

Axion Stars: Toward the Planck Scale

Joshua Eby
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Kashiwa, Japan

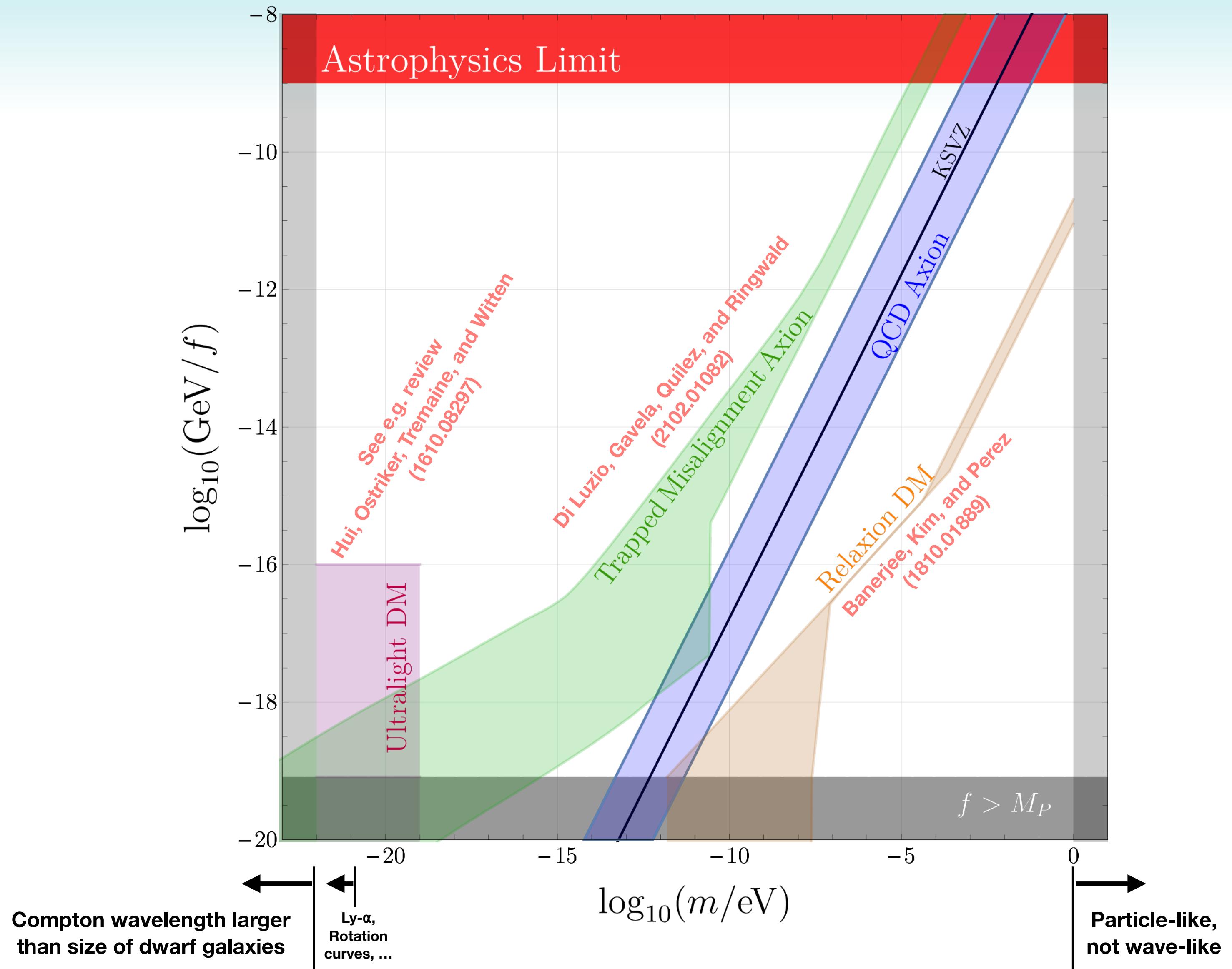
Quarks ~~2020~~ **2021**
Virtual Seminar
24/06/2021

-
- Axion Stars
 - What happens to axion stars as $f \rightarrow \text{Planck Scale}$?
 - Don't extrapolate beyond $f \gtrsim 10^{17} \text{ GeV}$!
 - How can we detect such axions?
 - Relativistic axion bursts may be detectable, even at large f !

JE, Street, Suranyi, Wijewardhana (2011.09087)

JE, Shirai, Stadnik, Takhistov (210x.xxxxx)

Axions: Tale of Two Parameters



Axions: Tale of Two Parameters

Couplings to SM will be
 $\propto 1/f$

“Generically”:

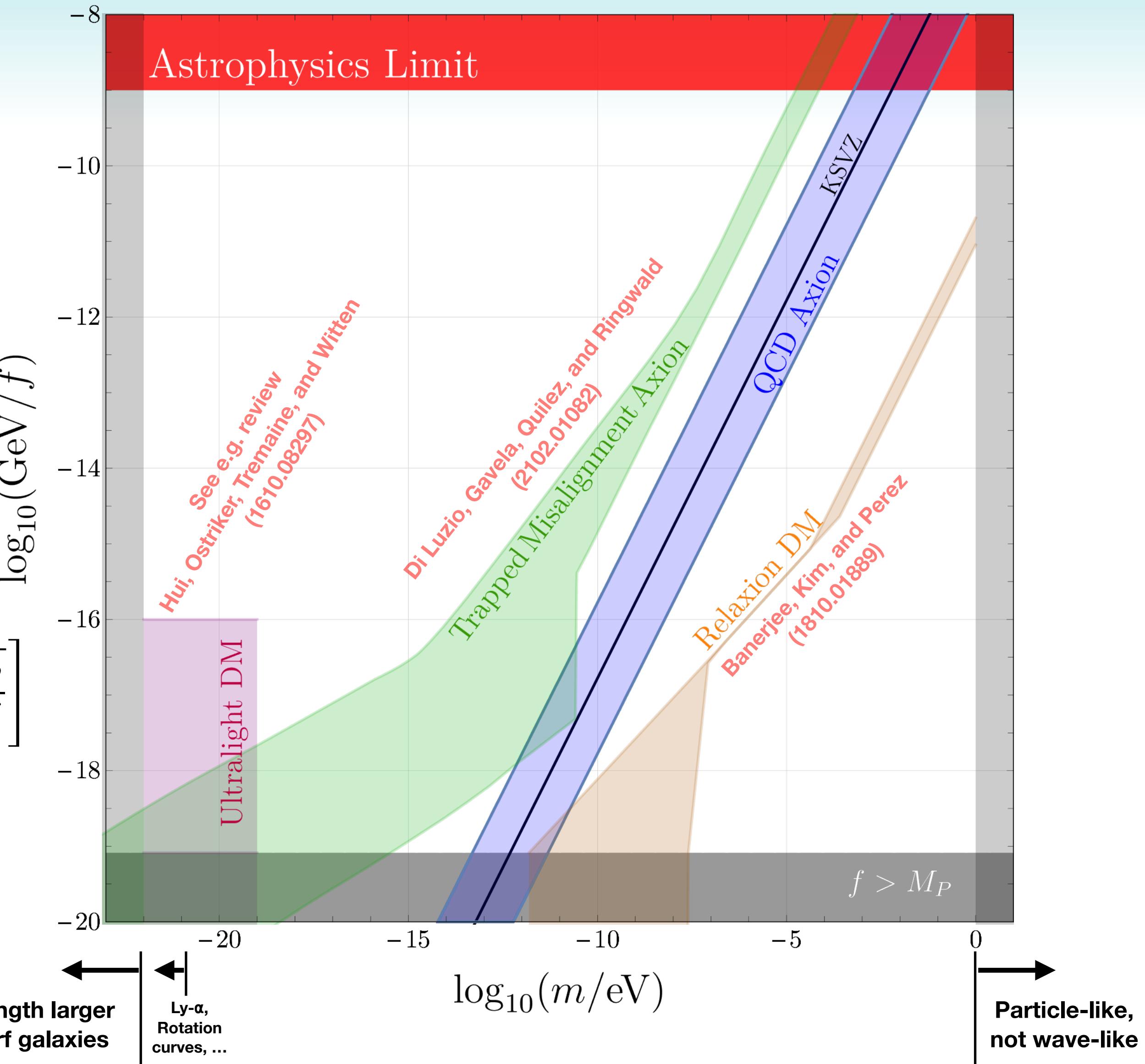
$$V(\phi) = m^2 f^2 \left[1 - \cos \left(\frac{\phi}{f} \right) \right]$$

QCD axions:

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

$$z = m_u/m_d \approx 0.56$$

Compton wavelength larger
than size of dwarf galaxies



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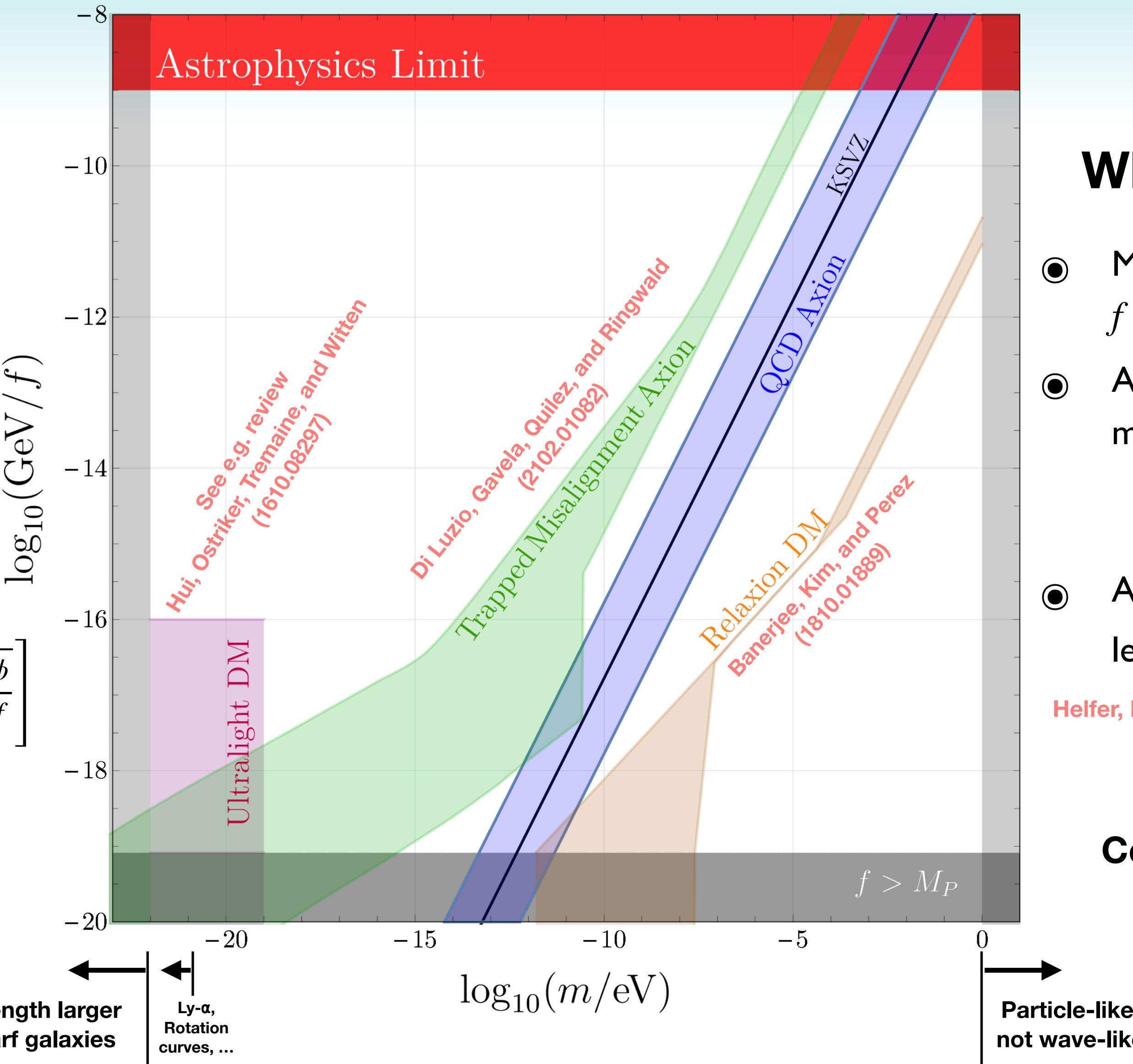
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Why approach $f \rightarrow M_P$?

- Many axion models predict (or allow) $f \simeq M_P$
- Axion stars may be neutron star mimickers if $m \sim 10^{-10}$ eV and $f \sim M_P$
[Clough, Dietrich, Niemeyer \(1808.04668\)](#)
[with Day, Coughlin \(1808.04746\)](#)
- Axion star collapse near $f \sim M_P$ may lead to black hole formation
[Helfer, Marsh, Clough, Fairbairn, Lim, Becerril \(1609.04724\)](#)
[Chavanis \(1710.06268\)](#)
[Michel and Moss \(1802.10085\)](#)

Could explain e.g. intermediate mass black holes?

Axions: Tale of Two Parameters

$$m_5 = \frac{m}{10^{-5} \text{ eV}}$$

$$f_{12} = \frac{f}{6 \times 10^{11} \text{ GeV}}$$

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 $\propto 1/f$

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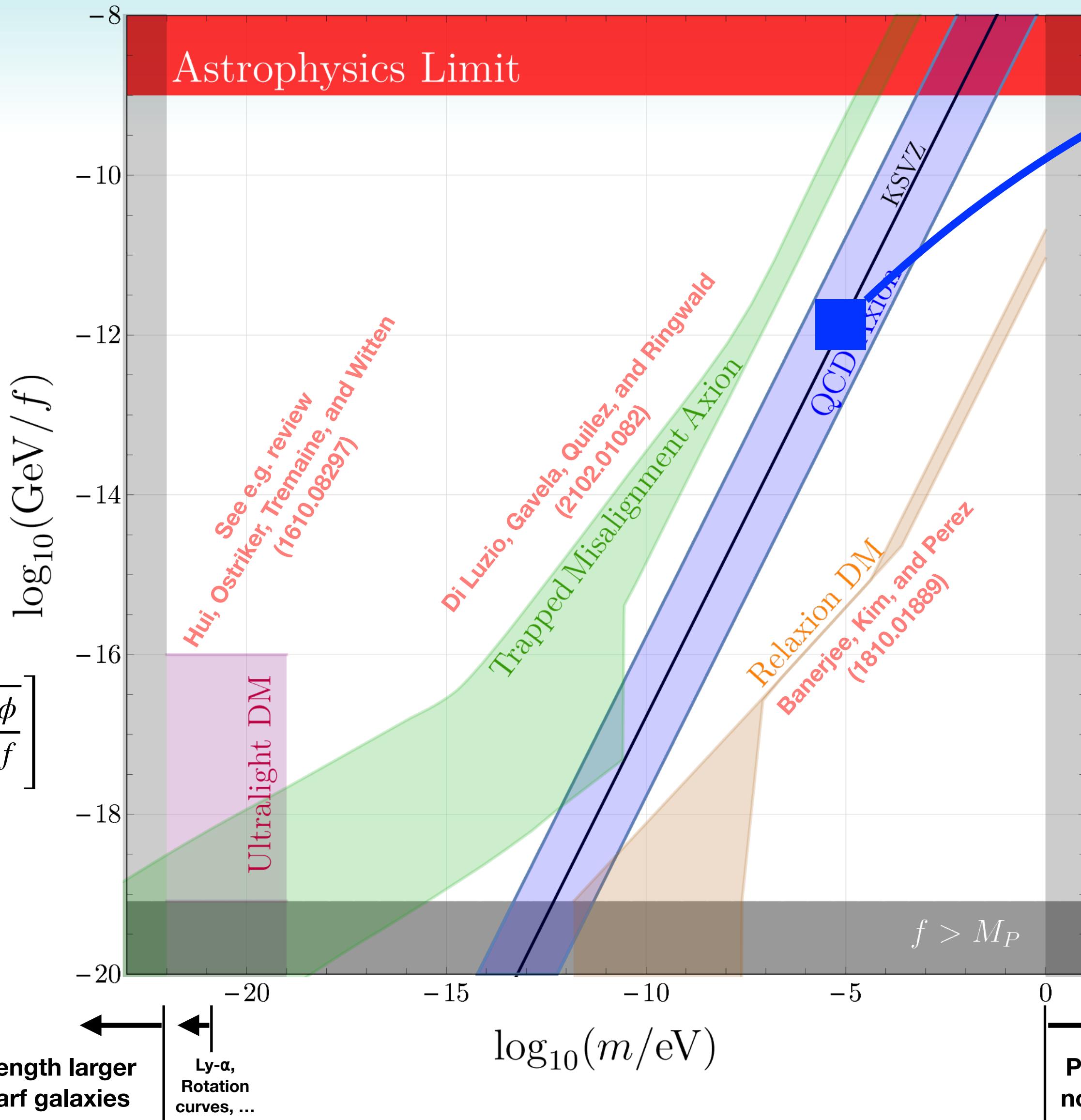
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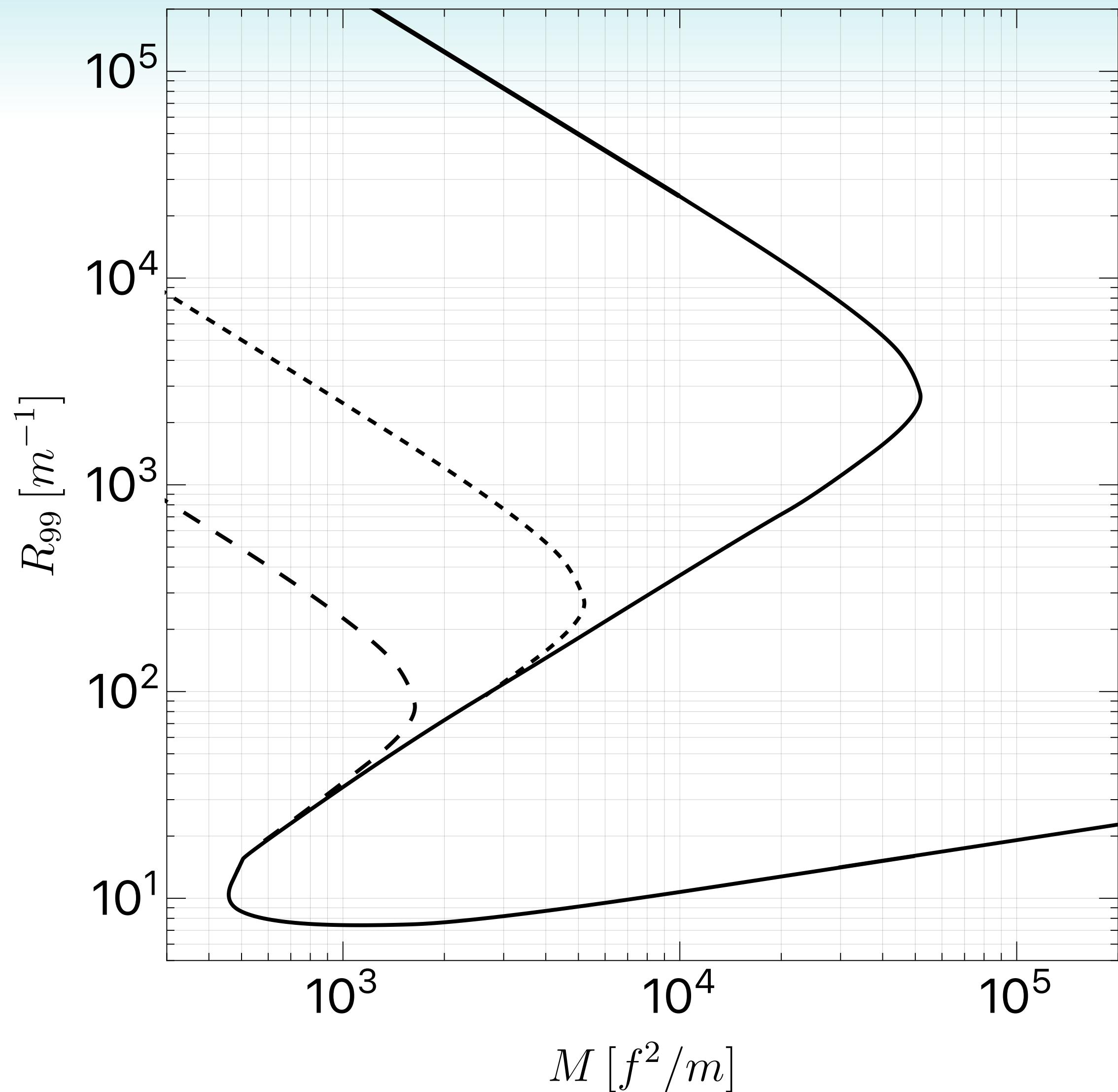


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What's an Axion Star



What's an Axion Star

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

Use Gross-Pitaevskii+Poisson Eqs.

$$(\mu_0 - m)\psi = \left[-\frac{\nabla^2}{2m} + V_g(|\psi|^2) - \frac{|\psi|^2}{8f^2} \right] \psi$$

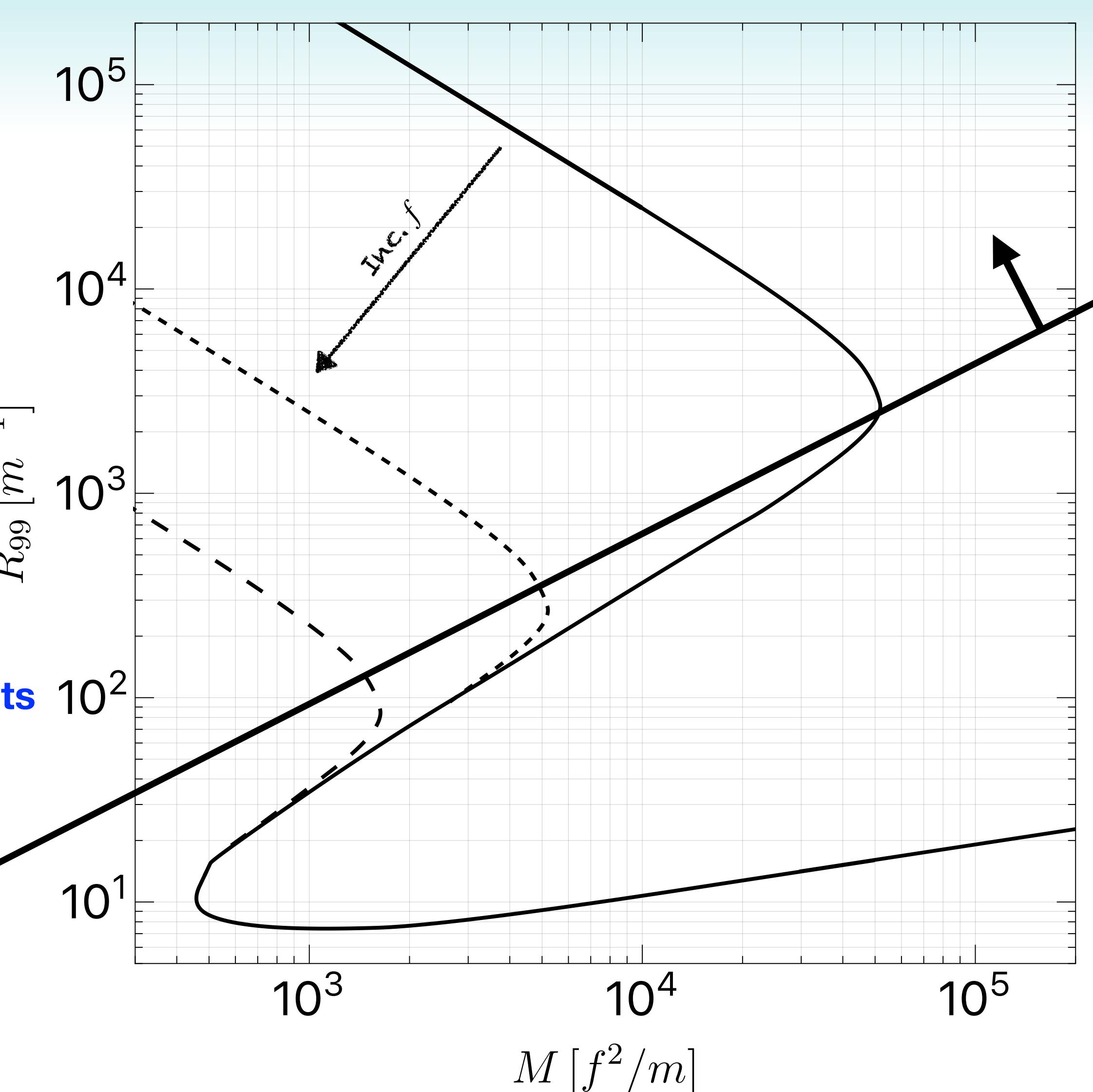
$$\nabla^2 V_g = 4\pi G m^2 |\psi|^2$$

Low density, balance gravity+gradients

$$R \simeq \frac{M_P^2}{m^2 M}$$

"[Dilute] Axion Star"

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



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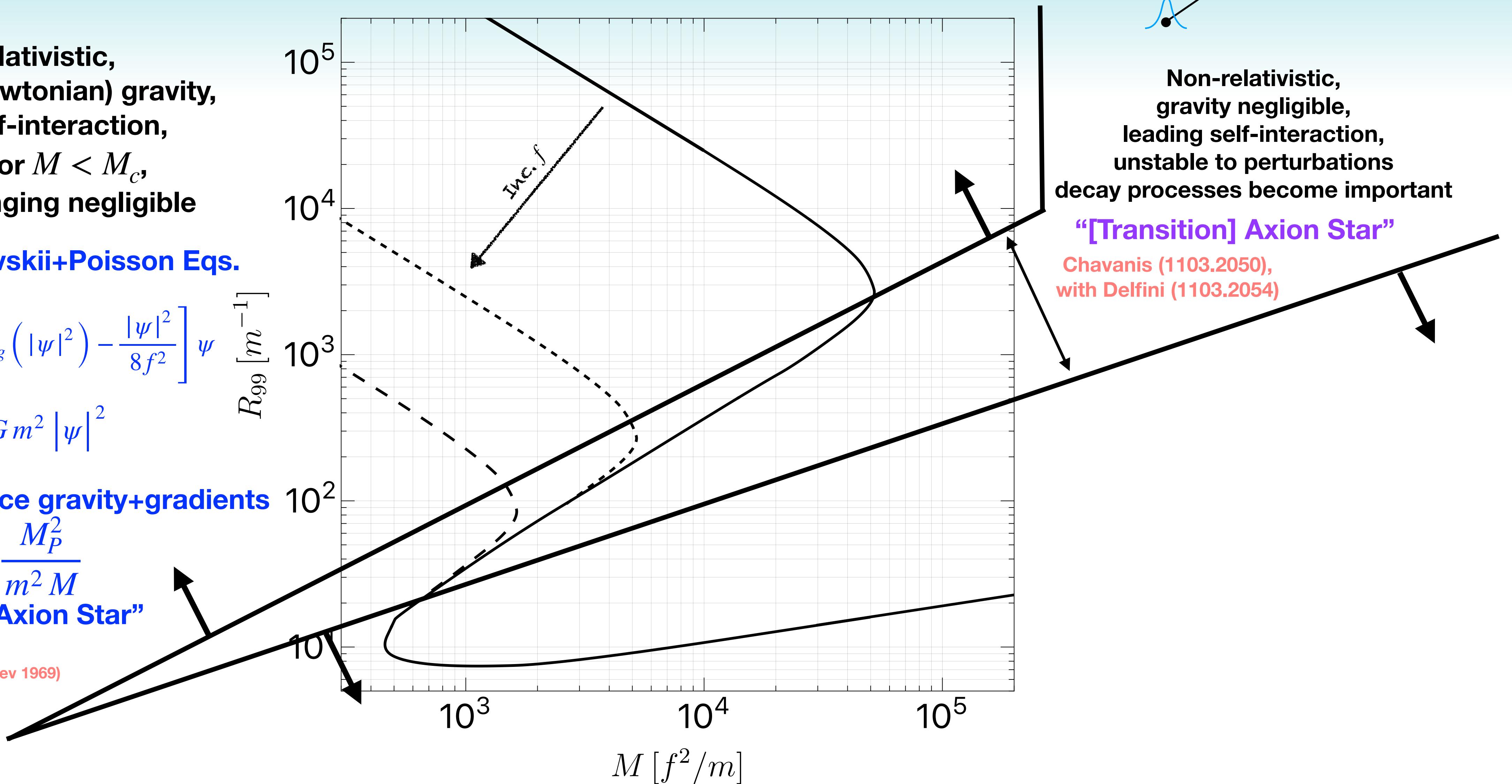
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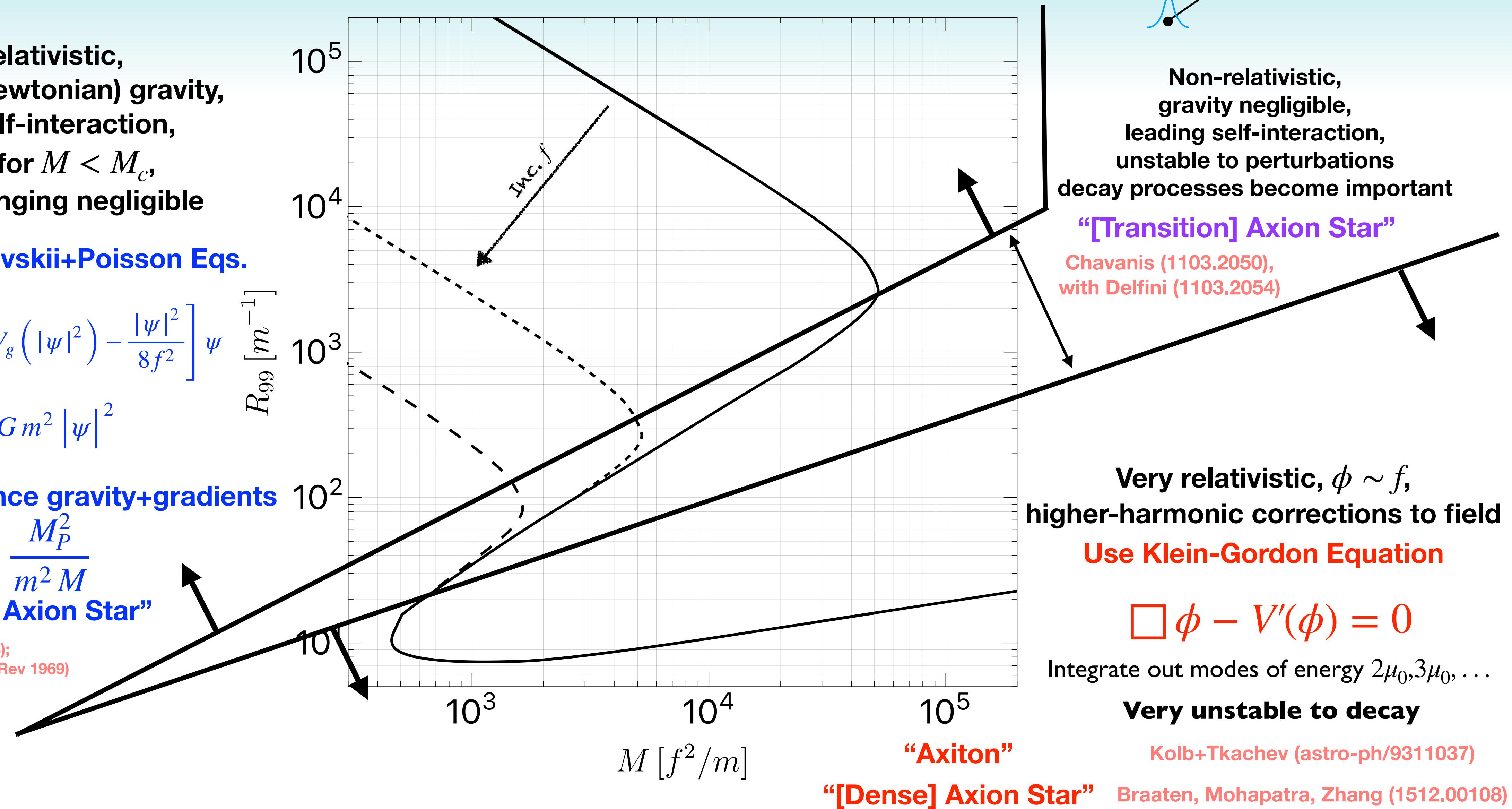
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Classical Non-Relativistic Effective Field Theory of Scalar Fields

Our Method

- ⦿ Basic insight (Ruffini+Bonazzola '69):

Expand scalar field in powers of creation/annihilation operators of the ground state

$$\phi_{RB}(t, r) = \hat{a}_0 R(r) e^{i\mu_0 t} + \text{h.c.}$$

Systems of Self-Gravitating Particles in General Relativity and the Concept of an Equation of State

REMO RUFFINI and SILVANO BONAZZOLA
Phys. Rev. **187**, 1767 – Published 25 November 1969

Article

References

Citing Articles (359)

PDF

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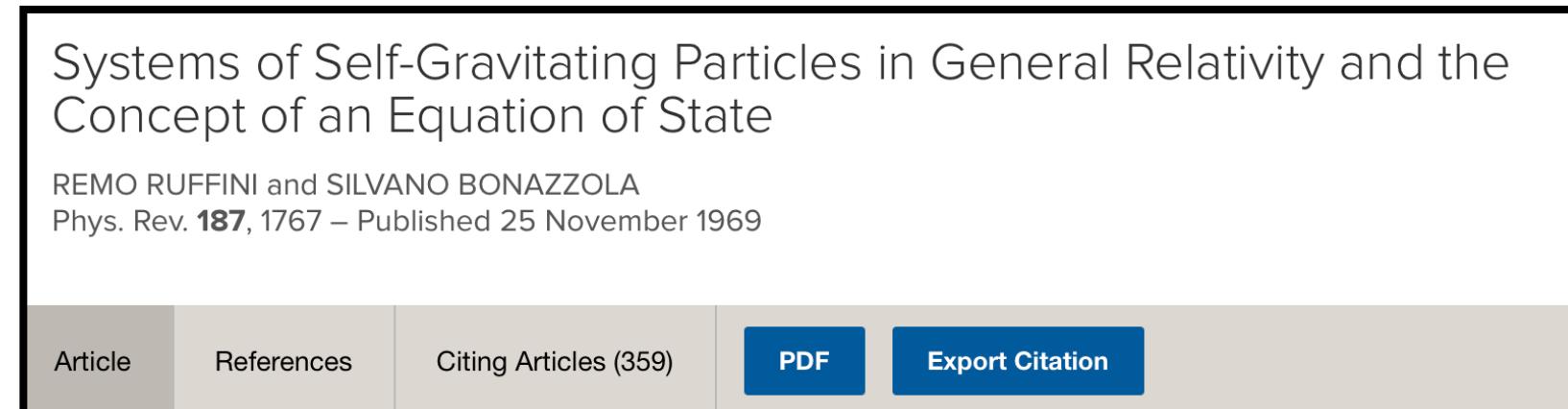
- Our Generalized Ruffini-Bonazzola field operator:

$$\phi(t, r) = \sum_k [\hat{a}_0^k R_k(r) e^{ik\mu_0 t} + \text{h.c.}] + [\varphi(r, t) + \varphi^\dagger(r, t)]$$

Our Method

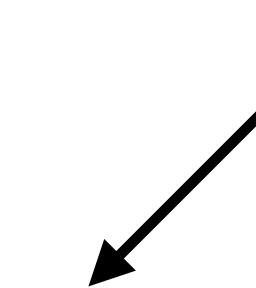
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k=1 reproduces original RB

[JE, Suranyi, Vaz, Wijewardhana \(1412.3430\)](#)

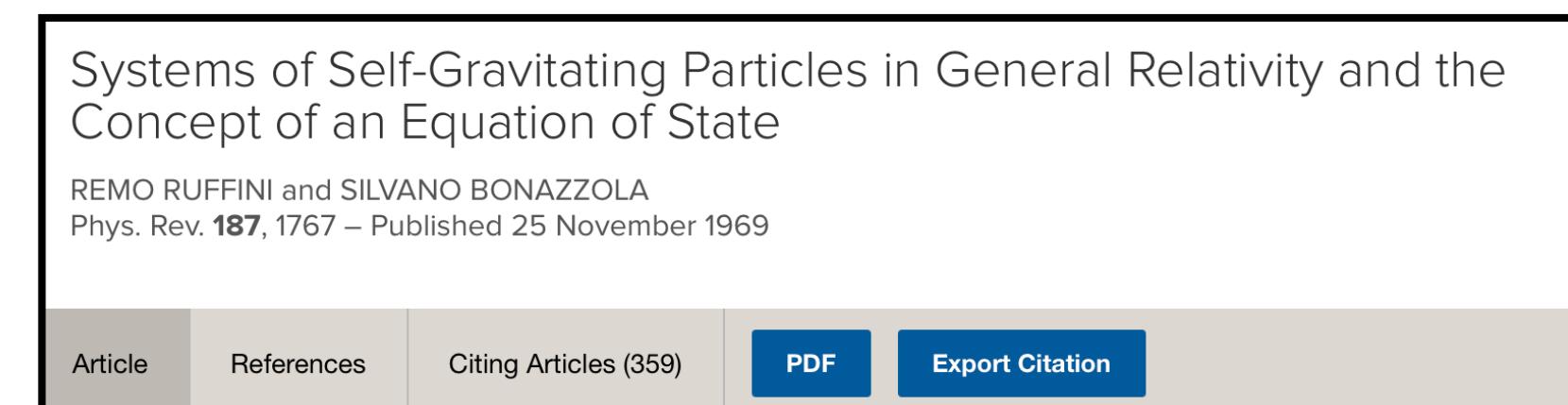
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[JE, Leembruggen, Suranyi,
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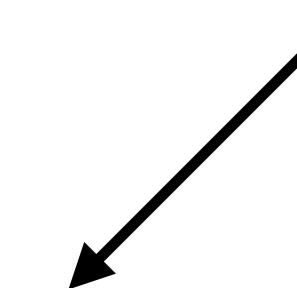
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k>1 contributions to bound state of energy $k\mu_0$

Organize in power series in binding energy parameter

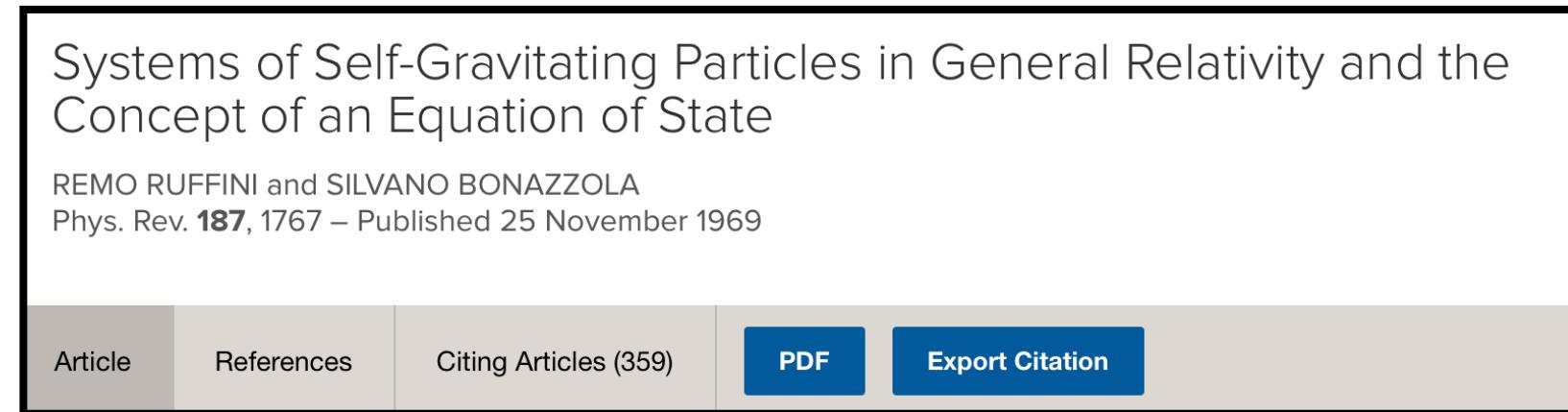
$$\Delta \equiv \sqrt{1 - \mu_0^2/m^2}$$

[JE, Suranyi, Wijewardhana \(1712.04941\)](#)

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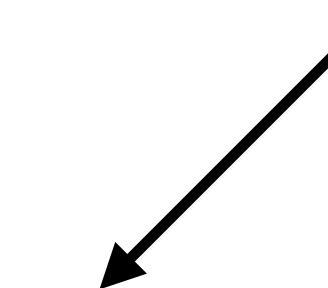
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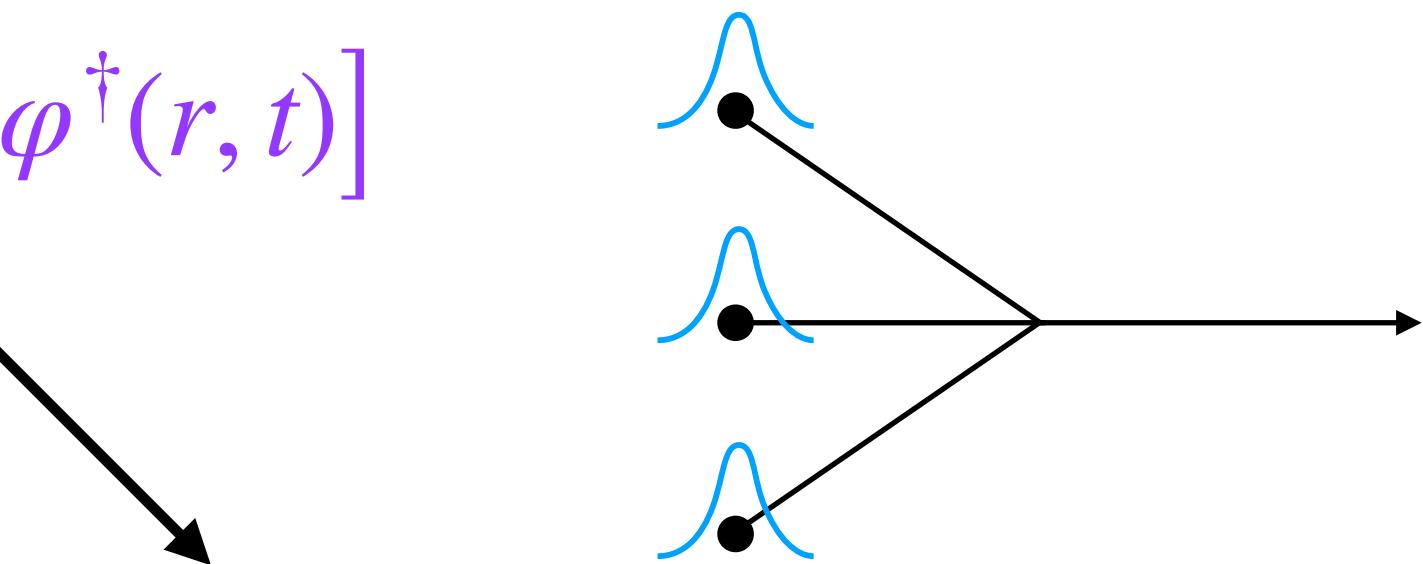
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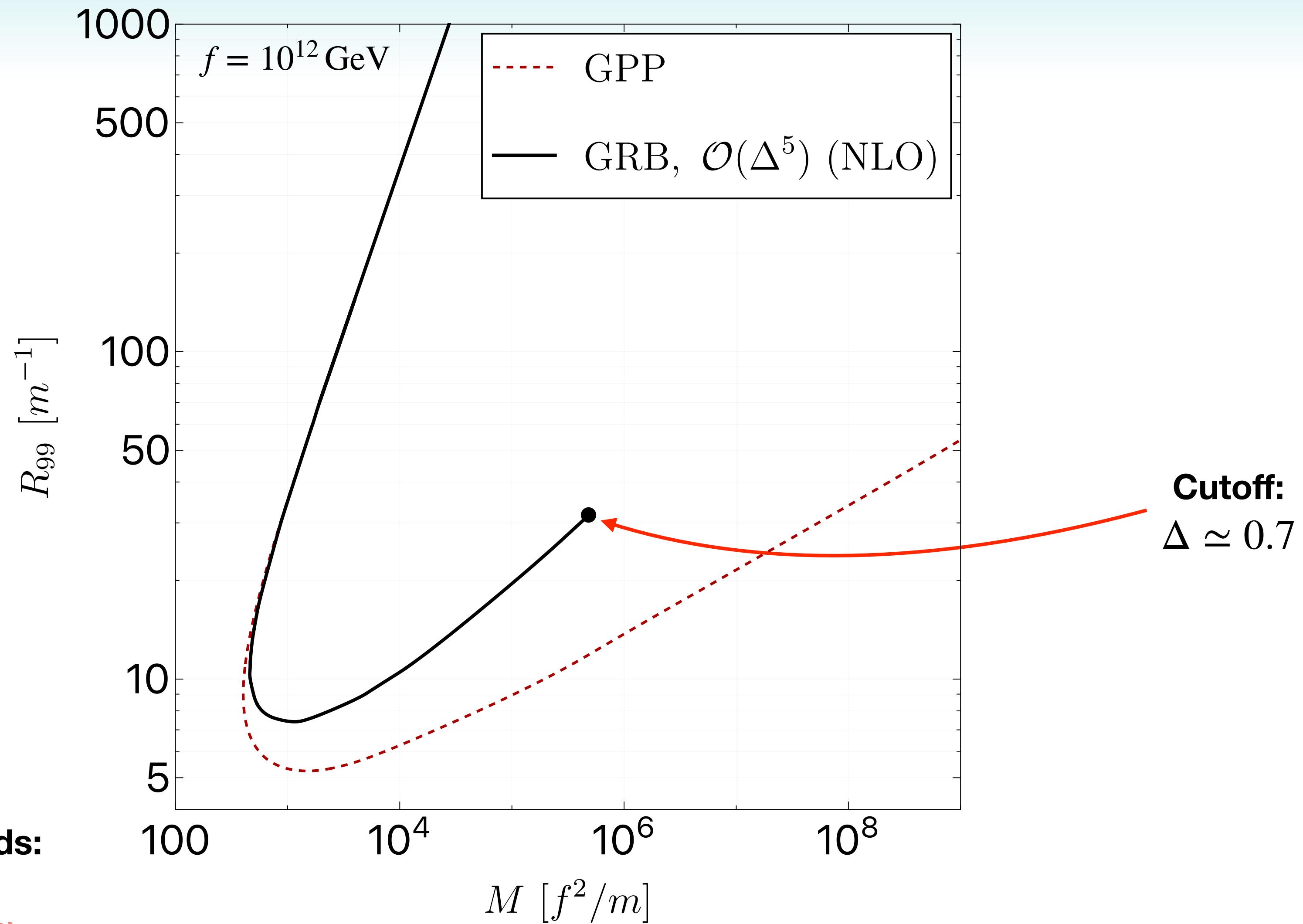


Scattering states, $\text{energy} > m$
Characterize decay processes
through transition matrix elements

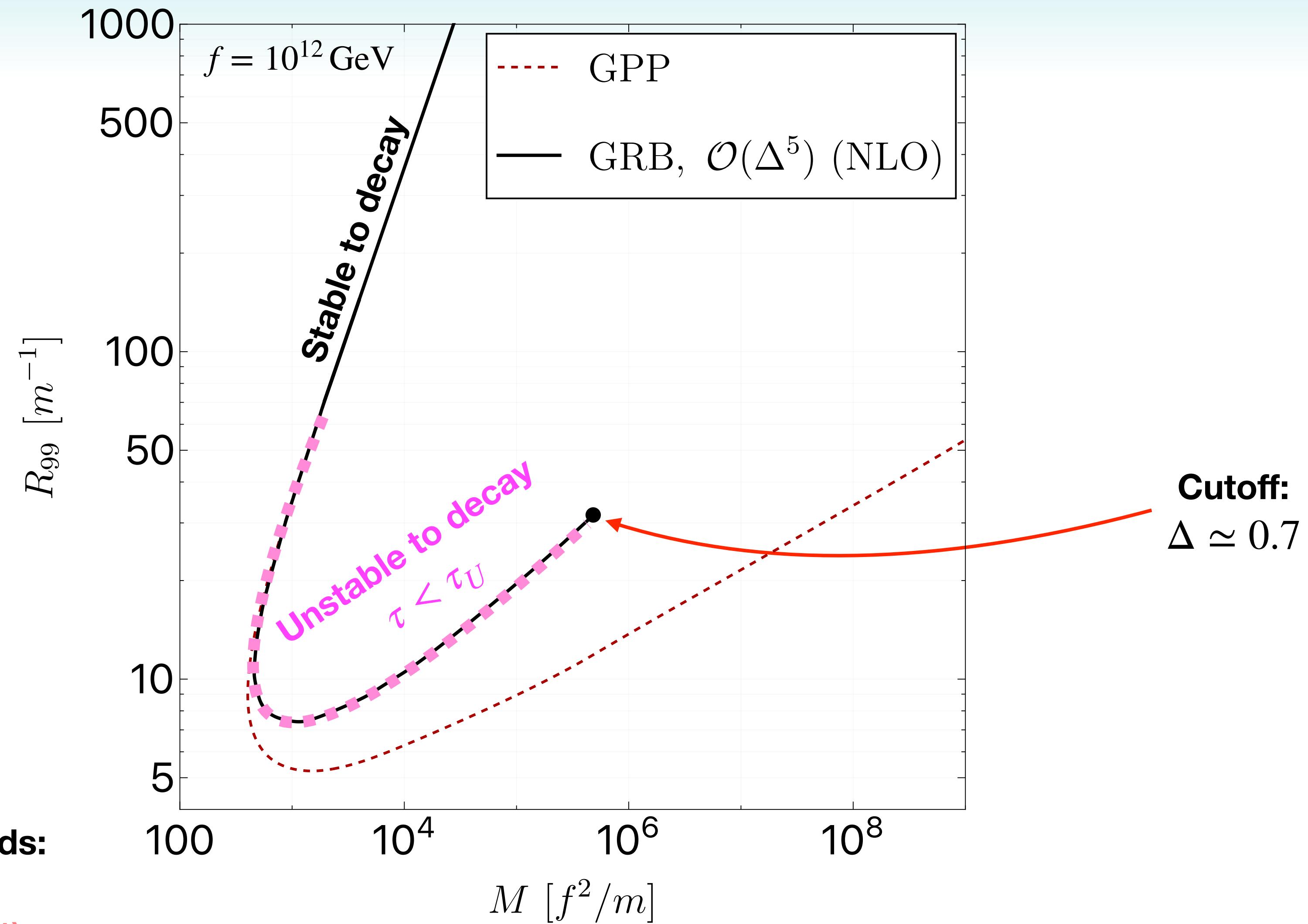
$$\langle N | V(\phi) | N - n, k_1, k_2, \dots \rangle$$

[JE, Suranyi, Wijewardhana \(1512.01709\)
with Ma \(1705.05385\)](#)

“Full” Mass Spectrum



“Full” Mass Spectrum



Approach to $f \rightarrow M_P$

- NLO GRB equations (Leading-order backreaction $\rightleftharpoons \mathcal{O}(\Delta^5)$ corrections)

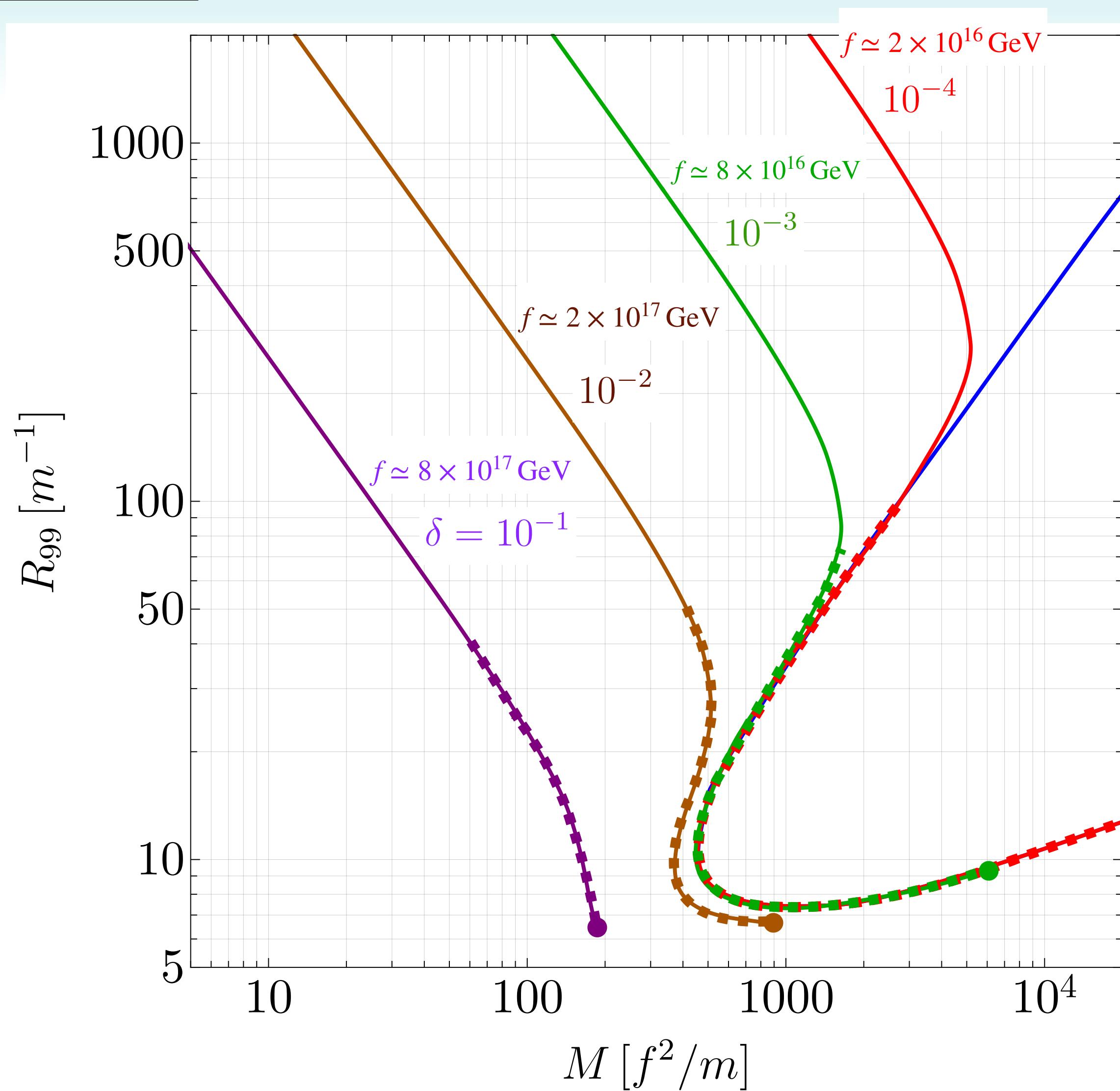
- Push expansion to its limit: $\Delta \simeq 0.7$

- Include gravity!

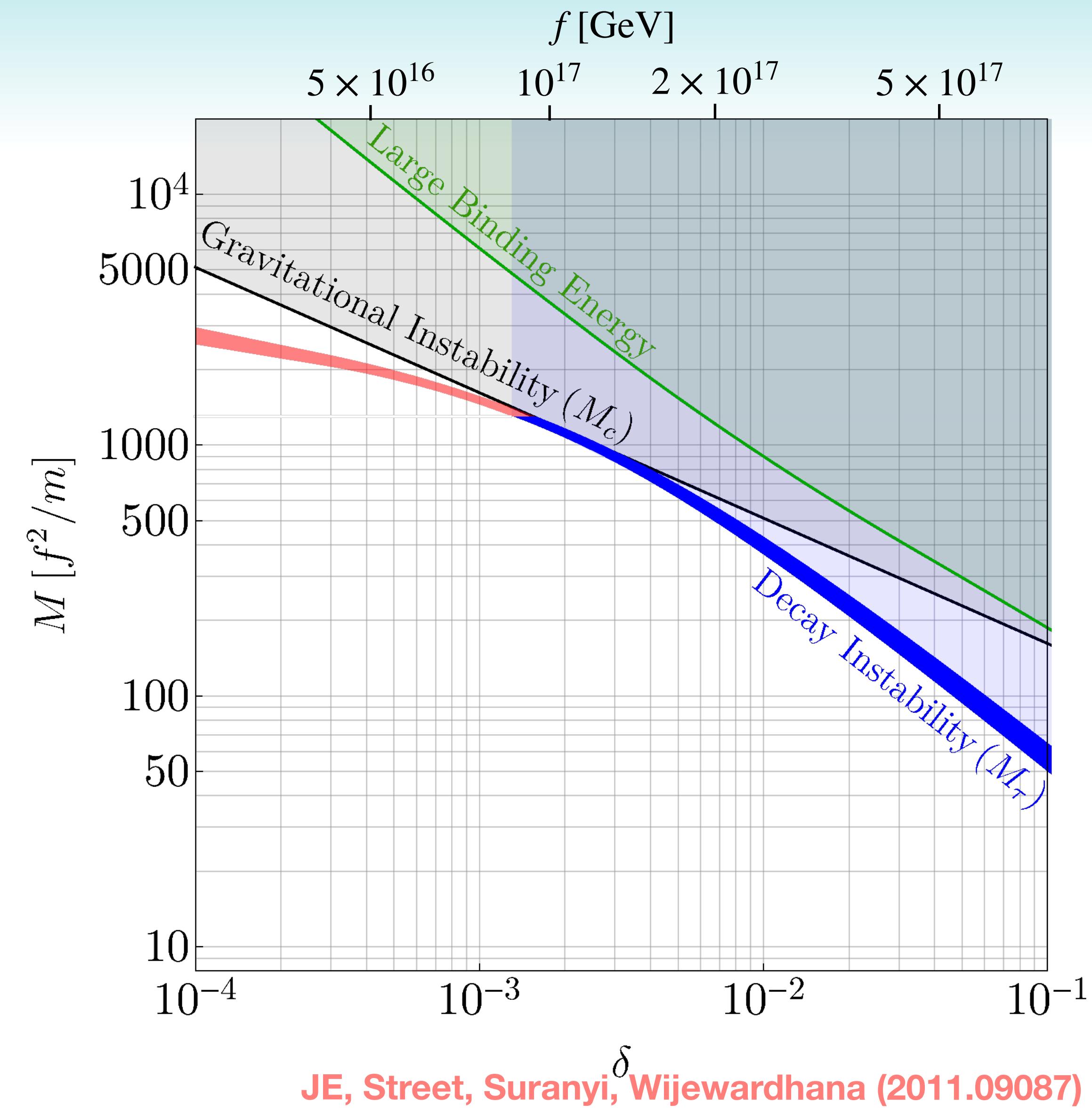
δ	10^{-4}	10^{-3}	10^{-2}	10^{-1}
f [GeV]	2.4×10^{16}	7.7×10^{16}	2.4×10^{17}	7.7×10^{17}
f/M_P	2×10^{-3}	6.3×10^{-3}	0.02	0.063
f/\tilde{M}_P	0.01	0.032	0.1	0.32

- Newtonian gravity appears proportionally to $\delta = \frac{8\pi f^2}{M_P^2}$, can't neglect if f large
- Extended our decay calculation to include contribution of gravity

- Solid:** Decay lifetime $\tau > \tau_U$
- Dashed:** Decay lifetime $\tau < \tau_U$
- Filled circles:** Cutoff $\Delta \simeq 0.7$

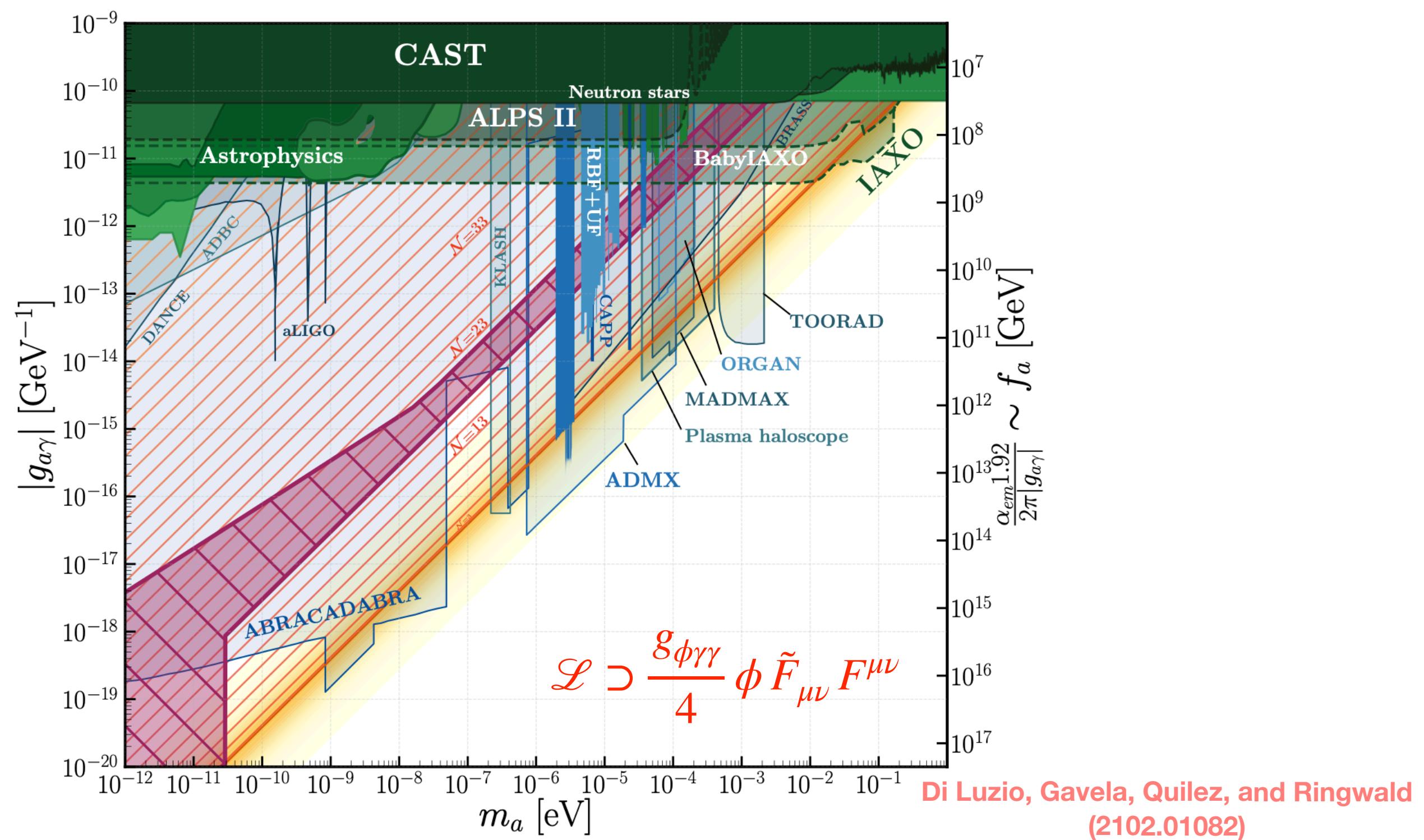


Axion Stars as $f \rightarrow M_P$



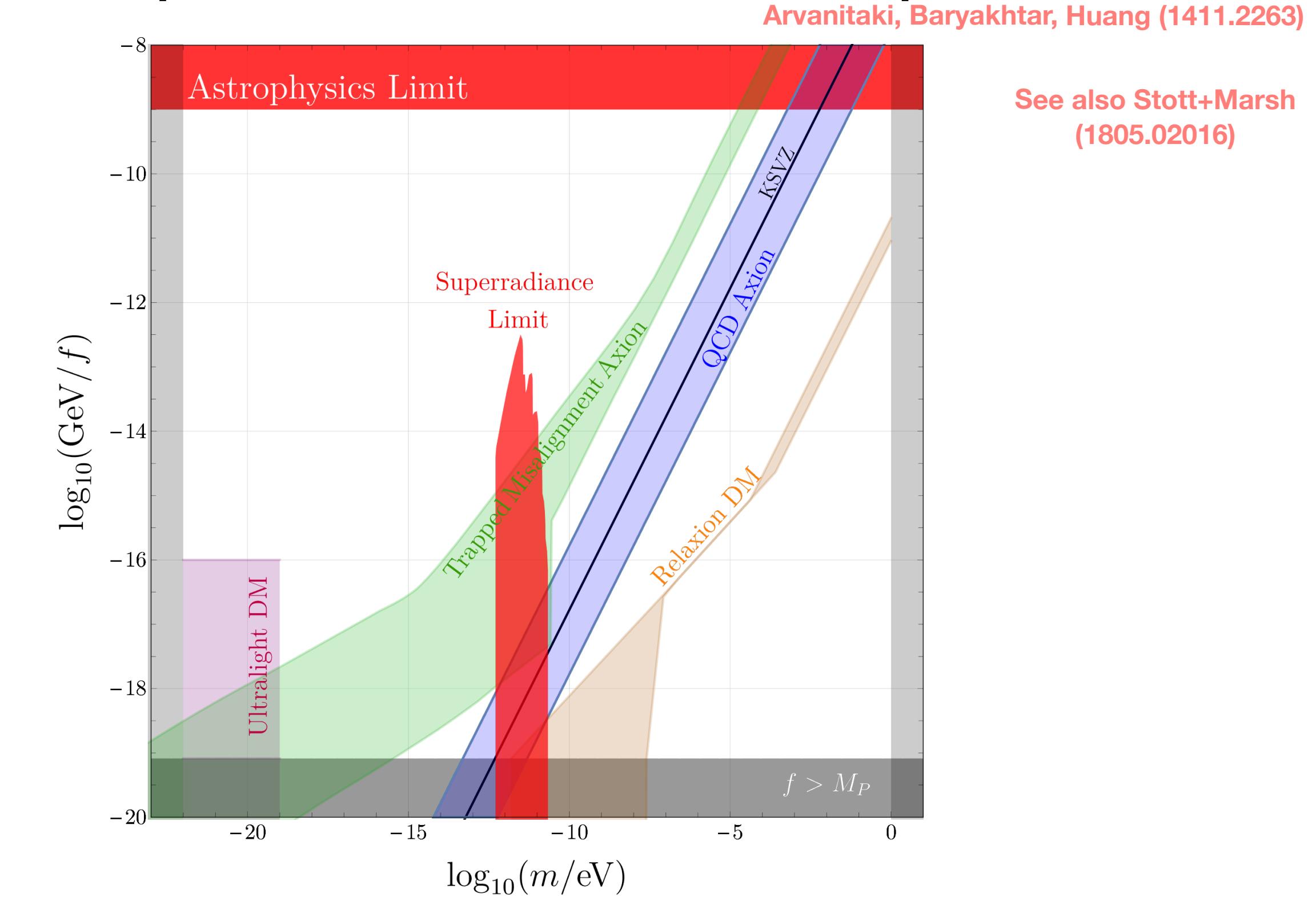
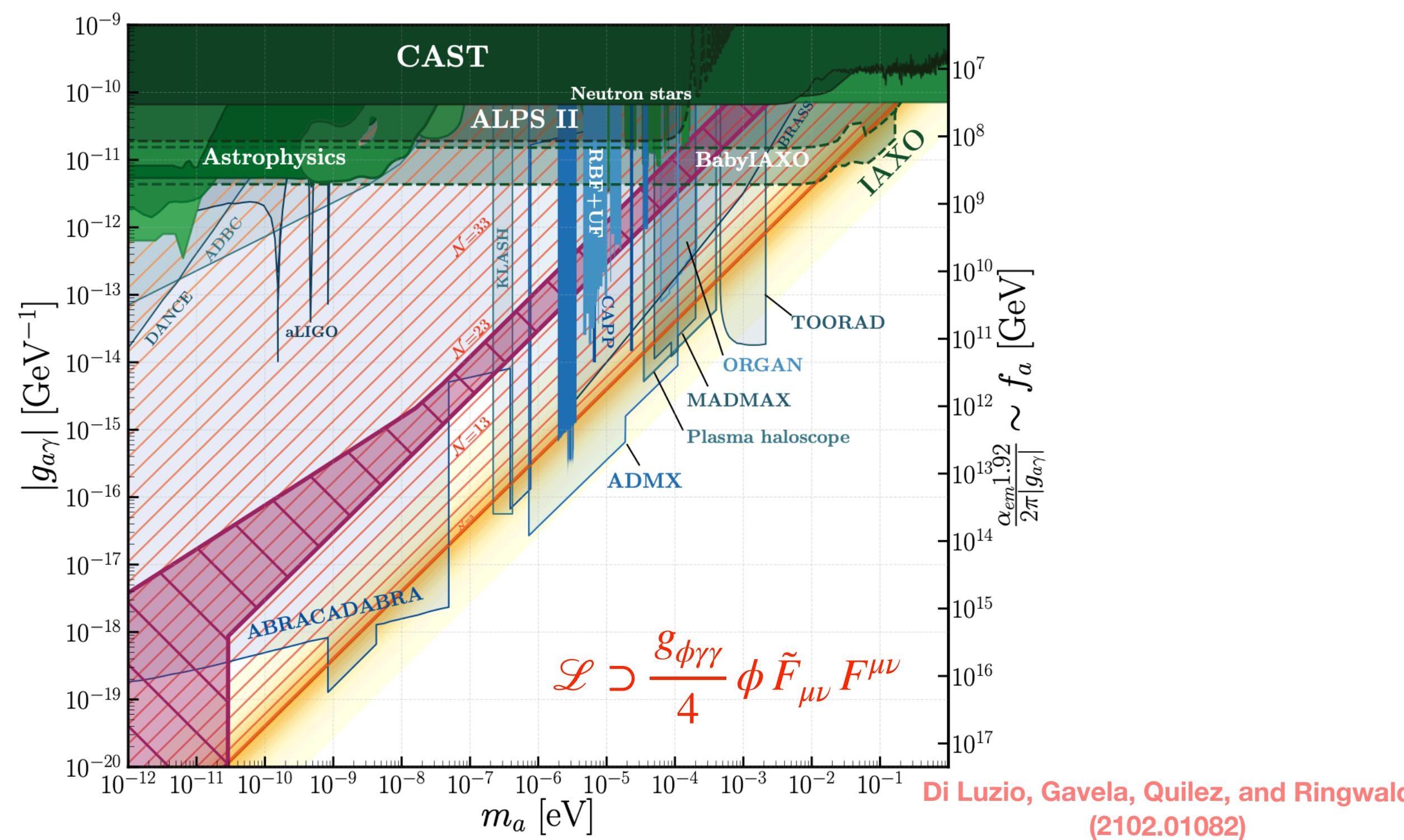
Detecting Large- f Axions

- A challenge!
- Couplings to SM $\propto 1/f$

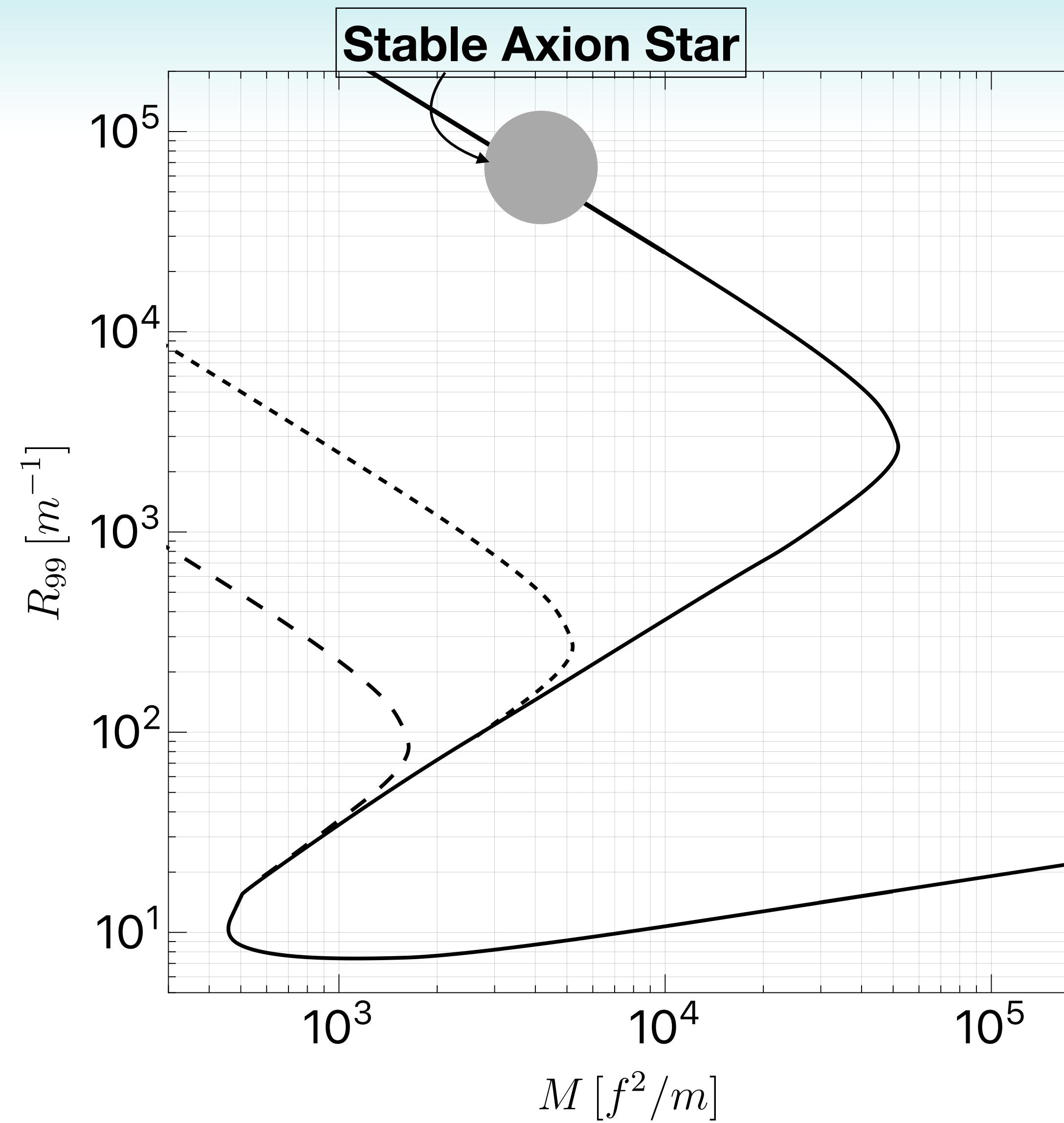


Detecting Large- f Axions

- A challenge!
- Couplings to SM $\propto 1/f$
- Strategy: Look for systems where large- f is a feature, not a bug
- Example: Axion-Black Hole Superradiance



Axion Star Collapse



arXiv.org > astro-ph > arXiv:1608.06911

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))

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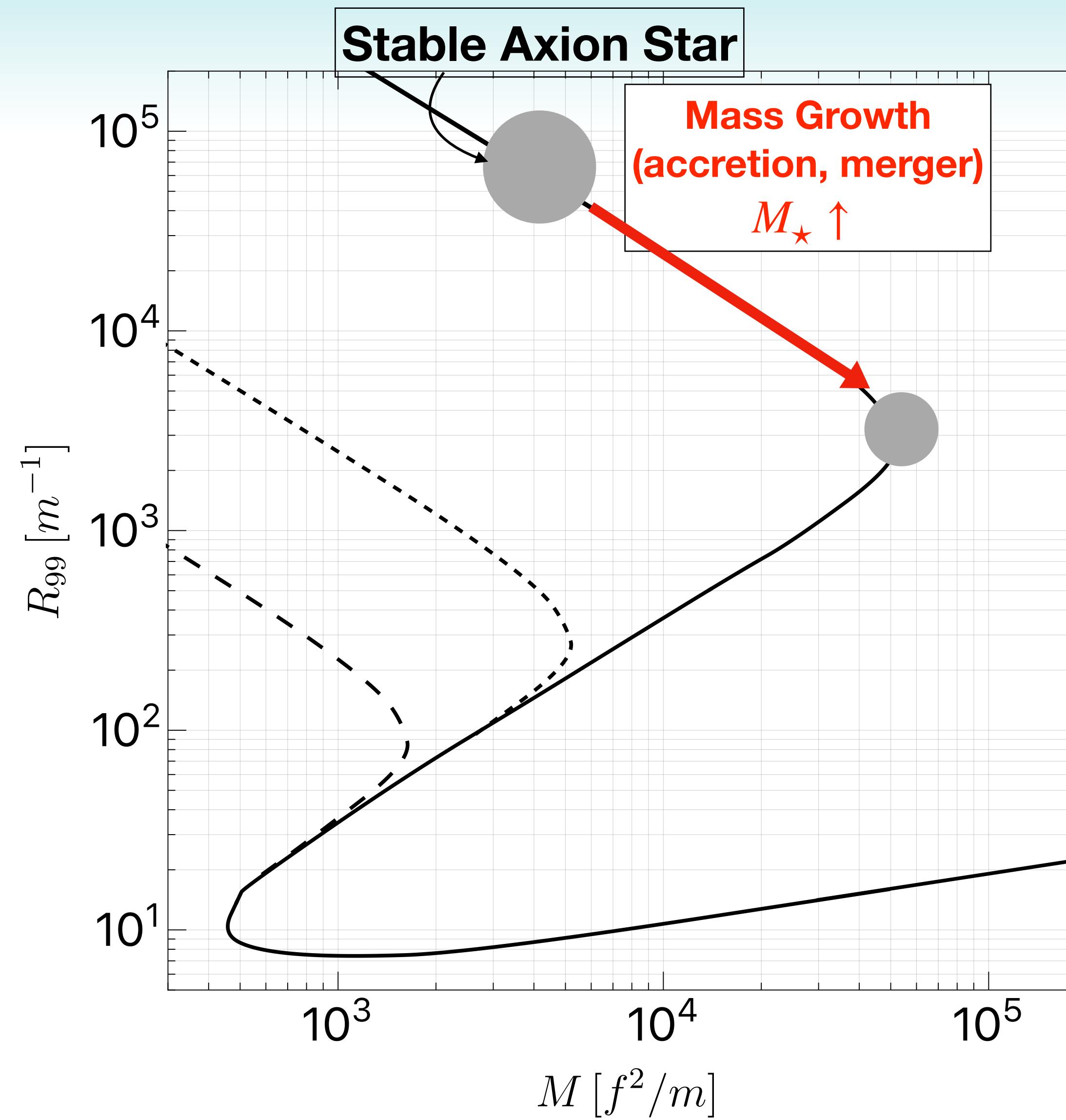
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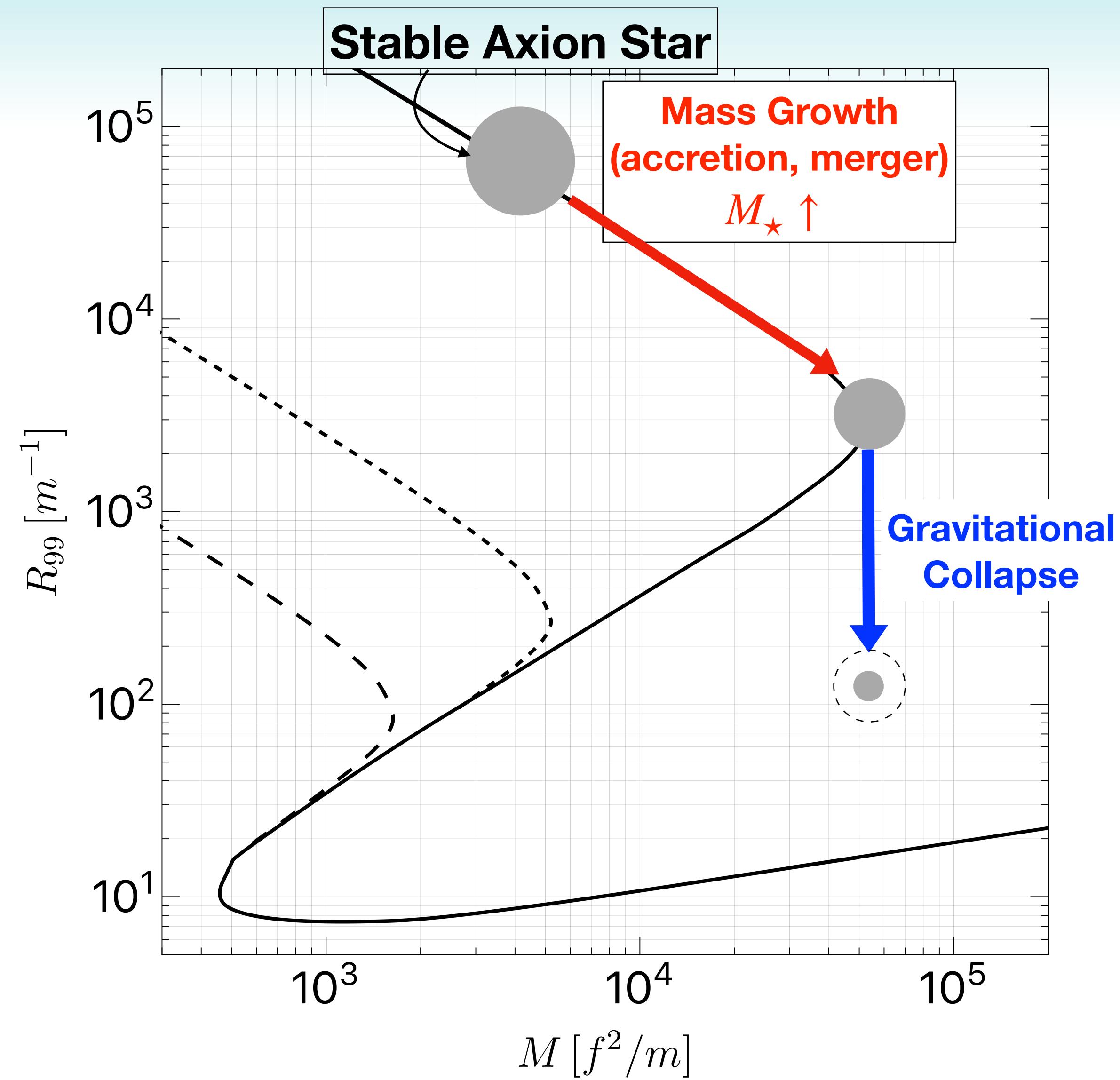
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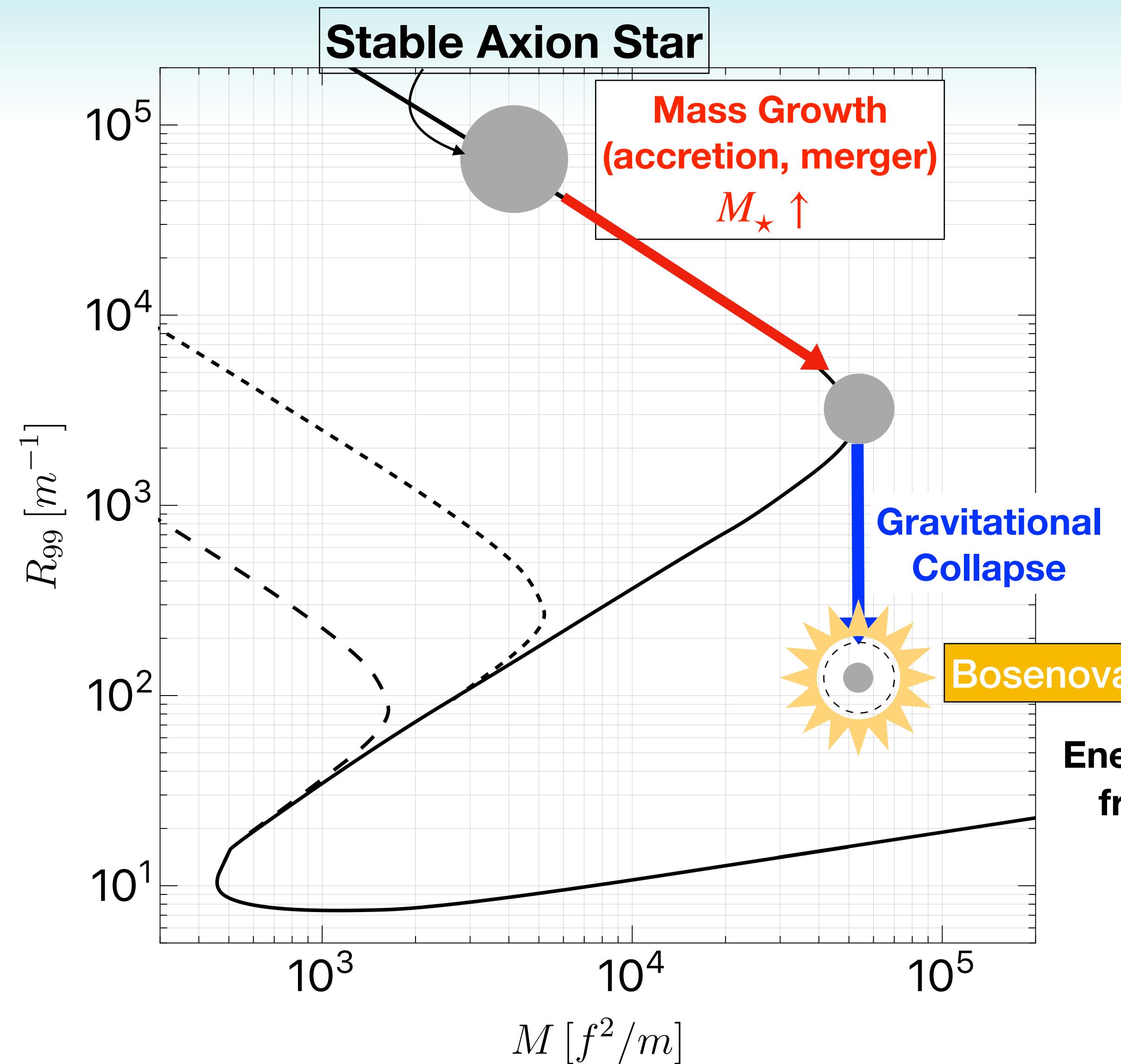
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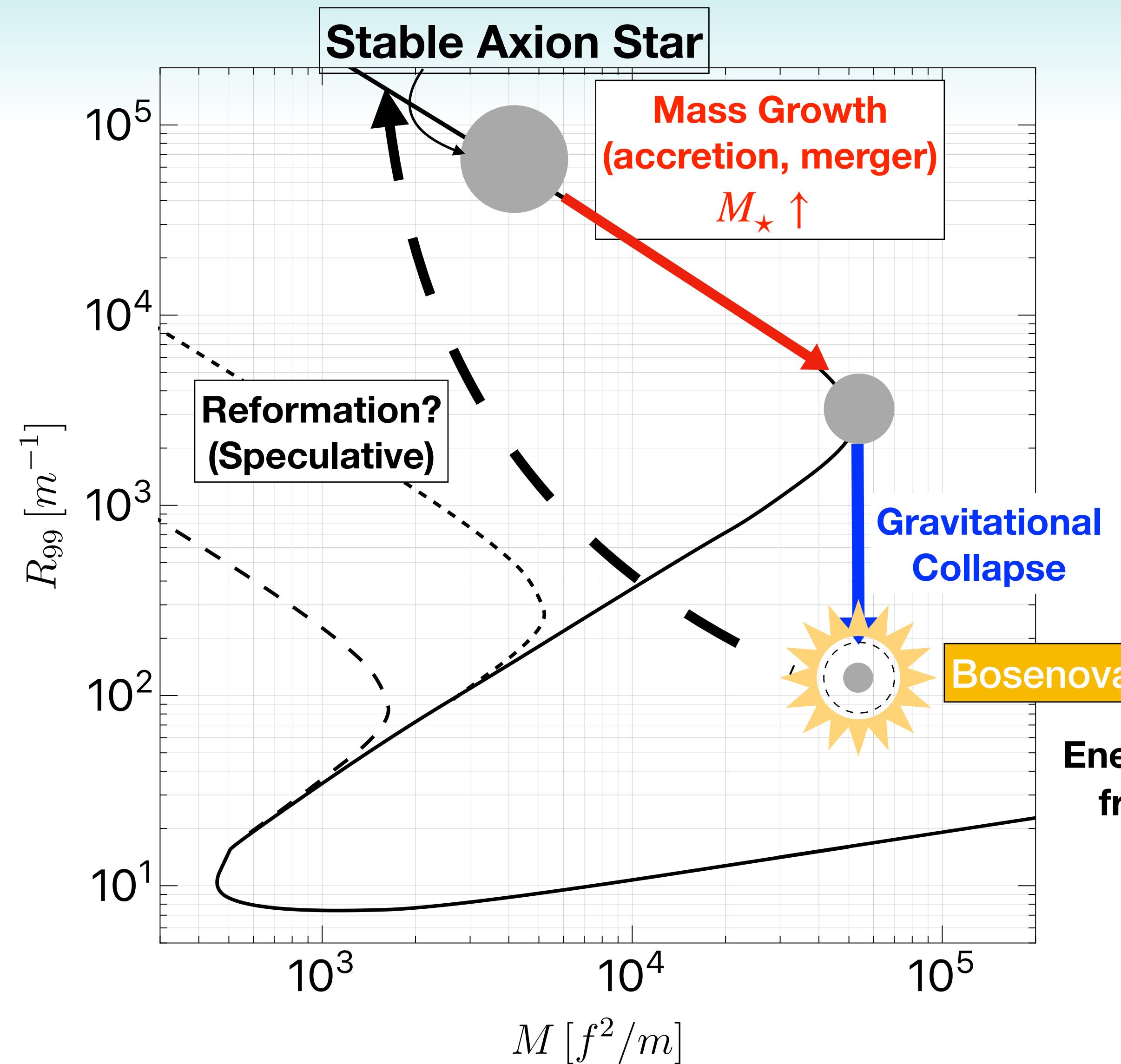
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Energy emitted can be an $\mathcal{O}(1)$ fraction of axion star mass

$$M_c \simeq 10^{-11} M_\odot \frac{f_{12}}{m_5}$$

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

What happens in other cases? (Ignored here)

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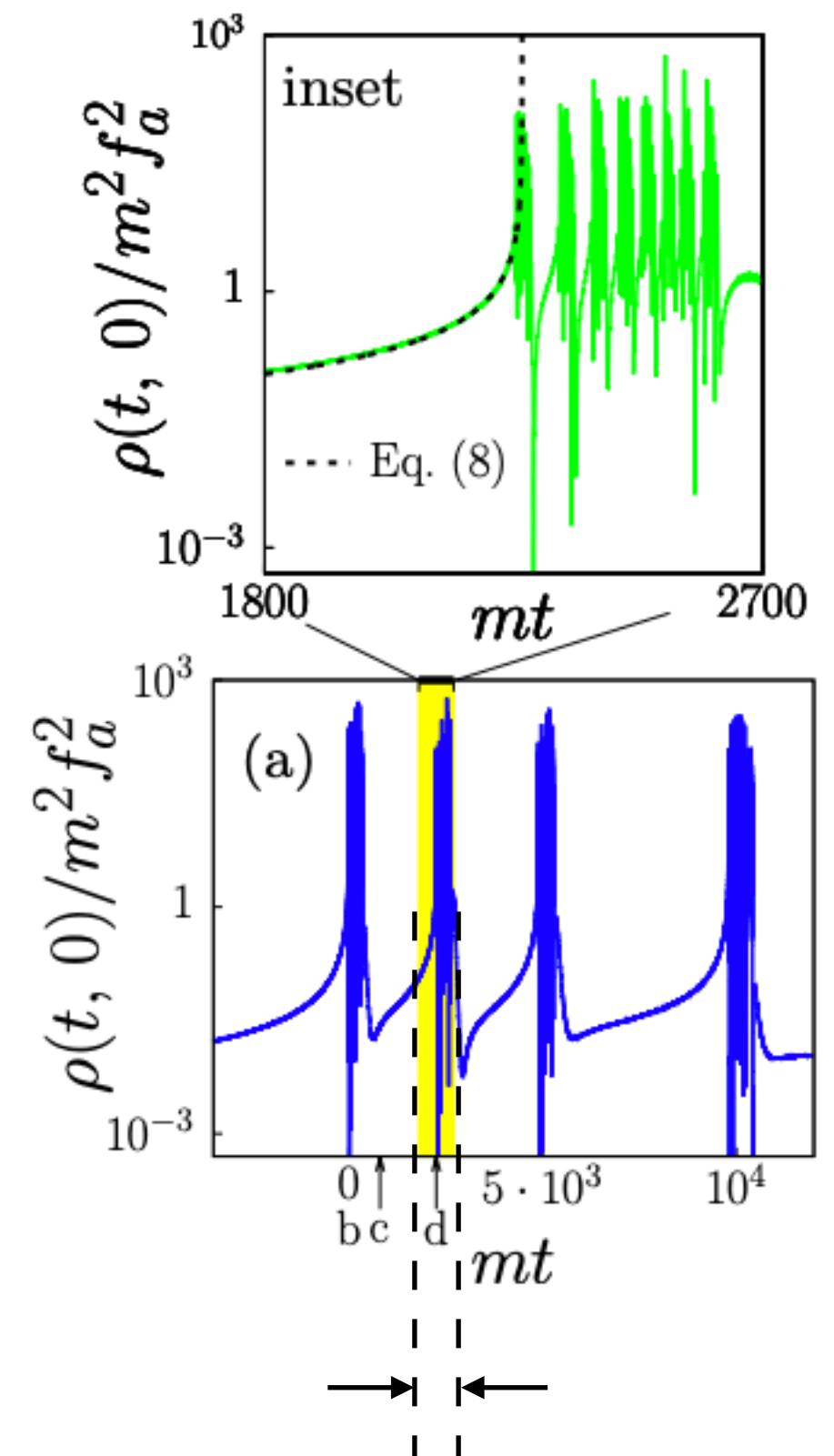
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Short duration

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

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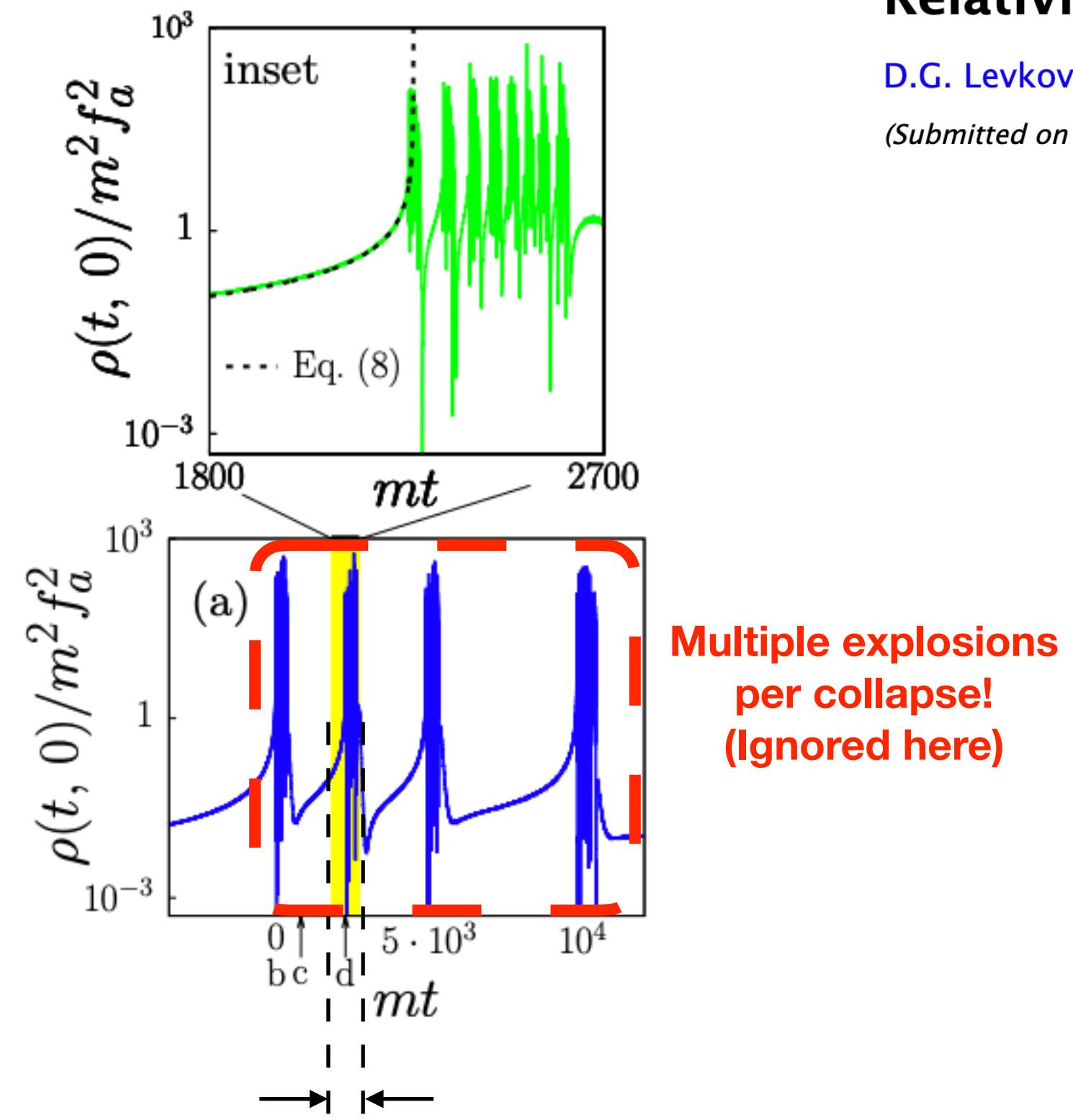
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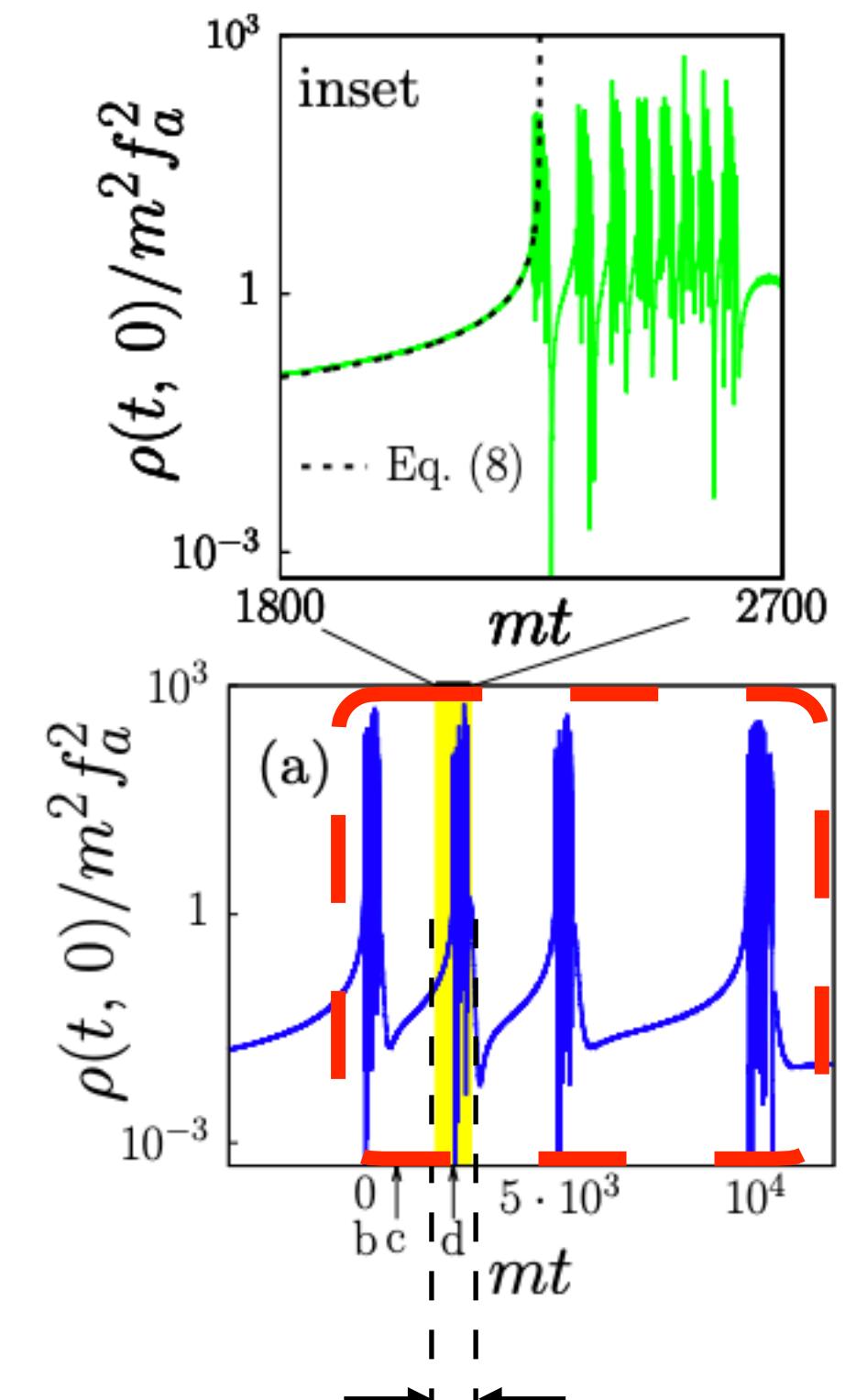
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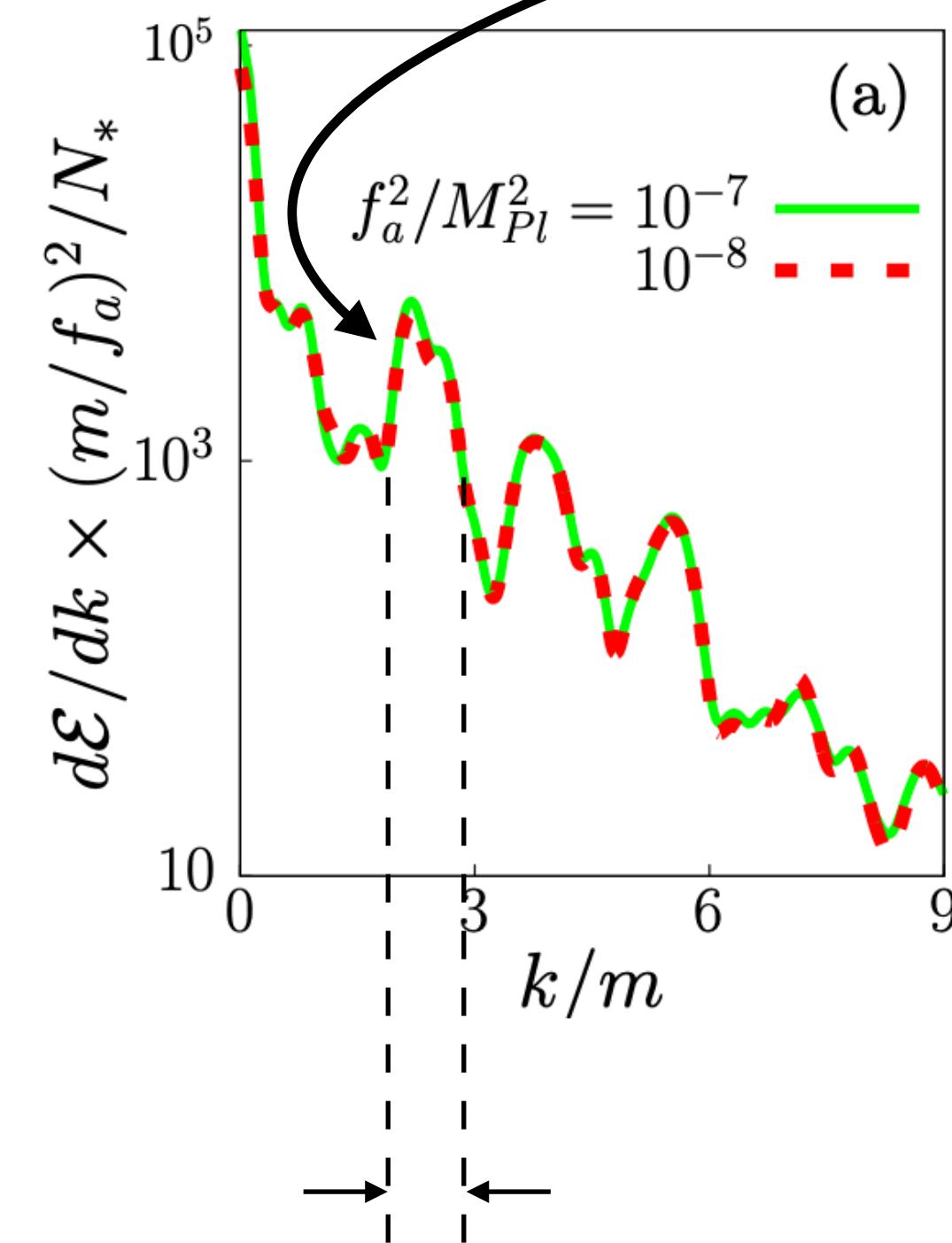
(Submitted on 12 Sep 2016 (v1), last revised 5 Dec 2016 (this version, v2))



Short duration

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

Momentum peak $k_0 \approx 2.4 m$
with spread of $\delta k \sim m$



Integrated energy in first peak

$$\mathcal{E}_{\text{peak}} \approx 3400 m \frac{f^2}{m^2} \simeq 10^{41} \text{ GeV} \frac{f_{12}^2}{m_5}$$

Used potential for QCD axions:

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

What happens in other cases? (Ignored here)

Axion Star Bosenovae

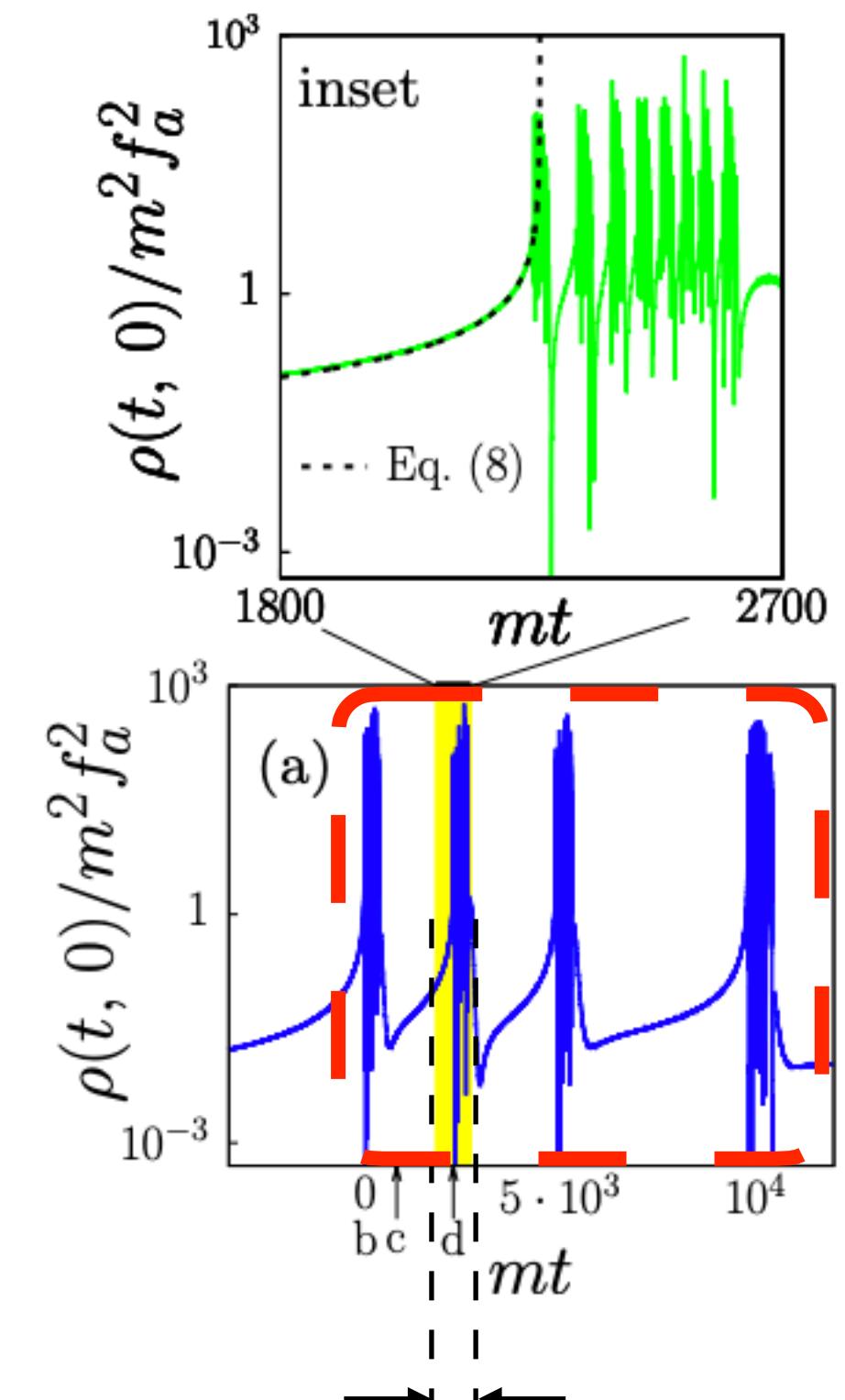
arXiv.org > astro-ph > arXiv:1609.03611

Astrophysics > Cosmology and Nongalactic Astrophysics

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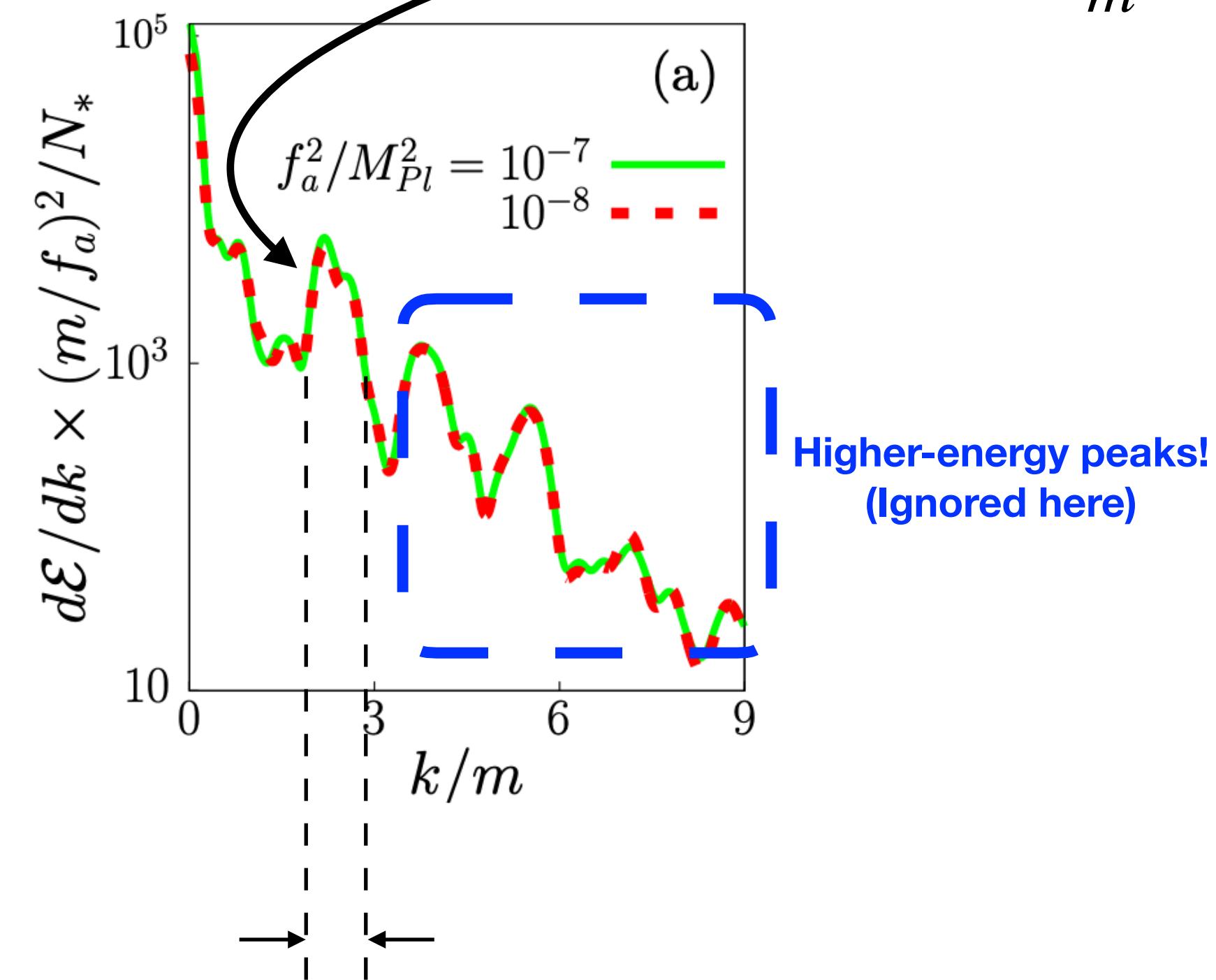
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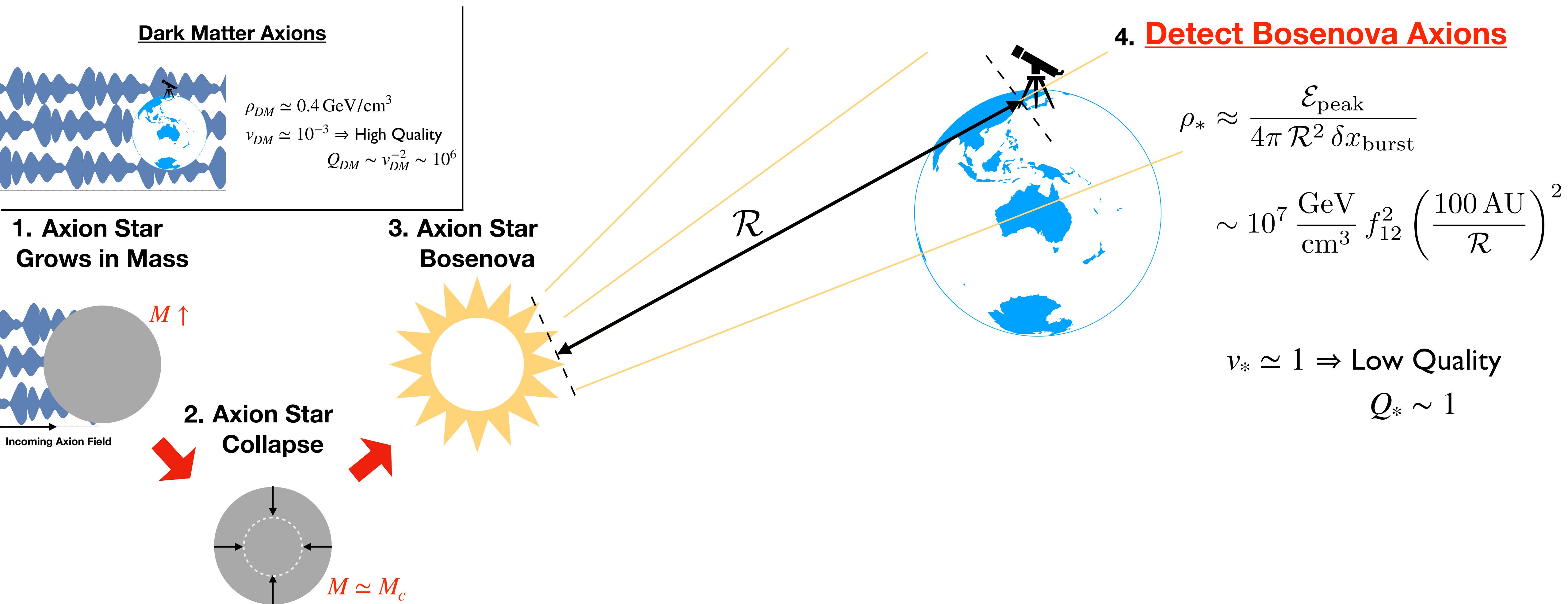
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Multiple explosions
per collapse!
(Ignored here)

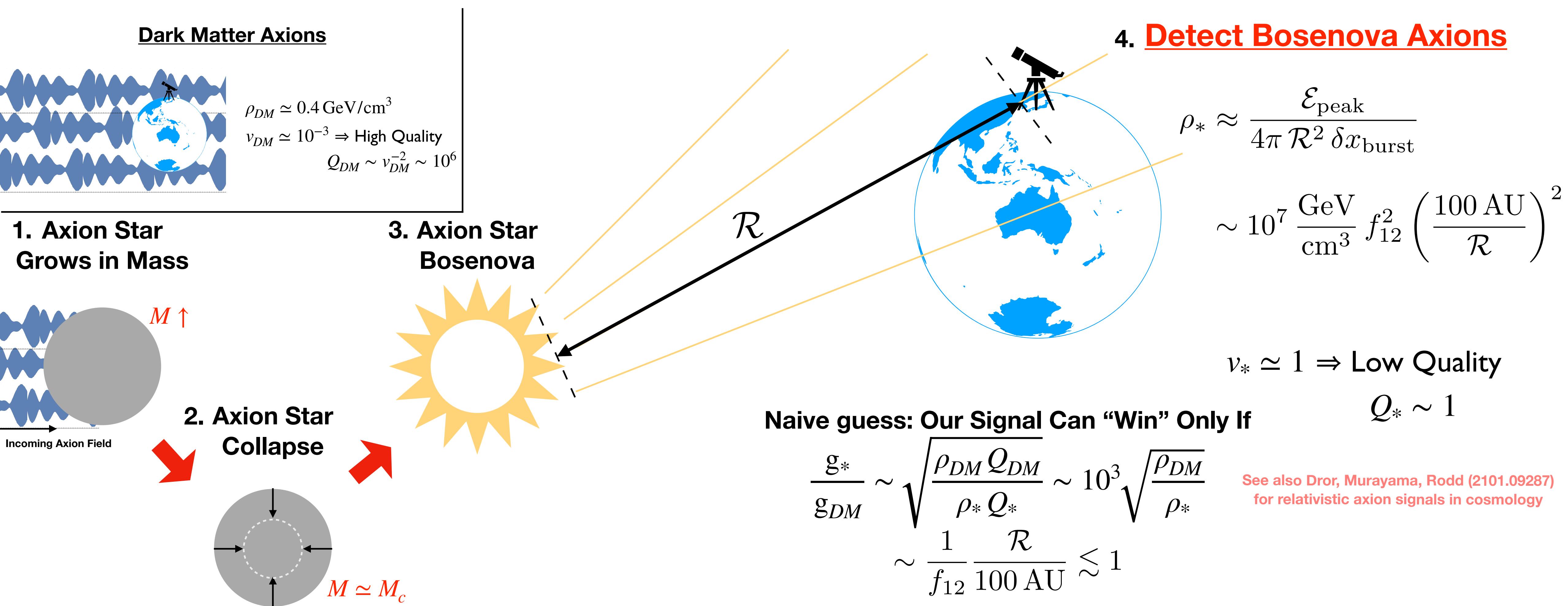
Detecting Axion Star Explosions

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



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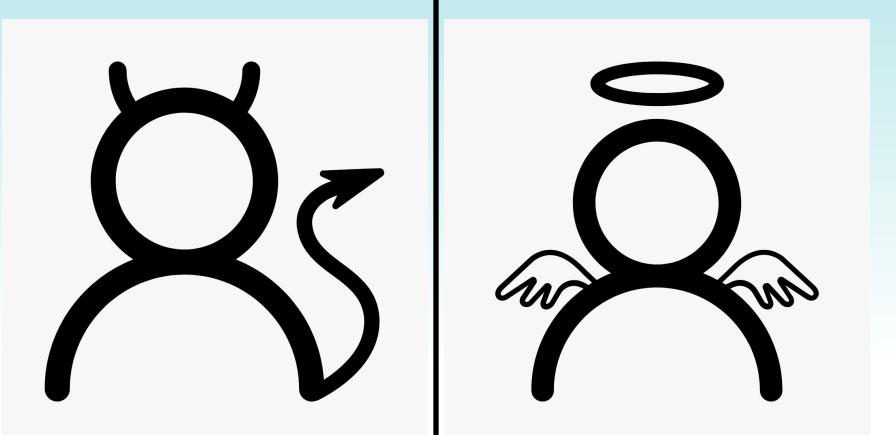


We Might Do Worse

13

Naive guess:

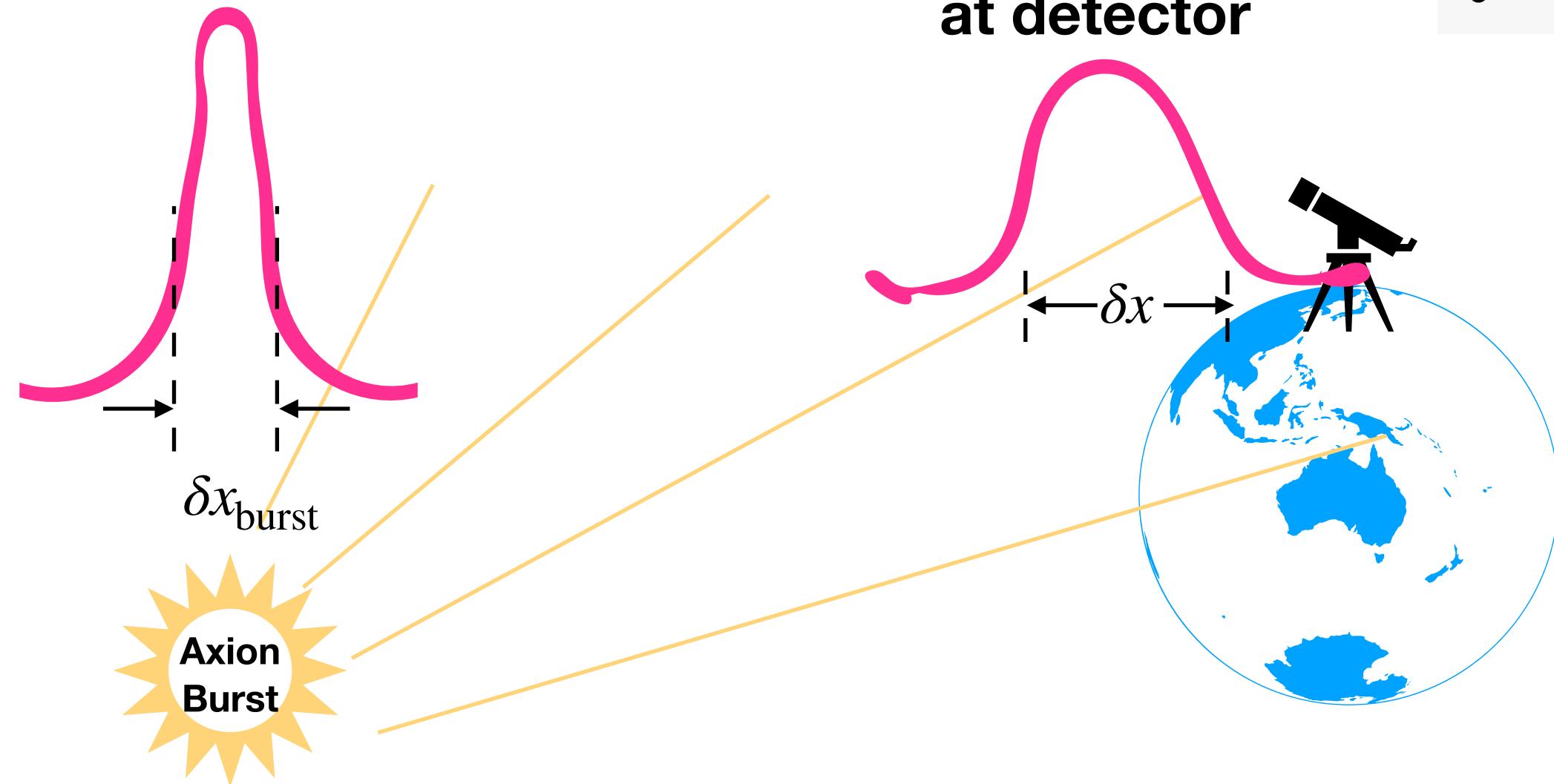
$$\frac{g_*}{g_{DM}} \sim \sqrt{\frac{\rho_{DM} Q_{DM}}{\rho_* Q_*}} \sim 10^3 \sqrt{\frac{\rho_{DM}}{\rho_*}} \lesssim 1$$



We Can Do Better!

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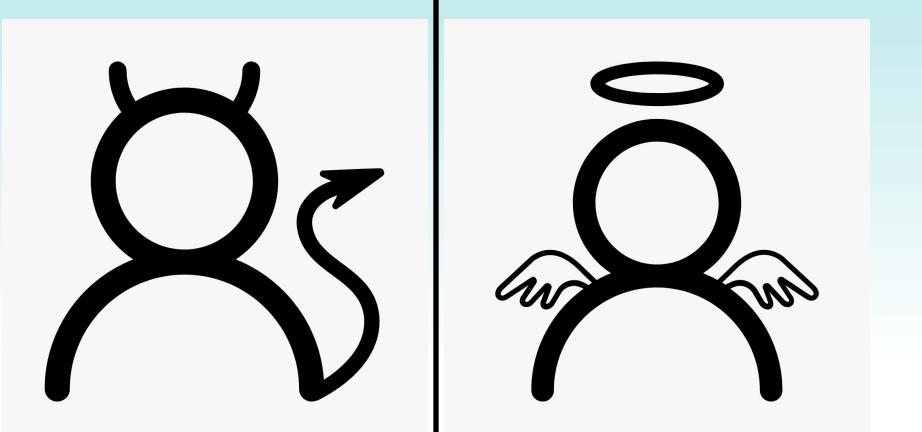
Short-duration
at source



Long duration
at detector

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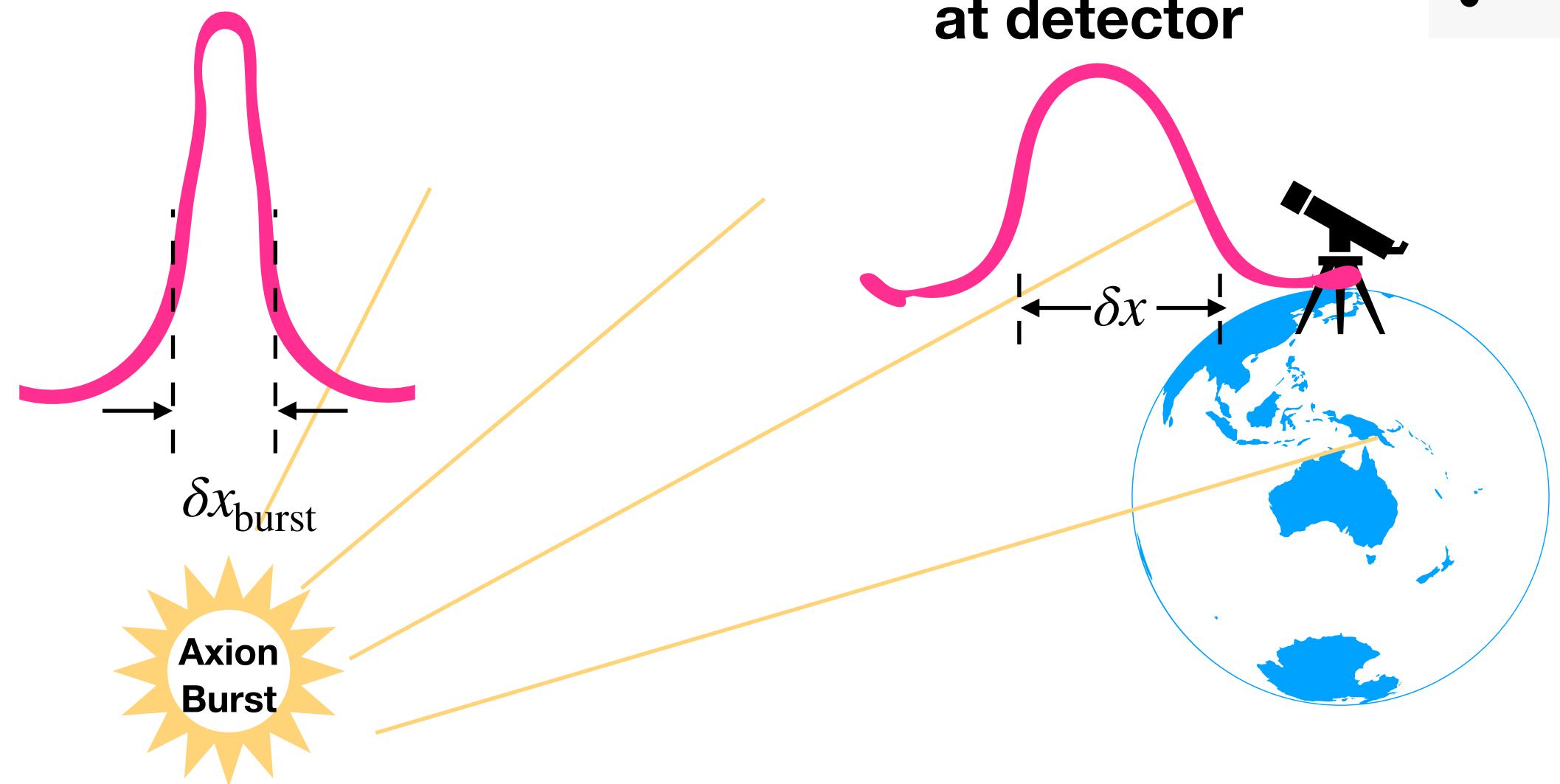
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We Can Do Better!

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**Short-duration
at source**



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

Wave spreading

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

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

**Long duration
at detector**

No wave spreading

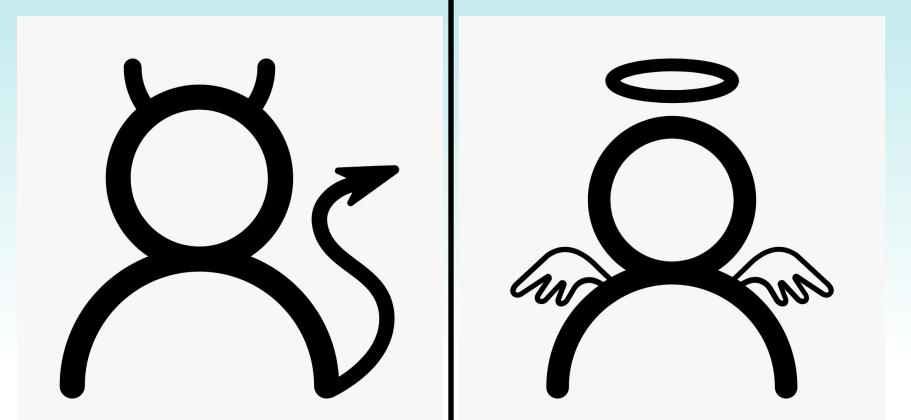
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c.f.

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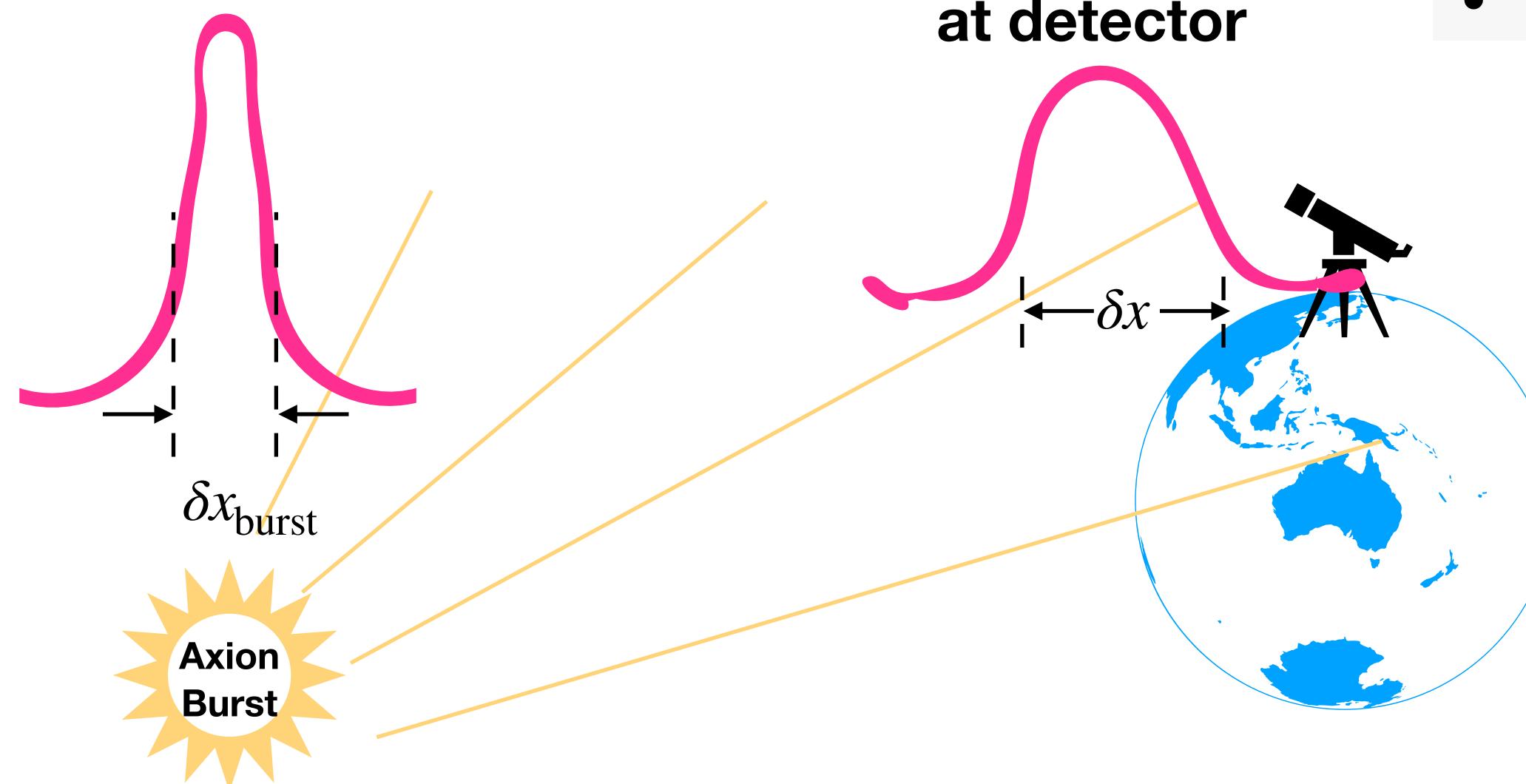
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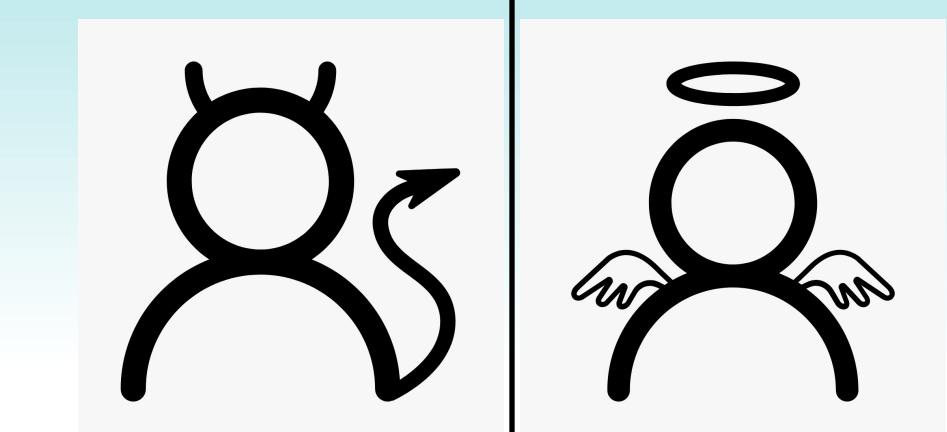
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We Can Do Better!

Though energy density decreases,
burst duration grows.
Can still ‘catch’ whole signal!

Wave spreading

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

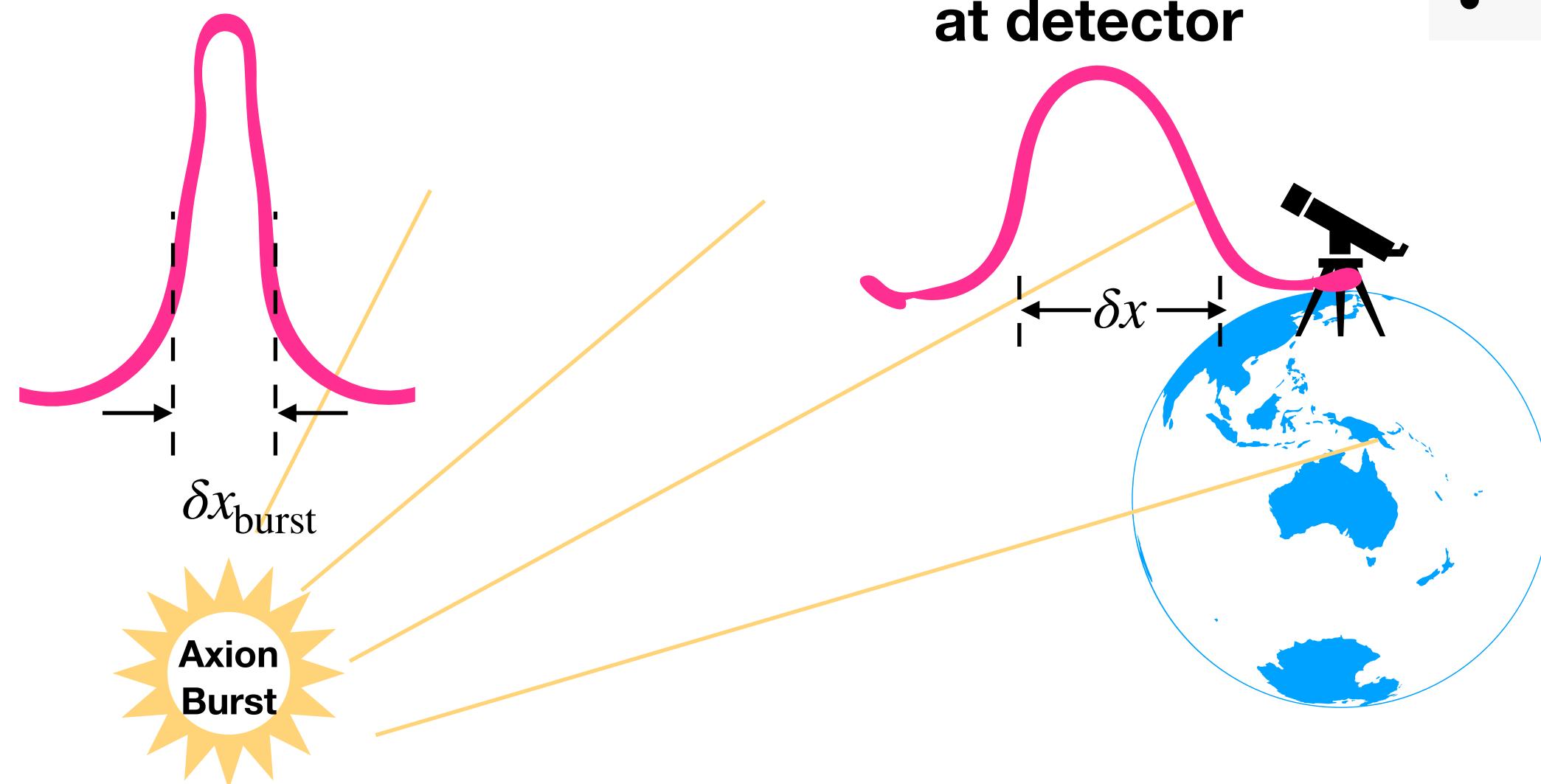
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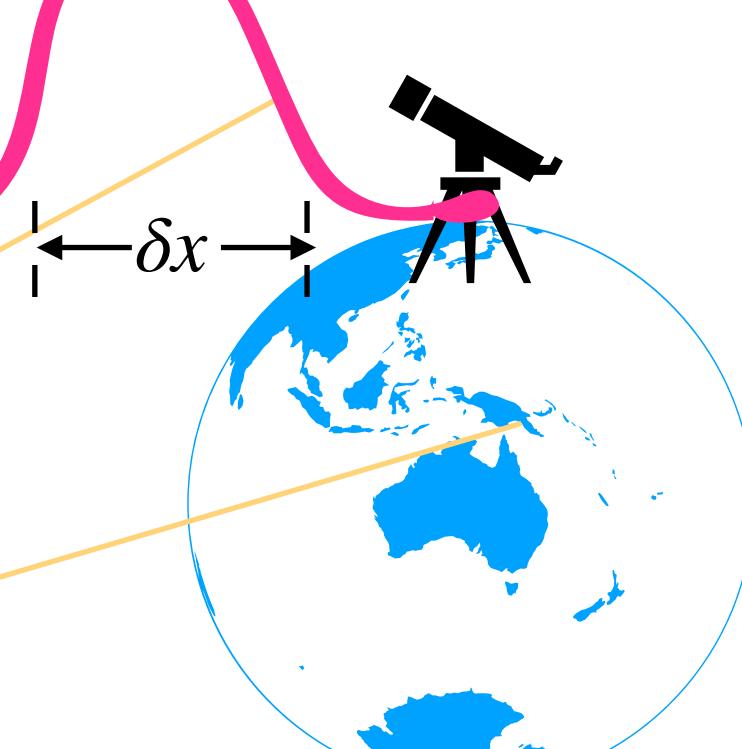
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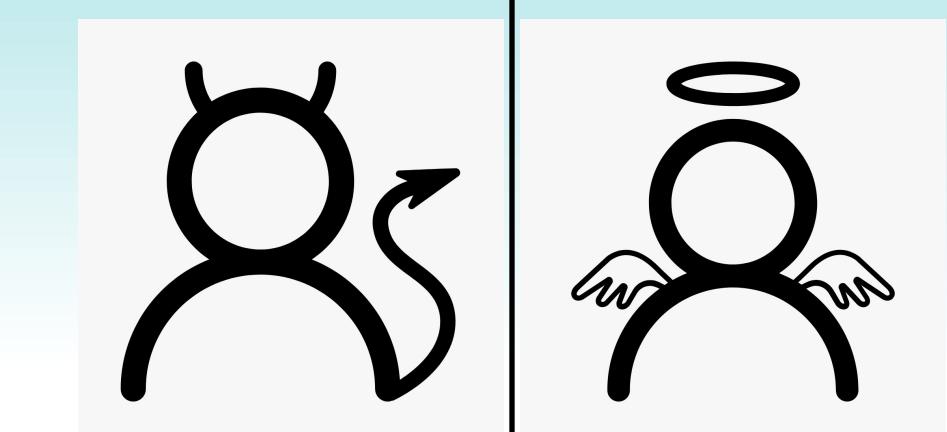
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c.f.

No wave spreading

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

Can **regain some coherence** at the detector,

Even though oscillator quality is $Q_* = \mathcal{O}(1)$ at source

Wave spreading

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

c.f.

No wave spreading

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

How to Search

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

Sensitivity Ratio

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

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

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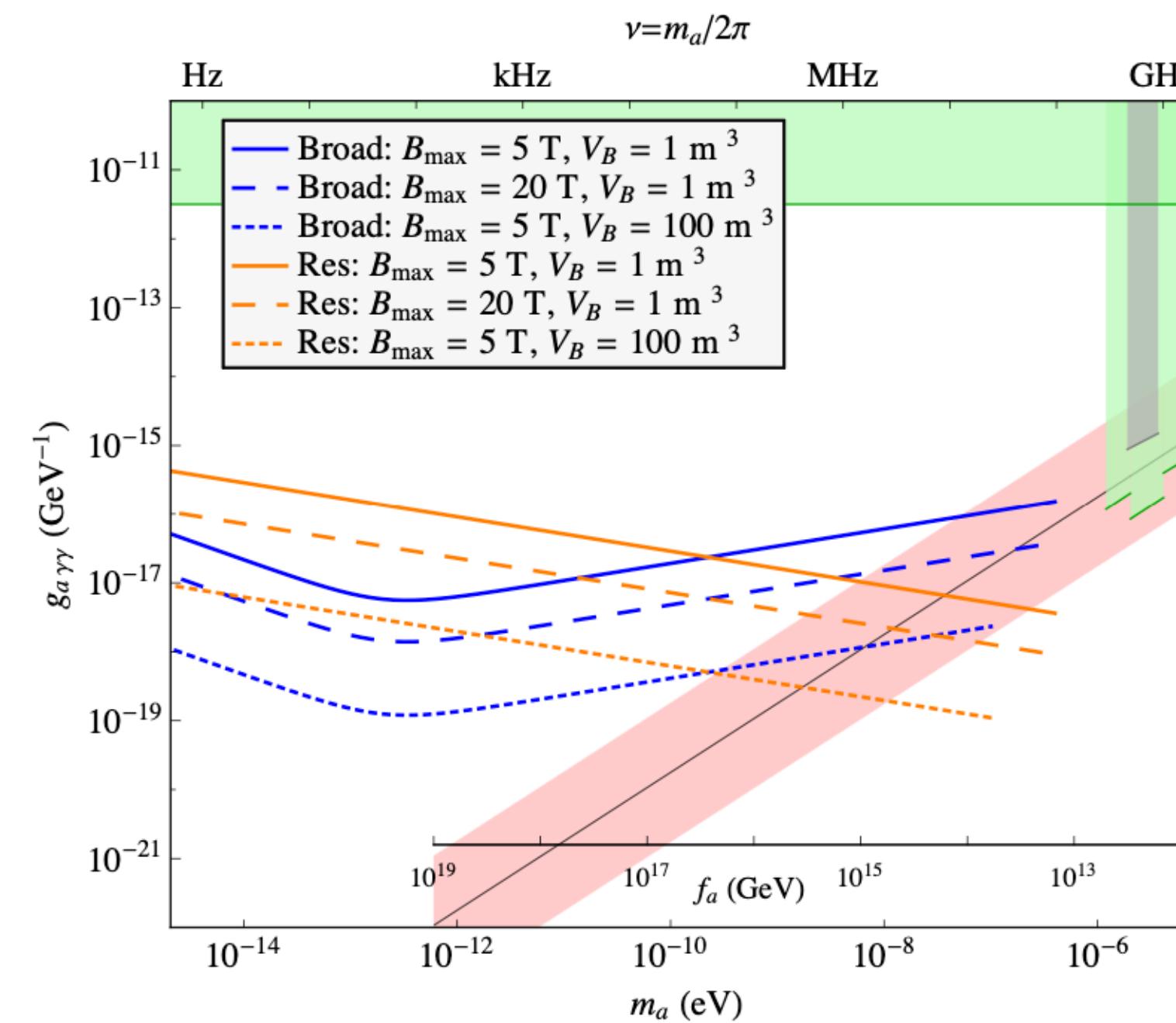
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For absolute sensitivity,
we use ABRACADABRA
long-term reach

Kahn, Safdi, Thaler (1602.01086)

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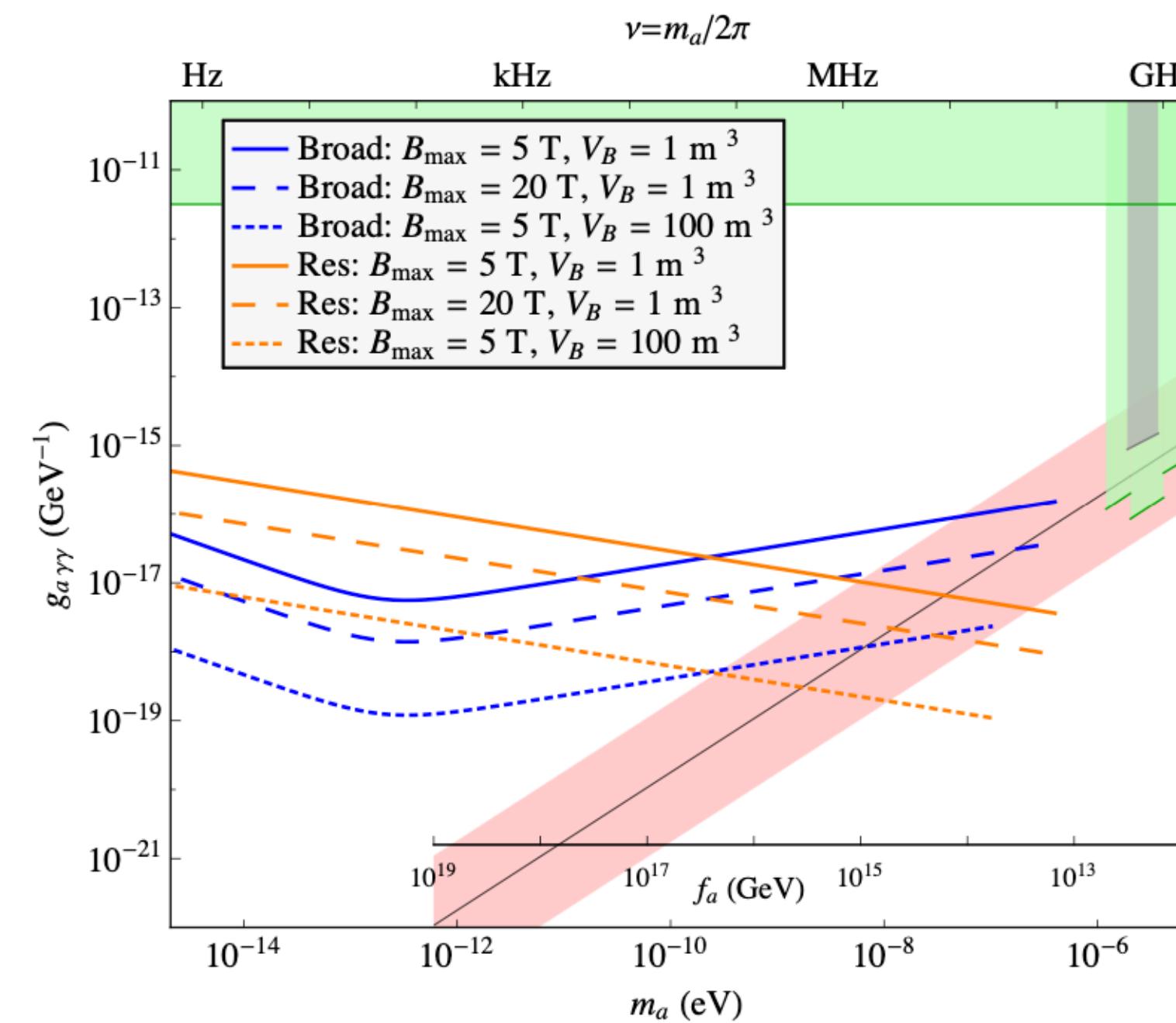
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Assume average time for burst $\tau = 10 \text{ Gyr}$

Check whether

$$\mathcal{N} \equiv N_{\text{star}}(\mathcal{R}) \left(\frac{1 \text{ year}}{\tau} \right) < 1$$

(1 burst within \mathcal{R} of Earth
per year)

“How likely is it for a ‘nearby’ burst to occur
within 1 year of experimental running?”

Define # burst-making objects

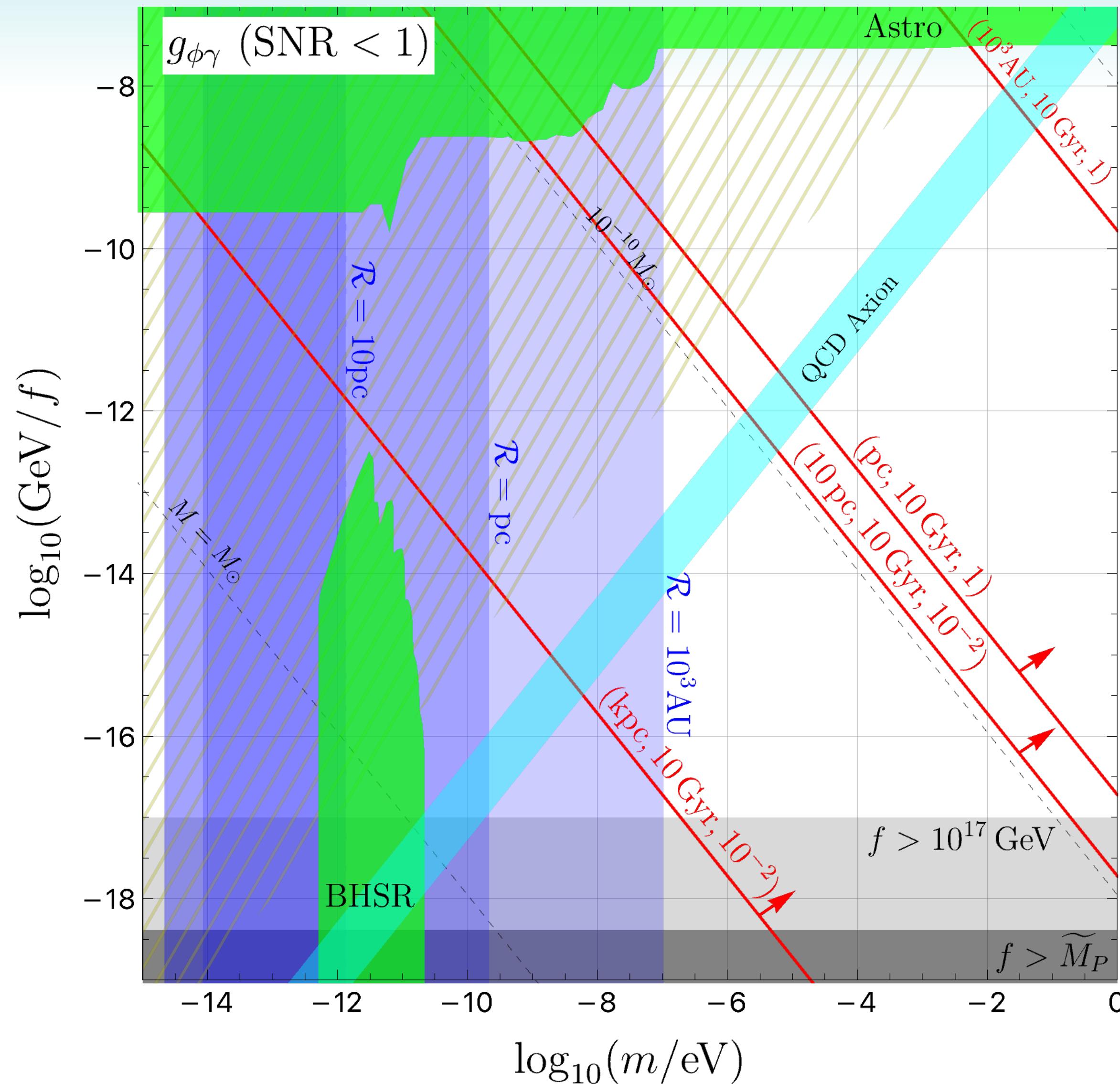
$$N(\mathcal{R}) = \frac{f_{\text{DM}} \rho_{\text{DM}}}{\mathcal{E}} \frac{4\pi \mathcal{R}^3}{3}$$

within \mathcal{R} of Earth

For axion stars,

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

Photon Couplings



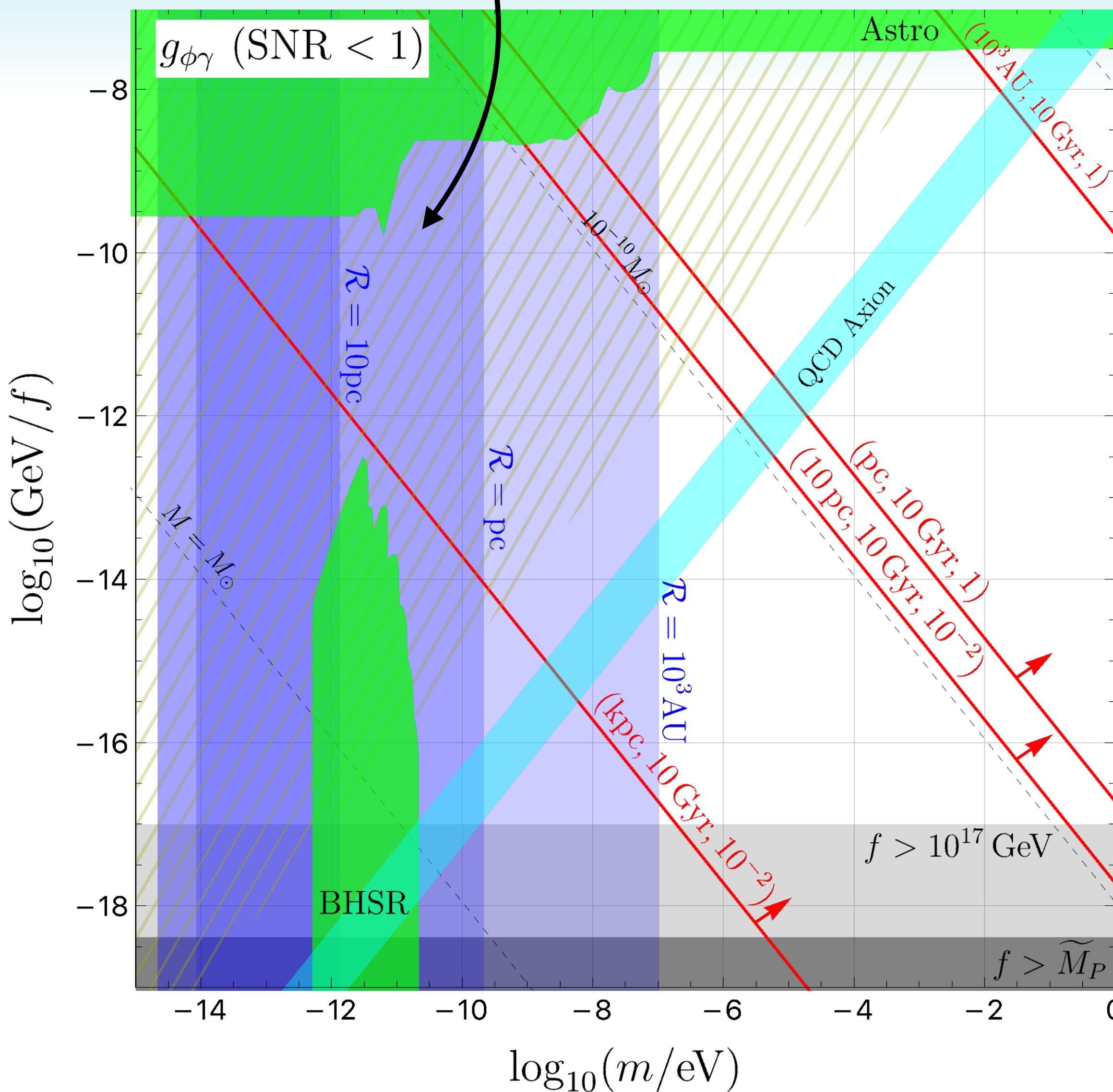
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Using ABRACADABRA sensitivity projection for g_{DM}



1. Sensitivity bands vertical:
coupling $\propto 1/f$
but signal $\propto \sqrt{\mathcal{E}} \propto f$



Photon Couplings

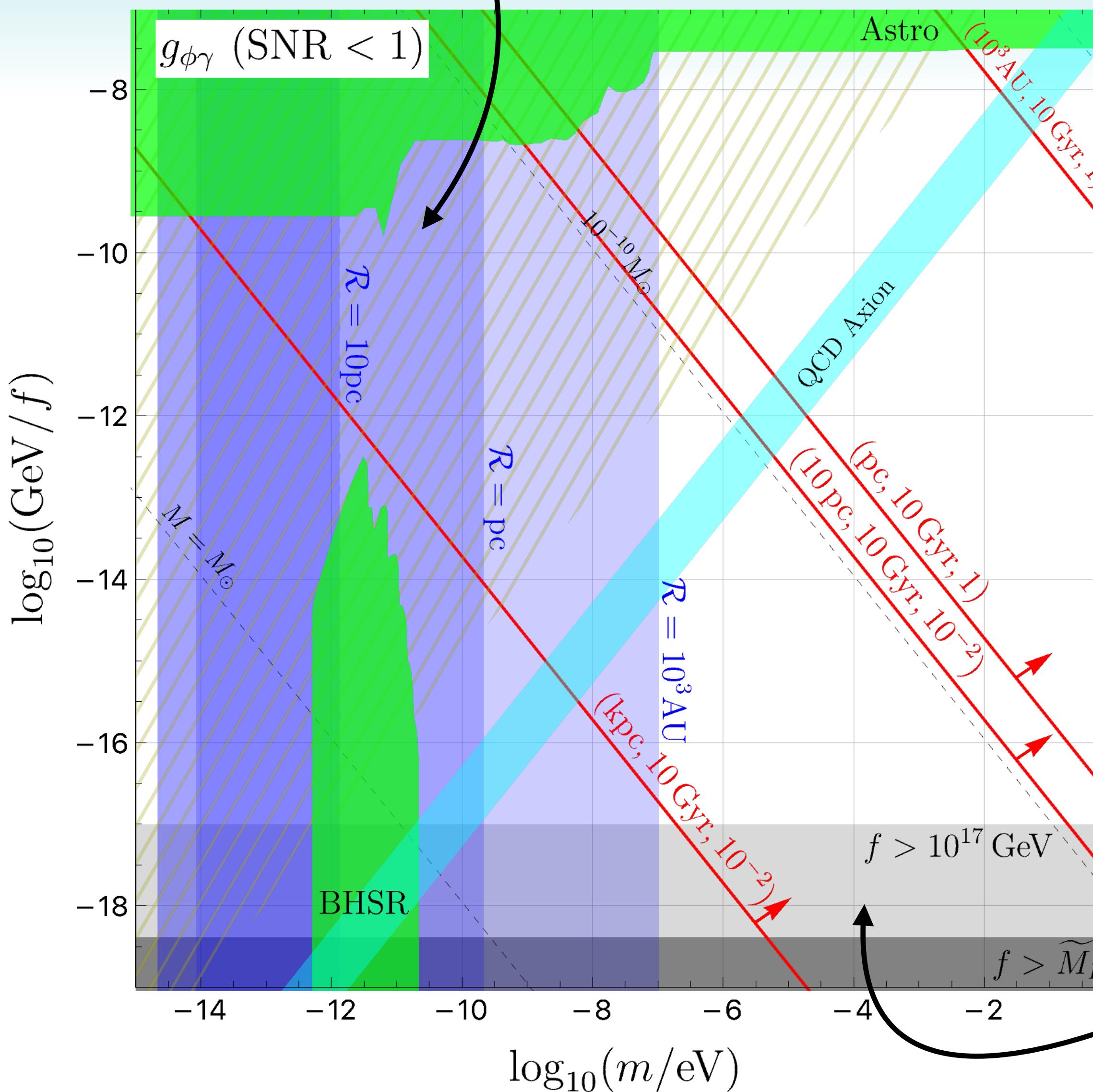
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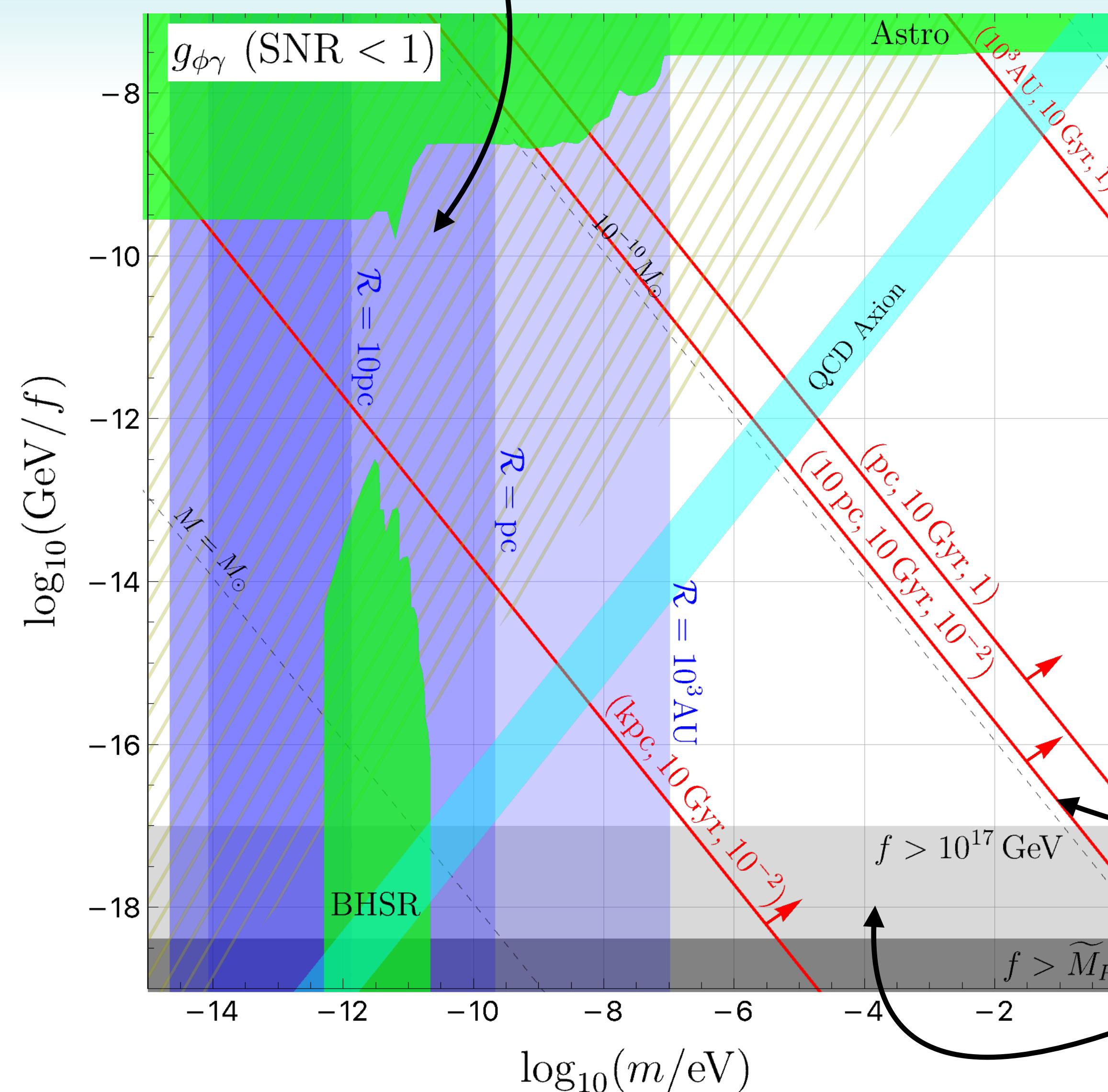
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2. Axion stars won't collapse
in the usual way for $f \gtrsim 10^{17} \text{ GeV}$

JE, Street, Suranyi, Wijewardhana (2011.09087)

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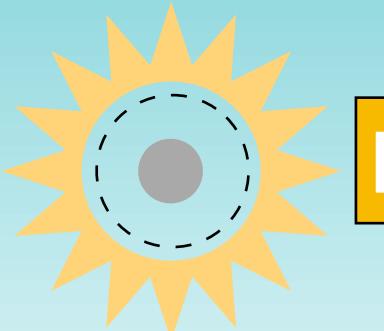
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Using ABRACADABRA sensitivity projection for g_{DM}

3. Contours for $(\mathcal{R}, \tau, f_{DM})$
Explosions infrequent in this case...
Shorter lifetime possible?

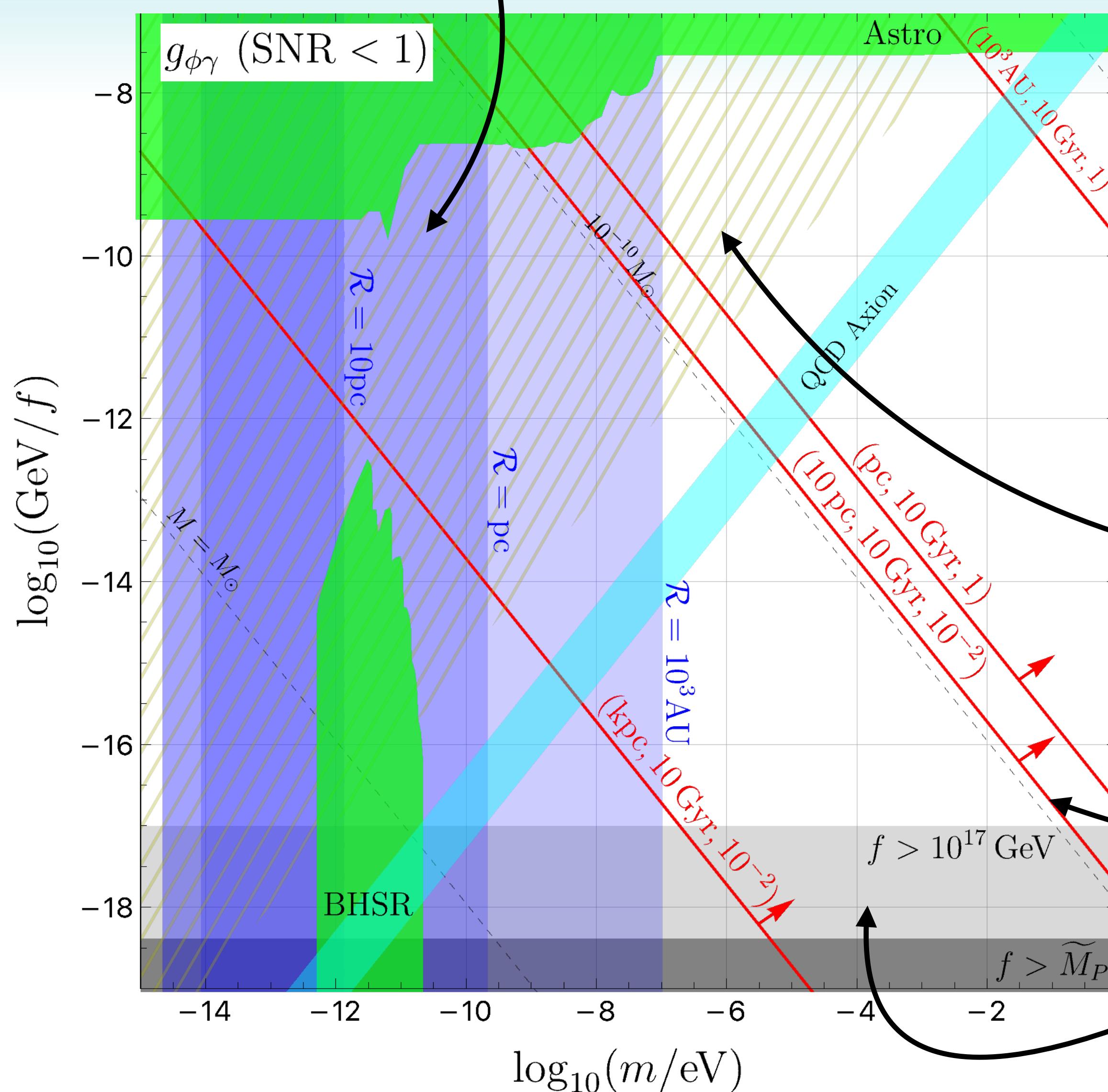
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Bosenova Explosion

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Using ABRACADABRA sensitivity projection for g_{DM}

- 4. Axion \rightarrow photons through parametric resonance**

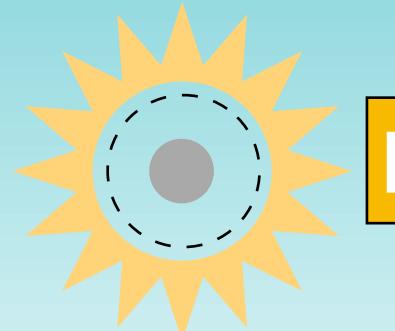
Levkov, Panin, Tkachev (2004.05179)

Feature or bug?
(Multi-messenger signal?)

- 3. Contours for (R, τ, f_{DM})**
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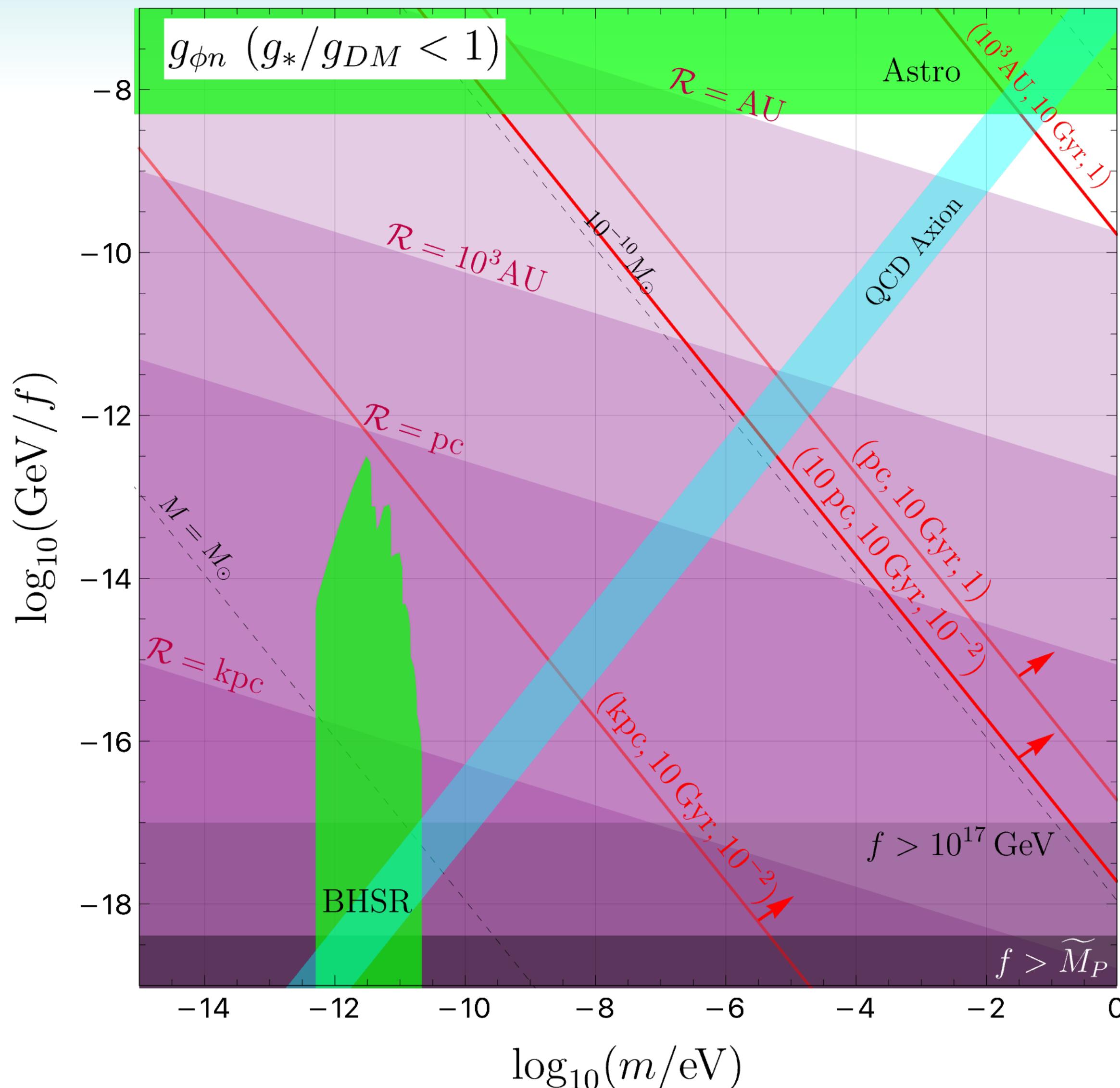
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Bosenova Explosion

Nucleon Couplings

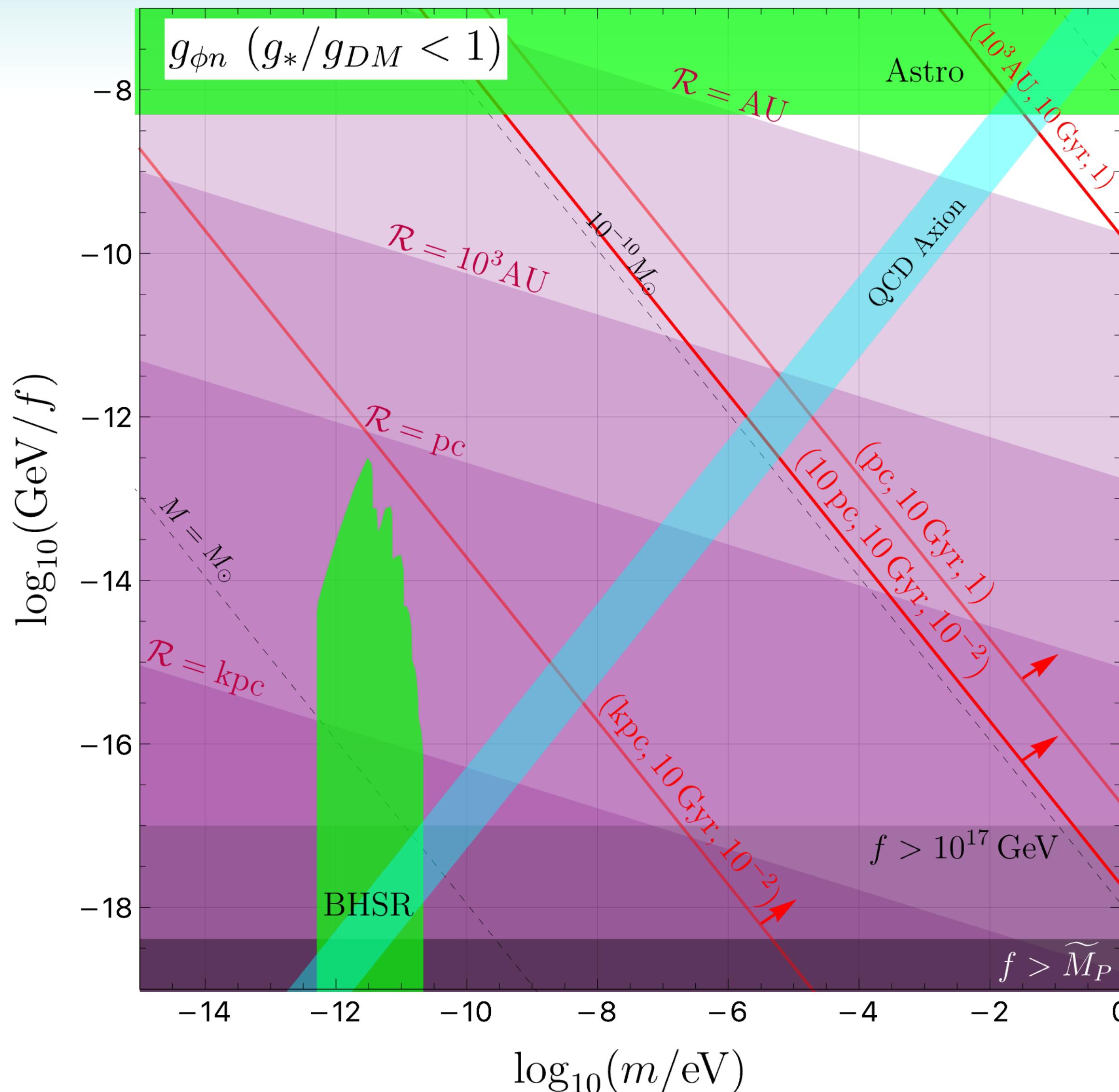


Sensitivity Ratio



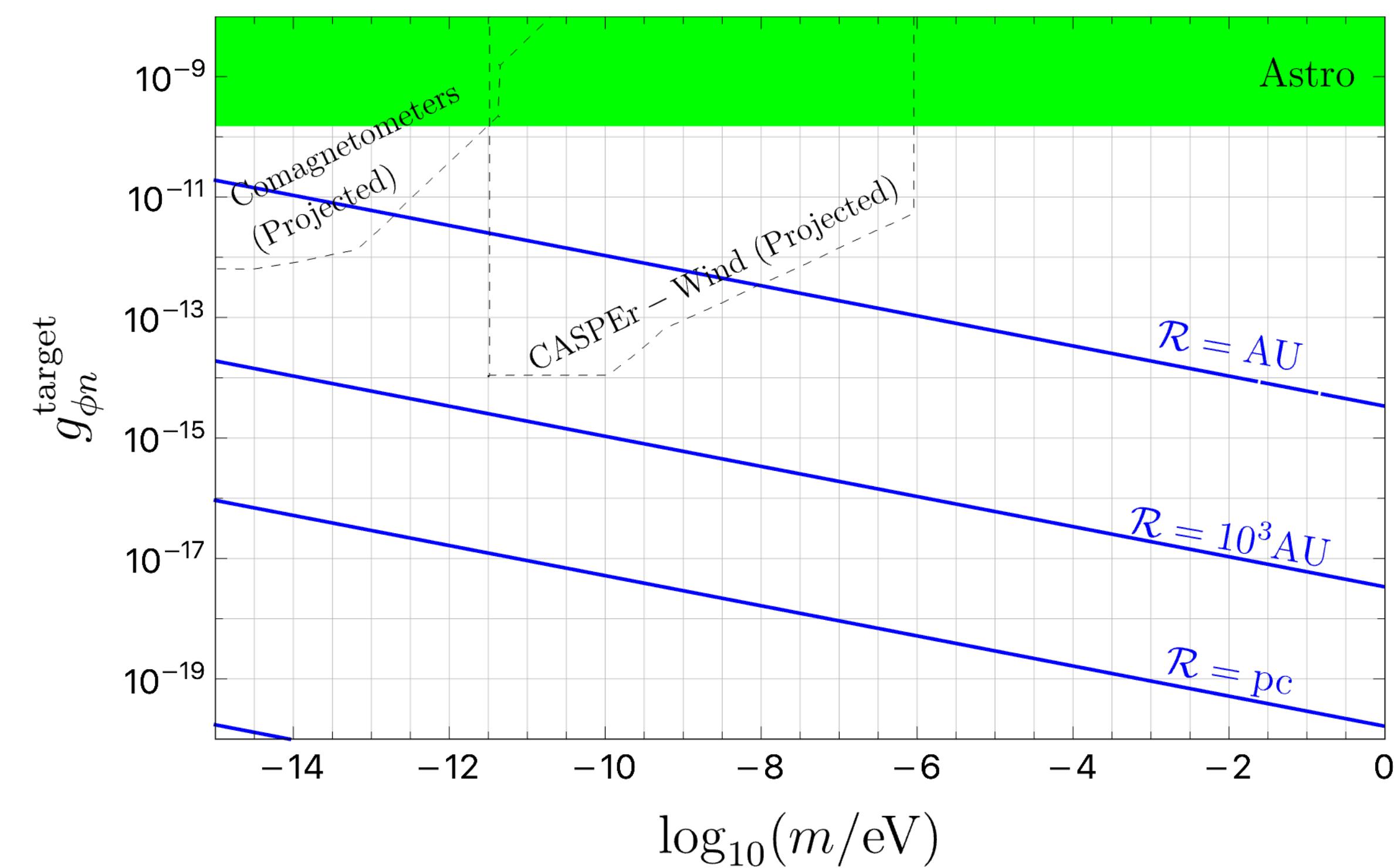
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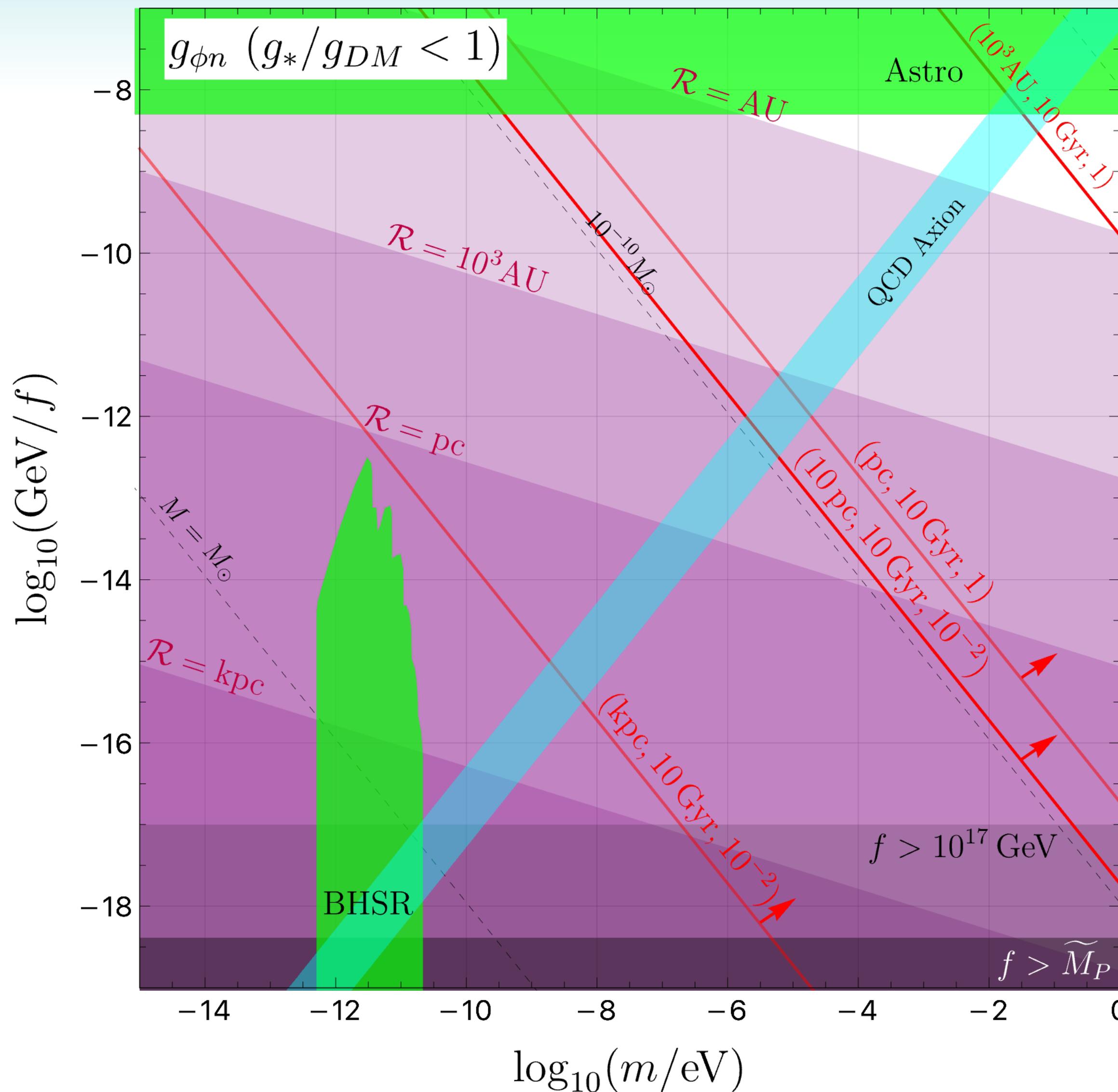


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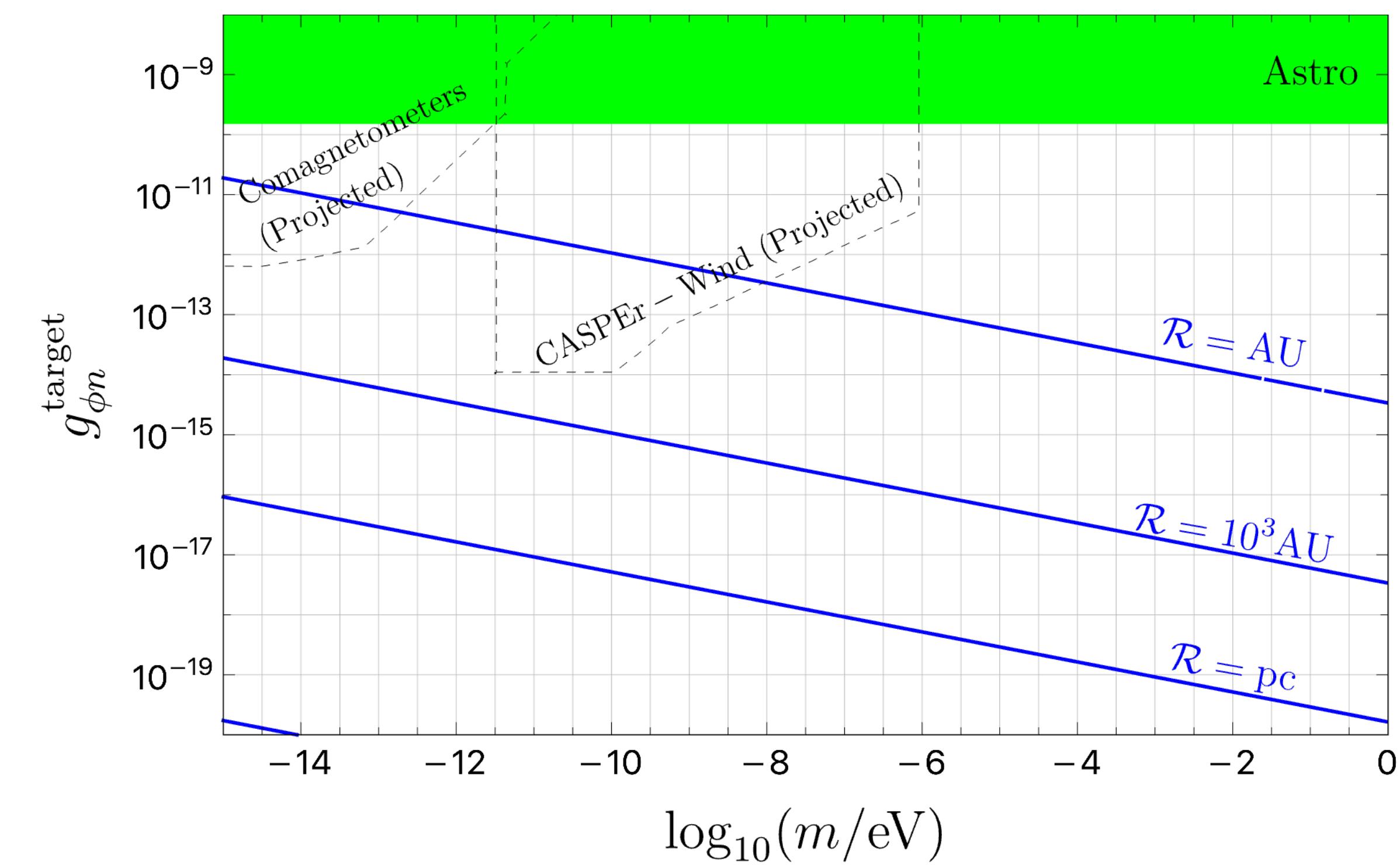


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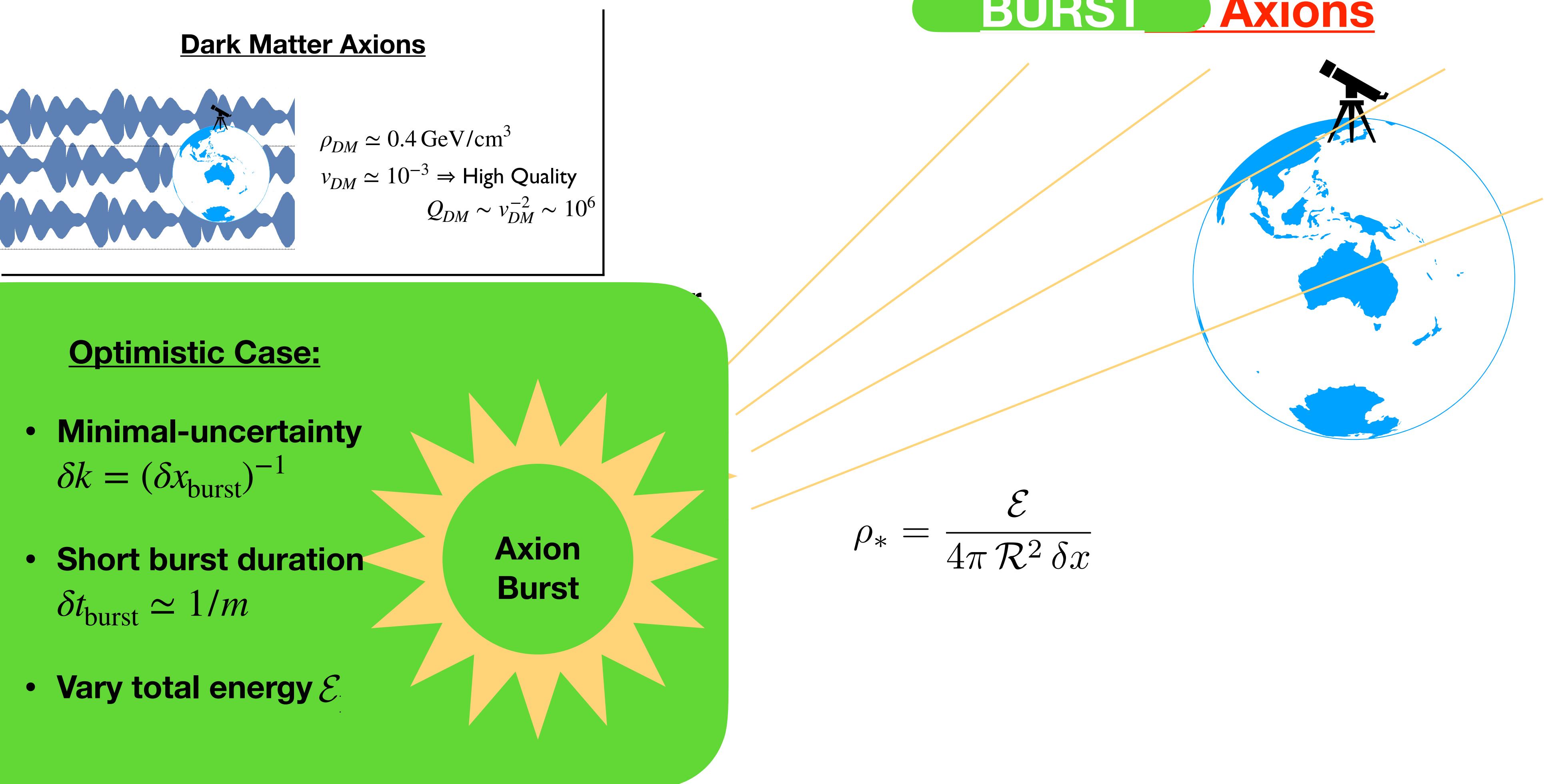


New broadband search strategies needed!

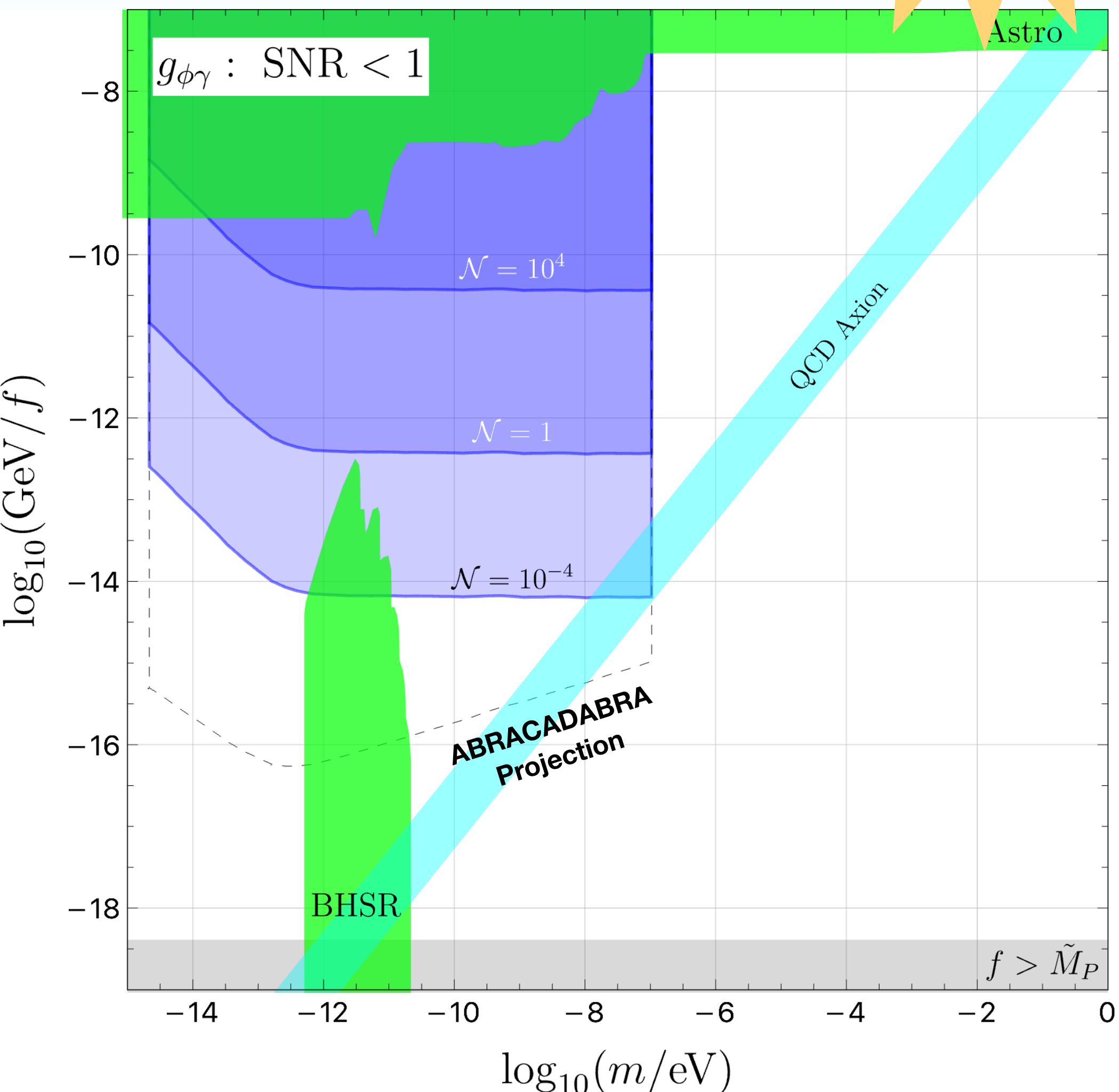
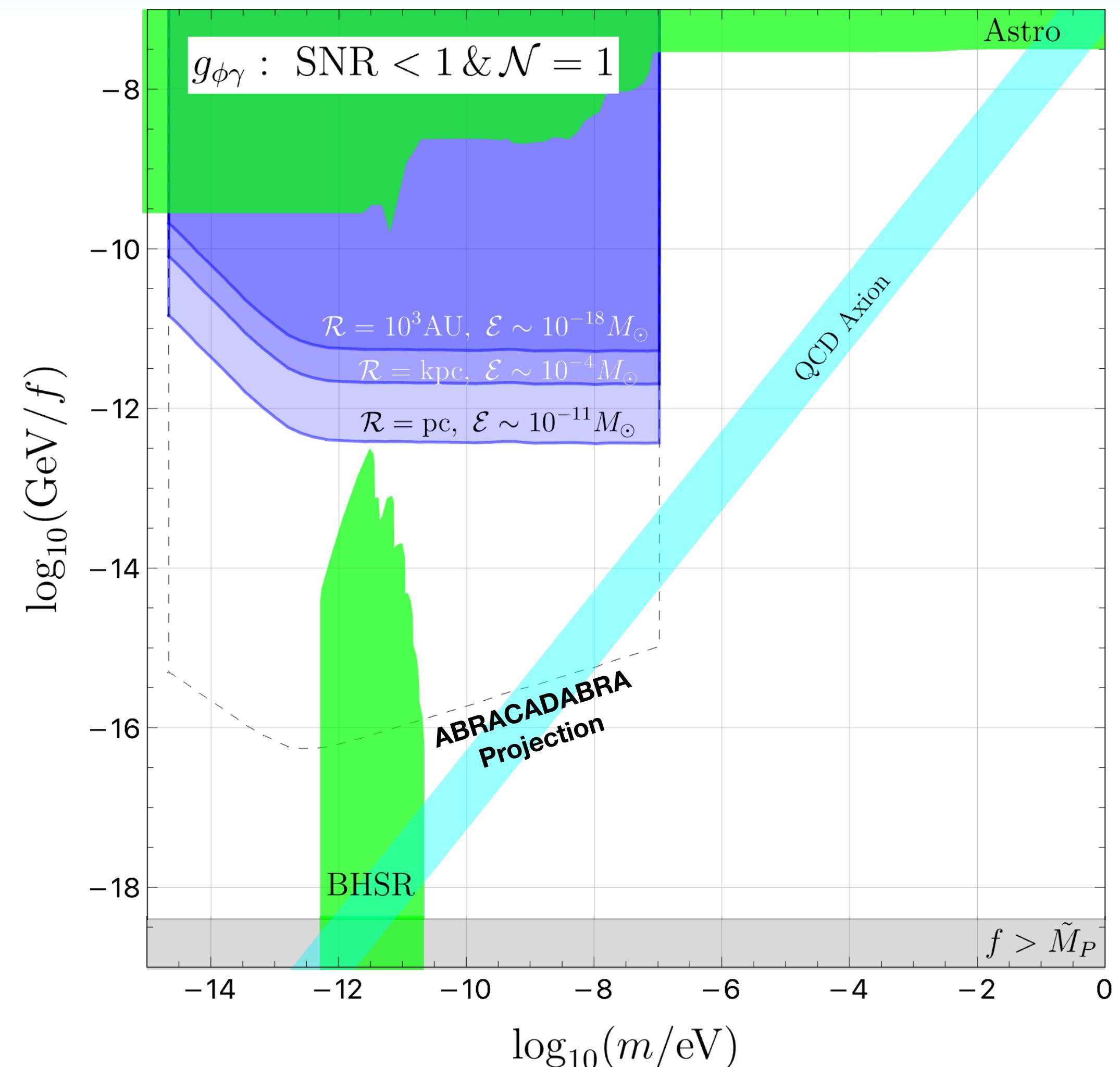
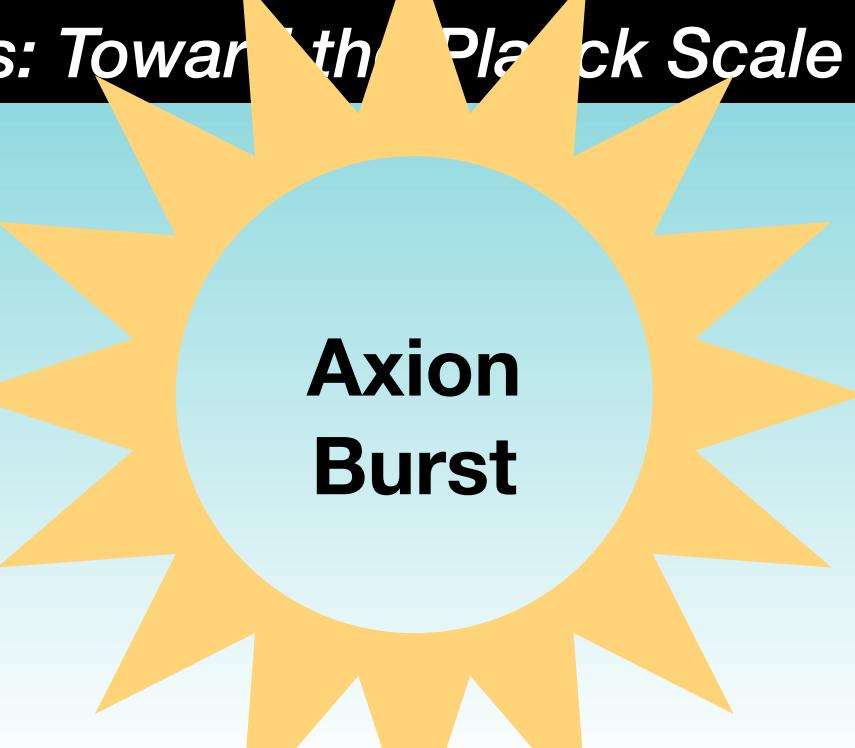


Detecting Explosions

- Idea: Detect high-energy axion burst !



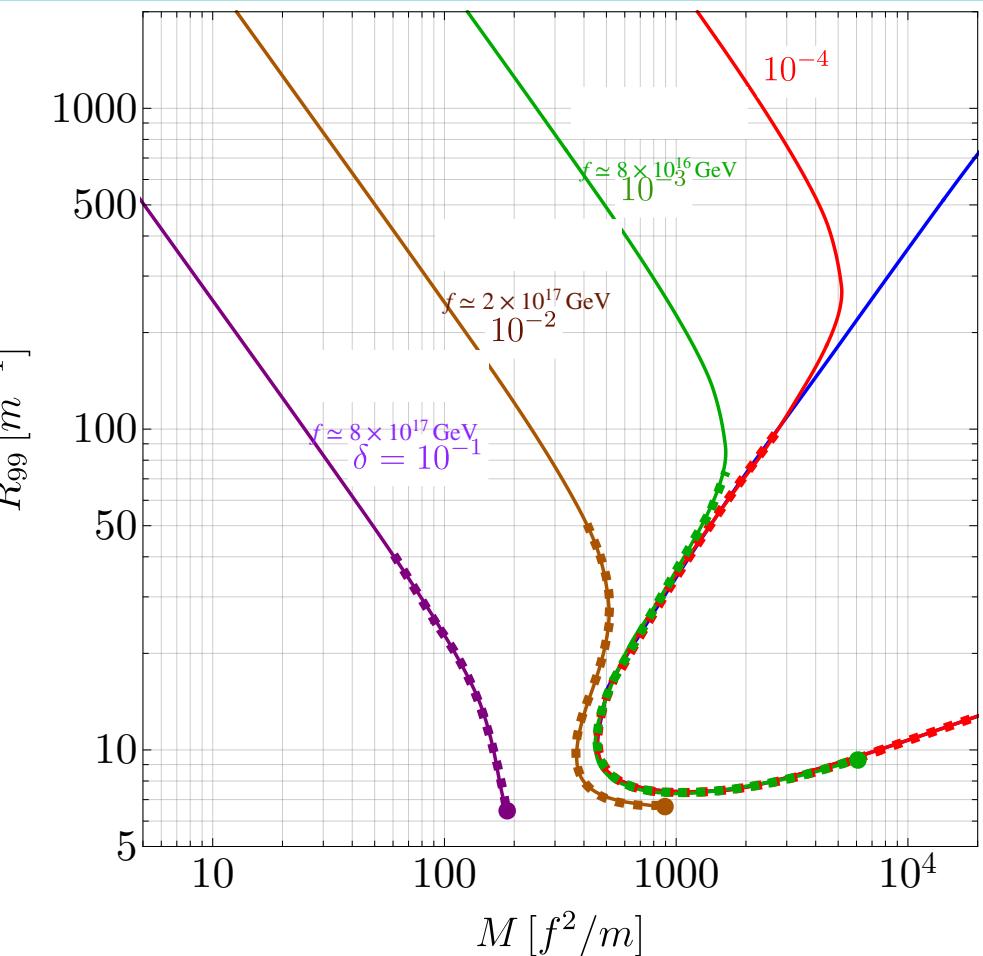
Sensitivity to General Explosions



Conclusions

- Axion stars are a unique prediction of light scalar field dark matter
- They are astrophysical objects, that can **form, accrete, collapse, decay, explode**
- When the decay constant $f \gtrsim 10^{17}$ GeV, states **on the dilute branch** can be unstable to decay
- Large- f axions may be detectable by their emission of relativistic bursts of axions (though in narrow case of axion star bosenovae they may be rare). General axion bursts are a new signature worth exploring!
- **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?

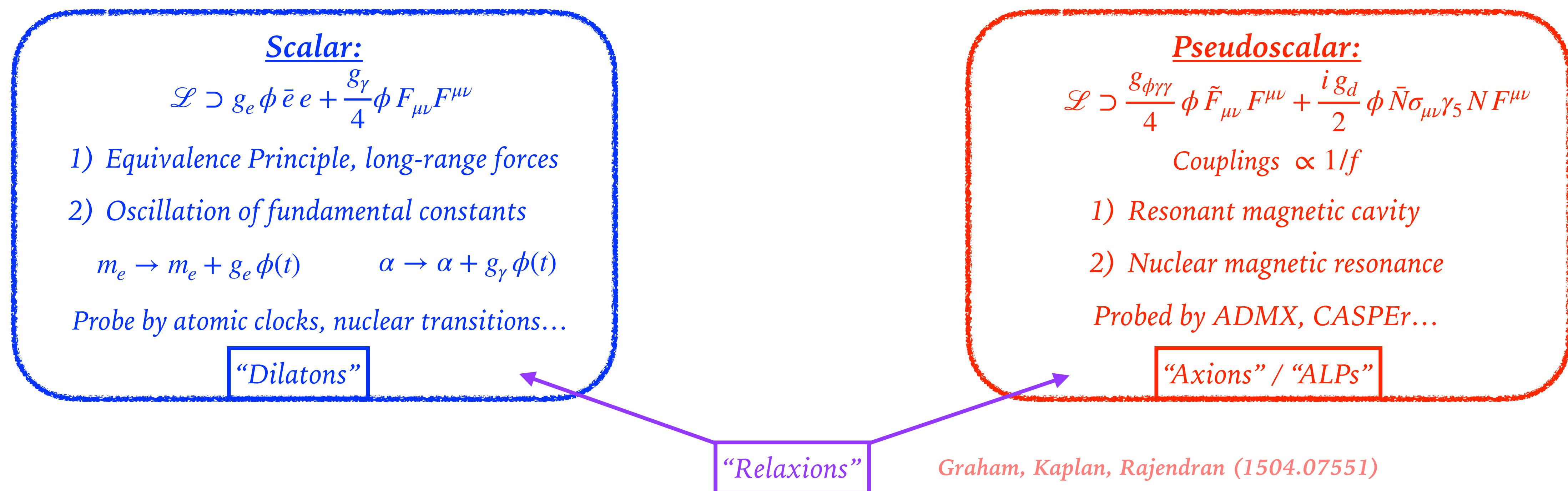
Thanks!



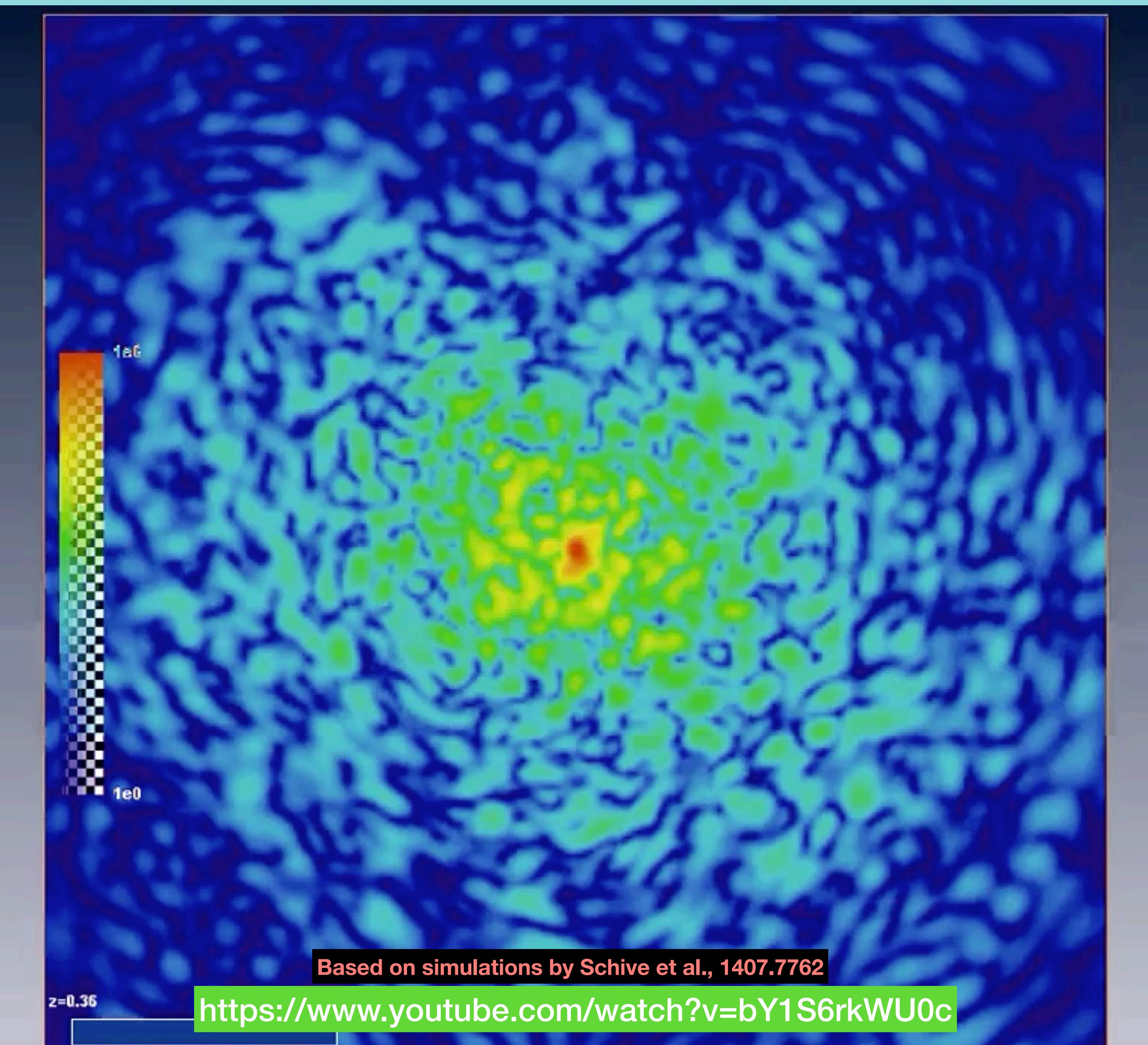
Bonus Round

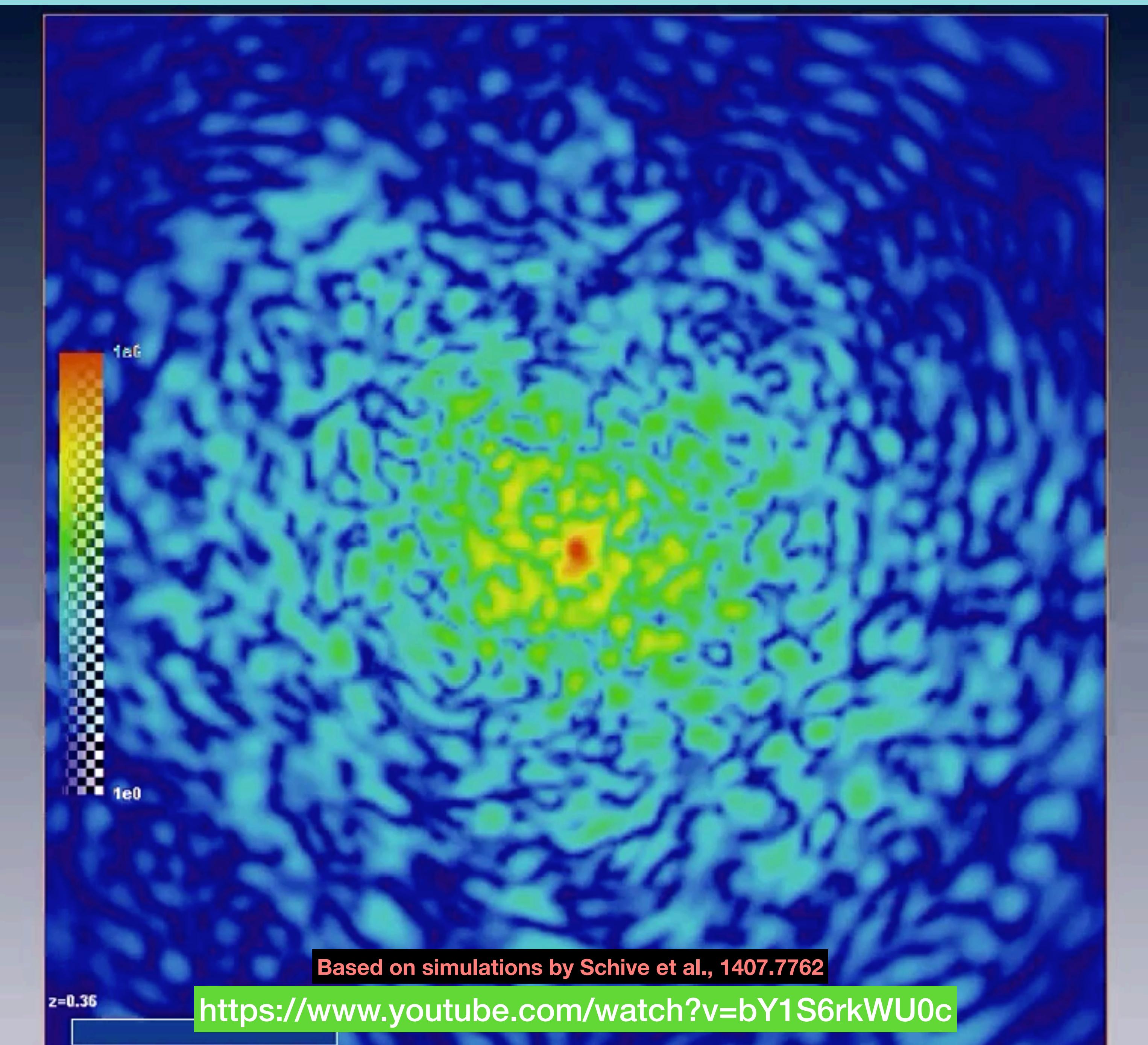
Light Scalars: Phenomenological Story

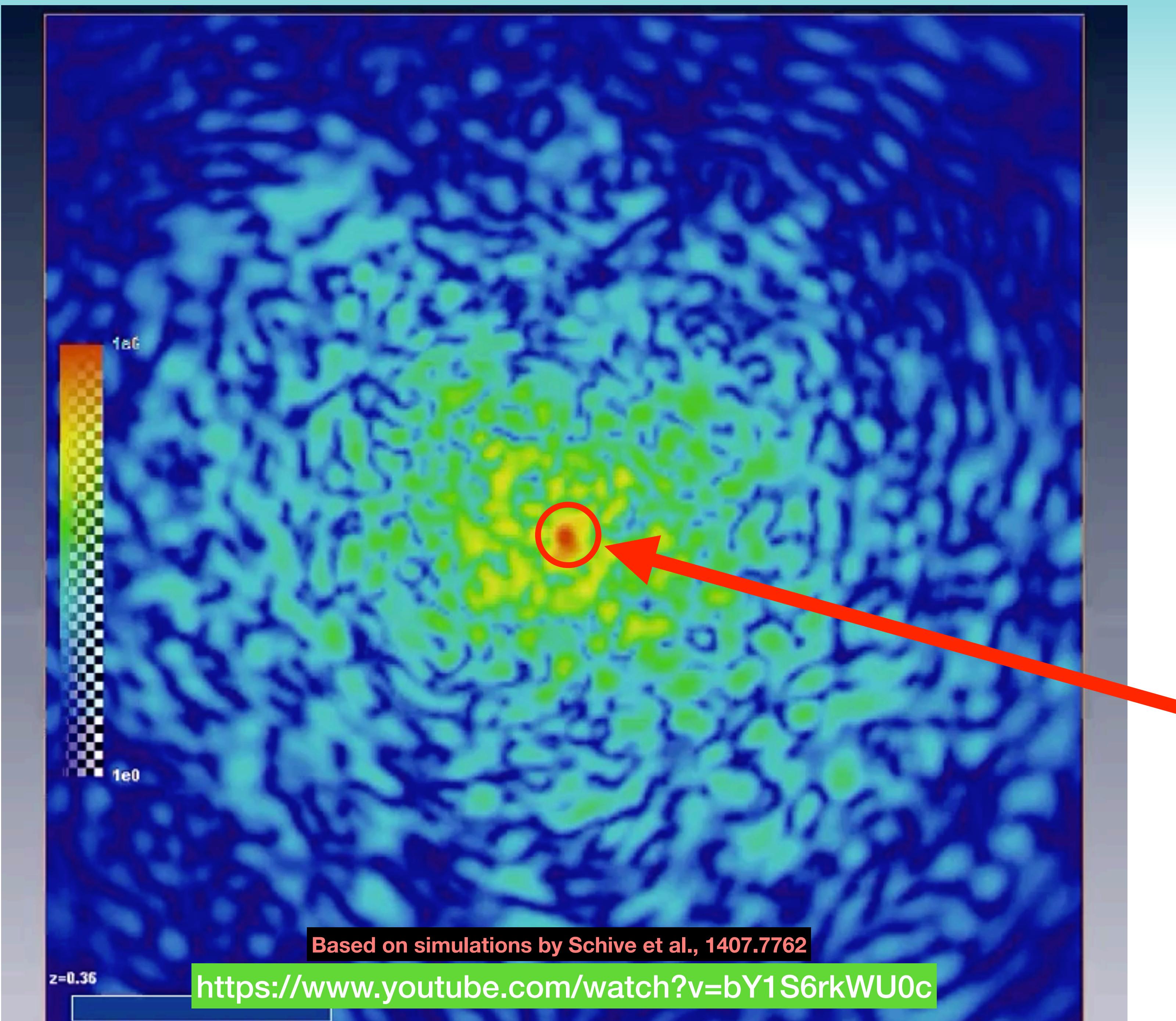
- DM field ϕ with extremely small mass $10^{-22} \text{ eV} \lesssim m_\phi \lesssim \text{eV}$
- Can have **scalar** or **pseudoscalar** couplings to matter

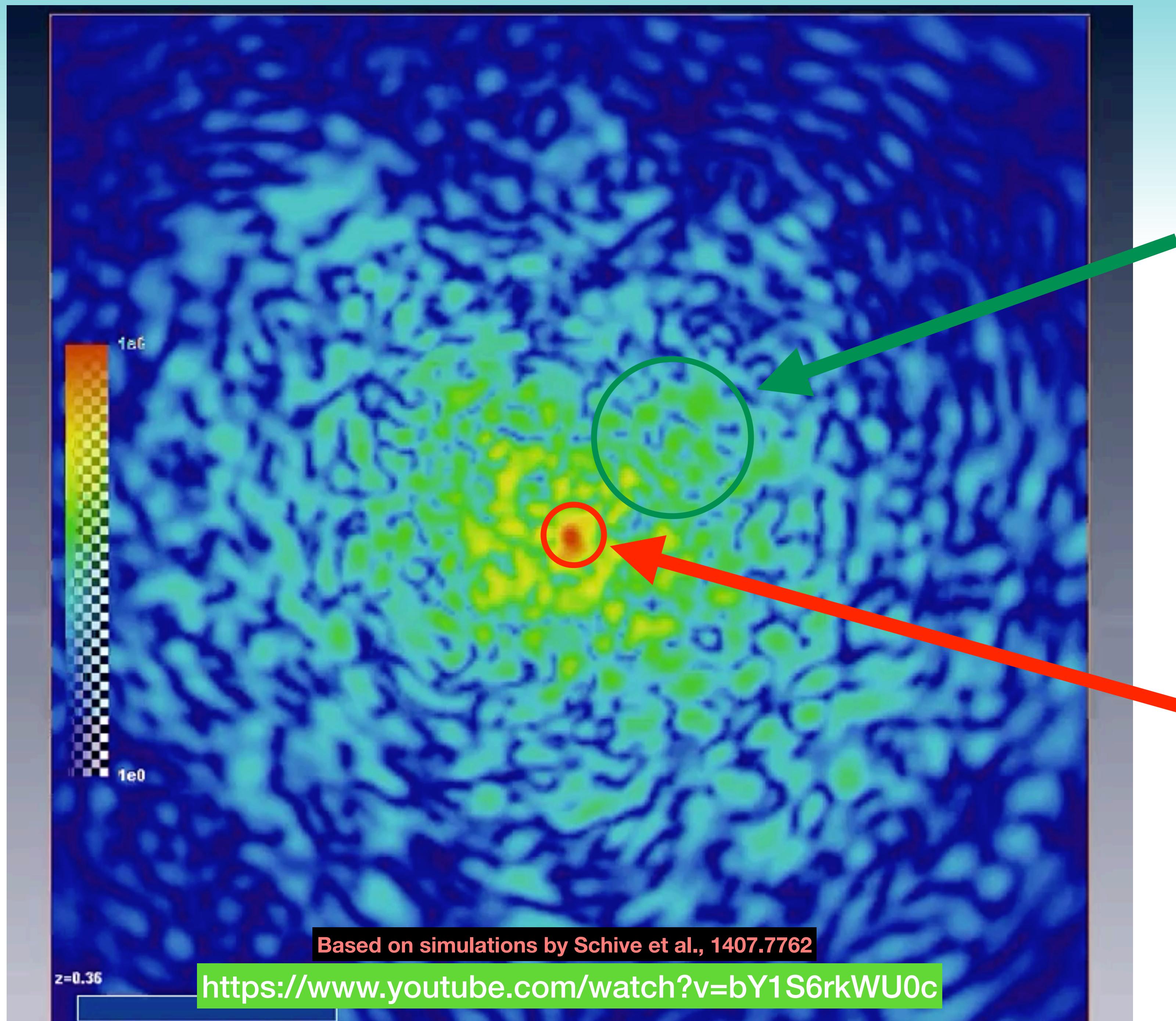


- Might couple only gravitationally...!



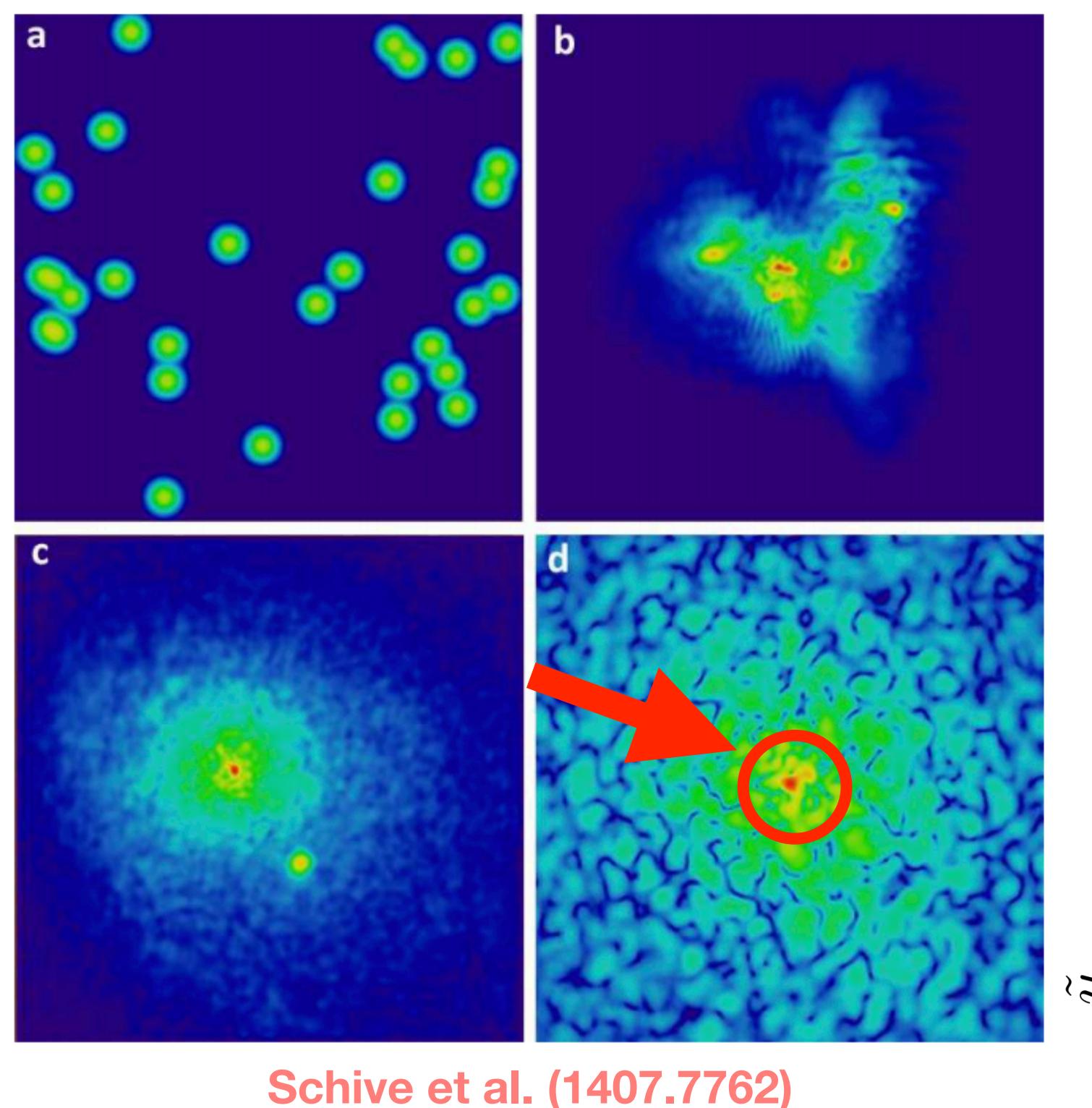






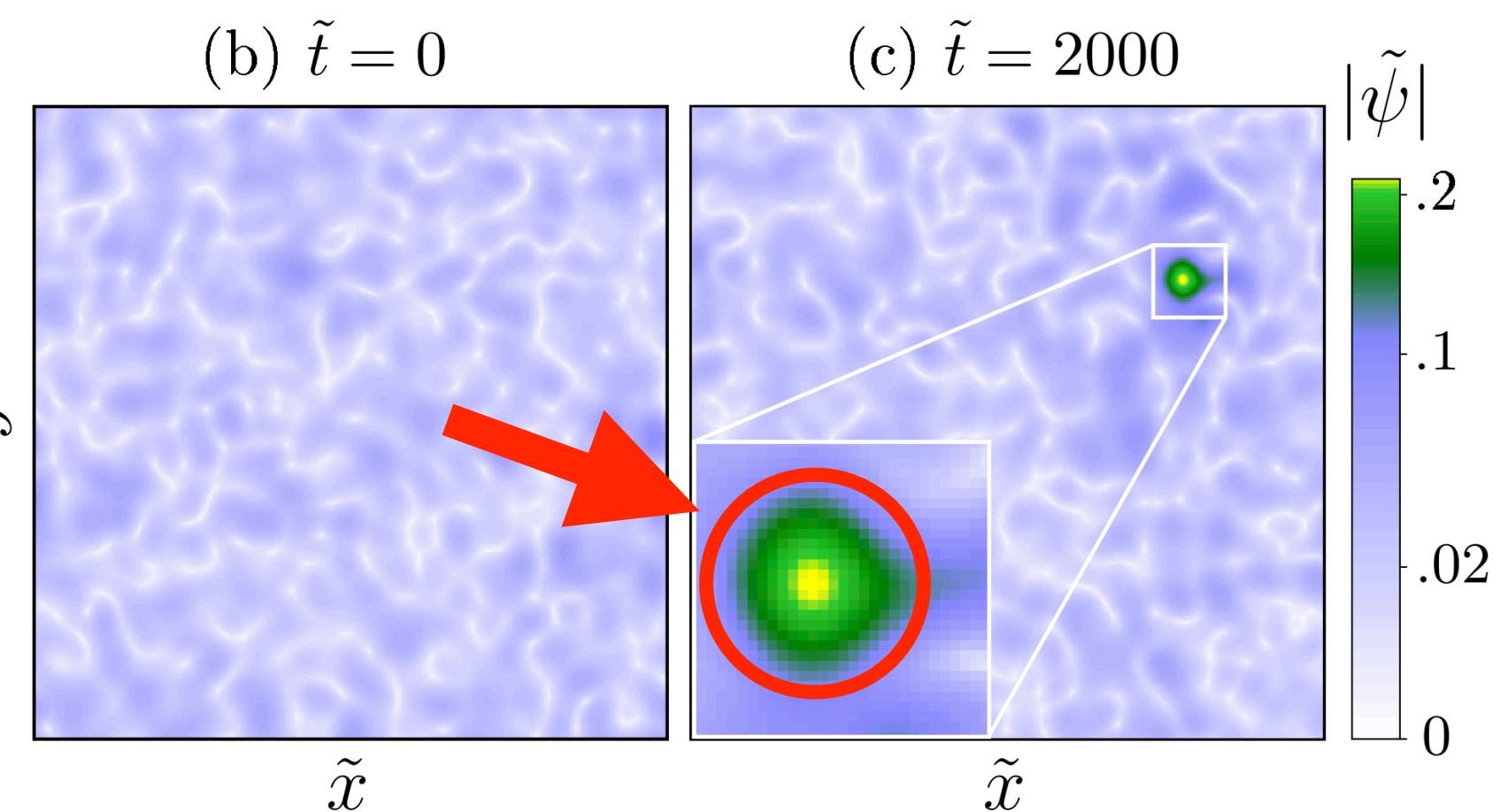
Do Axion Stars Really Form?

Mocz et al. (1705.05845)

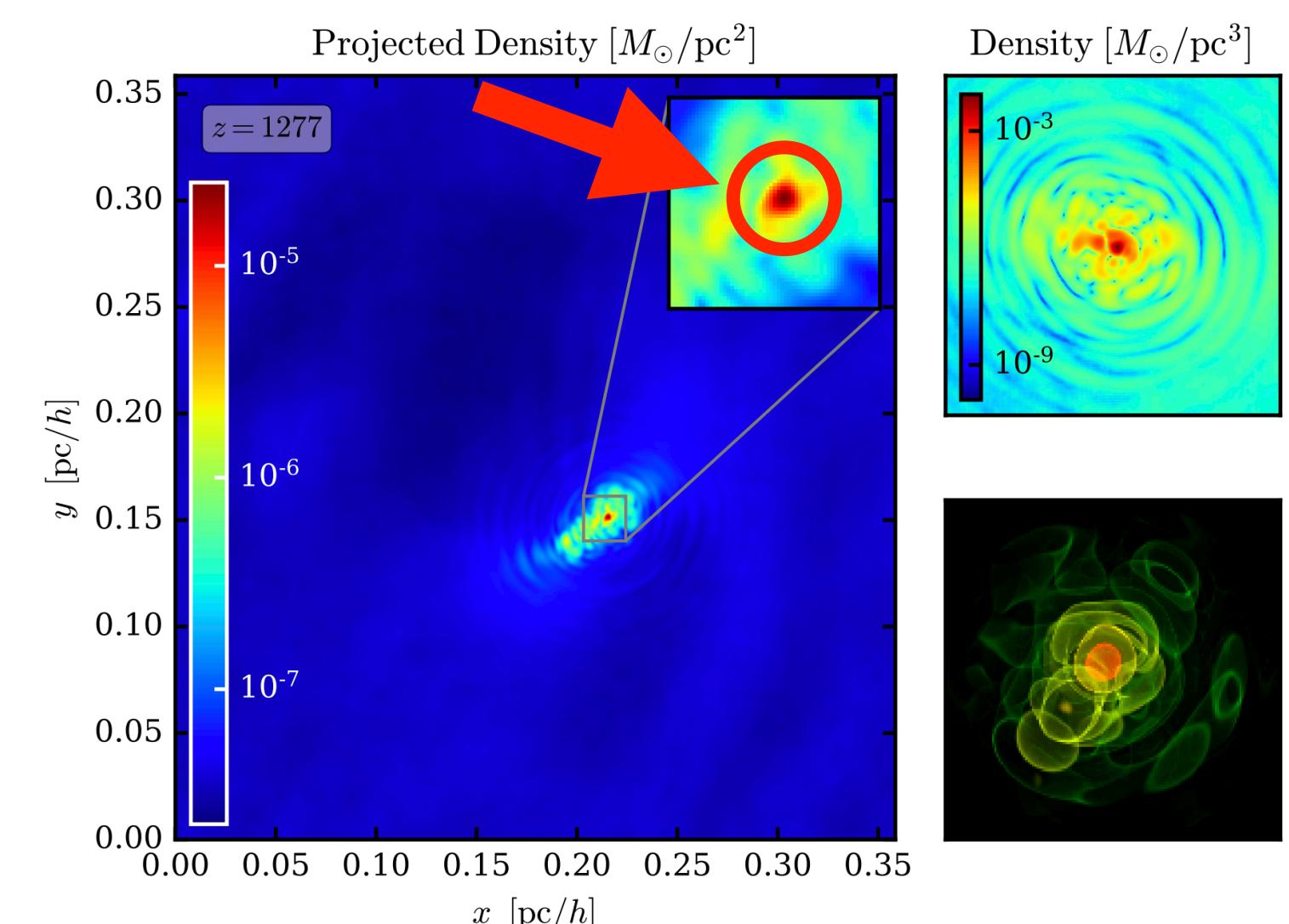


Schive et al. (1407.7762)

Levkov, Panin, Tkachev (1804.05857)



Eggemeier and Niemeyer (1906.01348)



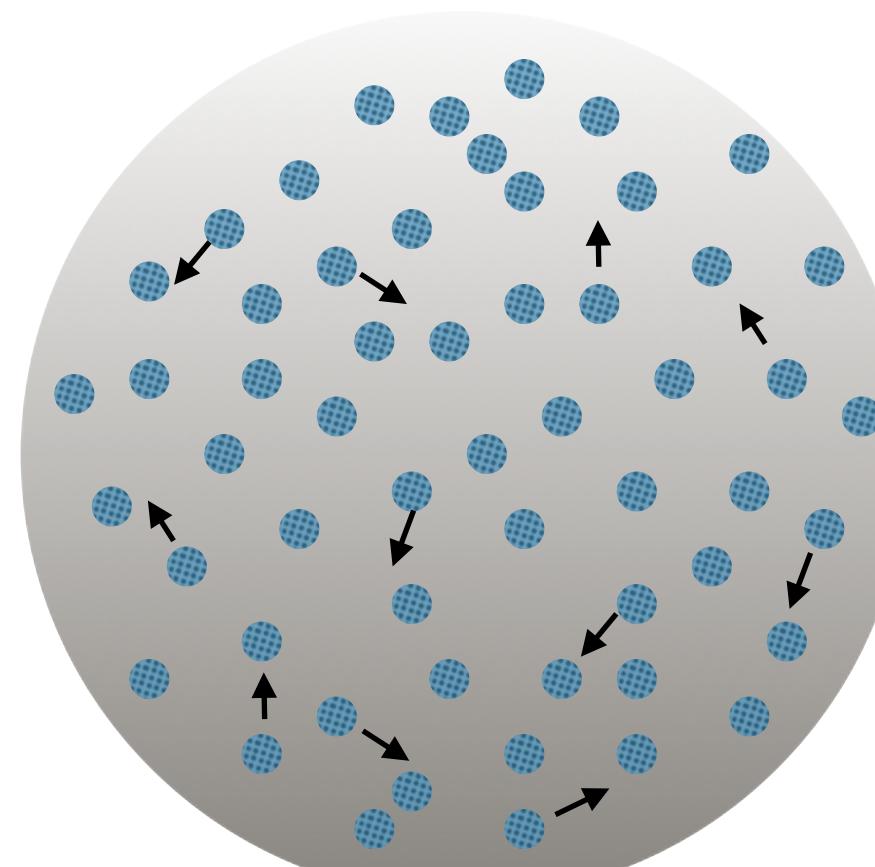
Do Axion Stars Really Form? (2)

- Evidence 2: Analytic argument

- Gravitational relaxation of quasiparticles sufficient for formation

Velocity change per crossing

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



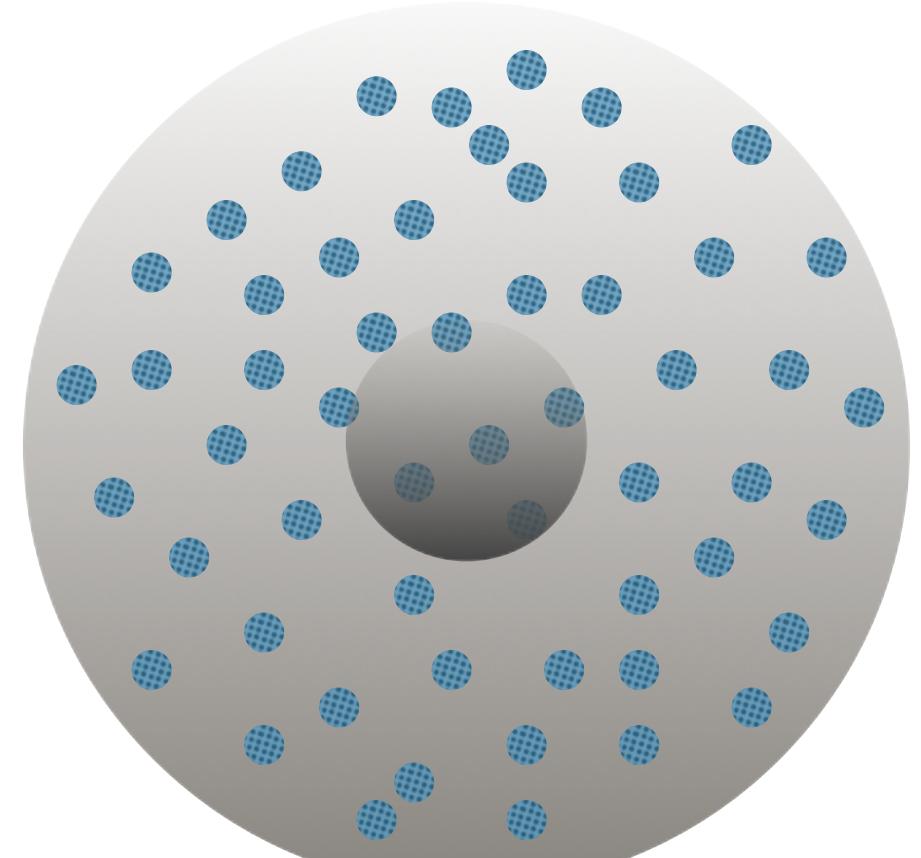
Quasiparticle dispersion

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

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

Fractional velocity change

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



Soliton formation

Relaxation to ground state

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

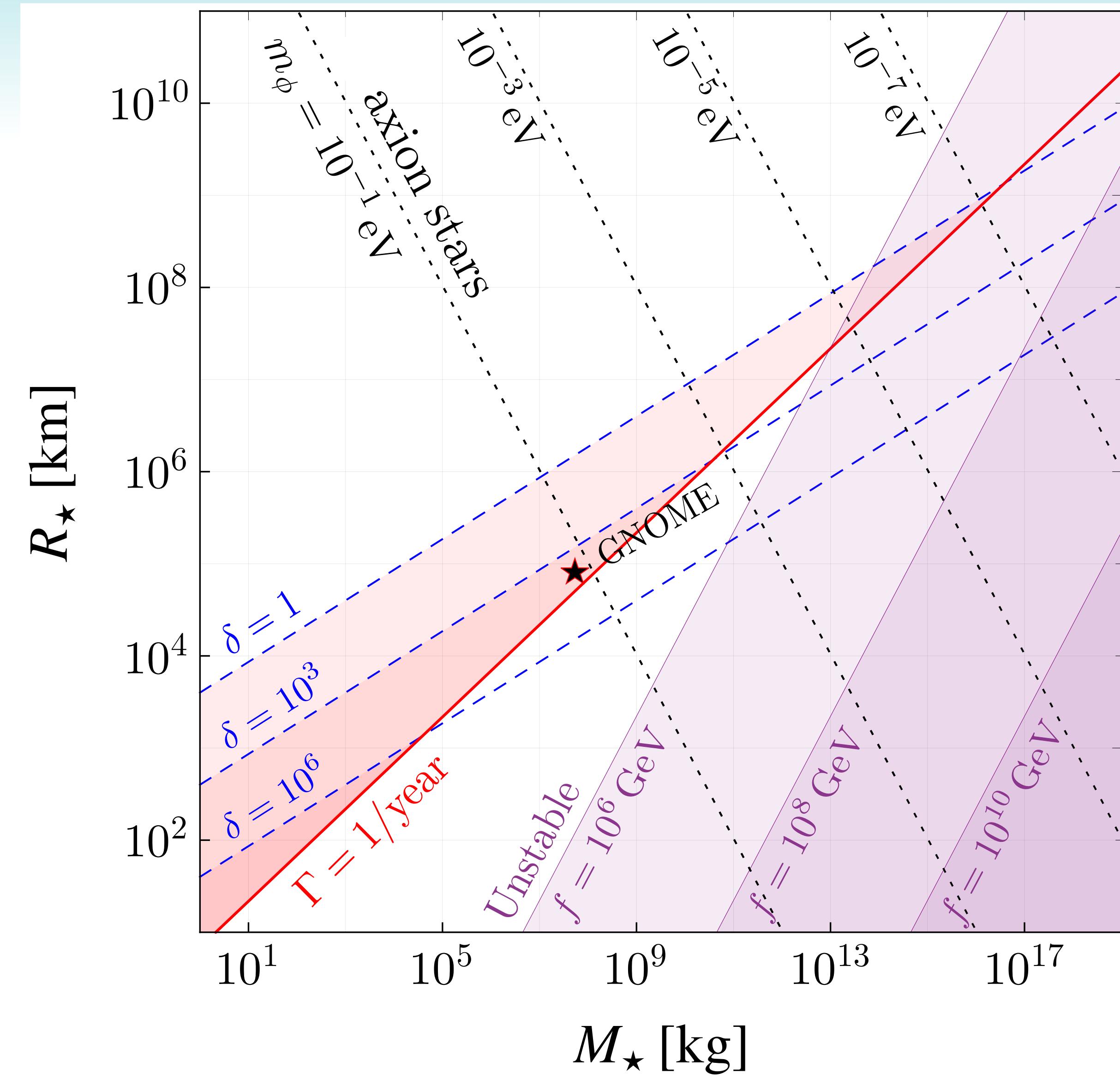
Analytic timescale matches simulation results!

See also Levkov, Panin, Tkachev (1804.05857)

Transient axion stars encounters with Earth?

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

$$\Gamma \propto \rho_{local} R_\star^3 m_\phi^2$$

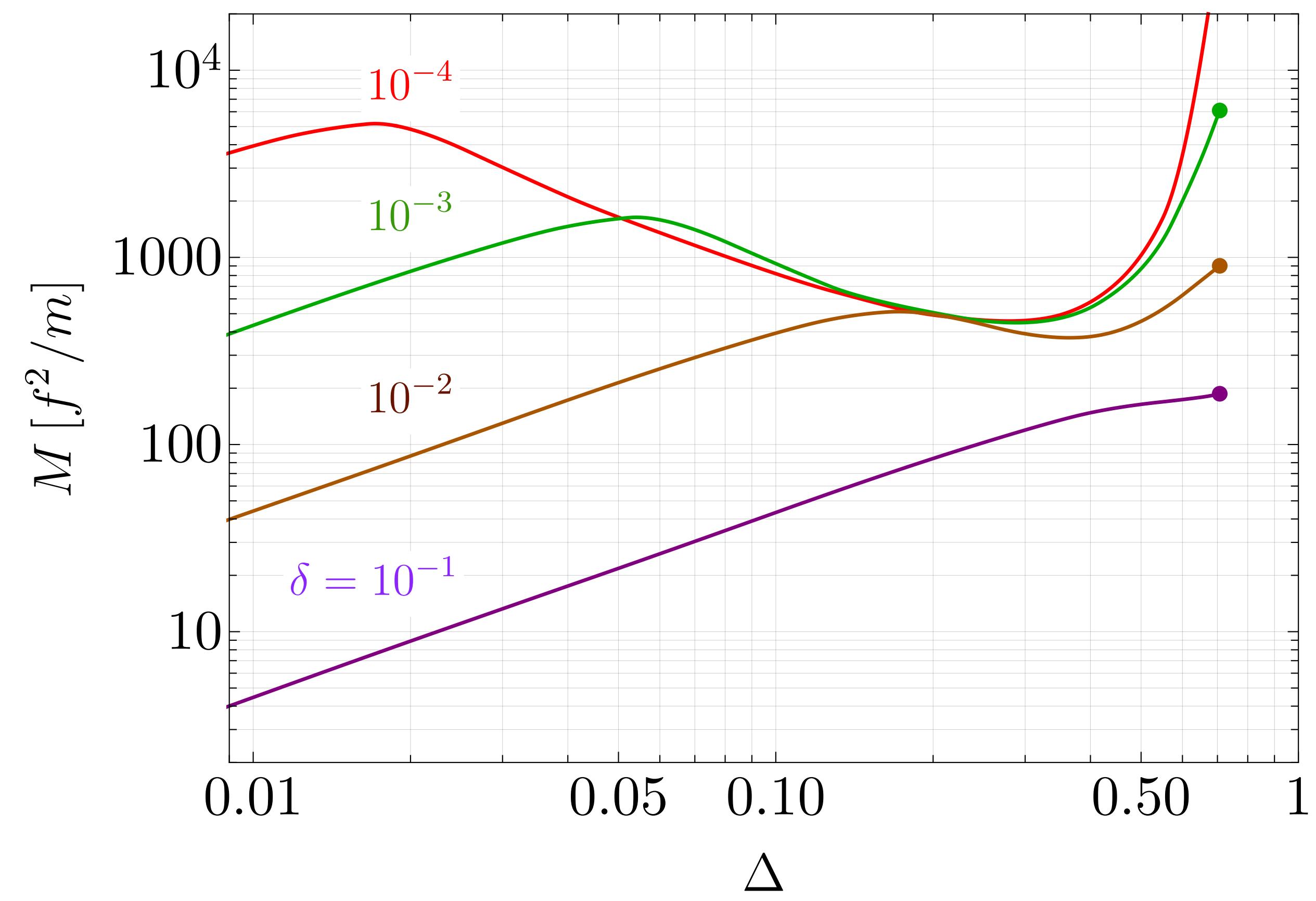


(Difficult)

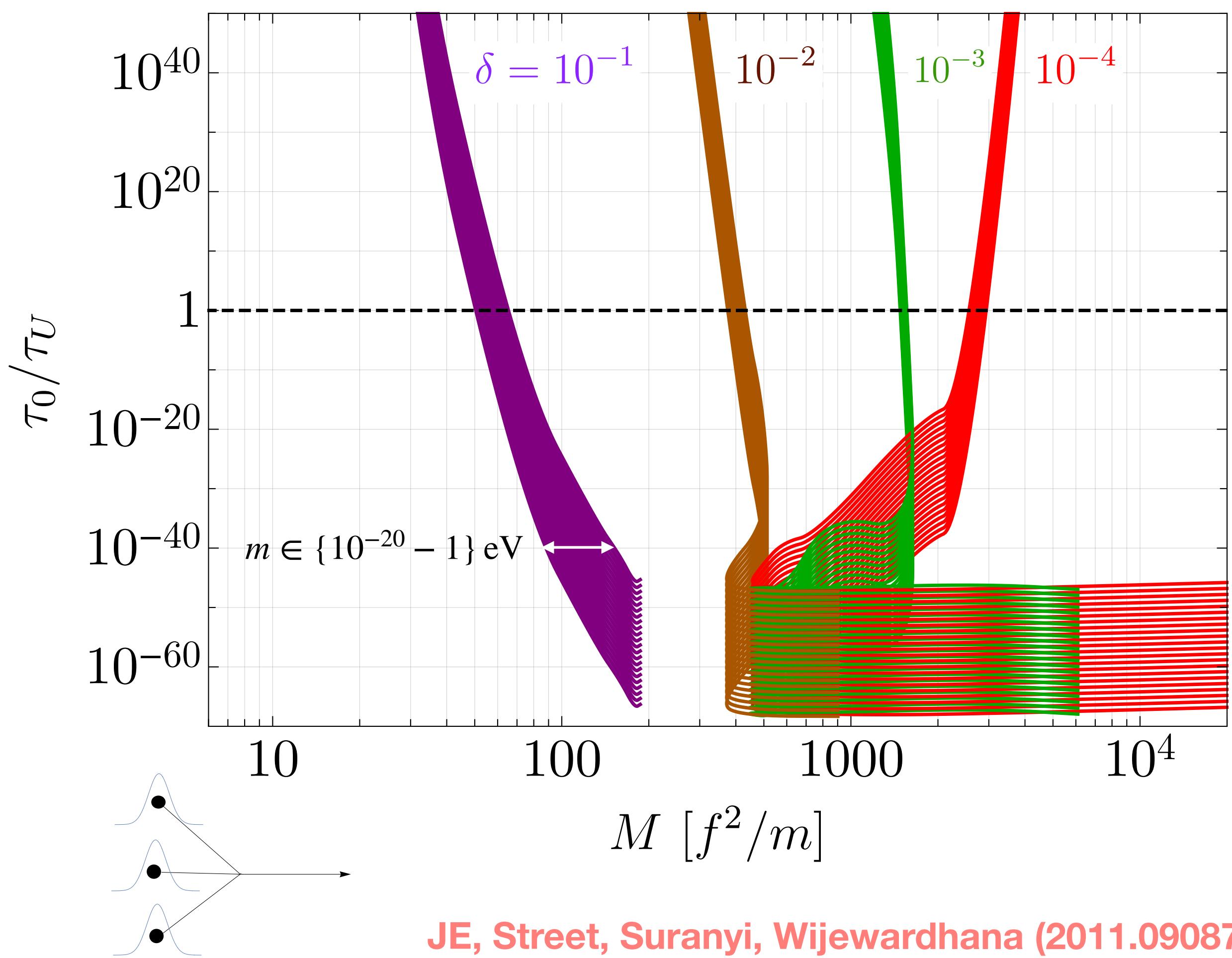
Banerjee, Budker, JE, Kim,
Perez (1902.08212)

Results

Mass- Δ



Lifetime-Mass



A Field-Theoretic Method

- Start from the UV theory: Einstein+Klein-Gordon (EKG) equations

$$\square \phi - V'(\phi) = 0$$

Ansatz for the quantum theory:

$$\phi(t, \vec{r}) = \sum_{n\ell m} \hat{a}_{n\ell m} R_{n\ell}(r) Y_{\ell m}(\hat{r}) e^{i\mu_{n\ell} t} + \text{h.c.}$$

↓
Ground-State
Only
↓

$$\phi(t, \vec{r}) = \hat{a}_0 R(r) e^{i\mu_0 t} + \text{h.c.} \quad (\star)$$

N-Particle Ground State $|N\rangle = \frac{(\hat{a}_0^\dagger)^N}{\sqrt{N!}} |0\rangle$

$$\langle N | \square \phi - V'(\phi) | N-1 \rangle = 0$$

If $V(\phi) = \frac{1}{2}m^2\phi^2$: Then (\star) is an exact solution for appropriately-chosen $R(r)$

$$(\mu_0^2 - m^2 + \nabla^2) R(r) + (\text{gravity}) = 0$$

$$G^{\mu\nu} = 8\pi G T^{\mu\nu}$$

$$ds^2 = B(r) dt^2 - A(r) dr^2 - r^2 d\Omega^2$$

$$T_\mu^\nu = \text{diag}(\rho_E, -p_r, -p_\perp, -p_\perp)$$

LHS: Classical GR

RHS: Semi-classical (expectation values)

$$\langle N | T^{\mu\nu} | N \rangle \supset \langle N | \phi^2 | N \rangle = 2NR(r)^2$$

Systems of Self-Gravitating Particles in General Relativity and the Concept of an Equation of State

REMO RUFFINI and SILVANO BONAZZOLA
Phys. Rev. **187**, 1767 – Published 25 November 1969

Article

References

Citing Articles (359)

PDF

Export Citation

EKG Equations

- Coupled equations of motion for $R(r), A(r), B(r)$

$$\langle N | \square \phi - V'(\phi) | N - 1 \rangle = 0 \quad \rightarrow \quad R'' + \left(\frac{2}{r} + \frac{B'}{2B} - \frac{A'}{2A} \right) R' + \left(\frac{\mu_0^2 A}{B} - m^2 \right) R = 0$$

$$G^{\mu\nu} = 8\pi G \langle N | T^{\mu\nu} | N \rangle \quad \rightarrow \quad \begin{aligned} \frac{A'}{A^2 r} + \frac{A-1}{A r^2} &= \frac{8\pi}{M_P^2} \left[\frac{\mu_0^2 N R^2}{B} + \frac{N R'^2}{A} + N m^2 R^2 \right] \\ \frac{B'}{A B r} - \frac{A-1}{A r^2} &= \frac{8\pi}{M_P^2} \left[\frac{\mu_0^2 N R^2}{B} + \frac{N R'^2}{A} - N m^2 R^2 \right] \end{aligned}$$

- Ruffini+Bonazzola (RB): No self-interactions, solved EKG equations numerically

Ruffini and Bonazzola, Phys Rev '69

- Barranco+Bernal: Extend RB to leading self-interactions, but found equations too difficult to solve in some regions of parameter space

Barranco and Bernal (1001.1769)

Double Expansion

JE, Suranyi, Vaz, Wijewardhana (1412.3430)

- Take the non relativistic limit, keeping track of small parameters

- Two approximations:

- Weak binding (NR limit):** $|\mu_0 - m| \ll m$, or define $\Delta \equiv \sqrt{1 - \frac{\mu_0^2}{m^2}} \ll 1$

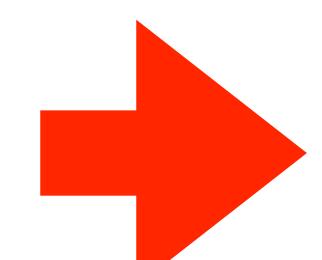
- Rescale $x = \Delta m r$, $Y(x) = \frac{2\sqrt{N} R(r)}{m \Delta}$

- Weak gravity:** $A(r) = 1 + \delta a(x)$, $B(r) = 1 + \delta b(x)$ with $\delta \equiv \frac{8\pi f^2}{M_P^2} \ll 1$

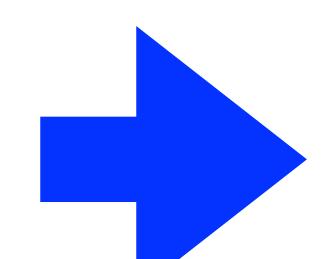
$$R'' + \left(\frac{2}{r} + \frac{B'}{2B} - \frac{A'}{2A} \right) R' + \left(\frac{\mu_0^2 A}{B} - m^2 \right) R - \frac{ANR^3}{2f^2} = 0$$

$$\frac{A'}{A^2 r} + \frac{A-1}{Ar^2} = \frac{8\pi}{M_P^2} \left[\frac{\mu_0^2 NR^2}{B} + \frac{NR^2}{A} + Nm^2 R^2 - \frac{N^2 R^4}{4f^2} \right]$$

$$\frac{B'}{ABr} - \frac{A-1}{Ar^2} = \frac{8\pi}{M_P^2} \left[\frac{\mu_0^2 NR^2}{B} + \frac{NR^2}{A} - Nm^2 R^2 + \frac{N^2 R^4}{4f^2} \right]$$

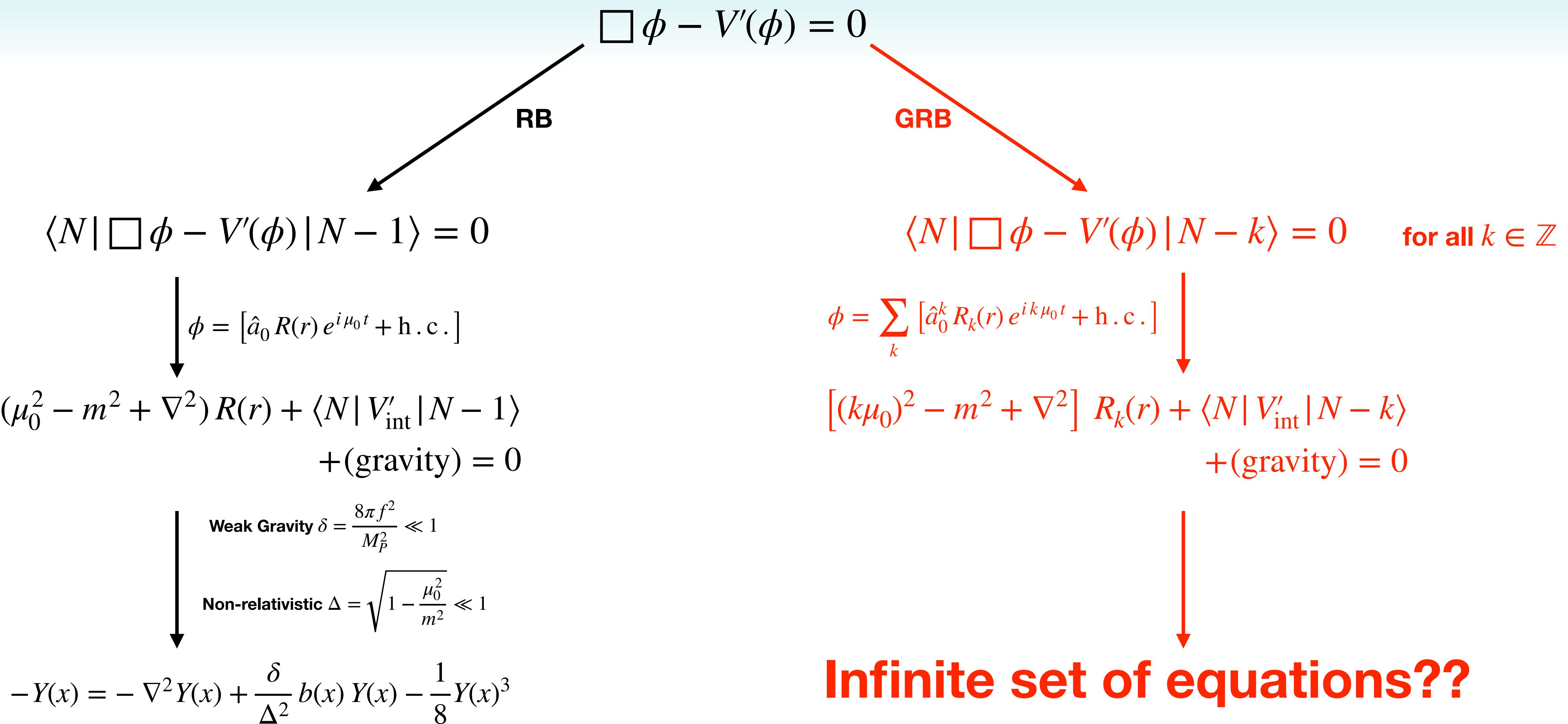


$$-Y(x) = -\nabla^2 Y(x) + \frac{\delta}{\Delta^2} b(x) Y(x) - \frac{1}{8} Y(x)^3$$



$$\nabla^2 b(x) = \frac{Y(x)^2}{2}$$

RB vs GRB



Contributions to k th GRB Equation

- Consider axion potential: $V_{\text{int}}(\phi) = V(\phi) - \frac{m^2}{2}\phi^2 = -\frac{1}{4!} \left(\frac{m}{f}\right)^2 \phi^4 + \frac{1}{6!f^2} \left(\frac{m}{f}\right)^2 \phi^6 - \dots$

$$V'_{\text{int}}(\phi) = -\frac{1}{3!} \left(\frac{m}{f}\right)^2 \phi^3 + \frac{1}{5!f^2} \left(\frac{m}{f}\right)^2 \phi^5 - \dots$$

- Apply GRB operator:

$$\phi^3 = \left[\sum_k [\hat{a}_0^k R_k(r) e^{ik\mu_0 t} + \text{h.c.}] \right]^3 = [\hat{a}_0 R_1(r) e^{i\mu_0 t} + \text{h.c.}]^3 + [\hat{a}_0^3 R_3(r) e^{i3\mu_0 t} + \text{h.c.}]^3$$

$$+ [\hat{a}_0 R_1(r) e^{i\mu_0 t} + \text{h.c.}]^2 [\hat{a}_0^3 R_3(r) e^{i3\mu_0 t} + \text{h.c.}] \\ + [\hat{a}_0 R_1(r) e^{i\mu_0 t} + \text{h.c.}] [\hat{a}_0^3 R_3(r) e^{i3\mu_0 t} + \text{h.c.}]^2 \\ + \dots$$

$|N-6\rangle$

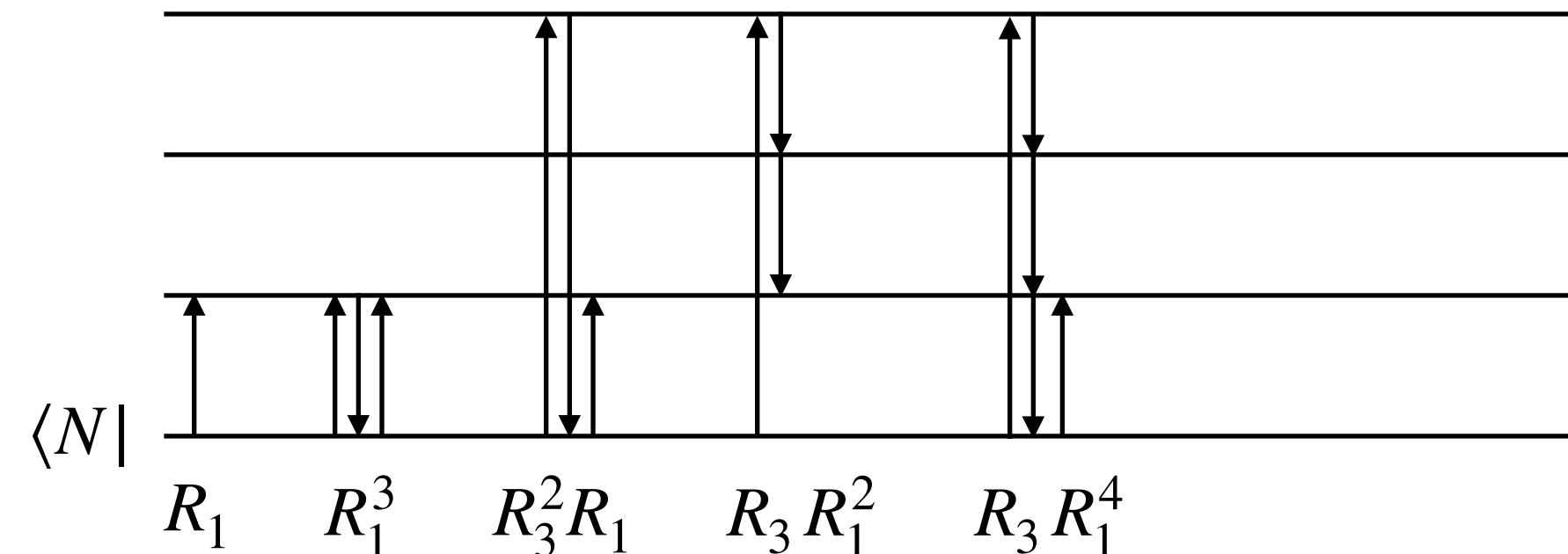
$|N-5\rangle$

$|N-4\rangle$

$|N-3\rangle$

$|N-2\rangle$

$|N-1\rangle$



$$\langle N | \phi^3 | N-1 \rangle \supset \{R_1^3, R_3 R_1^2, R_3 R_1^4, R_3^2 R_1, R_3^2 R_1^3, \dots\}$$

$$\langle N | \phi^5 | N-1 \rangle \supset \{R_1^5, R_3 R_1^2, R_3^2 R_1^5, \dots\}$$

GRB Expansion

- Organize higher-harmonic contributions in a power series in $\Delta \ll 1$:

RB

$$Y(x) = \frac{2\sqrt{N} R(r)}{m \Delta}$$

↓

GRB

$$Y_k(x) = \frac{2N^{k/2} R_k(r)}{m \Delta^k}$$

$$V_{\text{int}}(\phi) = -\frac{1}{4!} \left(\frac{m}{f} \right)^2 \phi^4 + \frac{1}{6!f^2} \left(\frac{m}{f} \right)^2 \phi^6 - \dots$$

$$V'_{\text{int}}(\phi)$$

ϕ^3	ϕ^5	ϕ^7
$\sum_k \hat{a}_0^k R_k(r) e^{ik\mu_0 t} + \text{h.c.}$		
Leading Order: $\mathcal{O}(\Delta^3)$	$R_1(r)^3 \propto \Delta^3 Y_1(x)^3$	✗
Next-To-Leading Order: $\mathcal{O}(\Delta^5)$	$R_3 R_1^2 \propto \Delta^5 Y_3 Y_1^2$	$R_1^5 \propto \Delta^5 Y_1^5$
NN-Leading Order: $\mathcal{O}(\Delta^7)$	$R_5 R_1^2 \propto \Delta^7 Y_5 Y_1^2$ $R_3^2 R_1 \propto \Delta^7 Y_3^2 Y_1$	$R_1^7 \propto \Delta^7 Y_1^7$ $R_3 R_1^4 \propto \Delta^7 Y_3 Y_1^4$

(Can set $R_{2k} = 0$,
since potential is even
function of ϕ)

- Even better: dynamical equation for R_k is $\langle N | \square \phi - V'(\phi) | N - k \rangle = 0$
 \Rightarrow At $\mathcal{O}(\Delta^k)$, need to solve at most $k-2$ equations!

GRB for Axion Stars

Ignoring gravity for now

JE, Suranyi, Wijewardhana (1712.04941)

- First GRB Equation: ($k=1$ at $\mathcal{O}(\Delta^5)$)

$$\langle N | \square \phi - V'(\phi) | N - 1 \rangle = 0 \quad \Rightarrow \quad -Y_1 + \nabla_x^2 Y_1 + \frac{1}{8} Y_1^3 - \frac{\Delta^2}{24} Y_1^5 + \frac{\Delta^2}{8} Y_1^2 Y_3 + \mathcal{O}(\Delta^7) = 0$$

Mass Term **Kinetic Term** **LO SI Term** **NLO SI Term** **LO GRB Correction**

- Second GRB Equation: ($k=3$ at $\mathcal{O}(\Delta^5)$)

$$\langle N | \square \phi - V'(\phi) | N - 3 \rangle = 0 \quad \Rightarrow \quad (8 - 9\Delta^2)Y_3 + \nabla_x^2 Y_3 + \frac{1}{24} Y_1^3 - \frac{\Delta^2}{16} Y_1^5 + 6\Delta^2 Y_1^2 Y_3 + \mathcal{O}(\Delta^7) = 0$$

- Third GRB Equation for Y_5 couples only at $\mathcal{O}(\Delta^7)$

Dense (Relativistic) Axion Stars

- Originally “axitons”, cosmological origin and short lifetime

Kolb+Tkachev (astro-ph/9311037)

- Resurrected in NR limit

Braaten, Mohapatra, Zhang (1512.00108)

- Relativistic corrections:

- Bound state: Backreaction of higher-harmonic modes

Vissinelli, Baum, Redondo, Freese, Wilczek (1710.08910)

- Think of integrating out modes of energy $2\mu_0, 3\mu_0, \dots$

- Organize as power series in Δ : $\phi(t, \vec{r}) \propto \sum_k [\Delta^k \hat{a}_0^k Y_k(r) e^{i k \mu_0 t} + \text{h.c.}]$

JE, Suranyi, Wijewardhana (1712.04941)

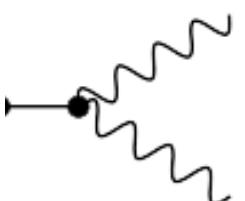
See also decay of oscillons,
Hertzberg (1003.3459)

Or for repulsive self-interactions,

Hertzberg, Rompineve, Yang (2010.07927)

- Scattering states: Decay processes in the star

- $\phi \rightarrow \gamma\gamma$ is super slow: $\tau_{\phi \rightarrow \gamma\gamma} \gg \tau_U$



- Self-interaction induces $(2k \phi \rightarrow 2k' \phi)$ “quantum decay” for on-shell axions

Braaten, Mohapatra, Zhang (1609.05182)

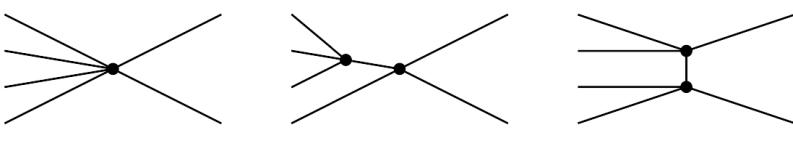
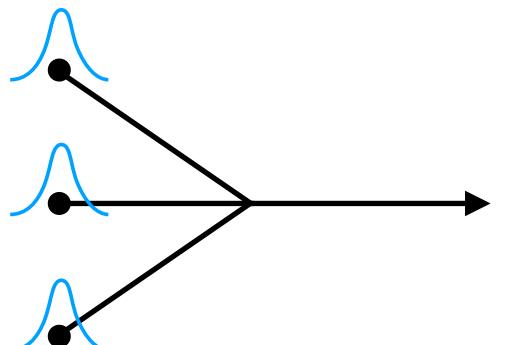


FIG. 1: Tree diagrams for $4a \rightarrow 2a$ in the relativistic axion theory.

- Inside axion star, axions not in momentum eigenstates: “classical decay” through forbidden channels

JE, Suranyi, Wijewardhana (1512.01709)
with Ma (1705.05385)



- Decay rate

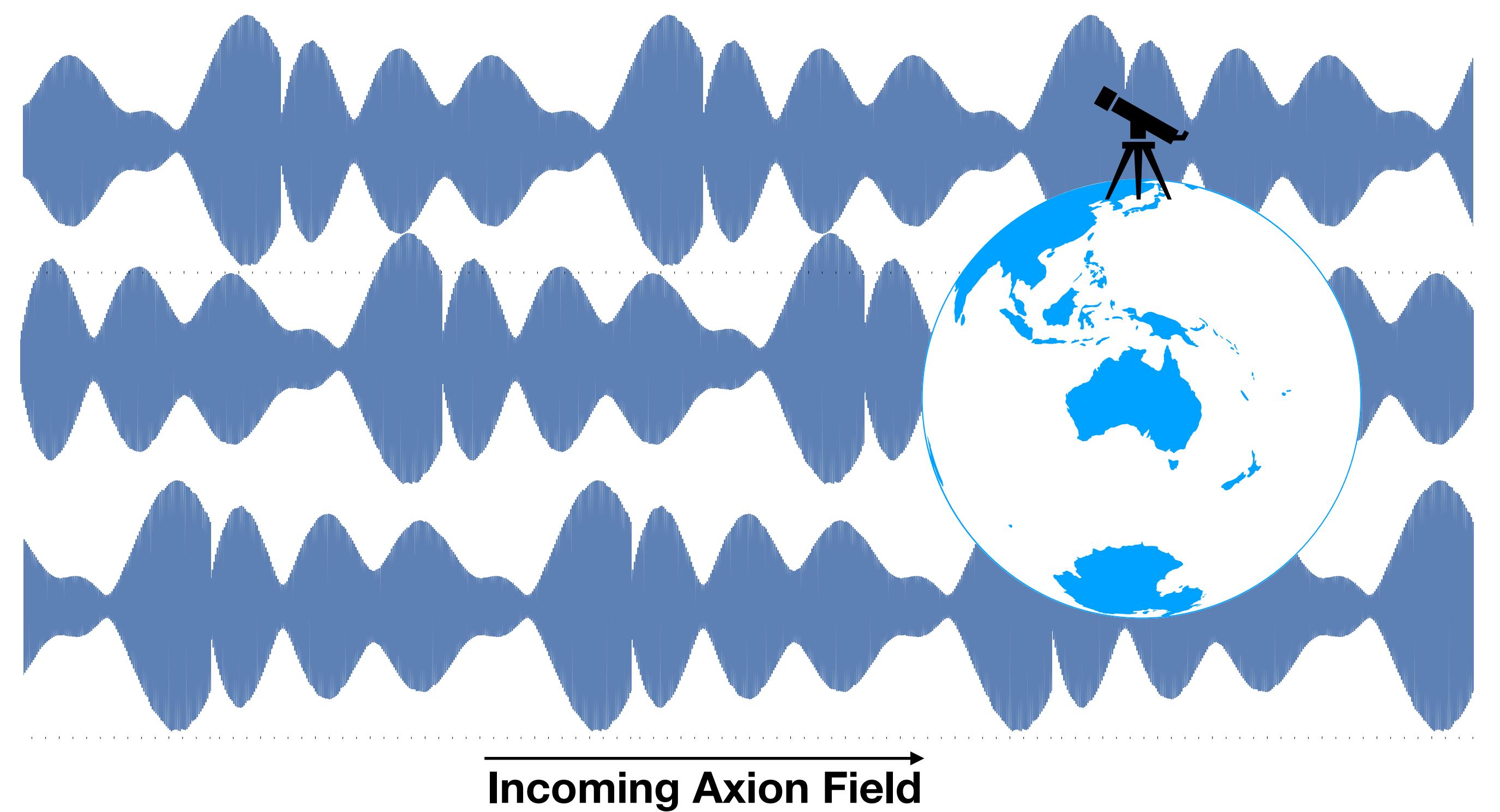
$$\Gamma_{3 \rightarrow 1} = \frac{1}{T} \int \frac{dp}{(2\pi)^3 2\omega_p} \left| \int d^4x \langle N | V(\phi) | N - 3, p \rangle \right|^2 \propto m \Delta e^{-1/\Delta}$$

only fast when Δ is relatively large: $\Delta \gtrsim 0.05$

Seeking A Fresh Idea

- Recall how detection of axion field usually works:

Dark Matter Axions



$$\rho_{DM} \simeq 0.4 \text{ GeV/cm}^3$$

$$v_{DM} \simeq 10^{-3} \Rightarrow \text{High Quality}$$

$$Q_{DM} \sim v_{DM}^{-2} \sim 10^6$$