Primordial black holes and gravitational waves from long-range scalar forces

IRN - Terascale

Marcos M. Flores — 27, Oct., 2023

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DE L'ÉCOLE NORMALE SUPÉRIEURE

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: arXiv:2308.09094]

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)]

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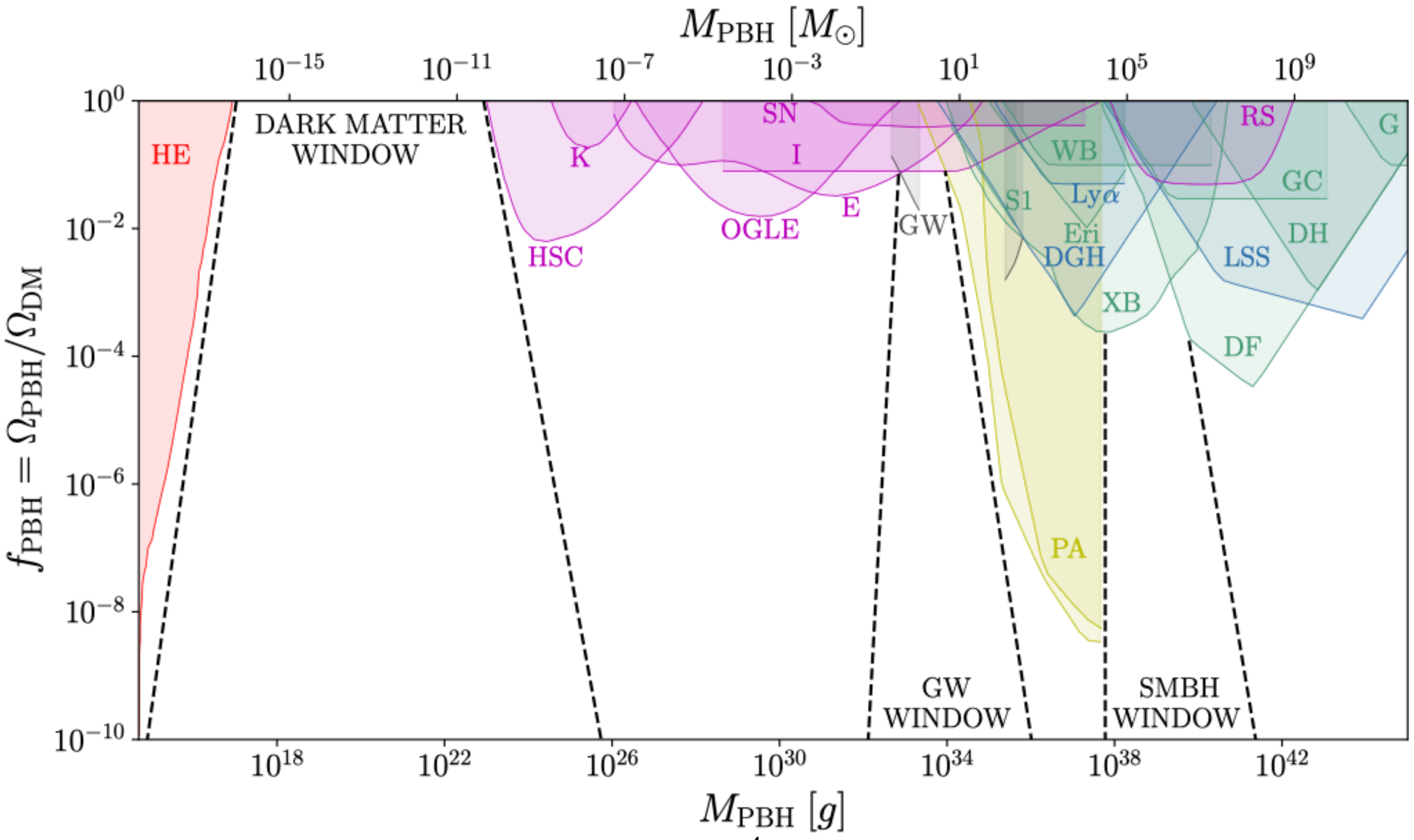
- Can account for some or all of ***dark matter***
- Astrophysical implications:
    - Can account for some LIGO events
    - Can seed supermassive black holes
    - Can account for all or part of *r*-process nucleosynthesis
    - G objects (discussed later)
    - Many more!

Primordial black holes: An overview



[Carr et. al 2020]

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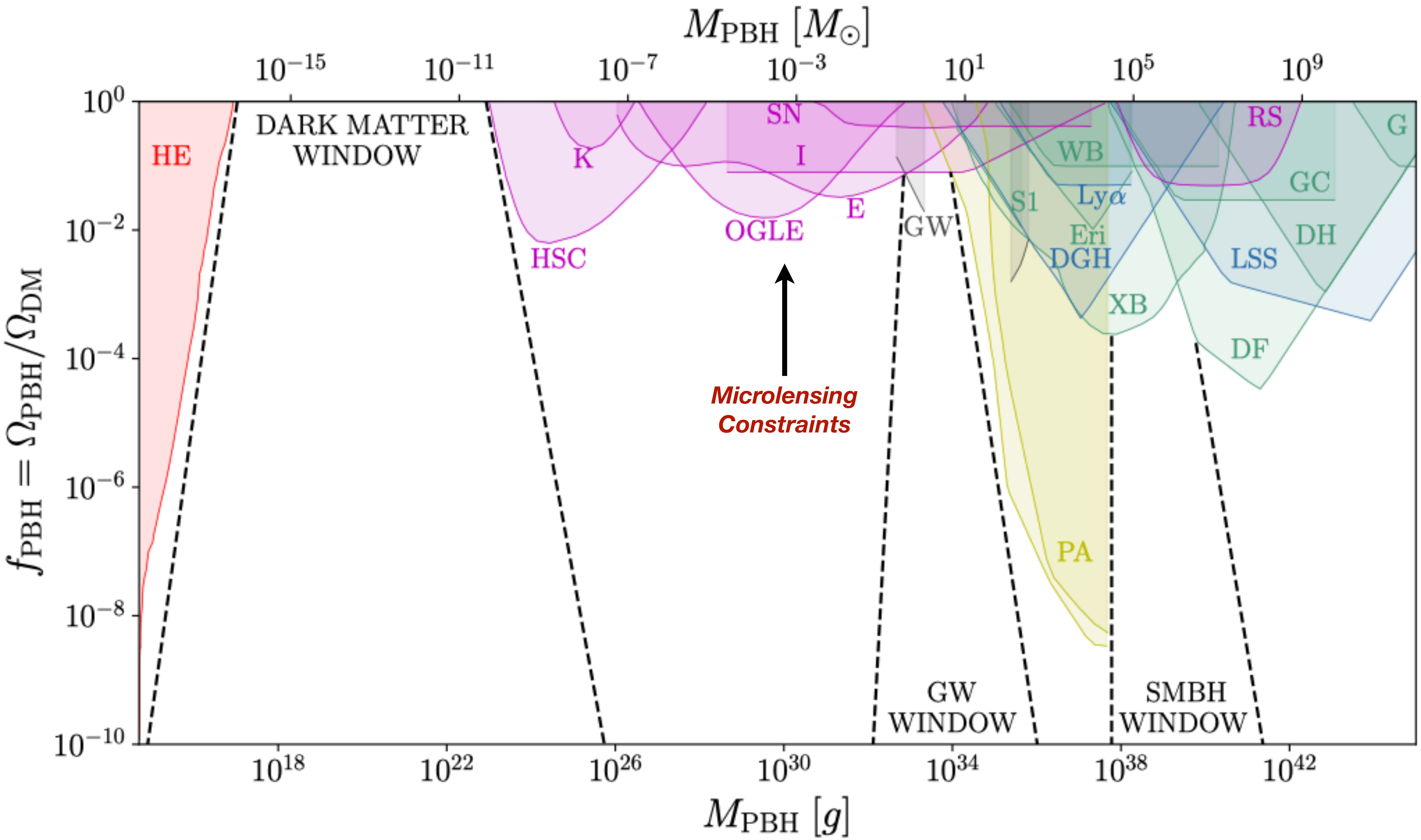
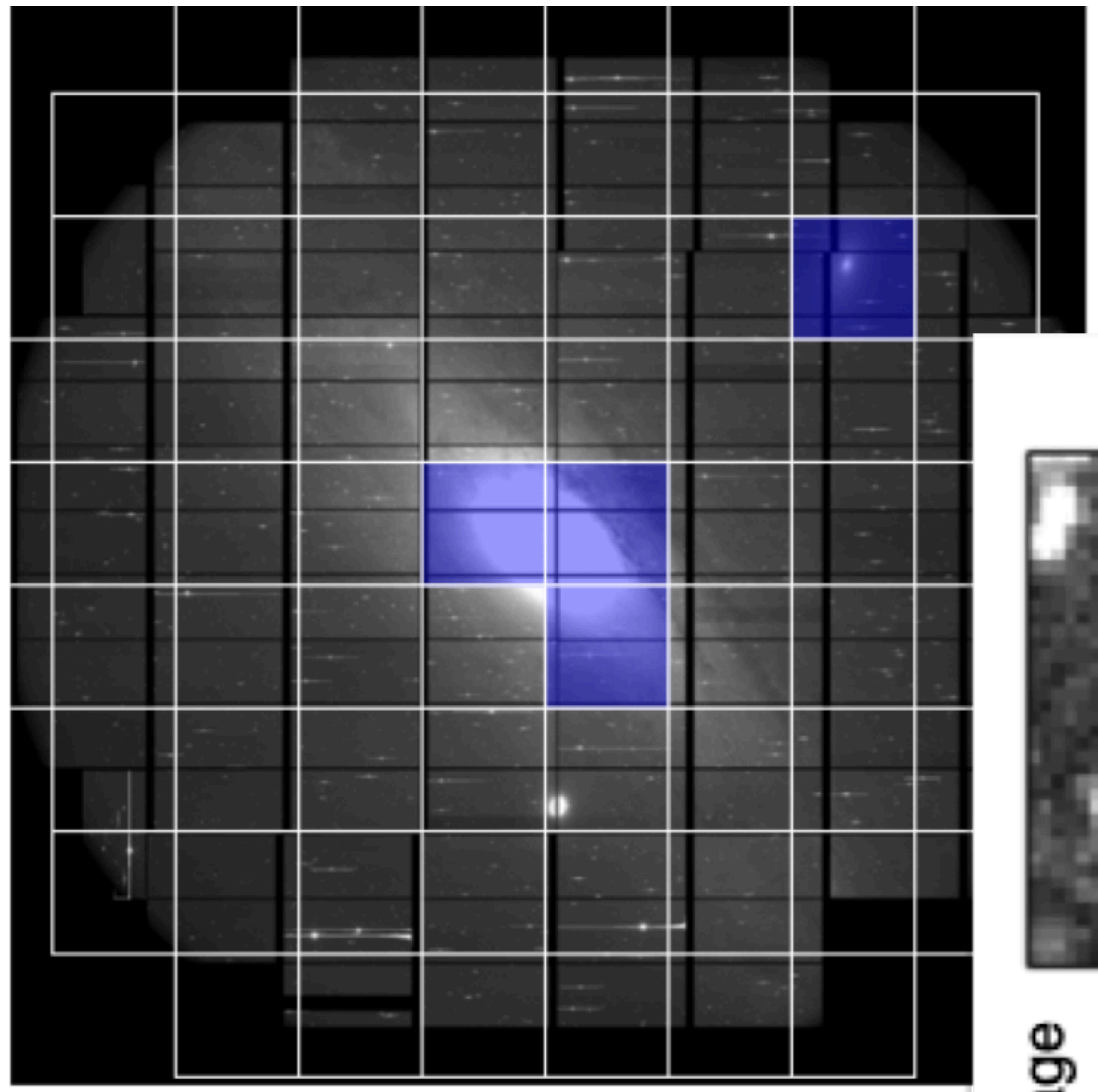


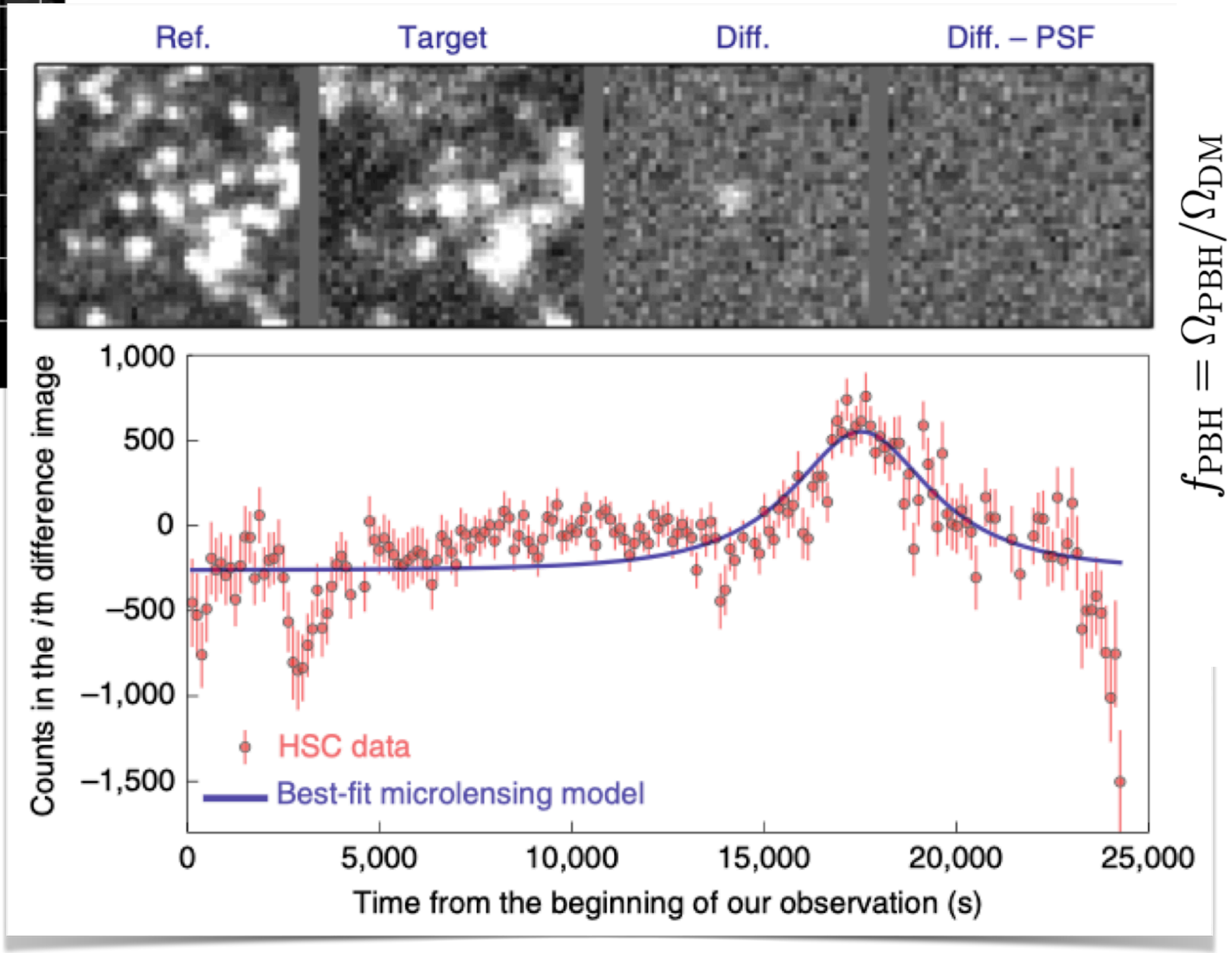
[Carr et. al 2020]

Primordial black holes: Candidate Events

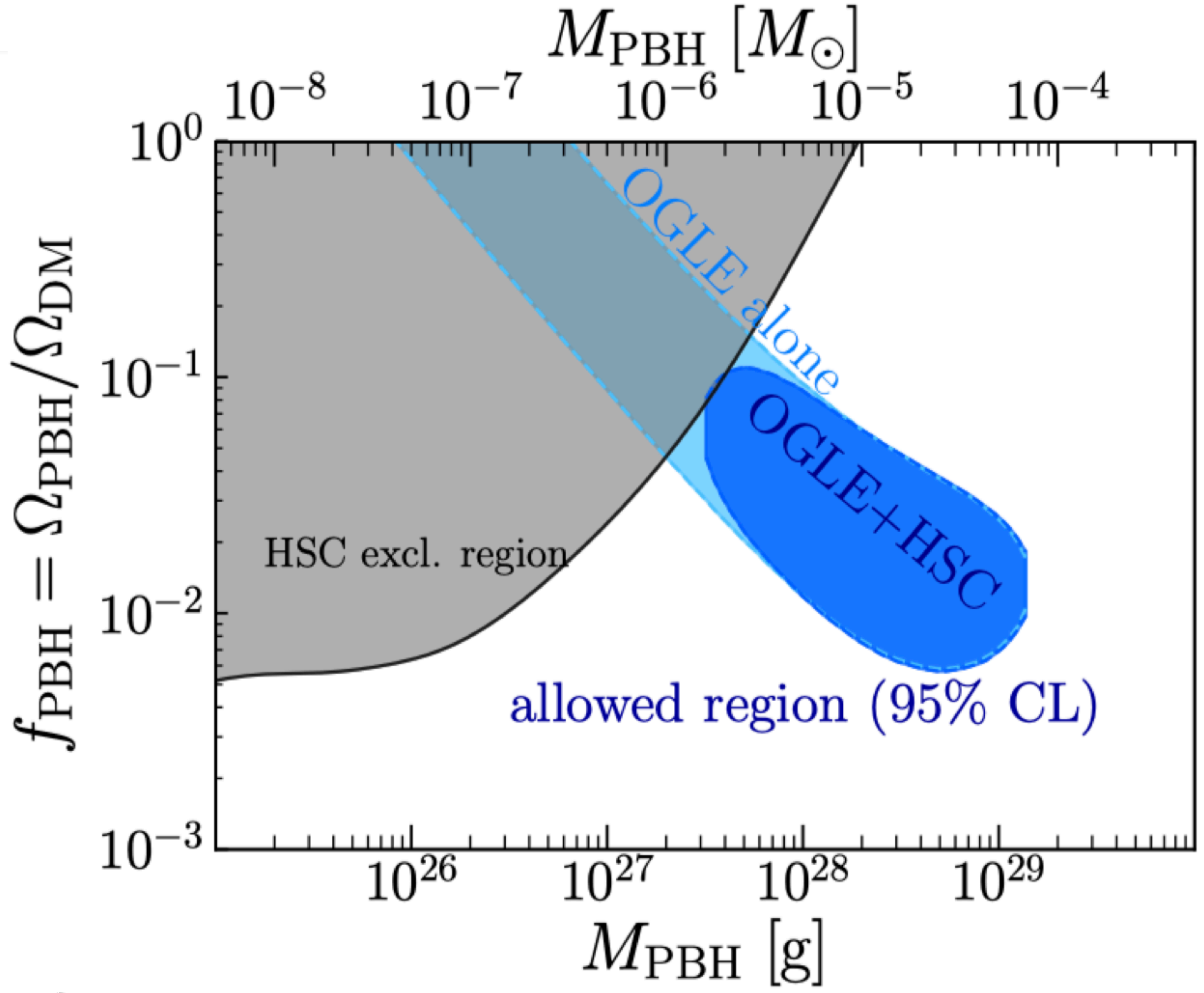


M31

HSC Candidate Event



OGLE Events



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

Primordial black holes: Formation

Formation Mechanism	**Mass Range**
Inflationary Perturbations [A. Green review: arXiv:2007.10722]	DM, LIGO, supermassive
SUSY flat directions, Q-balls & IMD [1612.02529, 1706.09003, 1907.10613]	DM
Light scalar Q-balls (not SUSY) [1612.02529, 1706.09003, 1907.10613]	DM, LIGO, supermassive
First order phase transitions See talk by Iason Baldes, [2106.05637, 2212.14037, 2307.11639]	DM, LIGO, supermassive
Multiverse bubbles [1512.01819, 1710.02865, 2001.09160]	DM, LIGO, supermassive
Primordial structure formation and collapse [**MMF**, A. Kusenko: PRL 126 (2021) 4, 041101] [**MMF**, A. Kusenko: *JCAP* 05 (2023) 013] [**MMF**, Y. Lu, A. Kusenko: arXiv:2308.09094]	DM, LIGO, supermassive

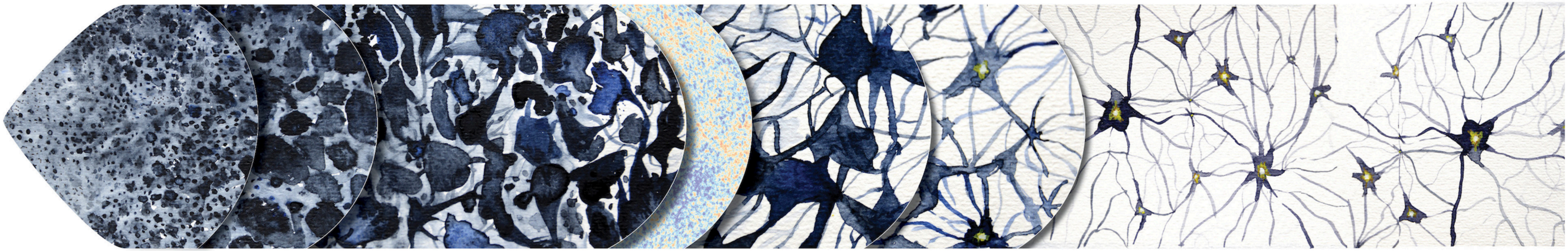
Goal of PBH Model Building

$$f_{\rm PBH} = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} \quad \& \quad M_{\rm PBH}$$

The paradigm of ***primordial*** structure formation

Cosmological timeline

Beginning of the Universe



10^{-32} seconds — **Inflation**
Accelerated expansion of the Universe

1 second — **Formation of light and matter**

100 seconds — **Light and matter are coupled**
Dark matter evolves independently: it starts clumping and forming a web of structures

380 000 years — **Light and matter separate**
- Protons and electrons form atoms
- Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)

Dark ages
Atoms start feeling the gravity of the cosmic web of dark matter

300–500 million years — **First stars**
The first stars and galaxies form in the densest knots of the cosmic web

Billions of years — **Galaxy evolution**

13.8 billion years — **The present Universe**

[Credit: European Space Agency]

Cosmological timeline

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Conventional structure formation: Basics

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

$$\Downarrow$$

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

$$\Downarrow$$

System of Coupled Differential Equations

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

Conventional structure formation by example

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

↓

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

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$$\downarrow$$

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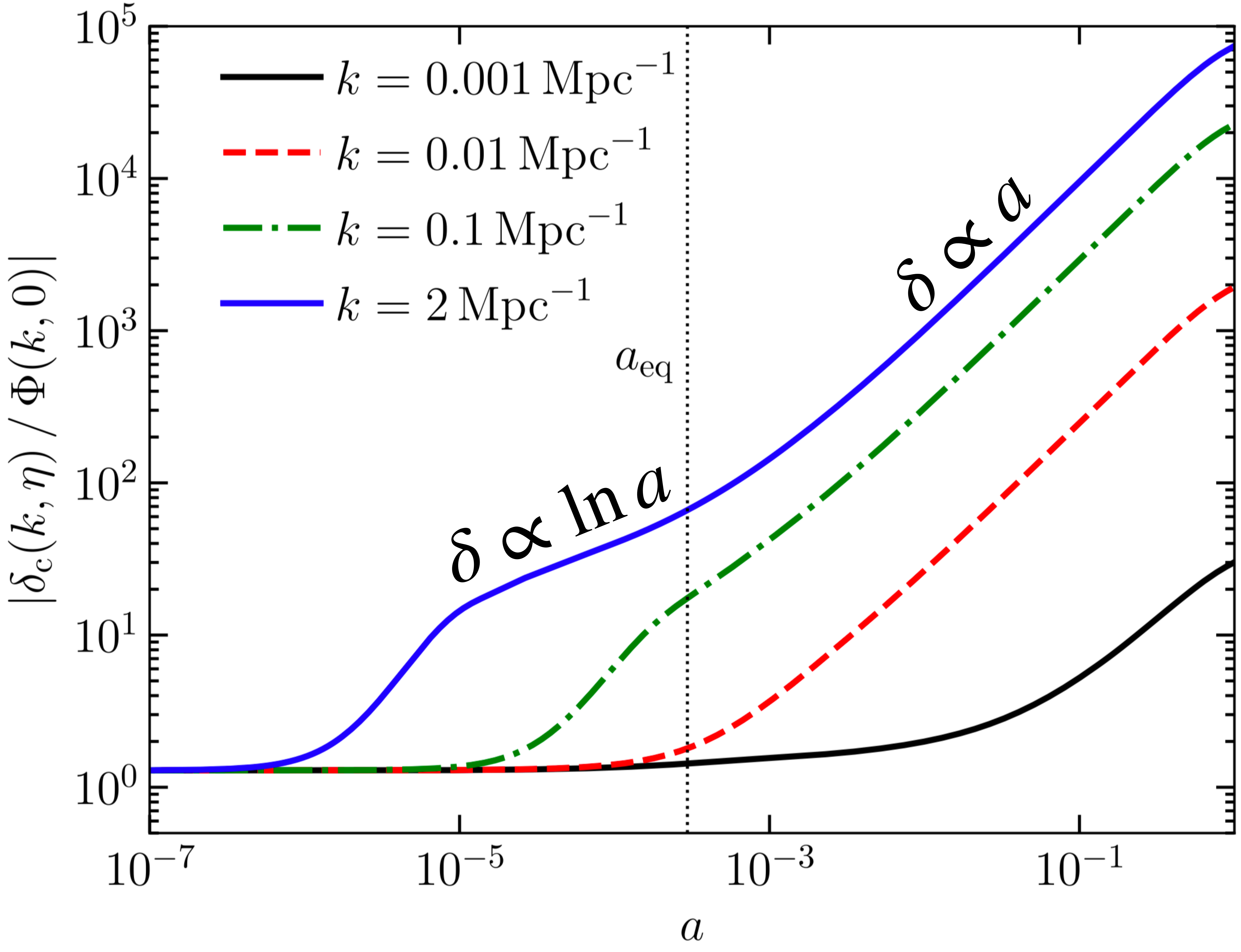
Conclusion:* *Matter perturbations only grow logarithmically during a radiation dominated era

Conventional structure formation by example



[Credit: Dodelson, Modern Comology]

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

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

Initial conditions for primordial structure formation

- Before the formation of structure can occur, we require:
  - $\bar{\psi}\psi \leftrightarrow \chi\chi$ interactions to freeze-out
  - ψ particles become non-relativistic
  - χ-radiation pressure is negligible.
- Our calculations occur in the region of parameter space where the average distance between particles remains larger than m_ψ^{-1}.
- We anticipate that early structure formation begins when $T \sim m_\psi$

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]

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

Numerical simulations

[G. Domènech et. al., arXiv:2304.13053]

Growth of perturbations

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

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

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

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There are *four* possible dissipation channels:

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

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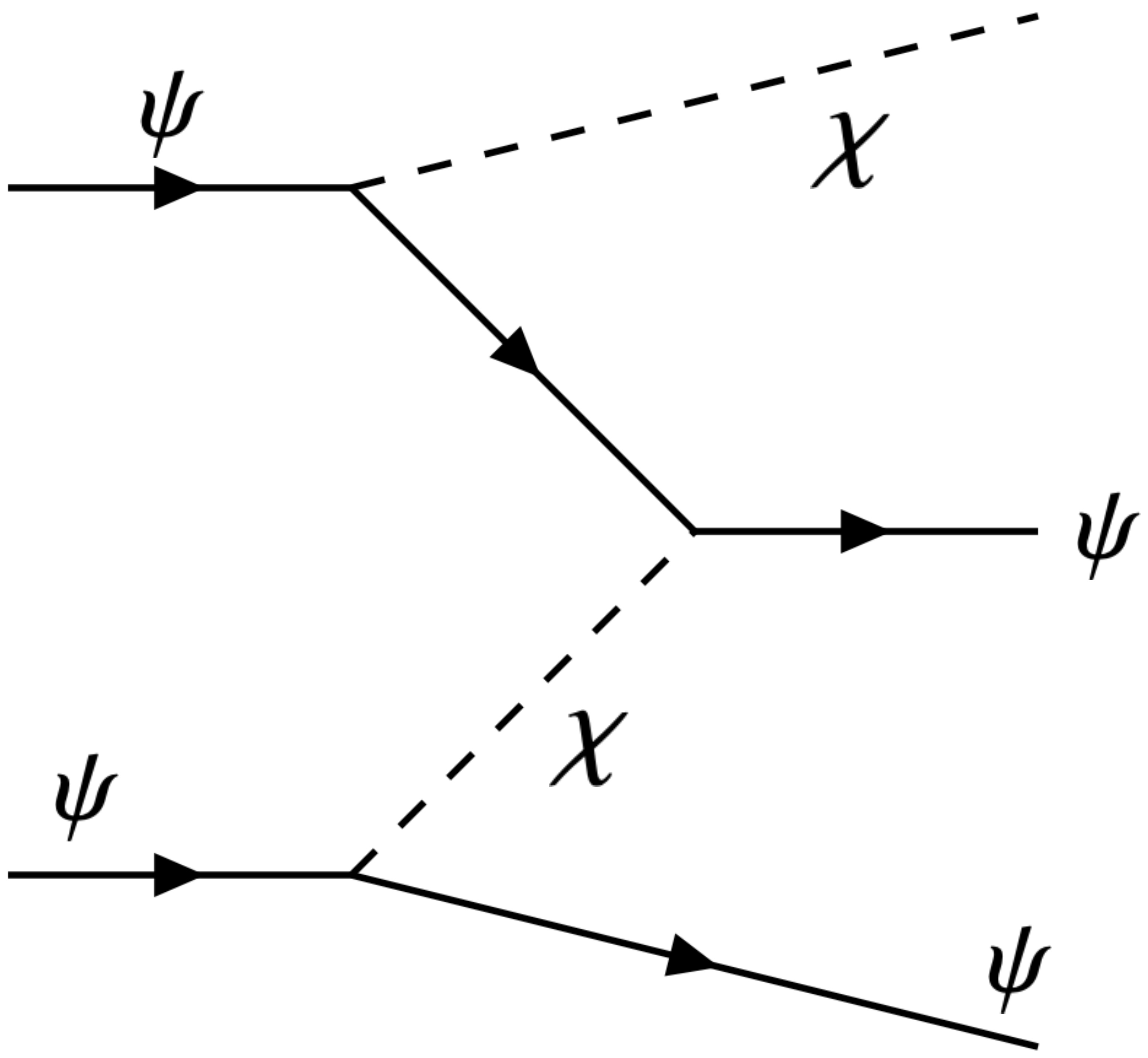

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Bremsstrahlung and surface radiation will be the most important channels for our discussion

Energy dissipation through scalar radiation

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

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

General algorithm for collapse:

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

PBH Formation: primordial structure formation

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

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:

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

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

PBH Mass Distribution

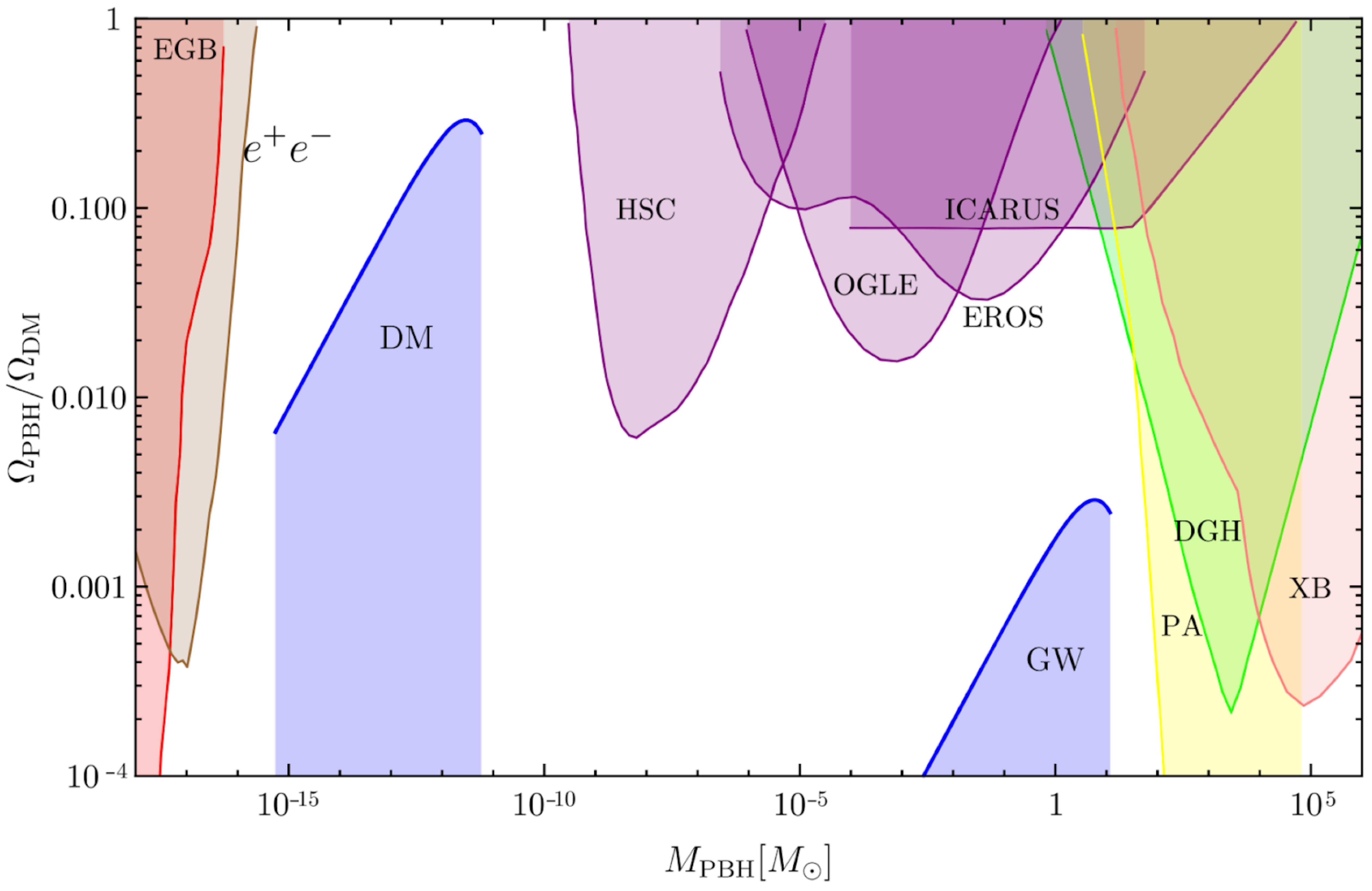
- Again, the strength of the scalar interaction will lead to rapid PBH formation. Thus, we expect the mass function of PBHs to represent the structure of the ψ - fluid at the time of formation.
- We need N-body simulations to accurately describe the details of ψ - structure formation.
- In the absence 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:

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



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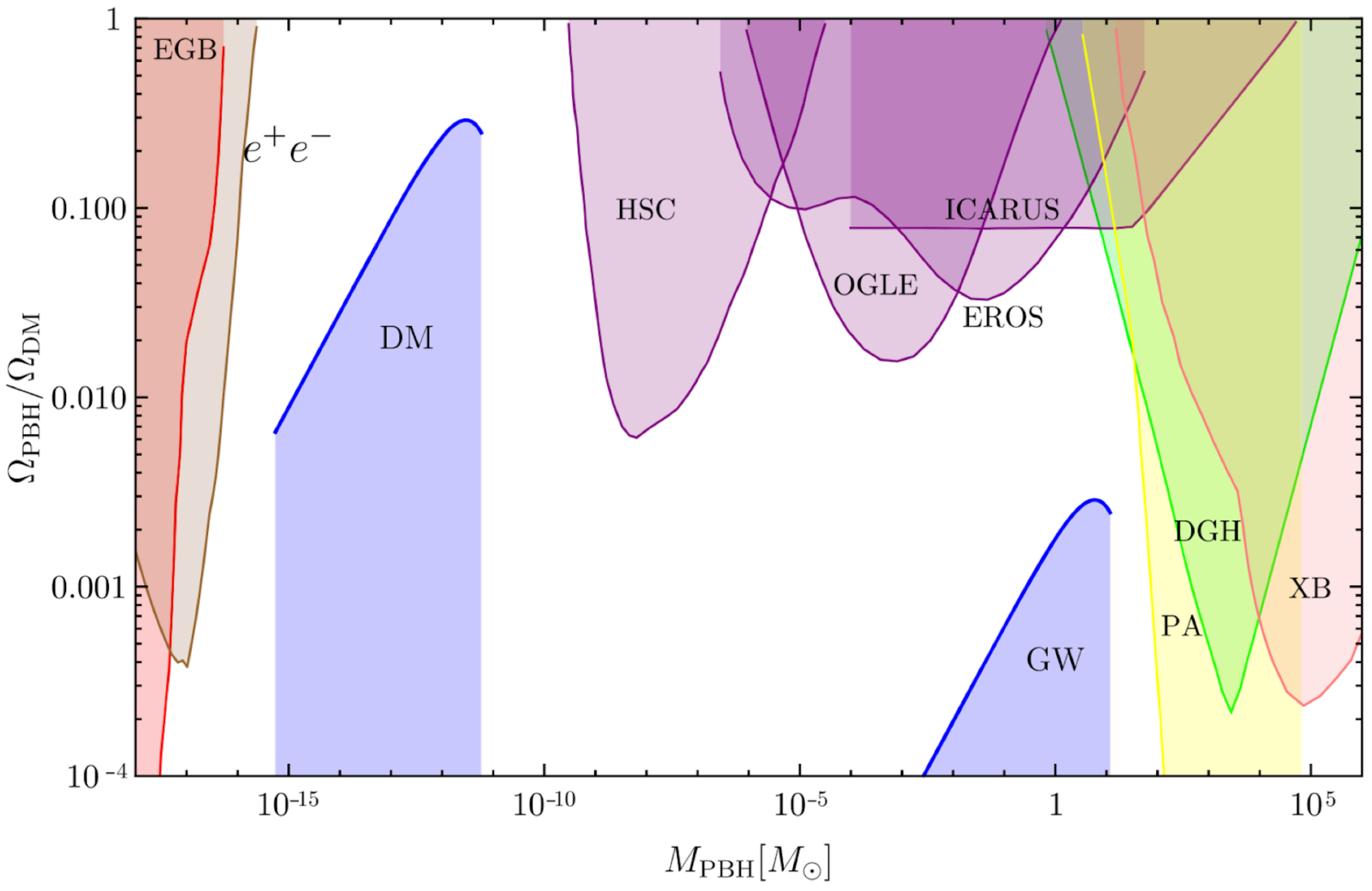
- Relevant to LIGO

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

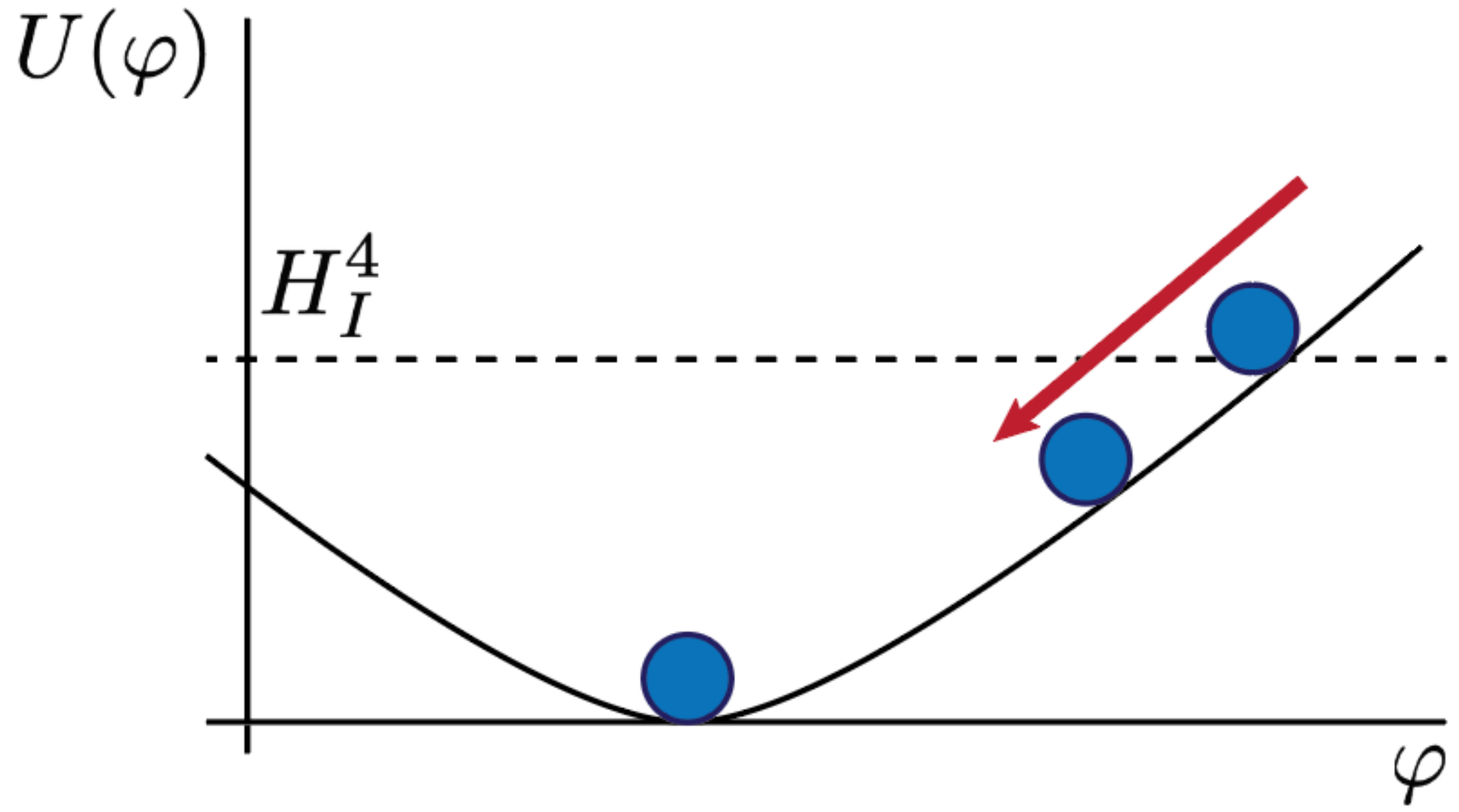


Primordial black holes, scalar forces & supersymmetry

[**MMF**, A. Kusenko: *JCAP* 05 (2023) 013]
[**MMF**, A. Kusenko, L. Pearce, Y. F. Perez-Gonzales, G. White: arXiv: 2308.15522]

PBHs from Scalar Forces & SUSY Q-balls

- Utilize well understood dynamics of scalar fields in early Universe
  - The initial conditions of this scenario are *very similar* to Affleck-Dine baryogenesis. See [M. Dine, A. Kusenko hep-ph/0303065]
  - Scalar fields are generic inclusion if BSM physics
  - In particular, supersymmetry — contains many scalar fields with 100+ flat directions [Gherghetta et. al '95] which are *lifted* by SUSY breaking terms



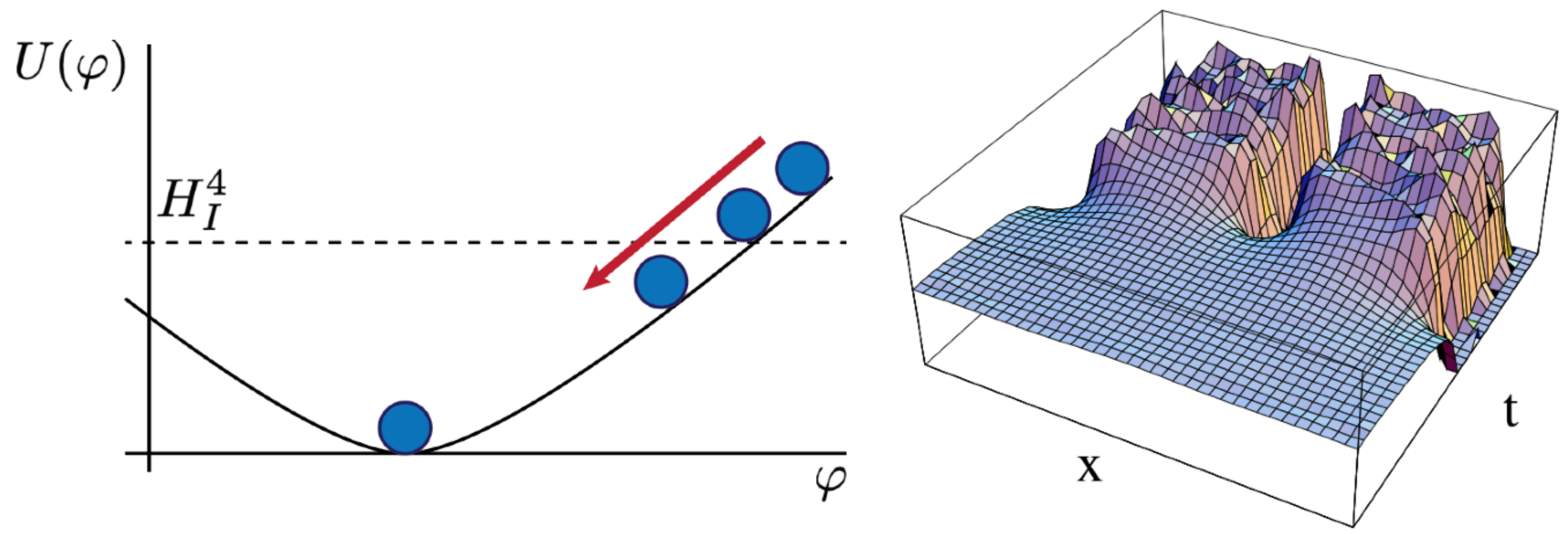
Key: Scalar fields acquire a VEV in de Sitter space during inflation

From inflation to Q-balls

$$U(\langle\varphi\rangle) \sim H_I^4$$

Inflation
&
Development of Large VEV

→



Sliding Down the Potential
&
Scalar Fragmentation

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$$M_Q = \Lambda Q^{3/4}$$
$$R_Q = Q^{1/4}/\Lambda$$

Q-ball Formation

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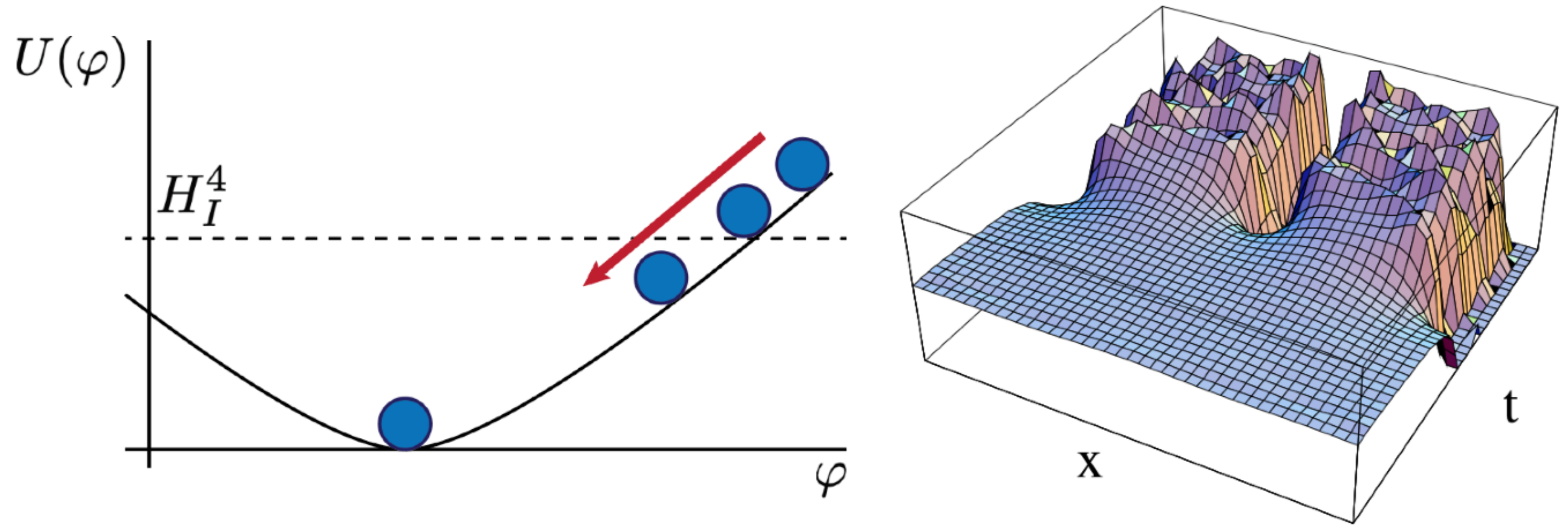

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Intermediate matter domination & gravitational forces *can* produce PBHs

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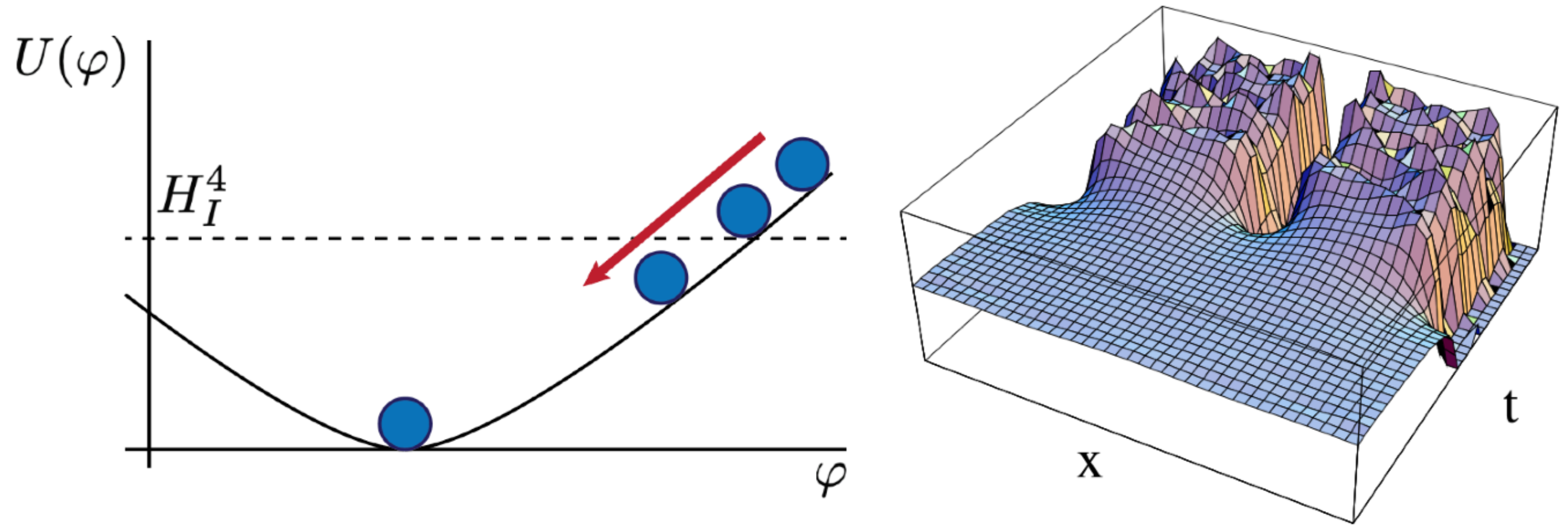

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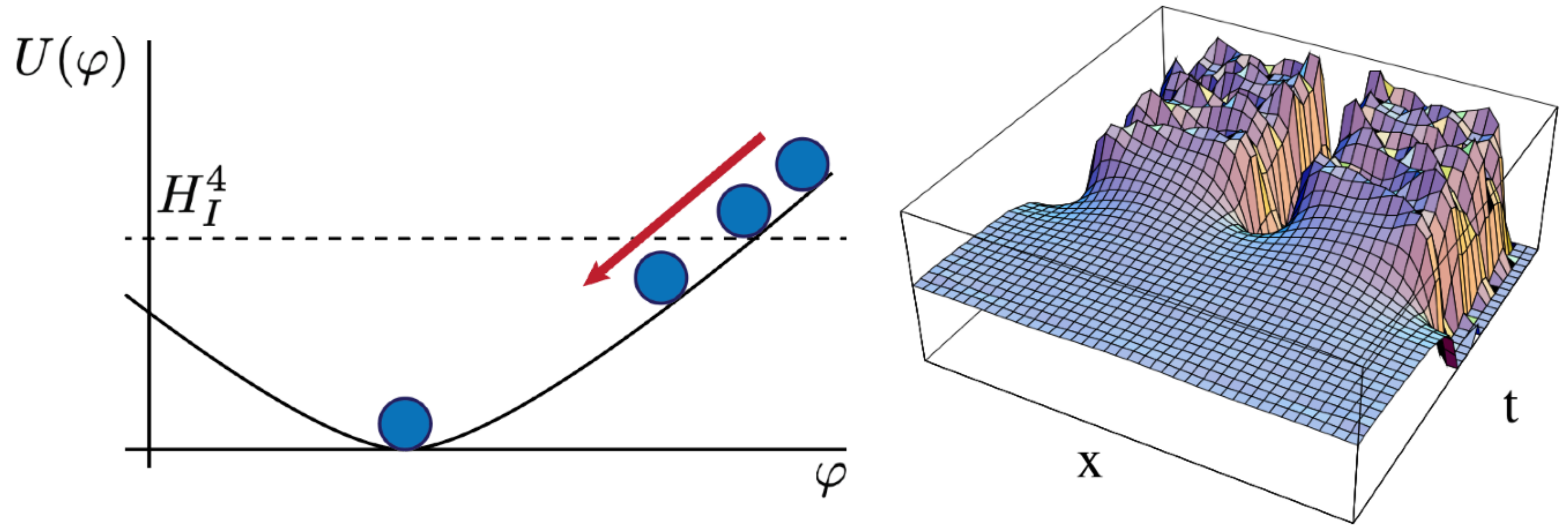

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Intermediate matter domination & gravitational forces *can* produce PBHs

$\implies$ *but* it's very inefficient
$\implies$ need special, spherical configurations

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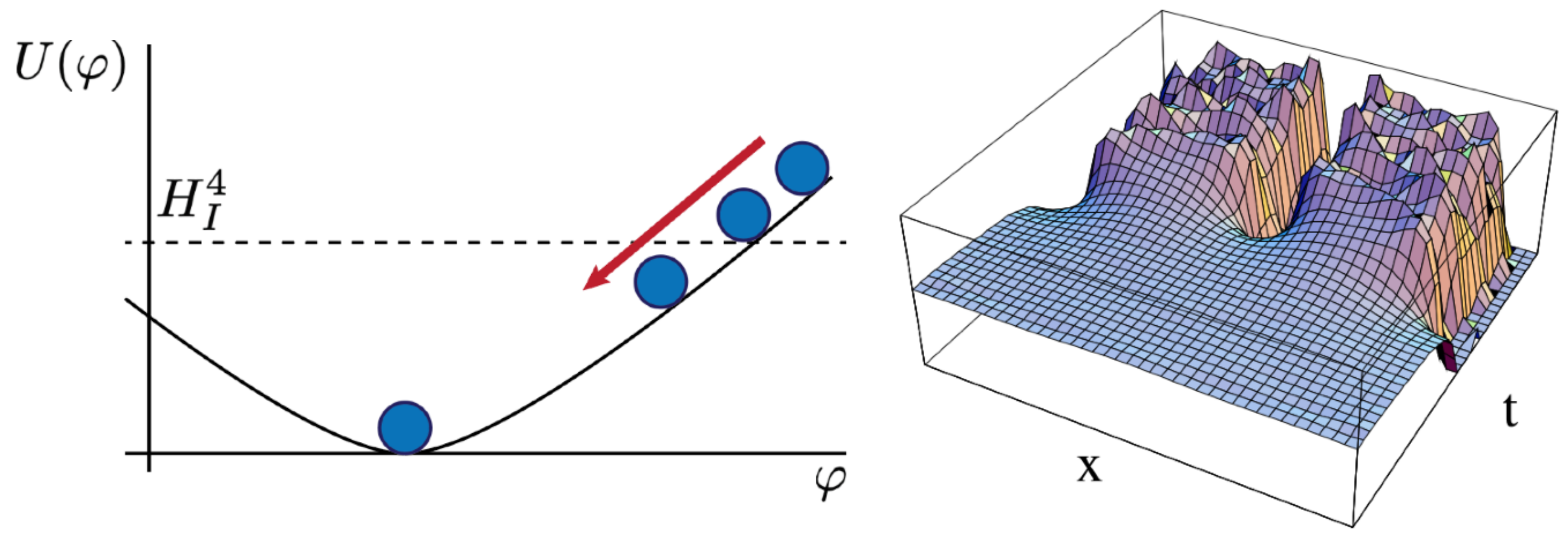

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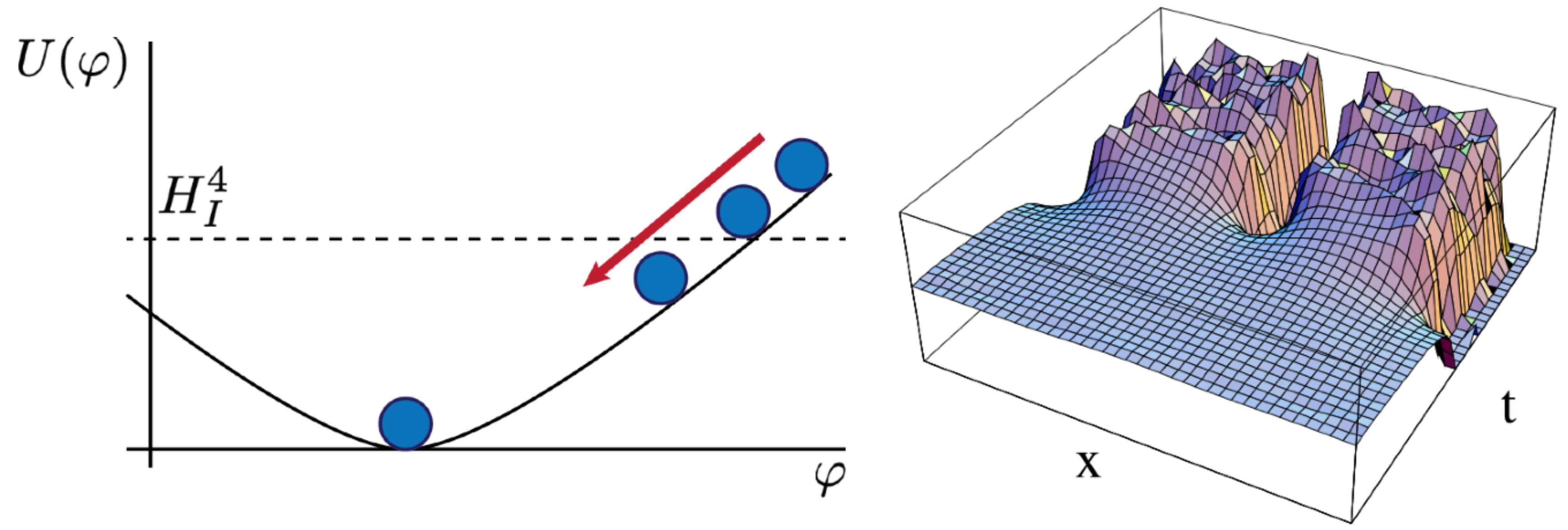

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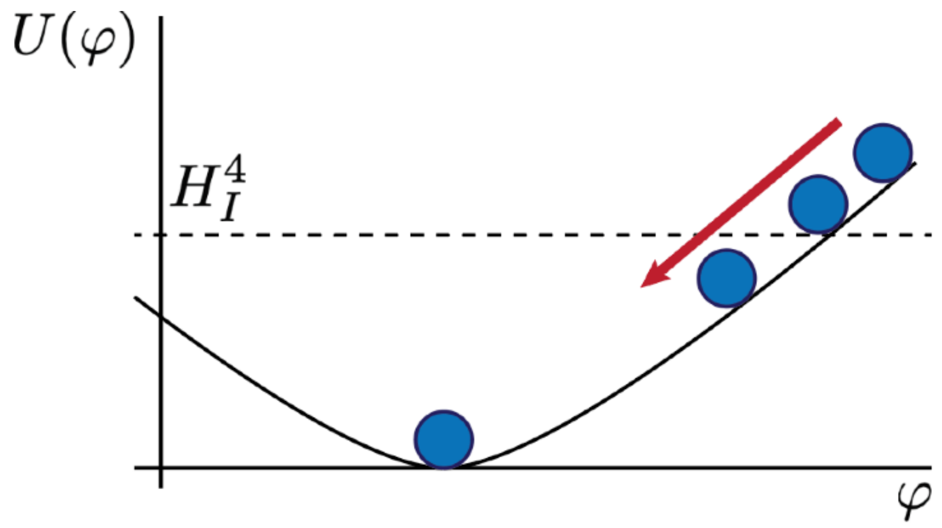

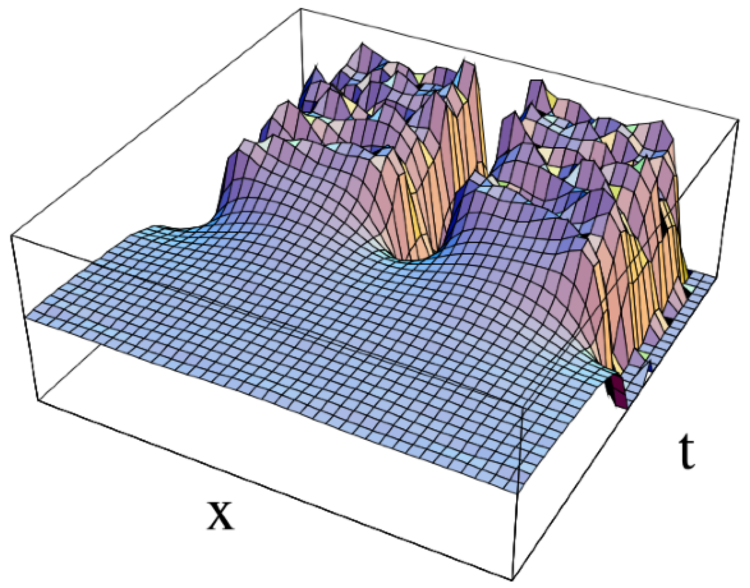

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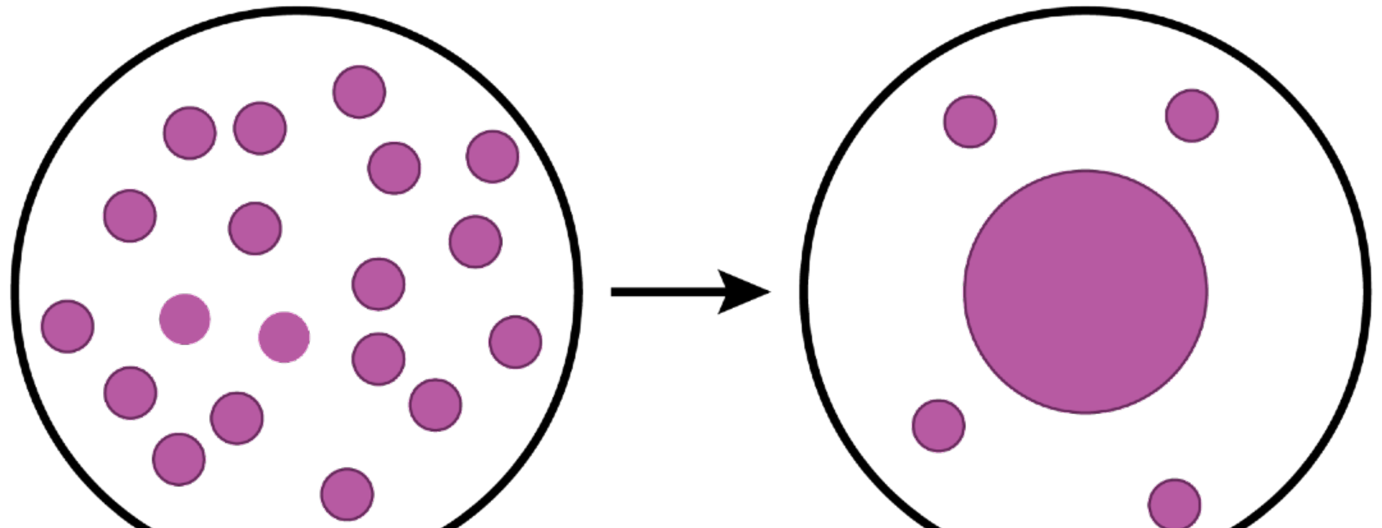
Mergers lead to
larger and larger charges



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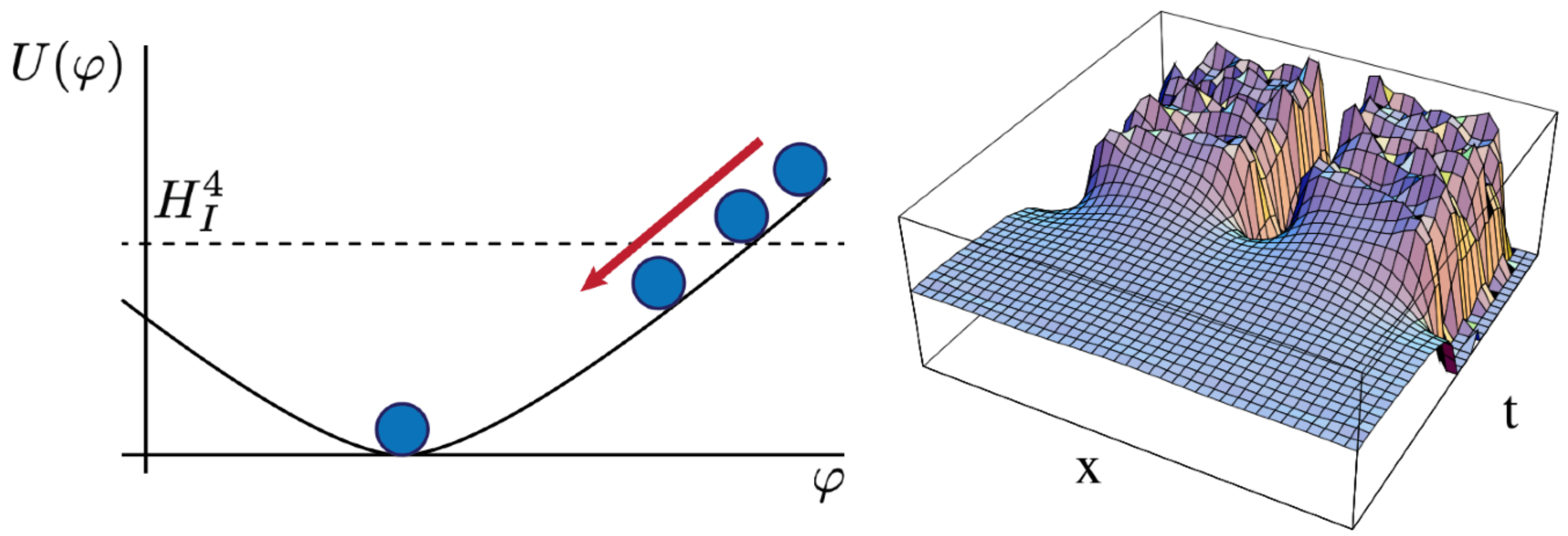

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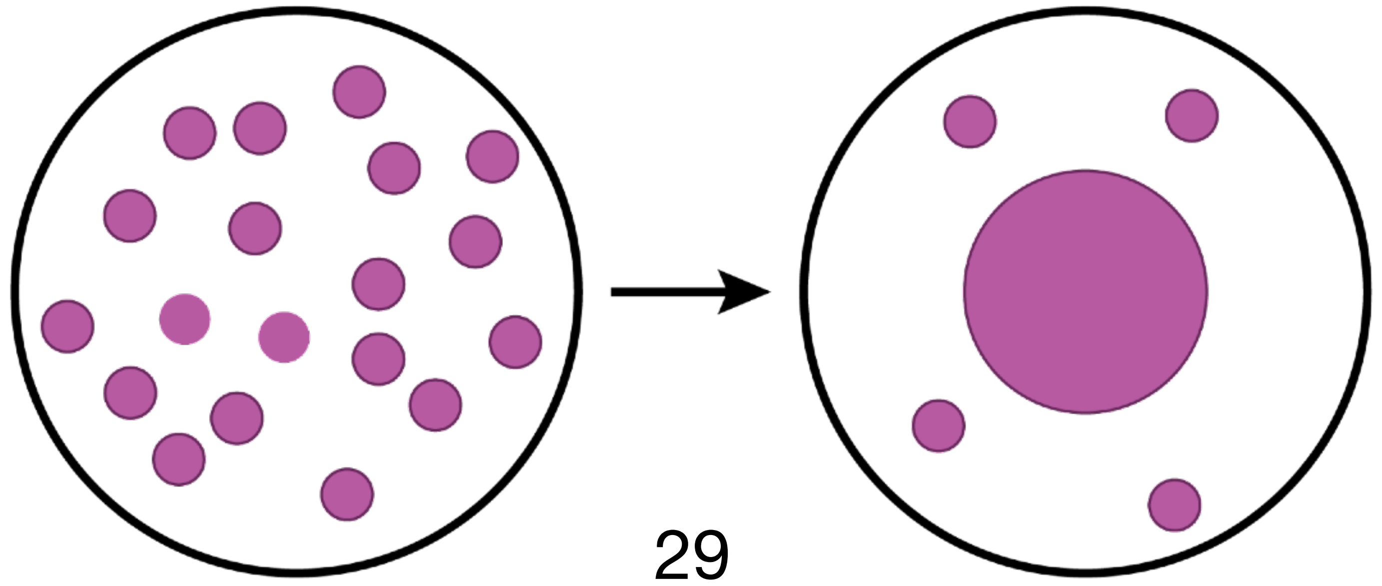

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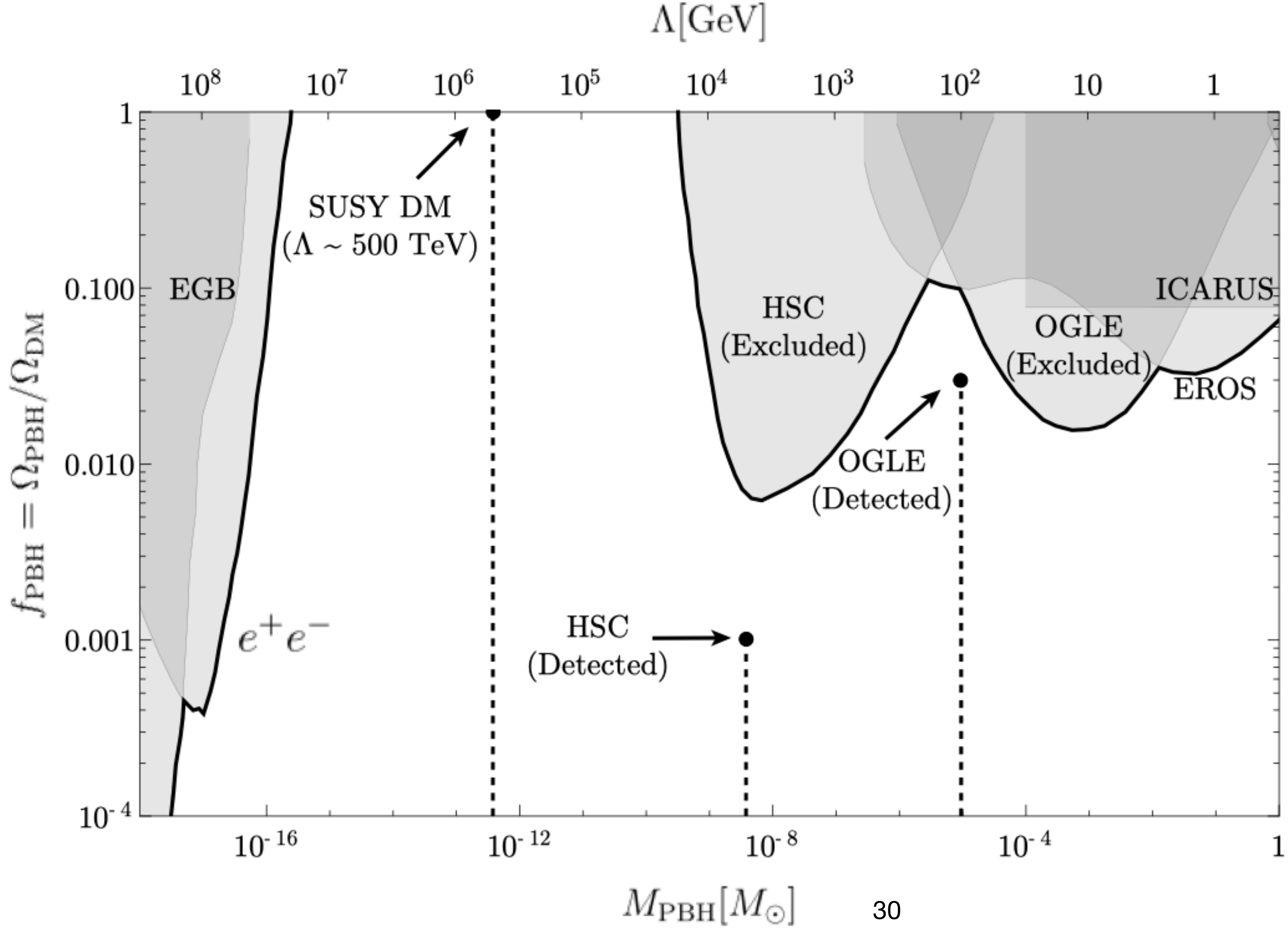
$$M_{\rm PBH} \sim 10^{22}\, g \left(\frac{100\ \text{TeV}}{\Lambda}\right)^2$$

PBHs from Scalar Forces & SUSY Q-balls



$$M_{\mathrm{PBH}} \sim 10^{22}\, g \left(\frac{100\ \mathrm{TeV}}{\Lambda}\right)^2$$

Observational Implications: 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***

See also:
I. Dalianis, C. Kouvaris [arXiv:2106.06023]

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

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  - Standard methods, like cosmological perturbation theory *do not* include forces which couple to charge/number density as a means of generating perturbations

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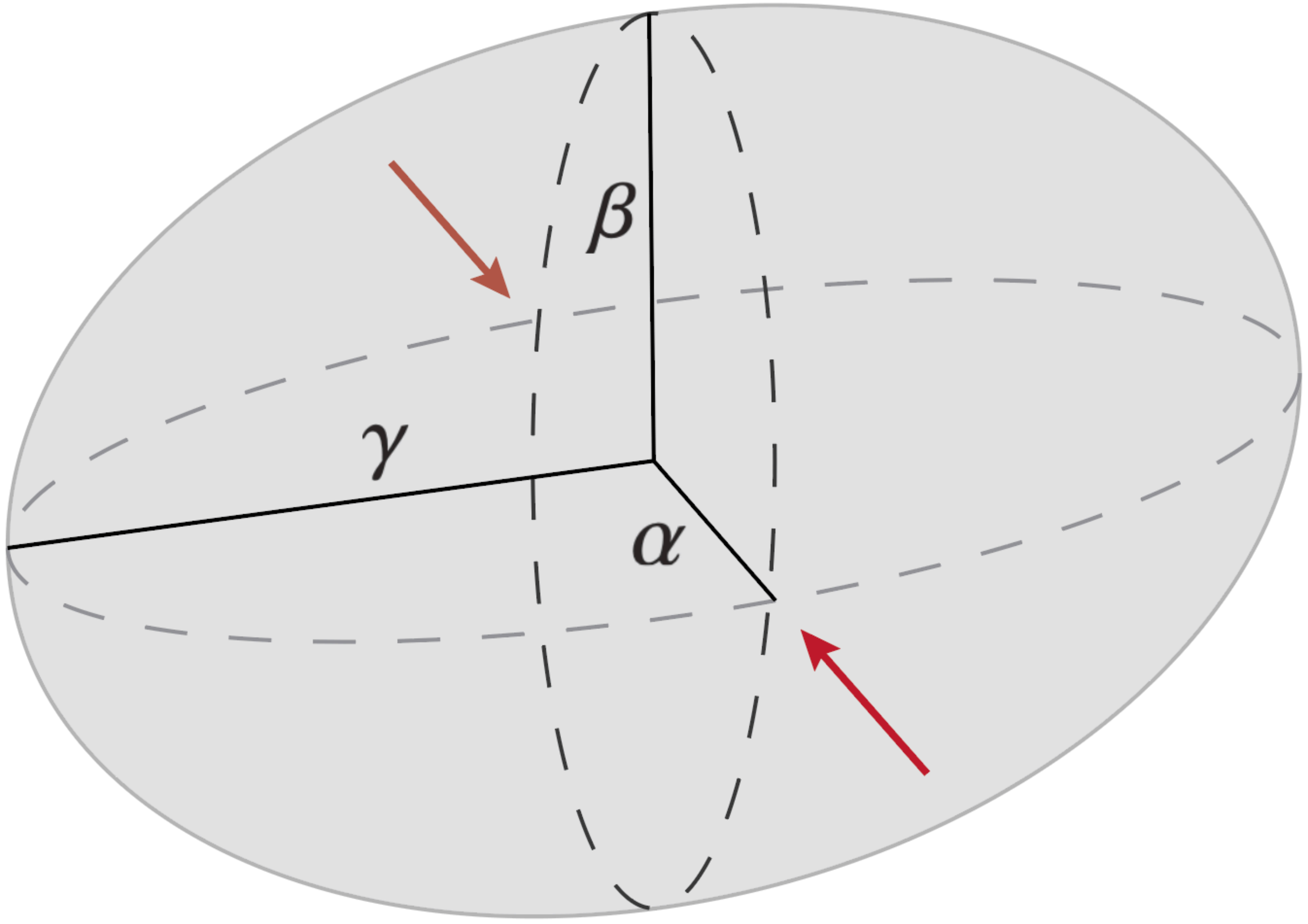
  - Standard methods, like cosmological perturbation theory *do not* include forces which couple to charge/number density as a means of generating perturbations
- We utilized the *Zel'dovich approximation* to directly determine the quadrupole moment, allowing for a calculation of the expected GW spectrum

See also:
I. Dalianis, C. Kouvaris [arXiv:2106.06023]

Zel’dovich Approximation

δ enters the horizon - t_q



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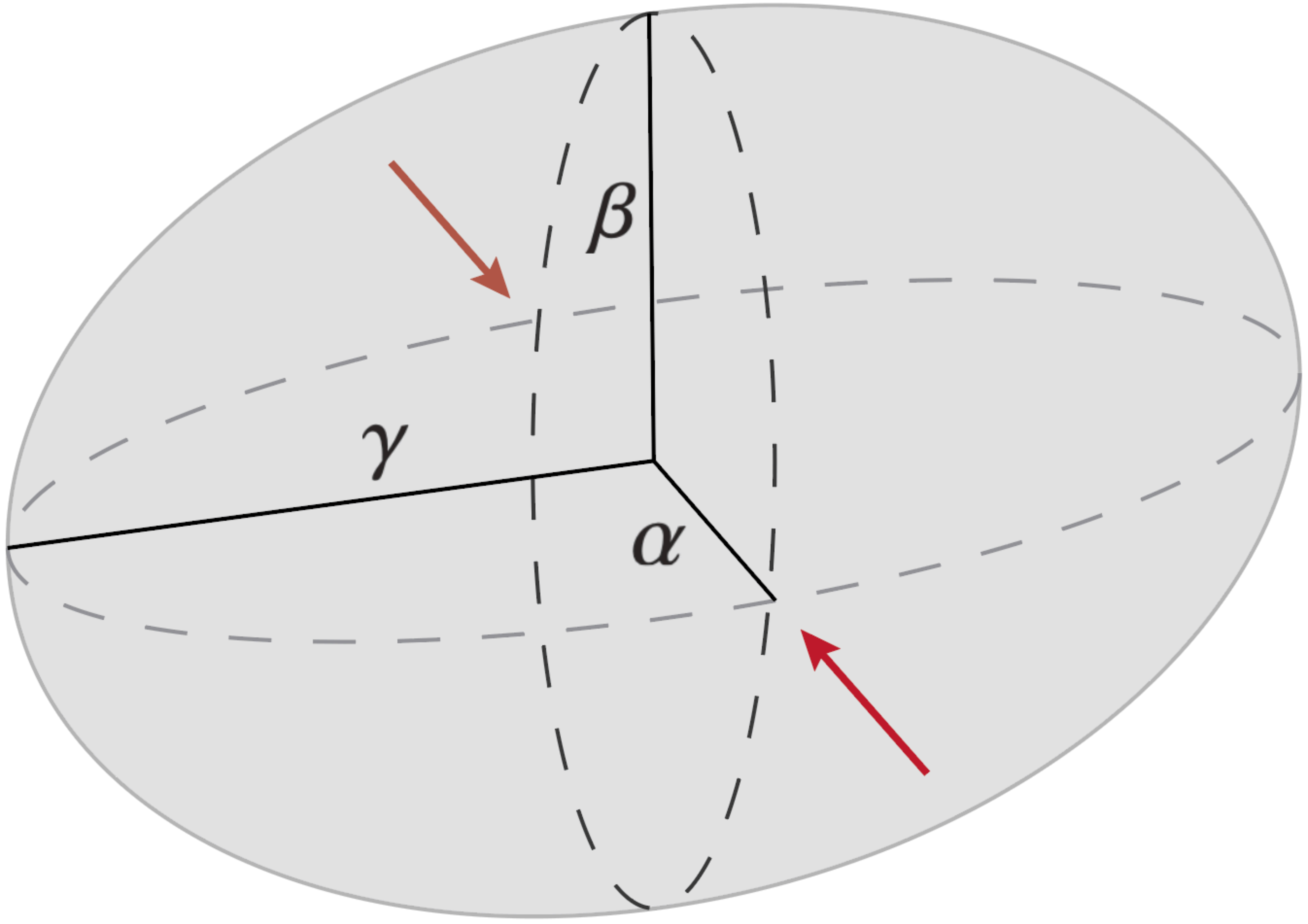
Zel’dovich Approximation

δ enters the horizon - t_q

$\Downarrow$

Overdensity increases to maximum size - t_{max}



See also:
I. Dalianis, C. Kouvaris [arXiv:2106.06023]

Zel'dovich Approximation

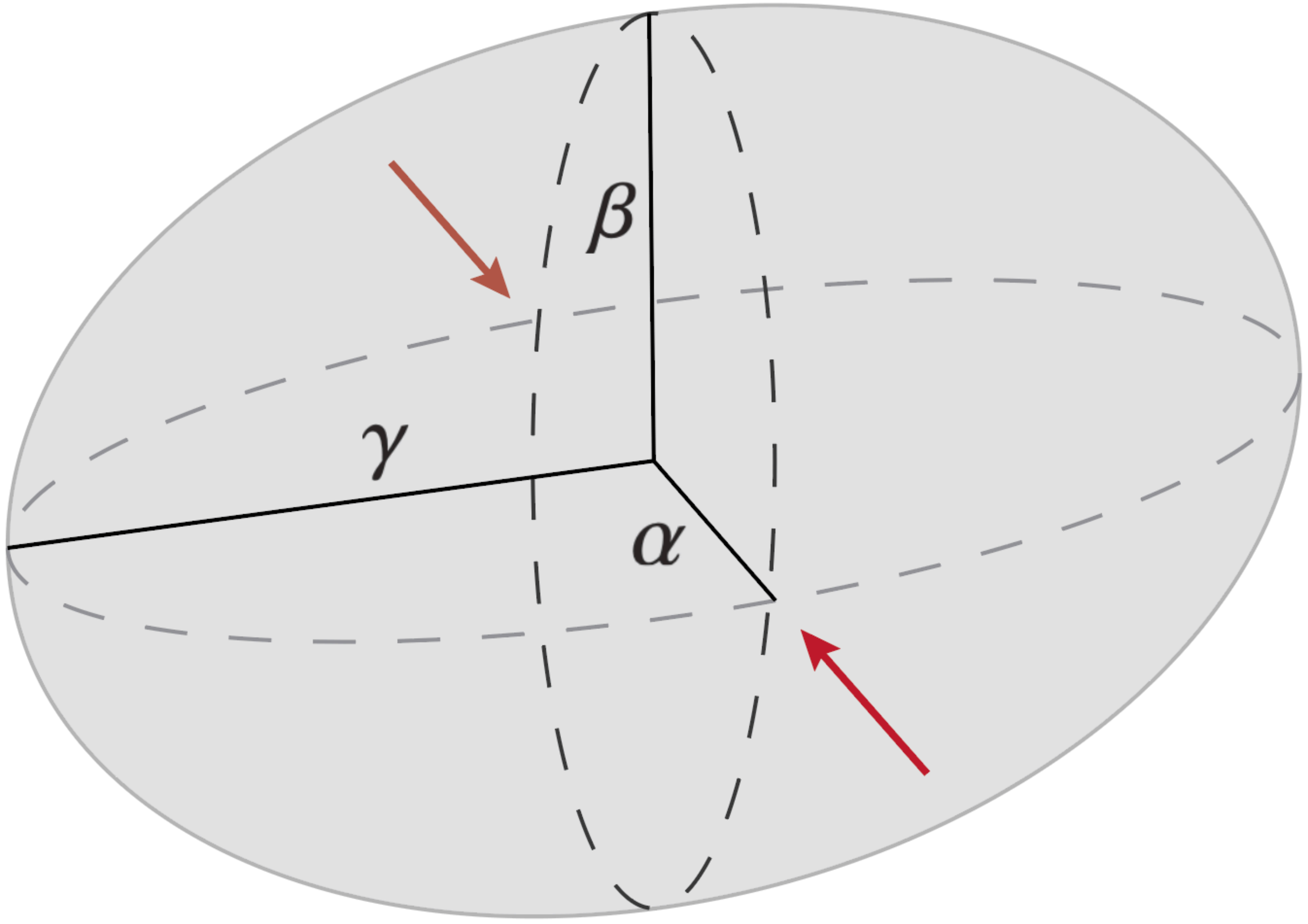
δ enters the horizon - t_q

$\Downarrow$

Overdensity increases to maximum size - t_{max}

$\Downarrow$

Collapse begins



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Zel'dovich Approximation

δ enters the horizon - t_q

$\Downarrow$

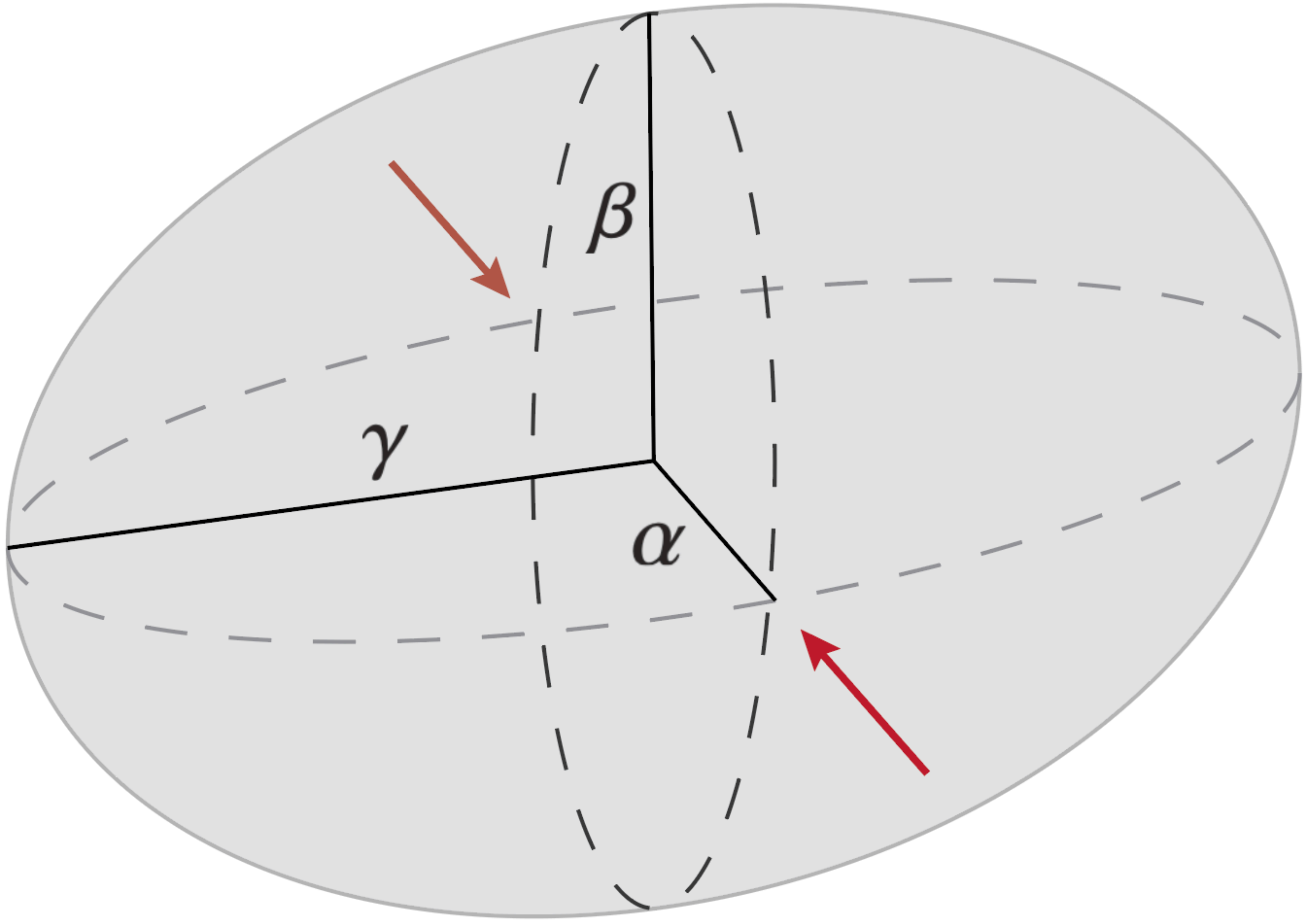
Overdensity increases to maximum size - t_{max}

$\Downarrow$

Collapse begins

$\Downarrow$

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



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Zel'dovich Approximation

δ enters the horizon - t_q

$\Downarrow$

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

$\Downarrow$

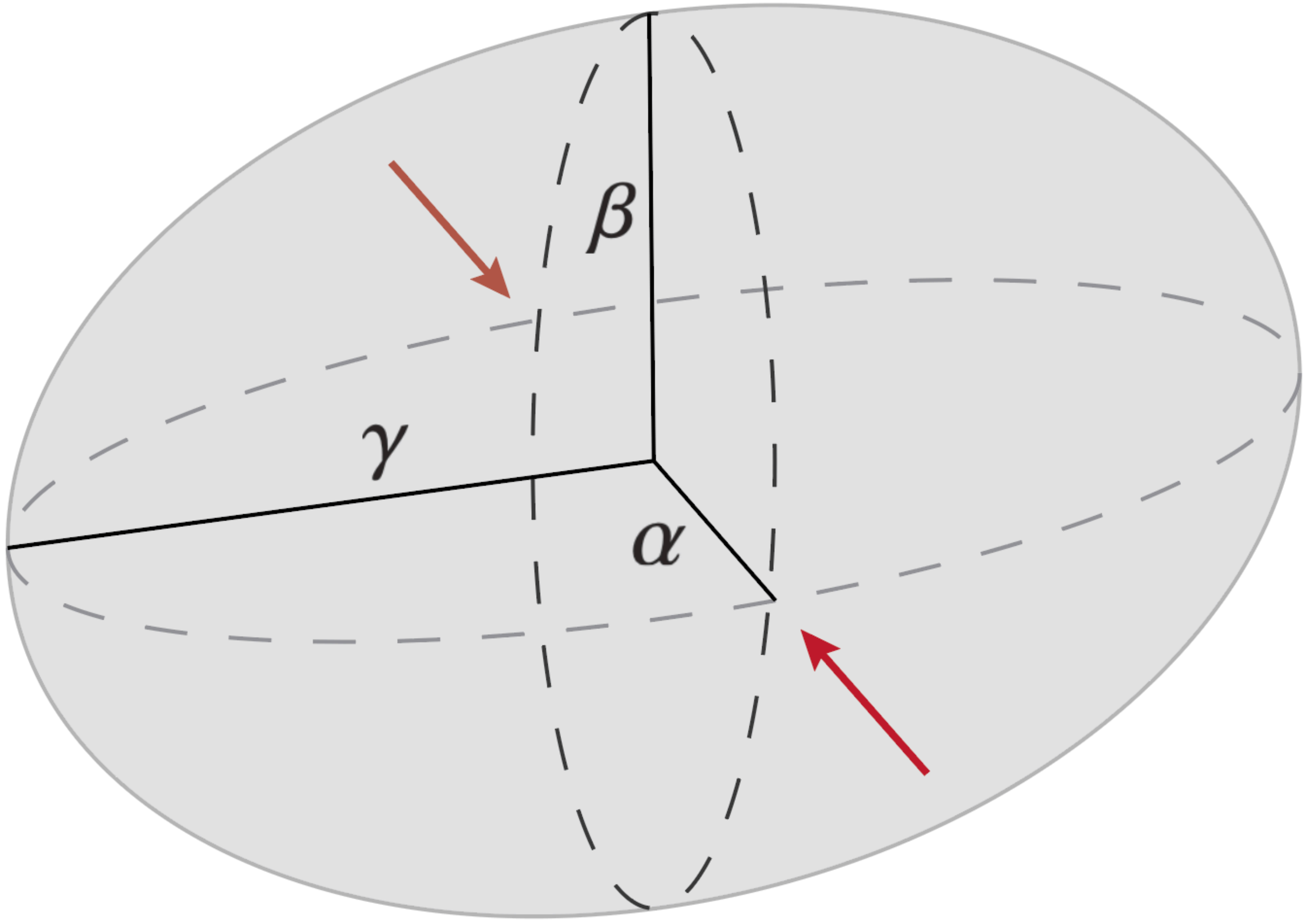
Collapse begins

$\Downarrow$

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

$\Downarrow$

BH formation or halo annihilation



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Zel'dovich Approximation

δ enters the horizon - t_q

$\Downarrow$

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

$\Downarrow$

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$\Downarrow$

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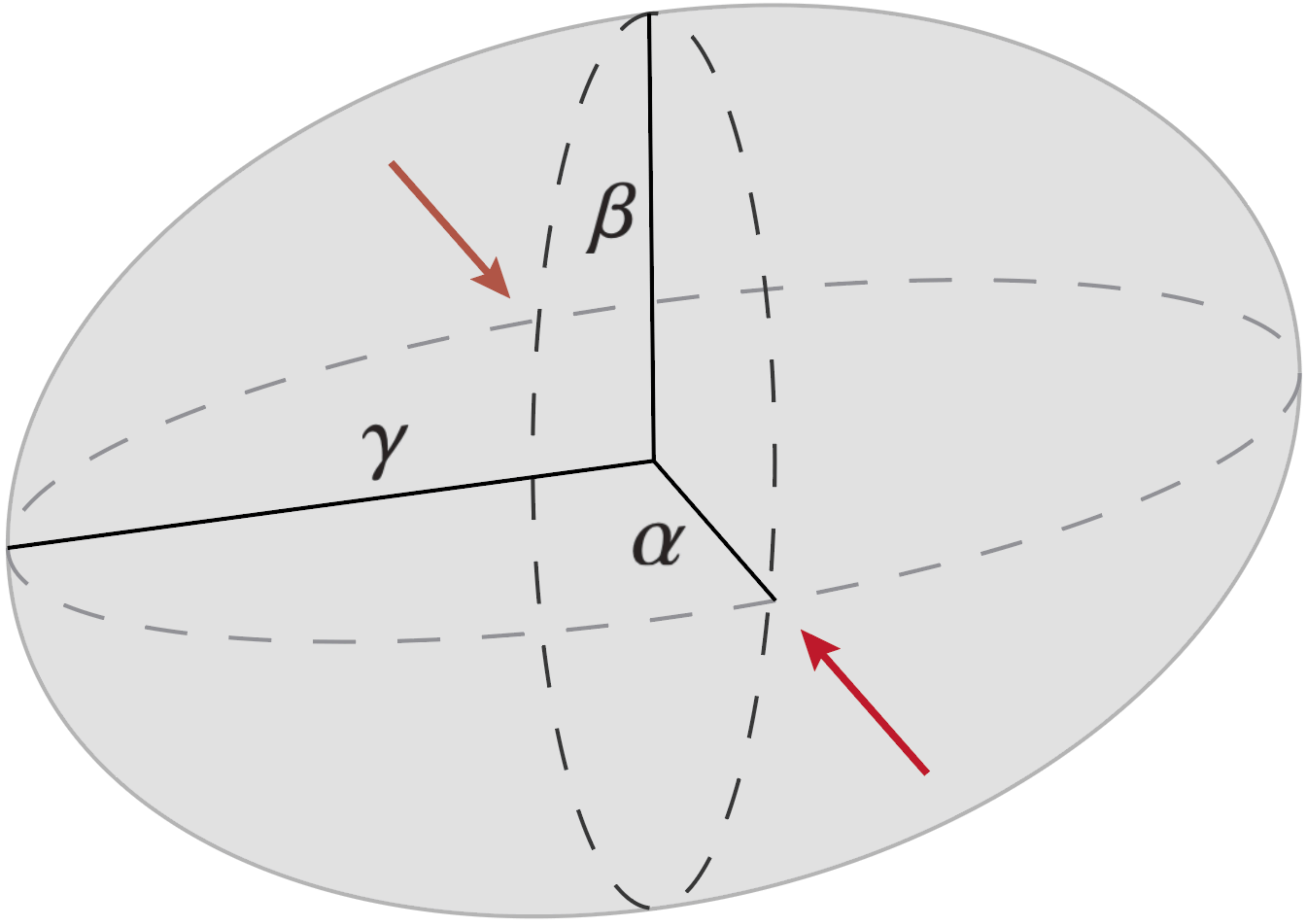
BH formation or halo annihilation



See also:
I. Dalianis, C. Kouvaris [arXiv:2106.06023]

Growth of perturbations

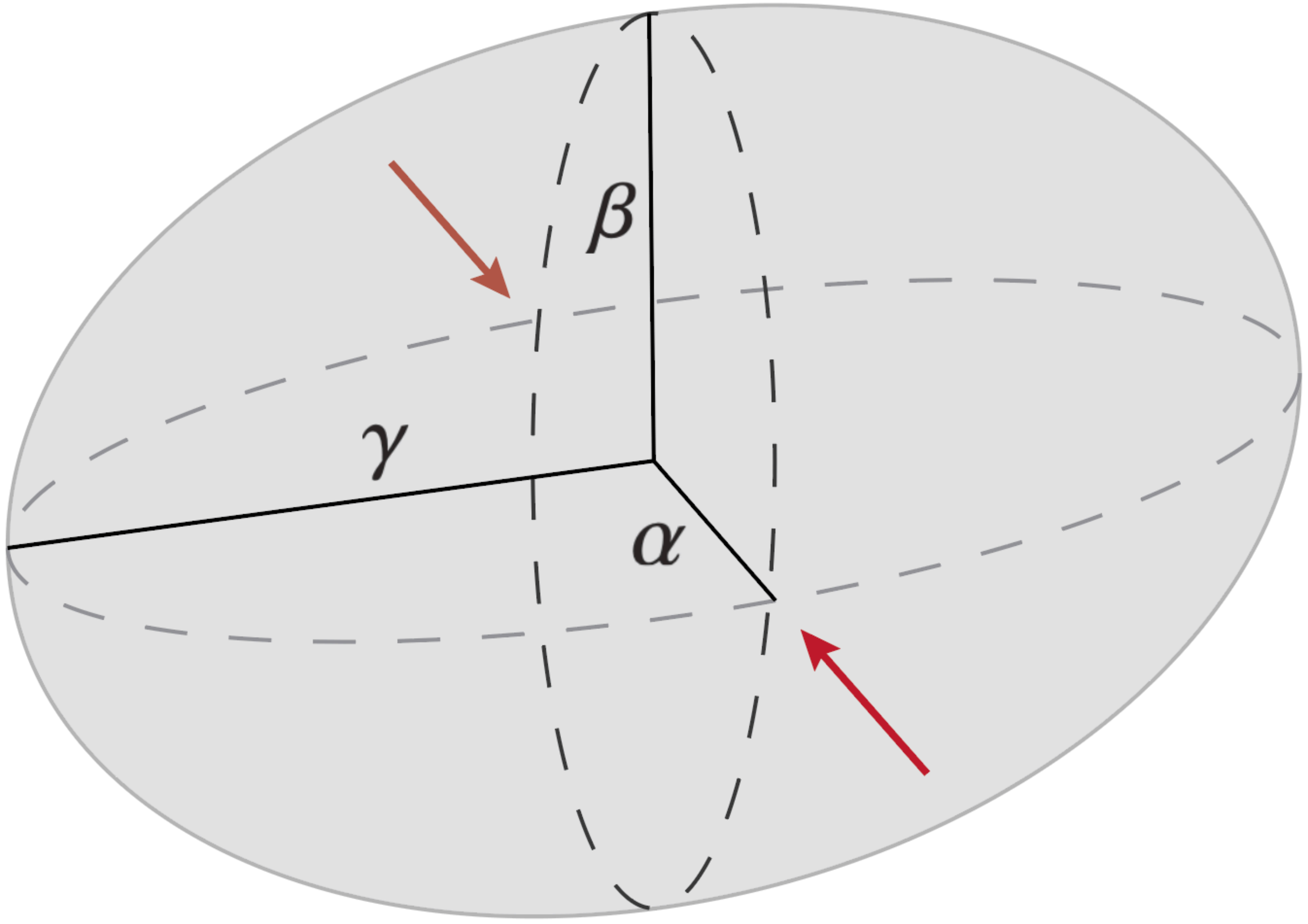
A reminder of the traditional result:

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

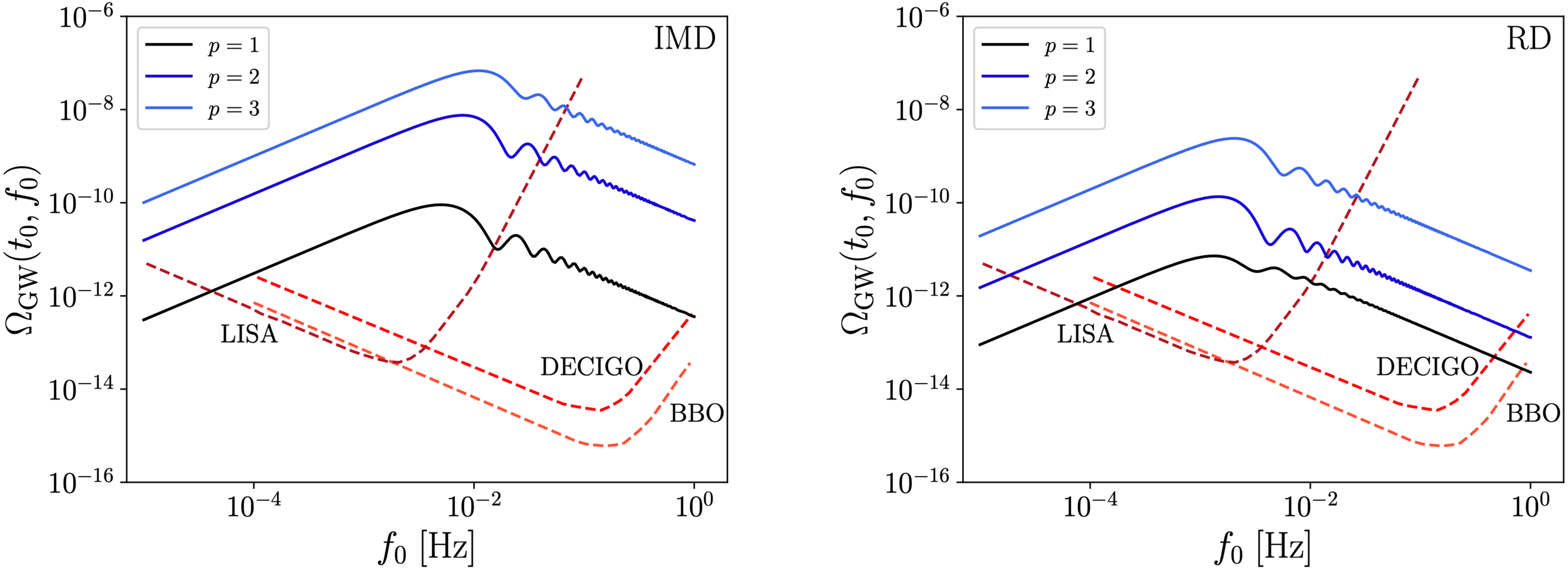
Here, ***<u>our fundamental assumption will be that</u>***

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

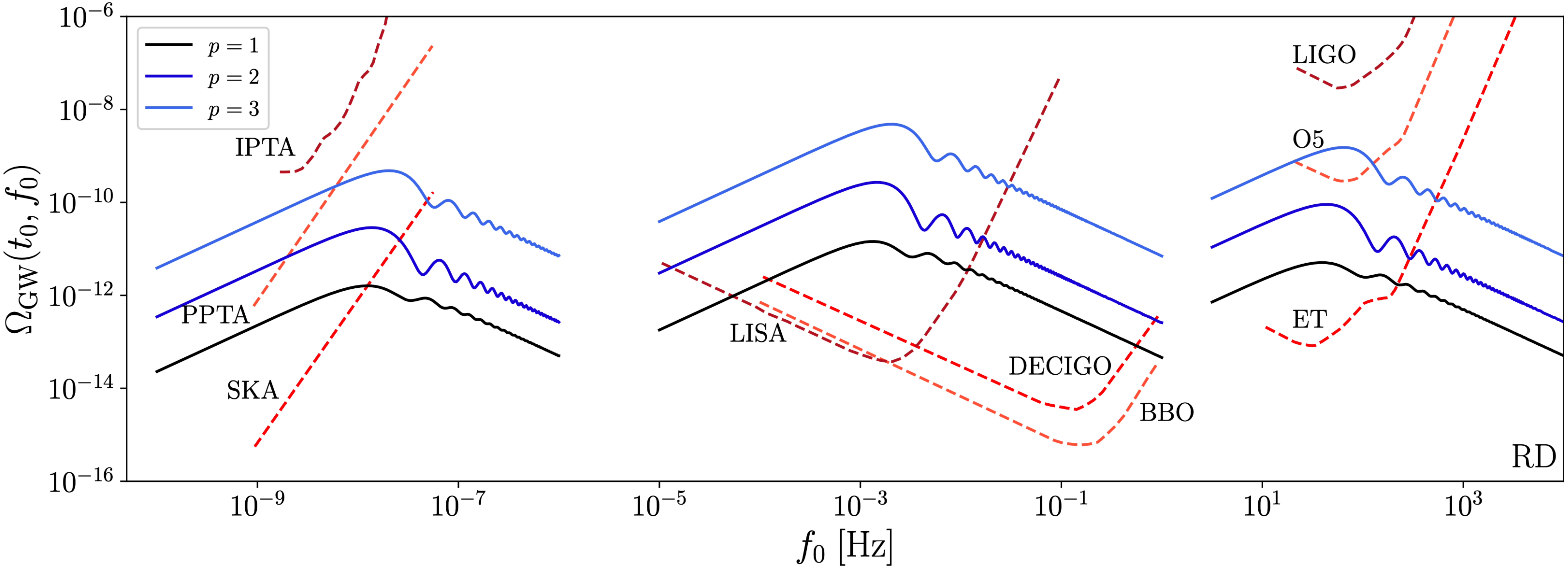
As before p characterizes the strength of the force.



GW Spectrum


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

GW Spectrum



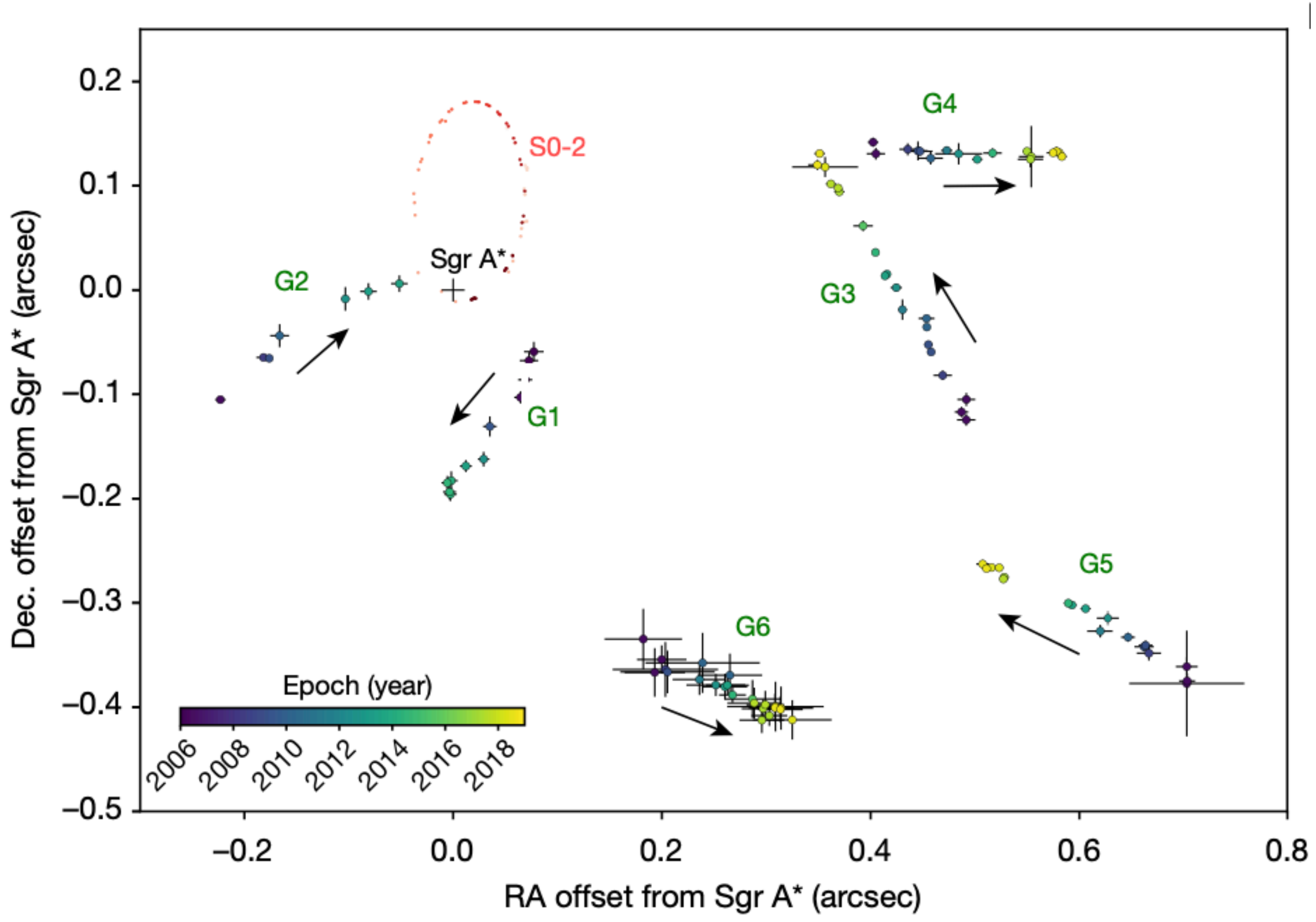
$p = 1$
$p = 2$
$p = 3$
IPTA
PPTA
SKA
LISA
DECIGO
BBO
LIGO
O5
ET
RD
$\Omega_{\rm GW}(t_0, f_0)$
f_0 [Hz]
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{1}
10^{3}

Primordial black holes and the Galactic Center

[**MMF,** A. Kusenko, A. M. Ghez, S. Naoz; PRD 108 (2023) 6, L061301]

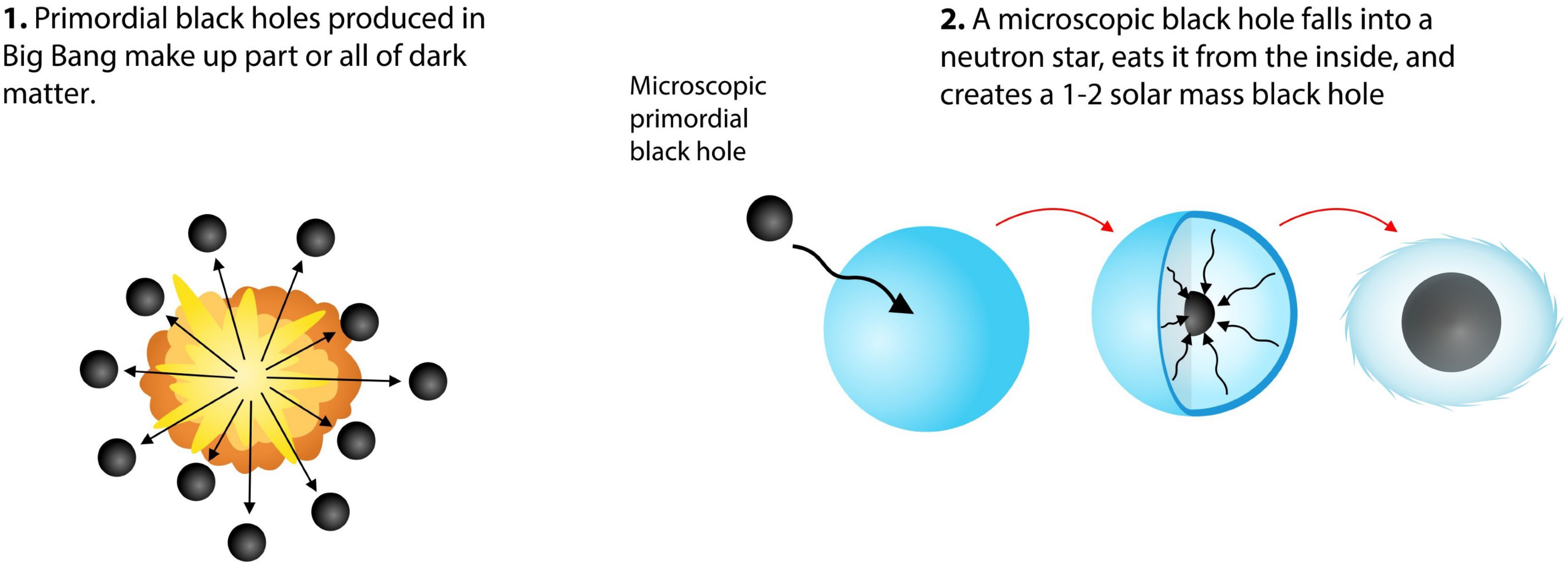
Brief review of G objects

- Population of unresolved objects which show both ***thermal and dust emission***.
- Simultaneously, they display the ***dynamical properties of stellar-mass objects***
- Various proposed formation mechanisms:
    - **Merger of binary systems**
    - See Prodan, S., Antonini, F. & Perets (2015), Stephan, A. P. et al. (2016)
    - **Low-mass star that has retained a protoplanetary disk**
        - Murray-Clay, R. A. & Loeb, A; (2015)



[Ciurlo et. al. 2020]

PBH-Neutron star interactions



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

$$\Longrightarrow \quad \text{stellar} - \text{mass black holes surrounded by gas} \overset{?}{\Longleftrightarrow} G \text{ objects}$$

[Takhistov, Fuller, Kusenko, PRL 119 (2017) 6, 061101]
[Takhistov, Fuller, Kusenko, PRL 126, 071101 (2021)]
[Takhistov, arXiv:1707.05849]

G objects as converted neutron stars

$$N_{\mathrm{NS}\to\mathrm{BH}} \quad \& \quad l = \frac{L_B}{L_{\mathrm{Ed}}}$$

PBH-Neutron star interactions

Time for PBH to settle in core of NS

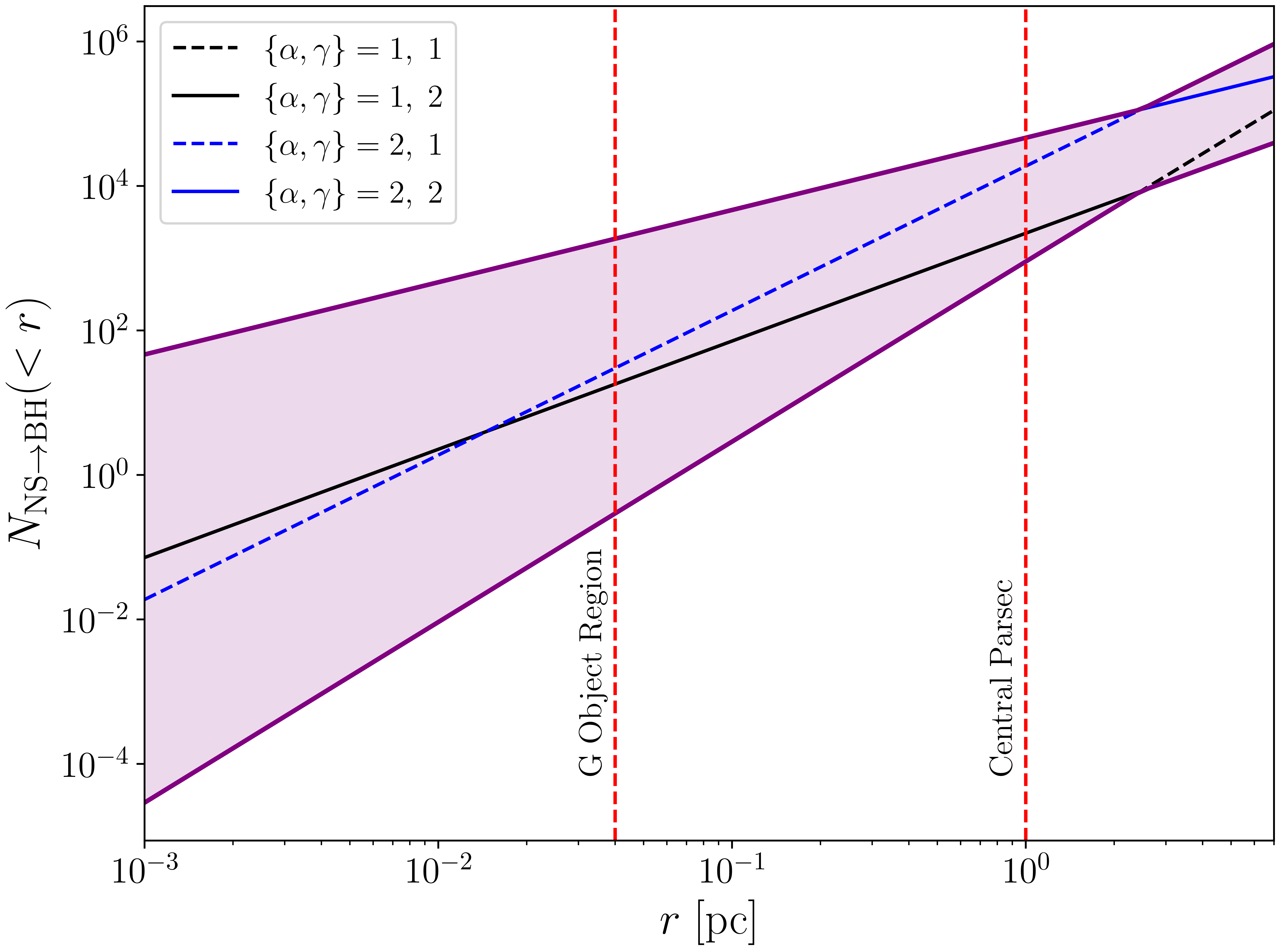
$$\langle t_{\mathrm{NS}} \rangle = F^{-1} + t_{\mathrm{loss}} + t_{\mathrm{con}}$$

PBH-NS capture rate

Accretion timescale

[Takhistov, Fuller, Kusenko, PRL 119 (2017) 6, 061101]
[Takhistov, Fuller, Kusenko, PRL 126, 071101 (2021)]
[Takhistov, arXiv:1707.05849]

Number of Converted NS



$$\rho_{\mathrm{DM}}(r) \simeq \rho_{\odot}\left(\frac{r}{r_{\odot}}\right)^{-\alpha}$$

$$n_{\mathrm{NS}}(r) \simeq n_{\mathrm{NS},0}\left(\frac{r}{r_{\mathrm{NS}}}\right)^{-\gamma}$$

PBH-Neutron star interactions

For simplicity, we will assume spherical Bondi accretion.

$$\dot{m} \equiv \frac{\dot{M}_{\rm B}}{\dot{M}_{\rm Ed}} = 1.7 \times 10^{-7} \left(\frac{M}{M_\odot}\right) \left(\frac{n_\infty}{1 \ {\rm cm}^{-3}}\right) \left(\frac{T_\infty}{10^4 \ {\rm K}}\right)^{-3/2}$$

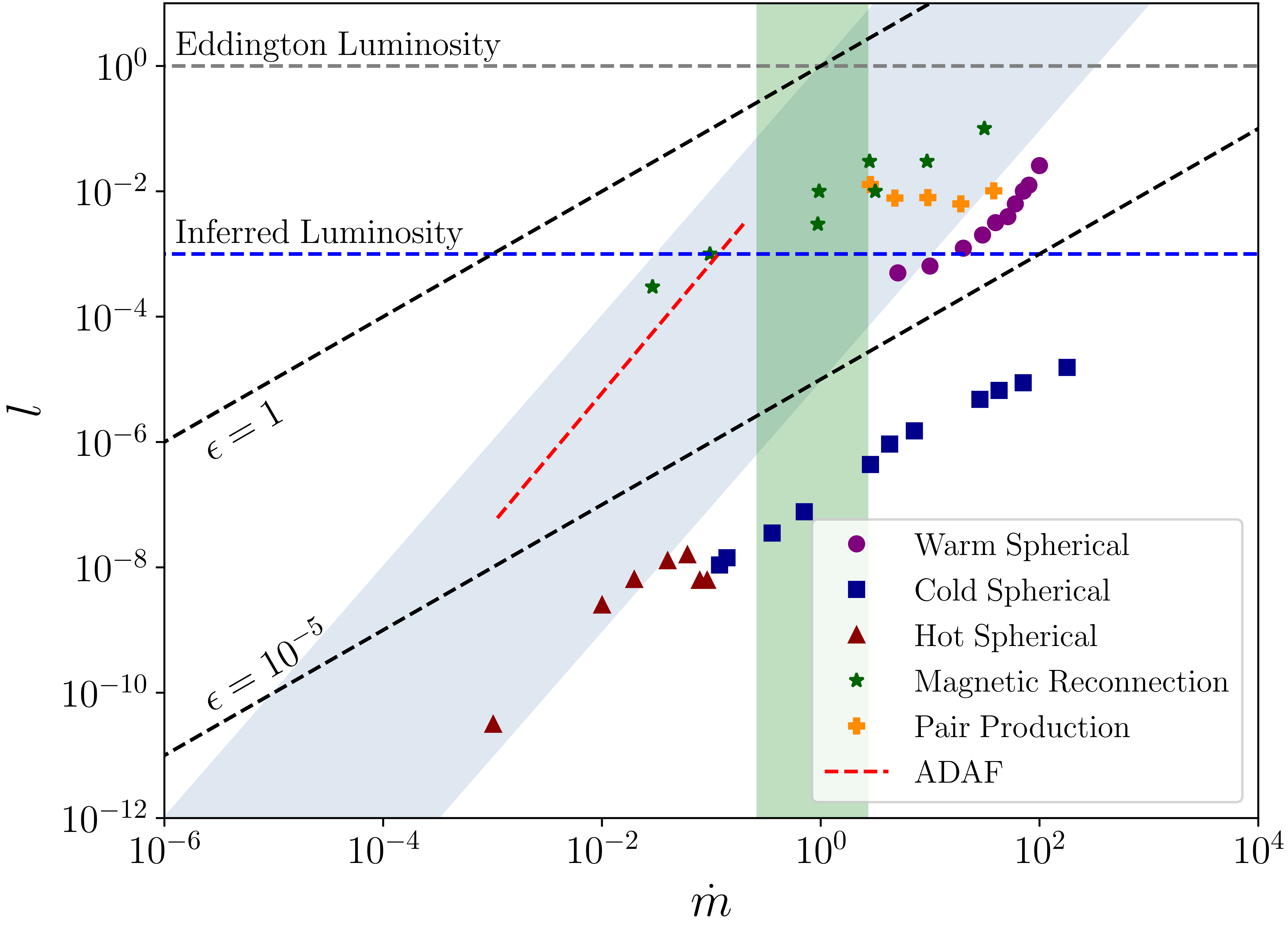
Define the efficiency,

$$l \equiv \epsilon \dot{m}, \qquad l = \frac{L_B}{L_{\rm Ed}}$$

Generally, $\epsilon = \eta \dot{m} \implies l = \eta \dot{m}^2$

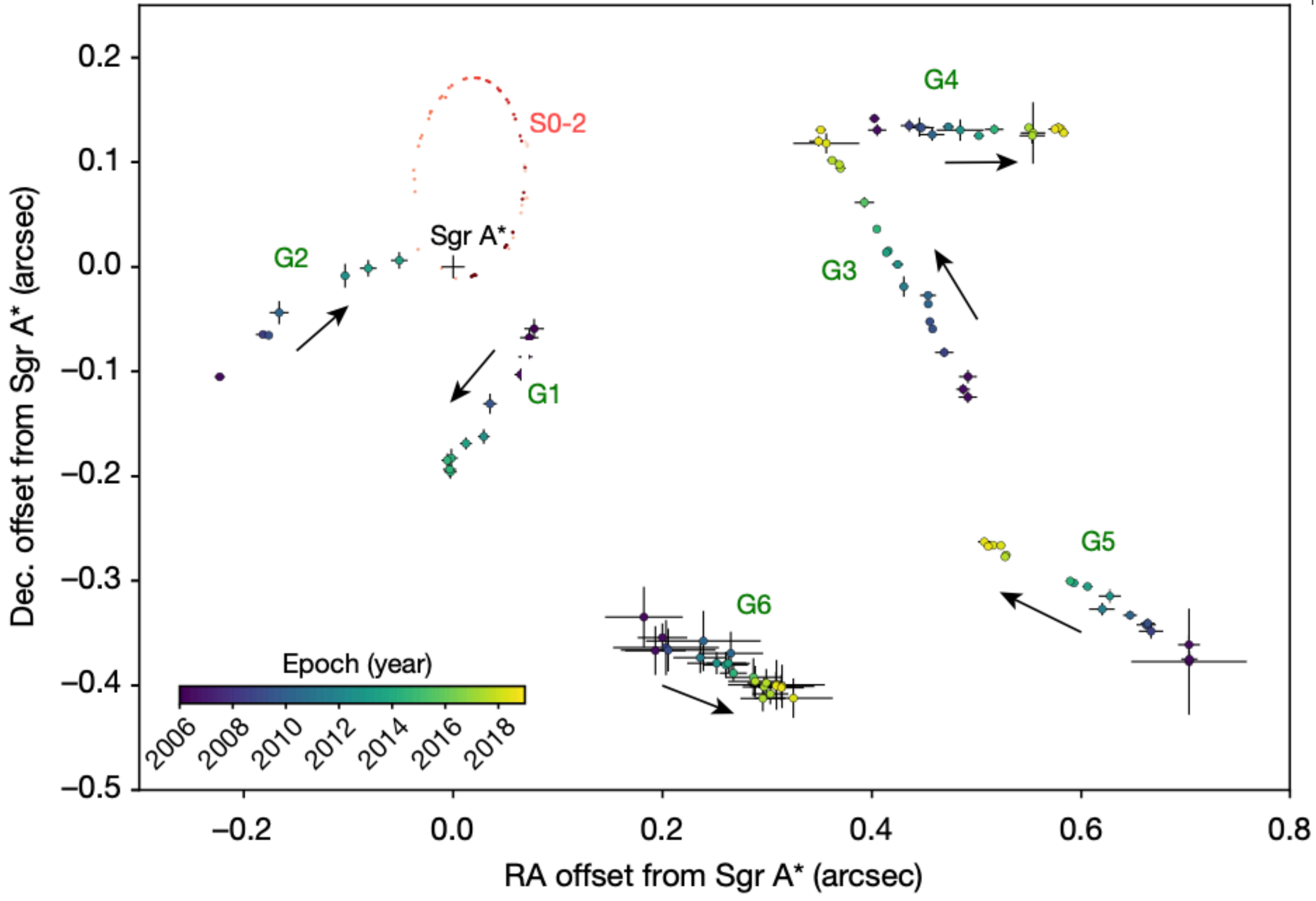
Key: Parameterize theoretical and observational uncertainty in η

Accretion Estimates



Benefits of the PBH — G objects interpretation

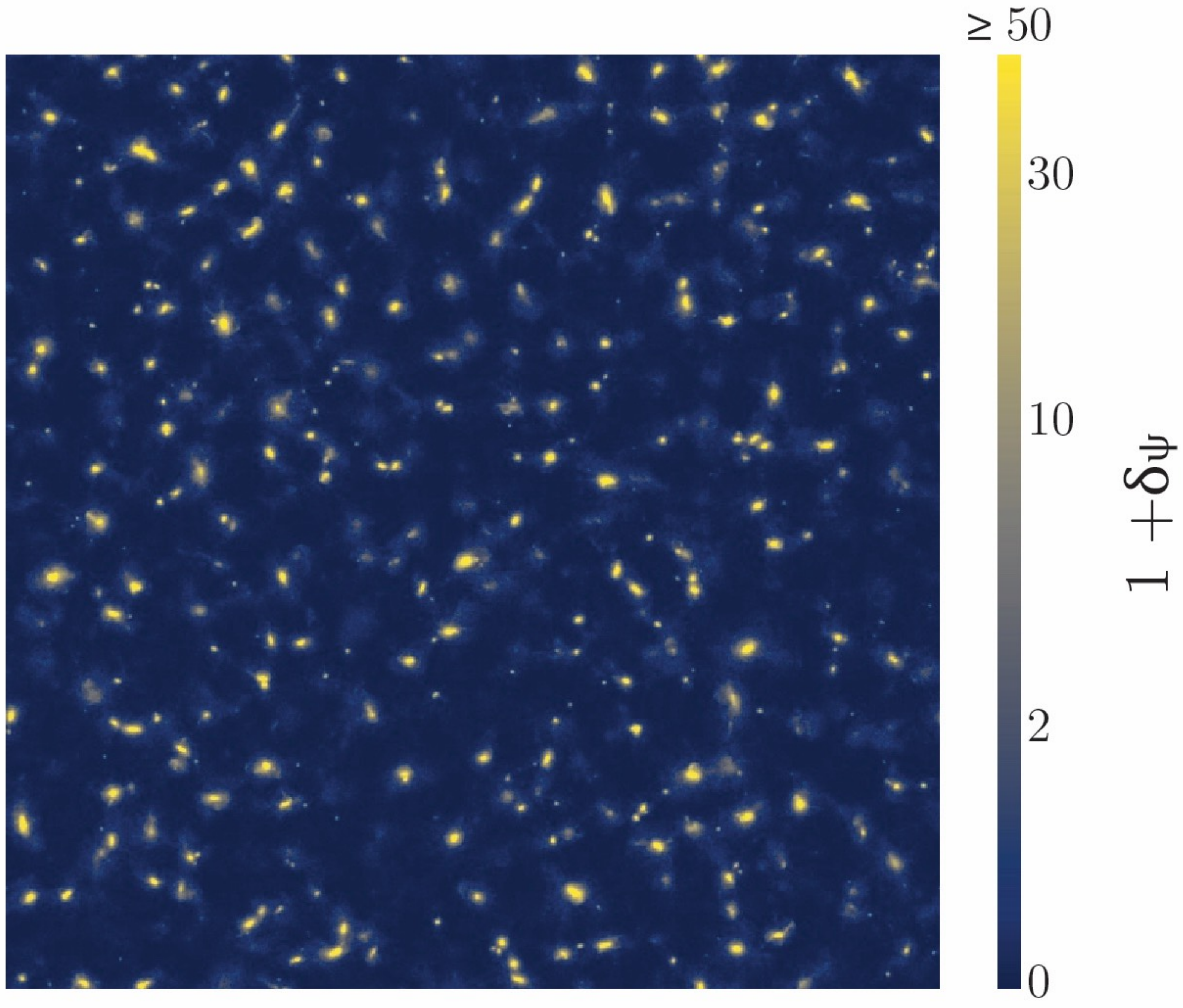
- Relates
  - Dark matter as PBHs
  - Mysterious nature of G objects
  - Missing pulsar problem
    - Observed absence of pulsars within the Galactic Center



[Ciurlo et. al. 2020]

Conclusion

- Primordial structure formation *<u>can occur</u>* 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



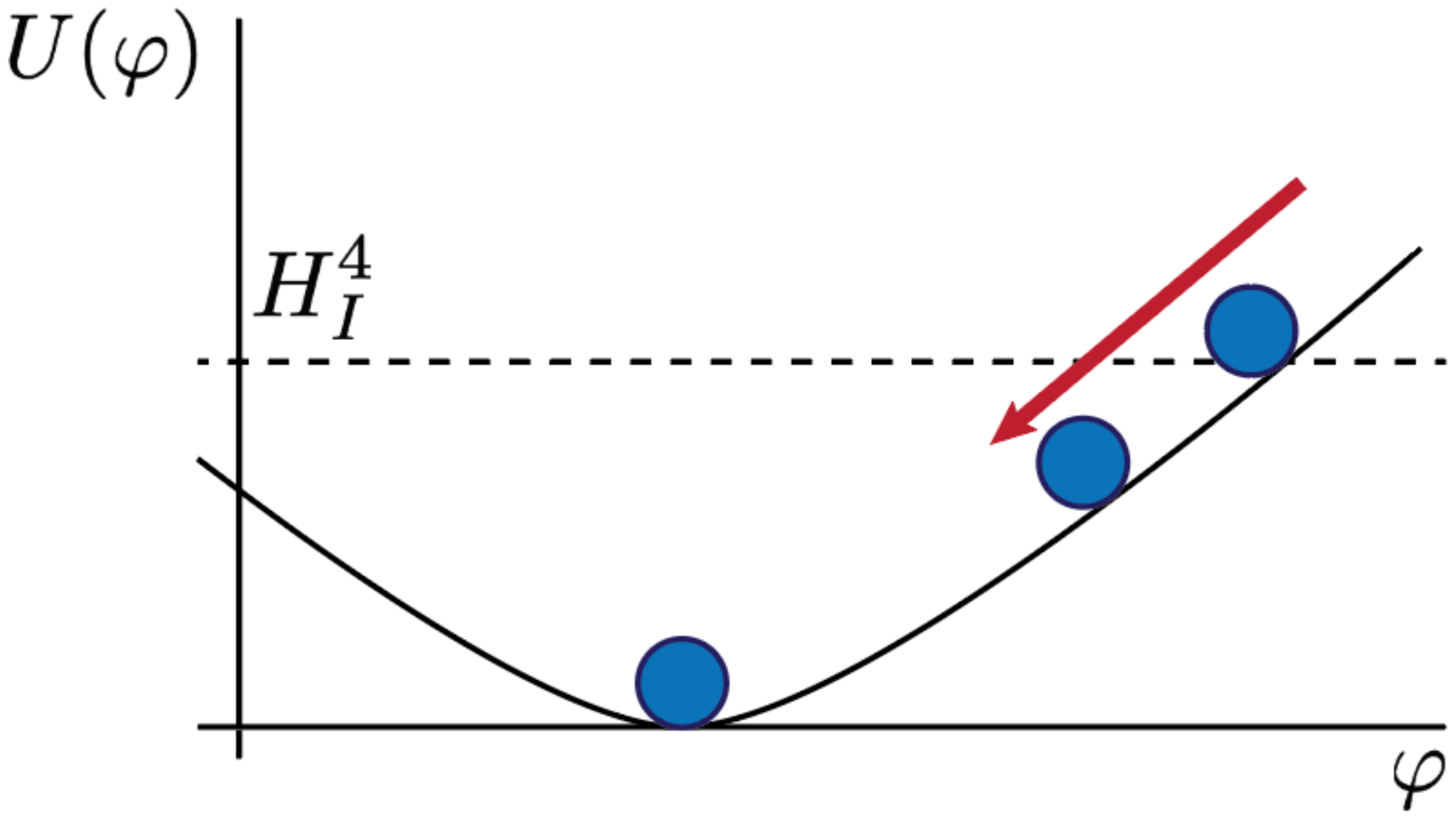
Extra Slides

Scalar fields in de Sitter space during inflation

$$U(\langle\varphi\rangle) \sim H_I^4$$

&

$$H_I = \sqrt{\frac{U_{\rm tot}}{3M_{\rm Pl}^2}} \approx \sqrt{\frac{U_I(\Phi_I)}{3M_{\rm Pl}^2}}$$



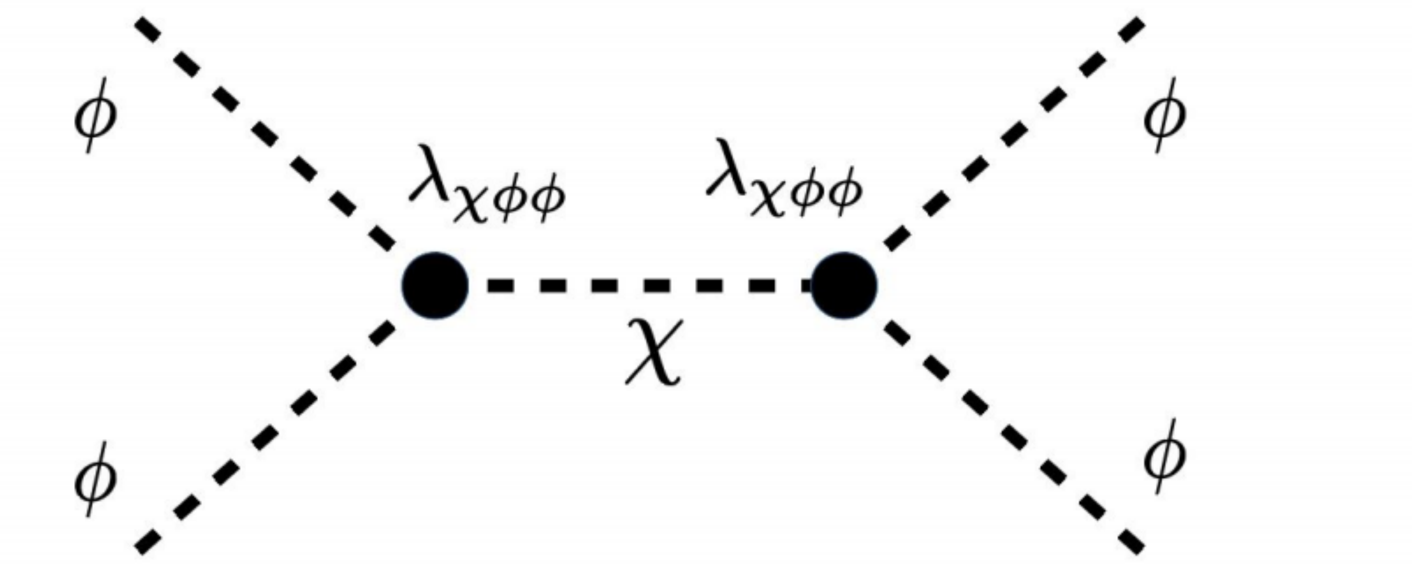
Scalar fields and fragmentation

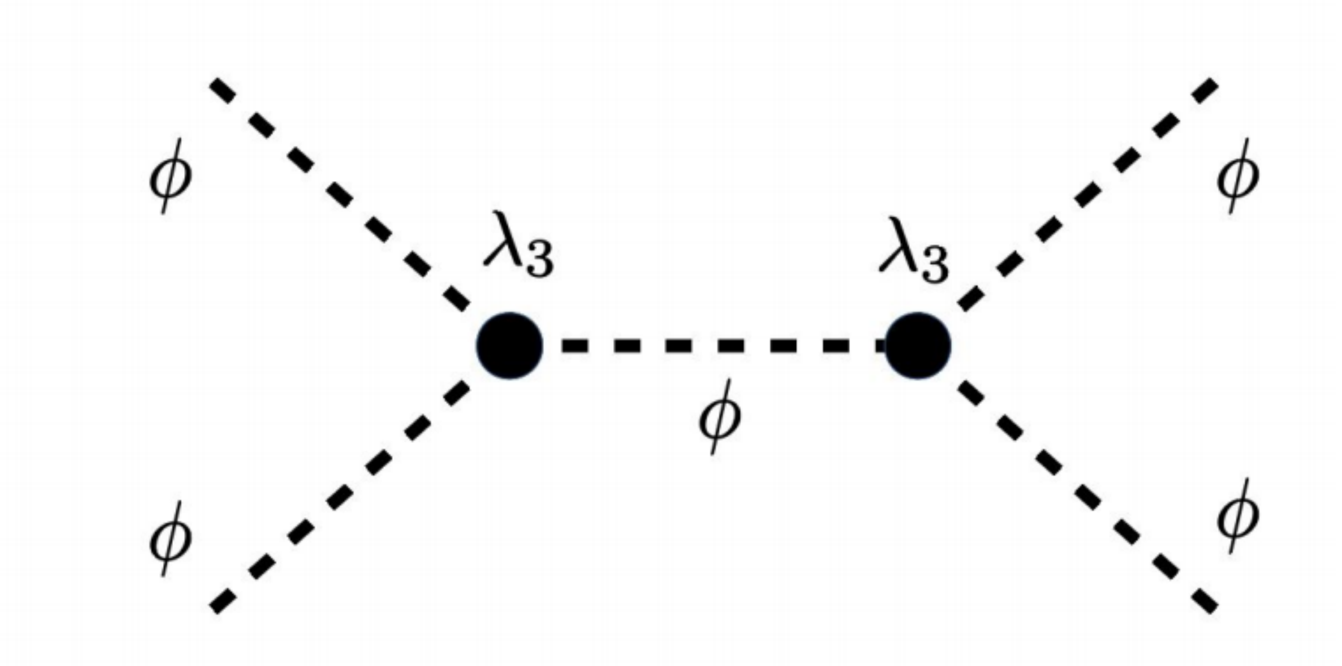
- Attractive forces induce an ***instability*** in scalar condensate

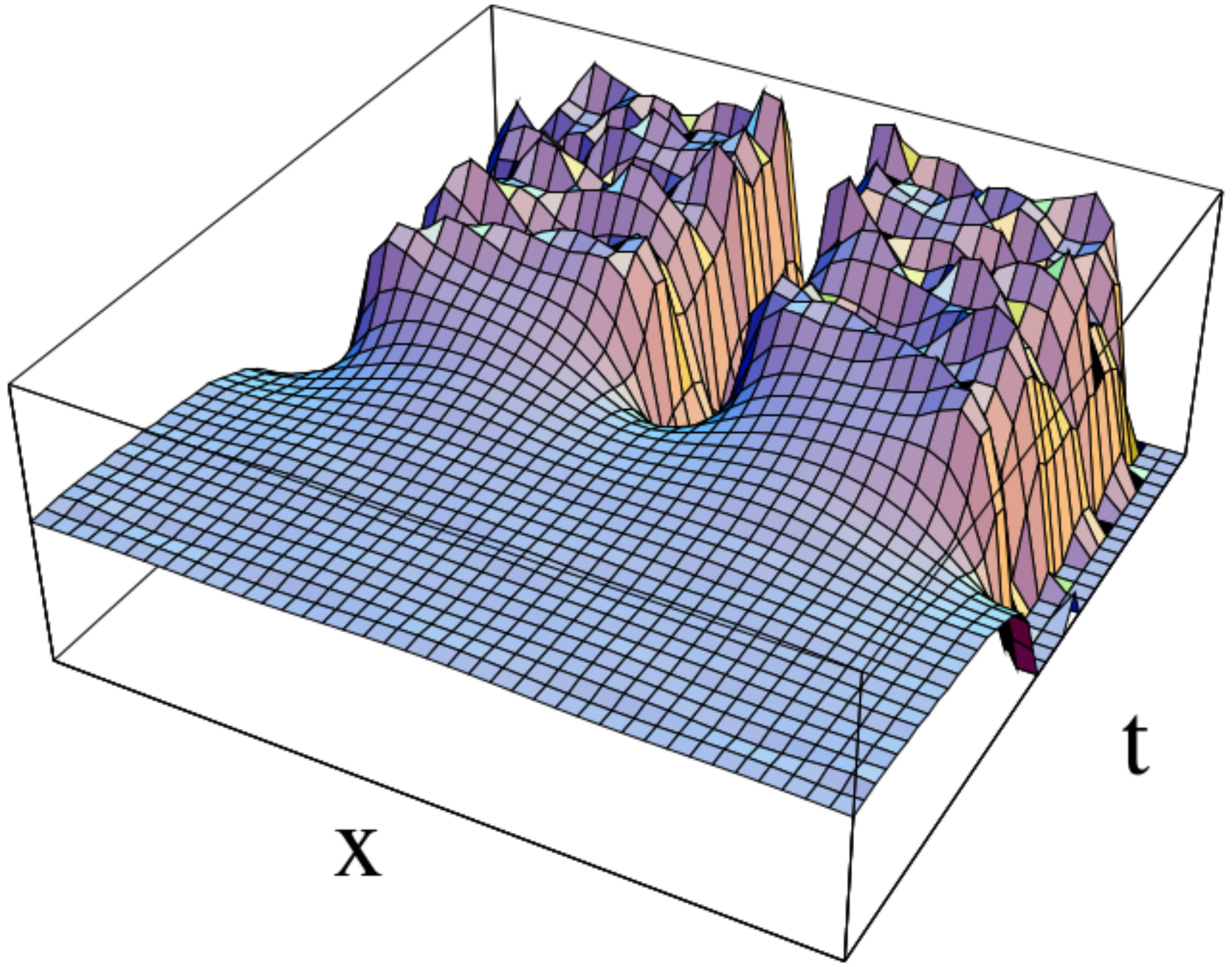
$$U(\varphi) \supset \lambda_3 \varphi^3$$

or

$$U(\varphi) \supset \lambda_{\chi\varphi\varphi} \chi \varphi^\dagger \varphi$$







[Cotner, Kusenko, Sasaki, Takhistov, JCAP 1910 (2019) 077]
[Kusenko, Shaposhnikov, hep-ph/9709492]

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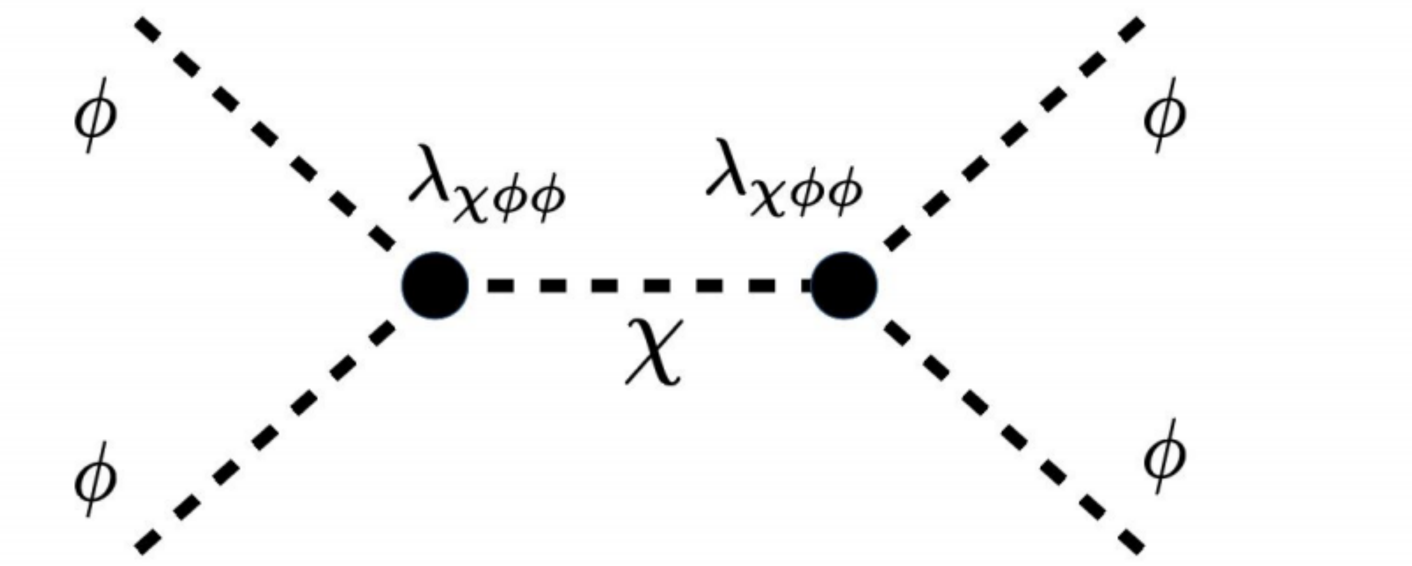
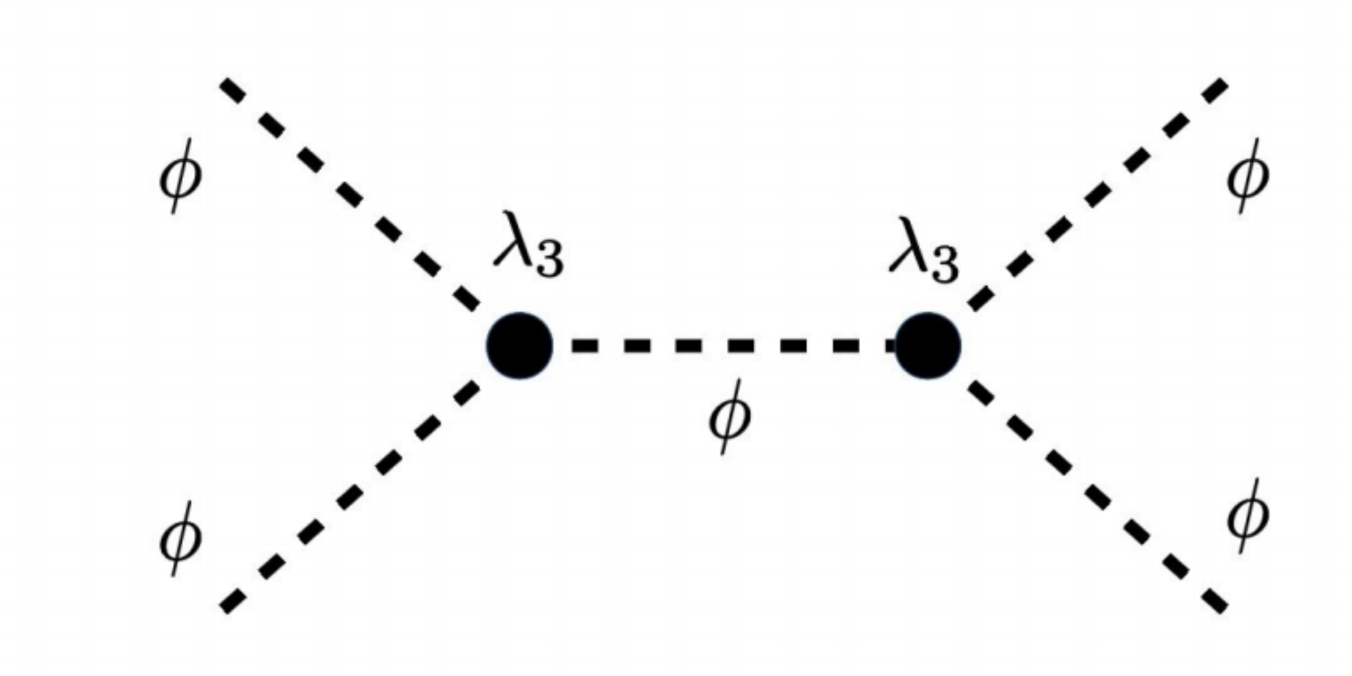
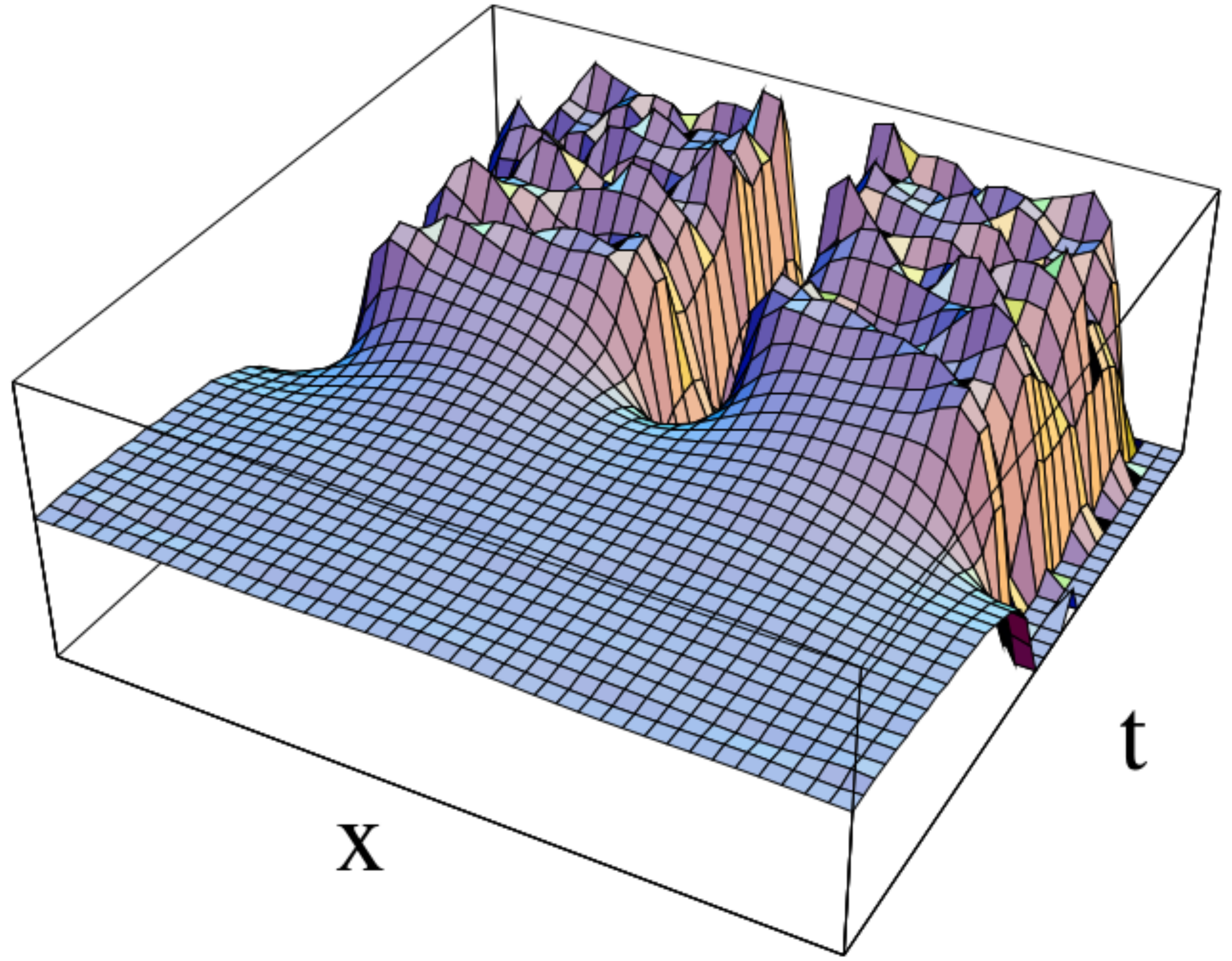






$\Longrightarrow$ Leads to the formation of Q-balls

[Cotner, Kusenko, Sasaki, Takhistov, JCAP 1910 (2019) 077]
[Kusenko, Shaposhnikov, hep-ph/9709492]

Scalar fragmentation leads to Q-balls

- Complex scalar field with $U(1)$ symmetry (B, L, B - L in SUSY)

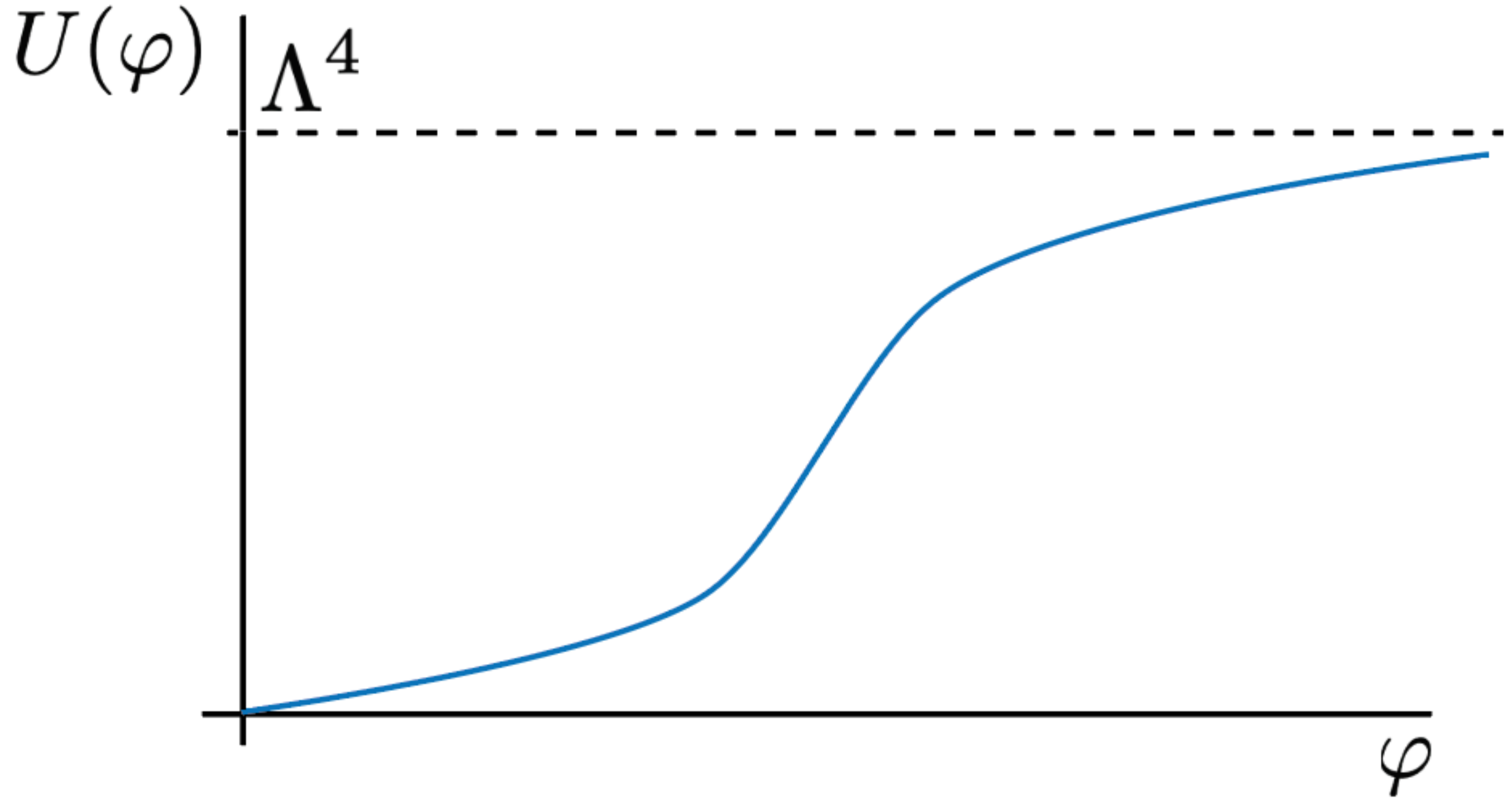
$$Q = \frac{1}{2i}\int \left(\varphi^\dagger \overleftrightarrow{\partial_0} \varphi\right)\ d^3x$$

- ***Q***: Is there a ground state with $Q \neq 0$?
    - ***A***: Yes! If $U(\varphi)/\varphi^2 = \min\,, \quad \varphi = \varphi_0 > 0$

- ***Key***: Q-balls can form from SUSY flat directions lifted by some scale Λ

$$M_Q = \Lambda Q^{3/4}$$

$$R_Q = Q^{1/4}/\Lambda$$



[Coleman; Rosen; Friedberg, Lee, Sirlin]

PBH-Neutron star interactions

Capture rate is given by:

$$F = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} F_0^{\rm MW}$$

where

$$F_0^{\rm MW} = \sqrt{6\pi} \frac{\rho_{\rm DM}}{m_{\rm PBH}\bar{v}} \left(\frac{2GM_{\rm NS}R_{\rm NS}}{1 - 2GM_{\rm NS}R_{\rm NS}} \right) \left(1 - e^{-3E_{\rm loss}/(m_{\rm PBH}\bar{v}^2)} \right).$$

[Takhistov, Fuller, Kusenko, PRL 119 (2017) 6, 061101]
[Takhistov, Fuller, Kusenko, PRL 126, 071101 (2021)]
[Takhistov, arXiv:1707.05849]

Observational Implications: Spin

[**MMF**, A. Kusenko PRD 104 (2021) 6, 063008]

Scalar radiation and angular momentum dissipation

- For PBHs to form, scalar radiation needs to remove both energy and angular momentum from dark matter halos.

See also:
Harada et. al. [arXiv:1707.03595]
Harada et. al. [arXiv:2011.00710]

Scalar radiation and angular momentum dissipation

- For PBHs to form, scalar radiation needs to remove both energy and angular momentum from dark matter halos.
- Angular momentum losses can be considered in two contexts:
  - Oscillatory channels (coherent/incoherent)
  - Non-oscillatory channels (bremsstrahlung/surface)

See also:
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- Angular momentum losses can be considered in two contexts:
  - Oscillatory channels (coherent/incoherent)
  - Non-oscillatory channels (bremsstrahlung/surface)
- ***Moral:*** Strong long range scalar forces efficiently remove angular momentum from dark matter halos. The resulting PBHs will have low spins at the time of formation.

See also:
Harada et. al. [arXiv:1707.03595]
Harada et. al. [arXiv:2011.00710]

Angular momentum losses for oscillatory channels

- For oscillatory charge distributions, we can find decompose the outgoing waves in a spherical basis. The energy losses and angular momentum losses for a given mode are:

$$\frac{dE_{\ell m}}{dt} = \frac{1}{2}|\Lambda_{\ell m}|^2, \qquad \frac{dJ_{\ell m}}{dt} = \frac{m}{2\omega}|\Lambda_{\ell m}|^2 = \frac{m}{\omega}\left(\frac{dE_{\ell m}}{dt}\right)$$

- Here, $m = -\ell, \ldots, \ell$. This shows that if the $\ell = 0$ mode dominates, angular momentum losses are not significant.

$\Longrightarrow$ Different for electromagnetistm

Angular momentum losses for non-oscillatory channels

- For non-oscillatory motion, radiation escapes isotropically when the viewed from the co-rotating frame of the dark matter halo.
- In the lab frame, scalar quanta are **blueshifted** (**redshifted**) when emitted in the direction parallel (antiparallel) to the motion of the halo

$$\frac{dJ}{dt} = -R\frac{dE}{dt}f(v)$$

Angular momentum losses for non-oscillatory channels

- We can compare the angular momentum loss to the cooling rate (i.e. the energy loss):

$$\frac{\tau_{\text{cool}}}{\tau_J} = \mathcal{A}\left(\frac{R_0}{R}\right)\frac{f(v)}{v}, \qquad \mathcal{A} \equiv \frac{M_h}{R_0}\left(\frac{\beta}{M_{\text{Pl}}}\right)^2 \gg 1$$

- For $v \ll 1$ and $R \ll R_0$ then we find that,

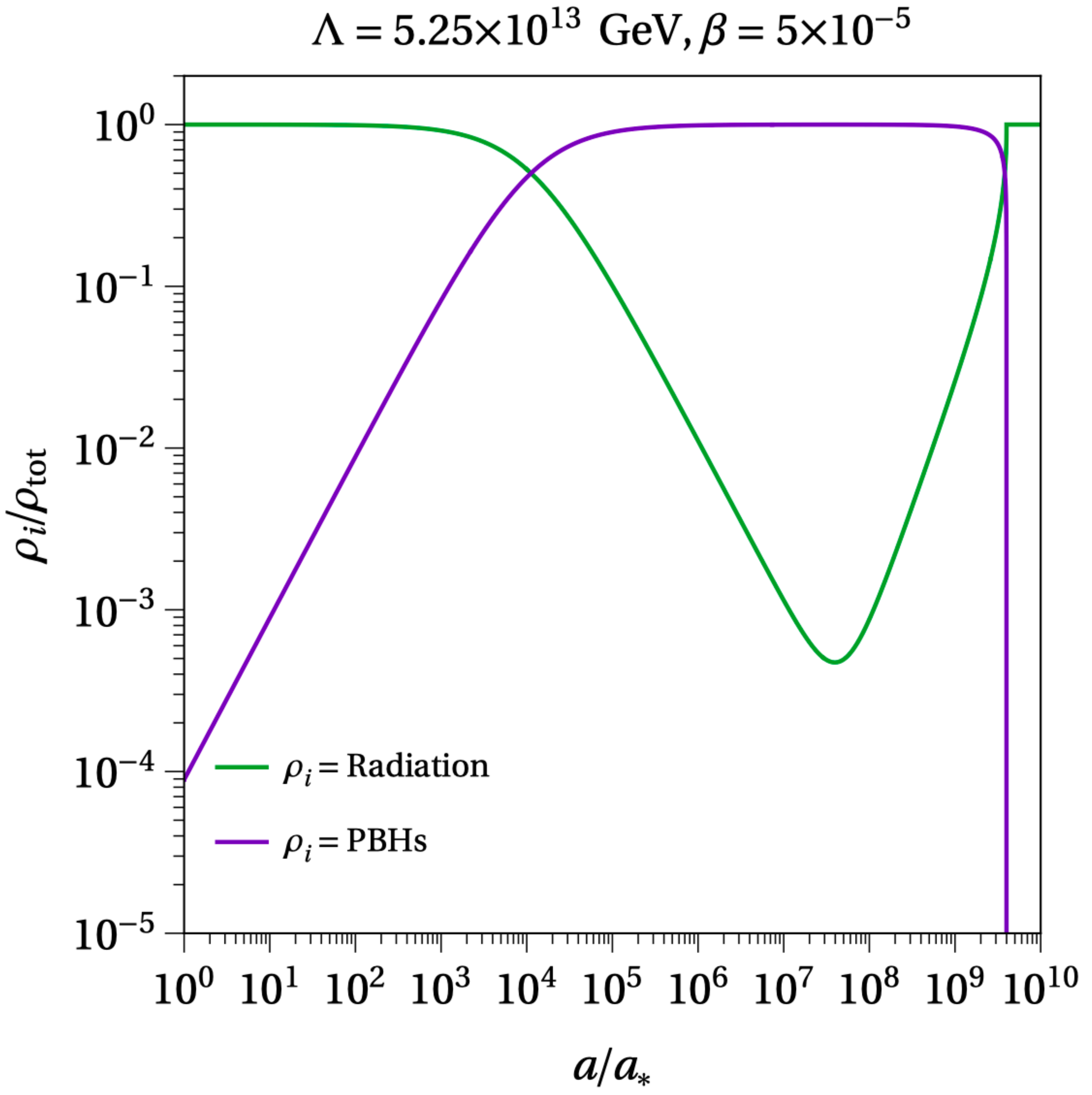
$$J(R) = J_0\left(\frac{R}{R_0}\right)\exp\left[-\mathcal{A}\left(\frac{R_0}{R}\right)\right]$$

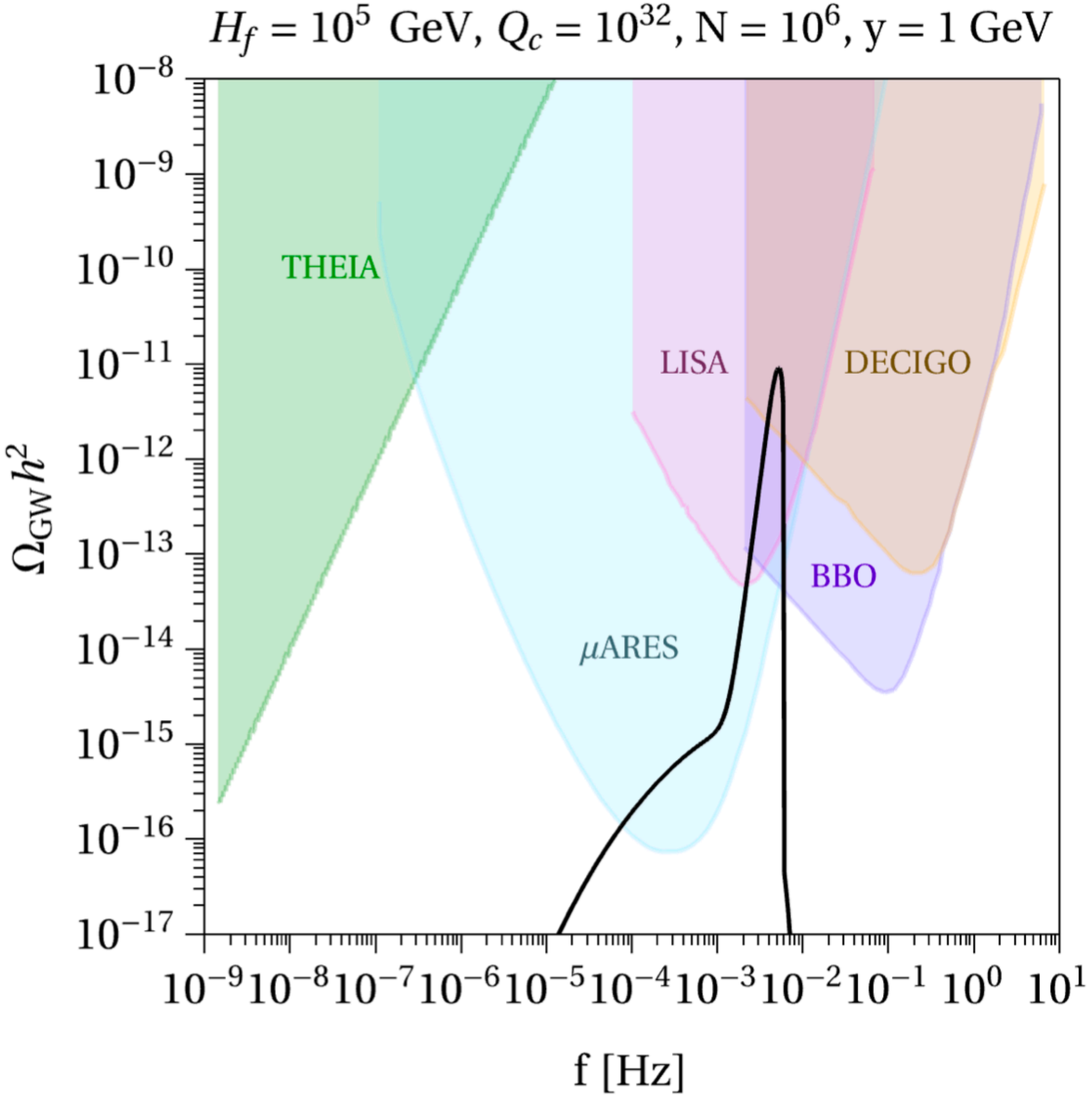
- Angular momentum is removed *very* efficiently. Black holes formed will be spinless.

Primordial black holes: Spins

Formation Mechanism	Mass Range	Spins
Inflationary Perturbations [A. Green review: arXiv:2007.10722]	DM, LIGO, supermassive	Small
SUSY flat directions, Q-balls & IMD [1612.02529, 1706.09003, 1907.10613]	DM	Large
Light scalar Q-balls (not SUSY) [1612.02529, 1706.09003, 1907.10613]	DM, LIGO, supermassive	Large
First order phase transitions See talk by I. Baldes, [2106.05637, 2212.14037, 2307.11639]	DM, LIGO, supermassive	Small (***?***)
Multiverse bubbles [1512.01819, 1710.02865, 2001.09160]	DM, LIGO, supermassive	Small
Early structure formation and collapse [**MMF**, A. Kusenko: PRL 126 (2021) 4, 041101] [**MMF**, A. Kusenko: *JCAP* 05 (2023) 013] [**MMF**, Y. Lu, A. Kusenko: arXiv:2308.09094]	DM, LIGO, supermassive	Small [**MMF**, A. Kusenko PRD 104 (2021) 6, 063008]

Evaporating PBHs as a test of high-scale SUSY





[**MMF**, A. Kusenko, L. Pearce, Y. F. Perez-Gonzales, G. White: arXiv: 2308.15522]