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

Focus Week on Primordial Black Holes
Kavli IPMU

Marcos M. Flores — 14th, Nov., 2023

LPENS
LABORATOIRE DE PHYSIQUE
DE L'ÉCOLE NORMALE SUPÉRIEURE

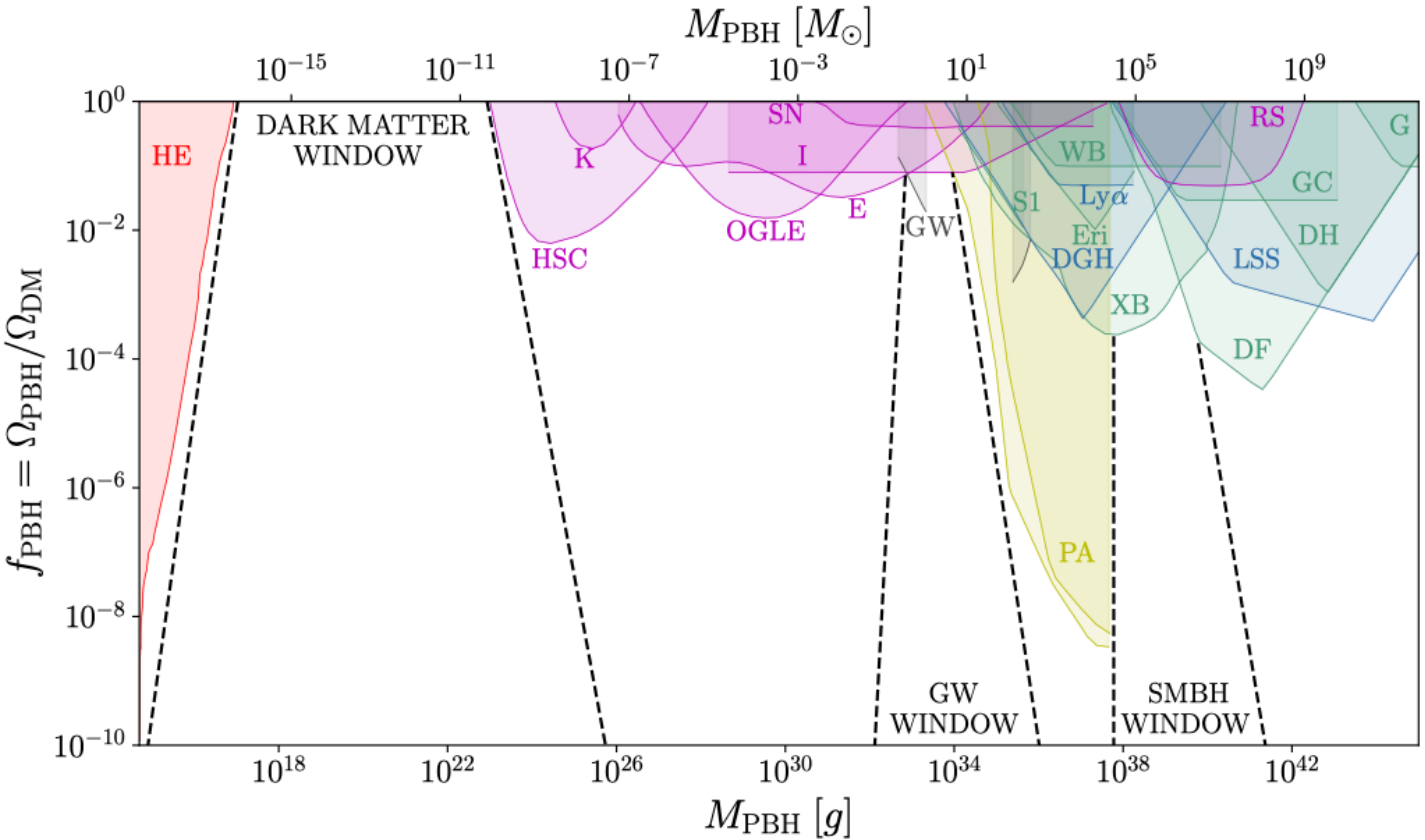
Primordial black holes
&
early structure formation

[**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)]
- 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



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

Primordial black holes: Formation

- PBH formation appears to be a generic feature of many existing theories
  - i.e., inflation, supersymmetry, first-order phase transitions, confinement
    - Just see the Focus Week on PBH Timetable!
- ***Goal:*** Develop a generic, distinguishable, scenario for PBH formation

$$\Longrightarrow \ \text{early structure formation}$$

The paradigm of *early* structure formation

Cosmological timeline

“Early”

Structure Formation

Beginning of the Universe

10^{-32} seconds

1 second

100 seconds

380 000 years

300–500 million years

Billions of years

13.8 billion years

Inflation
Accelerated expansion of the Universe

Formation of light and matter

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

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

First stars
The first stars and galaxies form in the densest knots of the cosmic web

Galaxy evolution

The present Universe

Most interesting second in the history of the Universe

[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

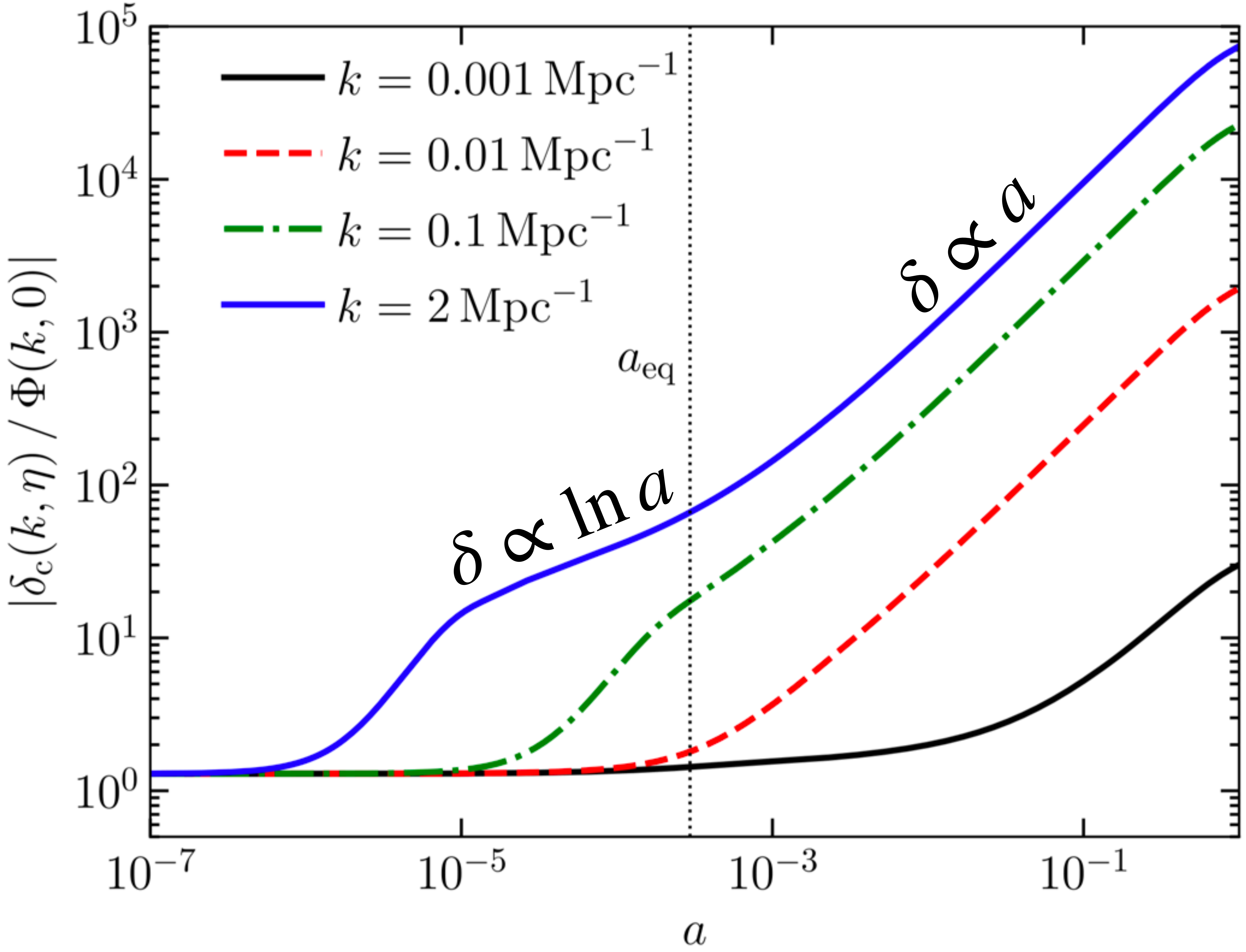
$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G\bar{\rho}_m\delta, \qquad H = \frac{1}{2t}, \qquad \bar{\rho}_m \sim \Omega_m \sim 0$$

$$\Big\downarrow$$

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

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

Conventional structure formation by example



[Credit: Dodelson, Modern Comology]

How can you have *early* structure formation?

How can you have *early* structure formation?

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

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

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

How can you have *early* 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

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

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.
- 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:

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

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

Growth of perturbations

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

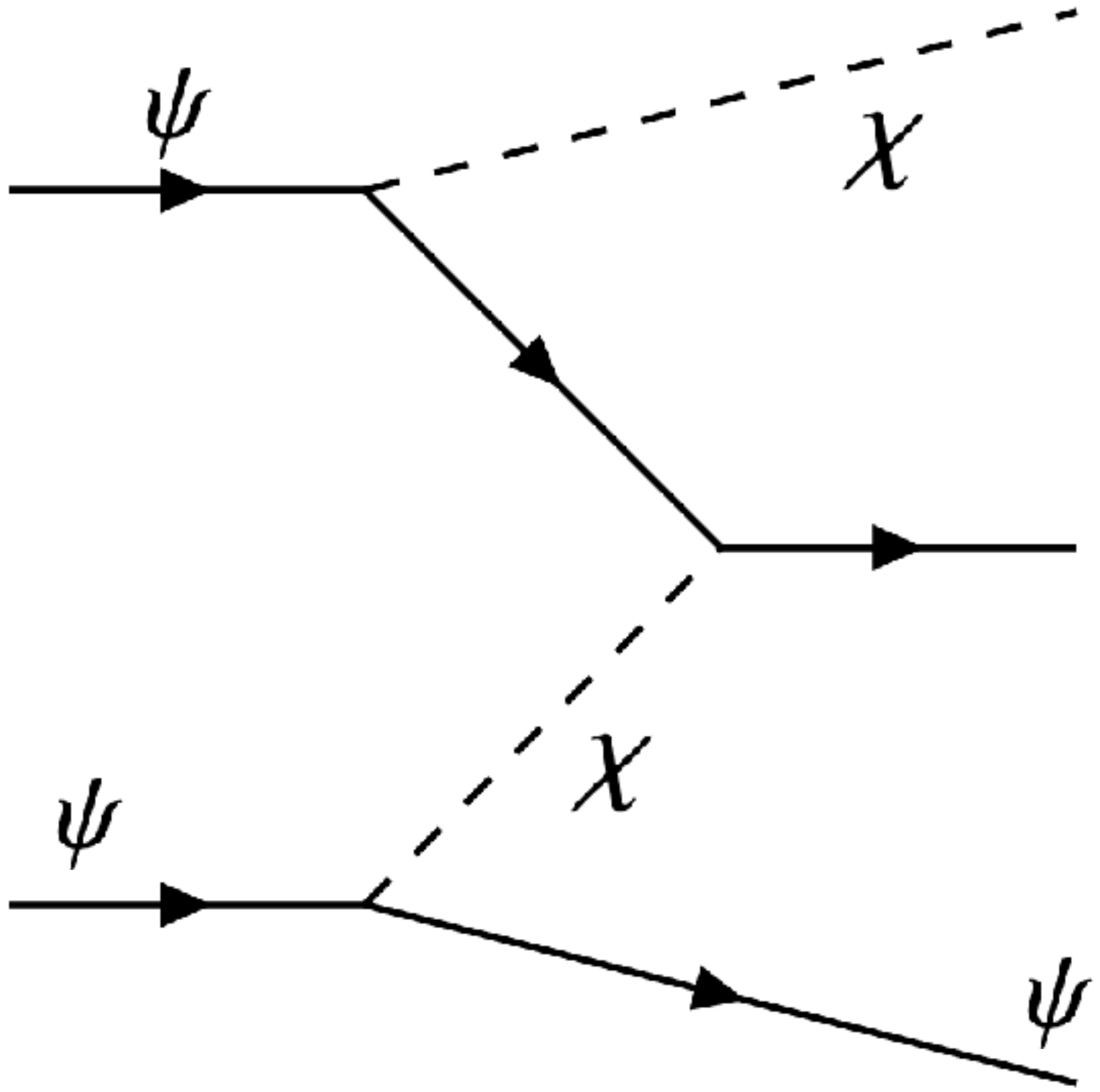
Without dissipation, halos will remain viralized until the constituent particles decay

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

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

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

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

Energy dissipation through scalar radiation

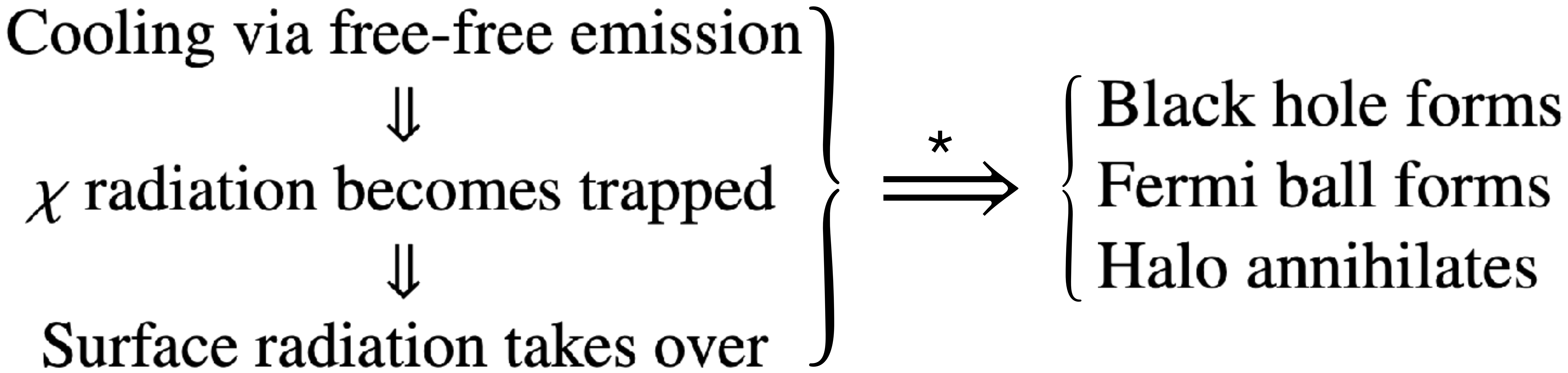
Given a halo of size R can lose energy and contract as long as,

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

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



Cooling via free-free emission

$\Downarrow$

χ radiation becomes trapped

$\Downarrow$

Surface radiation takes over

$\overset{*}{\Longrightarrow}$

Black hole forms
Fermi ball forms
Halo annihilates

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:

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

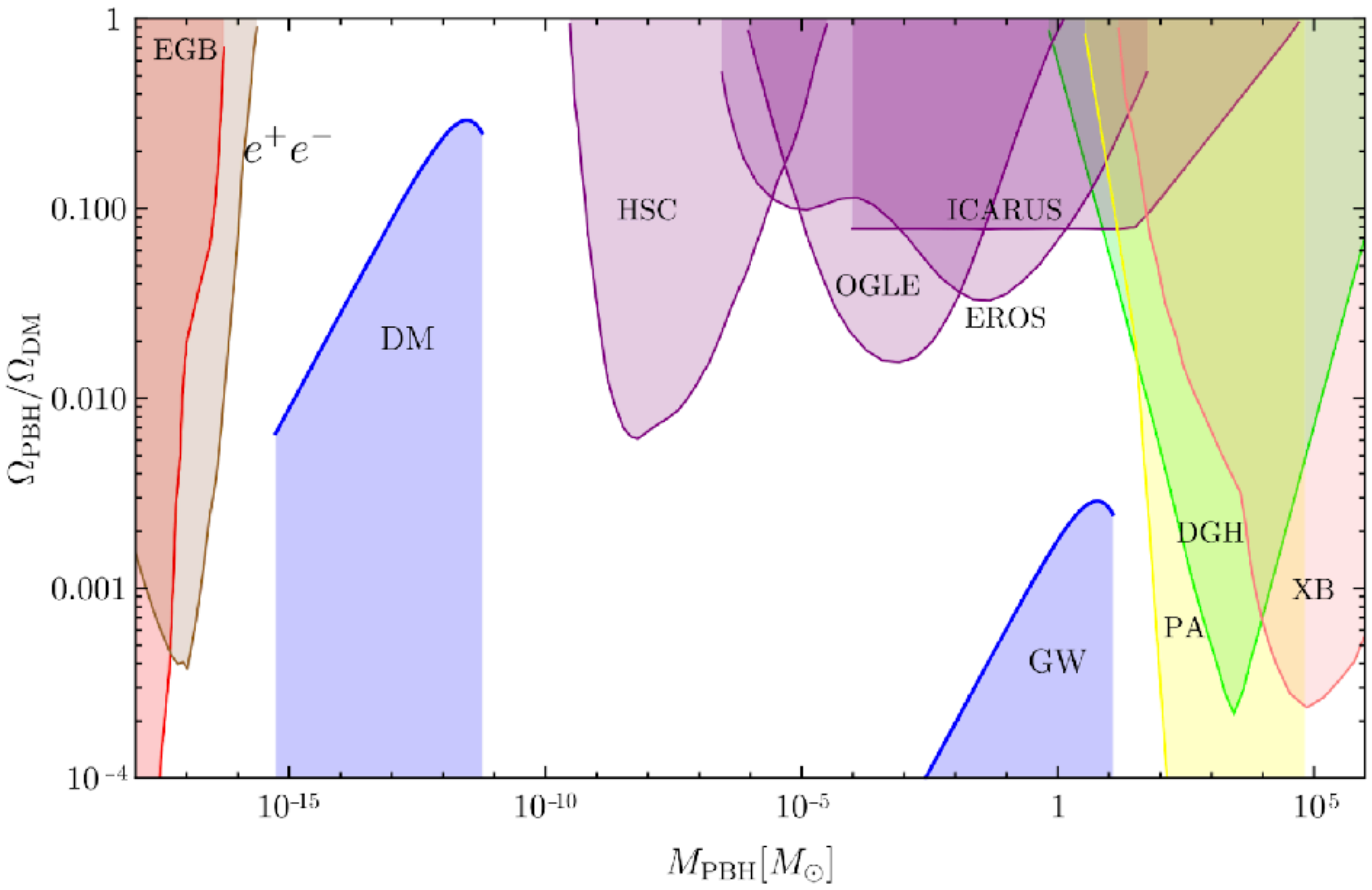
Illustrative examples

- PBH dark matter:

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

- Relevant to LIGO

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

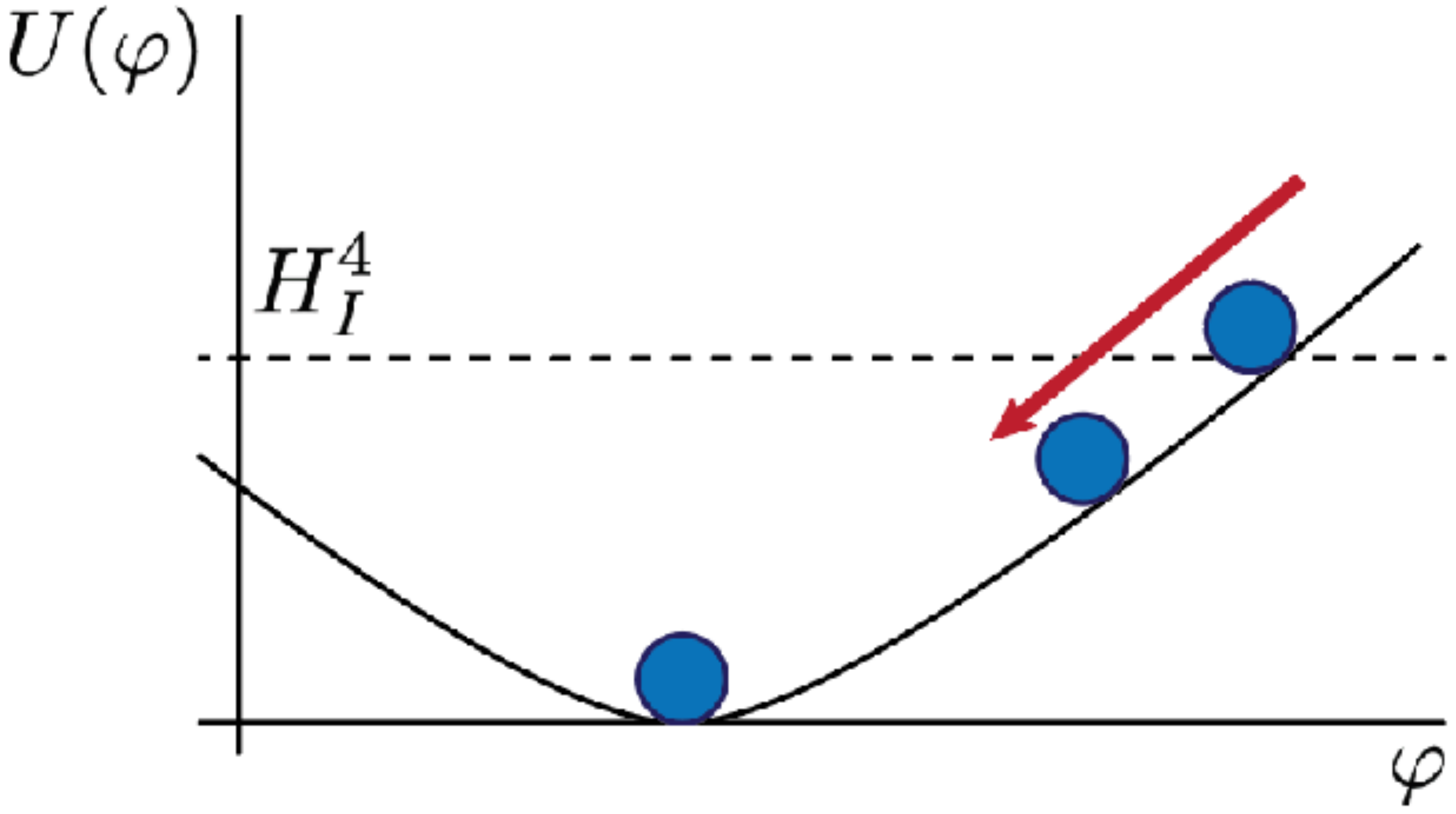


Primordial black holes, scalar forces & supersymmetry

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

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



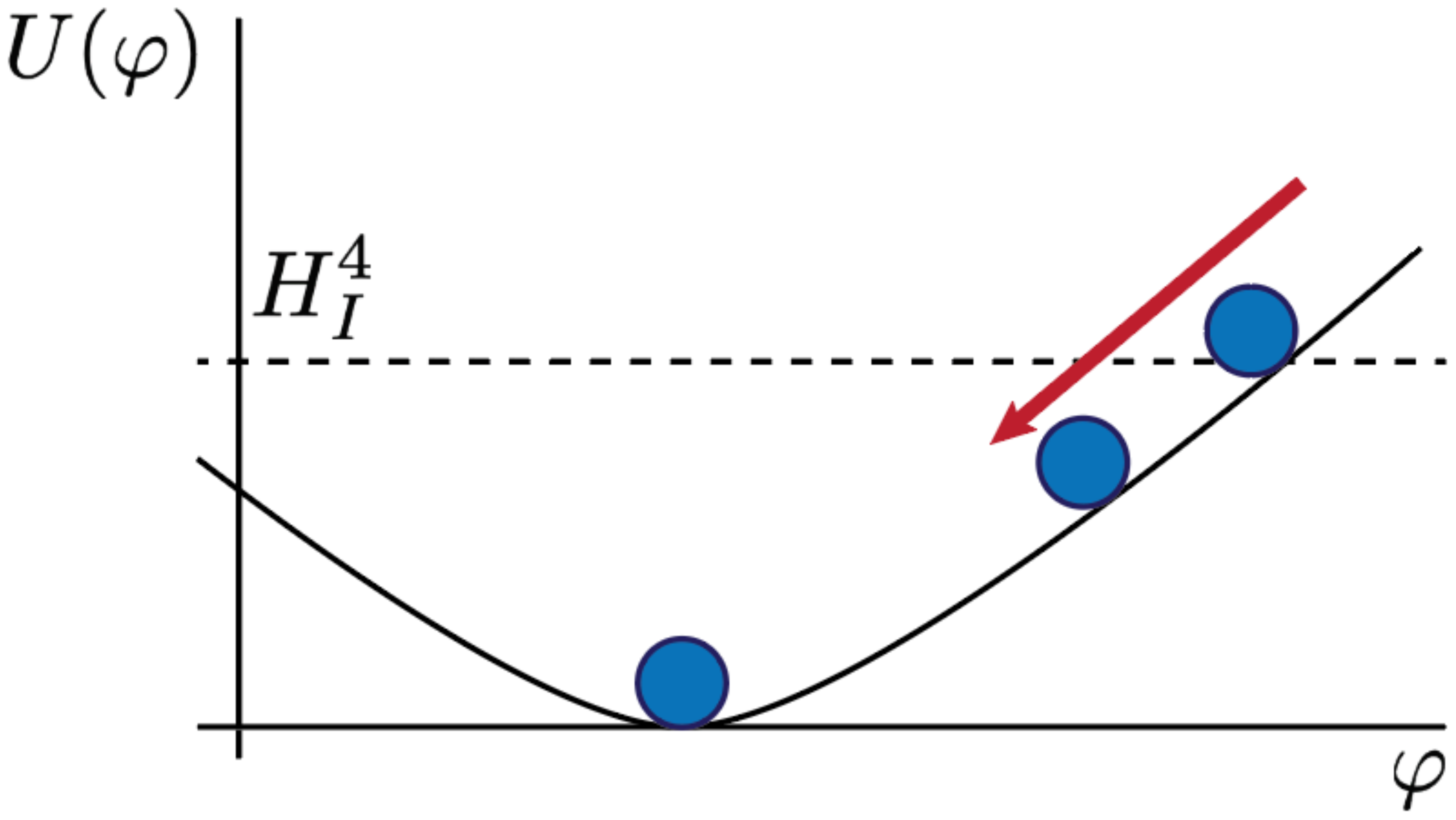
Key: Scalar fields acquire a VEV in de Sitter space during inflation

Scalar fields in de Sitter space during inflation

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

&

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



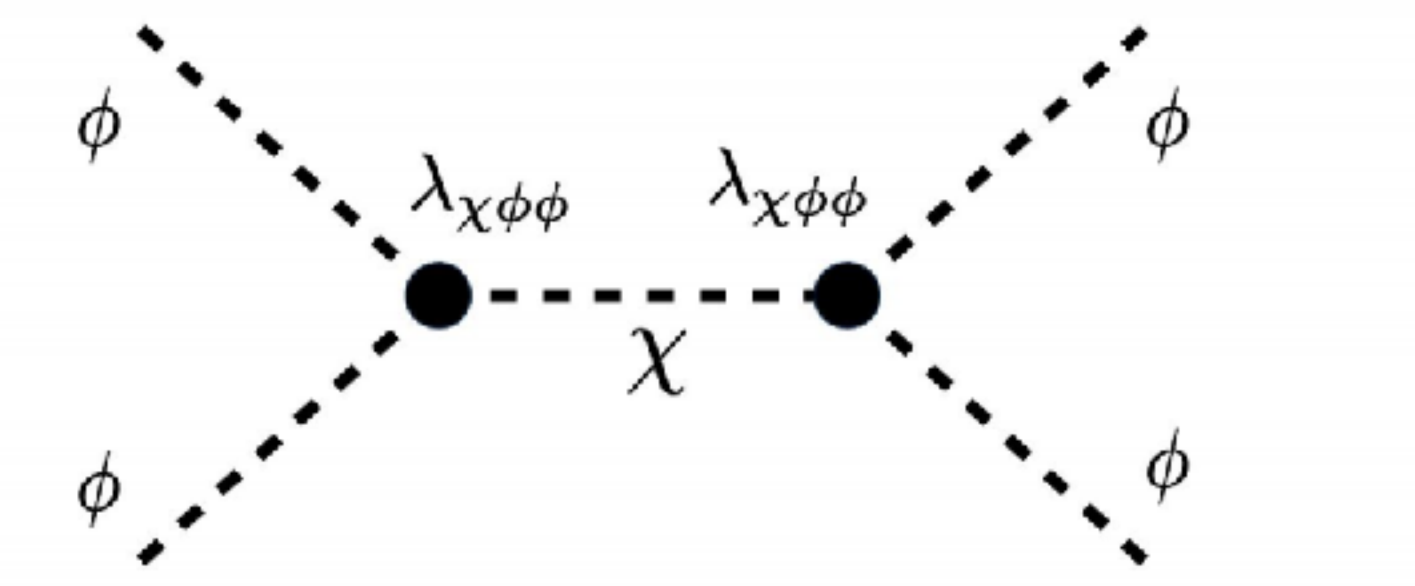
Scalar fields and fragmentation

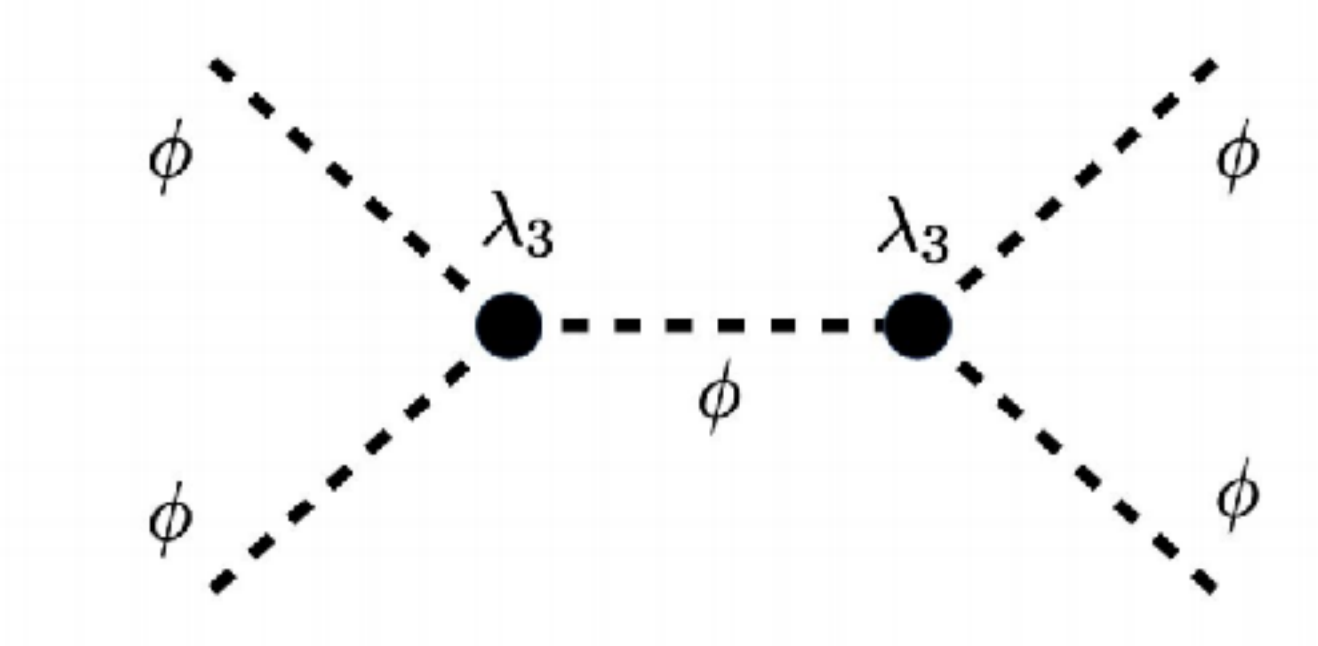
- Attractive forces induce an ***instability*** in scalar condensate

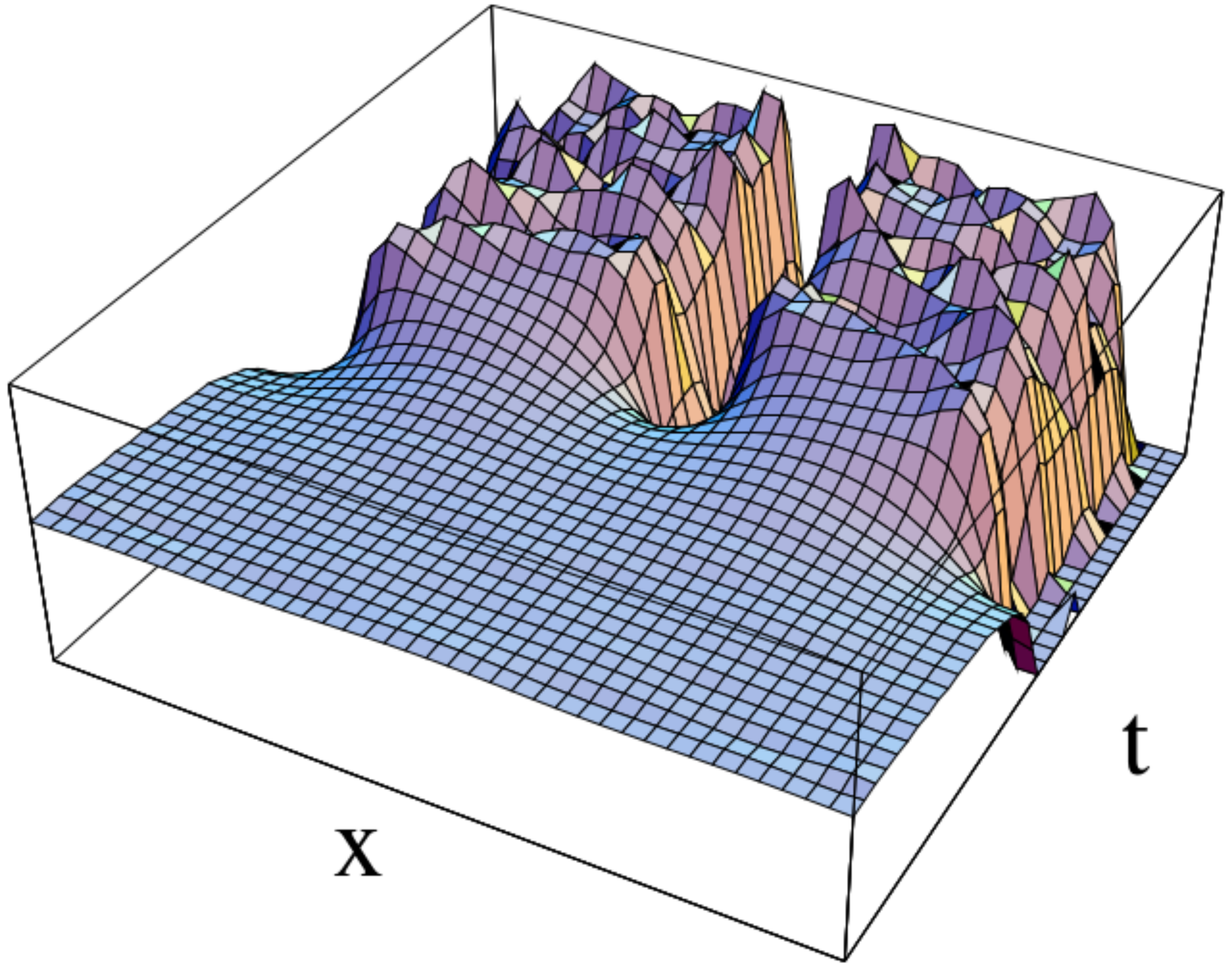
$$U(\varphi) \supset \lambda_3 \varphi^3$$

or

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







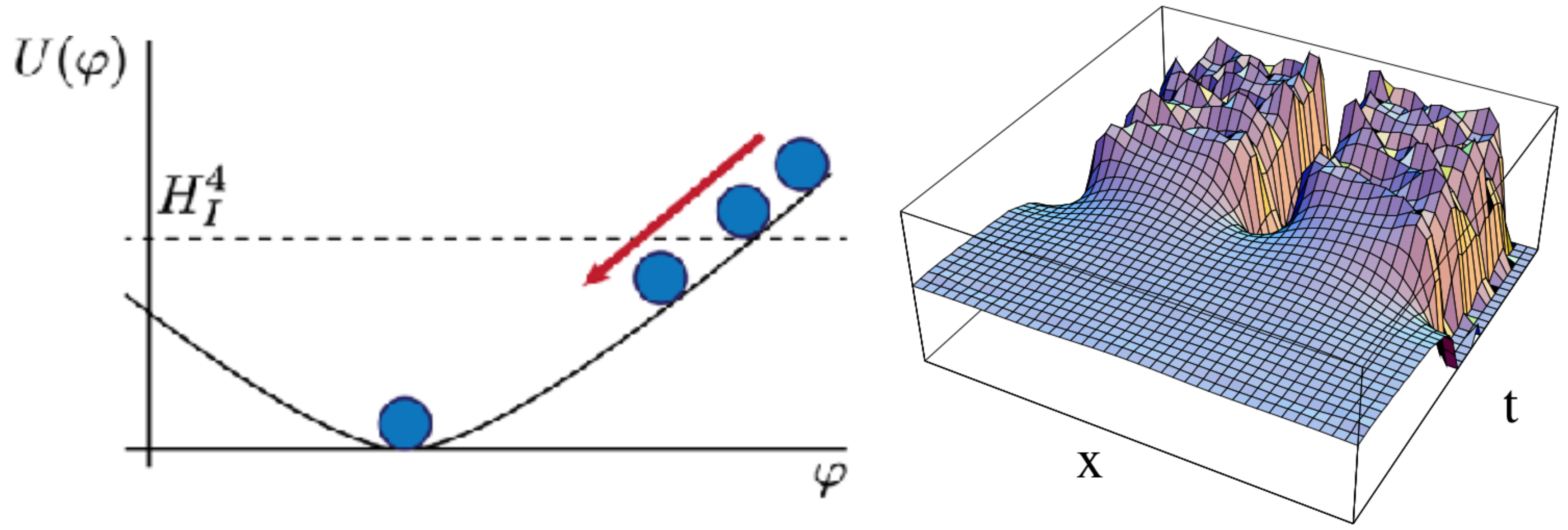
$\Longrightarrow$ Leads to the formation of Q-balls

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

From inflation to Q-balls

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

Inflation
&
Development of Large VEV



Sliding Down the Potential
&
Scalar Fragmentation

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

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

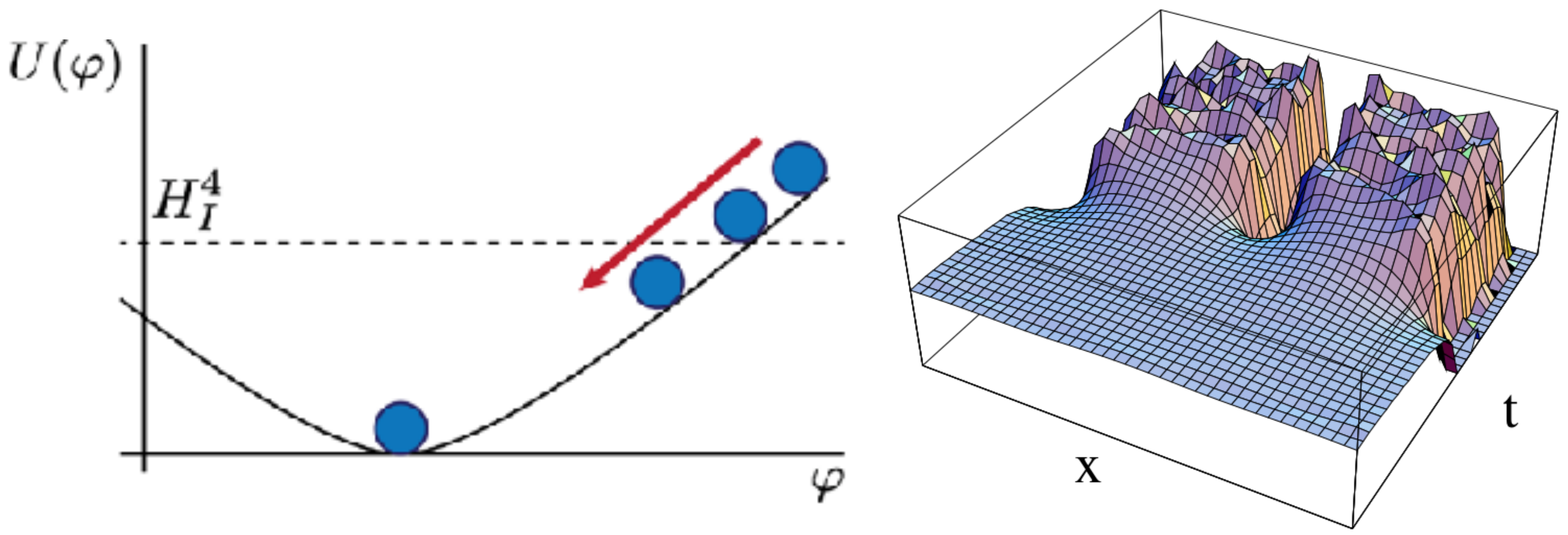
Q-ball Formation

[Cotner, Kusenko, Sasaki, Takhistov, JCAP 1910 (2019) 077]

From inflation to Q-balls

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

Inflation
&
Development of Large VEV



Sliding Down the Potential
&
Scalar Fragmentation

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

Q-ball Formation

Intermediate matter domination & gravitational forces *can* produce PBHs

$\Longrightarrow$ *but* it’s very inefficient
$\Longrightarrow$ need special, spherical configurations

[Cotner, Kusenko, Sasaki, Takhistov, JCAP 1910 (2019) 077]

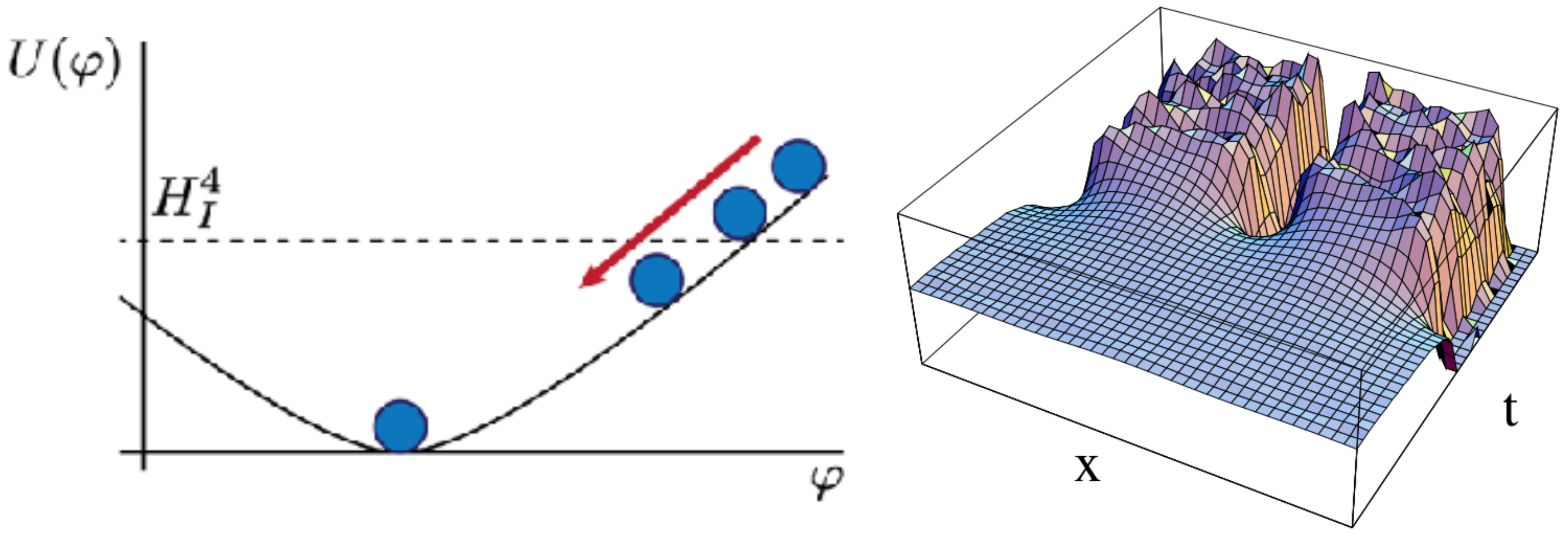
From inflation to Q-balls

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

Inflation

&

Development of Large VEV



Sliding Down the Potential

&

Scalar Fragmentation

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

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

Q-ball Formation

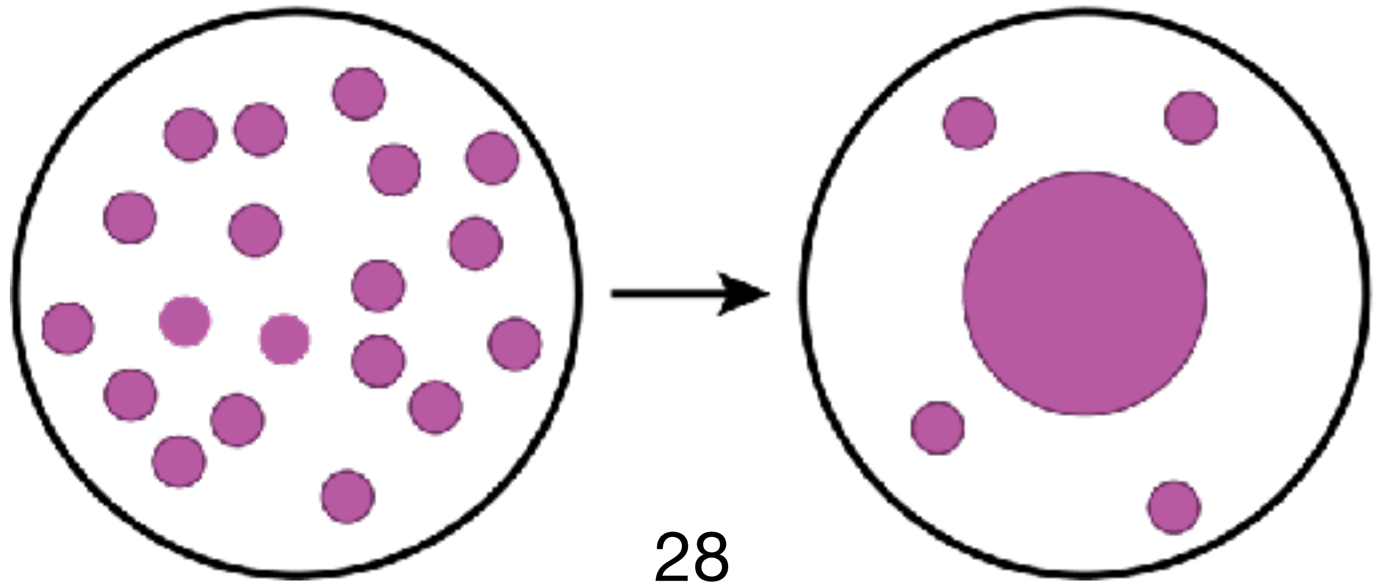
Scalar Forces

&

Scalar Radiation

$$\tau_{\text{cool}} = \frac{E}{dE/dt} = \frac{E}{P_{\text{brem}} + P_{\text{surf}} + \cdots}$$

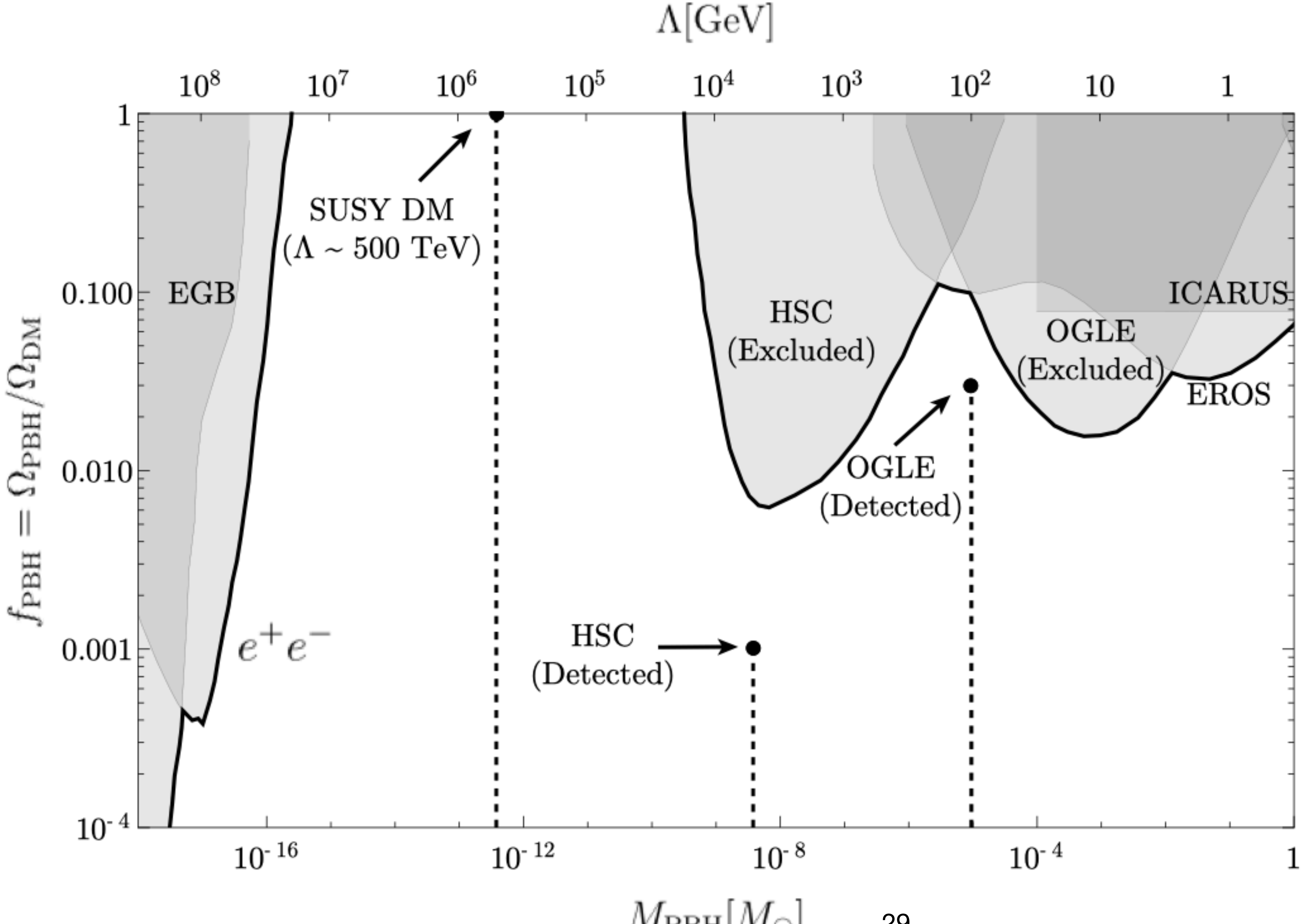
Mergers lead to larger and larger charges



PBH Formation

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

PBHs from Scalar Forces & SUSY Q-balls



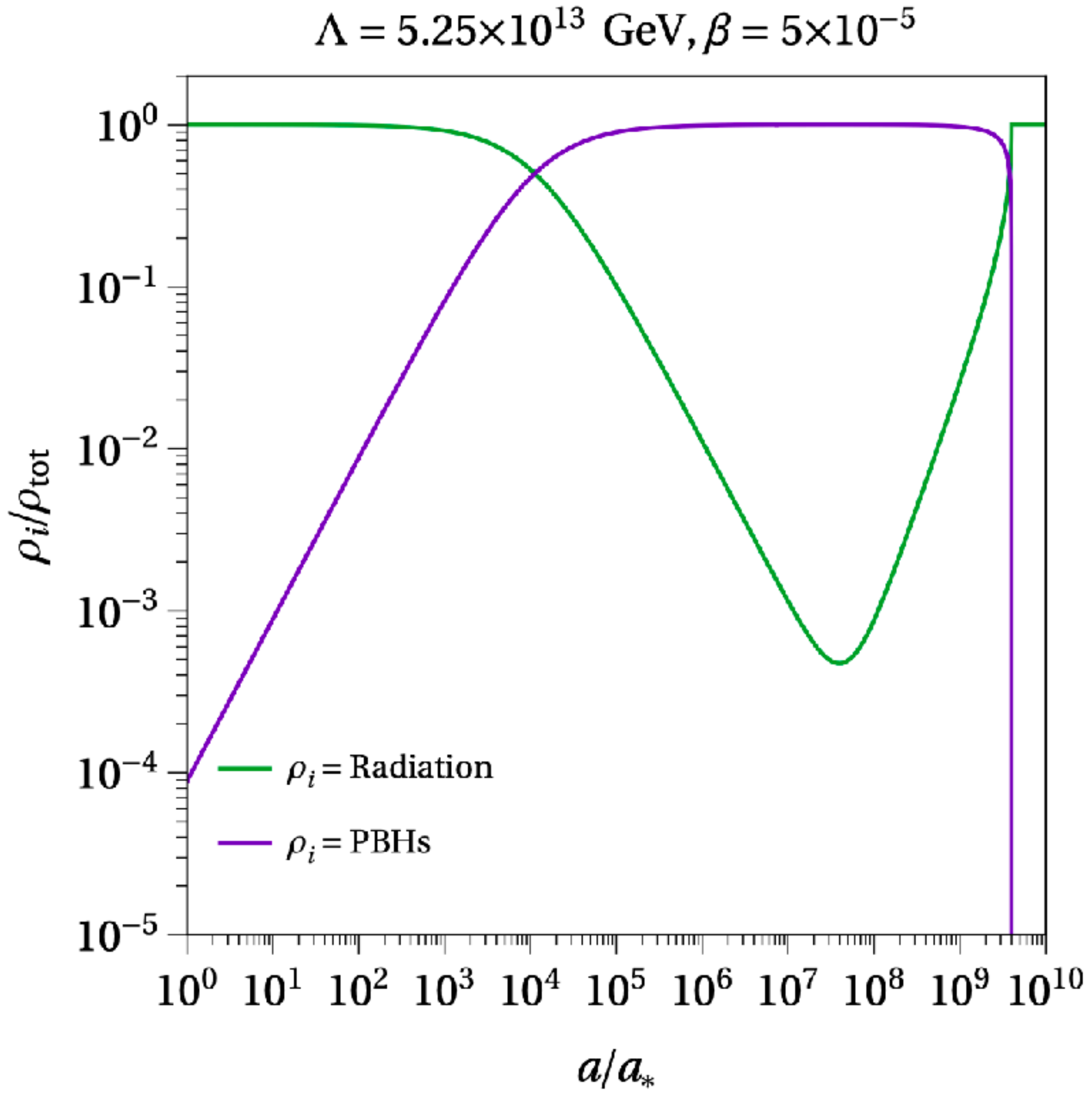
$$M_{\rm PBH} \sim 10^{22}\, g \left(\frac{100\ {\rm TeV}}{\Lambda}\right)^2$$

Evaporating PBHs & the poltergeist mechanism

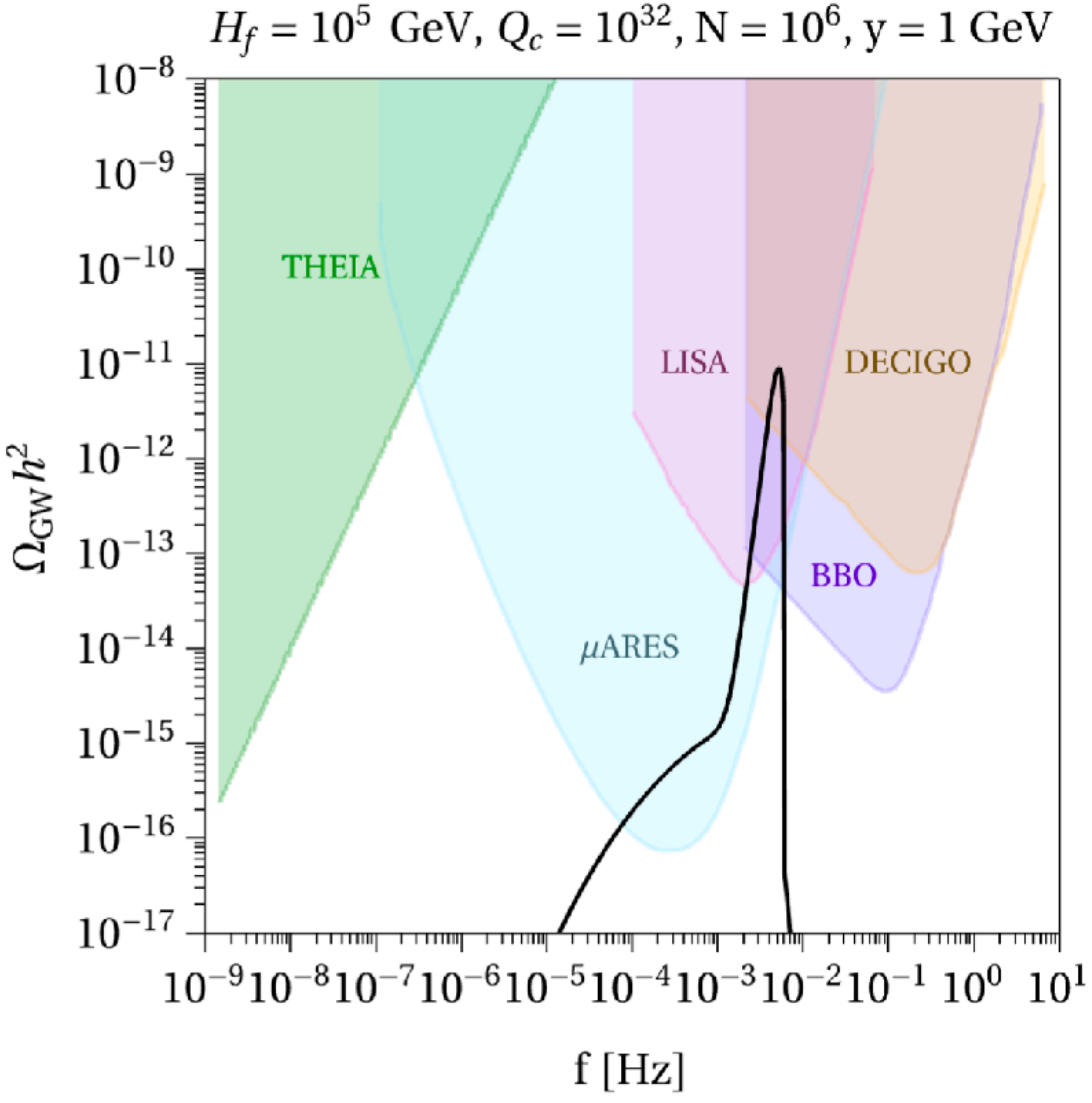
- The *poltergeist mechanism* realized in numerous physical scenarios:
  - PBH evaporation
    - [K. Inomata, M. Kawasaki, K. Mukaida, T. Terada, T. T. Yanagida]
  - Q-ball evaporation
    - [G. White, D. Vagie, A. Kusenko, L. Pearce]
  - Axion poltergeist
    - [K. Harigaya, K. Inomata, T. Terada]
  - Many more…

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

Evaporating PBHs as a test of high-scale SUSY



$\Lambda = 5.25\times10^{13}$ GeV, $\beta = 5\times10^{-5}$



$H_f = 10^5$ GeV, $Q_c = 10^{32}$, N $= 10^6$, y = 1 GeV

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

Observational implications: PBH 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.
- Angular momentum losses can be considered in two contexts:
  - Oscillatory channels (coherent/incoherent)
  - Non-oscillatory channels (bremsstrahlung/surface)

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):

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

- 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 [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]

Observational implications of early 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***

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

- It's still not obvious which methodology is best suited to tackling this problem
    - Standard methods, like cosmological perturbation theory <u>*do not*</u> 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

$\Downarrow$

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

$\Downarrow$

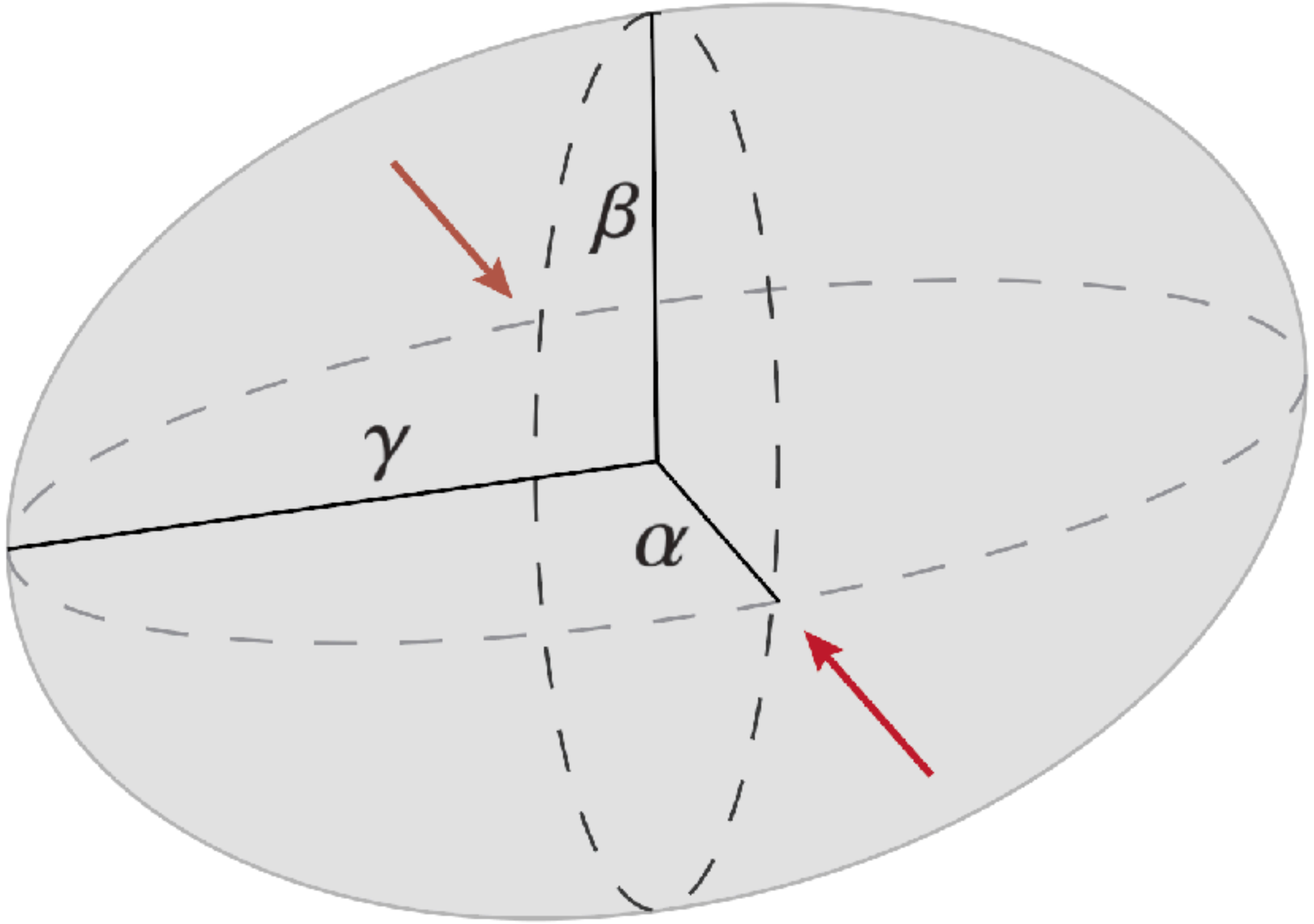
Collapse begins

$\Downarrow$

“Pancake” forms and shell crossing occurs - t_{col}

$\Downarrow$

BH formation or halo annihilation



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

Growth of perturbations

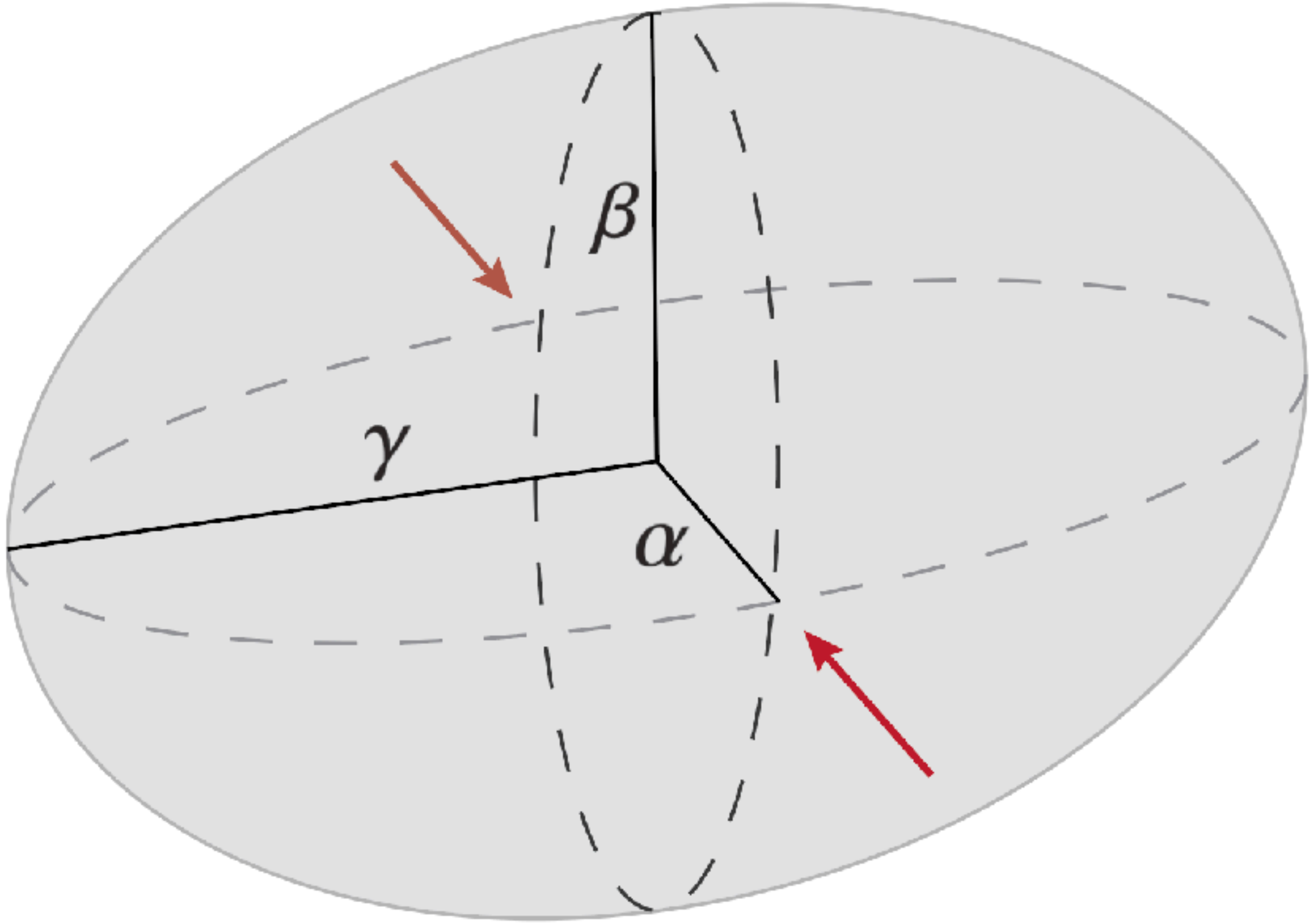
A reminder of the traditional result:

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

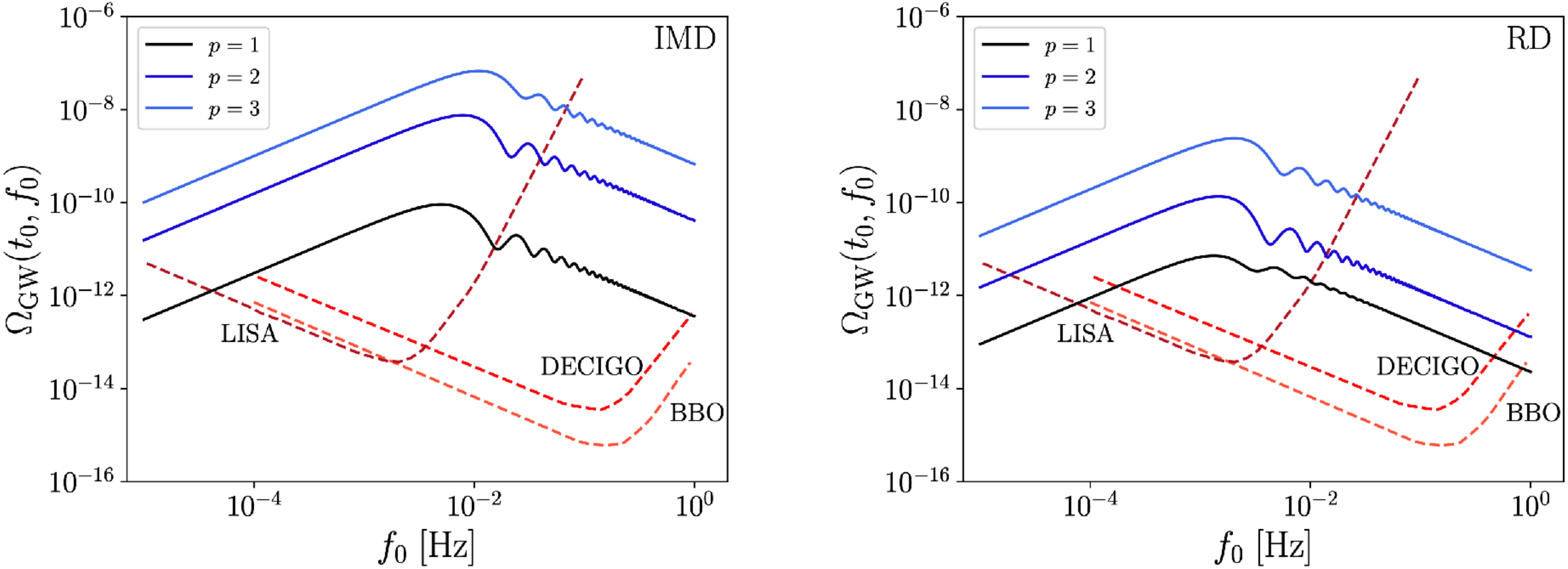
Here, ***<u>our fundamental assumption will be that</u>***

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

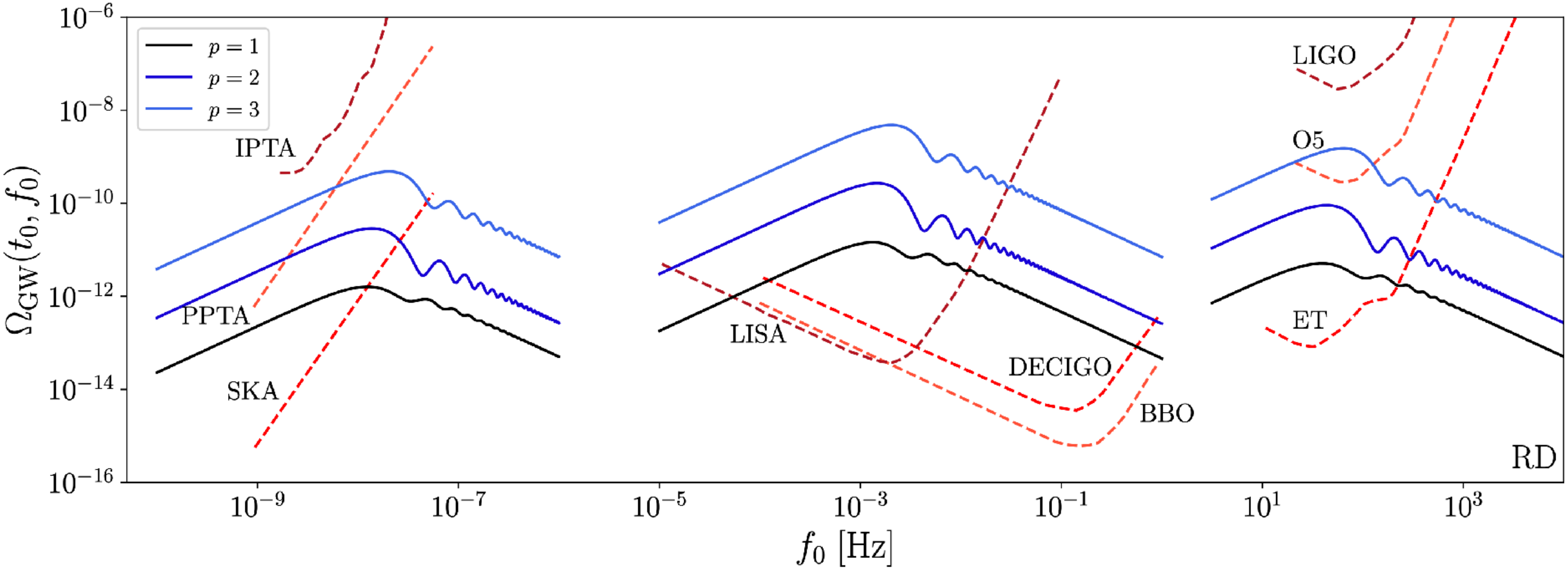
As before p characterizes the strength of the force.



GW Spectrum

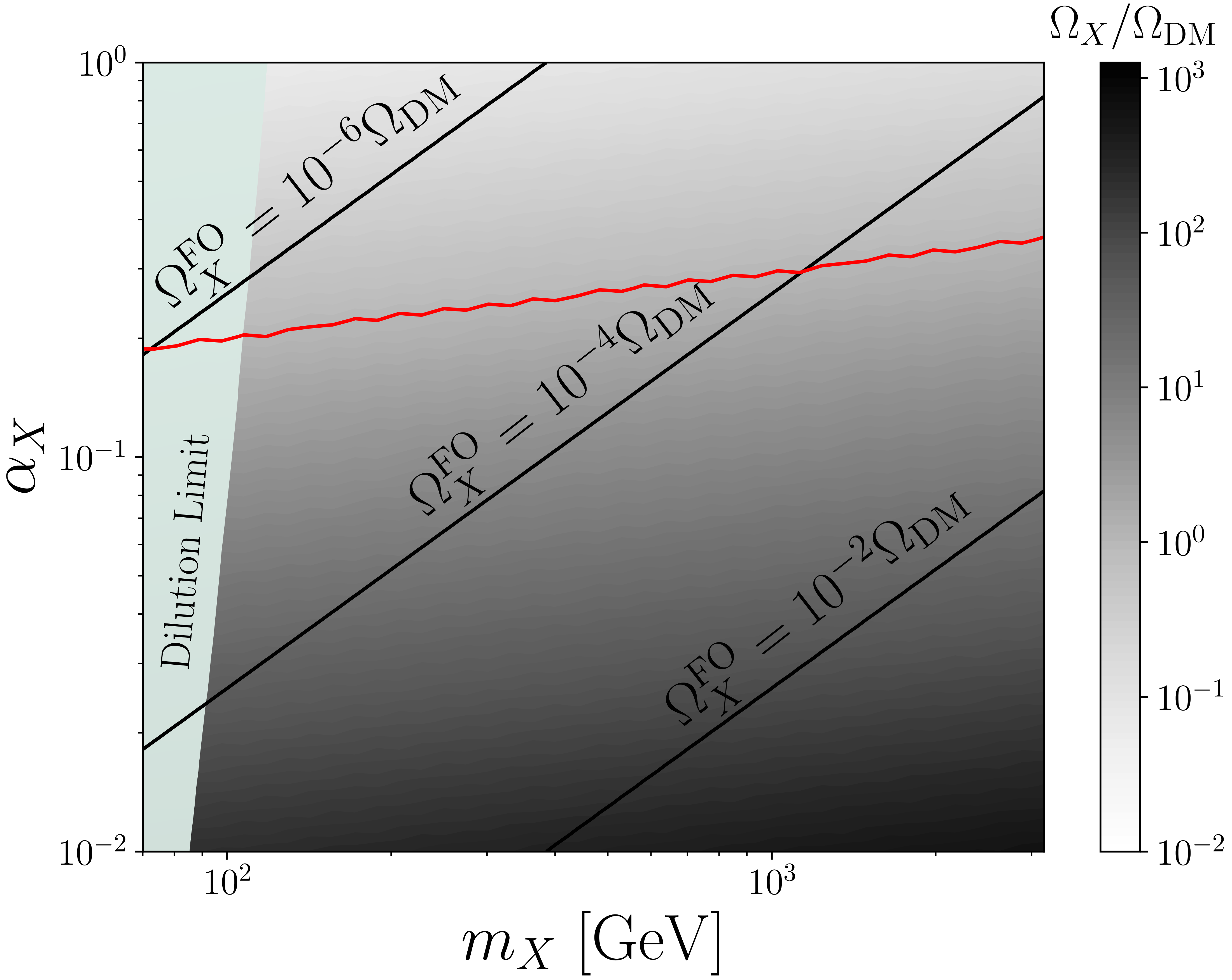

$p = 1$
$p = 2$
$p = 3$
IMD
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
$\Omega_{\rm GW}(t_0, f_0)$
LISA
DECIGO
BBO
10^{-4}
10^{-2}
10^{0}
f_0 [Hz]
$p = 1$
$p = 2$
$p = 3$
RD
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
$\Omega_{\rm GW}(t_0, f_0)$
LISA
DECIGO
BBO
10^{-4}
10^{-2}
10^{0}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

GW Spectrum


$p = 1$
$p = 2$
$p = 3$
IPTA
PPTA
SKA
LISA
DECIGO
BBO
LIGO
O5
ET
RD
$\Omega_{\rm GW}(t_0, f_0)$
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}
f_0 [Hz]

Before moving on…

- Early structure formation has proven useful in areas of cosmology *outside of PBH formation:*
  - Matter-antimatter asymmetry
    - [**MMF**, A. Kusenko, L. Pearce, G. White, 2208.09789]
  - Dark matter production ($\Longrightarrow$)
    - [**MMF**, C. Kouvaris, A. Kusenko, 2306.04056]
  - Large-scale magnetic fields
    - [R. Durrer, A. Kusenko; 2209.13313]

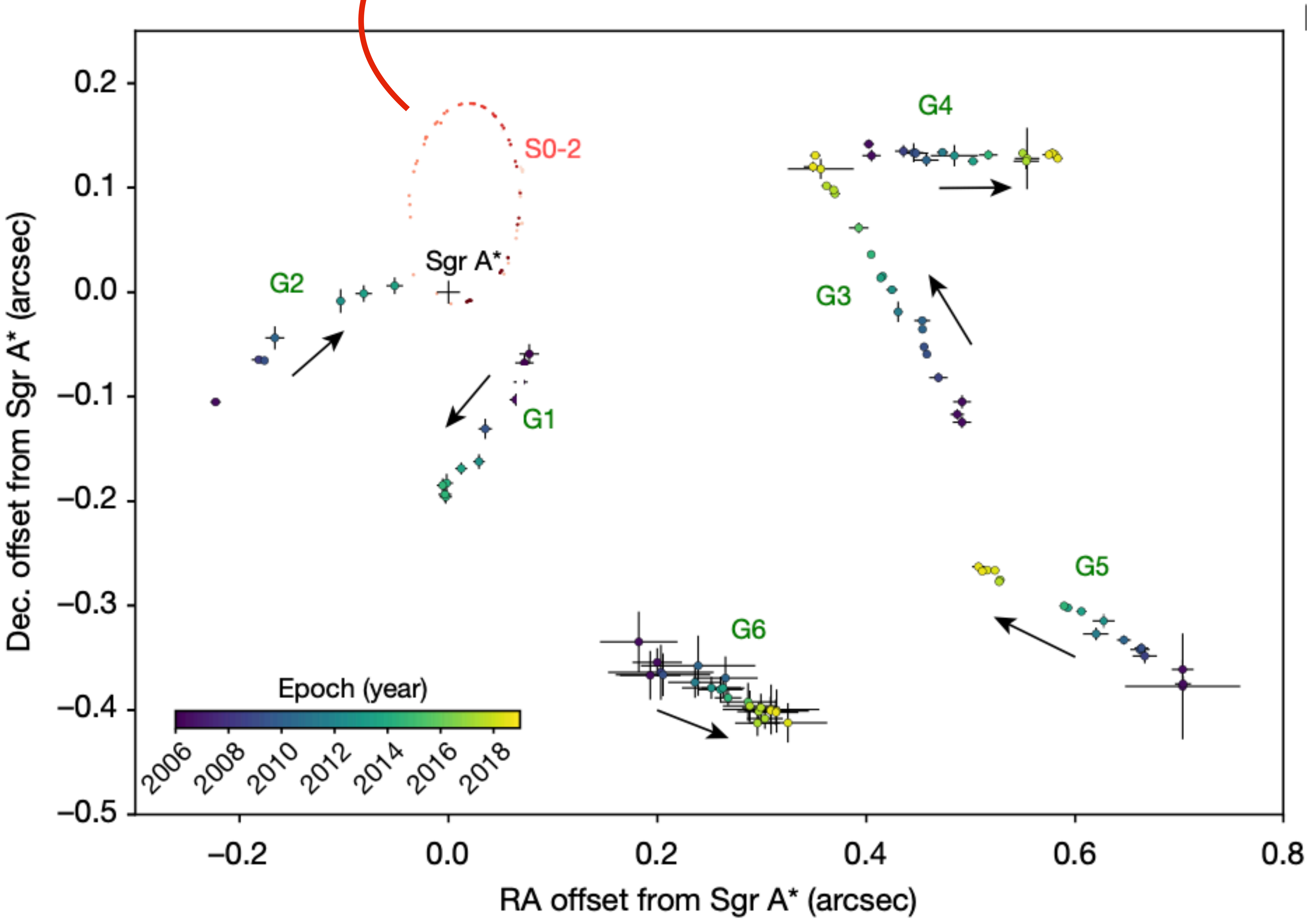


Primordial black holes and the Galactic Center

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

Brief review of G objects

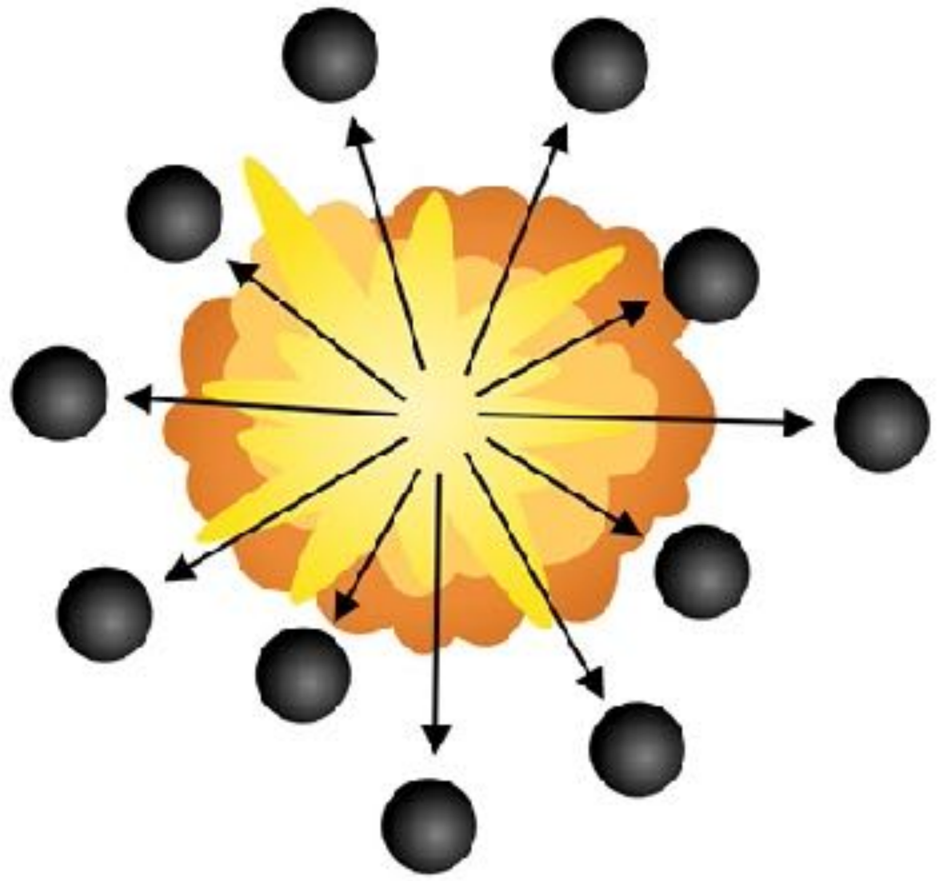
- Population of unresolved objects which show both ***thermal and dust emission***.
- Simultaneously, they display the ***dynamical properties of stellar-mass objects***
- These objects, particularly $G2$, seem ***resilient*** to tidal disruption
- Various proposed formation mechanisms:
  - **Merger 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)



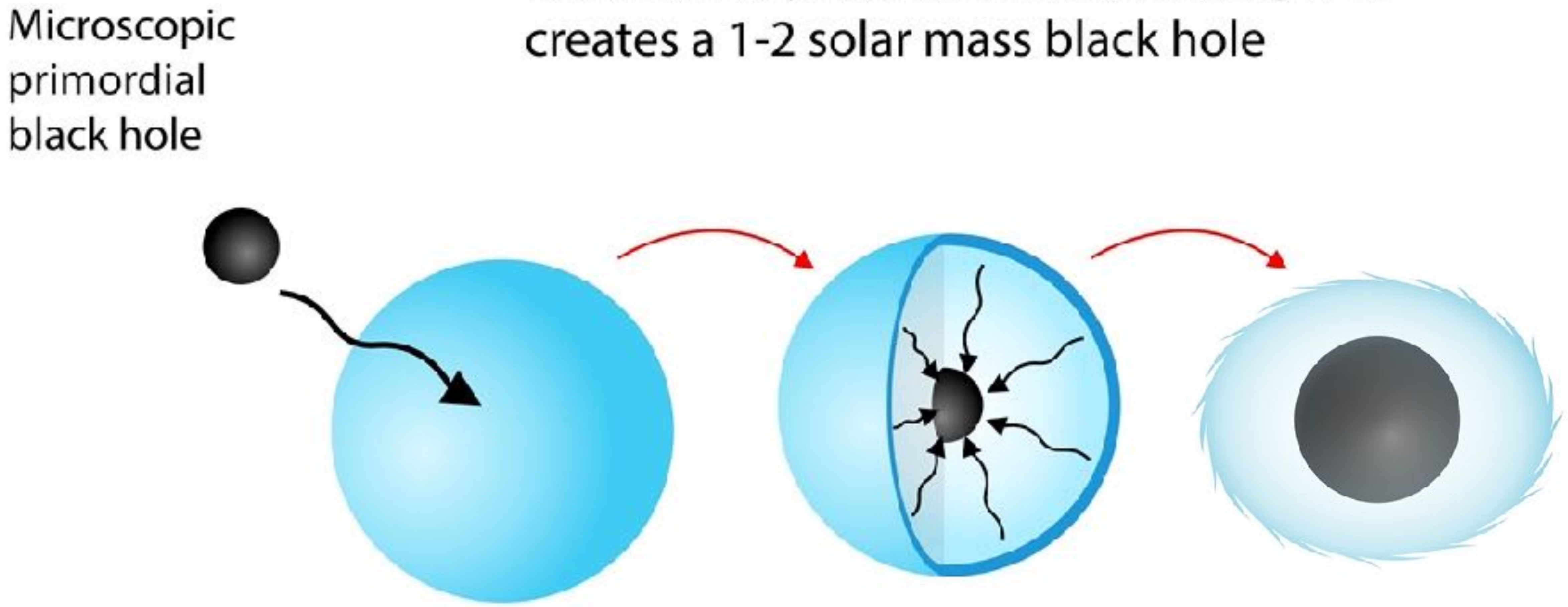
[Ciurlo et. al. 2020]

PBH-Neutron star interactions

1. Primordial black holes produced in Big Bang make up part or all of dark matter.



2. A microscopic black hole falls into a neutron star, eats it from the inside, and creates a 1-2 solar mass black hole



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

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

[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

$$\langle t_{\mathrm{NS}} \rangle = \underbrace{F^{-1}}_{\text{PBH-NS capture rate}} + \overbrace{t_{\mathrm{loss}}}^{\text{Time for PBH to settle in core of NS}} + \underbrace{t_{\mathrm{con}}}_{\text{Accretion timescale}}$$

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

PBH-Neutron star interactions

Capture rate is given by:

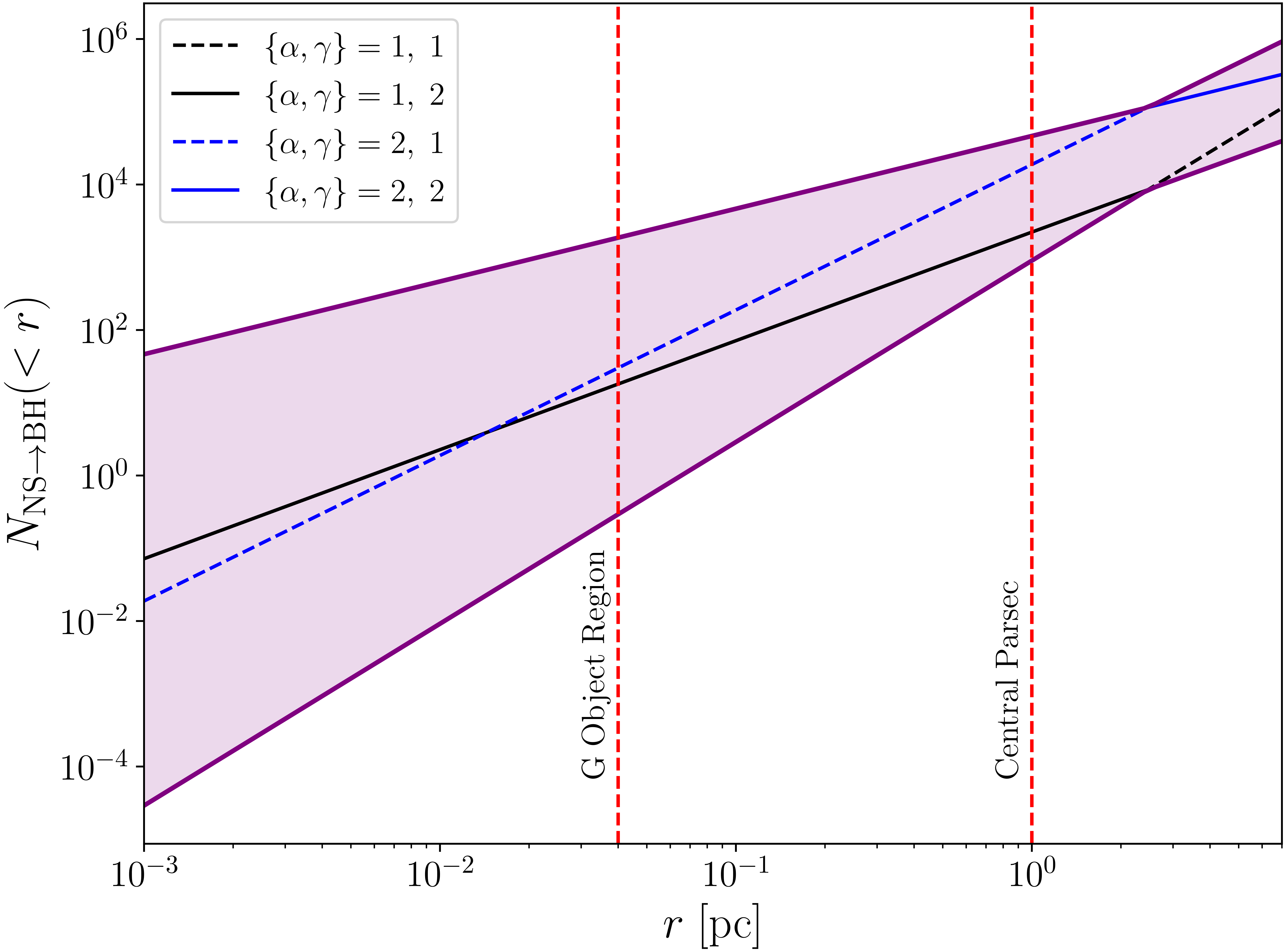
$$F = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} F_0^{\rm MW}$$

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]

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.

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

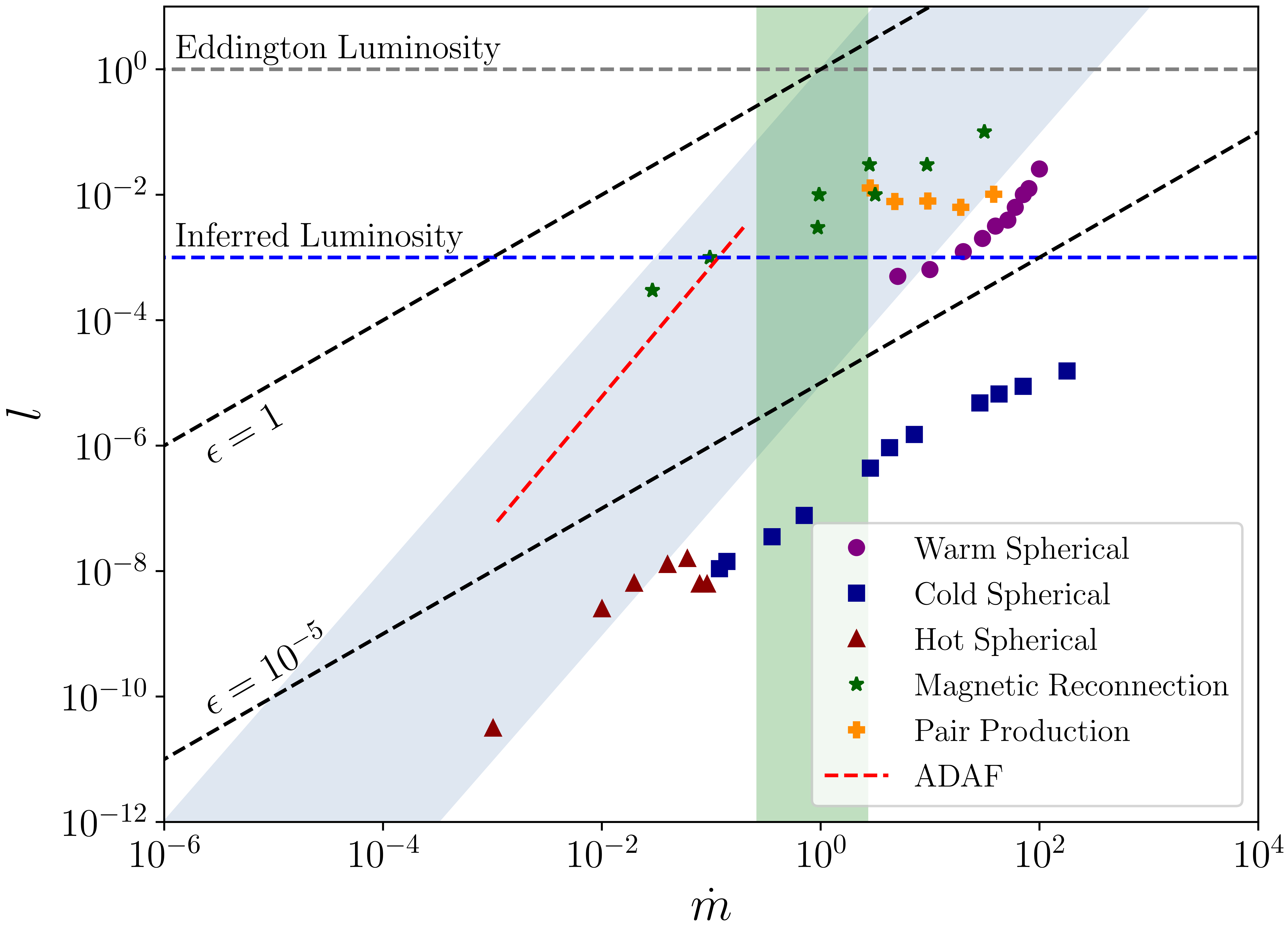
Define the efficiency,

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

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

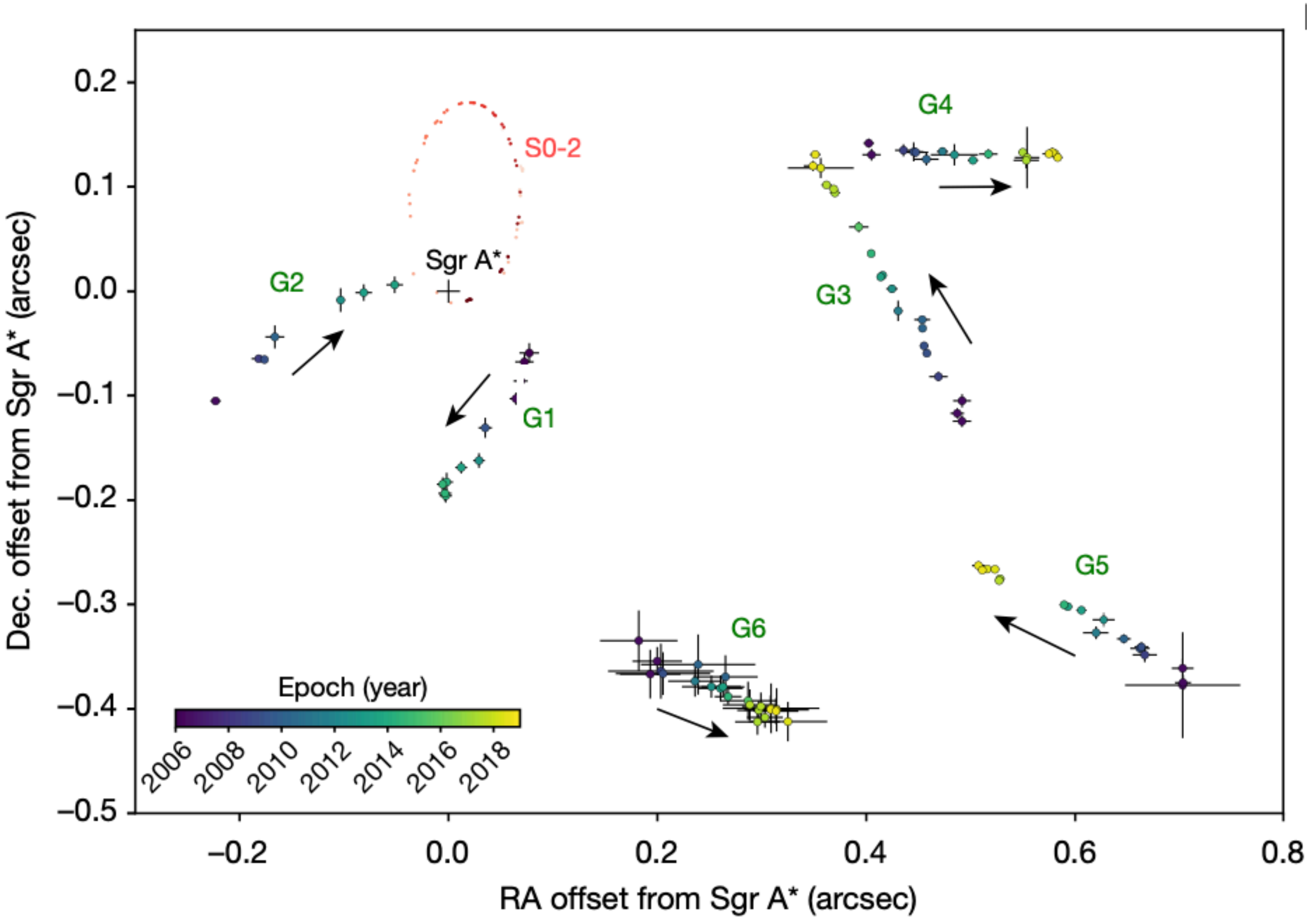
Key: Parameterize theoretical and observational uncertainty in η

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

- Early 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
    - G objects
    - Many more out there!