



MAKING A UNIVERSE WITH AXIONS

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Outline

- Is it a BEC?
- How do we calculate its evolution?
- What other cosmological purposes might the axion serve?
- Astrophysics as next gen high energy physics

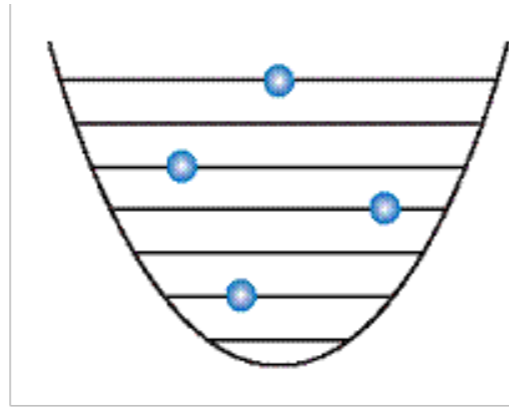
Axion, ALP, Fuzzy DM, WISP

- (Relic) QCD axions: made in the early ($z \gg 1100$) universe during the Peccei-Quinn symmetry breaking; thermal: made in stars?
- Axion-like particles (ALPs): particles with shift symmetries like axion but maybe not solving QCD problems; motivated by string theory! (Maybe don't solve DM either.)
- Ultralight axions (ULAs): ALPs that are down to 10^{-33} eV, different phenomenology from QCD axion @ 10^{-5} eV
- Weakly interacting slim particles (WISPs): light bosons, sometimes complex rather than real fields, not always scalars
- **axions and ALPs are interesting even if not dark matter**

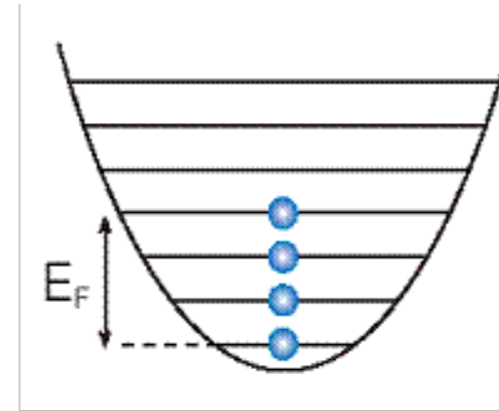
Is it a BEC?

- For cosmological purposes is it a classical or quantum field?
- Mean field approximation *is* a quantum calculation that allows treatment as a classical field

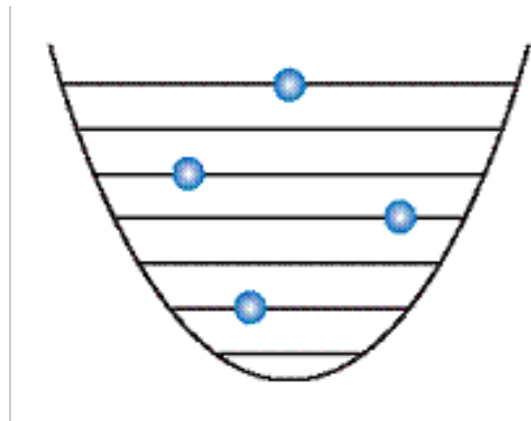
Fermions vs. Bosons



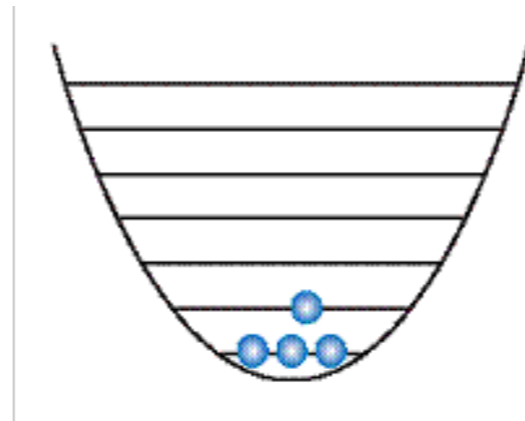
Thermal Fermions: $T > T_F$



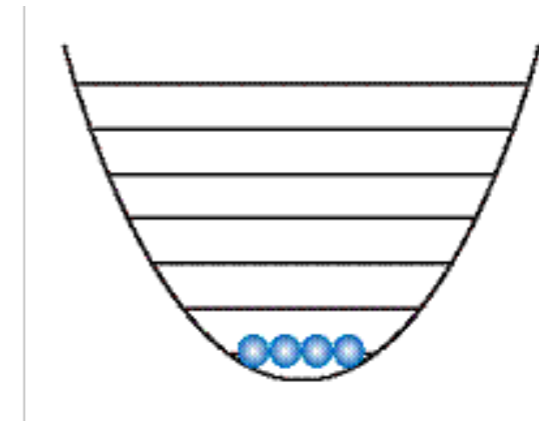
Degenerate Fermions: $T \ll T_F$



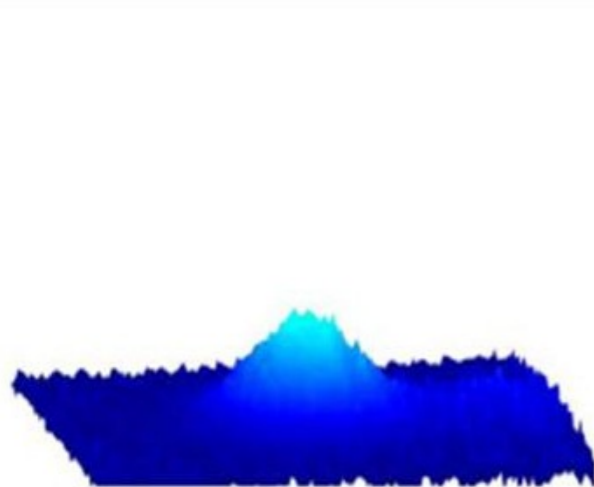
Thermal Bosons: $T > T_c$



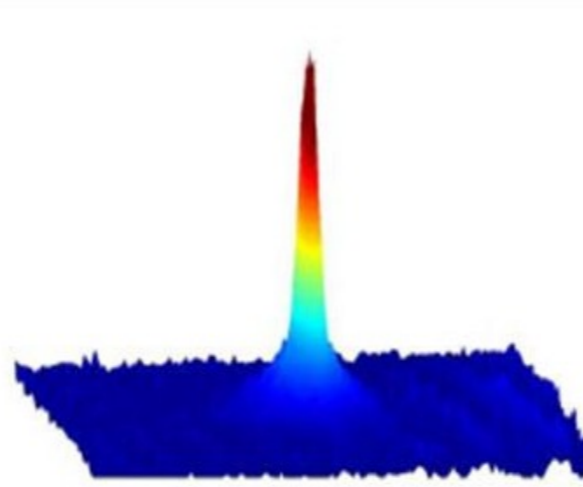
BEC+Thermal Bosons: $T \lesssim T_c$



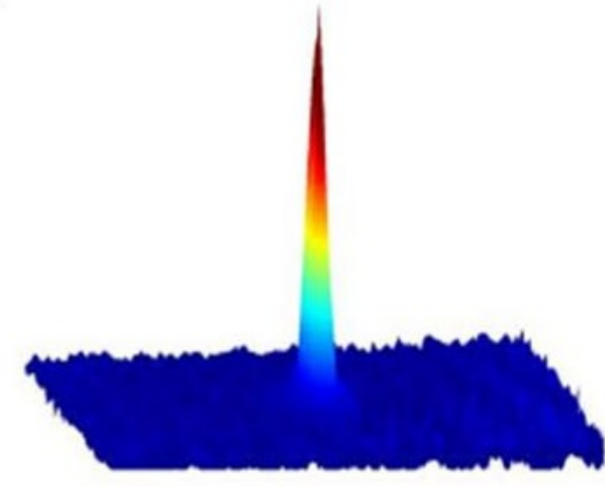
pure BEC: $T \ll T_c$



Thermal Rb-87: $T > T_c$



BEC+Thermal Rb-87: $T \lesssim T_c$



Rb-87 BEC: $T \ll T_c$

Equation of Evolution

time evolution

$$i \dot{\psi} = -\frac{1}{2m} \nabla^2 \psi - \frac{\lambda}{8m^2} |\psi|^2 \psi - Gm^2 \psi \int d^3 x' \frac{|\psi(x')|^2}{|x - x'|}$$

Kinetic term

Self-interaction, with coupling constant λ

Gravitational interactions

The diagram illustrates the components of the equation of evolution. A red arrow points from the text 'time evolution' to the left-hand side of the equation, $i \dot{\psi}$. Three red arrows point upwards from the labels 'Kinetic term', 'Self-interaction, with coupling constant λ ', and 'Gravitational interactions' to the corresponding terms on the right-hand side: $-\frac{1}{2m} \nabla^2 \psi$, $-\frac{\lambda}{8m^2} |\psi|^2 \psi$, and $-Gm^2 \psi \int d^3 x' \frac{|\psi(x')|^2}{|x - x'|}$ respectively.

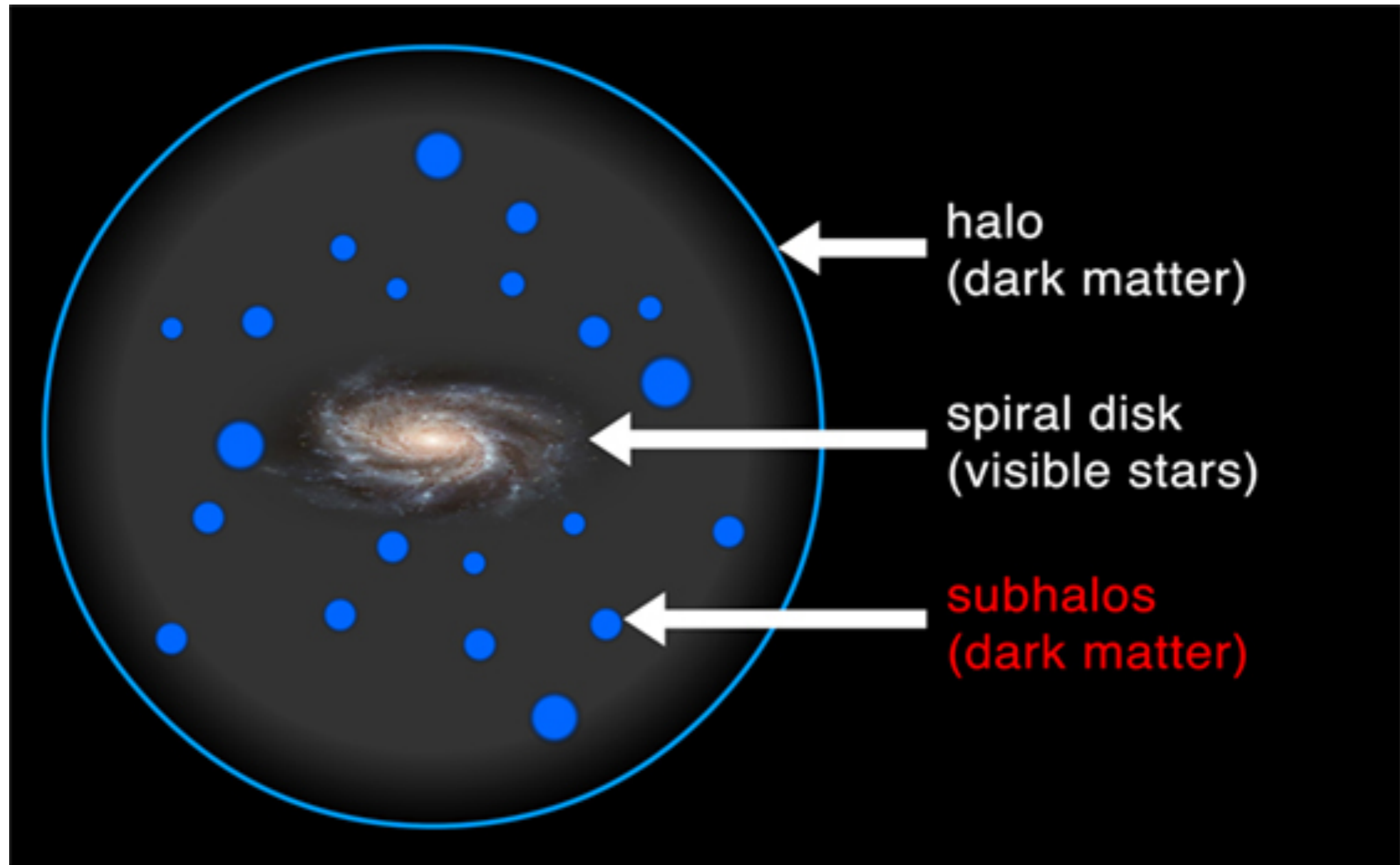
BECs in Space

- Sikivie & Yang (2009) propose that QCD **axion** dark matter must form **Bose-Einstein condensates** during radiation era, $m=10^{-5}$ eV
- Motivation: $\mathcal{N} \sim 10^{61}$ & $T_{BEC} \sim 500\text{eV} * \left(\frac{f_a}{10^{12}\text{GeV}}\right)^{\frac{1}{2}}$
- BEC from gravitational thermalization, not ϕ^4 (self) interactions
- BEC has correlation length that is Hubble scale

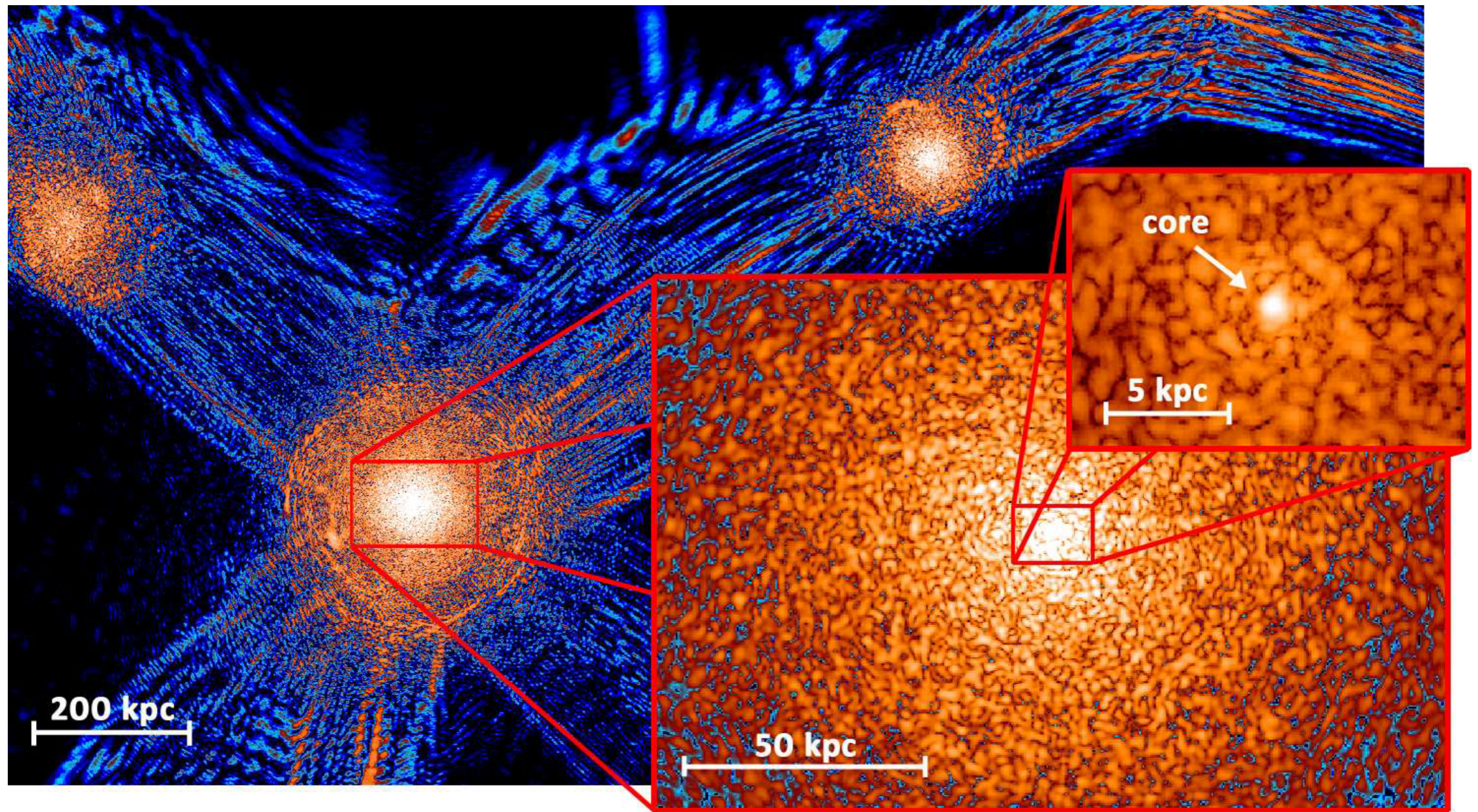
Does ALP Dark Matter form Bose–Einstein Condensates?

- Yes!
- QCD: in small, locally-correlated solitons — bose stars/axsteroids.
- ULA: halos with solitons at their core
- **Sign of the interaction determines coherence length/soliton size.**

A schematic picture



Fuzzy Dark Matter



The Problem of Axion Fields

- For cosmological purposes is it a classical or quantum field?
- Mean field approximation *is* a quantum calculation that allows treatment as a classical field
- But how do we account for interactions?
- Levkov et al. (2018) argue axions evolving under their self-gravity (without self-interactions) not a standard Boltzmann collision process
- Ignore self-interactions in the analysis

Don't use Boltzmann! Get your times sorted!

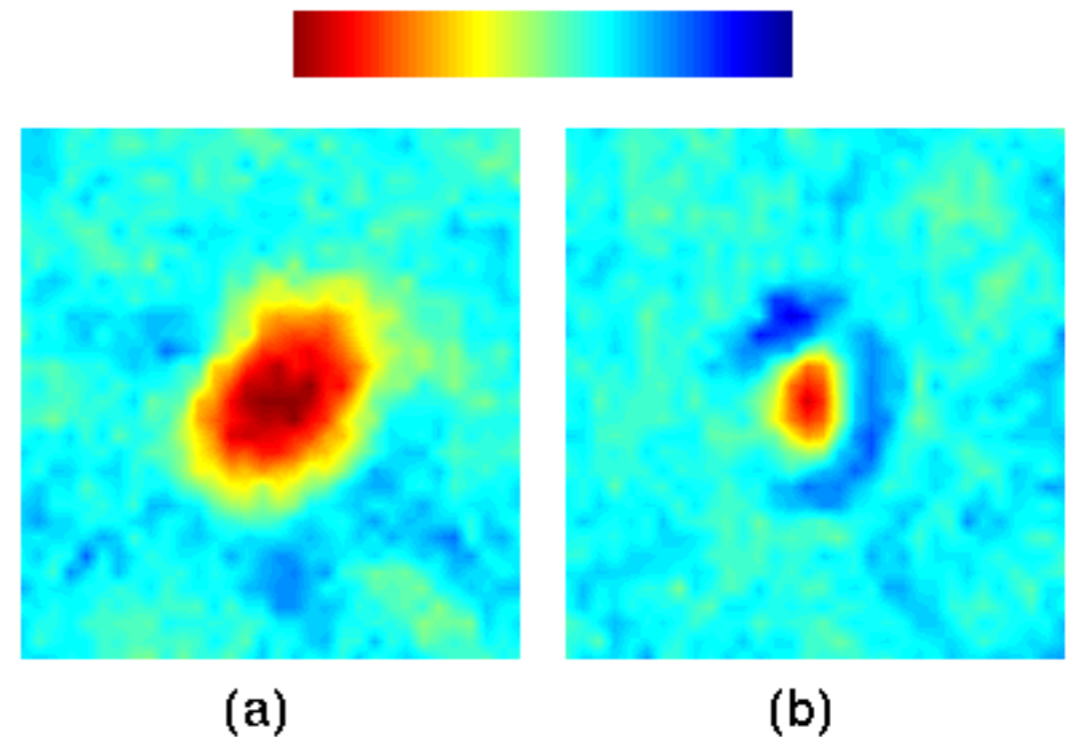
- Kirkpatrick, Mirasola, and Prescod-Weinstein (2020): high occupancy number implies **axions cannot be localized to a definite position and momentum in phase space, even during short-range self-interactions**
- Use the four-point correlation function, not Boltzmann
- Time scales involving self-interactions different from gravity-only
- Sikivie was right: **you cannot get thermalization into a coherent momentum state during lifetime of universe without gravity**

But self-interactions can still have an impact

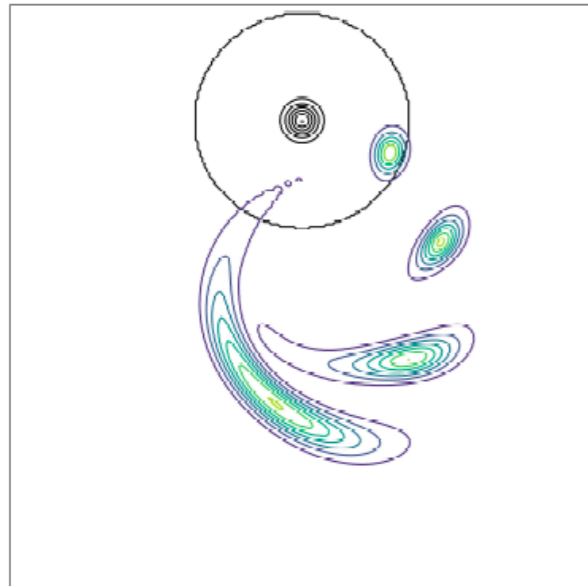
- Kirkpatrick, Mirasola, and CPW find that self-interactions are subdominant in setting time scale for initial condensation
- Glennon and CPW find that self-interactions are significant for the dynamical evolution of the system
- Let's gain some intuition for why this might be the case:

Lab BEC in Attractive Interactions

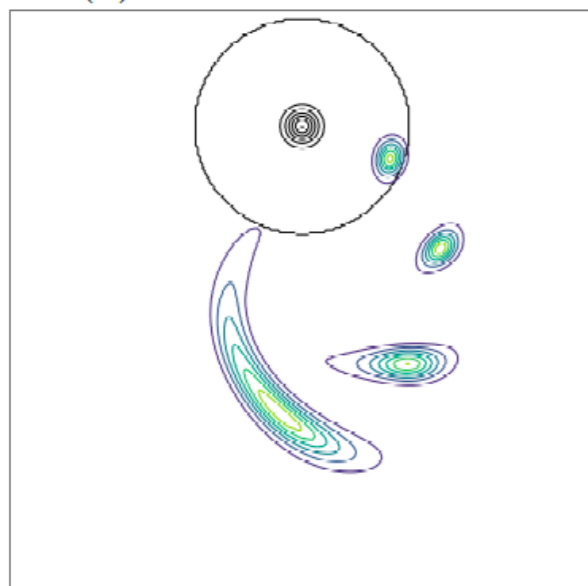
- Lithium-7 has 3 protons and 3 electrons \rightarrow boson
- Negative scattering length \rightarrow attractive interaction
- Theory said it should not form a stable BEC
- But it did! For ~ 1000 atoms or less.
- **Lots of intriguing questions here.**



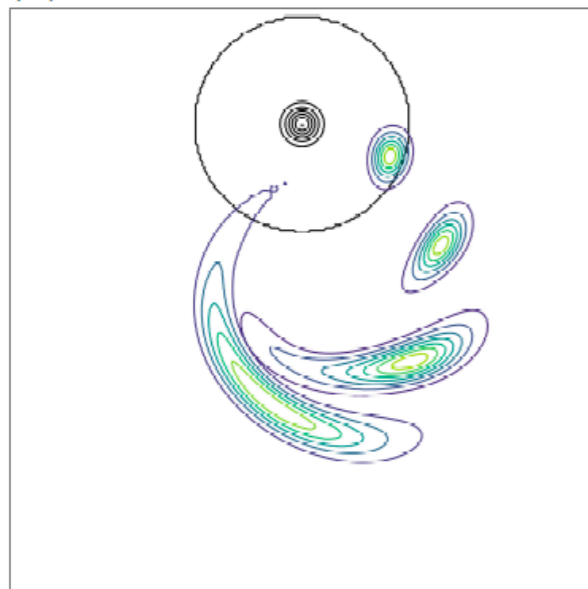
Hulet Group, Rice University



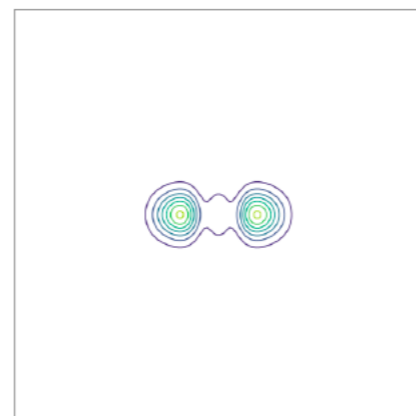
(a) No self-interactions



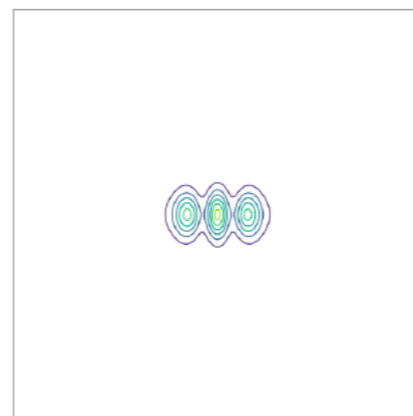
(b) Attractive self-interactions



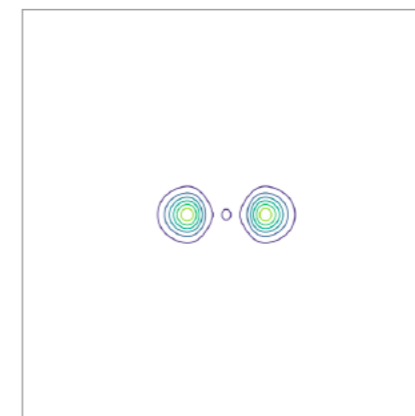
(c) Repulsive self-interactions



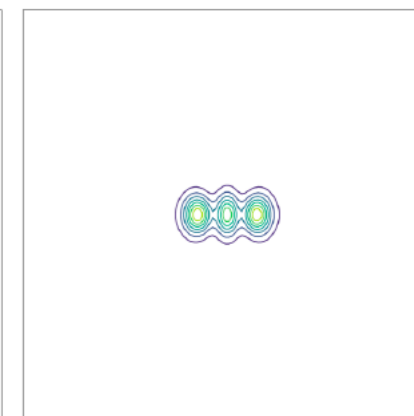
(c) $t = 0.03$



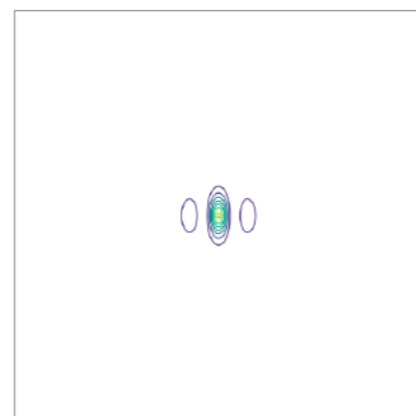
(d) $t = 0.04$



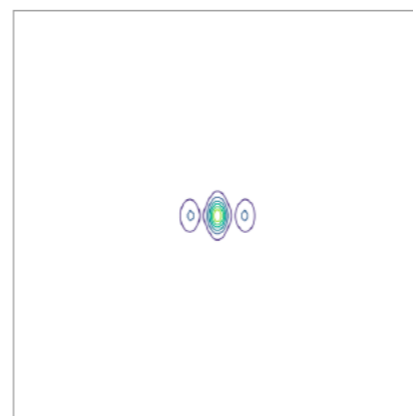
(c) $t = 0.03$



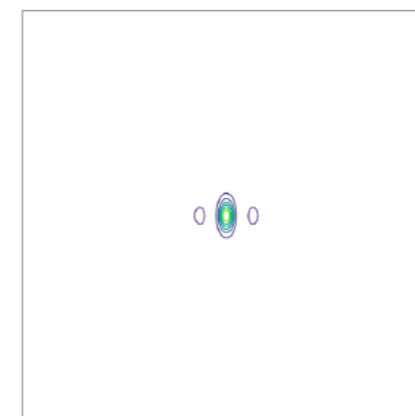
(d) $t = 0.04$



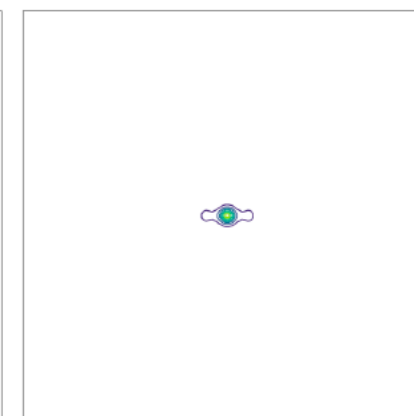
(e) $t = 0.05$



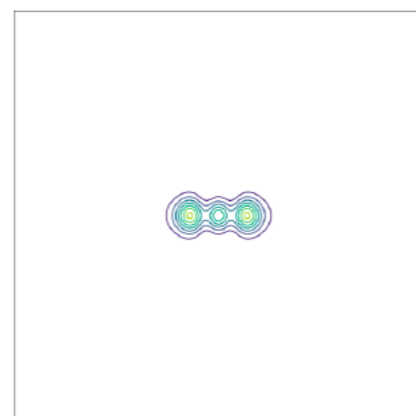
(f) $t = 0.06$



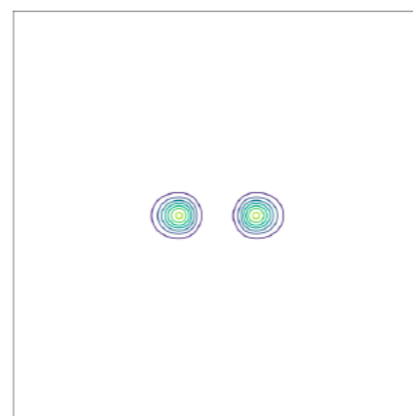
(e) $t = 0.05$



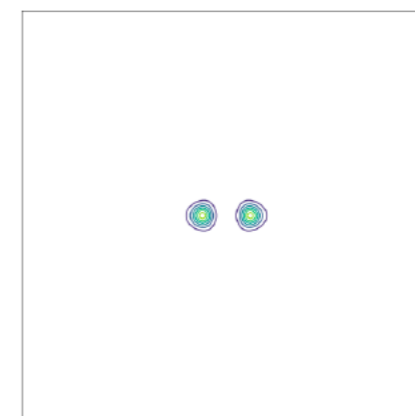
(f) $t = 0.06$



(g) $t = 0.07$



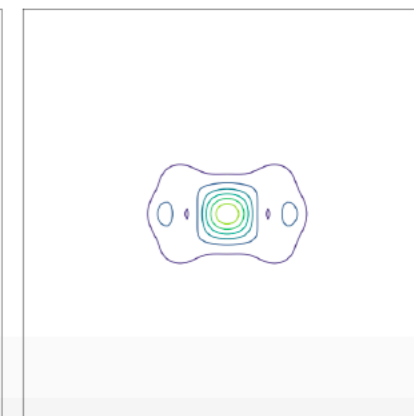
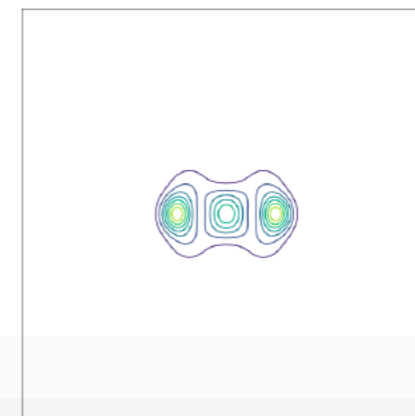
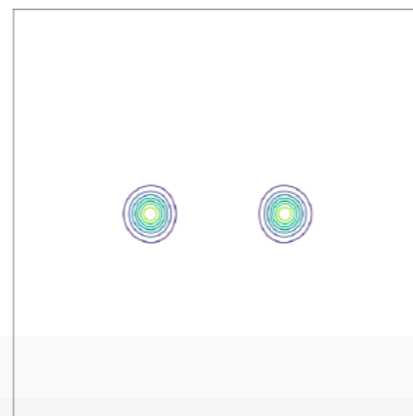
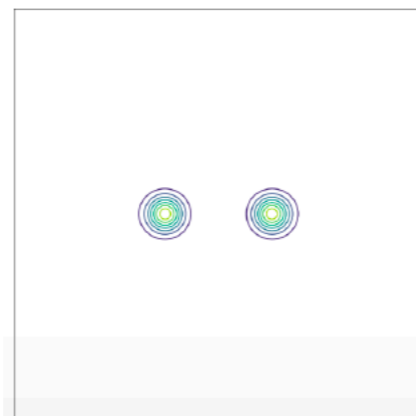
(h) $t = 0.08$



(g) $t = 0.07$



(h) $t = 0.08$

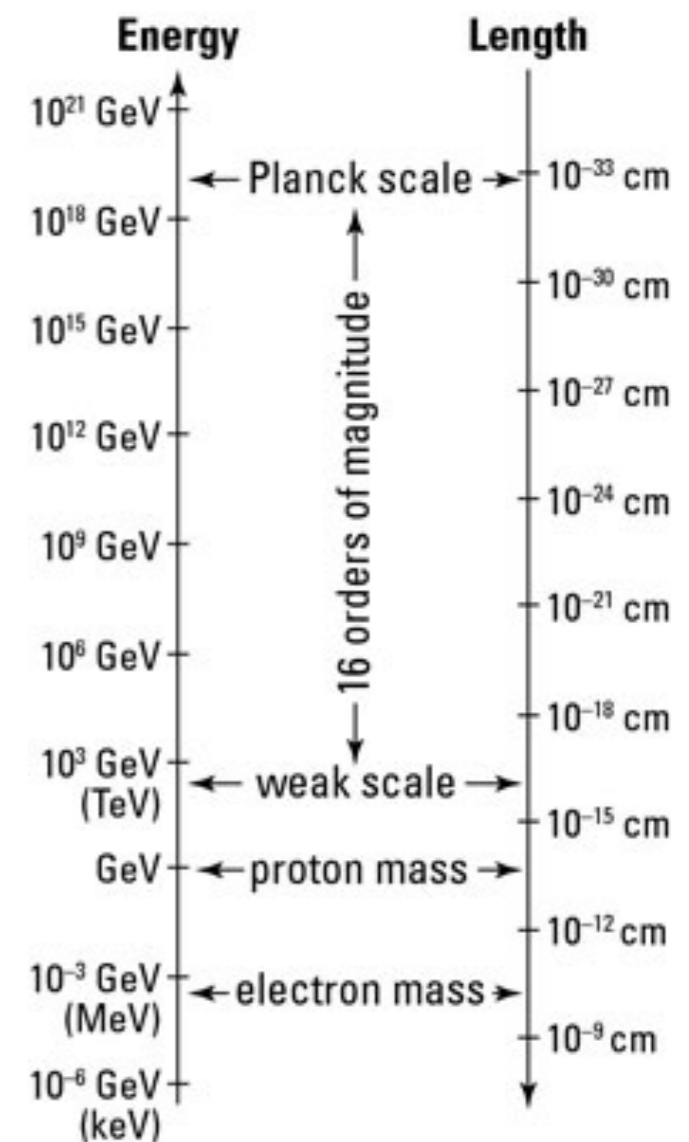


The Incredible Flexible Axion (Like Particle)

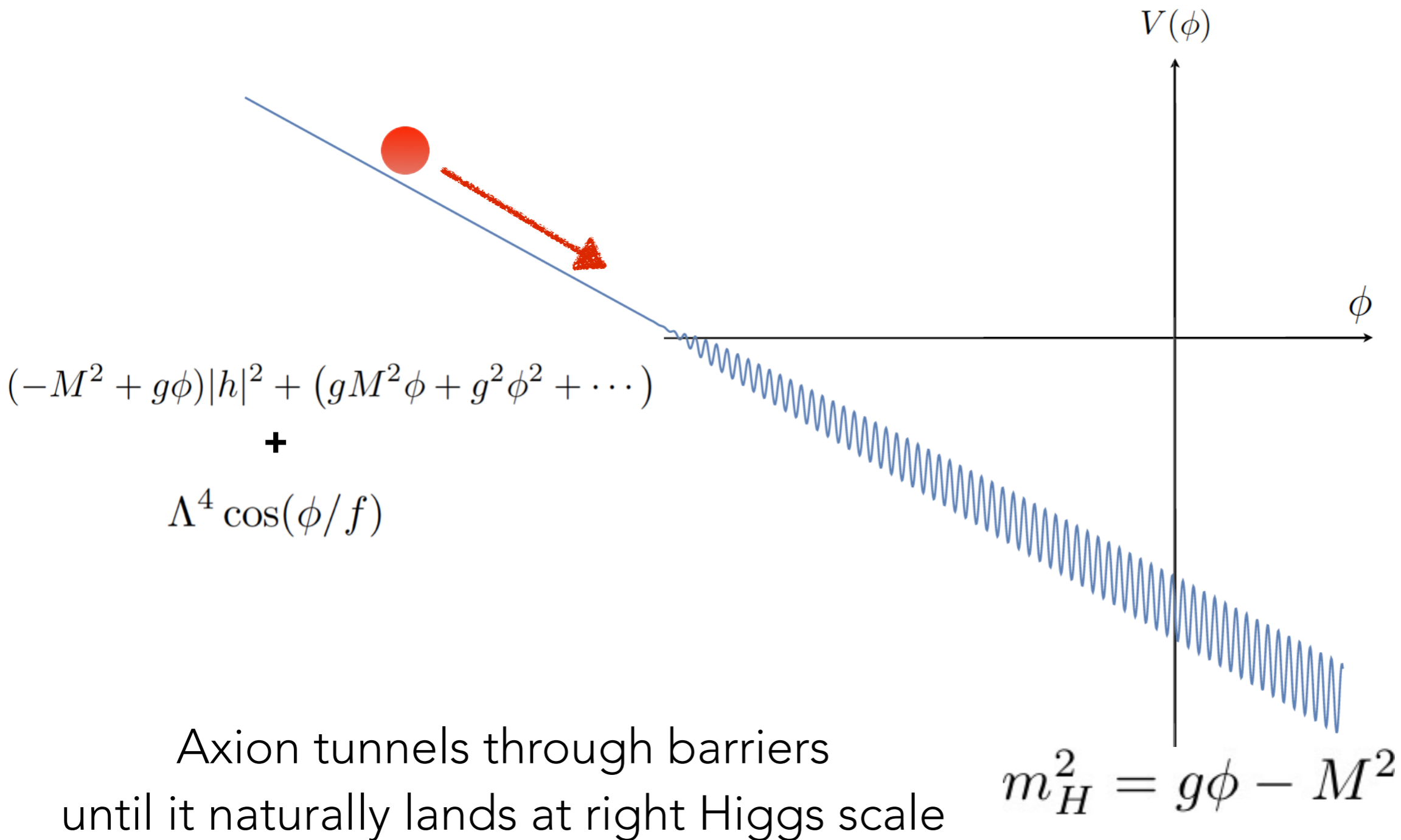
- Strong CP problem?
- Dark matter?
- **Solving the electroweak hierarchy problem?**

Electroweak Hierarchy Problem

- Electroweak Scale/Higgs Mass is $\sim 10^{16}$ times smaller than Planck scale
- Why is the Higgs mass so light?
- Fine tuning problem
- Solvable with Anthropics
- And now the **relaxion** (Graham et al.)



Relaxion: Slow rolling during inflation



Constraints?

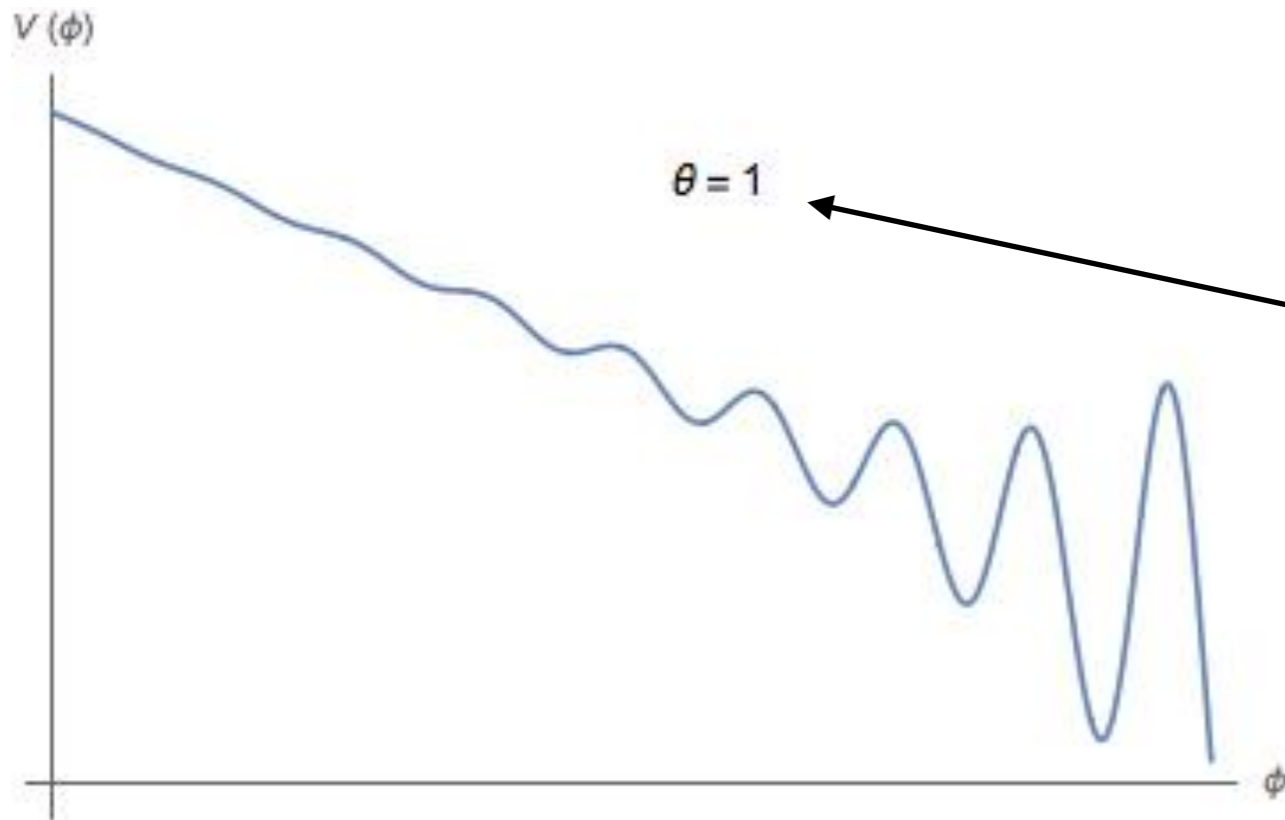
- $H \ll \Lambda_{QCD}$ so **classical evolution dominates**
- $H > \frac{M^2}{M_{pl}}$ to prevent back reaction onto inflaton
- inflation must be long-lasting $\sim 10^{50}$ e-folds
- the coupling g must be extremely small

SOLVED? PARTICLE PHYSICS PROBLEMS

- How do we solve the strong CP problem?
- What is the dark matter?
- How do we solve the hierarchy problem?
- What if we solved all three at once?
- Original relaxion mechanism can't.

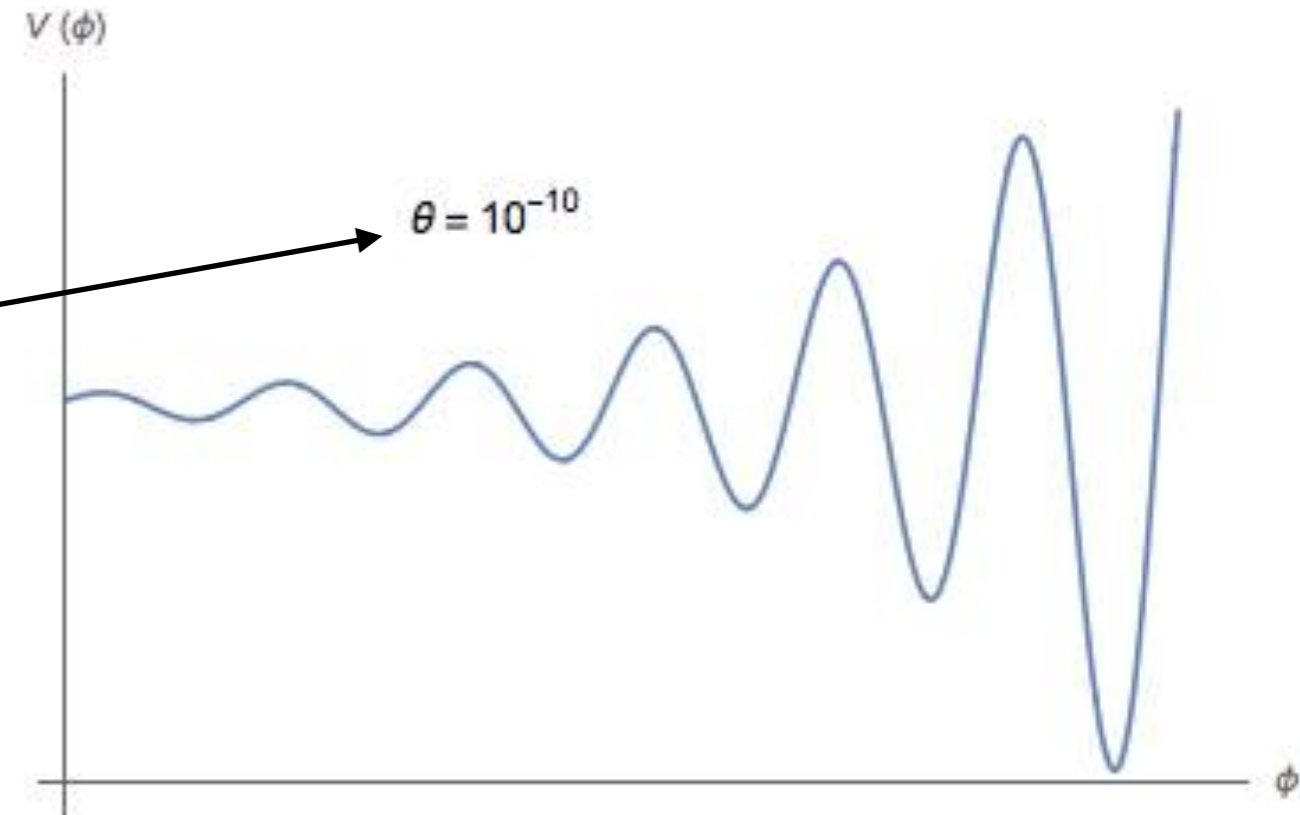
$$- \frac{n_f g^2 \theta}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

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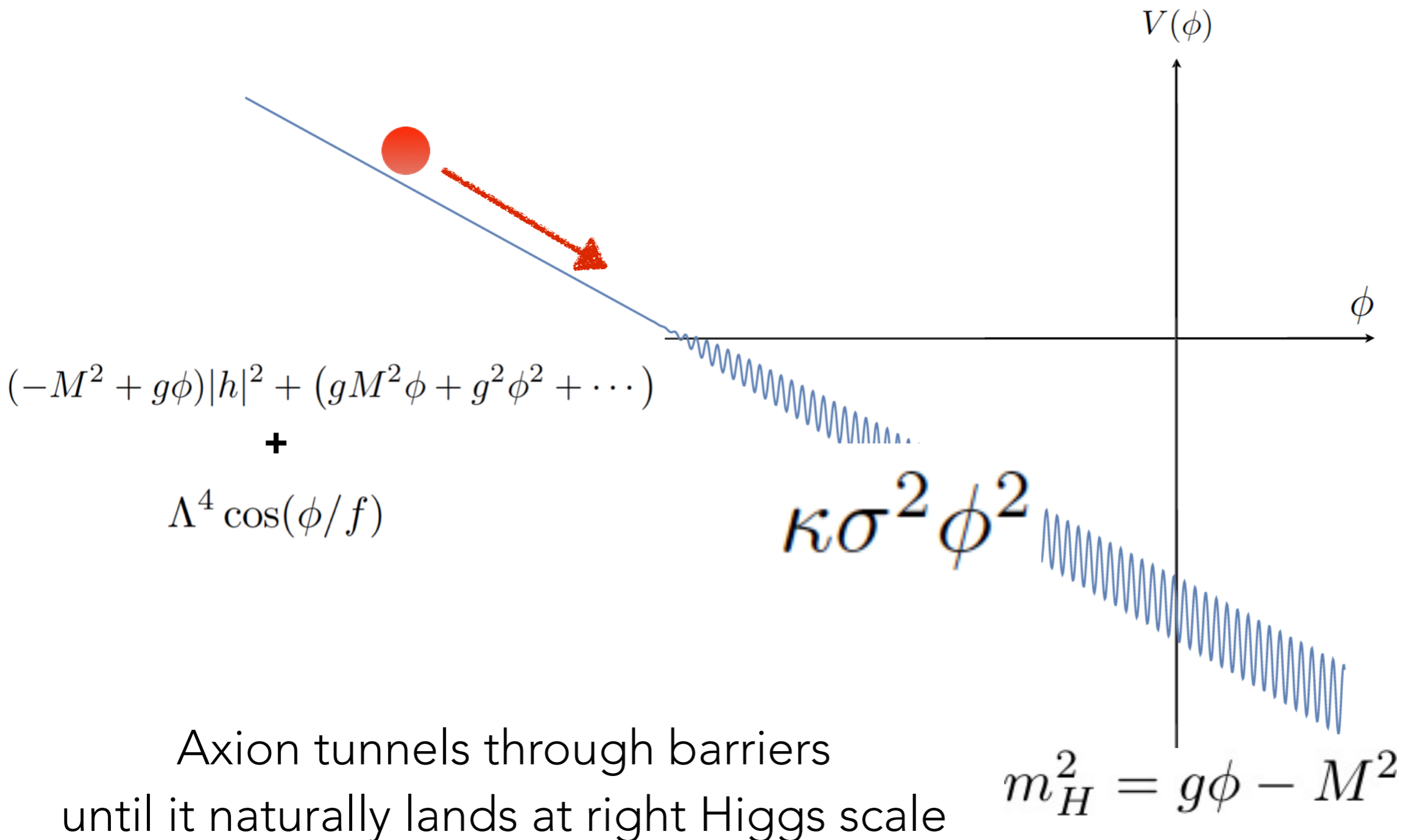


BAD

GOOD



Relaxion: Slow rolling during inflation



A Thermal Universe

- So far, studied in zero-temperature regime
- BUT axion mass is temperature-dependent

High temperatures

$$m_\phi(T) = (2 \times 10^{-2}) \left(\frac{\lambda}{f_a} \right) \left(\frac{m_u m_d m_s}{\lambda^3} \right)^{1/2} \left(\frac{\lambda}{\pi T} \right)^4 [9 \ln(\frac{\pi T}{\lambda})]^3$$

“Low” temperature

$$m_\phi = \frac{1}{f_a} \frac{(m_u m_d)^{1/2}}{(m_u + m_d)} f_\pi m_\pi$$

Account for Temperature-Dependence

$$-gM^2\phi + (M^2 - g\phi)|h^2| - (F(h)/r)(m_a^2 f_a^2) \cos(\phi/f_a)$$

$\propto v.e.v_H$

$r = m(T=0)/m(T)$

Temperature dependence means:
QCD contribution during inflation \ll after inflation

Relaxion solves three problems in our patch if

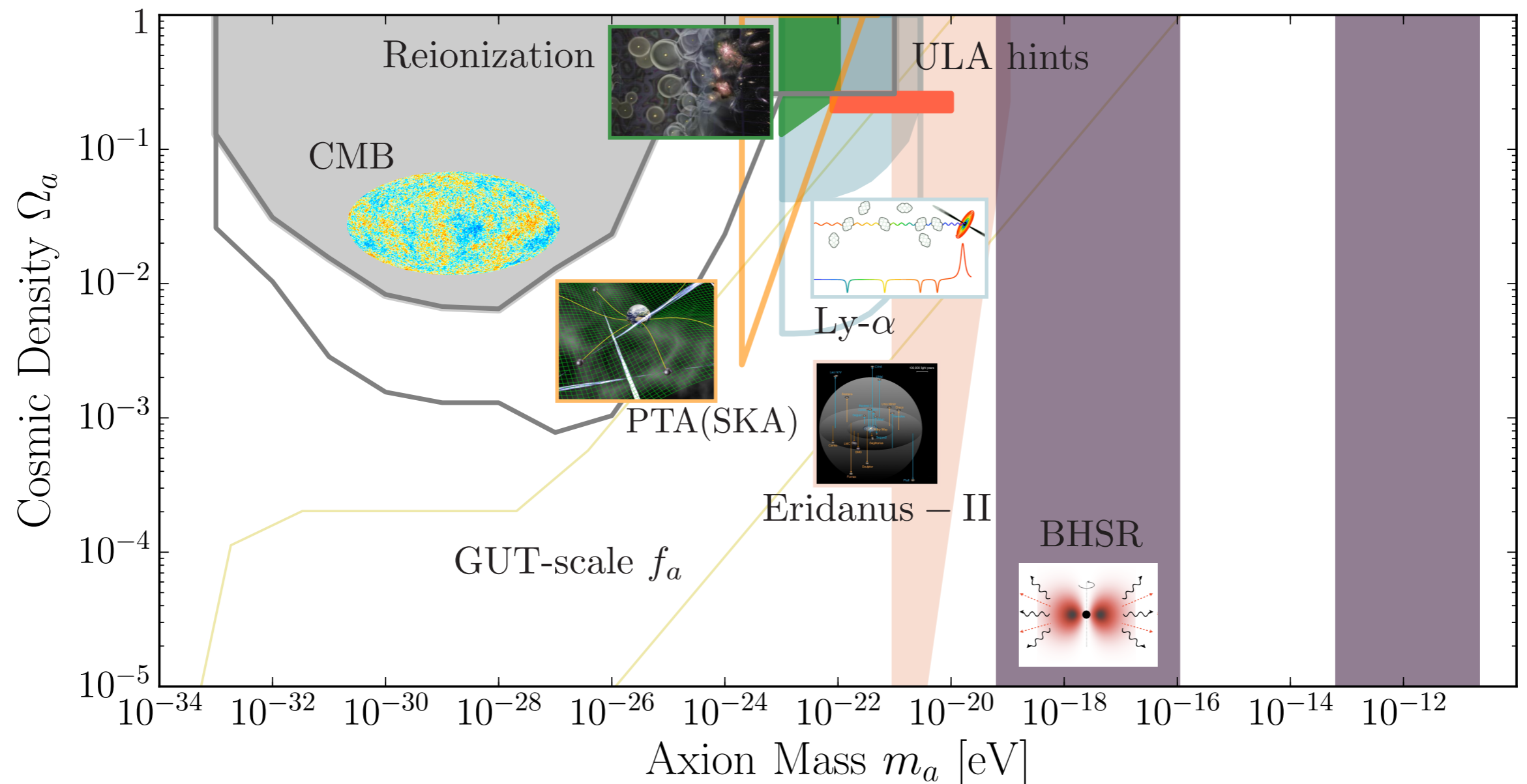
$$r > 10^{10}$$

The Right Value/Patch

- If relaxion is no longer classical, then backreaction produces several causally disconnected patches
- How do we know we are in the right patch, with the right relaxion value?
- We use the Fokker-Planck equation to show that the typical patch will have the right values

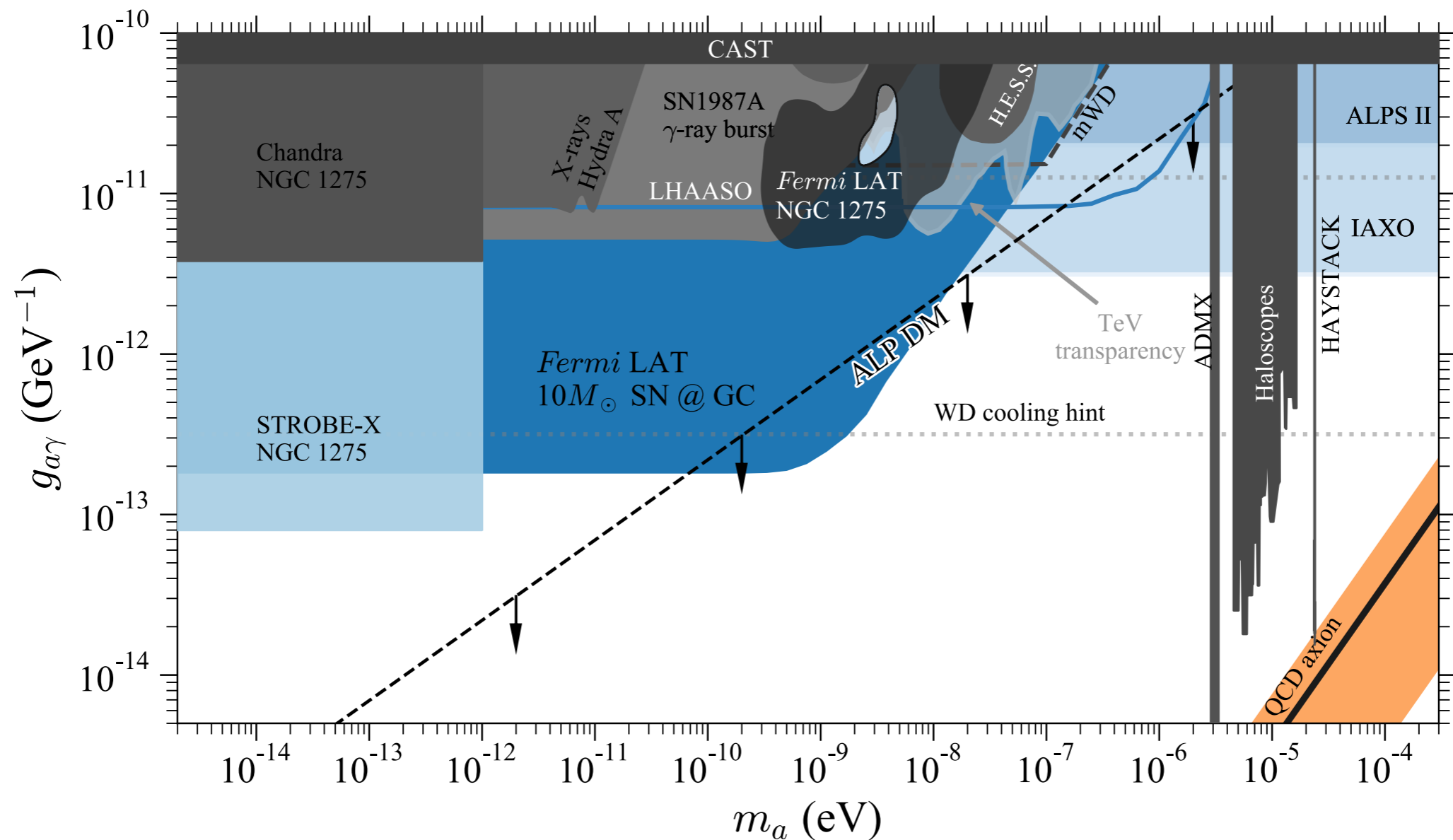
$$\frac{\partial P}{\partial t} = \frac{\partial}{\partial \phi} \left(\frac{H^3}{8\pi^2} \frac{\partial P}{\partial \phi} + \frac{V' P}{3H} \right)$$

Ultralight Axions



Amin, Gluscevic, Grin, Hlozek, Marsh, Poulin, Prescod-Weinstein, & Smith 2019
 arXiv:**1904.09003**

Is HEA the future of HEP?



Team STROBE-Ax, led by Prescod-Weinstein, produced for NASA white paper
arxiv:1903.03035

We're just beginning!

But, this is the end of the talk.

- Axions are worth your attention for many reasons!
- The phenomenology of the axion is an exciting for astrophysics and early universe cosmology
- Ongoing work: understanding galaxy-halo connection in context of axion physics
- Thank you!