Tales of axion dark matter substructure

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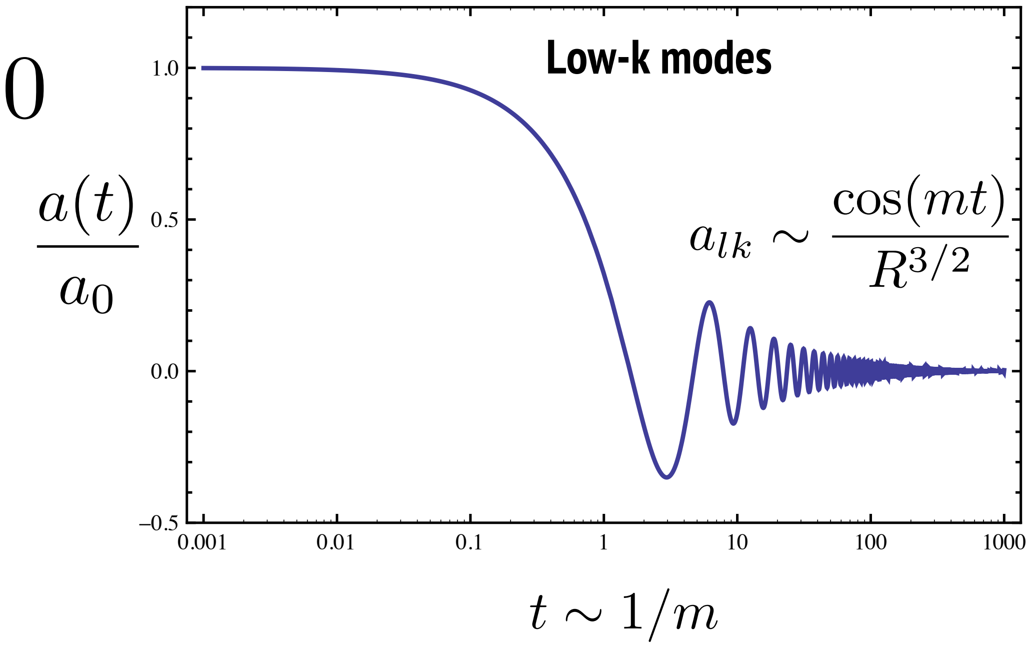
Axion (NR-Field) dark matter

- **Cold dark matter means ...** $\rho \propto 1/R^3, p/\rho \sim 0$

- **(decoupled) scalar field, a** $S = \int d^4x\sqrt{-g}\left(\frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}m^2a^2\right)$

EOM (FRW) $\ddot{a} + 3H\dot{a} - \frac{1}{R^2}\nabla^2 a + m^2 a = 0$



EM-tensor $\langle T^\mu{}_\nu \rangle \sim \mathrm{diag}\,(\rho, -p, -p, -p)$

Low-k modes

$$\rho = \frac{1}{2}(\dot{a})^2 + V(a) \sim \rho_1/R^3$$

$$p = \frac{1}{2}(\dot{a})^2 - V(a) \sim \rho\cos(2mt)$$ **(~0 in a time averaged sense)**

Gradient terms bring some fun to the game ...

Bose stars 1

- **Spherical Solutions of the EOM + Gravity (assume NR)**

$$\ddot{a} - a_{rr} - \frac{2a_r}{r} + (1 + 2\phi)m^2 a = 0$$

$$\nabla^2 \phi = 4\pi G\, \rho$$

$$\rho \simeq \frac{1}{2}(\dot{a})^2 + \frac{1}{2}m^2 a^2$$

Equilibrium with gradient pressure

- **Basic equations (amplitude vs Star Mass)**

$$a(r,t) \sim A(r)\cos mt \qquad \rho \sim \frac{1}{2}m^2A^2(r) \qquad M \sim m^2A^2R^3$$

- **Energy for a given Mass** $U = \int dV \left(\frac{1}{2}\dot{a}^2 + \frac{1}{2}m^2a^2 + \frac{1}{2}(\nabla a)^2 - \text{grav}\right)$

$$M \quad \sim \frac{A^2}{R^2} \times R^3 \quad \sim -\frac{GM^2}{R}$$

- **Equilibrium**

$$U \sim M + \frac{M}{m^2R^2} - \frac{GM^2}{R}$$

$$\boxed{\frac{dU}{dR} = 0 \rightarrow R_{\mathrm{eq},99} \sim \frac{10}{Gm^2M}}$$

gradient pressure
decreases energy
expanding

gravity
decreases energy
contracting

[sometimes called quantum pressure]

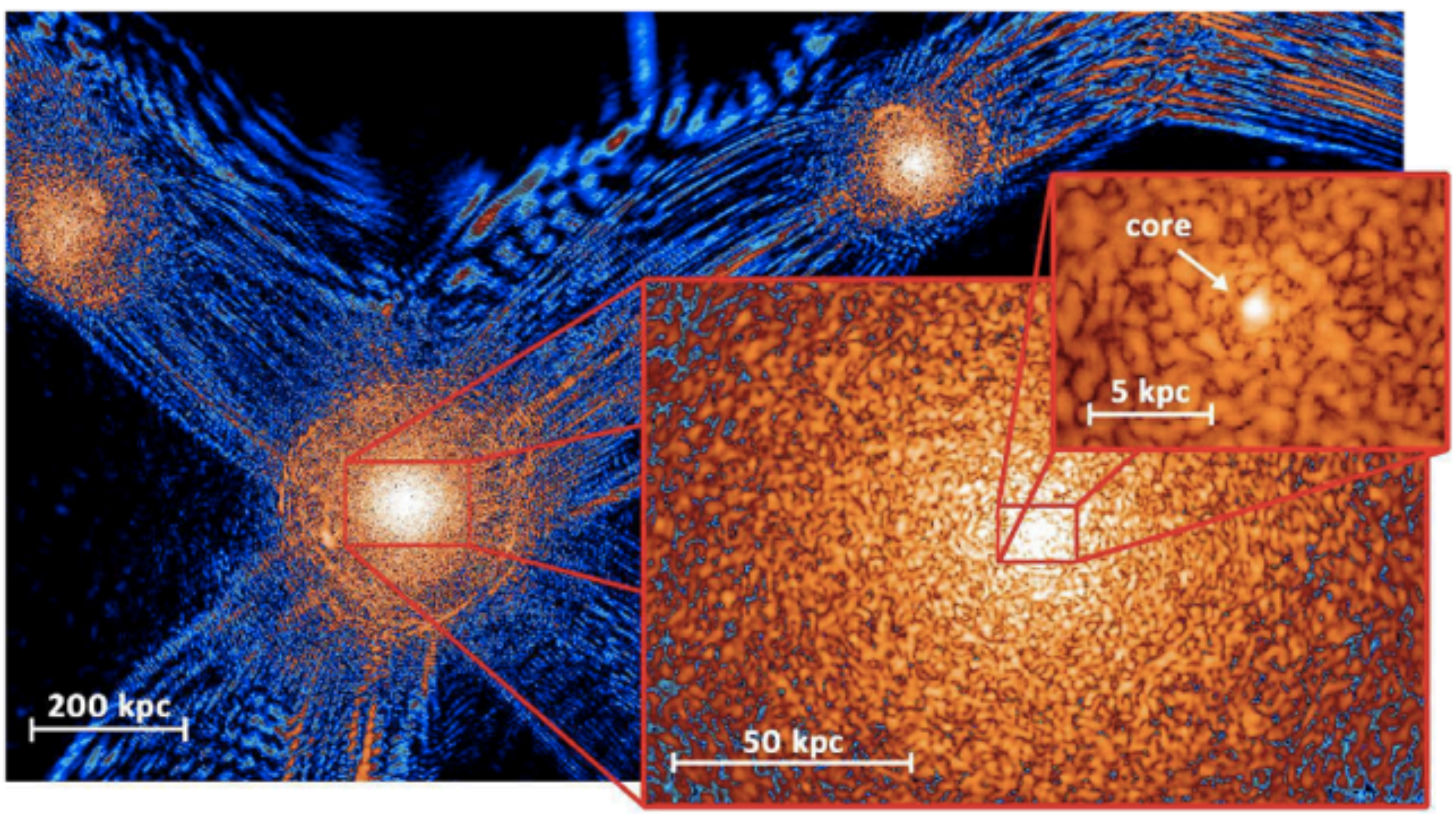
Fuzzy DM and small-scale structure problems

(Hu 2000,..., Hui 2017)

- Minimum radius 4 given mass $R \sim \dfrac{10}{Gm^2 M}$

- Gradient pressure implies a Jeans mass in structure formation, which suppresses small scale features (cusps, # low mass satelites...)

- Typical value $m \sim 10^{-22}\mathrm{eV}$ at odds with Ly-alpha



Halos composed of central cores' (Bose star) + CDM-like halo

Schive 2014

Axion dark matter

- **Axion is the promotion of the theta-angle of QCD to a field**

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\alpha_s}{4\pi} G\widetilde{G}\theta$$

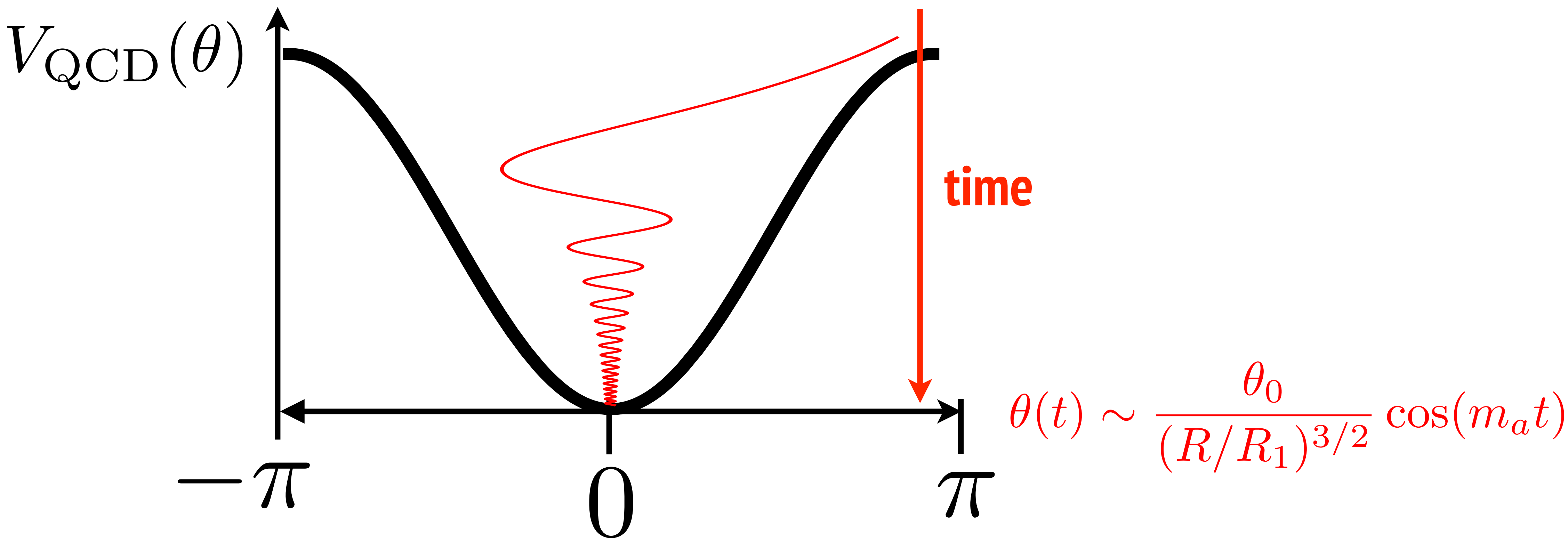
CP violation, neutron EDM, etc...

Axion dark matter

- Axion is the promotion of the theta-angle of QCD to a field

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\alpha_s}{4\pi} G\widetilde{G}\theta + \frac{f_a^2}{2}(\partial_\mu \theta)(\partial^\mu \theta) + \ldots$$

- QCD gives the axion a potential with a minimum at zero [strong CP solved!]



- Relaxation is incomplete ... -> cold dark matter

Axion dark matter

- Axion is the promotion of the theta-angle of QCD to a field

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \underline{\frac{\alpha_s}{4\pi} G\widetilde{G}\theta} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + \ldots$$

- canonically normalised axion $a = \theta \times f_a$, new energy scale

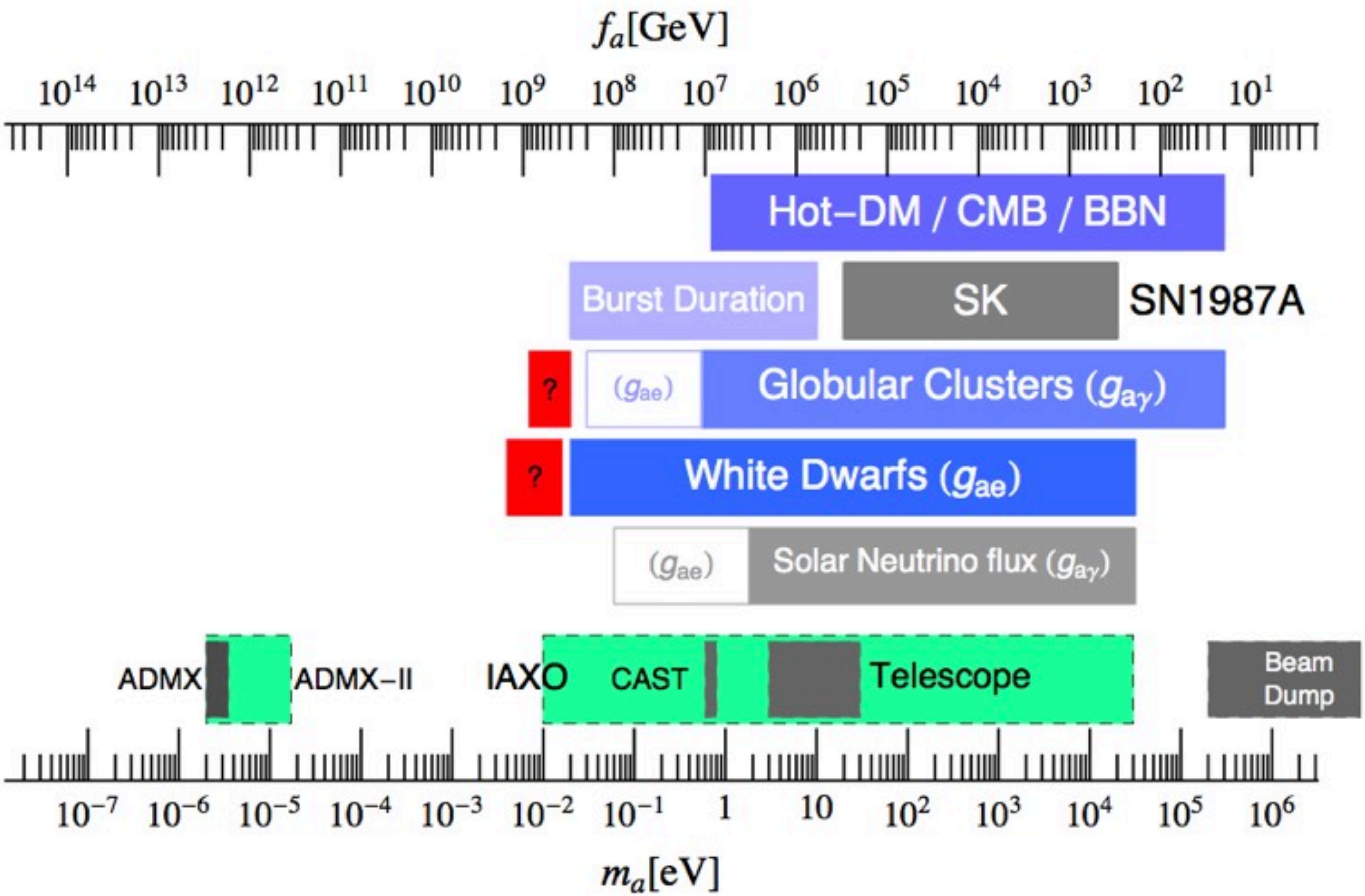
- In the low-energy-lagrangian appears as $\theta = a/f_a$

- Axion mass suppressed by fa $$m_a^2 = \frac{1}{f_a^2}\frac{\partial^2 V_{\rm QCD}}{\partial\theta^2} = \frac{\chi}{f_a^2}$$

- Axion interactions too ...

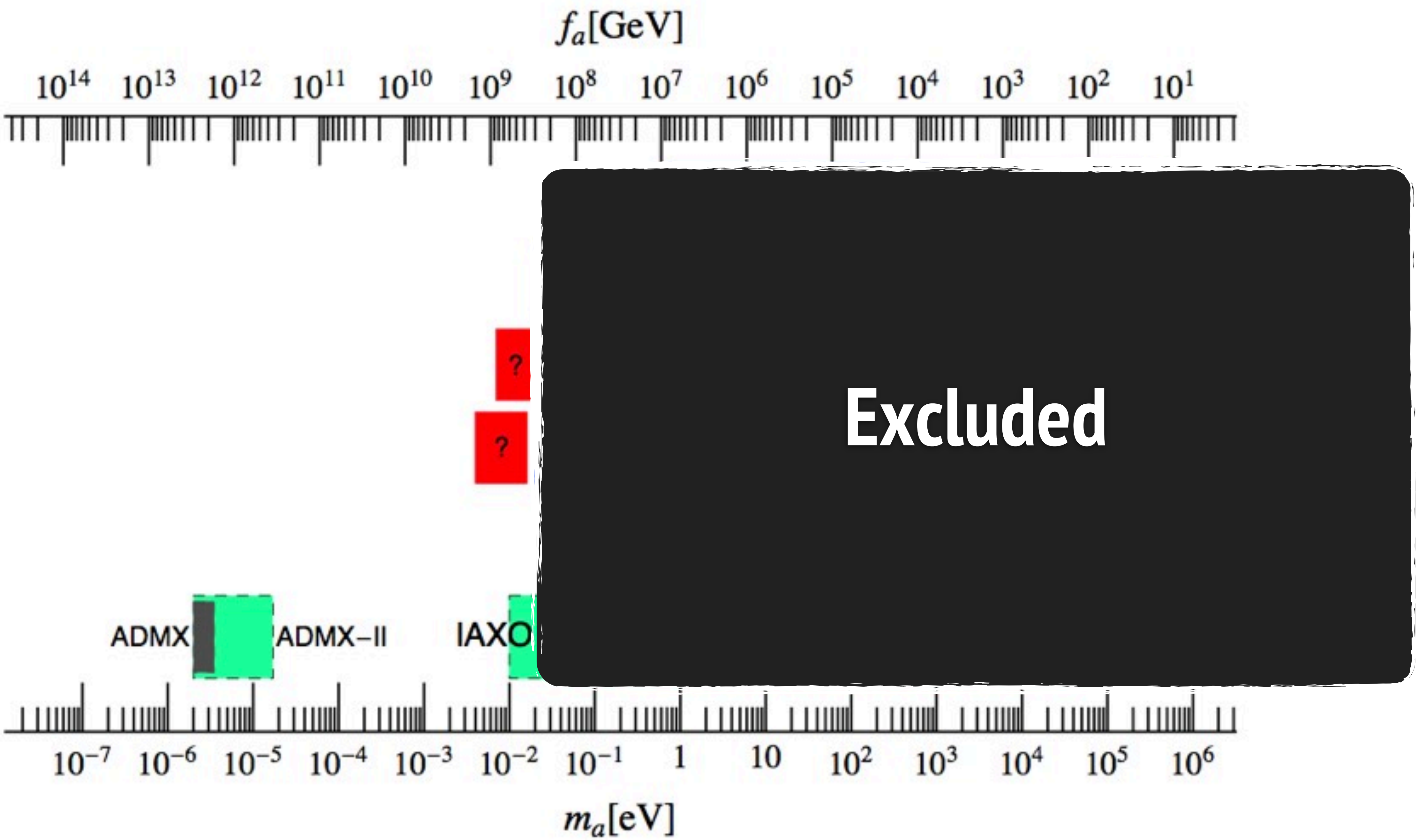
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\alpha_s}{4\pi} G\widetilde{G}\frac{a}{f_a} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + c_{a\gamma}\frac{\alpha}{4\pi}F\widetilde{F}\frac{a}{f_a} + \ldots$$

Landscape, what do we know?



If axions exist, they are very light and VERY weakly interacting!

Landscape, what do we know?



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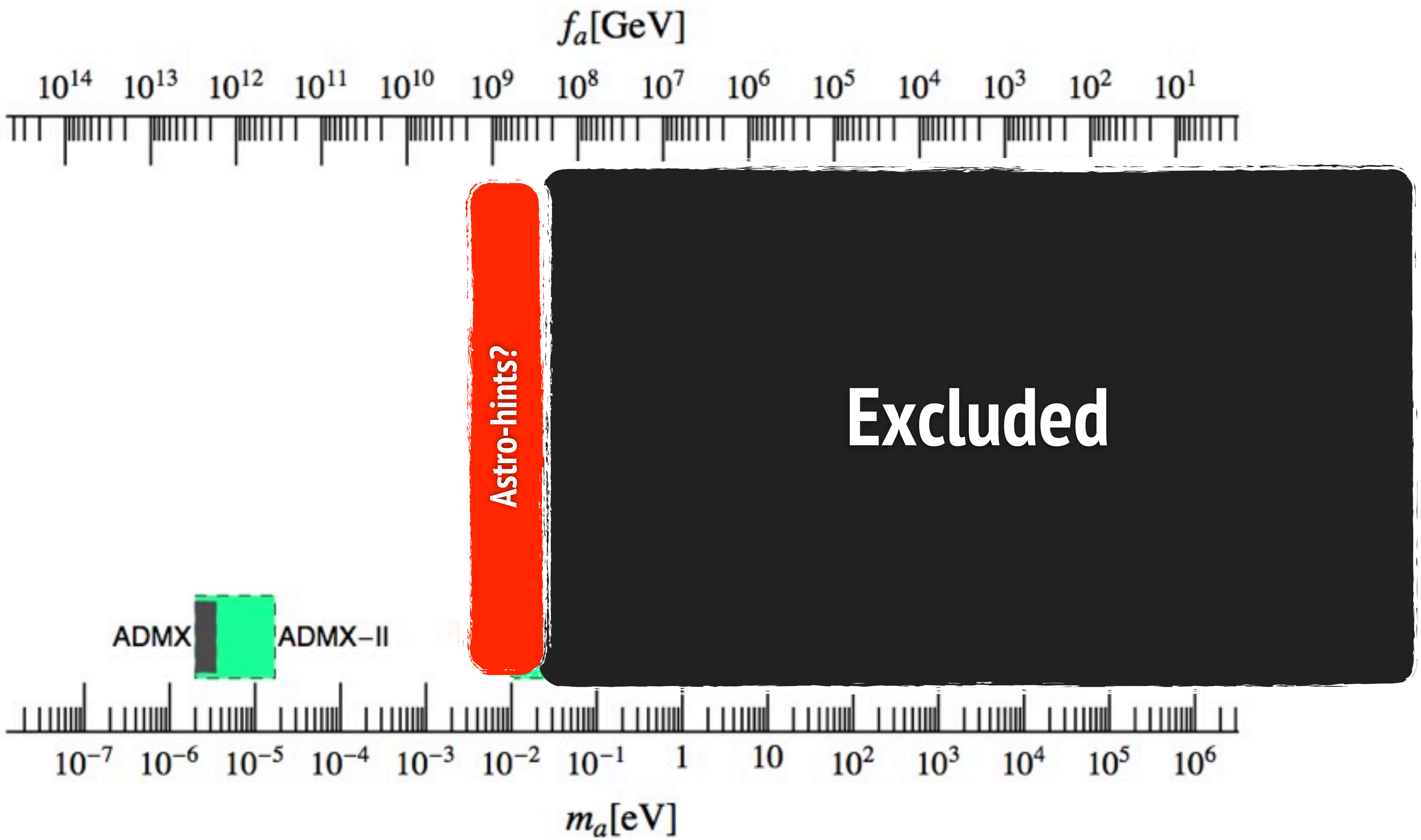
Landscape, what do we know?



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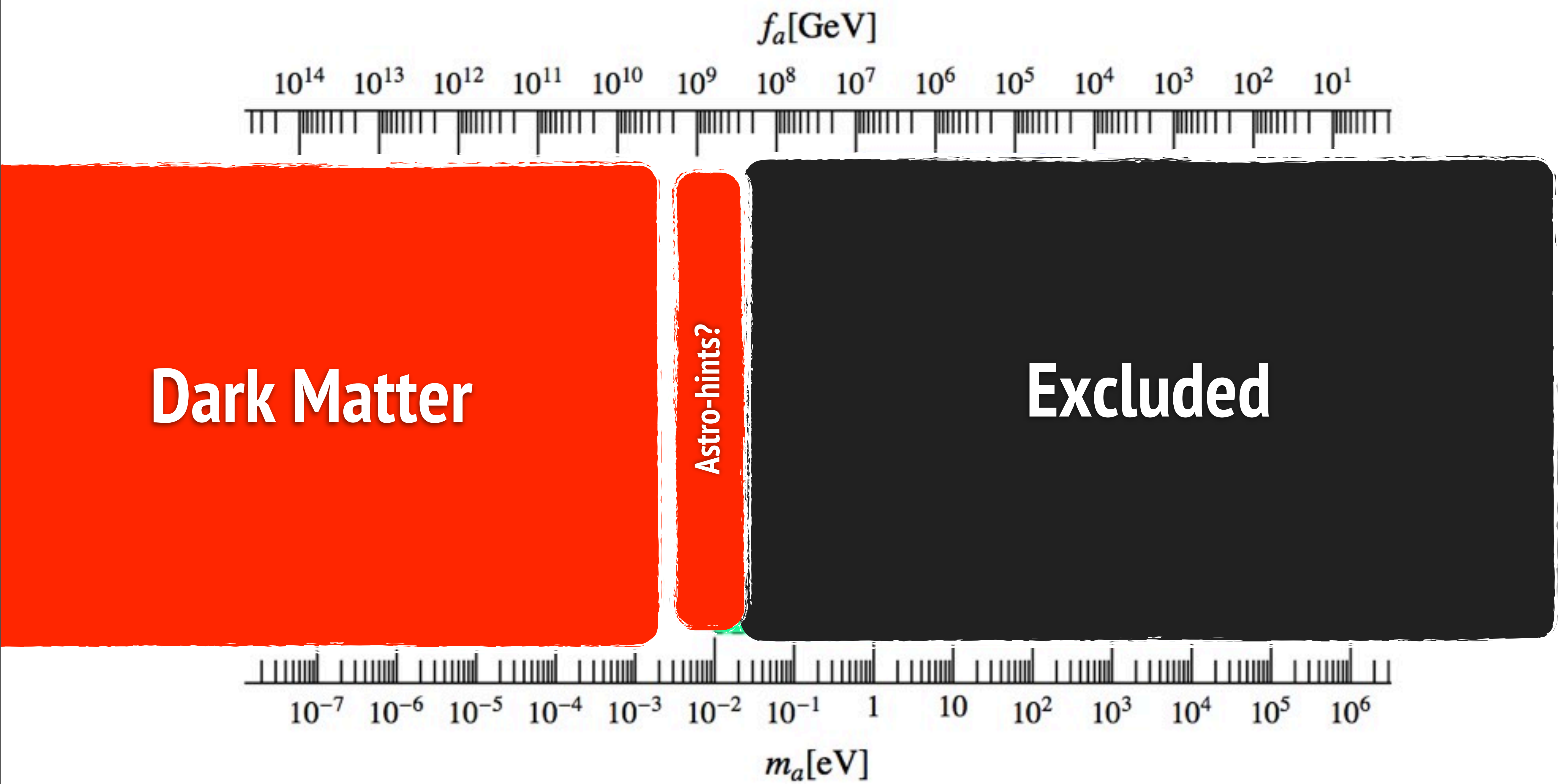
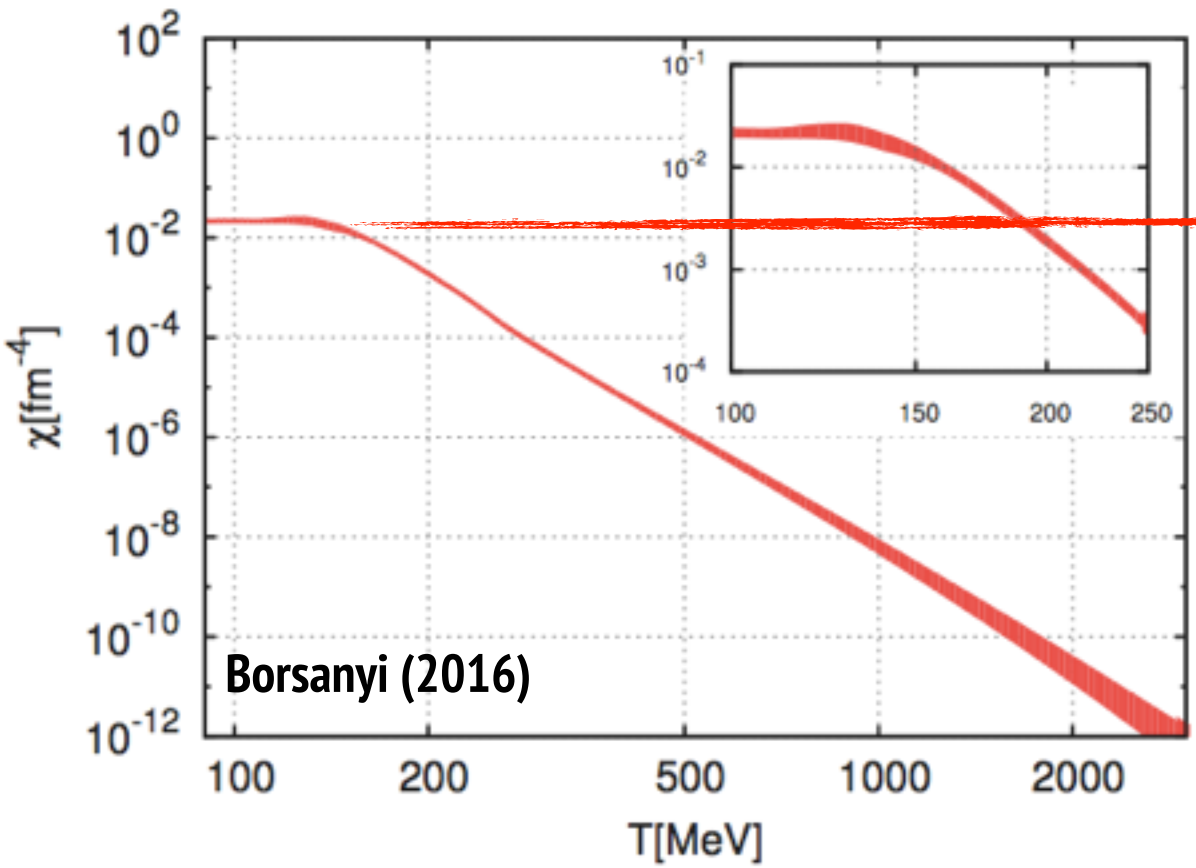
Landscape, what do we know?



If axions exist, they are very light and VERY weakly interacting!

Axion mass

$$\chi = \chi(T)$$

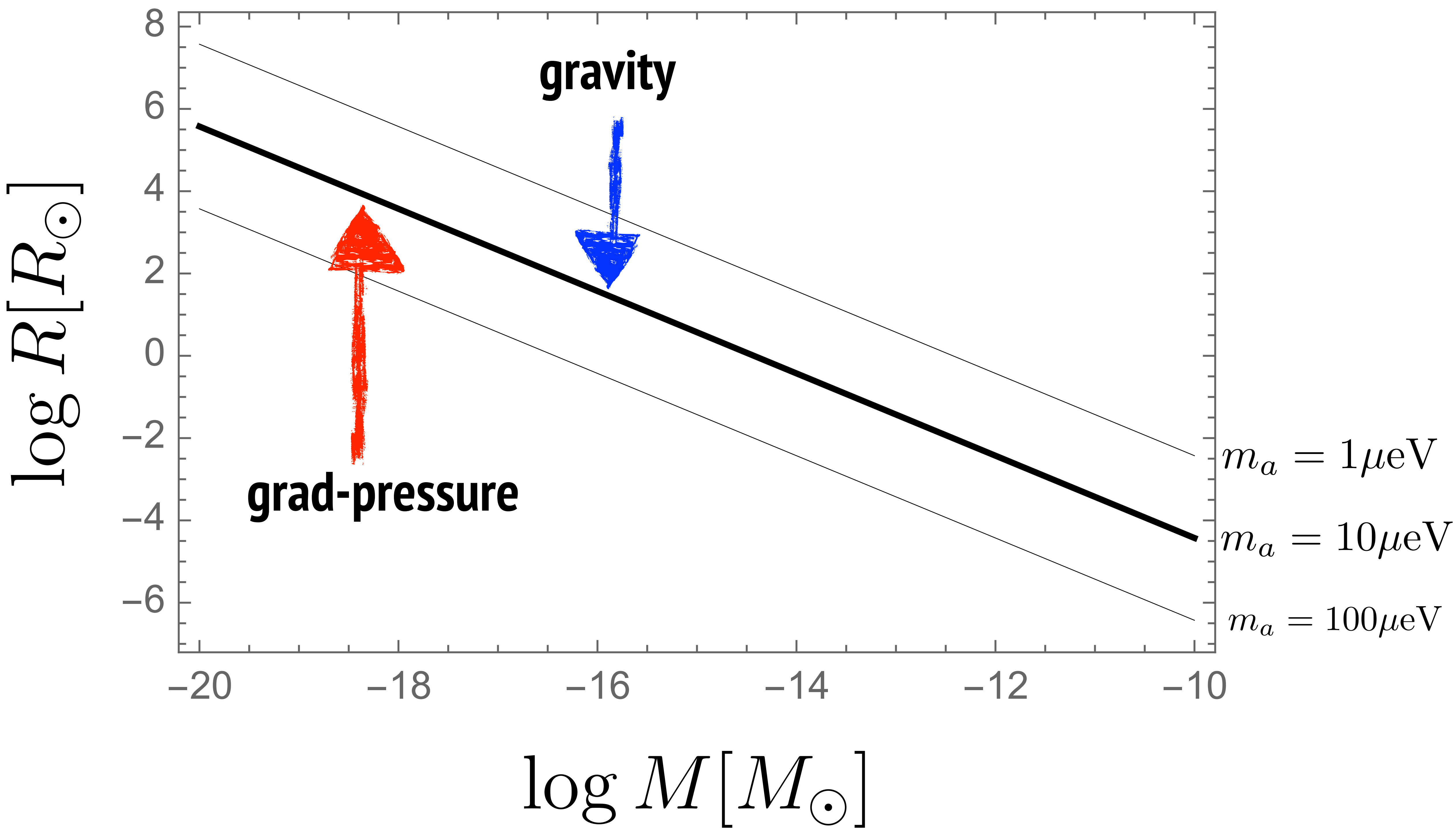


$$\chi_0 = (75.5(5)\,\mathrm{MeV})^4 \sim (m_\pi f_\pi)^2$$

$$f_a < M_p \rightarrow m_a > 5 \times 10^{-13} eV$$

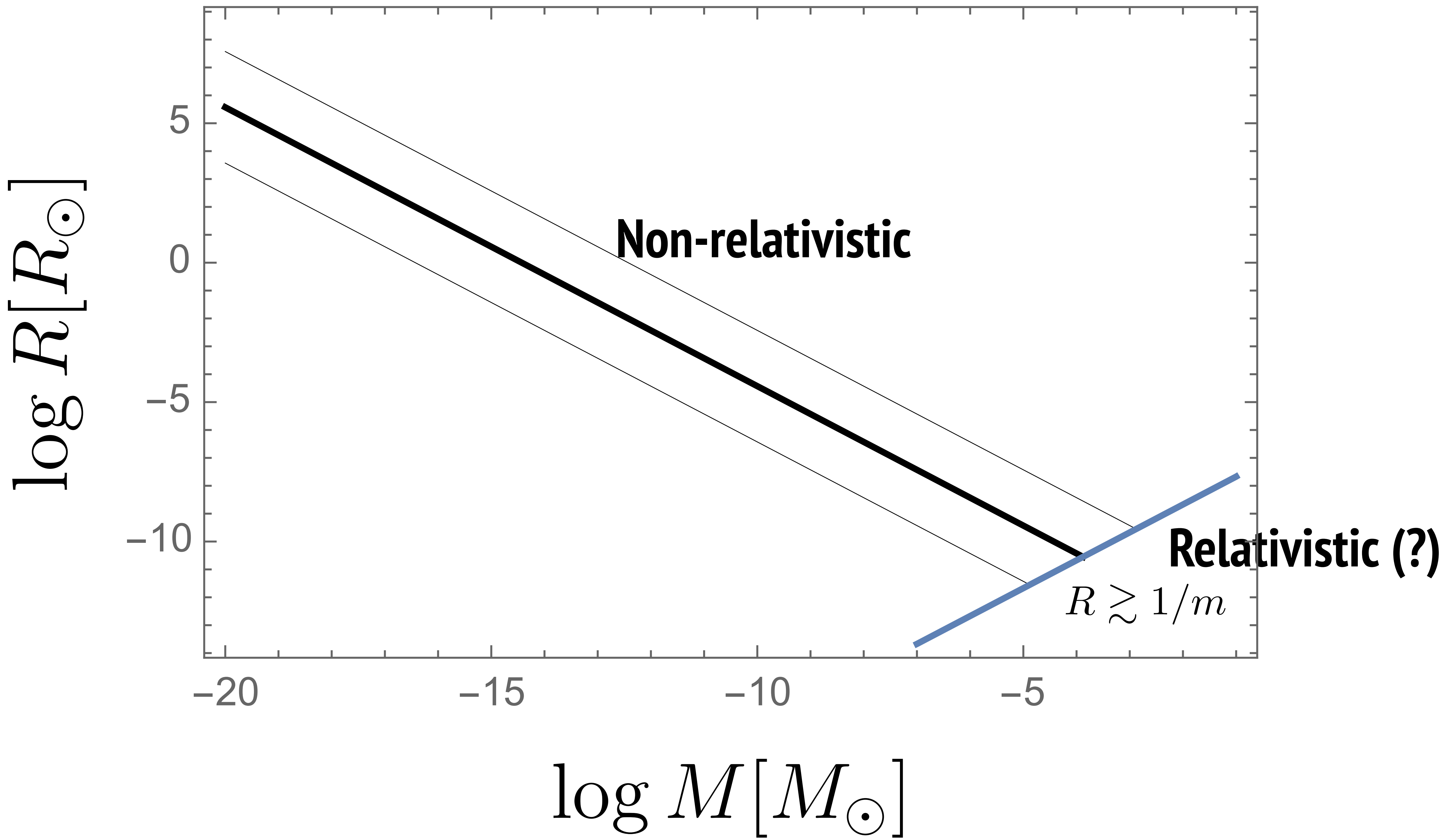
- **Gradient pressure effects happen at much smaller scales**
- **Relic abundance (see later) favors** $m_a \sim 1 - 300\mu\mathrm{eV}$

Bose star



gravity
grad-pressure
$m_a = 1\mu\text{eV}$
$m_a = 10\mu\text{eV}$
$m_a = 100\mu\text{eV}$
8
6
4
2
0
−2
−4
−6
−20
−18
−16
−14
−12
−10
$\log R[R_\odot]$
$\log M[M_\odot]$

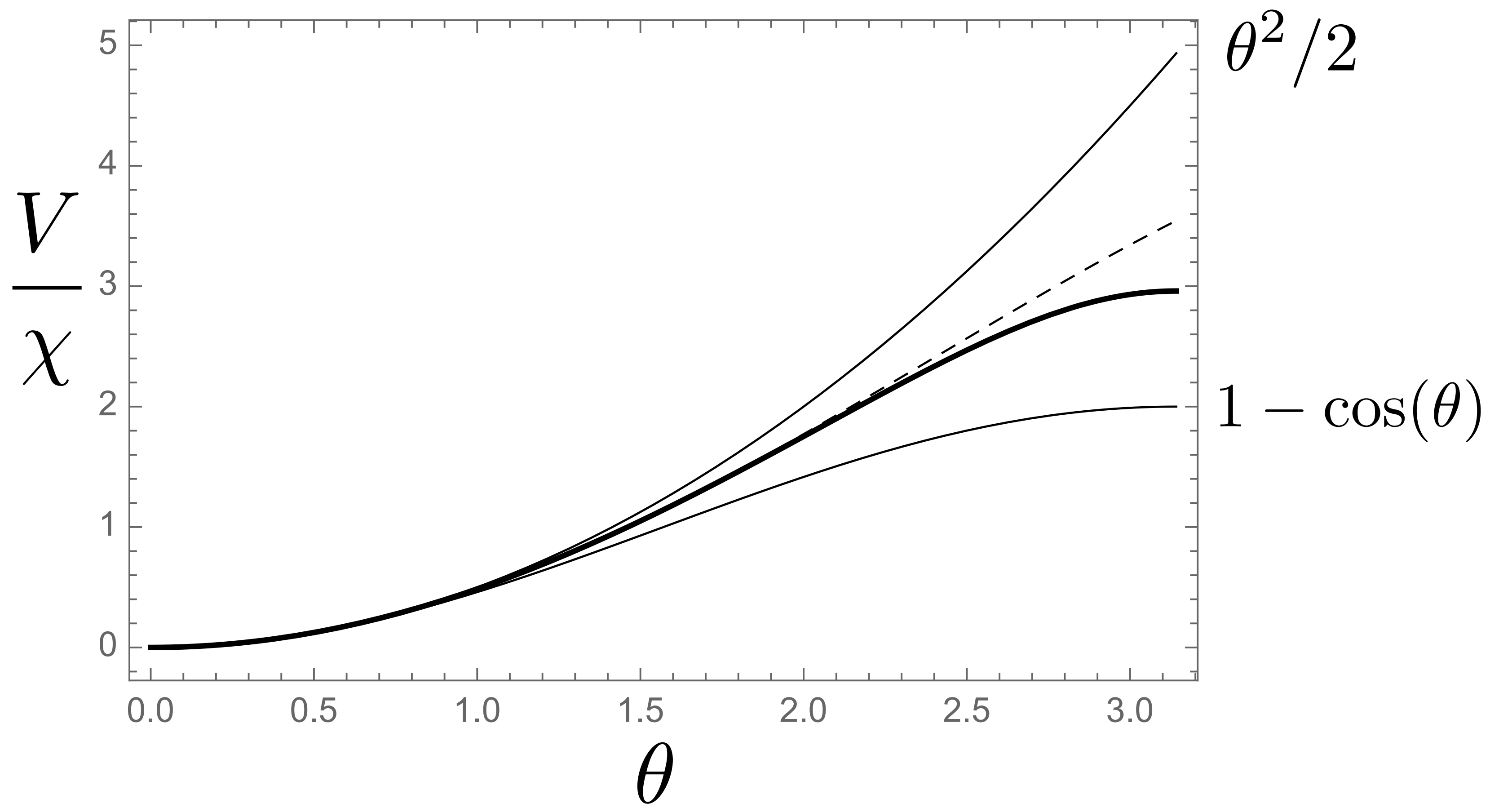
Bose star


Non-relativistic
Relativistic (?)
$R \gtrsim 1/m$
5
0
−5
−10
−20
−15
−10
−5
$\log R[R_\odot]$
$\log M[M_\odot]$

Instability

- Axions have negative self-interactions

$$V(a) = m_\pi^2 f_\pi^2 \left(1 - \sqrt{1 - \frac{4m_u}{(m_u+m_d)^2}\sin^2(\theta/2)}\right) \sim \frac{1}{2}\chi\theta^2 - \frac{1}{24}\chi\frac{m_d^2 - m_u m_d + m_u^2}{(m_u+m_d)^2}\theta^4 + \ldots$$



- small amplitude ~ $V \sim \frac{1}{2}m_a^2 a^2 - \frac{0.34}{24}\frac{\chi}{f_a^4}a^4 + \ldots$

Equilibrium with self-interactions

- Basic equations (amplitude vs Star Mass) ... assumptions

$$a(r,t) \sim A(r)\cos mt \qquad \rho \sim \frac{1}{2}m^2A^2(r) \qquad M \sim m^2A^2R^3$$

$$U = \int dV \left(\frac{1}{2}\dot{a}^2 + \frac{1}{2}m^2a^2 + \frac{1}{2}(\nabla a)^2 - \text{grav} - \lambda a^4 + \ldots \right)$$

$$M \qquad \sim \frac{A^2}{R^2} \times R^3 \sim -\frac{GM^2}{R} \qquad \sim -\lambda A^4 R^3$$

- Equilibrium

$$U \sim M + \frac{M}{m^2R^2} - \frac{GM^2}{R} - \lambda\frac{M^2}{m^4R^3}$$

gradient pressure
decreases energy
expanding

gravity
decreases energy
contracting

self-interactions
decrease energy
contracting

FASTER THAN GRAD-PRESSURE

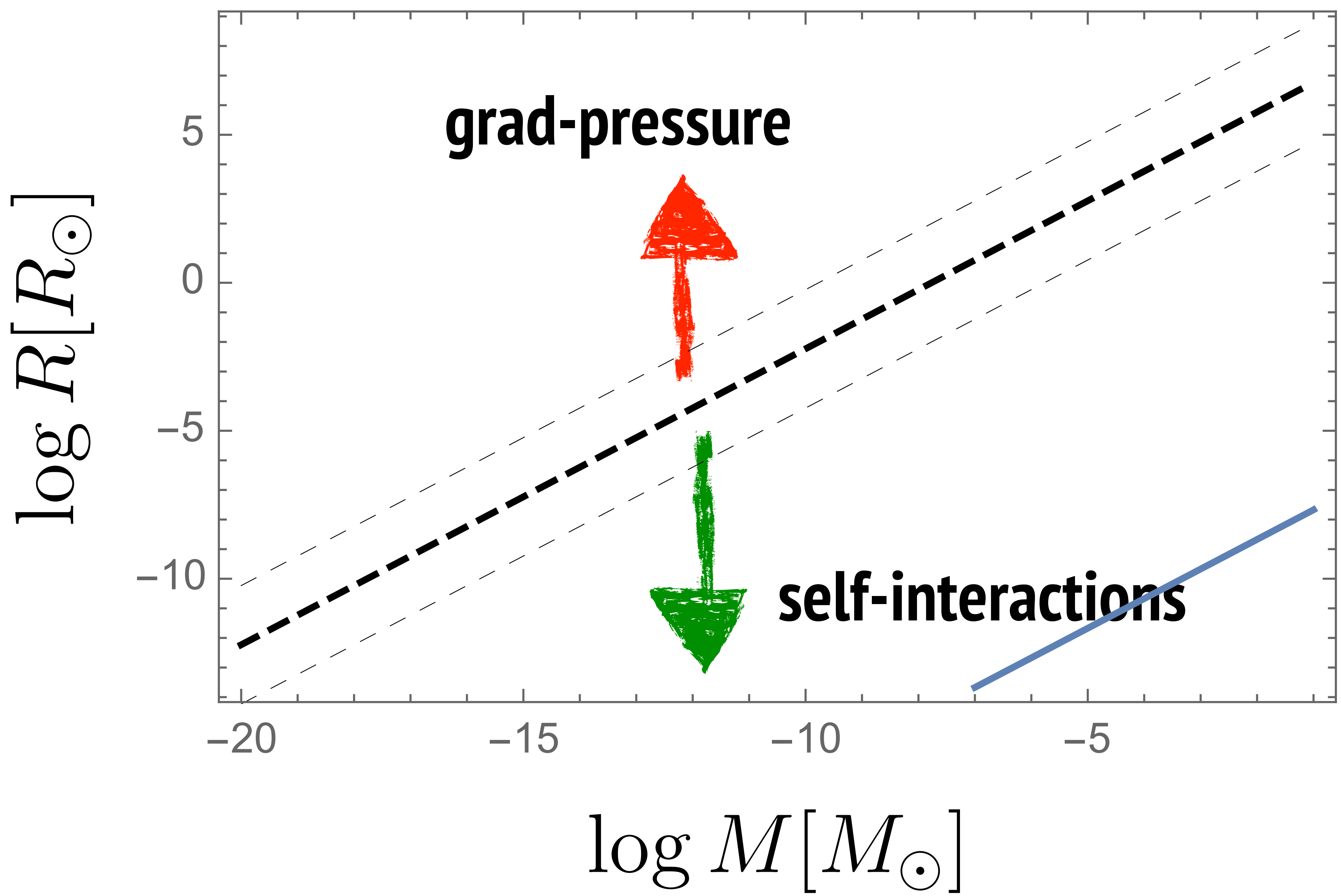
[sometimes called quantum pressure]

Instability

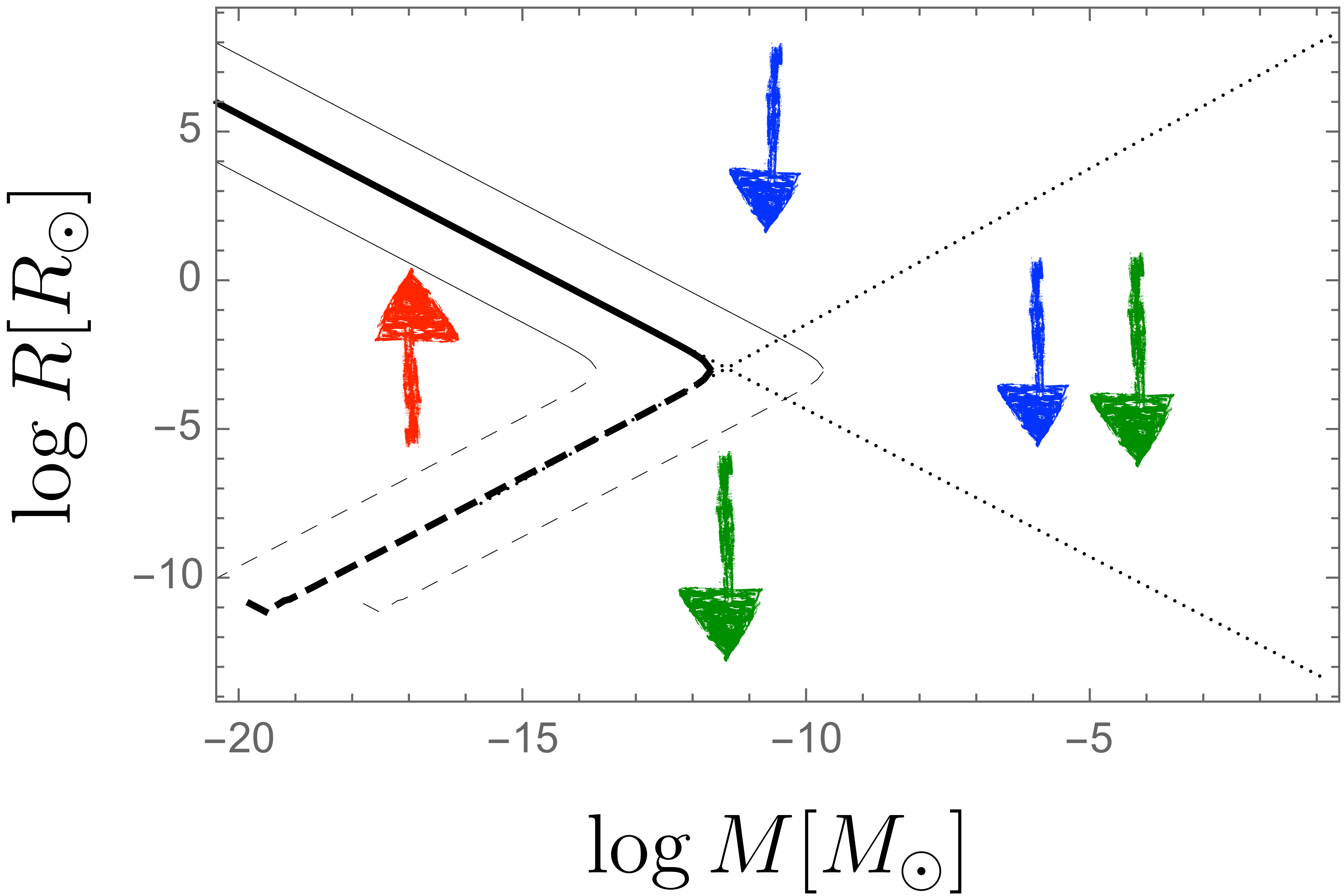
Leave gravity aside $U \sim M + \frac{M}{m^2 R^2} - \lambda \frac{1}{m^4 R^3}$

$$\frac{dU}{dR} = 0 \to R \sim \frac{\lambda M}{m^2} \to \frac{\chi M}{m^2 f_a^4} \sim \frac{M}{f_a^2}$$

but unstable point $U_{RR} < 0$



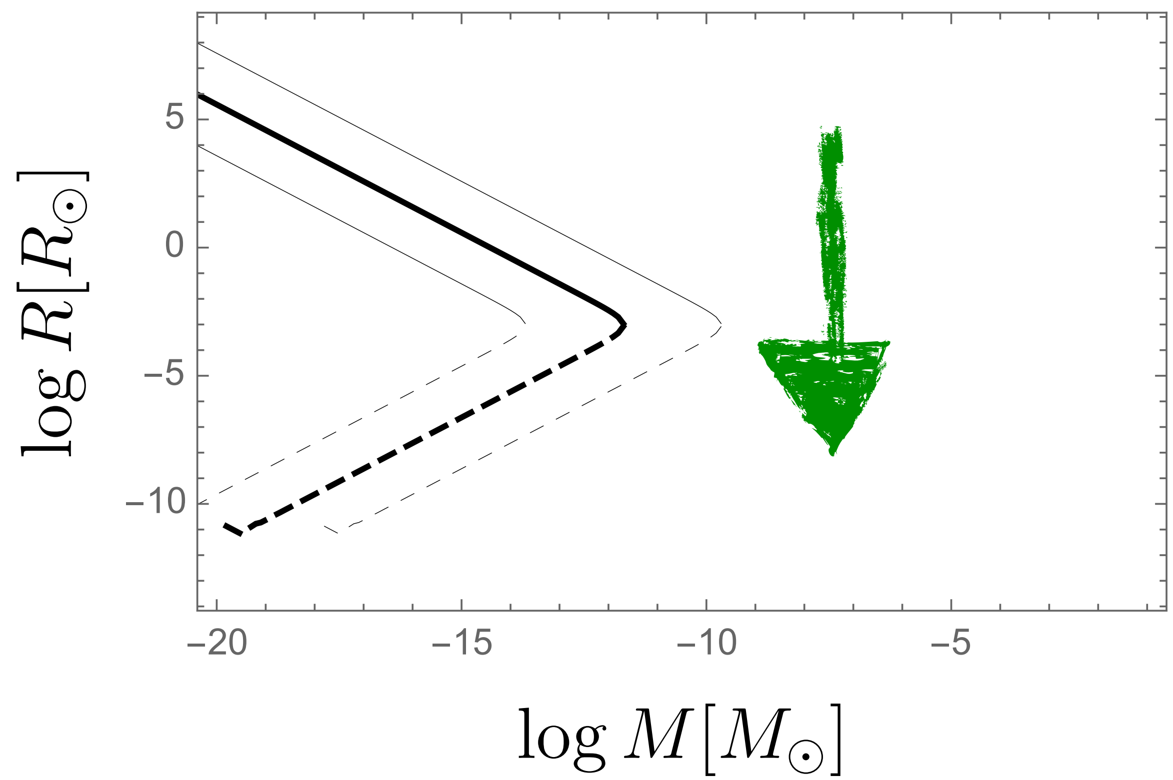
Stability region



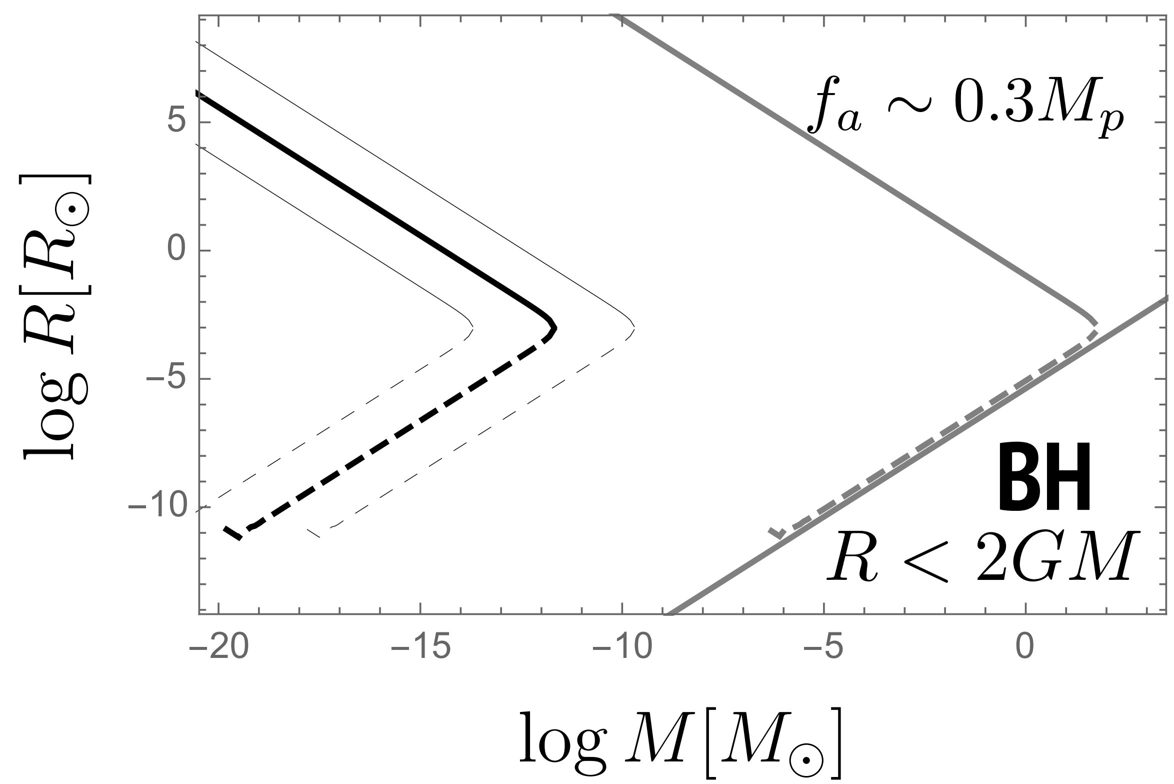
- **Maximum mass for axion star**
- **Universal minimum Radius** $R^2 \sim \frac{1}{G\chi_0}$

the fate of the fat

- what is the fate of unstable stars?

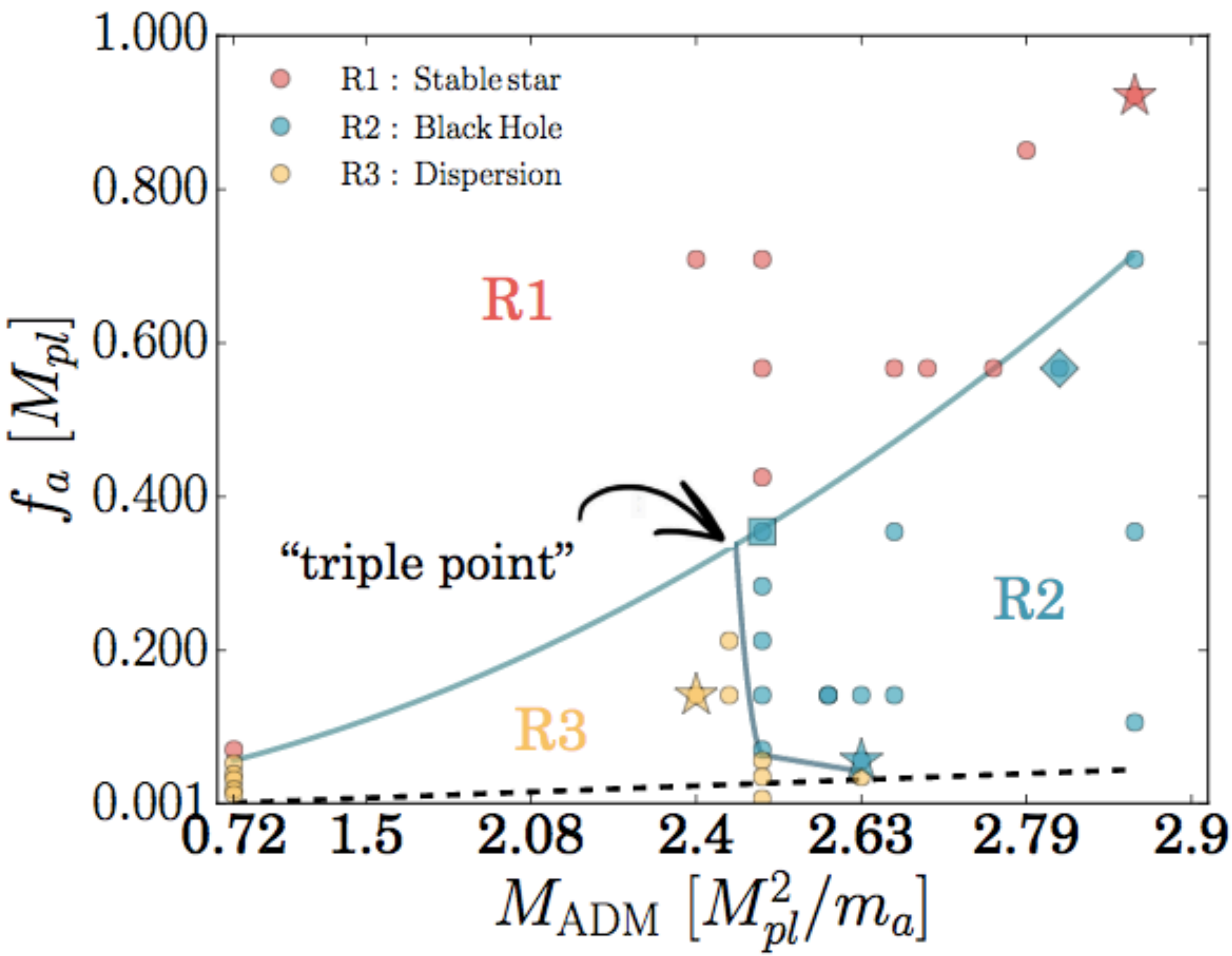


- Black hole?



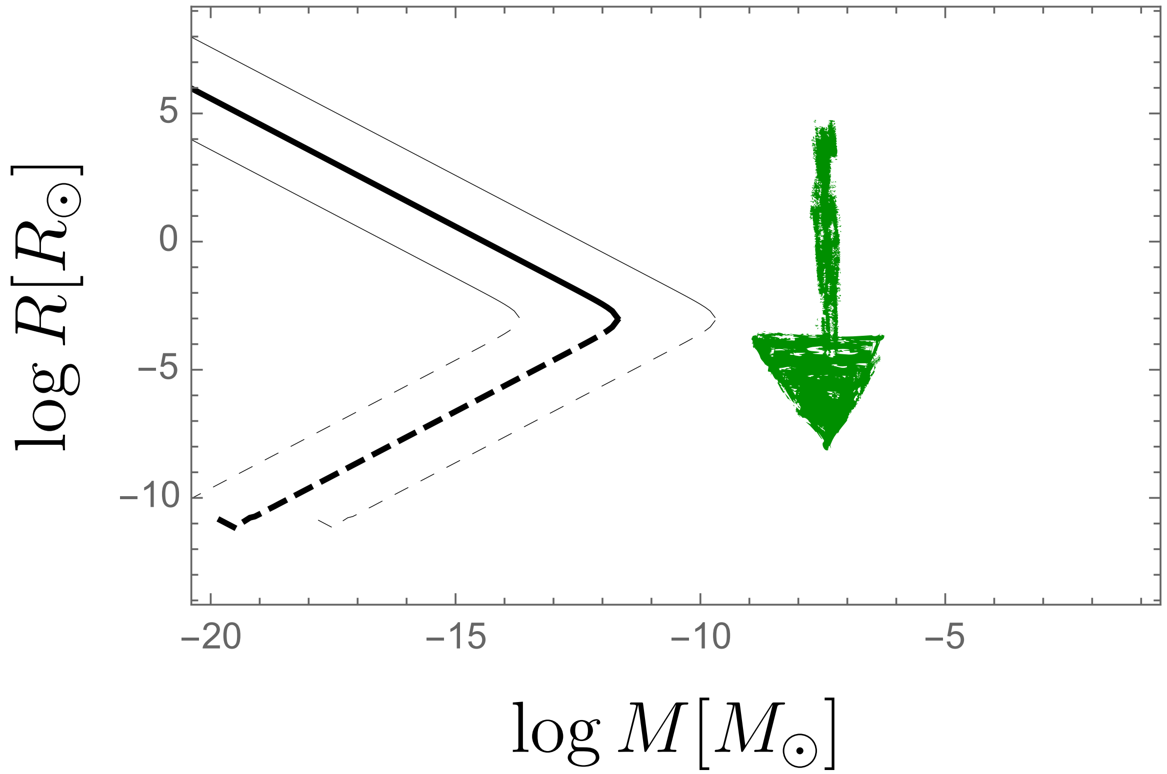
Black hole production from axion stars

Helfer (2017)



the fate of the fat

- **what is the fate of unstable stars? (smaller fa)**



- **Expectations: Explosive collapse and saturation**

$$F \propto -\frac{dU}{dR} \sim -\lambda \frac{M^2}{m^4 R^4}$$

but at some point $\theta \sim O(1)$

and the Taylor expansion is not valid

Dense axion stars

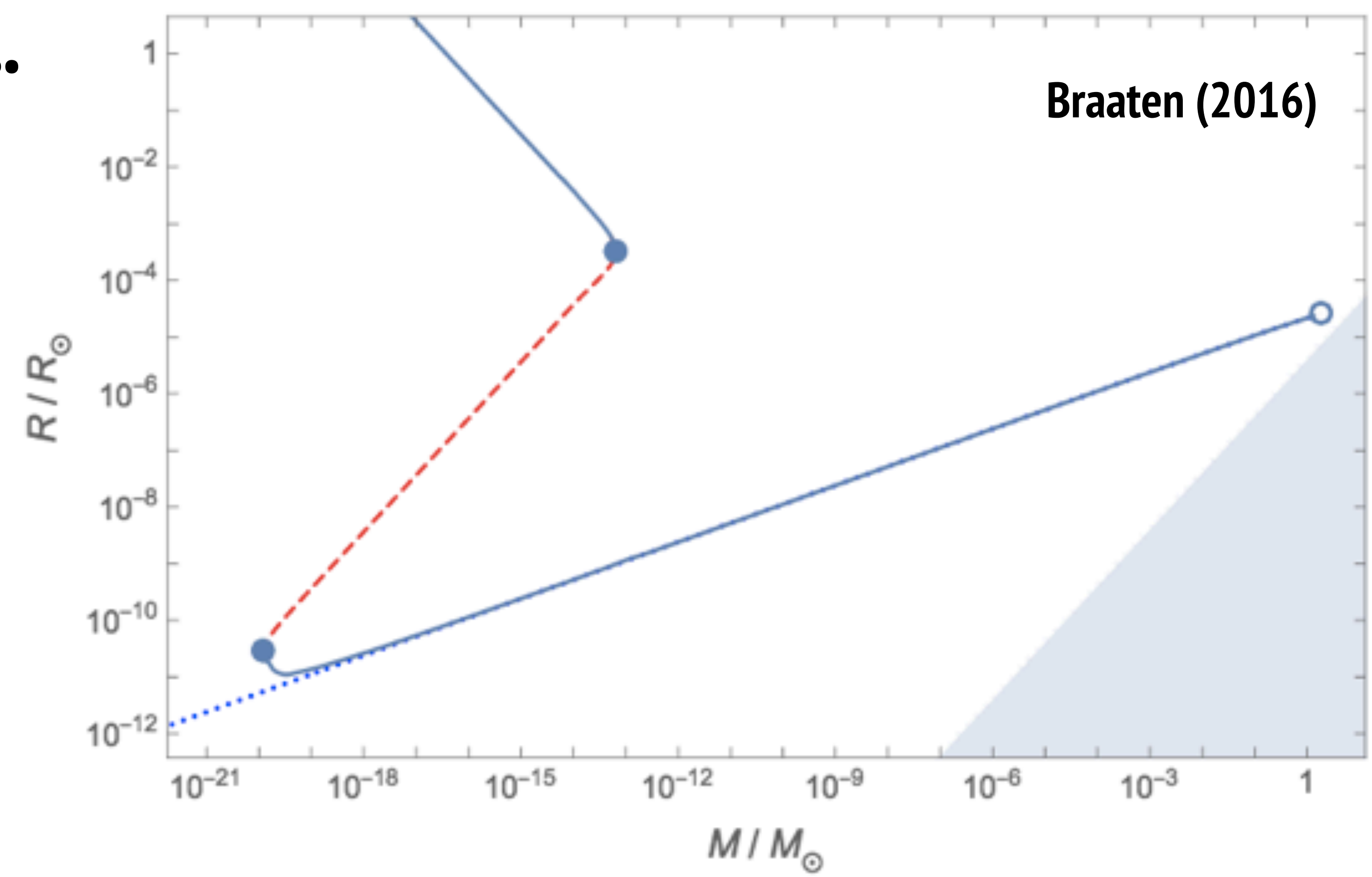
- **A new stable branch?** Braaten (2016)

at sufficiently large amplitude, new terms might give positive pressure

$$U = \int dV \left(\frac{1}{2}\dot{a}^2 + \frac{1}{2}m^2 a^2 + \frac{1}{2}(\nabla a)^2 - \mathrm{grav} - \lambda a^4 + \lambda' a^6 + \ldots \right)$$

this can prevent the collapse Eby (2016)

allowing denser configurations ...



Dense Axion stars ?

Visinelli et al ... yet to come

- Non-relativistic EFT, Thomas-Fermi approx (neglect ∇a) Braaten (2016)

DAS supported by grav vs repulsive axion self interactions

- Non-relativistic EFT, no approx Visinelli et al ... yet to come

DAS supported by attractive self-interactions vs gradient pressure

- Beyond NR, classical EOM Visinelli et al ... yet to come

$$\ddot{\theta} - \theta_{rr} - \frac{2\theta_r}{r} + m_a^2 \sin\theta = 0$$

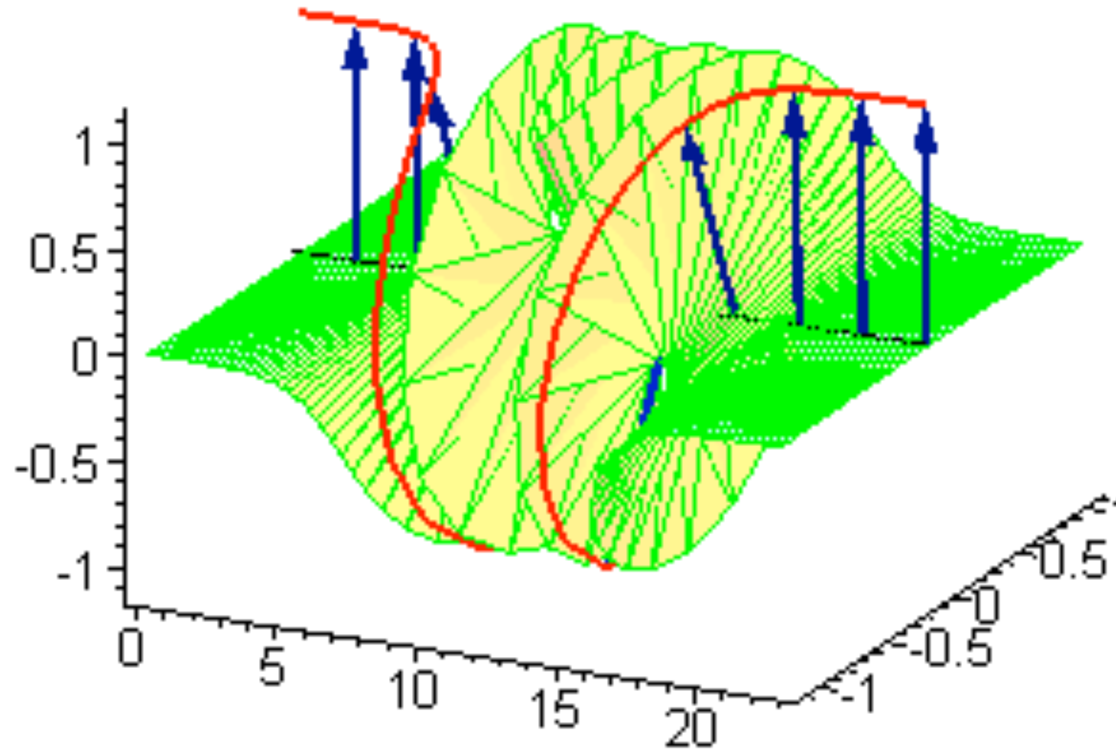
$\theta > \pi$ Breathers in 1D, 2D ... but not in 3D ... they are METASTABLE (pseudo-breathers)

Piette 1998, Hormuzdiar 1999, Alfimov 2000, ...

- Lifetimes are O(100/m)
- Do not have single frequency but infinite harmonics

some breathers...

$$u = 4\arctan\left(\frac{\sqrt{1-\omega^2}\ \cos(\omega t)}{\omega\ \cosh(\sqrt{1-\omega^2}\ x)}\right),$$

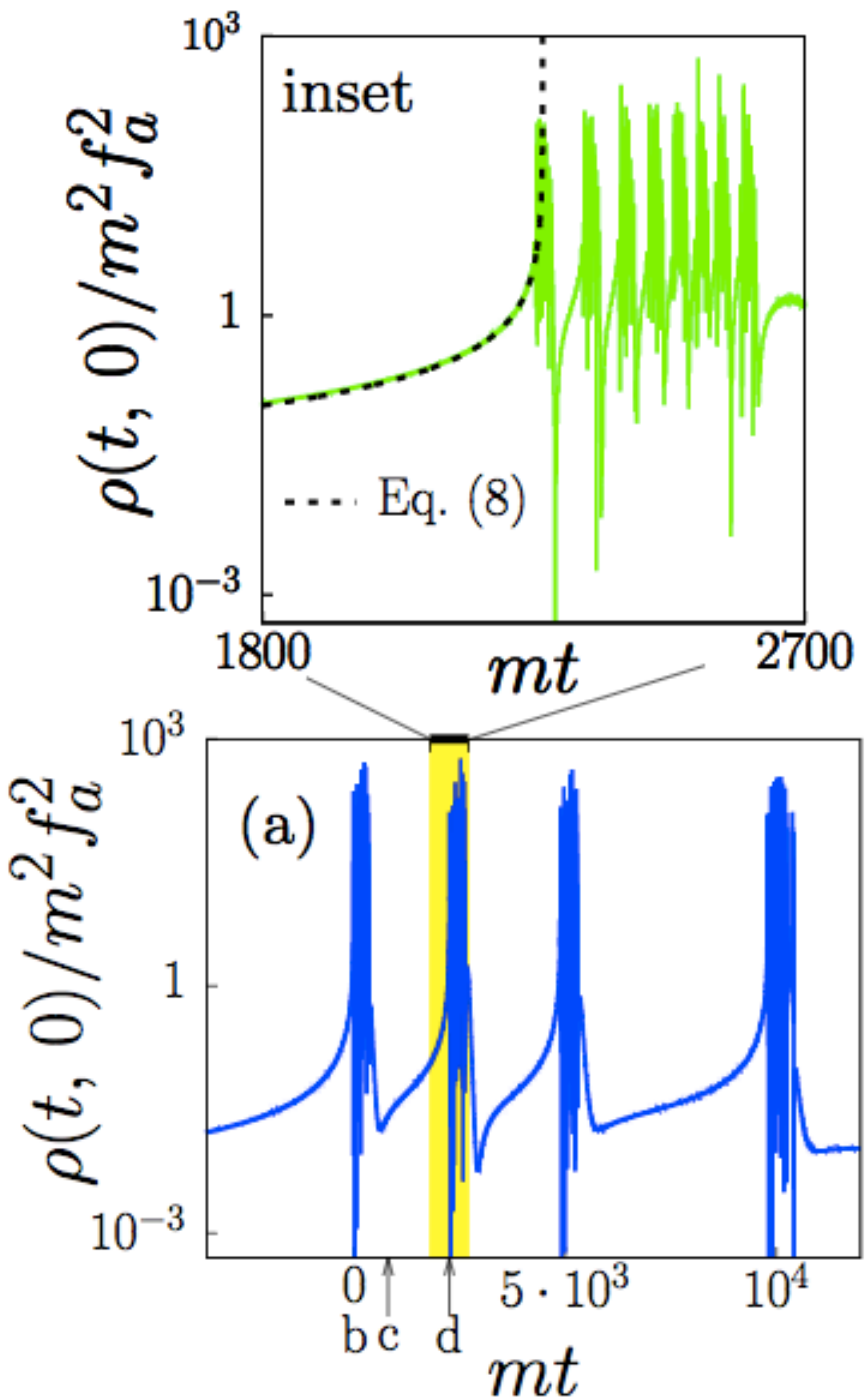


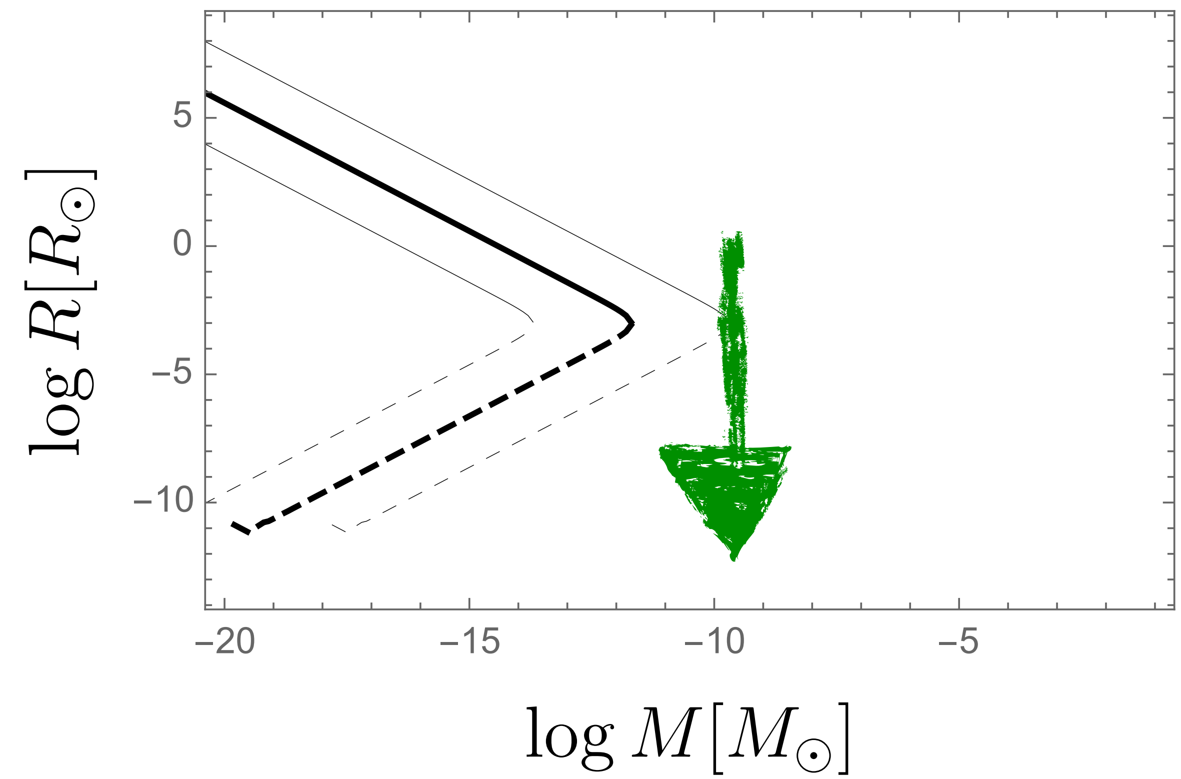
Numerical simulations

Levkov, Tkachev (2016)

- Collapsing Axion stars (full EOM)

Central density/chi

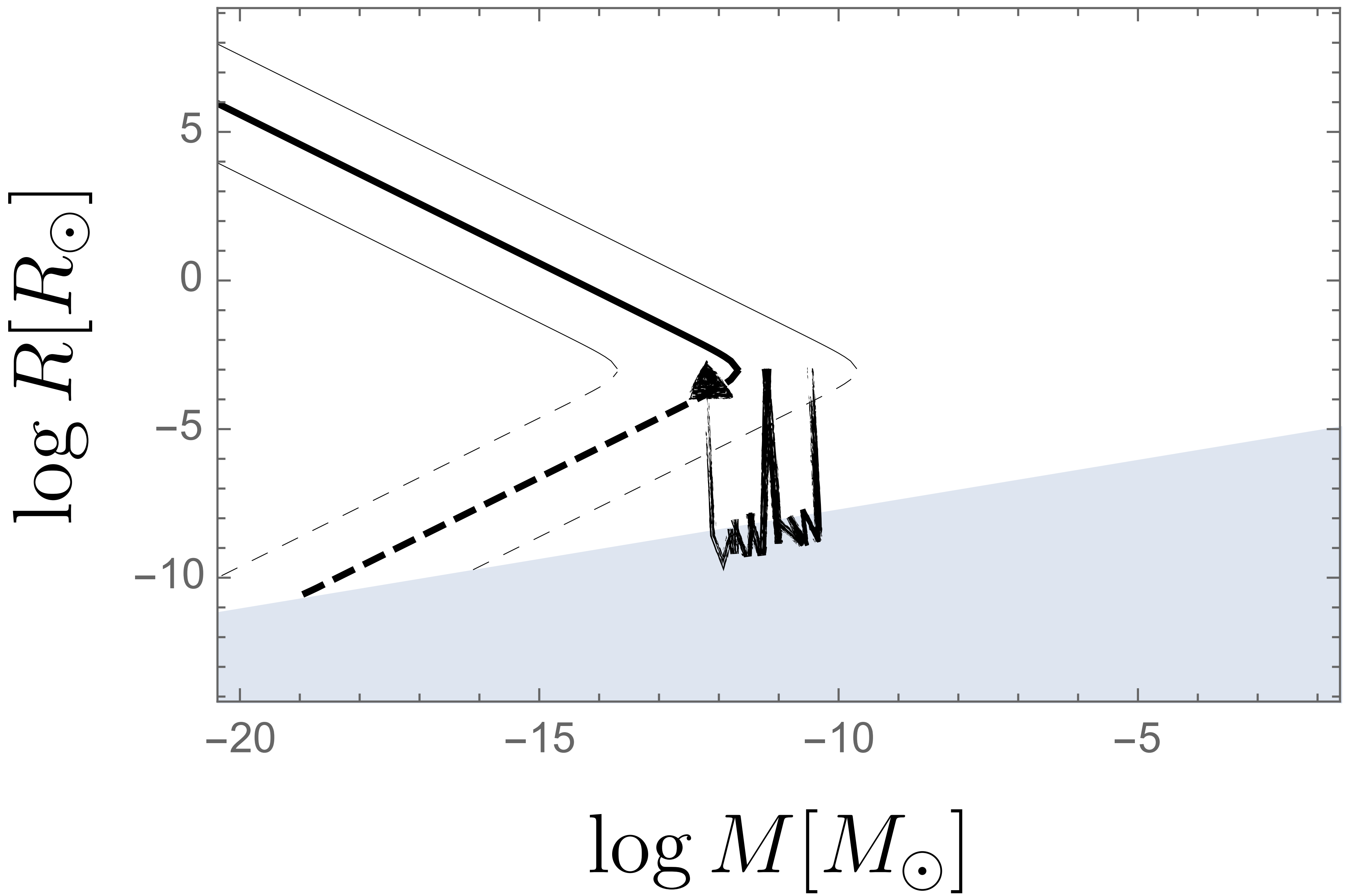




- Self similar collapse
- Large amplitude Oscillations (pB) with emission of relativistic axions
- relaxation

Numerical simulations

Levkov, Tkachev (2016)

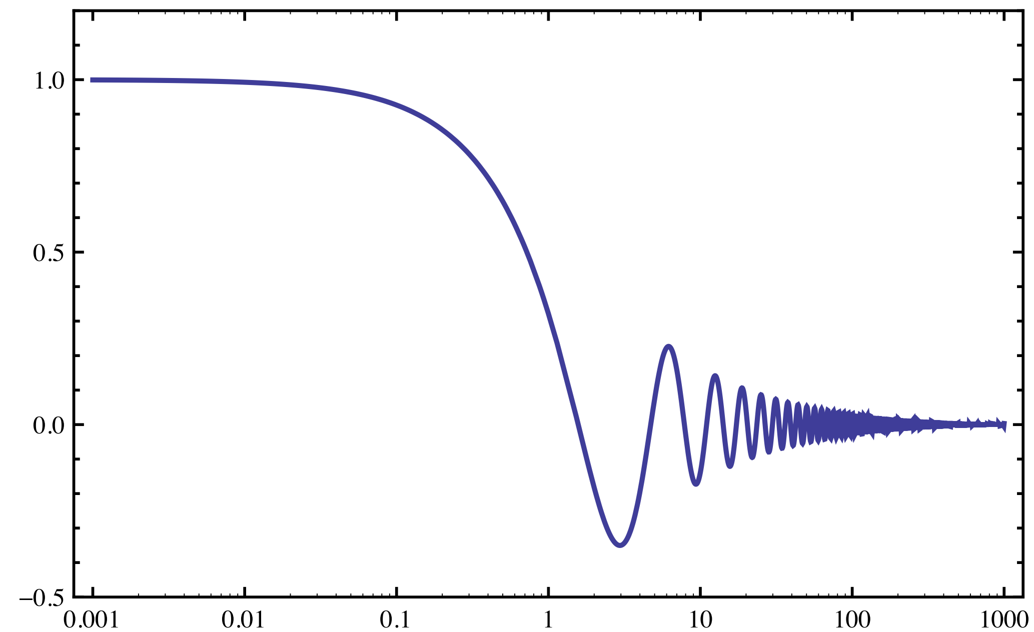


- Emission of relativistic axions, mass loss, final state grav. bound
- No dense star equilibrium found

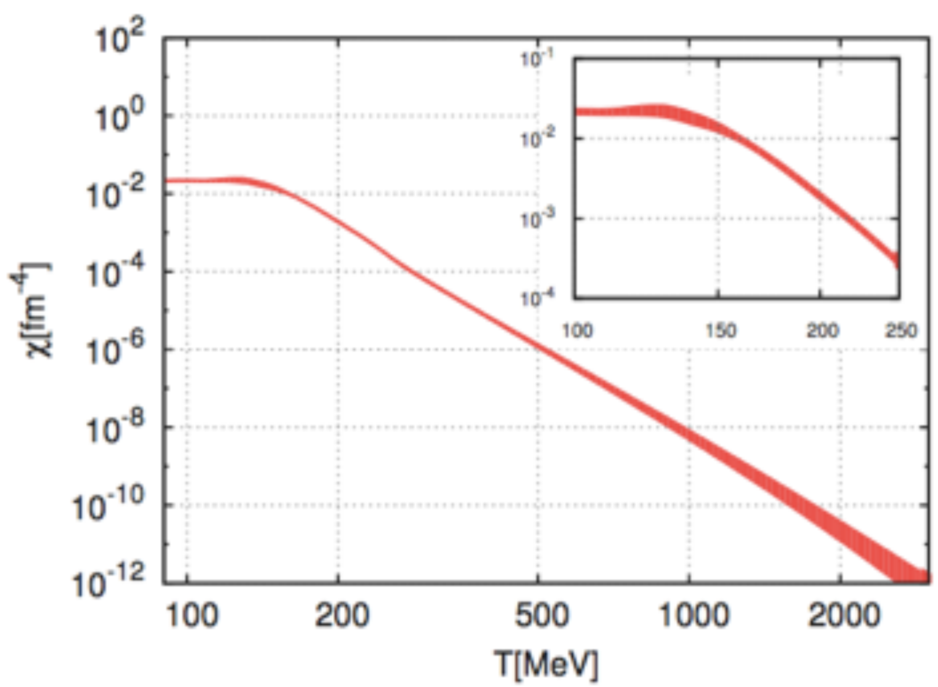
Early Universe

- Dark matter highly inhomogeneous in one scenario
- axion = Goldstone boson, Phase Transition after inflation
- High-T no axion mass, all values of theta equivalent
- Around t~1/m axions become DM

$$\ddot{\theta} + 3H\dot{\theta} - \frac{1}{R^2}\nabla^2\theta + m^2 \sin\theta = 0$$



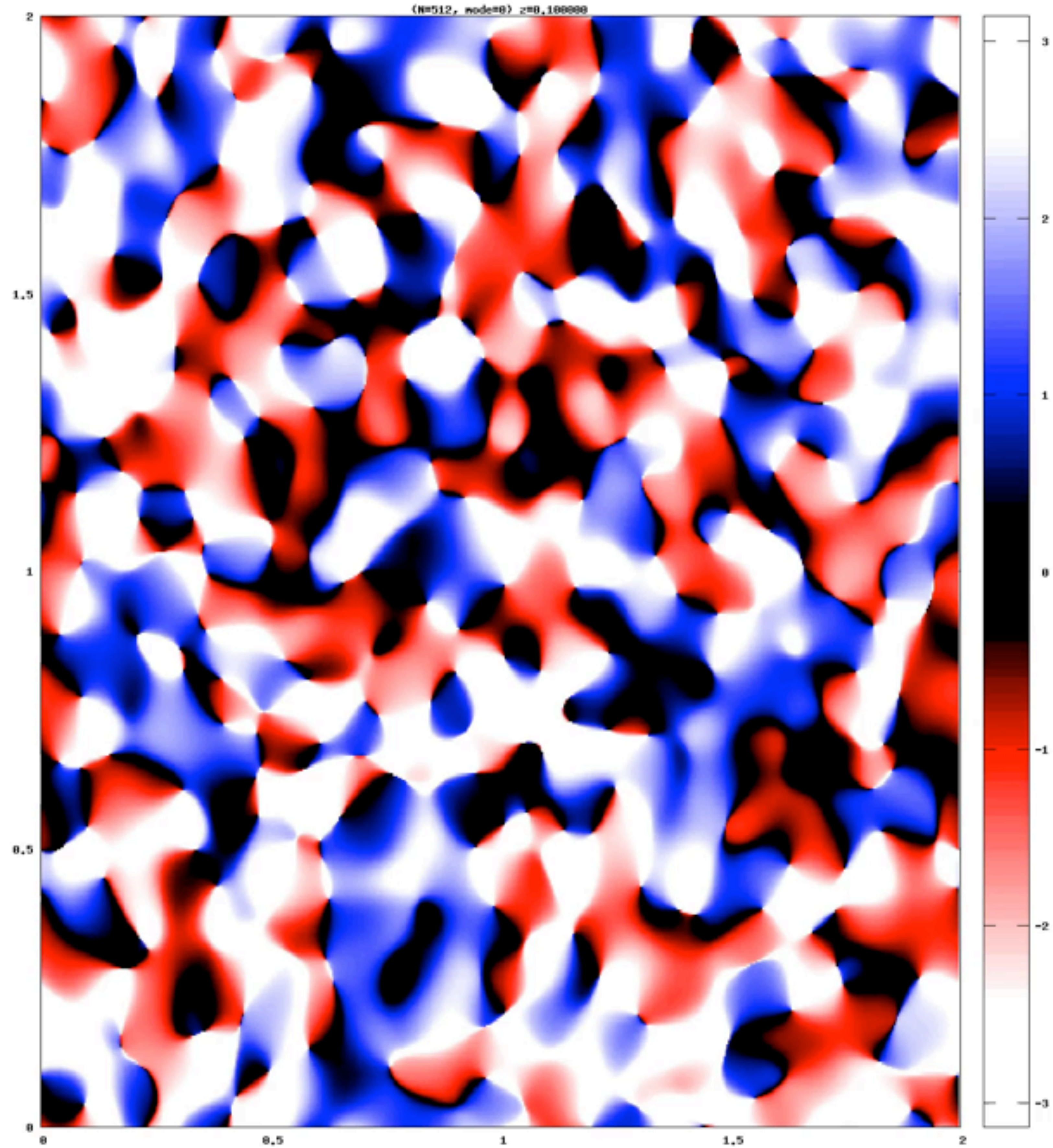
- Kolb-Tkachev 1993/94 (theta only) (axitons found ... !)
- with axionic strings ?



2 D slice of theta around t~1/m

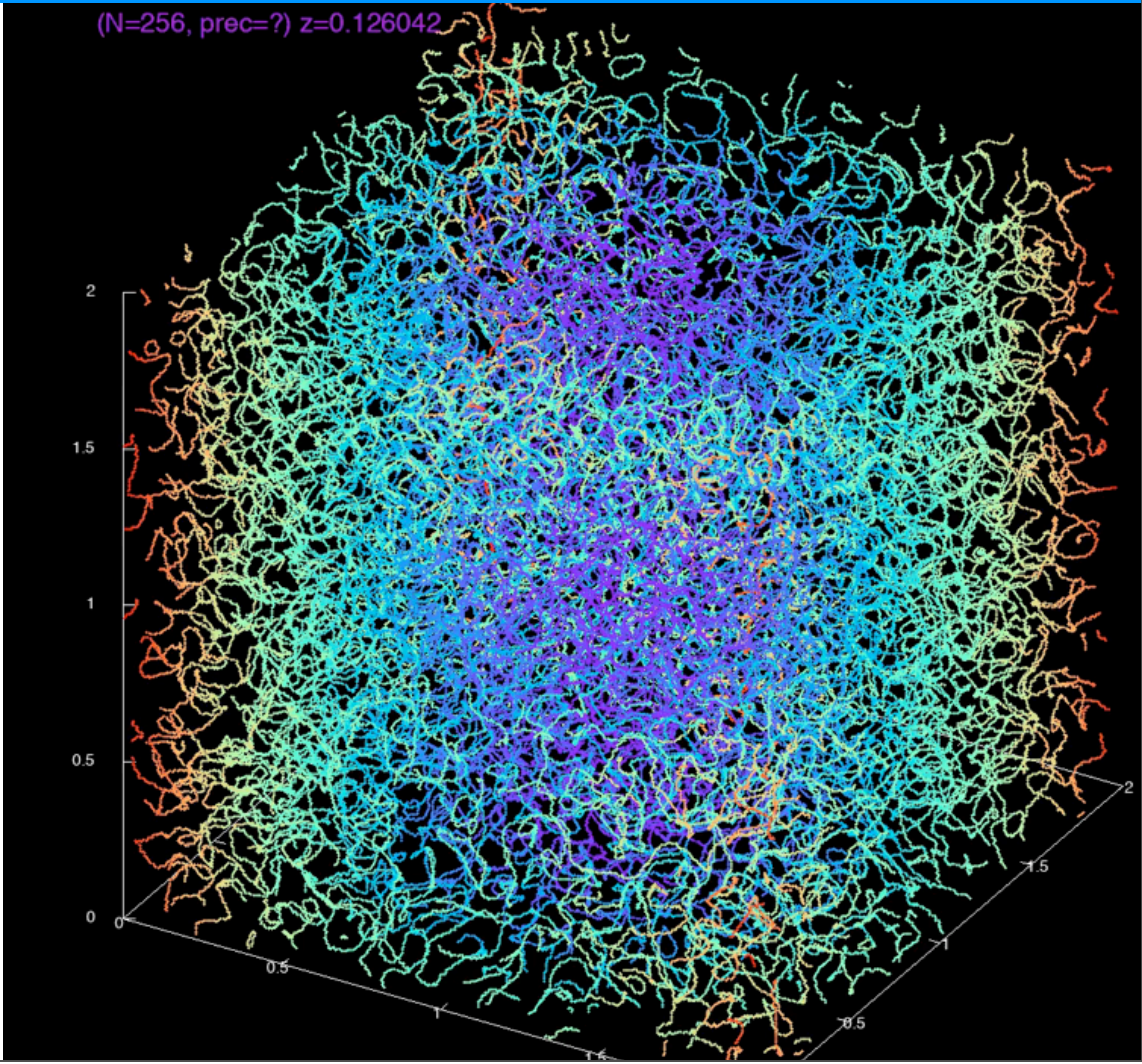
- Temp ~ 10-0.4 GeV

- Correlation length increases
- string cores
- t ~ 1/m
- theta -> 0
- domain walls take their time



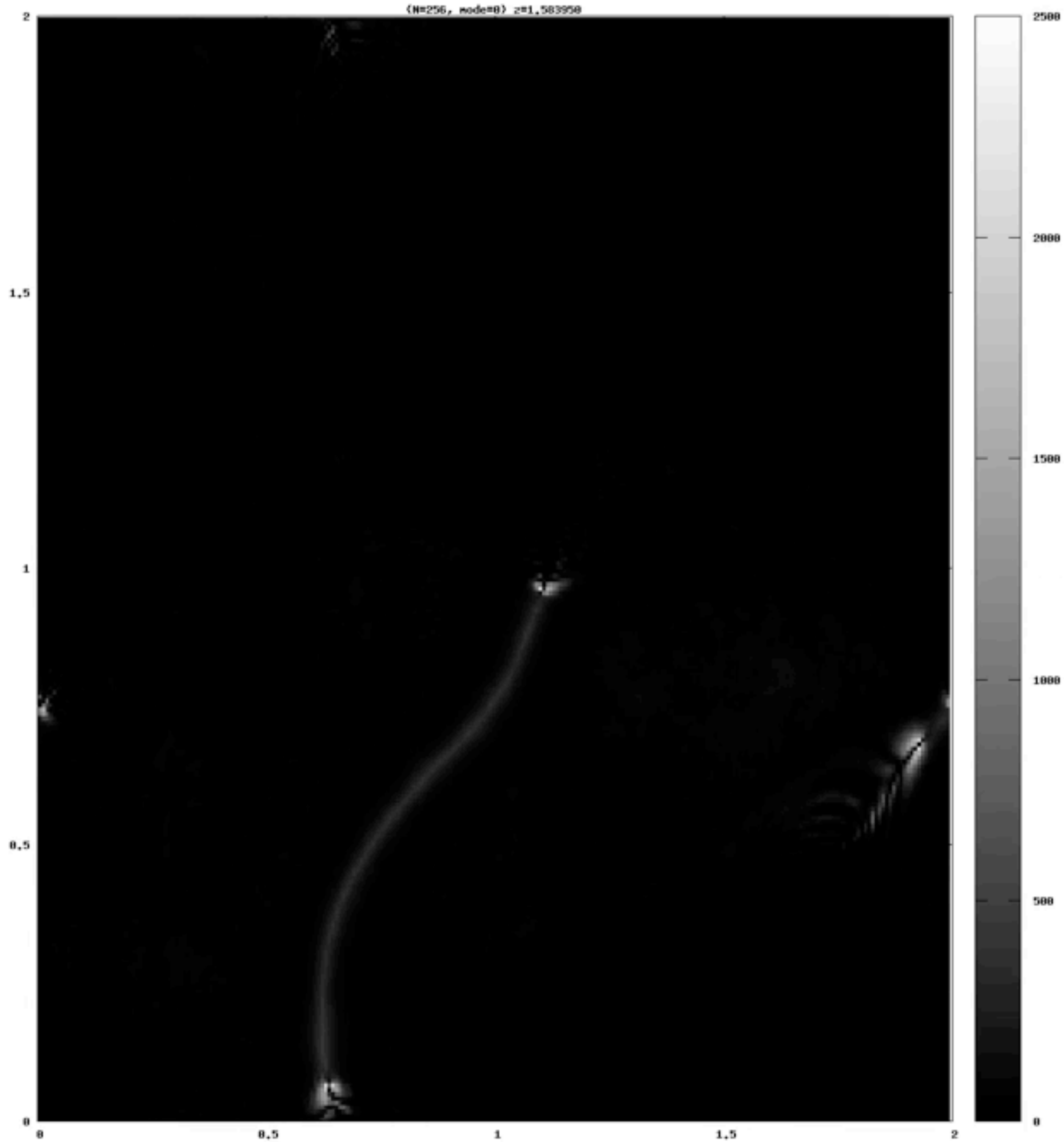
3 D string network

- UV completion when Theta=0...2pi



2 D energy density

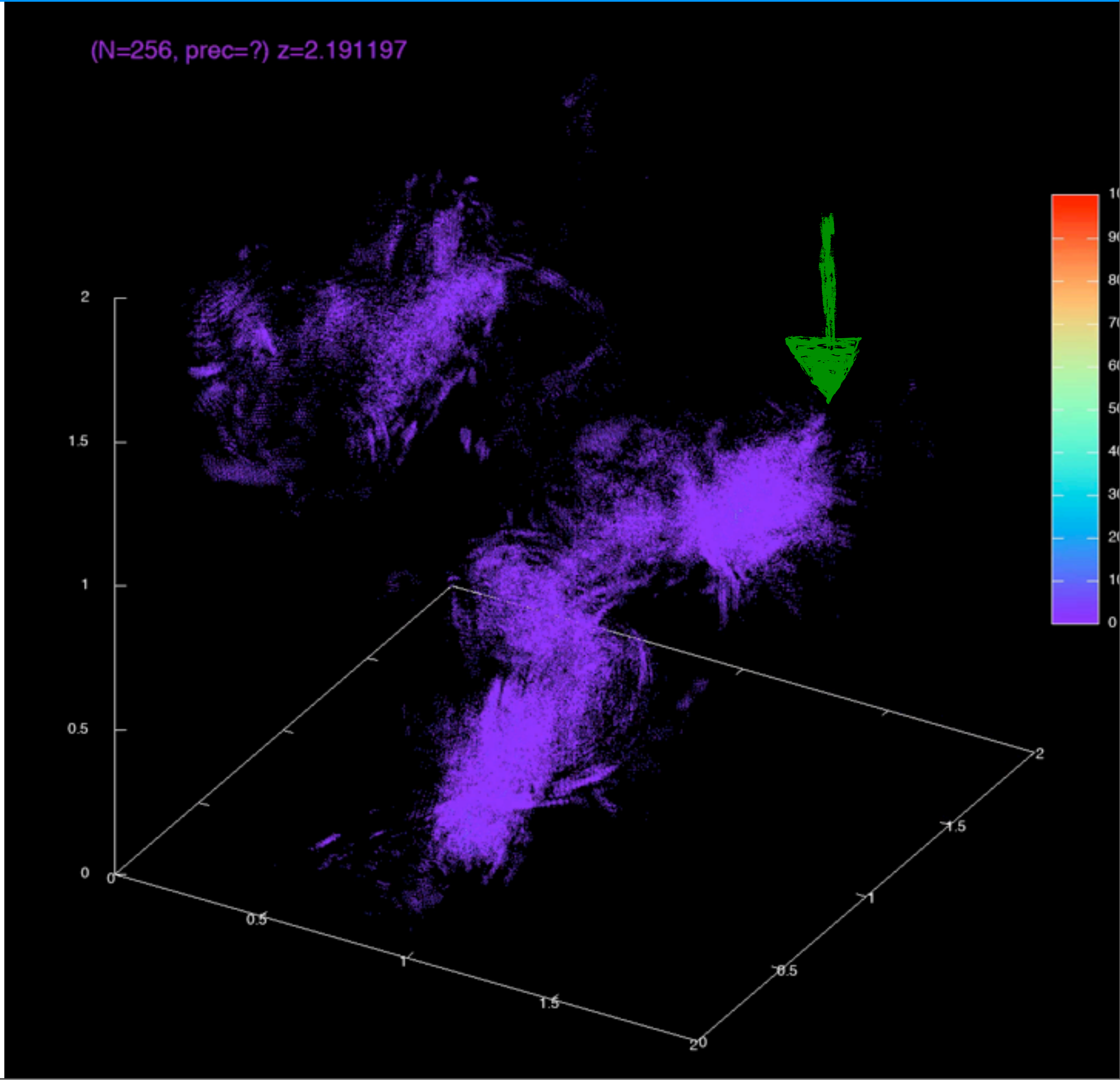
- strings
- domain walls
- NR axions
- some rel axions are visible



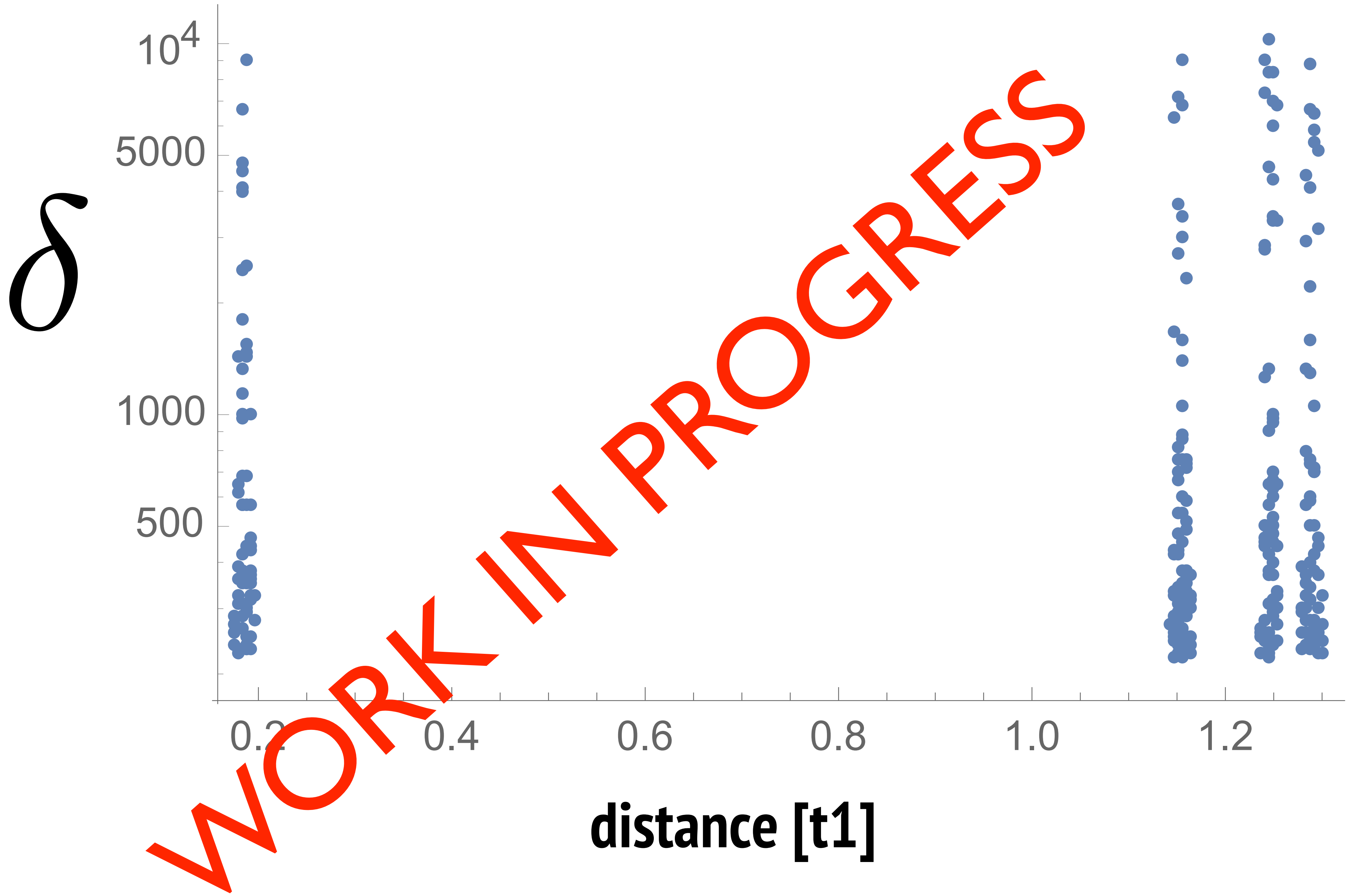
3 D energy density

$$\delta = \frac{\rho - \langle\rho\rangle}{\langle\rho\rangle} > 10$$

- axion miniclusters
- axitons (axion stars in core)

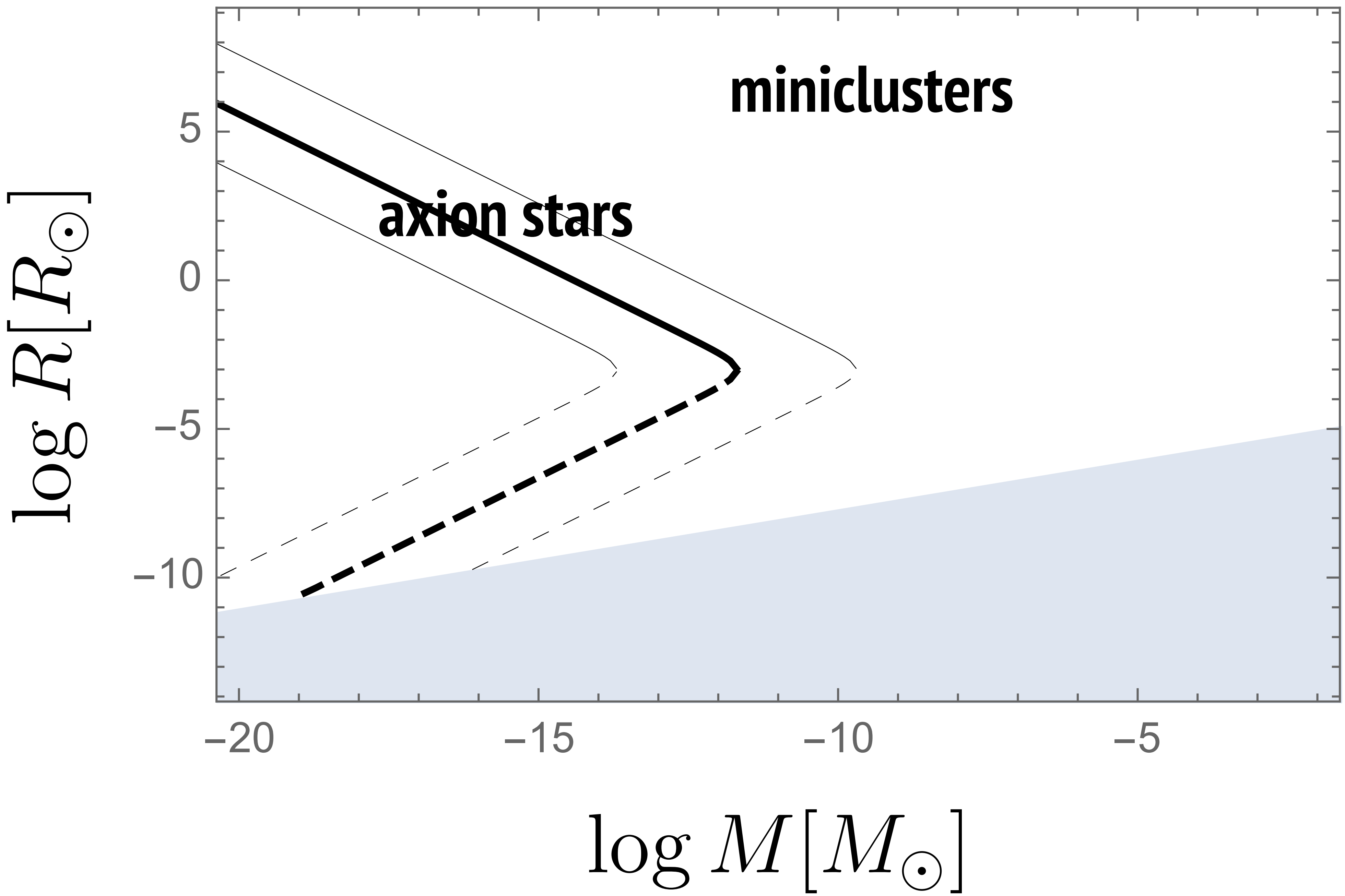


Clustering (Largest overdense points)



... getting more statistics

A picture



miniclusters
axion stars
5
0
−5
−10
−20
−15
−10
−5
$\log R[R_\odot]$
$\log M[M_\odot]$

Microlensing constraints

Fairbairn 2017

Eros (LMC) 1-1000 days

HyperSuprimeCam (M31) 2 min-7h

fraction of DM in MC's