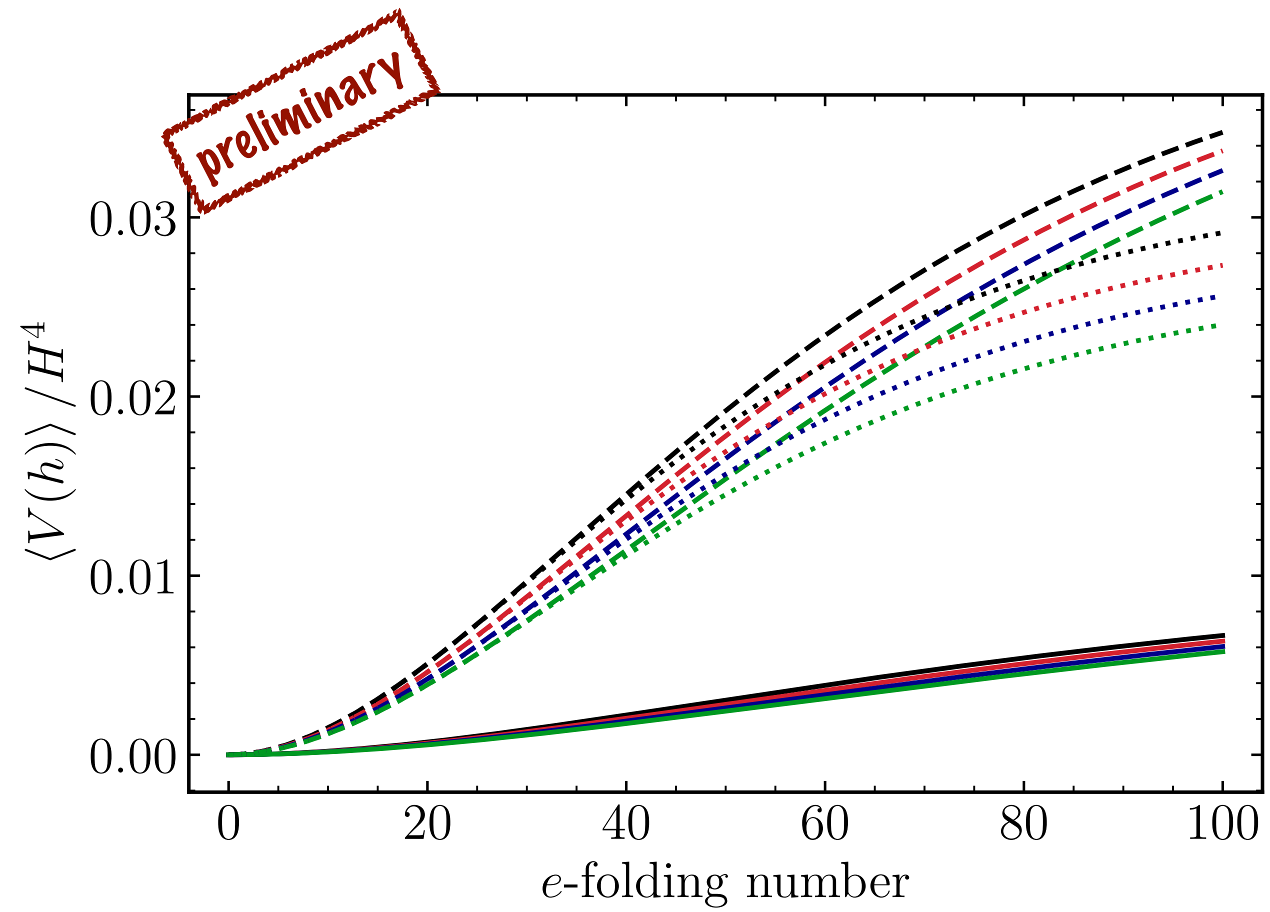
[Adshead, Pearce, JS, Weiner (to appear)]

STOCHASTIC SPECTATOR FIELDS

- Apply to SM Higgs:

$$V(h) = -b_0 \ln\left(\frac{H^2 + h^2}{\sqrt{e}\Lambda_{\rm max}^2}\right)\frac{h^4}{4}$$





[…; East, Kearney, Shakya, Yoo, Zurek; Adshead, Pearce, JS, Weiner (to appear)]

SUMMARY AND CONCLUSIONS

- Many possible dark thermal histories
  - most of them do not predict terrestrially relevant interaction rates with SM particles
    - look instead to astrophysics/cosmology for signals
- Decoupled dark sectors
  - minimal population with asymmetric reheating, mild conditions on reheating (T_{RH}/m_ϕ)
  - early cannibal domination: novel imprint of dark particle interactions in small-scale structure
- Stochastic spectators
  - stochastic population depends on dimensionality of field space (linear reps)
  - recover in unitary gauge
- Population from SM:
  - direct detection now sensitive to cosmic history, not just particle content
  - predictive, fun phenomenology: sub-GeV DM, self-interacting DM, …