credit: Kavli IPMU

# Diffuse Axion Background

Joshua Eby
Oskar Klein Centre
Stockholm University

*Athens symposium on Exploring the Universe*
*ATHEXIS*
*2024/06/10*

**Based on**

**Eby**, Shirai, Stadnik, Takhistov (2106.14893)
Arakawa, **Eby**, Safronova, Takhistov, Zaheer (2306.16468)
Arakawa, Zaheer, **Eby**, Takhistov, Safronova (2402.06736)
**Eby**, Takhistov (2402.00100)

EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY
COSMIC WISPERS
CA21106

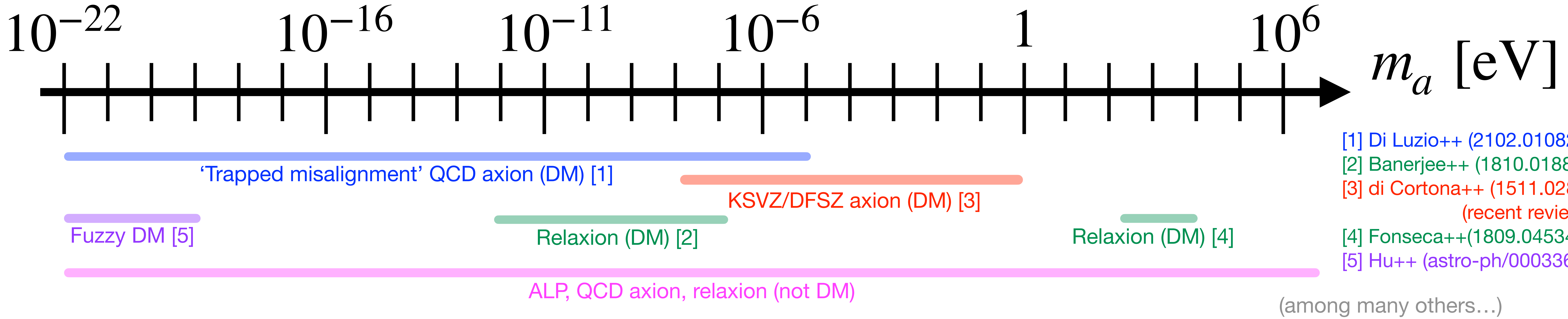
# Axions / Axion-like Particles*

*in this talk, same thing

(1) Light or ultralight

(2) Scalar or pseudoscalar

(3) Dark matter or not



‘Trapped misalignment’ QCD axion (DM) [1]

KSVZ/DFSZ axion (DM) [3]

Fuzzy DM [5]

Relaxion (DM) [2]

Relaxion (DM) [4]

ALP, QCD axion, relaxion (not DM)

[1] Di Luzio++ (2102.01082)
[2] Banerjee++ (1810.01889)
[3] di Cortona++ (1511.02867) (recent review)
[4] Fonseca++(1809.04534)
[5] Hu++ (astro-ph/0003365)

(among many others…)

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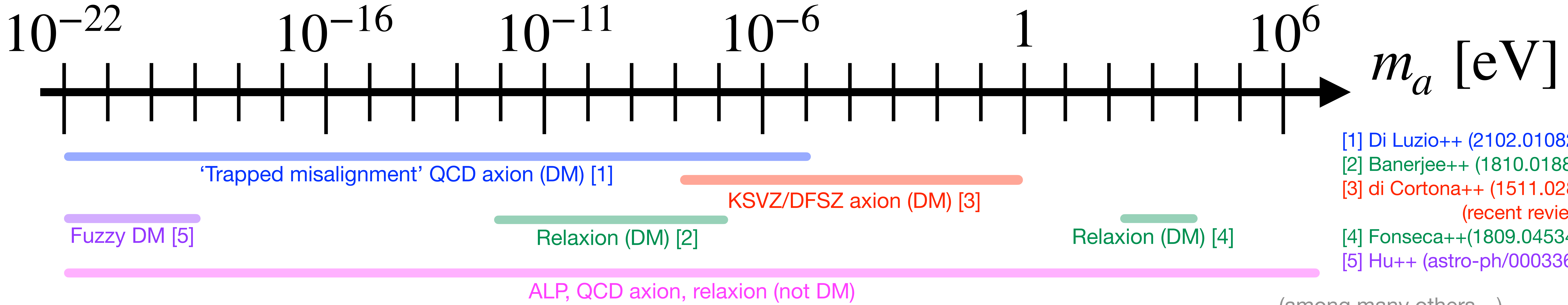

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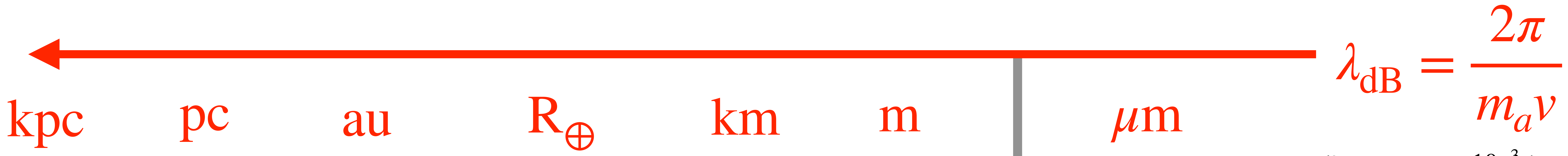


$$\lambda_{\rm dB} = \frac{2\pi}{m_a v}$$

(for $v = v_{\rm dm} = 10^{-3}c$)

macro micro

waves particles

## Solutions for the axion field

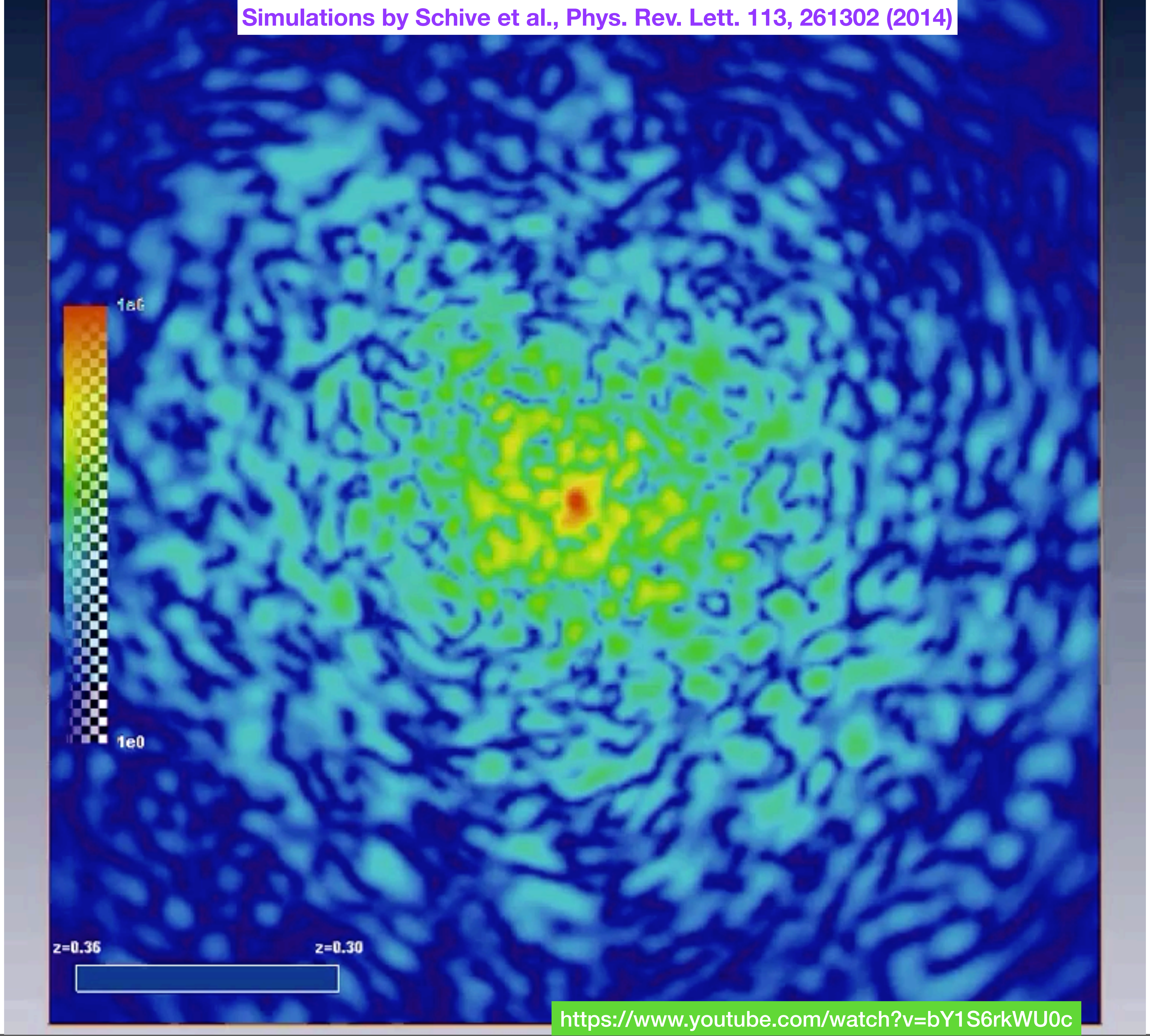
$$a(\vec{x},t) \simeq a_0 \cos\left(m_a t + m_a \vec{v}_{\rm dm} \cdot \vec{x} + \delta\right)$$

amplitude $a_0 \simeq \sqrt{2\rho_{\rm dm}}/m_a$ DM velocity arbitrary phase

Simulations by Schive et al., Phys. Rev. Lett. 113, 261302 (2014)

Density field

$$\rho(\vec{x},t) \simeq m_a^2\, a(\vec{x},t)^2$$



https://www.youtube.com/watch?v=bY1S6rkWU0c

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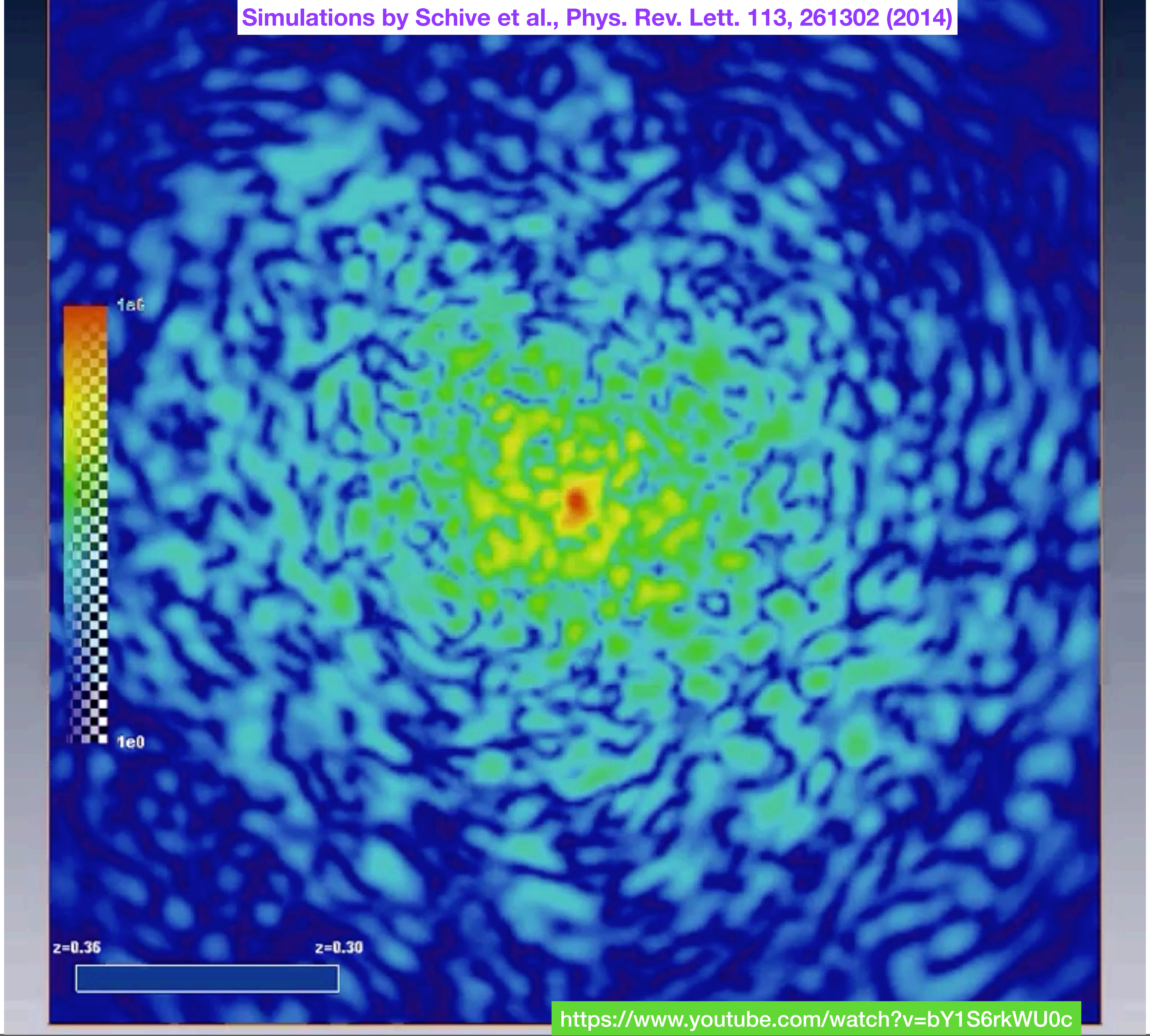

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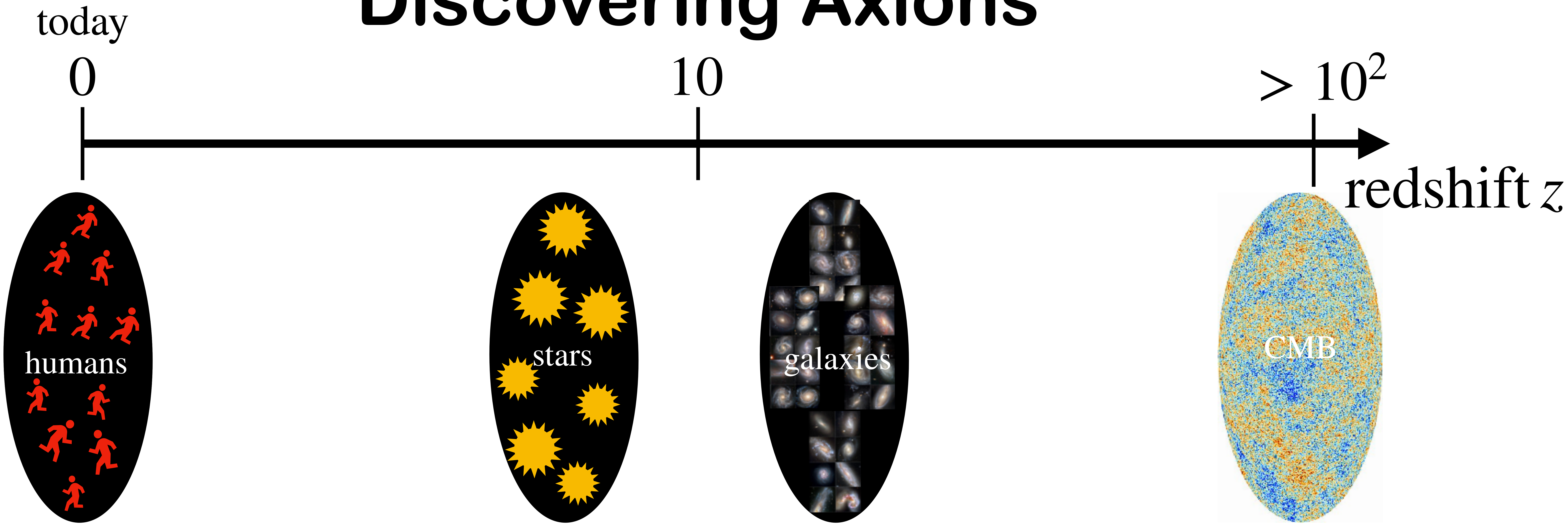
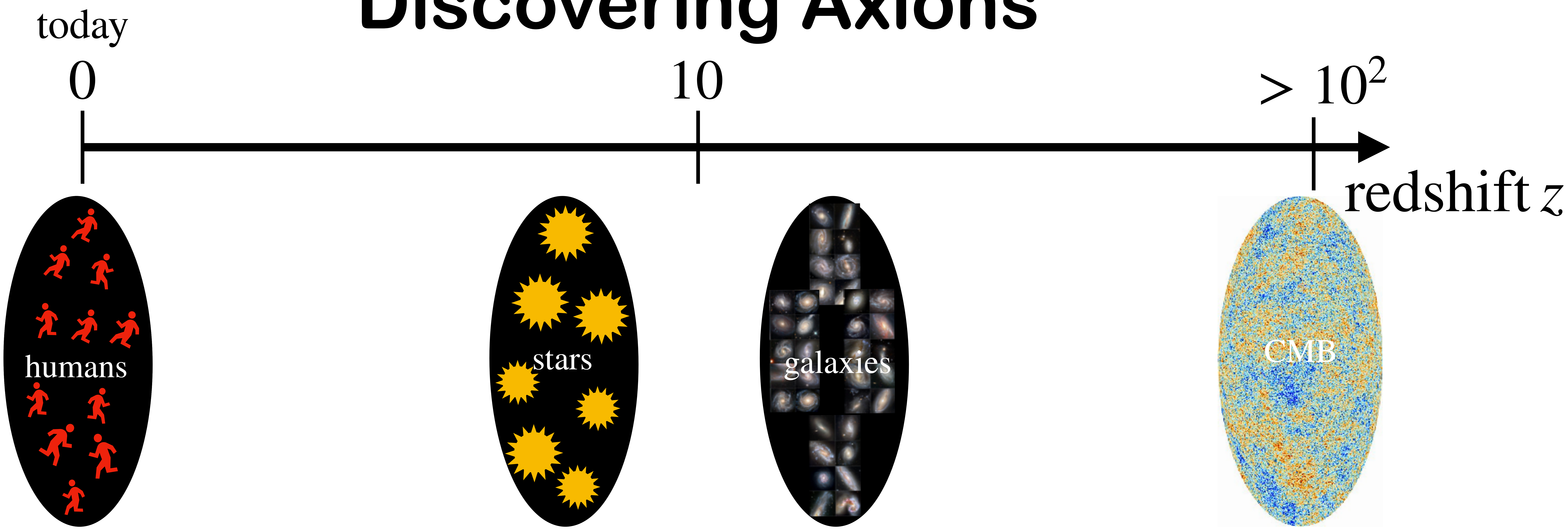
# Discovering Axions



# Discovering Axions

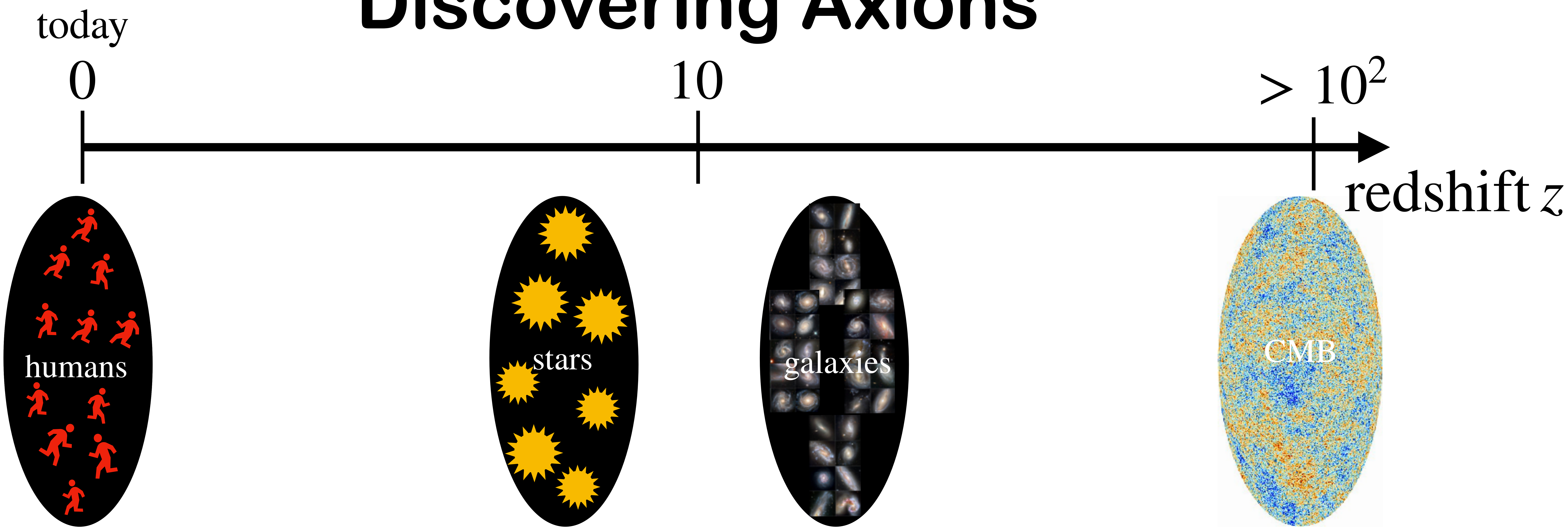


traditional DM searches

$z \sim 0$

- cold, $v_{\rm dm} \sim 10^{-3}c$
- direct detection: local DM with $\rho_{\rm dm} \simeq 0.4\,{\rm GeV/cm^3}$
- indirect detection: annihilation flux from e.g. galactic center

# Discovering Axions



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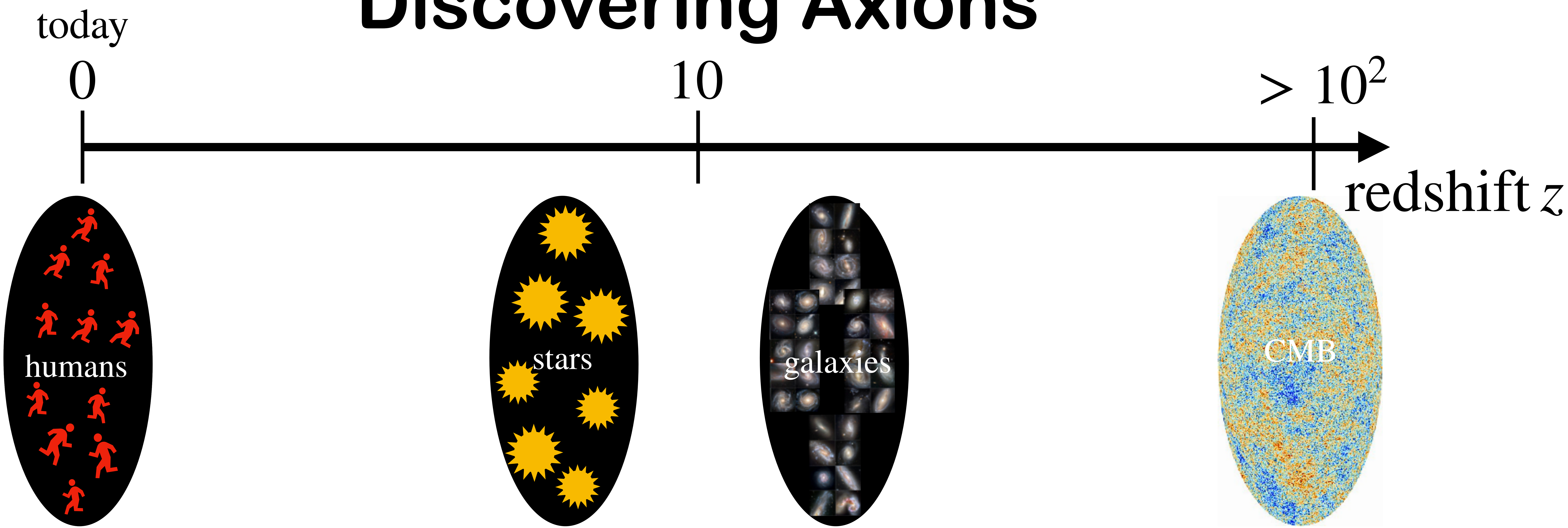
cosmic axion background

$z \gg 30$

- “Hot”, $v \sim c$
- Relativistic population of axions from cosmological sources

Conlon and Marsh (1304.1804, 1305.3603)
Dror, Murayama, Rodd (2101.09287)

# Discovering Axions



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**transient searches**

$z \sim 0 - \text{few}$

- Relativistic burst passes Earth, leaving detectable signal
- Galactic or extragalactic

**Eby**, Takhistov,
with Shirai, Stadnik (2106.14893)
with Arakawa, Safronova, Zaheer,
(2306.16468, 2402.06736)

**diffuse axion background**

$z \sim \text{few} - 30$

- build-up of large population of relativistic axions originating in astrophysical bursts
- direct and indirect signals

**Eby**, Takhistov (2402.00100)

cosmic axion background

$z \gg 30$

- “Hot”, $v \sim c$
- Relativistic population of axions from cosmological sources

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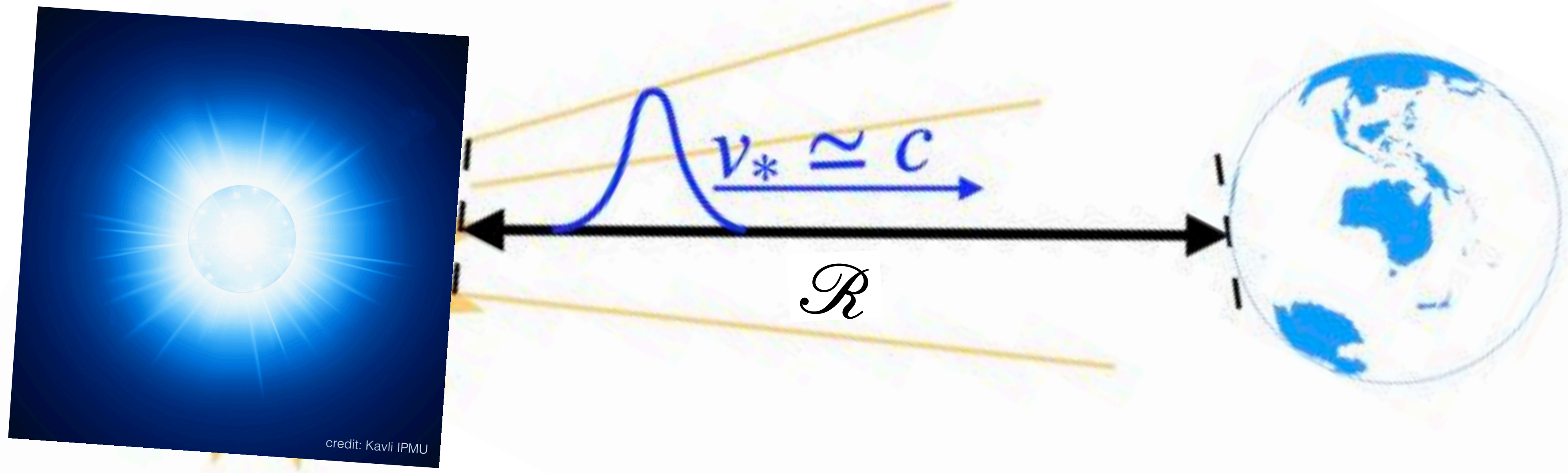
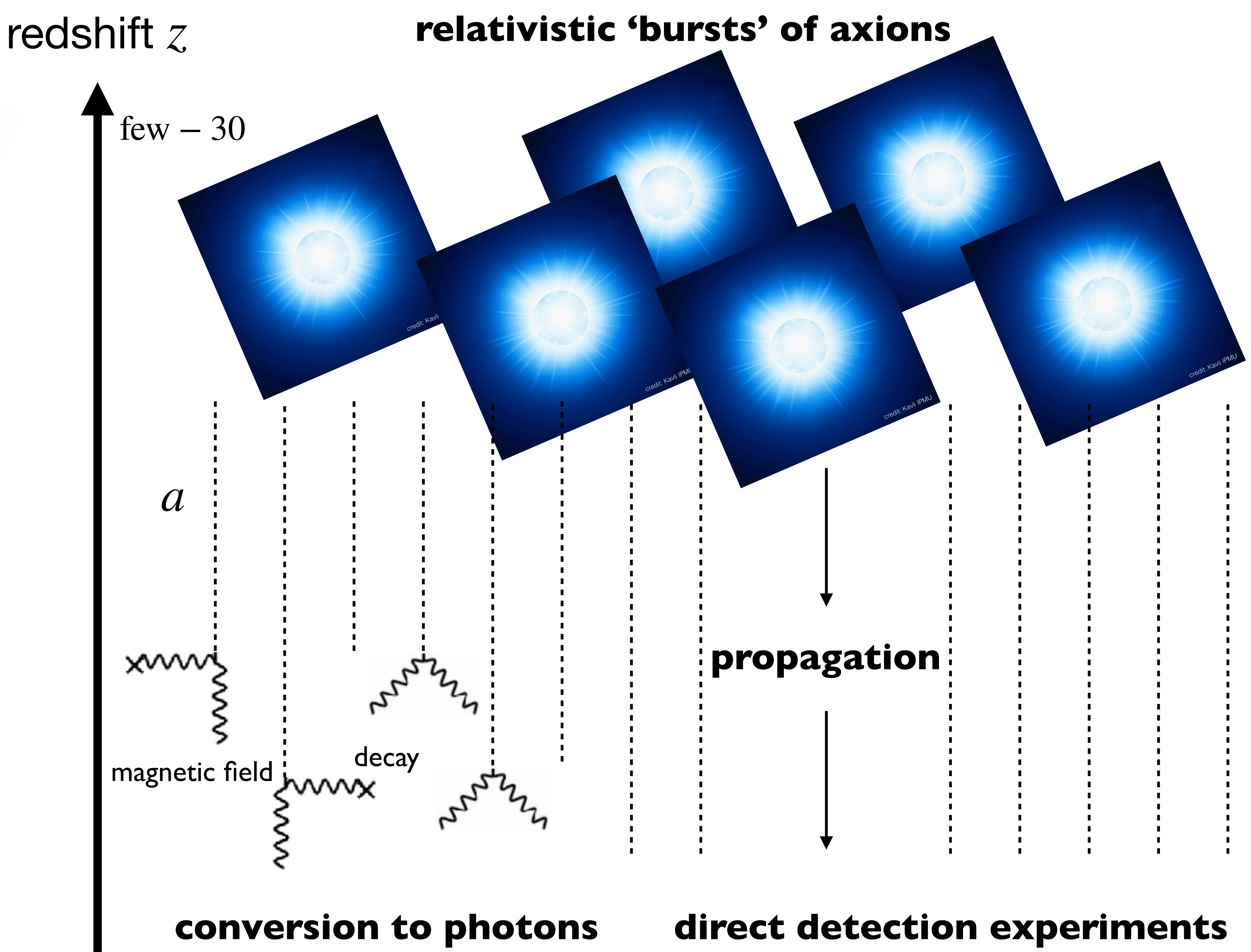
# Outline



1. Direct searches for transient signals from relativistic axion bursts



**relativistic ‘bursts’ of axions**

**propagation**

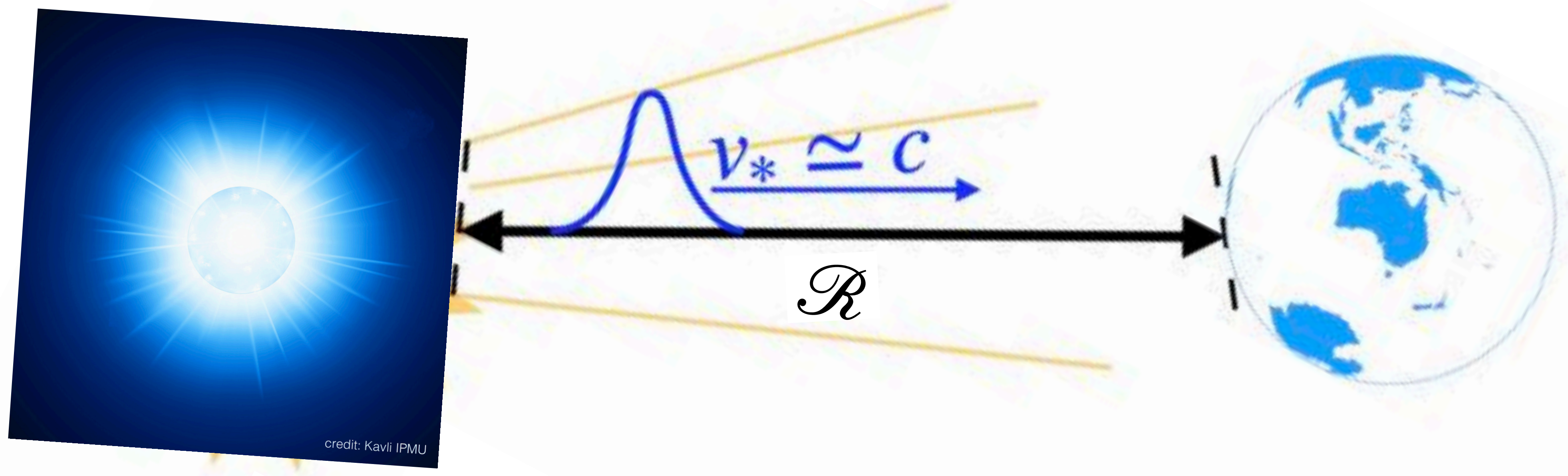
**conversion to photons**

**direct detection experiments**

**Signal**: Photons

**Signal**: Relativistic axions

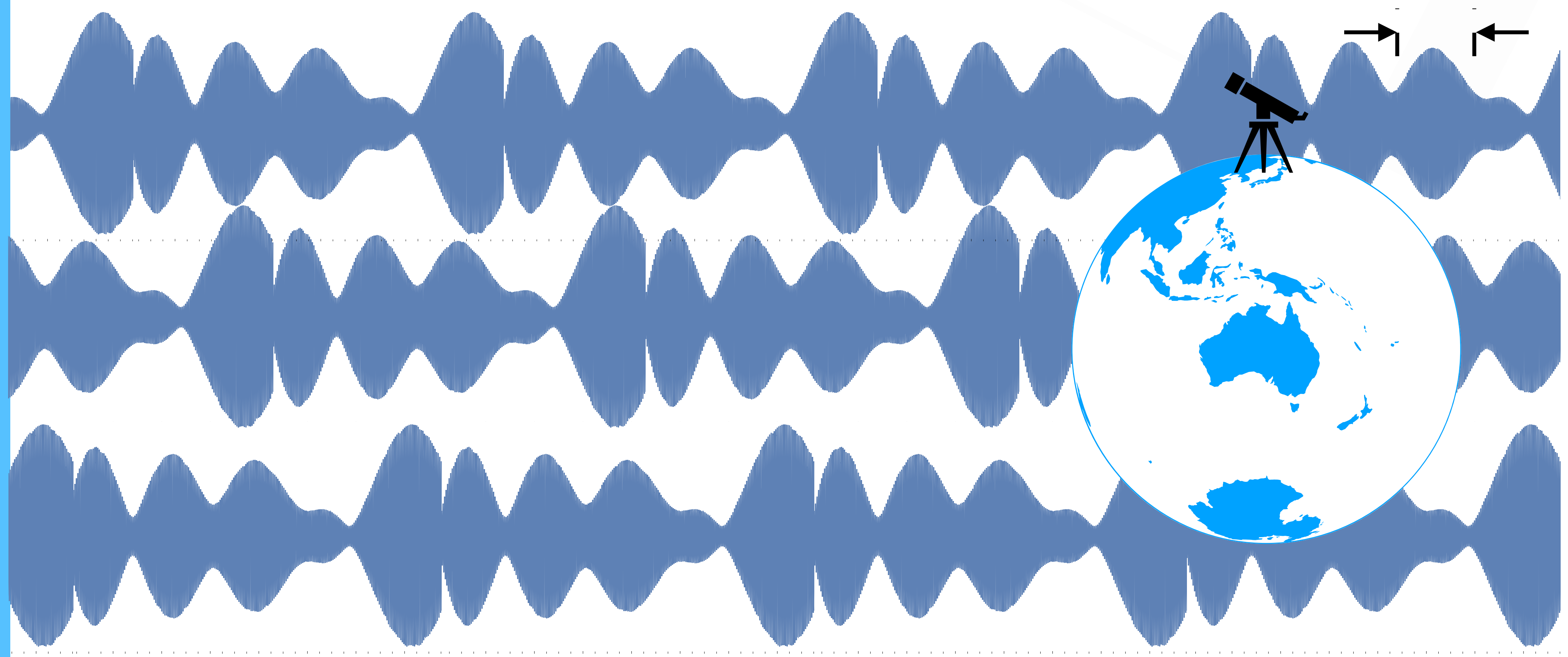
2. Diffuse Axion Background



1. Direct searches for transient signals from relativistic axion bursts

Key takeaway: DM search experiments can discover axions by detecting bursts

**c.f. Cold Dark Matter**

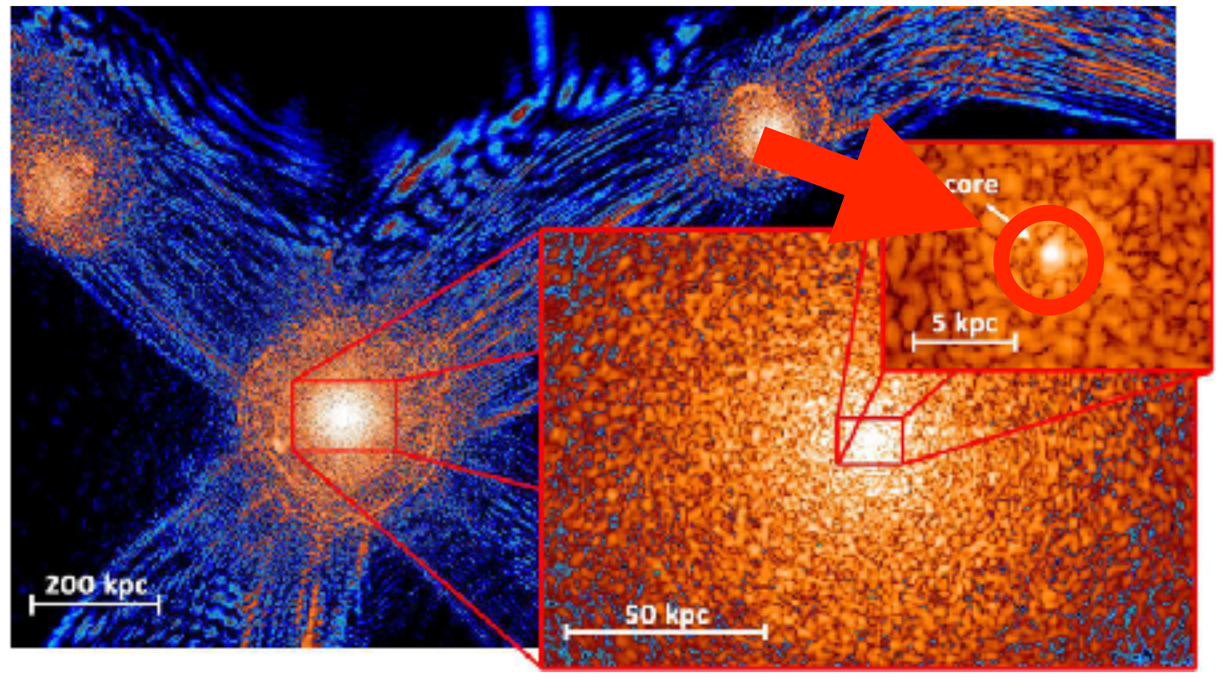


Local DM density: $\rho_{\rm dm} \simeq 0.4\,{\rm GeV/cm^3}$

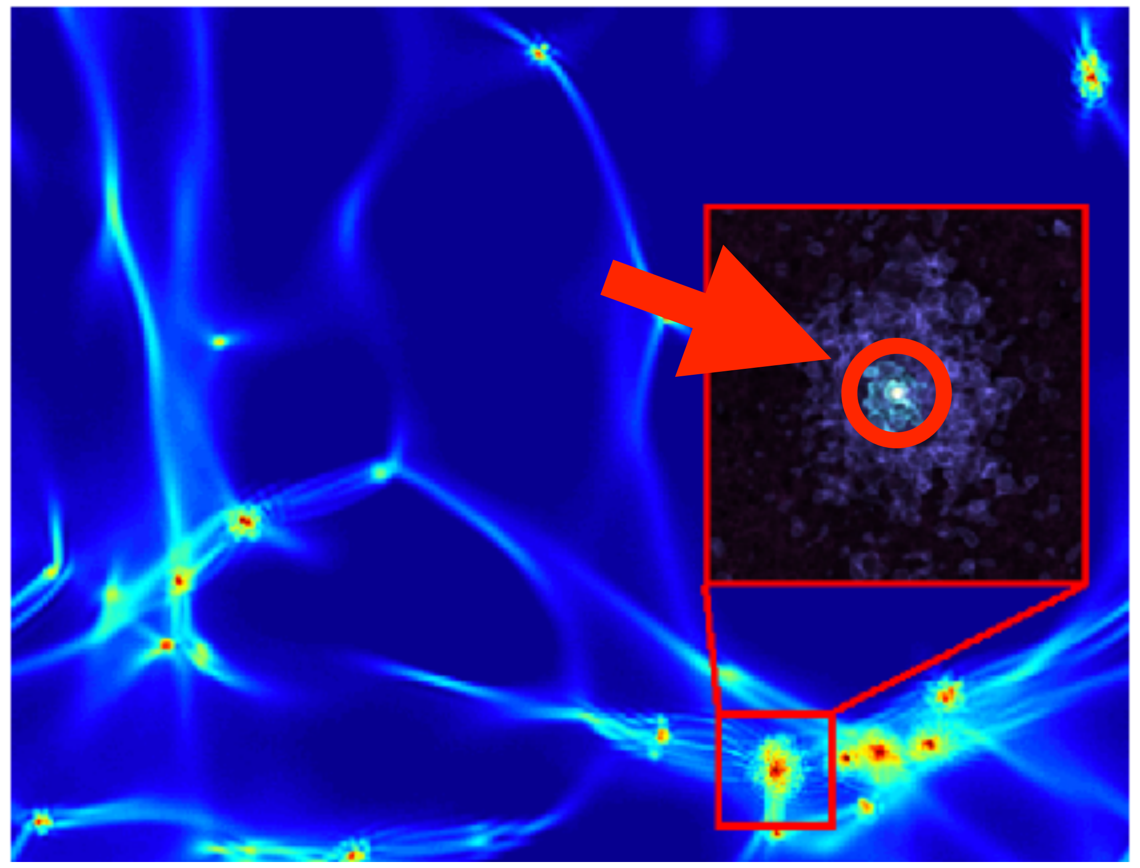
Ultralight scalars are high 'quality' oscillators: $v_{\rm dm} \simeq 10^{-3}c$

$$\tau_{\rm dm} \sim 2\pi v_{\rm dm}^{-2} m_a^{-1} \sim 10^6/m_a$$

# Burst Source of Interest: Boson Stars

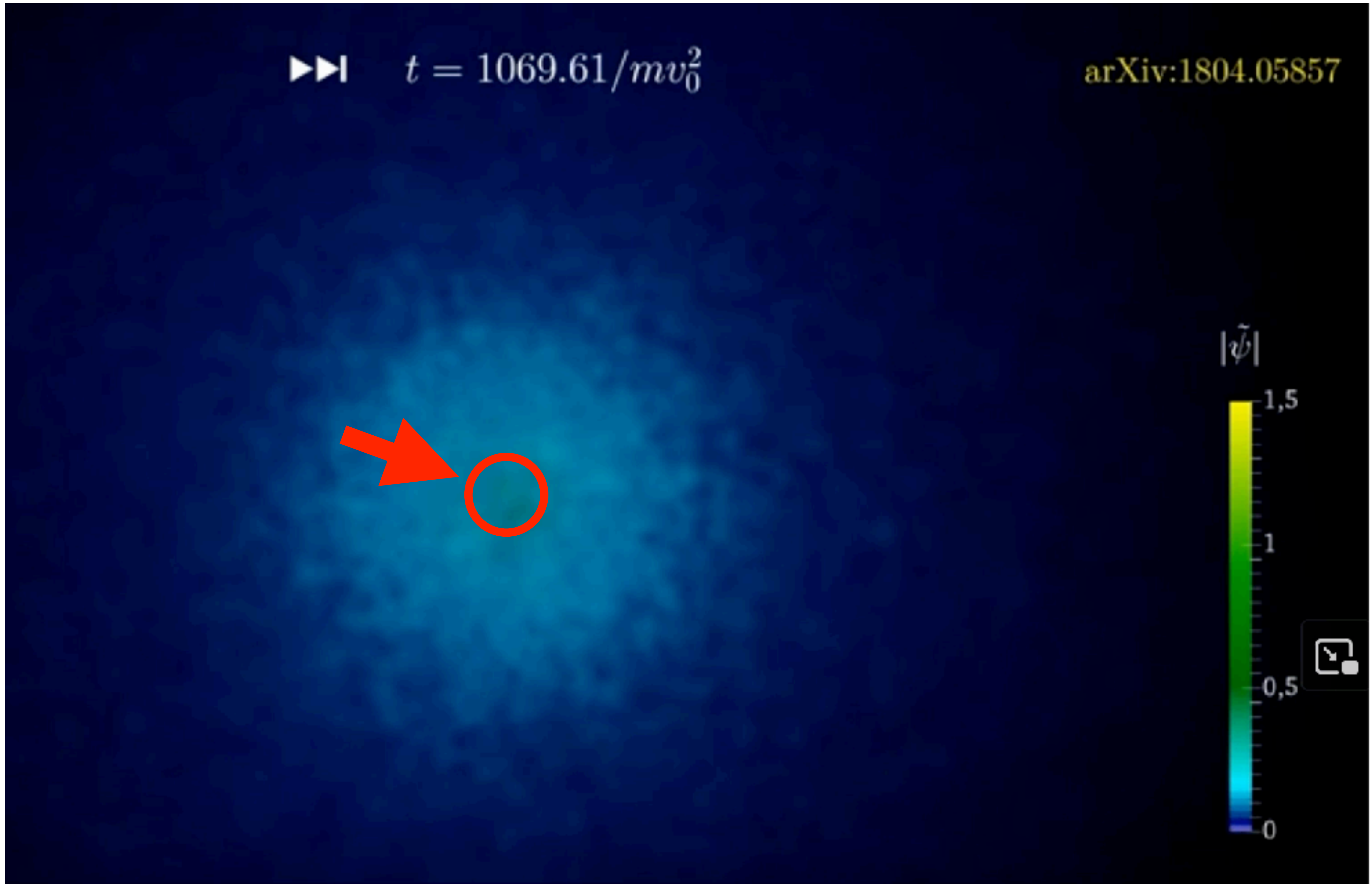


Schive++ (1406.6586)

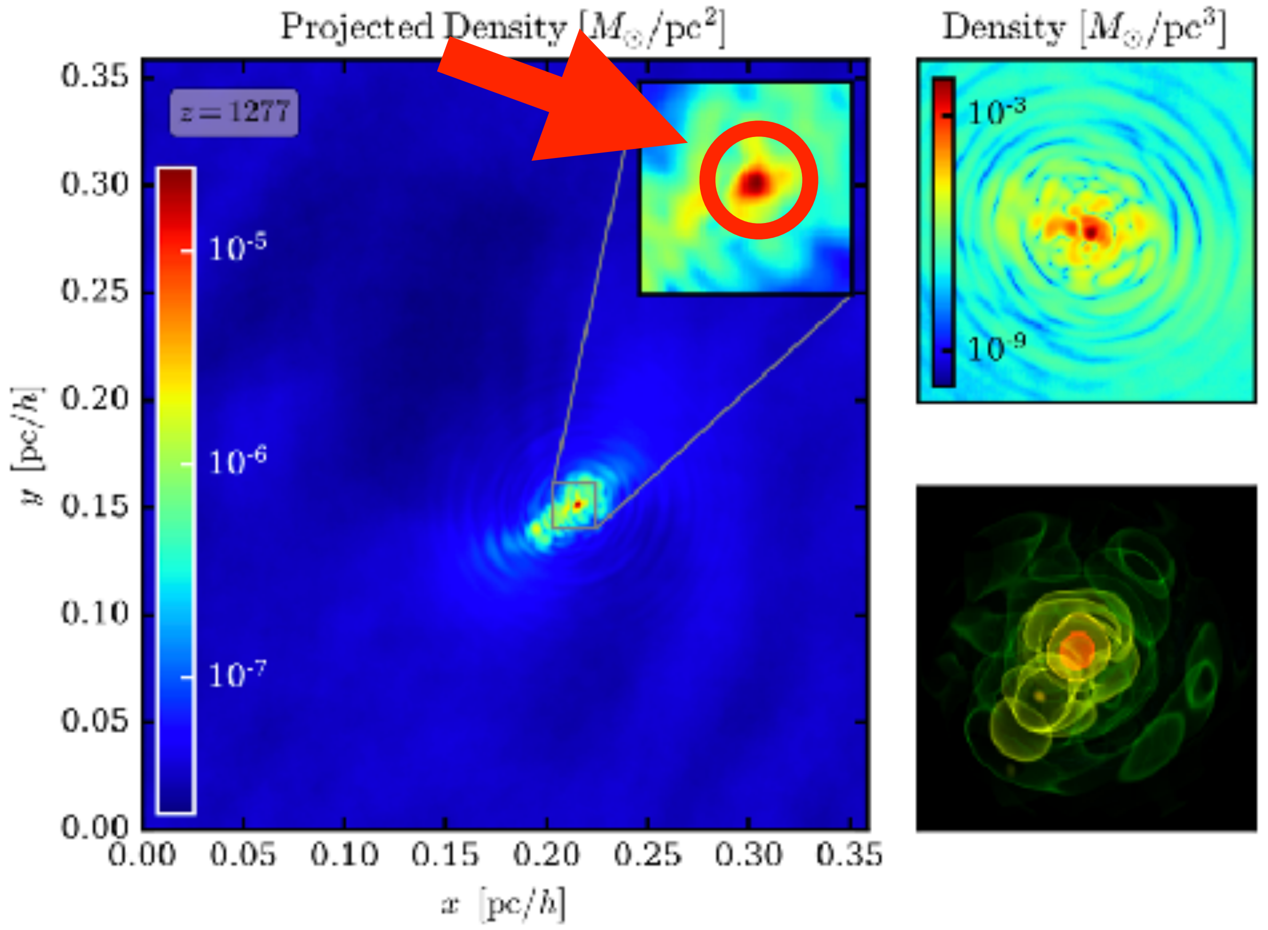


Mocz++ (1705.05845)

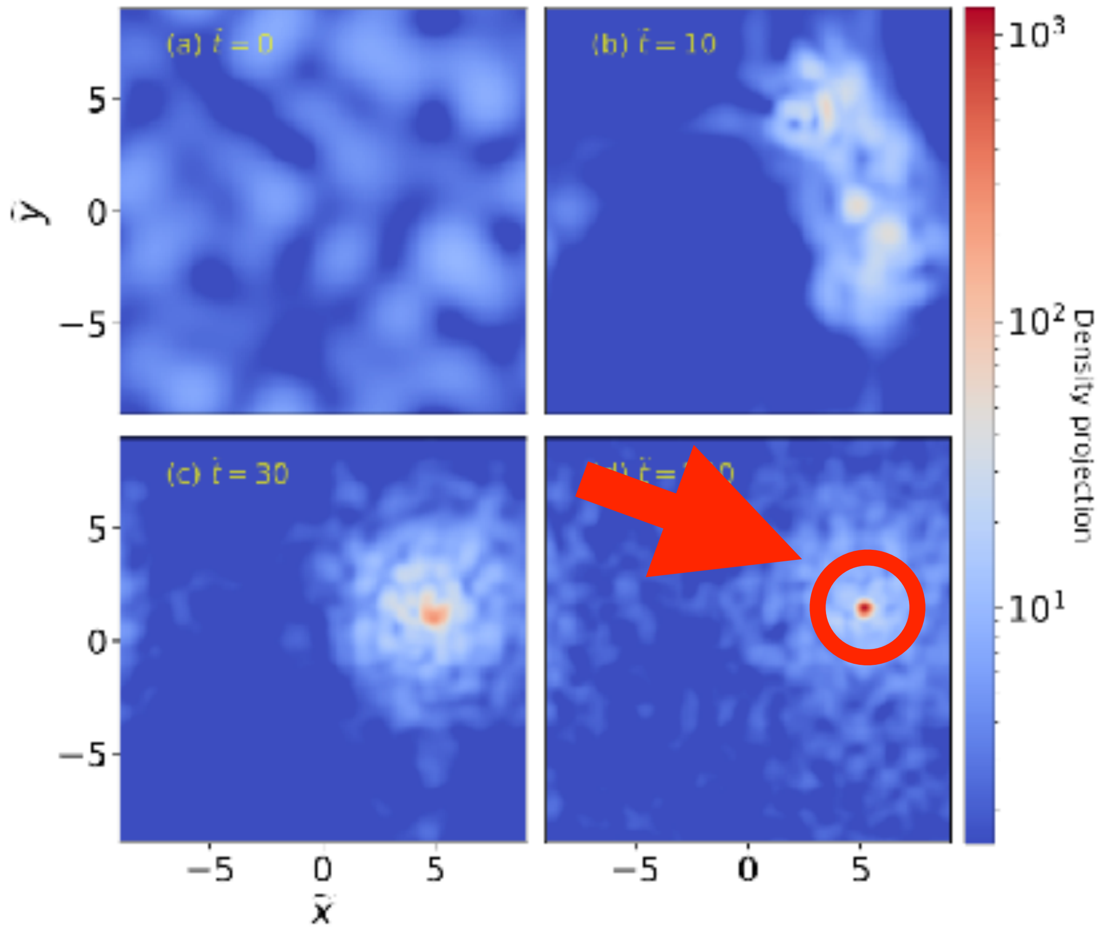
**These dense configurations form in astrophysical DM halos**



Levkov, Panin, Tkachev (1804.05857)
Video via Alexander Panin on YouTube



Eggemeier and Niemeyer (1906.01348)



Chen++ (2011.01333)

(among others!)

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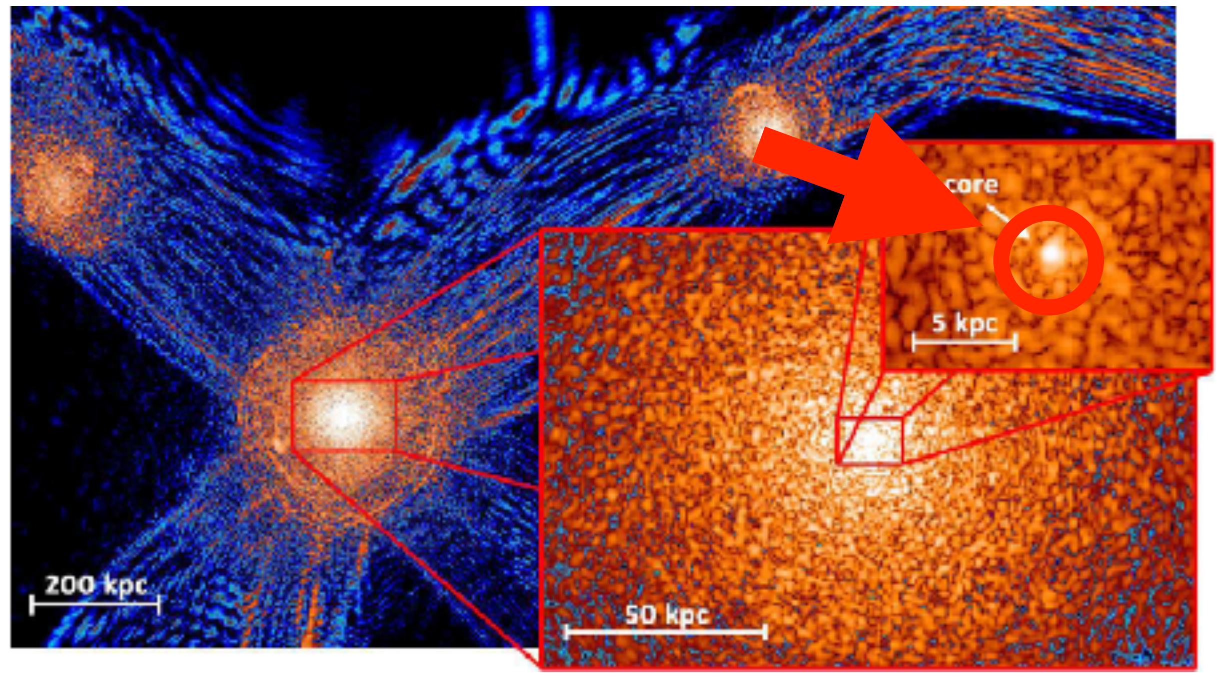

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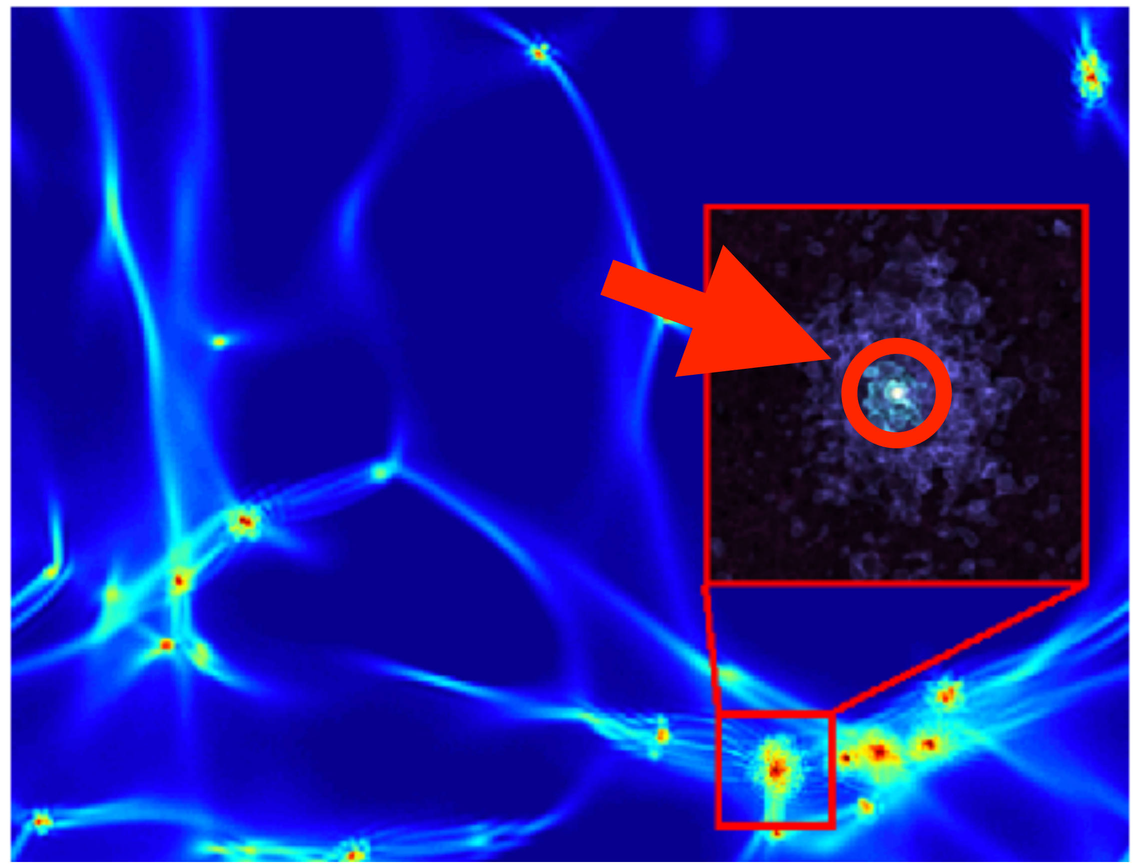

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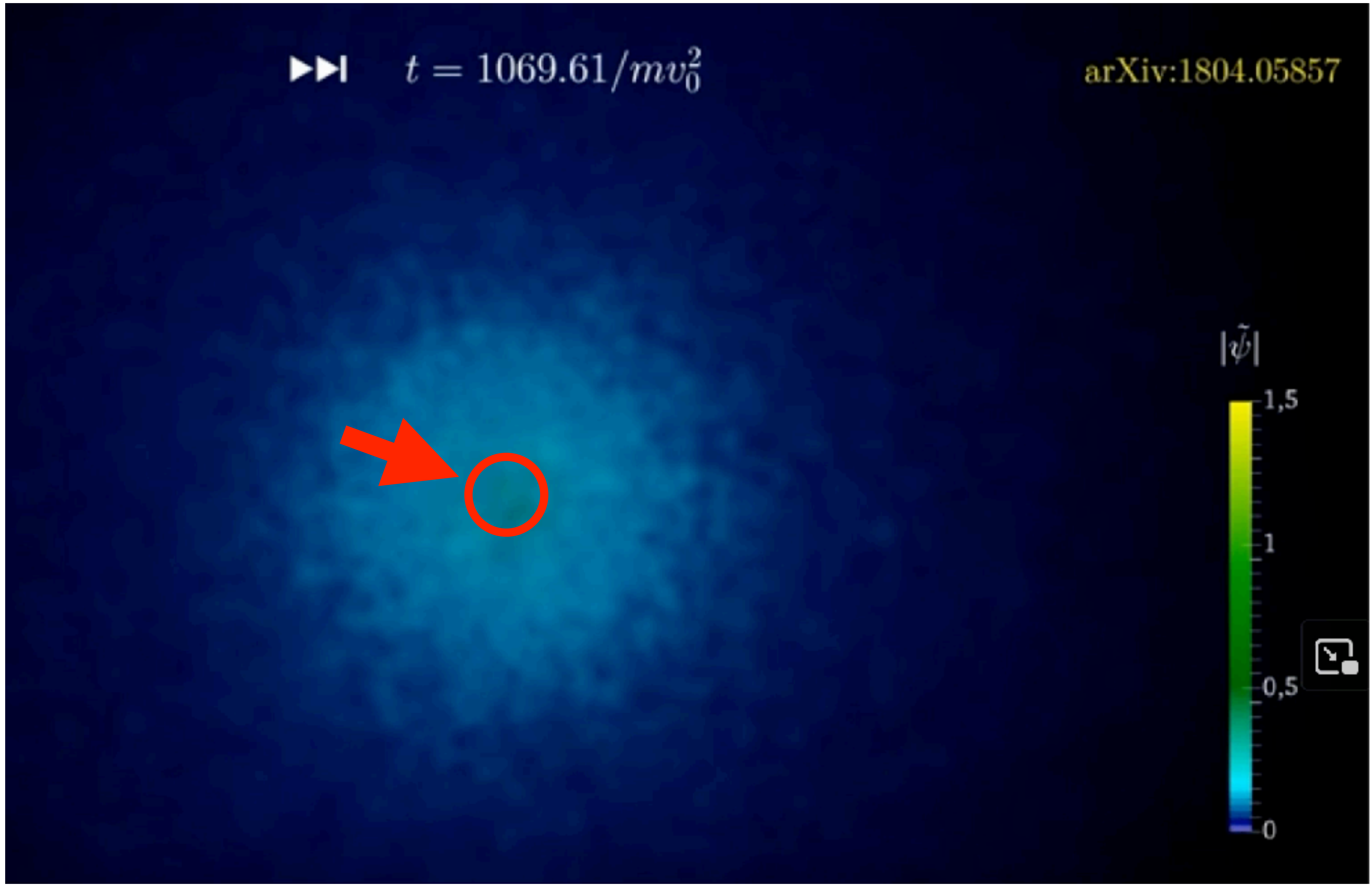

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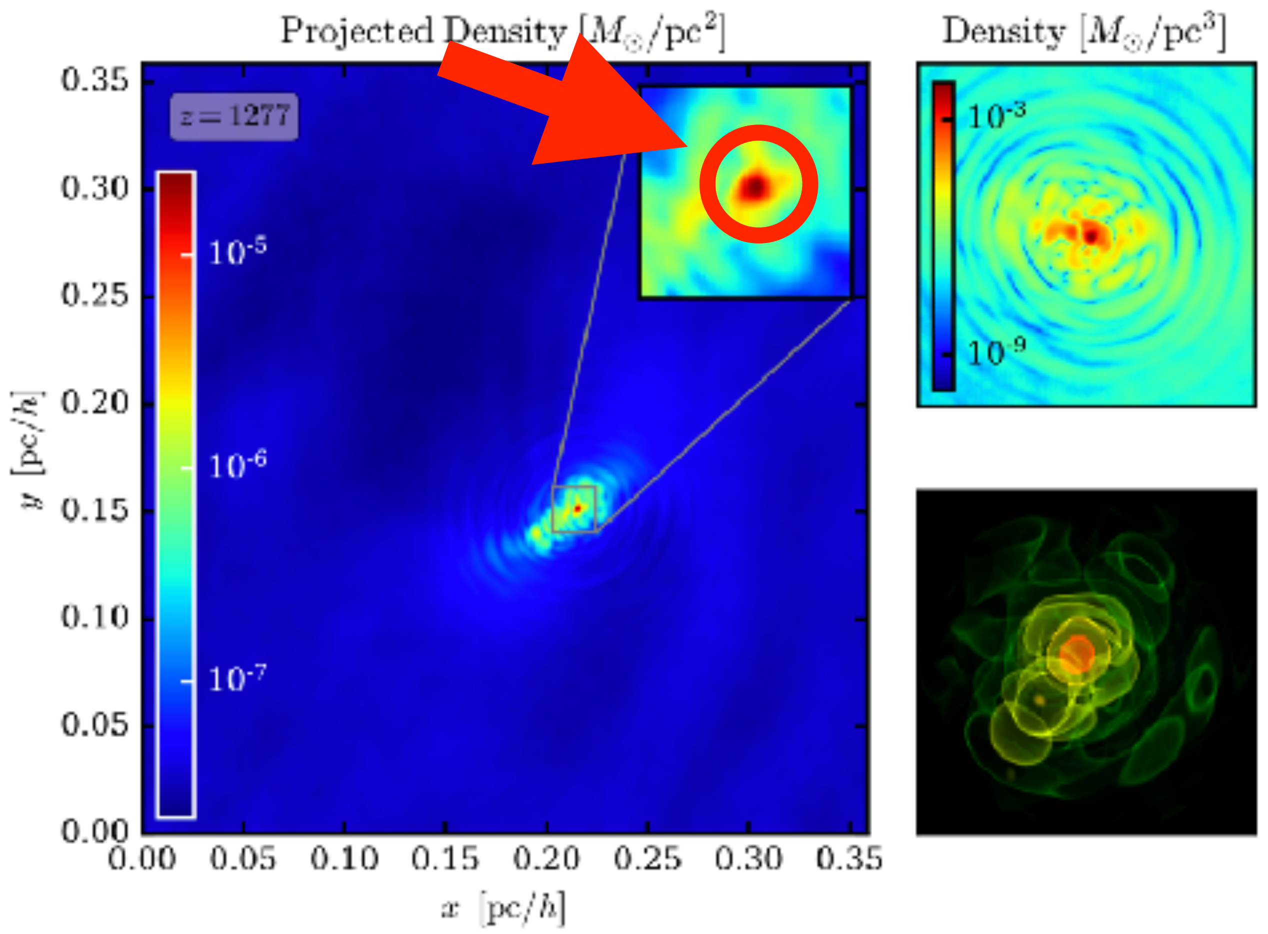

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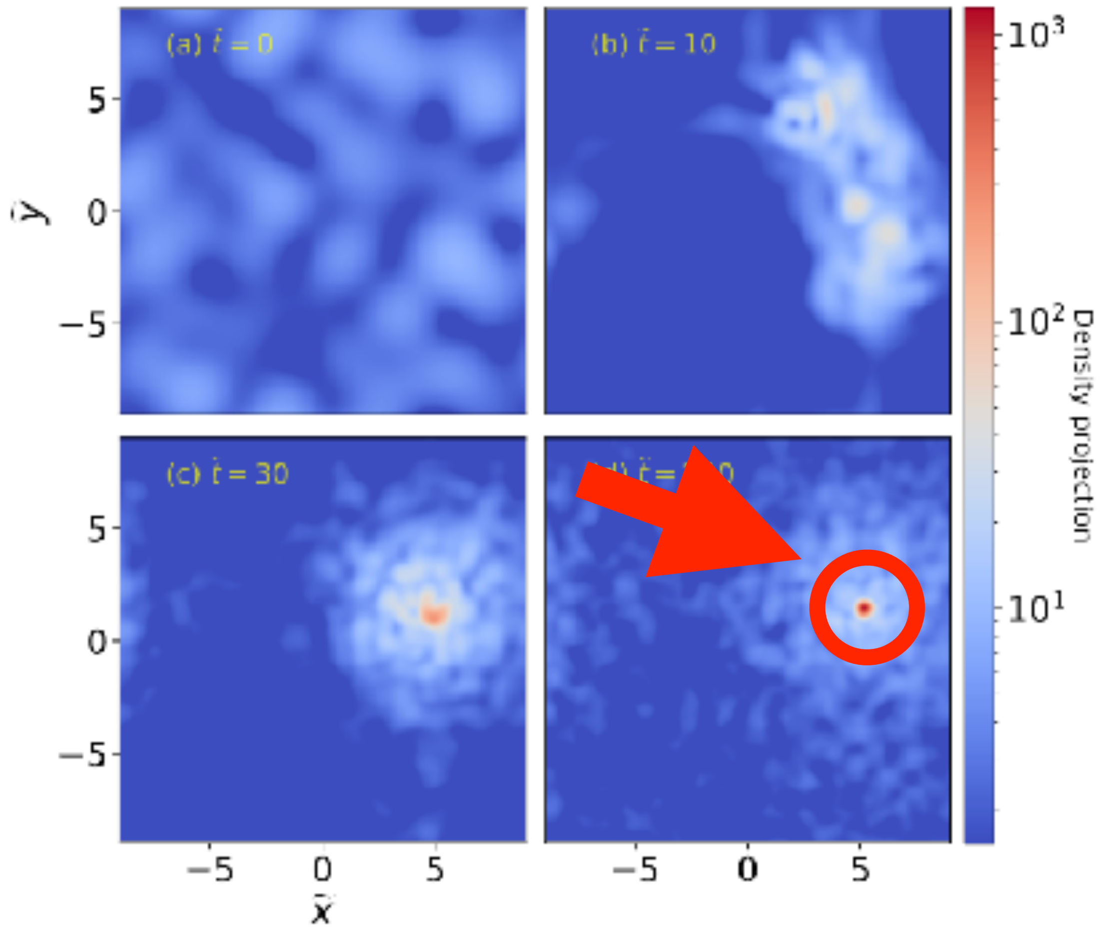

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# Equations of Motion

$$\mathscr{L}_a \supset \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{m_a^2}{2}a^2 + \frac{\lambda}{4!}a^4 - \dots$$

Axions are
- non-relativistic
- classical field
- gravitating

$$i\frac{\partial \psi}{\partial t} = \left[-\frac{\nabla^2}{2m_a} + V_g\left(|\psi|^2\right) + V_{int}\left(|\psi|^2\right)\right]\psi$$

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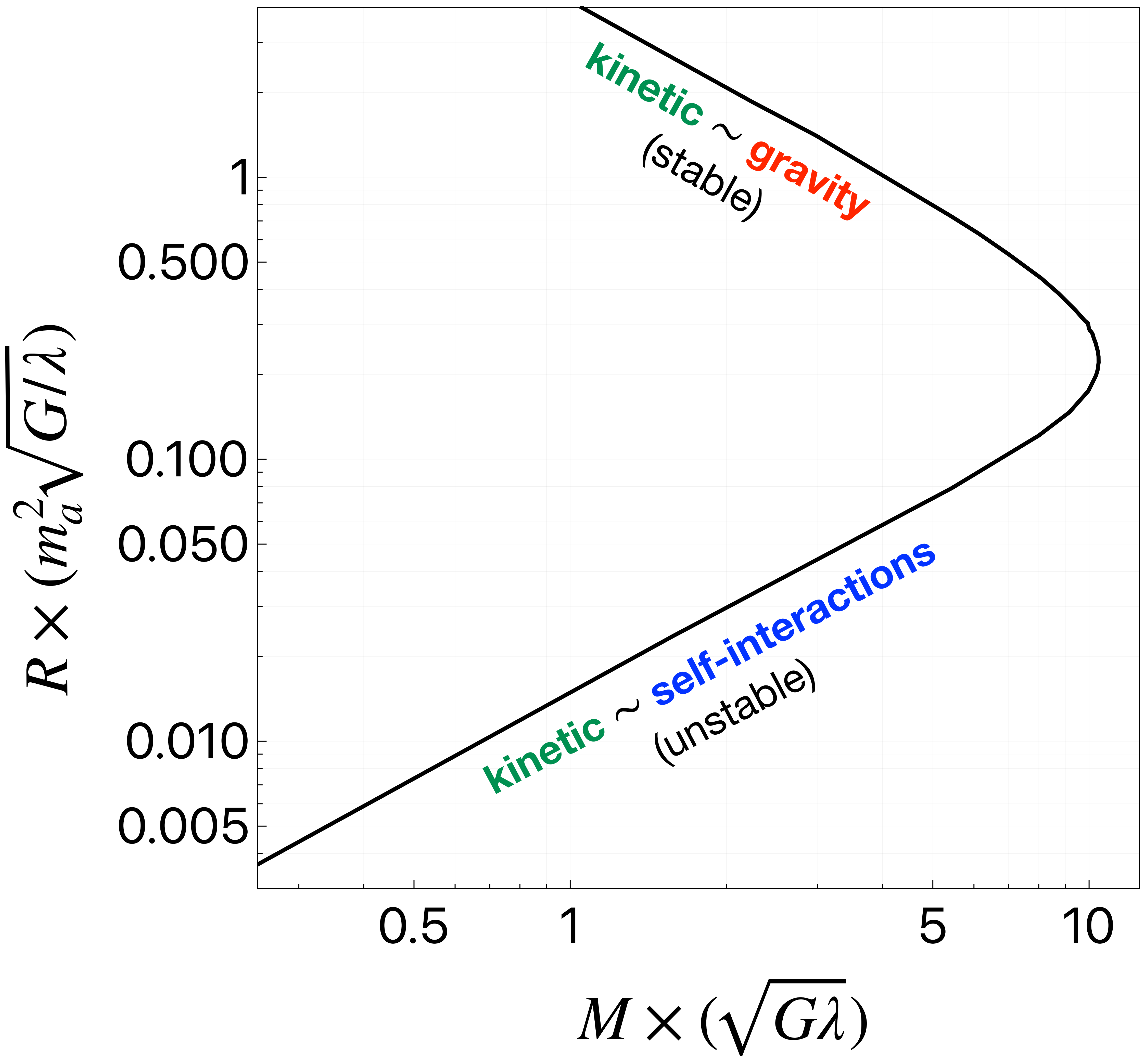
**Boson star:**
ground state of Schrödinger eq. with self-gravity

**kinetic**
$\propto \frac{1}{m_a R^2}$

**gravity**
$\propto -\frac{G m_a M}{R}$

**self-interactions**
$\propto -\frac{|\lambda| M}{m_a^3 R^3} + \dots$



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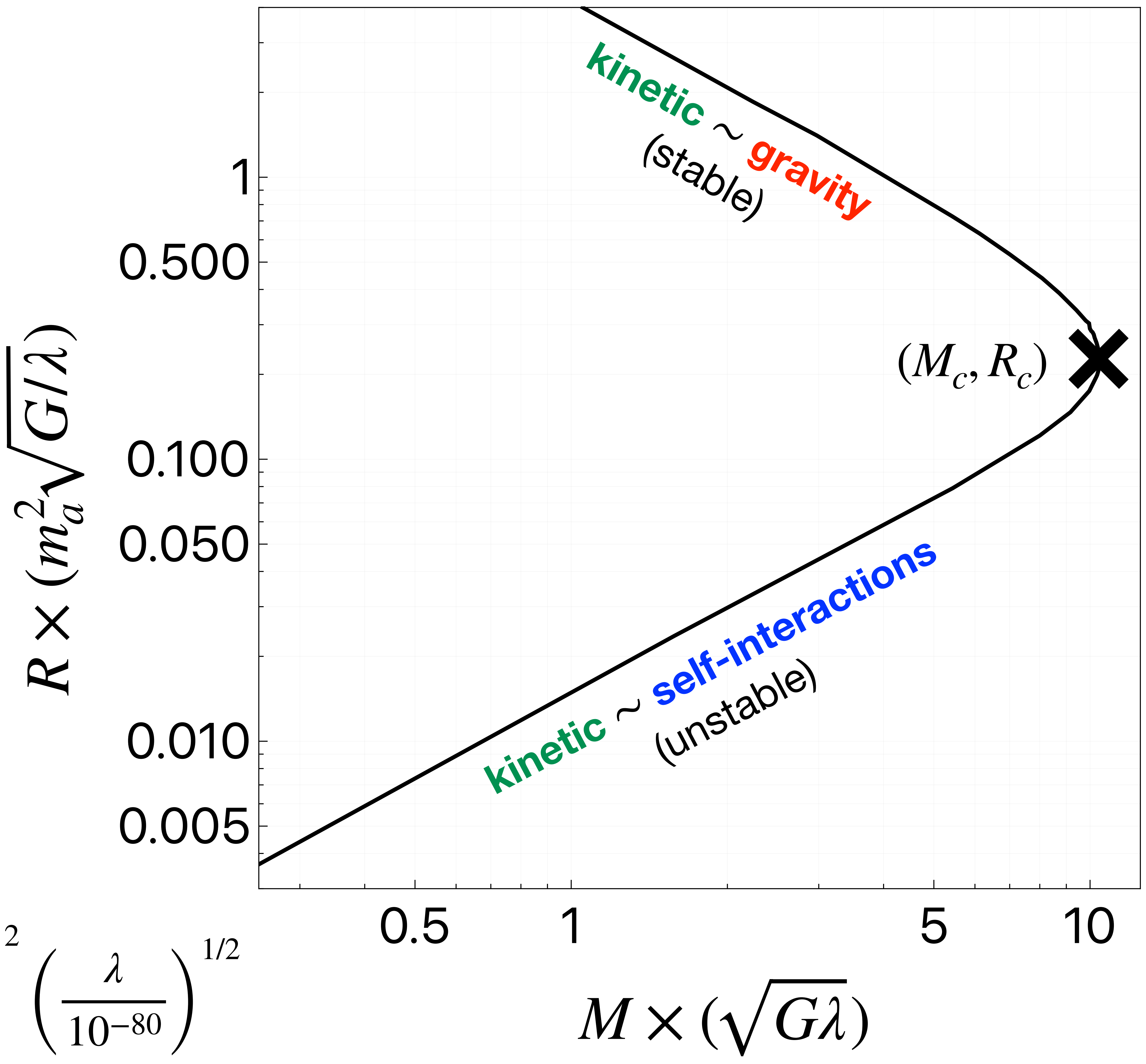
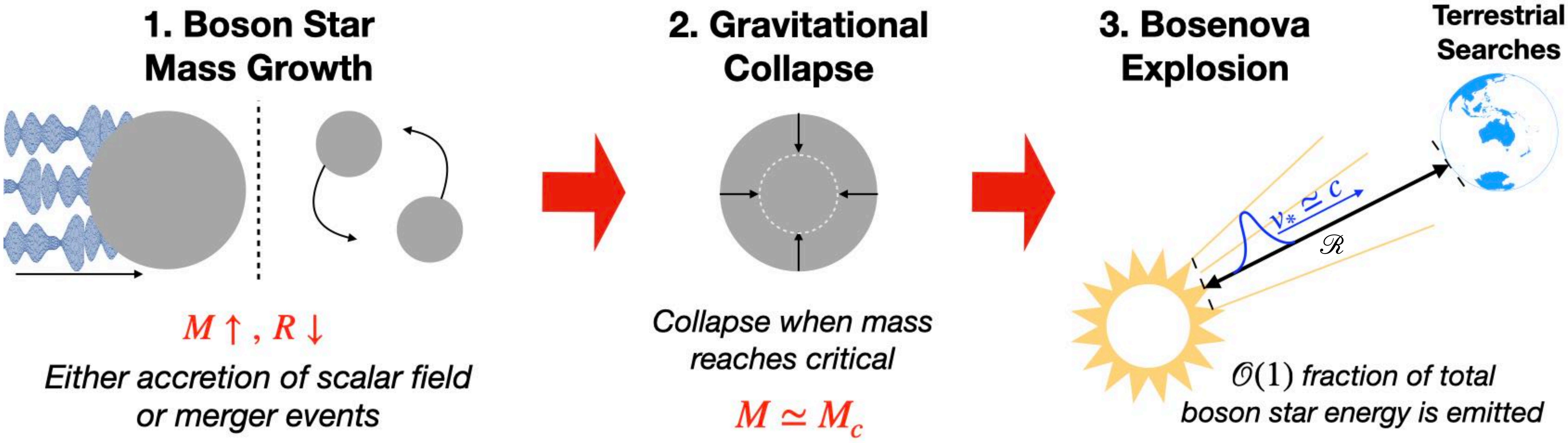


$$M_c \simeq \frac{10}{\sqrt{G\lambda}} \simeq 10^3 M_\odot \left(\frac{10^{-80}}{\lambda}\right)^{1/2}$$

$$R_c \simeq \frac{0.2}{m_a^2}\sqrt{\frac{\lambda}{G}} \simeq 70\,R_\odot \left(\frac{10^{-15}\,\mathrm{eV}}{m_a}\right)^2 \left(\frac{\lambda}{10^{-80}}\right)^{1/2}$$

# Life Cycle of a Boson Star



**1. Boson Star Mass Growth**

$M \uparrow \,, R \downarrow$

*Either accretion of scalar field or merger events*

**2. Gravitational Collapse**

*Collapse when mass reaches critical*

$M \simeq M_c$

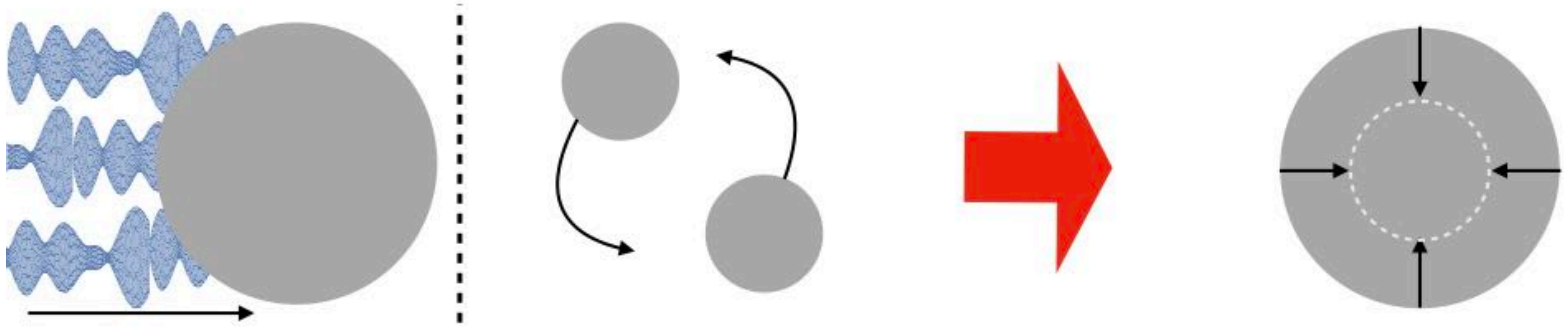
**3. Bosenova Explosion**

$\mathcal{O}(1)$ *fraction of total boson star energy is emitted*

# Event Rate vs Burst Flux

**1. Boson Star Mass Growth**

**2. Gravitational Collapse**



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***Highly*** **model-dependent!**

- *Cosmology (formation history, mass fraction)*
- *Astrophysics (mass growth, merger history)*
- *Particle physics (interactions→relaxation rate)*

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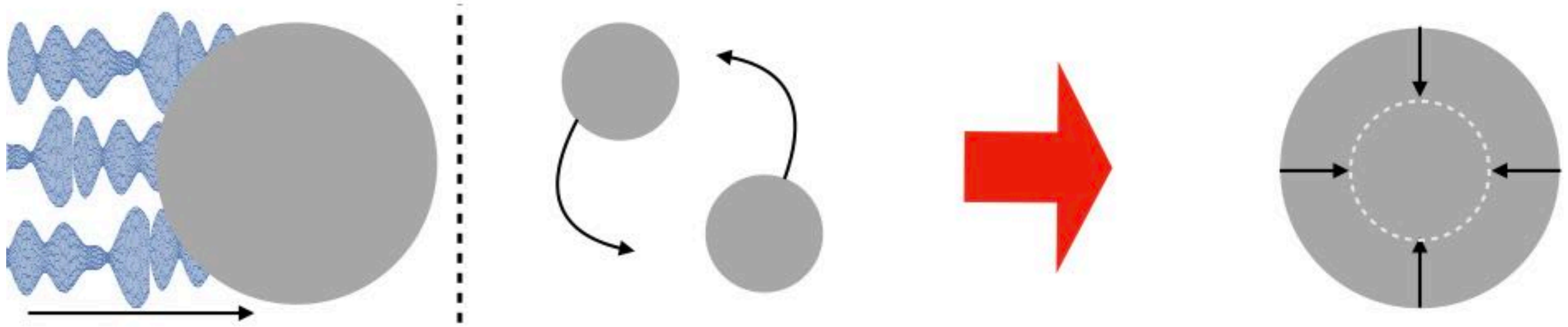

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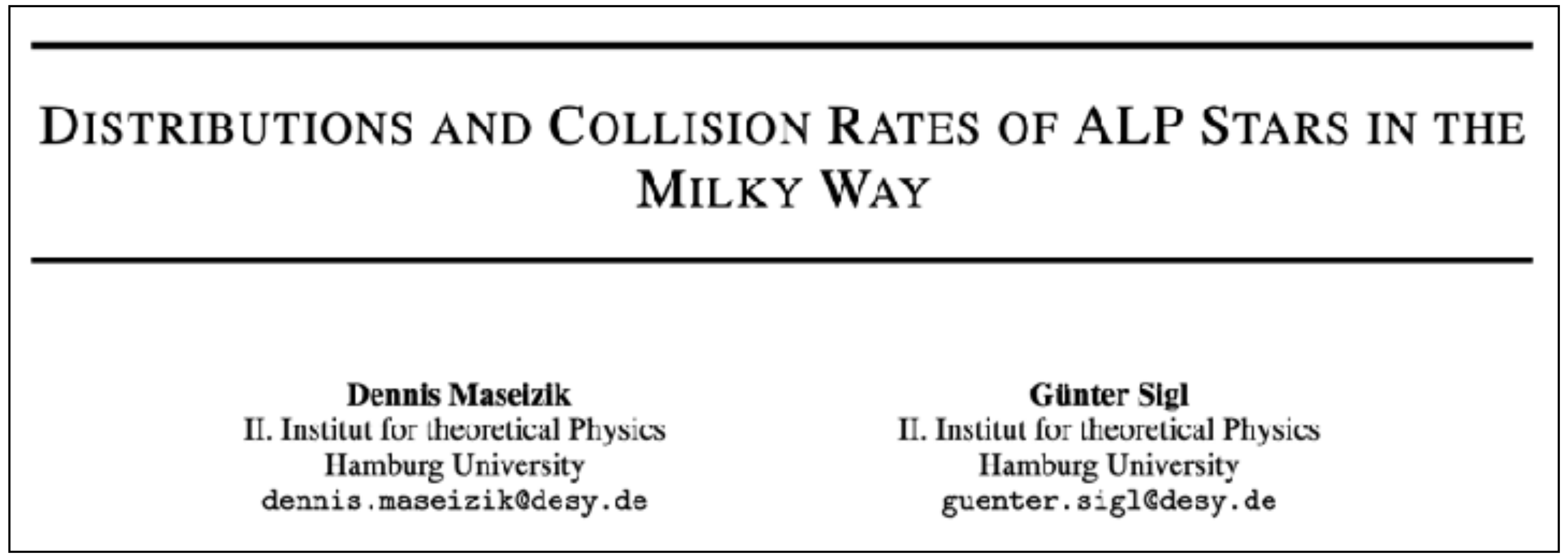

DISTRIBUTIONS AND COLLISION RATES OF ALP STARS IN THE MILKY WAY

**Dennis Maseizik**
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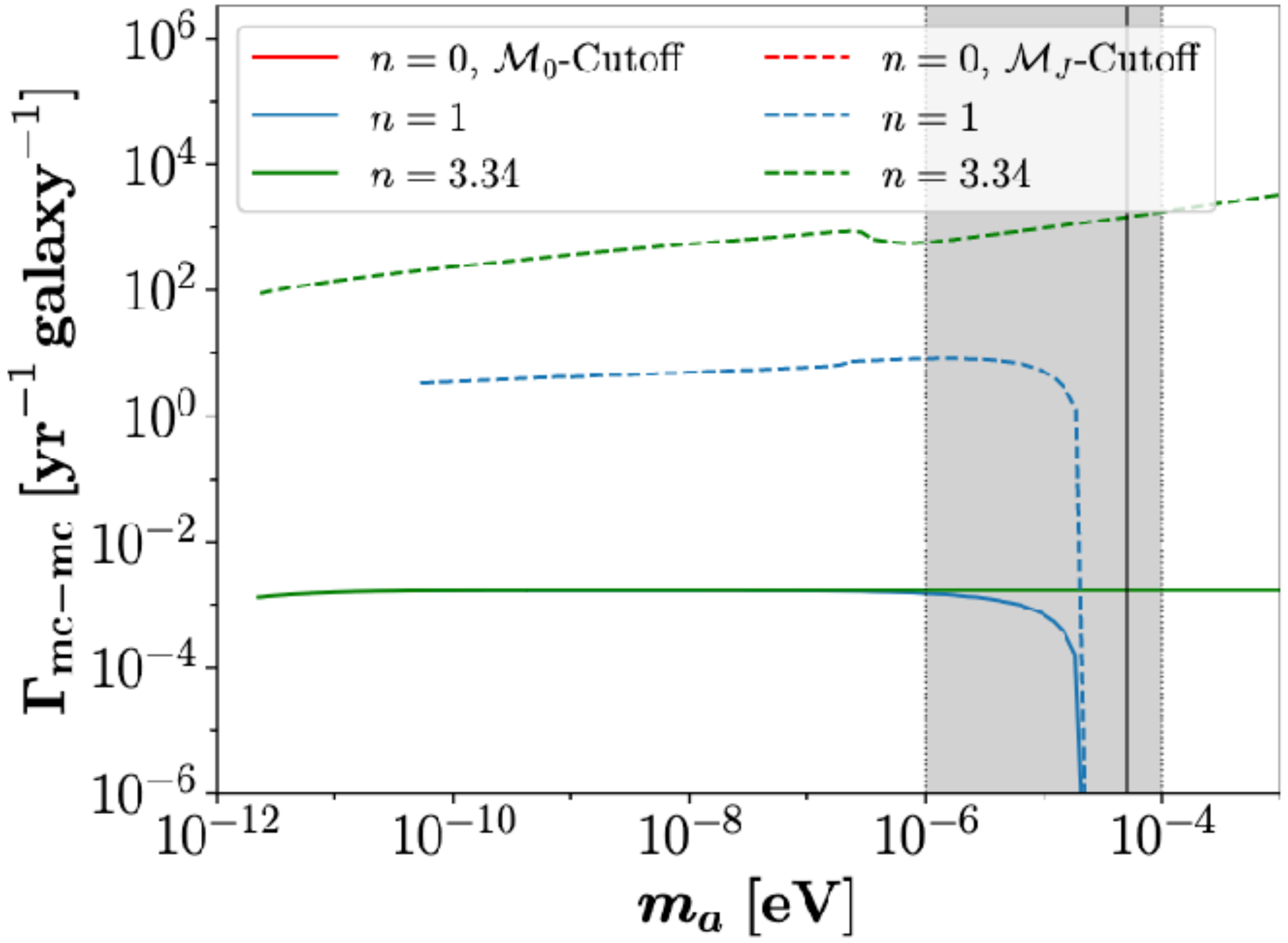
**Günter Sigl**
II. Institut for theoretical Physics
Hamburg University
guenter.sigl@desy.de

Maseizik, Sigl (2404.07908)



Arakawa, **Eby**, Safronova, Takhistov, Zaheer (2306.16468)

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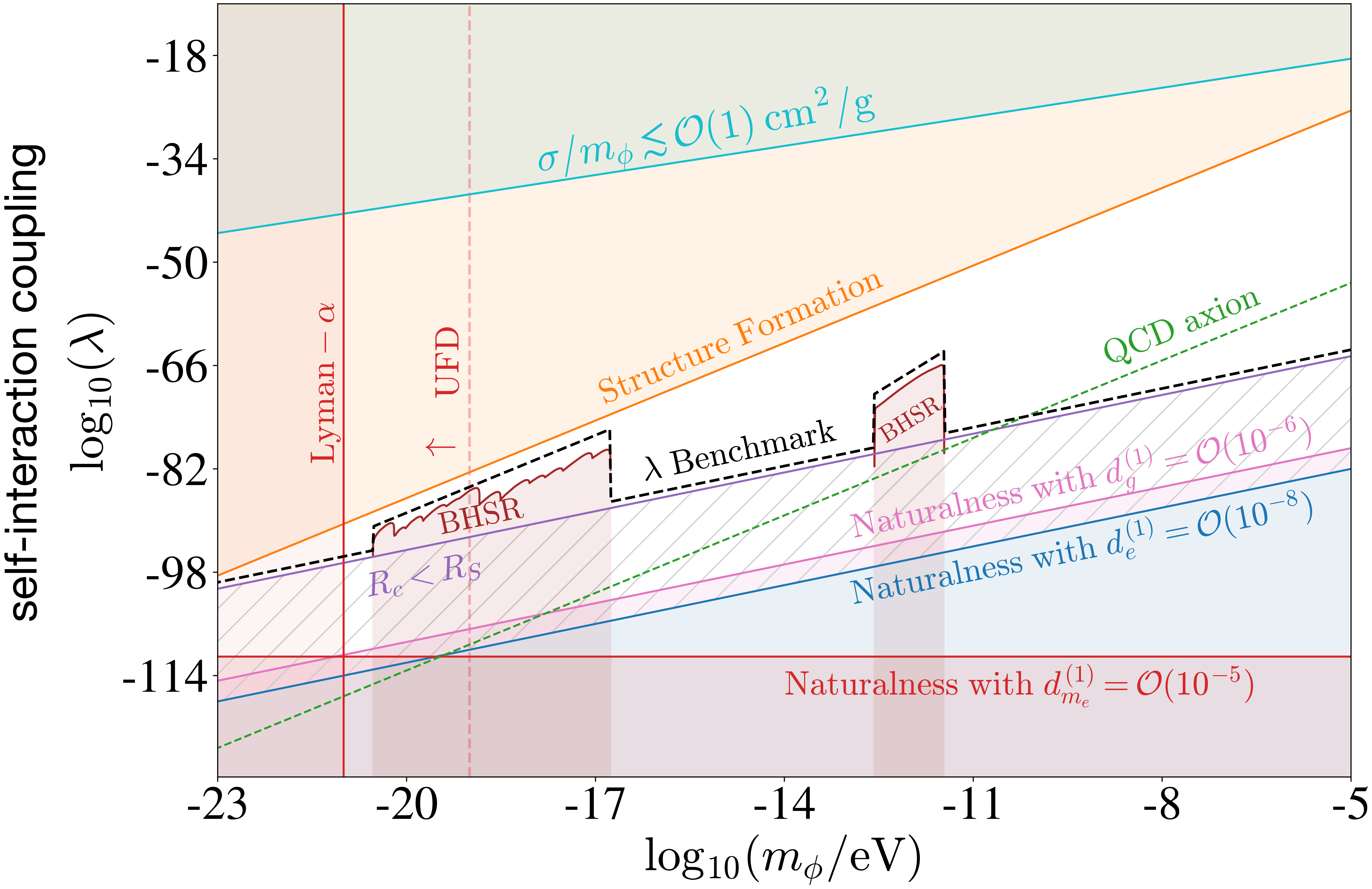

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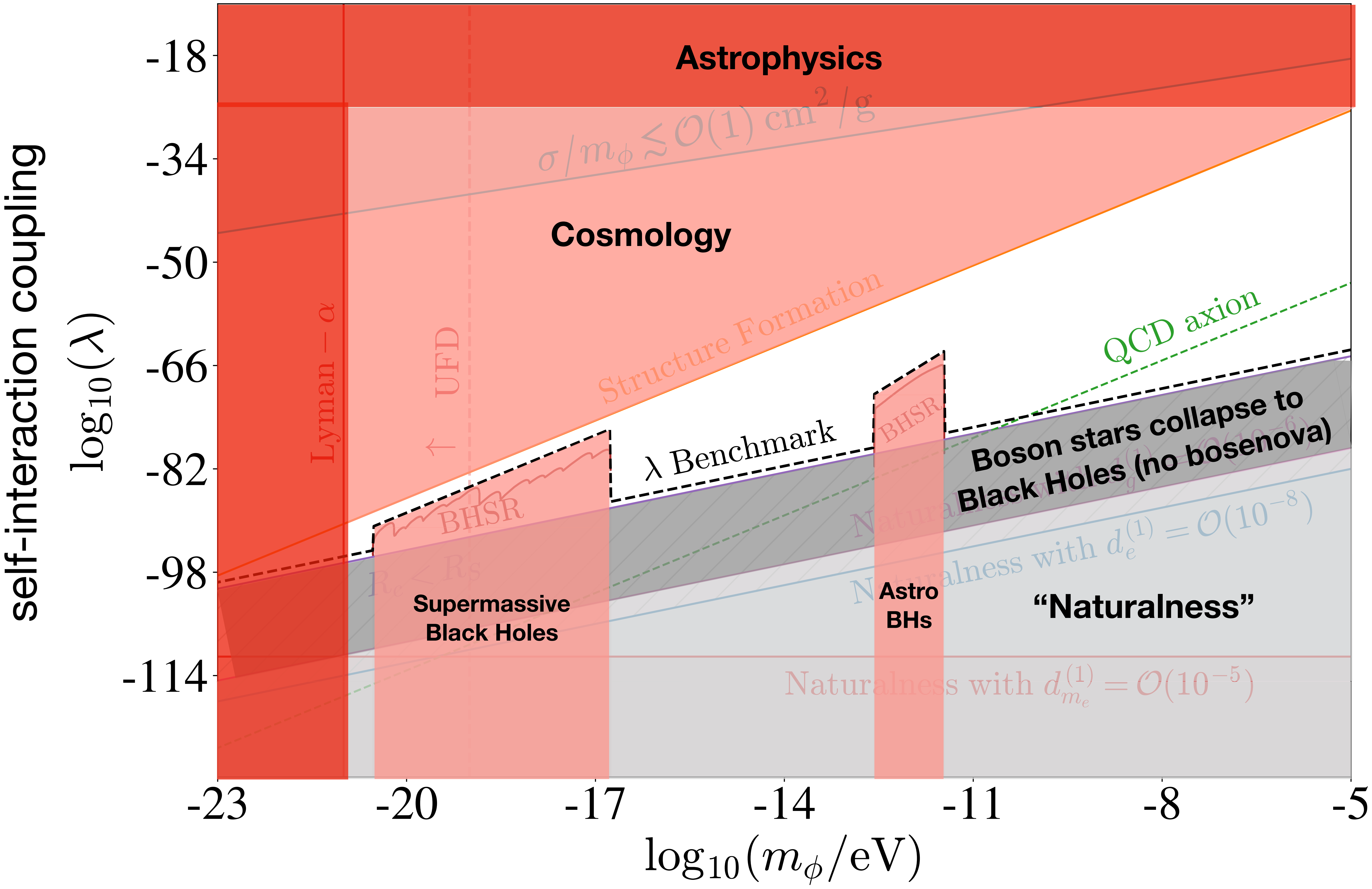

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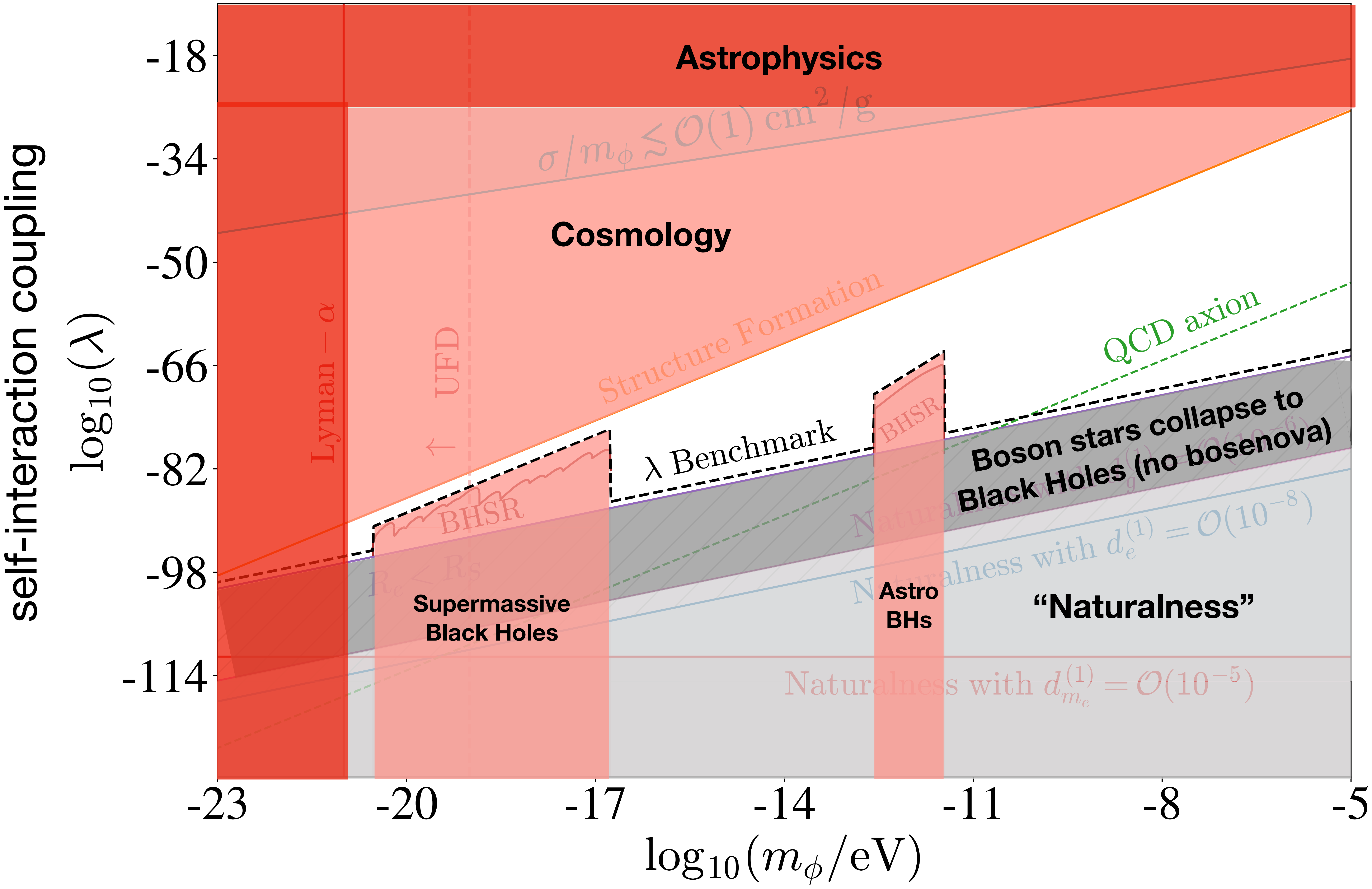


Smaller $M_c$ (signal)
Larger $\Gamma$ (rate)

↕

Larger $M_c$ (signal)
Smaller $\Gamma$ (rate)

**Recall that**

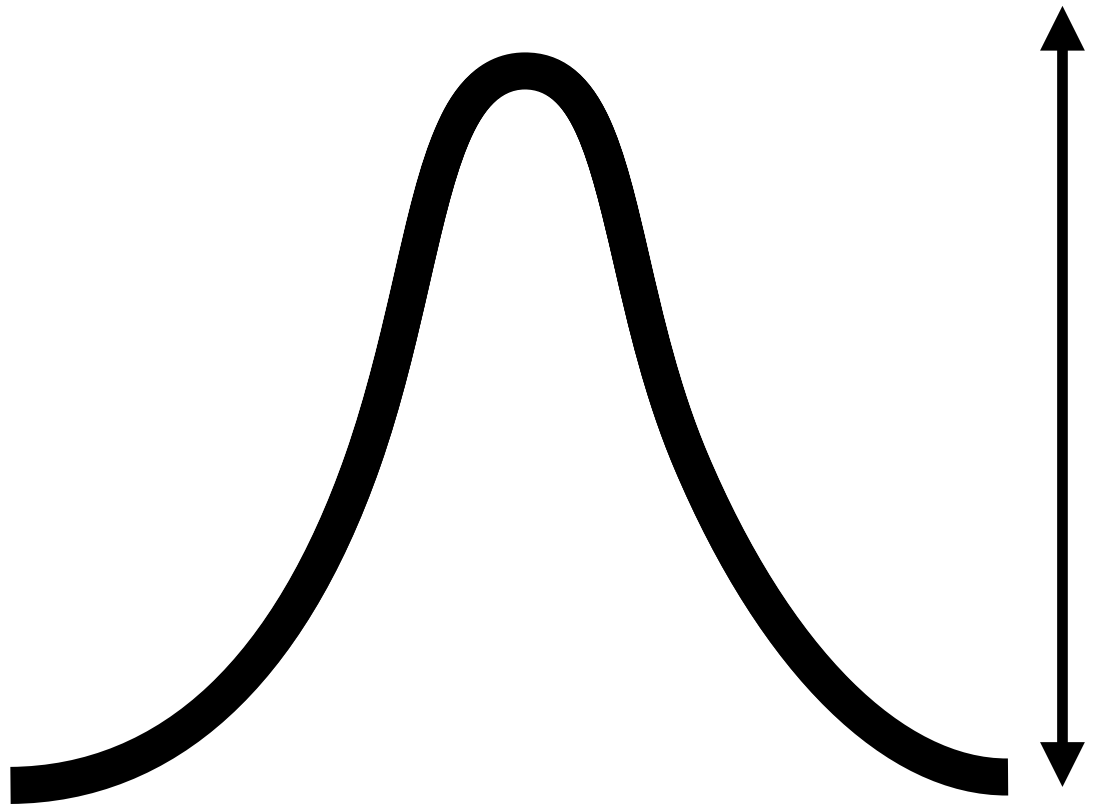
$$M_c \simeq \frac{10}{\sqrt{G\lambda}} \simeq 10^3 M_\odot \left(\frac{10^{-80}}{\lambda}\right)^{1/2}$$

**Future work is needed to fully estimate the rate across range of models**

**Eby**, Shirai, Stadnik, Takhistov (2106.14893)

# Event Rate vs Burst Flux

## Burst properties:



momentum spectrum of emission:

peaked at $k_0 \sim \text{few} \times m_a$

with width $\delta k \sim m_a$

total emitted energy,

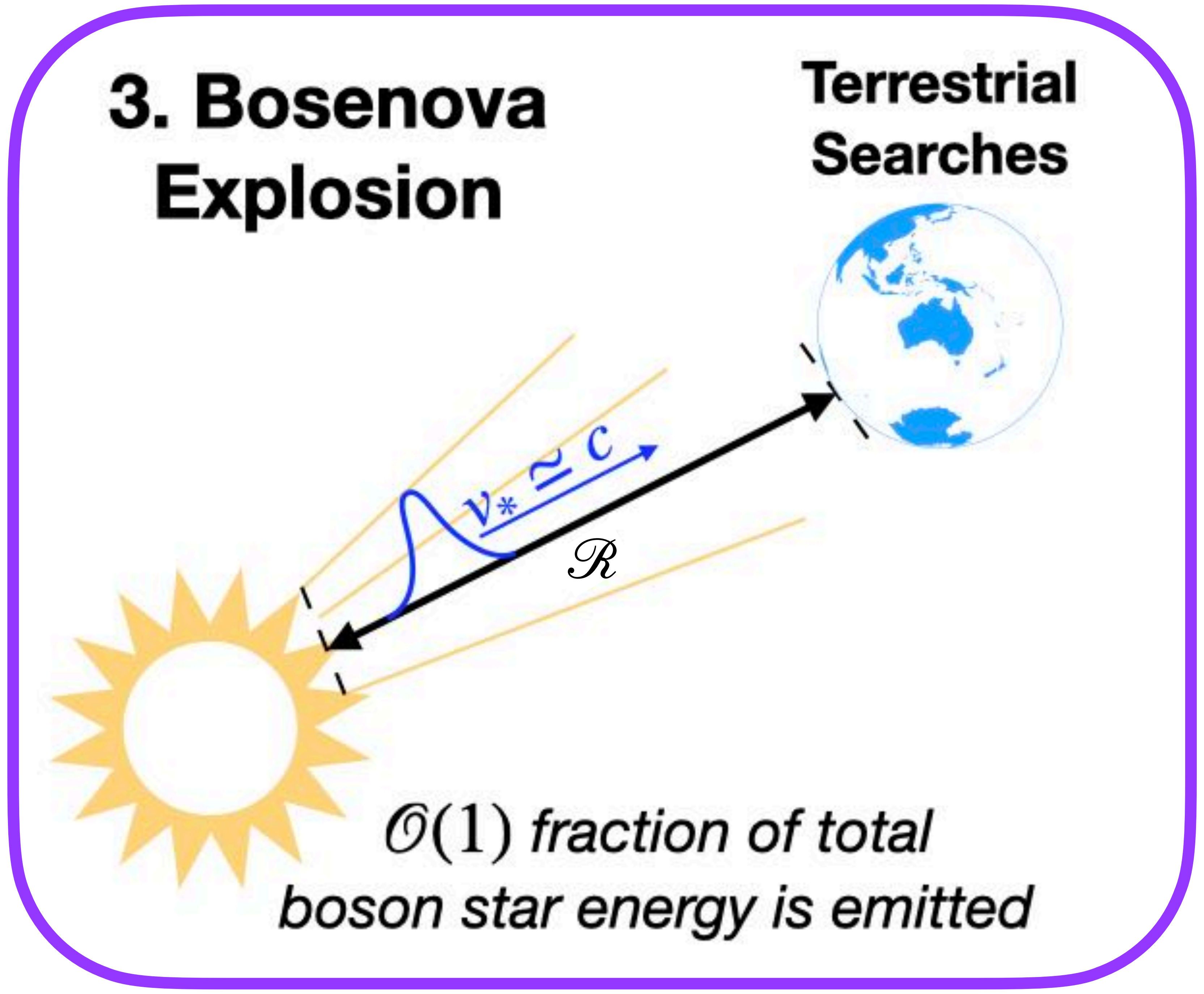
$$\sim M_c = \frac{10 M_{\rm Pl}}{\sqrt{\lambda}}$$

$$\rho_* \sim \frac{E_{\rm tot}}{4\pi \mathscr{R}^2 \delta x}$$

distance to burst

burst ‘size’ (duration)

**Energy density in burst**



**Prediction of Bosenova**

**Eby**, Leembruggen, Suranyi, Wijewardhana (1608.06911)

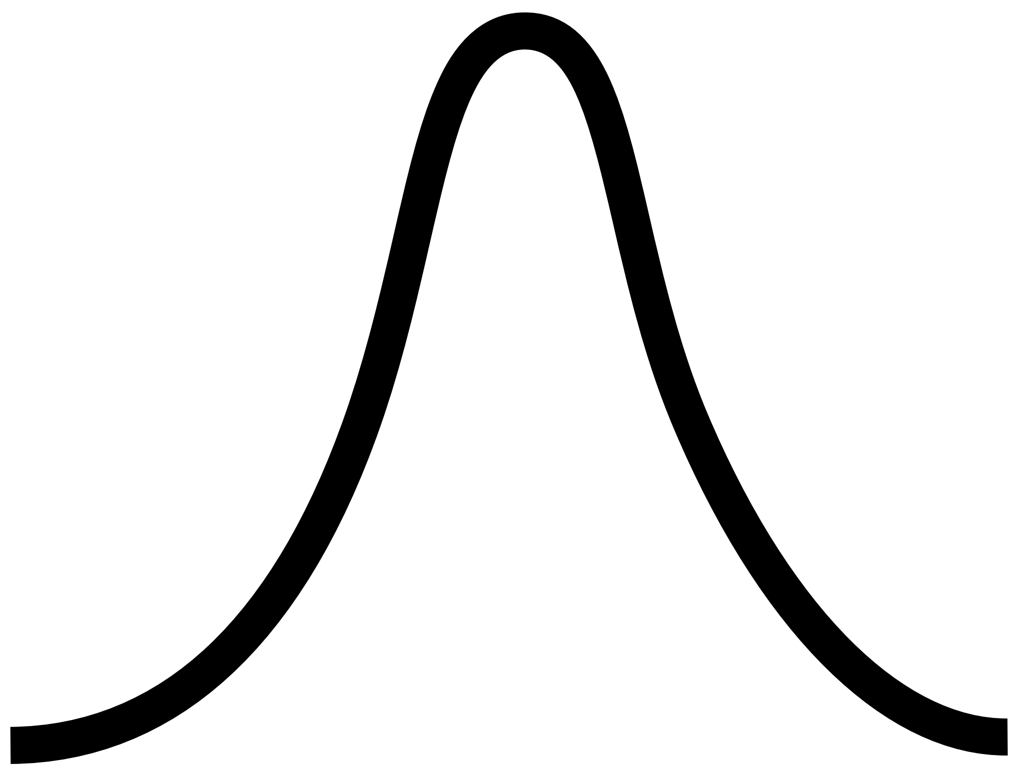
**Numerical simulations of collapse+Bosenova process**

Levkov, Panin, Tkachev (1609.03611)

**Eby**, Shirai, Stadnik, Takhistov (2106.14893)

# Wave Spreading in Flight

## At Source



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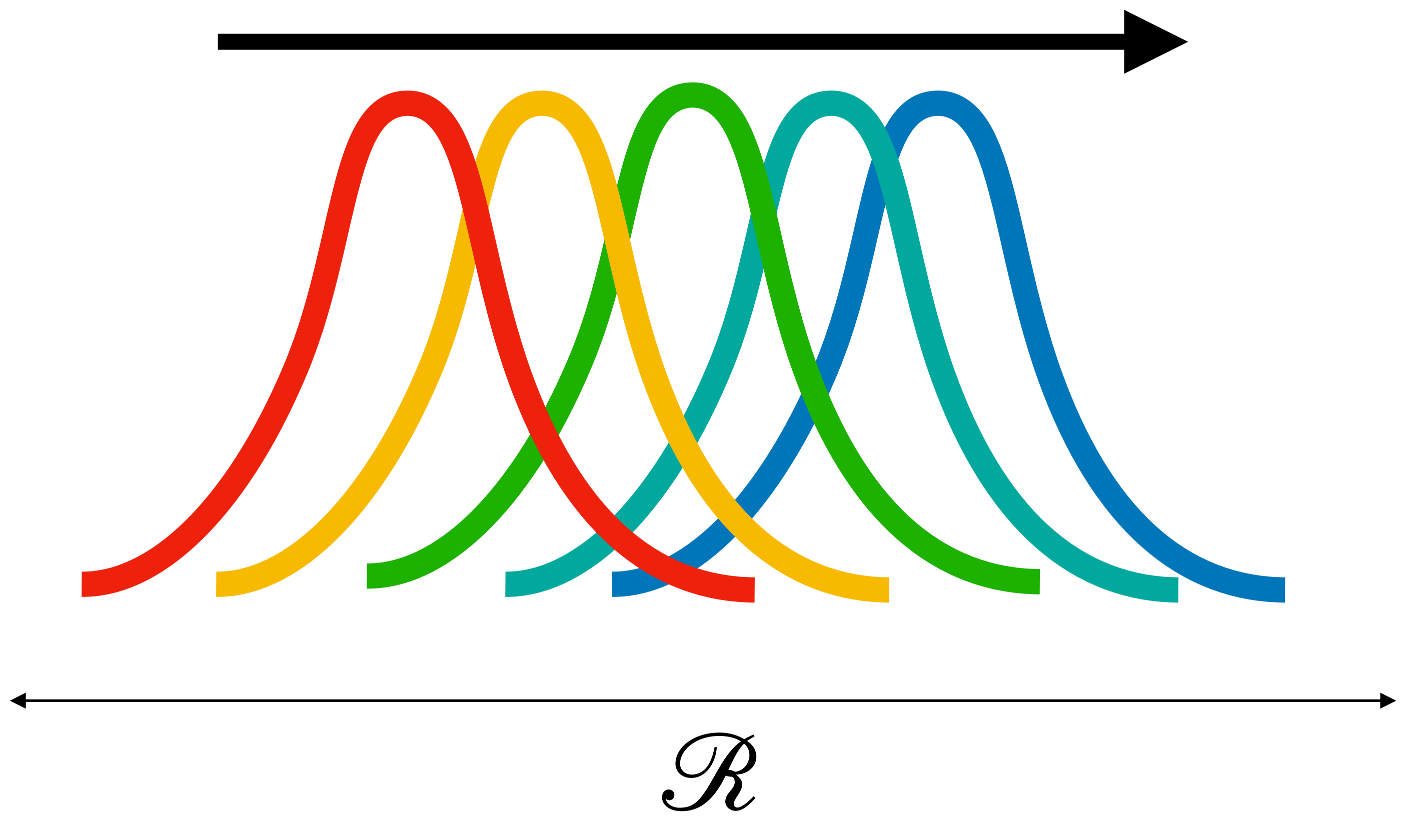
peaked at $k_0 \sim \text{few} \times m_a$
with width $\delta k \sim m_a$

imagine discrete momentum modes
$k_1, k_2, k_3, \ldots$

Fastest momentum modes "escape" from slower ones during propagation

$k_1 < k_2 < k_3, \ldots$



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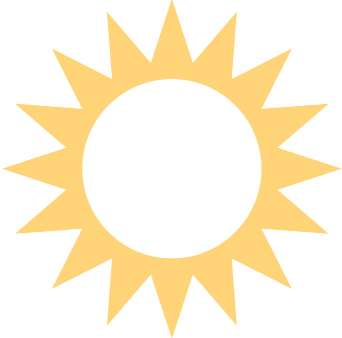

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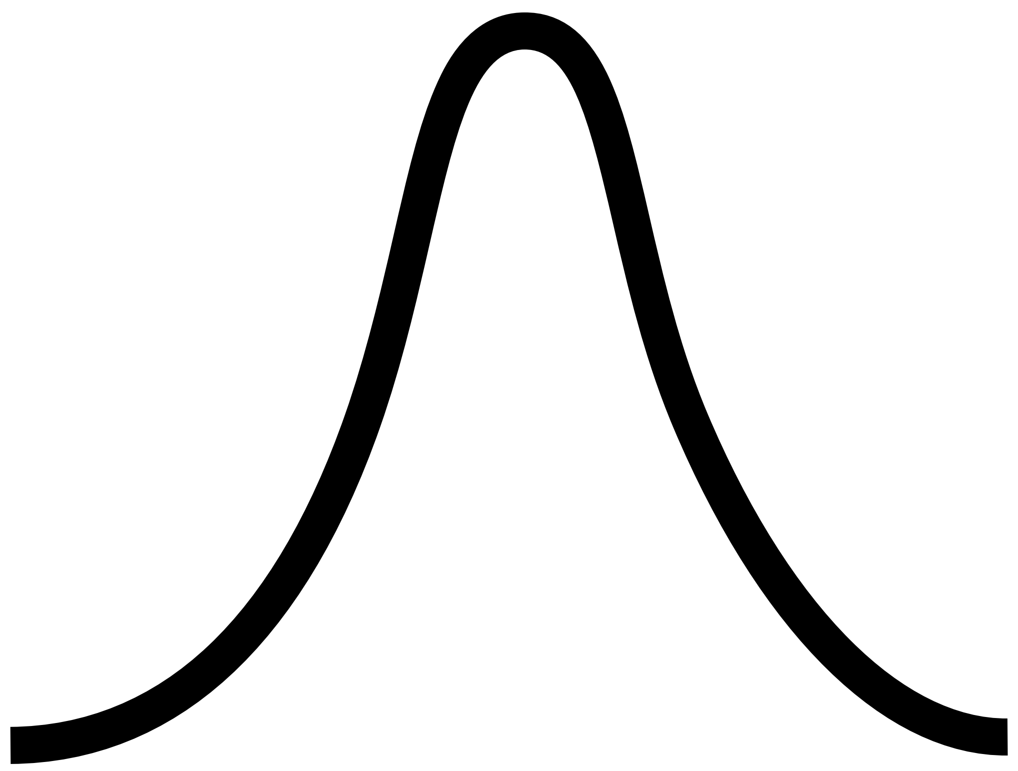

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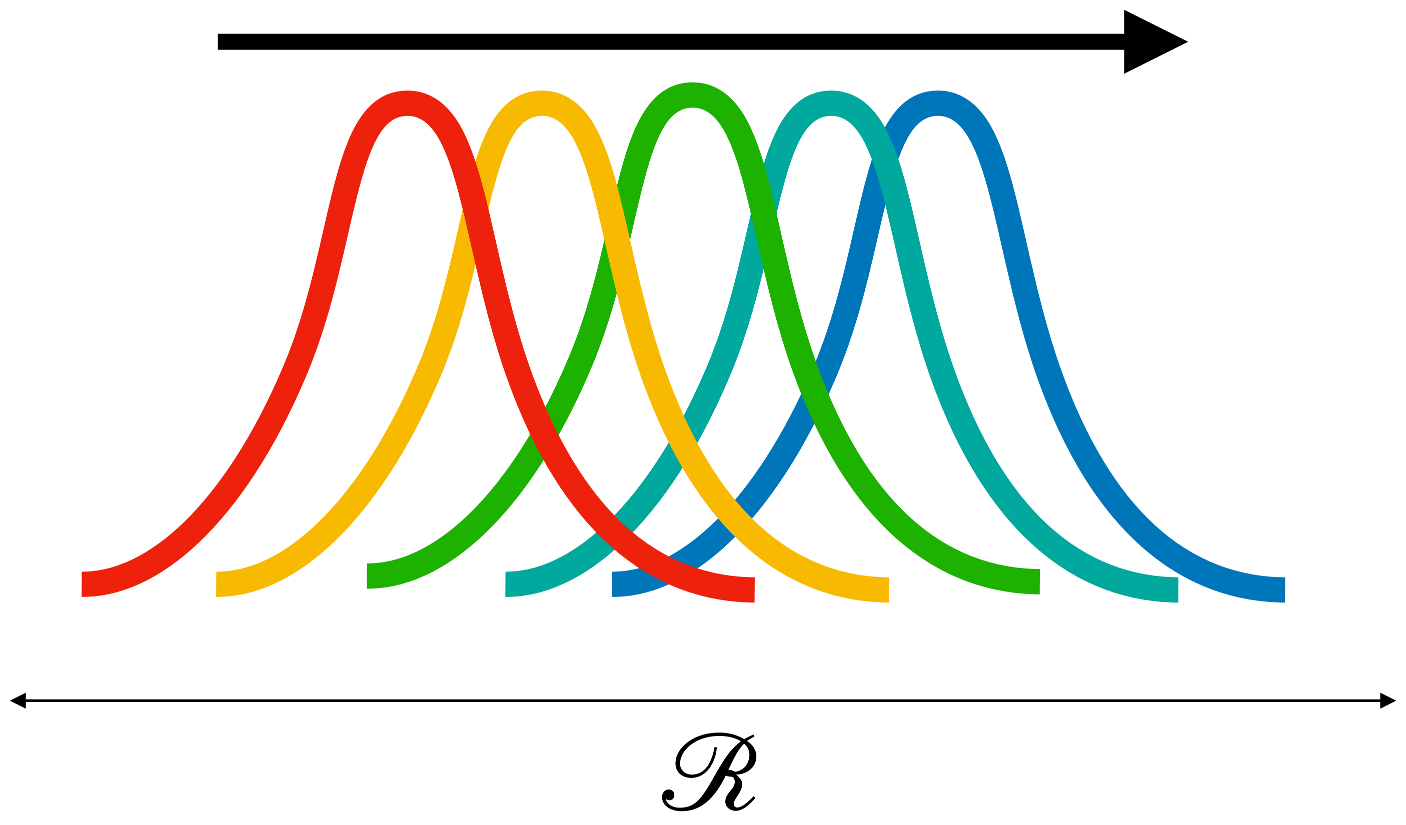
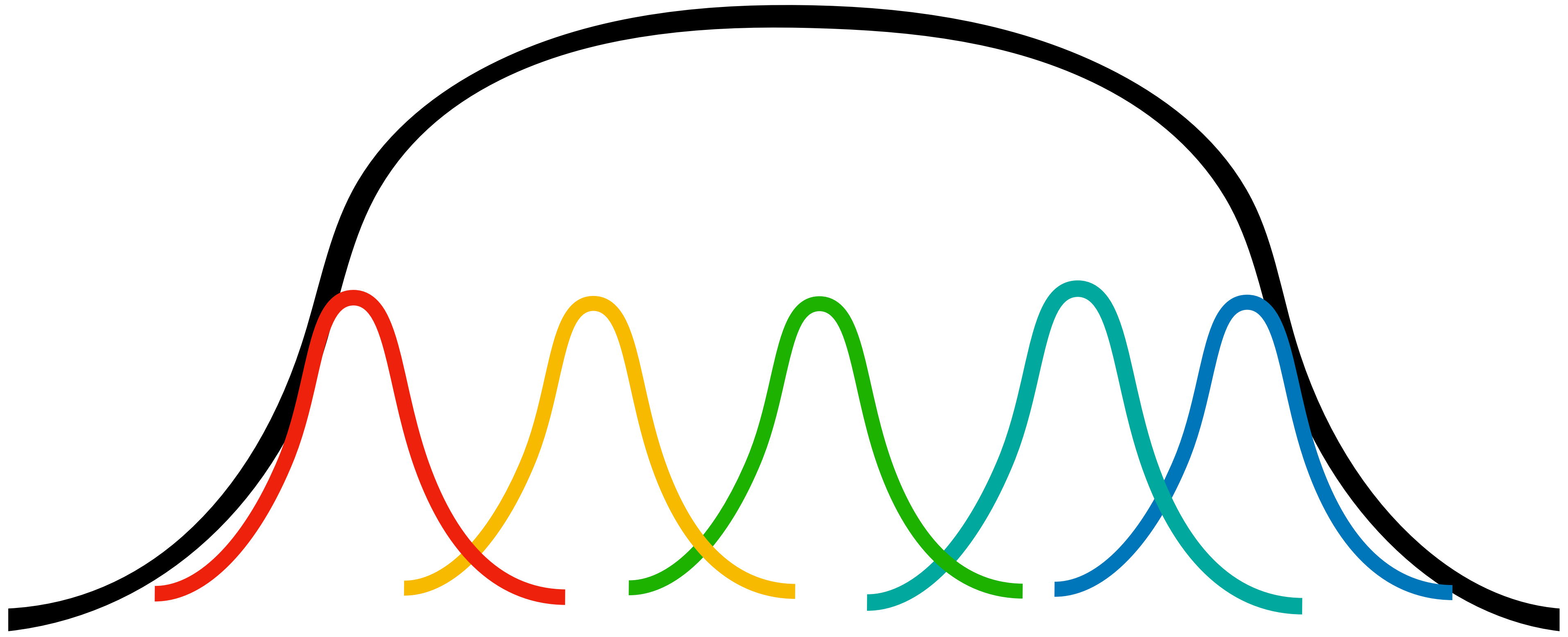


## At Detector



1. Long duration $\delta t \sim \text{month}\left(\frac{\mathscr{R}}{\text{pc}}\right)$

2. At any given moment in the detector, one sees a **narrow** distribution of momentum / energy

$\Rightarrow$ "effective coherence time" $\tau_* \sim 10^{-2}\mathscr{R}$

**Eby**, Shirai, Stadnik, Takhistov (2106.14893)

# Sensitivity to Transient Signal

**Sensitivity Ratio**
**to SM coupling $d_i$ at**
**fixed frequency $\omega_0$**

$$\frac{\text{(burst)}\ d_{i,*}(\omega_0)}{\text{(DM)}\ d_i(\omega_0)} \sim \left(\frac{\rho_{\rm dm}}{\rho_*}\right)^n \frac{t_{\rm int}^{1/4}\min\left(\tau_{\rm dm}^{1/4}, t_{\rm int}^{1/4}\right)}{\min\left(\delta t^{1/4}, t_{\rm int}^{1/4}\right)\min\left(\tau_*^{1/4}, t_{\rm int}^{1/4}\right)}$$

**"Is a given DM experiment equally/more sensitive to relativistic bursts compared to cold DM search?"**

**Timescales:**

| | |
|---|---|
| Interrogation time[†] | $t_{\rm int}$ |
| DM coherence time | $\tau_{\rm dm}$ |
| Burst coherence time | $\tau_*$ |
| Burst duration | $\delta t$ |

[†] laser coherence, natural linewidth, …

**Eby**, Shirai, Stadnik, Takhistov (2106.14893)

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**to SM coupling $d_i$ at**
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usual scaling of DM signal

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**Eby**, Shirai, Stadnik, Takhistov (2106.14893)

# Sensitivity to Transient Signal

**Sensitivity Ratio to SM coupling $d_i$ at fixed frequency $\omega_0$**

**depends on axion-SM coupling:**

$n = 1/2$ (linear coupling)

$n = 1$ (quadratic coupling)

**usual scaling of DM signal**

$$\begin{matrix}\text{(burst)}\\[1.5em] \text{(DM)}\end{matrix}\ \frac{d_{i,*}(\omega_0)}{d_i(\omega_0)} \sim \left(\frac{\rho_{\rm dm}}{\rho_*}\right)^n \frac{t_{\rm int}^{1/4}\min\left(\tau_{\rm dm}^{1/4}, t_{\rm int}^{1/4}\right)}{\min\left(\delta t^{1/4}, t_{\rm int}^{1/4}\right)\min\left(\tau_*^{1/4}, t_{\rm int}^{1/4}\right)}$$

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| Burst coherence time | $\tau_*$ |
| Burst duration | $\delta t$ |

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**Eby**, Shirai, Stadnik, Takhistov (2106.14893)

# Sensitivity to Transient Signal

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$n = 1/2$ (linear coupling)

$n = 1$ (quadratic coupling)

**usual scaling of DM signal**

$$\frac{\text{(burst)}\ d_{i,*}(\omega_0)}{\text{(DM)}\ d_i(\omega_0)} \sim \left(\frac{\rho_{\mathrm{dm}}}{\rho_*}\right)^{n} \frac{t_{\mathrm{int}}^{1/4}\min\left(\tau_{\mathrm{dm}}^{1/4}, t_{\mathrm{int}}^{1/4}\right)}{\min\left(\delta t^{1/4}, t_{\mathrm{int}}^{1/4}\right)\min\left(\tau_*^{1/4}, t_{\mathrm{int}}^{1/4}\right)}$$

**energy density in the burst**

**“did we catch all/most of the signal?”**

**“is the signal coherent for the whole integration time?”**

**“Is a given DM experiment equally/more sensitive to relativistic bursts compared to cold DM search?”**

**Timescales:**

| | |
|---|---|
| Interrogation time[†] | $t_{\mathrm{int}}$ |
| DM coherence time | $\tau_{\mathrm{dm}}$ |
| Burst coherence time | $\tau_*$ |
| Burst duration | $\delta t$ |

[†] laser coherence, natural linewidth, …

| | | | |
|---|---|---|---|
| coupling: | **linear, psuedoscalar** | **linear, scalar** | **quadratic, scalar** |
| Lagrangian: | $\mathscr{L} \supset g_{a\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$ | $\mathscr{L} \supset d_e^{(1)} \frac{a}{2M_{\mathrm{Pl}}} F^{\mu\nu} F_{\mu\nu}$ | $\mathscr{L} \supset d_e^{(2)} \left( \frac{a}{2M_{\mathrm{Pl}}} \right)^2 F^{\mu\nu} F_{\mu\nu}$ |
| example field: | **QCD axion** | **relaxion** | **QCD axion** or **relaxion** |
| experiments: | **ABRACADABRA, DM-Radio, …** | **Quantum sensors** | **Quantum sensors** |
| reference: | **Eby**, Shirai, Stadnik, Takhistov (2106.14893) | Arakawa, **Eby**, Safronova, Takhistov, Zaheer (2306.16468) | Arakawa, Zaheer, **Eby**, Takhistov, Safronova (2402.06736) |

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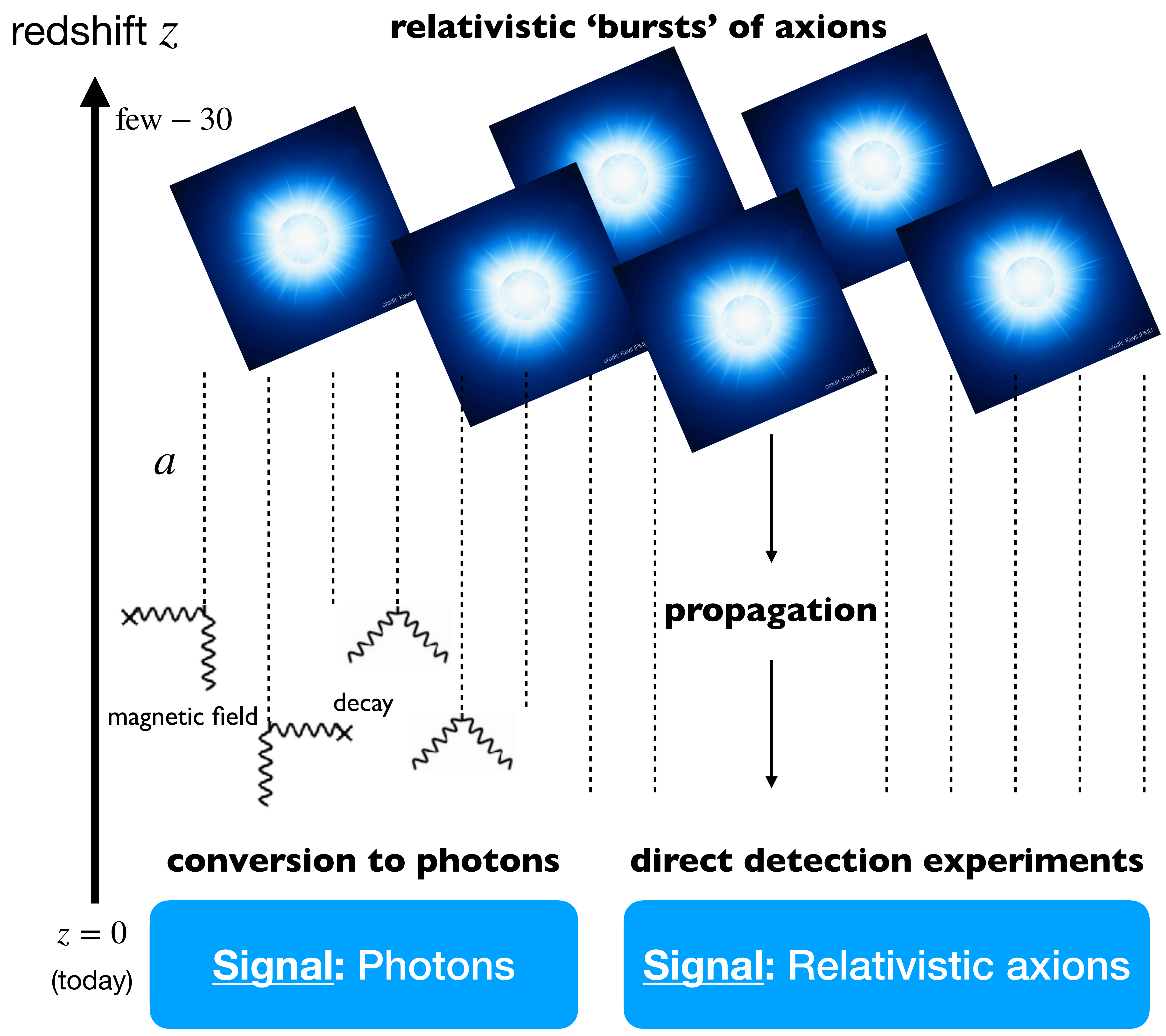


redshift $z$

**relativistic 'bursts' of axions**

few – 30

$a$

magnetic field

decay

**propagation**

**conversion to photons**

**direct detection experiments**

$z = 0$

(today)

**Signal**: Photons

**Signal**: Relativistic axions

## 2. Diffuse Axion Background (DaB)

# Astrophysical bursts of relativistic axions

generally characterised by

flux

$$\frac{dN_a}{d\omega}(\omega)$$

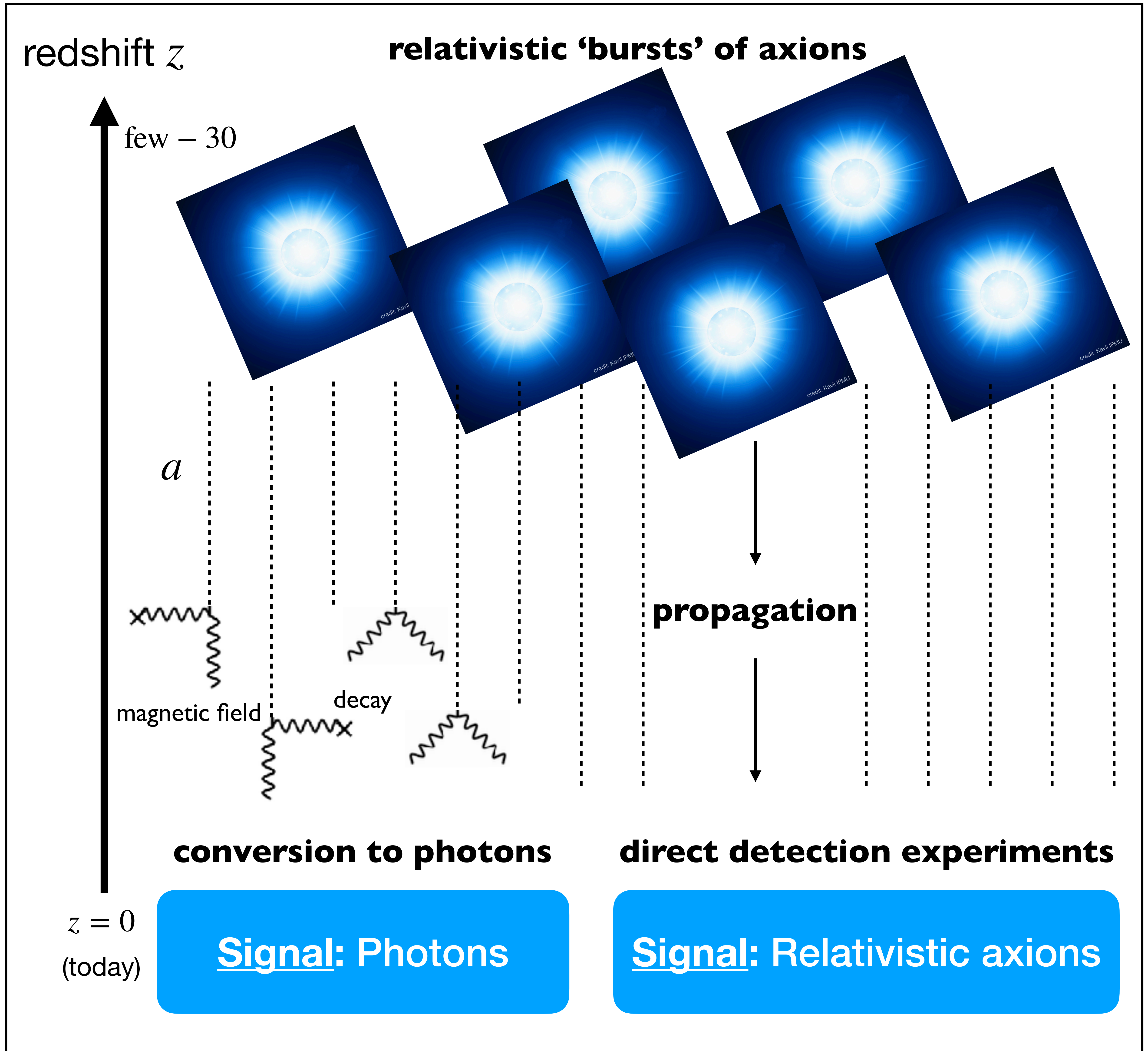
rate

$$R_{\text{burst}}(z)$$

DaB flux* in present day

$$\frac{d\phi}{d\omega}(\omega) = \int_0^\infty dz \frac{dN_a(\omega(1+z))}{d\omega}\frac{R_{\text{burst}}(z)}{H(z)}$$

*note: flux $\frac{dN_a}{d\omega}$ (# of particles) vs flux $\frac{d\phi}{d\omega}$ (# per area per time)



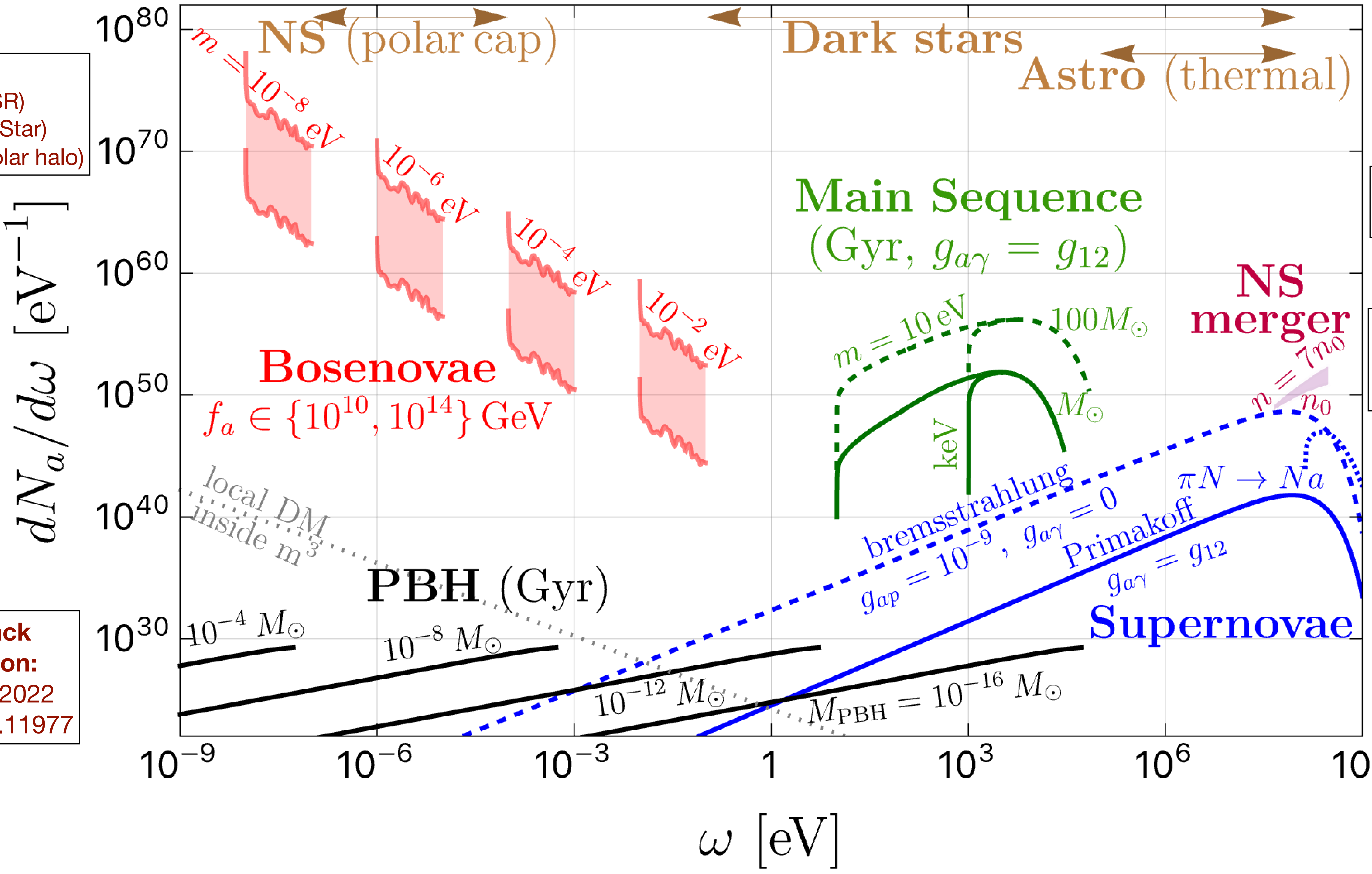
## 2. Diffuse Axion Background (DaB)

# Bursts Abound

**NS polar cap:**
Prabhu, PRD 2021
Noordhuis++, PRL 2023, arXiv:2307.11811

**Dark stars:**
Maselli++, PRD 2017
Curtin and Setford, PRL 2019
Hippert++, PRD 2021

**Bosenovae:**
Yoshino++, PTP 2012 (BHSR)
Levkov++, PRL 2016 (Boson Star)
Budker, **J Eby**++, JCAP 2023 (Solar halo)



**Main sequence stars:**
e.g. Nguyen++, JCAP 2023

**Neutron star mergers:**
Harris++, JCAP 2020
Fiorillo++, PRD 2022

**Primordial black hole evaporation:**
Agashe++, PRD 2022
Jho++, arXiv:2212.11977

**Supernovae:**
fits via
Carenza++, JCAP 2019
Calore++, PRD 2020
***(First DaB proposal!)***

**Eby**, Takhistov (2402.00100)

**Eby**, Takhistov,
(2402.00100)

# Parameterization: DaB

$$\frac{dN_a}{d\omega}(\omega) \propto \frac{E_{\rm tot}}{m_a^2} \frac{\exp\left(-\frac{(\omega-\bar{\omega})^2}{\delta\omega^2}\right)}{\delta\omega/m_a}$$

$$R_{\rm burst}(z) \propto \frac{\mathscr{F}\bar{\rho}_{\rm U} H_0}{E_{\rm tot}} f(z)$$

$\mathscr{F}$ : total DM fraction converted to DaB

$f(z)$ : dimensionless rate of bursts

$\bar{\omega}$ : peak burst energy per particle

$\delta\omega$ : spread in burst energy per particle

$E_{\rm tot}$ : energy emitted per burst

DaB flux in present day

$$\frac{d\phi}{d\omega}(\omega) = \int_0^\infty dz \frac{dN_a(\omega(1+z))}{d\omega} \frac{R_{\rm burst}(z)}{H(z)}$$

**Eby**, Takhistov,
(2402.00100)

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## input parameters

particle physics

$m_a, f_a, g_{a\gamma}, \ldots$

burst parameterisation

$\mathscr{F}, f(z)$ , $\bar{\omega}, \delta\omega, \cancel{E_{\rm tot}}$ cancels in product

(cosmology) (individual bursts)

**Eby**, Takhistov,
(2402.00100)

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(cosmology) (individual bursts)

**How to search for DaB:** (1) direct detection, (2) photon signals, [more to come]

**Eby**, Takhistov, (2402.00100)

# DaB Flux vs DM Flux

Locally, $\left(\frac{d\phi}{d\omega}\right)_{\text{local DM}} \simeq \frac{n_a v_{\rm dm}}{m_a} \simeq \frac{\rho_{\rm dm}}{m_a^2} v_{\rm dm}$

DaB flux in present day

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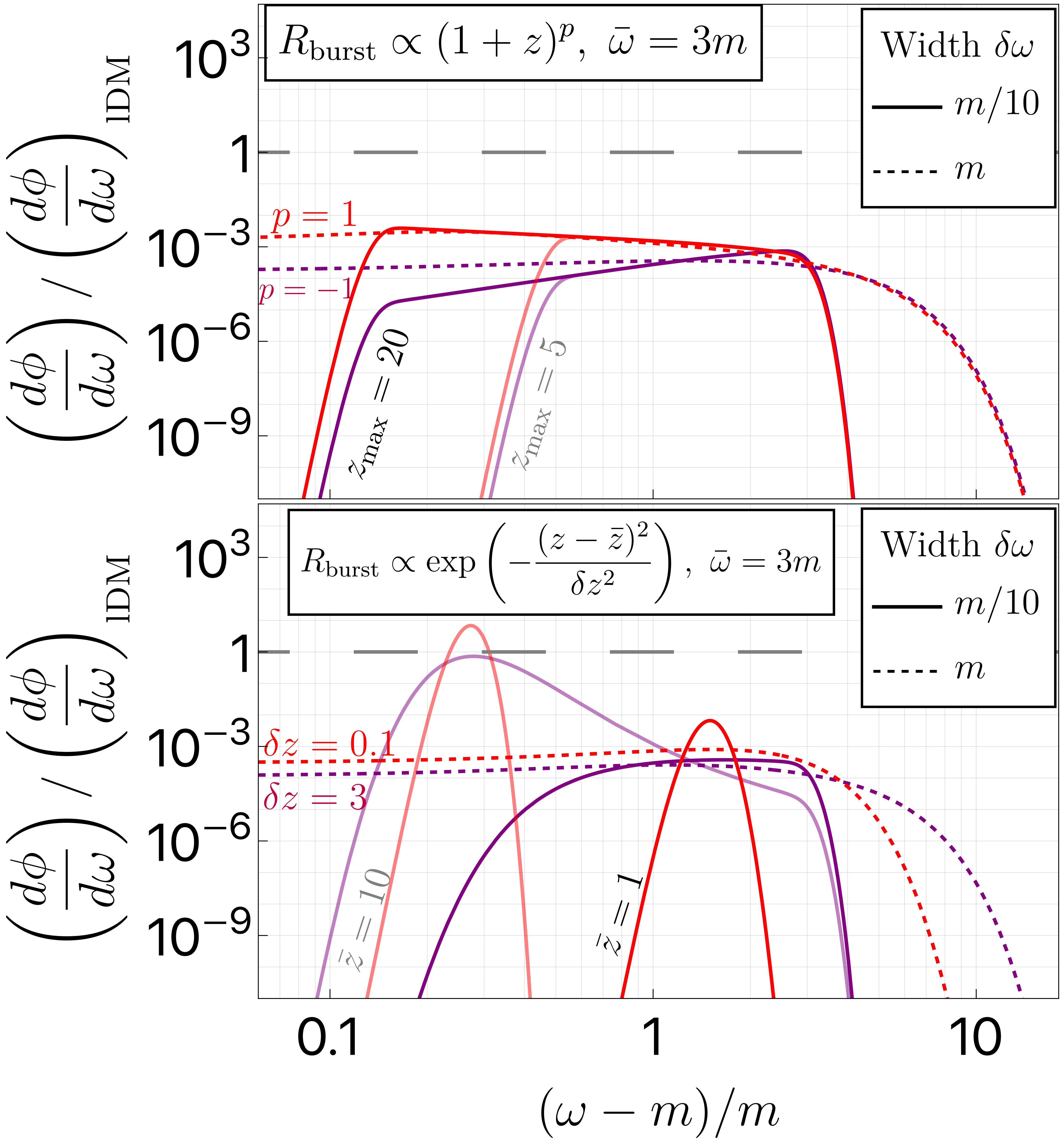

**Eby**, Takhistov, (2402.00100)

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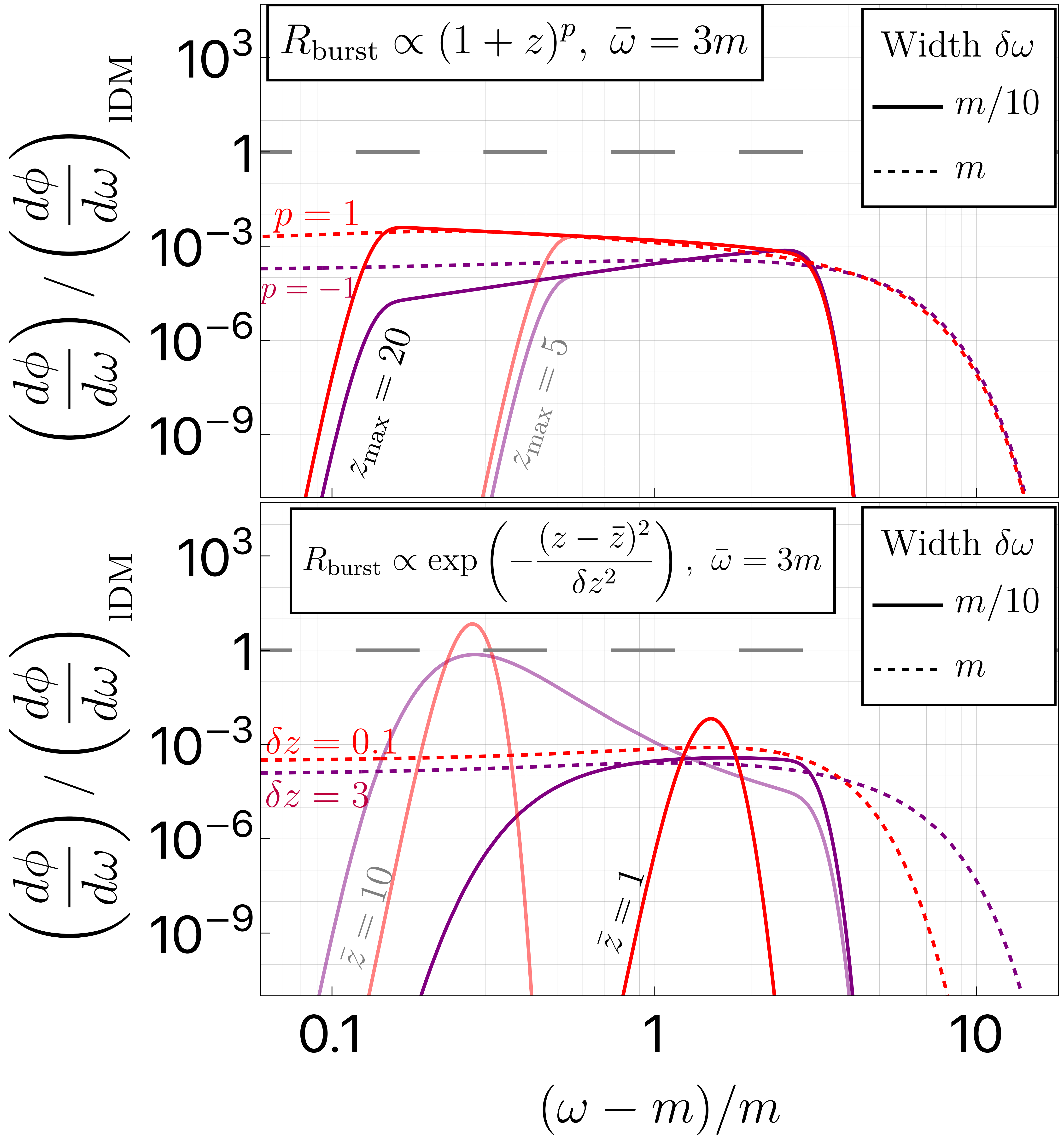
Parameterise flux and rate $\sim$

$$\frac{\mathcal{F}\bar{\rho}_{\text{U}}}{m_a \delta\omega} \int dz f(z) \frac{H_0}{H(z)} \exp\left[-\left(\frac{(\omega(1+z)-\bar{\omega})}{\delta\omega}\right)^2\right]$$



**Eby**, Takhistov, (2402.00100)

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Parameterise flux and rate

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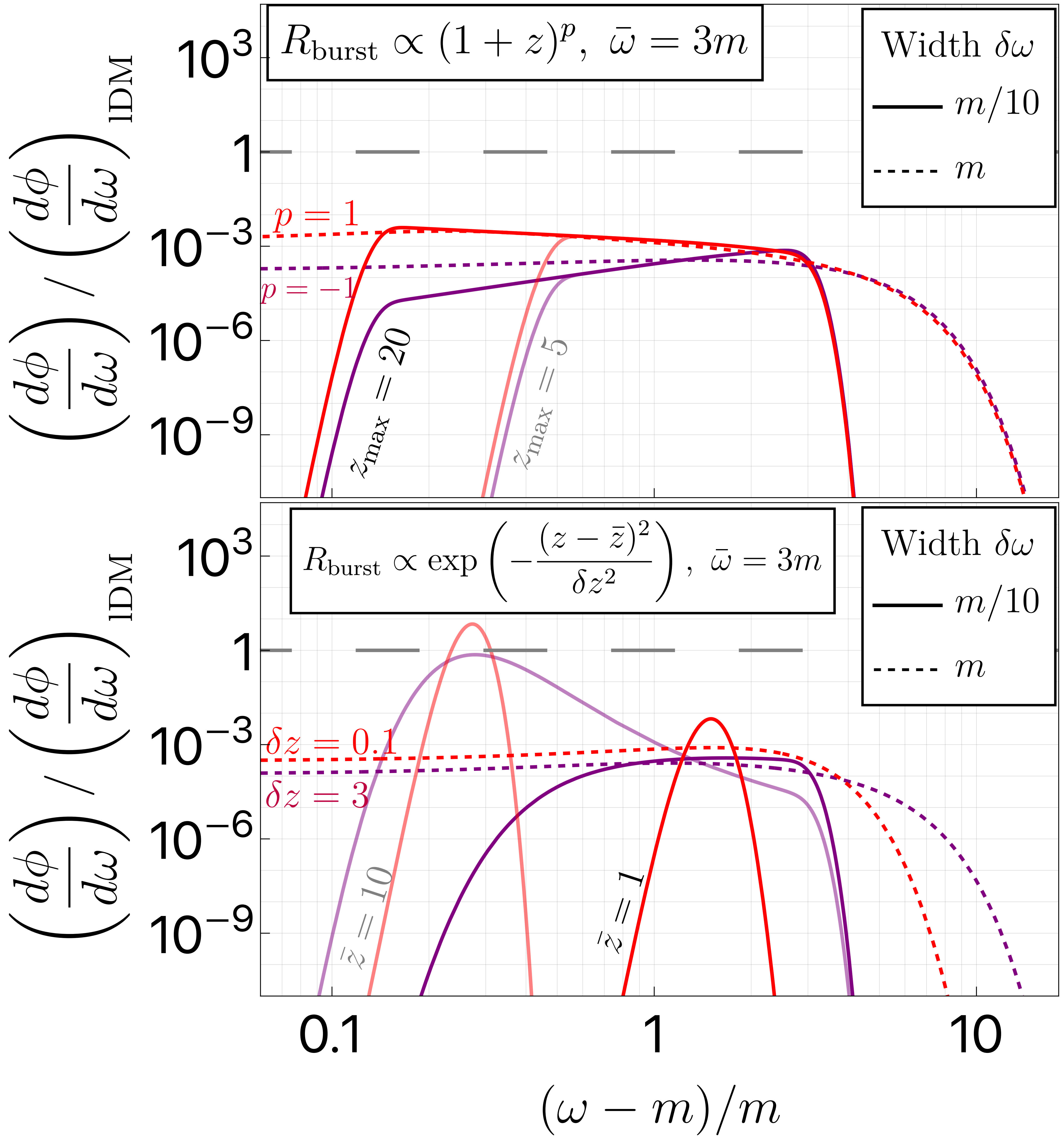
narrow: $\dfrac{\delta\omega}{\omega} \to 0$

recent: $z \sim 0$

$$\sim \quad \frac{\mathscr{F}\bar{\rho}_U}{\bar{\omega}^2}$$



**Eby**, Takhistov, (2402.00100)

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recent: $z \sim 0$

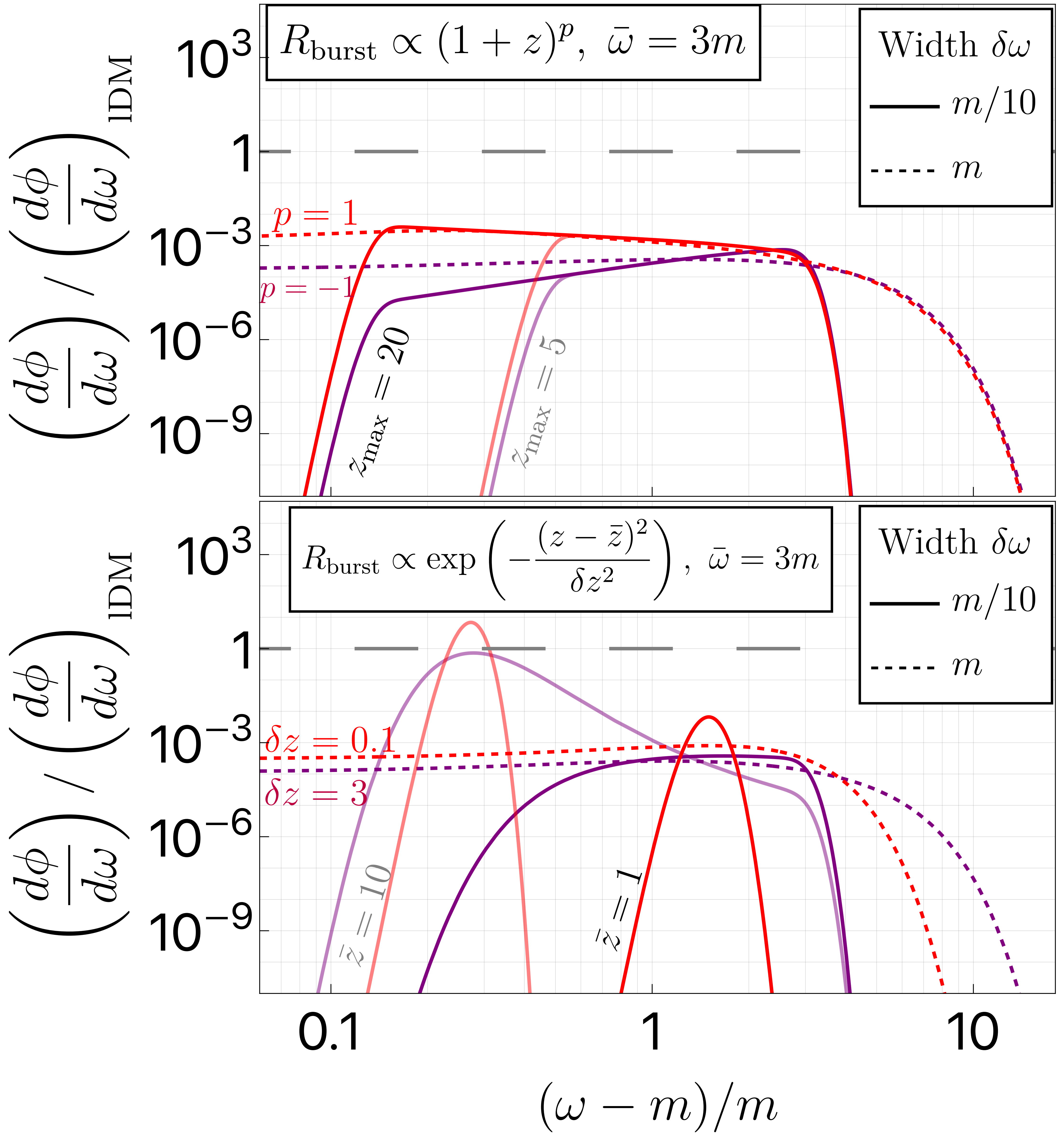
$$\sim \frac{\mathcal{F}\bar{\rho}_U}{\bar{\omega}^2}$$

$$\frac{d\phi/d\omega}{(d\phi/d\omega)_{\rm lDM}} \simeq \left(\frac{1}{v_{\rm dm}}\right)\left(\frac{m_a}{\bar{\omega}}\right)^2\left(\frac{\mathcal{F}\bar{\rho}_U}{\rho_{\rm dm}}\right) \simeq 3 \cdot 10^{-3}\mathcal{F}\left(\frac{m_a}{\bar{\omega}}\right)^2$$

(large)

(small)

(small)



**Eby**, Takhistov,
(2402.00100)

# Direct Detection

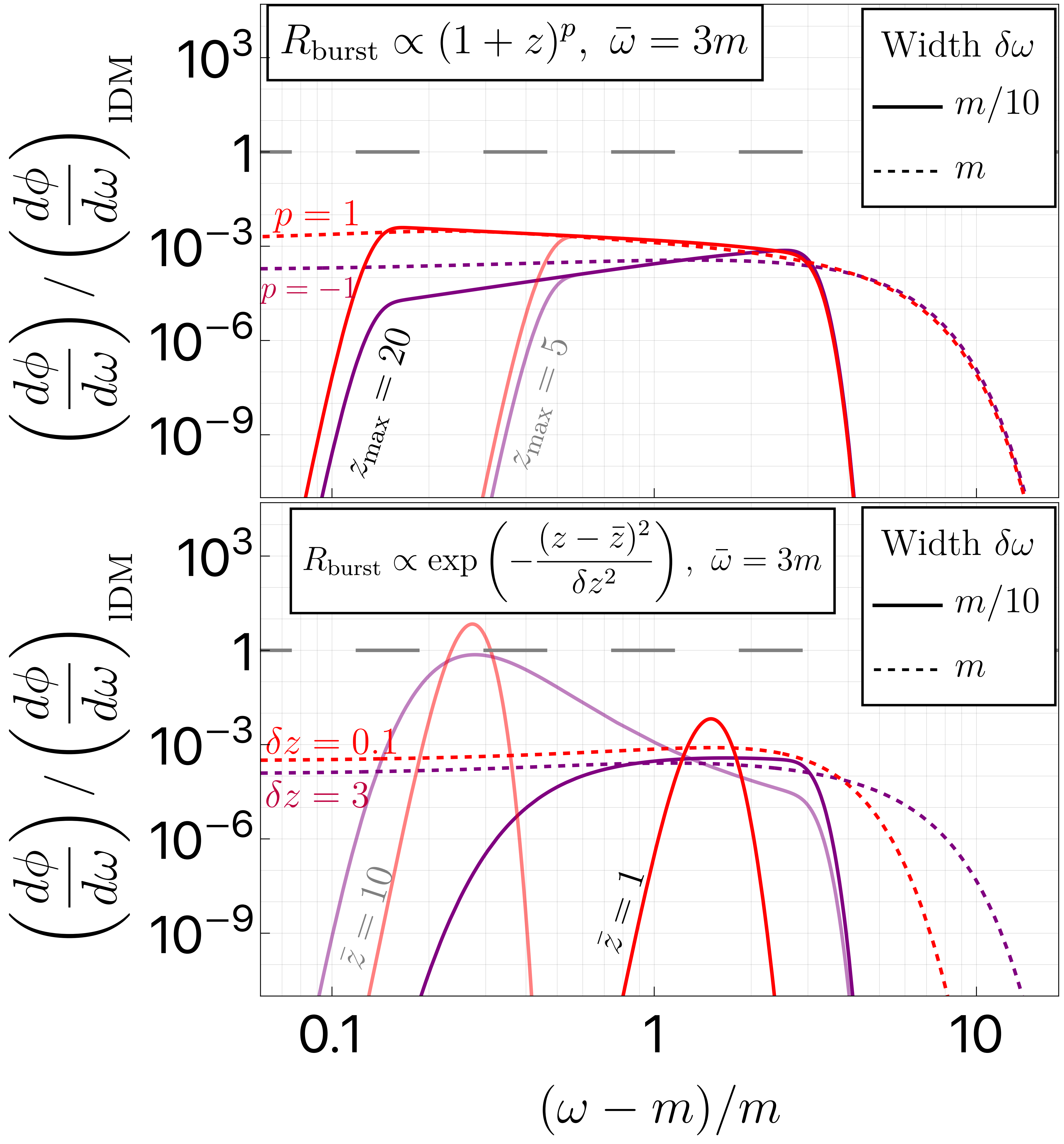
## Likely challenging!

- DaB flux generally $\lesssim$ local DM flux
- Signal likely much less coherent than local DM

$$\tau_{\rm coh} \simeq \frac{2\pi}{m_a v^2}, \quad v_{\rm dm} \sim 10^{-3} \text{ vs } v_{\rm DaB} \sim 1$$

## Worth investigating!

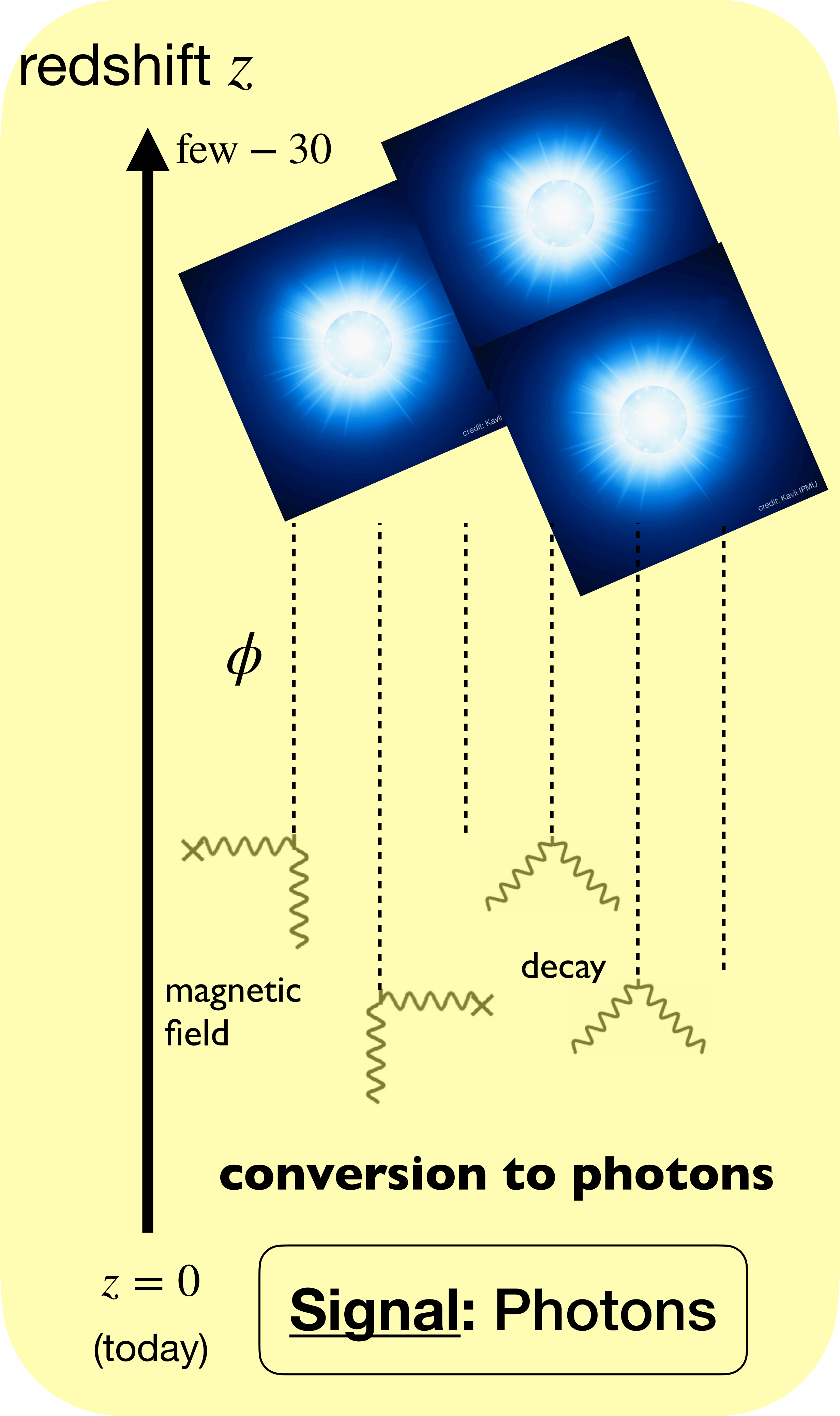
- Nontrivial energy distribution encodes cosmological evolution and source properties
- Can also encode information about fundamental axion potential, e.g. self-interactions



**Eby**, Takhistov,
(2402.00100)

# Photon Signals from DaB

$$\mathscr{L} \supset \frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$$



**conversion to photons**

**Signal**: Photons

**Eby**, Takhistov,
(2402.00100)

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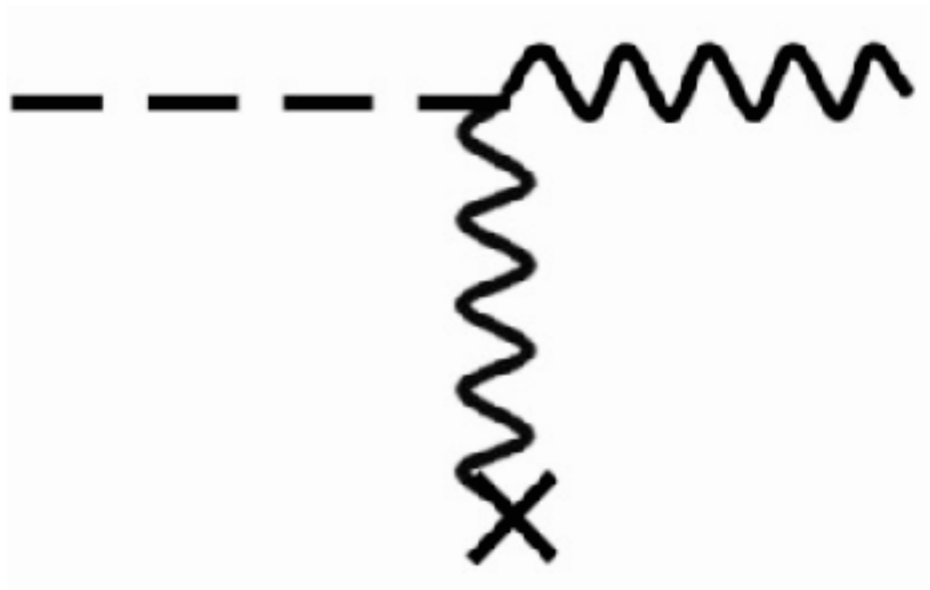
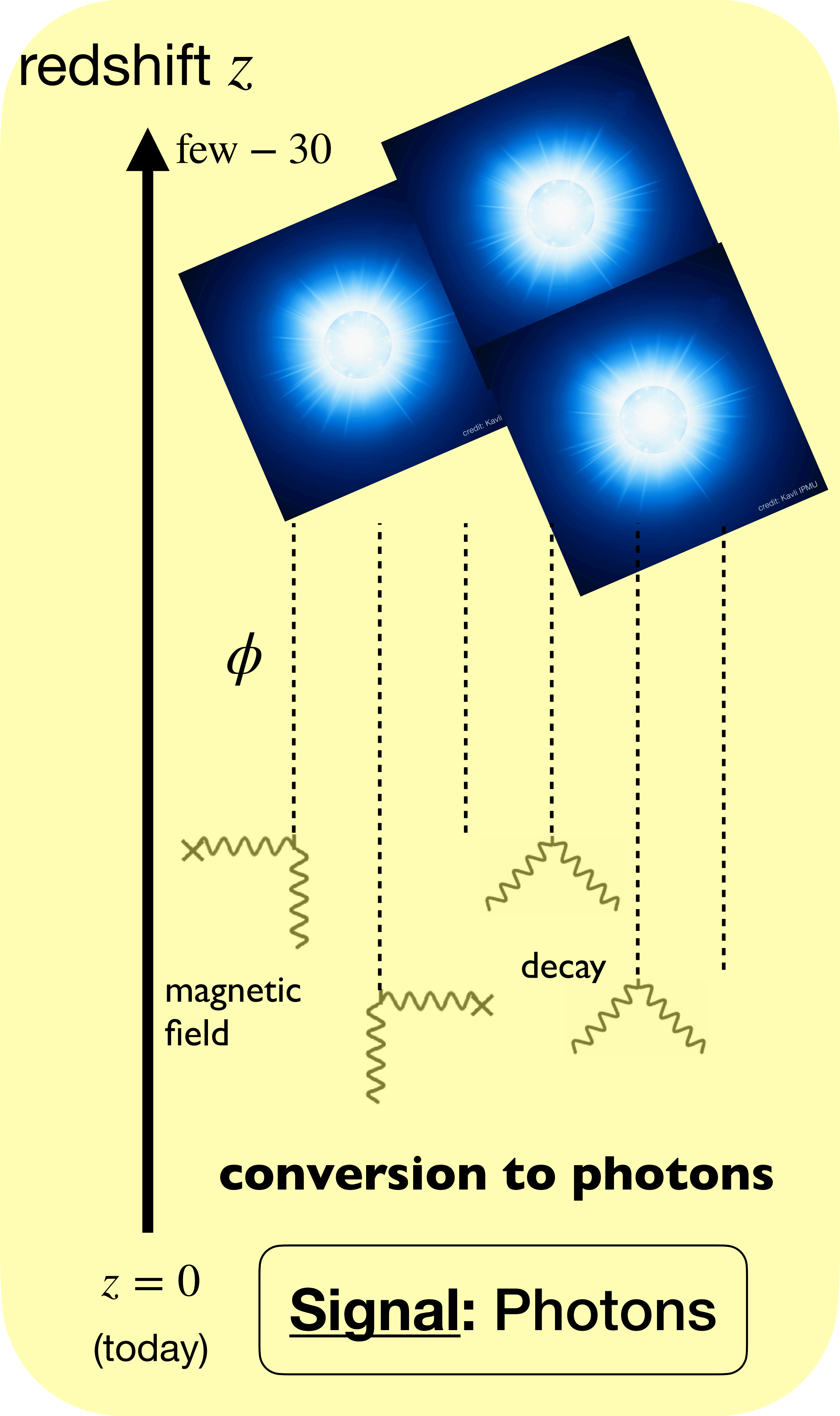
## Magnetic field conversion

$$\left.\frac{d\phi_\gamma}{d\omega}\right|_{B-\text{field}} = P_{\gamma\to a}\frac{d\phi}{d\omega}$$



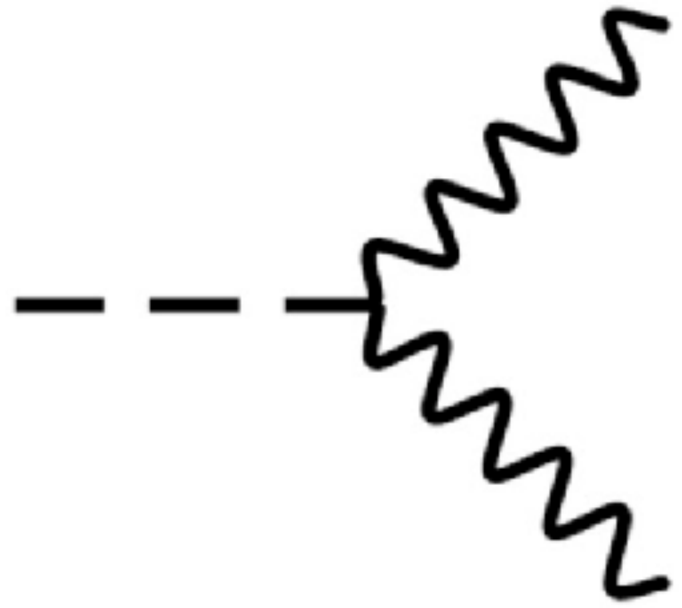


**conversion to photons**

**Signal**: Photons

## Axion decay to photons

$$\left.\frac{d\phi_\gamma}{d\omega}\right|_{\text{decay}} \simeq P_{\text{decay}}\frac{d\phi}{d\omega}$$



**Eby**, Takhistov,
(2402.00100)

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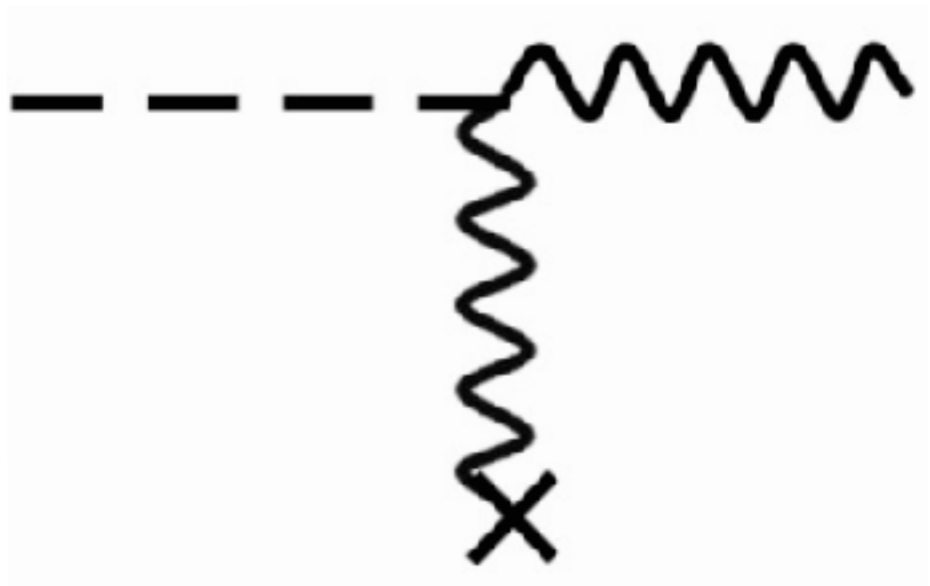
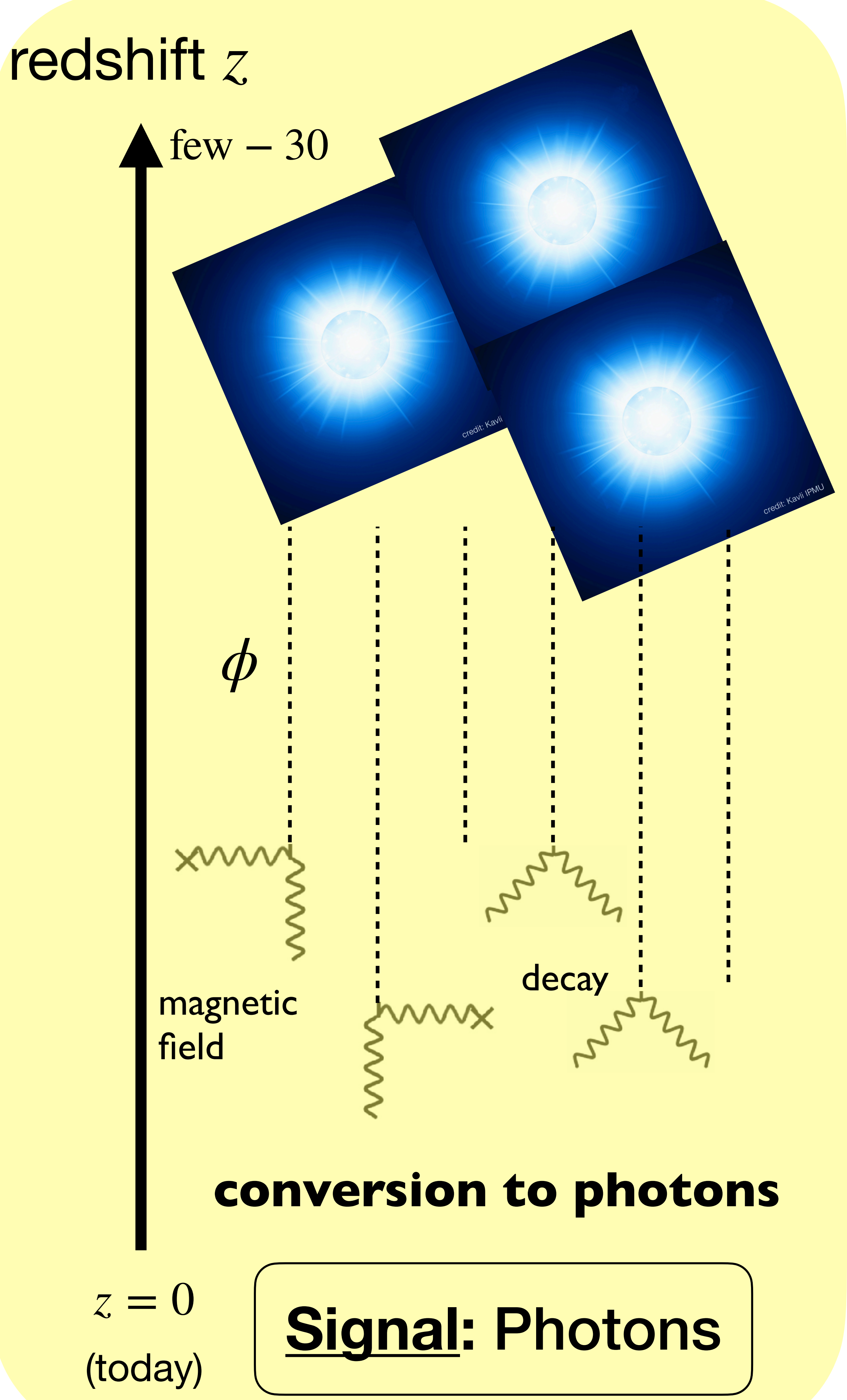


- Galactic magnetic fields of $\sim \mu\mathrm{G}$ dominate (typical distances $\sim \mathrm{kpc}-\mathrm{Mpc}$)
- $P_{\gamma\to a}$ grows with large $\omega$ and small $m_a$

$\Rightarrow$ largest when $\omega \gg m_a$ with small $m_a$



**Signal**: Photons

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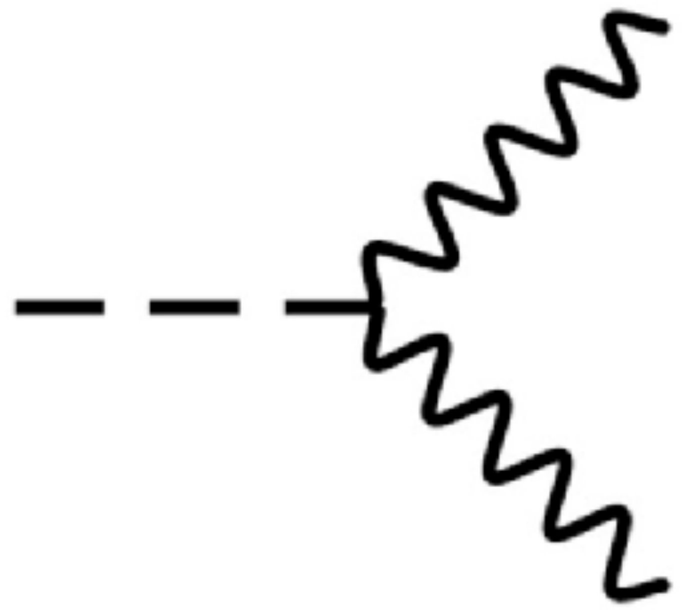

- Decay can occur anywhere in space (typical distances $\sim \mathrm{Gpc}$)
- $P_{\mathrm{decay}}$ grows with small $\omega$ and large $m_a$

$\Rightarrow$ largest when $\omega \gtrsim m_a$ with large $m_a$

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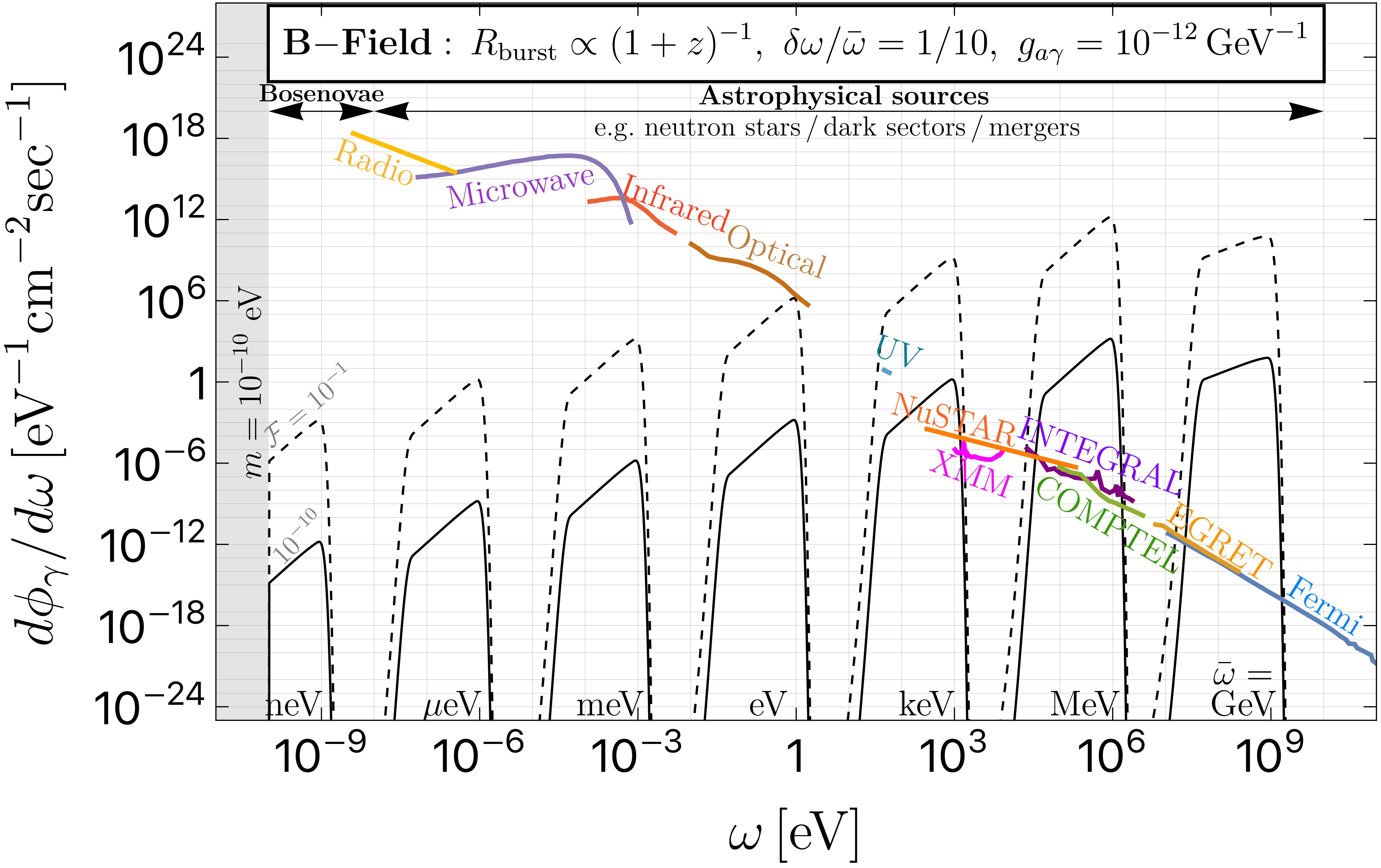
(2402.00100)

# Where to Search: Today



**Eby**, Takhistov,
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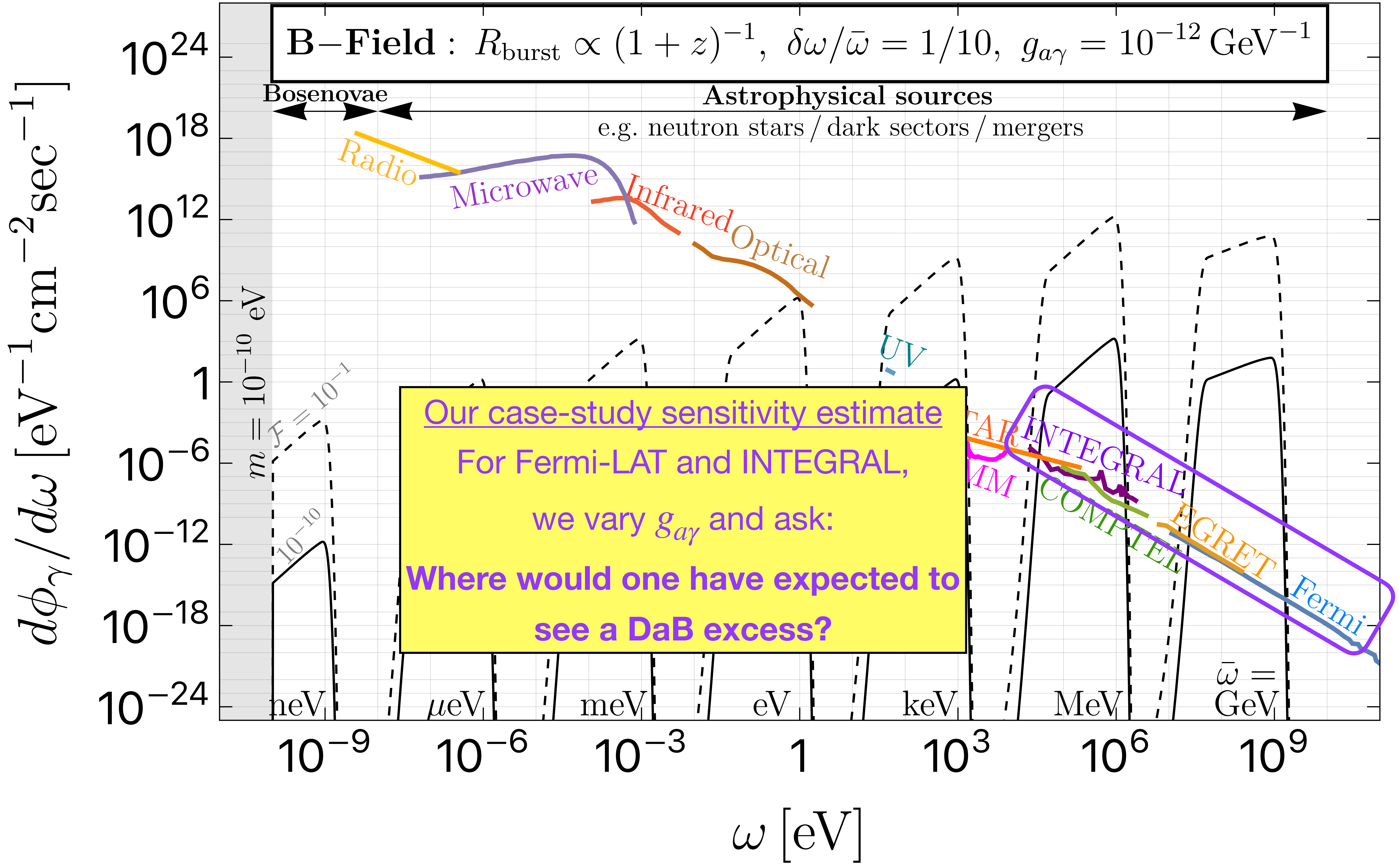


Our case-study sensitivity estimate

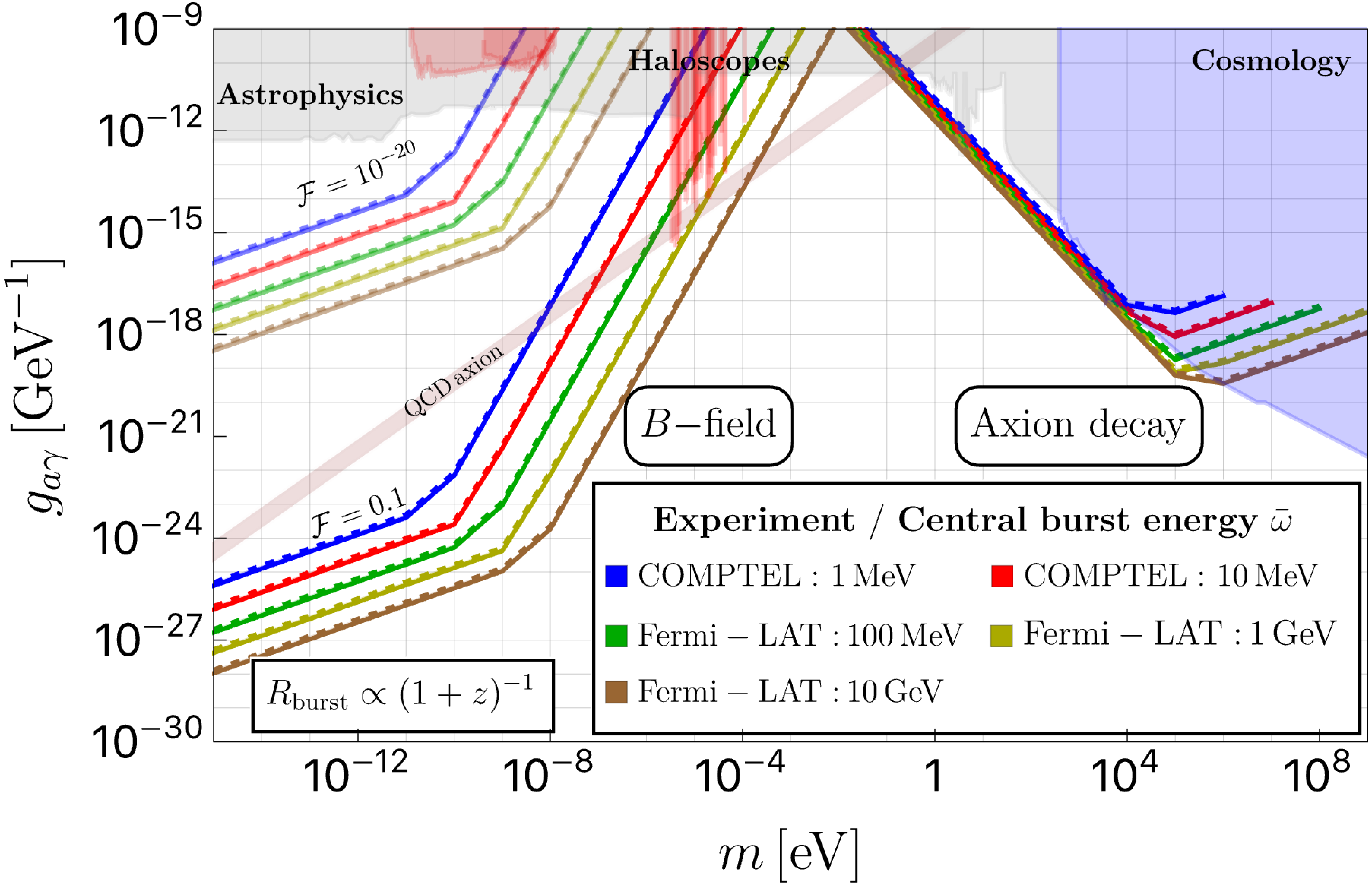
For Fermi-LAT and INTEGRAL,

we vary $g_{a\gamma}$ and ask:

**Where would one have expected to see a DaB excess?**

**Eby**, Takhistov, (2402.00100)

# Searches for DaB Gamma-Rays



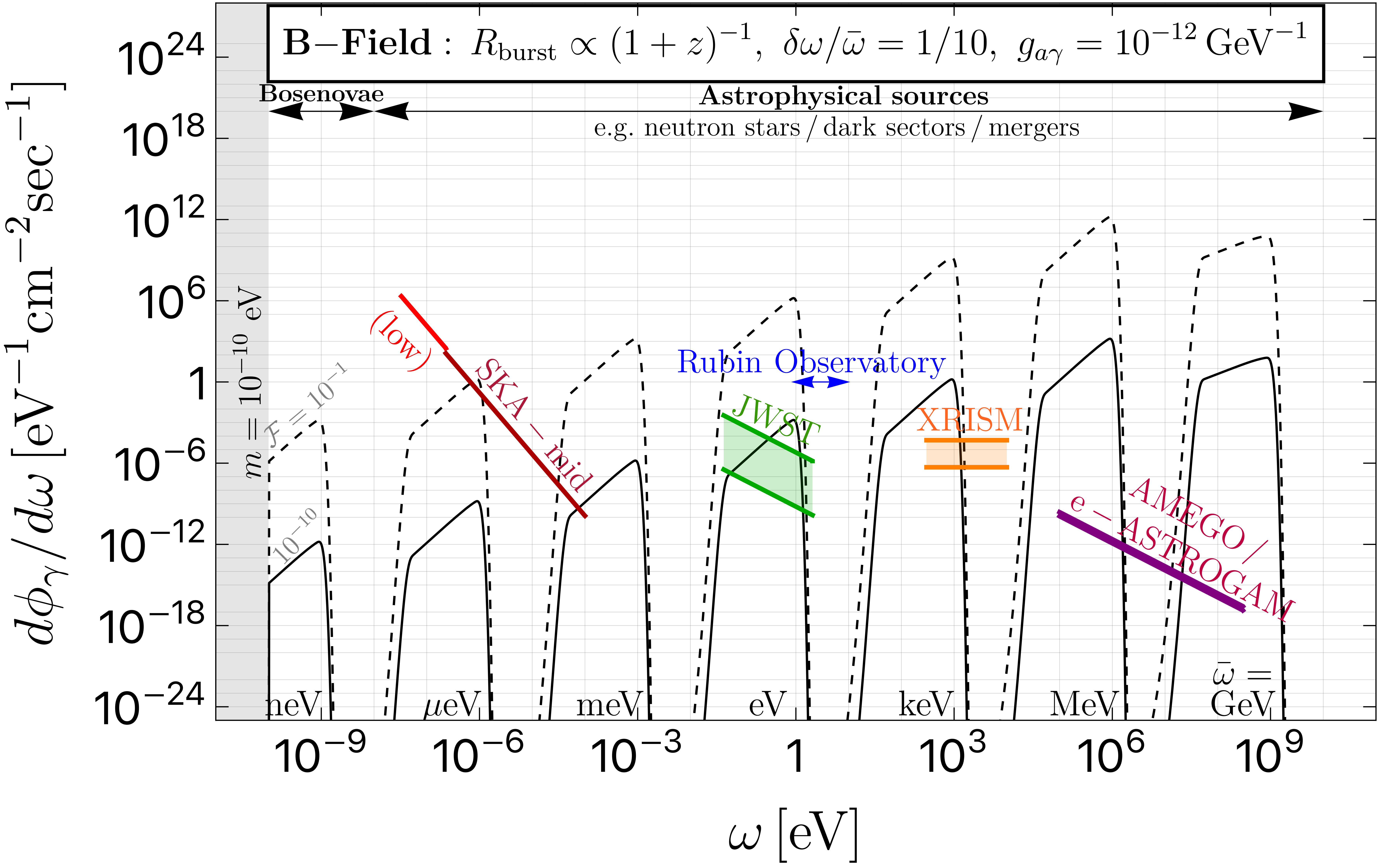
A very tiny energy fraction in DaB can give rise to striking signals!

Best sensitivity when $\bar{\omega} \gg m_a$

What about low-energy signals?

**Eby**, Takhistov,
(2402.00100)

# Where to Search: Future

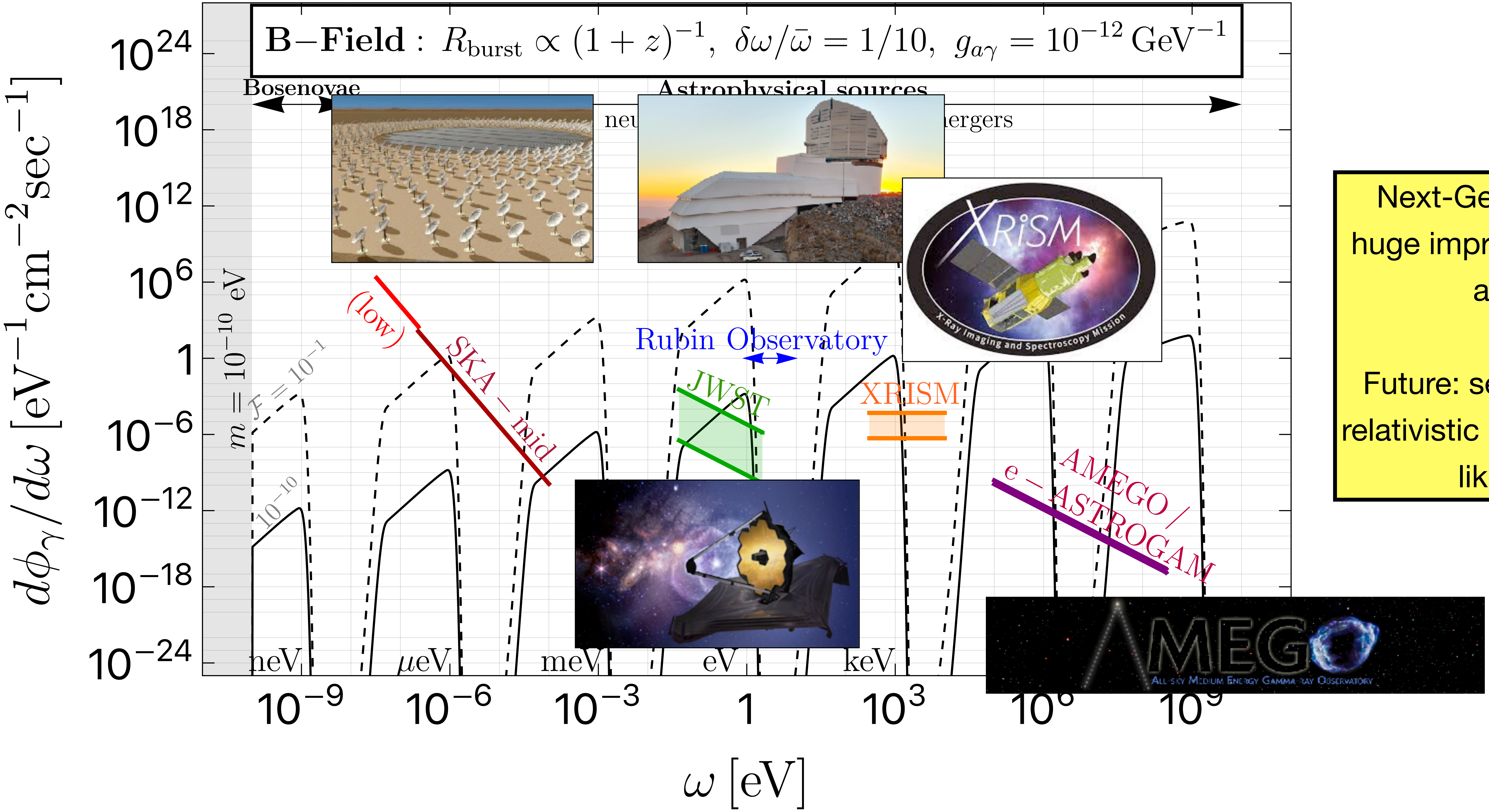


Next-Gen searches will see huge improvements, especially at low energy

Future: search even for semi-relativistic burst sources of DaB, like bosenovae!

**Eby**, Takhistov,
(2402.00100)

# Where to Search: Future



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Future: search even for semi-relativistic burst sources of DaB, like bosenovae!

# Conclusions

- Relativistic bursts of axions commonly originate in astrophysical processes, both in SM / dark sectors; give rise to a diffuse axion background (DaB)

- Axions emitted in recent transient bursts, e.g. from *bosenovae* in boson star collapse, lead to direct-detection signals which can exceed sensitivity of local DM searches. At present, detection viable but exclusion difficult; need stronger prediction of burst rate

- The DaB encodes novel information about cosmology and burst sources, implying complementarity with existing DM searches. Direct detection difficult but promising!

- Existing photon-search experiments (e.g. Fermi) can already constrain DaB using photon couplings. In progress: investigate signals from other couplings, e.g. electrons and quarks

- Further characterization of burst sources is worthy of dedicated study, strong discovery potential!

# Thank you for your attention!

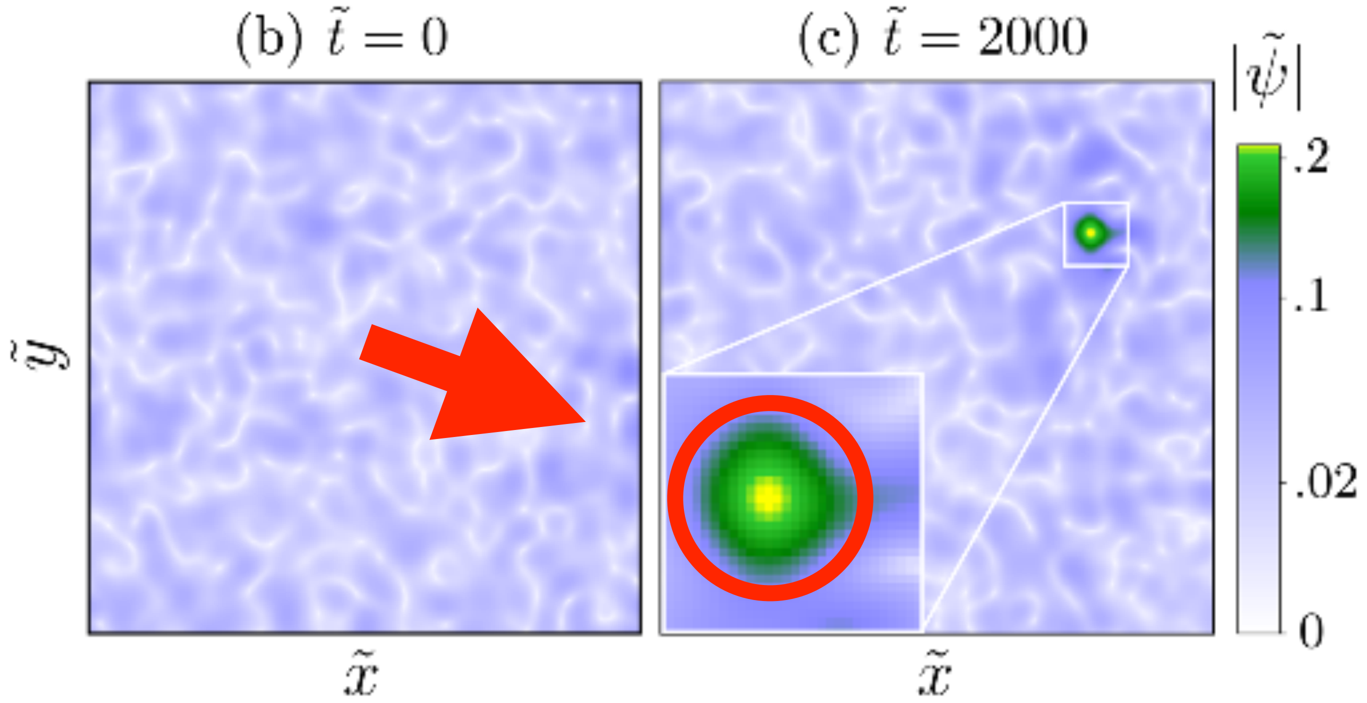
DALL-E 3 illustration:
“Athens symposium on
Exploring the Universe”

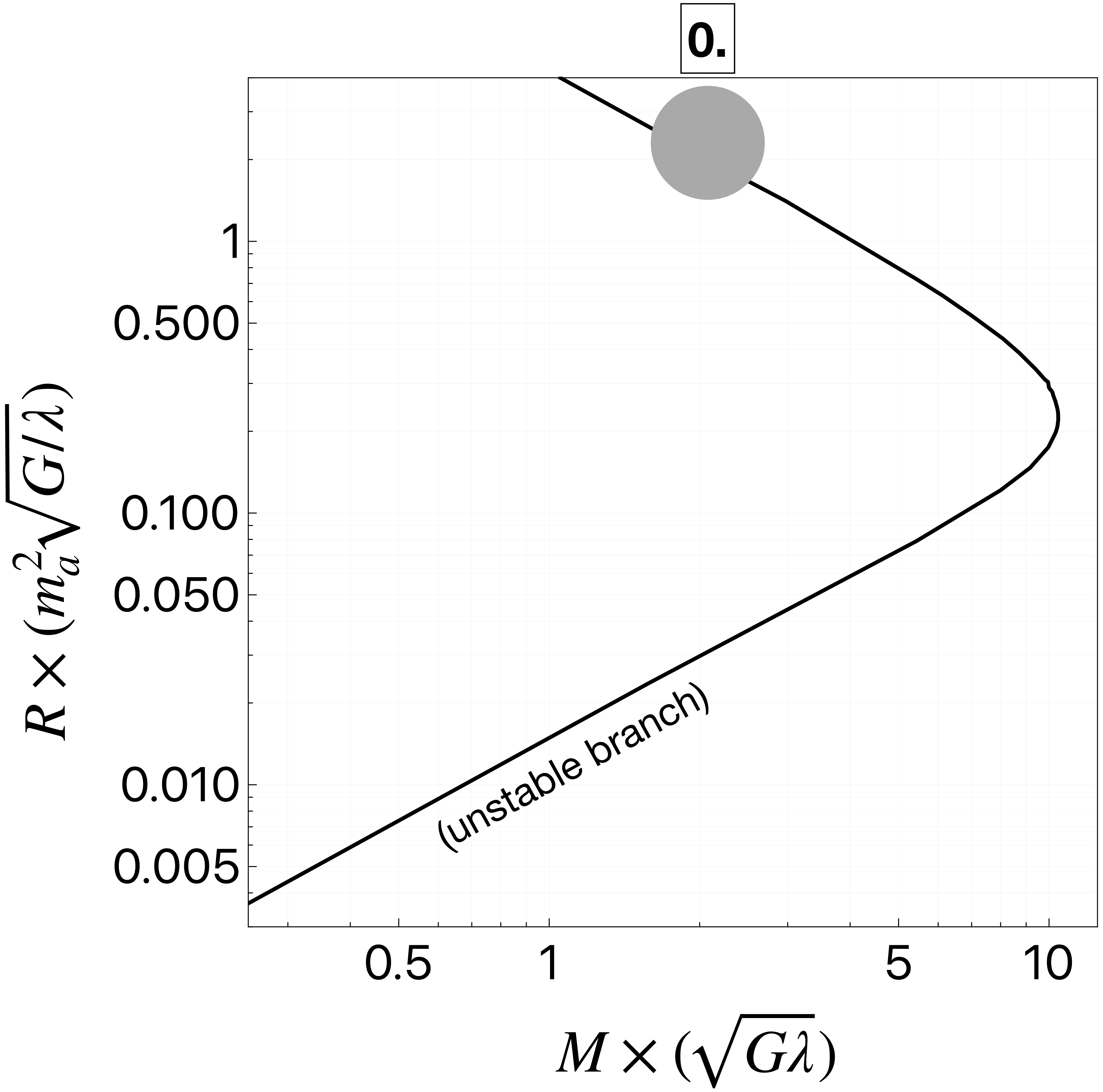
# Backup Slides

credit: Kavli IPMU

# Life Cycle of a Boson Star

0. Birth





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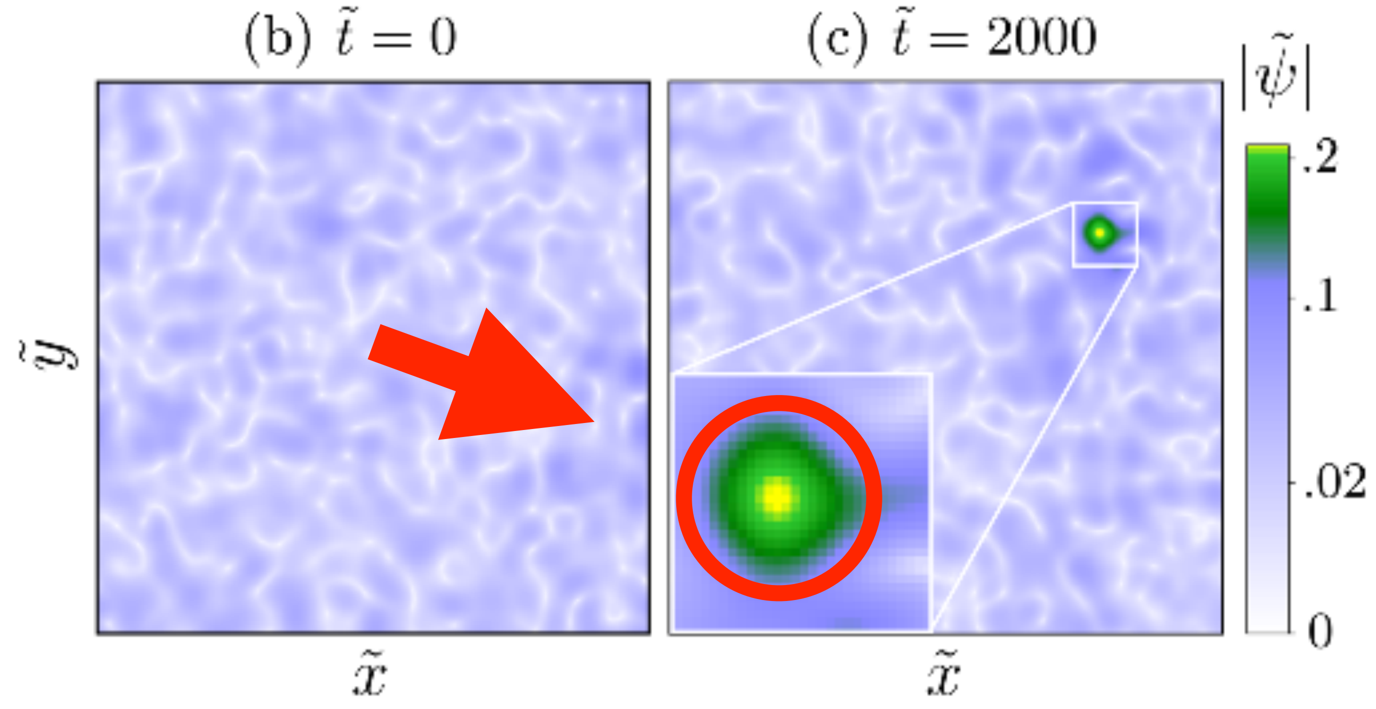
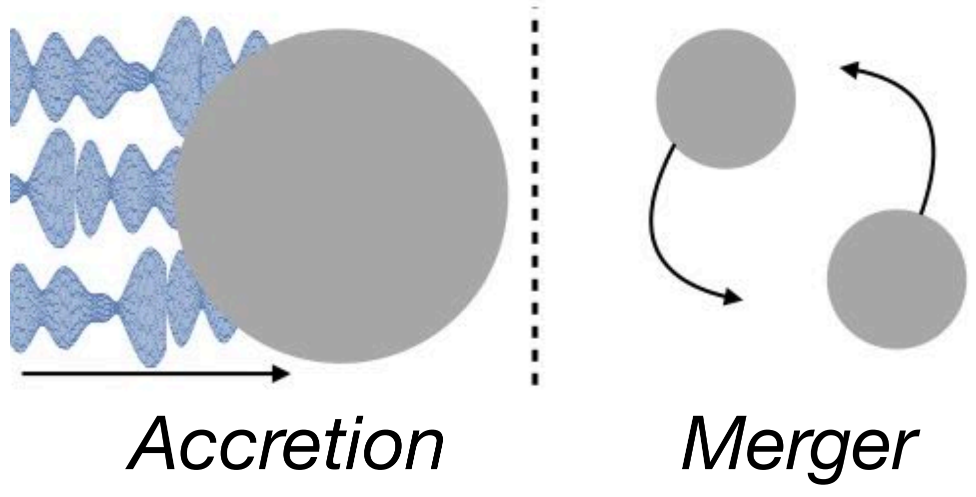
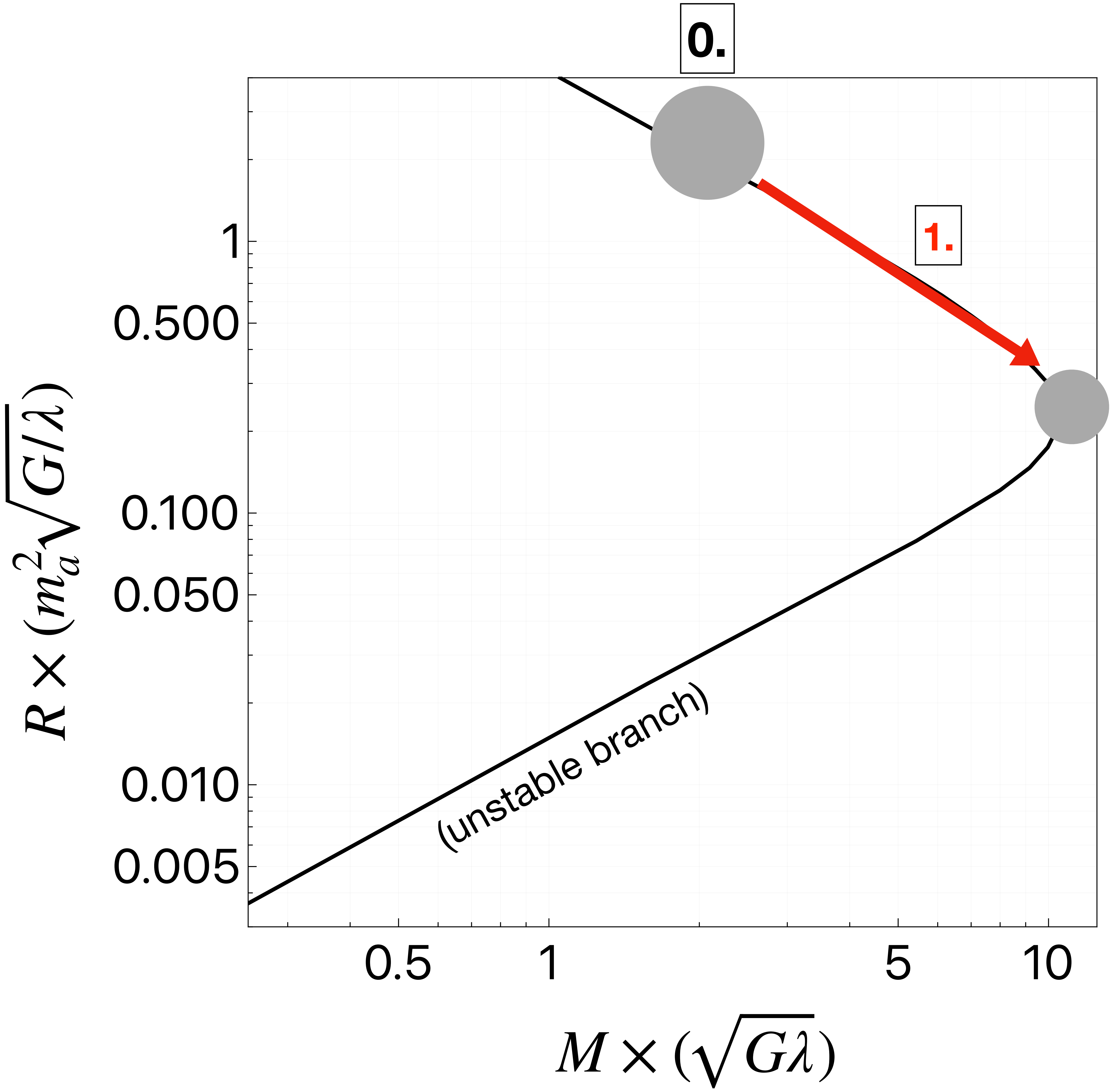


1. Growing up





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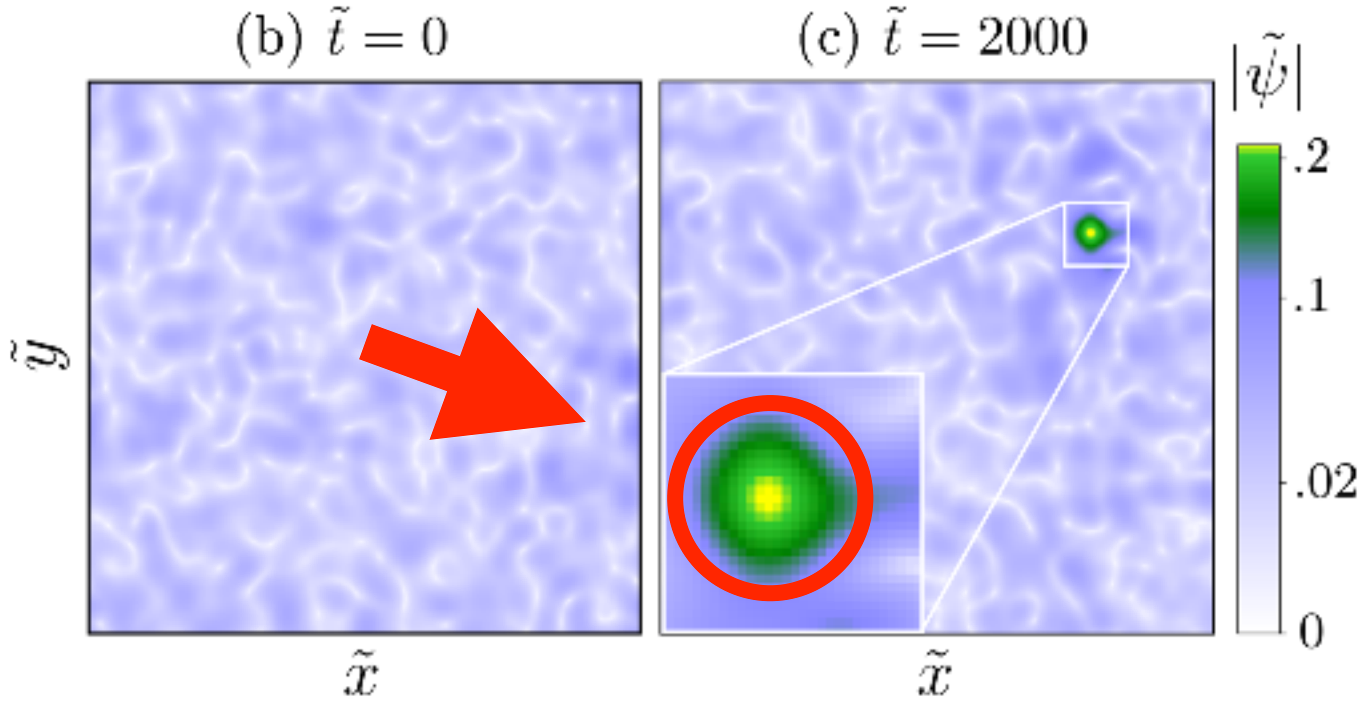

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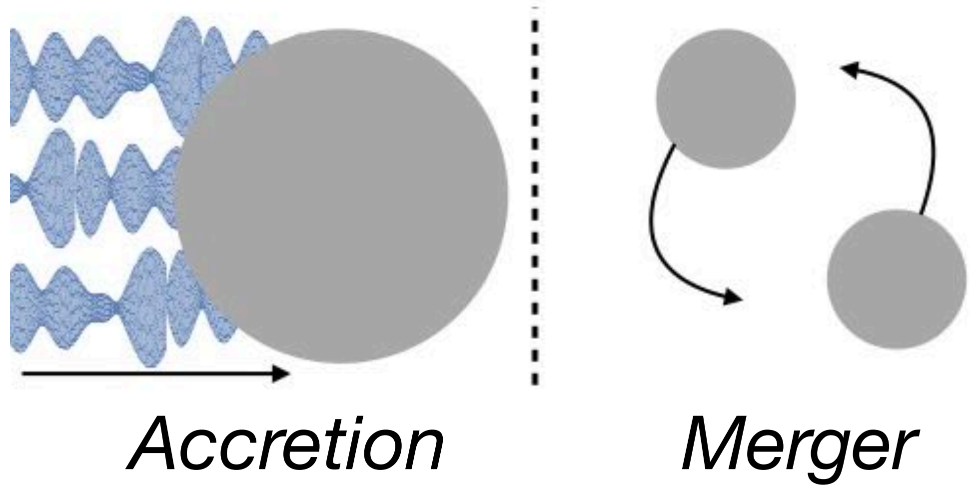
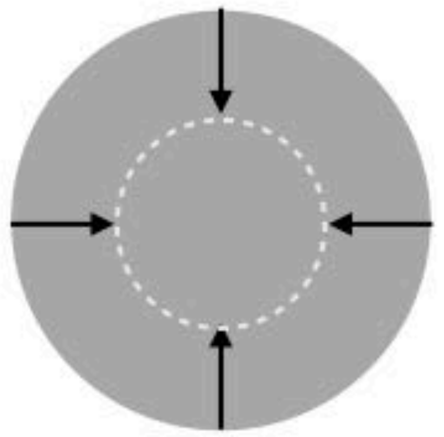
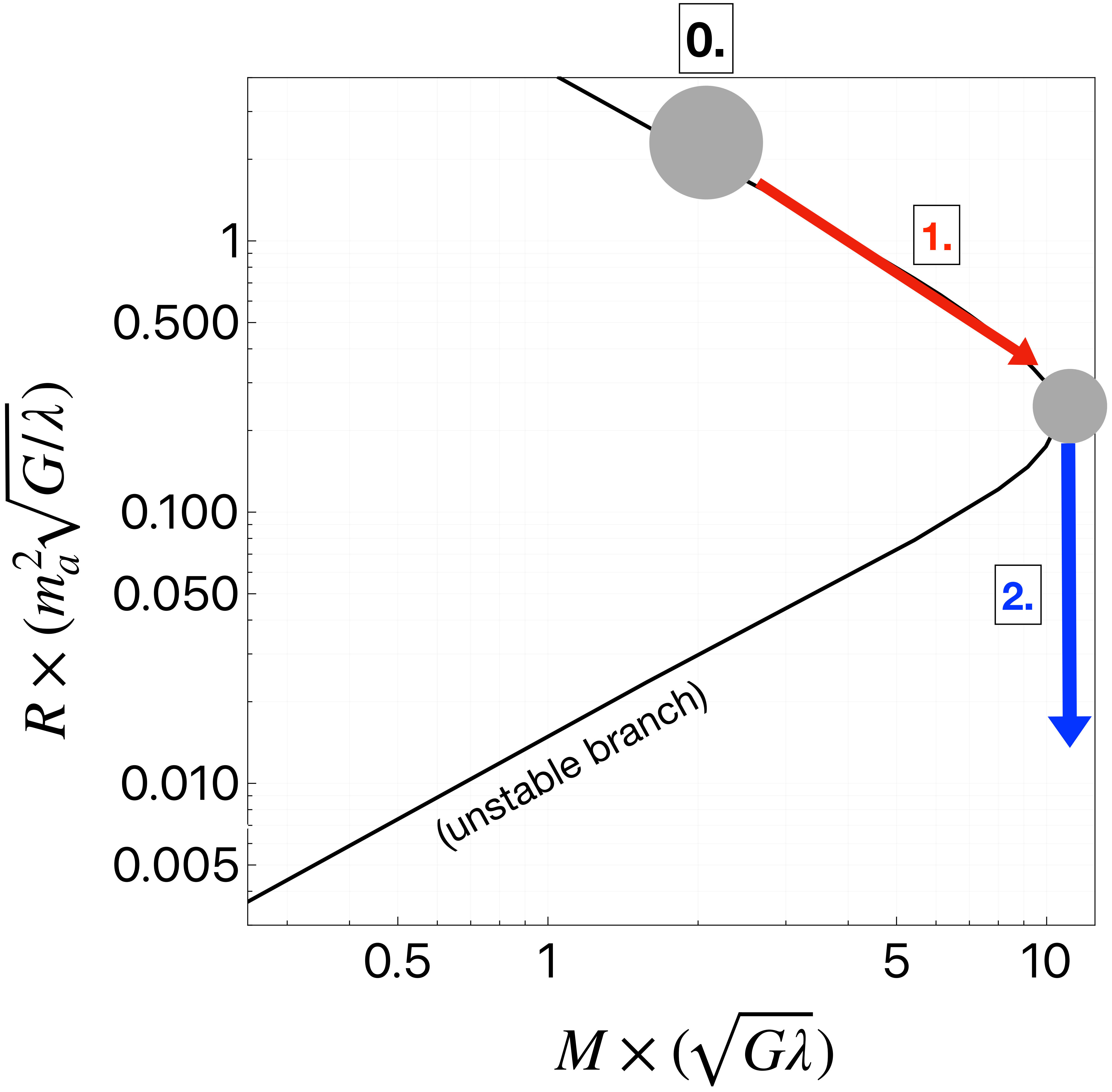


2. Gravitational collapse



at $M = M_c$



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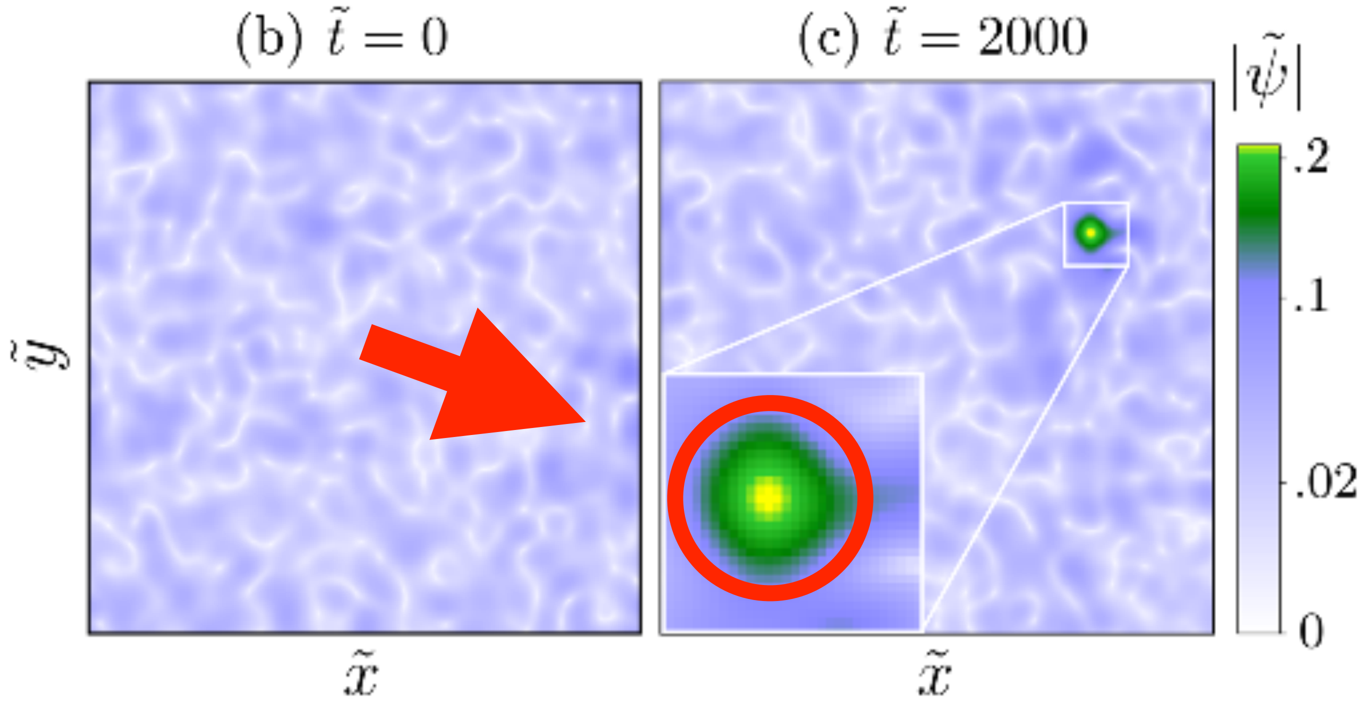

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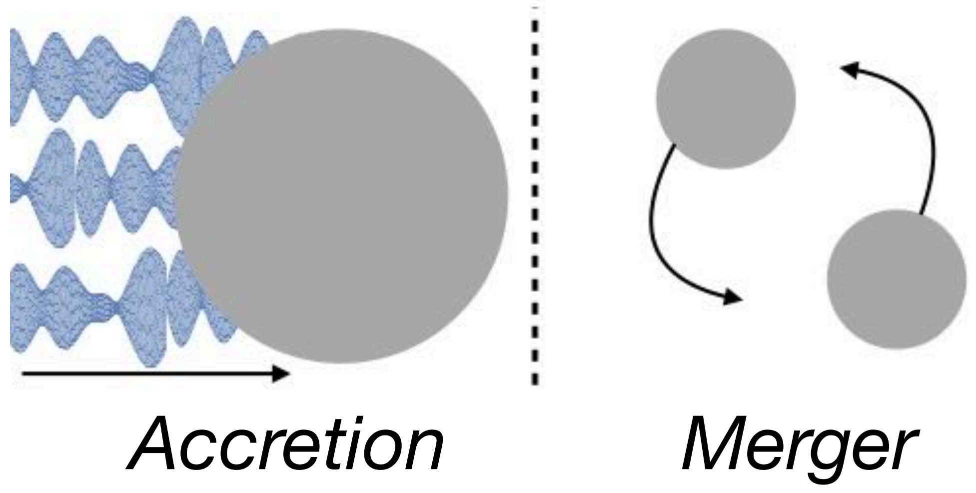

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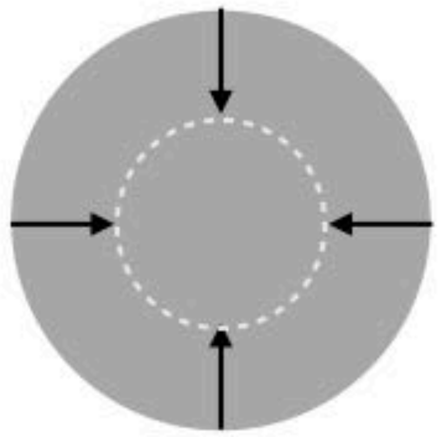
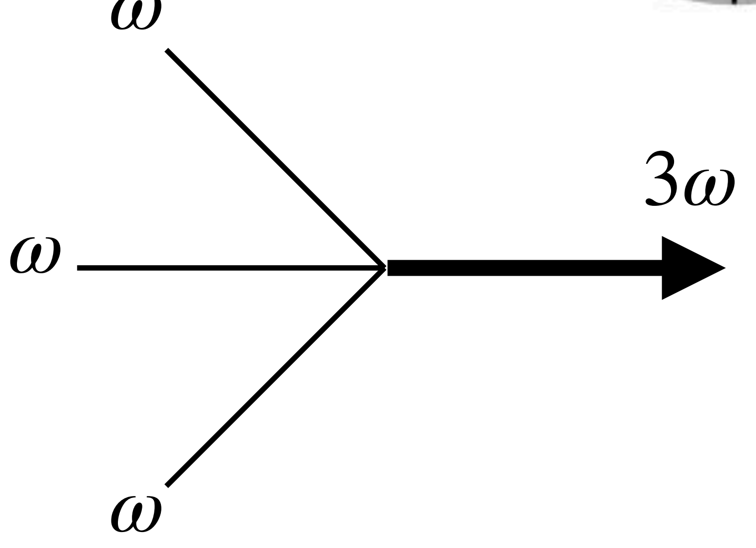
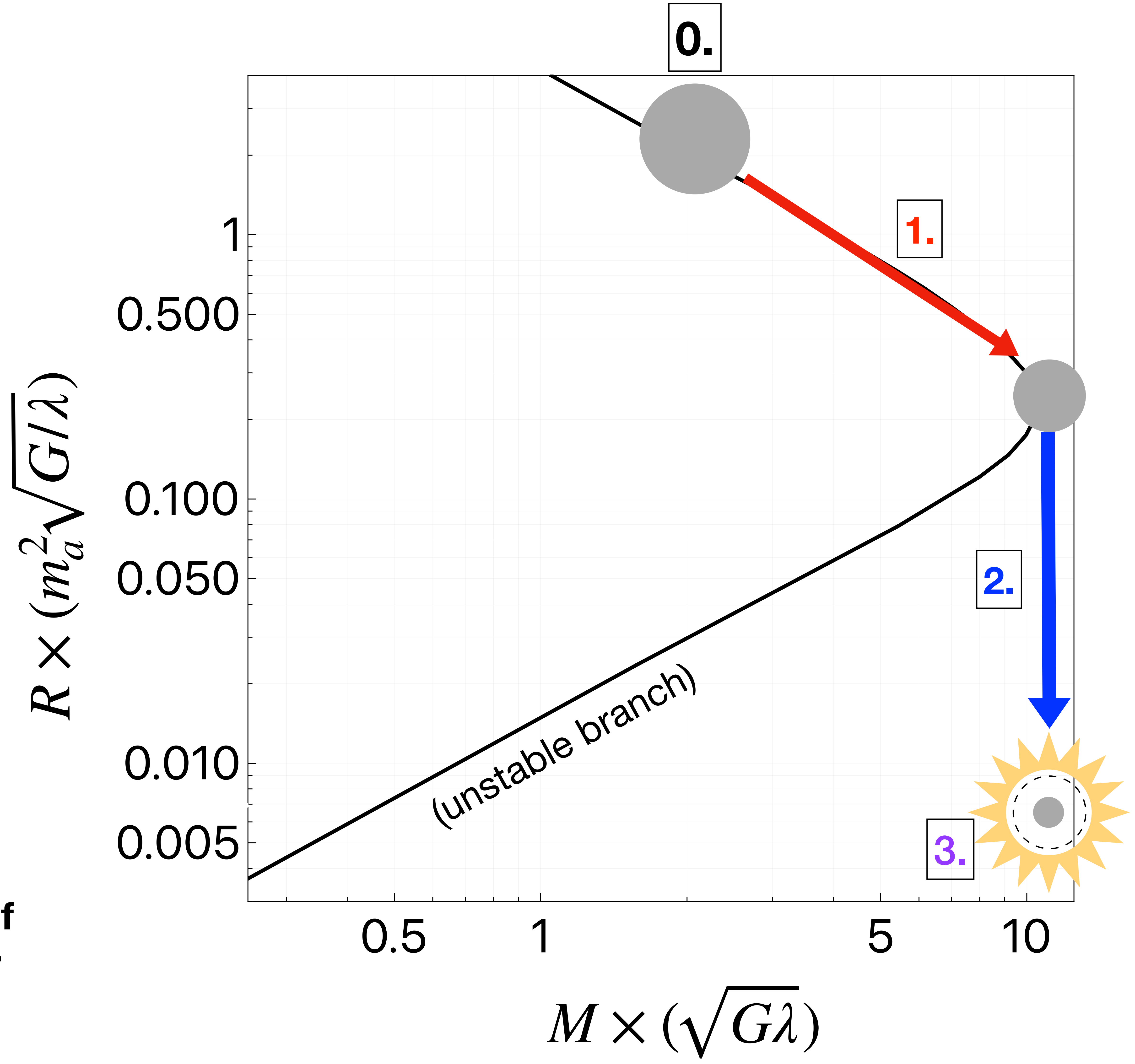


at $M = M_c$

3. “**Bosenova**”



**Annihilations in core of collapsing boson star rapidly expel energy**



# Life Cycle of a Boson Star

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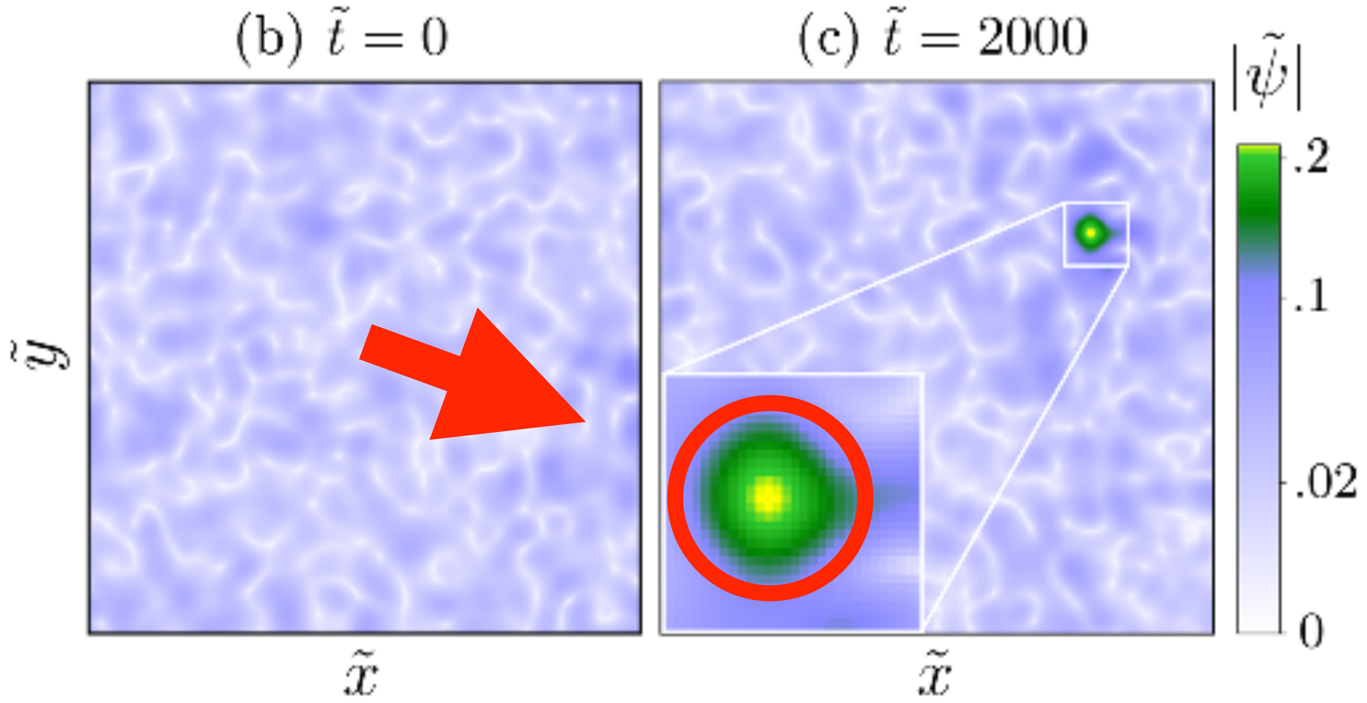

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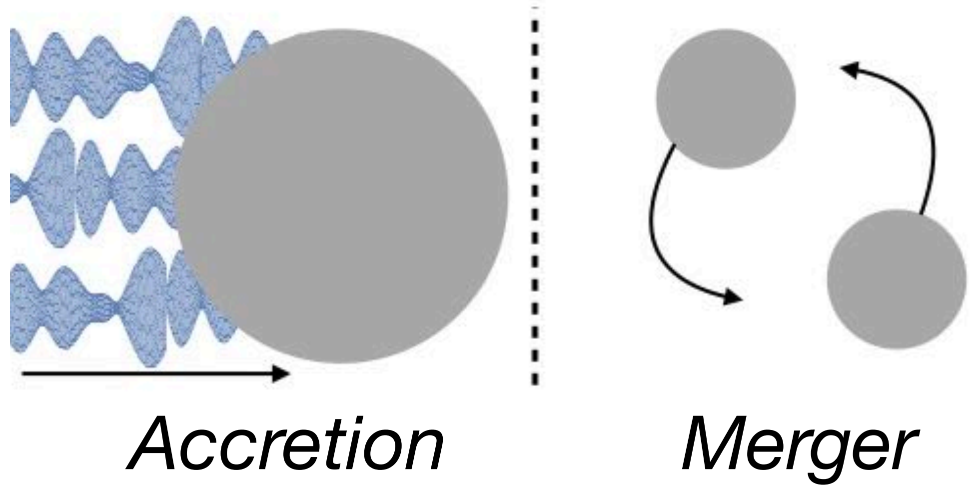

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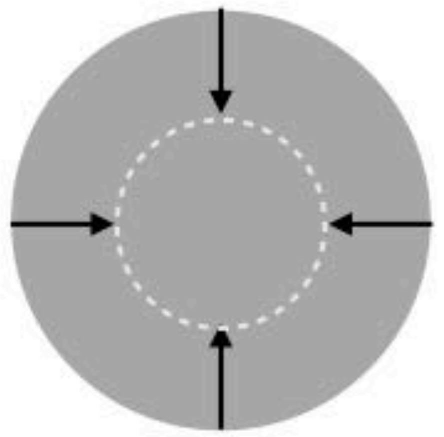

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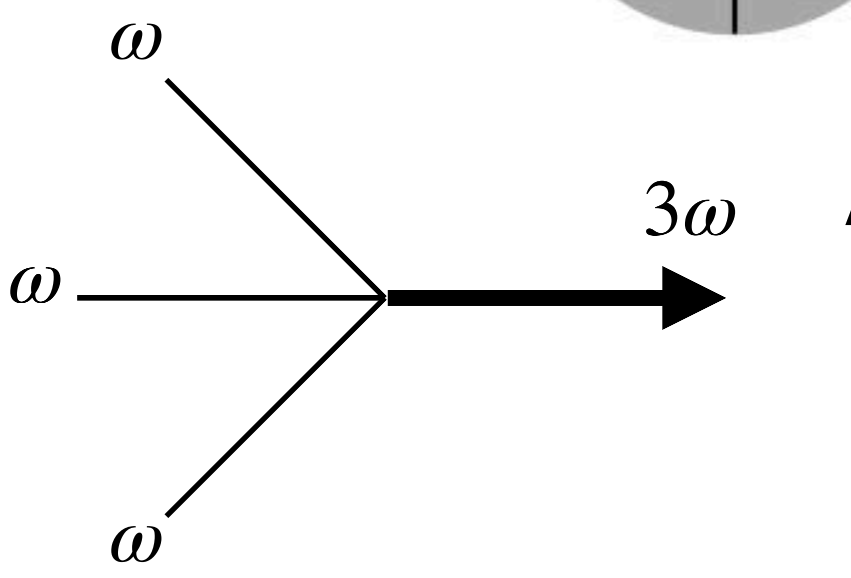

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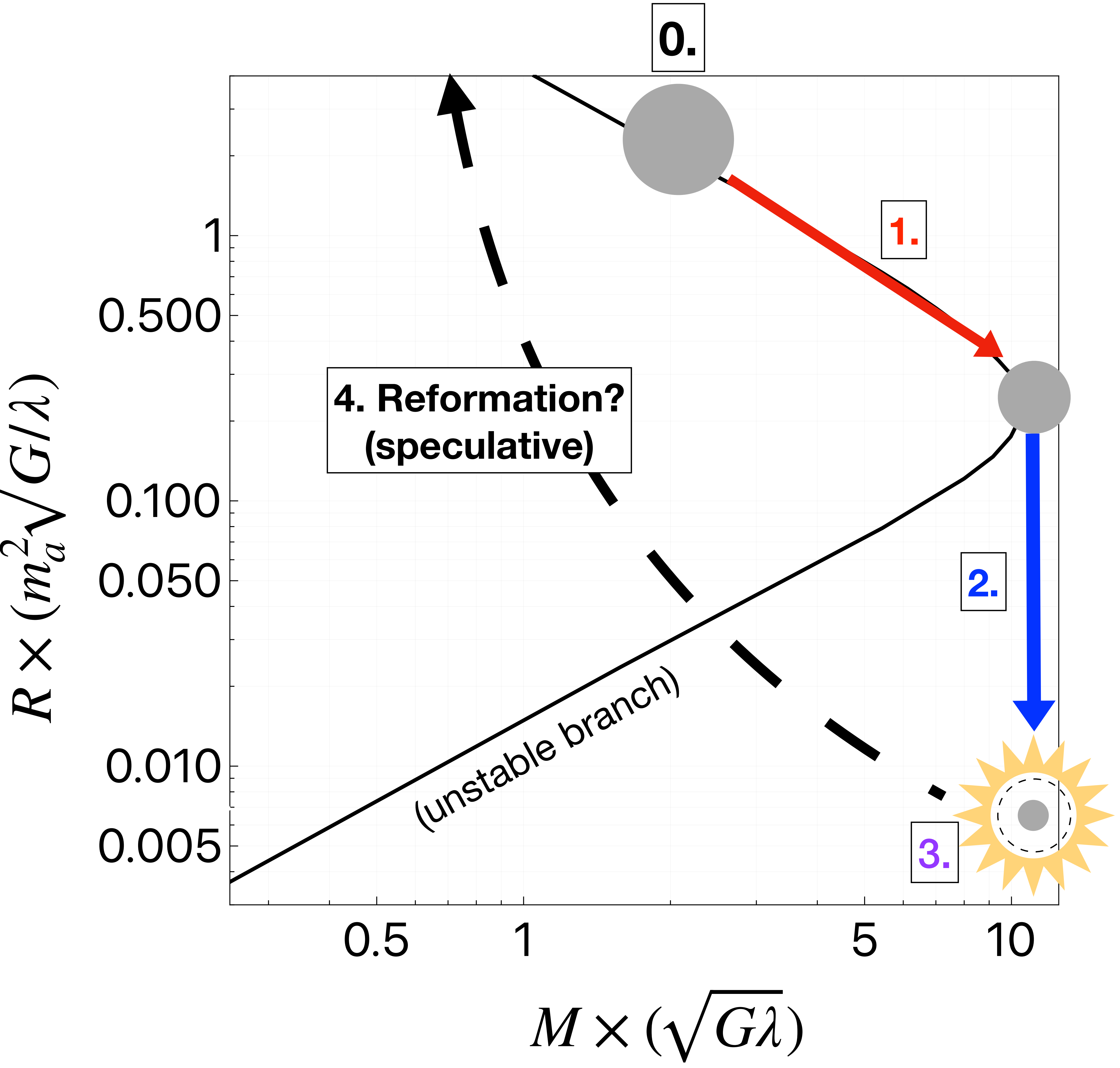
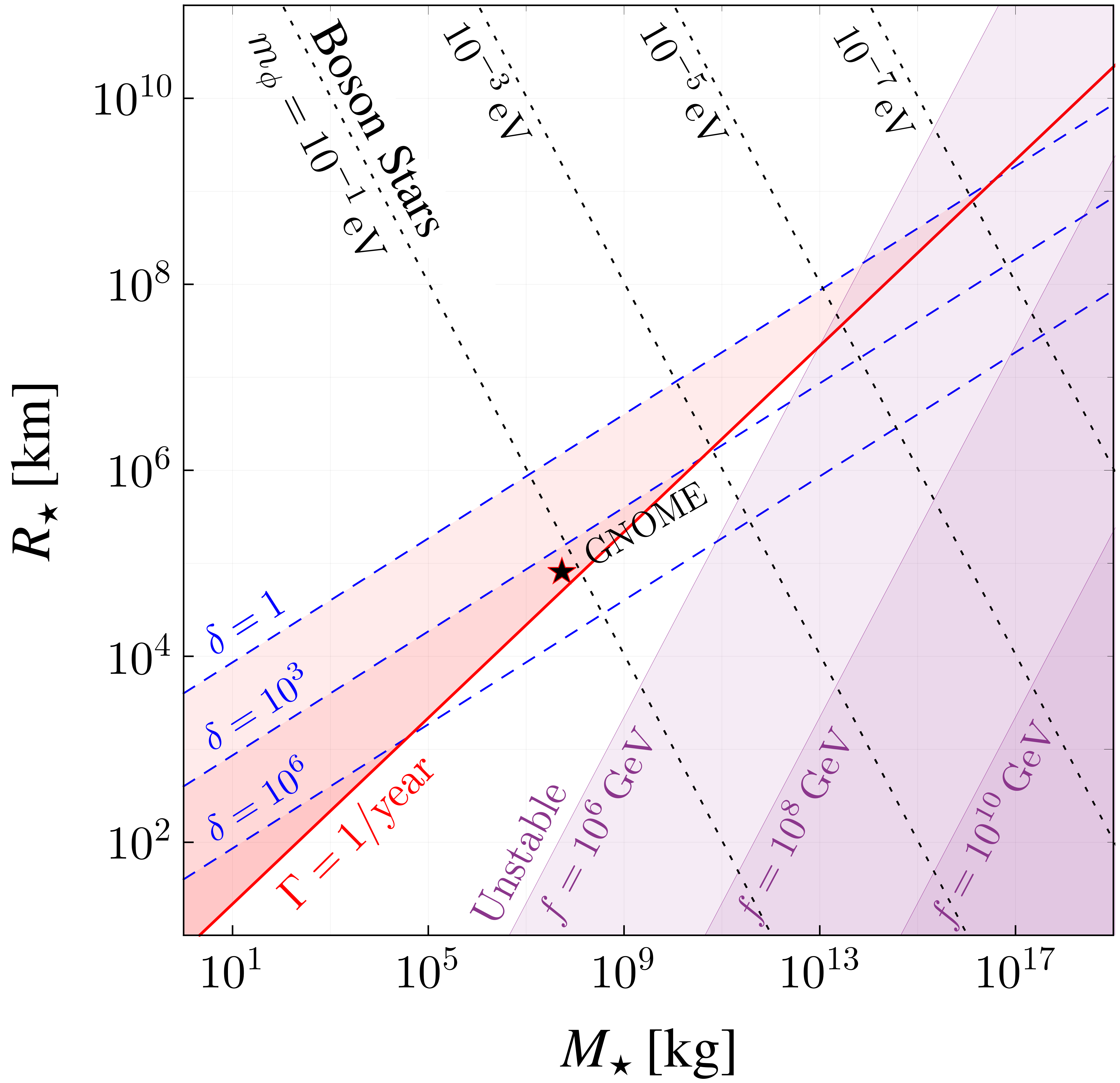


# Boson Star Encounters

Budker, Banerjee, **Eby**, Kim, Perez (1902.08212)



**Overdensity**

$$\delta \equiv \frac{\rho_\star}{\rho_{\rm dm}} \propto \rho_{local}^{-1} R_\star^{-4} m_\phi^{-2}$$

**Encounter rate**

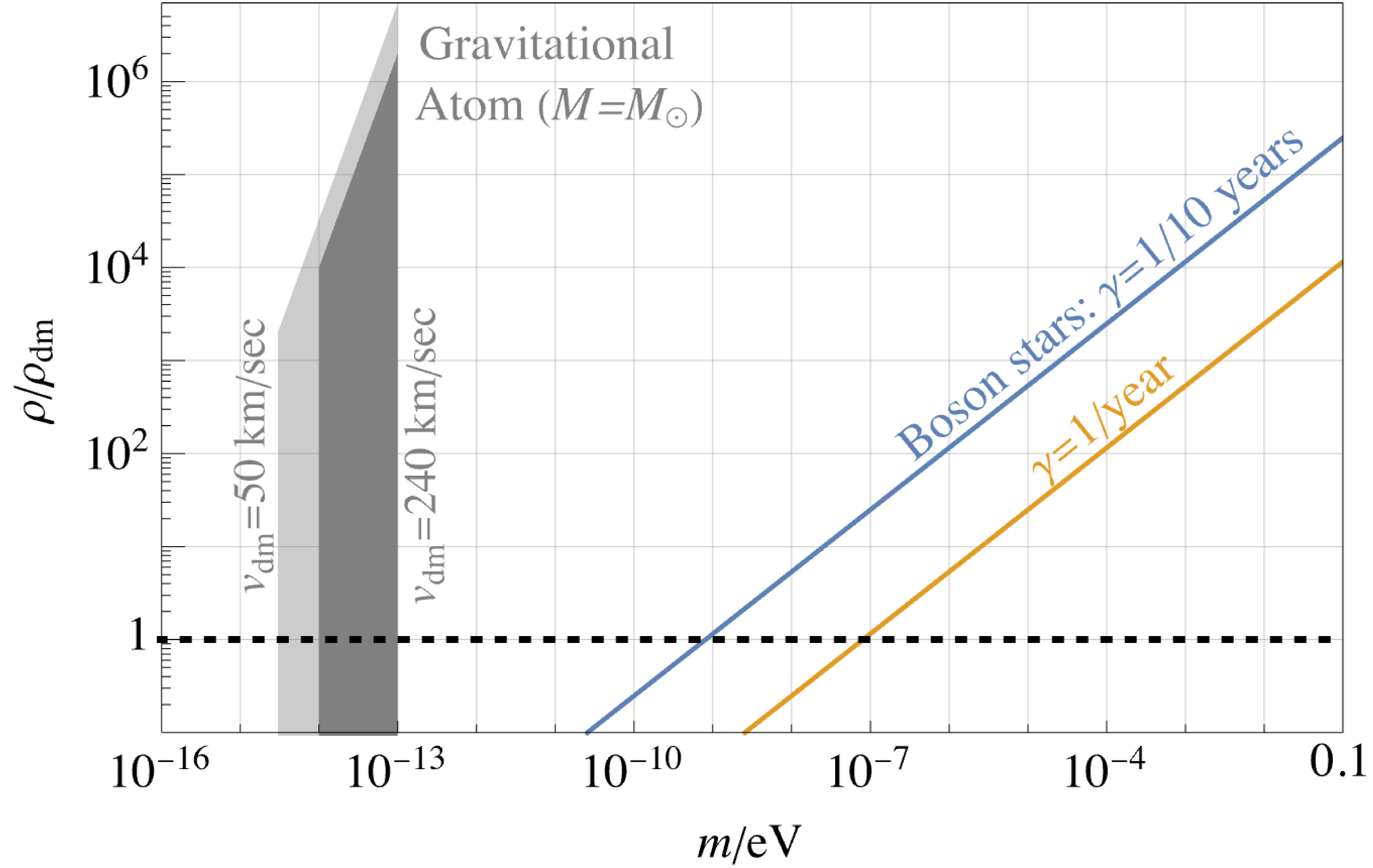
$$\Gamma \equiv \frac{\rho_{\rm dm}}{M_\star} \sigma_\star v_\star \propto \rho_{local} R_\star^3 m_\phi^2$$

**Both parameters are only significant when**

$$m_\phi \gtrsim 10^{-7}\,\text{eV}$$

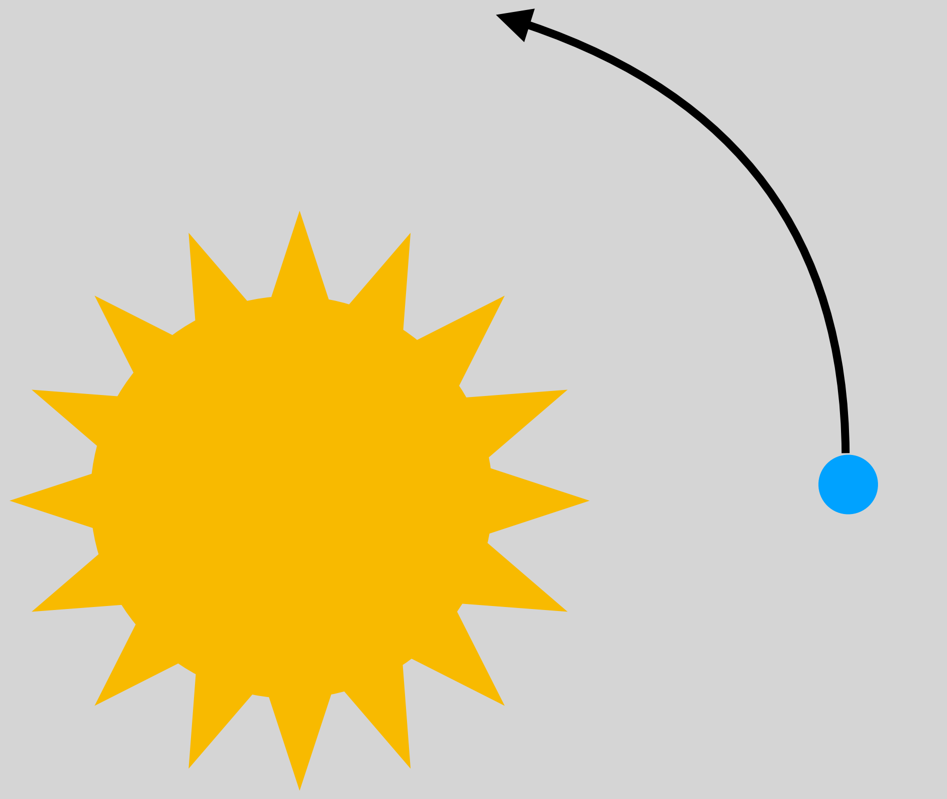
# Boson Star Encounters (2)

Budker, **Eby**, Gorghetto, Jiang, Perez (2306.12477)



# The <u>Very Local</u> DM Density

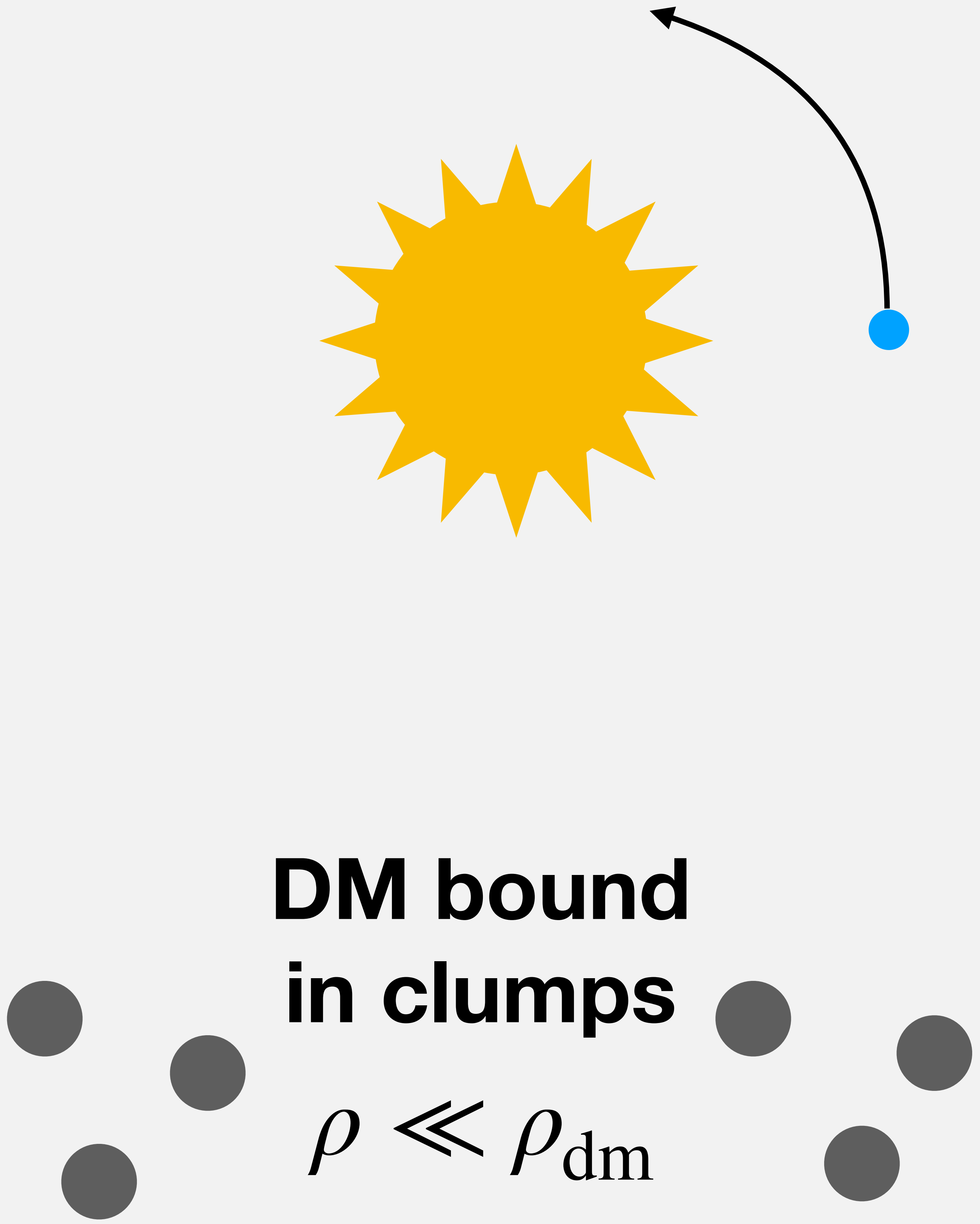
## Standard Scenario



No small-scale overdensities

$$\rho = \rho_{\rm dm}$$

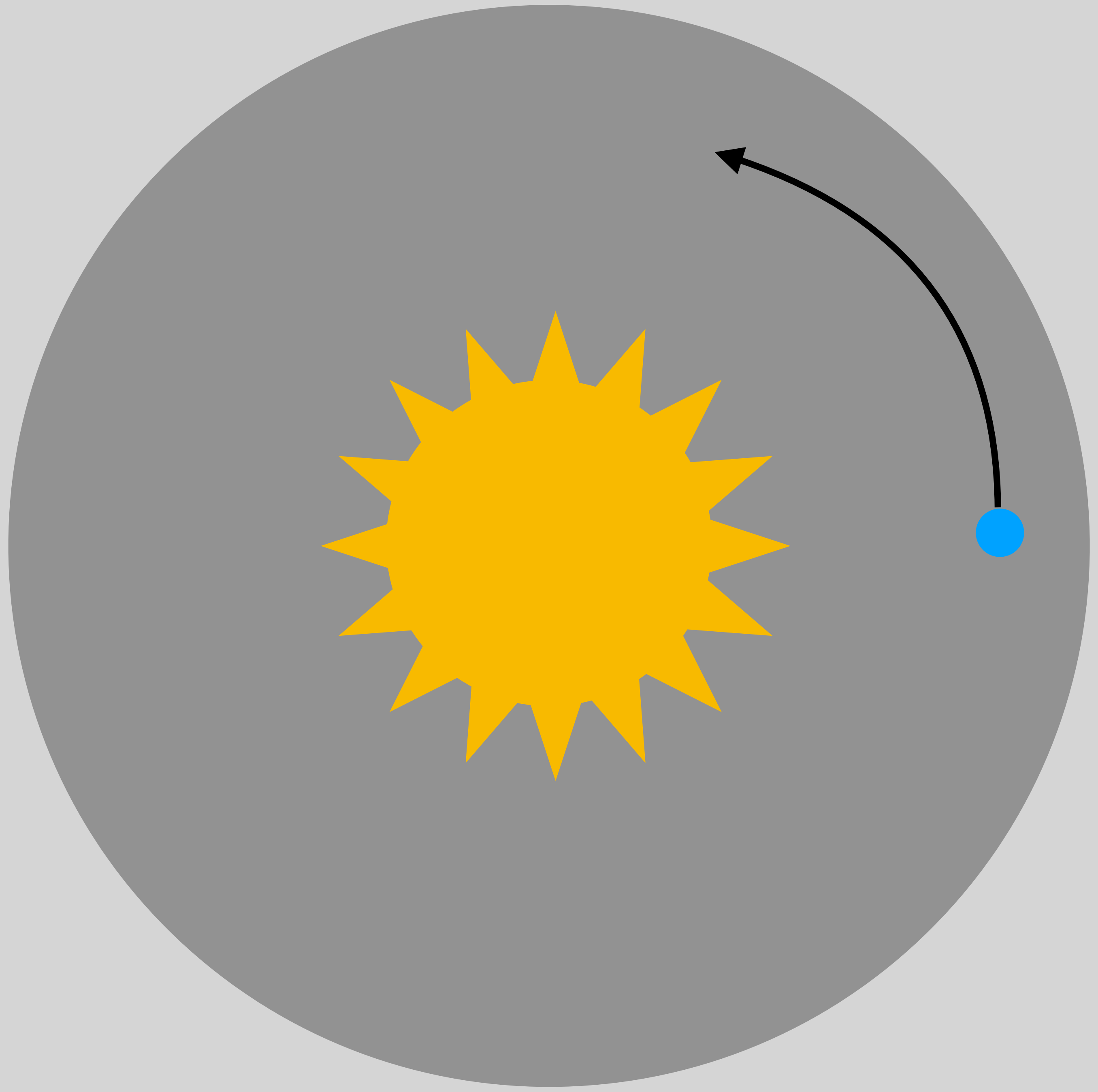
## Boson Stars



DM bound in clumps

$$\rho \ll \rho_{\rm dm}$$

## Gravitational Atoms

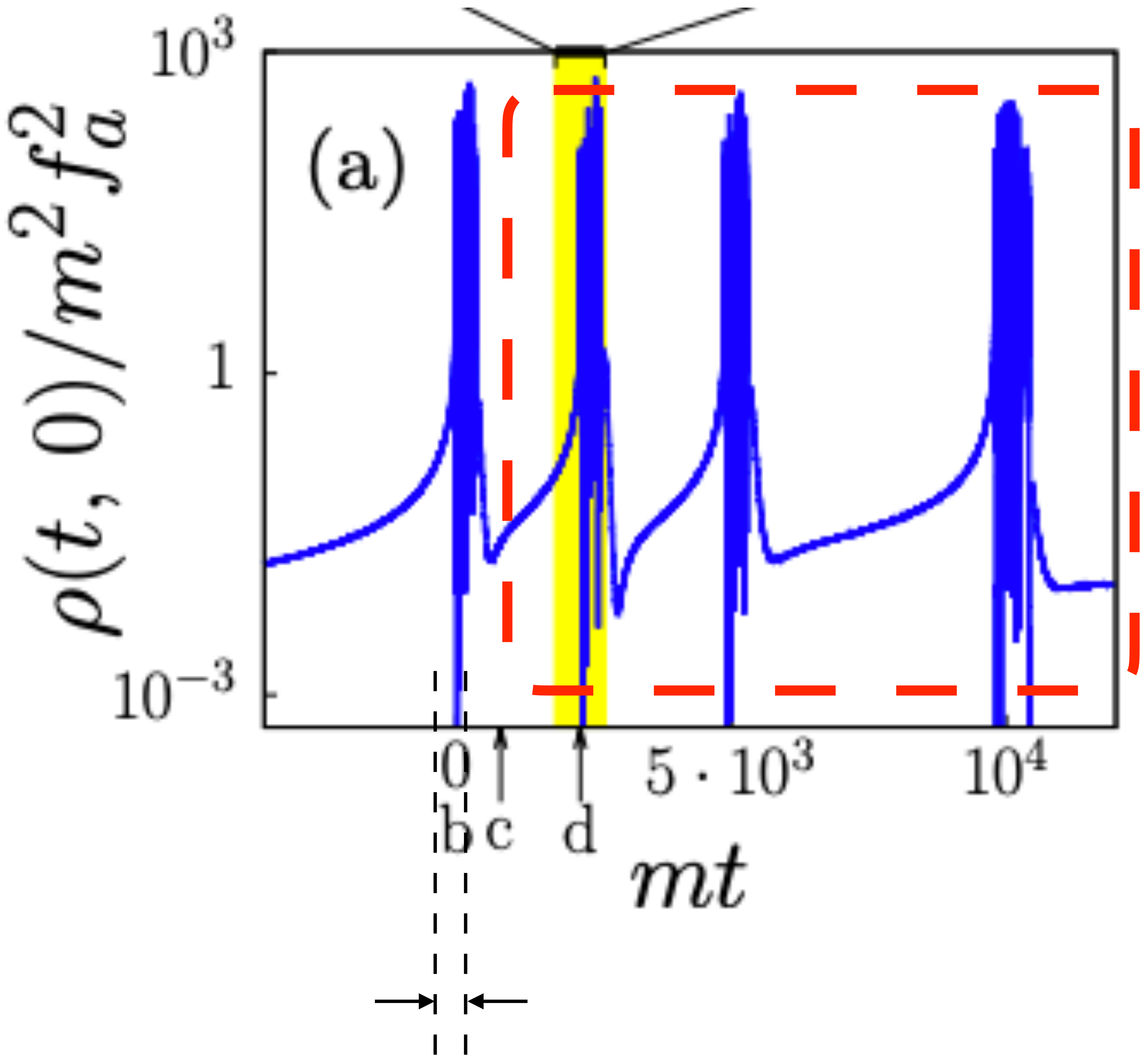


Overdensities inside the Solar System

$$\rho \gg \rho_{\rm dm}$$

Levkov, Panin, Tkachev (1609.03611)

# Bosenova Simulation Results

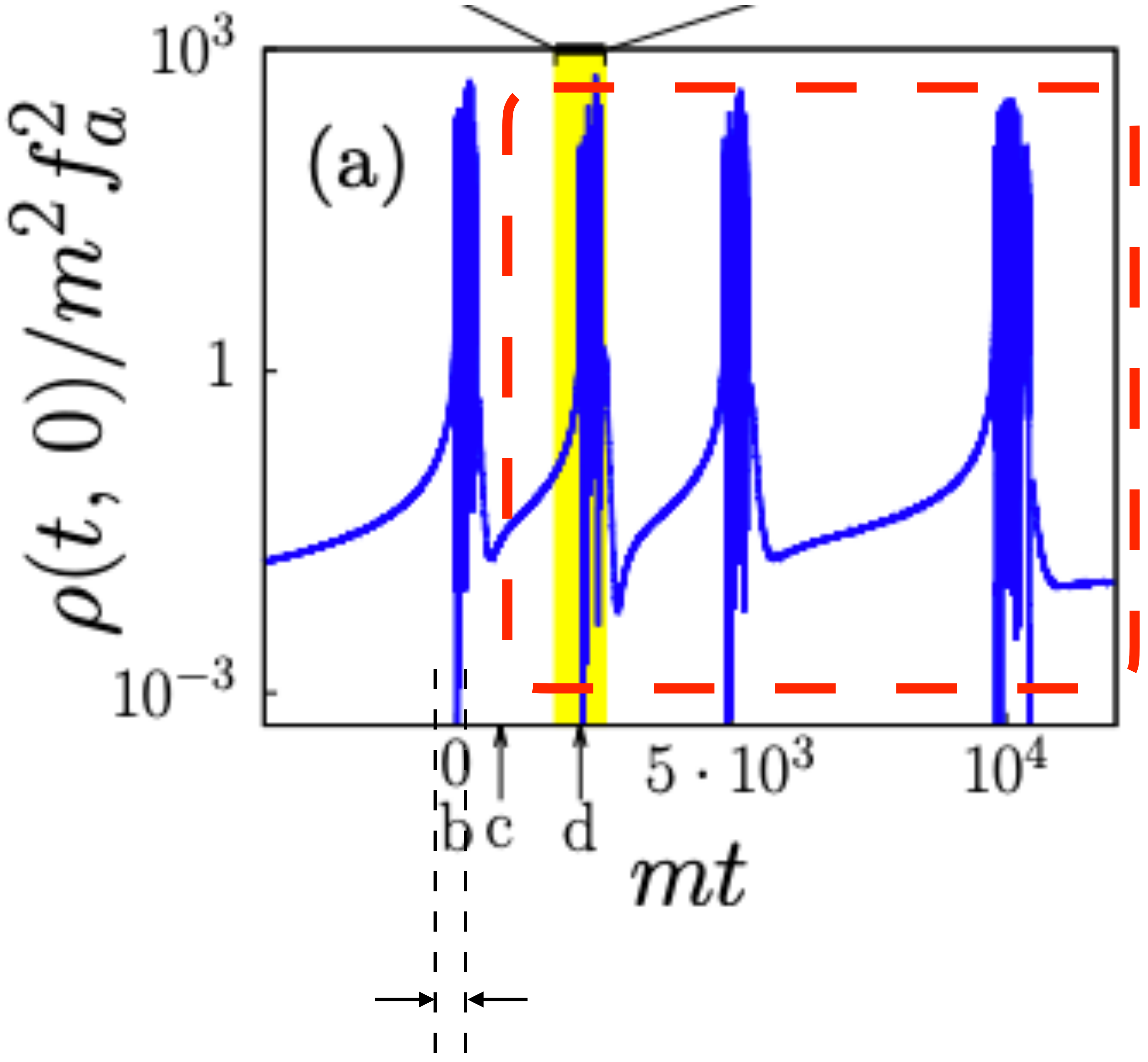


Multiple explosions
per collapse!
(Ignored here)

**Short duration** $\delta t_{\text{burst}} \sim \mathcal{O}(400)/m$

Levkov, Panin, Tkachev (1609.03611)

# Bosenova Simulation Results

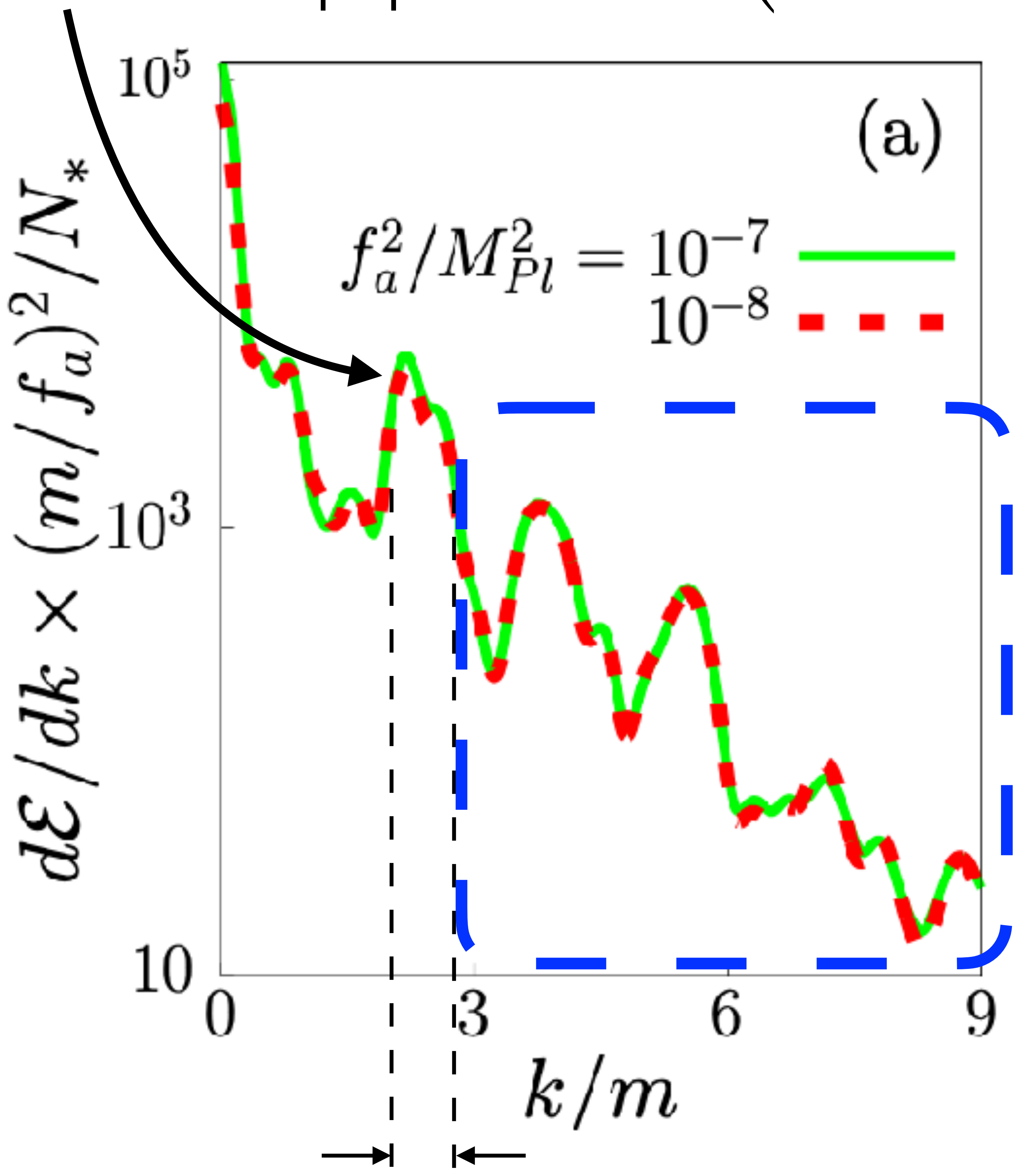


**Multiple explosions per collapse! (Ignored here)**

**Short duration** $\delta t_{\rm burst} \sim \mathcal{O}(400)/m$

**Large integrated energy! In first peak alone,**

$$\mathcal{E}_{\rm peak} \approx 3400\frac{m}{|\lambda|} \simeq 10^2 M_\odot \left(\frac{f}{10^{16}\,\mathrm{GeV}}\right)^2 \frac{10^{-15}\,\mathrm{eV}}{m}$$



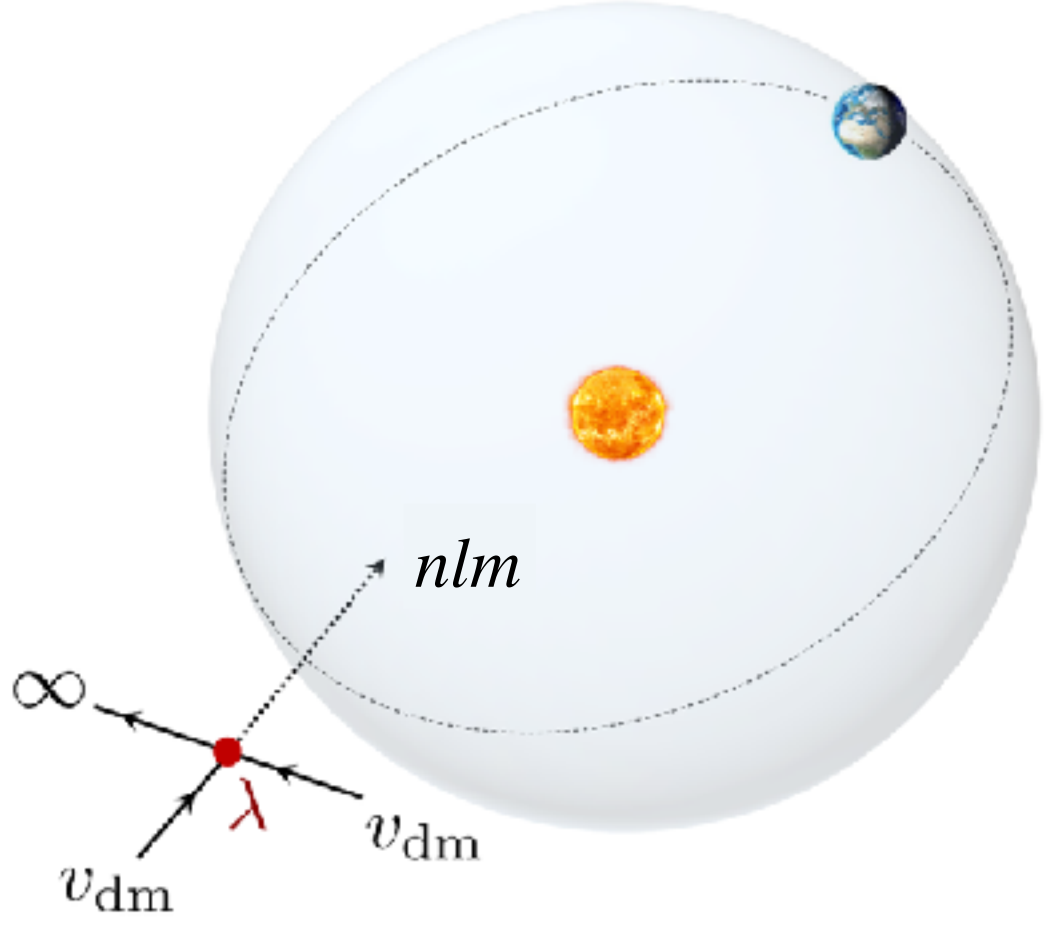
**Higher-energy peaks! (Ignored here)**

**Momentum peak** $k_0 \simeq 2.4\,m$

**with spread of** $\delta k \sim m$

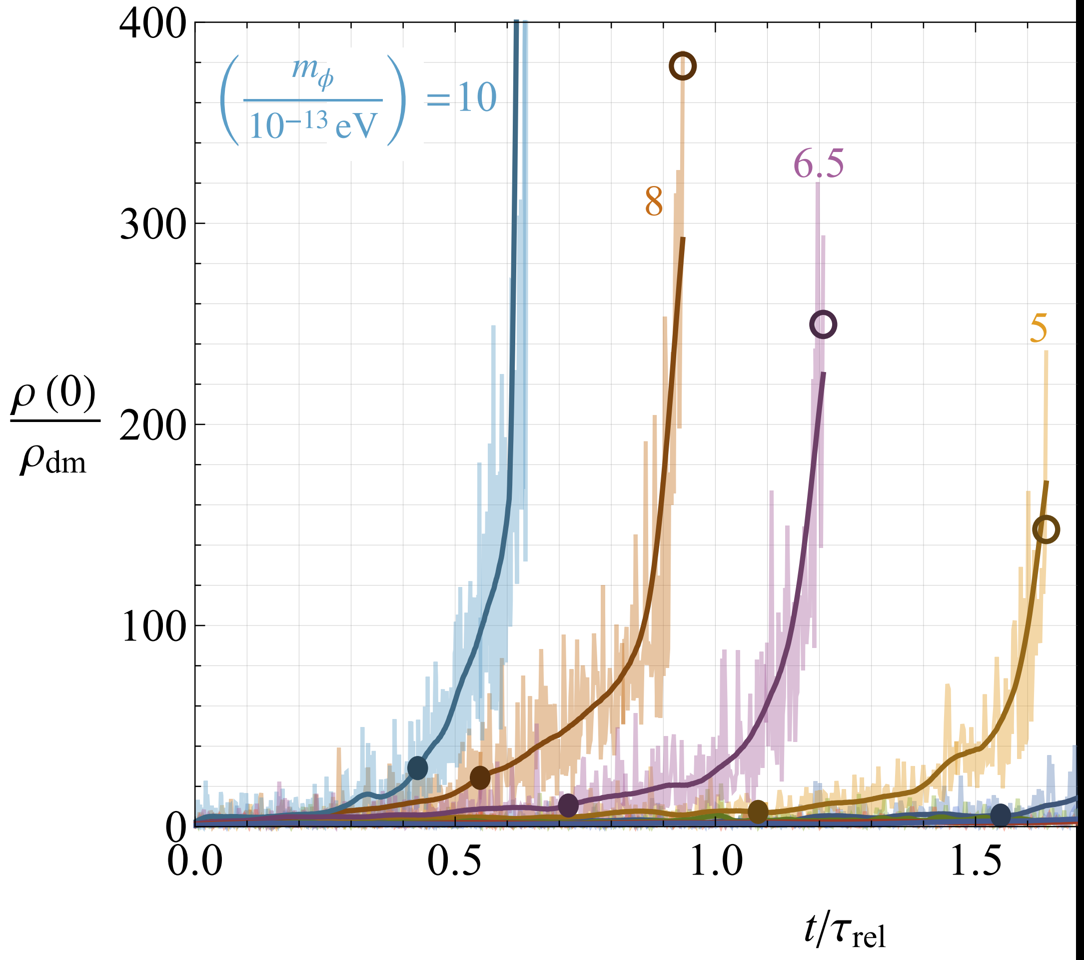
# Other sources of Bosenovae

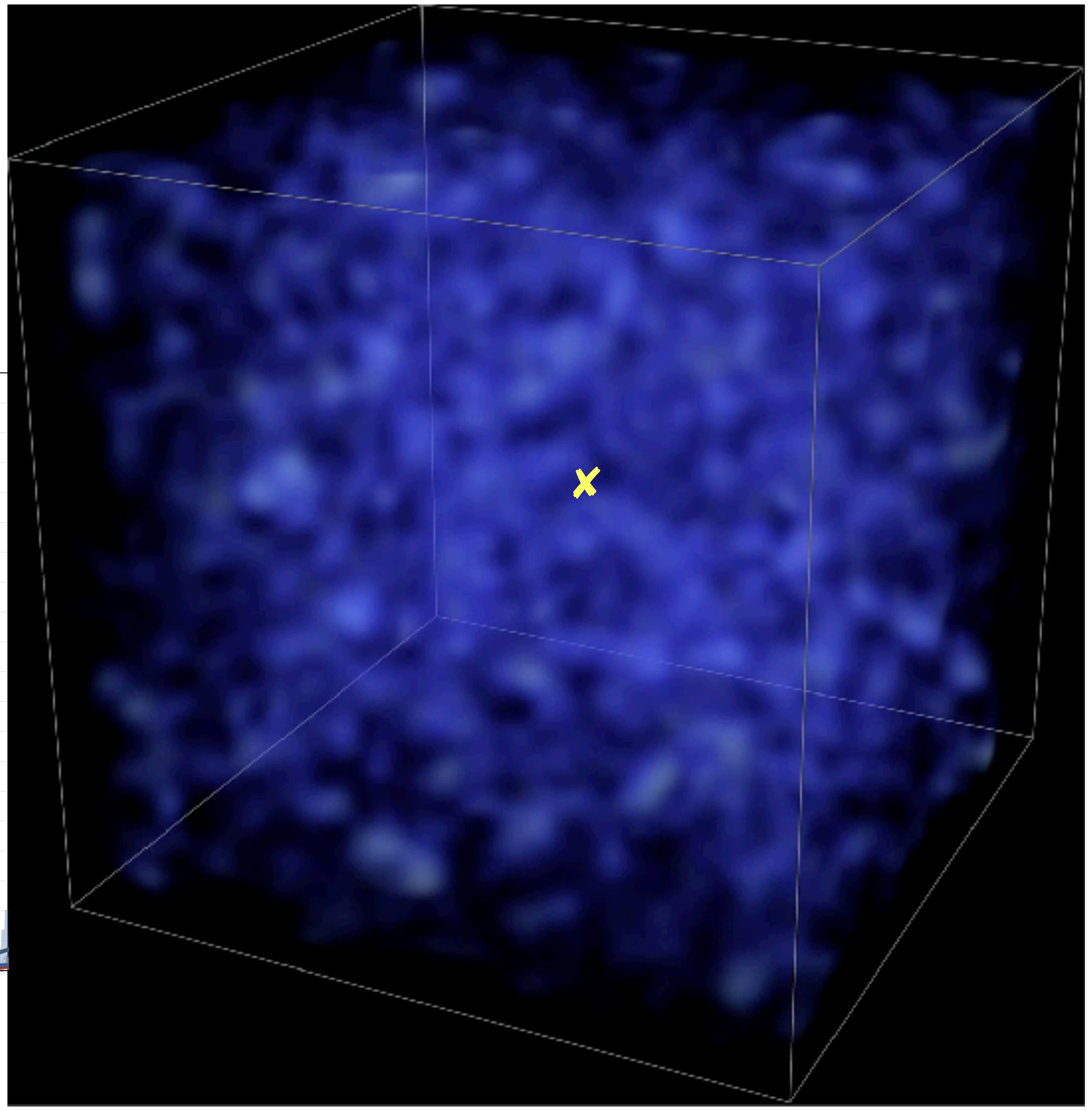
## *Gravitational Atoms*



Budker, Banerjee, **J Eby**, Kim,
Perez, Comm Phys 2020
with Matsedonskyi and Flambaum, JCAP 2020

Budker, **J Eby**, Gorghetto, Jiang,
Perez, JCAP 2023





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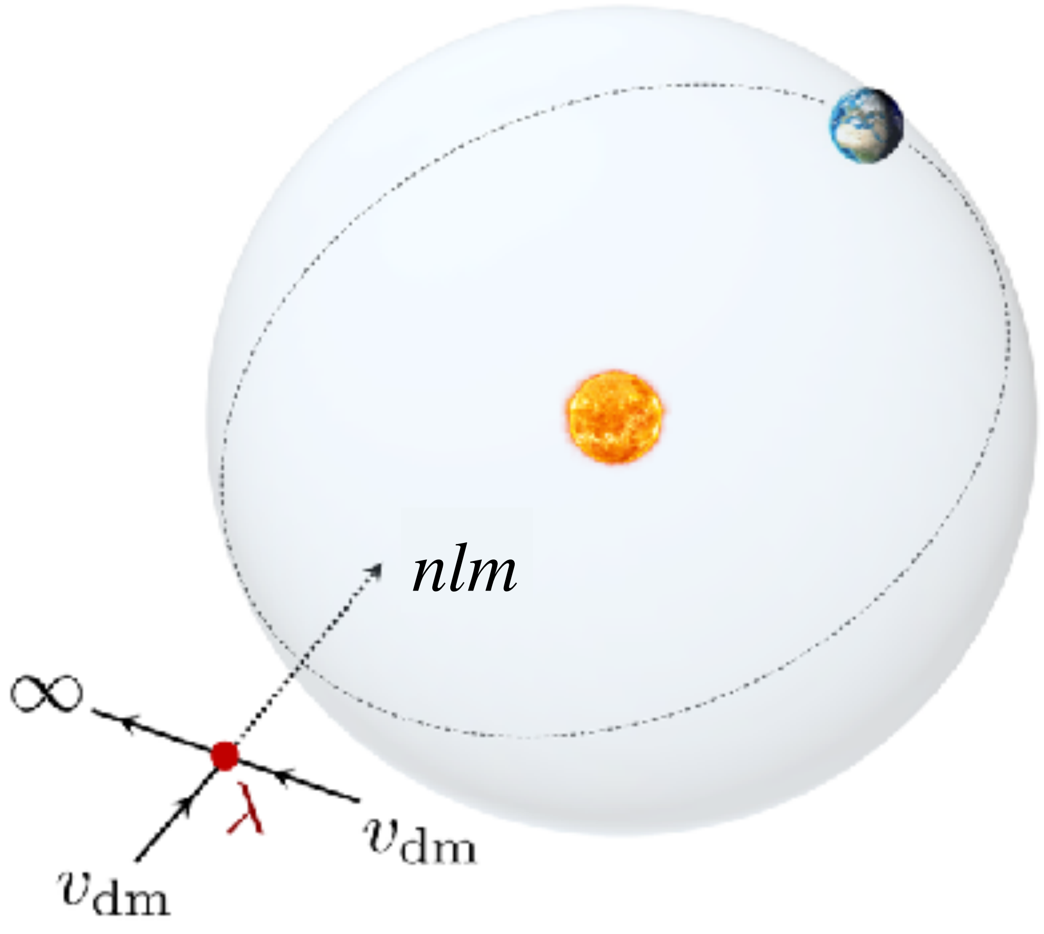

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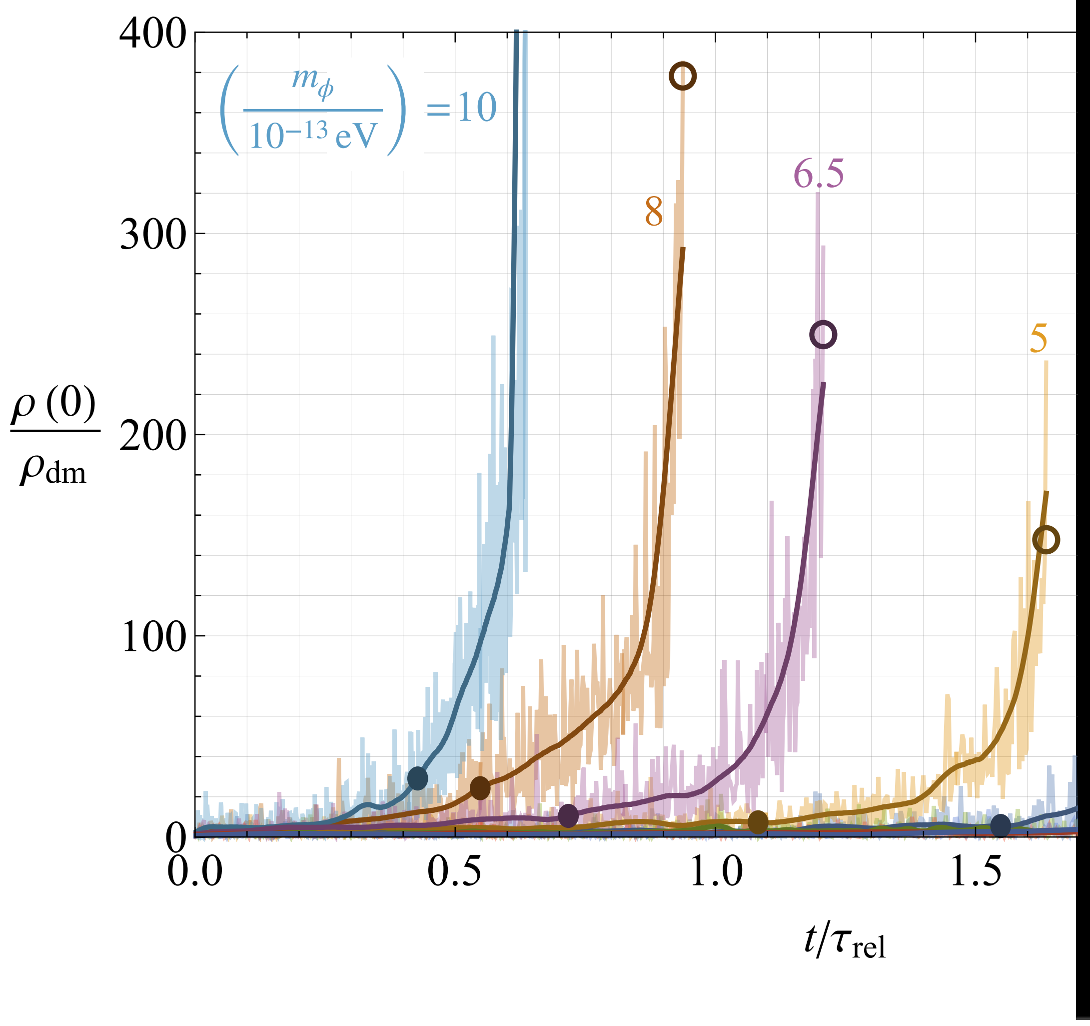
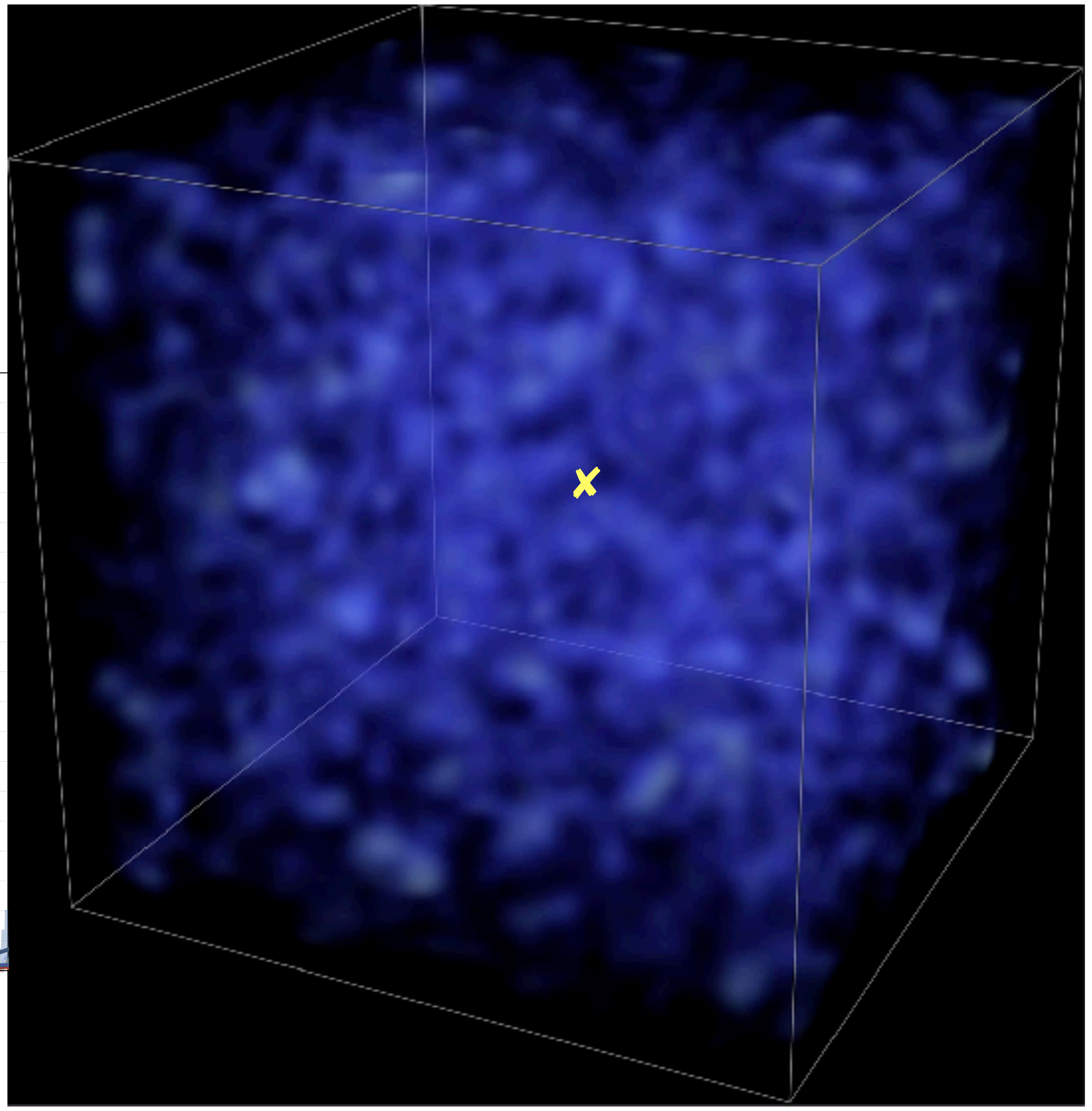
Perez, JCAP 2023





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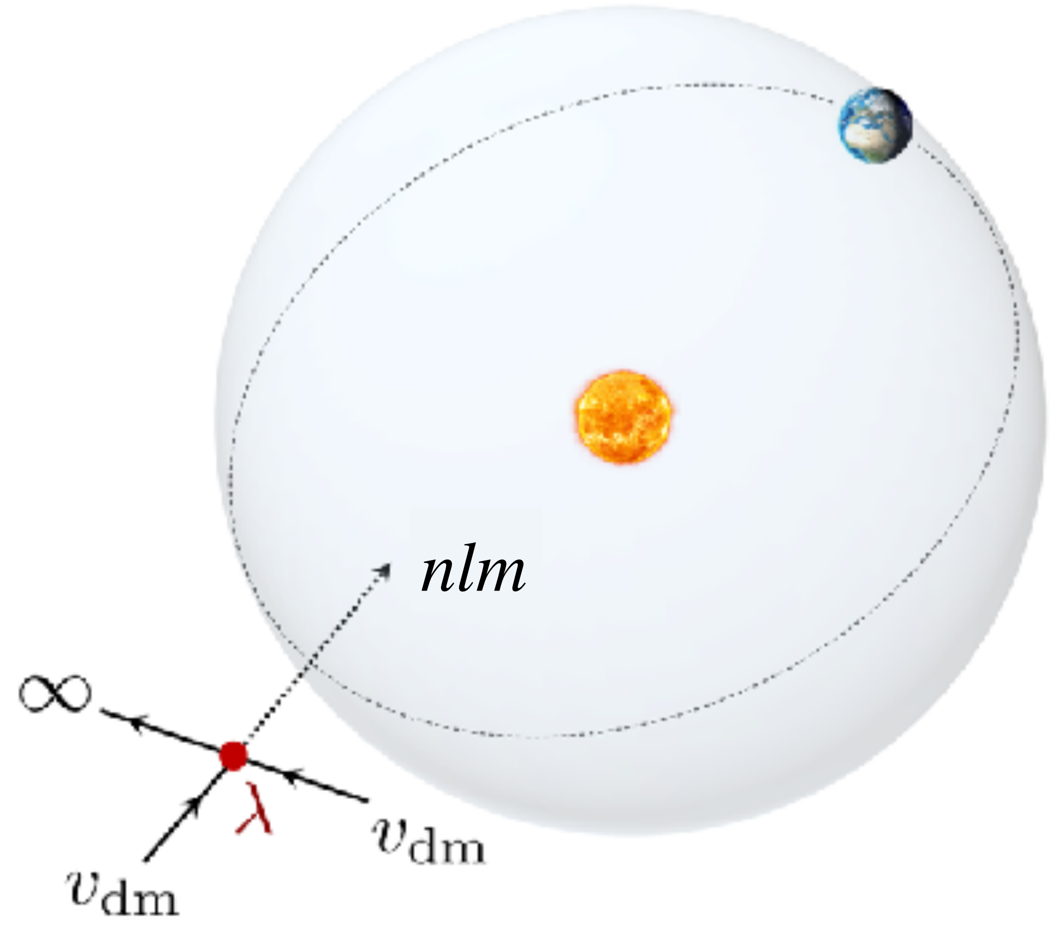

Budker, Banerjee, **J Eby**, Kim,
Perez, Comm Phys 2020
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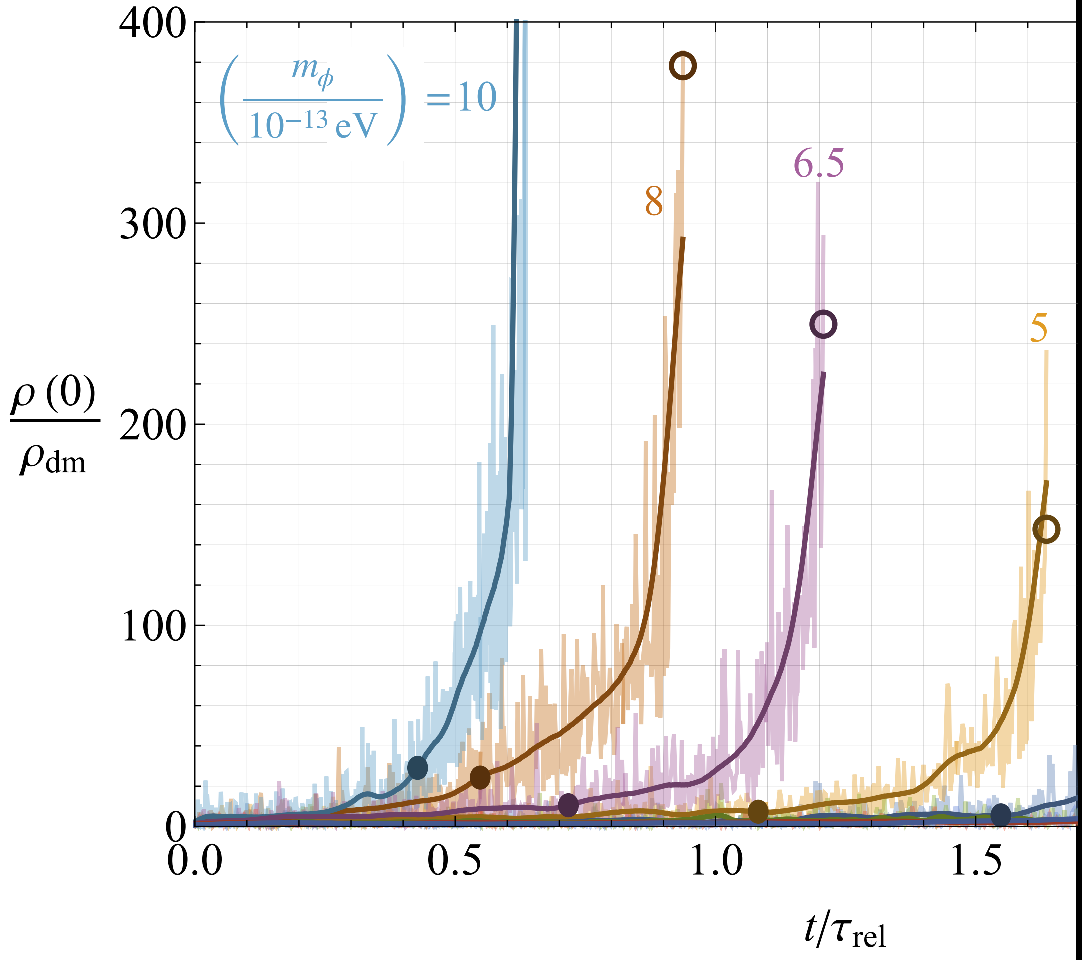
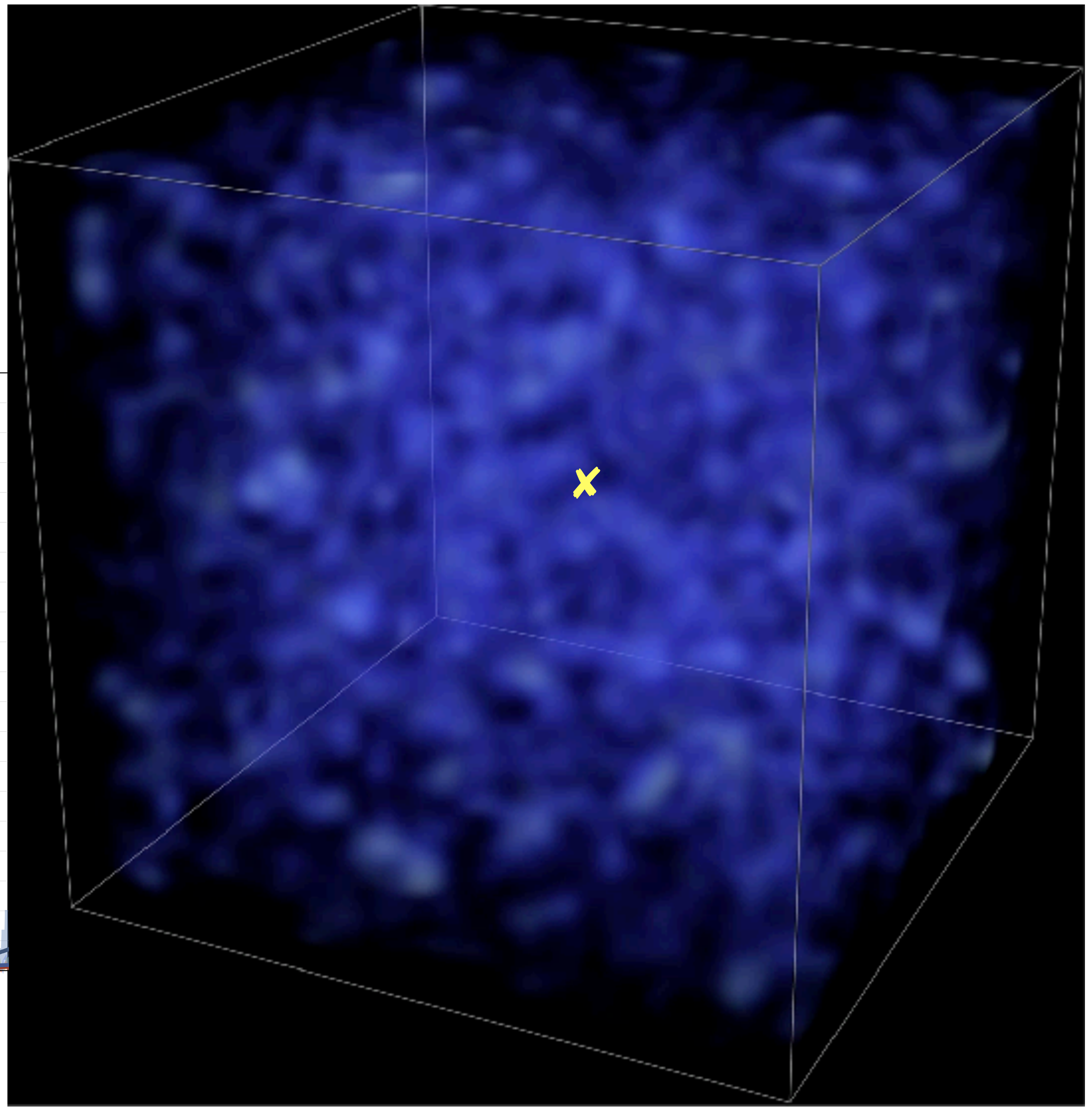
Perez, JCAP 2023





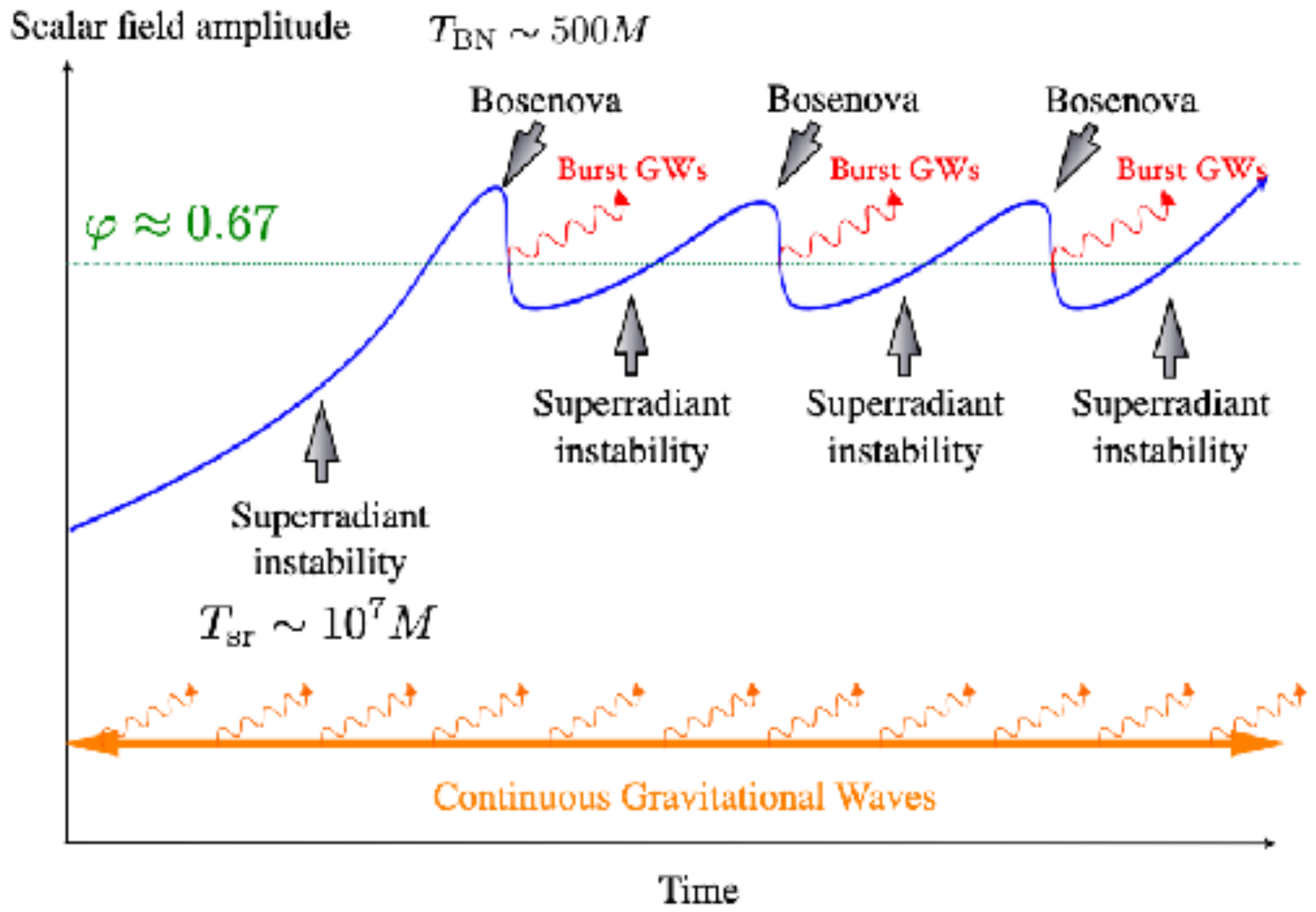
## *Black Hole Superradiance*

Bosenova predicted in Arvanitaki and Dubovsky, PRD 2011

Weak self-interactions

→ bosenova

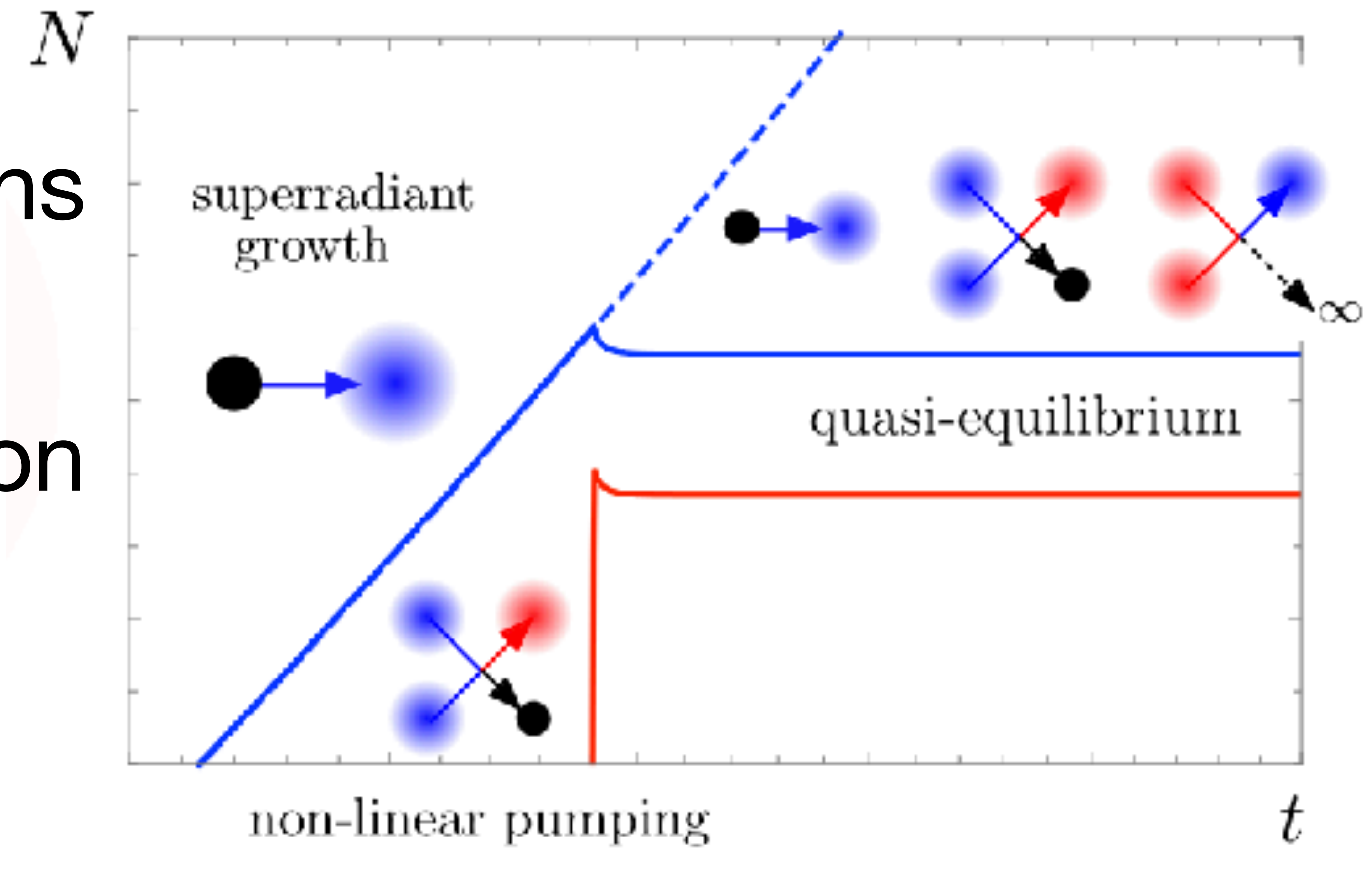
Yoshino and Kodama,
PTP 2012, CQG 2015



Large self-interactions

→ axion wave emission

Baryakhtar++, PRD 2021

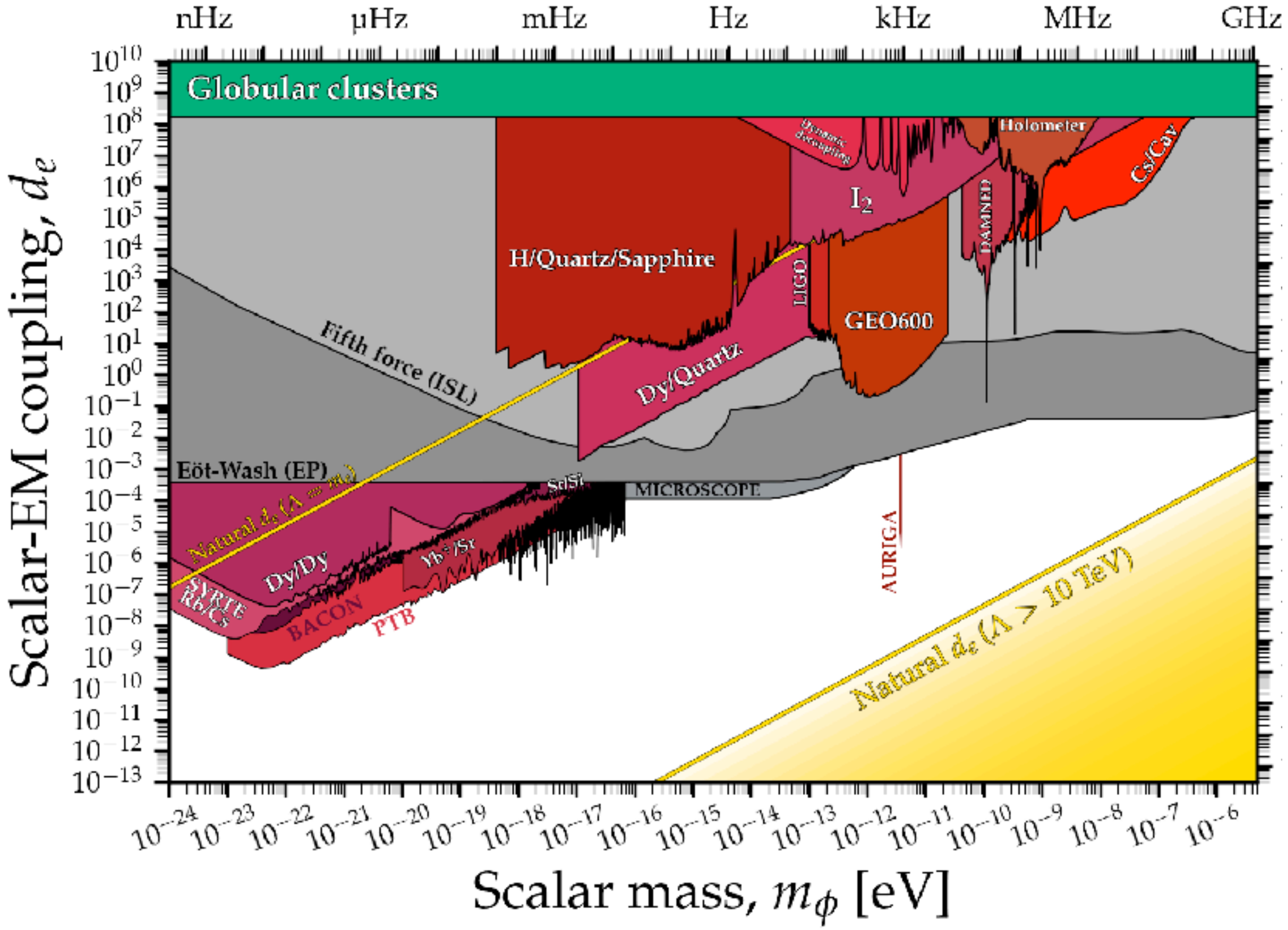


# Other Couplings

**Coupling to photons**

Oscillation of
fine-structure constant

$$\mathscr{L} \supset d_e \frac{\phi}{2M_{\rm Pl}} F^{\mu\nu}F_{\mu\nu} \longrightarrow \alpha \to \alpha + \delta\alpha(d_e, \rho, m_\phi)$$



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**Coupling to <u>photons</u>**

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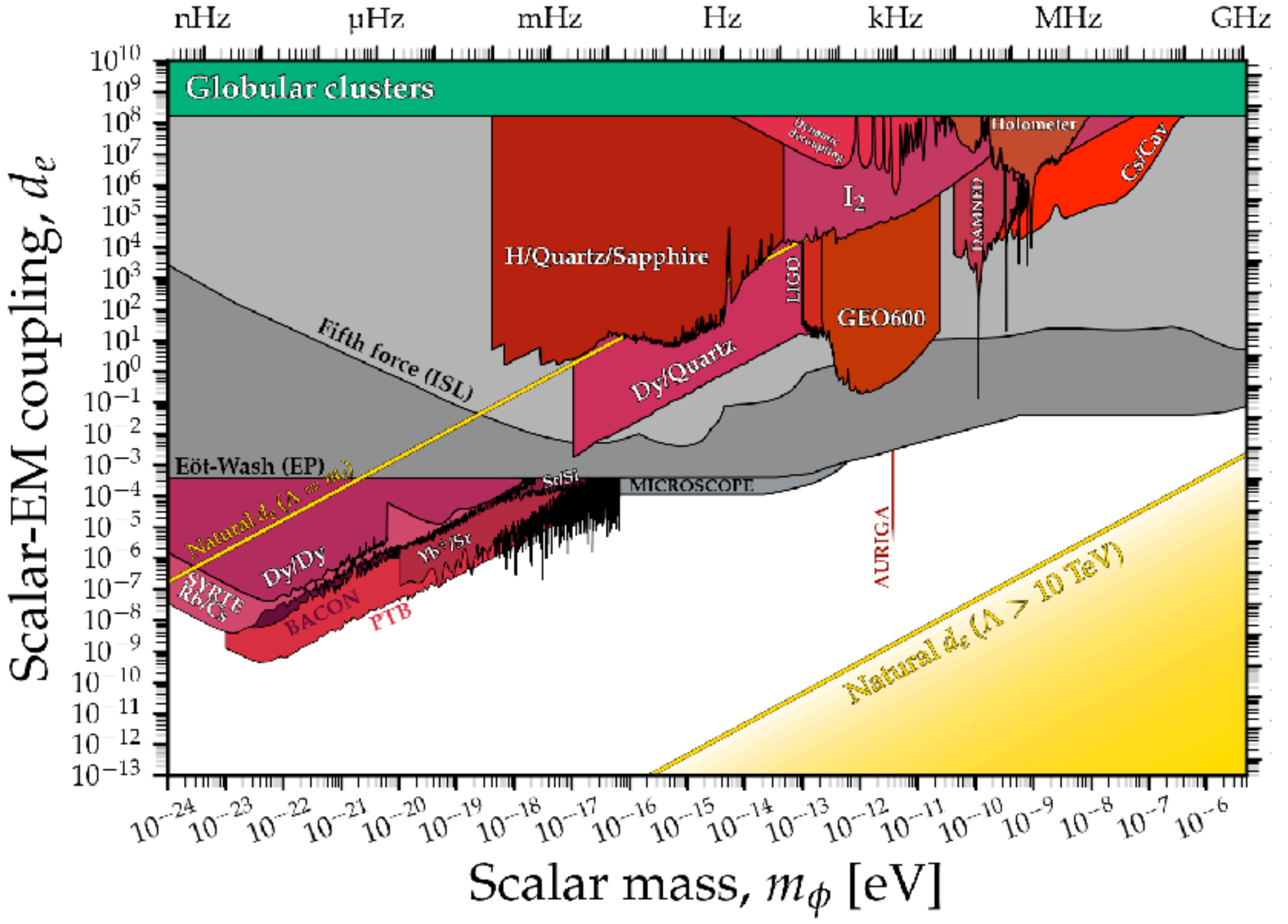

**Coupling to <u>electrons</u>**

Oscillation of
electron-proton mass ratio

$$\mathscr{L} \supset d_{m_e} \frac{\phi}{2M_{\rm Pl}} \bar{e}e \longrightarrow \frac{m_e}{m_p} \to \frac{m_e}{m_p} + \frac{\delta m_e(d_{m_e}, \rho, m_\phi)}{m_p}$$

# Other Couplings

**Coupling to <u>photons</u>**

Oscillation of fine-structure constant

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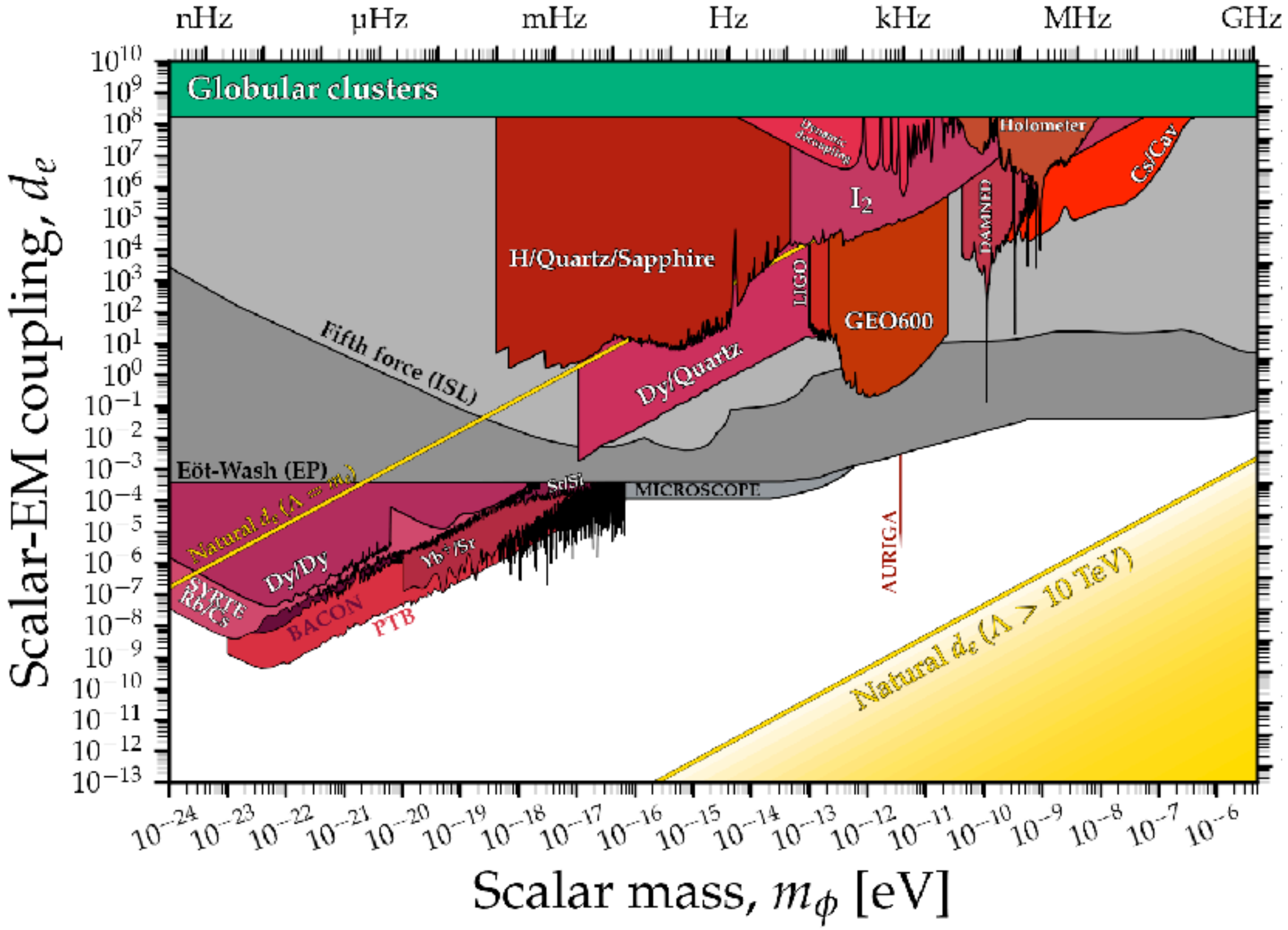

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**Coupling to <u>gluons</u>**

$$\mathscr{L} \supset d_g \frac{\phi}{2M_{\rm Pl}} G^{a\mu\nu}G^a_{\mu\nu}$$

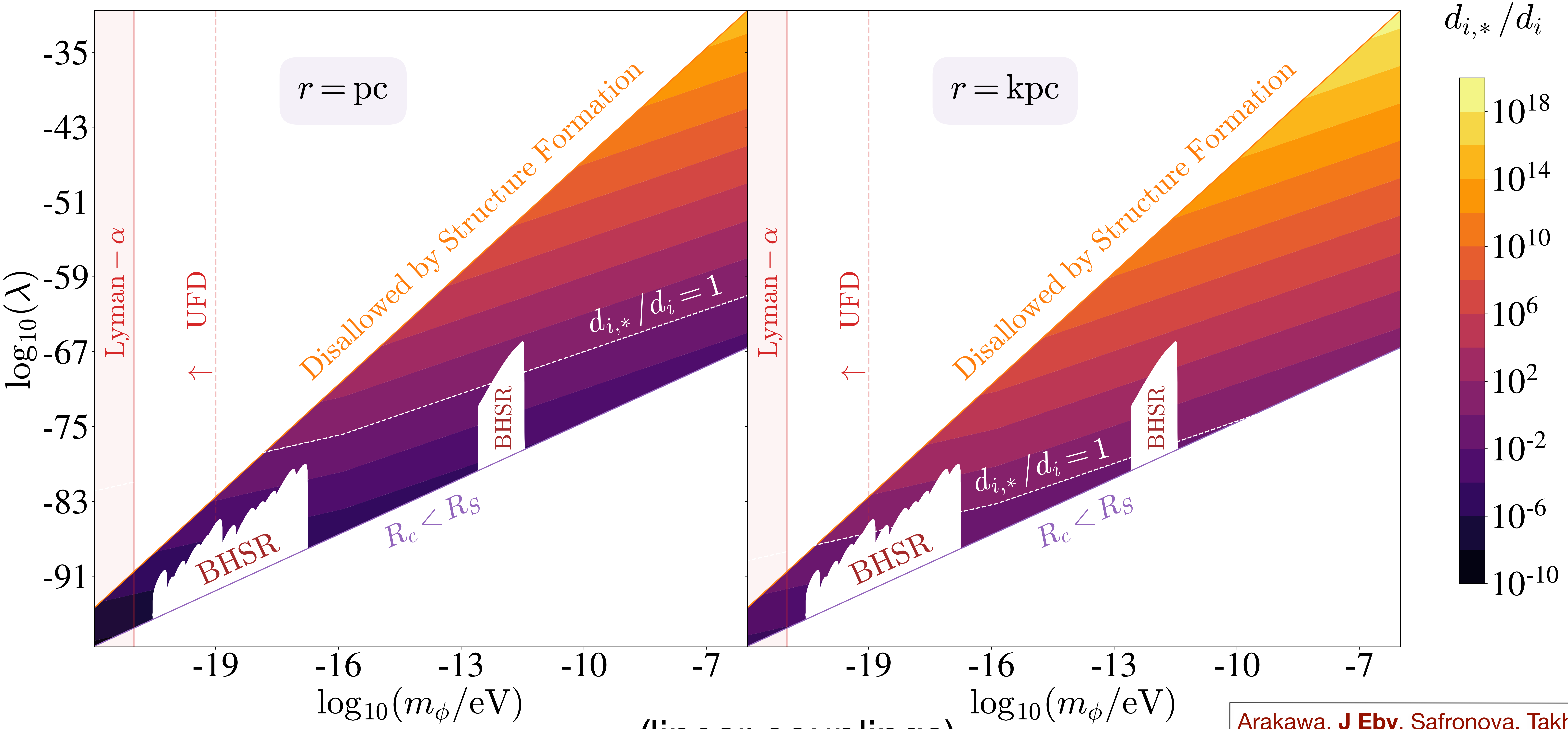
**Coupling to <u>quarks</u>**

$$\mathscr{L} \supset d_{m_q} \frac{\phi}{2M_{\rm Pl}} \bar{q}q$$

$$\frac{m_q}{\Lambda_{\rm QCD}} \to \frac{m_q}{\Lambda_{\rm QCD}} + \delta\left(\frac{m_q}{\Lambda_{\rm QCD}}\right)(d_{m_q}, d_g, \rho, m_\phi)$$

Oscillation of ratio of quark mass to QCD scale

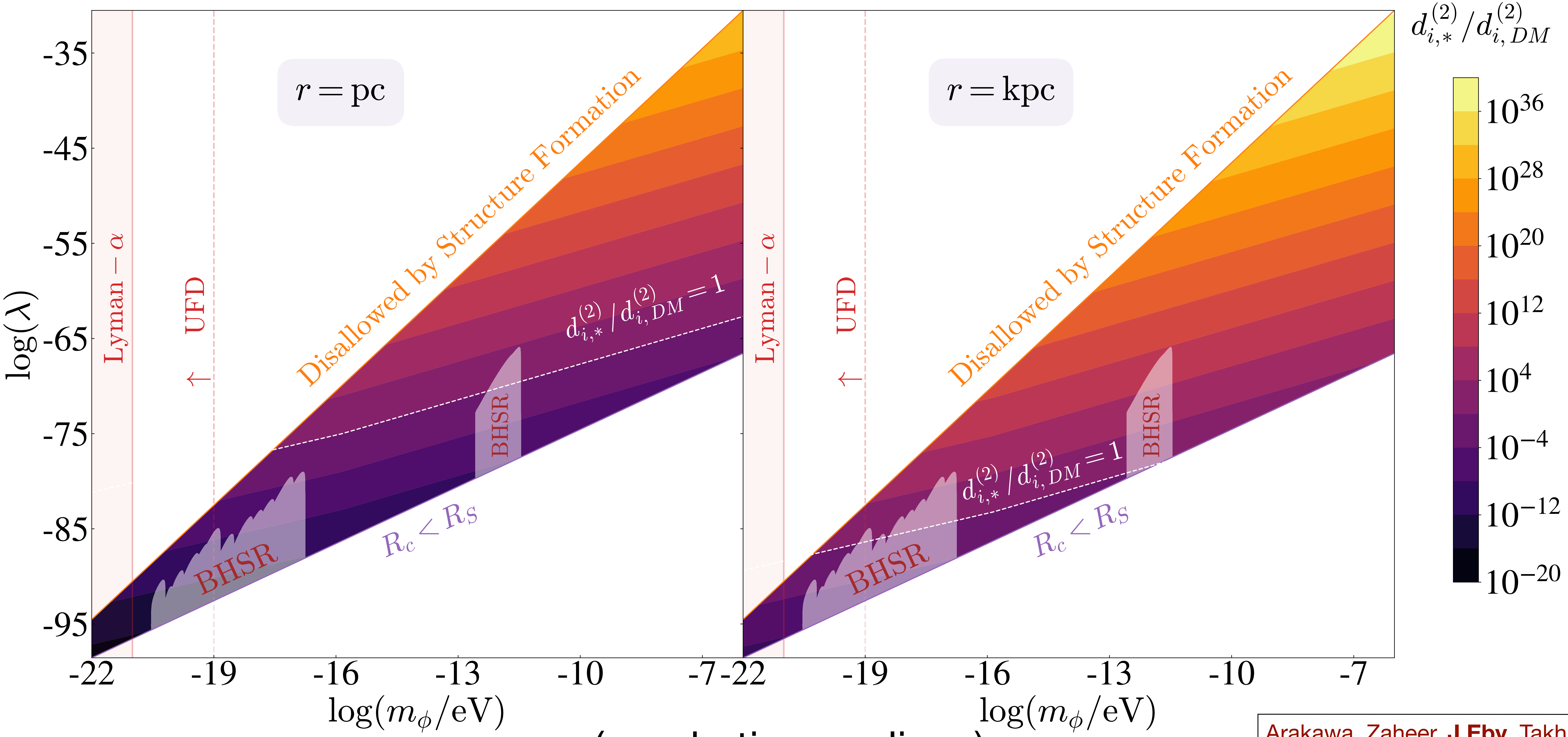
# “Experiment-Independent” Sensitivity



(linear couplings)

Arakawa, **J Eby**, Safronova, Takhistov, Zaheer (2306.16468)

# "Experiment-Independent" Sensitivity (2)



(quadratic couplings)

Arakawa, Zaheer, **J Eby**, Takhistov, Safronova (2402.06736)

**Eby**, Takhistov, (2402.00100)

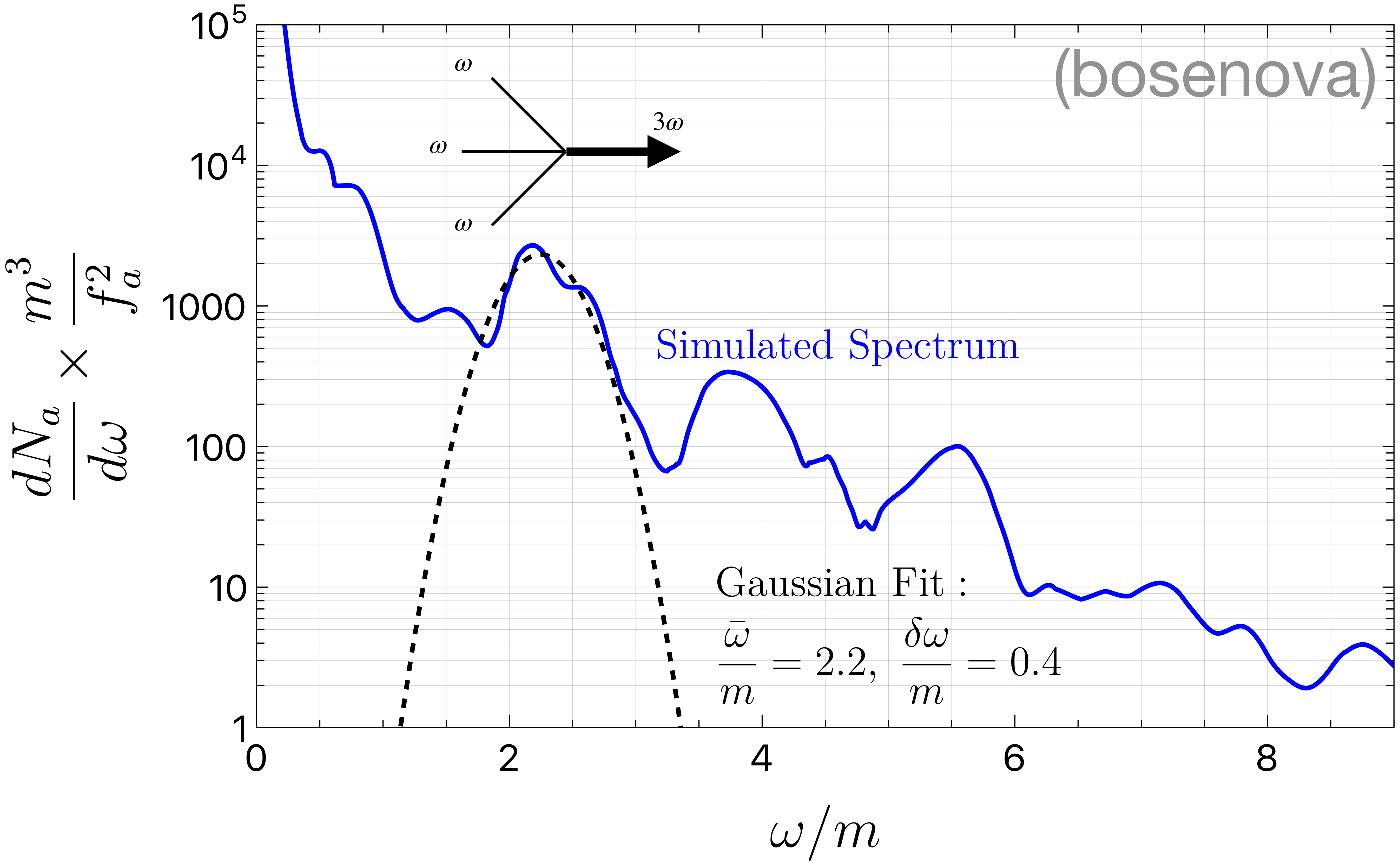
# Parameterization: Flux

$$\frac{dN_a}{d\omega}(\omega) \propto \frac{E_{\rm tot}}{m_a^2} \frac{\exp\left(-\frac{(\omega-\bar{\omega})^2}{\delta\omega^2}\right)}{\delta\omega/m_a}$$

$E_{\rm tot}$: total energy emitted in single burst

$\bar{\omega}$: peak energy

$\delta\omega$: energy width



- easily captures peaked distribution
- computationally simple
- sum of Gaussians can be used for asymmetric distributions, e.g. power-law

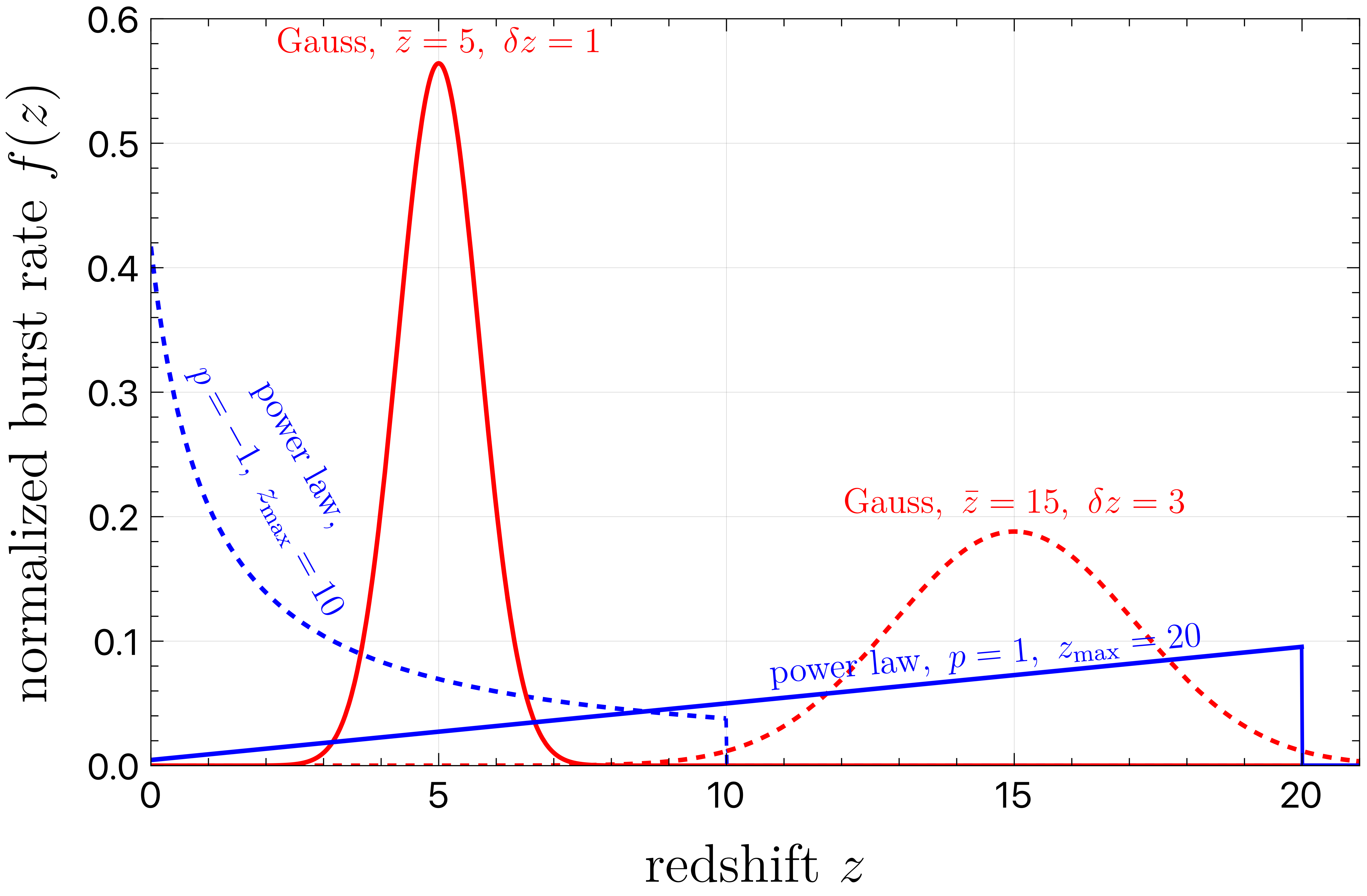
**Eby**, Takhistov, (2402.00100)

# Parameterization: Rate

$f(z) = (1+z)^{p}\Theta(z - z_{\text{max}})$ for power-law ← $R_{\text{burst}}(z) \propto \dfrac{\rho_{\text{loss}} H_0}{E_{\text{tot}}(z)} f(z)$

$f(z) = \exp\left(-\dfrac{(z-\bar{z})^2}{\delta z^2}\right)$ for Gaussian

$\rho_{\text{loss}}$: total relativistic energy density emitted across all $z$



Convenient normalisation:

$$\rho_{\text{loss}} \equiv \mathscr{F}\,\bar{\rho}_U$$

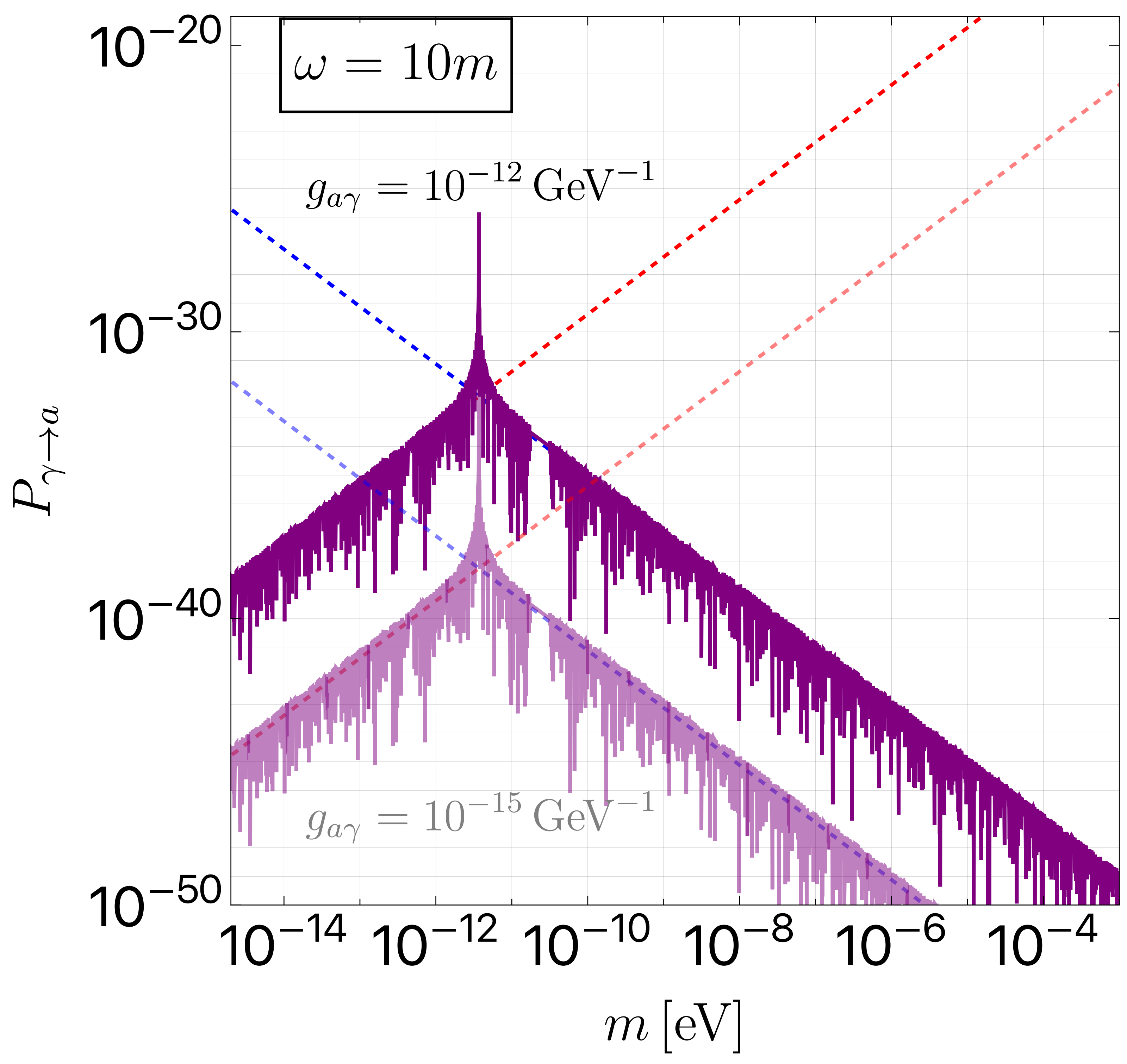
with $\bar{\rho}_U \simeq 10^{-6}\,\text{GeV/cm}^3$

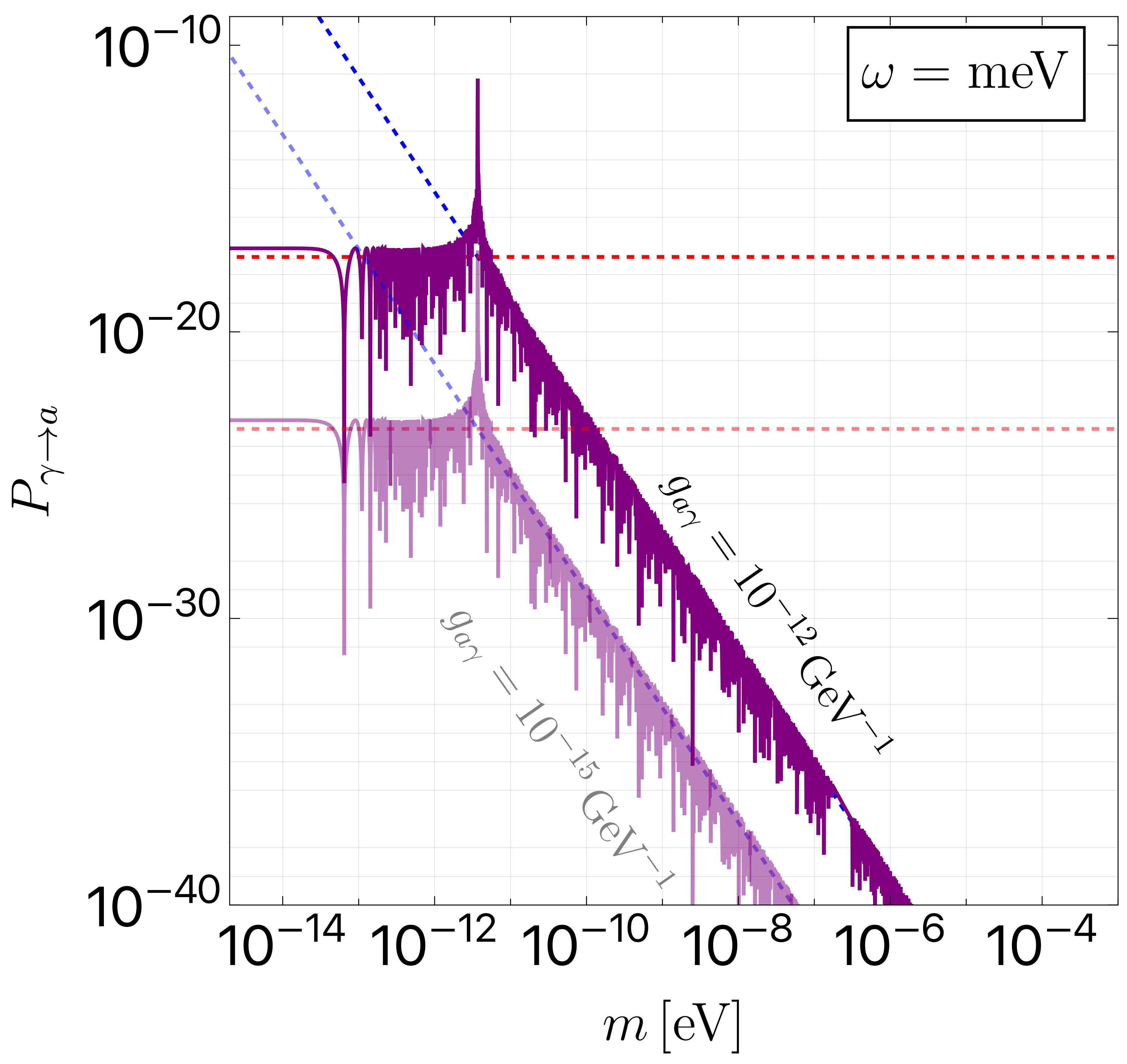
**Eby**, Takhistov,
(2402.00100)

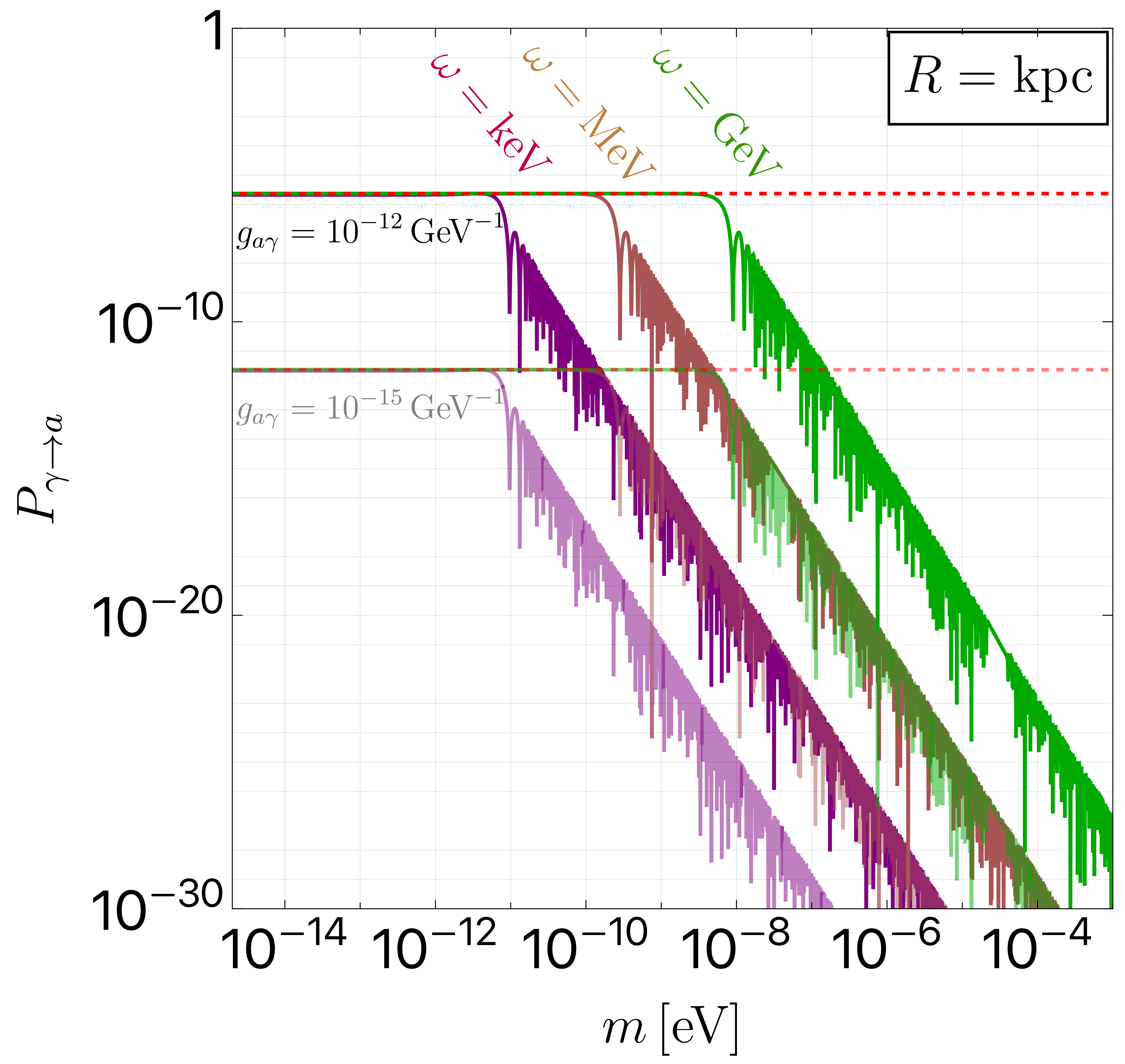
# $B$-Field Conversion Probability

$$P_{\gamma\to a} = (\Delta_{a\gamma} R)^2 \, \frac{\sin^2(\Delta_{\rm osc} R/2)}{(\Delta_{\rm osc} R/2)^2}$$

$$\begin{aligned}
\Delta_{a\gamma} &\equiv \frac{g_{a\gamma} B_T}{2} \simeq 1.5 \cdot 10^{-4} \left(\frac{g_{a\gamma}}{10^{-12}\,\mathrm{GeV}^{-1}}\right) \left(\frac{B_T}{\mu\mathrm{G}}\right) \mathrm{kpc}^{-1}\,, \\
\Delta_a &\equiv -\frac{m^2}{2\omega} \simeq -7.8 \cdot 10^{13} \left(\frac{m}{10^{-11}\,\mathrm{eV}}\right)^2 \left(\frac{10^{-10}\,\mathrm{eV}}{\omega}\right) \mathrm{kpc}^{-1}\,, \\
\Delta_{\rm pl} &\equiv -\frac{\omega_{\rm pl}^2}{2\omega} \simeq -1.1 \cdot 10^{13} \left(\frac{n_e}{10^{-2}\,\mathrm{cm}^{-3}}\right) \left(\frac{10^{-10}\,\mathrm{eV}}{\omega}\right) \mathrm{kpc}^{-1}\,,
\end{aligned}$$



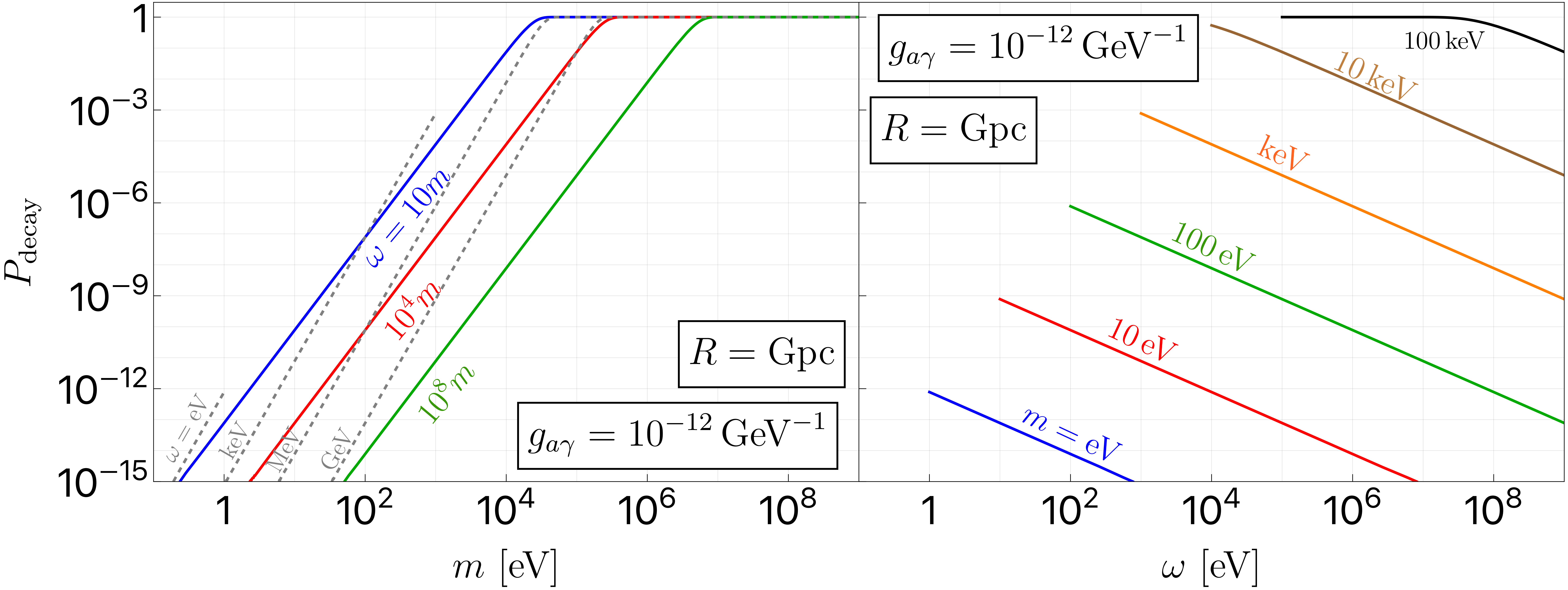




**Eby**, Takhistov,
(2402.00100)

# Decay Probability

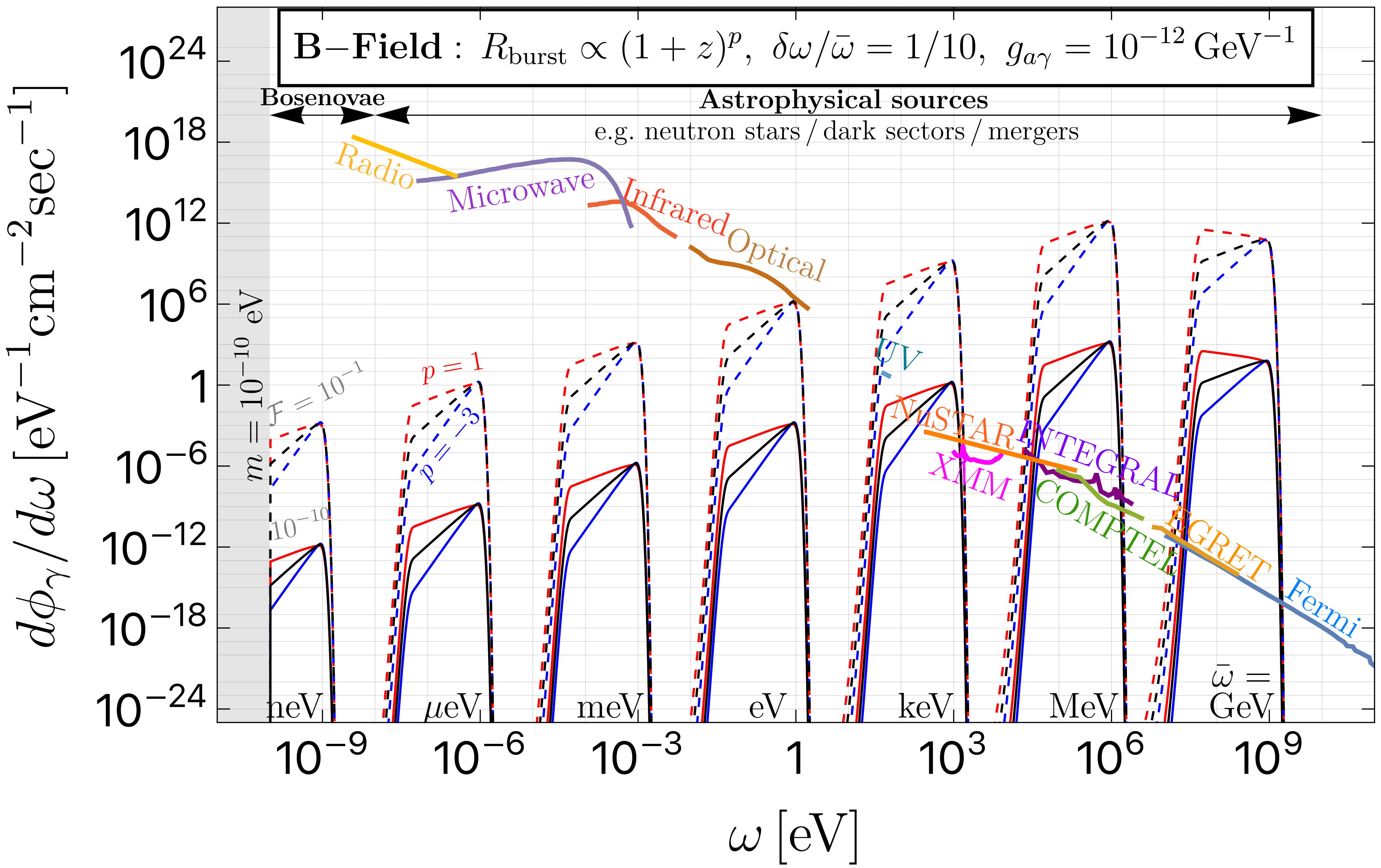
$$\ell(\omega) \simeq \frac{\gamma v_{\rm burst}}{\Gamma_{\gamma\gamma}} \simeq \left(\frac{\omega}{m}\right)\frac{64\pi}{g_{a\gamma}^2 m^3} \simeq \text{Mpc}\left(\frac{\omega}{\text{MeV}}\right)\left(\frac{100\,\text{keV}}{m}\right)^4\left(\frac{10^{-12}\,\text{GeV}^{-1}}{g_{a\gamma}}\right)^2$$



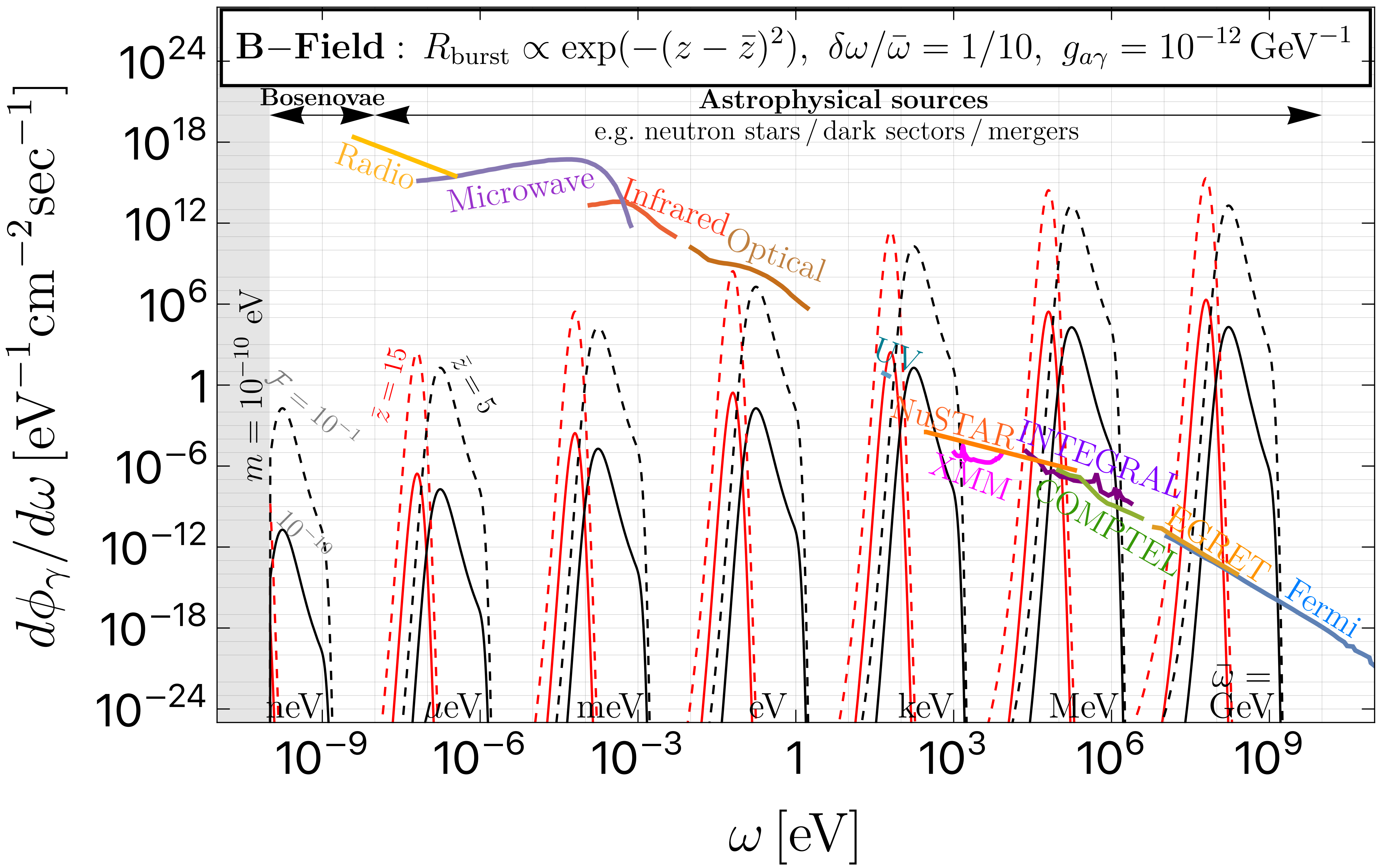
**Eby**, Takhistov,
arXiv:2402.00100

# DaB Flux: Other $f(z)$

Power law

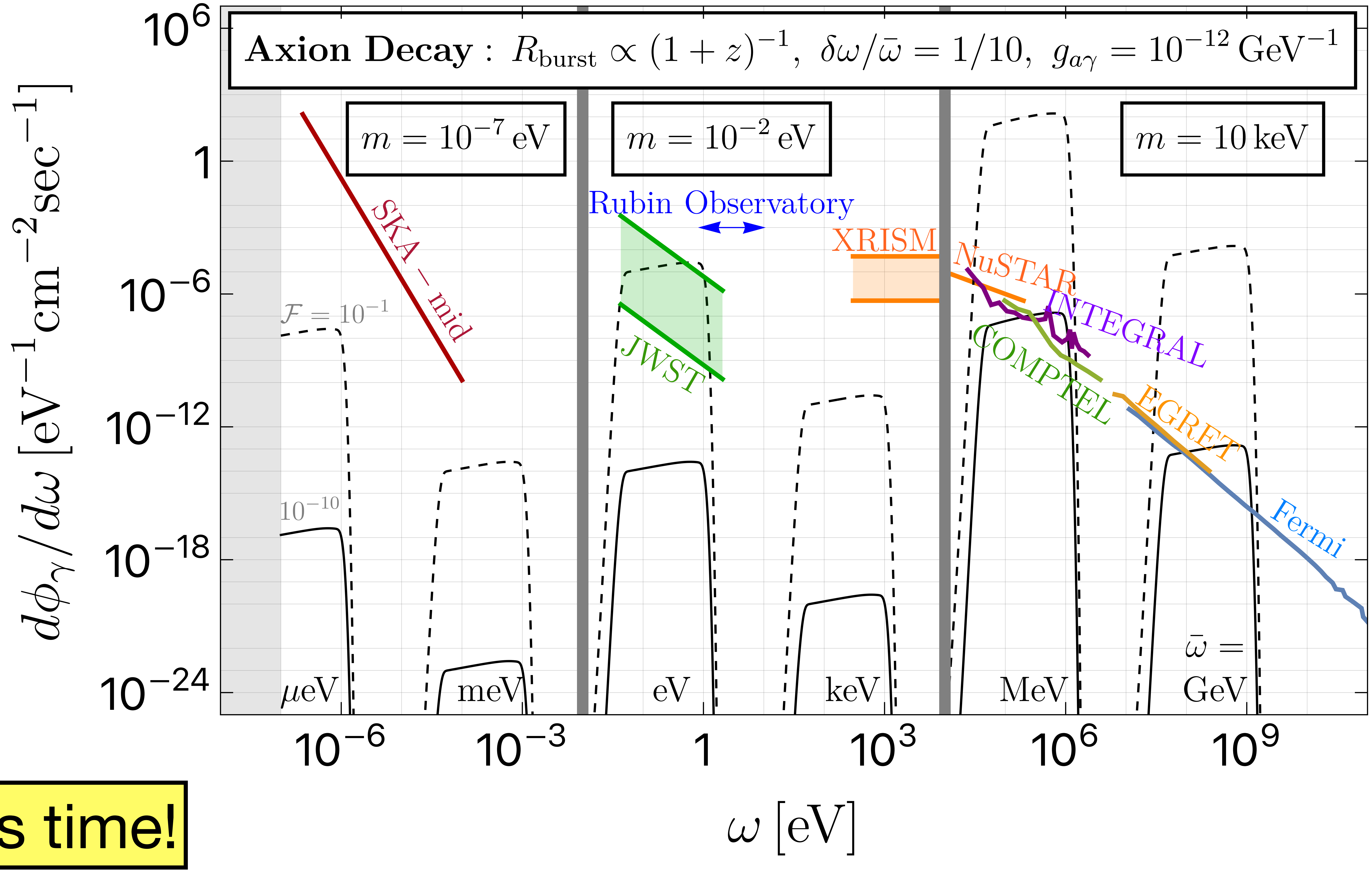


Gaussian



**Eby**, Takhistov,
(2402.00100)

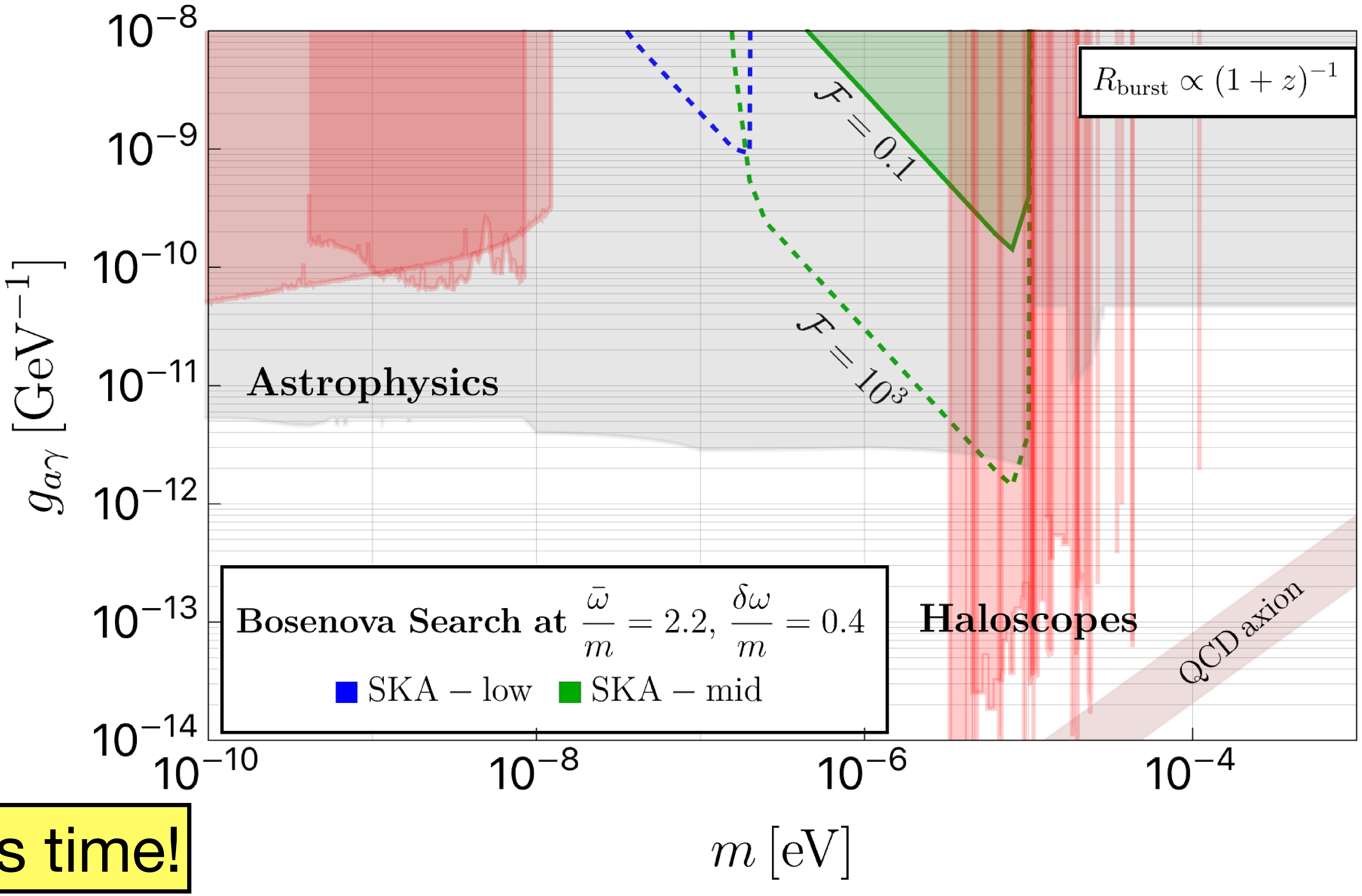
# DaB Flux from Decay



If there's time!

**Eby**, Takhistov,
(2402.00100)

# Case Study: DaB From Bosenovae in SKA



If there's time!