COSMIC PROBES OF THE DARK SECTOR: A THEORY PERSPECTIVE

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JWST Deep Field: NASA, ESA, CSA, and STScI

THE POINT:

Cosmic probes still have something to say about dark matter!

Astrophysics is an *essential* probe of particle physics.

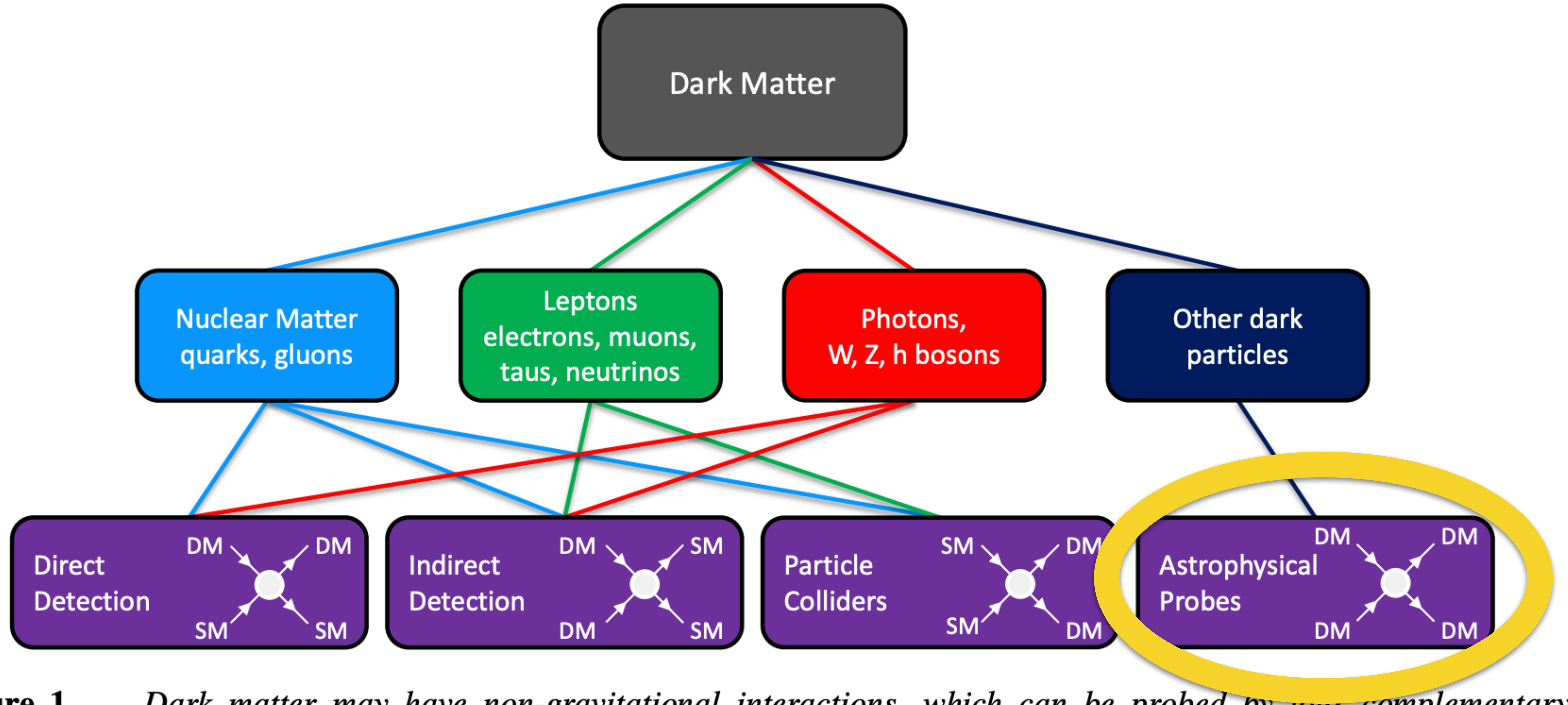
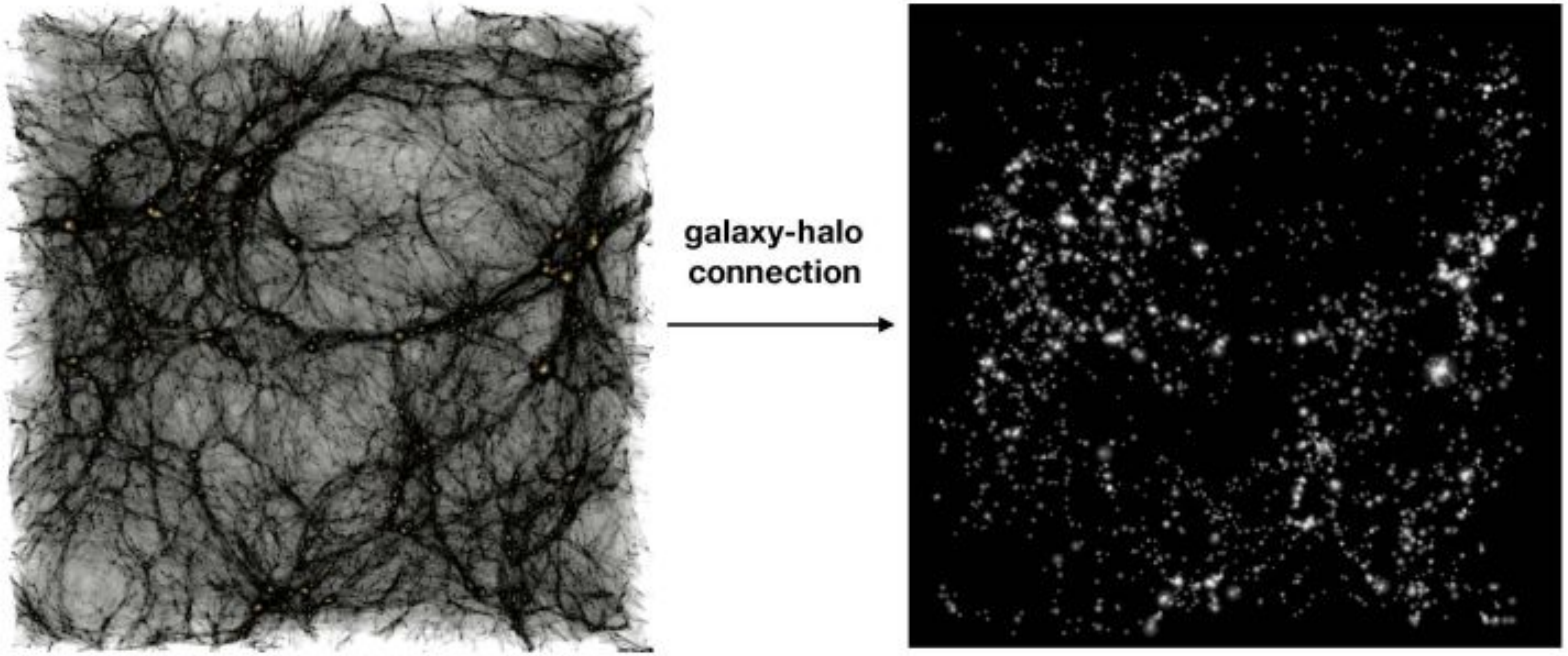


Figure 1. *Dark matter may have non-gravitational interactions, which can be probed by four complementary approaches: direct detection, indirect detection, particle colliders, and astrophysical probes. The lines connect the experimental approaches with the categories of particles that they most stringently probe (additional lines can be drawn in specific model scenarios). Figure taken from the Snowmass CF4 Report (Bauer et al., 2015).*

The galaxy-halo connection



Approaches to modeling the galaxy-halo connection

← physical models — empirical models →

Hydrodynamical Simulations	Semi-analytic Models	Empirical Forward Modeling	Subhalo Abundance Modeling	Halo Occupation Models
Simulate halos & gas; Star formation & feedback recipes	Evolution of density peaks plus recipes for gas cooling, star formation, feedback	Evolution of density peaks plus parameterized star formation rates	Density peaks (halos & subhalos) plus assumptions about galaxy—(sub)halo connection	Collapsed objects (halos) plus model for distribution of galaxy number given host halo properties

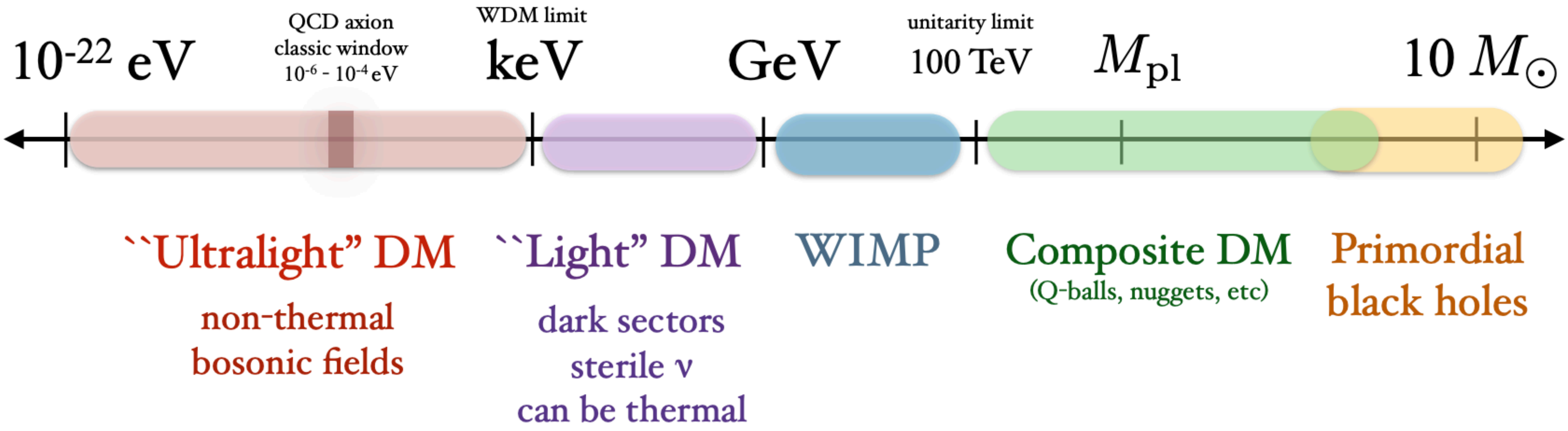
Wechsler and Tinker 2018

Angular Momentum in the Halo

Molly Peeples and the FOGGIE collaboration (foggie.science)

Mass scale of dark matter

(not to scale)



Tongyan Lin, arXiv:1904.07915

Axion, ALP, Fuzzy DM

- **QCD axions**: made in the early (z >> 1100) universe (~ 10^{-5} eV or 10^{-41} kg)

- **Axion-like particles (ALPs)/Ultralight Axions/Fuzzy Dark Matter**: motivated by string theory, don't solve Strong CP! (~ 10^{-33} - 10^{-18} eV)

- **all: <u>scalars (bosons)</u> with a sinusoidal potential**

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4!}\phi^4$$

Bose-Einstein Condensates in Space?

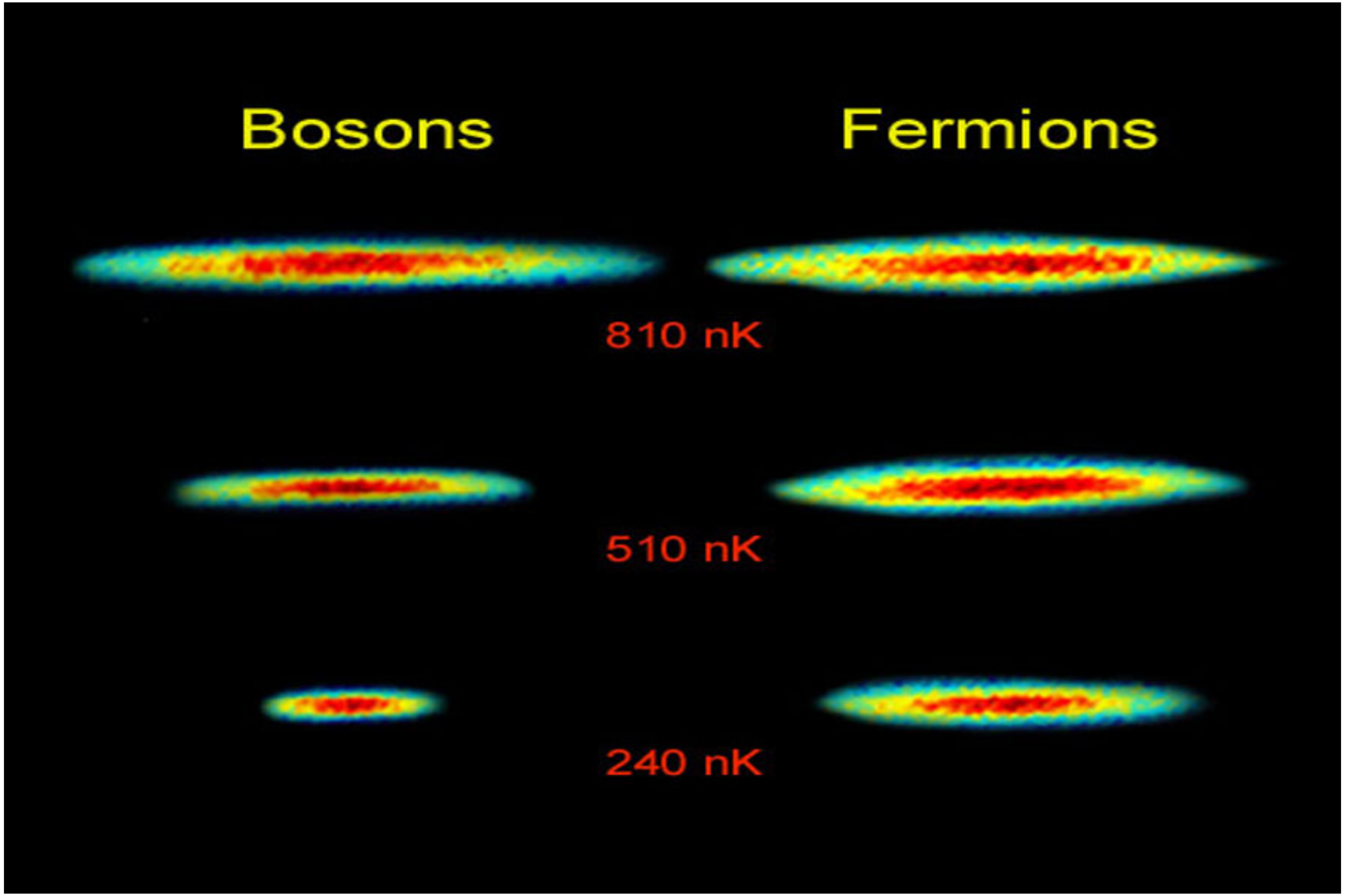
time evolution

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

Self-interaction, with coupling constant λ

Gravitational interactions

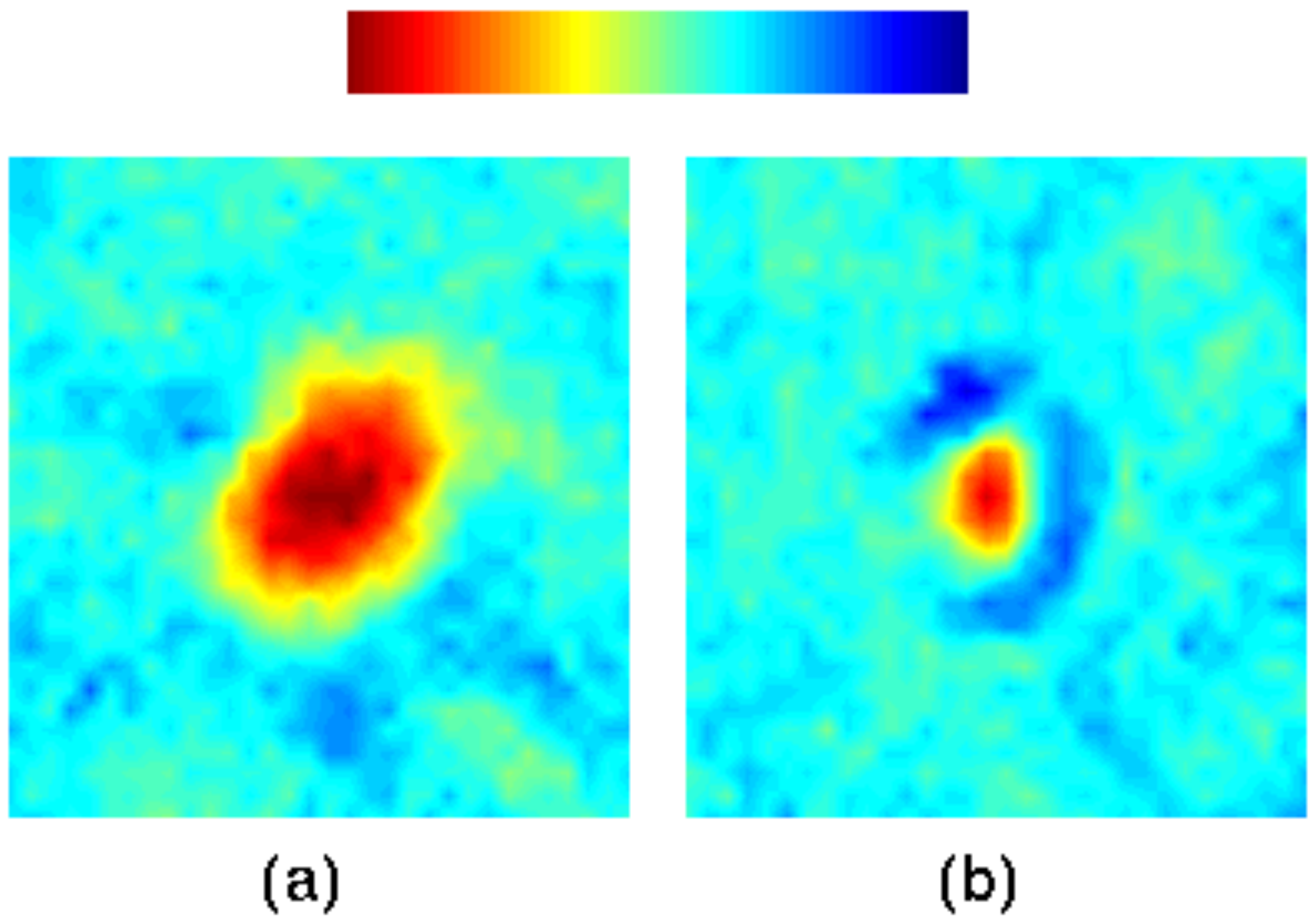
Kinetic term



Andrew Truscott & Randy Hulet

Lab BEC in Attractive Interactions

- Lithium-7 has 3 protons and 3 electrons —> boson
- Negative scattering length —> attractive interaction
- Theory said it should not form a stable BEC
- **But it did! For ~ 1000 atoms or less.**



Hulet Group, Rice University

Does Axion Dark Matter form Bose-Einstein Condensates?

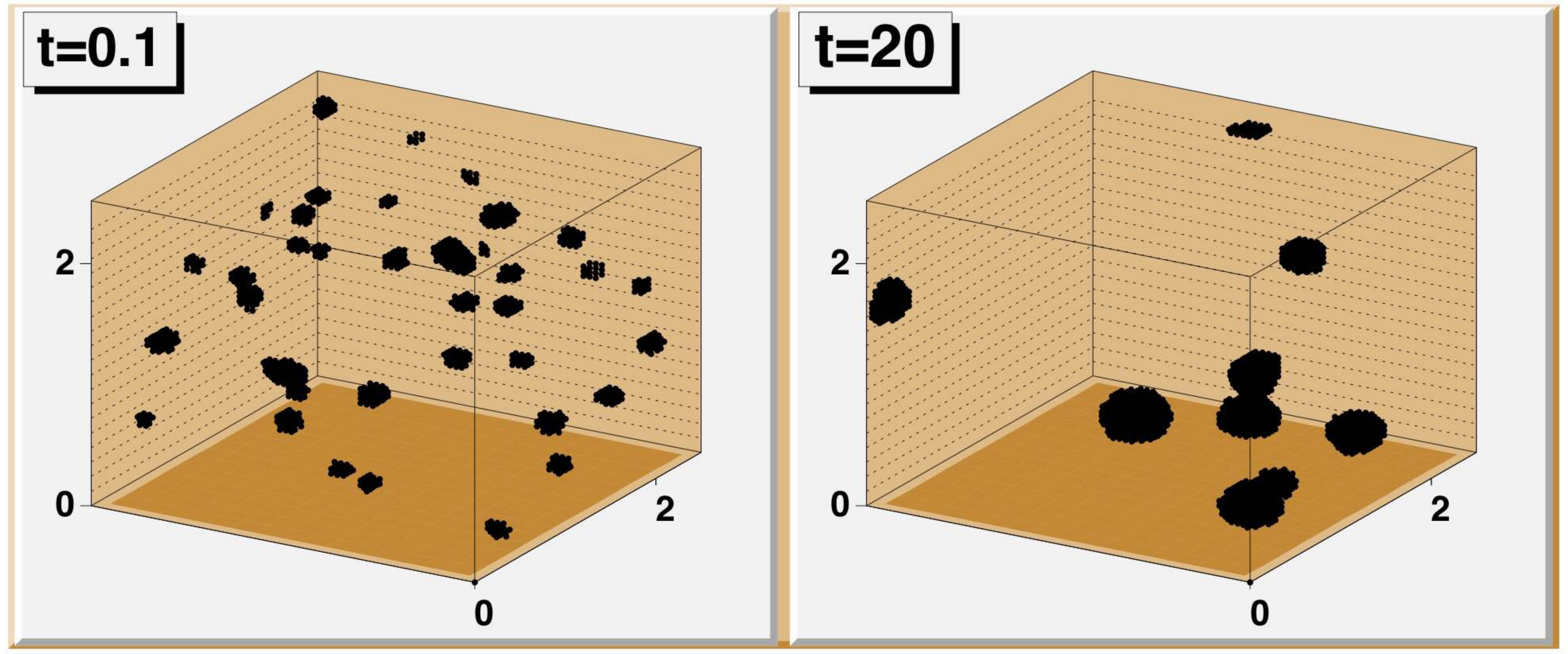
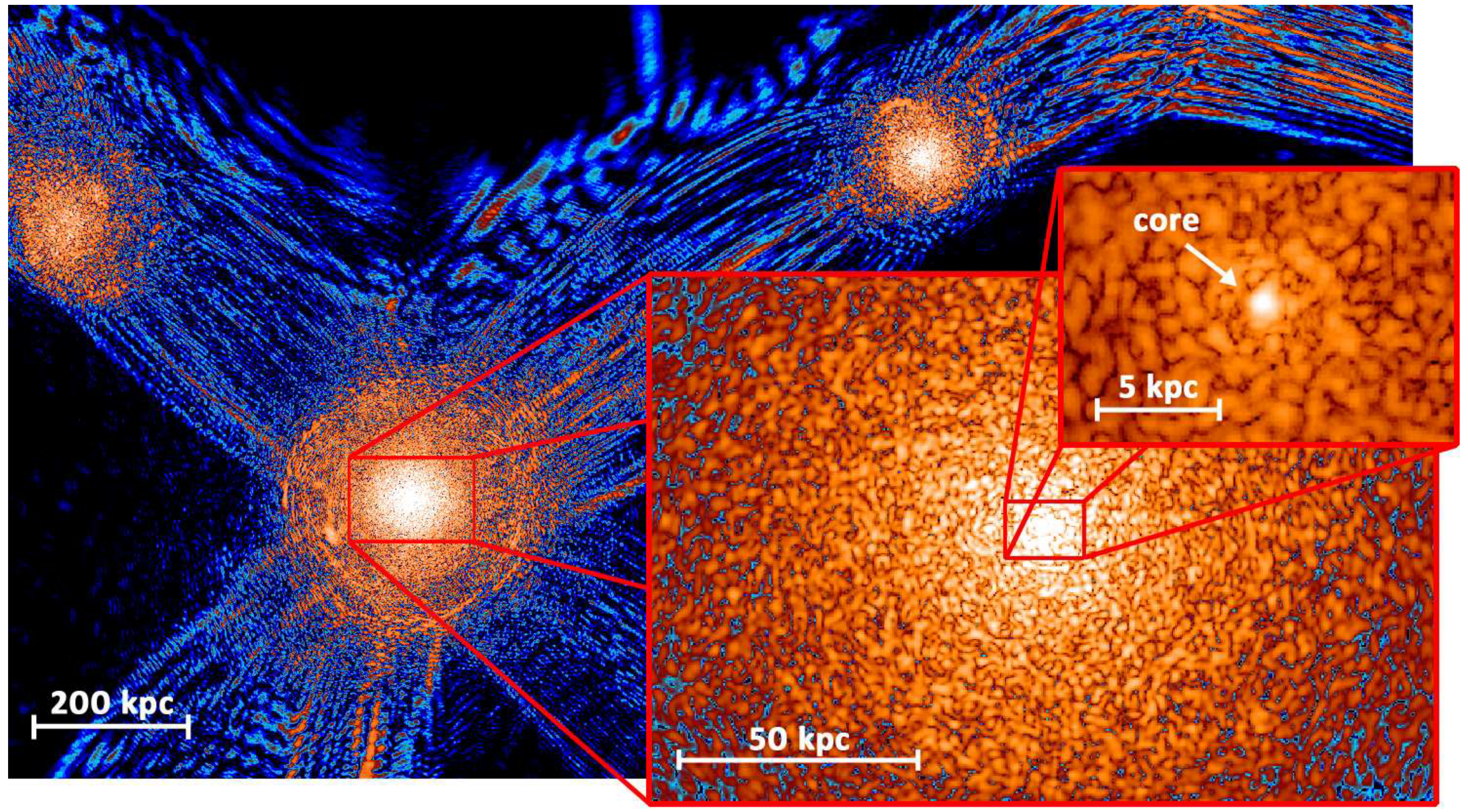


FIG. 1. Drops of dew at different moments of time.



- Yes! (Guth, Hertzberg, & CPW, **arXiv:1412.5930**)
- QCD: in small, locally-correlated solitons — bose stars/standing waves.

- **Sign of the interaction** and **mass** determines coherence length**.**
- Ultralight axions: halos with solitons at their core

Khlebnikov & Tkachev 2000

Schive et al arXiv:1406.6586

Correctly Modeling Cosmic Axions

- For cosmological purposes is it a classical or quantum field?
- *When* do self-interactions matter?
- Axion evolution is not a standard Boltzmann collision process — **this is a different kind of CDM**.
- We show you need the Wigner formalism: Boltzmann, but for waves

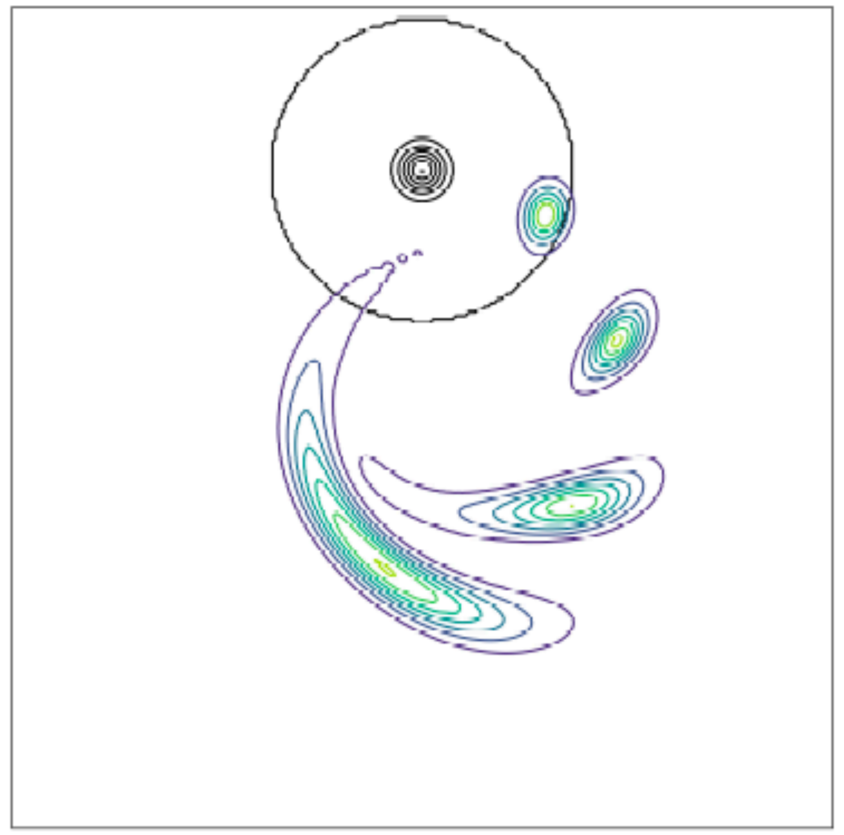
$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4!}\phi^4$$

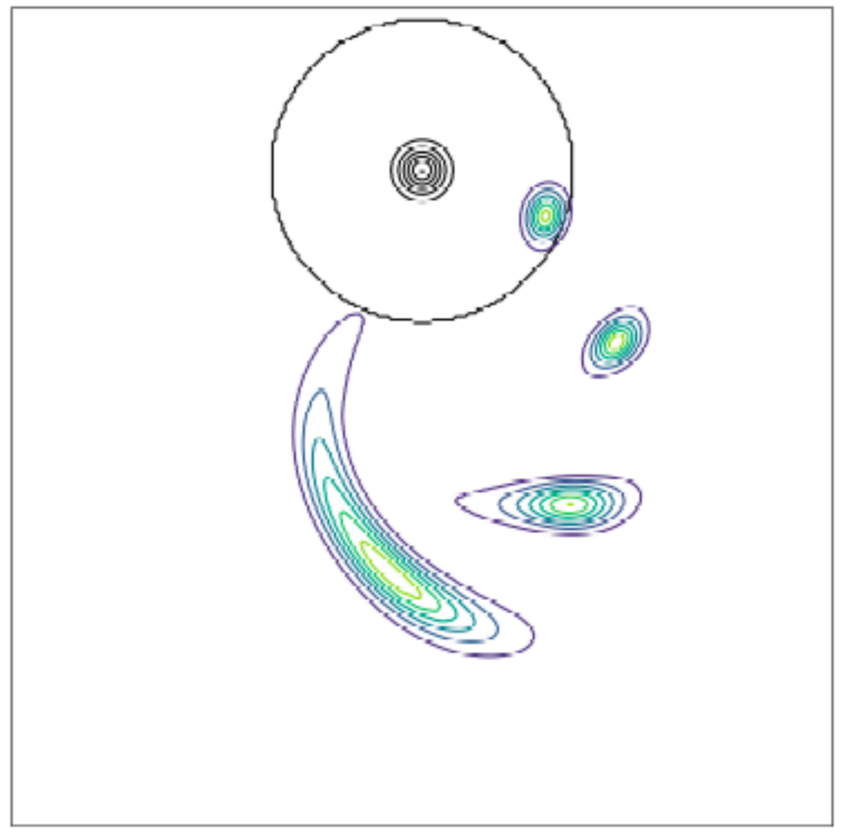
Kirkpatrick, Mirasola & CPW, **arXiv:2007.07438, 2110.08921**

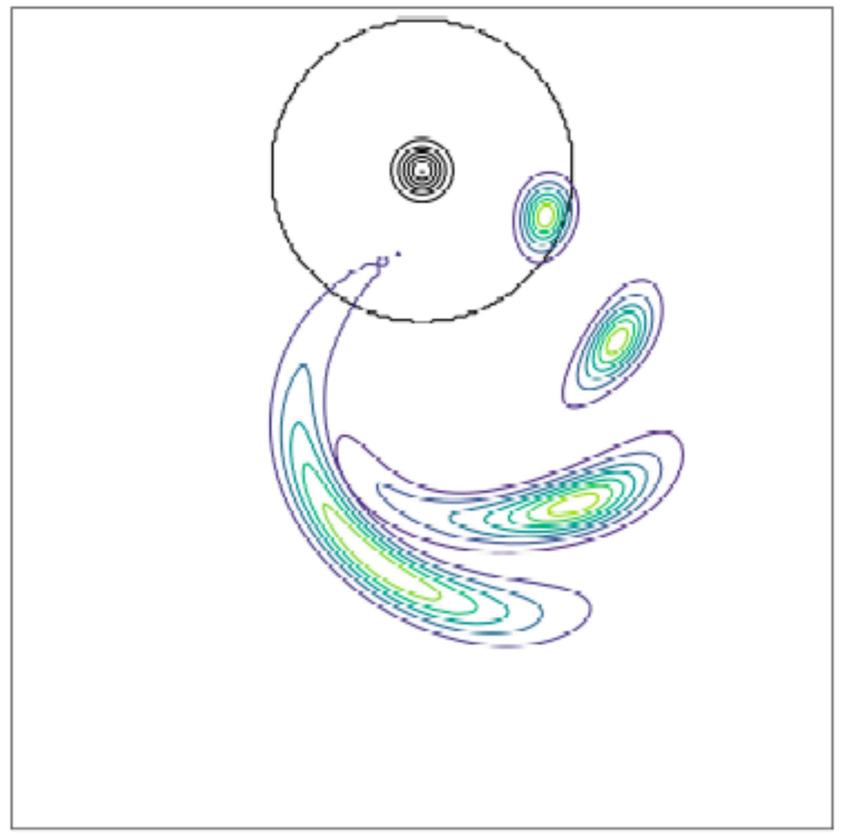
Impact of Self-Interactions: A Matter of When

- Self-interactions are subdominant in setting time scale for initial condensation

- Self-interactions are significant for the dynamical evolution of the system:

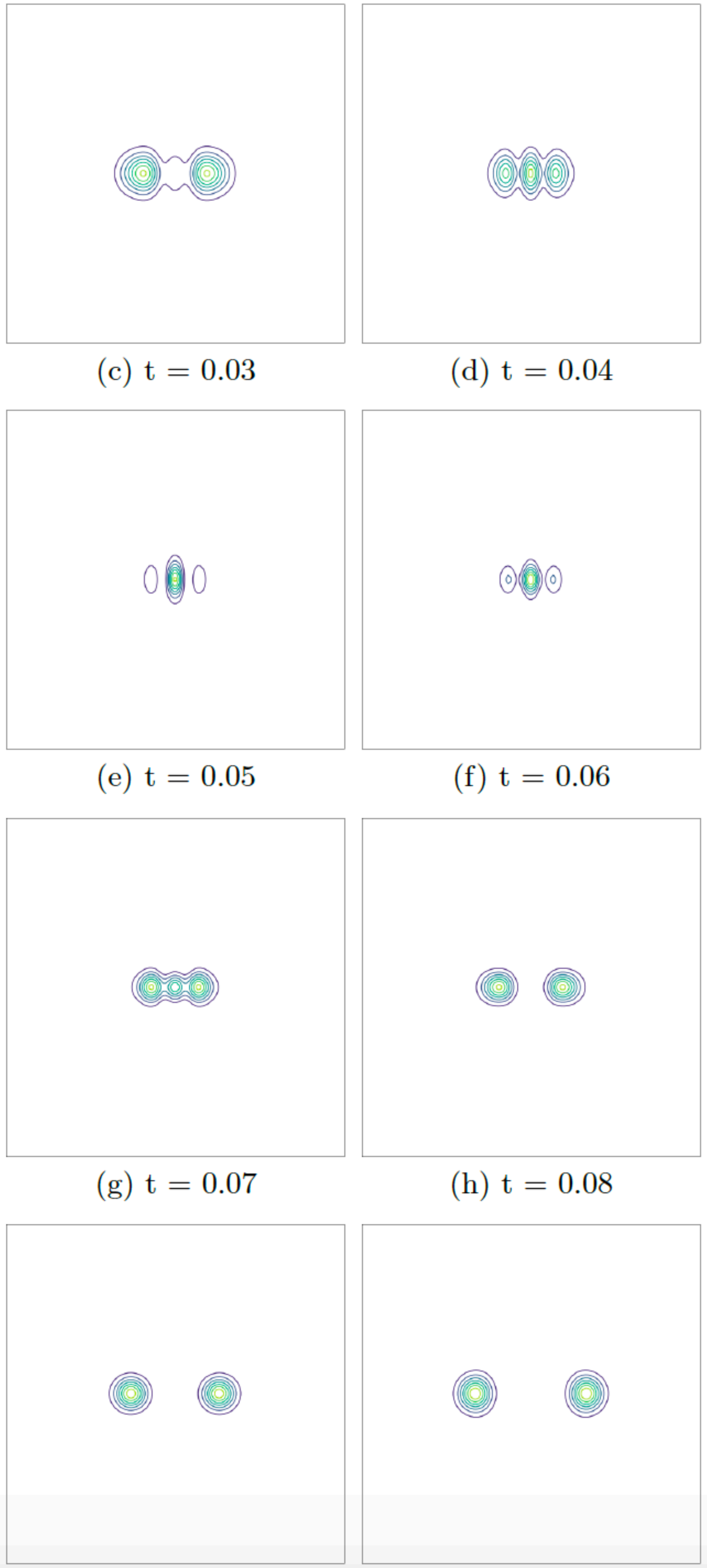

(a) No self-interactions

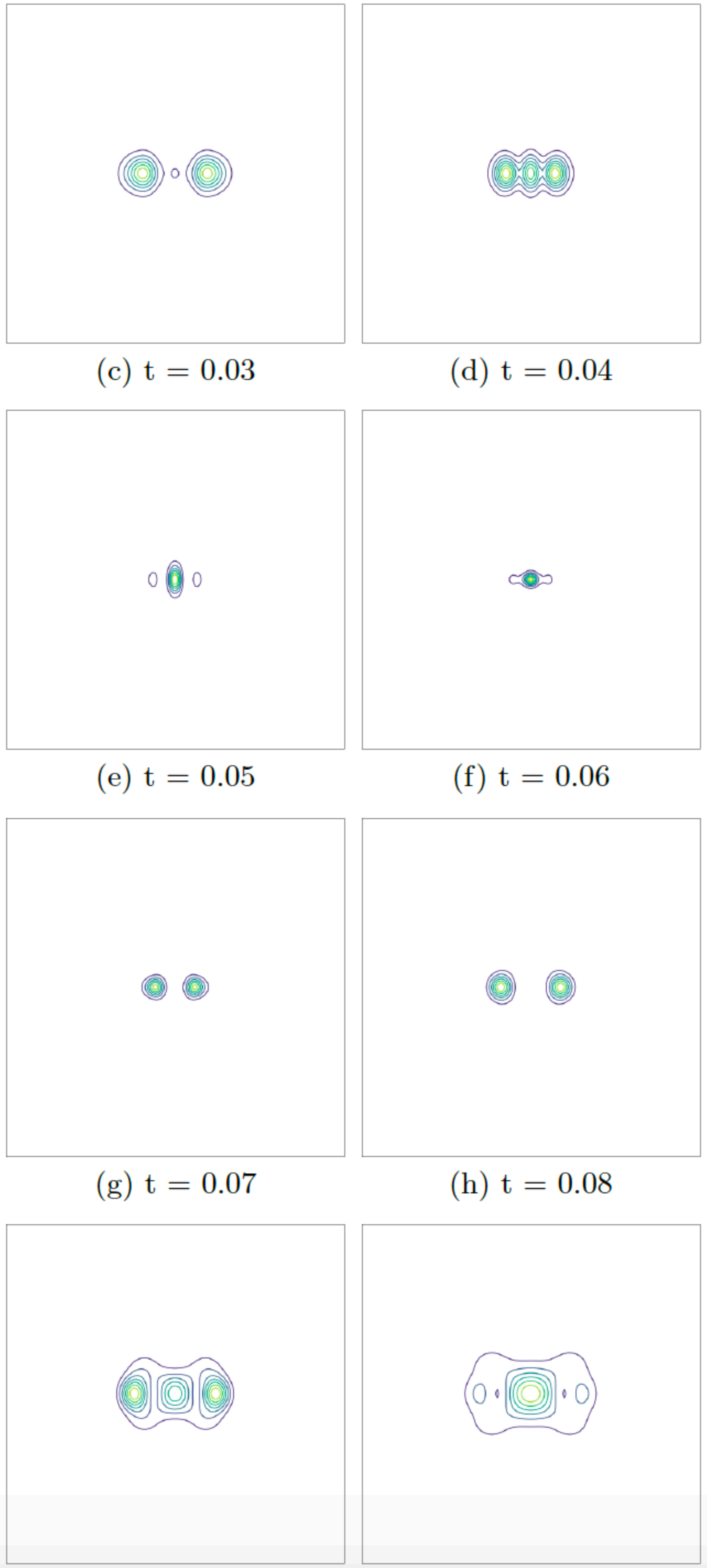

(b) Attractive self-interactions


(c) Repulsive self-interactions

Kirkpatrick, Mirasola & CPW, **arXiv:2007.07438, 2110.08921**

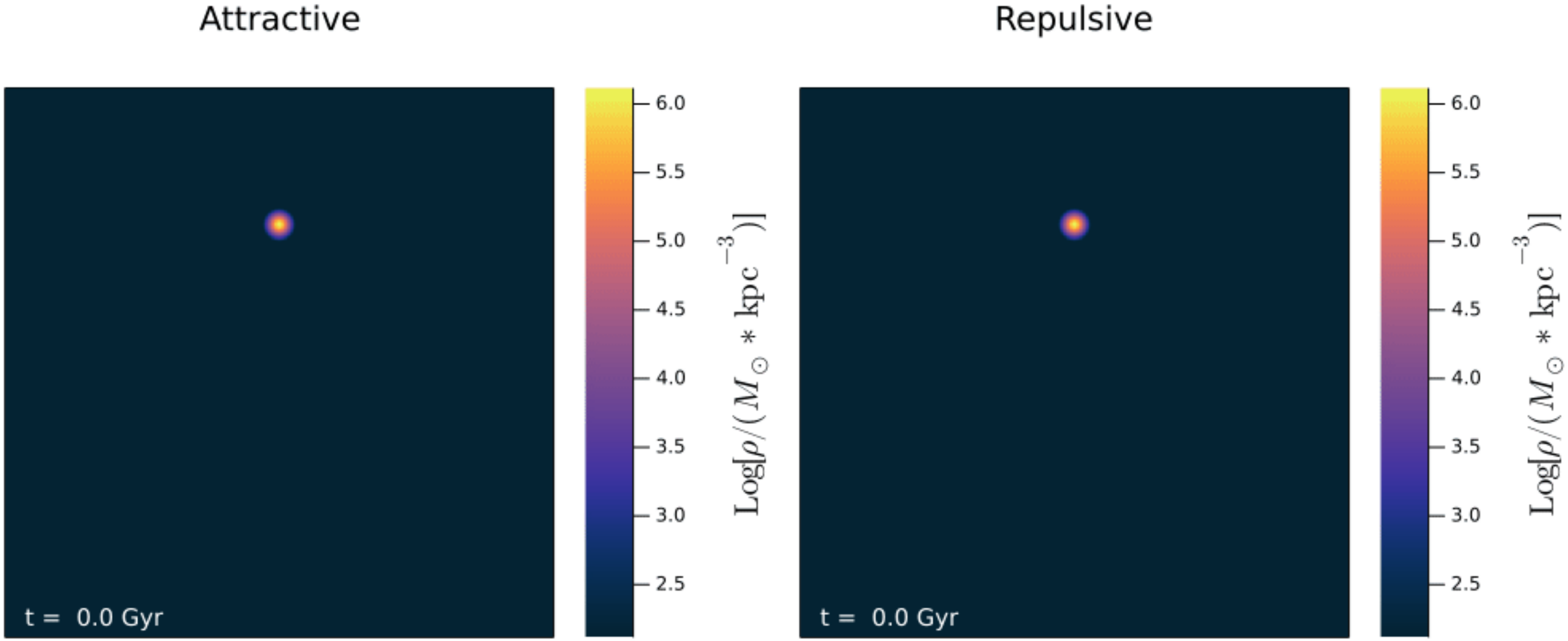
Glennon and CPW, **arXiv:2011.09510**





Glennon and CPW, **arXiv:2011.09510**

Tidal Stripping Time Depends on Self-Interactions:



Glennon, Nadler, Musoke, Banerjee, CPW, & Wechsler **arXiv:2205.10336**

Standard Model of Axions?

- No reason to believe dark sector is one particle

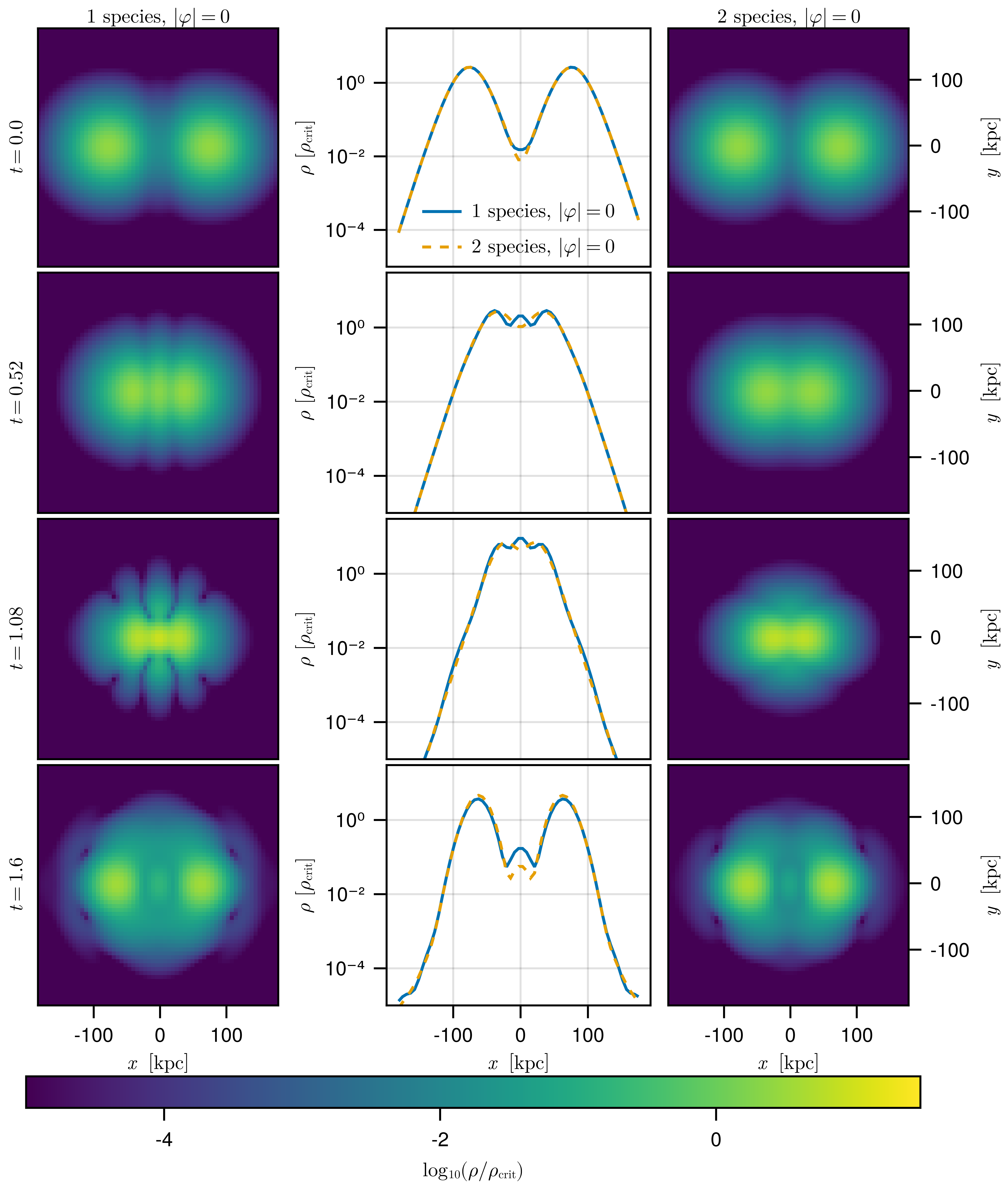
c

- Quantum gravity (string theory) motivates us to think past a single solution! (Arvanitaki et al 2010)

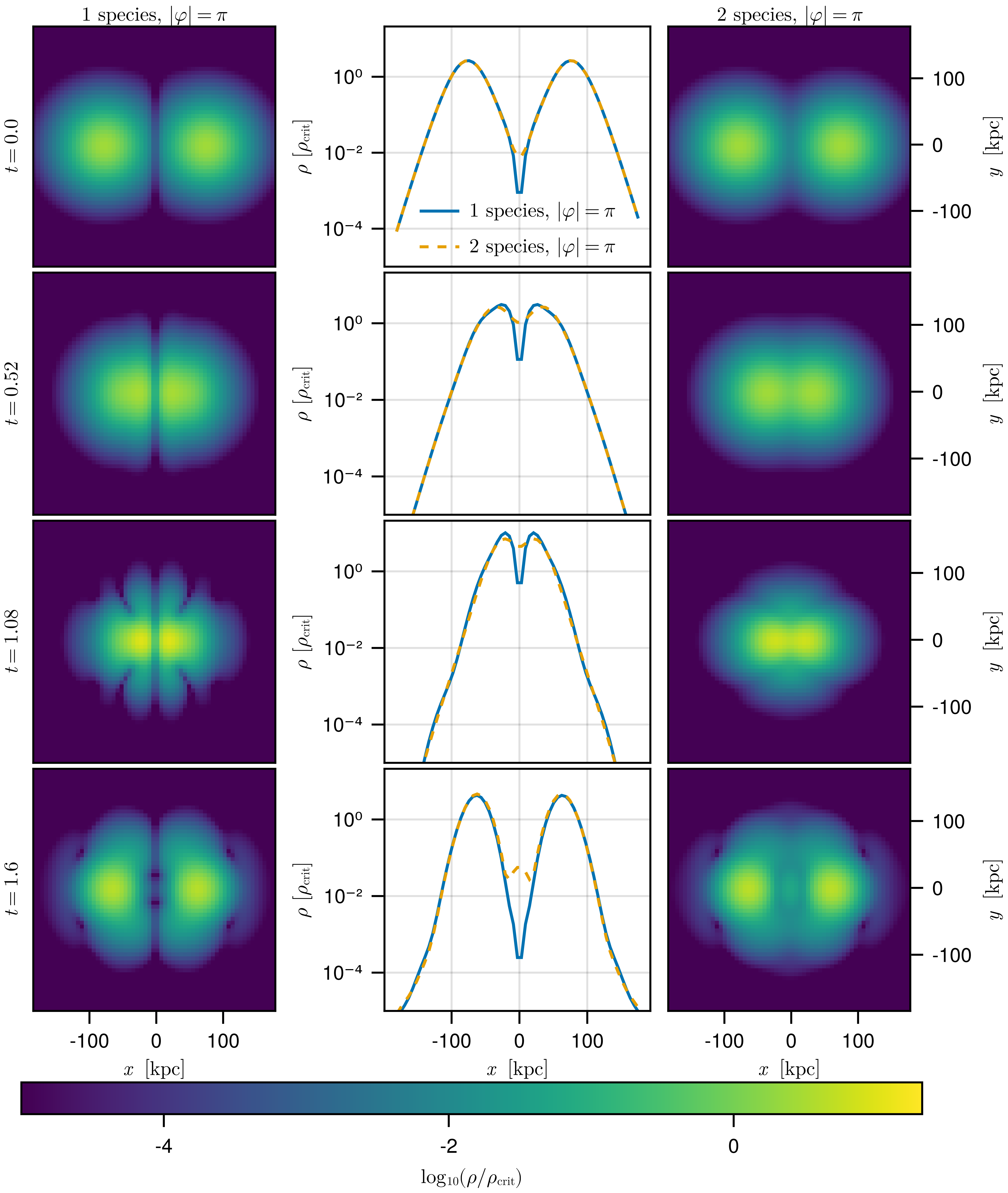
$$\mathcal{L}_{\text{ALP}} = \sum_j \left(-\frac{1}{2} g^{\mu\nu} \partial_\mu \phi_j \partial_\nu \phi_j - \frac{1}{2} m_j^2 \phi_j^2 \right) - \sum_j \sum_{k \geq j} \lambda_{jk} \phi_j^2 \phi_k^2$$

$$i\hbar \frac{\partial \psi_j}{\partial t} = -\frac{\hbar^2}{2 m_j a^2} \nabla^2 \psi_j + m_j \Phi \psi_j + \frac{\hbar^3}{2 m_j^2 c} \lambda_{jj} |\psi_j|^2 \psi_j + \frac{\hbar^3}{4 m_j^2 c} \sum_k \lambda_{jk} |\psi_k|^2 \psi_j$$

Glennon, Musoke, and CPW arXiv:2302.0



Glennon, Musoke,
and CPW arXiv:2302.04302



Glennon, Musoke,
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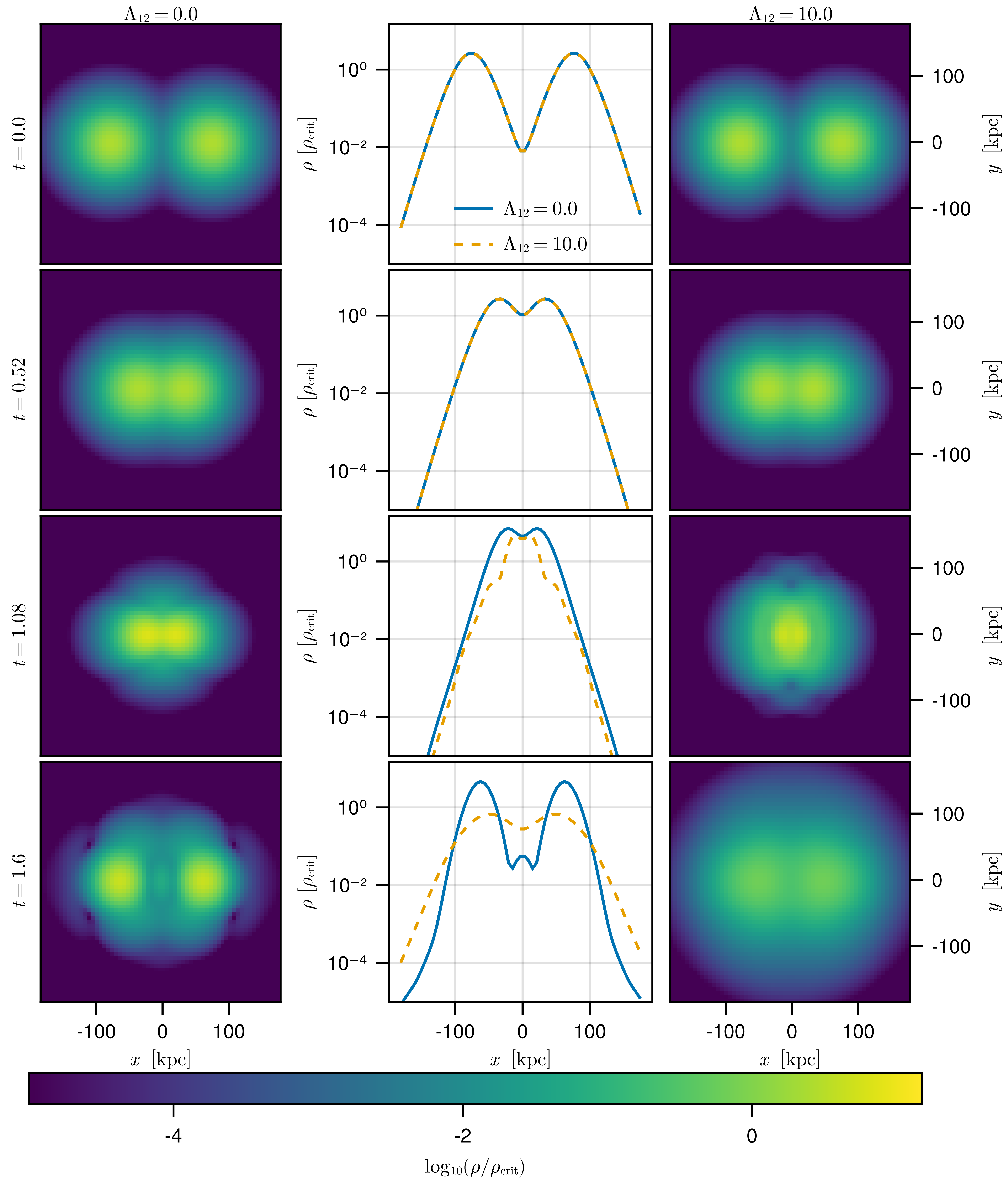

Glennon, Musoke,
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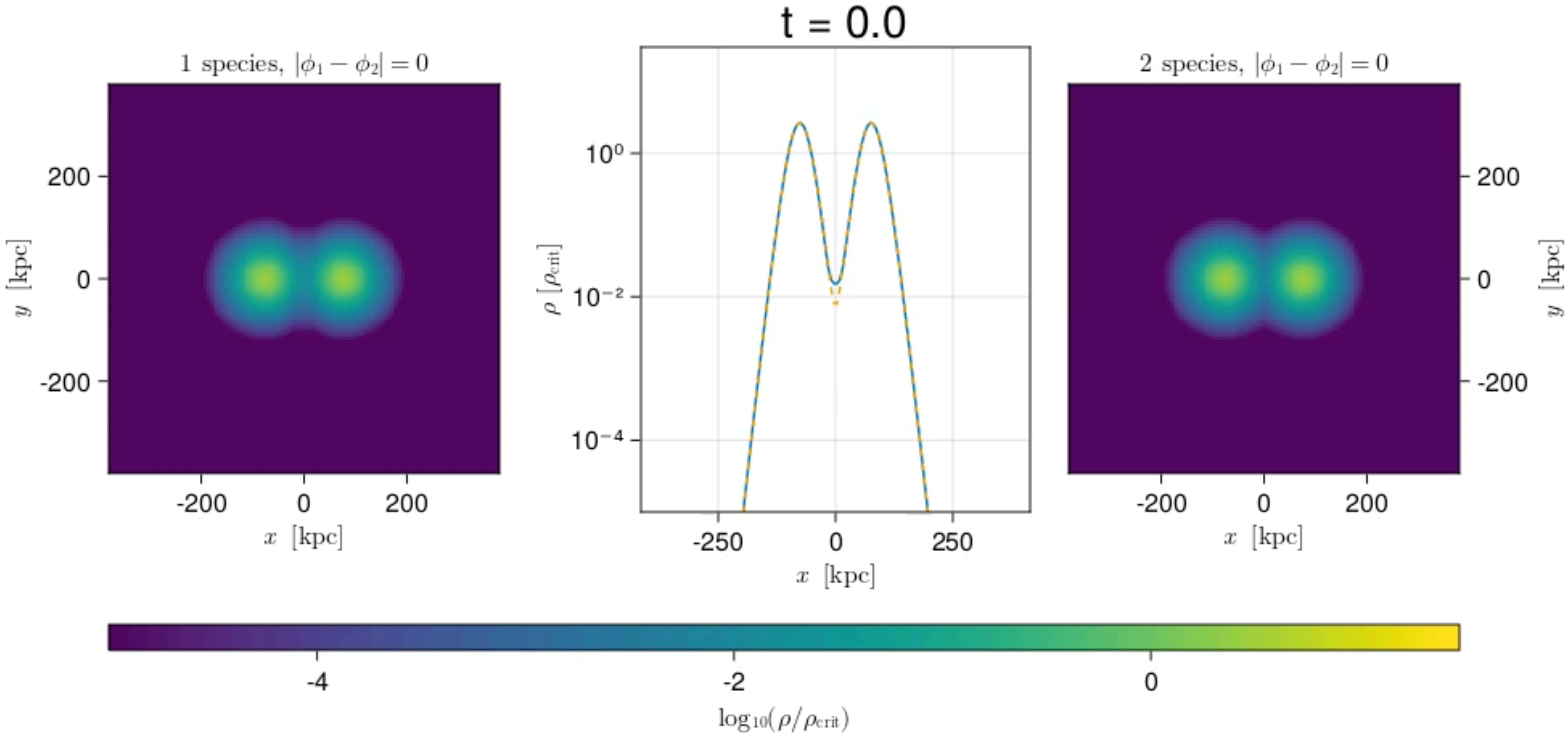
Standard Model of Axions?



Glennon, Musoke,
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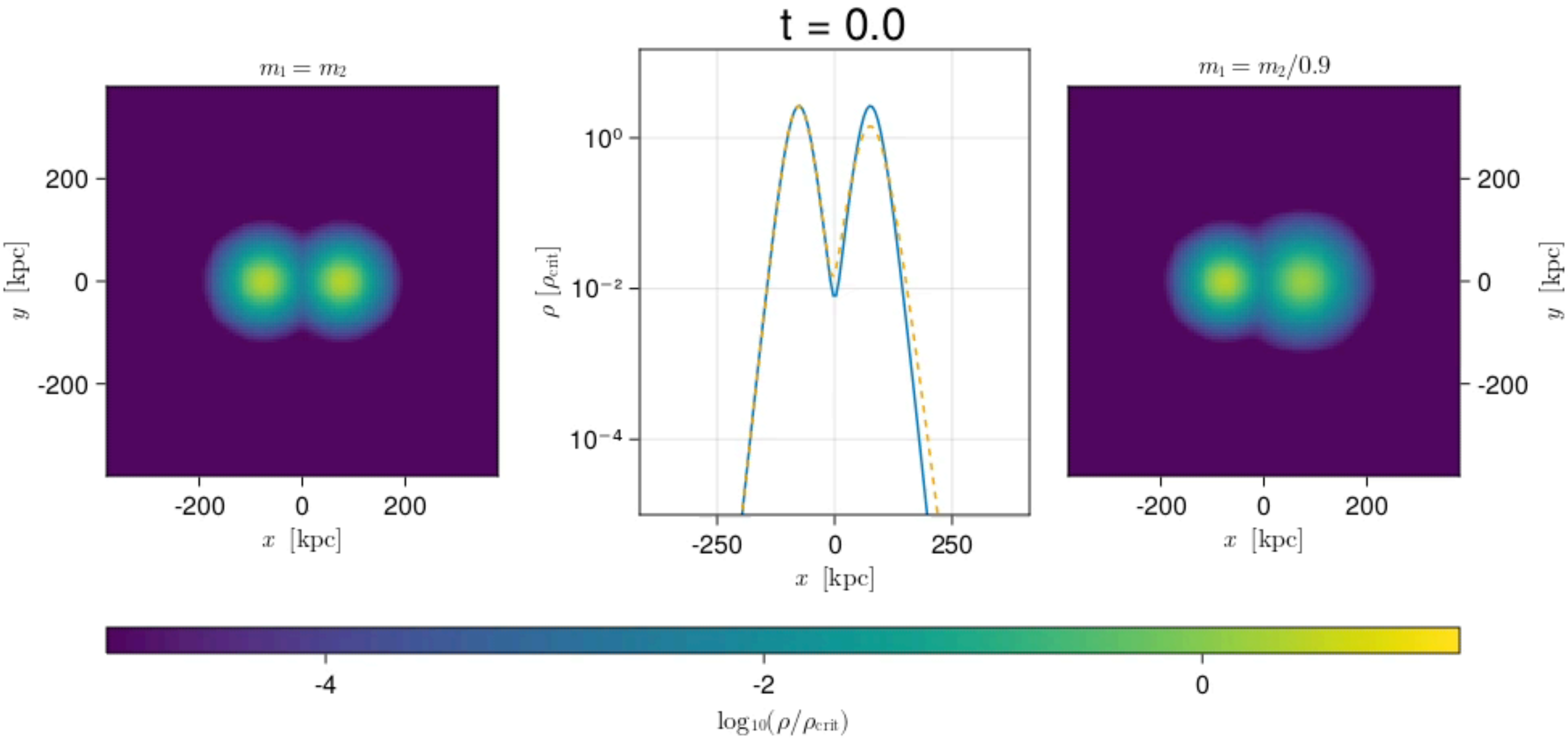
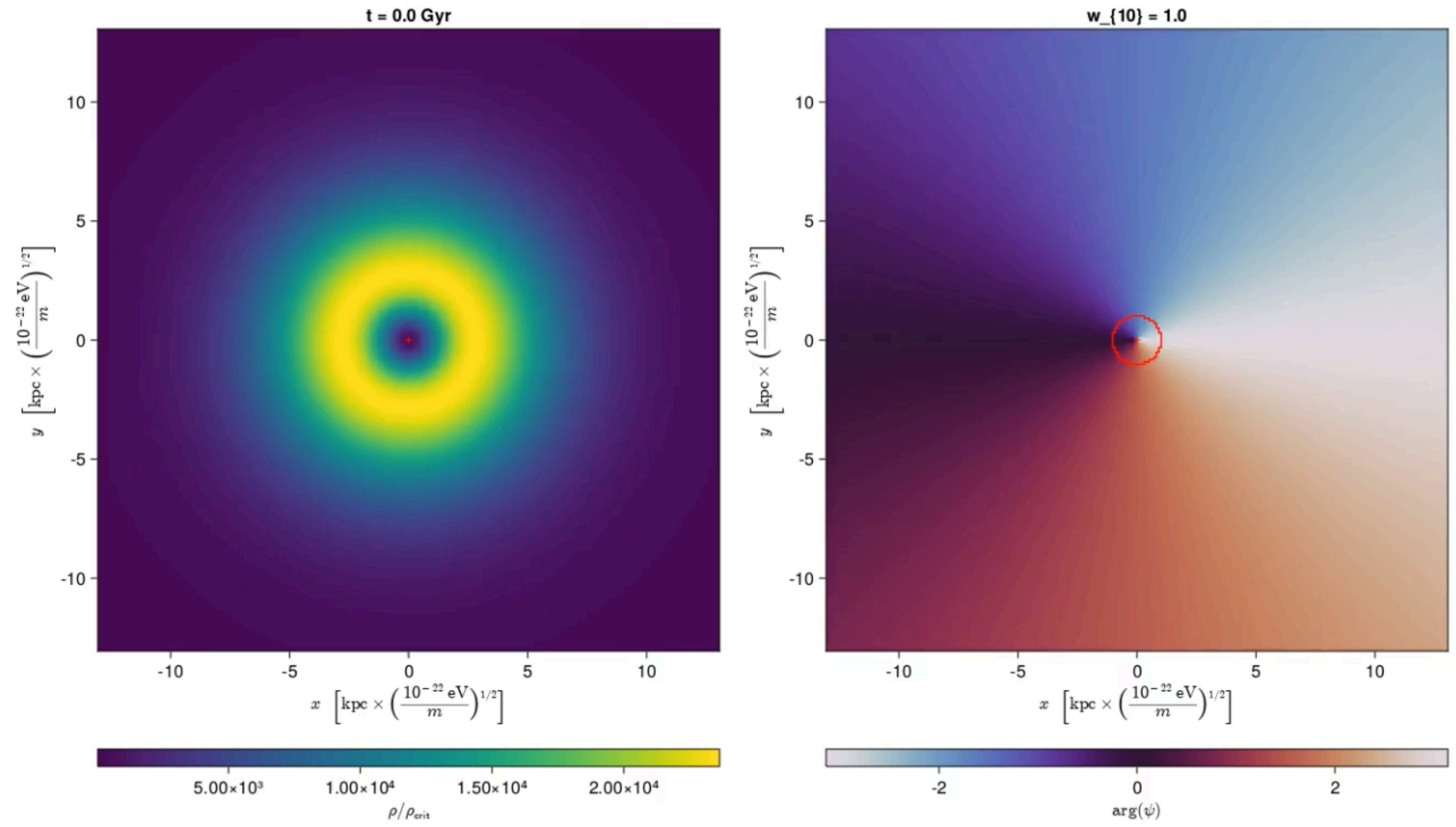
Standard Model of Axions?



and CPW arXiv:2302.04302

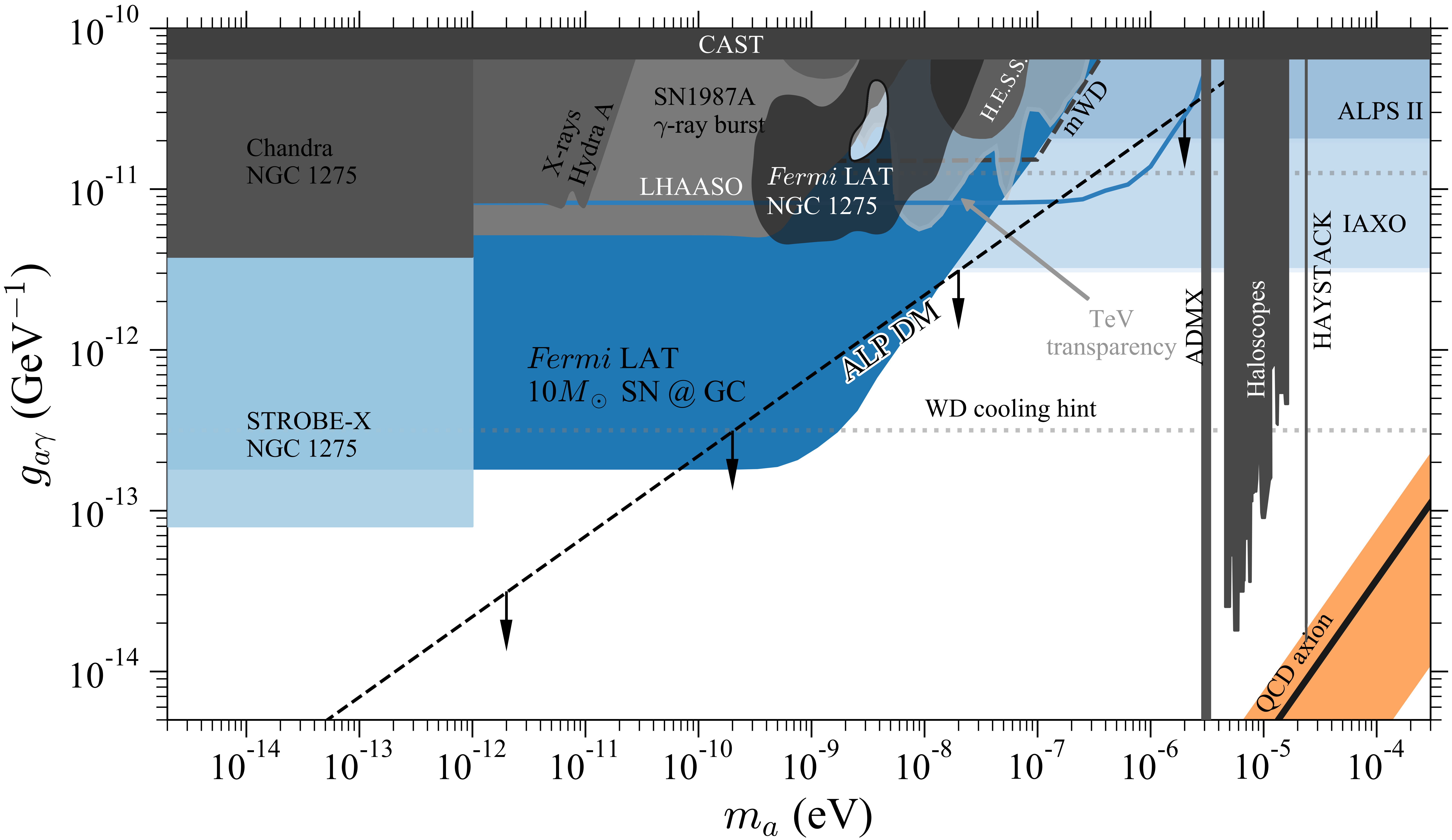
Solving Galactic Rotation?



Creating Stable Vortices in Axion/Scalar Dark Matter

Glennon, Mirasola, Musoke, Neyrinck, & CPW **arXiv:2301.13220**

Is HEA the future of HEP?



Team STROBE-Ax, led by CPW, produced for NASA white paper

arxiv:1903.03035

We're just beginning!

Vorticity Formation

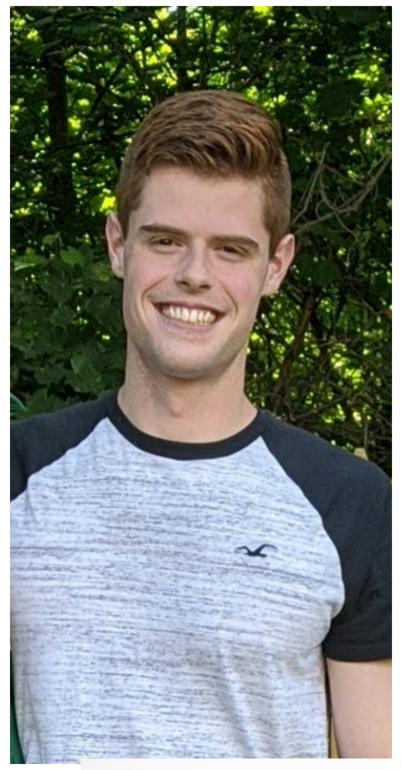
Analytic formalism

Axions

Subhalo dynamics

Lensing observations

Neutron star equation of state



Asymmetric Dark Matter

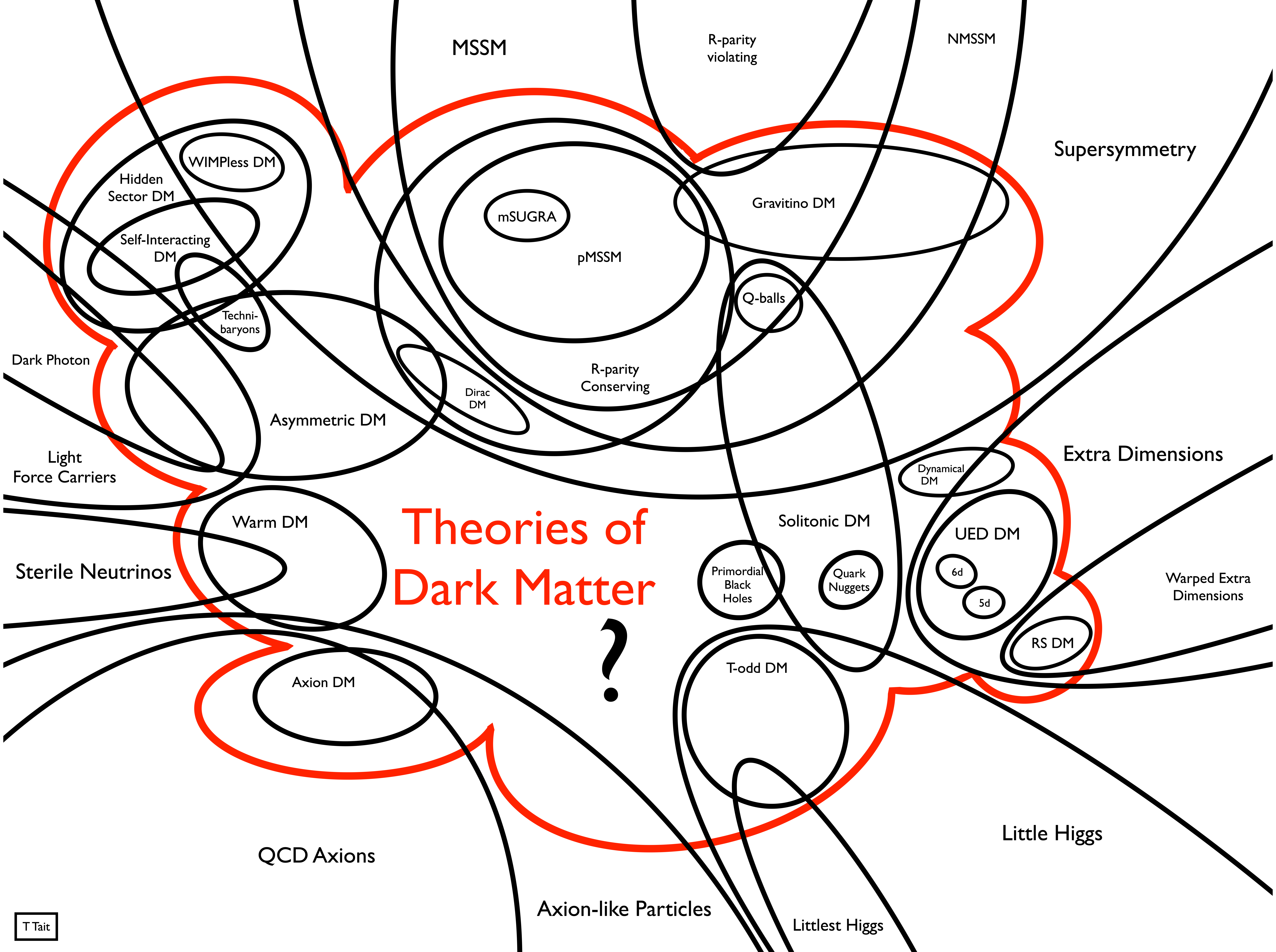
With NS mergers?

High-energy Astro observations









Theories of
Dark Matter
?
MSSM
R-parity
violating
NMSSM
Supersymmetry
WIMPless DM
Hidden
Sector DM
Self-Interacting
DM
Techni-
baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity
Conserving
Dirac
DM
Dark Photon
Asymmetric DM
Light
Force Carriers
Extra Dimensions
Dynamical
DM
Solitonic DM
UED DM
6d
5d
Warm DM
Sterile Neutrinos
Primordial
Black
Holes
Quark
Nuggets
Warped Extra
Dimensions
RS DM
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

Instanton Approximation

$$V(\phi) = \Lambda^4(1 - cos(\phi/f_a))$$

Axion potential

The QCD scale ~ 0.1 GeV

The symmetry breaking scale/ axion decay constant

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4!}\phi^4$$

$m = \Lambda^2/f_a$

$\lambda = -\Lambda^4/f_a^4 < 0$

Axion Dark Matter

- Problems in the Standard Model! A neutron electric dipole moment??

$$\theta \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

- Solvable by introducing Peccei-Quinn mechanism

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{a(x)}{f_a}\frac{\alpha_s}{8\pi} G\tilde{G}$$

-> spin-0 boson, **the axion**

$$V(\phi) = \Lambda^4 (1 - cos(\phi/f_a))$$

Bose-Einstein Condensates in Space?

time evolution

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

Kinetic term

Self-interaction, with coupling constant λ

Gravitational interactions