FORMATION OF DARK GALAXIES

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This talk is carbon neutral. www.cooleffect.org

A pessimistic scenario:

Dark matter does not have any detectable non-gravitational interactions with the SM

Liu Bolin

If the dark sector interacts only gravitationally with us…

…what can we learn from its particle nature?

A COMPLETELY DARK, DARK SECTOR

- Progress can be made based uniquely in *astronomical and cosmological observations.*
- High precision astronomical observatories (LSST, GAIA,LIGO, etc.) will test the behavior of DM on small scales.

How do we turn this experimental program into a dark matter theory program?

SM FORMS STARS DUE TO DISSIPATION

- SM forms compact objects since:
  1. It has self-interactions
  2. The baryonic gas can dissipate energy (can *cool*)
- Properties of these objects (how did they form, sizes, masses) gives information on *particle interactions.*

ASTRONOMICAL PROPERTIES FIXED BY LAGRANGIAN PARAMETERS

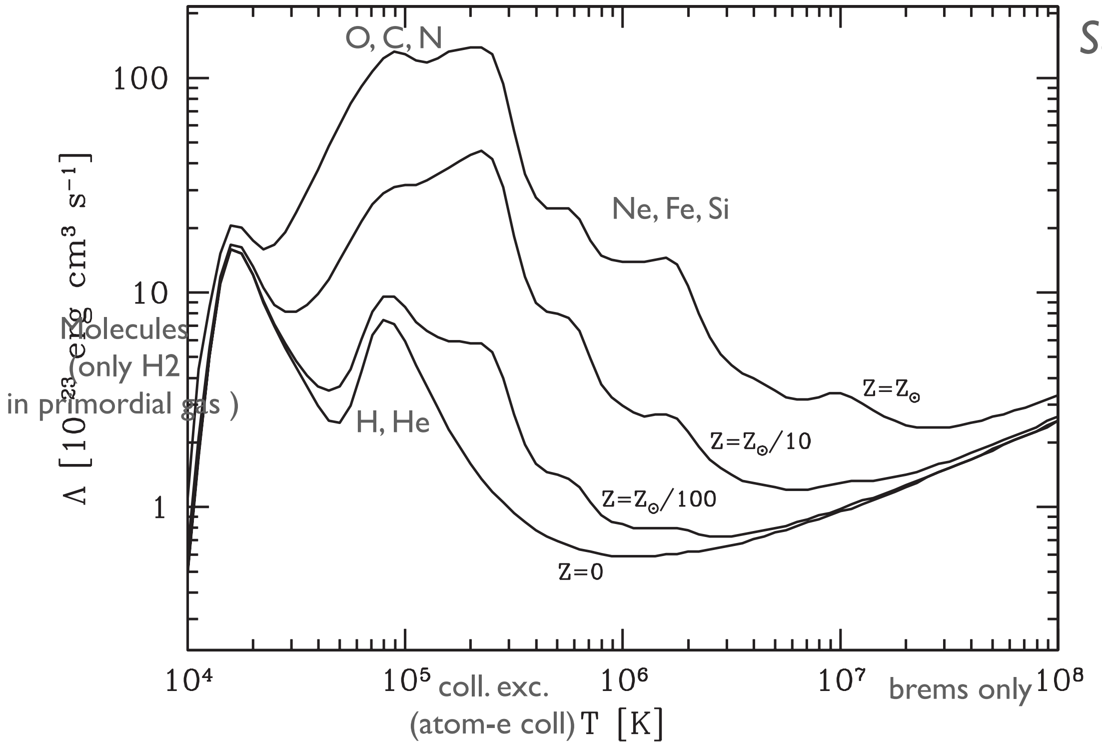
- Example: Chandrasekhar limit for White dwarf

$$M_C \sim \frac{M_{\rm Pl}^3}{m_p^2}$$

In principle, it is possible to obtain a <u>map</u> between astronomical properties and lagrangian parameters

CAN DM FORM GALAXIES AND COMPACT OBJECTS?

- Halo and star formation is a complex problem in the SM. Chemistry, multiple cooling rates…
- Example: the SM cooling rate functions



Sutherland & Dopita, ApJS, 88, 253

Bremsstrahlung, collisional excitation, ionization, recombination… All dependent on metallicity…

OUTLINE

A complete history of structure formation in a dissipative dark-sector

1. Present the simplest *dark-sector model* that has *cooling and self-interactions*

2. Discuss the initial, *linear evolution* of dark-sector perturbations starting from the primordial power spectrum.

3. Continue into the non-linear regime, and discuss galactic evolution and the *formation of exotic compact objects*, or "dark stars".

Simplified Models
for Dark-Sector Astronomy

The Standard Model

Our talk

A MODEL WITH ONLY TWO PARTICLES

- Dark-electron dark-photon model

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

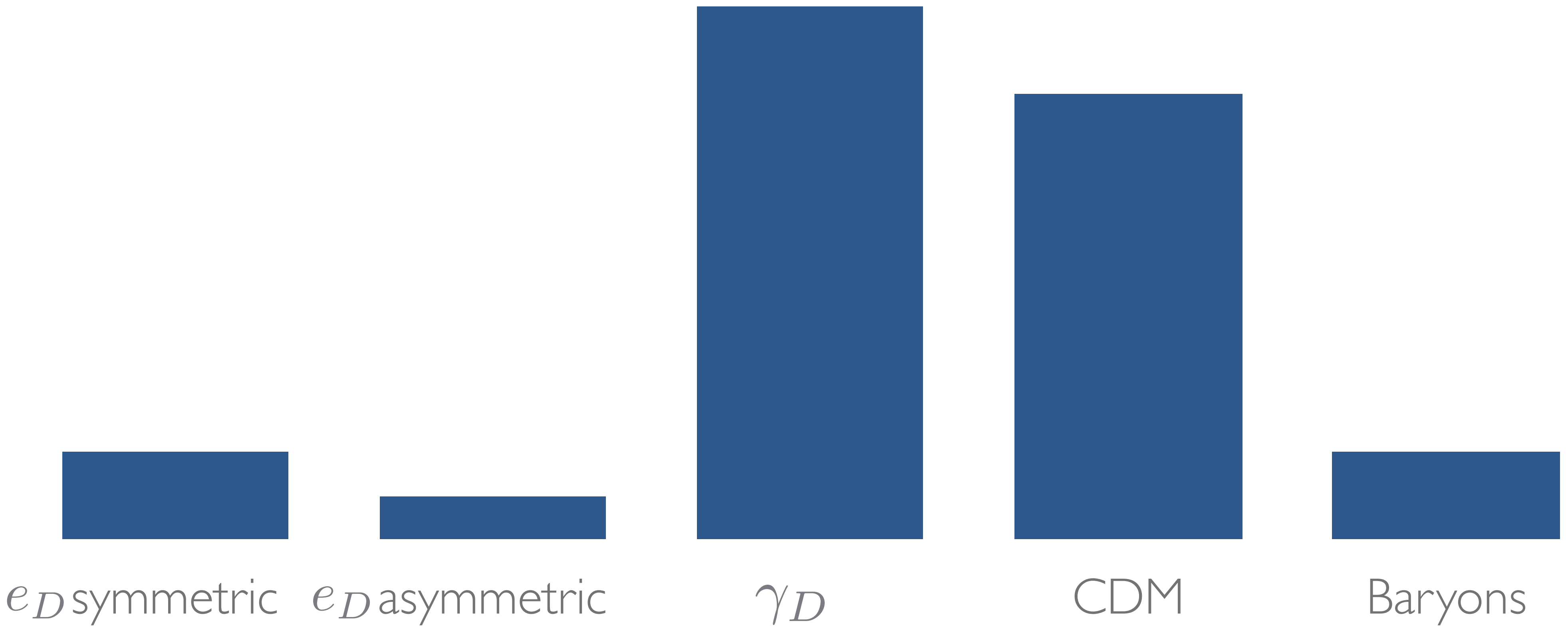
$$e_D^-, e_D^+, \gamma_D$$

$$m_{e_D}\ ,\ m_{\gamma_D}\ ,\ \alpha_D$$

This model has only three parameters

COSMOLOGICAL ABUNDANCES

- In general, all species may have a significant cosmological abundance.



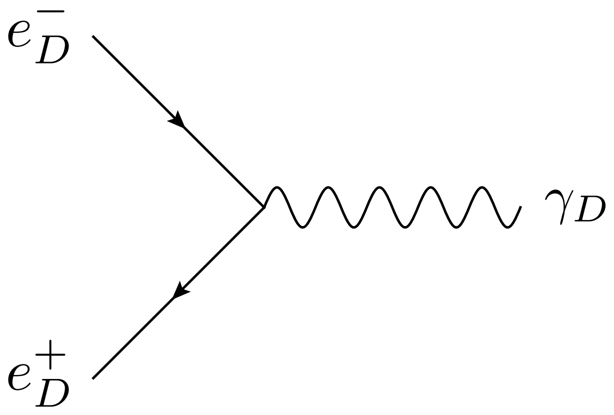
- Dark sector is asymmetric:

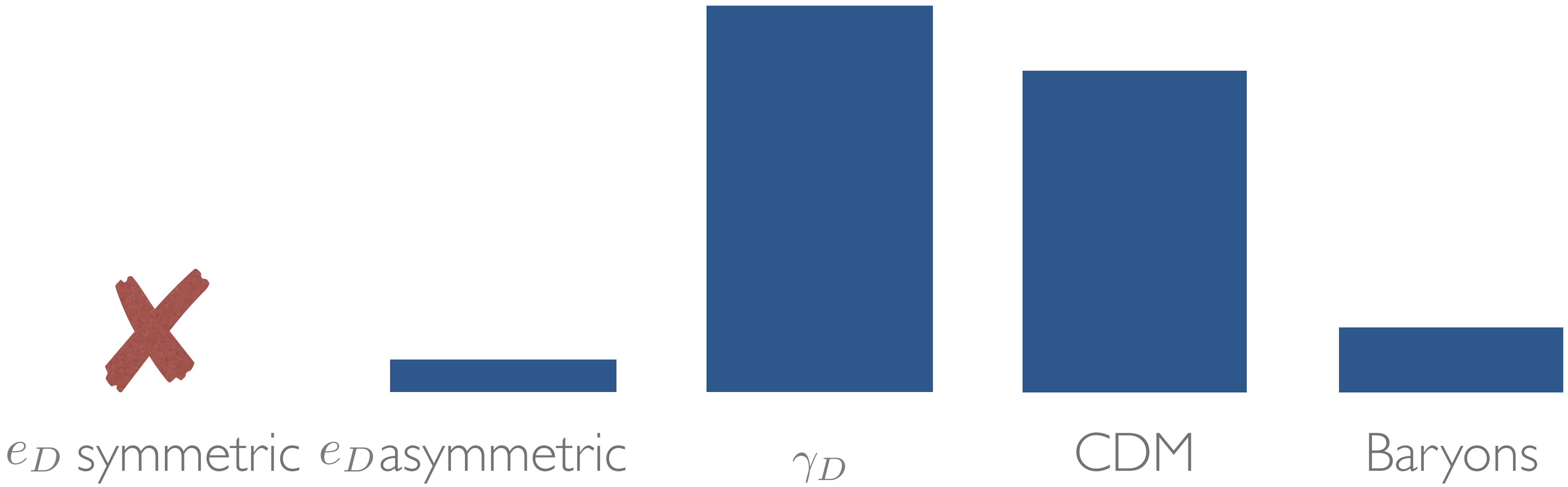
1. No annihilations within a compact object.
2. Avoids complications of bound states.

How to generate the asymmetry?
Petraki, Pearce, Kusenko
1403.1077

SYMMETRIC PART DEPLETED BY ANNIHILATIONS

- The symmetric part is depleted by annihilations





$$\alpha_D \geq 4.6 \times 10^{-7} \left[\frac{m_{e_D}}{1\,\mathrm{MeV}}\right] \left[\frac{10^{-2}}{f}\right]^{1/2} \left[\frac{T_{e_D}|_{e_D\,\mathrm{dec}}}{T_{\mathrm{SM}}|_{e_D\,\mathrm{dec}}}\right]^{1/2}$$

Condition for efficient depletion of symmetric part

DARK SECTOR COLD ⟶ FEW DARK PHOTONS

- Dark photons may lead to overclosure or large $\Delta N_{\rm eff}$

$$\rho^{\gamma_D} \sim m_{\gamma_D} T^3_{\gamma_D}$$

Dark photon matter density

$$T_{\gamma_D}|_{\gamma_D\,\rm dec} \leq 0.2 \left[\frac{g_{*S}|_{\gamma_D\,\rm dec}}{10}\right]^{1/3} \left[\frac{1\,\rm keV}{m_{\gamma_D}}\right]^{1/3} T_{\rm SM}|_{\gamma_D\,\rm dec}$$

Overclosure bound

$$T_{\gamma_D}|_{\rm BBN} \leq 0.5\, T_{\rm SM}|_{\rm BBN}$$

$\Delta N_{\rm eff}$

(see also DAO, Cyr-Racyne et.al.1310.3278)

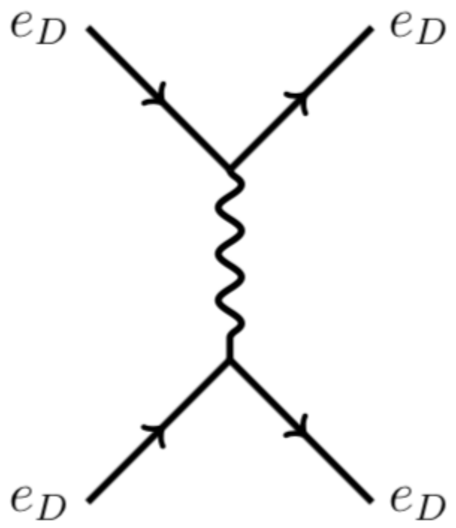
MATTER BUDGET OF OUR MODEL

- Asymmetric part is a small component of matter: no bounds form bullet cluster/halo shapes

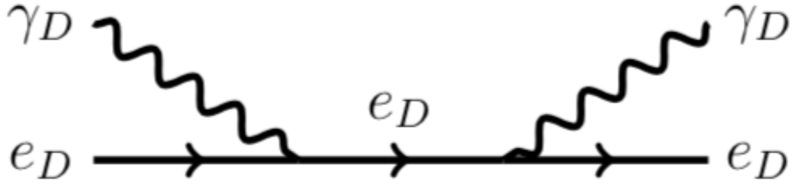
$$f \equiv \frac{\rho_0^{e_D}}{\rho_0^{\mathrm{DM}}} \leq 10\%$$

Katz et. al. 1303.1521

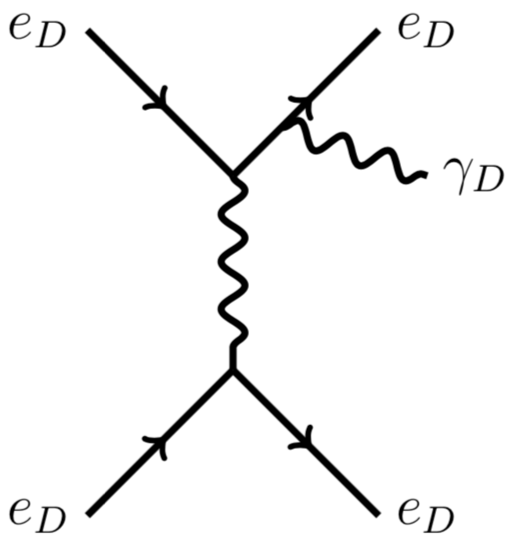
ONLY THREE PROCESSES MATTER



Dark-electron self-interactions



Compton scattering

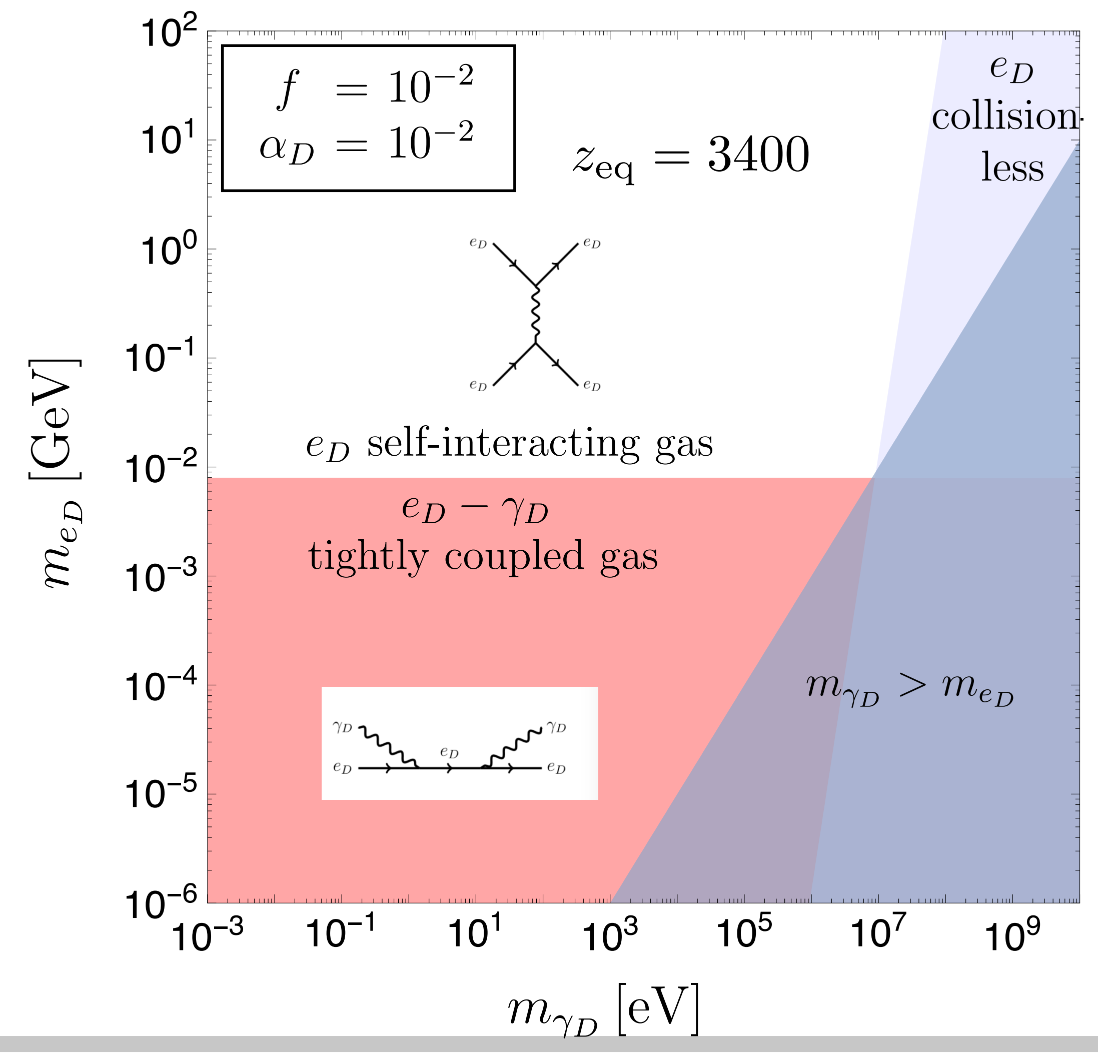


Bremsstrahlung

DARK ELECTRON THERMODYNAMICS

- Even within this simple model there are three thermodynamic regimes

$$\ell^{\rm mfp} \text{ vs. } L_{\rm MW} \quad , \quad \ell^{\rm mfp} = 1/(n\sigma)$$



$$\sigma_C \propto \frac{\alpha^2}{m_{e_D}^2}$$

$$\sigma_M \propto \alpha^2 \frac{m_{e_D}^2}{m_{\gamma_D}^4}$$

Objective

Study the formation of dark-electron galaxies
and their substructure

We will concentrate on the formation
and evolution of the dark electron galaxy
within our Milky Way

STRUCTURE FORMATION HAS TWO MAIN STAGES

1. Linear growth of matter overdensities

$$\delta = \frac{\delta\rho}{\rho} < 1$$

2. Non-linear evolution of the resulting (dark) matter clumps

LINEAR GROWTH OF PERTURBATIONS

- Initial conditions: *Harrison-Zeldovich* power spectrum

$$\langle \delta_{\mathbf{k}} \delta^*_{\mathbf{k}} \rangle \equiv (2\pi)^3 P(k) = Ak$$

- Linear evolution of perturbations

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

$$c_s = \sqrt{\frac{T_e}{m_e} + \frac{4\pi\alpha n_e}{m_e^2 m_\gamma^2}}$$

Kouvaris et.al. 1507.00959

Matter overdensities grow only on scales larger than the Jeans length

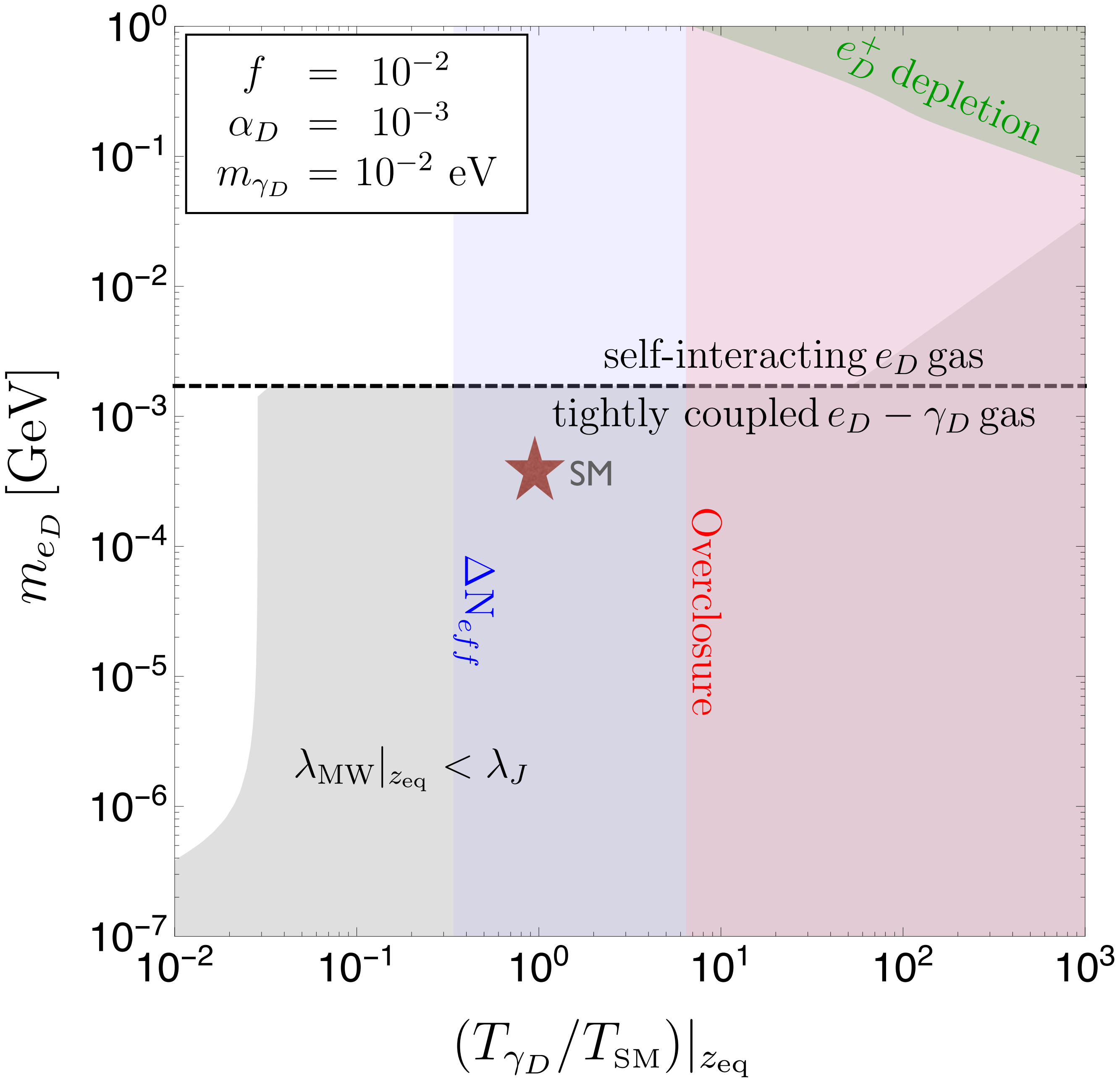
JEANS CRITERION DECIDES WHICH PERTURBATIONS GROW

- The Jeans criterion is

$$M > m_J = \frac{\pi}{6} c_s^3 \left(\frac{\pi}{\rho_0(z) G} \right)^{3/2} \rho_{e_D},$$

$$\Rightarrow \quad \frac{\delta\rho}{\rho} \propto a$$

ONLY IN PARTS OF PARAMETER SPACE A MW CAN BE FORMED



$$\sigma_C \propto \frac{\alpha^2}{m_{e_D}^2}$$

White: regions of parameter space where a Milky Way-sized perturbation may grow after equality

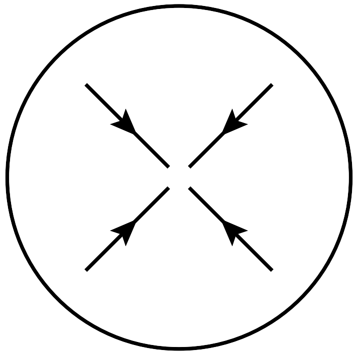
GALAXY GOES NON-LINEAR AT $z \approx 2$

- At some point, perturbations become non-linear

$$\frac{\delta\rho}{\rho} \sim 1$$

- Gravitational pull overcomes Hubble expansion: perturbations "turn-around"

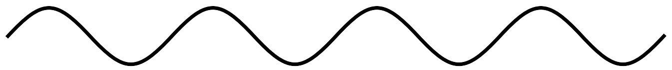
$$t_{\rm ff} \equiv \left(\frac{1}{16\pi G\rho}\right)^{1/2} \qquad t_{\rm ff} \sim H^{-1}$$



- The galaxy's turnaround redshift can be estimated by

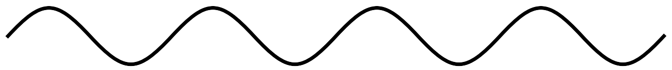
$$\frac{k_{\rm MW}^3}{2\pi^2} P(k_{\rm MW}, z_{\rm ta}) = 1 \quad \rightarrow \quad z_{\rm ta} \approx 2$$

Summary of linear perturbation growth



Primordial regions of under- and over-densities

Summary of linear perturbation growth



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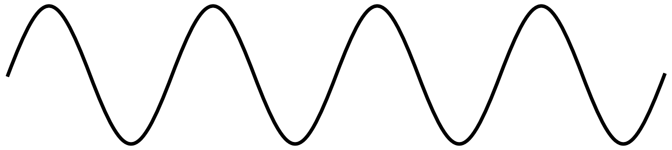
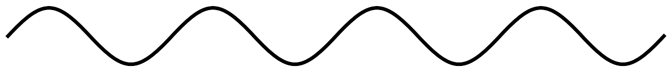


Density contrast grows as $\frac{\delta\rho}{\rho} \sim a \left.\frac{\delta\rho}{\rho}\right|_0$

Summary of linear perturbation growth



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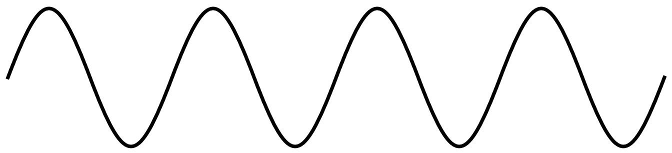

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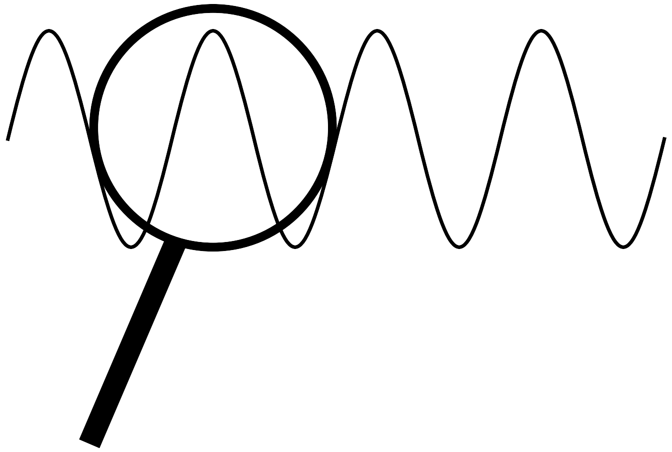
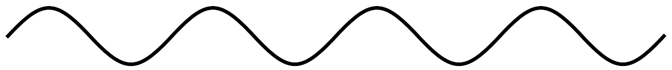


$\frac{\delta\rho}{\rho} \sim 1$ Nonlinearities and *turnaround*

$$t_{\rm ff} \equiv \left(\frac{1}{16\pi G\rho}\right)^{1/2} \qquad t_{\rm ff} \sim H^{-1}$$

Summary of linear perturbation growth



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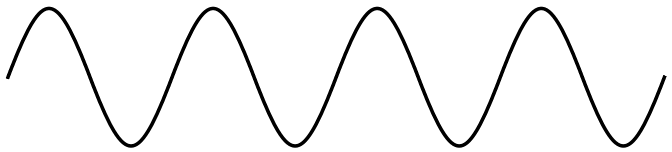

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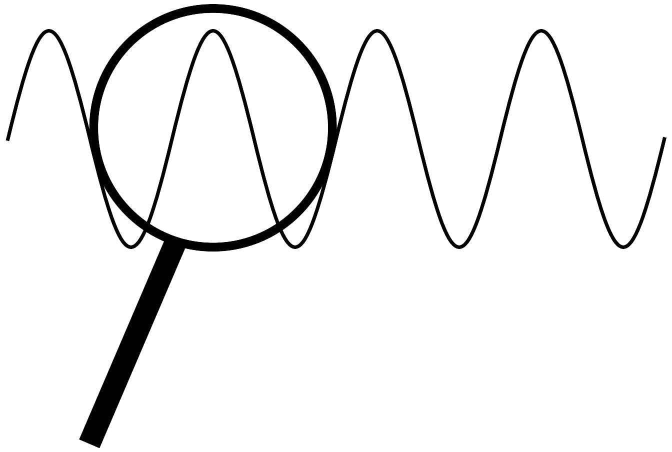

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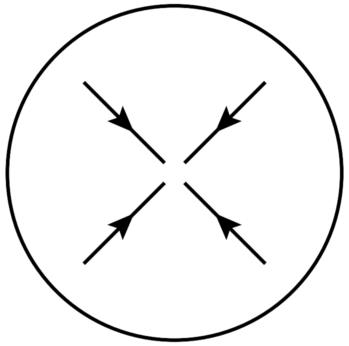


Nonlinear regime: self-gravitating gas decoupled from Hubble flow

STRUCTURE FORMATION HAS TWO MAIN STAGES

1. Linear growth of matter overdensities

2. Non-linear evolution of the resulting (dark) matter clumps

$$\delta = \frac{\delta\rho}{\rho} \gg 1$$

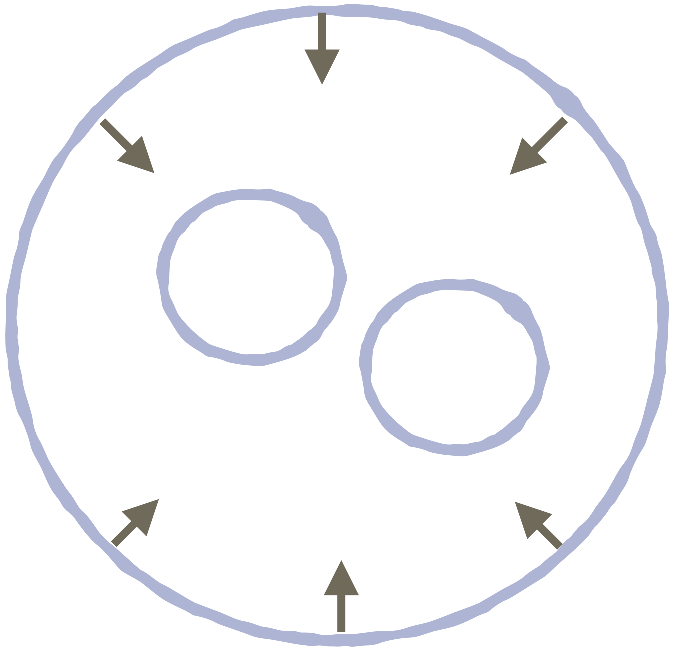
ASTRONOMY BEFORE BIG COMPUTERS

Jeans Mass:
max mass of gas that
pressure can support

$$M > m_J = \frac{\pi}{6} c_s^3 \left(\frac{\pi}{\rho_0(z) G} \right)^{3/2} \rho_{e_D},$$

for collapse to happen

Fragmentation:
Jeans mass
decreases as mother
halo collapses



Halo fragmentation is the origin of stars

Low, Linden-Bell 1976
Rees, Ostriker, 1977
Silk, 1977

JEANS MASS EVOLUTION IS FIXED BY ENERGY CONSERVATION

- First law of thermodynamics

$$dE_{\text{thermal}} = -PdV - \Lambda_{\text{cooling}}\, dt \qquad \left(\Lambda_{\text{BS}} = \frac{32\alpha_D^3 \rho_{e_D} T_{e_D}}{\sqrt{\pi} m_{e_D}^4} \sqrt{\frac{T_{e_D}}{m_{e_D}}} e^{-m_{\gamma_D}/T_{e_D}}\right)$$

$$\Big\downarrow$$

$$\frac{d\log T_{e_D}}{d\log \rho_{e_D}} = \frac{2}{3}\frac{m_{e_D} P_{e_D}}{\rho_{e_D} T_{e_D}} - 2\,\frac{t_{\text{collapse}}}{t_{\text{cooling}}}$$

$$t_{\text{cooling}} \equiv \frac{3T_{e_D}}{m}\frac{1}{\Lambda_{\text{cooling}}} \quad , \quad t_{\text{collapse}} \equiv \left(\frac{d\log \rho_{e_D}}{dt}\right)^{-1} \quad .$$

Specifies a contour in the density-temperature plane as the galaxy collapses

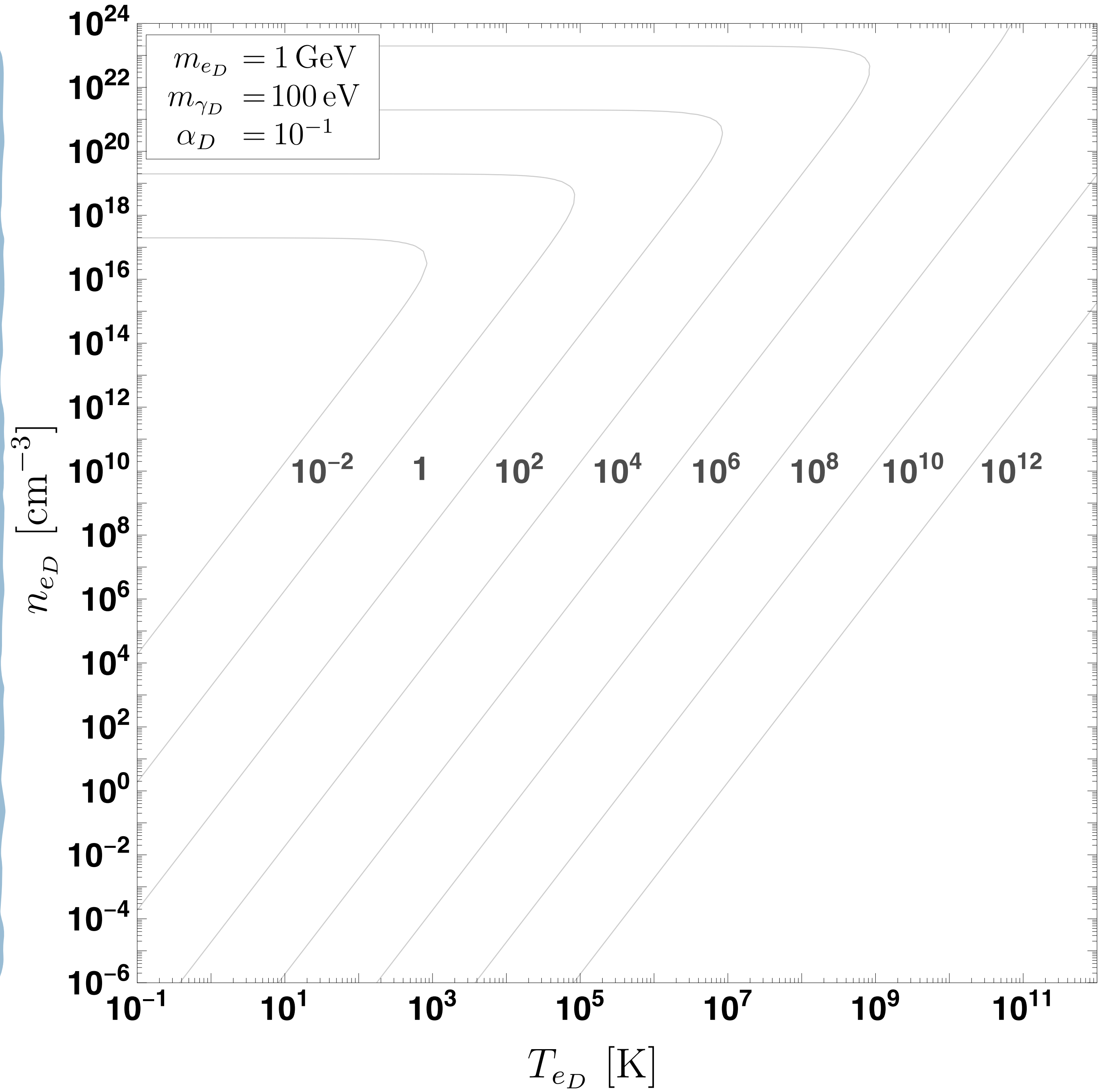
THE HISTORY OF A GALAXY: SETUP

We will now follow the evolution of a

$10^{10} M_\odot$

dark electron halo

(1% of our Milky Way)



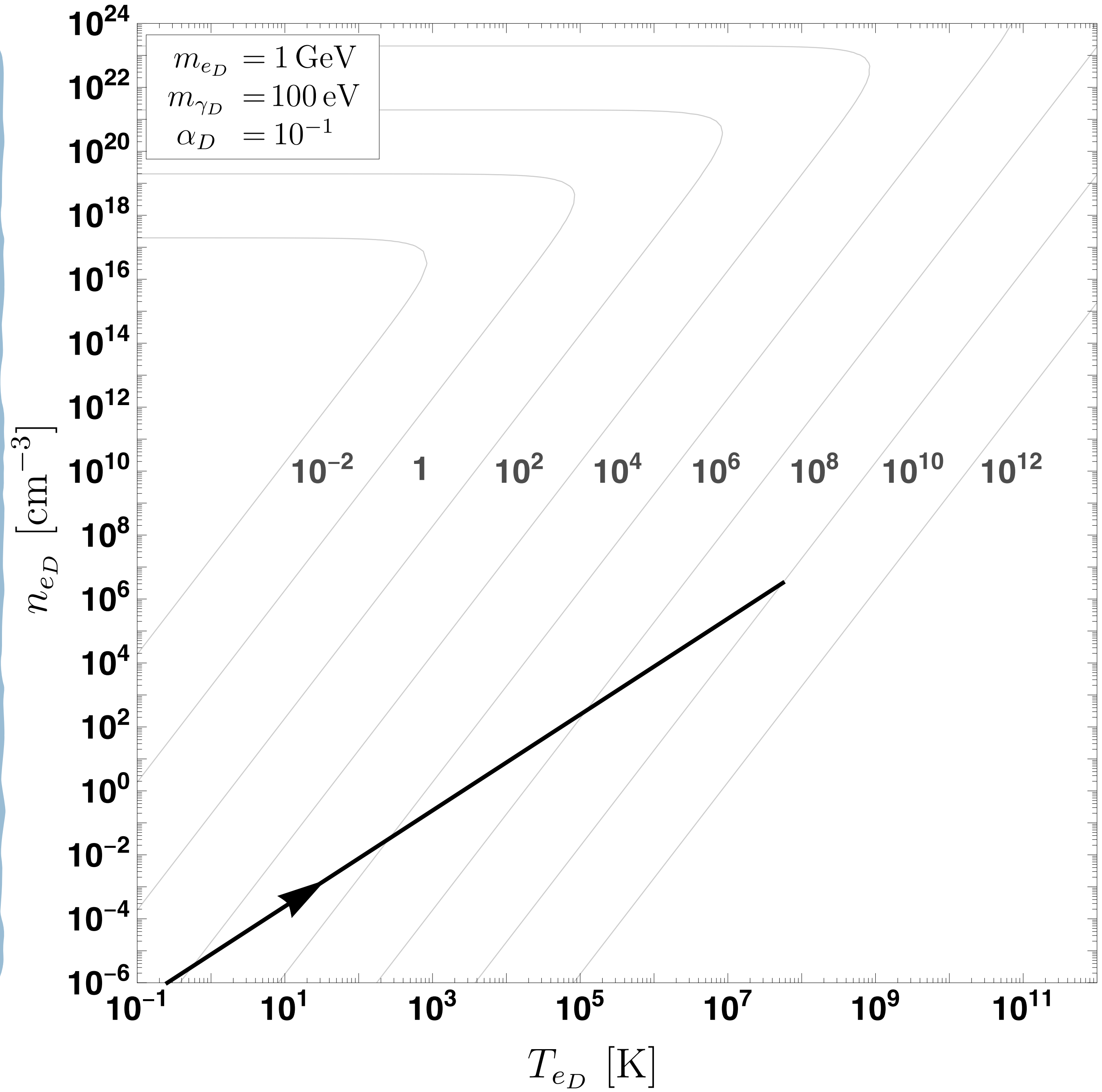
THE HISTORY OF A GALAXY: FREE-FALL

Free-fall and heating

$$\frac{d\log T}{d\log\rho} = \frac{2}{3}$$

Free-fall time

$$t_{\mathrm{ff}} = \left(\frac{3\pi}{32 G m_e n_e}\right)^{1/2}$$



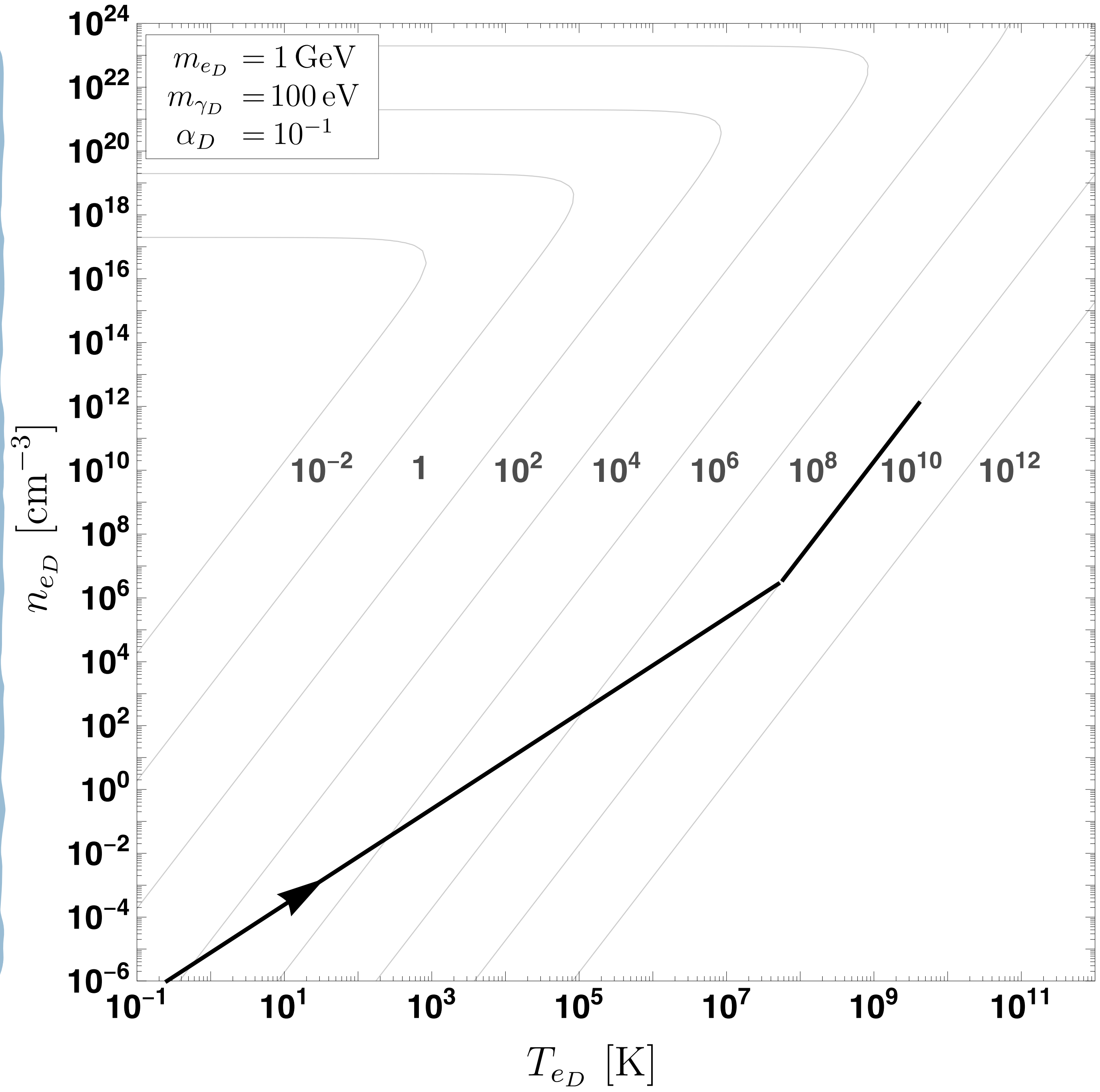
THE HISTORY OF A GALAXY: VIRIALIZATION

Virialization

$$\frac{d\log T}{d\log \rho} = \frac{1}{3}$$

Cooling time

$$t_{\text{cooling}} \sim \frac{m_e^2}{\alpha_D^3 n_e}\sqrt{\frac{m_e}{T_e}}\,e^{m_{\gamma_D}/T_e}$$



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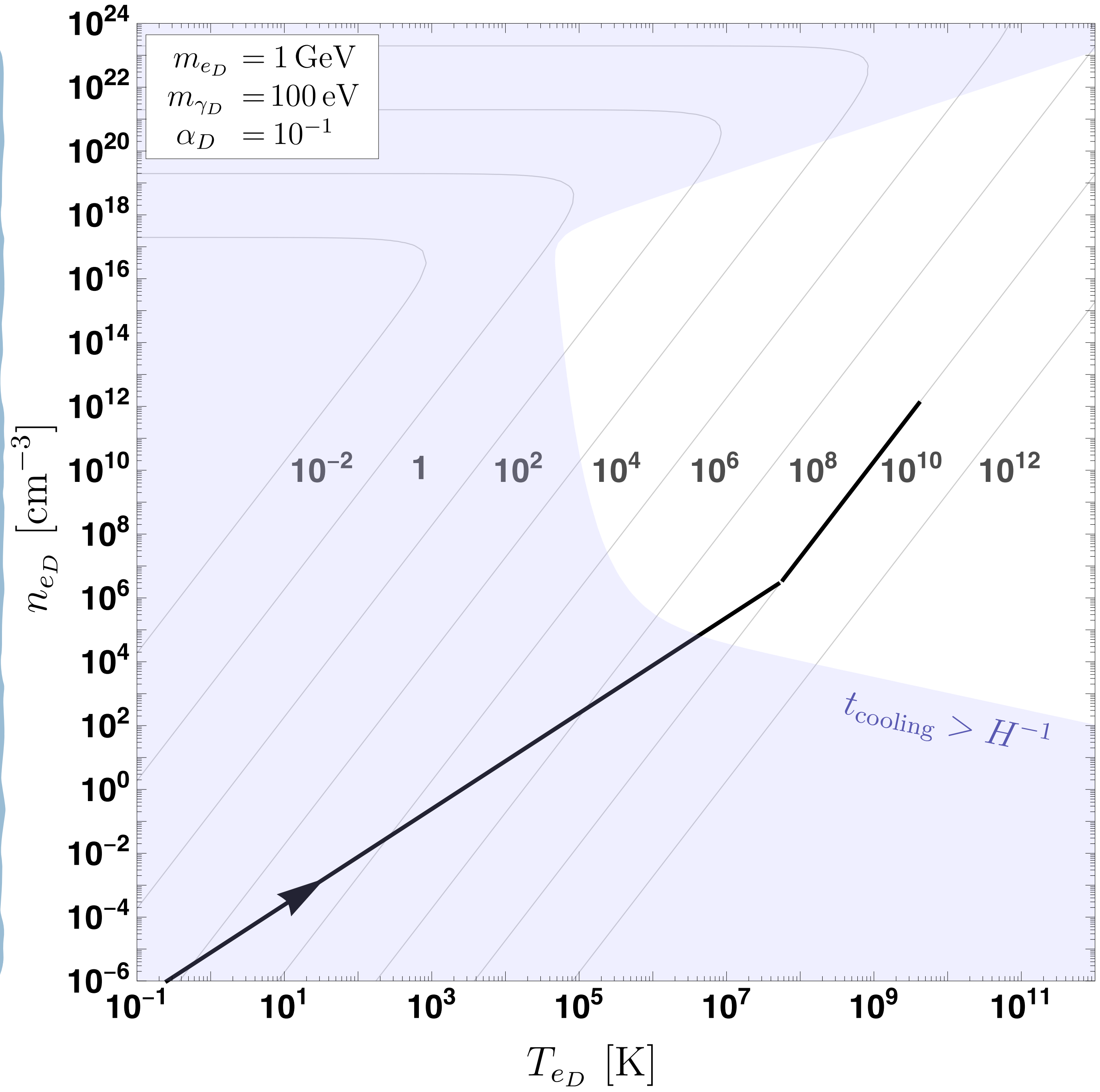


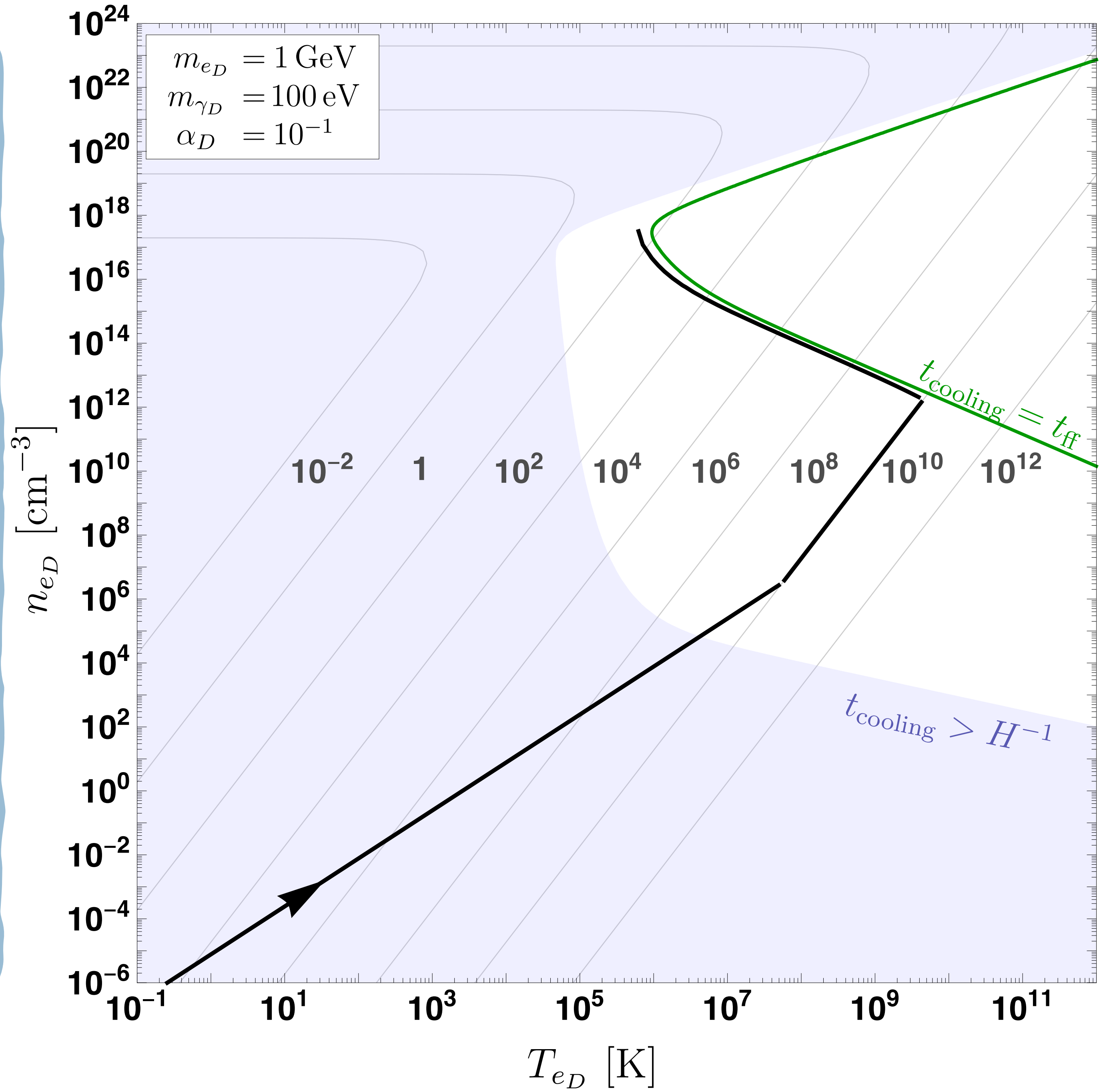
THE HISTORY OF A GALAXY: FRAGMENTATION

Fragmentation

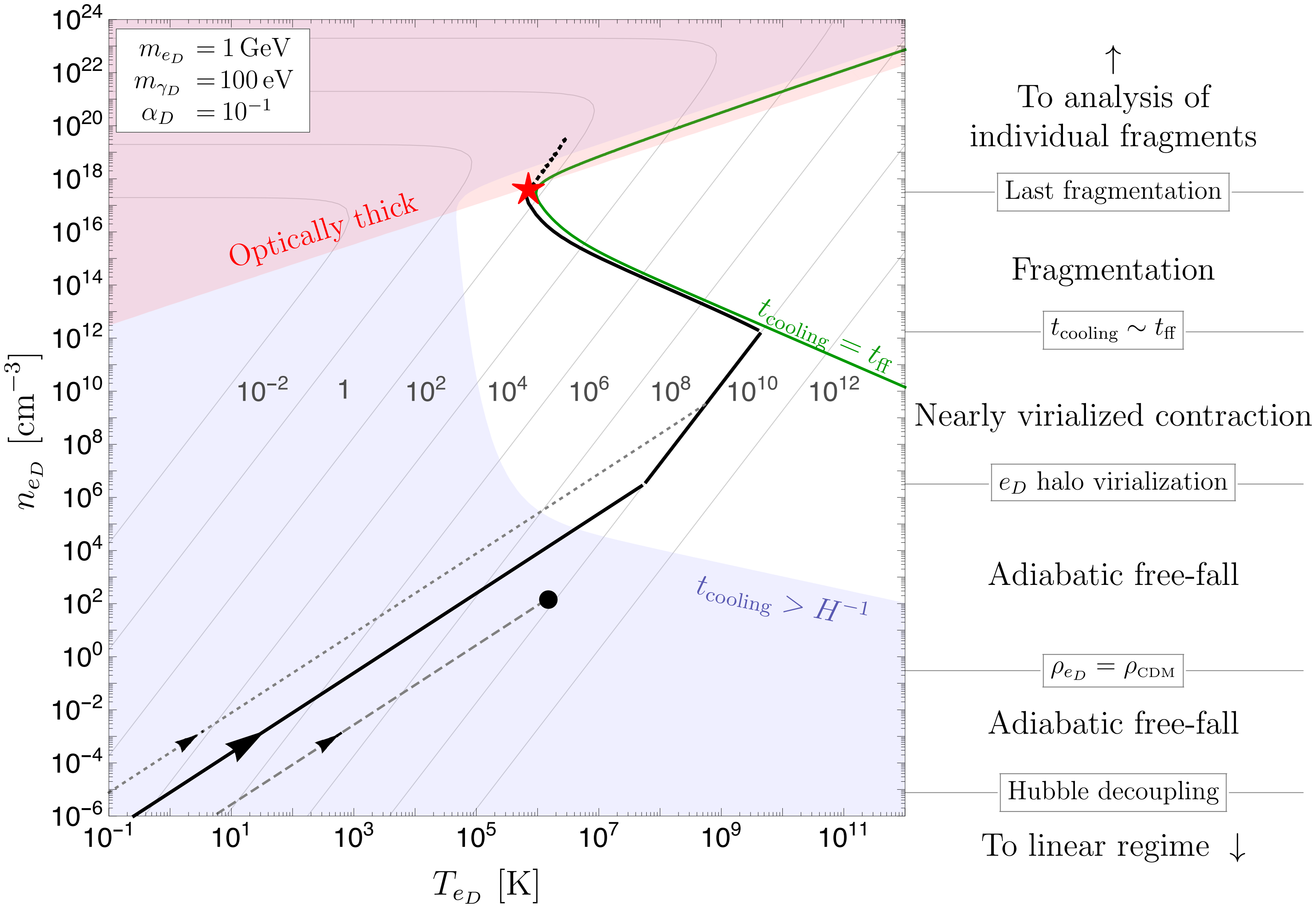
$$\frac{d\log T}{d\log\rho} = \frac{2}{3} - 2\frac{t_{\rm ff}}{t_{\rm cooling}}$$

Cooling time

$$t_{\rm cooling} \sim \frac{m_e^2}{\alpha_D^3 n_e}\sqrt{\frac{m_e}{T_e}}\,e^{m_{\gamma_D}/T_e}$$



END OF FRAGMENTATION: THE FIRST DARK STARS



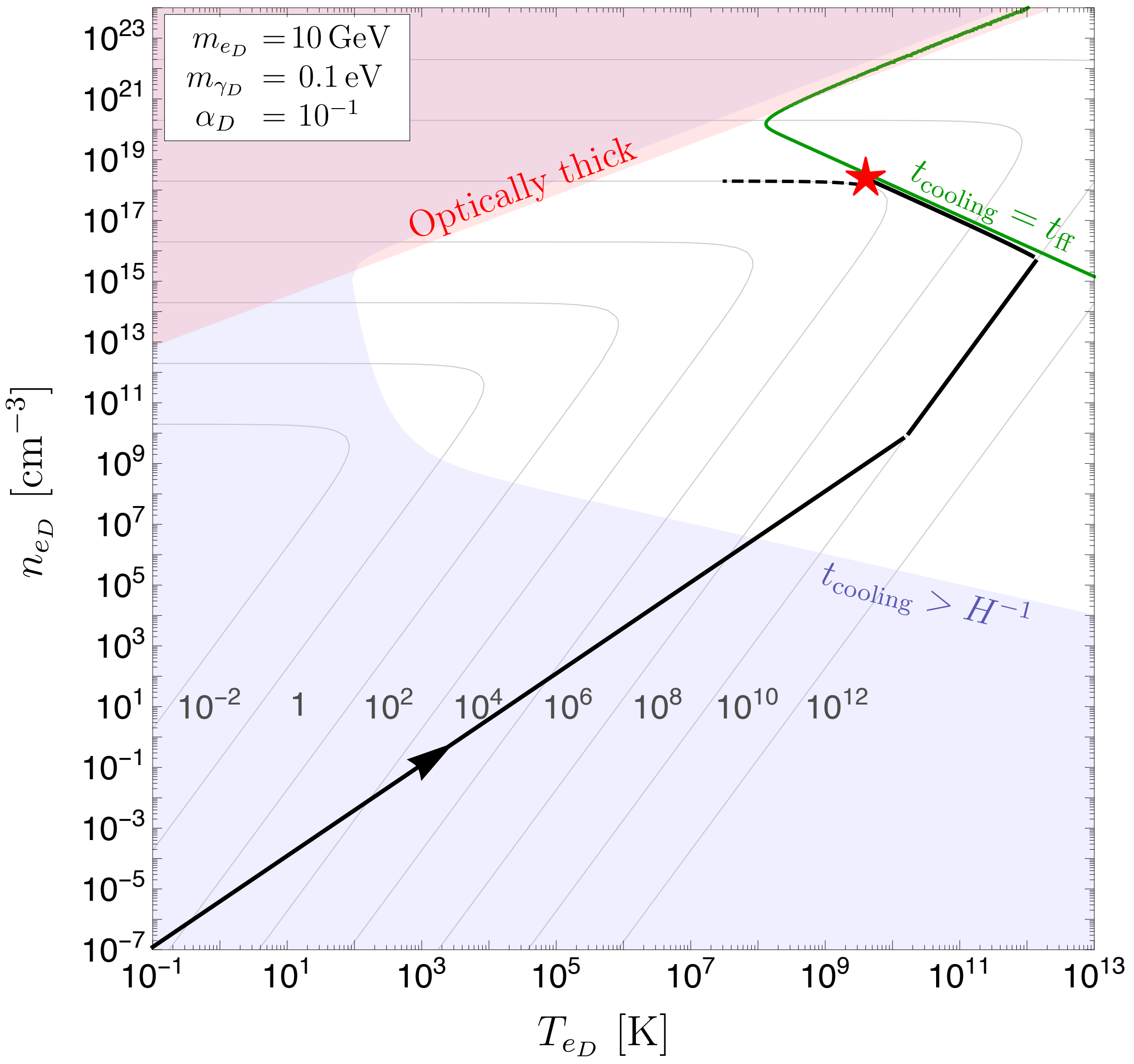
$$M_{\text{dark star}} = 10^2 M_\odot$$

$$n_{e_D} = 10^{18}\mathrm{cm}^{-3} \sim 10^{-6} n_\odot$$

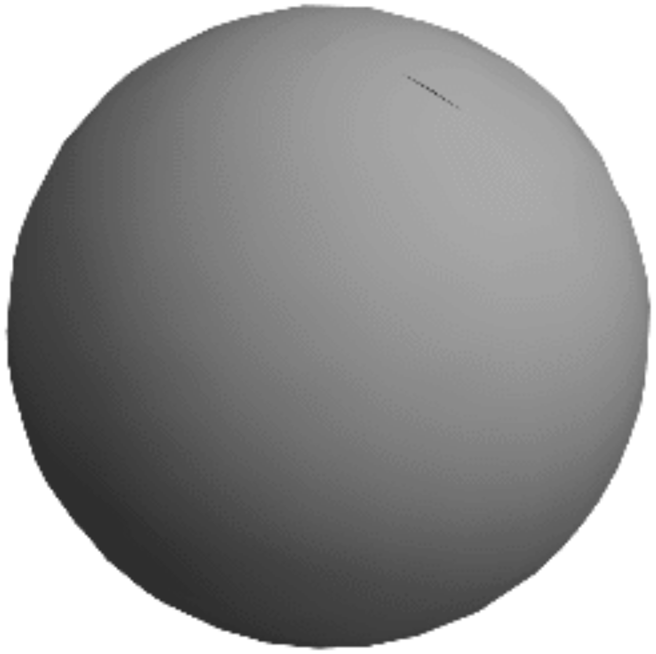
* "Star" here means dark-electron gas supported by repulsive force

A SECOND REASON WHY FRAGMENTATION ENDS

- In our model there is a second possibility: fragmentation limited by the dark-photon force



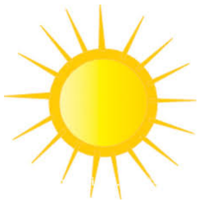
$m_e = 10.\ \text{GeV} \quad m_\gamma = 100\ \text{eV}$



Mass = 1.6 M_{Sun}

R = 3. R_{Sun}

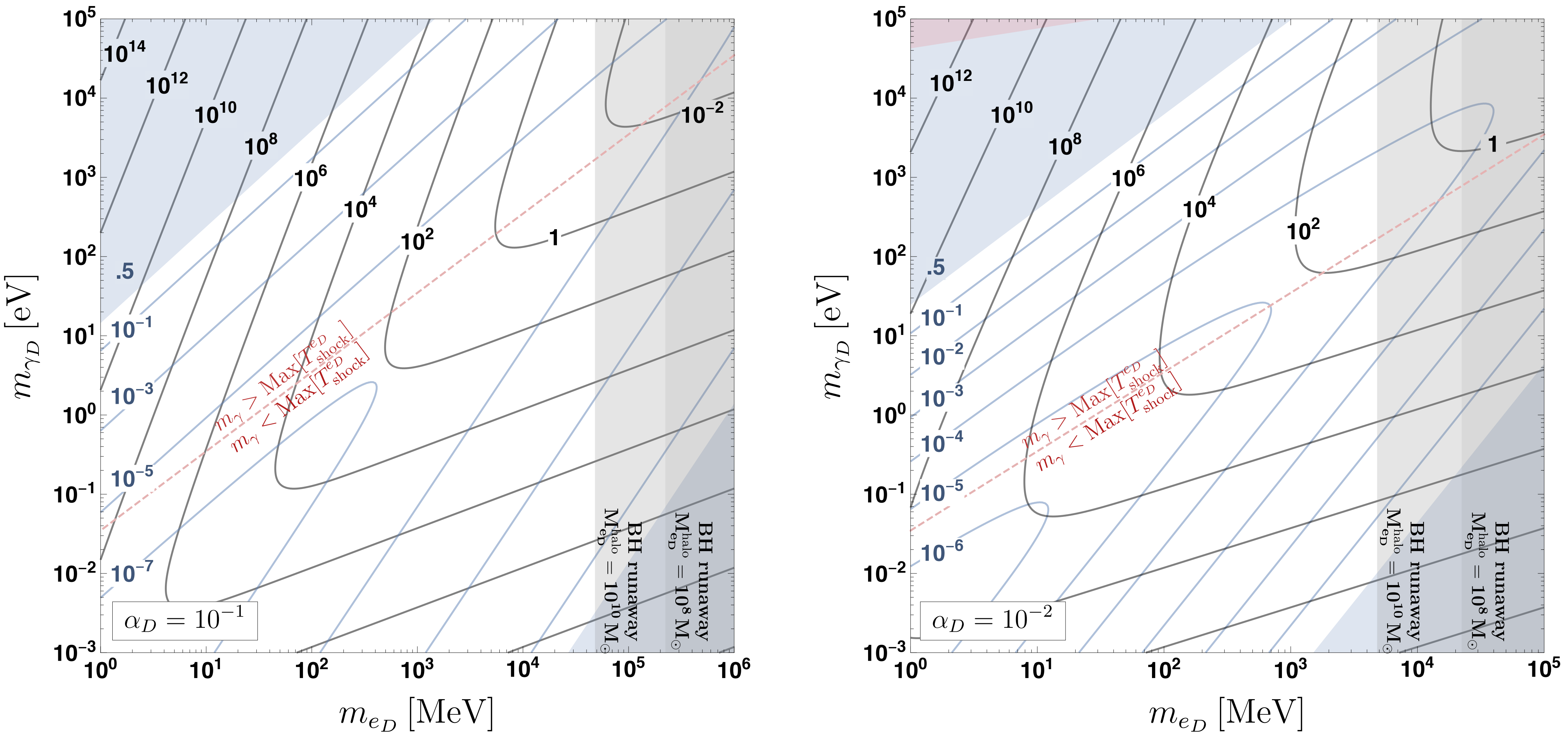
$$\alpha_D = 1/10$$



The Sun

FROM THE LAGRANGIAN TO ASTROPHYSICAL PROPERTIES

The dark-electron/photon masses and fine structure constant set the size of the typical "protostars"



$$T^{e_D}_{\rm shock} \simeq 3\times10^{-3}(1+z_{\rm ta})\left[\frac{m_{e_D}}{1\,{\rm MeV}}\right]\left[\frac{M^{e_D}_{\rm halo}}{10^{10}\,M_\odot}\right]^{2/3}{\rm eV}$$

Bertschinger, ApJS 58, 1985, 39

Some final remarks

IT IS IMPORTANT TO STUDY BSM STRUCTURE FORMATION

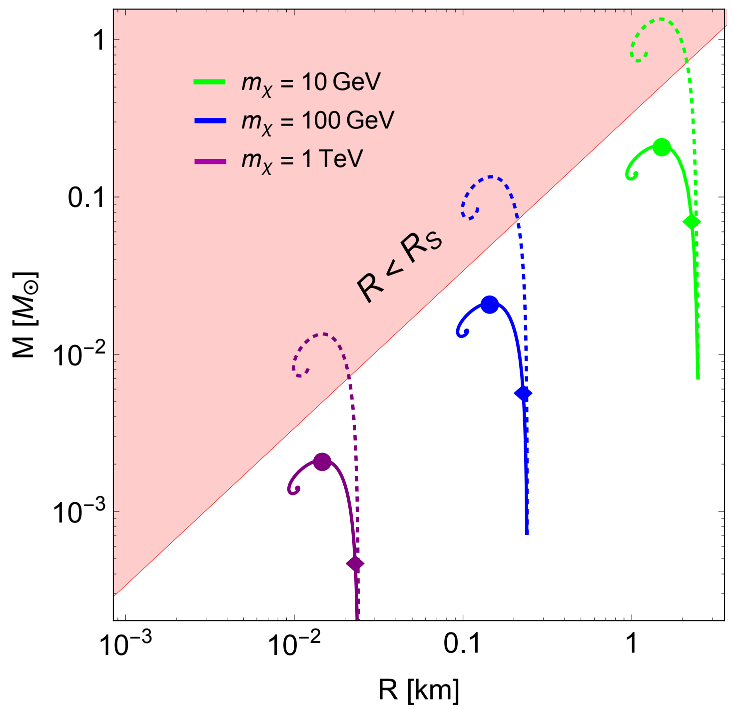


FIG. 3: In the left panels we show dark star mass vs radius relations with DM mass $m_\chi = 10$ GeV (Green), 100 GeV (blue), 1 TeV (purple). Upper, middle and bottom panels correspond to repulsive, no-interactions and attractive interactions respectively. We have fixed $\mu = 10$ MeV and $\alpha = 10^{-3}$. Solid curves represent full relativistic solutions

1507.00959

Usually, studying only the stability of the ECOs leads to unrealistic setups

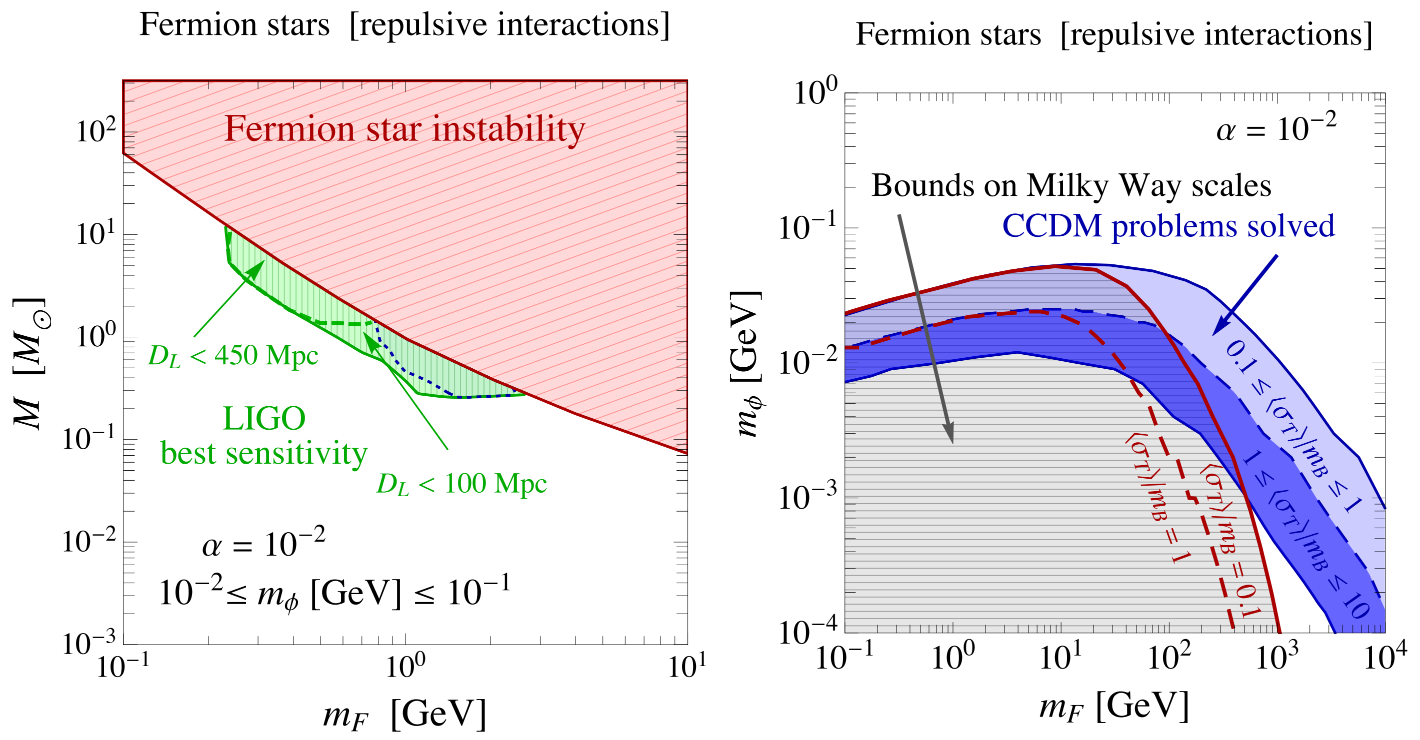


Figure 7: *Left panel. LIGO best sensitivity (region shaded in green, defined according to fig. 2 with $D_L = 450$ Mpc (dashed contour) and $D_L = 100$ Mpc (solid contour)) in terms of fermion star mass M and dark matter mass m_F. We restrict the analysis to mediator masses in the range $m_\phi = [10^{-2} - 10^{-1}]$ GeV. The red region is excluded by the condition*

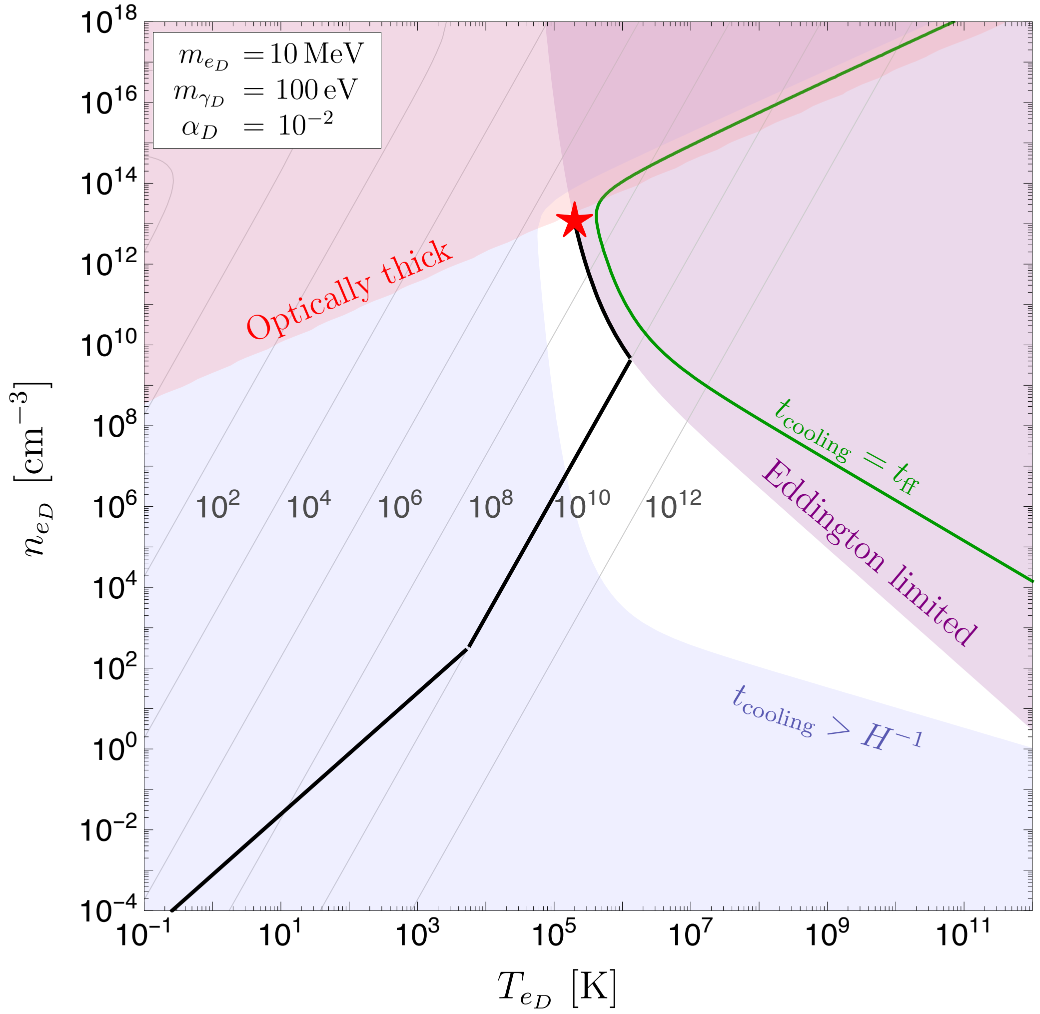
1605.01209

SOME THINGS WE CANNOT CALCULATE EASILY

Minimal mass of ECO	✓
Maximal mass of ECO	✓ Include accretion (not done here)
Compactness	✓
Abundance	Estimate only: $N_{\rm ECO} = M_{\rm dark\ galaxy}/M_{\rm ECO}$
Initial mass function	✗
Shape of galaxy/spatial distribution of ECOs	✗

INCLUDING RADIATION PRESSURE

- Note that our "stars" are all charged! Can their formation overcome radiation pressure?



$$\Lambda_{\rm BS} \geq \frac{L_{\rm edd}}{M} = \frac{4\pi G m_{e_D}}{\sigma_C}$$

Including radiation pressure does not significantly modify the results

PHENOMENOLOGY OF ECOS AND DDM

- The phenomenology is similar to PBH phenomenology.
  - Microlensing (e.g. Eros 06077207, Kepler 1307.5798)
  - Dynamical heating of stellar clusters (Brandt, 1605.03665)
  - Dynamical friction (Carr, Sakellariadoi, Apj 516,1999, 195)
  - Pulsar timing (Dror et. al. 1901.04490), astrometric lensing (Van Tilburg et. al.1804.01991), fast radio bursts (Muñoz et. al. 1605.00008), binaries at GW detectors (Giudice et. al.1605.01209), GW lensing (Jung, Sub Shin1712.01396).
- Accretion into baryonic objects (Fan et. Al 1312.1336, Cumberbatch 1005.5102). Is the formation of baryonic structure and dark electron structure correlated?
- Dark photons could <u>mix with the SM photon.</u> This leads to faint ECOs, can we see them? (Curtin et.al., 1909.04071/2)
- Super-massive BH formation? (D'amico et. Al 1707.03419, Outmezguine et. al. 1807.04750)

CONCLUSIONS

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

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

- A wide range of opportunities lies ahead,

    - What is the behavior of more complicated dark-matter models with cooling?

    - What are the astronomical signatures of such models?

    - Numerical simulations?

Lots of progress to make from the theory side, even if DM interacts with us only gravitationally

AN EXAMPLE UV COMPLETION

- Introduce lighter dark proton

$$-y_L \phi\, p_D p_D - y_R \phi^\dagger\, \bar{p}_D \bar{p}_D - m_{p_D} p_D \bar{p}_D + \mathrm{h.c.}$$

- Oscillations equilibrate the p_D^+, p_D^- abundance if

$$2yv_D = \omega_{\mathrm{osc}} > H$$

- These components annihilate if

$$M_D \geq 10^{-8}\, \frac{T_{p_D}}{T_{\mathrm{SM}}} \left[\frac{10^{-2}}{\alpha_D}\right]^{-3/2} \left[\frac{m_{p_D}}{\mathrm{keV}}\right]^2 \left[\frac{10^{-2}}{f}\right] \left[\frac{m_{e_D}}{\mathrm{GeV}}\right] \mathrm{eV}$$