Axion Relic Pockets —
A New Theory of Dark Matter

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Axion Quest, Quy Nhom, Vietnam

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A gauge theory has two parameters — quantum gravity has none

$$\mathscr{L} = -\frac{1}{2g^2}\mathrm{Tr}\left(F_{\mu\nu}F^{\mu\nu}\right) + \frac{\theta}{16\pi^2}\mathrm{Tr}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)$$

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↓

$$\mathscr{L} = -\frac{\phi}{2\Lambda}\mathrm{Tr}\left(F_{\mu\nu}F^{\mu\nu}\right) + \frac{a}{16\pi^2 f_a}\mathrm{Tr}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)$$

ϕ : ‘dilaton’

a : axion

Highly constrained interactions

$$V(\phi, a) = M^4 e^{-S_{\rm inst}} \Big(1 - \cos(\theta)\Big) = M^4 e^{-8\pi^2 \phi/\Lambda} \left(1 - \cos\left(\frac{a}{f_a}\right)\right)$$

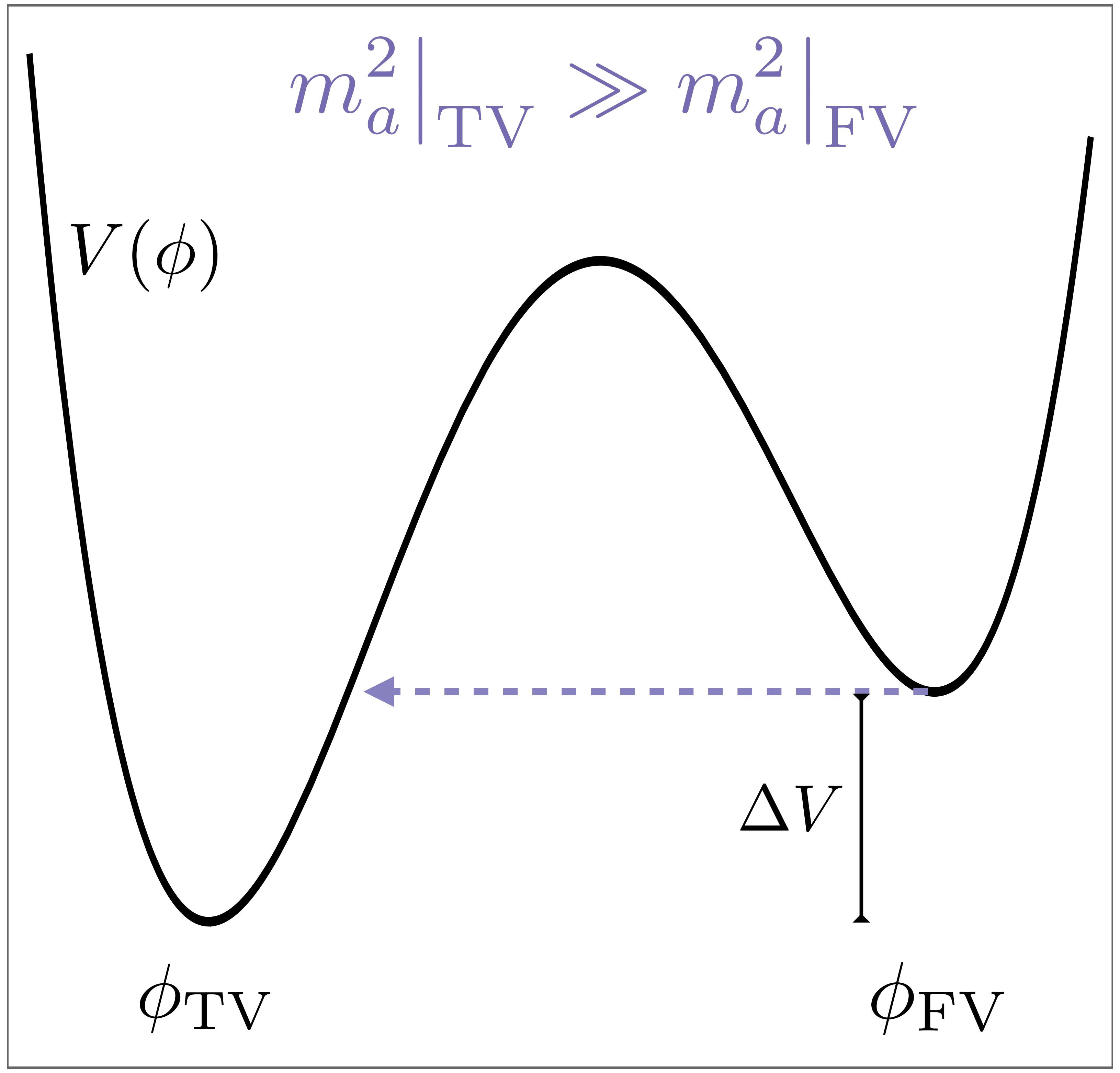
$$S_{\rm inst} = 8\pi^2/g^2$$

1. The axion potential is exponentially sensitive to ϕ .
2. Large instanton actions ($S_{\rm inst} \sim \mathcal{O}(100's)$) are common in high-energy physics, including string theory.
3. The dilaton receives additional perturbative and non-perturbative contributions to its potential.

Assumptions:

1. The dilaton tunnels quantum mechanically to a smaller value during radiation domination.

2. A (possibly tiny) axion abundance exists, e.g. as an oscillating condensate from the misalignment mechanism or as dark radiation.



Consequence:

The axion mass increases exponentially through the transition: $m_a^2\big|_{\mathrm{TV}} = m_a^2\big|_{\mathrm{FV}} \exp\!\left(S_{\mathrm{FV}} \cdot \frac{|\Delta\phi|}{\phi_{\mathrm{FV}}}\right)$.

$T > T_t$

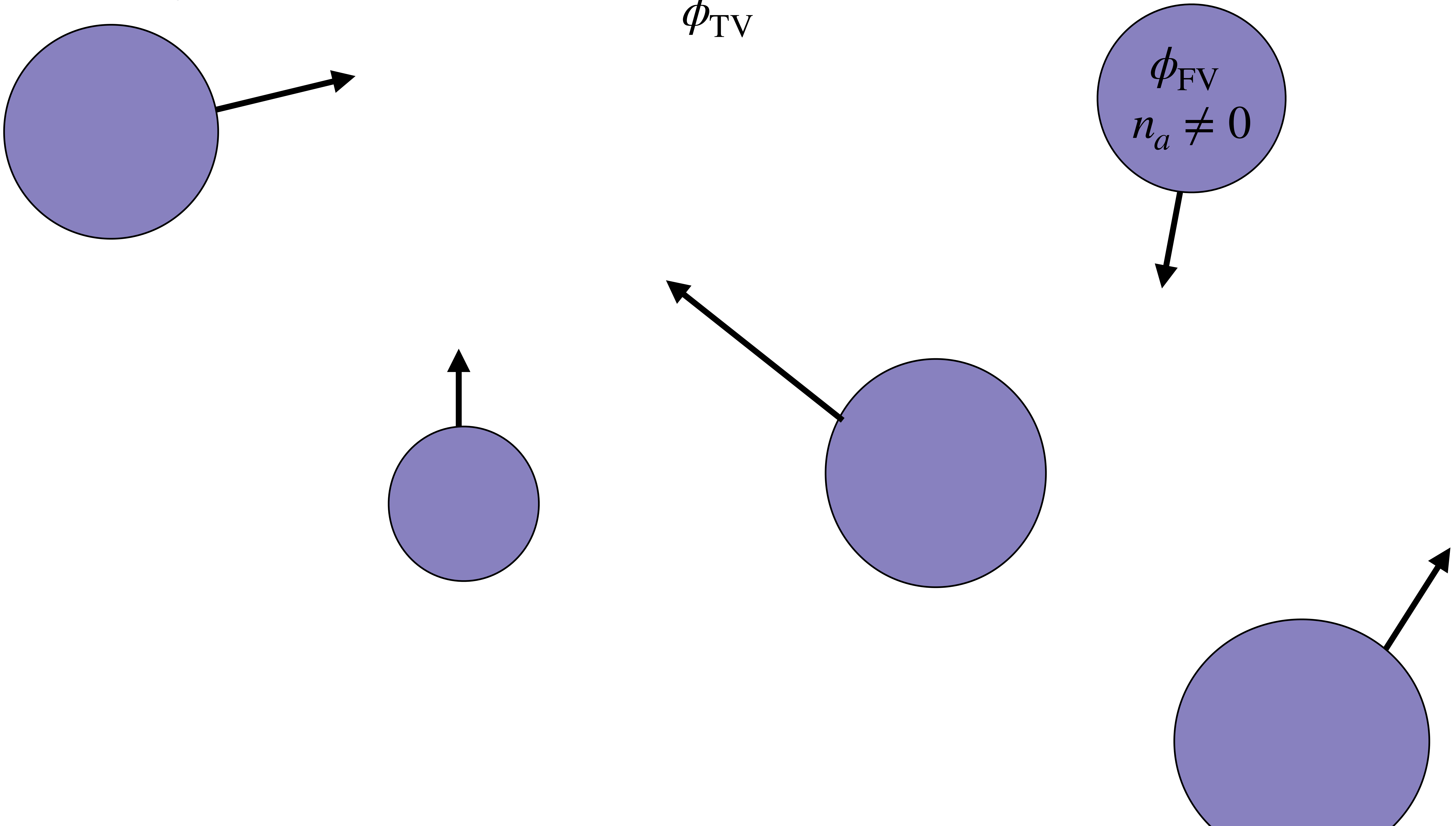
ϕ_{FV}

$n_a \neq 0$

$T = T_t$
ϕ_{FV}
$n_a \neq 0$
ϕ_{TV}


$T \approx T_{\rm coll}$
$\phi_{\rm FV}$
$n_a \neq 0$
$\phi_{\rm TV}$

$T_{\rm coll} < T < T_f$



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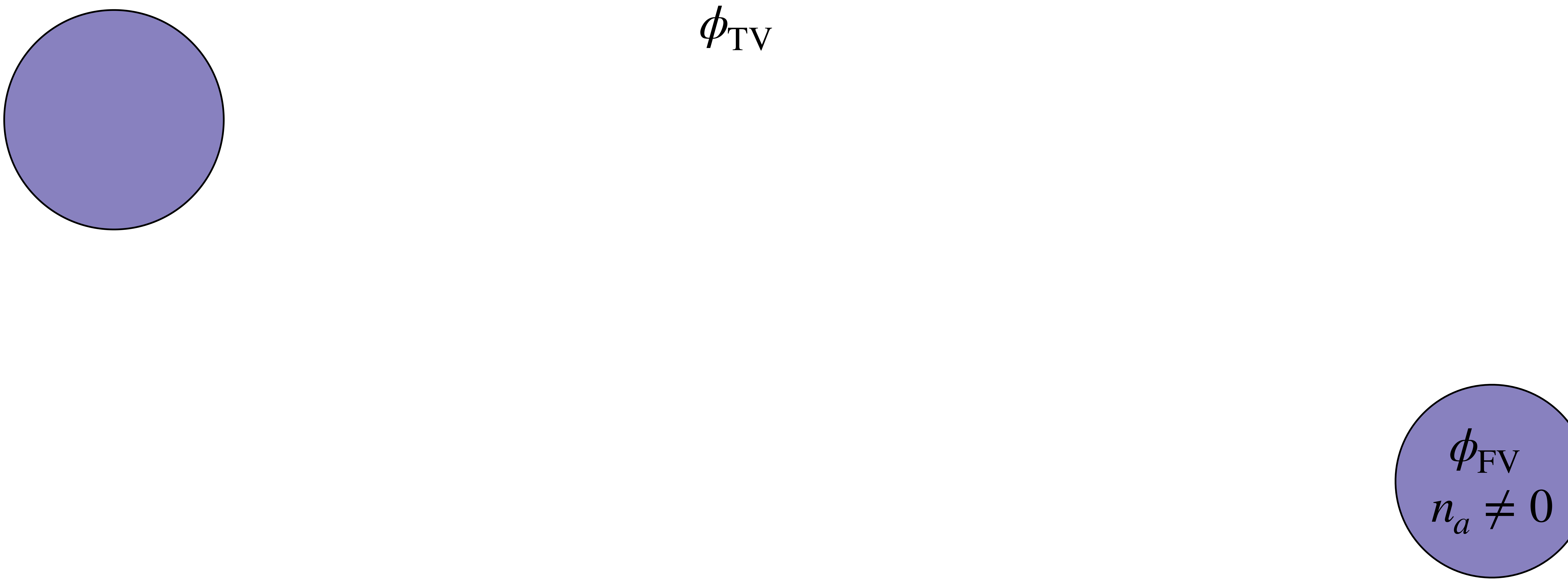


Bubble nucleation

The tunnelling rate is determined by the `bounce' action: $\frac{\Gamma}{\mathcal{V}} \sim e^{-S_4}$

cf. Coleman, 1977

S_4 depends on two parameters:

ΔV — `latent heat'

$\sigma = \int_{\phi_{\rm TV}}^{\phi_{\rm FV}} d\phi \sqrt{2V(\phi)}$ — `tension'

Transition happens at Standard Model temperature $T = T_t$ when

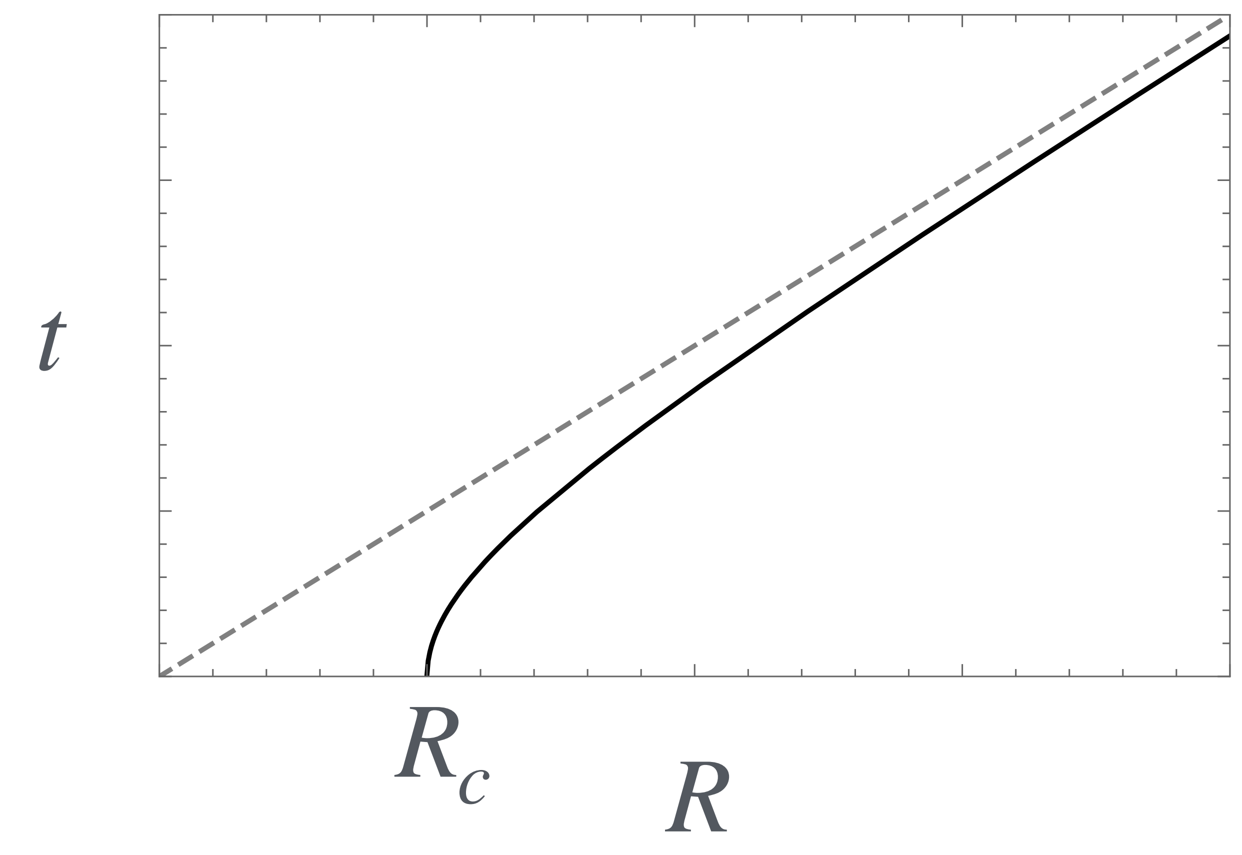
$$\Gamma/\mathcal{V} \sim H^4$$

Nucleated bubbles have radius $R_c = 3\sigma/\Delta V$ and are separated by $R_H = 1/H$.

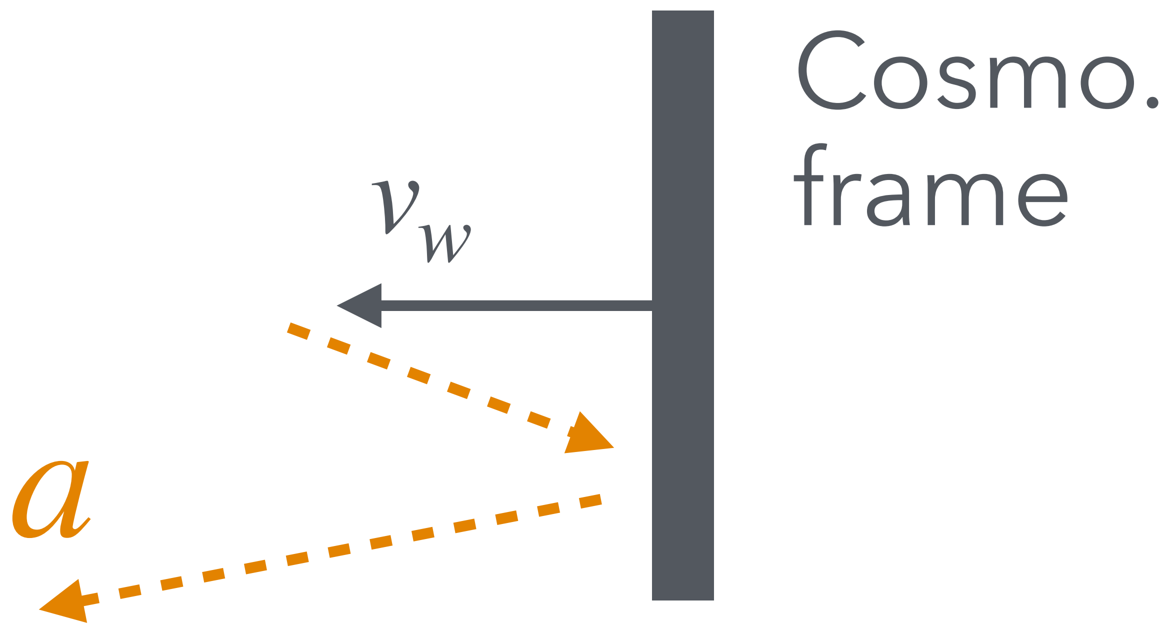
Mass-increase of axions can delay phase transition.

Bubble growth

The bounce solution is hyperbolic in spacetime.

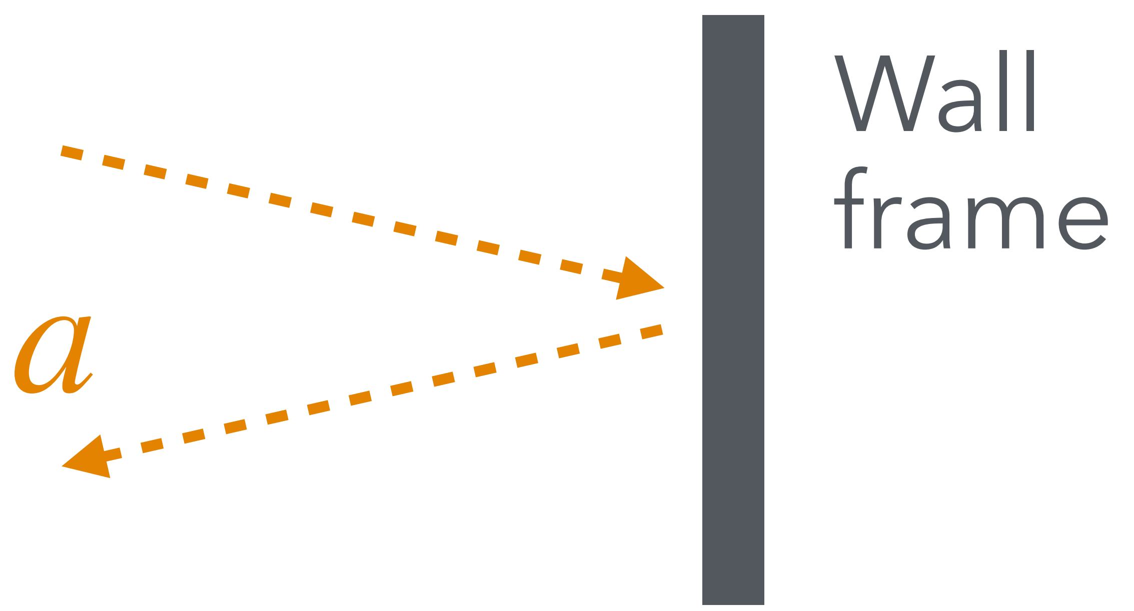


Axion pressure on wall:
Calculated by transforming to the wall frame, imposing reflective boundary conditions, and transforming back.



The pressure grows like $\Delta p \sim \gamma_w^2$.

Run-away:
For ambient dark matter axions, the pressure on the expanding bubbles is so small that it never becomes relevant before bubbles collide.

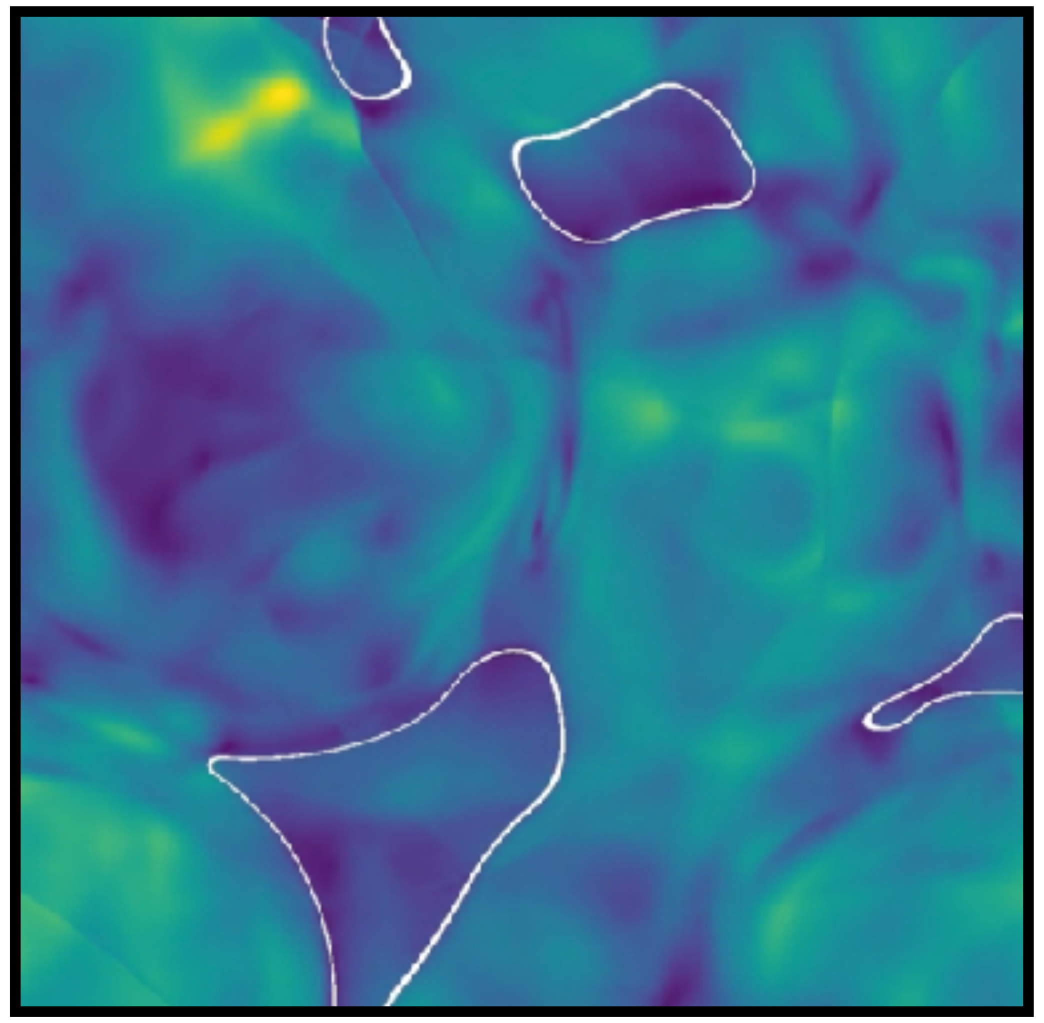


Colliding bubbles are highly relativistic.

Axion Relic Pocket Formation

The axion pockets are initially non-spherical and relativistic: (3+1)d simulations required to fully characterise.

Here, assume spherical symmetry of a single pocket, i.e. (1+1)d.



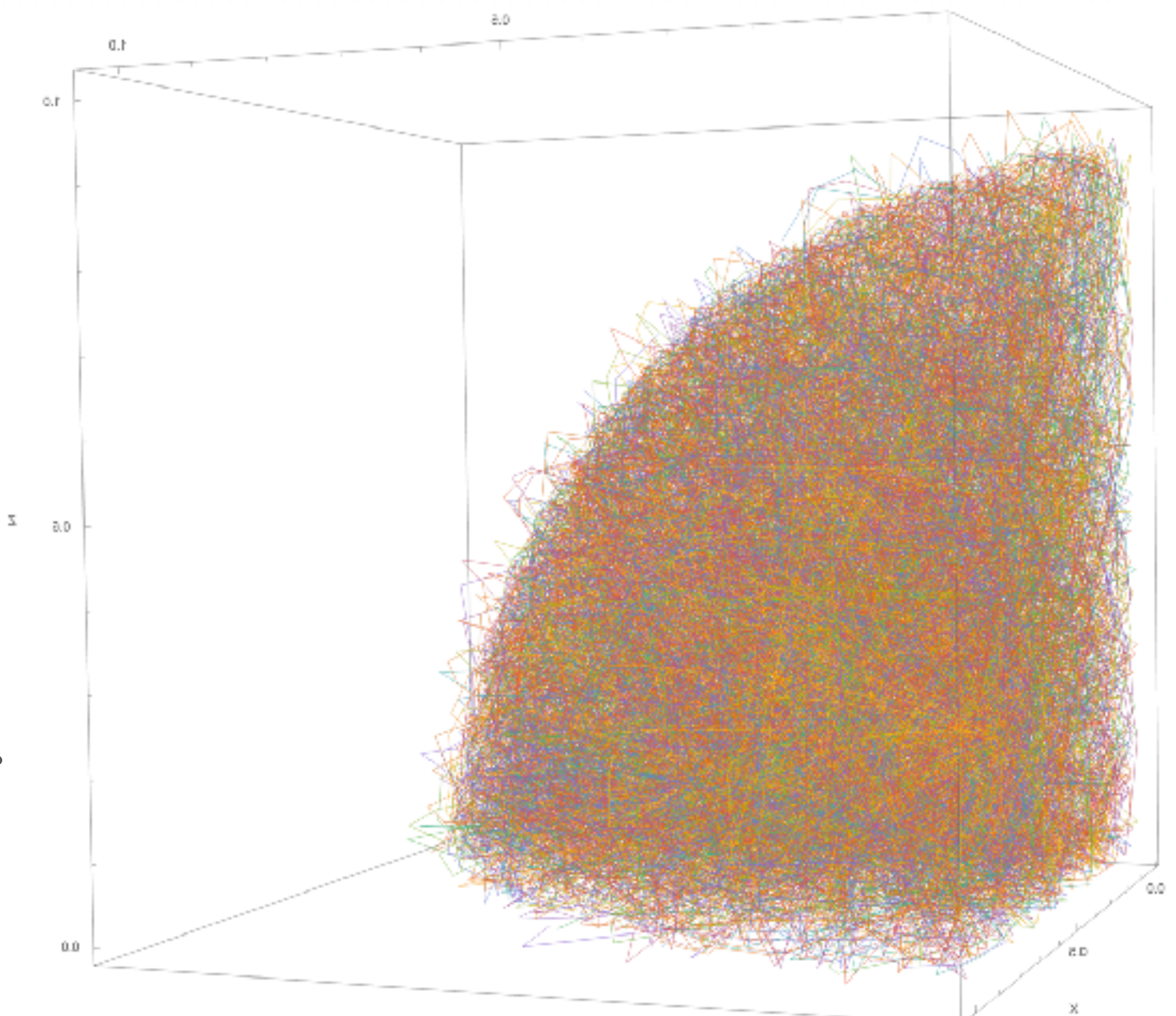
Cutting et al., 2019

Assuming also *homogeneous distribution functions*, one can derive a coupled system of ODEs for the pocket radius and axion gas pressure:

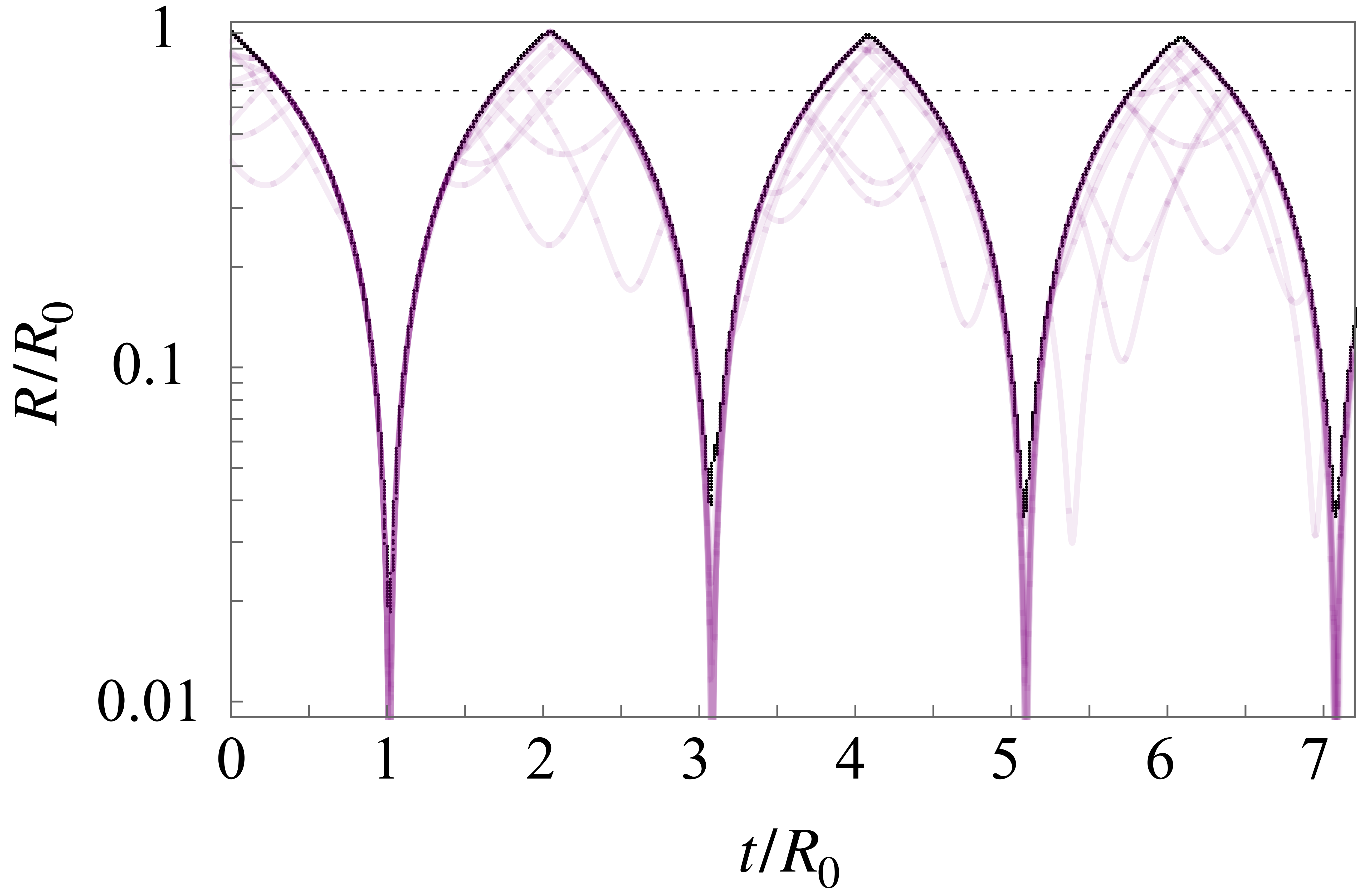
$$\begin{cases} \ddot{R} + 2\dfrac{1-\dot{R}^2}{R} &= \dfrac{(1-\dot{R}^2)^{3/2}}{\sigma}\left(-\Delta V + P_{\rm gas}\dfrac{(1-\dot{R})^2}{1+\dot{R}}\right) \\ \dfrac{d}{dt}\ln P_{\rm gas} &= -\dfrac{\dot{R}}{R}\left(3 + \dfrac{(1-\dot{R})^2}{1+\dot{R}}\right) \end{cases}$$

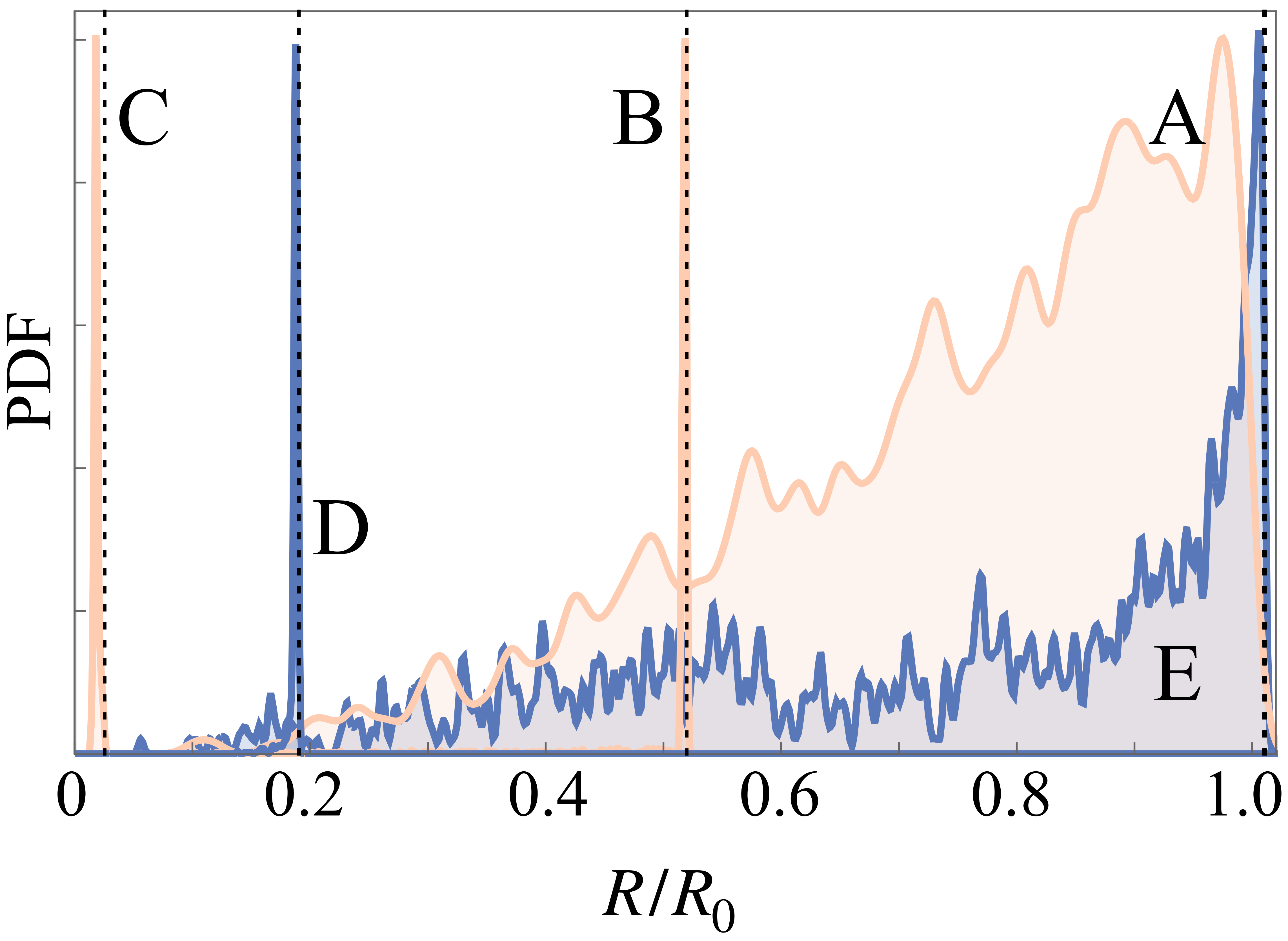
More generally, the system can studied through N-body simulations.

cf. Lewicki et al., 2022



Pulsating pockets

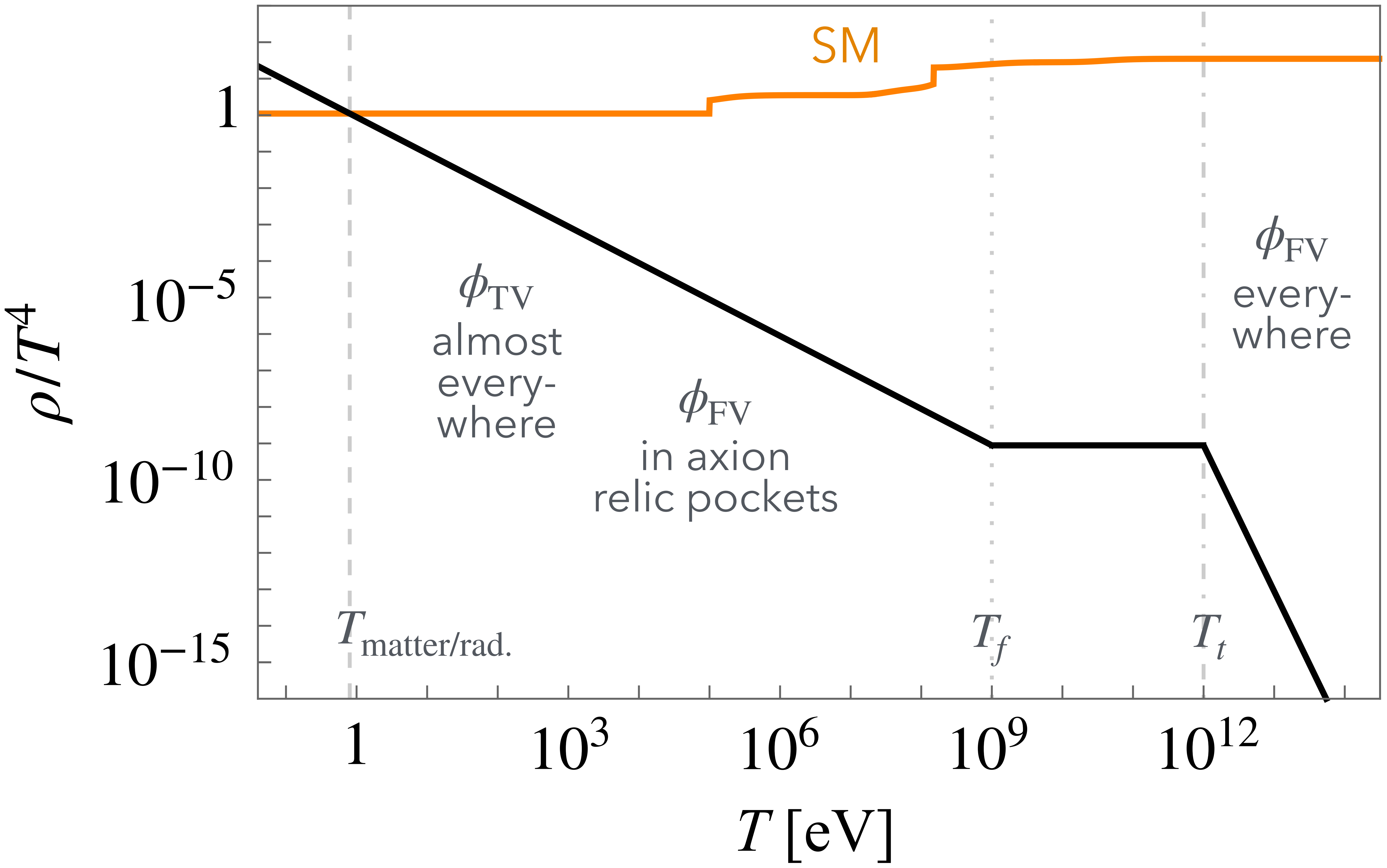




Radial oscillations for some time.

Axion Relic Pocket Cosmology

Axion relic pockets can comprise all of dark matter.



$$\rho_{\rm pocket}(t_0) = \epsilon^4 \Delta V \left(\frac{\mathfrak{a}(t_f)}{\mathfrak{a}(t_0)}\right)^3$$

Fixing the dark matter density amounts to fixing $\Delta V(T_t)$.

$$\Delta V\Big|_{\rm DM} \simeq 19.5\ {\rm GeV}^4\ \epsilon^{-4} \left(\frac{T_t}{\rm TeV}\right)^3$$

Transition must (naively) happen between inflation and matter/rad. equality:

$$1\ {\rm eV} \lesssim T_t \lesssim 10^{16}\,{\rm GeV}$$

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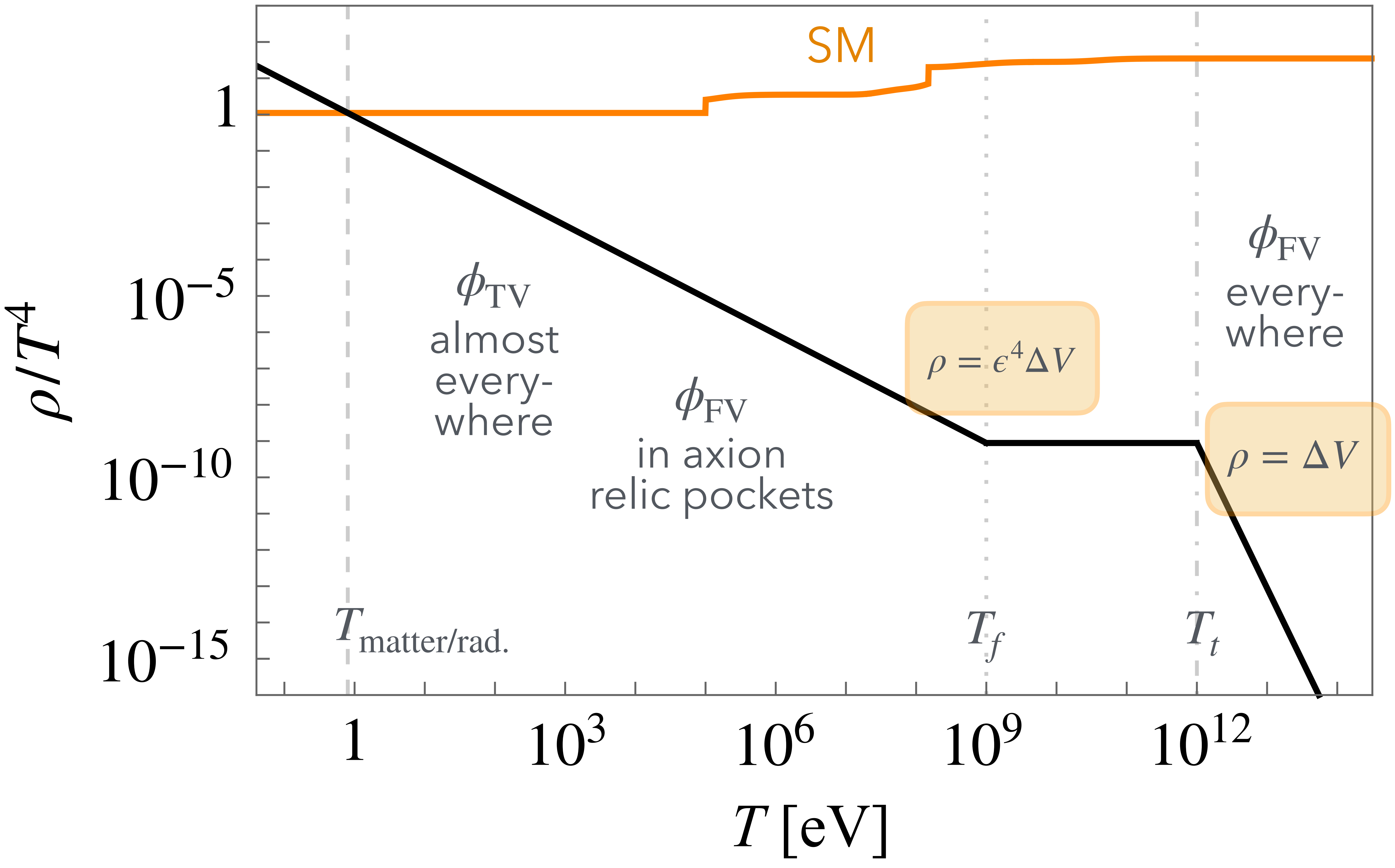

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Properties of Axion Relic Pockets

Pressure balance and energy conservation determine the macroscopic properties of axion relic pockets.

Radius:

$$R_{\text{eq}} = \frac{2}{3}\frac{R_c}{\mathscr{P}/\Delta V - 1} \sim R_H \sim 2 \times 10^{-4}\,\text{m}\left(\frac{\text{TeV}}{T_t}\right)^2$$

Mass:

$$M_{\text{pocket}} \sim \frac{4\pi}{3} R_0^3 \Delta V\Big|_{\text{DM}} = 4.9 \cdot 10^{38}\,\text{GeV}\left(\frac{1}{\epsilon}\right)\left(\frac{\text{TeV}}{T_t}\right)^3 = 4.3 \cdot 10^{-19} M_\odot \left(\frac{1}{\epsilon}\right)\left(\frac{\text{TeV}}{T_t}\right)^3$$

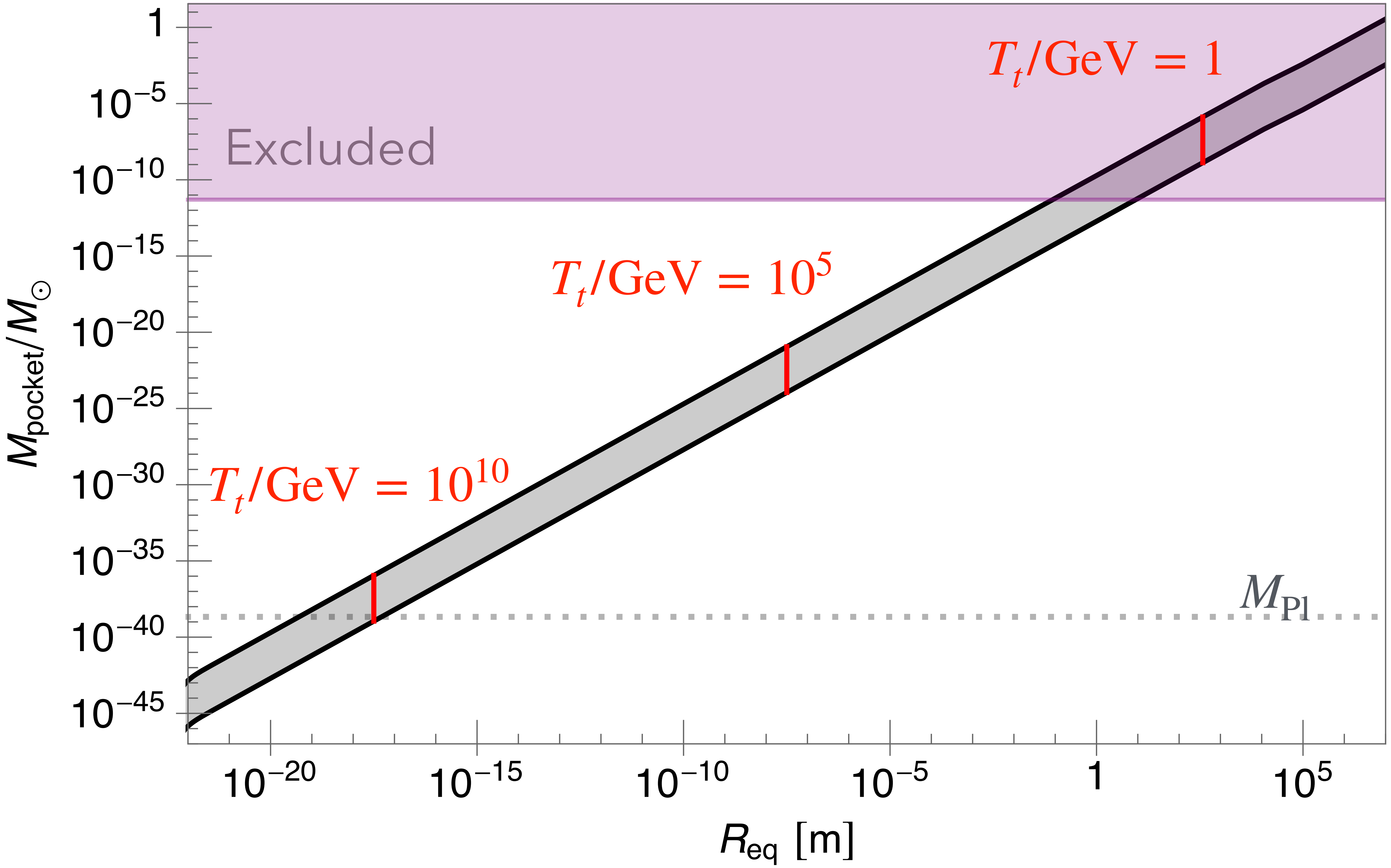
Axion gas temperature (thermal)**:**

$$T_{\text{eq}} \sim 5.3\ \text{GeV}\ \frac{1}{\epsilon^{1/4}}\left(\frac{T_t}{\text{TeV}}\right)^{3/4}$$

If gas thermalises, all properties become independent of initial axion abundance.

Mass v. Radius

Single-parameter solution, but with a broad range.



A priori, radius may run from point-like to galactic. Microlensing constraints rule out largest radii, corresponding to $1\,\mathrm{eV} < T_t \lesssim 13\,\mathrm{GeV}$.

Viable mass range:

$$10^{10}\,\mathrm{GeV} < M_{\mathrm{pocket}} \lesssim 5 \cdot 10^{-12}\,\mathrm{M}_{\odot}\,.$$

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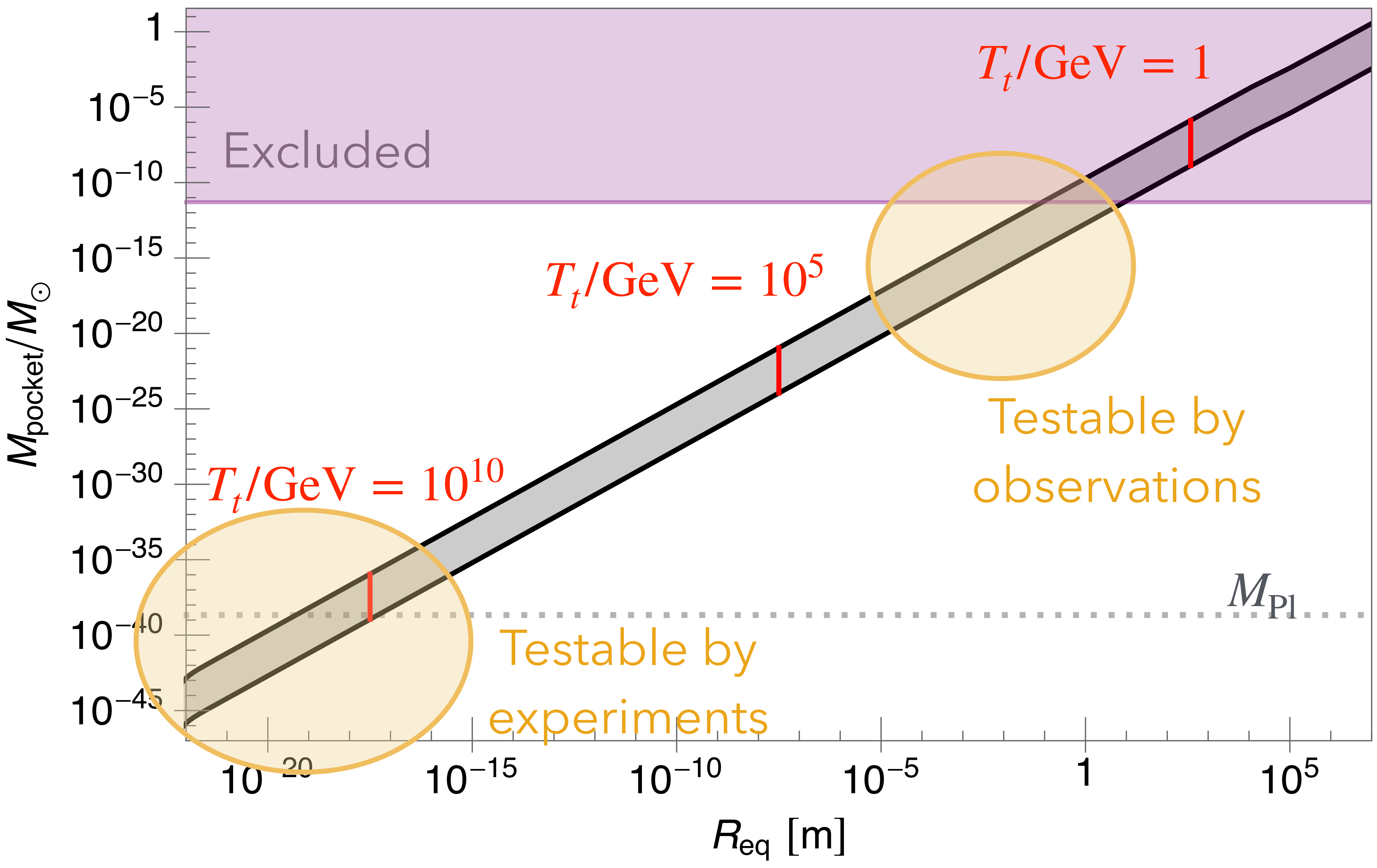

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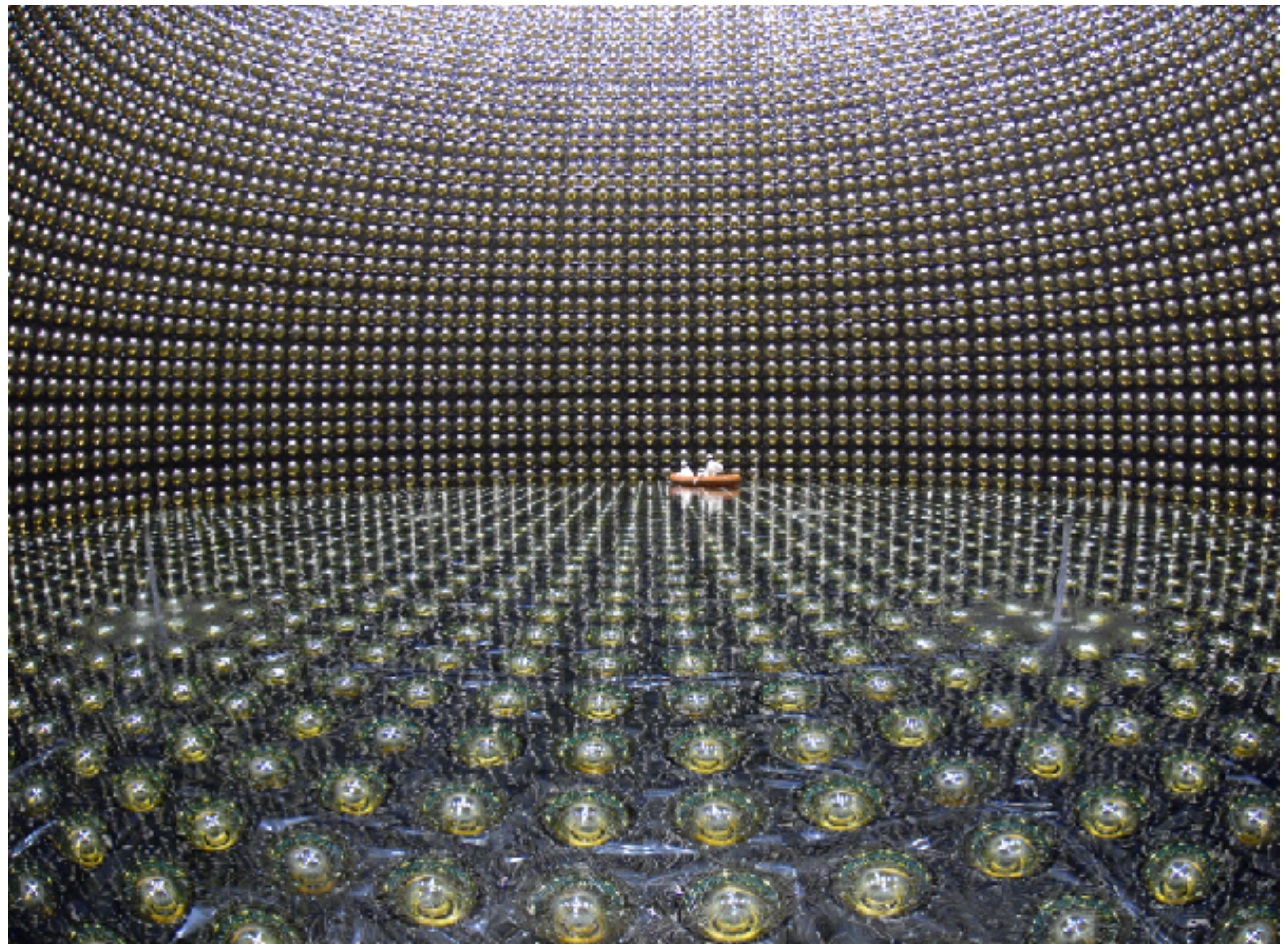
Laboratory searches for Axion Relic Pockets

Encounter rate: $\Gamma_{\rm encounter} \sim n_{\rm pocket}\sigma v_{\rm pocket} = 10^{-6}\epsilon\ {\rm year}^{-1}\left(\frac{R}{R_\oplus}\right)^2\left(\frac{T_t}{\rm TeV}\right)^3$

For $T_t \gtrsim 10^{12}\,{\rm GeV}$, a detector volume of $1\,{\rm m}^3$ would encounter 1 pocket/second.
Gas temperature ~$10^{10}\,{\rm GeV}$, and #axions/pocket $\sim 10^5$.



Super-Kamiokande

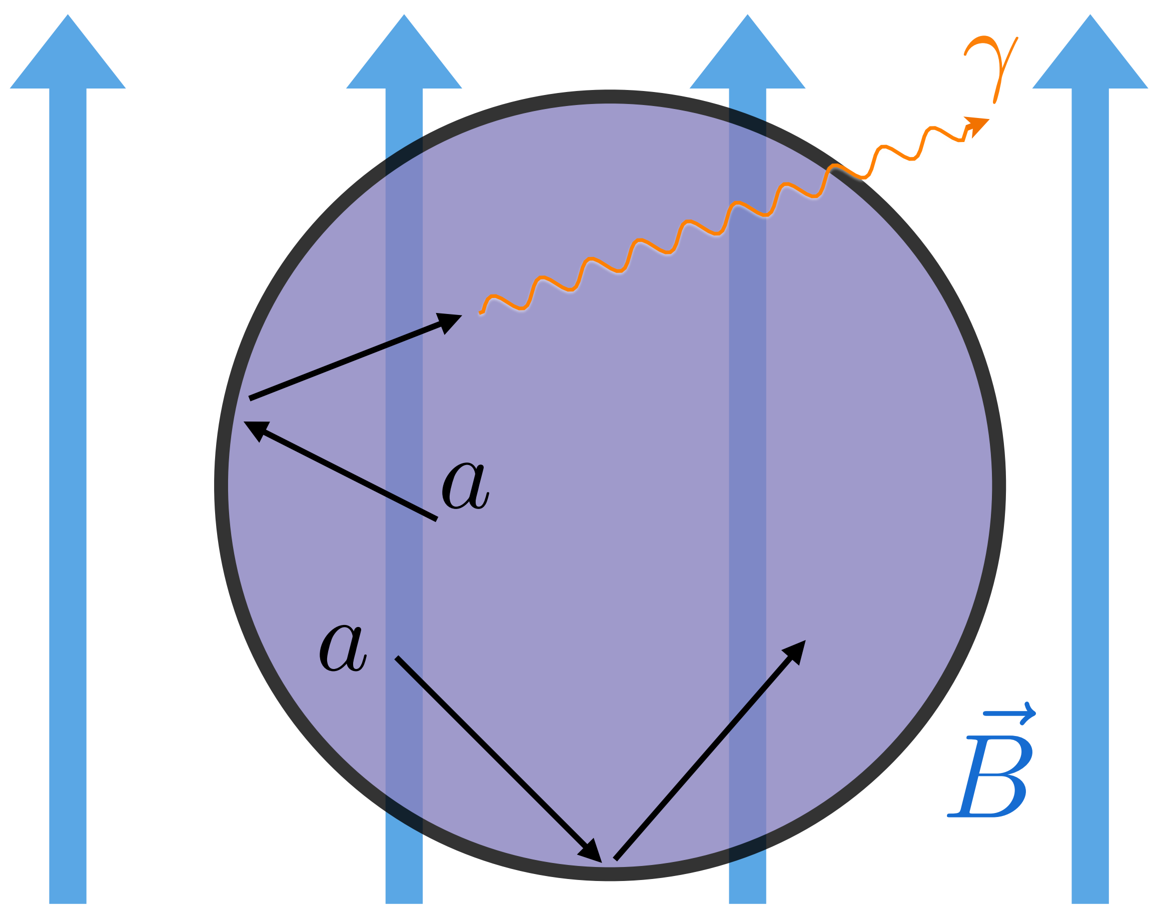
XENONnT

LHAASO, WCDA

Astronomical searches for Axion Relic Pockets

Axion-photon conversion rate:

$$\left|\frac{dN_{a\,\mathrm{pocket}}}{dt}\right| = \Gamma_{a\to\gamma} N_{a\,\mathrm{pocket}} = 200\ \mathrm{s}^{-1}\ \epsilon^{-3/4} \left(\frac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right)^2 \left(\frac{B}{\mu\mathrm{G}}\right)^2 \left(\frac{\mathrm{TeV}}{T_t}\right)^{23/4}$$



Rate is small enough for relic pockets to be long-lived.

Number flux is greatly enhanced at low temperatures. E.g., for $T_t = 15\,\mathrm{GeV}$ and $B_\perp = 15\,\mathrm{G}$,

$$\left|\frac{dN_{a\,\mathrm{pocket}}}{dt}\right| \sim 10^{37}\ \mathrm{s}^{-1} \left(\frac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right)^2$$

with photon energy set by $T_{\mathrm{eq}} \sim 230\ \mathrm{MeV}$.

Moderate-to-highly magnetised regions (e.g. magnetars with $B \sim 10^{15}\,\mathrm{G}$) may generate observable, characteristic signals.

Theory requirements

Initial axion population particle-like:

$$m_a\big|_{\mathrm{FV}} \gtrsim 3H(T_t)$$ (if produced by misalignment mech.)

Reflective boundary condition:

$$m_a\big|_{\mathrm{TV}} \gtrsim 10\,T_{\mathrm{eq}}$$ (transm. exponentially suppressed)

Required field displacement:

$$\ln\left(\frac{m_a^2\big|_{\mathrm{TV}}}{m_a^2\big|_{\mathrm{FV}}}\right) = S_{\mathrm{FV}} \cdot \frac{|\Delta\phi|}{\phi_{\mathrm{FV}}} \simeq 60.2 - \ln\left(\epsilon^{-1/2}\left(\frac{T}{\mathrm{TeV}}\right)^{5/2}\right)$$

S_{FV}: $\mathcal{O}(100\text{'s})$

$\frac{|\Delta\phi|}{\phi_{\mathrm{FV}}}$: $\mathcal{O}(10\text{–}50\%)$

No fine-tuning required.

Conclusions & Outlook

Economical new theory, natural ingredients from high-energy physics, axion physics, cosmology. Phenomenology distinct from existing paradigms.

Tantalising experimental opportunity. Window towards very early times ($t \sim 10^{-30}\,\mathrm{sec}$). Size of pocket set by Hubble radius at T_t. Detection would be evidence for radiation domination to very early times, and would constrain inflation.

Tractable astrophysical signals. Axion-photon conversion can generate gamma-ray (and possibly X-ray) signals. Strongly magnetised, dark-matter dense regions promising.

Much remains to be done. Expect significant progress in theory, simulations, phenomenology and observational/experimental progress over the coming years.