A Compact Primer on Dark Compact Objects

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Overview

What are they?

Why study them?

How do they form?

How can we observe them?

What are Dark Compact Objects?

What are dark compact objects?

An **overdense, bound** collection of **dark particles** or **exotic states of matter** too heavy to be composed of a single particle

What are dark compact objects?

Aliases


Blobs / clumps


Composites


DarCOs


Dark Stars

Examples

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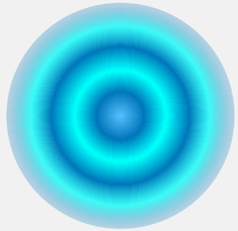

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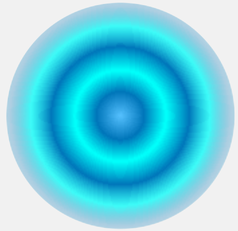

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Examples

- Primordial Black Holes (PBHs)
- Axion Stars / Boson Stars
- Quark Nuggets
- Asymmetric dark matter stars

An **overdense, bound** collection of **dark particles** or **exotic states of matter** too heavy to be composed of a single particle

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We have not found dark matter yet

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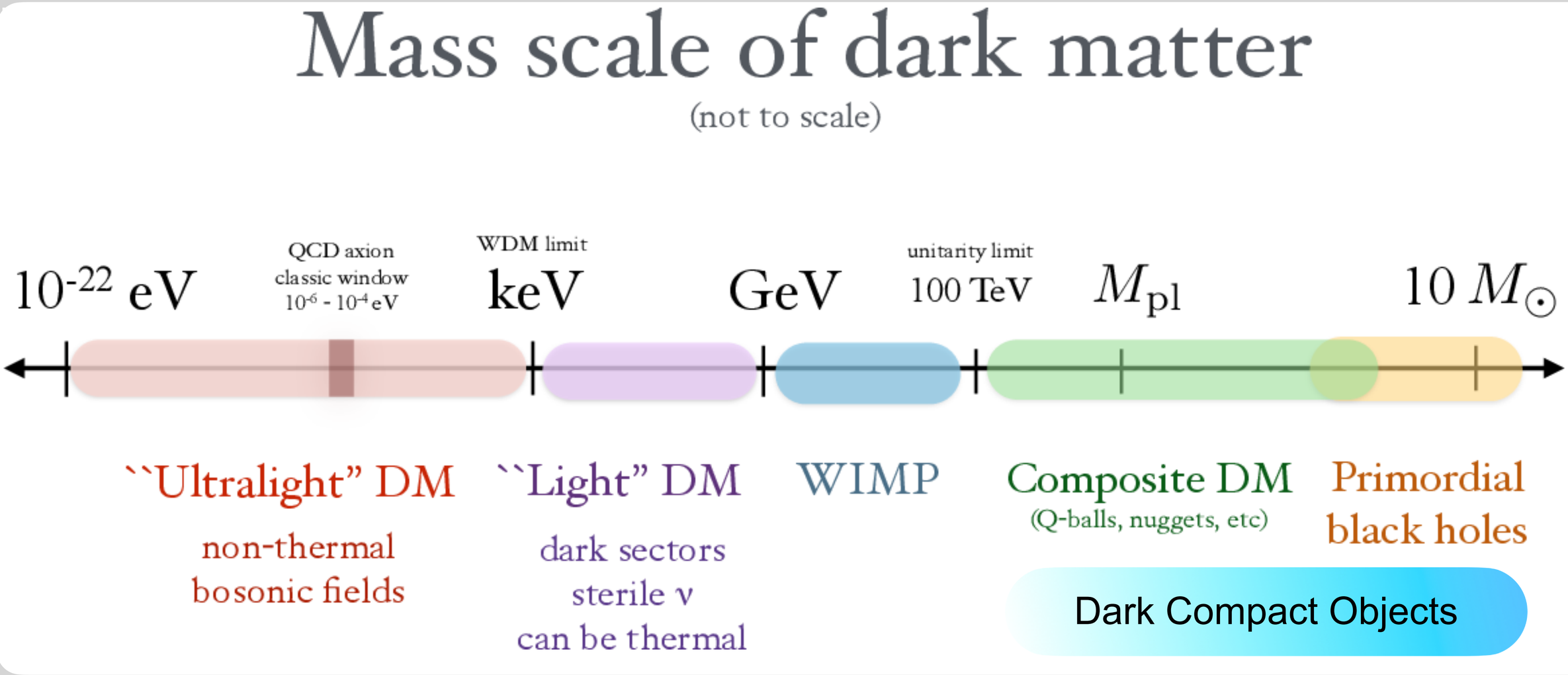

Tongan Lin, TASI lectures on dark matter models and direct detection (2019)

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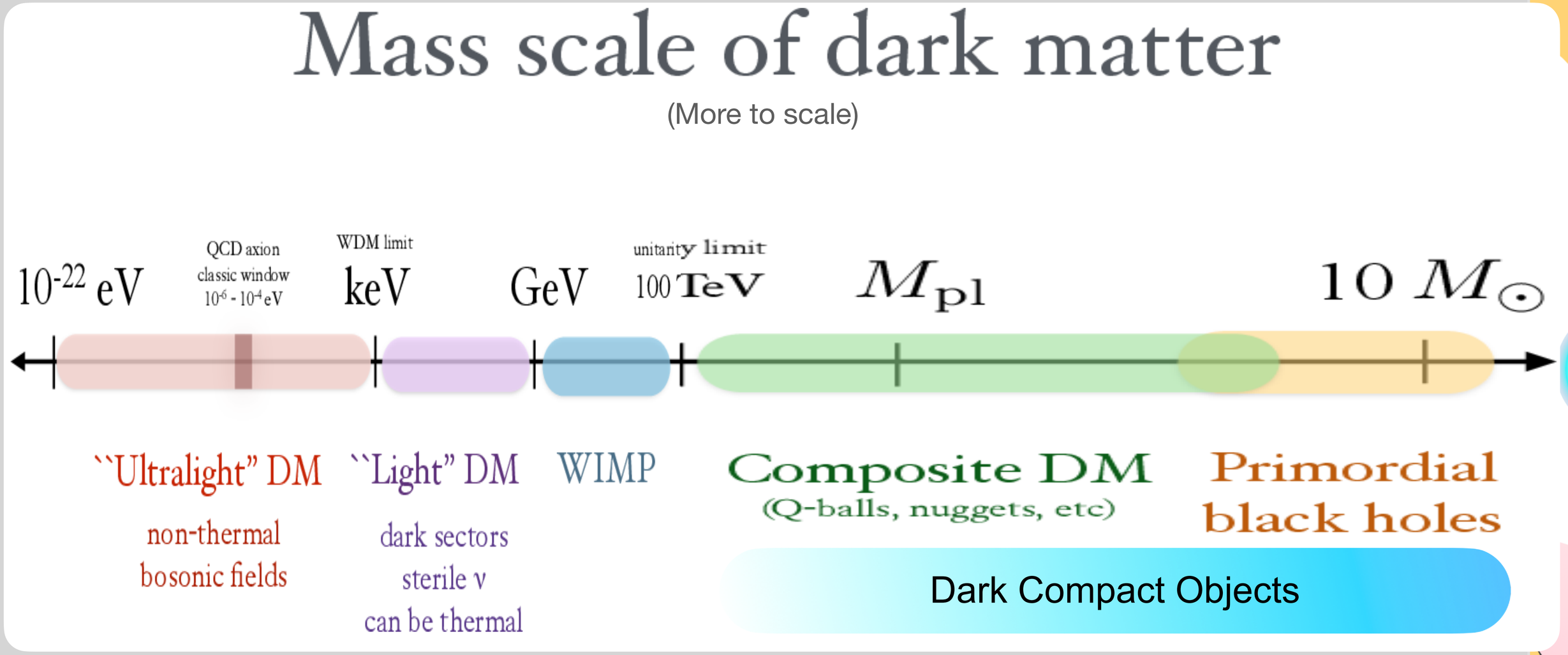
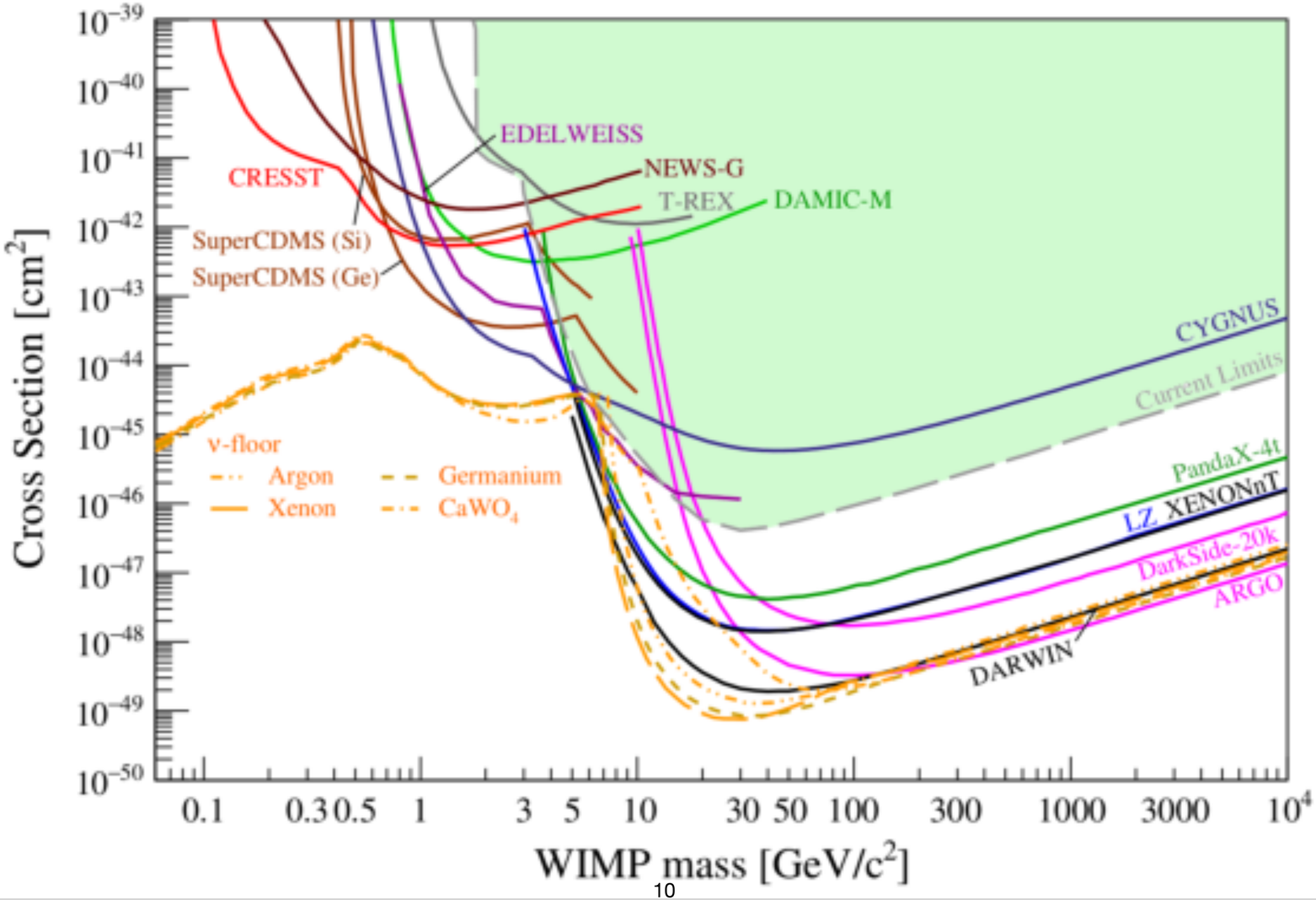


1. Much of the available DM parameter space is occupied by dark compact objects

Why study dark compact objects?

Why have we not found dark matter yet?



Direct detection of dark matter—APPEC committee report - Billard, Julien

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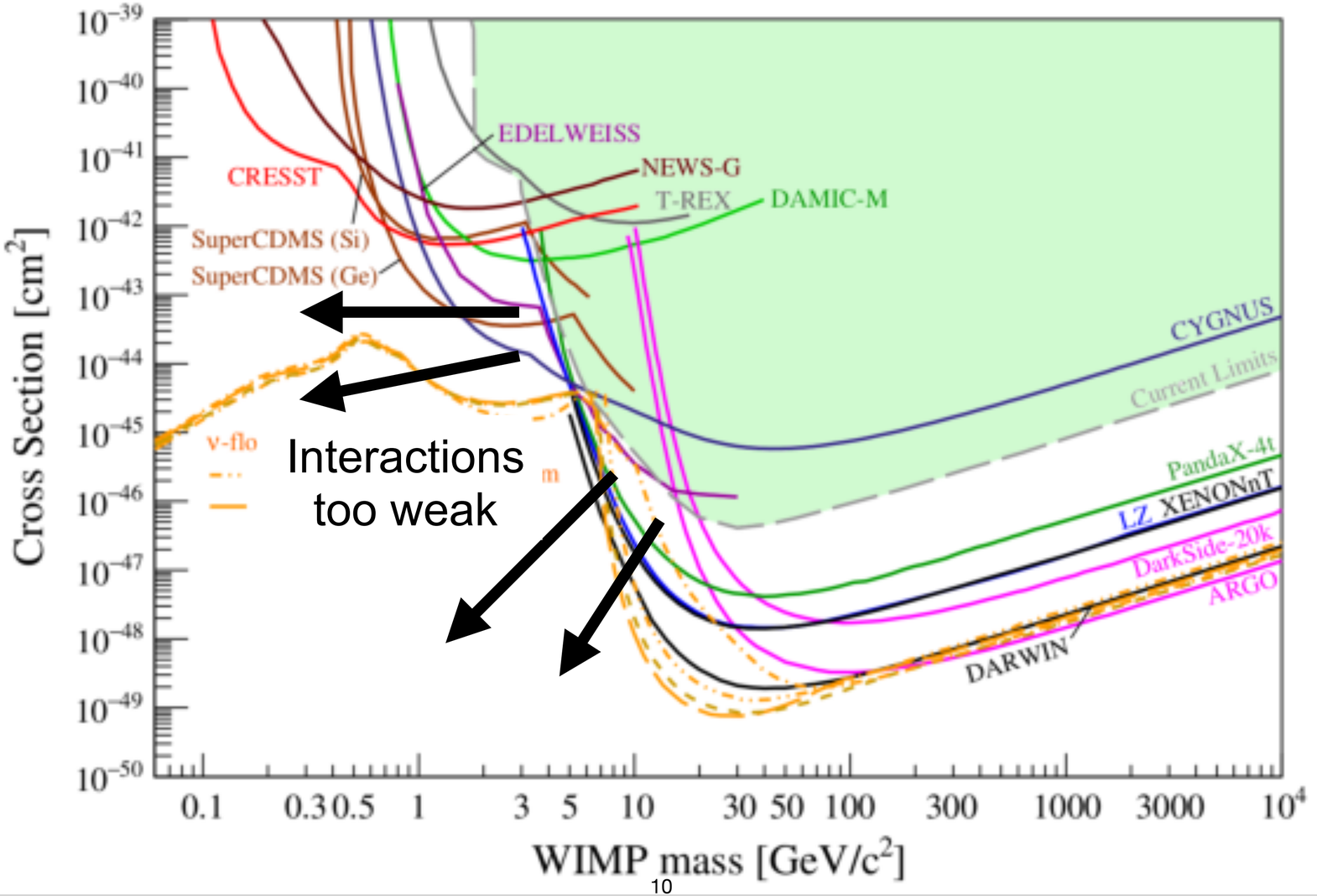

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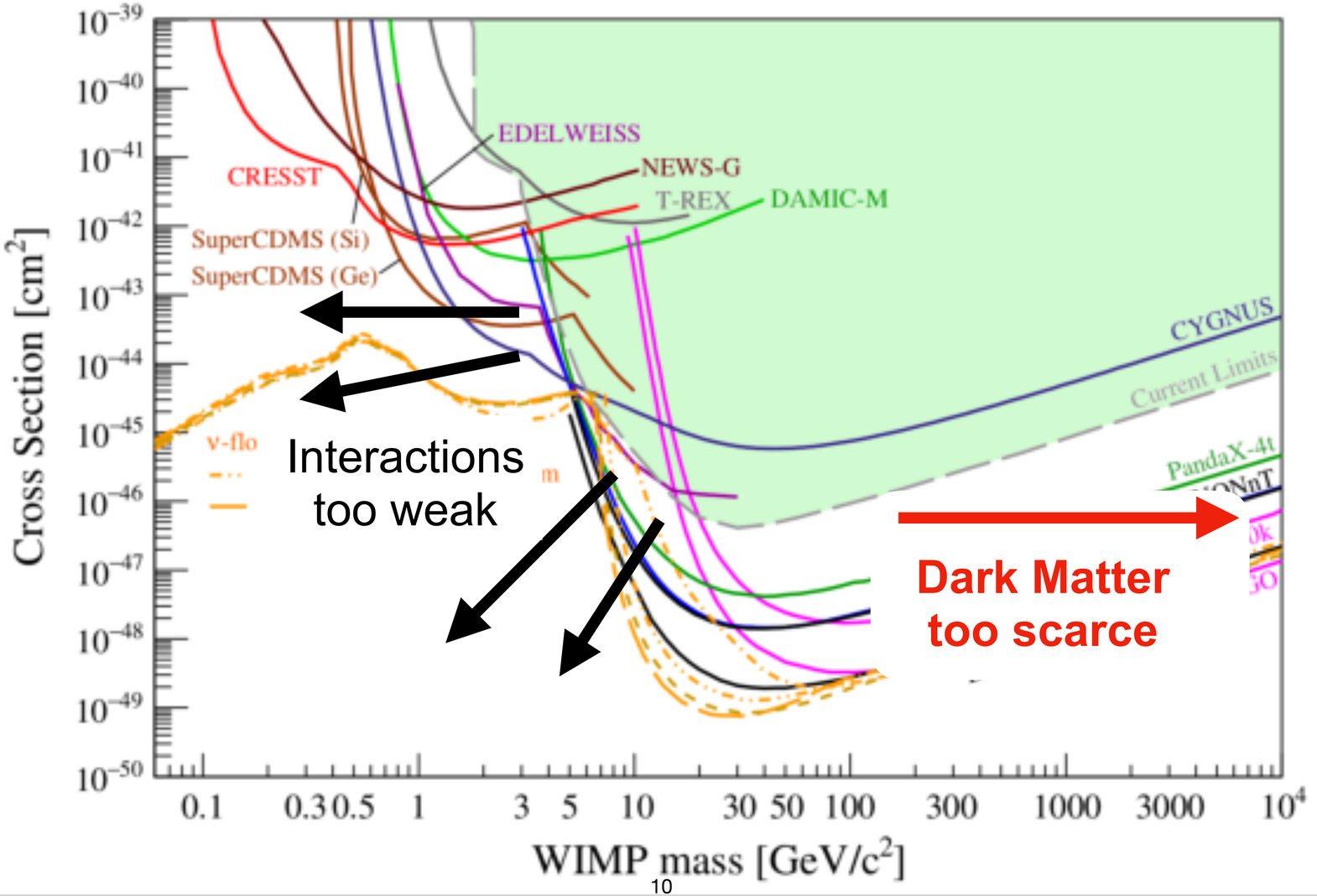

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Why study dark compact objects?

2. Dark matter being too heavy (scarce) to pass through the Earth regularly may explain why we have not seen it

~ 1 m_p dark matter / meter^2 / year

Detection System	Amount of DM passing through
Largest DM detectors	~0.1 mg over 10 years
Largest neutrino detectors	~50 g over 10 years
The Earth	~ 1e17 g over 1 Gyr

Why have we not found dark matter yet?

Why study dark compact objects?

3. They arise in many existing dark theories and exotic cosmologies

- Early Universe Phase Transitions
- Scalar dark matter (including axions) with and without self-interactions
- Enhanced small scale perturbations
- Early matter domination
- Self-Interacting dark matter

How do dark compact objects form?

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- Collapse of enhanced overdensities (Primordial black holes)
- Structures build up through strong self-attraction (Nuclear dark matter)
- Phase transitions (Q-balls, Quark nuggets)
- Bose-Einstein Relaxation (Axion Stars)
- Early Matter domination
- Dark dissipation leading to collapse of dark matter halo

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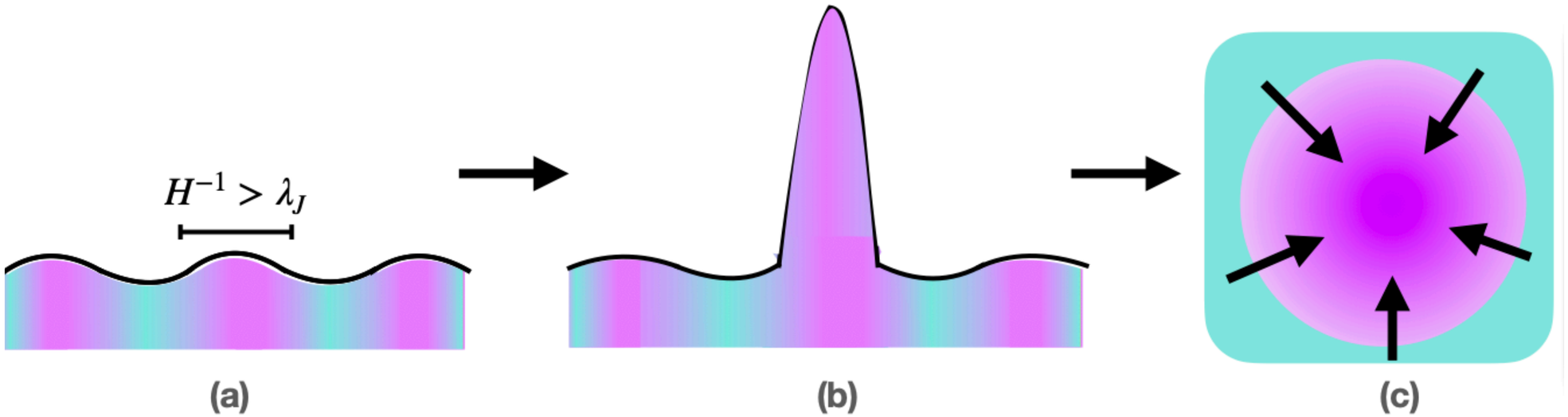
Making dark compact objects with dark dissipative interactions

How do dark compact objects form?

Forming dark matter halos *without* self-interactions



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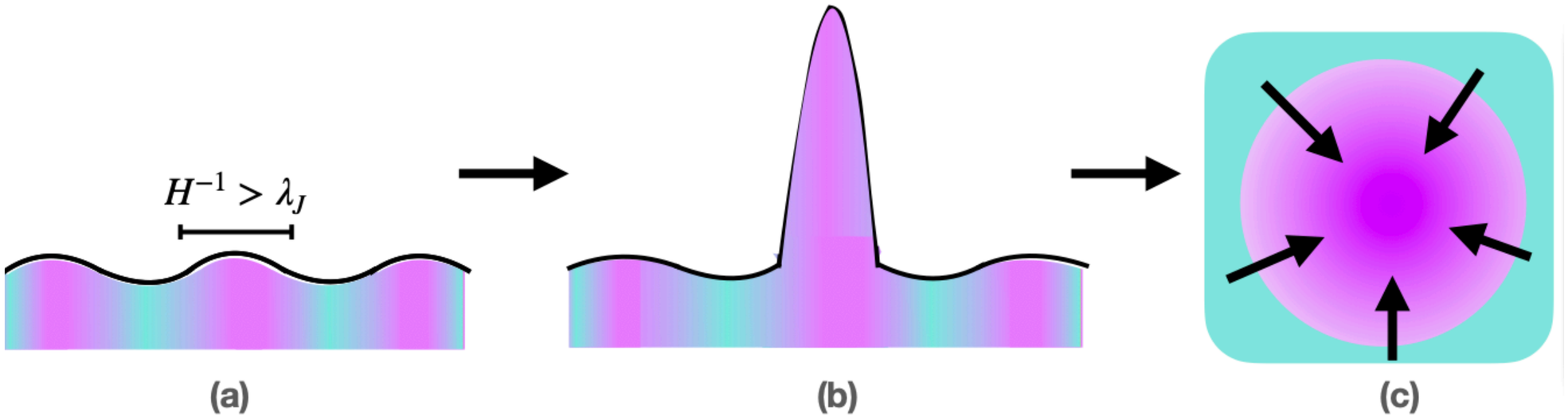

(a) Density perturbations begin growing during matter domination

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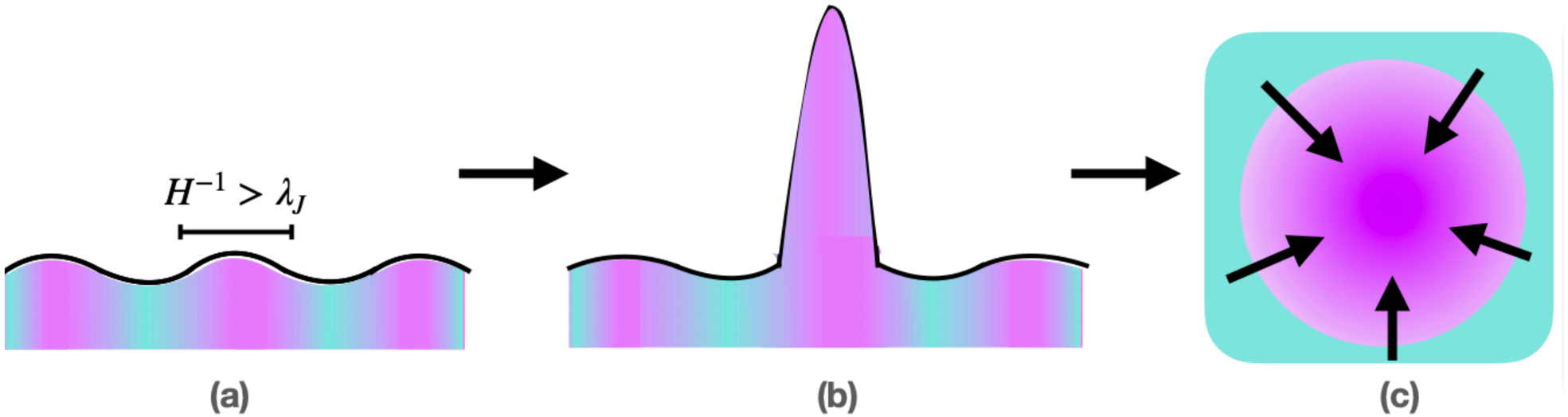

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(b) Perturbations grow linearly as the Universe expands

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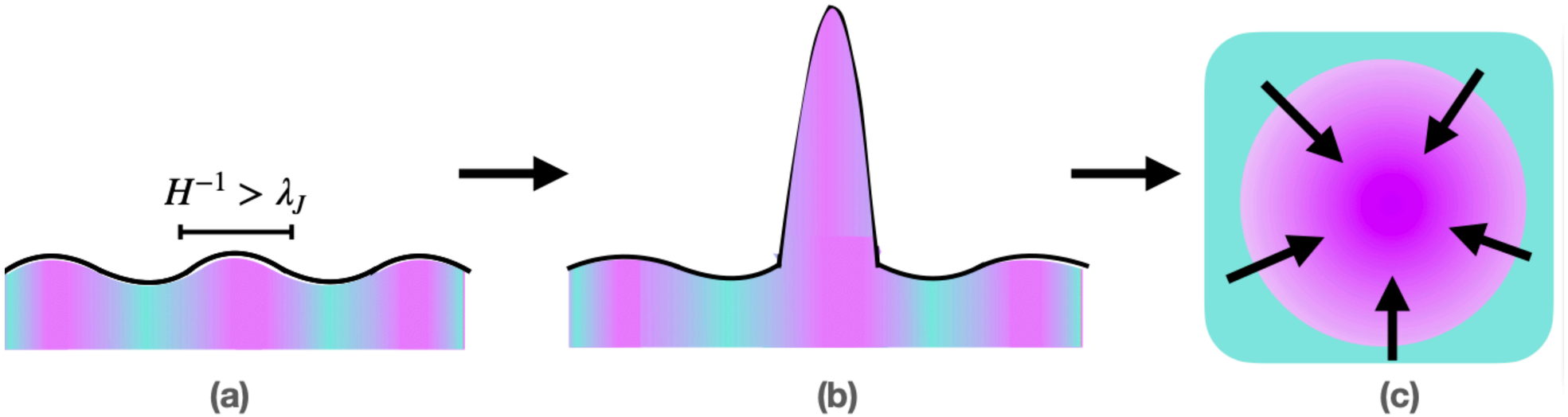

(a) Density perturbations begin growing during matter domination

(b) Perturbations grow linearly as the Universe expands

(c) Overdense ball of dark matter collapses it's own gravity and virializes

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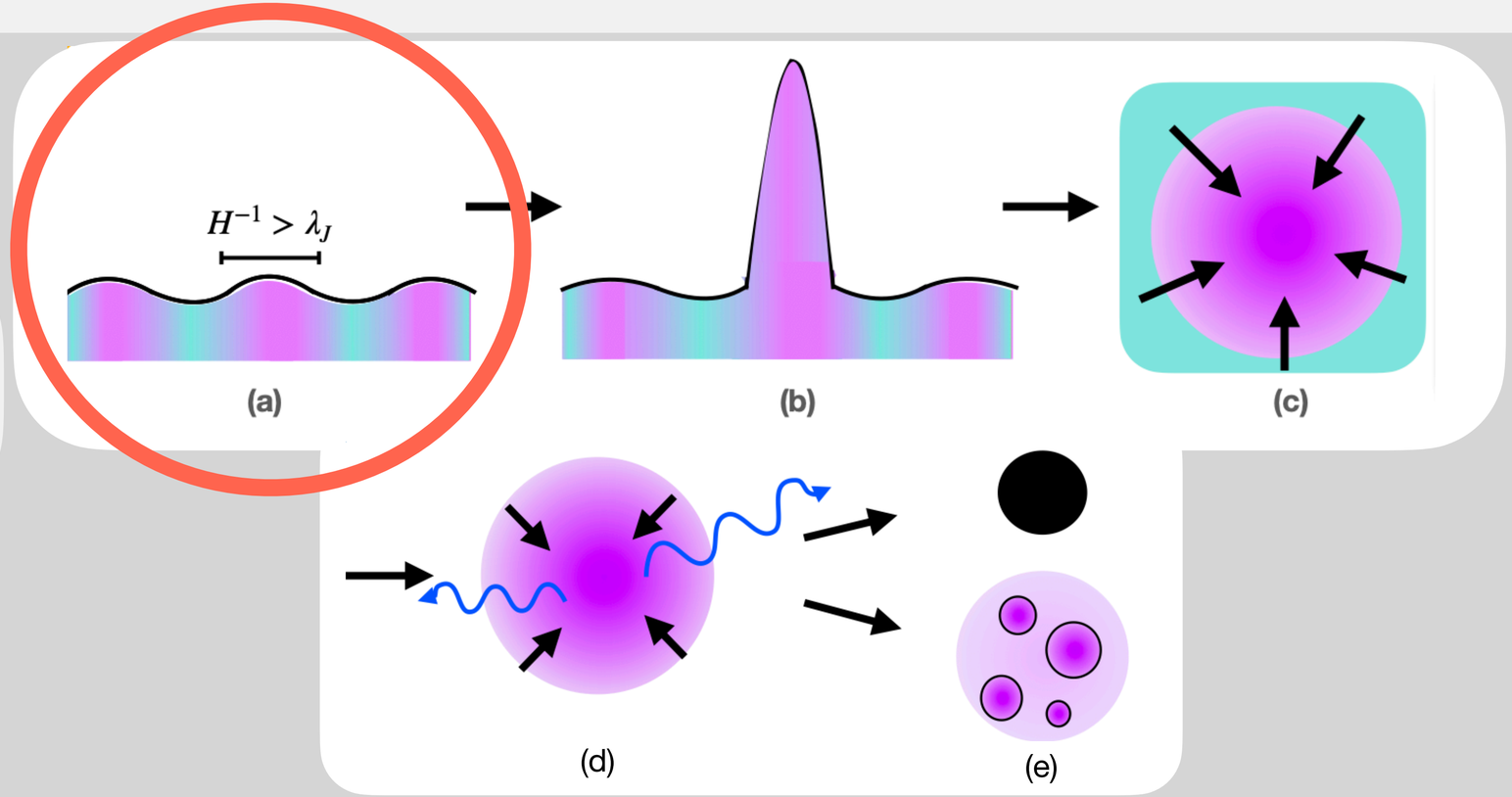
Forming dark matter halos *with* dissipative self-interactions

Self-interactions change the scale at which perturbations grow



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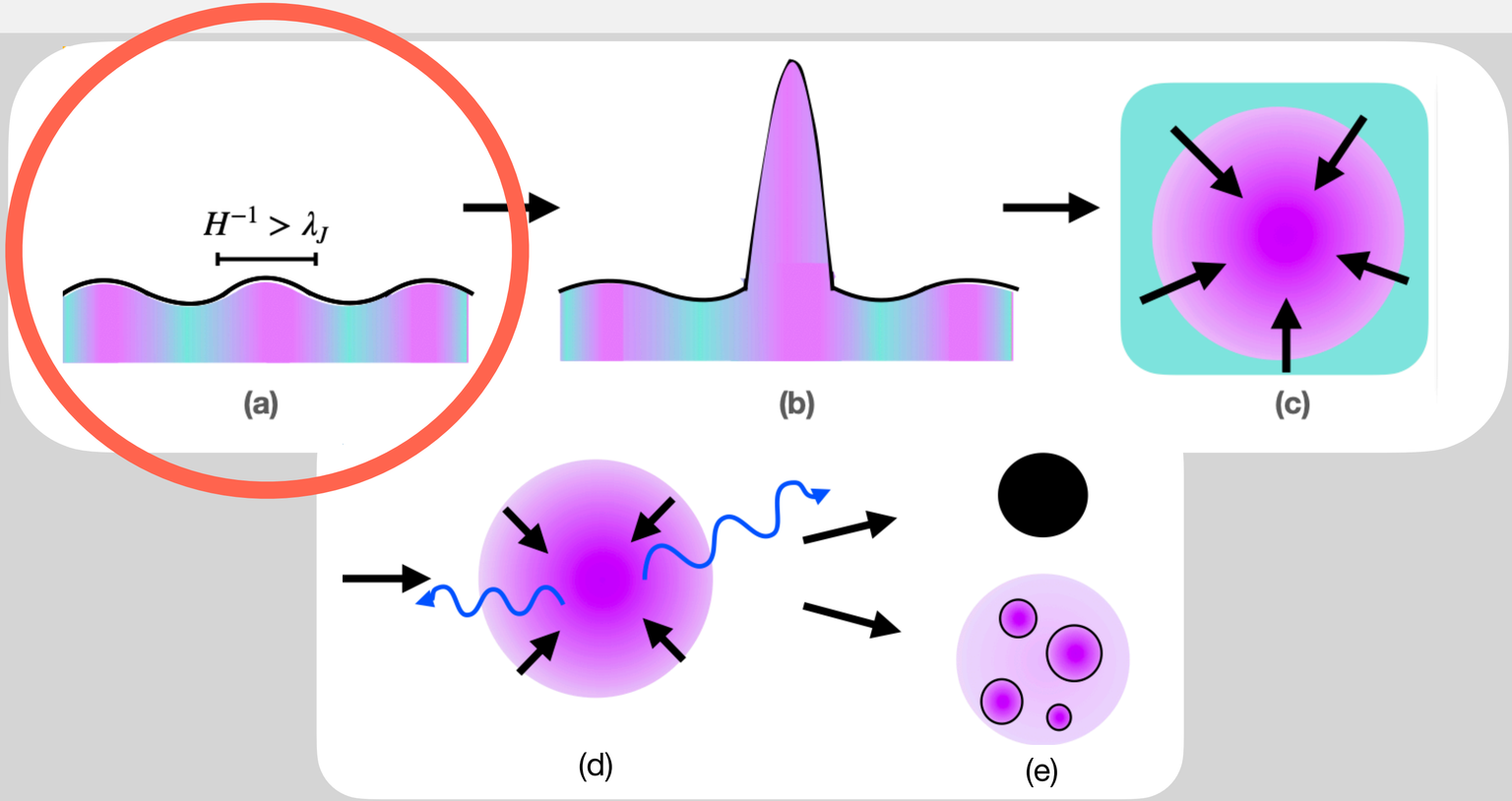

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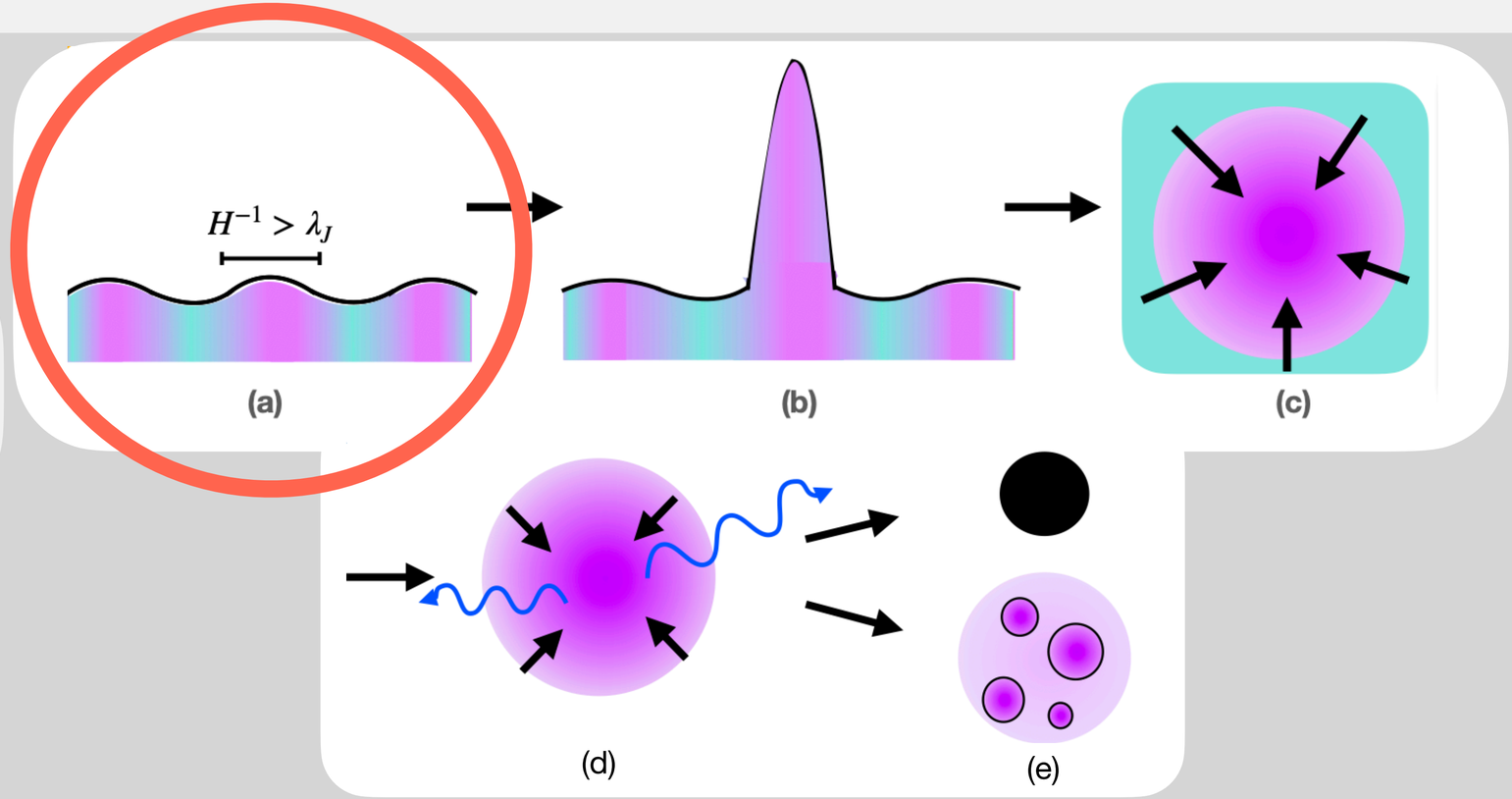

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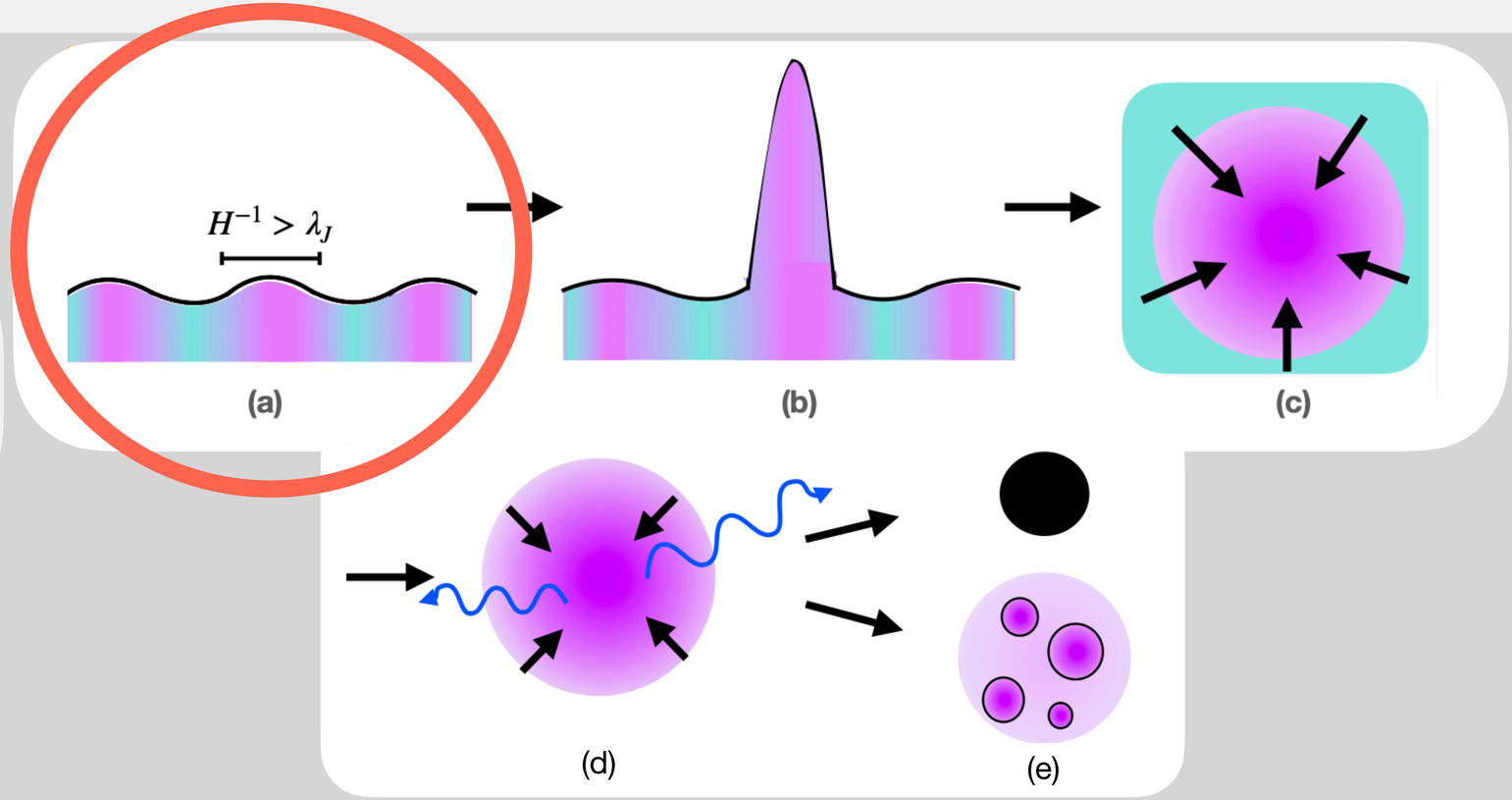

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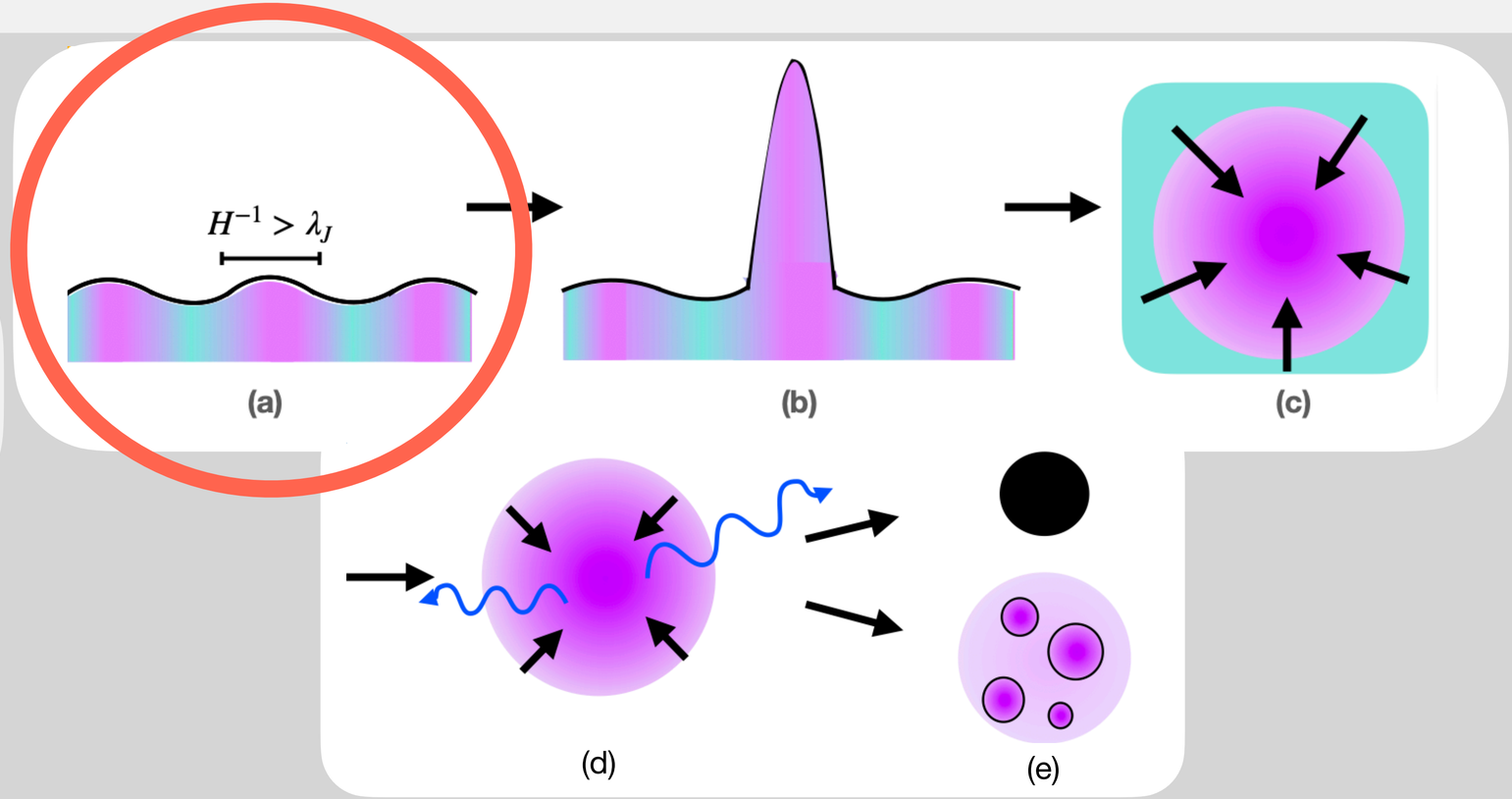

(a) Density perturbations begin growing during matter domination

(b) Perturbations grow linearly as the Universe expands

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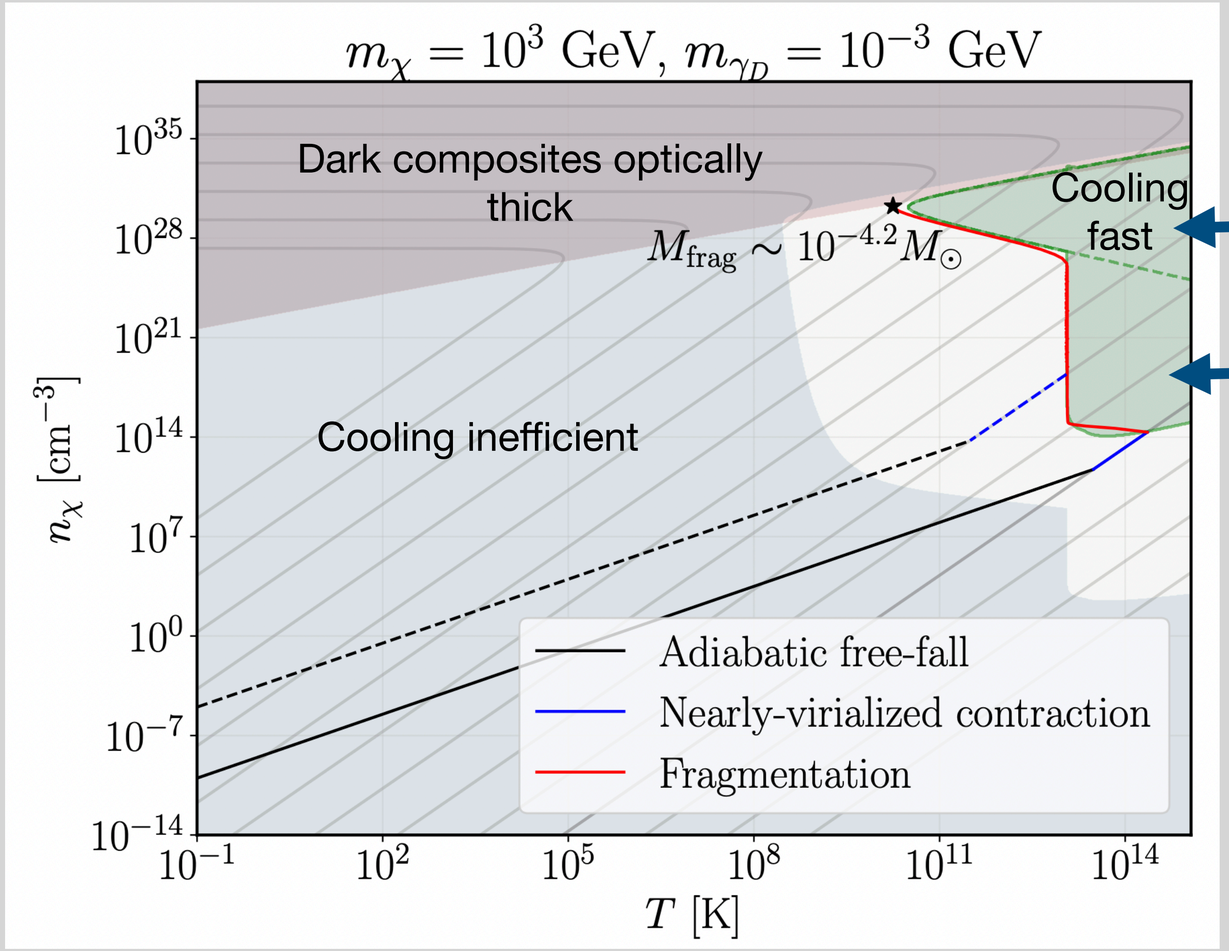
(d) Self-interactions release energy from the halo and cause it to collapse further

How do dark compact objects form?

The effect of multiple cooling channels on the formation of dark compact objects



Bremsstrahlung

Excitation and Decay

$$\mathscr{L} \supset g_D \chi_1 \gamma_\mu A^\mu \chi_2 + g_D \chi_1 \gamma_\mu A^\mu \chi_1 + g_D \chi_2 \gamma_\mu A^\mu \chi_2$$

$$\delta = m_{\chi_2} - m_{\chi_1}$$

JCAP02(2024)002

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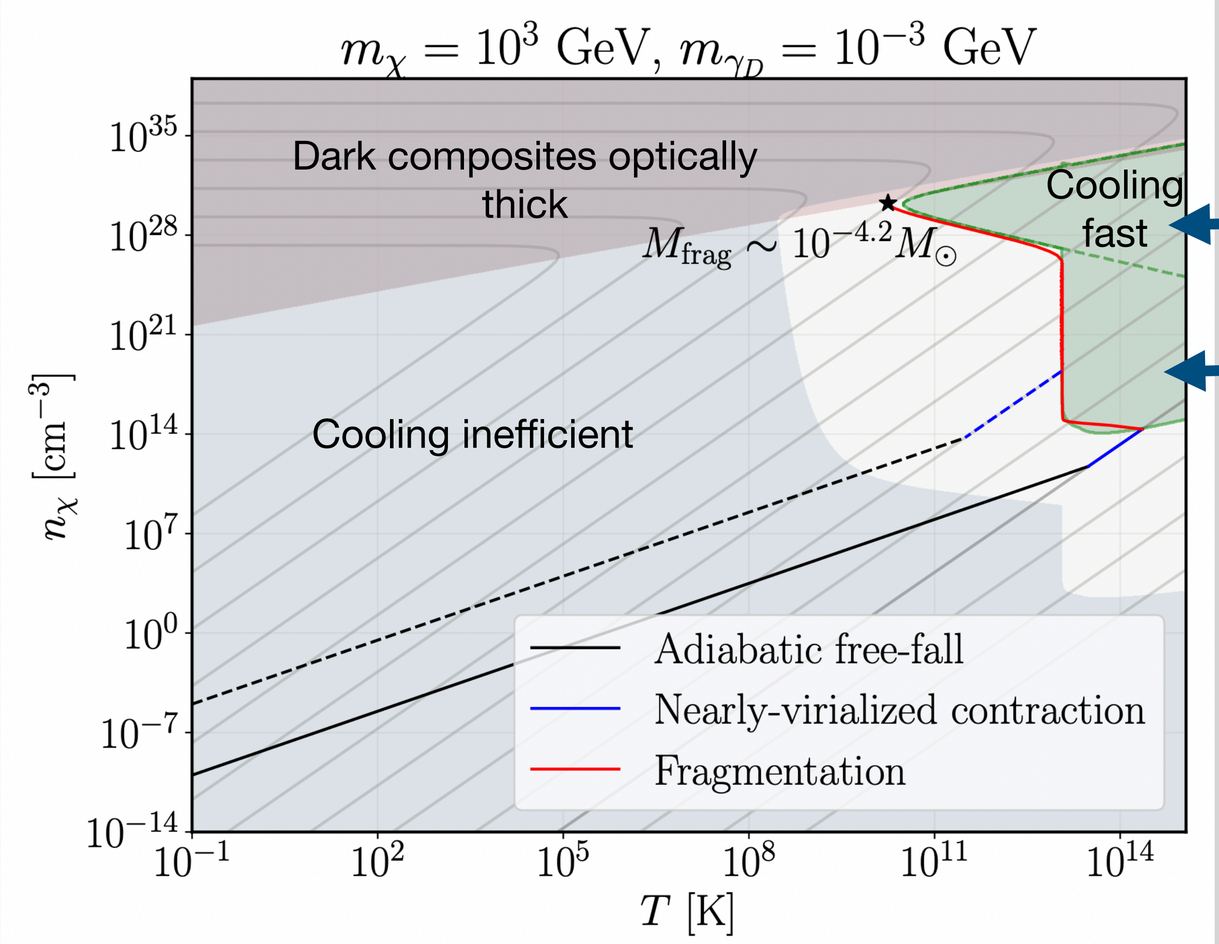

Bremsstrahlung

Excitation and Decay

Complex dark sector with 2 dark fermions and one dark photon

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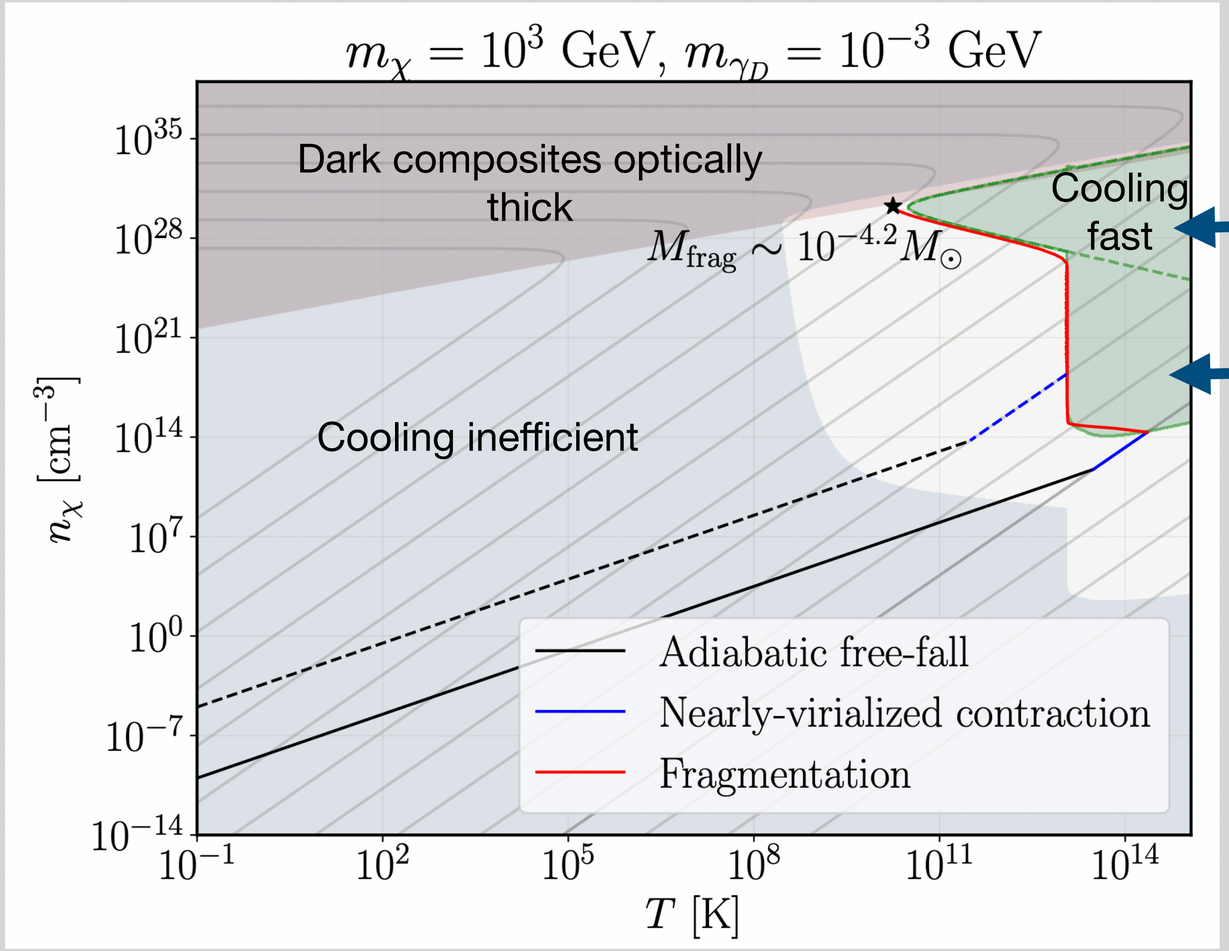

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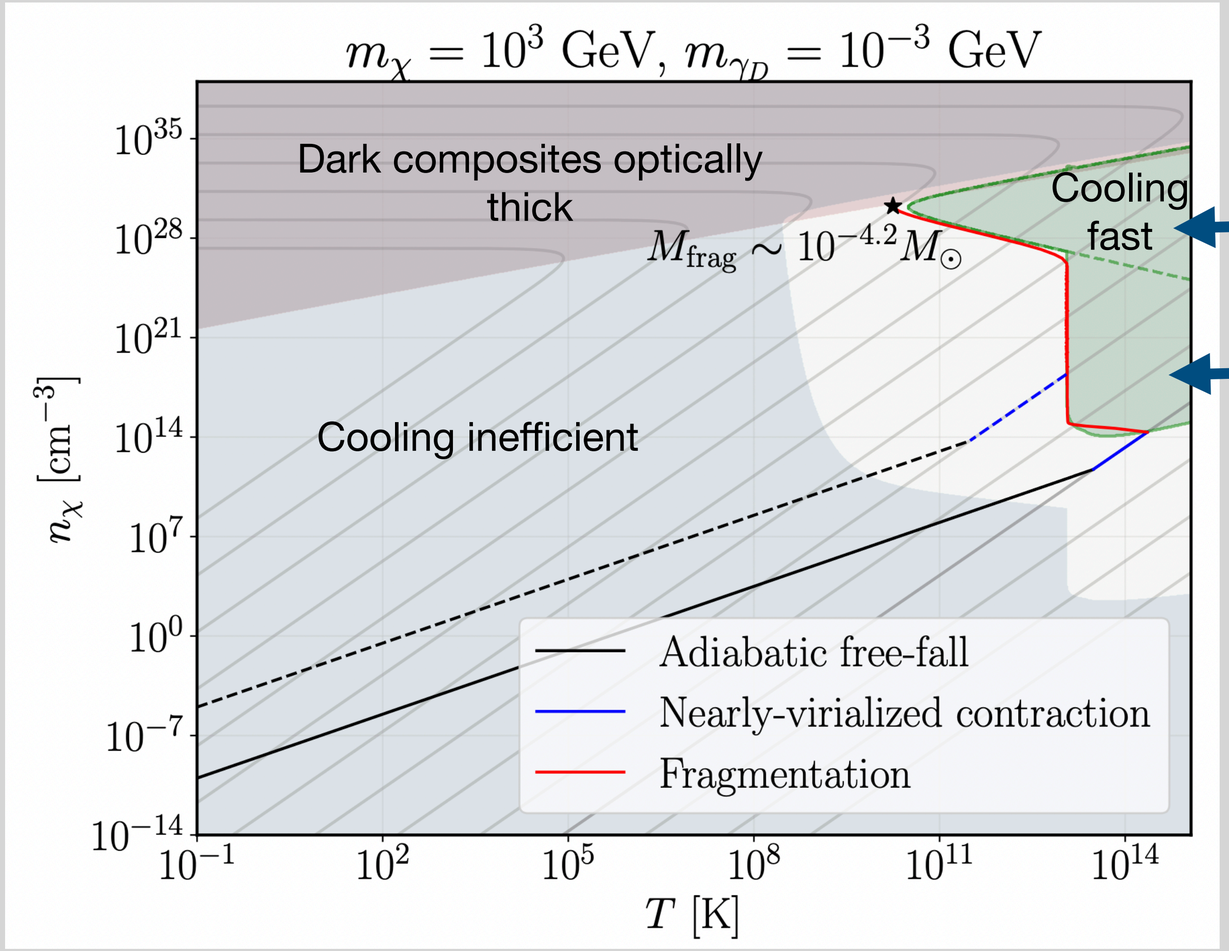

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The specific cooling mechanisms available to dark matter shape the types of objects it forms

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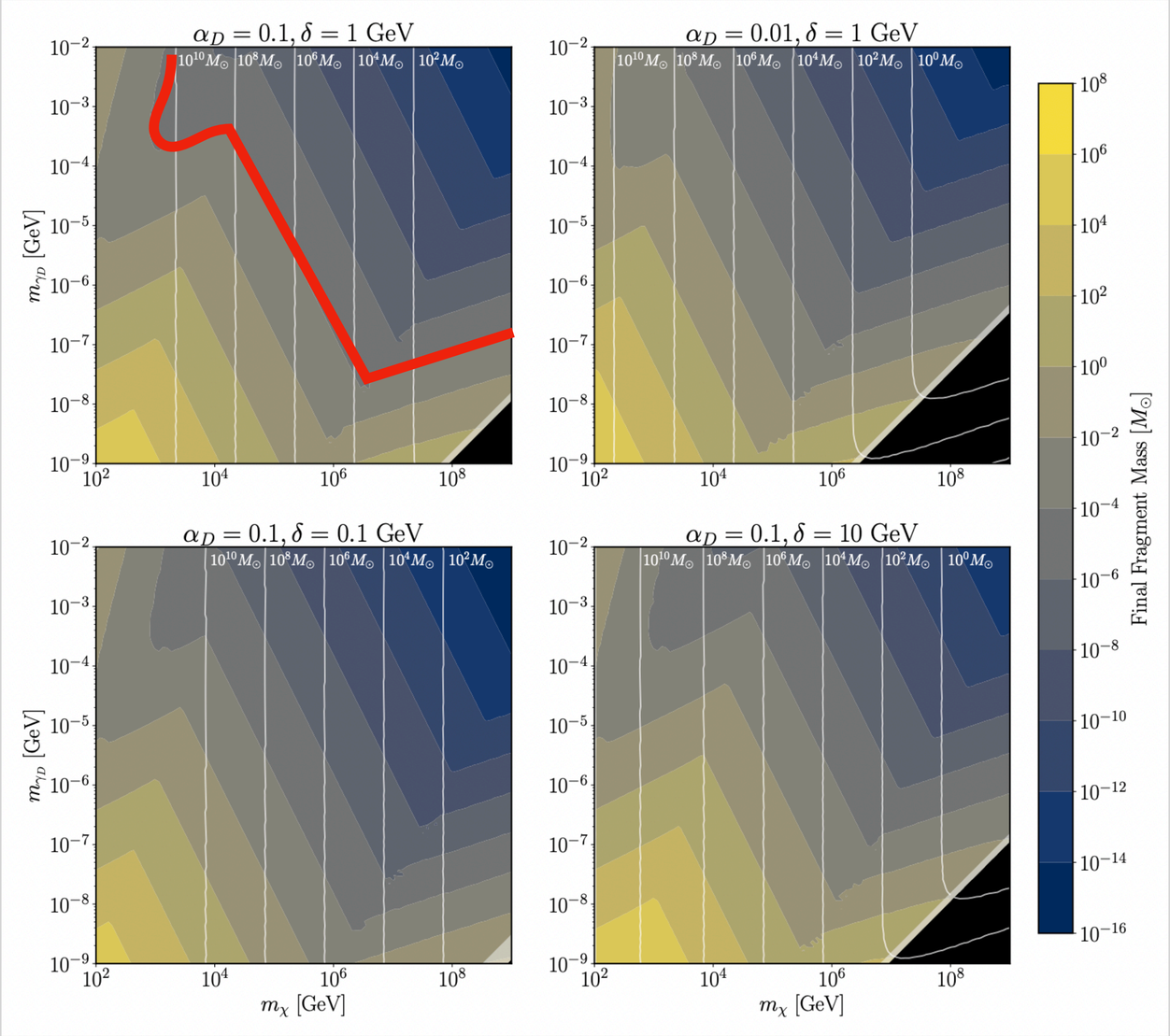
Self interactions control how dark matter composites form



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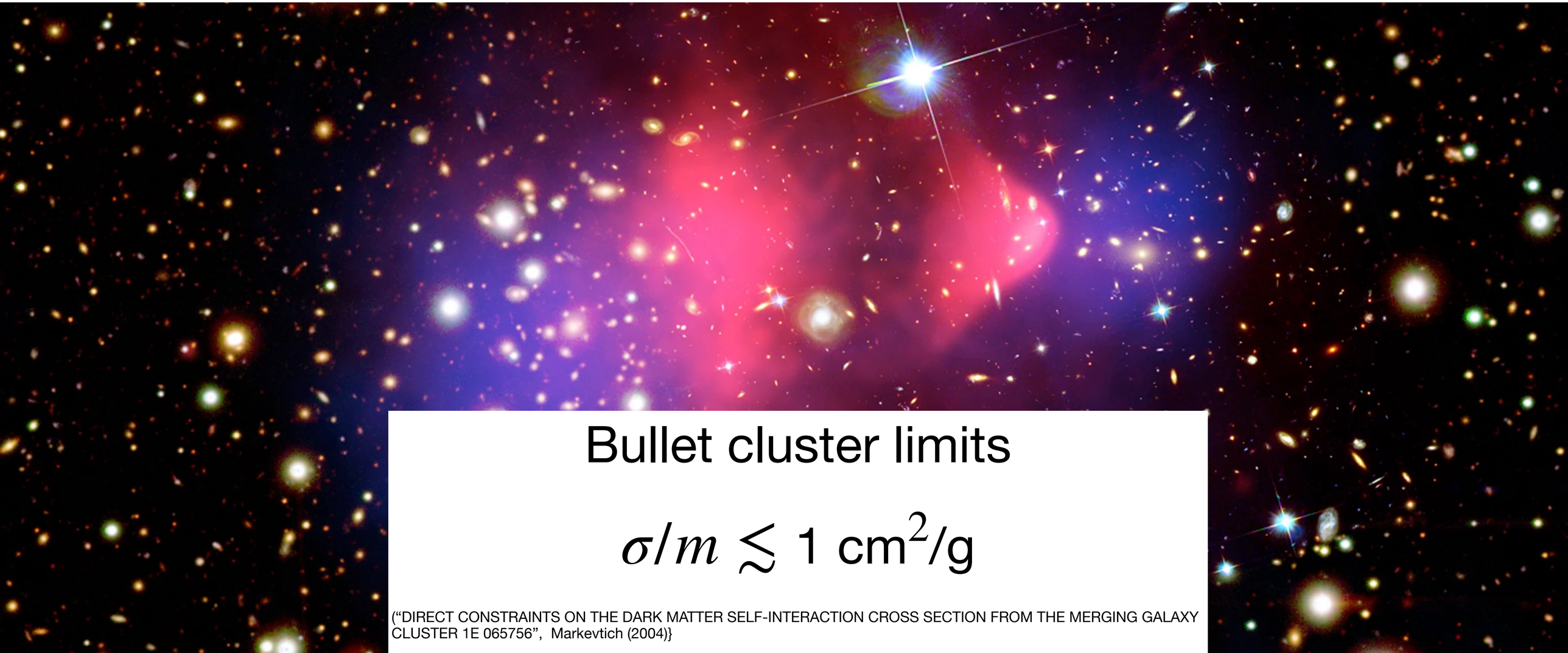
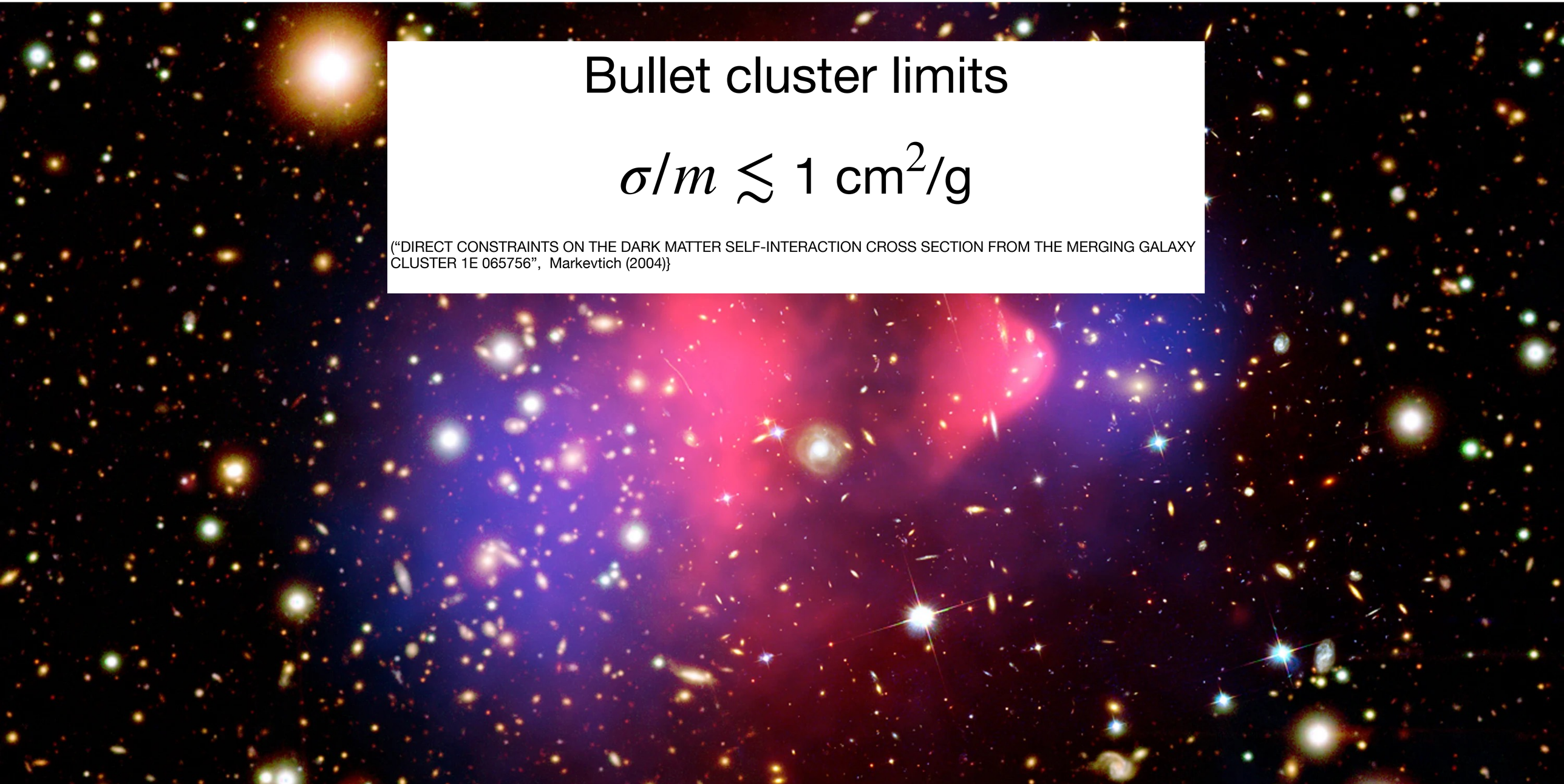


Bullet cluster limits

$$\sigma/m \lesssim 1\ \mathrm{cm}^2/\mathrm{g}$$

("DIRECT CONSTRAINTS ON THE DARK MATTER SELF-INTERACTION CROSS SECTION FROM THE MERGING GALAXY CLUSTER 1E 065756", Markevtich (2004)}

Many ways around these self-interaction limits



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- Dark particles are very heavy
- Self-interacting component only a fraction of all dark matter
- Dark structures form in the early universe at very high densities or through exotic cosmologies in the early universe
- Interactions are so strong that structures form quickly and then neutralize further interaction

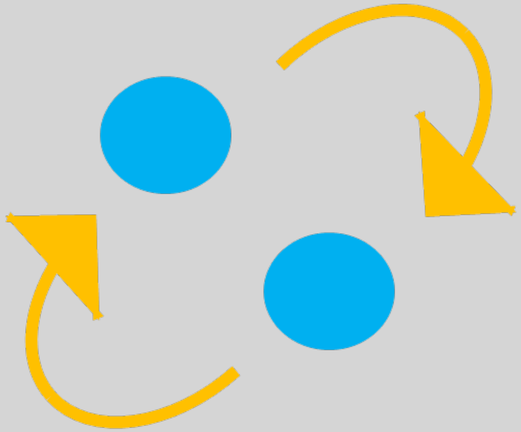
How do we search for dark compact objects?

How do we look for dark compact objects?

- Gravitational lensing
- Irregular gravitational wave inspirals
- Contributions to GW background
- Dark radiation
- Irregular multi particle events at direct detection experiments
- Stellar dimming
- Paleo-detection
- Much more!

How do we look for dark compact objects?

Inspirals + Mergers



- Compact objects will naturally form binary systems in the early universe (Diamond, M.D. et al J. High Energ. Phys. 2023, 136) or in over dense clusters

$$\Gamma \simeq 9 \times 10^4 \left(\frac{M}{10^{15}\mathrm{g}} \right)^{-32/37} f^{53/37}/\mathrm{s}$$

Merger rate in Milky Way due to early universe binary formation

- Merging compact objects may produce unique inspiral waveforms that can help differentiate them from black holes (Gian F. Giudice et al JCAP10(2016)001)

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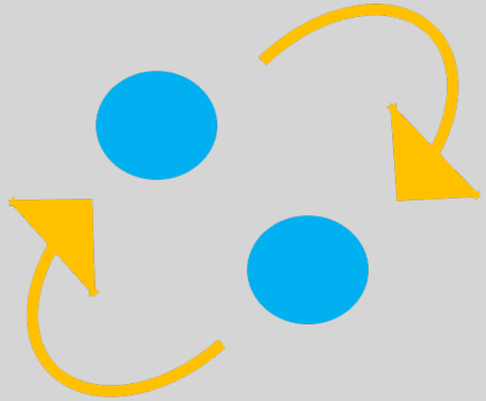
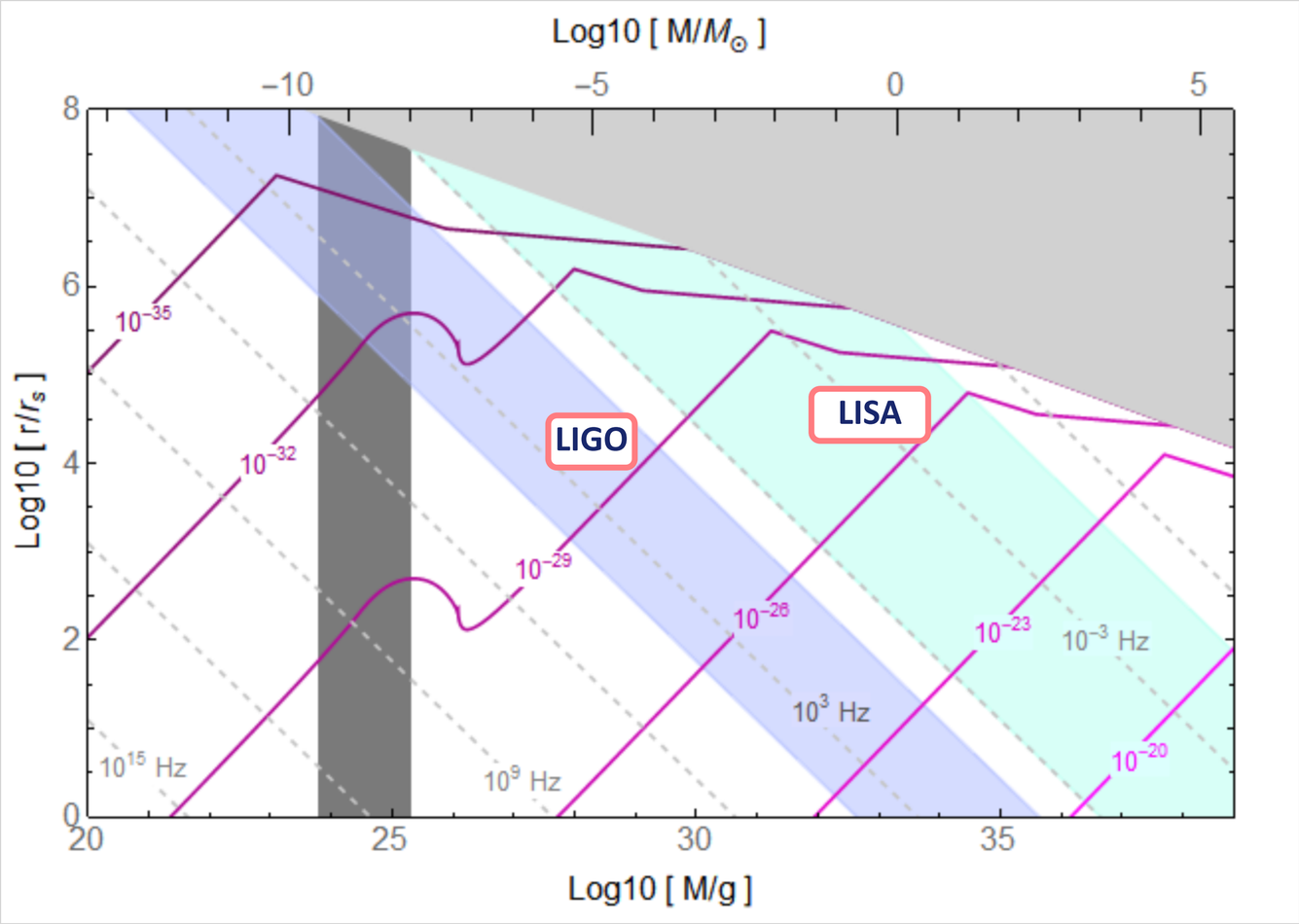


Strain and frequency of the expected nearest dark compact object merger after one year of observations

Gray dashed lines = frequency
Pink lines = peak strain

$$f = 10^{-2}$$

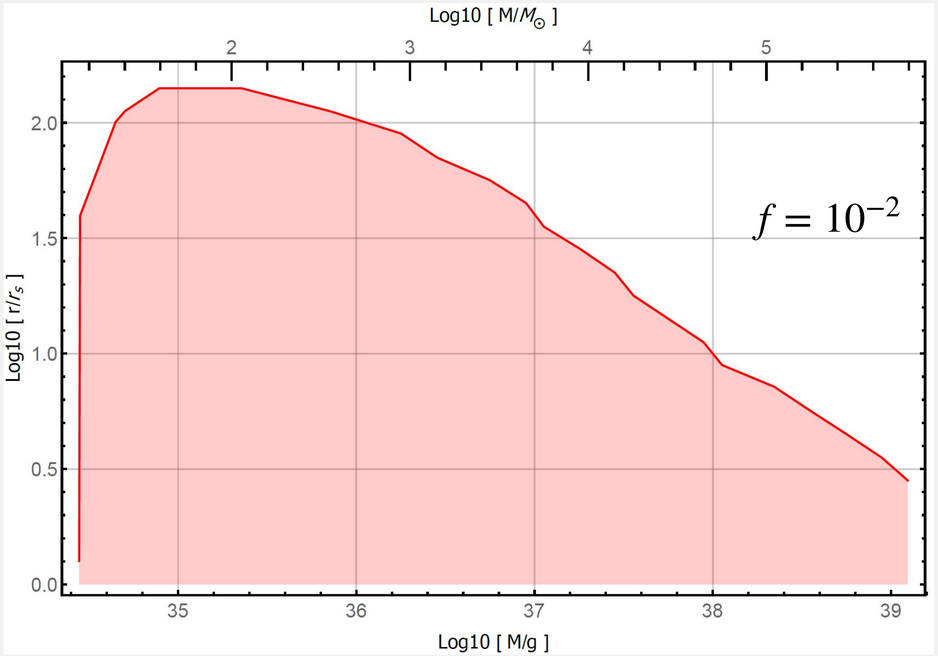


Diamond, M.D. et al J. High Energ. Phys. 2023, 136 (2023)

Contributions to the Stochastic Gravitational Wave Background

Many dark compact object binaries collectively contribute to the SGWB

Dark Compact Objects whose inspirals would contribution to the SGWB would be observable to LISA



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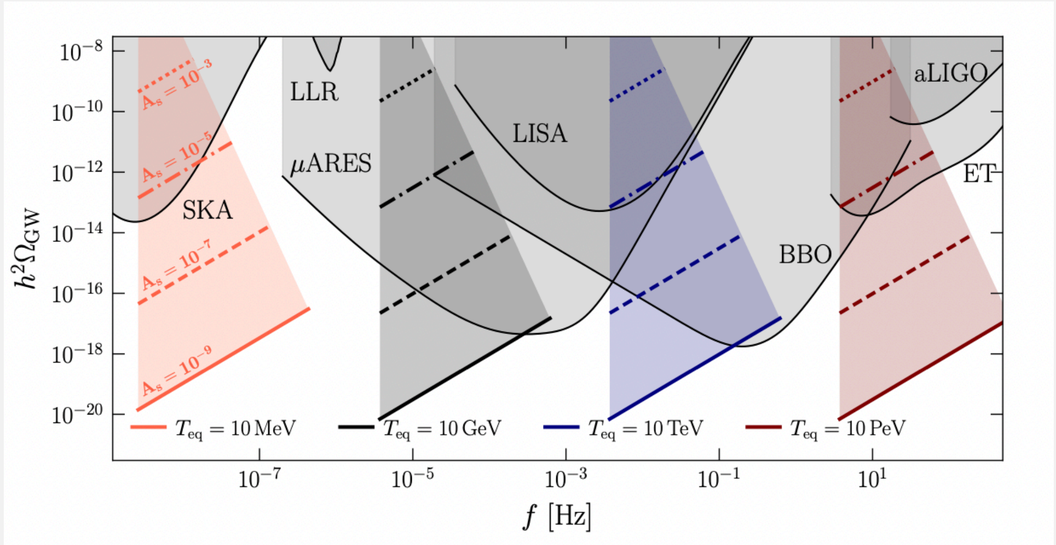
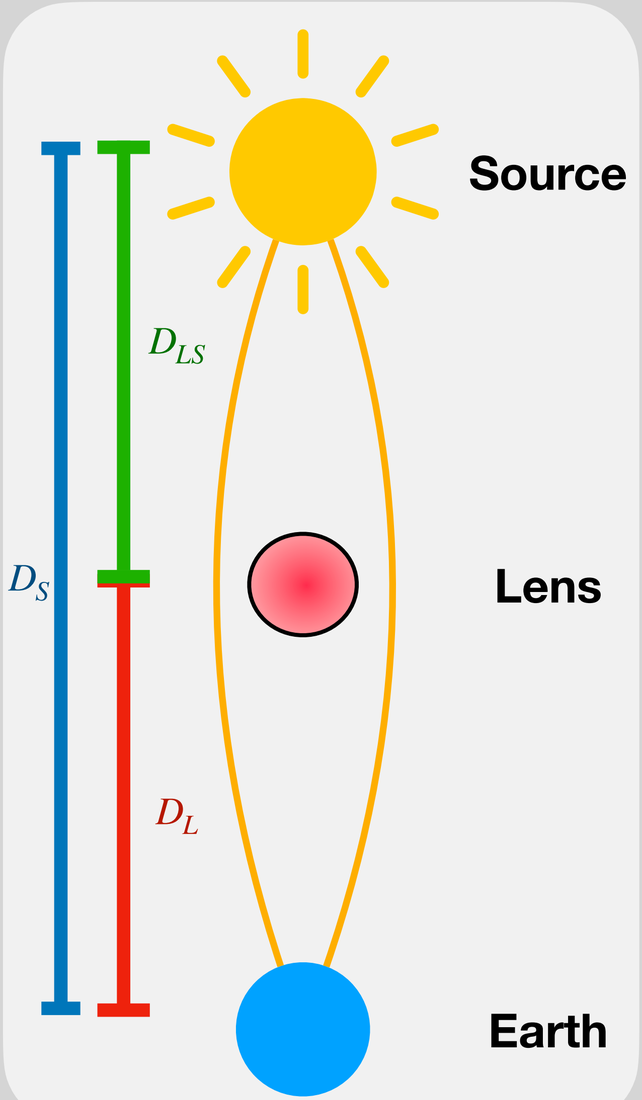
Exotic cosmologies and phase transitions that produce dark compact objects often produce SGWB signals

Predicted GW spectrum from various early matter domination scenarios



Foster, Fernandez, Lillard, Shelton (2024)

Gravitational Lensing



- Heavy objects bend space-time, bending the path of light from bright sources behind the “lens”
- Microlensing surveys such as MACHO, Subaru/HSC, OGLE and EROS-2 place some of the strictest limits on primordial black hole and dark compact object populations
- Works best for objects with

$$M > 10^{21} g \; (10^{-12} M_\odot)$$

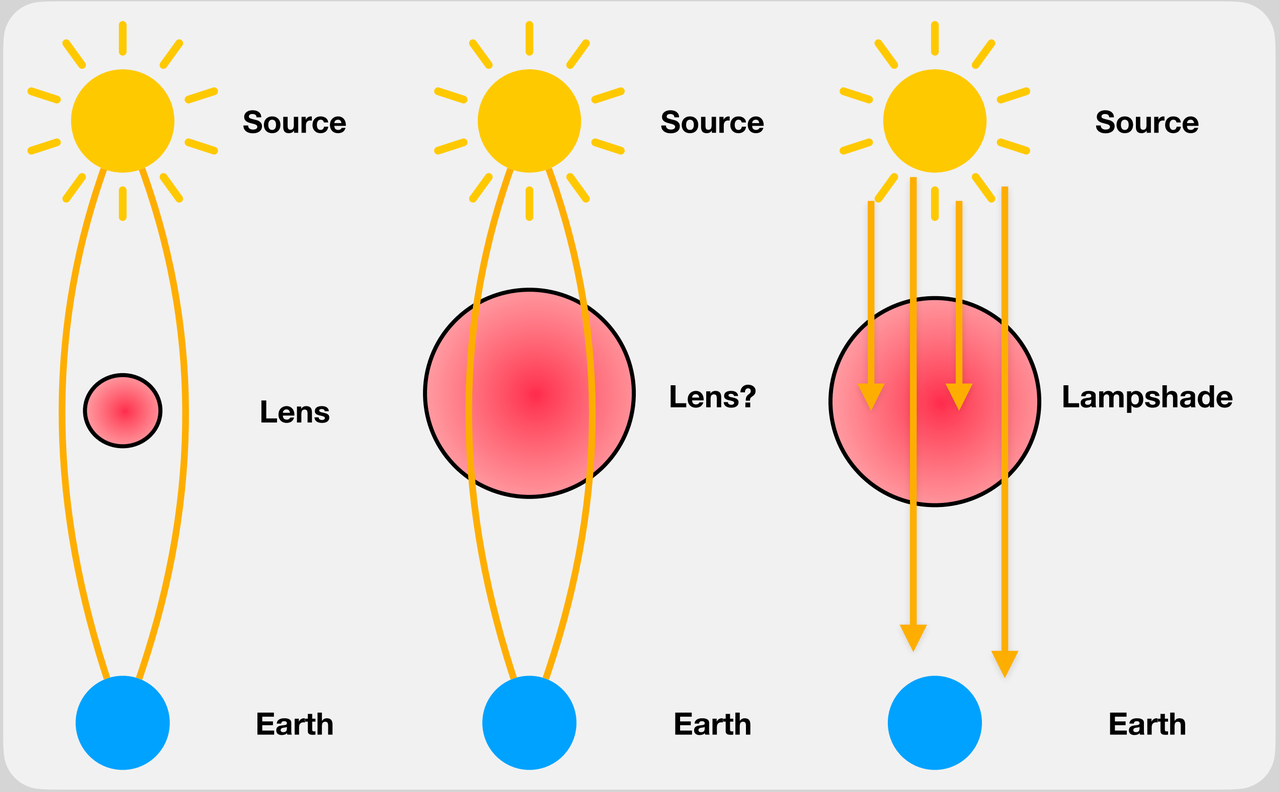
$$r < r_E = \left(D_L D_{LS}/D_S\right)^{1/2} M^{1/2} \sim 1 R_\odot$$

(For EROS and OGLE)

How do we look for dark compact objects?

Stellar Dimming

- Dark compact objects with some interactions with light can dim the light of sources they pass in front of
- Both exoplanet surveys and microlensing surveys can be sensitive to this dimming (Bai et al, Phys. Rev. D 108, 103026), (Diamond et al, Arxiv 2409.08322)
- Dimming light curve differs from those of baryonic objects (Bai et al, Phys. Rev. D 108, 103026)



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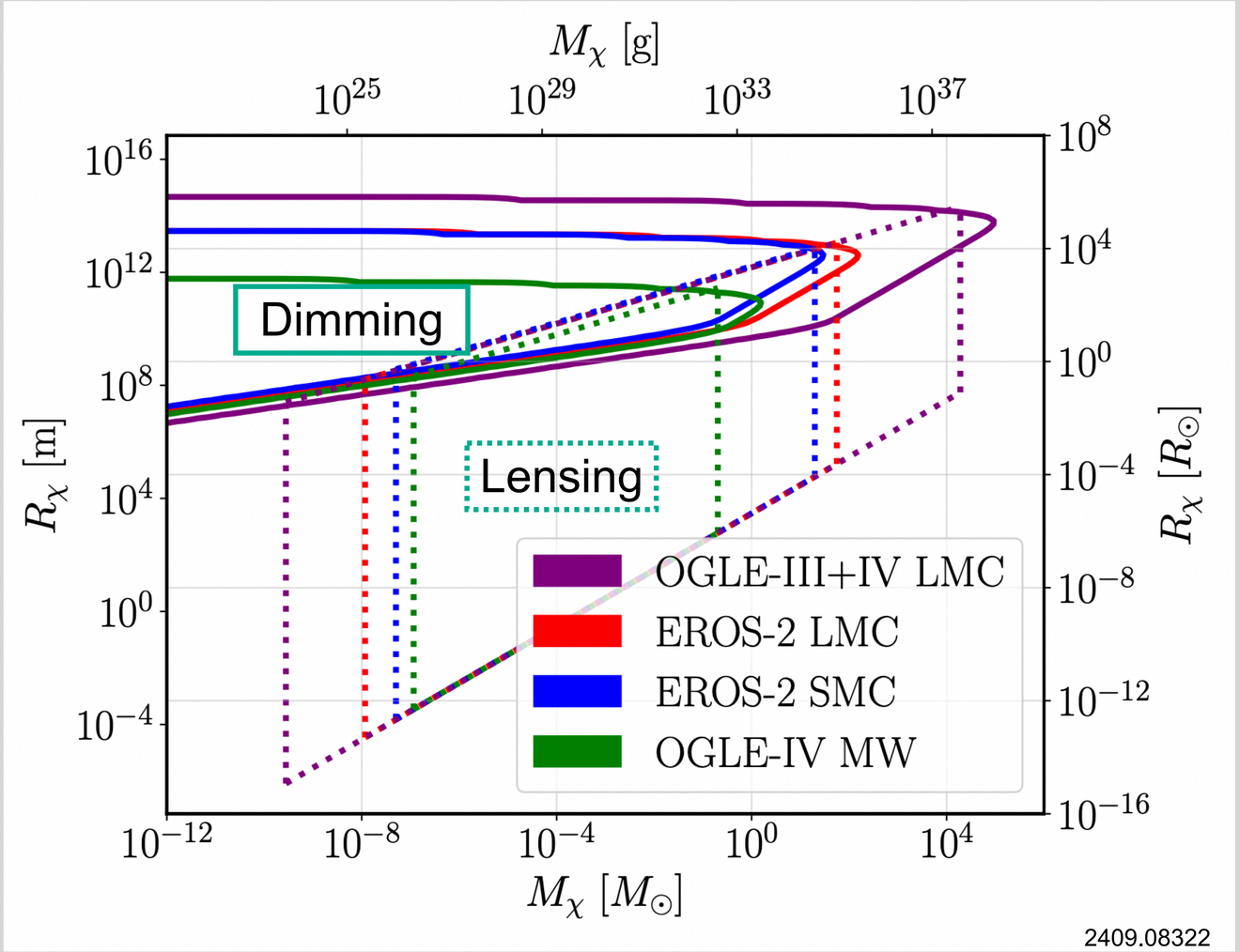

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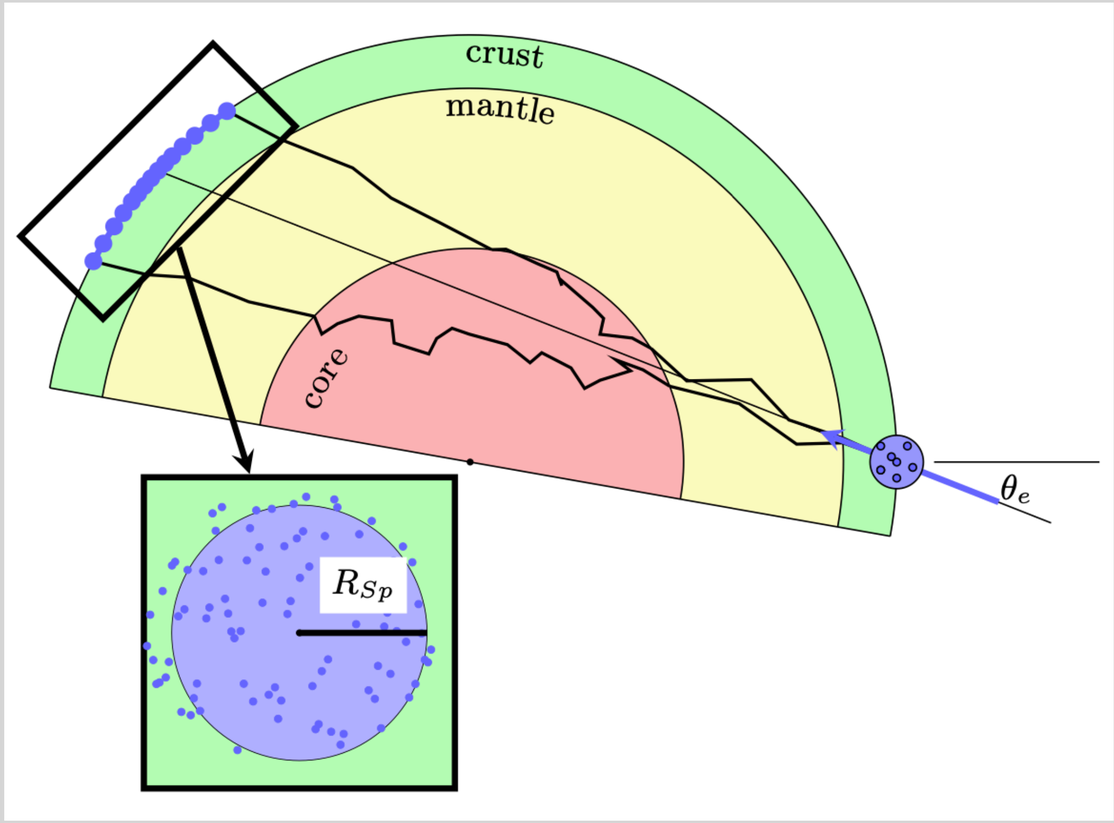
Multi- Scatter Events

- Loosely bound composites break apart when they pass through the Earth.
- Direct detection experiments may see rare many particle “splashes” instead of single particle events (Boukhtouchen et al arXiv:2512.16043)



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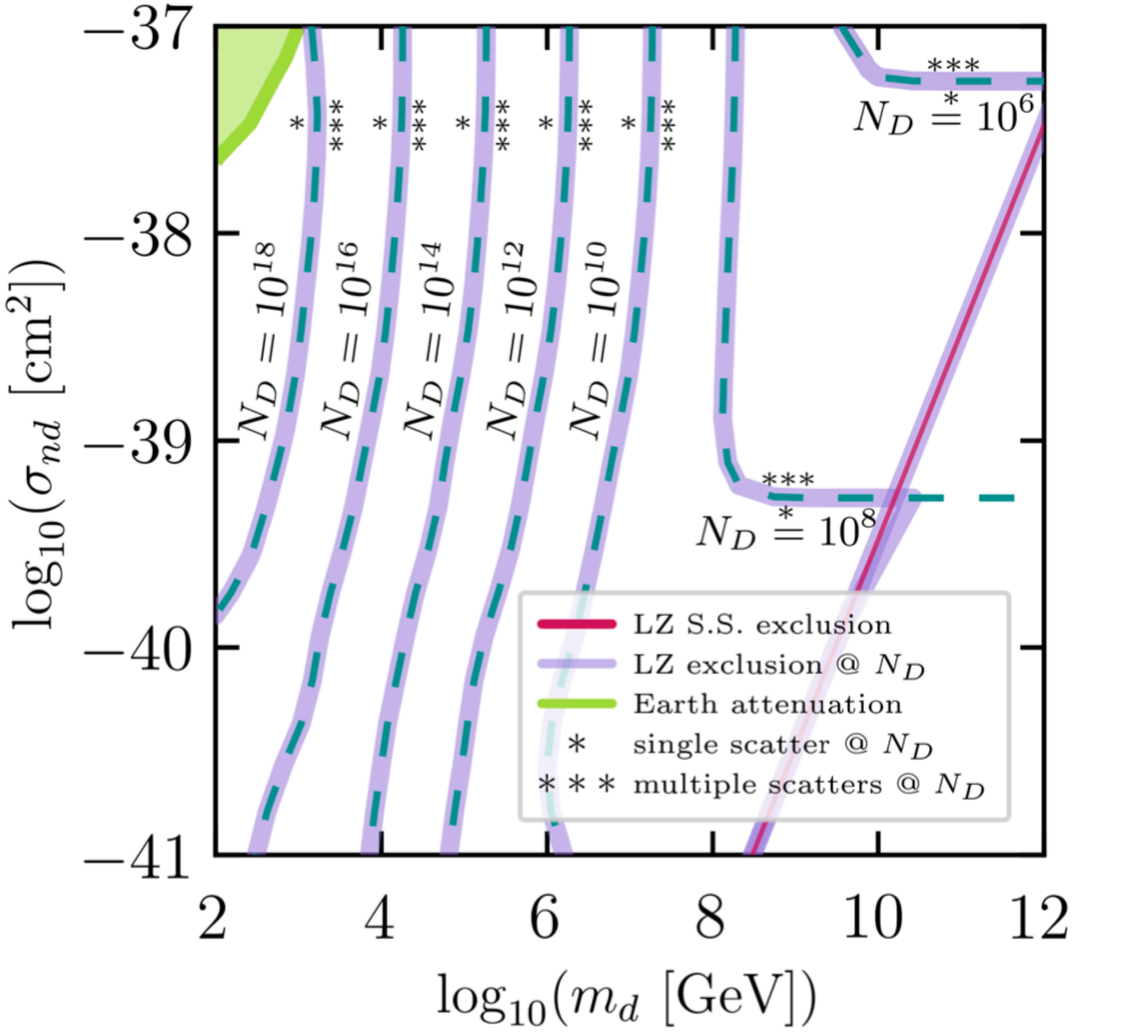
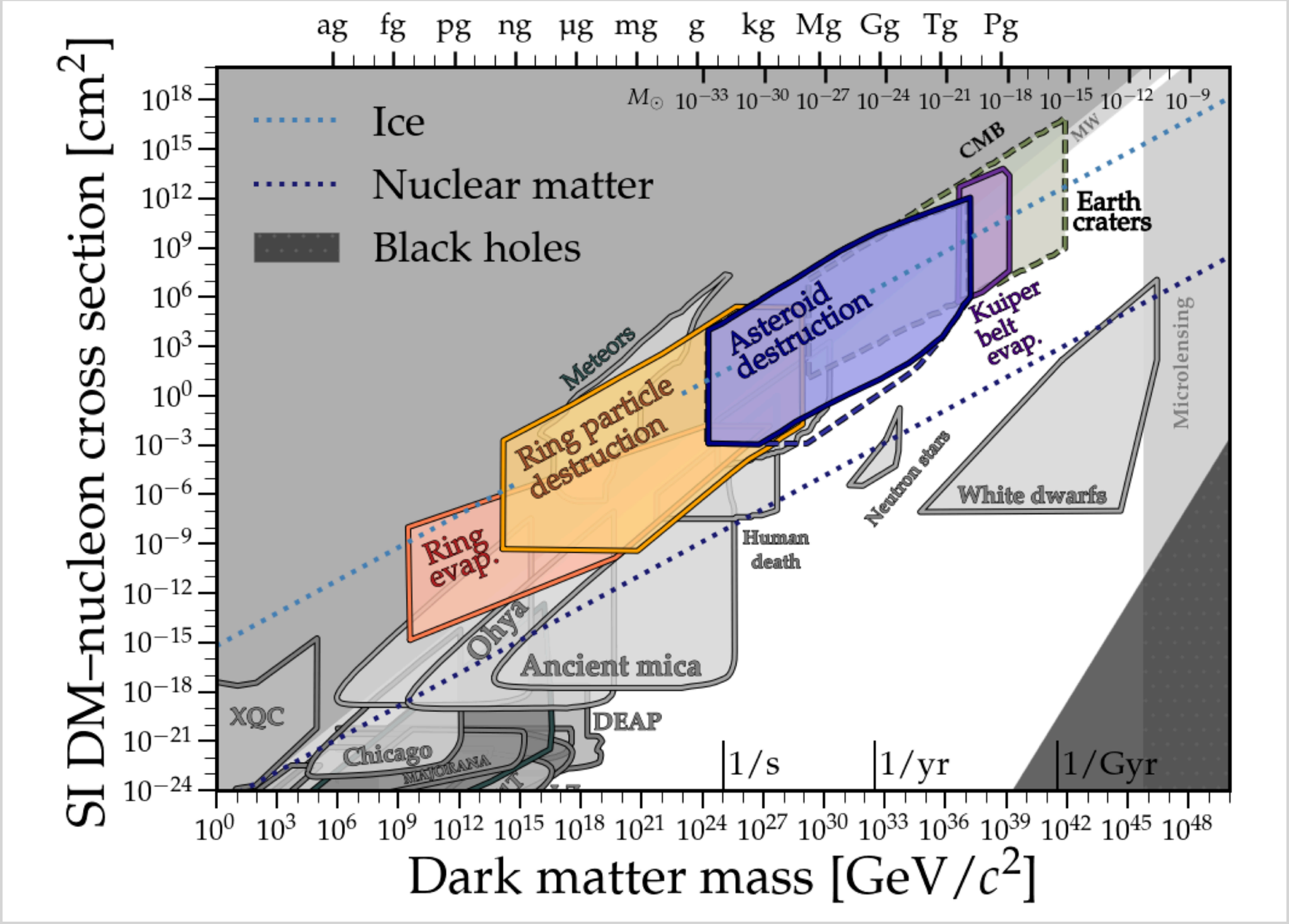


Conclusions

- Understanding dark compact objects is an important part of understanding the dark universe
- The heavy side of dark matter parameter space is theoretically and phenomenologically rich and diverse
- Great opportunity to collaborate with those working on star and galaxy formation, direct detection experiments, and gravitational wave and lensing searches

Thank you!


ag fg pg ng μg mg g kg Mg Gg Tg Pg
$M_\odot$ 10^{-33} 10^{-30} 10^{-27} 10^{-24} 10^{-21} 10^{-18} 10^{-15} 10^{-12} 10^{-9}
Ice
Nuclear matter
Black holes
CMB
MW
Earth craters
Asteroid destruction
Kuiper belt evap.
Meteors
Ring particle destruction
Ring evap.
Microlensing
Neutron stars
White dwarfs
Human death
Ohya
Ancient mica
XQC
DEAP
Chicago
MAJORANA
1/s
1/yr
1/Gyr
SI DM–nucleon cross section [cm^2]
Dark matter mass [GeV/c^2]

Where we go from here

- Improving predictions of dark compact object populations
- Predict and search for waveforms from dark compact object inspirals
- Predict and search for contributions of dark compact object inspirals to the gravitational wave background
- Understand impact of dark radiation emitted during collapse on cosmology
- More ideas welcome!