Long-range forces and the early Universe: primordial black holes and gravitational waves

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Marcos M. Flores — 6th, May, 2024

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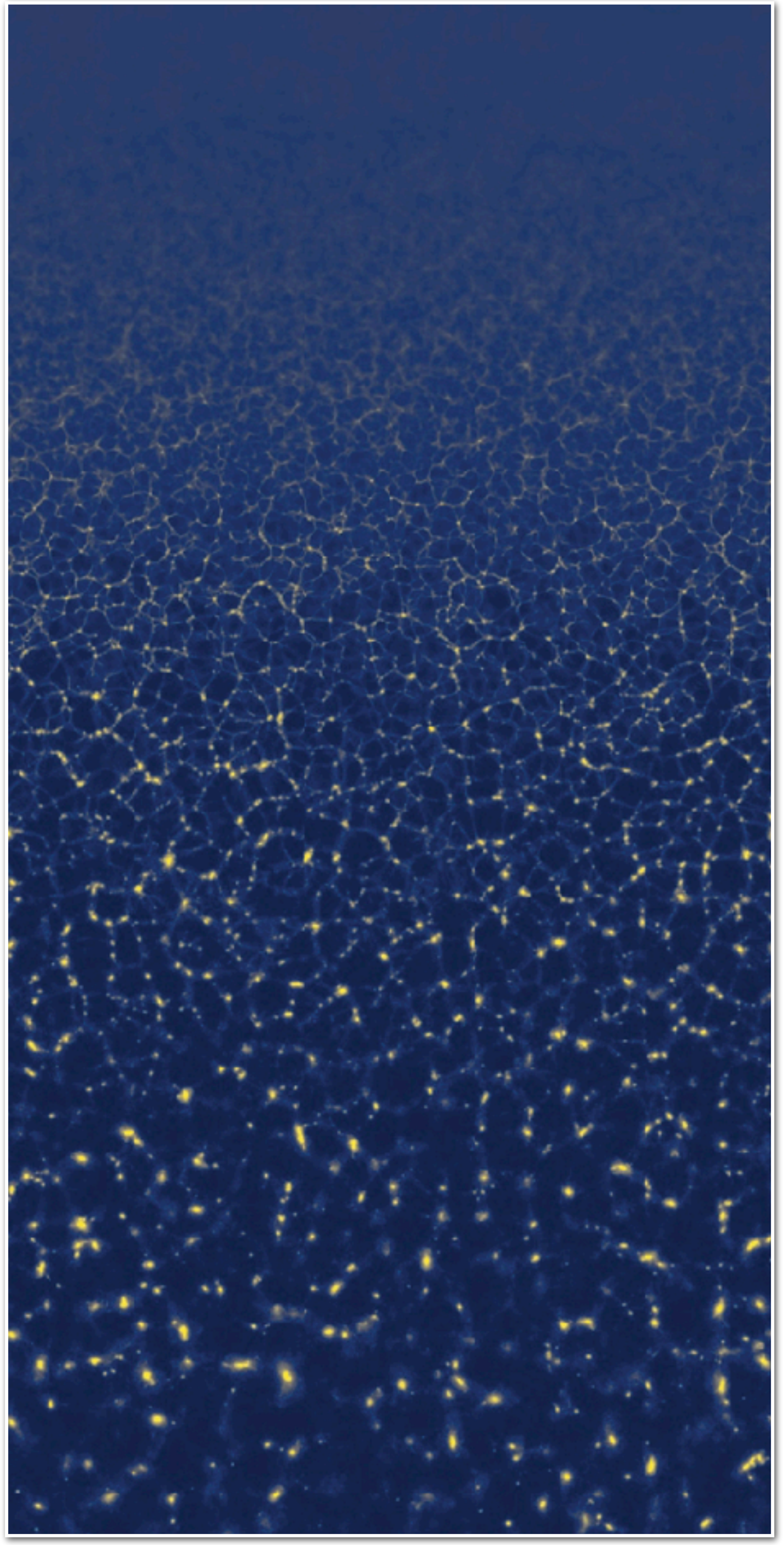
Overview

- Part I: Primordial structure formation
  - Definition & general picture
- Part 2: Applications
  - Primordial black holes
    - Review of standard PBH story
  - Gravitational waves
  - Baryogenesis i.e., matter-antimatter asymmetry
  - Generation of dark matter



$\hbar = c = k_B = 1$

The paradigm of *primordial* structure formation

Cosmological timeline

"Primordial"

Structure Formation

[Credit: European Space Agency]

Conventional structure formation: basics

$$\rho(x,t) = \bar{\rho}(t)\Big(1 + \delta(x,t)\Big)$$

$$\Downarrow$$

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}, \qquad \nabla_\mu T^{\mu\nu} = 0$$

$$\Downarrow$$

$$\text{System of Coupled Differential Equations}$$

$$\Big(\delta(x,t) \ll 1\Big)$$

Conventional structure formation by example

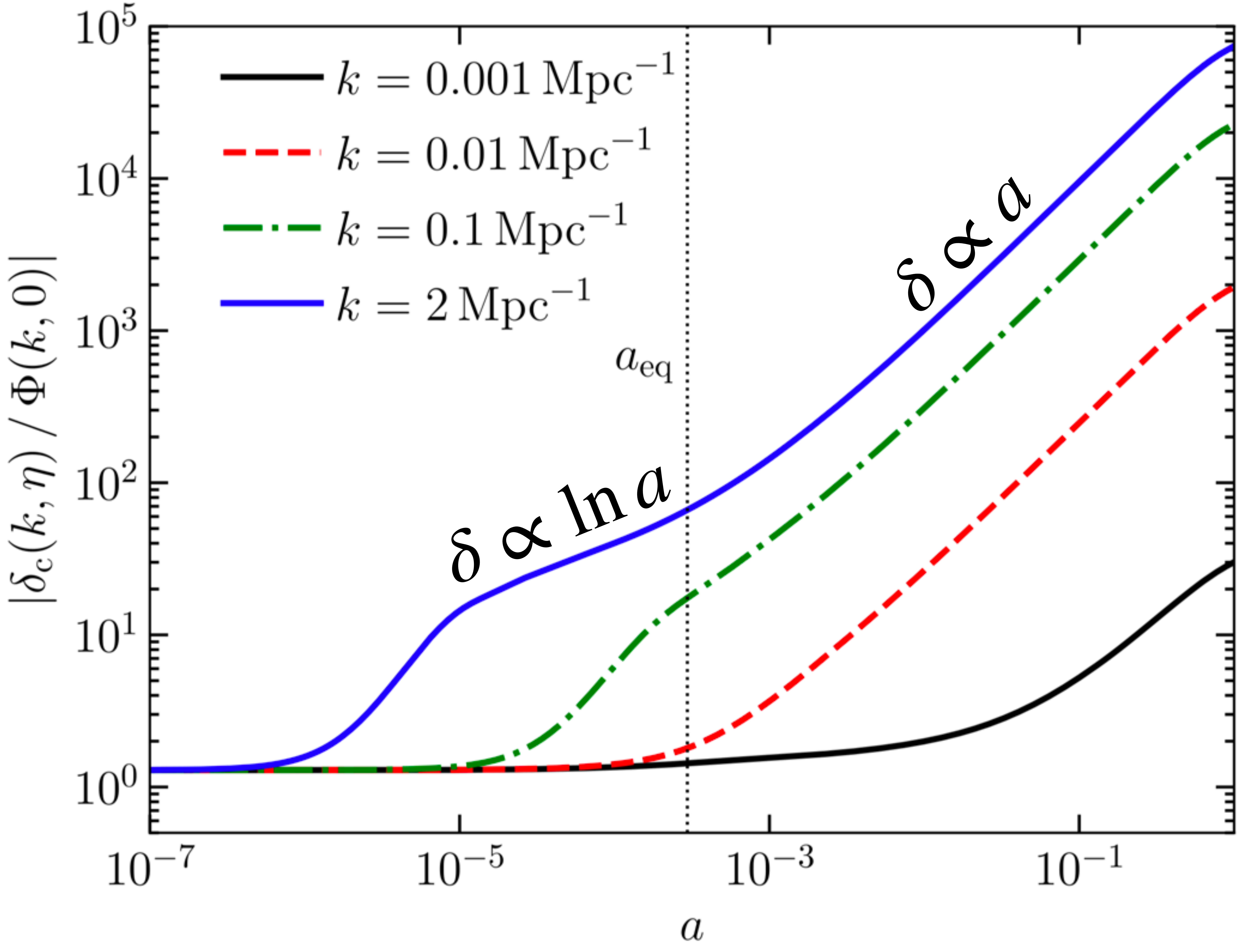
$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G\bar{\rho}_m\delta, \qquad H = \frac{1}{2t}, \qquad \bar{\rho}_m \sim \Omega_m \sim 0$$

$$\downarrow$$

$$\delta(t) = c_1 + c_2 \ln t$$

***Conclusion:** Matter perturbations only grow logarithmically during a radiation dominated era*

Conventional structure formation by example



[Credit: Dodelson, Modern Comology]

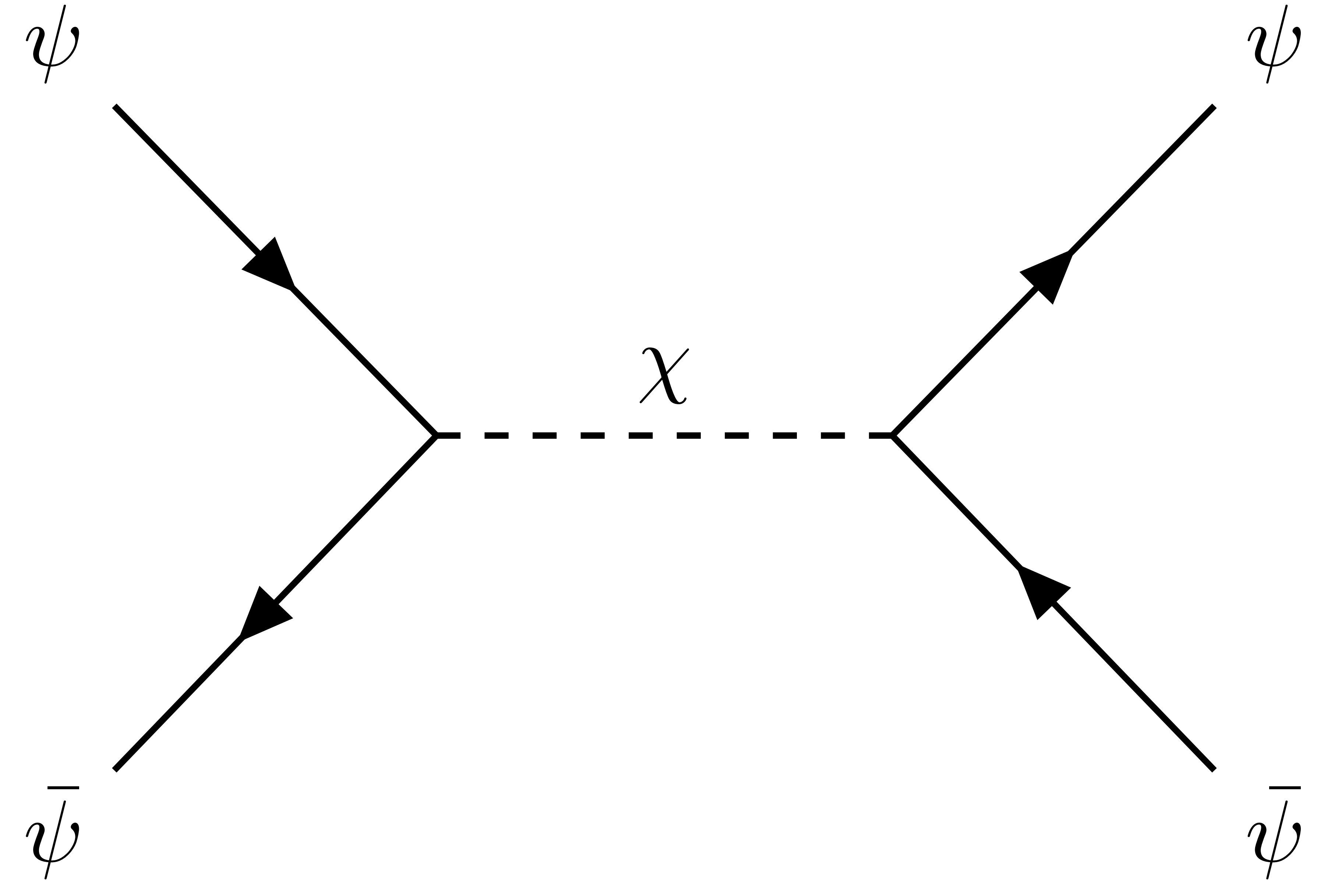
How can you have *primordial* structure formation?

How can you have *primordial* structure formation?

$$\mathcal{L} \supset y\chi\bar{\psi}\psi \implies V(r) = -\frac{y^2}{4\pi r}\exp\left(-m_\chi r\right)$$

ψ : fermion ($\sim$ dark electron)

$\chi \sim$ scalar mediator (Higgs)



$(\hbar = c = k_B = 1)$

How can you have *primordial* structure formation?

$$\mathscr{L} \supset y\chi\bar{\psi}\psi \implies V(r) = -\frac{y^2}{4\pi r}\exp\left(-m_\chi r\right)$$

$$r \ll m_\chi^{-1} \longleftrightarrow \text{long-range force}$$

$$\implies H^{-1} \ll m_\chi^{-1}$$

$(\hbar = c = k_B = 1)$

How can you have *primordial* structure formation?

$$\mathscr{L} \supset y\chi\bar{\psi}\psi \implies V(r) = -\frac{y^2}{4\pi r}\exp\left(-m_\chi r\right)$$

Yukawa interactions are *always* attractive*

$$\beta \equiv y\left(M_{\mathrm{Pl}}/m_\psi\right)$$

$(\hbar = c = k_B = 1)$

*For a scalar mediator

Growth of perturbations

- In Fourier space, the growth of ψ overdensities, denoted $\Delta(x, t) = \Delta n_\psi / n_\psi$ are given by a set of coupled differential equations:

$$\ddot{\delta}_k + 2H\dot{\delta}_k - \frac{3}{2}H^2(\Omega_r\delta_k + \Omega_m\Delta_k) = 0$$

$$\ddot{\Delta}_k + 2H\dot{\Delta}_k - \frac{3}{2}H^2\left[\Omega_r\delta_k + \Omega_m\underline{(1+\beta^2)}\Delta_k\right] = 0$$

[L. Amendola et. al., arXiv:1711.09915]
[S. Savastano et. al., arXiv:1906.05300]
[Domenech and Sasaki, arXiv:2104.05271]
[Domenech, et. al., arXiv:2303.13053]

Growth of perturbations

- For large scalar forces, the perturbations grow quickly as demonstrated by the approximate solution:

$$\Delta_k(t) \approx \frac{\Delta_k(t_0)}{\sqrt{8\pi}} \frac{\exp\left(4\sqrt{p}(t/t_{\rm eq})^{1/4}\right)}{p^{1/4}(t/t_{\rm eq})^{1/8}}, \qquad p = \frac{3}{8}(1+\beta^2)$$

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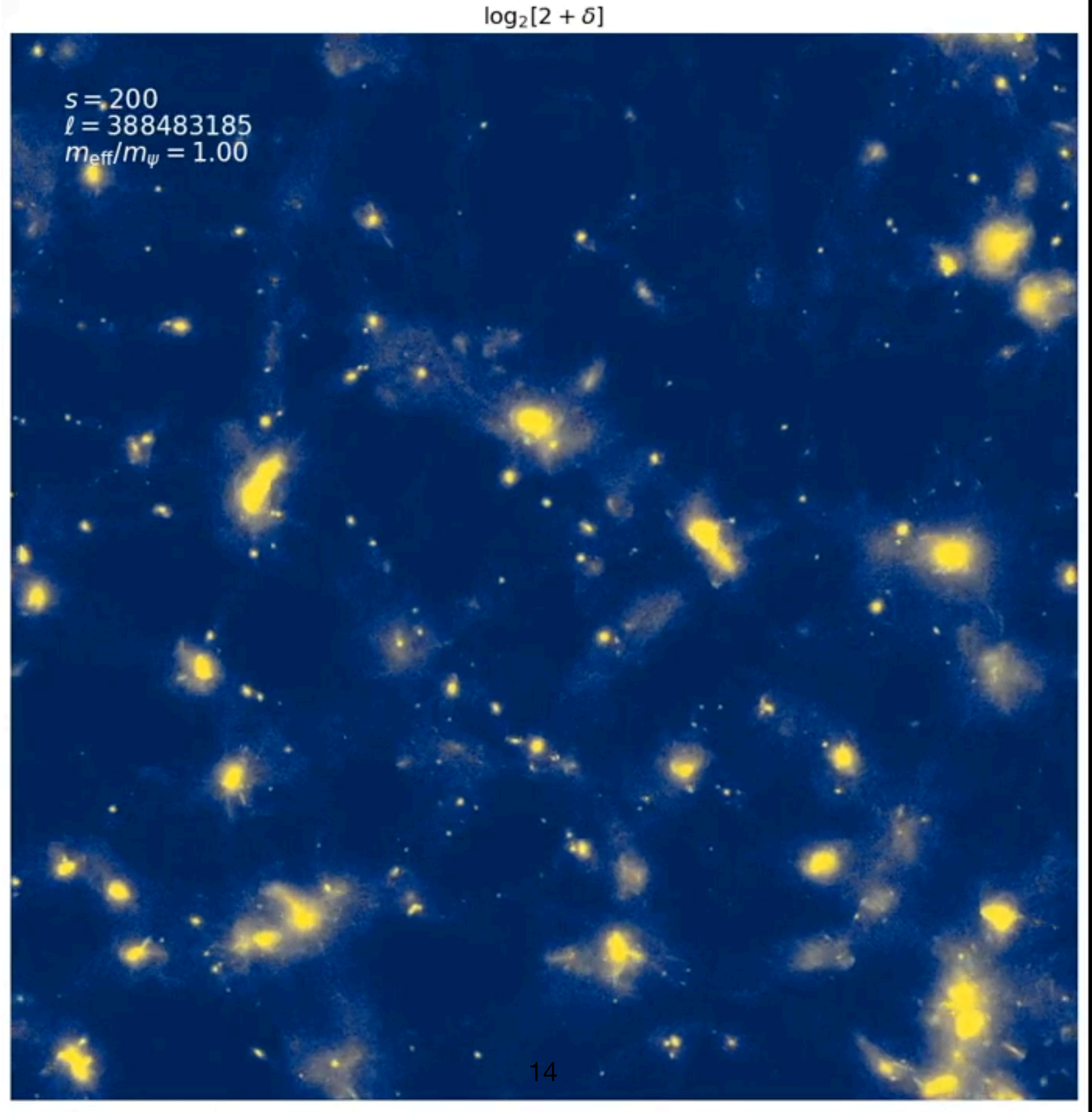
$$\text{For } p \gg 1 \implies \Delta_k/\dot{\Delta}_k \ll H^{-1} \implies \text{rapid structure formation}$$



Domenech, et. al., arXiv:2303.13053

Growth of perturbations

$$\Delta_k \ll 1 \implies \Delta_k \gtrsim 1 \iff \text{nonlinear regime} \implies \text{virialize}$$

Without dissipation, halos will remain viralized until the constituent particles decay

Energy dissipation through scalar radiation

The same long-range force that cause the growth of structure will also *cause accelerating particles to emit scalar waves*

There are *five* possible dissipation channels:

1. Coherent motion
2. Incoherent motion
3. Bremsstrahlung (free-free) emission
4. Bound state formation
5. Surface radiation

Bremsstrahlung and surface radiation will be the most important channels for our discussion

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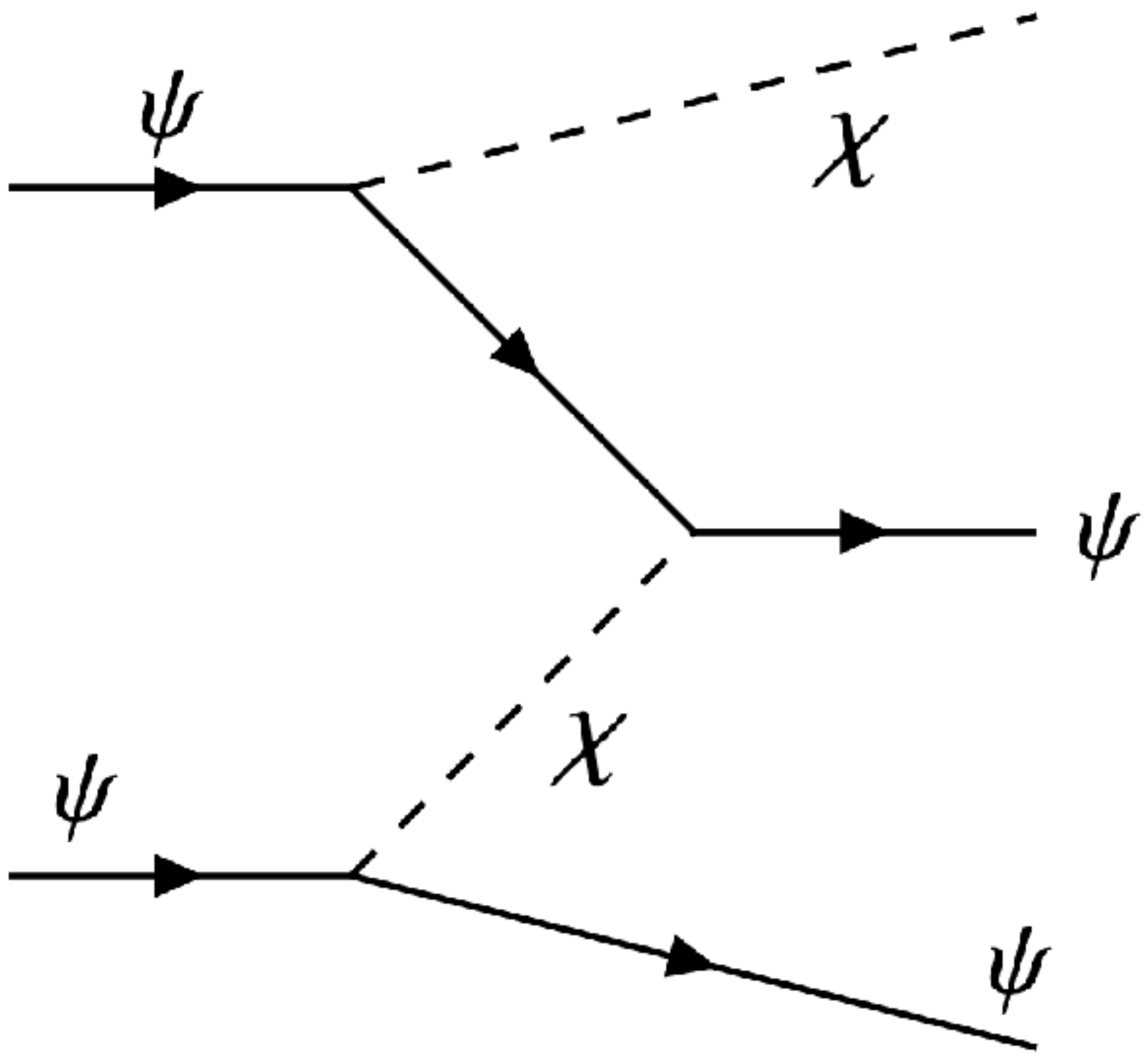

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$$\tau_{\rm cool} = \frac{E}{P_{\rm brem} + P_{\rm surf} + \cdots}$$

Bremsstrahlung and surface radiation will be the most important channels for our discussion

Energy dissipation through scalar radiation

Given a halo of size R can lose energy and contract as long as,

$$\tau_{\mathrm{cool}}(R) \ll H^{-1}$$

General algorithm for collapse:

$$\left.\begin{array}{c}\text{Cooling via free-free emission}\\ \Downarrow \\ \chi \text{ radiation becomes trapped} \\ \Downarrow \\ \text{Surface radiation takes over}\end{array}\right\} \overset{*}{\Longrightarrow} \begin{cases}\text{Black hole forms}\\ \text{Fermi ball forms}\\ \text{Halo annihilates}\end{cases}$$

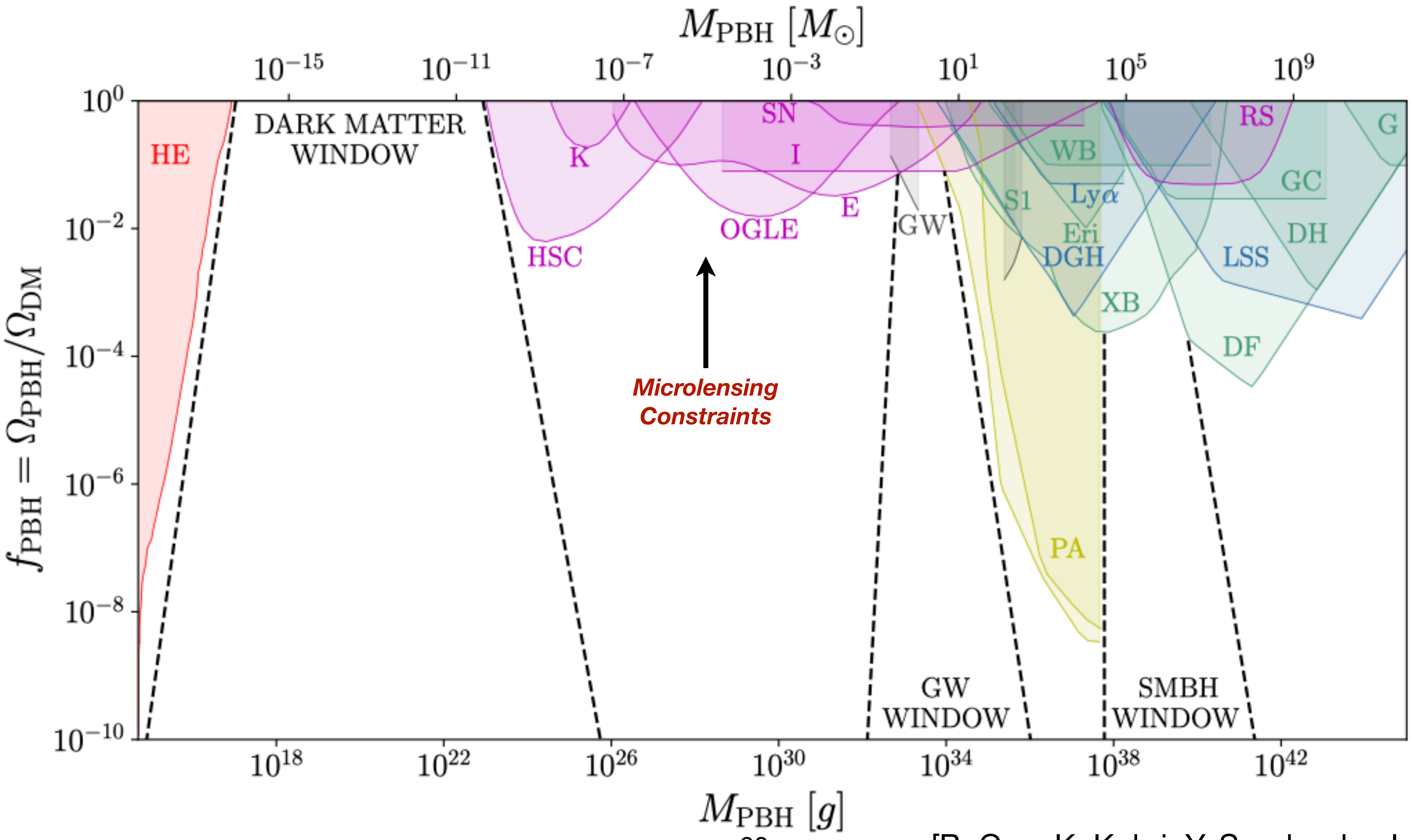
Primordial black holes
&
primordial structure formation

[**MMF**, A. Kusenko: ***PRL*** 126 (2021) 4, 041101]
[**MMF**, A. Kusenko: *JCAP* 05 (2023) 013]
[**MMF**, Y. Lu, A. Kusenko: *PRD* 108 (2023) 12, 123511]

Primordial black holes: An overview

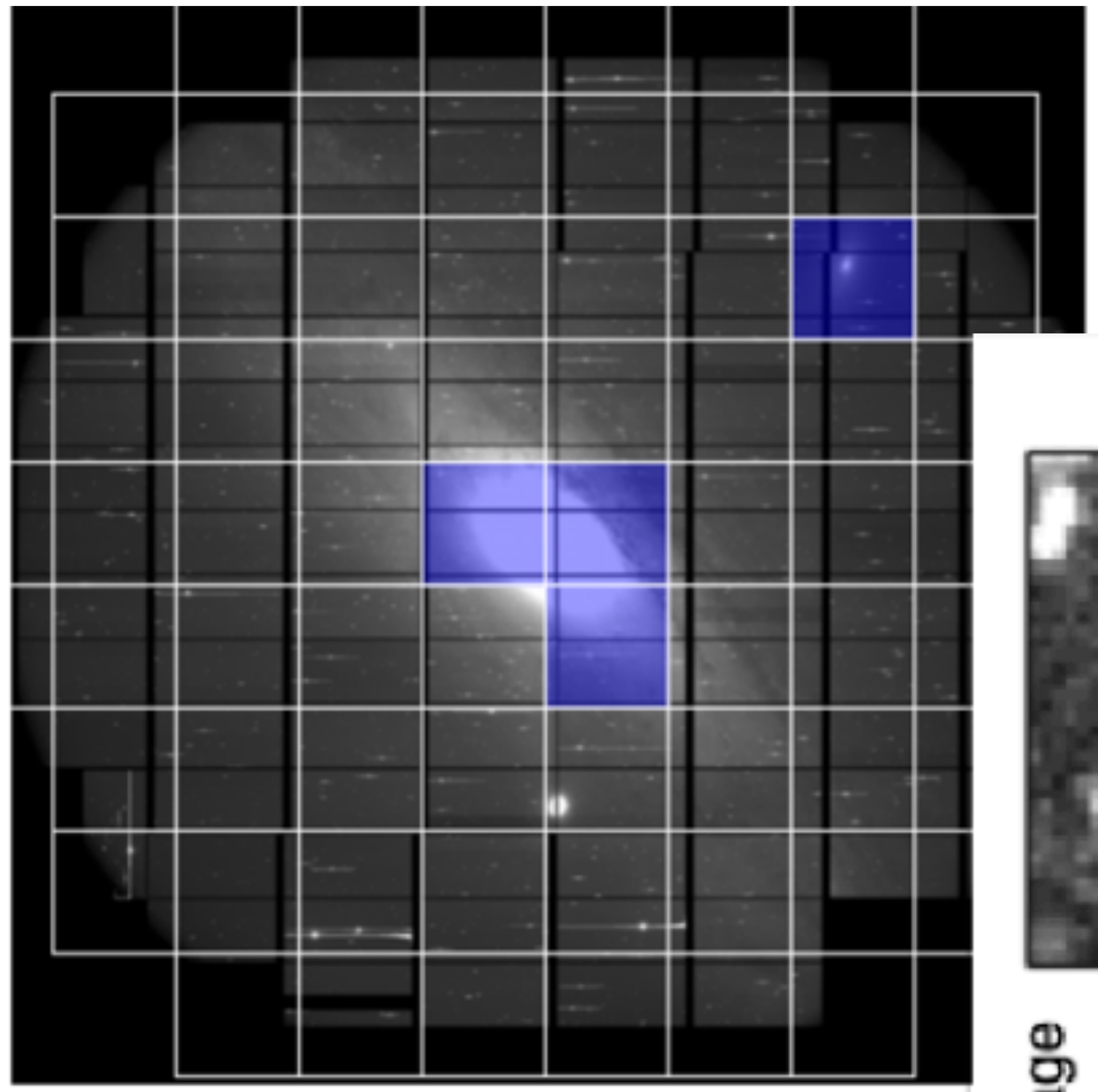
- PBHs are black holes formed in the ***early Universe*** before the formation of stars and galaxies [Zel'dovich, Novikov (1967); Hawking (1971)]
- Can account for some or all of ***dark matter***
- Astrophysical implications:
  - Can account for some LIGO events
  - Can seed supermassive black holes
  - Can account for all or part of *r*-process nucleosynthesis
  - G objects
    - [**MMF**, A. Kusenko, A.M. Ghez, S. Naoz, : *PRD* 108 (2023) 6, L061301]
  - Many more!

Primordial black holes: An overview



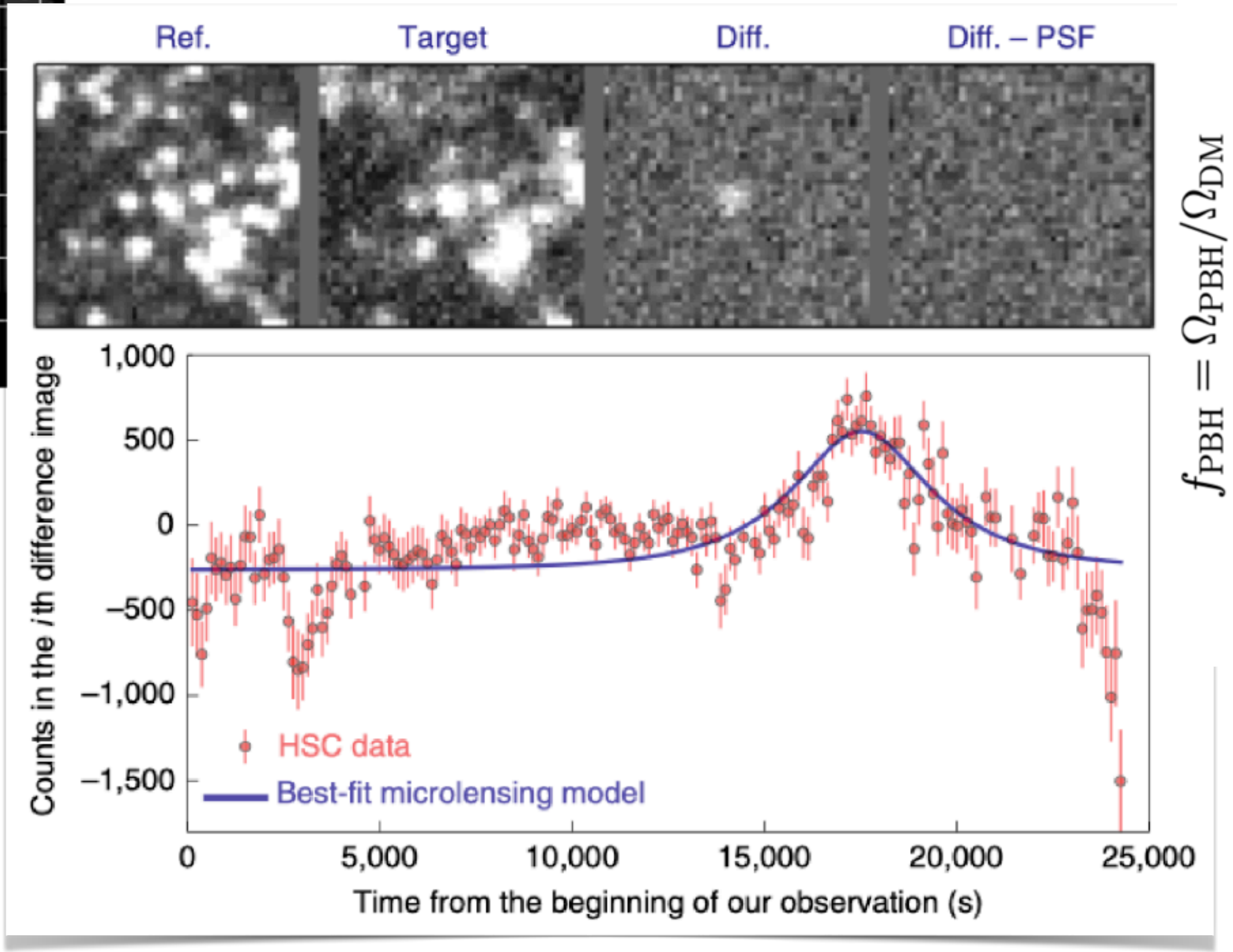
[B. Carr, K. Kohri, Y. Sendouda, J. Yokoyama, 2020]

Primordial black holes: Candidate Events

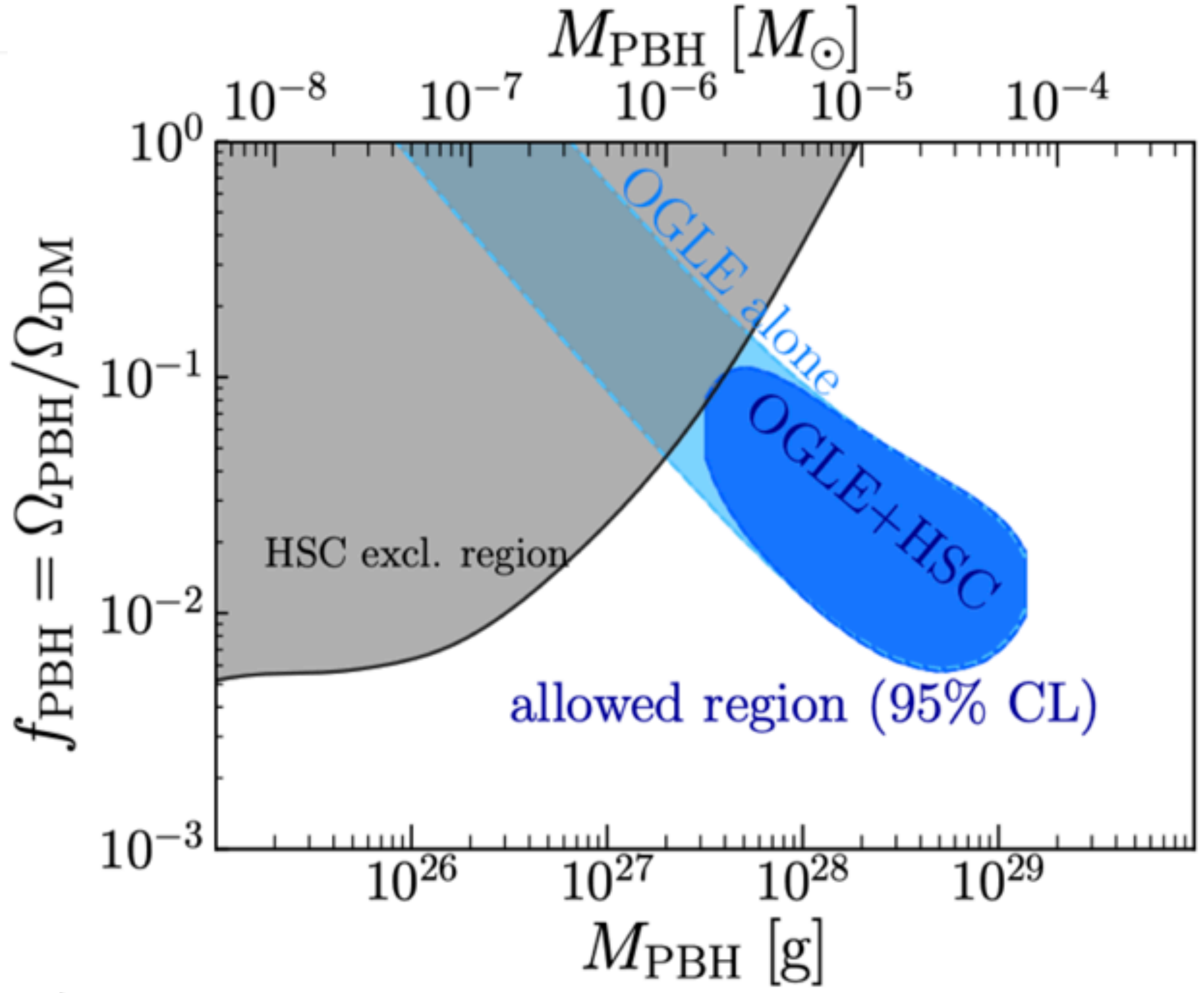


M31

HSC Candidate Event

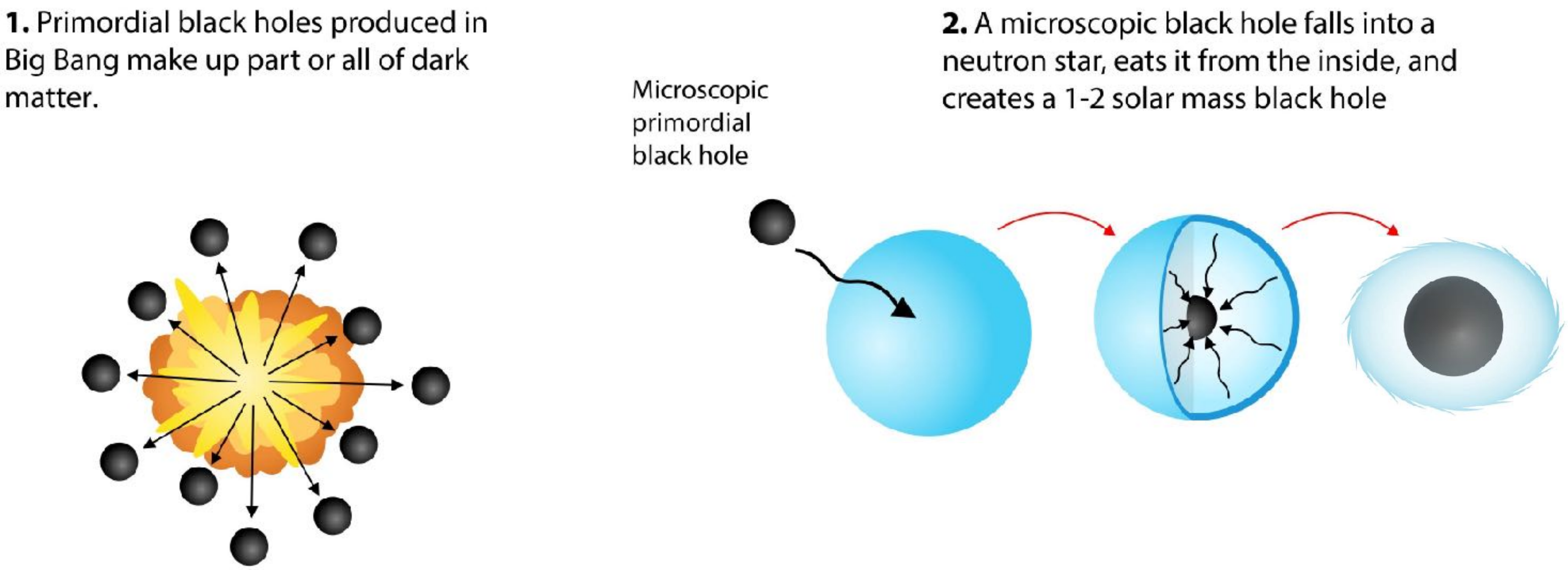


OGLE Events



[Niikura et al., Nature Astronomy arXiv:1701.02151, arXiv:1901.07120]

PBH-Neutron star interactions



$$\Longrightarrow \quad r - \text{process nucleosynthesis}$$

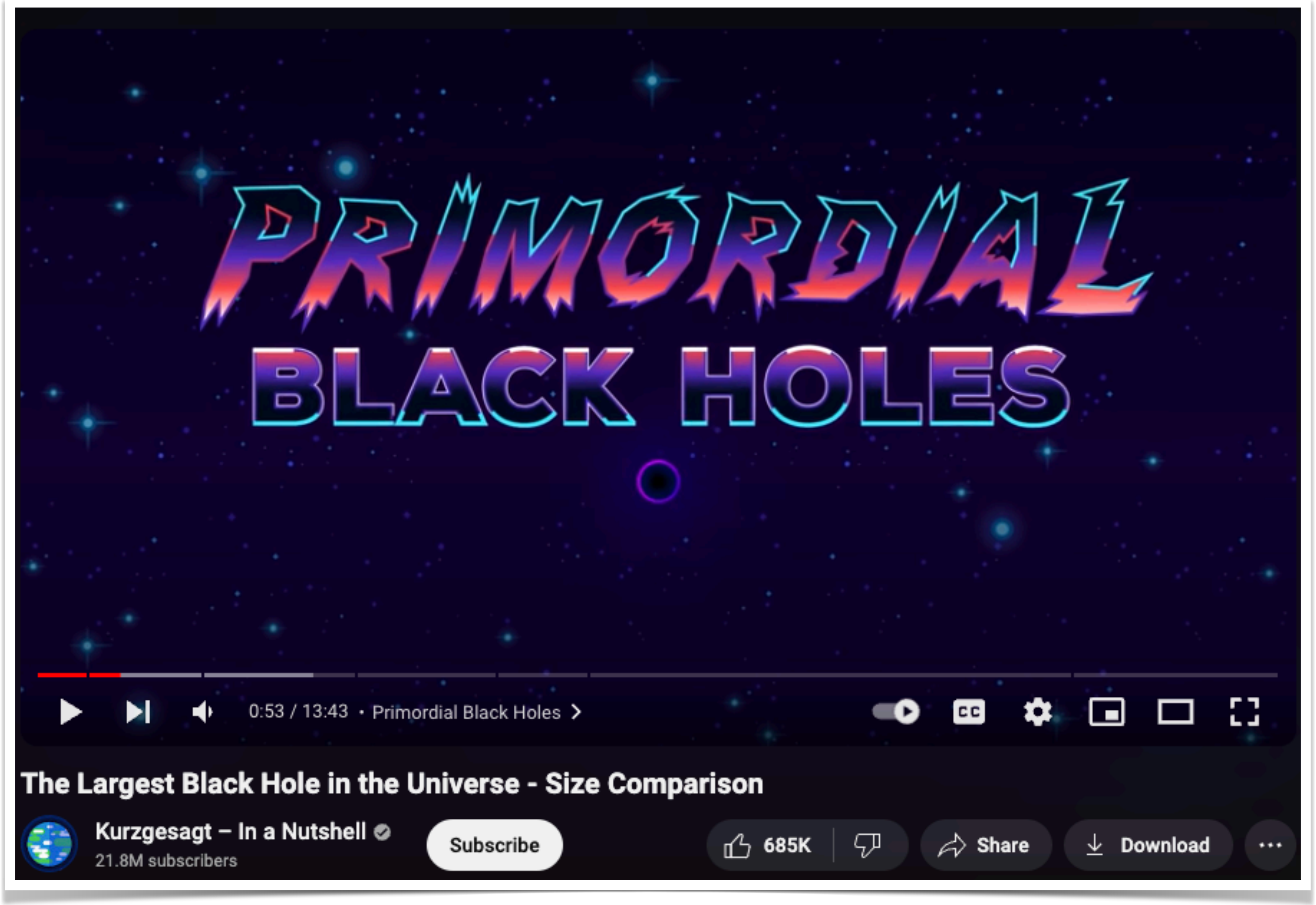
[Takhistov, Fuller, Kusenko, PRL 119 (2017) 6, 061101]
[Takhistov, Fuller, Kusenko, PRL 126, 071101 (2021)]
[Takhistov, arXiv:1707.05849]
[Caiozzo, Bertone, Kühnel, arXiv:2404.08057]
[Baumgarte, Shapiro, arXiv:2404.08735]

Primordial black holes; the canonical picture

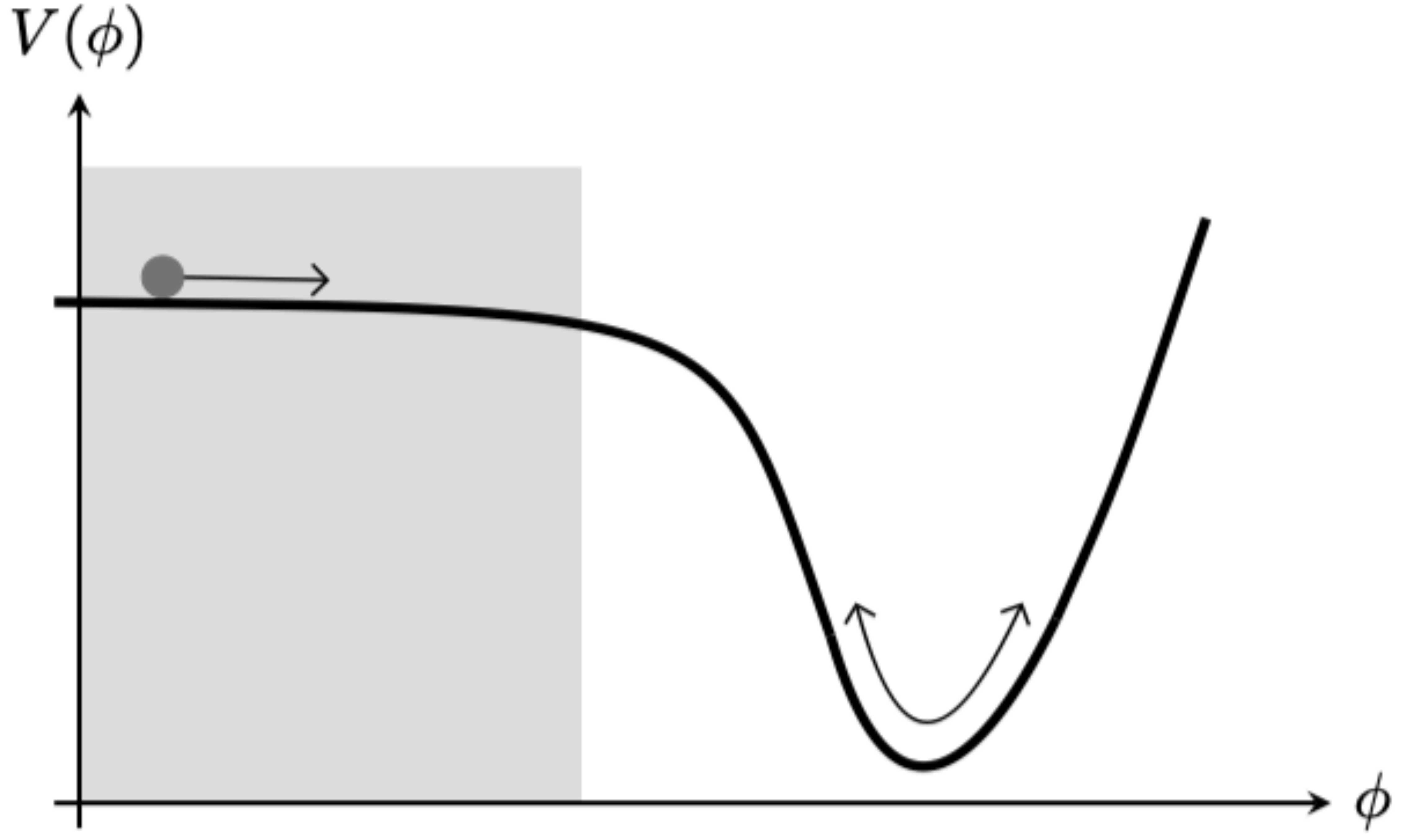
Cosmological Inflation

$$\Downarrow$$

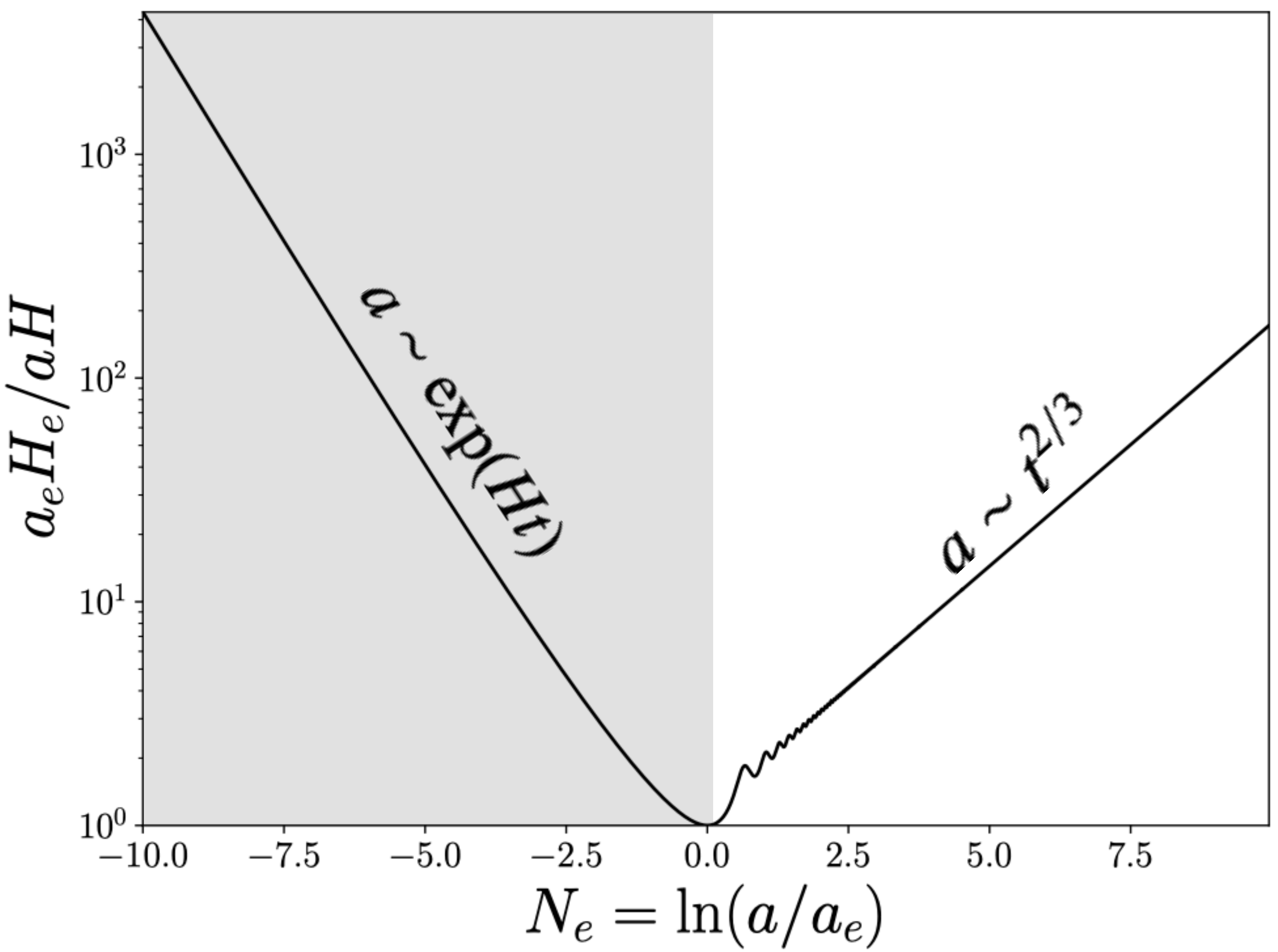
Primordial Black Holes



Slow-roll inflation in a few words

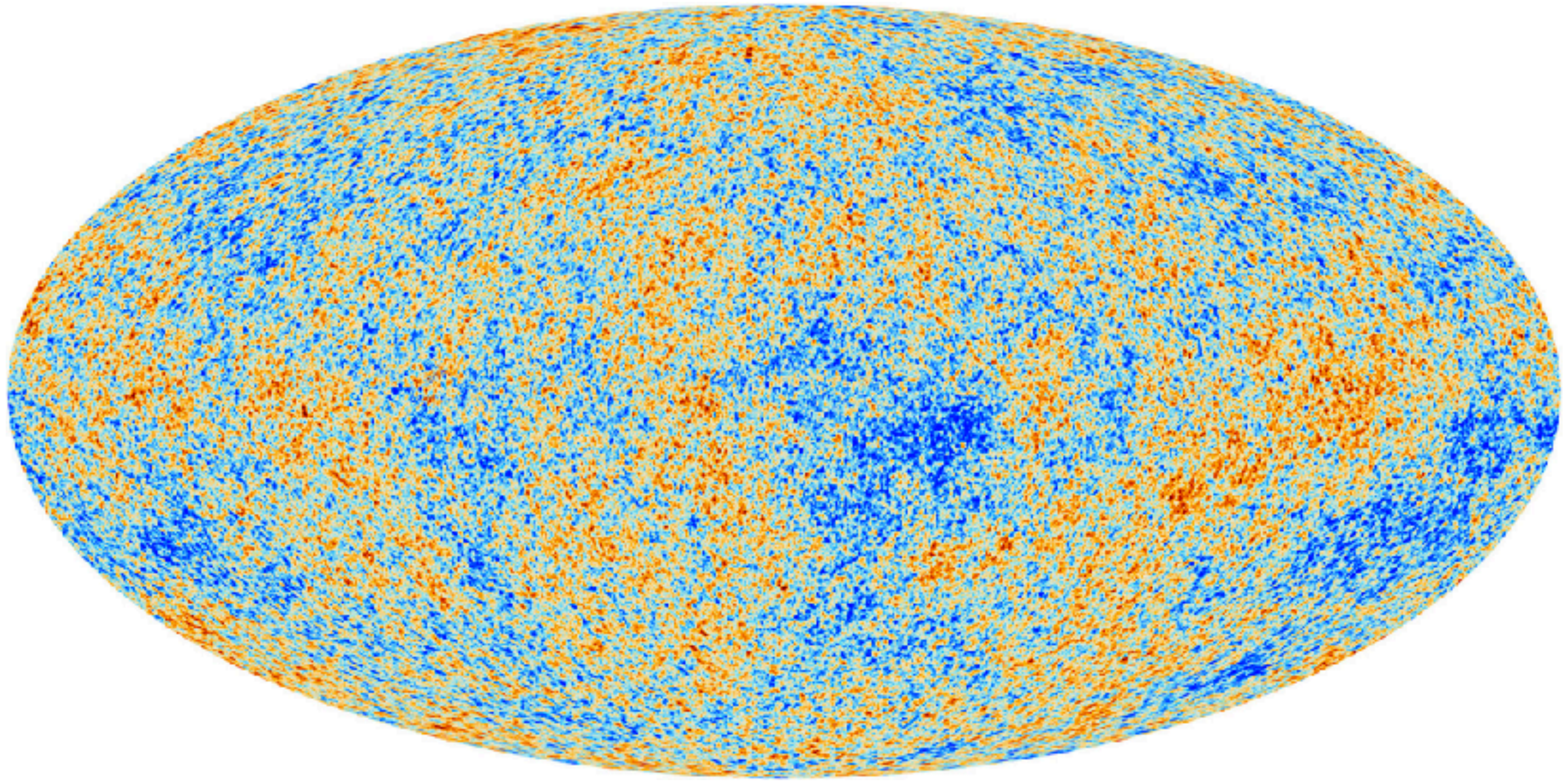


[Credit: Baumann, *Cosmology*, 2021]

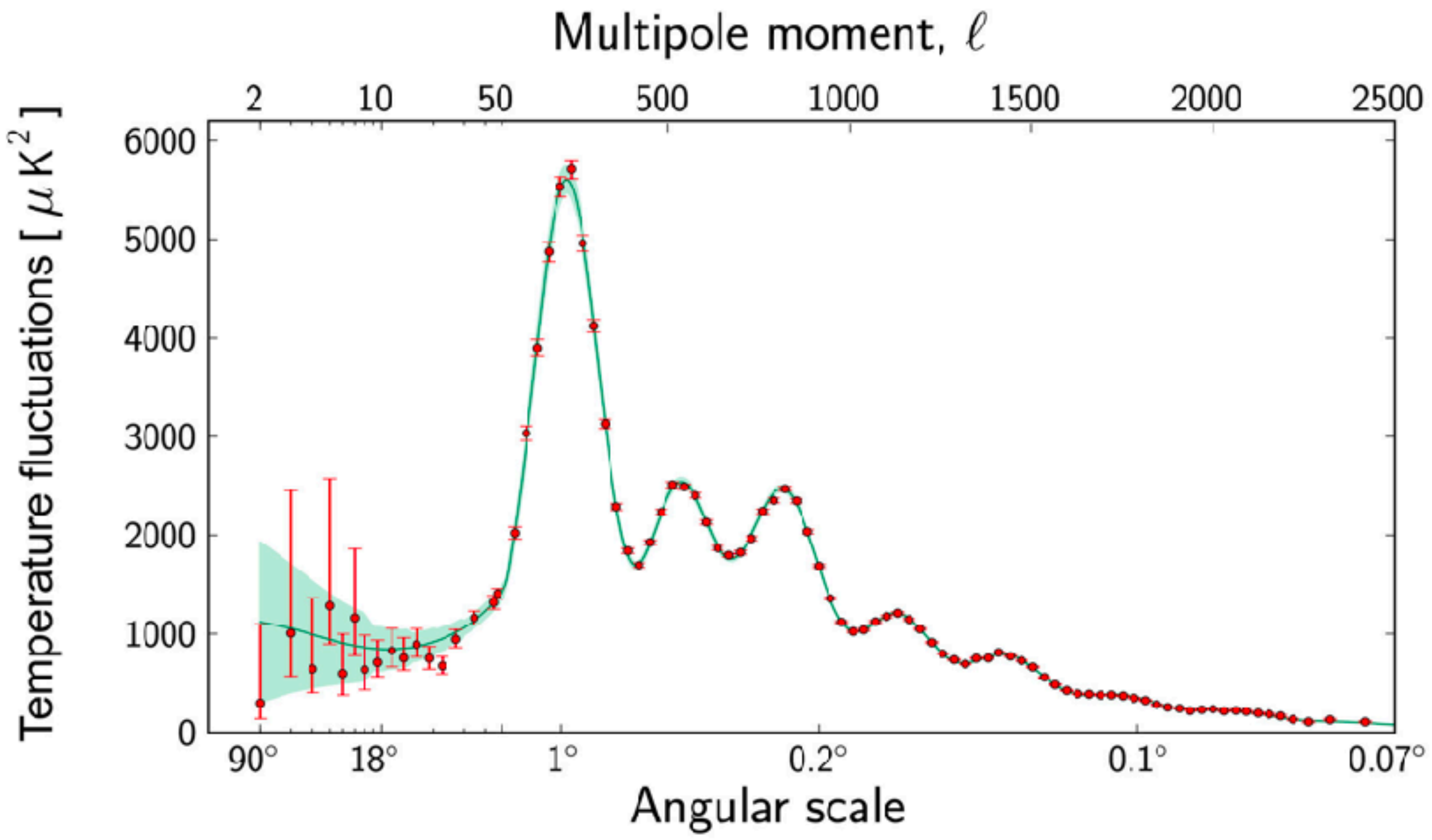


The standard inflationary scenario *predicts:*

$$\Delta^2_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

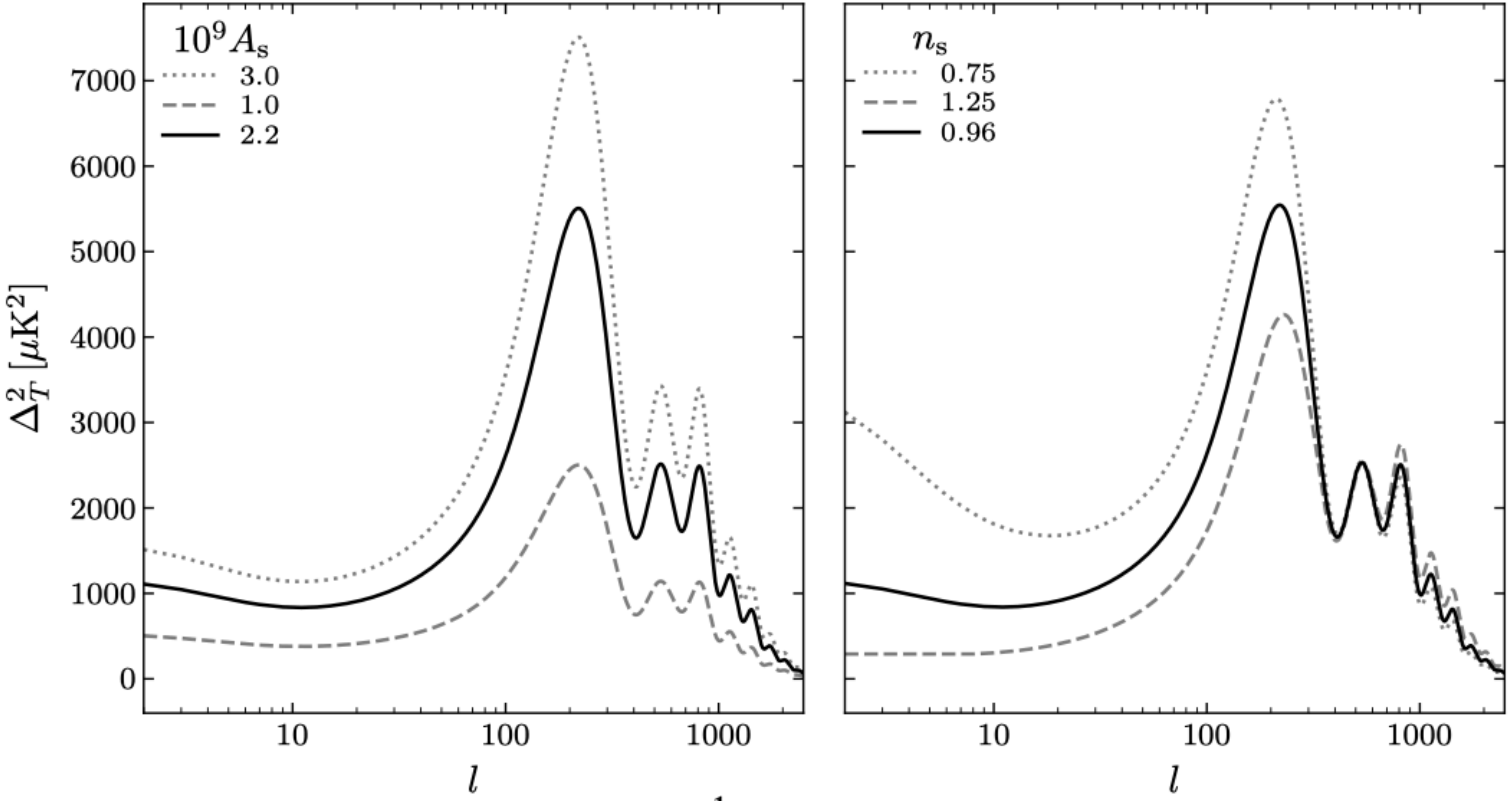


Measured Today



$(k \sim \ell)$

[Credit: European Space Agency]



$$\Delta_{\mathcal{R}}^2(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

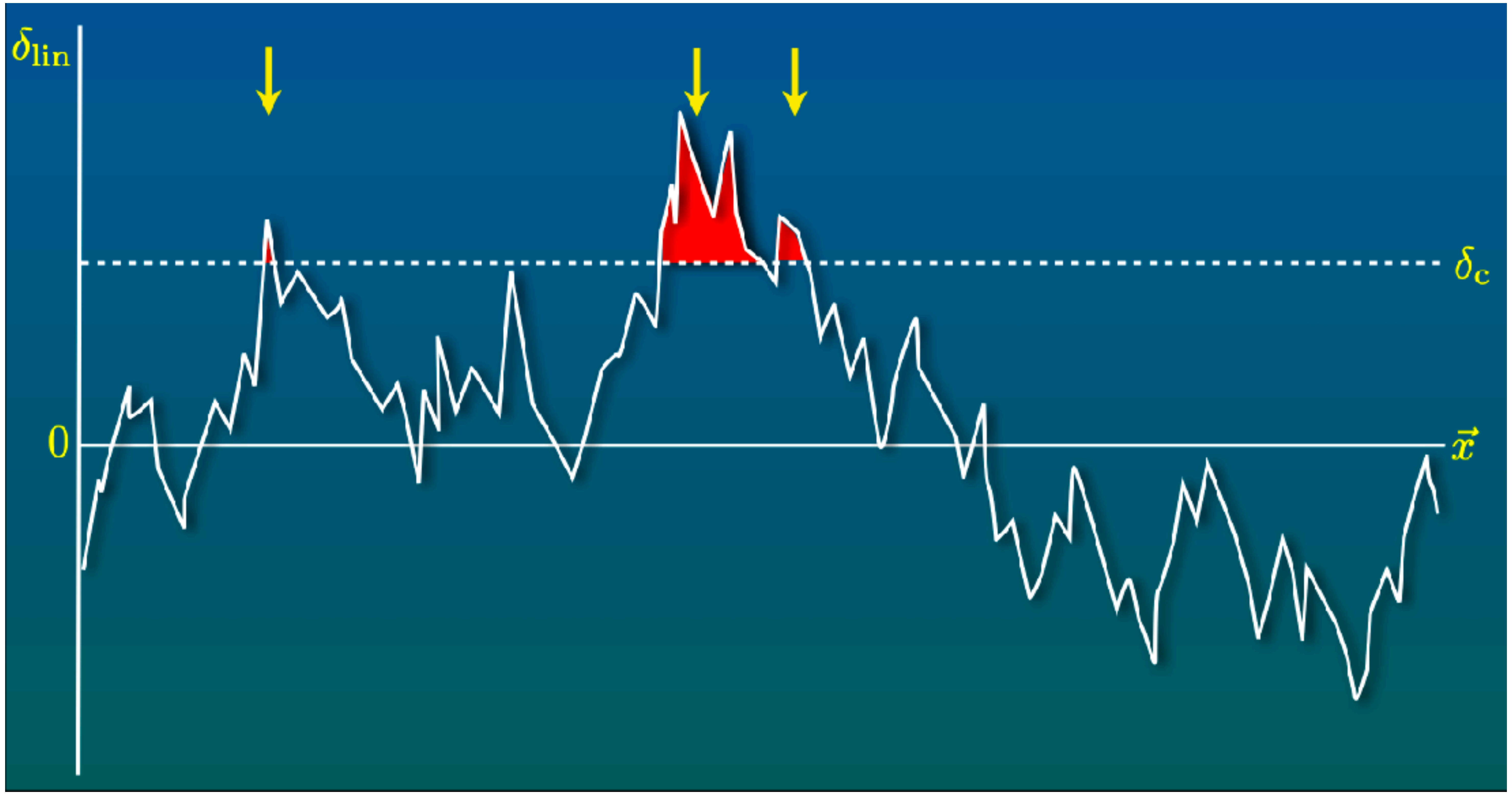
$(k \sim \ell)$

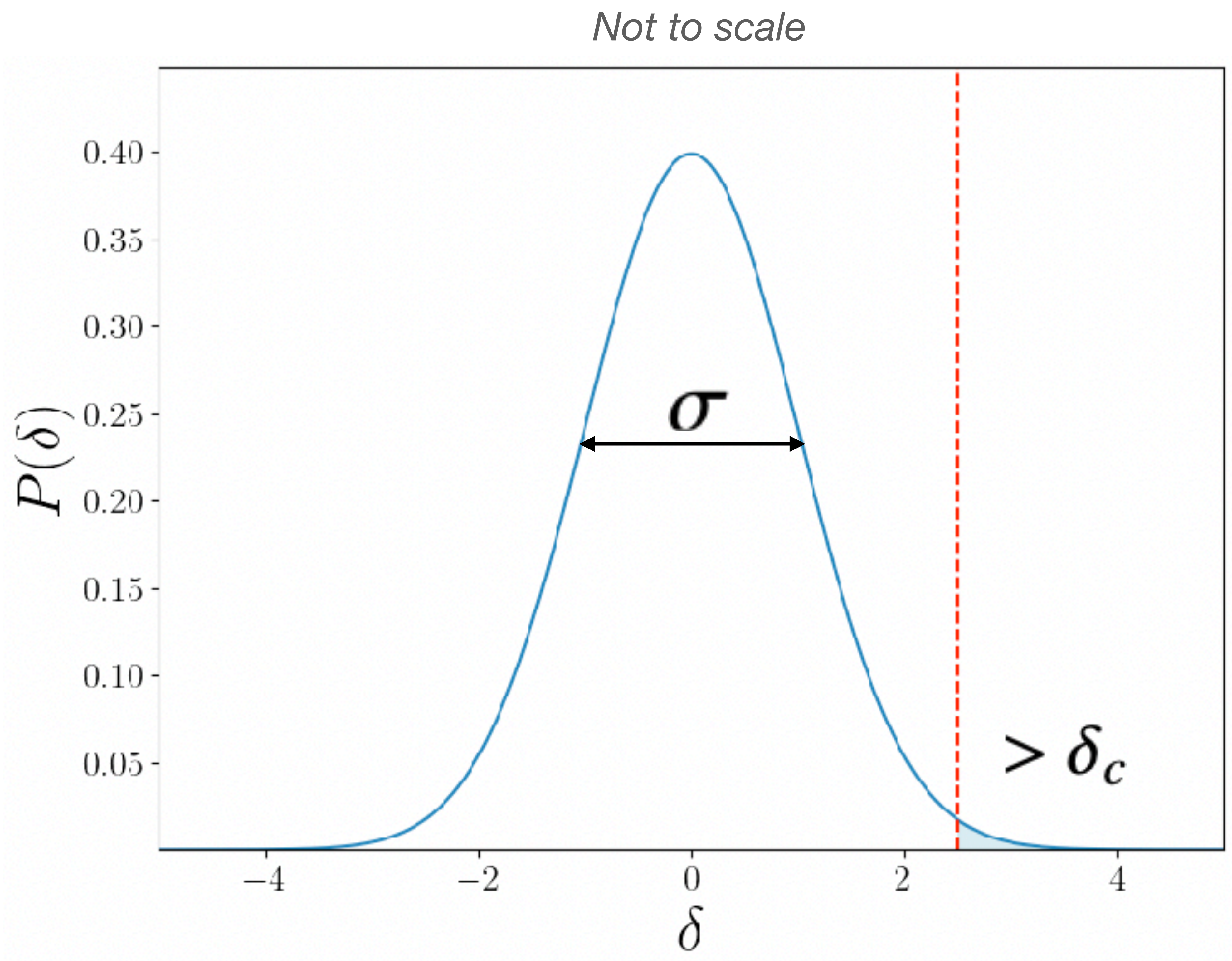
$$10^9 A_s = 2.098 \pm 0.023$$

$$n_s = 0.9603 \pm 0.0073$$

[Credit: Baumann, *Cosmology*, 2021]

Inflationary perturbations & PBHs



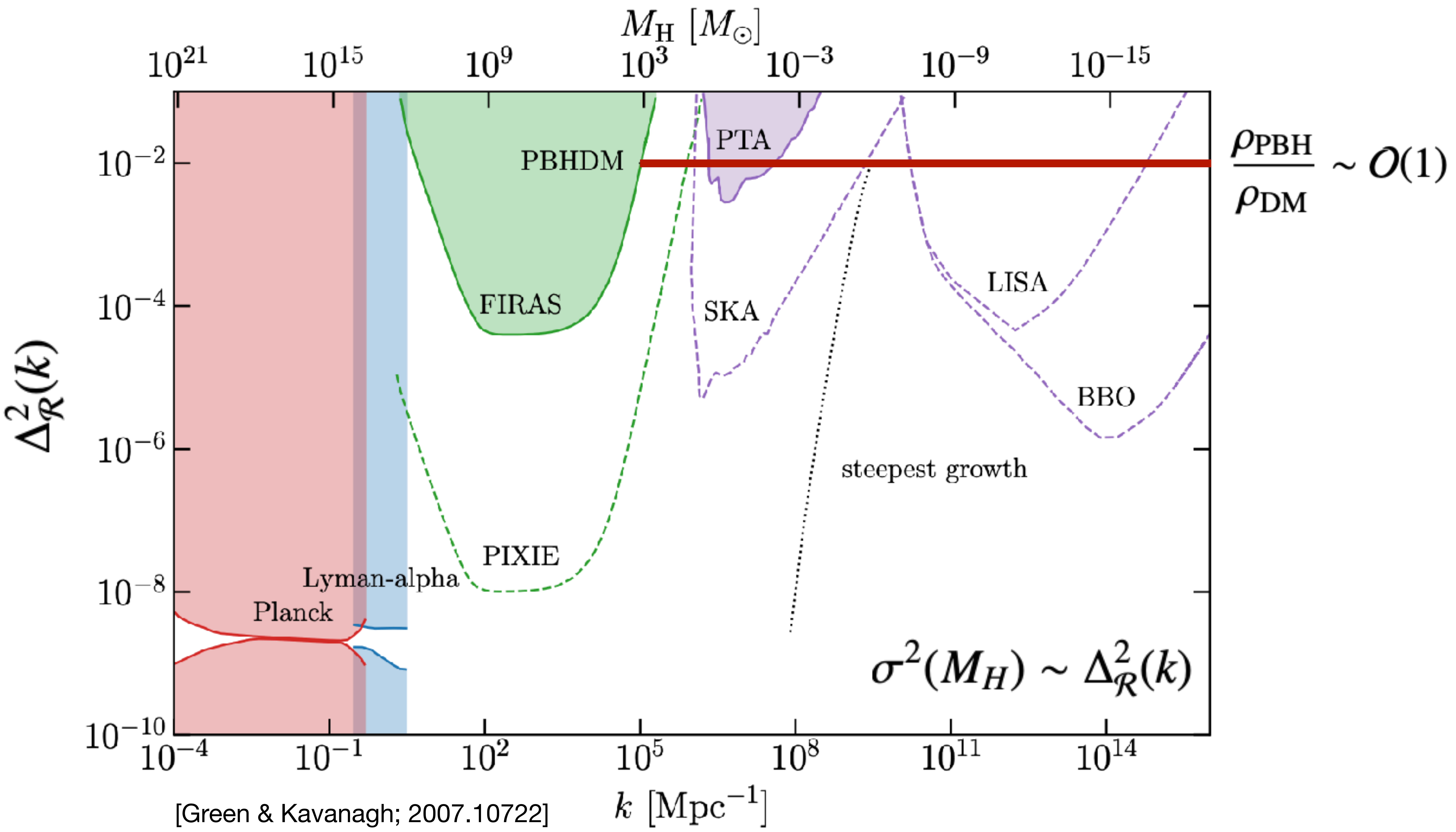


$$\beta(M_H) = \frac{\rho_{\rm PBH}}{\rho_{\rm tot}} = \int_{\delta_c}^{\infty} P(\delta)\, d\delta \sim \sigma(M_H) \exp\left(-\frac{\delta_c}{2\sigma^2(M_H)}\right)$$

$$\sigma^2(M_H) \sim \Delta^2_{\mathcal{R}}(k)$$

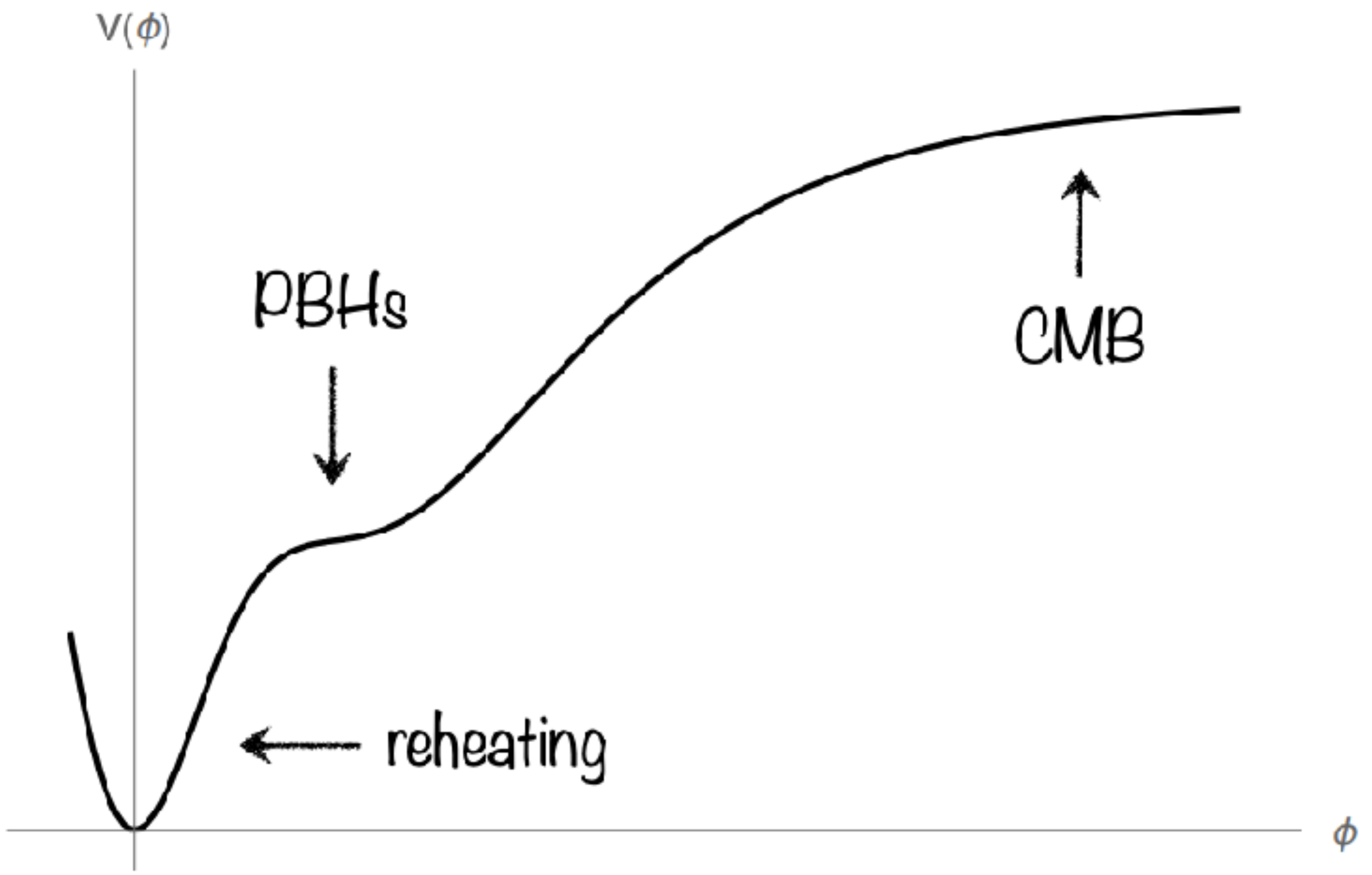
[Credit: Frank van den Bosch,Yale University]

Inflationary perturbations & PBHs

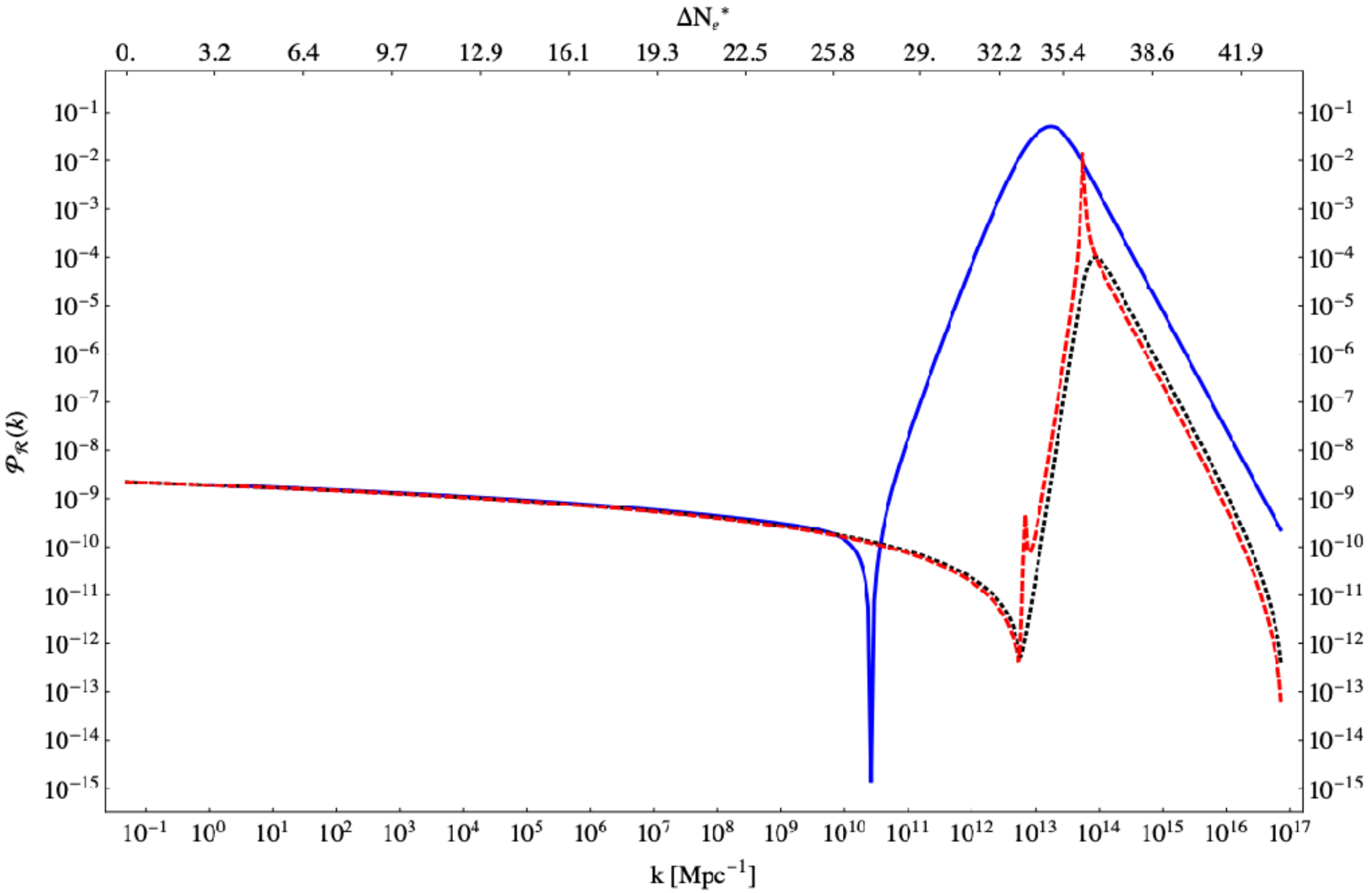


[Green & Kavanagh; 2007.10722]

Inflationary perturbations & PBHs



- Remarkably, is it possible to generate the necessary power spectrum using more complicated potentials.
- *However*, you start to have to *fine-tune* the inflaton potential.
- Other ways to accomplish this including multi-field inflation, etc.



[Ballesteros, Taoso; 1702.03901]

Can you form PBHs in a more "conventional" way?

PBH Formation: primordial structure formation

$$\left.\begin{array}{c}\text{Cooling via free-free emission}\\ \Downarrow \\ \chi\text{ radiation becomes trapped}\\ \Downarrow \\ \text{Surface radiation takes over}\end{array}\right\} \stackrel{*}{\Longrightarrow} \left\{\begin{array}{l}\text{Black hole forms}\\ \text{Fermi ball forms}\\ \text{Halo annihilates}\end{array}\right.$$

To *ensure* that a black hole forms, we will introduce an *asymmetric dark fermion* ψ

$$\mathcal{L} \supset y\chi\bar{\psi}\psi \quad \& \quad \eta_\psi = (n_\psi - n_{\bar{\psi}})/s \neq 0$$

Yukawa Interaction & Scalar Cooling + Fermion Asymmetry $\Longrightarrow$ PBHs

PBH abundance

- The strength of the long-range force we are considering is likely strong enough to capture all of the dark matter ψ particles in halos and therefore PBHs.
- Thus, the PBH-dark matter fraction is related to the baryon density:

$$f_{\rm PBH} = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} = 0.2 \frac{m_\psi}{m_p} \frac{\eta_\psi}{\eta_{\rm B}} = \left(\frac{m_\psi}{5 \text{ GeV}} \right) \left(\frac{\eta_\psi}{10^{-10}} \right)$$

- *Our mechanism can describe the closeness of* $\Omega_{\rm DM}$ *and* Ω_B.

PBH Mass Distribution

- Again, the strength of the scalar interaction will lead to rapid PBH formation. Thus, we expect the mass function of PBHs to represent the structure of the ψ - fluid at the time of formation.

- We need N-body simulations to accurately describe the details of ψ - structure formation.

- In the absence of this, we will approximate the mass function using the Press-Schechter function:

$$M^2 \frac{dN_h}{dM} \propto \frac{1}{\sqrt{\pi}} \left(\frac{M}{M_*} \right)^{1/2} e^{-M/M_*}$$

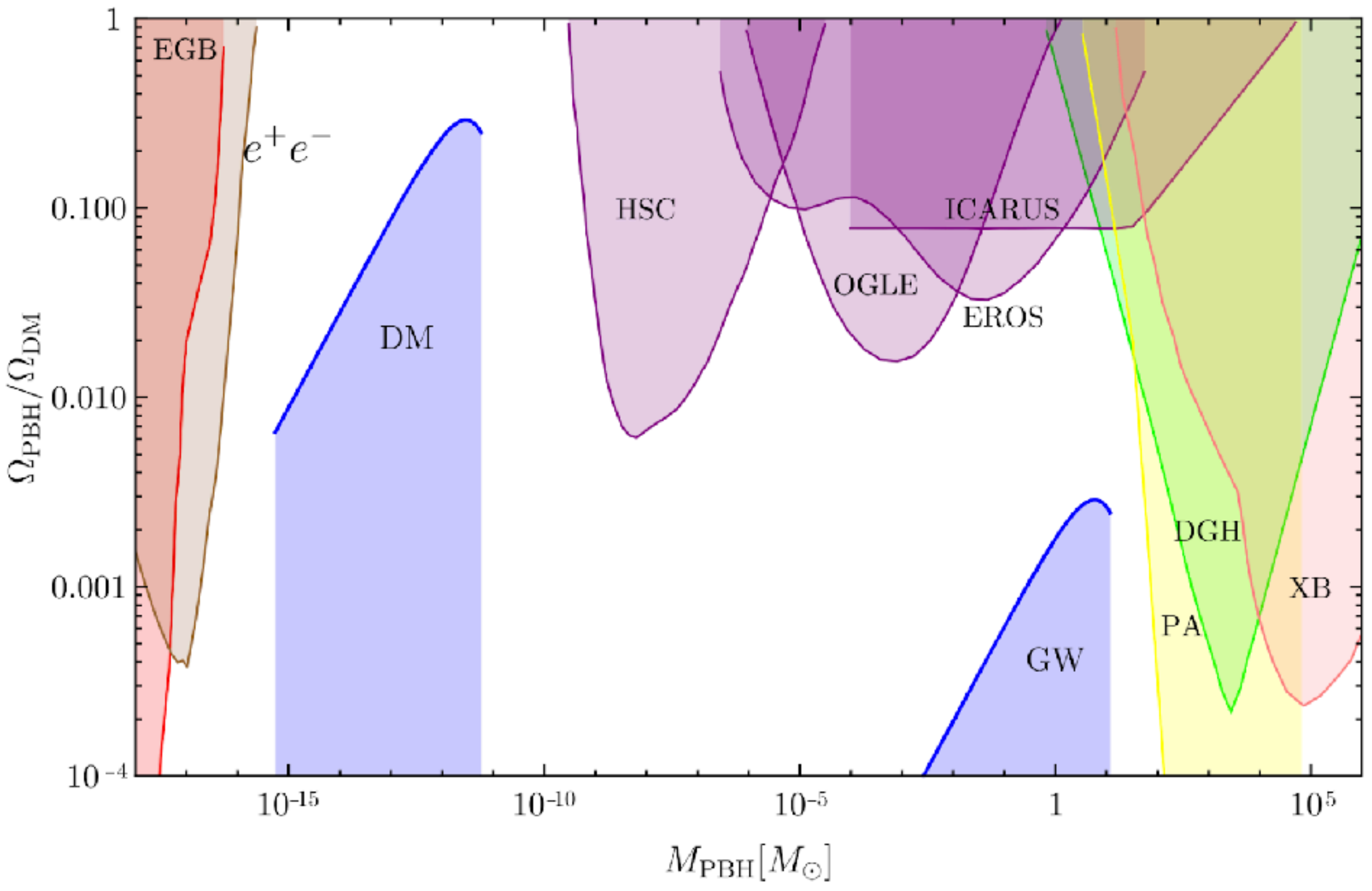
Illustrative examples

- PBH dark matter:

$$\left.\begin{array}{l}\eta_\psi \sim \eta_B \sim 10^{-10} \\ m_\psi = 5\ \text{GeV}\end{array}\right\} f_{\text{PBH}} = 1$$

- Relevant to LIGO

$$\left.\begin{array}{l}\eta_\psi \sim 10^{-9} \\ m_\psi = 5\ \text{MeV}\end{array}\right\} f_{\text{PBH}} \sim 10^{-3}$$



Observational implications of primordial structure formation: gravitational waves

[**MMF,** A. Kusenko, M. Sasaki; ***PRL*** 131 (2023) 1, 1]

Primordial structure formation & GWs

- Generically, the collapse of dark matter ψ halos will be ***aspherical***

$$\Longrightarrow \text{ Time changing mass quadrupole moment}$$

- It's still not obvious which methodology is best suited to tackling this problem
  - Standard methods, like cosmological perturbation theory *do not* include forces which couple to charge/number density as a means of generating perturbations
- We utilized the *Zel'dovich approximation* to directly determine the quadrupole moment, allowing for a calculation of the expected GW spectrum

See also:
I. Dalianis, C. Kouvaris [arXiv:2012.09255]

Zel'dovich Approximation

δ enters the horizon - t_q

$\Downarrow$

Overdensity increases to maximum size - $t_{\max}$

$\Downarrow$

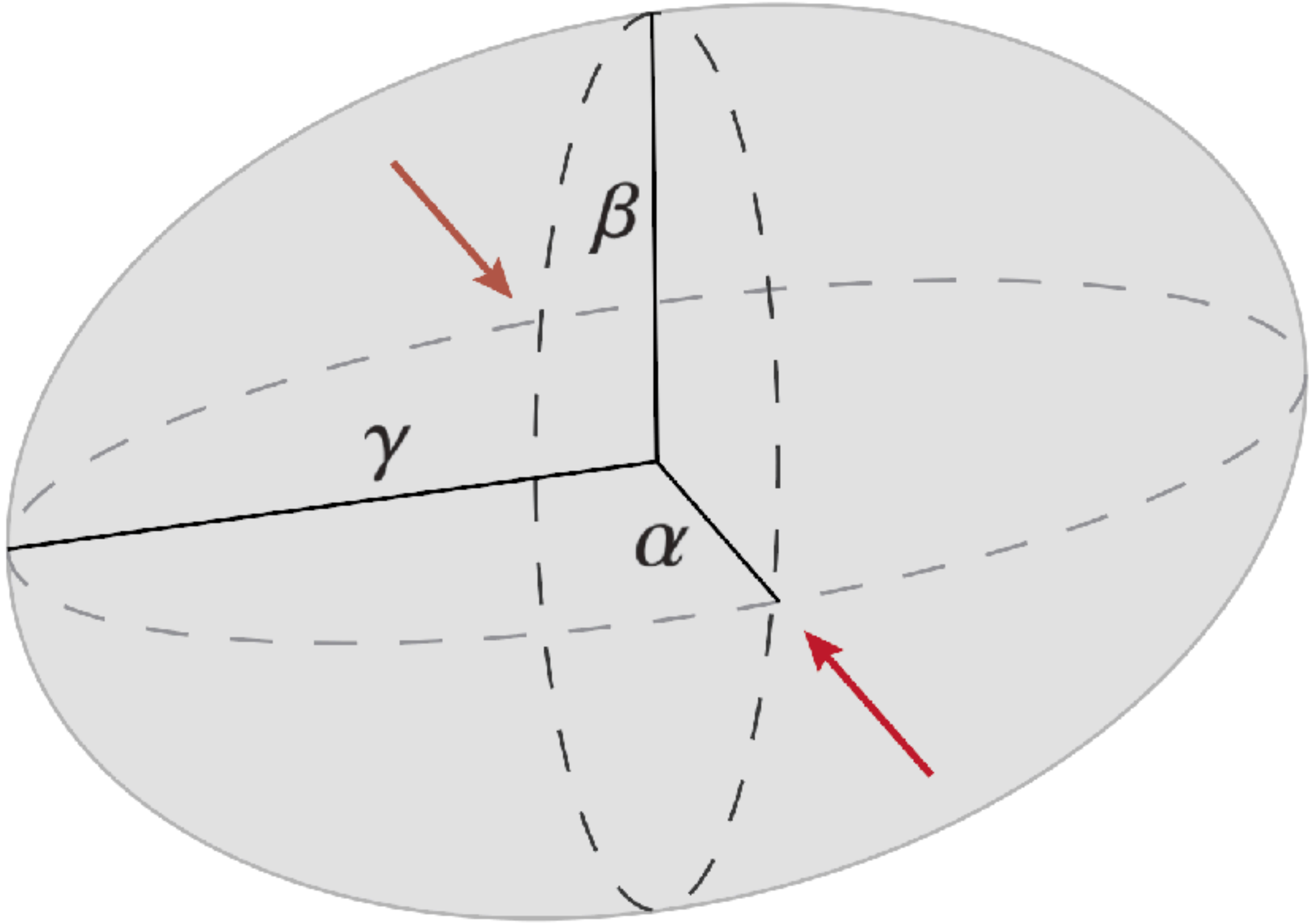
Collapse begins

$\Downarrow$

"Pancake" forms and shell crossing occurs - $t_{\rm col}$

$\Downarrow$

BH formation or halo annihilation



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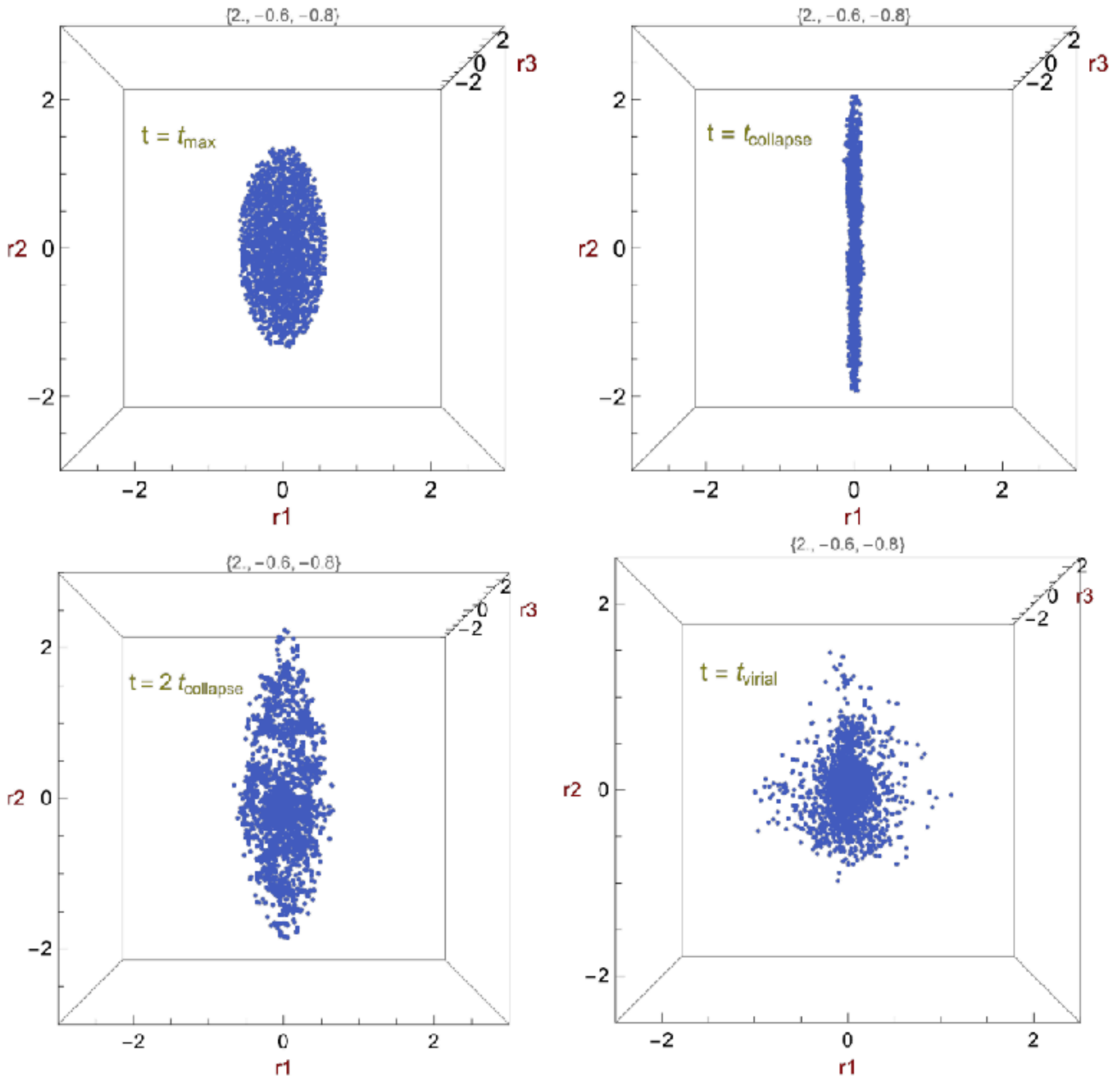

See also:
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Growth of perturbations

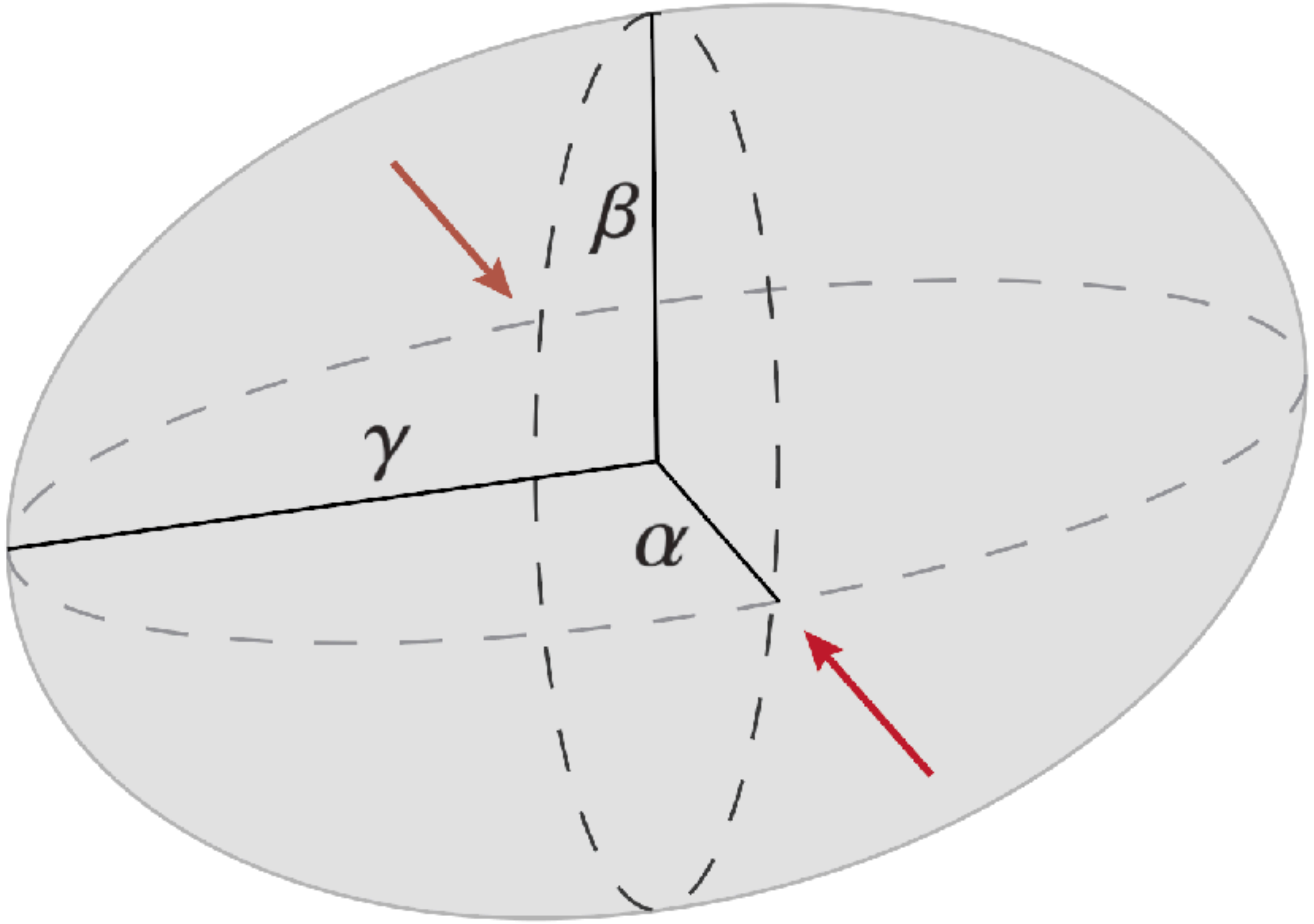
A reminder of the traditional result:

$$\delta \propto \begin{cases} \ln a & \text{for} \quad \text{(RD)} \\ a & \text{for} \quad \text{(MD)} \end{cases}$$

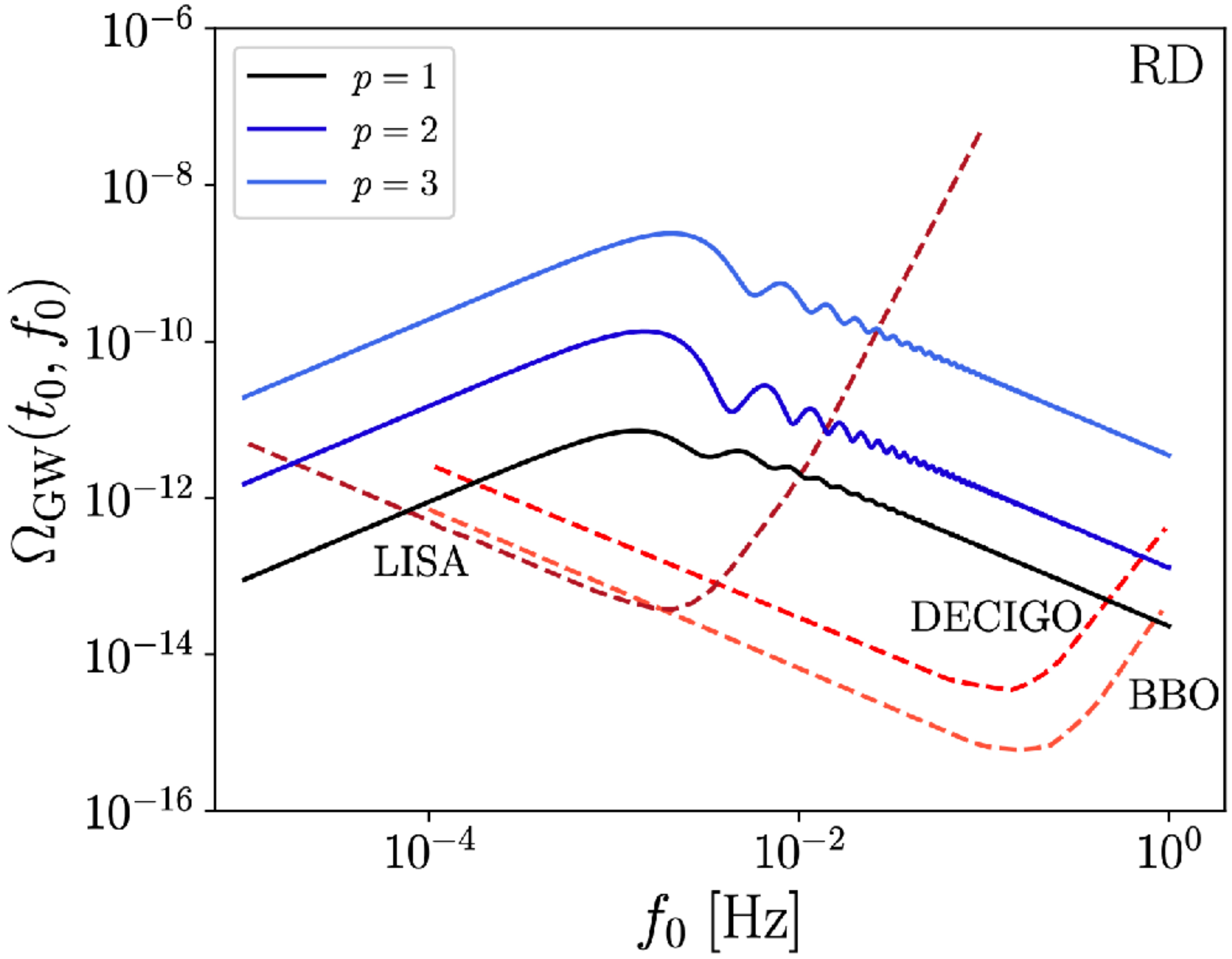
Here, ***<u>our fundamental assumption will be that</u>***

$$\delta \propto a^p, \qquad p \geq 1$$

As before p characterizes the strength of the force.



GW Spectrum



10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
$\Omega_{\rm GW}(t_0, f_0)$
$p = 1$
$p = 2$
$p = 3$
RD
LISA
DECIGO
BBO
10^{-4}
10^{-2}
10^{0}
f_0 [Hz]

GW Spectrum

$p = 1$
$p = 2$
$p = 3$
IPTA
PPTA
SKA
LISA
DECIGO
BBO
LIGO
O5
ET
RD
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
$\Omega_{\rm GW}(t_0, f_0)$
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{1}
10^{3}
f_0 [Hz]

Primordial structure formation
&
local heating

[**MMF**, A. Kusenko, L. Pearce, G. White: *PRD* 108 (2023) 9, 9]

[**MMF**, C. Kouvaris, A. Kusenko: *PRD* 108 (2023) 10, 10]

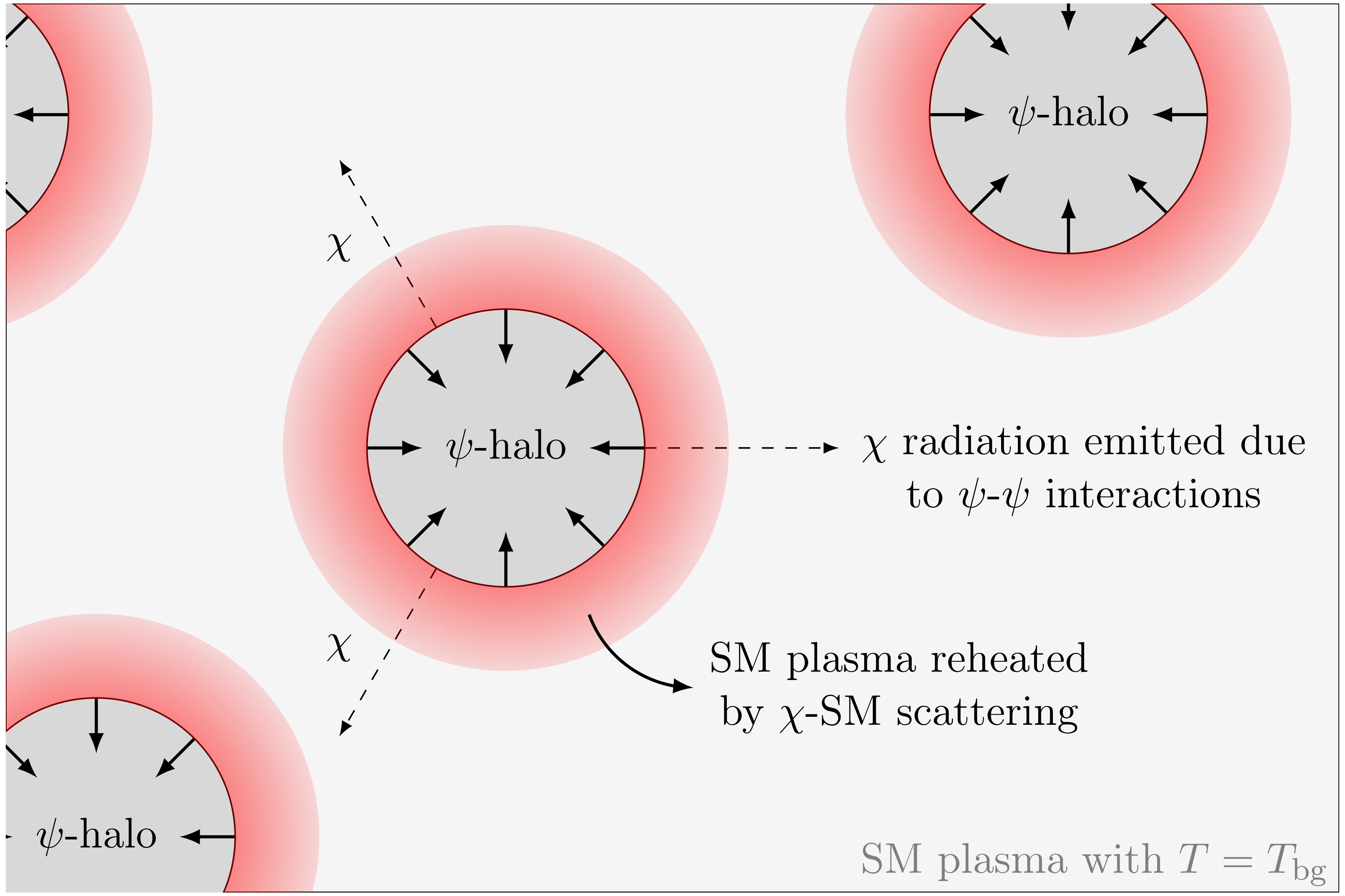
Primordial structure formation & local heating

- Dark matter halos release *a lot* of energy as they collapse

$$\Delta E \sim \frac{y^2 M_h^2}{m_\psi^2 R_c}\left(1 - \frac{R_c}{R_h}\right)$$

- If the mediator χ couples to the SM, the SM plasma can become locally heated.

- This heating can potentially *restart* sphaleron transitions or *restore* thermal equilibrium.



Primordial structure formation & local heating

$$\Gamma_{\text{ann, sph}} \sim H$$

however,

$$\Gamma_{\text{ann, sph}} \sim \tau_{\text{diss}}^{-1}$$

$$\tau_{\text{diss}} \ll H^{-1}$$

Primordial structure formation & local heating

- Once the plasma is heated locally, it can cool through:

$$\text{Diffusion} : \tau_{\text{diff}} \sim \frac{R_i^2}{4D}\left(\frac{T_i}{T}\right)^{8/3},$$

$$\text{Explosive expansion} : \tau_{\text{exp}} \sim \frac{4R_i}{\sqrt{3}}\left(1 + \frac{t - t_i}{\sqrt{3}R_i}\right)$$

- The SM plasma undergoes two phase transitions: a rapid one as it initially heats, and another one as it cools.

Primordial structure formation
&
WIMP Production

[**MMF**, C. Kouvaris, A. Kusenko: *PRD* 108 (2023) 10, 10]

Primordial structure formation & WIMP Production

- Traditional freeze-out paradigm:

$$\dot{n}_X + 3Hn_X = -\langle\sigma_{\rm ann}v\rangle\left(n_X^2 - (n_X^{\rm eq})^2\right)$$

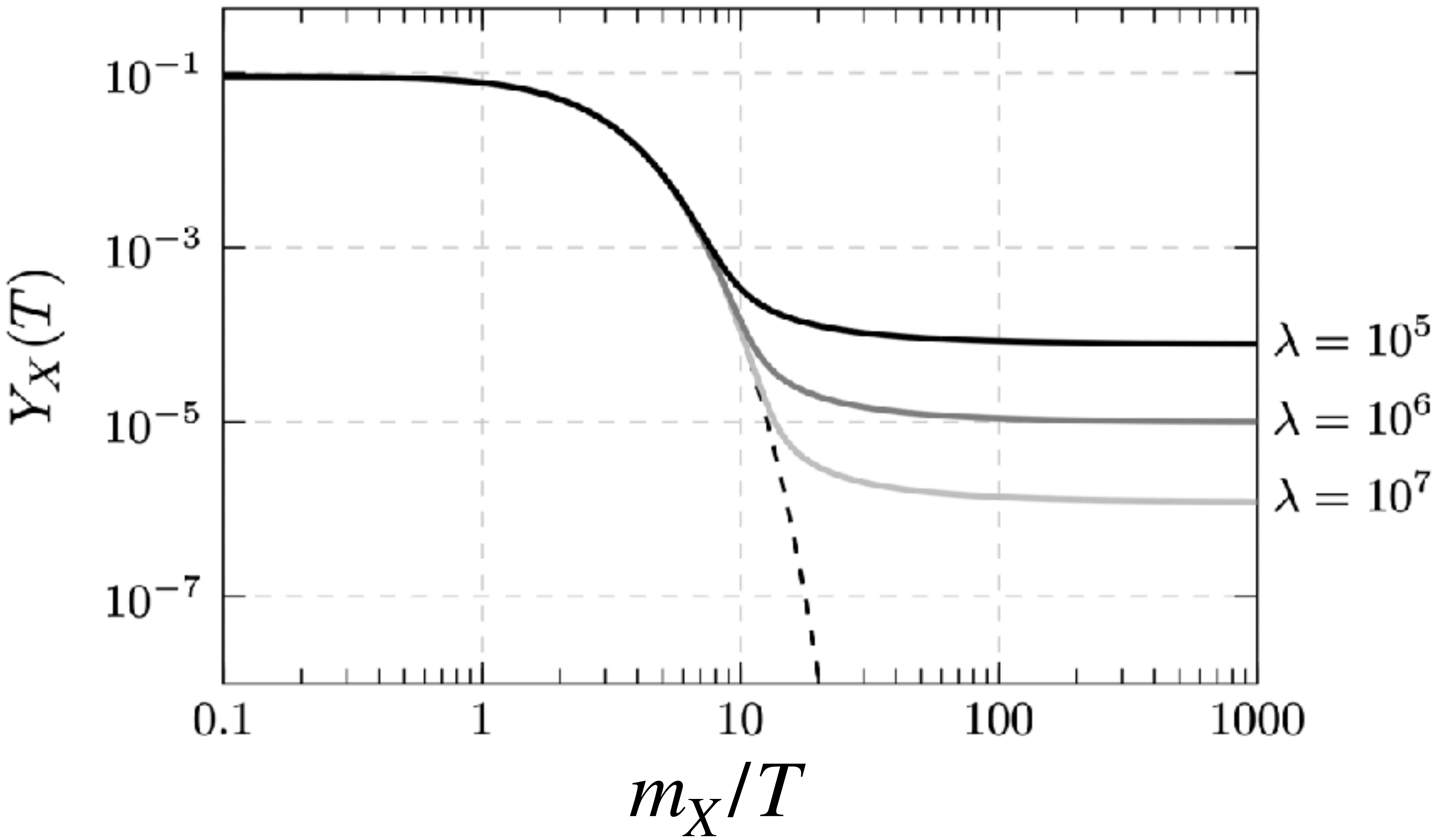
$$\Downarrow$$

$$\Gamma_{\rm ann}(T_{\rm FO}^X) \equiv \langle\sigma_{\rm ann}v\rangle n_X^{\rm eq}(T_{\rm FO}^X) = H(T_{\rm FO}^X)$$

$$\Downarrow$$

$$\Omega_X \simeq 5.2\times10^{-2}\frac{x_{\rm FO}^X}{\sqrt{g_*(M_X)}}\left(\frac{10^{-8}\ {\rm GeV}^{-2}}{\langle\sigma_{\rm ann}v\rangle}\right), \qquad x_{\rm FO}^X = m_X/T_{\rm FO}^X$$

[Credit: Baumann, Cosmology]



$$\lambda = \frac{\langle\sigma_{\rm ann}v\rangle m_X^3}{H(m_X)}$$

Primordial structure formation & WIMP Production

- Primordial structure formation offers a new fundamental time scale:

$$\frac{dn_X(T)}{d\ln T} = -\frac{\Gamma_X(T)}{\tau_{\rm diss}^{-1}(T)}\left[n_X^2 - (n_X^{\rm eq})^2\right]$$

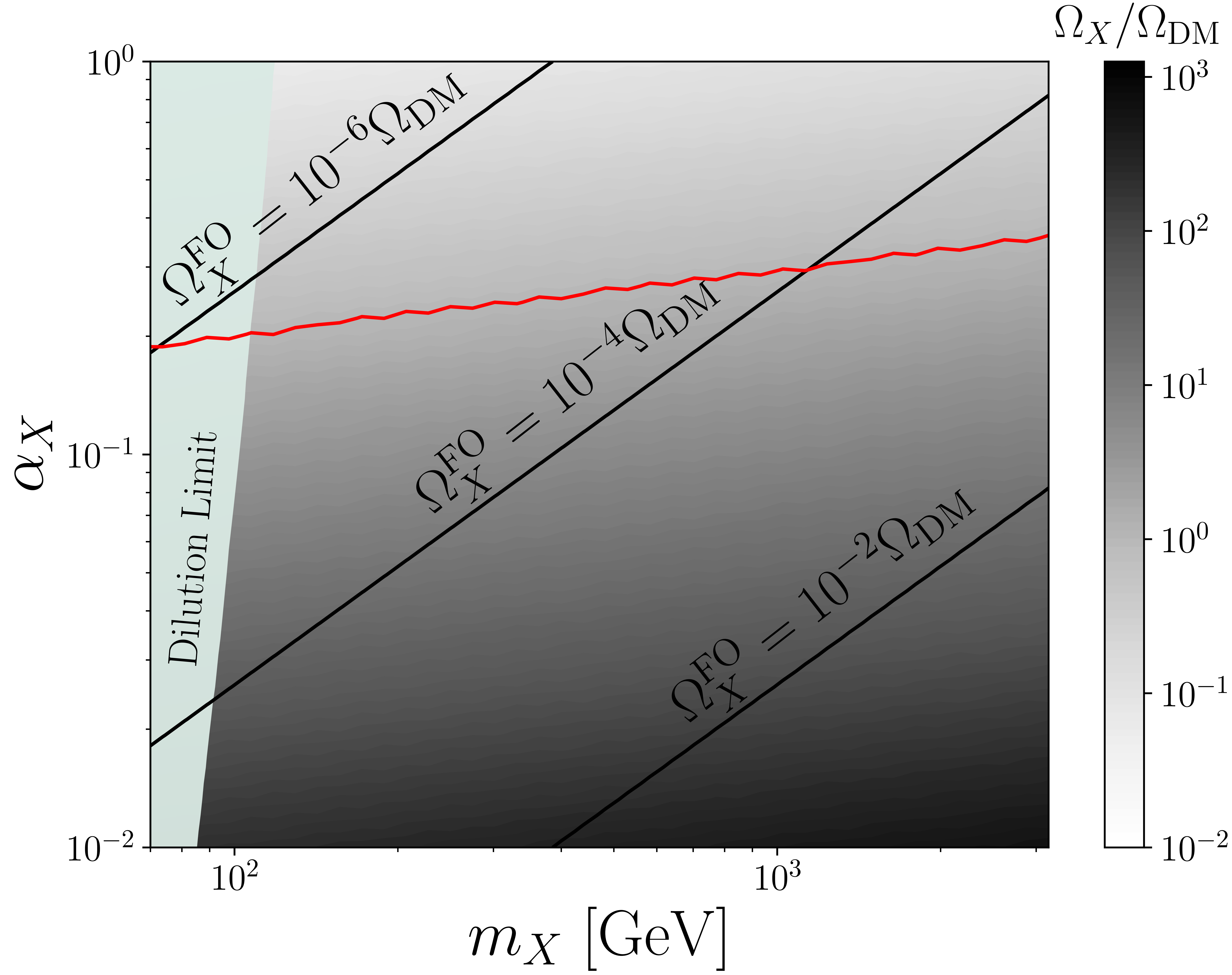
$$\Downarrow$$

$$\Gamma_X(T_f) = \tau_{\rm diss}^{-1}(T_f)$$

$$\Downarrow$$

$$\rho_X(T_{\rm bg}) \simeq f \cdot m_X n_X^{\rm eq}(T_f)$$

Primordial structure formation & WIMP Production



Primordial structure formation
&
Baryogenesis

[**MMF**, A. Kusenko, L. Pearce, G. White: *PRD* 108 (2023) 9, 9]

Brief baryogenesis review

- Fundamental to *most* baryogenesis scenarios are the Sakharov conditions, which state that three elements are required to generate an excess of baryons:

1. Baryon number violation $\Longrightarrow$ *sphaleron transitions*
2. C and CP violation
3. Out-of-equilibrium dynamics $\Longrightarrow$ *expansion of heated region*

Primordial structure formation & baryogenesis

- From the Sakharov conditions, we need some source of CP violation.
  - In principle, any EW baryogenesis scenario will be applicable here
- As a well motivated example, we considered the two Higgs doublet model
  - Leads to term in the Lagrangian, $\mathscr{L} \supset \dot{\theta} J_B^0$, similar as those in spontaneous baryogenesis

$$\mu_{\text{eff}} \sim \dot{\theta}$$

Primordial structure formation & baryogenesis

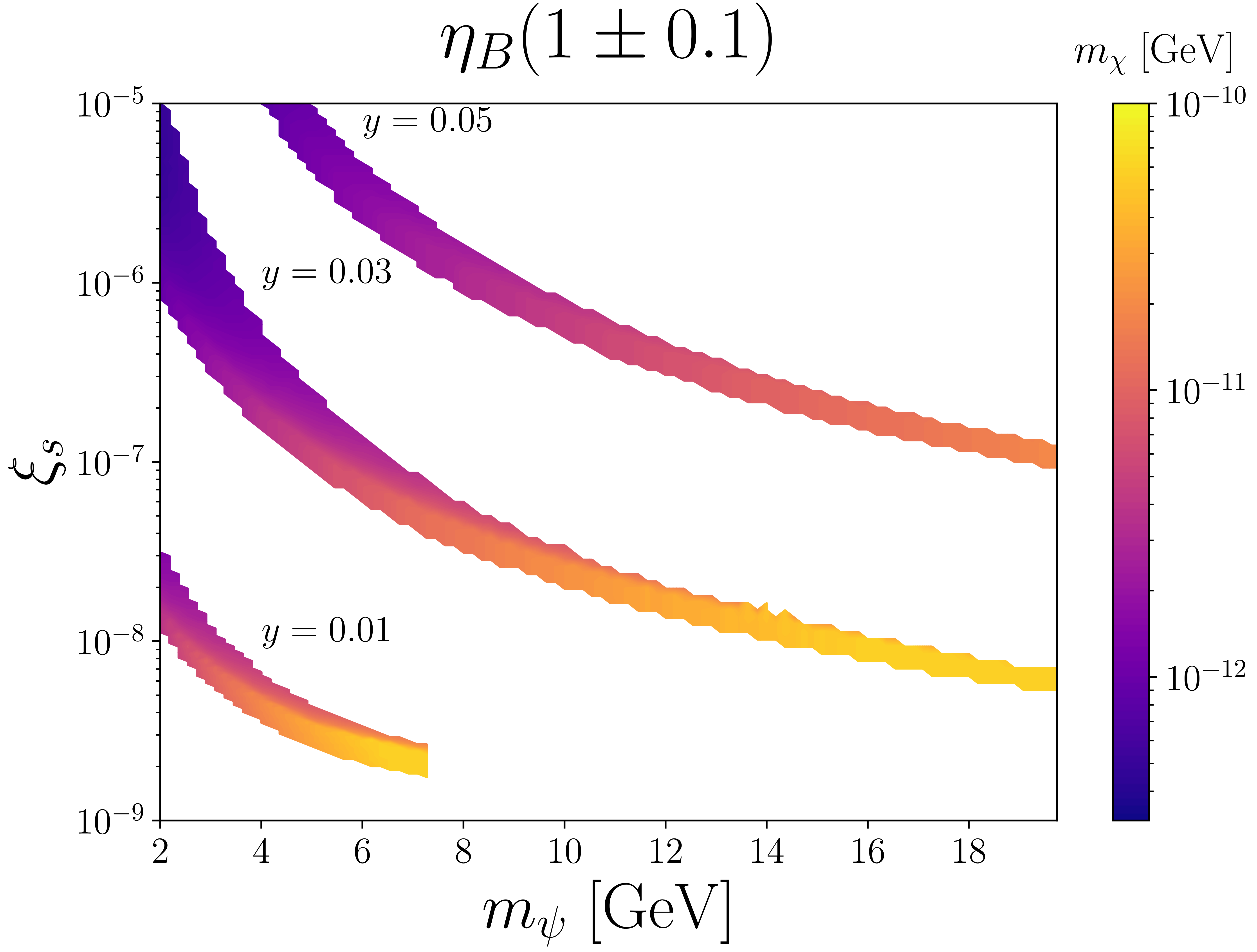
- The evolution of the baryonic number density is given by

$$\frac{dn_B(T)}{d\ln T} = \frac{\Gamma_{\rm sph}(T)}{\tau^{-1}_{\rm diss}(T)}\left(n_B(T) - \mu_{\rm eff}T^2\right)$$

- This is *very similar* to classical freeze-out equations. The number density in then frozen into

$$n_B \simeq \mu_{\rm eff}T^2\Big|_{T=T_f} \qquad \text{where} \quad \Gamma_{\rm sph}(T_f) = \tau^{-1}_{\rm diss}(T_f)$$

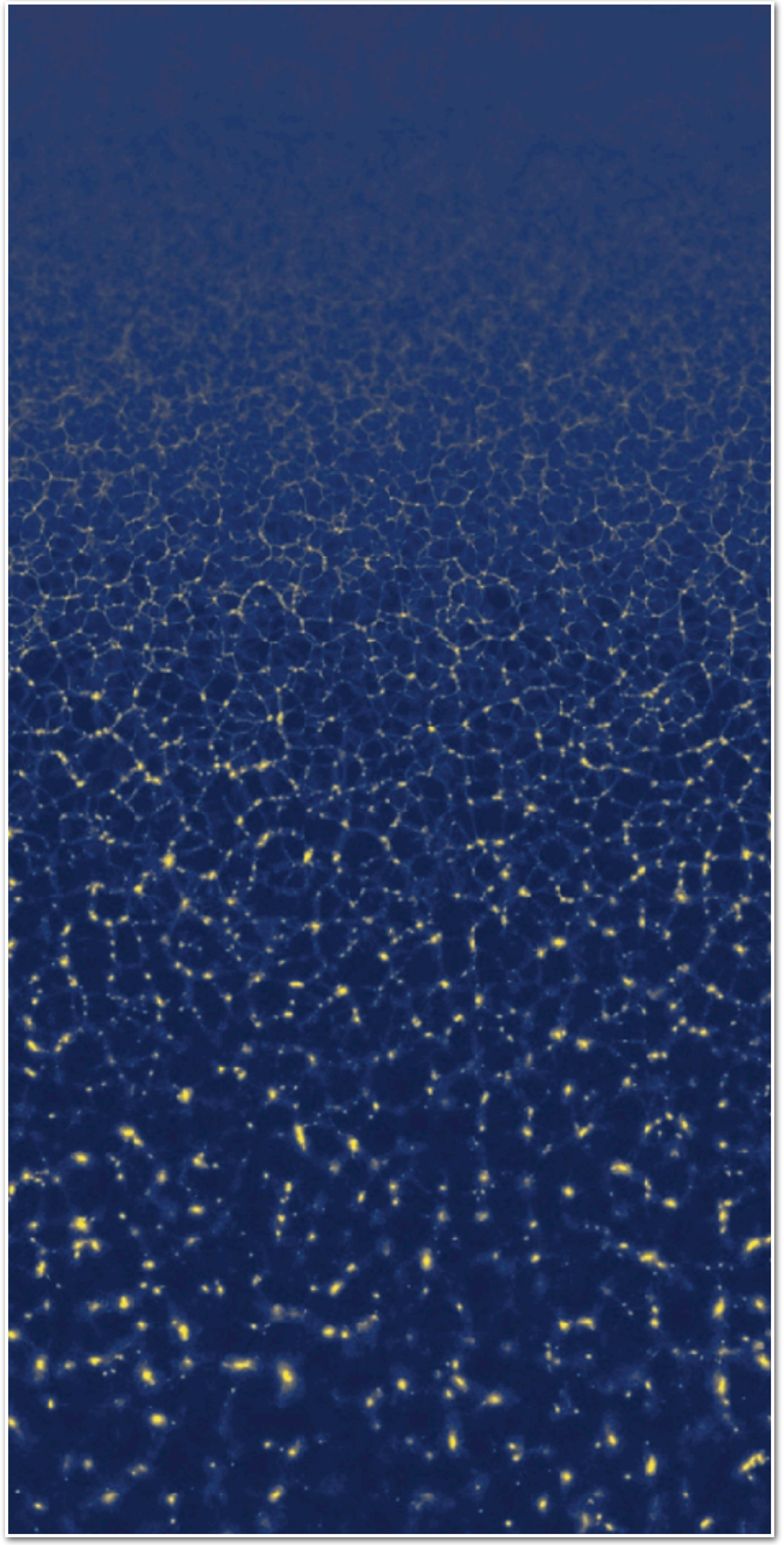
Primordial structure formation & baryogenesis



$$\eta_B \sim f \frac{n_B}{T_{\rm bg}^3}$$

Final thoughts

- Primordial structure formation *can occur* and has many interesting phenomenological implications
    - Primordial black holes
    - Matter-antimatter asymmetry
    - Generation of DM
    - Gravitational waves
- PBHs are a compelling DM candidate with numerous interesting astrophysical and cosmological implications
- Other interests:
    - Gravitational particle production and baryogengesis
        - [**MMF**, Y. Perez-Gonzalez, arXiv:2404.06530]
    - Unitarity & cosmology
        - [**MMF**, K. Petraki, arXiv:2405.02222]
    - Gravitational waves
        - [**MMF**, A. Kusenko, L. Pearce, Y. F. Perez-Gonzales, G. White: arXiv: 2308.15522]



Thank you!