EXOTIC COMPACT OBJECTS IN A DISSIPATIVE DARK SECTOR

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Collaboration with D. Egana-Ugrinovic, R. Essig and C. Kouvaris

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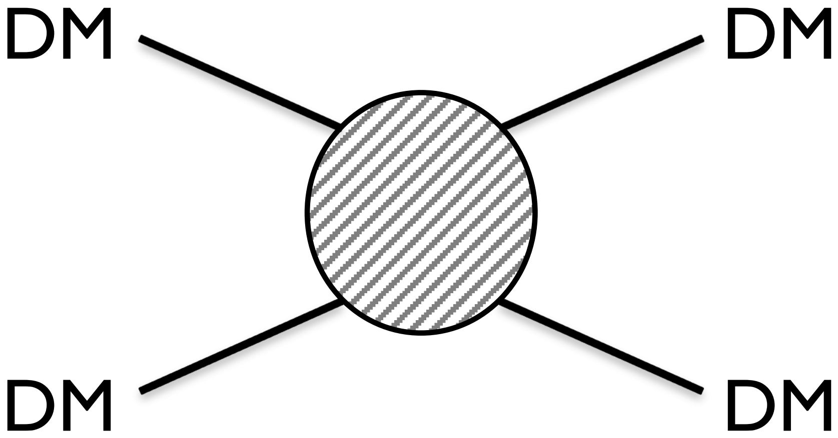
Q: Can we probe the particle nature of DM if it interacts with us only gravitationally?

A: Yes !



- By probing dark sector interactions from astronomical small-scale structures
- Dark sector interactions may lead to formation of dark galaxies and dark stars
- Dark stars are called "Exotic Compact Objects"
- Properties of such objects (e.g. size and mass) give information of particle nature

Goal of this Talk

- Introduce a simple dark sector model

- Study the complete history of structure formation including
  - Evolution of cosmological perturbations
  - Formation of exotic compact objects

- Provide a map between astrophysical properties and particle physics parameters

Conditions for the Model

- Self-interaction
  - Otherwise behaves like CDM
  - Sub-dominant (We assume 1% of total DM)

- DM does not annihilate
  - Want final compact objects to be stable
  - e.g. Asymmetry, Bound states, …

- Cooling
  - Necessary for "fragmentation"

Mimic Baryons?

- Of course, baryons satisfy all the conditions
- Can we think about a model like baryons?
- Yes, but baryons are too complicated!
- As a starting point, we consider the simplest DS model

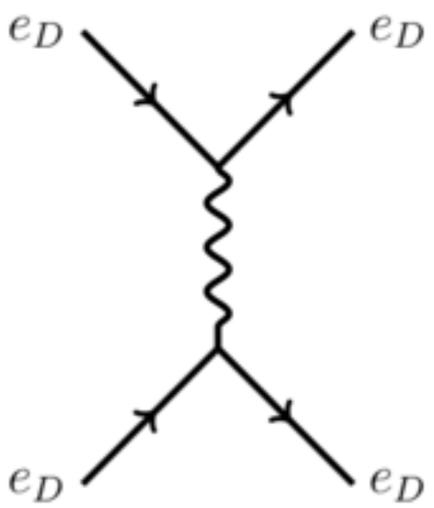
The Simplified Model in this Work

$$i\,\bar{\Psi}_{e_D}\gamma^\mu D_\mu \Psi_{e_D} - m_{e_D}\bar{\Psi}_{e_D}\Psi_{e_D} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + m_{\gamma_D}^2 A_\mu A^\mu$$

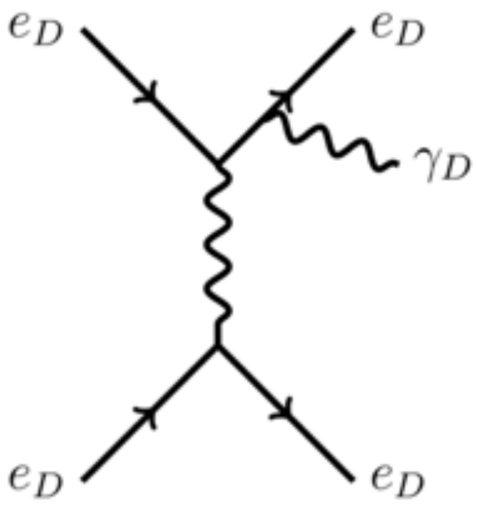
- Contains only two particles
  - Dark electron e_D^- : composes matter
  - Dark photon γ_D : mediates interactions
- Only 3 model parameters: $m_{e_D}, m_{\gamma_D}, \alpha_D$

Satisfies all the conditions!

- Self-interaction

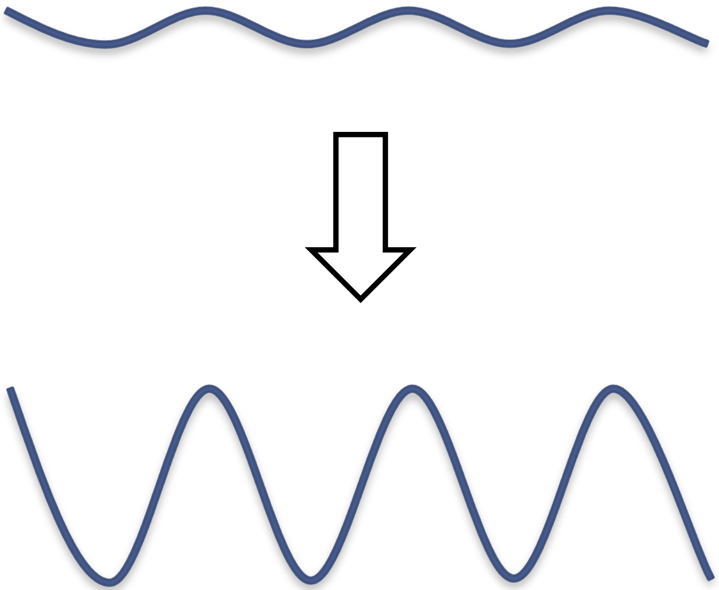


- Cooling via bremsstrahlung



- Assume charge asymmetry Petraki et al, 1403.1077
  - Negligible dark positron abundance
  - Final objects are stable

Linear Perturbation Growth

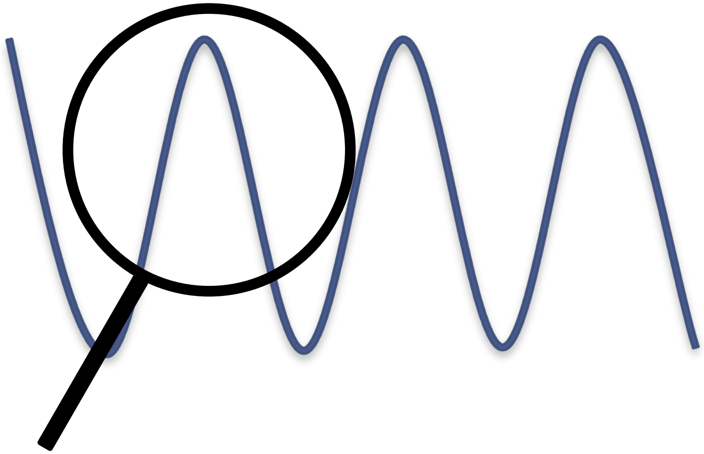


- Perturbations grow with time
- Can be analyzed with linear perturbation theory for

$$\delta \equiv \frac{\delta\rho}{\rho} \ll 1$$

$$\partial_t^2 \, \delta_{\mathbf{k}}(t) + 2H\partial_t \, \delta_{\mathbf{k}}(t) + \left[c_s^2 k^2/a^2 - 4\pi G\rho_0\right]\delta_{\mathbf{k}} = 0$$

Non-linear Regime



$$\delta_{\mathrm{ta}} \approx 1.686$$

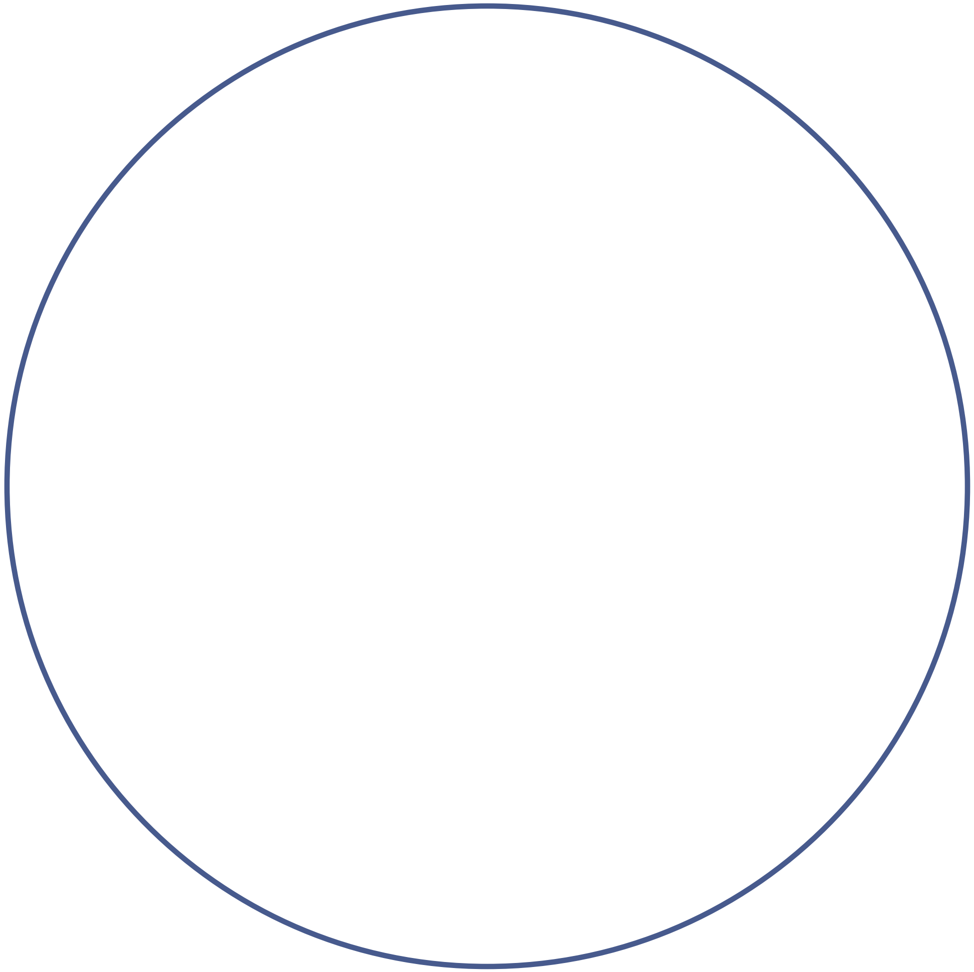
Calculated in the linear theory. See Mo, van den Bosch, and White 2010

- Gravitational pull overcomes Hubble expansion: perturbations “turn-around”
- Can analyze individual mass clumps with **Jeans Mass**

Jeans Mass M_J

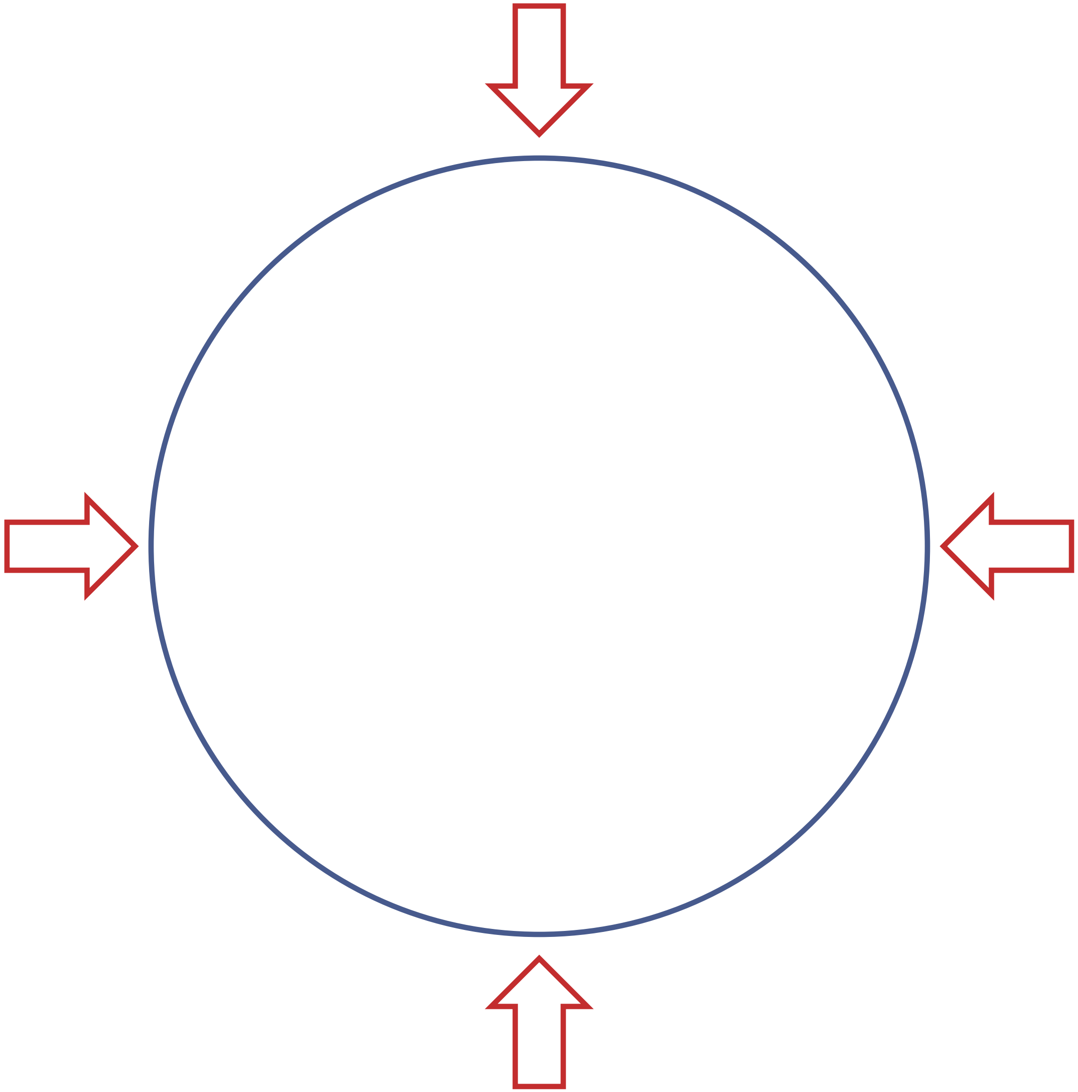
- Maximum mass of gas that pressure can support
- If $M > M_J$, a mass clump collapses
- $M_J = \frac{\pi}{6} c_s^3 \left(\frac{\pi}{G}\right)^{3/2} \left(\frac{1}{\rho}\right)^{1/2}$
- $c_s = \sqrt{\frac{T_e}{m_e} + \frac{4\pi\alpha n_e}{m_e^2 m_\gamma^2}}$

Schematic of Non-linear Regime



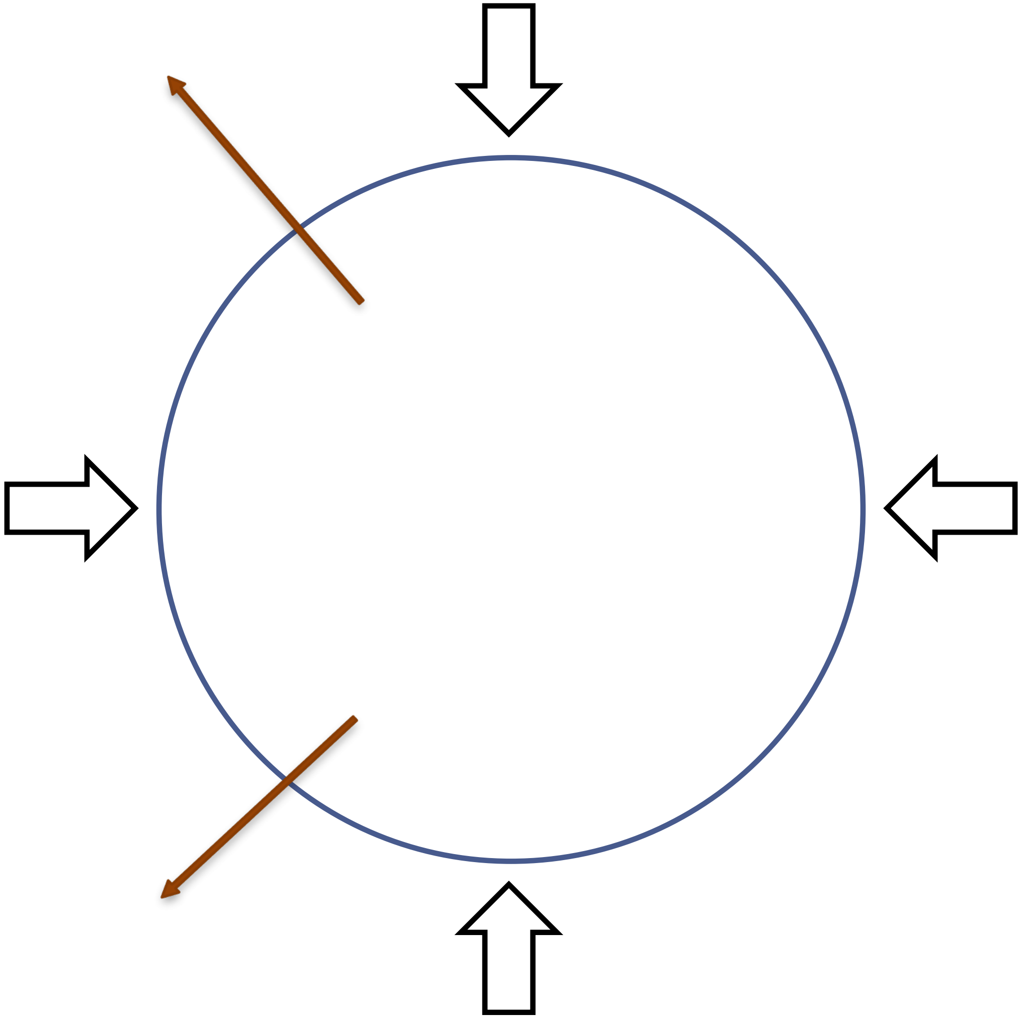
- A big mass perturbation after turnaround
- Suppose $M > M_J$
- Then it collapses

① Adiabatic Collapse



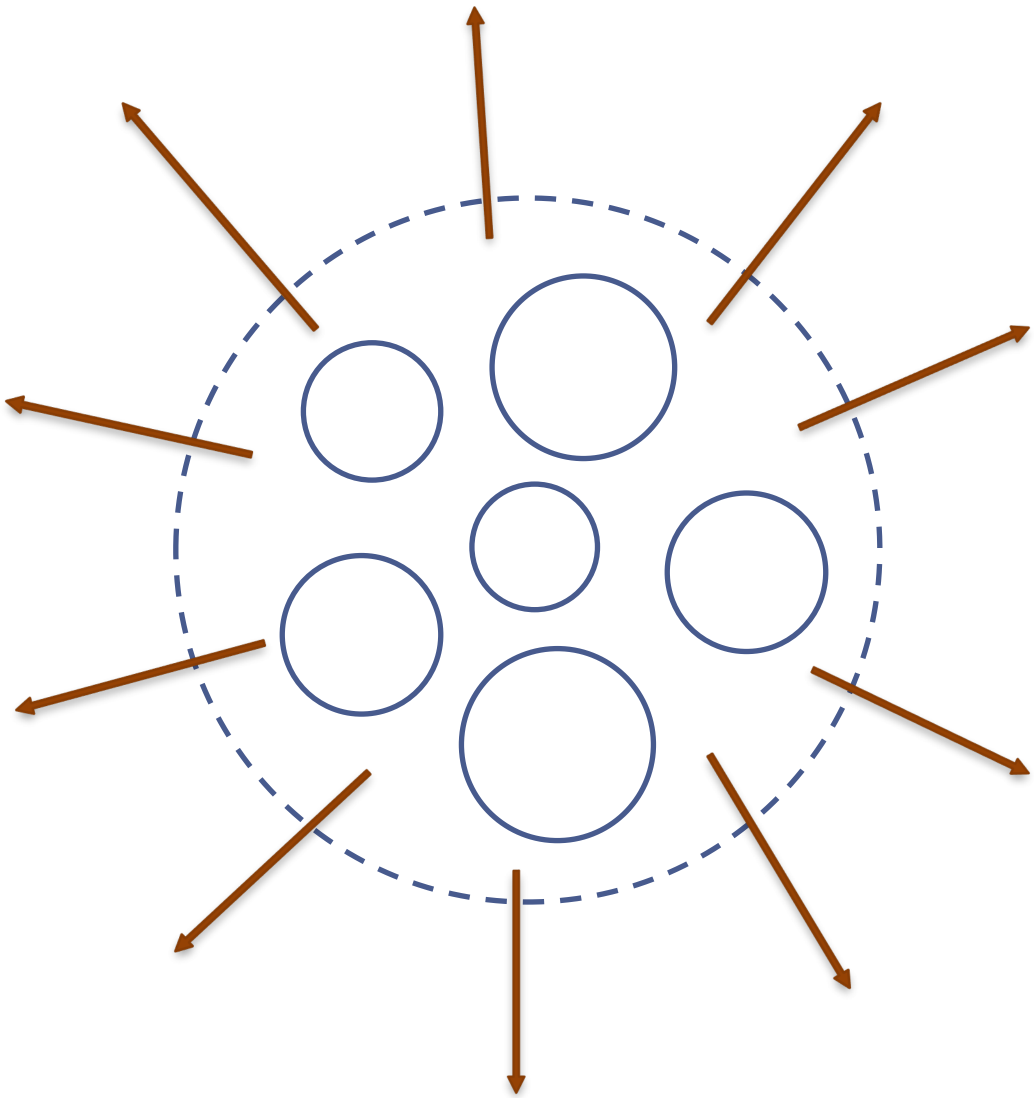
- Temperature increases
- $M_J \propto \sqrt{\frac{T^3}{\rho}}$ increases
- Adiabatic collapse stops at $M_J = M$

② Virialized Collapse



- If there's cooling, it keeps collapsing
- $M_J = M$ during the collapse
- Temperature increases (slower than adiabatic)

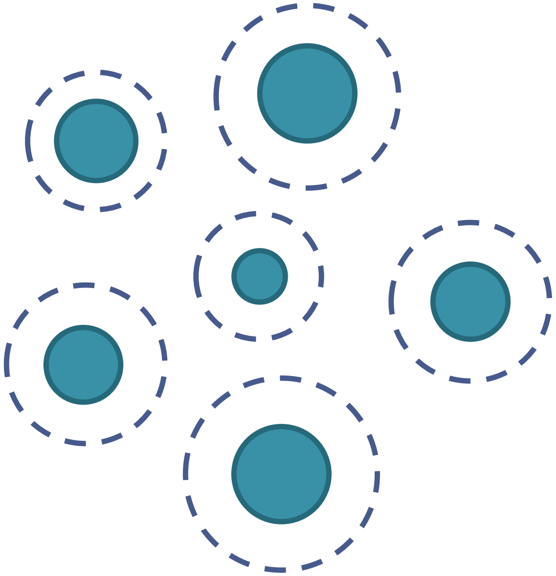
③ Fragmentation



- Cooling becomes efficient as number density increases

- Temperature decreases, so $M_J \propto \sqrt{\frac{T^3}{\rho}}$ decreases

④ Compact Objects Formation



- Cooling stops as optical depth becomes large

- Fragmentation stops

Master Equation

$$dE = -PdV - \Lambda dt$$

Λ is cooling rate

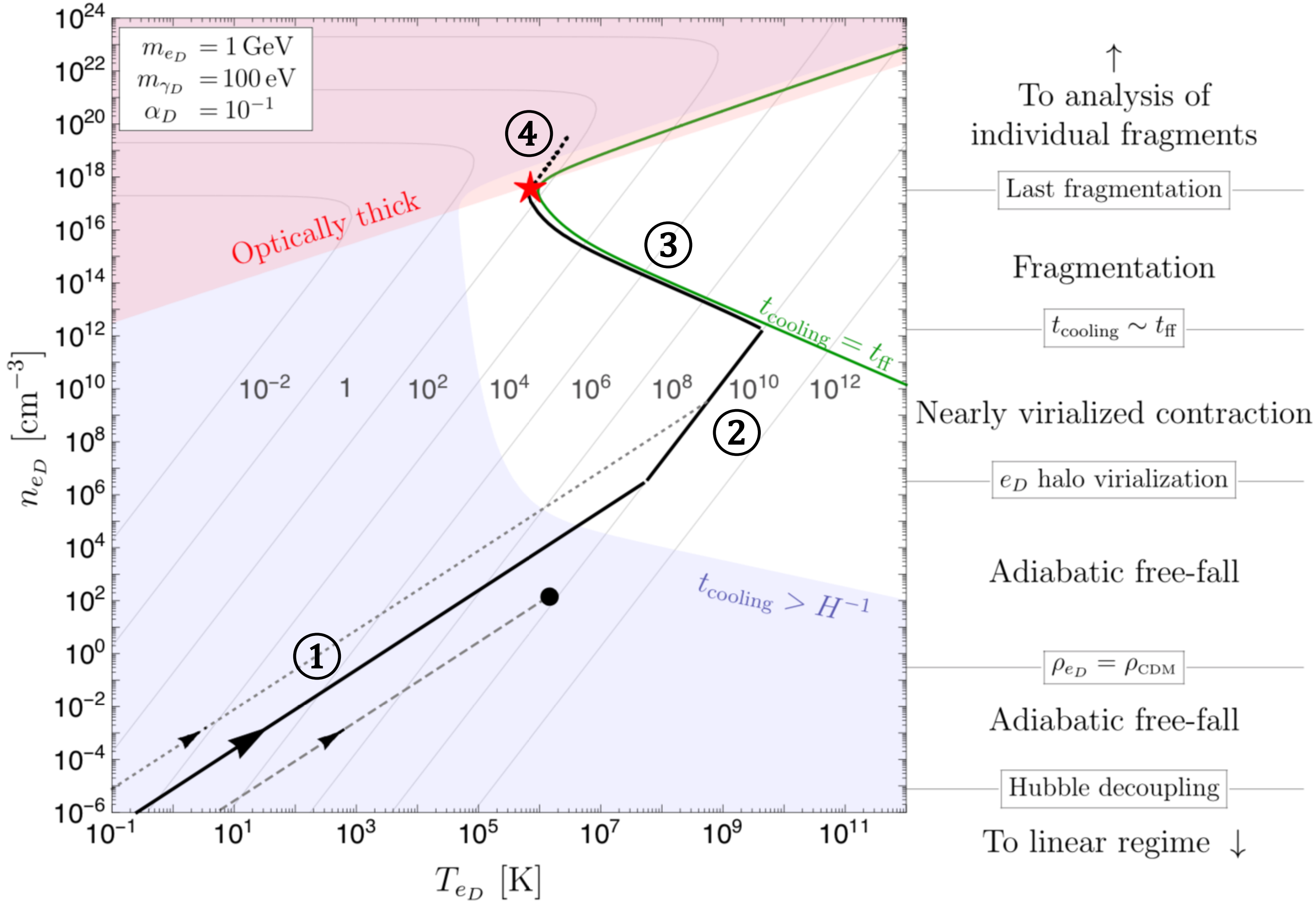
$$\Downarrow$$

$$\frac{d\log T}{d\log\rho} = \frac{2}{3}\frac{m}{\rho}\frac{P}{T} - \frac{2t_{\mathrm{ff}}}{t_{\mathrm{cooling}}}$$

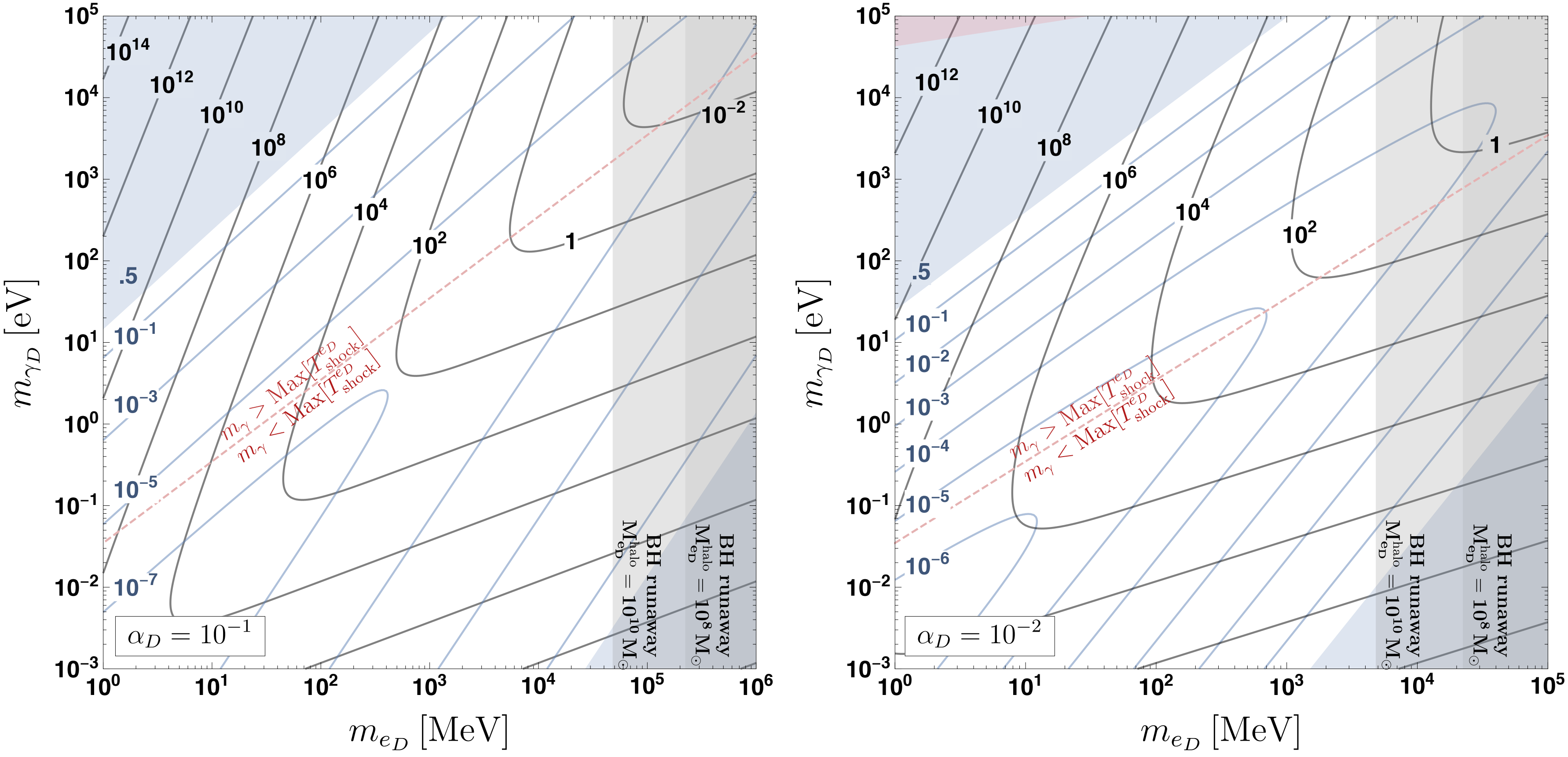
Low, Linden-Bell 1976

- Mass perturbation is parameterized with ρ and T

Evolution Trajectory ($M = 10^{10} M_\odot$)



Results According to Model Parameters



- Black lines : Minimum M_J in $M_\odot$ after fragmentation
- Blue lines : Corresponding compactness ($C = GM/R$)

Fragmentation Analysis

- Our analysis can be used for any dark sector model
- Even for baryons, it roughly estimates the typical mass of stars in a galaxy
- Studying only stability of compact objects (as done by many people in the literature) leads to unrealistic conclusions

Conclusions

- We described the complete history of structure formation of a simple dissipative dark sector model.

- We provided a map between astronomical properties and particle physics parameters.