Terrestrial Signals of Axion Star Explosions

(and other relativistic axion bursts)

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Kavli IPMU Postdoc Colloquium
19/11/2021

Outline

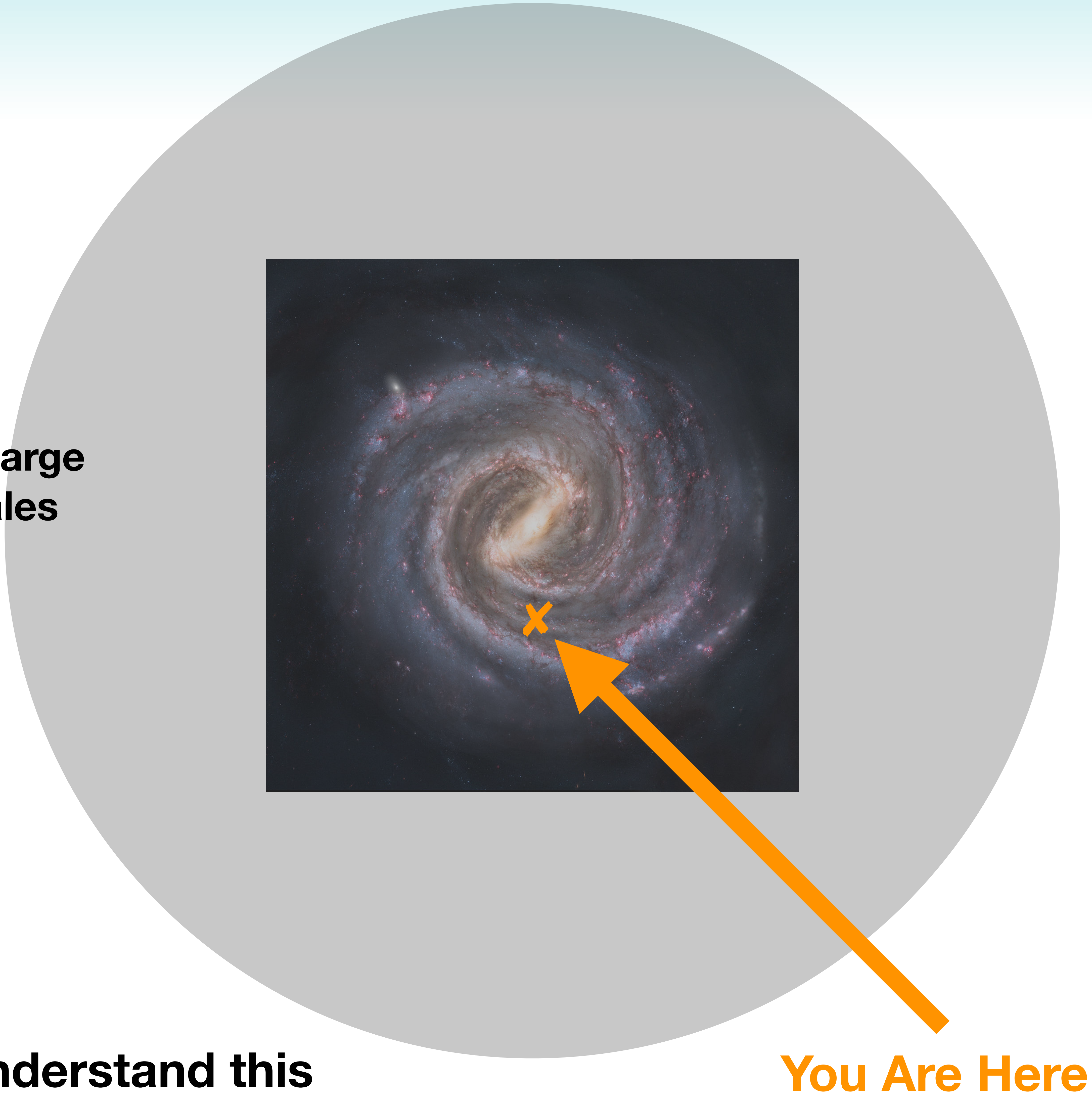
- Background and motivation
- What are axion stars?
- Axion star explosions!
- …and other transient axion bursts
- Conclusions and what's next

Our Galaxy, Our Halo

	Milky Way (That We Can See)	**Dark Matter Halo**
Radius	10-20 kiloparsecs (kpc) $\approx 10^{18}$ km	100-200 kpc $\approx 10^{19}$ km
Mass	$\sim 10^{11} M_\odot$	$\sim 10^{12} M_\odot$
Shape	Disk-like	Spherical
Local Mass Density	Very small (except for sun, planets, etc.)	$\rho_{\text{local}} = 0.4 \, \frac{\text{GeV}}{\text{cm}^3}$  ?
How do we know it's there?	*We can see it* (optical, IR, UV)	**Invisible**! Can only see effects indirectly (gravitational influence on stars, galaxy formation, etc.)

***At large scales**

Grand Goal: Understand this at the level of particle physics



Dark Matter Models

Mass of the DM "particle" m

$10^{-22}\,\mathrm{eV} \lesssim m \lesssim \mathrm{eV}$

Light Bosonic Dark Matter (sometimes "axions")

$\mathrm{keV} \lesssim m \lesssim 100\,\mathrm{TeV}$

Thermally-Produced Dark Matter

e.g. Weakly Interacting Massive Particles (WIMPs)

$M_\odot \lesssim m$

Macroscopic Dark Matter

e.g. black holes

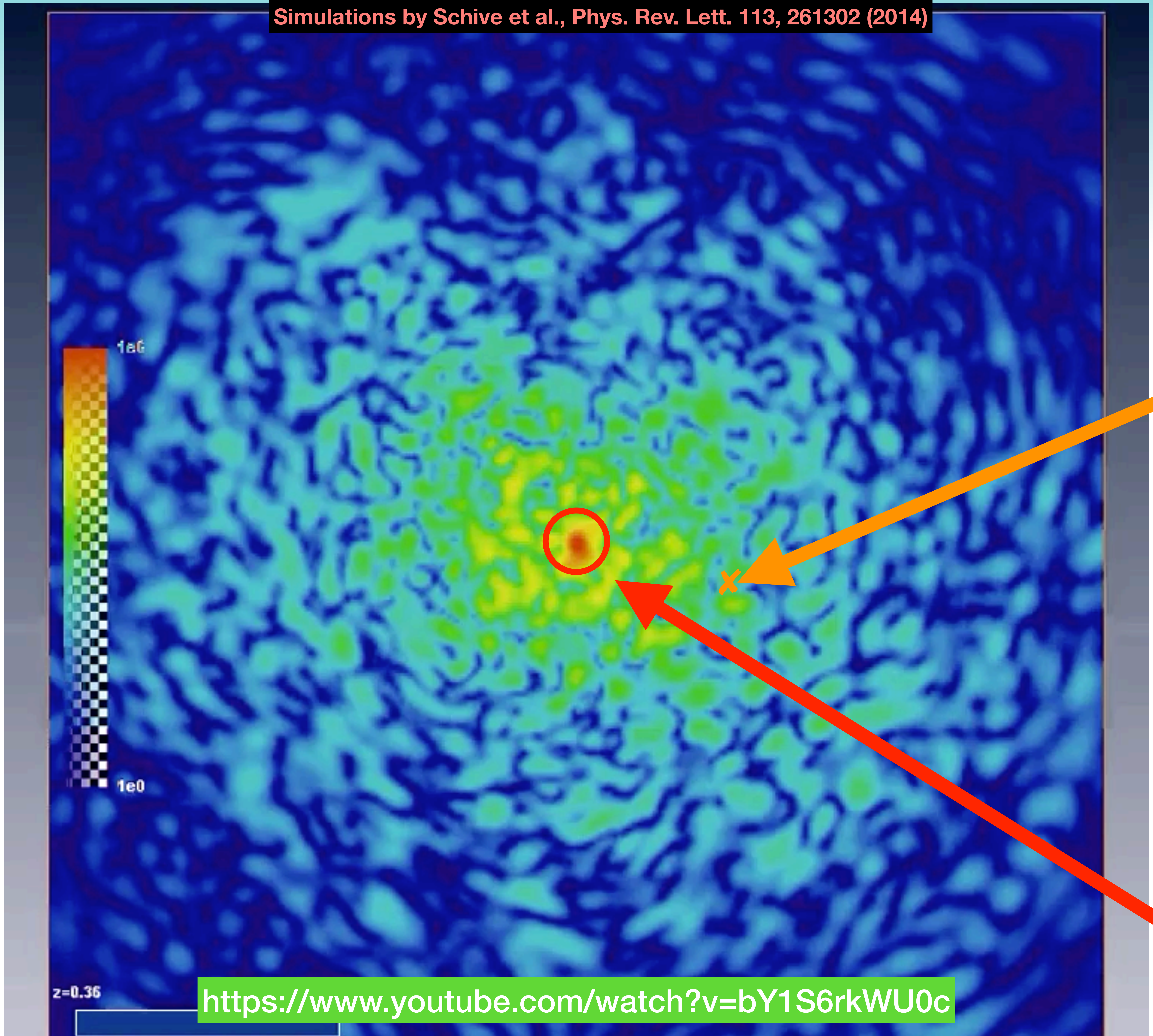
- Quantum mechanics: such particles must be bosons because phase space density $\mathcal{N}\ (\propto m^{-4}) \gg 1$

- Light bosonic DM is wave-like on distance scales of order

$$\lambda_{\mathrm{dB}} = \frac{1}{m\,\sigma_{\mathrm{vir}}} \sim R_E\left(\frac{10^{-10}\,\mathrm{eV}}{m}\right) \sim \mathrm{AU}\left(\frac{10^{-14}\,\mathrm{eV}}{m}\right) \sim \mathrm{kpc}\left(\frac{10^{-22}\,\mathrm{eV}}{m}\right)$$

with oscillatory frequencies of $\omega_\phi \sim 2\pi m \simeq \mathrm{MHz}\left(\dfrac{m}{10^{-10}\,\mathrm{eV}}\right)$

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



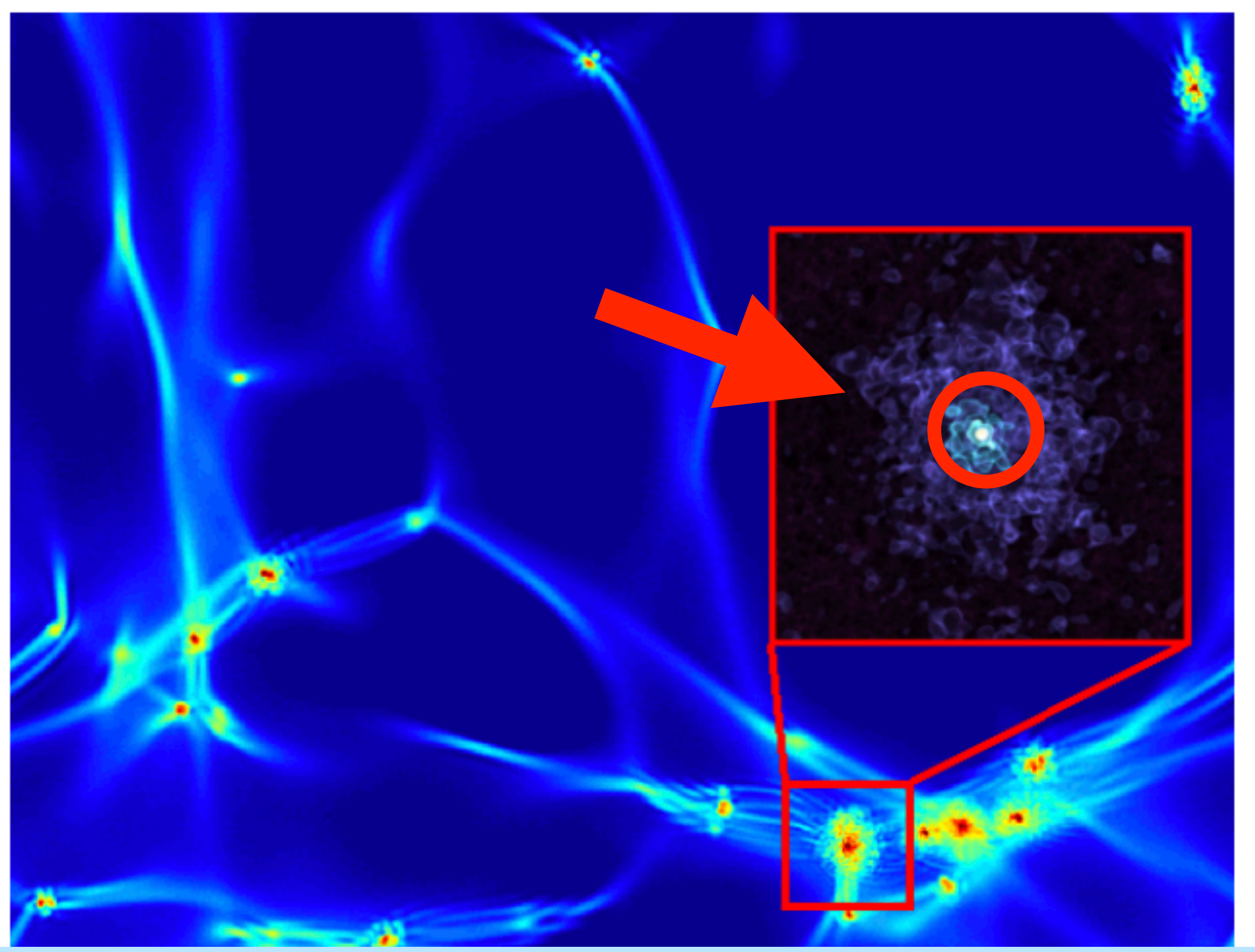
You Are Here (sort of)

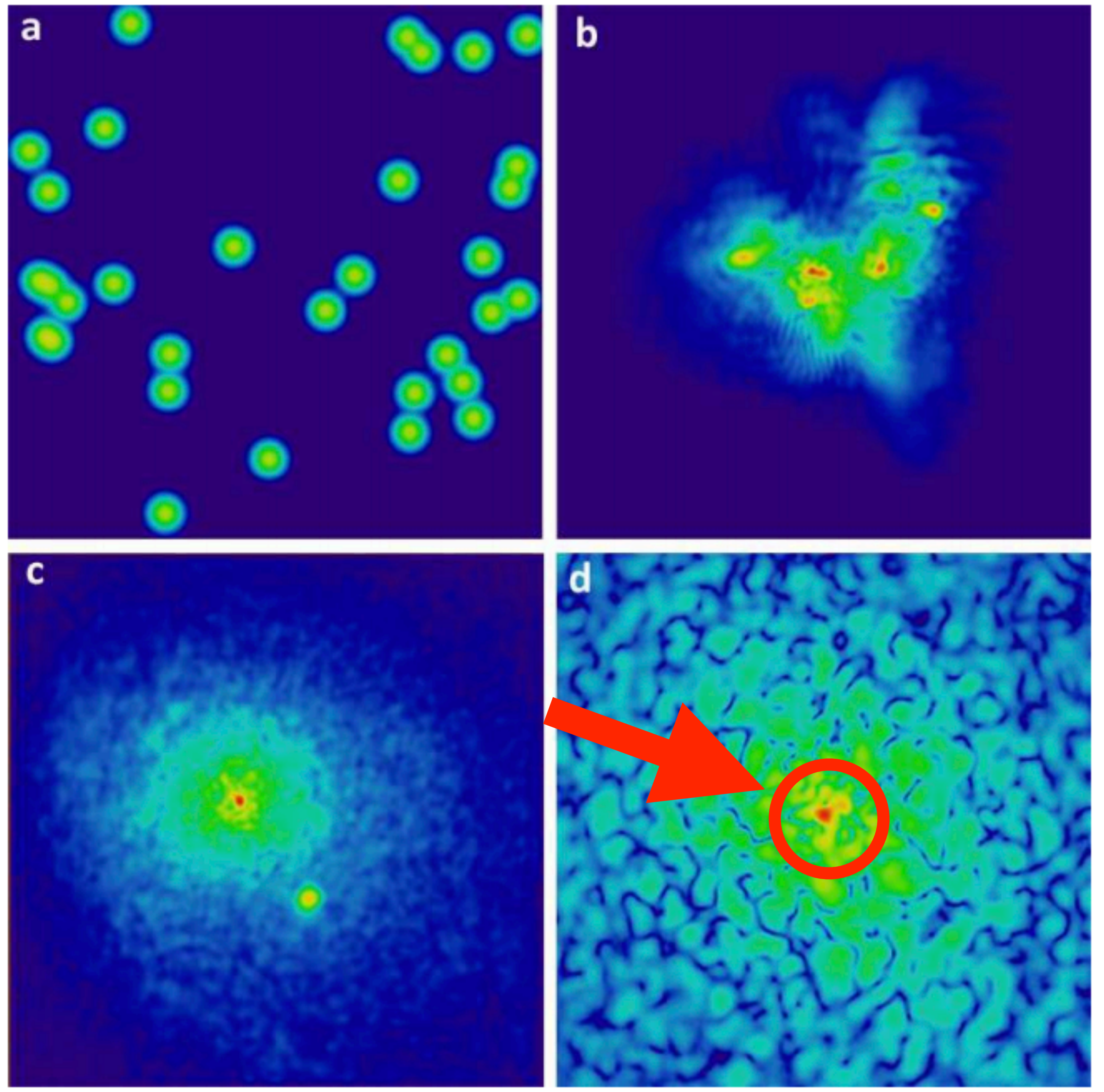
Axion Star

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

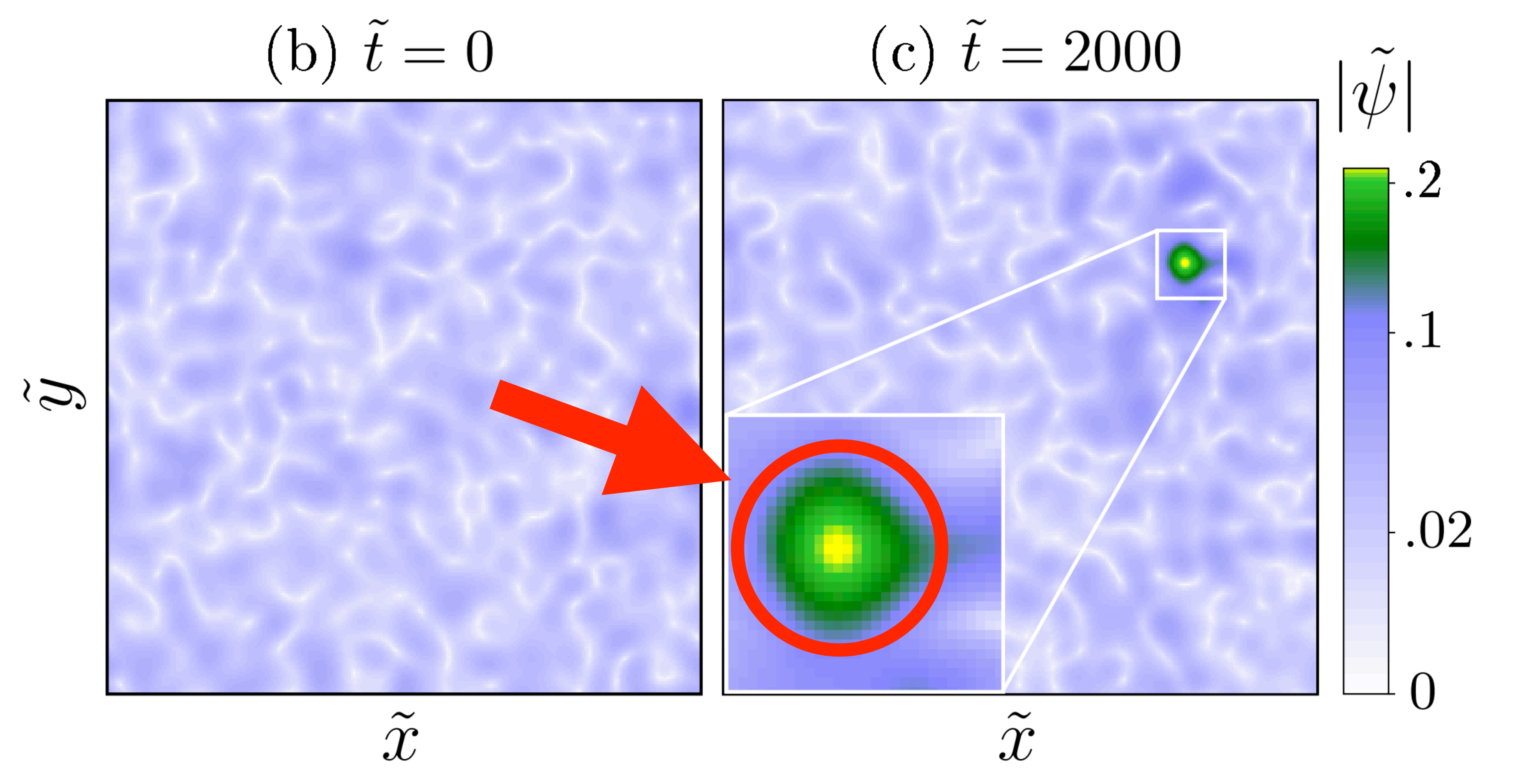
Formation of Axion Stars

Mocz et al.,
MNRAS, Volume 471, Issue 4, November 2017

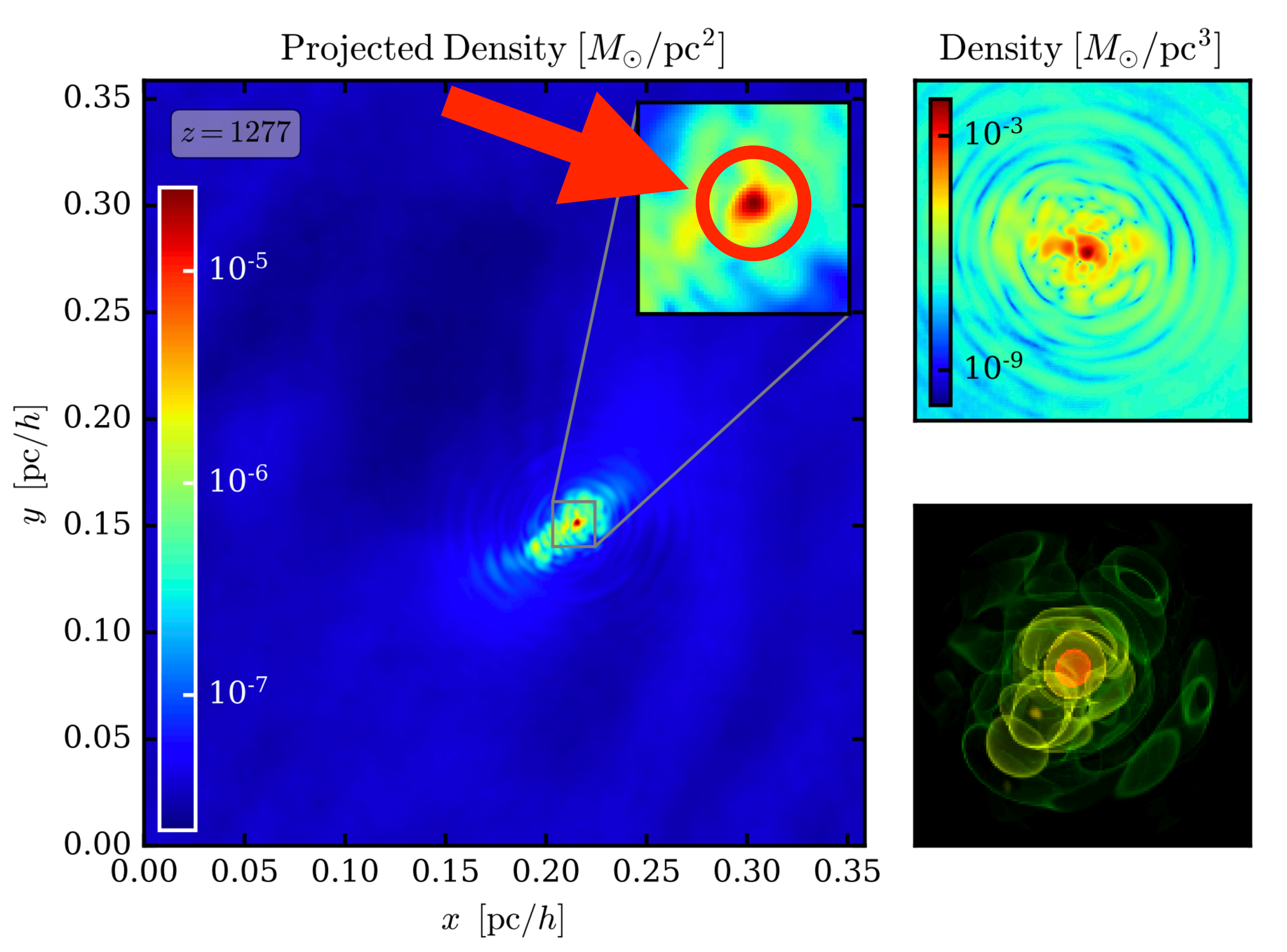




Schive et al.,
Phys. Rev. Lett. 113, 261302 (2014)



Levkov, Panin, Tkachev,
Phys. Rev. Lett. 121, 151301 (2018)



Eggemeier and Niemeyer,
Phys. Rev. D 100, 063528 (2019)

Equations of Motion

- Axion dark matter is non-relativistic field of very large occupation number ⇒ NR classical field
- Expand field ϕ in terms of non-relativistic wavefunction ψ : $\phi(t,r) = \frac{1}{\sqrt{2m}}\left[e^{-imt}\psi(t,r) + c.c.\right]$
- E.o.M is Gross-Pitaevskii+Poisson (GPP) equation:

Poisson Gravity
$\nabla^2 V_g = 4\pi G m^2 |\psi|^2$
(Attractive)

Coherent state → Oscillates
Leading time dependence
$\dot\psi \sim (m - \mu_0)\psi \ll m\psi$

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

Normalization
$$m\int d^3r\,|\psi|^2 = M_\star$$

Kinetic energy
(Repulsive)

Self-interactions
For ALP potential,

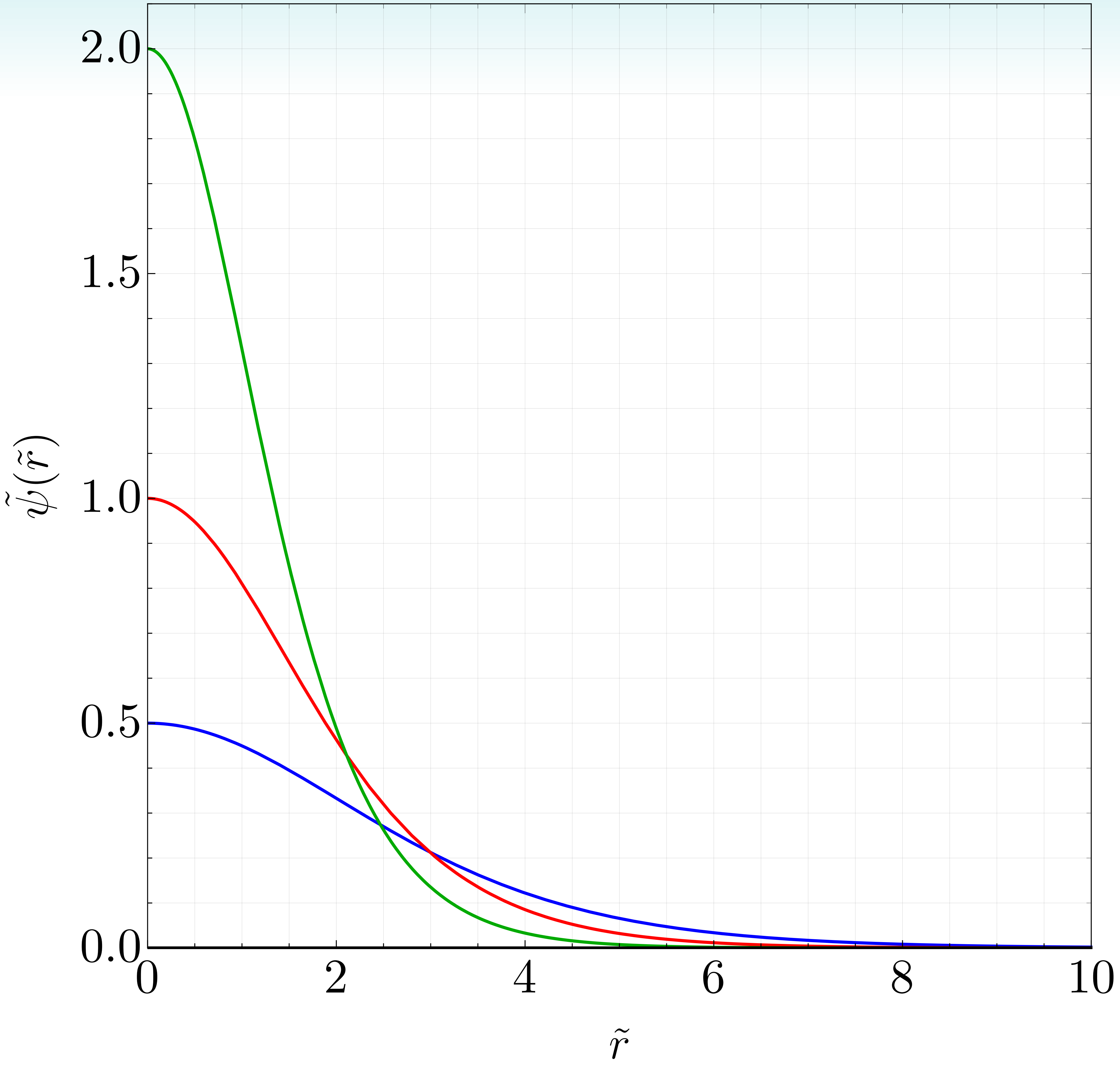
$$V(\phi) = m^2 f^2\left[1 - \cos\left(\frac{\phi}{f}\right)\right] = \frac{m^2}{2}\phi^2 - \frac{1}{4!}\left(\frac{m}{f}\right)^2\phi^4 + \frac{1}{6!f^2}\left(\frac{m}{f}\right)^2\phi^6 - \ldots$$

(Attractive) **(Repulsive)**

What is an Axion Star?

Normalization

$$m_\phi \int d^3r\, |\psi|^2 = M$$



Ground-state solutions of the Gross-Pitaevskii+Poisson (GPP) Equations

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

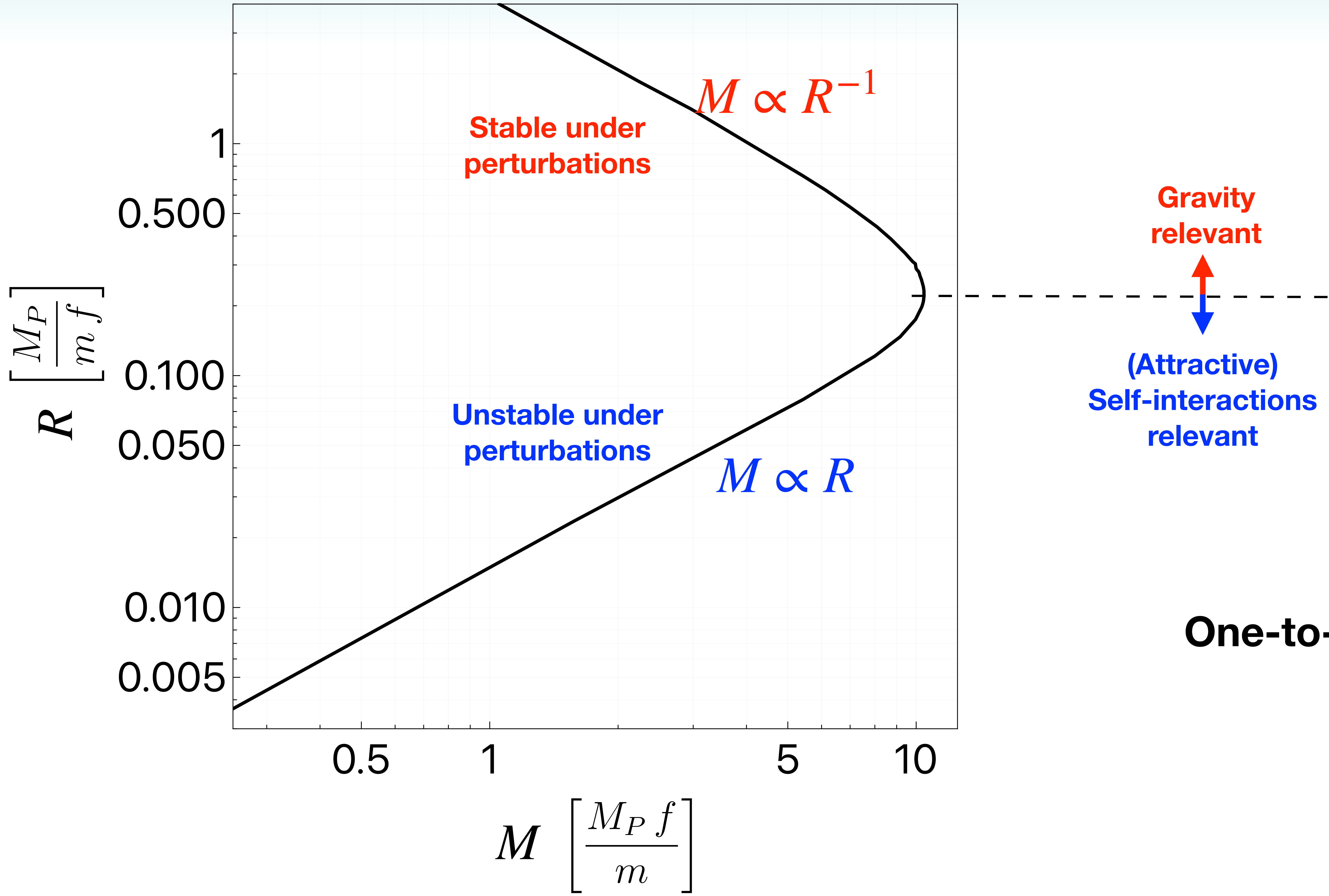
$$\propto \frac{1}{R^2} \qquad \propto -\frac{M}{R} \qquad \propto -\frac{M}{R^3} + \frac{M^2}{R^6} - \ldots$$

- Low density → ~~Self-interactions~~, [kinetic ~ gravity]

$$M \simeq \frac{10^{-12}\,M_\odot}{m_5^2}\left(\frac{2000\,\text{km}}{R}\right)$$

"Dilute boson star"

Mass-Radius Relation



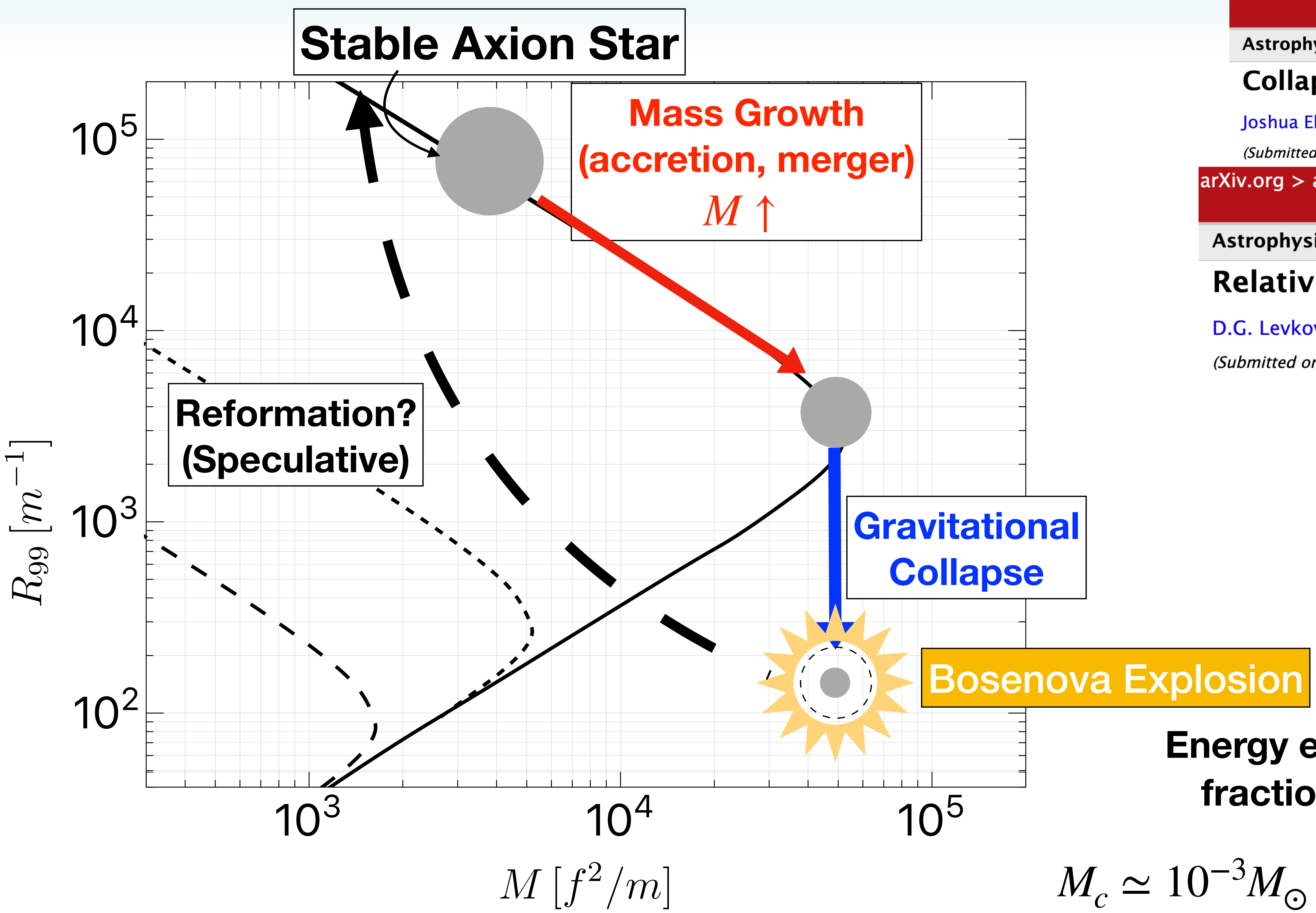
$$M_c \simeq 10\frac{M_P f}{m} \simeq 10^{-3} M_\odot \left(\frac{f}{10^{16}\,\mathrm{GeV}}\right)\left(\frac{10^{-10}\,\mathrm{eV}}{m}\right)$$

$$R_c \simeq 0.2\frac{M_P}{mf} \simeq 10^5\,\mathrm{km}\left(\frac{10^{16}\,\mathrm{GeV}}{f}\right)\left(\frac{10^{-10}\,\mathrm{eV}}{m}\right)$$

One-to-one relationship between:

$M, R, \psi(0), \mu_0, \ \ldots$

Axion Star Collapse



arXiv.org > astro-ph > arXiv:1608.06911

Prediction

Astrophysics > Cosmology and Nongalactic Astrophysics

Collapse of Axion Stars

Joshua Eby, Madelyn Leembruggen, Peter Suranyi, L.C.R. Wijewardhana

(Submitted on 24 Aug 2016 (v1), last revised 29 Apr 2017 (this version, v3))

arXiv.org > astro-ph > arXiv:1609.03611

Simulation

Astrophysics > Cosmology and Nongalactic Astrophysics

Relativistic axions from collapsing Bose stars

D.G. Levkov, A.G. Panin, I.I. Tkachev

(Submitted on 12 Sep 2016 (v1), last revised 5 Dec 2016 (this version, v2))

Energy emitted can be an $\mathcal{O}(1)$ fraction of axion star mass

$$M_c \simeq 10^{-3} M_\odot \left(\frac{f}{10^{16}\,\mathrm{GeV}}\right)\left(\frac{10^{-10}\,\mathrm{eV}}{m}\right)$$

arXiv.org > astro-ph > arXiv:1609.03611

Astrophysics > Cosmology and Nongalactic Astrophysics

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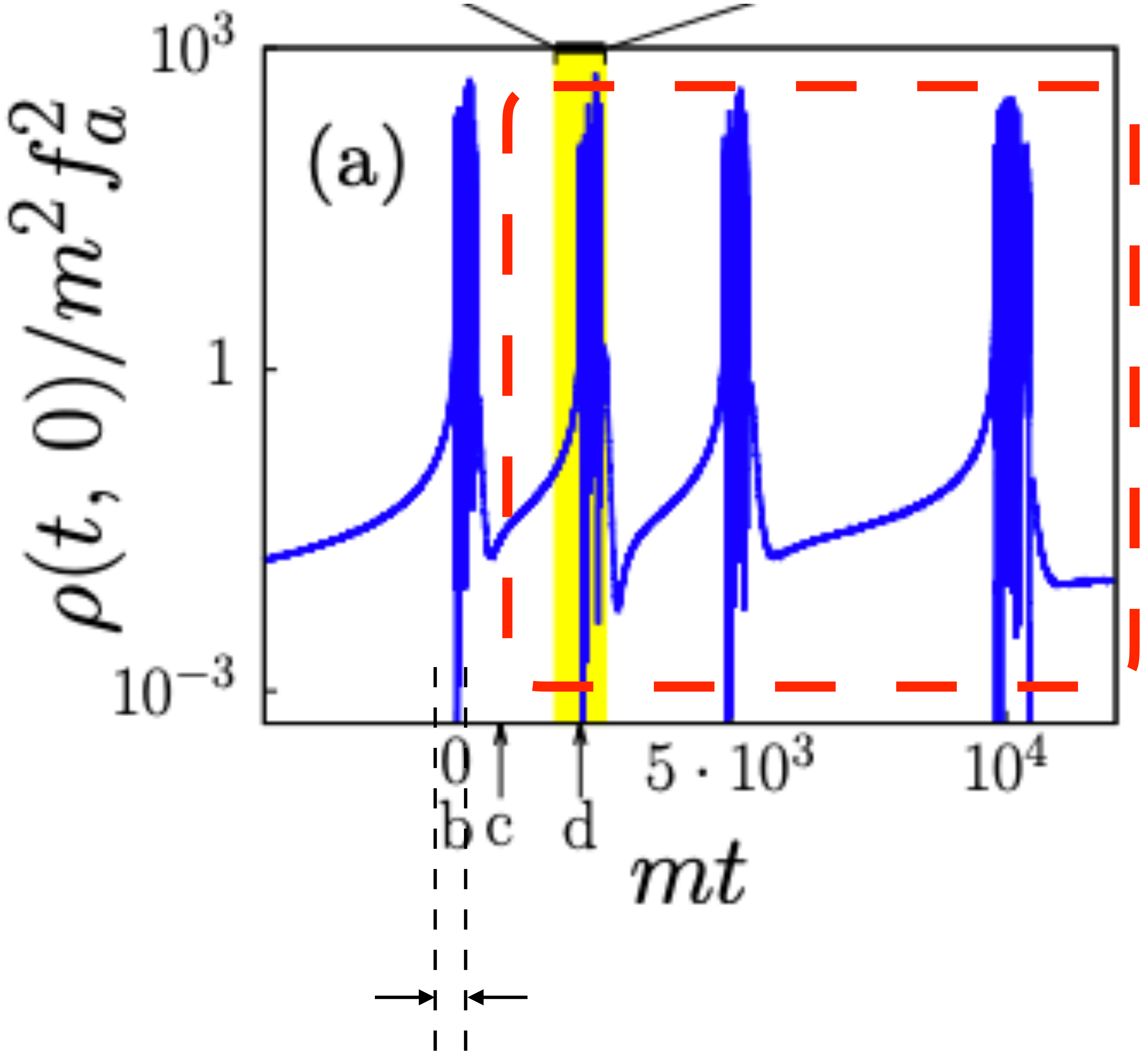
Simulation Results

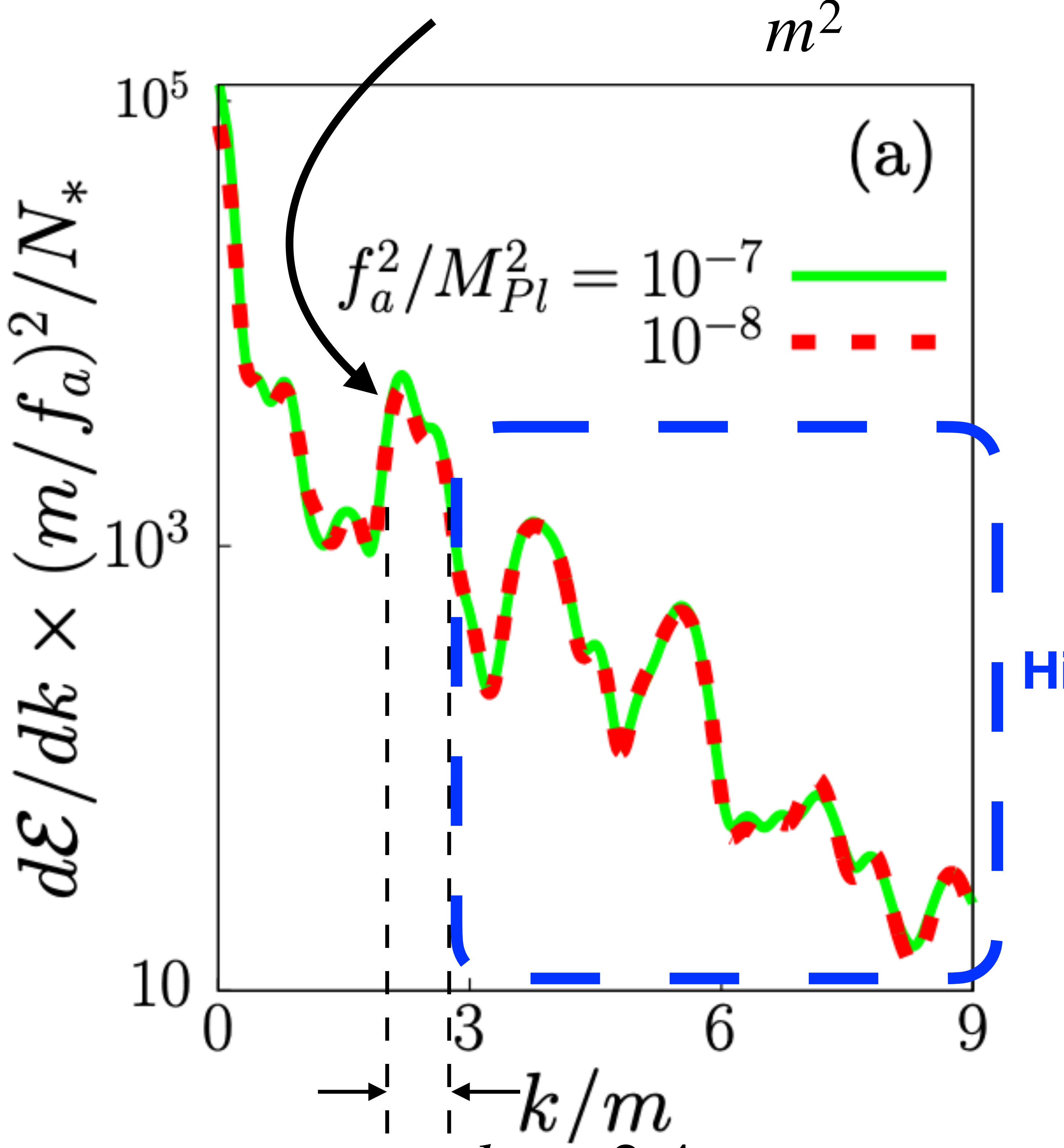
Large integrated energy!
In first peak,

$$\mathcal{E}_{\rm peak} \approx 3400\, m\, \frac{f^2}{m^2} \simeq 10^{52}\,{\rm GeV}\, \frac{f_{16}^2}{m_{10}}$$



Multiple explosions per collapse! (Ignored here)

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



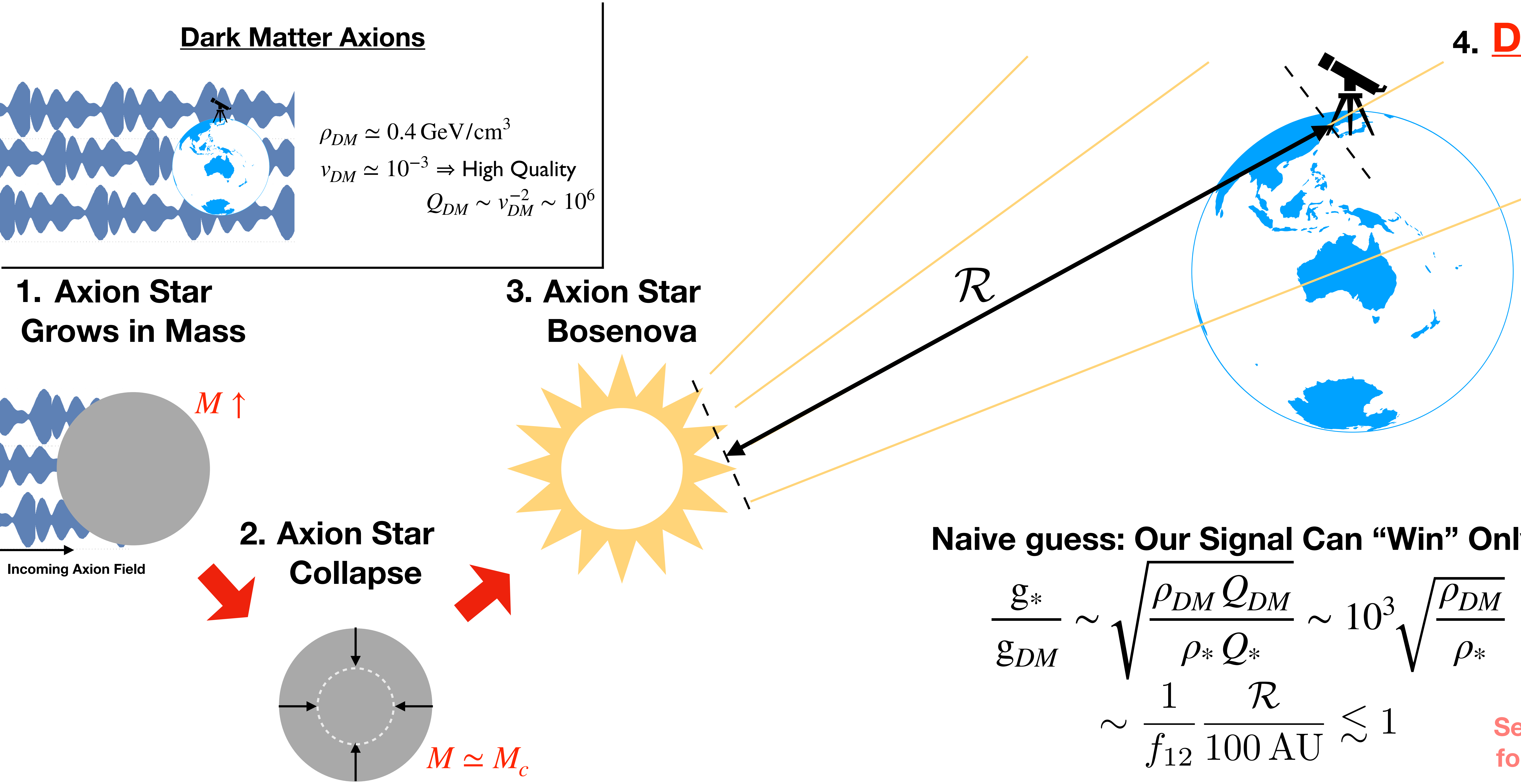
Higher-energy peaks! (Ignored here)

Momentum peak $k_0 \simeq 2.4\, m$

with spread of $\delta k \sim m$

Naive Sensitivity Reach

- Idea: Detect high-energy axion burst from axion star collapse + Bosenova!



4. **Detect Bosenova Axions**

$$\rho_* \approx \frac{\mathcal{E}_{\rm peak}}{4\pi\,\mathcal{R}^2\,\delta x_{\rm burst}}$$

$$\sim 10^7\,\frac{\mathrm{GeV}}{\mathrm{cm^3}}\,f_{12}^2\left(\frac{100\,\mathrm{AU}}{\mathcal{R}}\right)^2$$

$v_* \simeq 1 \Rightarrow$ Low Quality

$Q_* \sim 1$

Naive guess: Our Signal Can "Win" Only If

$$\frac{g_*}{g_{DM}} \sim \sqrt{\frac{\rho_{DM}\,Q_{DM}}{\rho_*\,Q_*}} \sim 10^3\sqrt{\frac{\rho_{DM}}{\rho_*}}$$

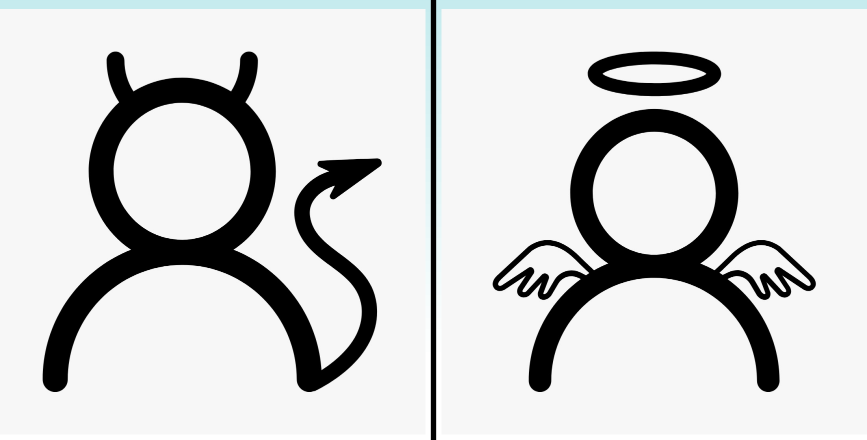
$$\sim \frac{1}{f_{12}}\,\frac{\mathcal{R}}{100\,\mathrm{AU}} \lesssim 1$$

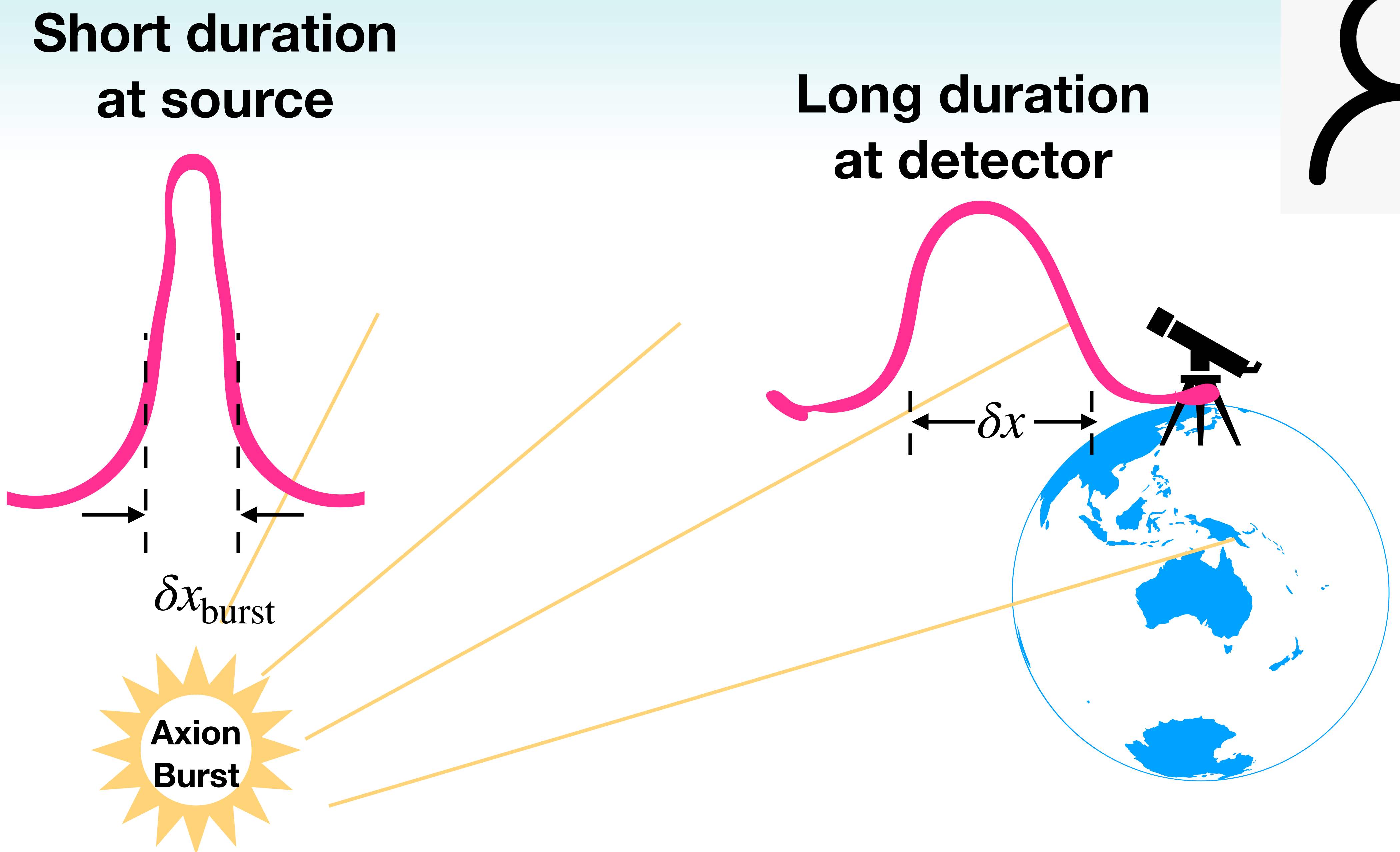
See also Dror, Murayama, Rodd (2101.09287) for relativistic axion signals from cosmology

Naive guess:

$$\frac{g_*}{g_{DM}} \sim \sqrt{\frac{\rho_{DM}\, Q_{DM}}{\rho_*\, Q_*}} \sim 10^3 \sqrt{\frac{\rho_{DM}}{\rho_*}} \lesssim 1$$

We Might Do Worse





Energy density at detector drops fast with distance, $\propto \mathcal{R}^{-3}$

No wave spreading

$$\rho_* \approx \frac{\mathcal{E}_{\rm peak}}{4\pi\, \mathcal{R}^2\, \delta x_{\rm burst}}$$

$$\delta x_{\rm burst} \simeq \xi/m$$

$\longrightarrow$

Wave spreading

$$\rho_* \approx \frac{\mathcal{E}_{\rm peak}}{4\pi\, \mathcal{R}^2\, \delta x}$$

$$\delta x \sim \frac{m^2\, \delta k}{k^3}\,\mathcal{R}$$

We Can Do Better!

Though energy density decreases,
burst duration grows.
Can still 'catch' whole signal (up to a point)!

No wave spreading

$$\delta t_{\rm burst} \sim \xi/m$$

$\longrightarrow$

Wave spreading

$$\delta t \sim \frac{m^2\, \delta k}{k^3}\,\mathcal{R} \sim \mathcal{R}$$

Momentum modes naturally separate in-flight:
Can *regain* some coherence at the detector,

No wave spreading

$$\tau_{*,\rm burst} \sim 2\pi/m$$

$\longrightarrow$

Wave spreading

$$\tau_* \sim \frac{2\pi m^2\, \delta k}{\xi\, k^3}\,\mathcal{R} \sim \frac{\mathcal{R}}{\xi}$$

How to Search

Total experimental integration time $t_{\text{int}} = \text{yr}$

Sensitivity Ratio

$$\frac{g_*(\omega_0)}{g_{\text{DM}}(\omega_0)} \sim \sqrt{\frac{\rho_{\text{DM}}}{\rho_*}}\, \frac{t_{\text{int}}^{1/4} \min\left(\tau_{\text{DM}}^{1/4}, t_{\text{int}}^{1/4}\right)}{\min\left[(\delta t)^{1/4}, t_{\text{int}}^{1/4}\right] \min\left(\tau_*^{1/4}, t_{\text{int}}^{1/4}\right)}$$

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

Assume average time for burst $\tau = 10\text{Gyr}$

Check whether

$$\mathcal{N} \equiv N_{\text{star}}(\mathcal{R}) \times \left(\frac{1\,\text{yr}}{\tau}\right) > 1$$

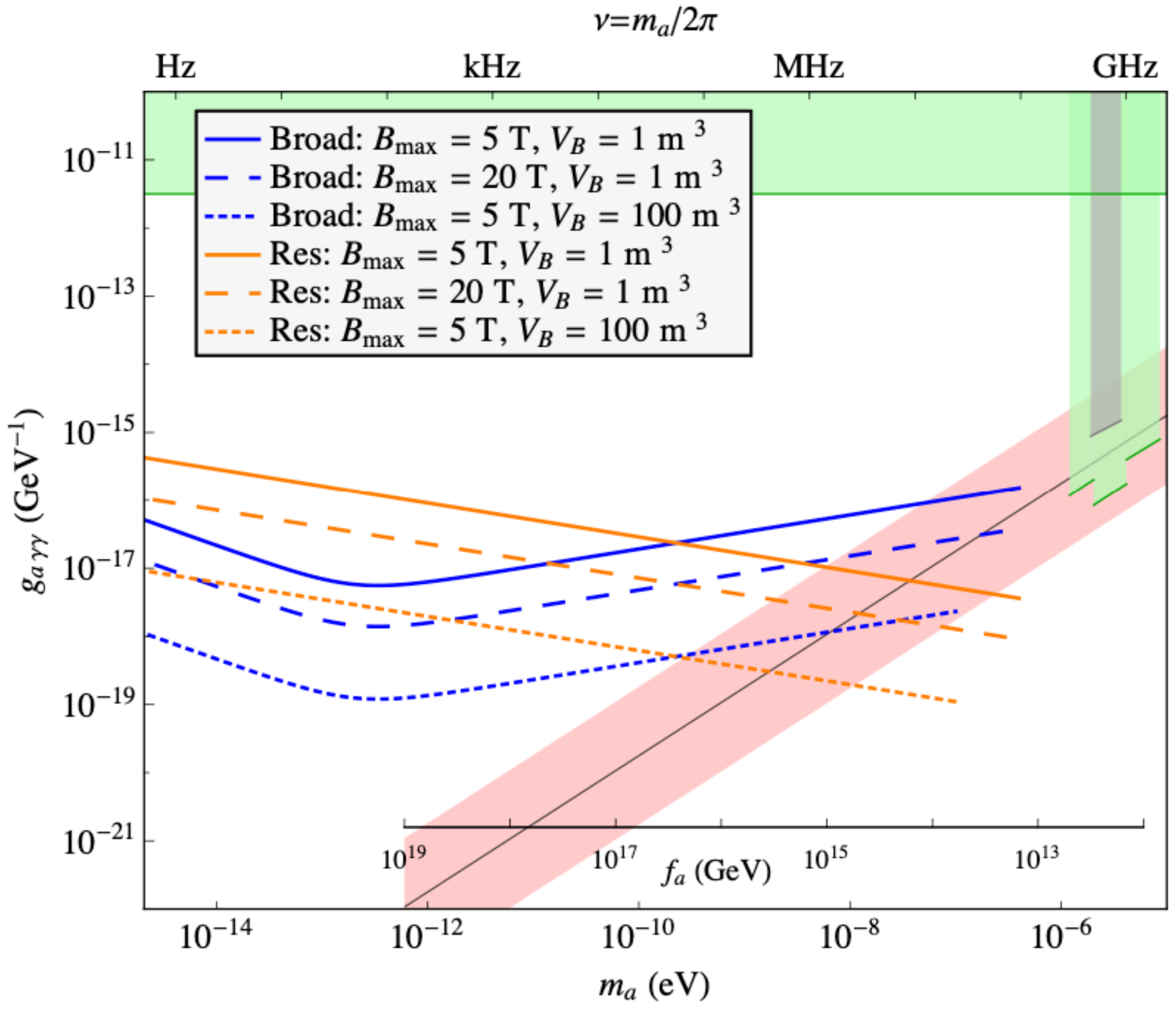
(# bursts within $\mathcal{R}$ of Earth per year)

"How likely is it for a 'nearby' burst to occur within 1 year of experimental running?"

For absolute sensitivity, we use ABRACADABRA long-term reach

Kahn, Safdi, Thaler (1602.01086)

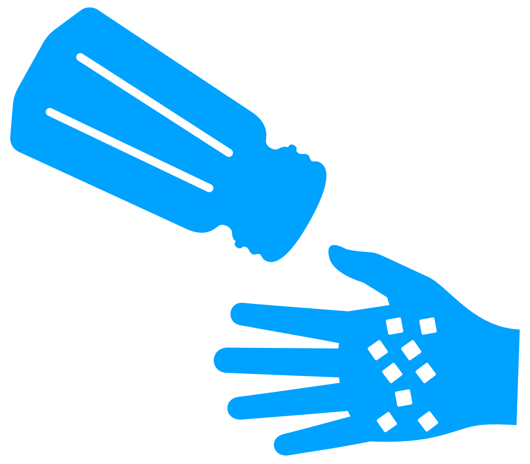
Though see also DMRadio (Snowmass2021) and SHAFT (2003.03348)



Define # burst-making objects

$$N(\mathcal{R}) = \frac{f_{\text{DM}}\rho_{\text{DM}}}{\mathcal{E}} \frac{4\pi\mathcal{R}^3}{3}$$

within $\mathcal{R}$ of Earth



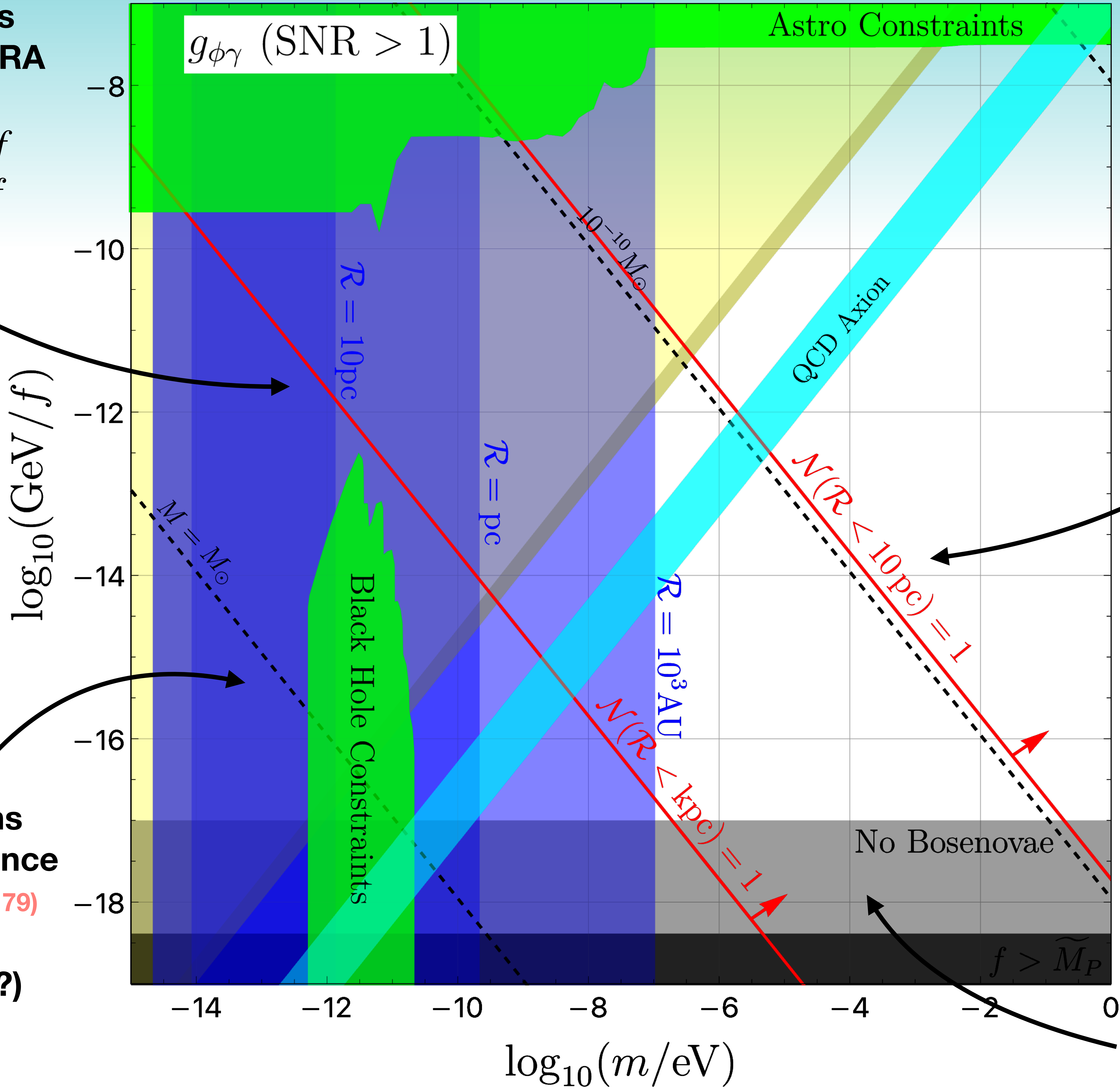
For axion stars,

$$N_{\text{star}}(\mathcal{R}) \approx f_{\text{DM}} \left(\frac{\mathcal{R}}{100\,\text{AU}}\right)^3 \frac{m_5}{f_{12}}$$

1. Blue: sensitivity bands for future ABRACADABRA

Note: coupling $\propto 1/f$

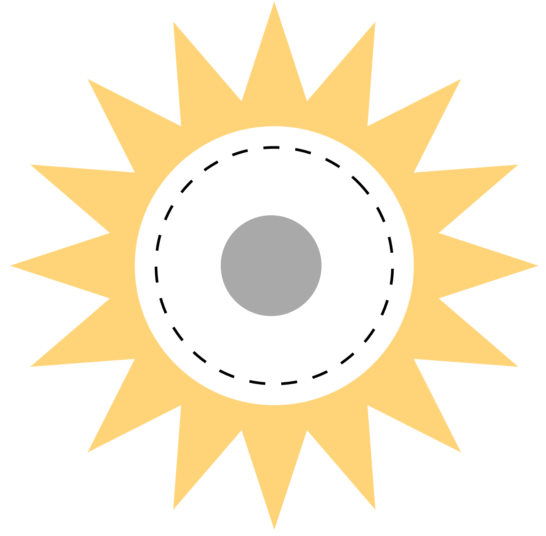
but signal $\propto \sqrt{\mathcal{E}} \propto f$



3. Red: Contours for $\tau = 10\,\text{Gyr}$

Explosions infrequent?

Shorter lifetime possible?



Bosenova Explosion

4. Yellow: Axion→photons through parametric resonance

Levkov, Panin, Tkachev (2004.05179)

Feature or bug?

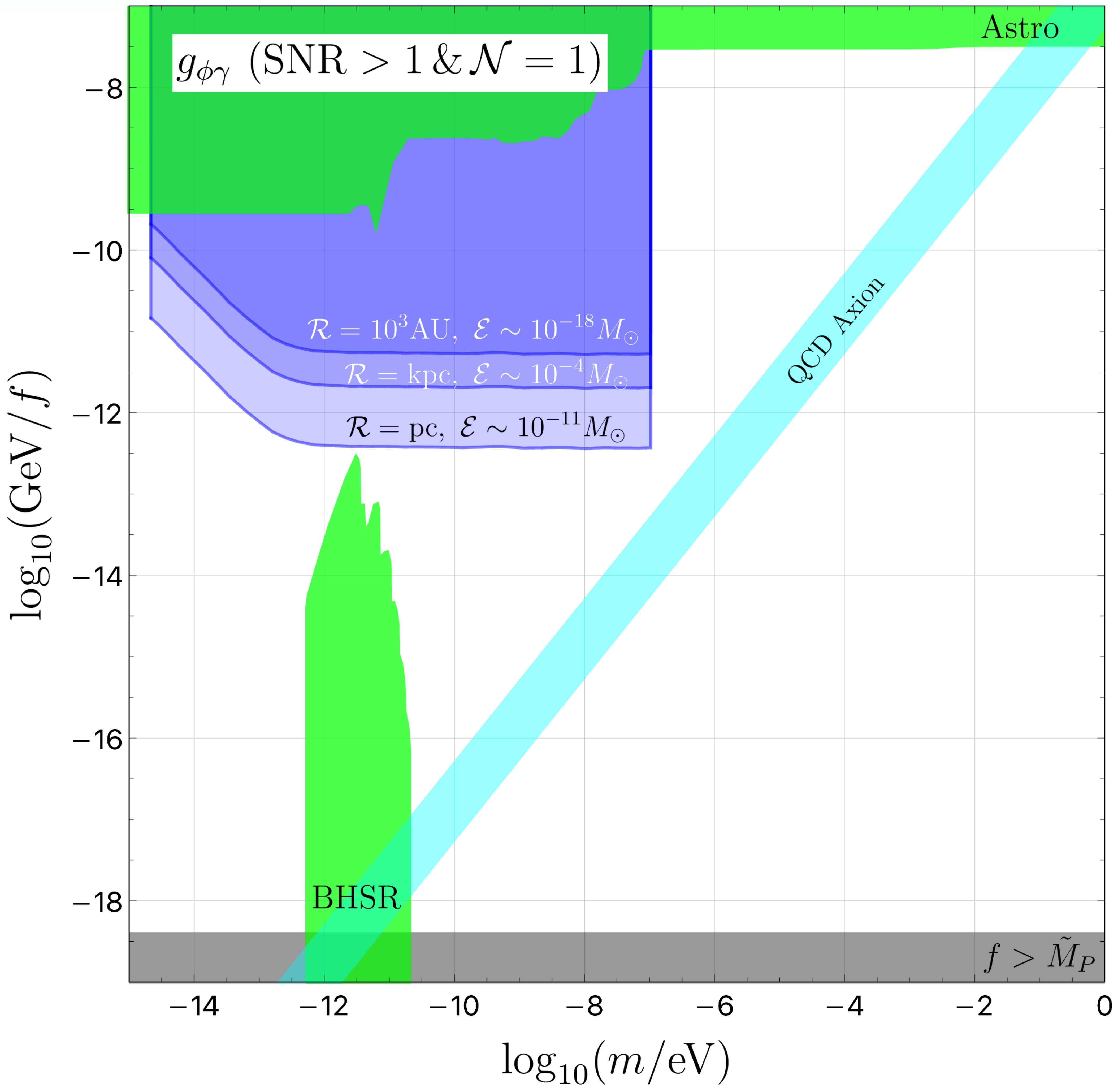
(Multi-messenger signal?)

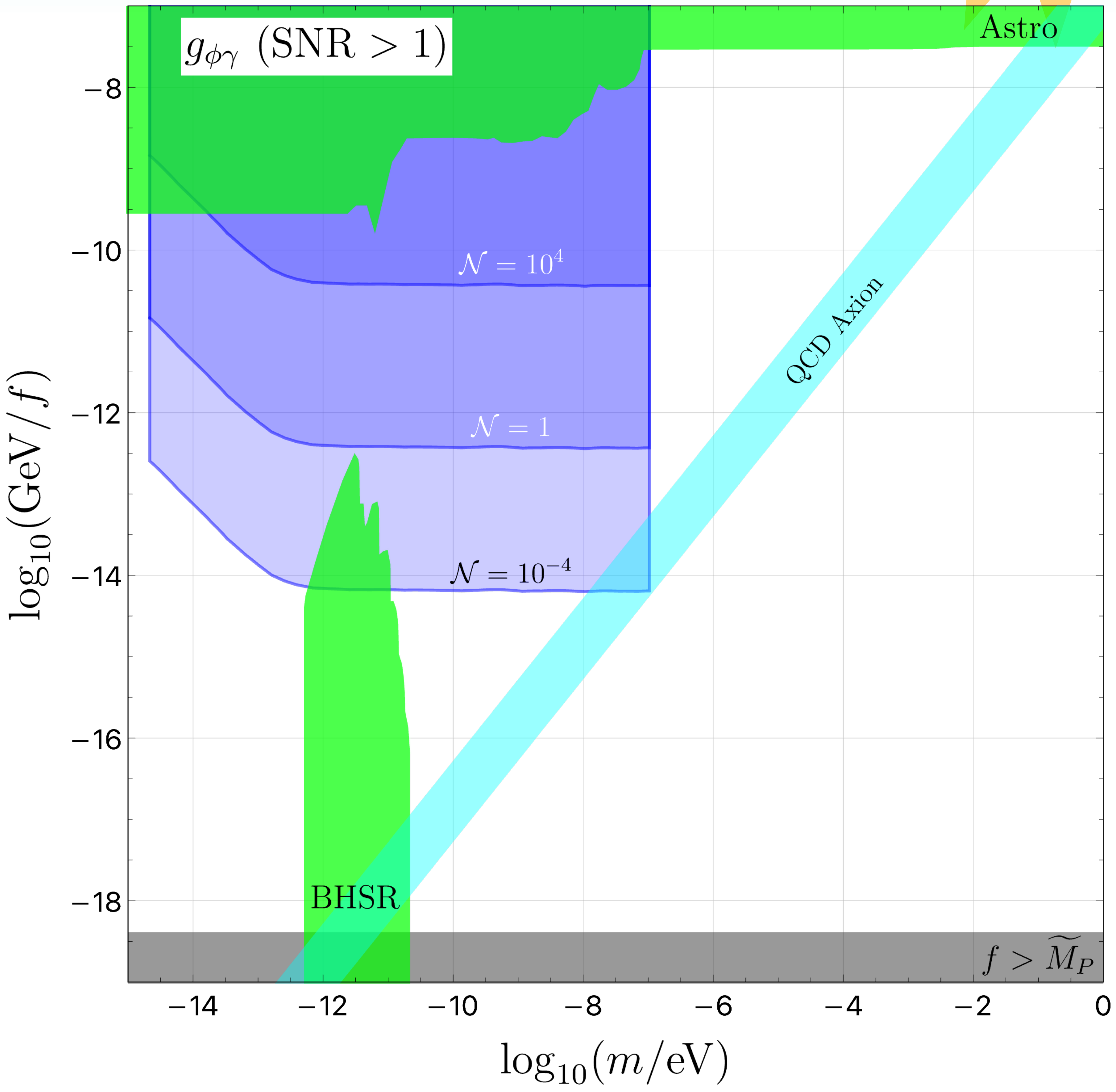
2. Gray: Axion stars won't collapse in the usual way for $f \gtrsim 10^{17}\,\text{GeV}$

JE, Street, Suranyi, Wijewardhana (2011.09087)

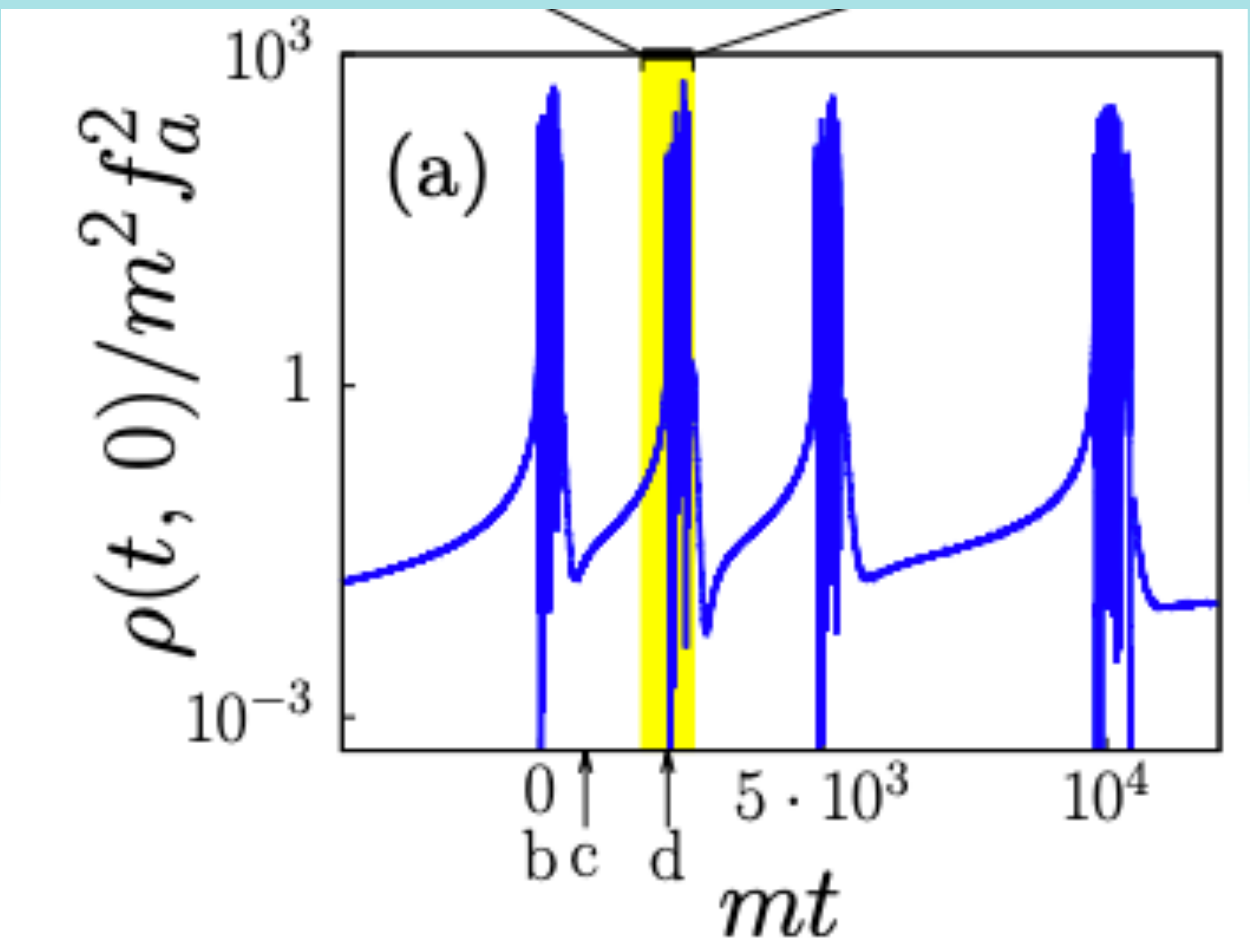
Sensitivity to General Explosions

Total burst energy *E* as free parameter





Open Questions



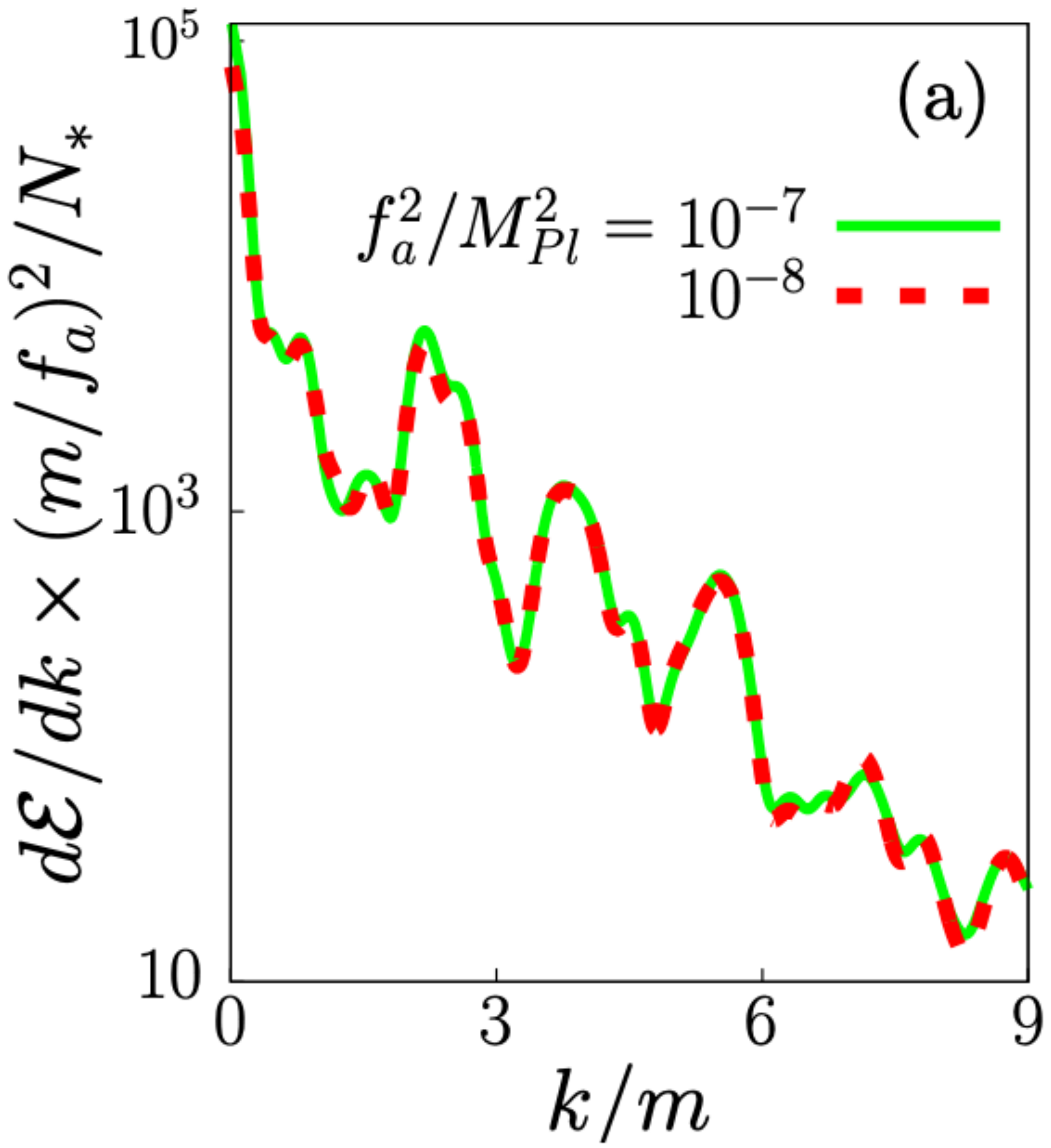
- We ignored multiple peaks + multiple explosions, but this could be key in identifying the burst signal shape

- Emission spectrum computed for QCD axion potential

$$V(\phi) = \frac{m^2 f^2 (1+z)}{z}\left[1 + z - \sqrt{1 + z^2 + 2z\cos\frac{\phi}{f}}\right]$$

  - How does the spectrum change for other potentials?
  - Possible direct probe of fundamental axion potential!!

- Axion star mass distribution is unknown
  - Burst frequency needs clarification!



Conclusions

- Axion stars are a unique prediction of light scalar field dark matter

- Axion stars in our galaxy can decay, collapse, and even explode!

- **Potential probe of fundamental axion potential**, *very* difficult in conventional DM search (How do details of self-int. potential modify emission spectrum? **More simulations!**)

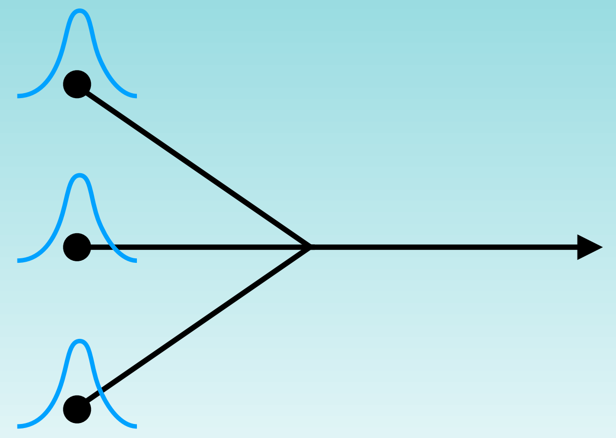
- More speculative implications:
  - Many explosions in distant past → relic background from transients?
  - Coincident photon / GW bursts (e.g. asymmetric collapses or mergers) → multi-messenger signals?

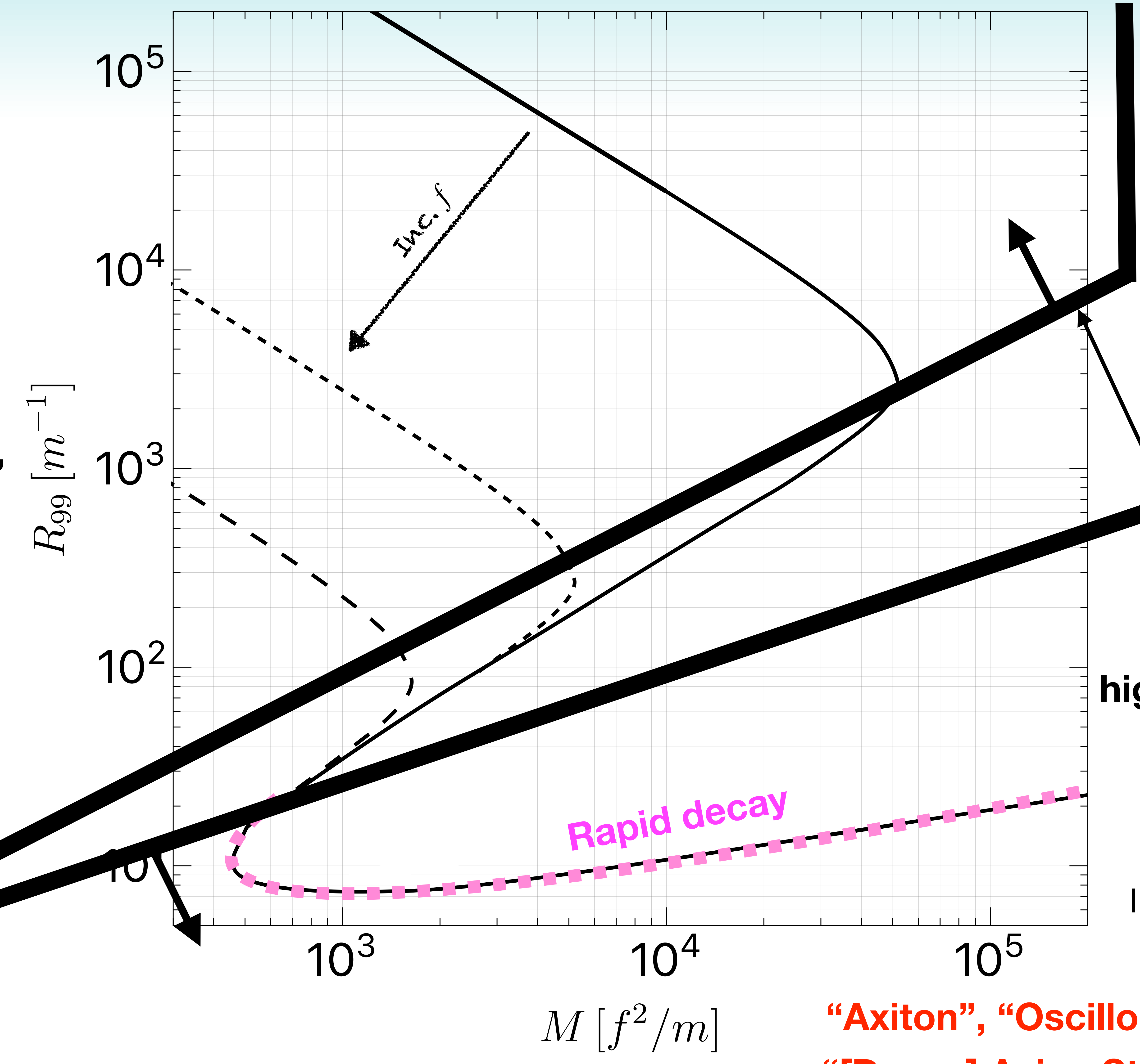
Thanks!

This work was supported by the World Premier International Research Center Initiative (WPI), MEXT, Japan and by the JSPS KAKENHI Grant Numbers 21H05451 and 21K20366.

Bonus Round

What is an Axion Star





Non-relativistic,
coupled to (Newtonian) gravity,
leading self-interaction,
STABLE for $M < M_c$,
number-changing negligible

“[Dilute] Axion Star”,
“Soliton”, “Oscillaton”

Kaup (Phys Rev 1968);
Ruffini+Bonazzola (Phys Rev 1969)

Non-relativistic,
gravity negligible,
leading self-interaction,
unstable to perturbations
decay processes become important

“[Transition] Axion Star”,
“Oscillon”

Chavanis (1103.2050),
+Delfini (1103.2054)

Very relativistic, $\phi \sim f$,
higher-harmonic corrections to field

Use Klein-Gordon Equation

$$\Box\,\phi - V'(\phi) = 0$$

Integrate out modes of energy $2\mu_0, 3\mu_0, \ldots$

Very unstable to decay

“Axiton”, “Oscillon”,
“[Dense] Axion Star”

Kolb+Tkachev (astro-ph/9311037)
Braaten, Mohapatra, Zhang (1512.00108)

Axions / Experiments

- Axions (Axion-like particles)

$$V(\phi) = m_\phi^2 f^2 \left(1 - \cos\frac{\phi}{f}\right)$$

$$\simeq \frac{m_\phi^2}{2}\phi^2 - \frac{\lambda}{4!}\phi^4 + \frac{g}{6!}\phi^6 - \ldots$$

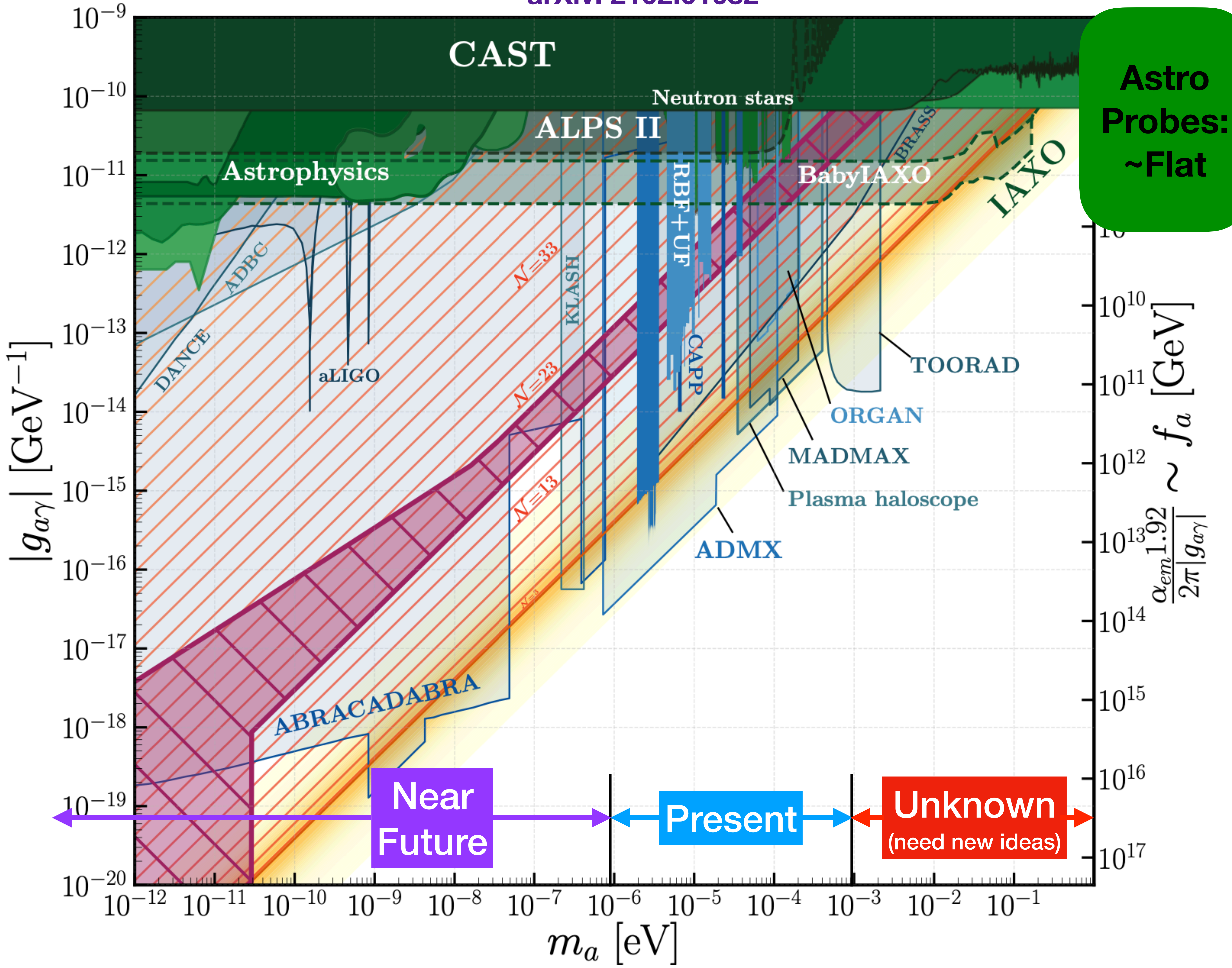
- Decay constant *f* also dictates axion couplings to ordinary matter

$$g_a \propto \frac{1}{f}$$

- A concrete model: QCD axion

$$(m_\phi^2 f^2) \sim \Lambda_{QCD}^4$$

Luzio, Gavela, Quilez, Ringwald, arXiv: 2102.01082



Boson Star Formation

- Analytic argument
  - Gravitational relaxation of quasiparticles sufficient for formation

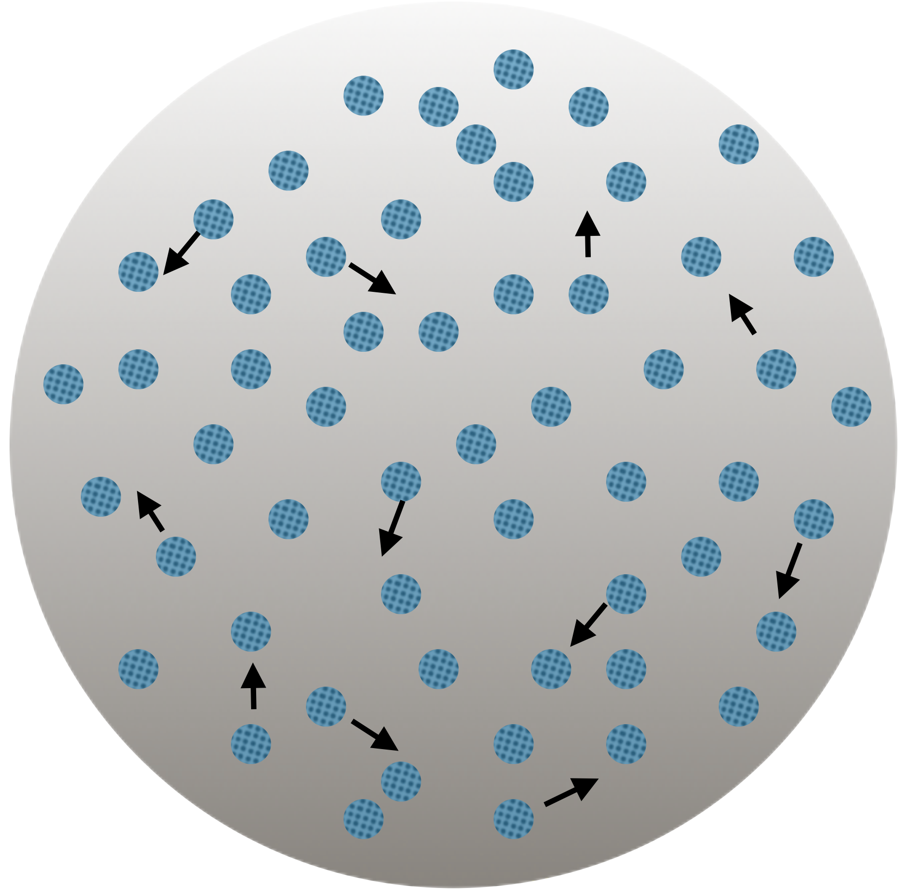
See e.g. Binney and Tremaine, “Galactic Dynamics, 2nd Edition”

Velocity change per crossing

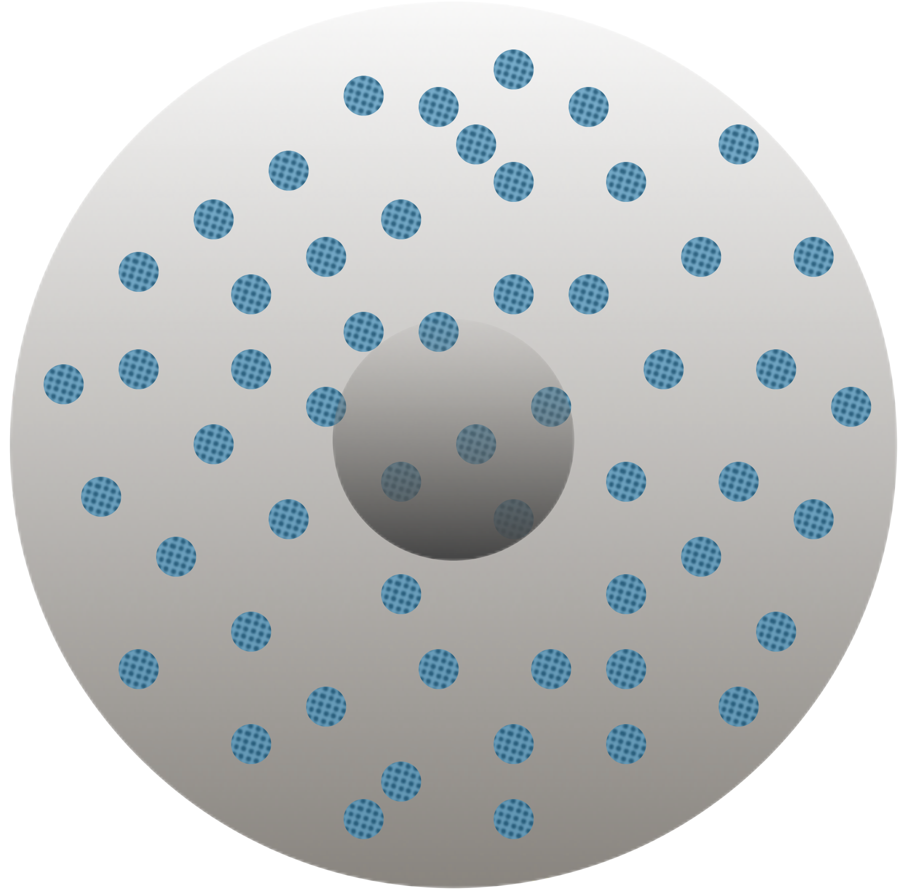
$$\Delta v^2 \simeq 8\,N \left(\frac{G\,M}{R_{\rm gal}\,v}\right) \ln N$$

Fractional velocity change

$$\frac{\Delta v^2}{v^2} \simeq \frac{8\,\ln N}{N}$$



Quasiparticle dispersion



Boson star formation

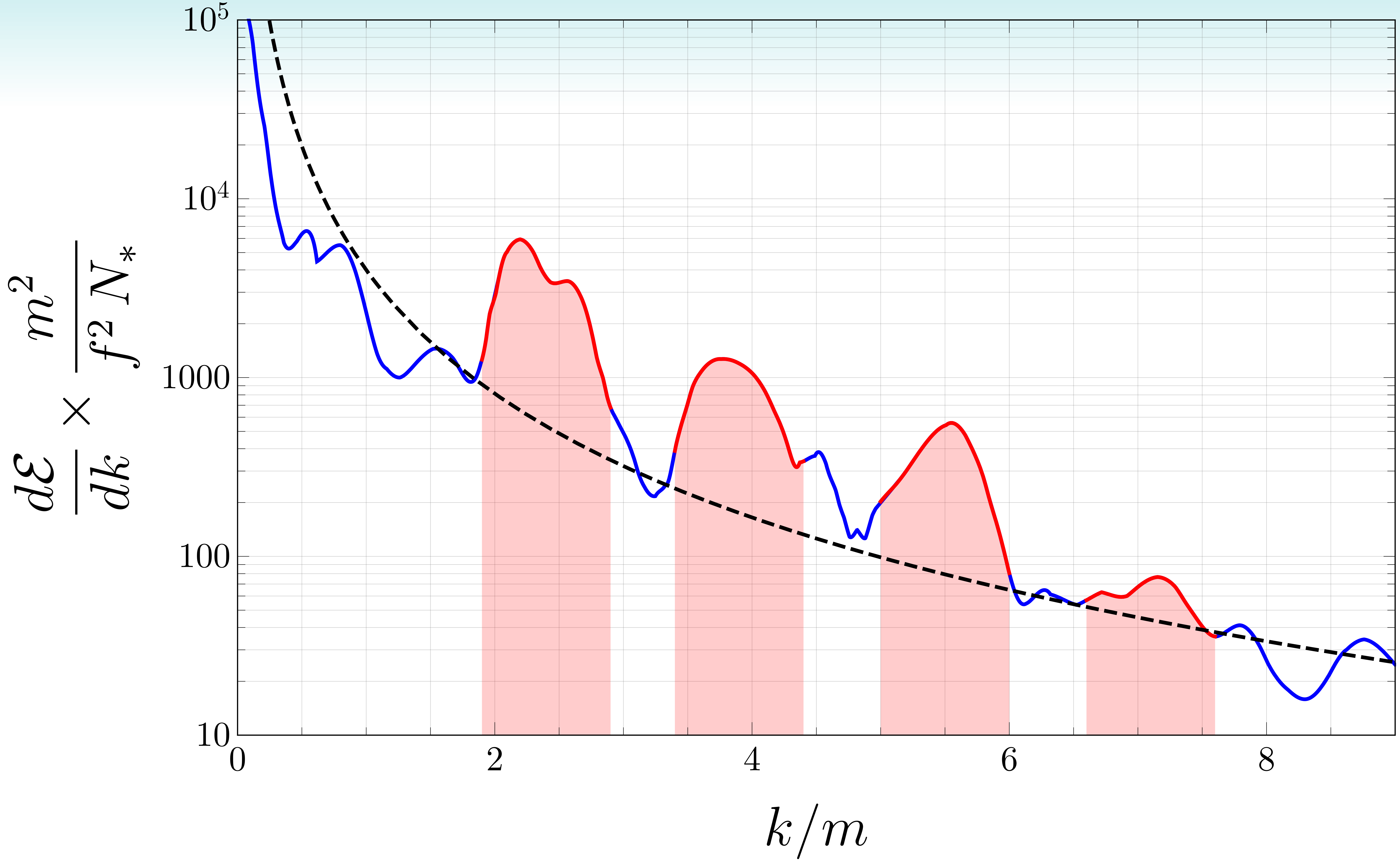
Hui, Ostriker, Tremaine, Witten (1610.08297)
Bar-Or, Fouvry, Tremaine (1809.07673)

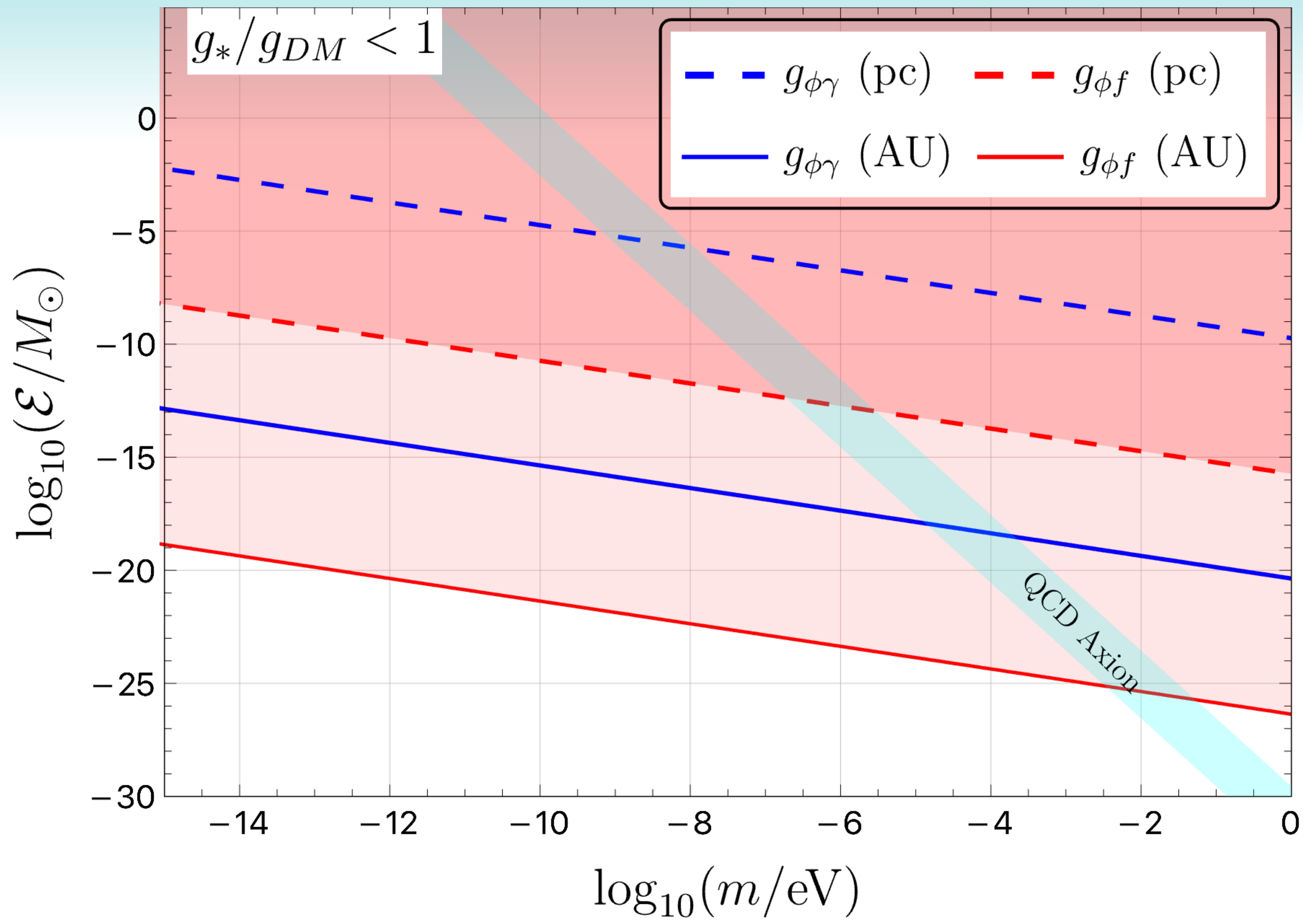
Relaxation to ground state

$$t_{\rm relax} \simeq \frac{0.1\,N}{\ln N} t_{\rm cross}$$

Analytic timescale matches simulation results!

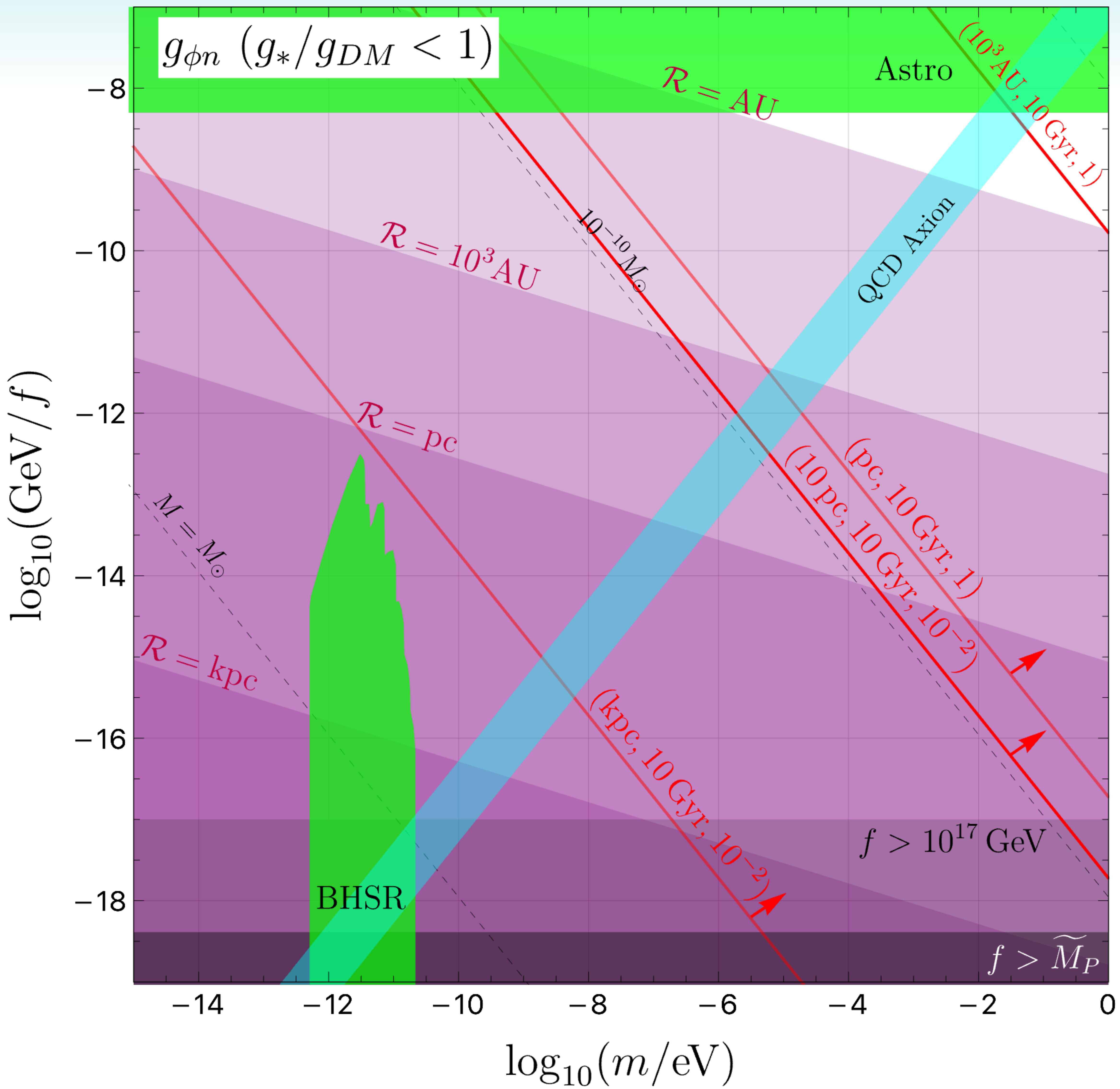
See also Levkov, Panin, Tkachev (1804.05857)


$\frac{d\mathcal{E}}{dk} \times \frac{m^2}{f^2 N_*}$
10^5
10^4
1000
100
10
0
2
4
6
8
k/m


$g_*/g_{DM} < 1$
$g_{\phi\gamma}$ (pc)
$g_{\phi f}$ (pc)
$g_{\phi\gamma}$ (AU)
$g_{\phi f}$ (AU)
QCD Axion
0
−5
−10
−15
−20
−25
−30
$\log_{10}(\mathcal{E}/M_\odot)$
−14
−12
−10
−8
−6
−4
−2
0
$\log_{10}(m/\text{eV})$

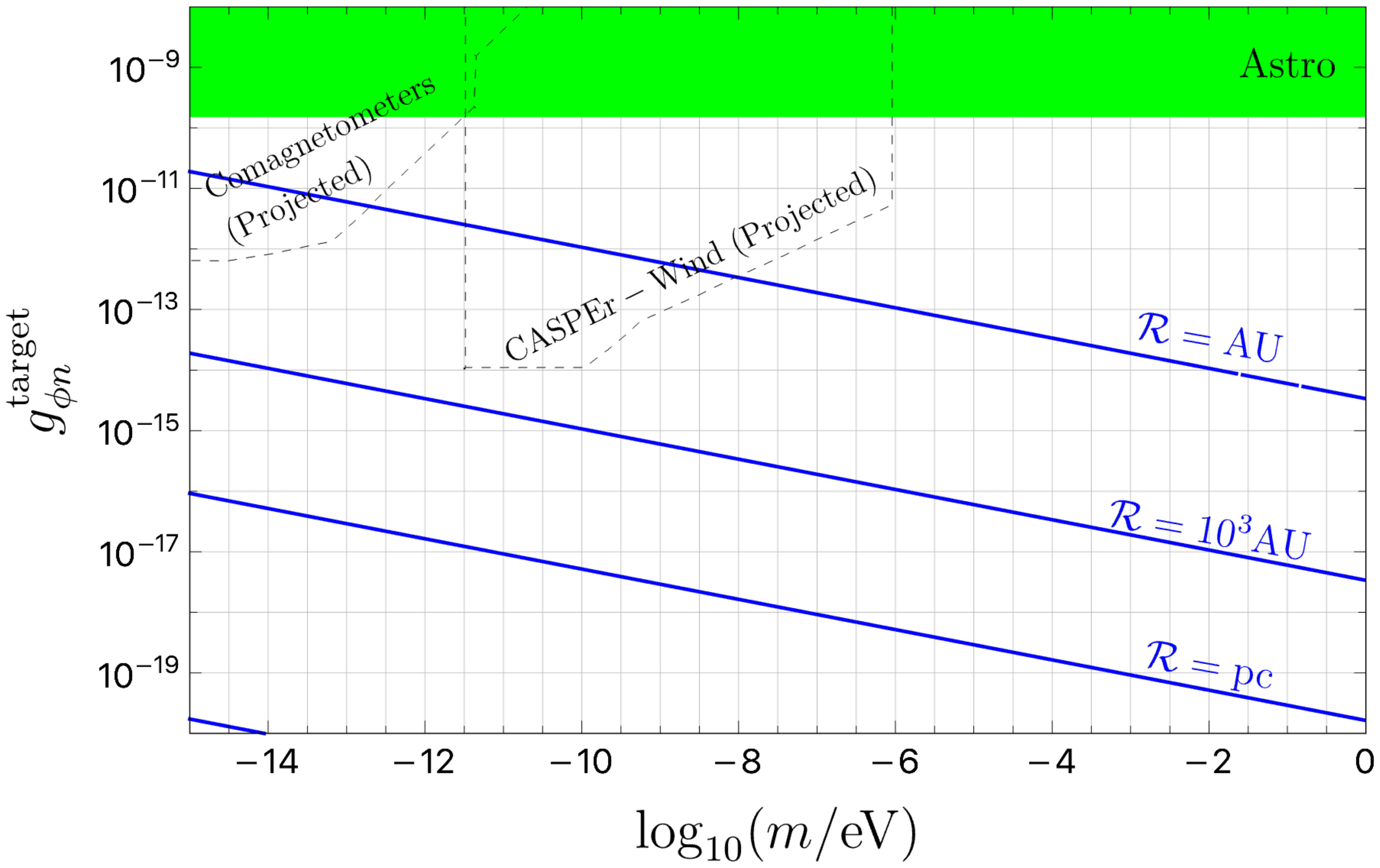
Nucleon Couplings

Bosenova Explosion



Sensitivity Ratio

$$\frac{g_*}{g_{\rm DM}} \sim v_{\rm DM}\sqrt{\frac{\rho_{\rm DM}}{\rho_*}}\,\frac{t_{\rm int}^{1/4}\min\left(\tau_{\rm DM}^{1/4}, t_{\rm int}^{1/4}\right)}{\min\left[(\delta t)^{1/4}, t_{\rm int}^{1/4}\right]\min\left(\tau_*^{1/4}, t_{\rm int}^{1/4}\right)}$$



New broadband search strategies needed!