Dissipative Dark Matter:

Introduction to Models and Expected Signals

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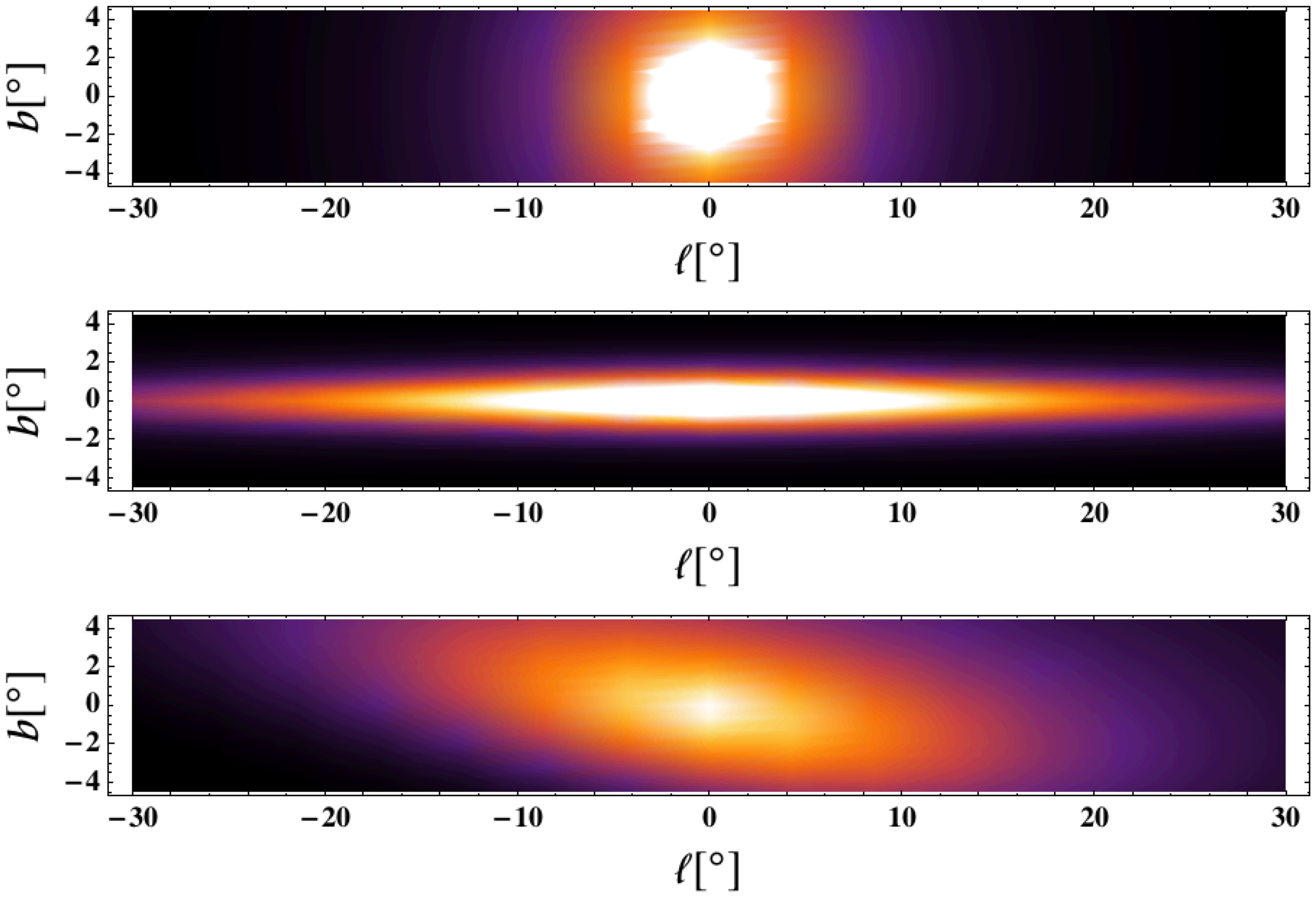
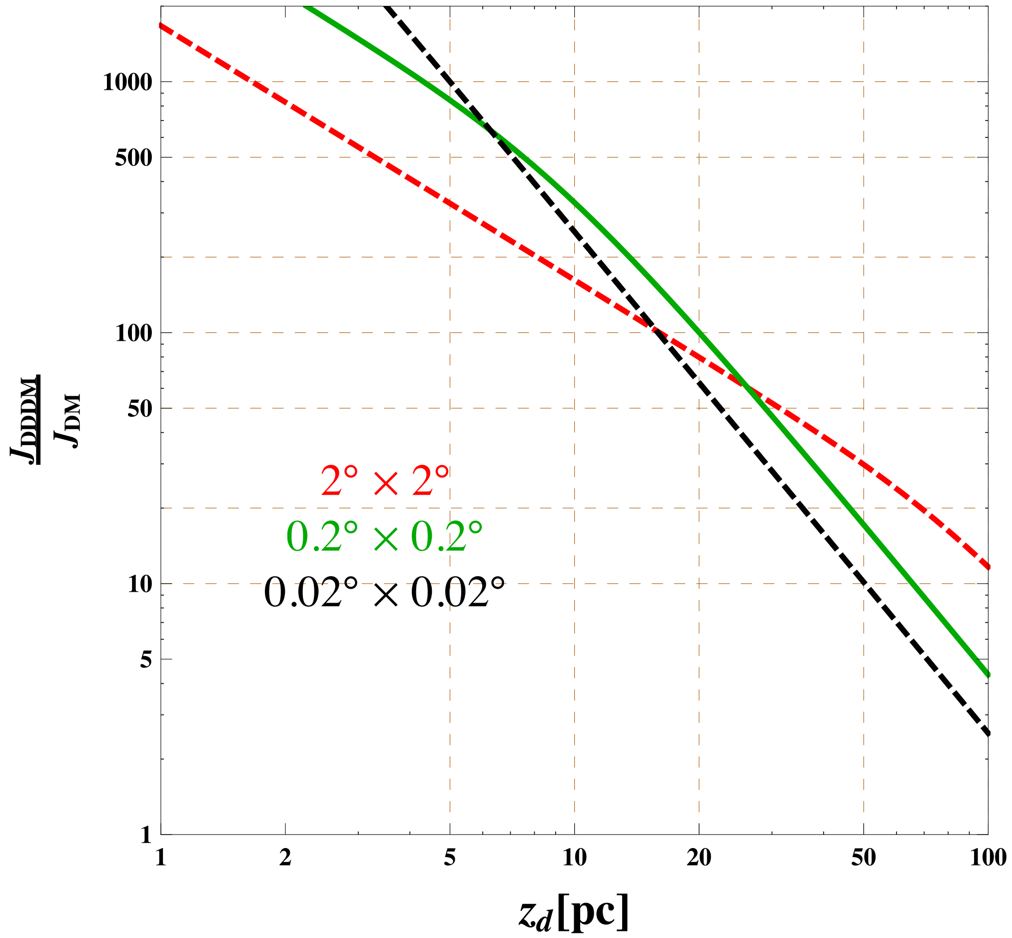
Original Motivation:
increase self-annihilation signals





Dissipative Dark Matter

Double Disk Dark Matter

Fan, Katz, Randall, Reece: 1303.1521

Dark Matter is made out of two sectors

~95%: CDM

The usual story…

~5% Dissipative :

X^+_α	C^-_α
spin 1/2	spin 1/2
m_X~100GeV	$m_C \lesssim$1MeV

Making it Dissipative

Both X and C are charged under an unbroken U(1):
Dark Photon

$$\mathcal{L} = -\frac{1}{4}\Phi^{\mu\nu}\Phi_{\mu\nu} + e_D\bar{X}\phi_\mu\gamma^\mu X - e_D\bar{C}\phi_\mu\gamma^\mu C \qquad \alpha_D = \frac{e_D^2}{4\pi}$$

Since they have opposite charges, they form a hydrogen-like bound state:

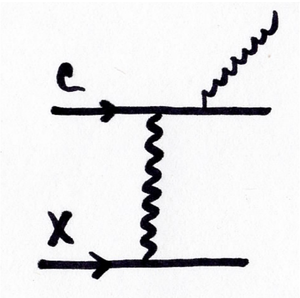
$$B = \frac{\alpha_D^2 m_C}{2}$$

There is also a dark CMB (dCMB) with its own temperature

Dissipation

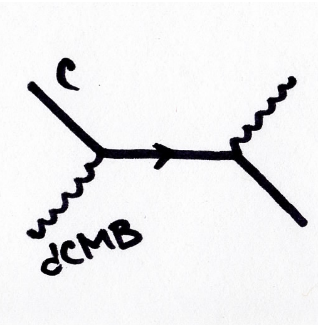
Cooling Down

Since the Dark Photon is massless, C and X can dissipate, i.e. cool. The cooling rate can be fast:



$$t_{\mathrm{brem}} \approx \frac{3}{16}\,\frac{n_X + n_C}{n_X n_C}\,\frac{m_C T_{\mathrm{vir}}}{\alpha_D^3}$$

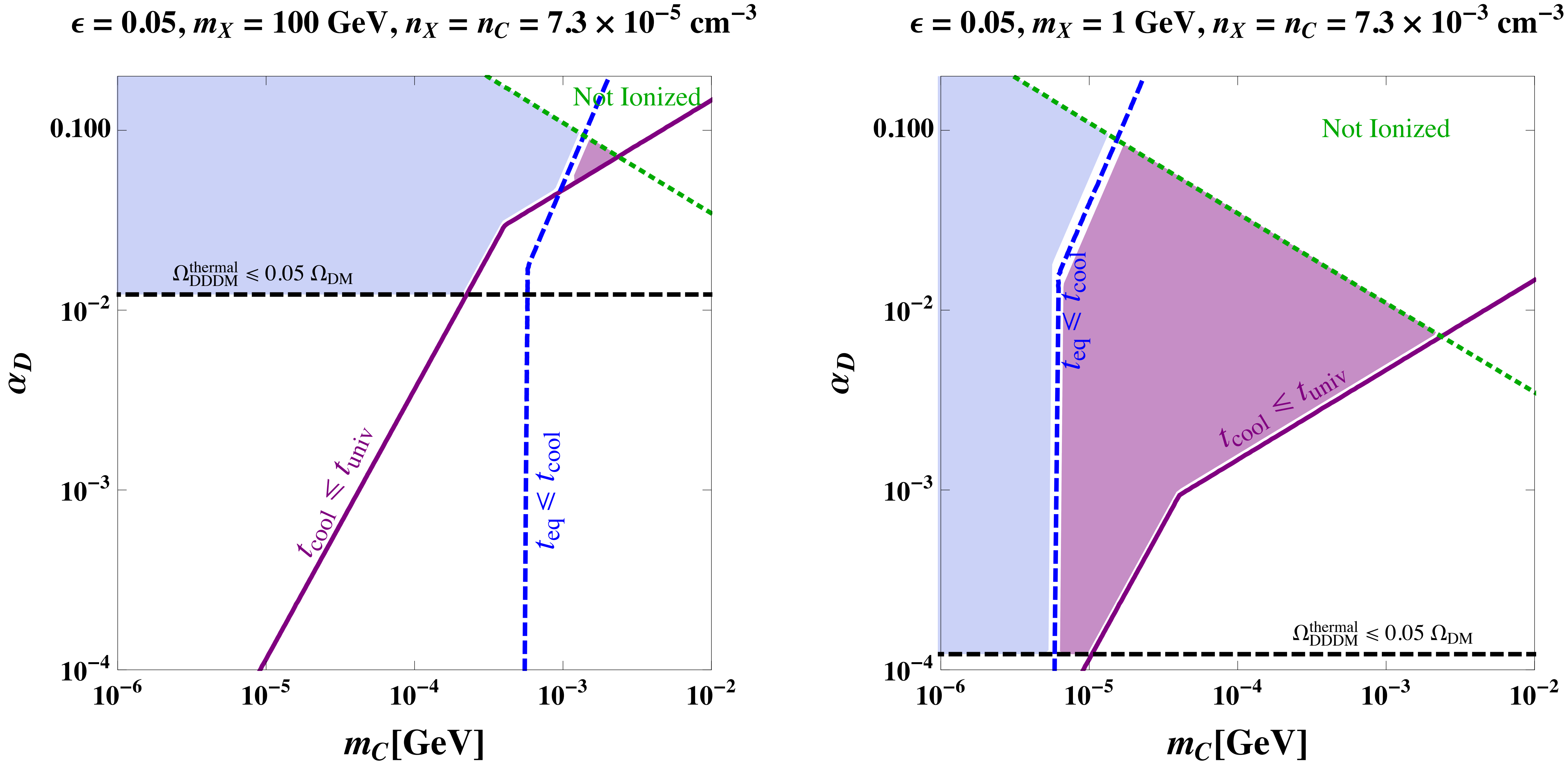
$$\approx 10^4\ \mathrm{yr}\sqrt{\frac{T_{\mathrm{vir}}}{\mathrm{K}}}\,\frac{\mathrm{cm}^{-3}}{n_C}\left(\frac{\alpha_{\mathrm{EM}}}{\alpha_D}\right)^3\left(\frac{m_C}{m_e}\right)^{\frac{3}{2}}$$



$$t_{\mathrm{Compton}} \approx \frac{135}{64\pi^3}\,\frac{n_X + n_C}{n_C}\,\frac{m_C^3}{\alpha_D^2\left(T_D^0\,(1+z)\right)^4}$$

$$\approx 4 \times 10^{12}\,\mathrm{yr}\,\frac{n_X + n_C}{n_C}\left(\frac{\alpha_{\mathrm{EM}}}{\alpha_D}\right)^2\left(\frac{2\,\mathrm{K}}{T_D^0\,(1+z)}\right)^4\left(\frac{m_C}{m_e}\right)^3$$

Cooling Down



$\epsilon = 0.05,\ m_X = 100\ \mathrm{GeV},\ n_X = n_C = 7.3 \times 10^{-5}\ \mathrm{cm}^{-3}$

$\epsilon = 0.05,\ m_X = 1\ \mathrm{GeV},\ n_X = n_C = 7.3 \times 10^{-3}\ \mathrm{cm}^{-3}$

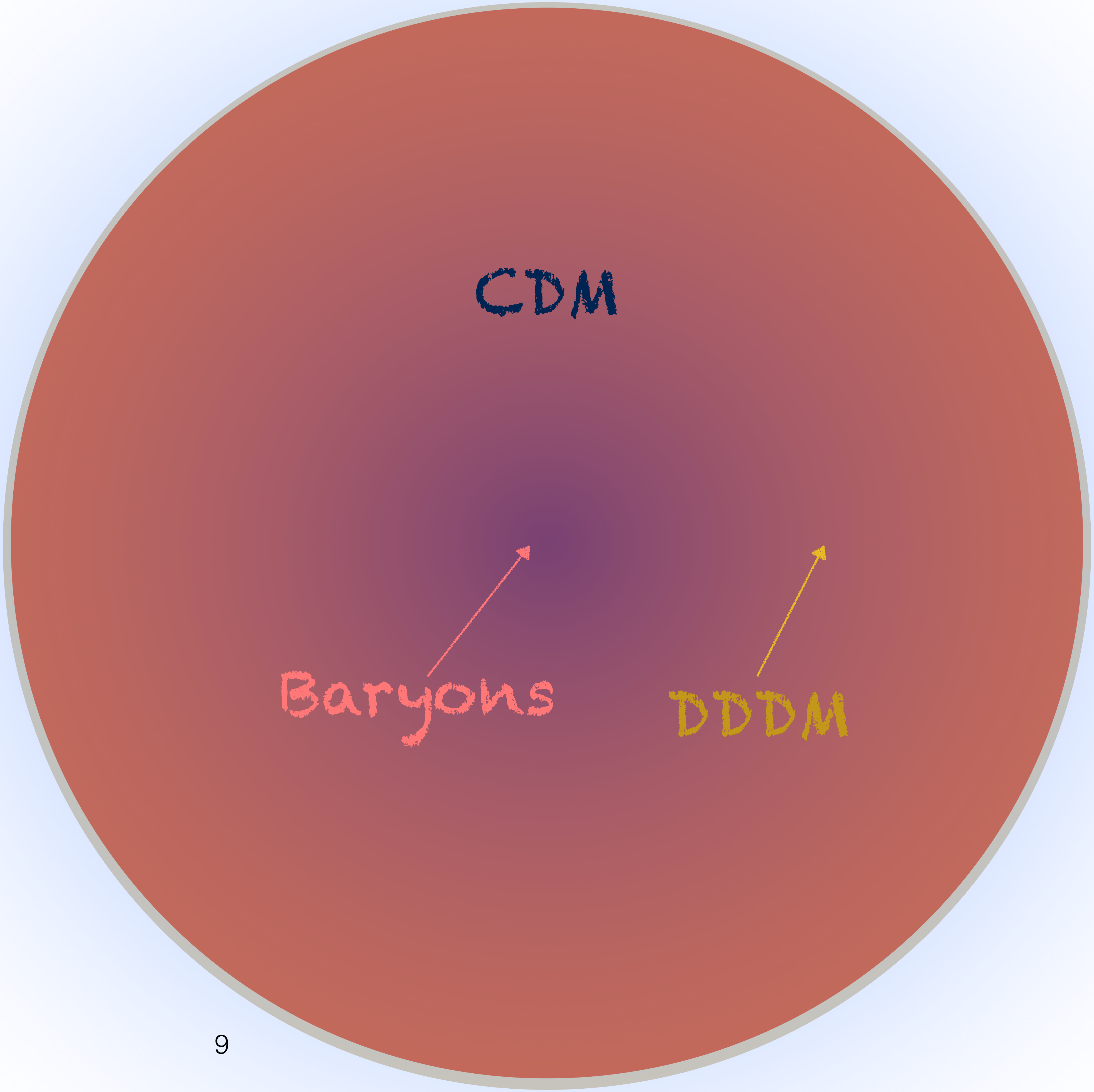
[1303.1521]

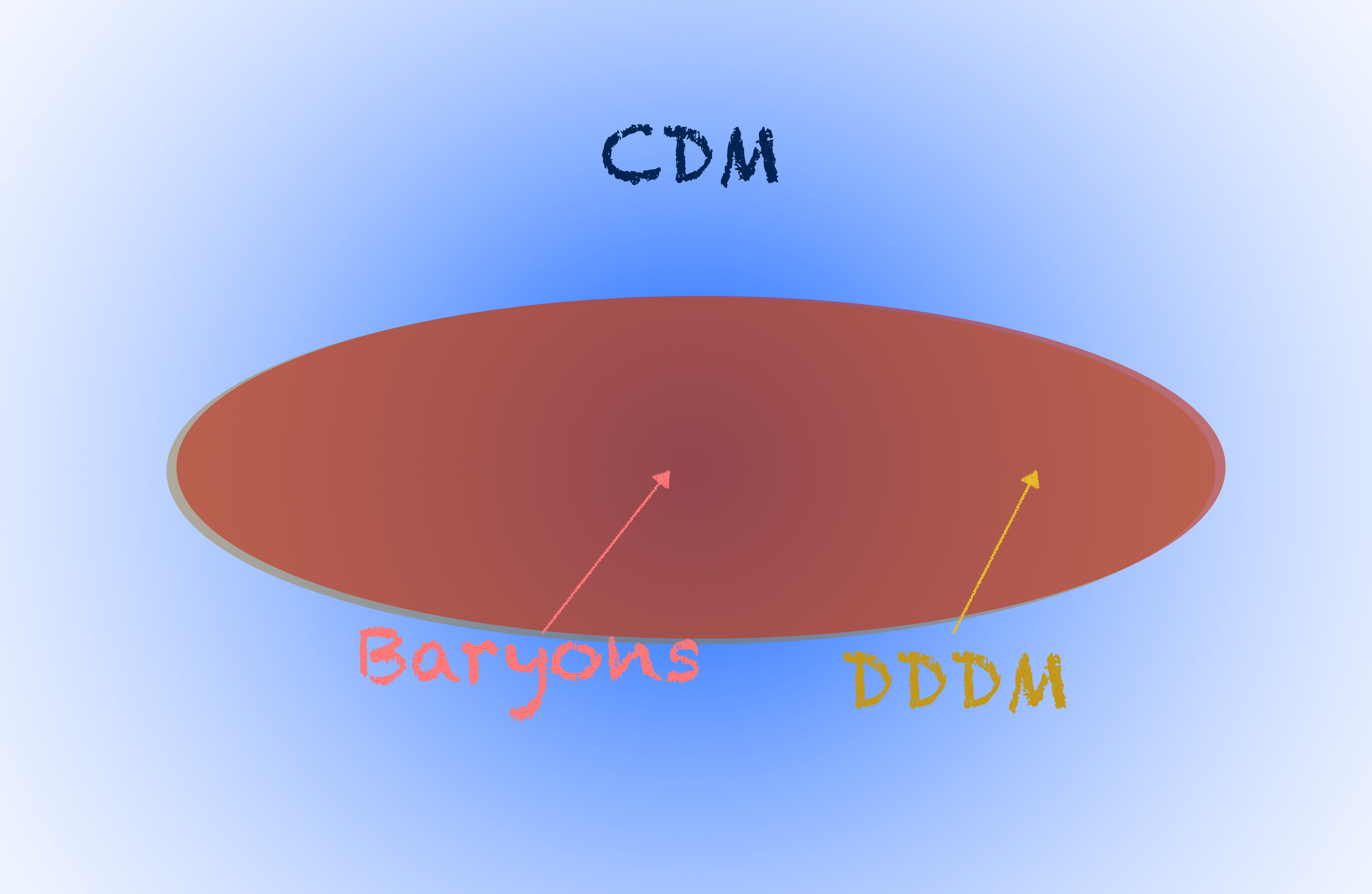
Cooling Eventually Stops

The Compton scattering and Bremsstrahlung effectively turn off when the gas recombines into neutral atoms:

$$T \approx \frac{B}{10} = \frac{\alpha_D^2 m_C}{20}$$ Saha Equation

$$\langle \sigma^2 \rangle = \frac{\alpha_D^2}{10} \frac{m_C}{m_X}$$


CDM
Baryons
DDDM


CDM
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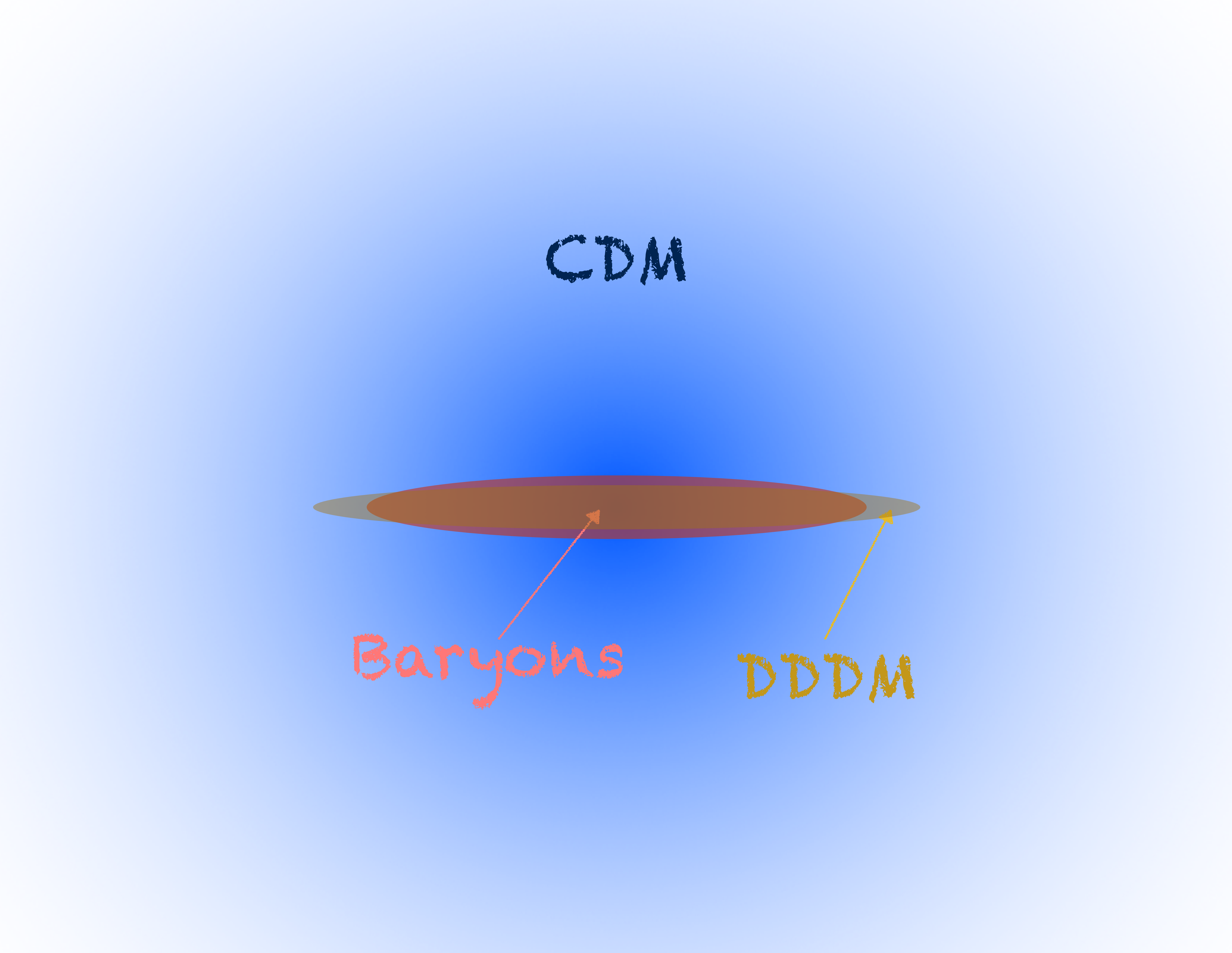
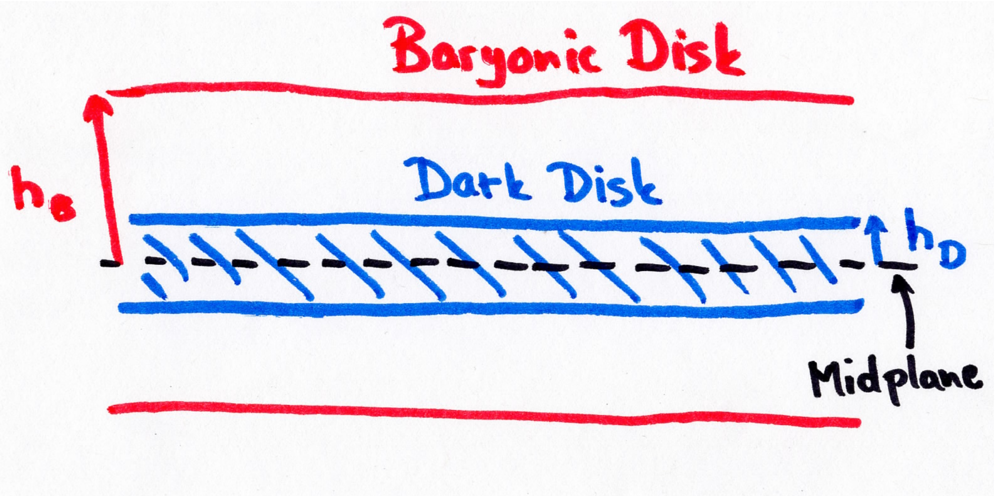

CDM
Baryons
DDDM

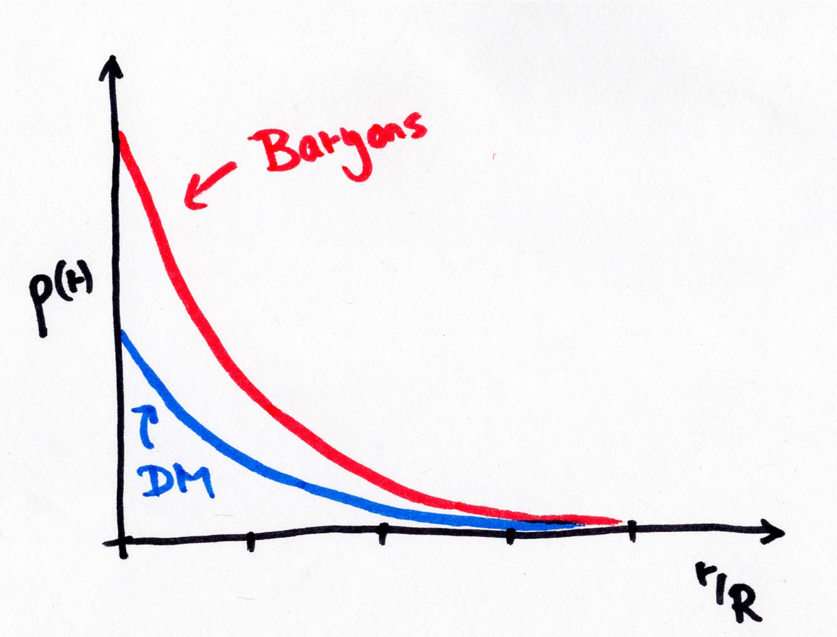
The Dark Disk

- As the gas cools down, it forms a disk just like the baryons. The scale height of the disk is given by the velocity dispersion of the dark matter.



$$h_D = \frac{\sigma^2}{\pi G \Sigma} = \frac{\alpha_D^2 c^2}{\pi G \Sigma} \frac{m_C}{m_X}$$

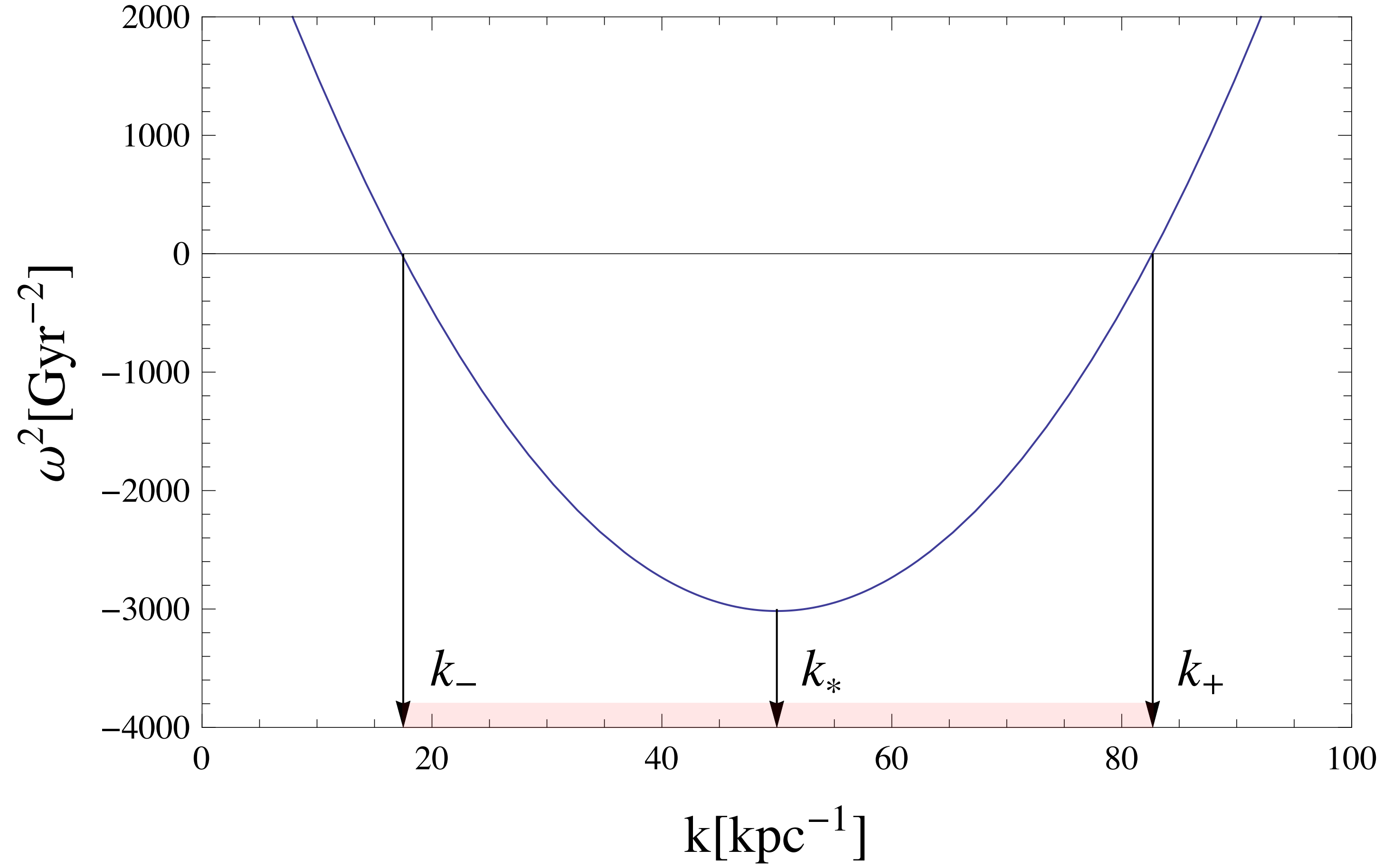
- The scale radius of the disk is given by the angular momentum stored in the disk and so should be similar to the scale radius of the baryons.



Gravitational Instabilities

The Toomre stability criterion determines the scales on which the density perturbations grow or oscillate:

$$\kappa^2 - 2\pi G\Sigma(R)|k| + \sigma^2 k^2 = \omega(k)^2 \qquad \kappa = \sqrt{2}\Omega$$



Is this allowed?

Partially Interacting DM

Since only ~5% of DM is dissipative, then from the SIDM perspective, this is unconstrained:

i. Ellipticity of halos
ii. Subhalo evaporation
iii. Cluster Collisions
iv. …

Relativistic Degrees of Freedom

$$\xi = \left(\frac{5.5}{2} \times \frac{3.36}{86.25}\right)^{1/3} \approx 0.5 \text{ for } \mathrm{U}(1)_D,$$

$$\xi = \left(\frac{2\left(N^2-1\right)+\frac{7}{2}N}{2\left(N^2-1\right)} \times \frac{3.36}{86.25}\right)^{1/3} \quad \text{for } \mathrm{SU}(N)_D$$

Assuming thermal decoupling at the weak scale

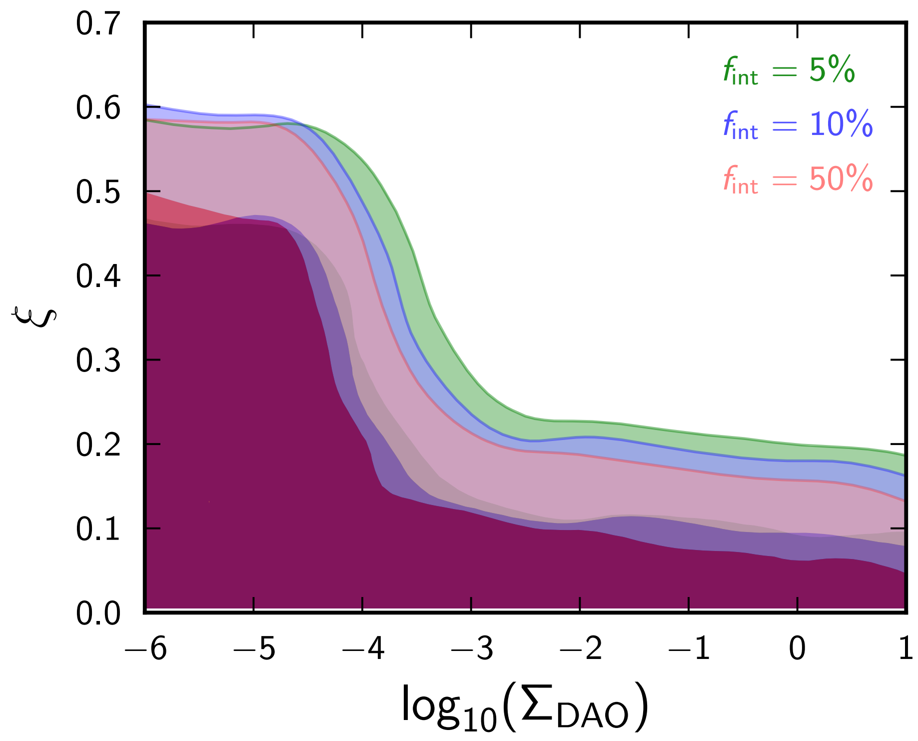
$$\Delta N_{\mathrm{eff},\nu}^{\mathrm{CMB}} = 0.22 \text{ for } \mathrm{U}(1)_D,$$

$$\Delta N_{\mathrm{eff},\nu}^{\mathrm{CMB}} = 4.4(N^2-1)\xi^4 \text{ for } \mathrm{SU}(N)_D$$

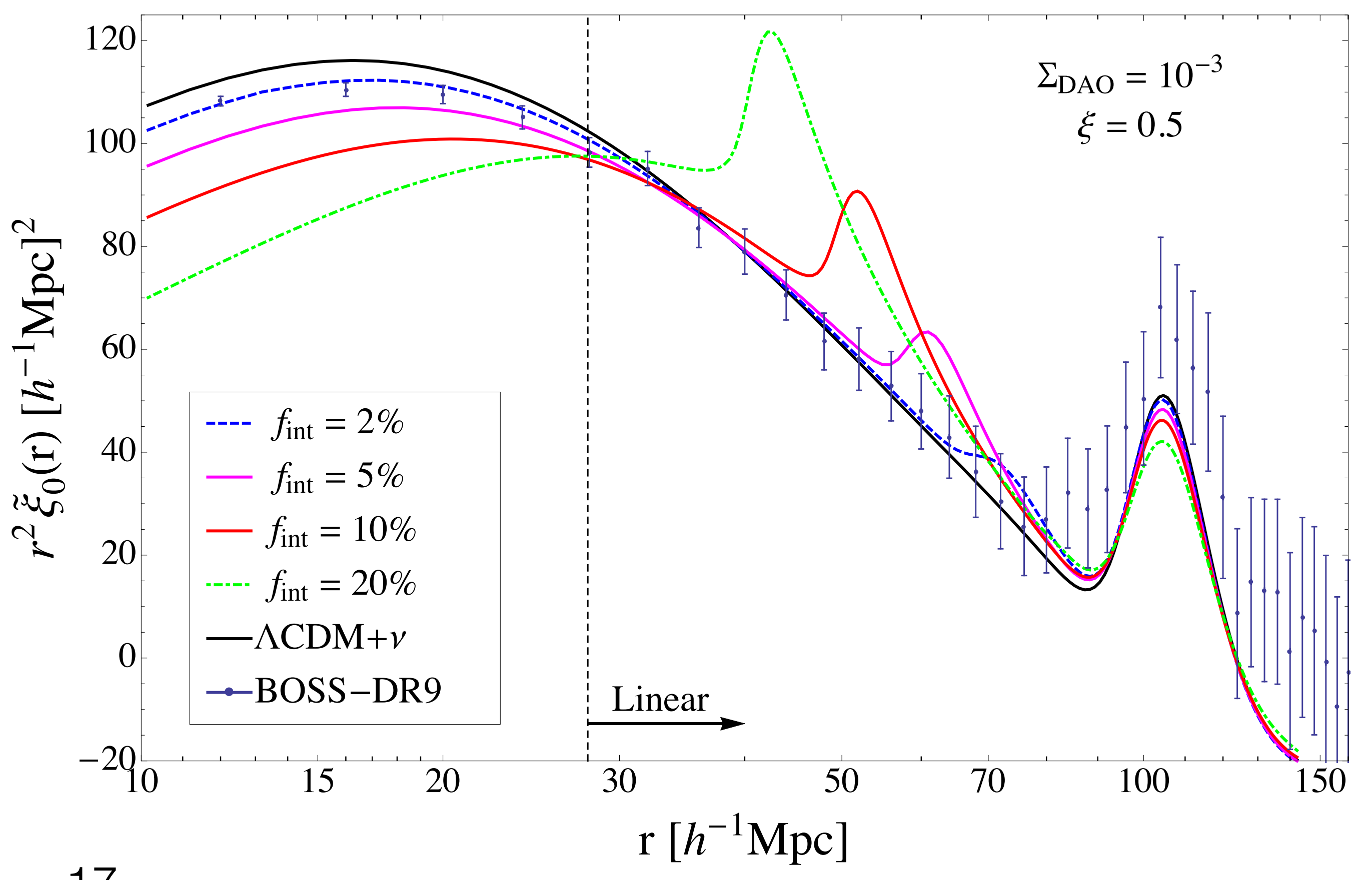
SU(2) —> 0.49
SU(3) —> 0.91
SU(4) —> 1.45

Is this allowed?

- Cyr-Racine & Sigurdson determined the cosmological limits in 1209.5752
- There are bounds from Dark Acoustic Oscillations, analyzed in 1310.3278 (Cyr-Racine, de Putter, Raccanelli, Sigurdson)

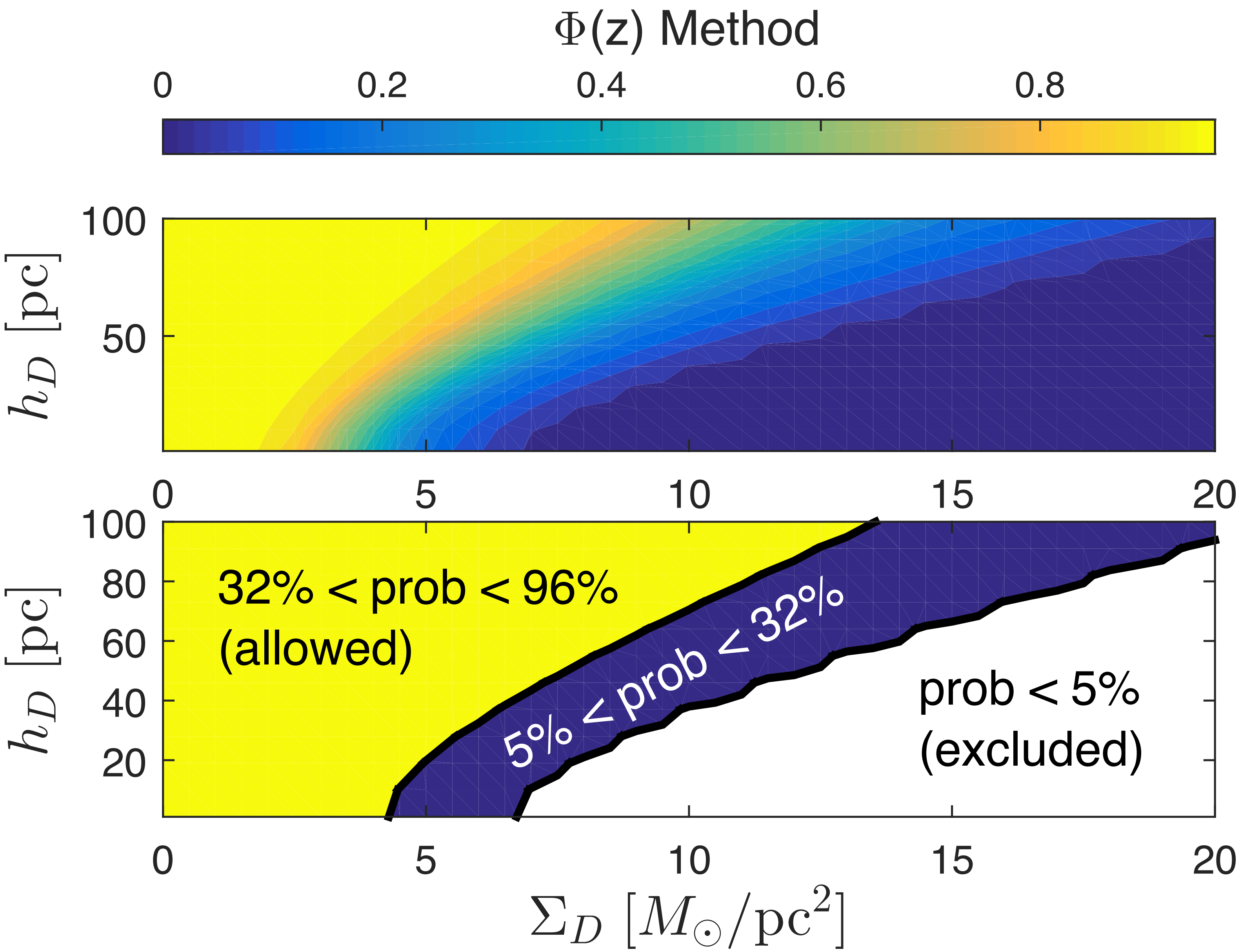


$$\Sigma_{\rm DAO} \equiv \alpha_D \left(\frac{B_D}{\rm eV}\right)^{-1} \left(\frac{m_D}{\rm GeV}\right)^{-1/6}$$



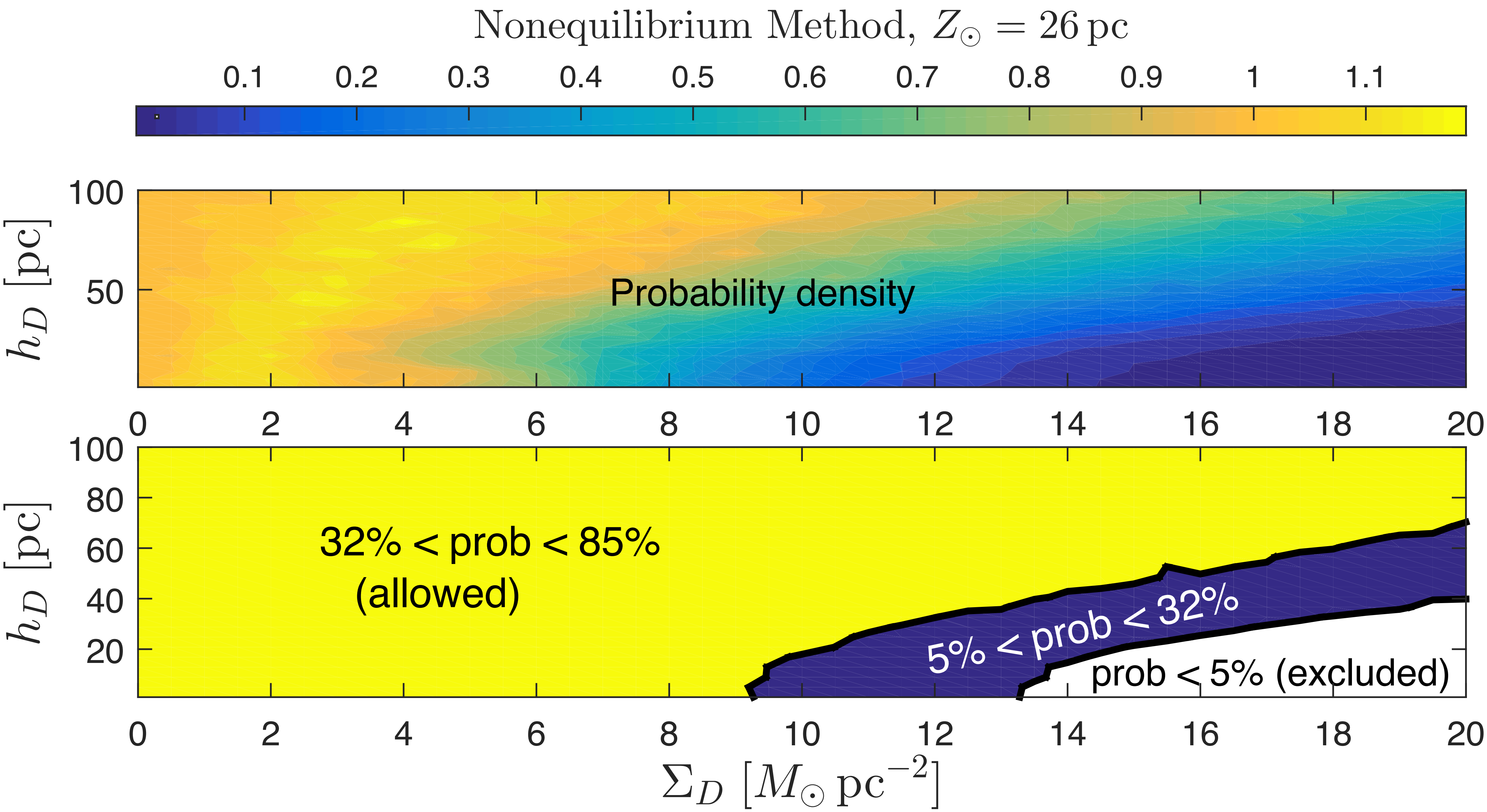
Is this allowed?

- Lisa & her student Eric Kramer worked out an analysis of the stellar and gas constraints of the dark disk [1604.01407]



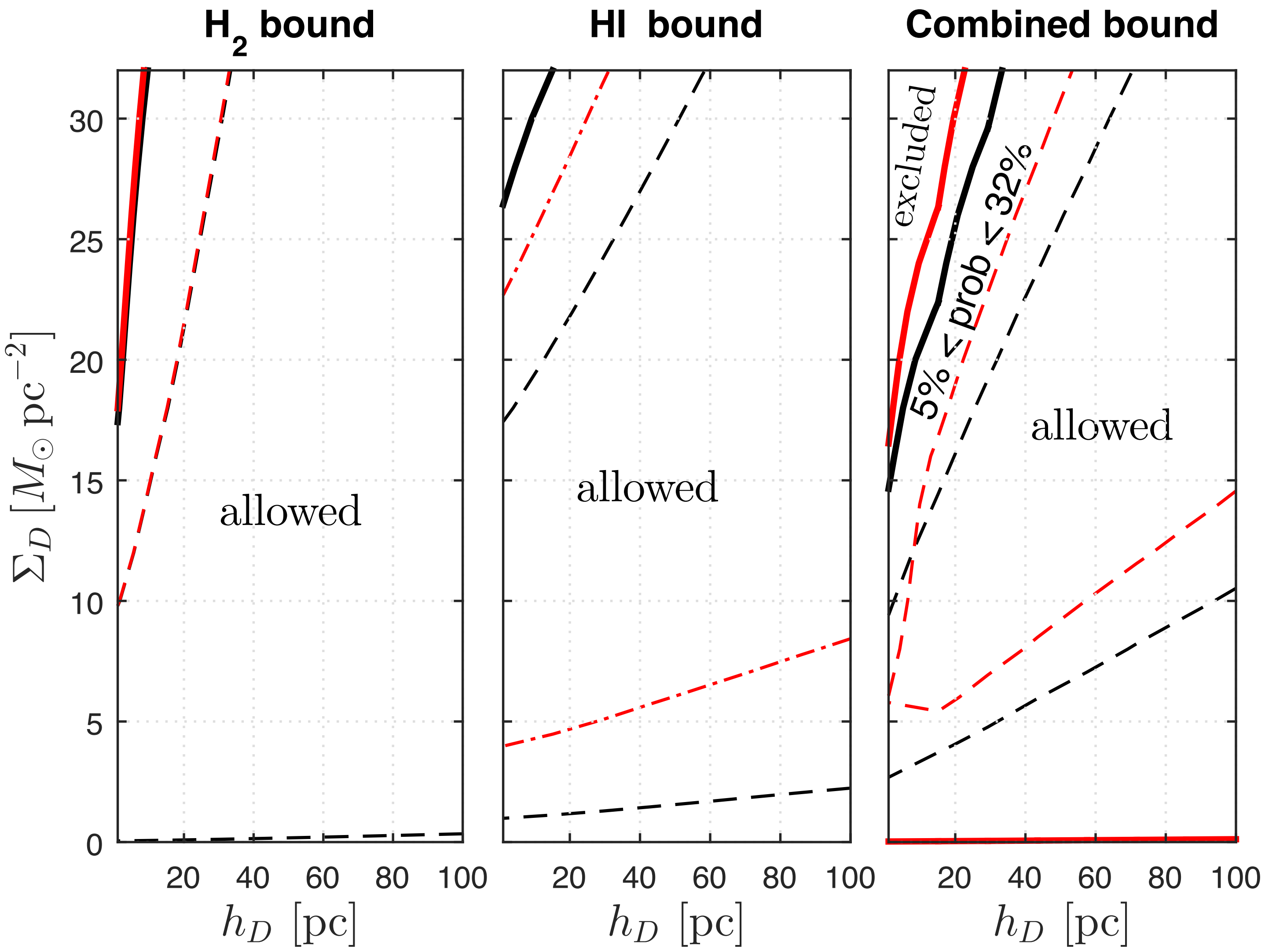
Is this allowed?

- Abandoning the static solution: [1604.01407]



Is this allowed?

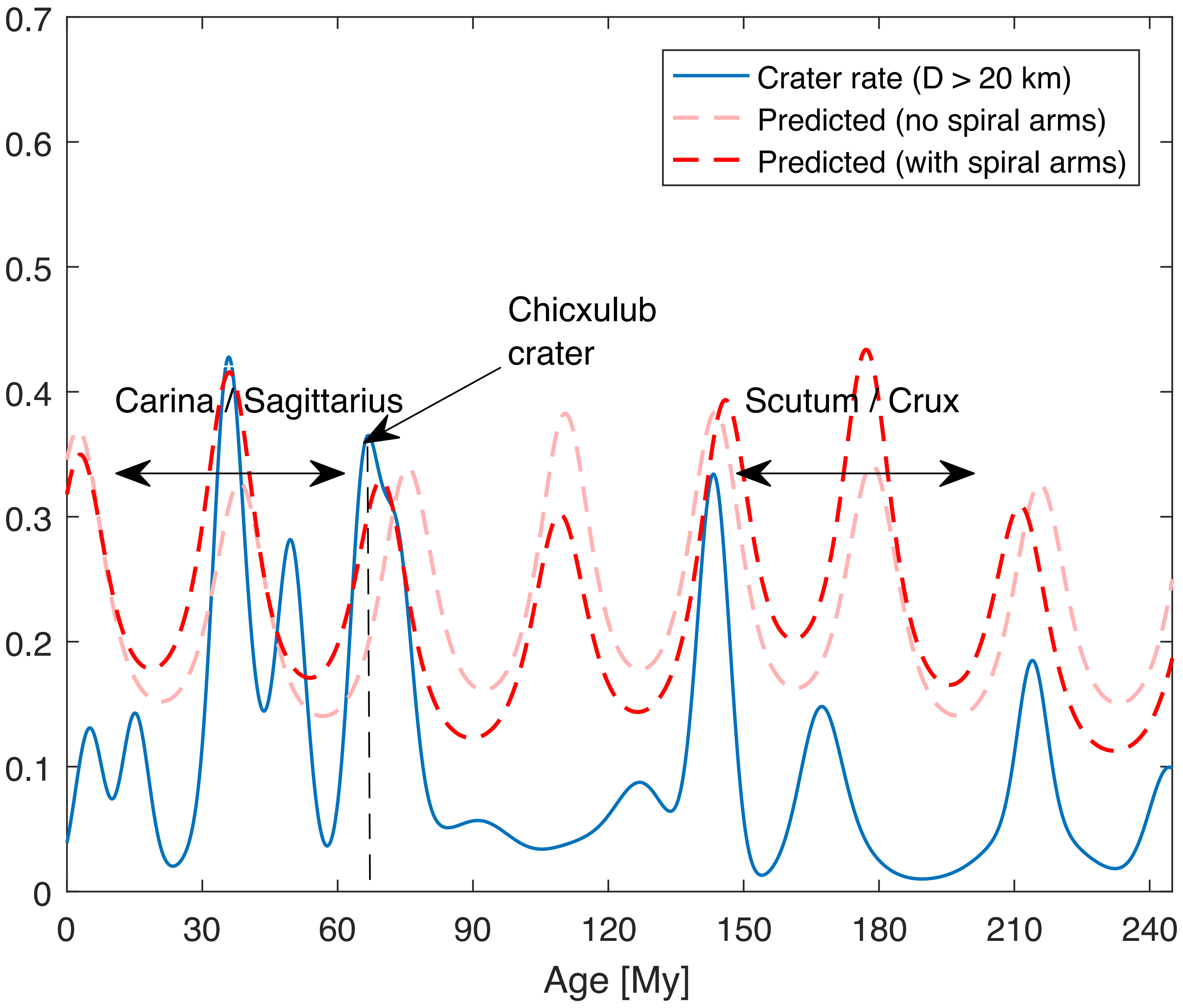
- Using Gas [1603.03058]:



DDDM and the death of dinosaurs

Crossing this disk might release periodic meteor strikes. With period of order the oscillation of the sun through the galactic disk ~ 35-60 million years.

Killing the dinosaurs



[1403.0576]
[1610.04239]

Unified Models ?

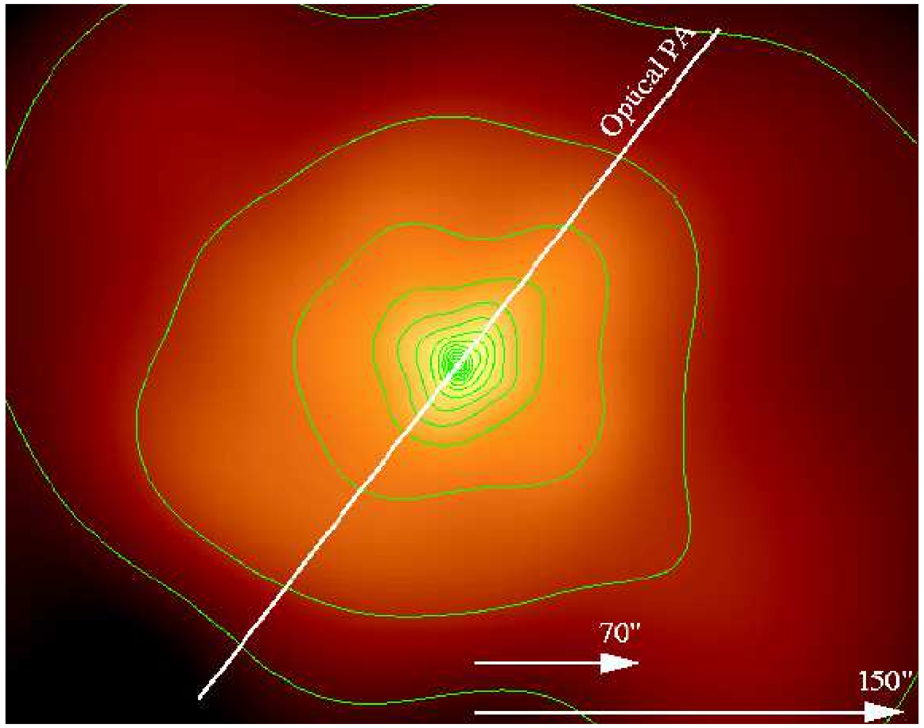
XC Dark Matter

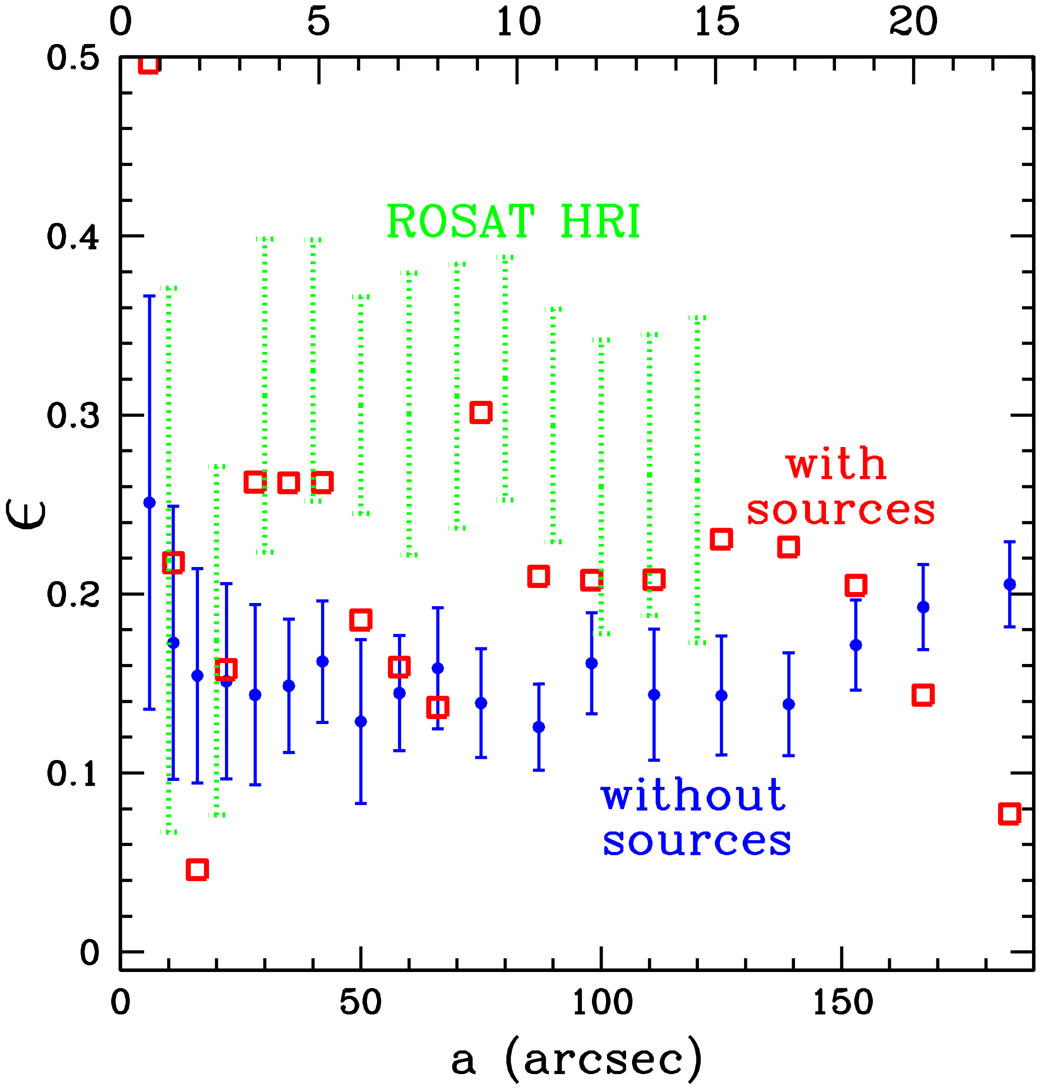
- We tried to explain both CDM and Dissipative DM components in Dark Catalysis: [1702.05482]
- Particle contents:
  - X: heavy (1TeV), charged, mostly symmetric, majority of dark matter
  - C: light (1MeV), charged, mostly asymmetric
  - A': Massless dark photon, no mixing with our photon
- Dark Matter composition:
  - 95% : $X, \bar{X}$
  - 5%: X, C
- The X behave like a WIMP
- The C behave like a coolant/catalyst (dissipation)
- The C and X can form (XC) bound state, neutralizing the plasma and turning of some of the interactions to a degree.

95%: $X, \bar{X}$

Ellipticity of DM halos

- We expect the DM halos to be triaxial with smallish ellipticity. Moreover, we have an observation (NGC 720) in which we see non-zero ellipticity of the gravitational potential at R=3kpc.[astro-ph/0205469]
- We can think about ellipticity of a halo as determined by the difference between velocity dispersions in different directions.
- The dark matter self-interactions tend to equalize the velocity dispersions and erase ellipticity.
- We require that the DM self-interactions have not had enough time to randomize a typical particle velocity.

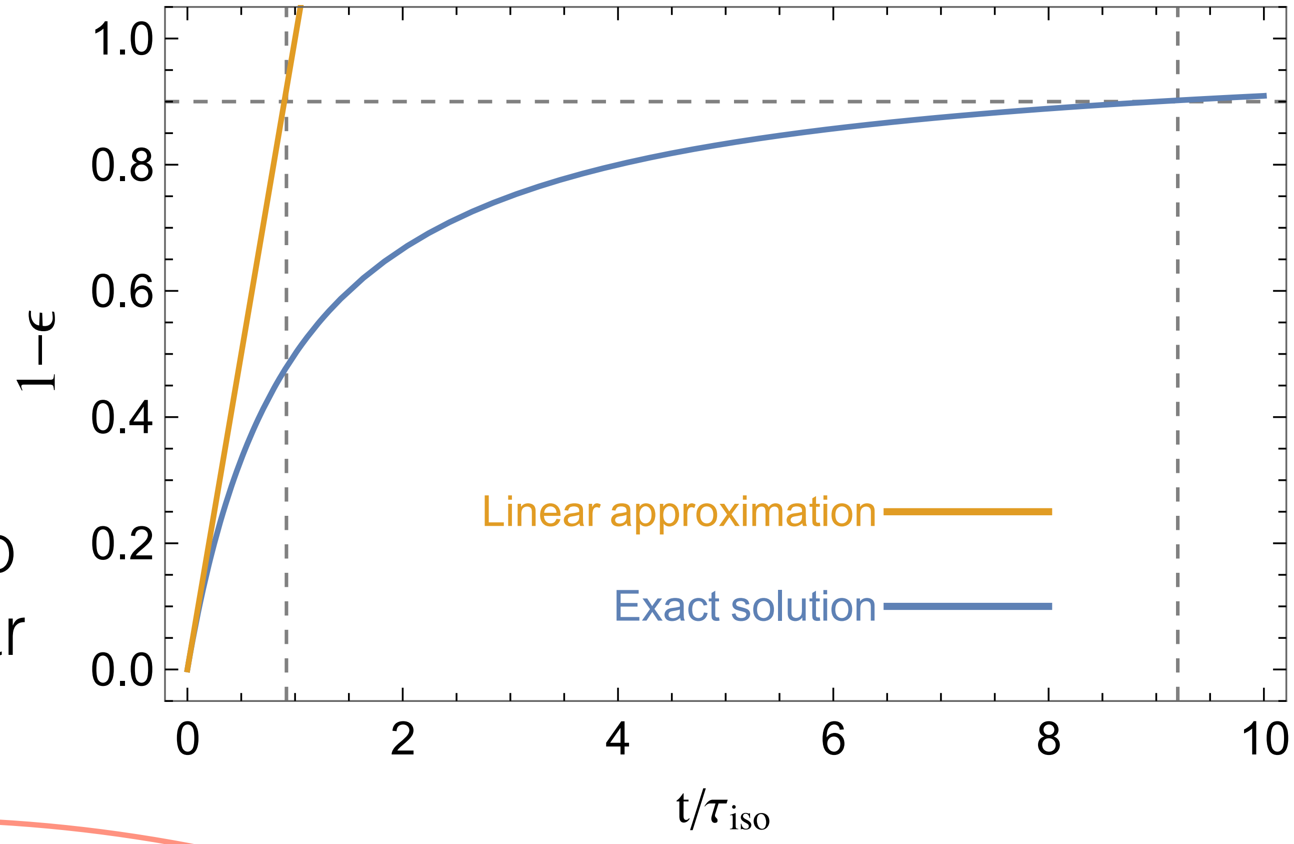




Time Scales

- Previous calculations use a typical time scale this happens in:

$$\tau_1 = E/\dot{E}$$



- However, the form of the solution to the differential equation is not linear and this time scale is not a good estimate

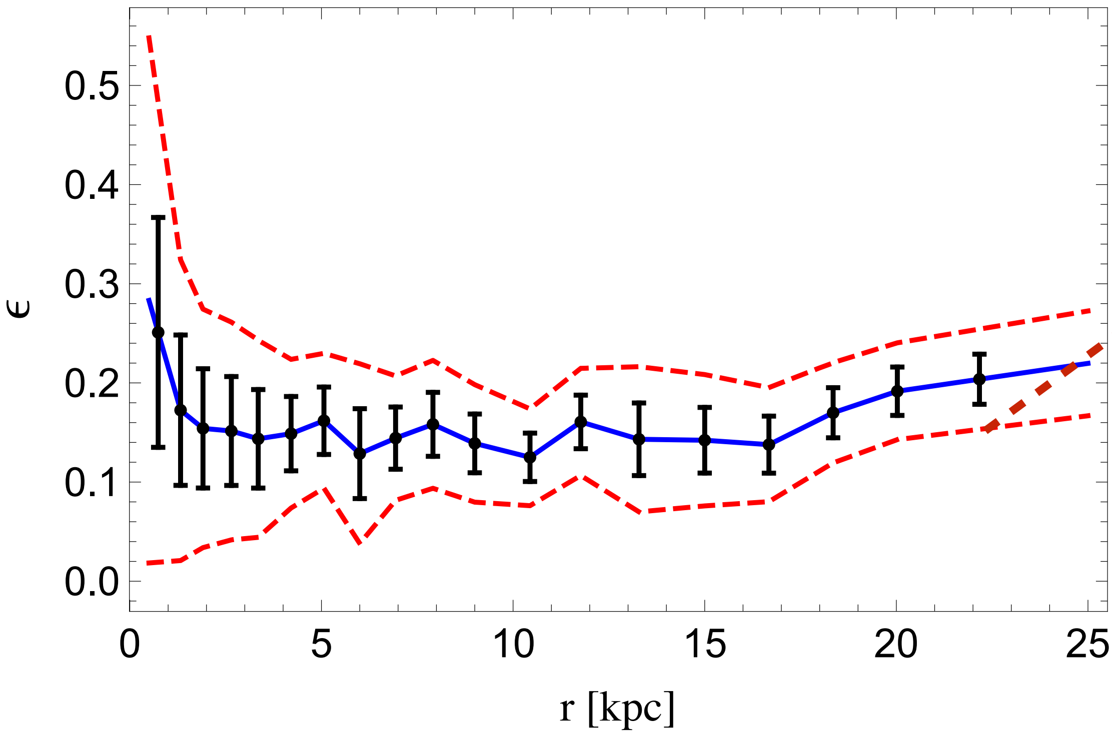
$$v_c \dot{v}_c = -\frac{8\sqrt{\pi}\alpha_D^2 n_h}{3m_X^2 v_h^5}\left(v_c^2 - v_h^2\right)^2 \log\Lambda,$$

Density and velocity dependent

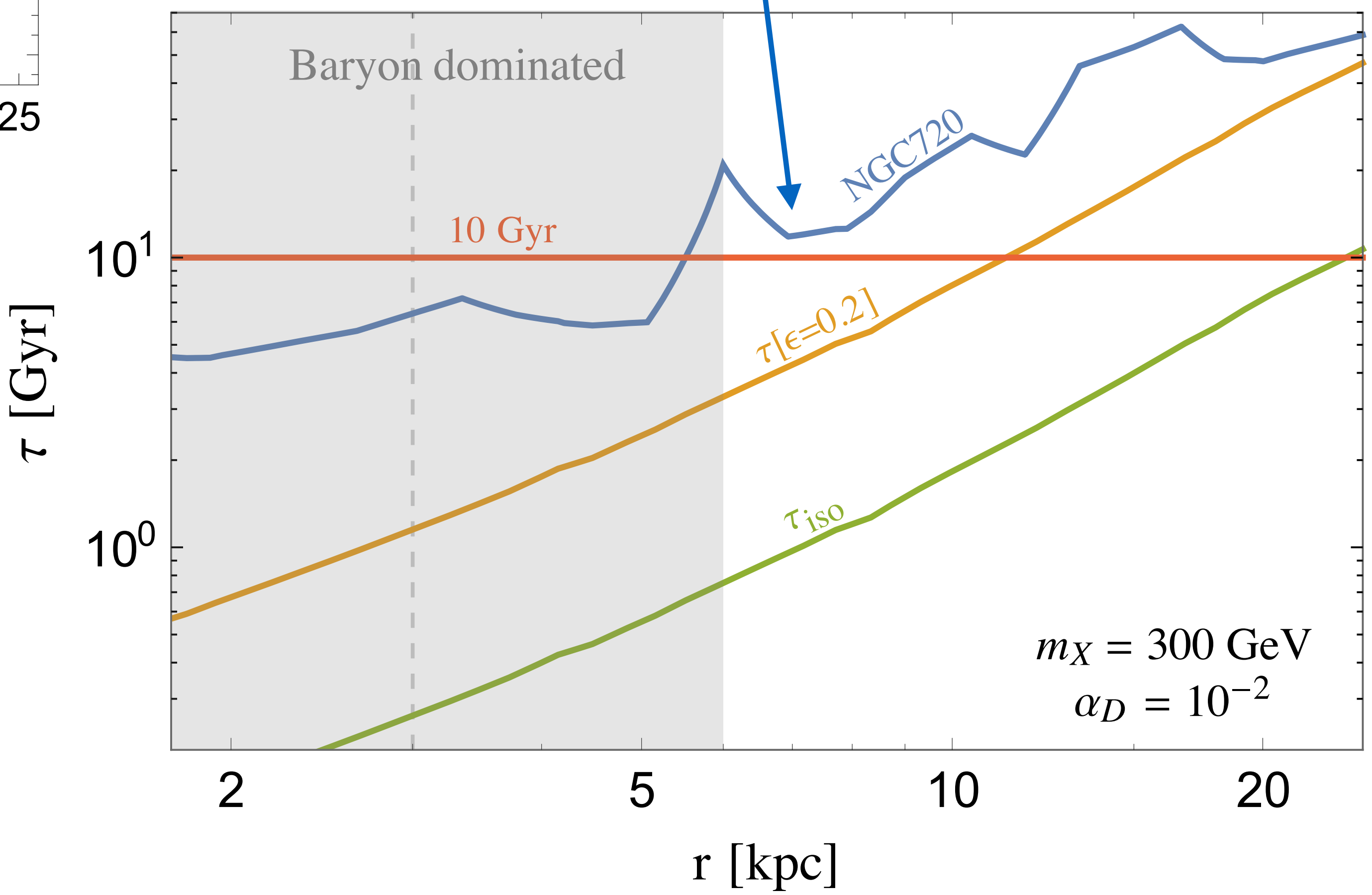
- We solve the full Boltzmann equation:

$$\frac{df(v_1)}{dt} = \int d^3v_2 d\Omega' |v_1 - v_2| \frac{d\sigma}{d\Omega'} \left(f(v_1)f(v_2) - f(v_3)f(v_4)\right)$$

Ellipticity Constraints



Take constraints from [astro-ph/0205469]



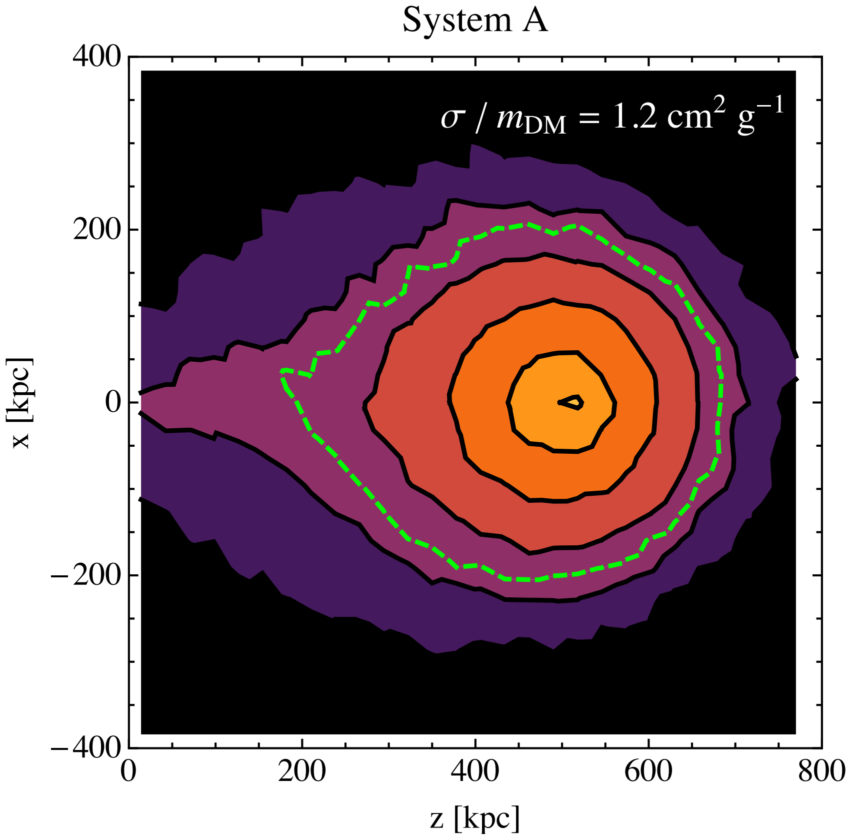
Other Constraints

- Merging clusters: Bullet cluster analysis requires that DM-DM cross-section is small-ish: at most nuclear sized [1308.3419]:

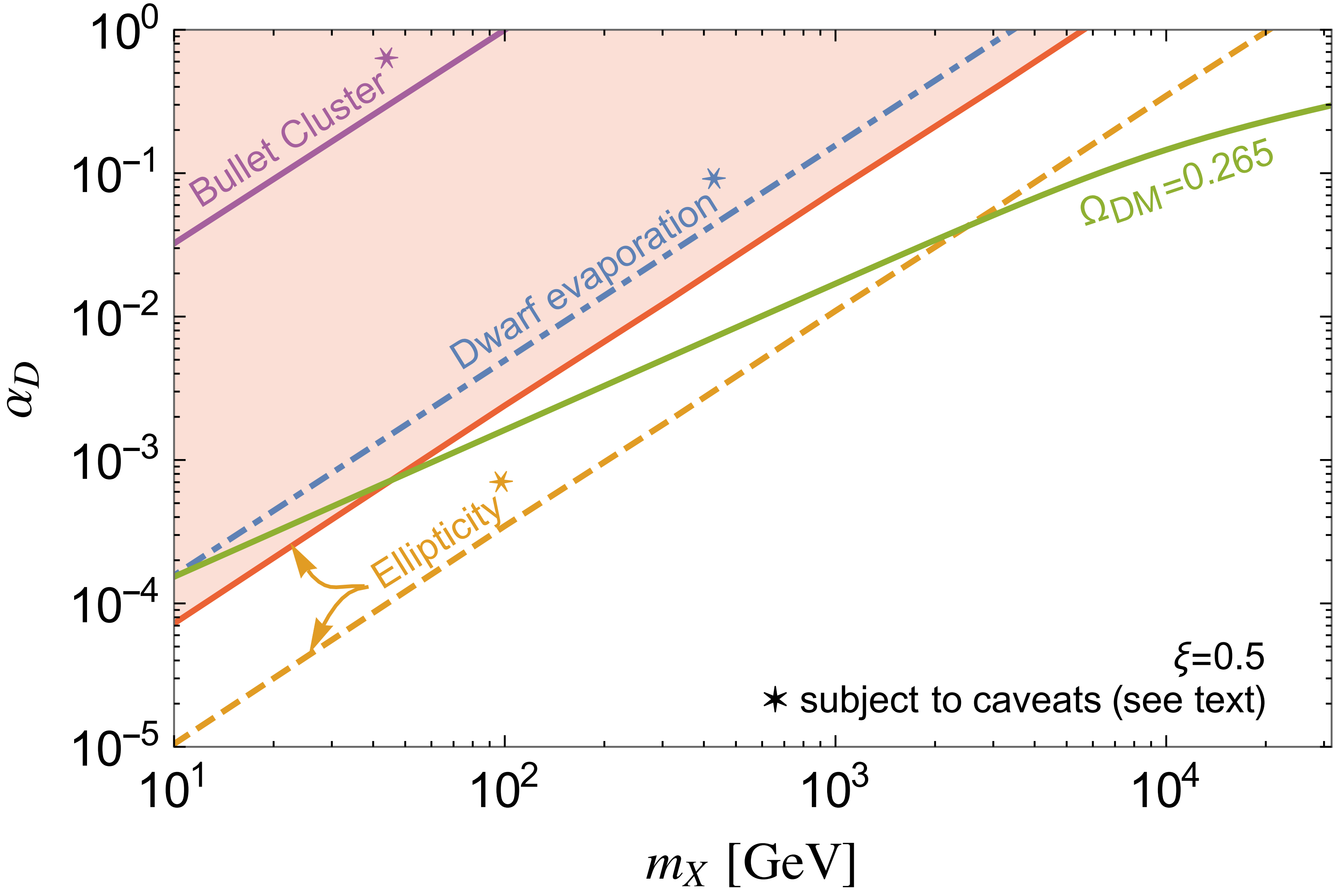
$$\frac{\alpha'^2}{m_{\mathrm{DM}}^3} \lesssim 550\,\mathrm{GeV}^{-3}$$

- As dwarf galaxies travel through the DM halos of their hosts, they experience drag and stripping: since we see them after 10GYr, the cross-section can't be too large. [1308.3419]

$$\frac{\alpha'^2}{m_{\mathrm{DM}}^3} \lesssim 10^{-11}\,\mathrm{GeV}^{-3}$$



Charged Dark Matter Conclusion



As a result, even a frozen-out charged dark matter is safe as long as

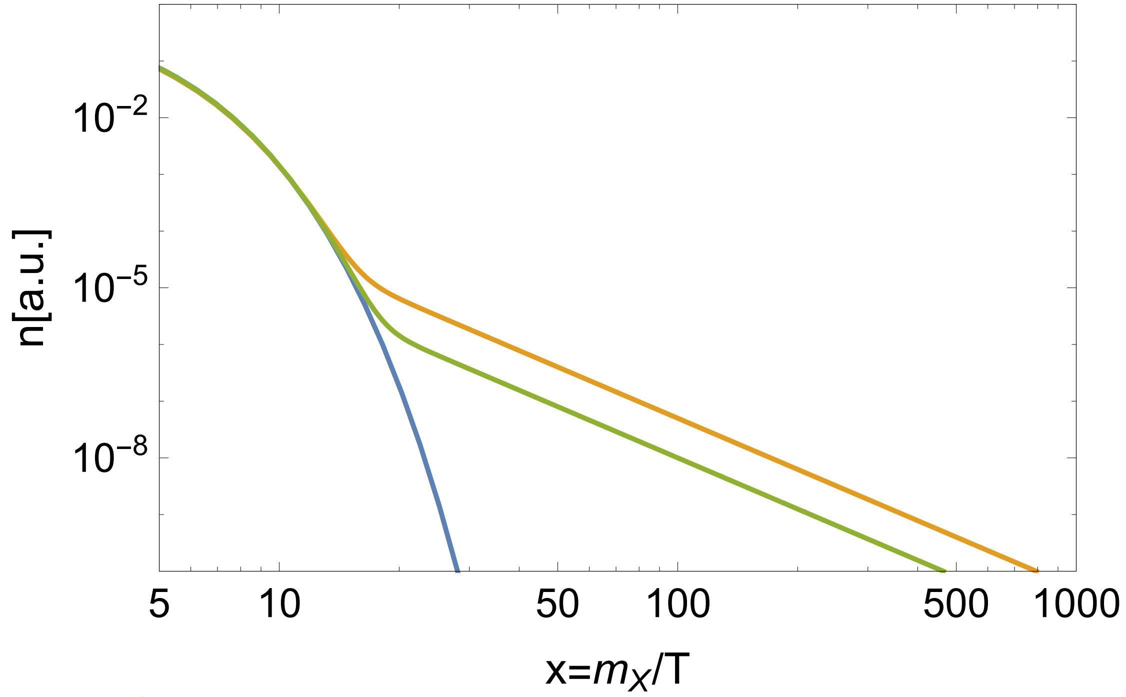
$$m_X \gtrsim 50\ \mathrm{GeV}$$

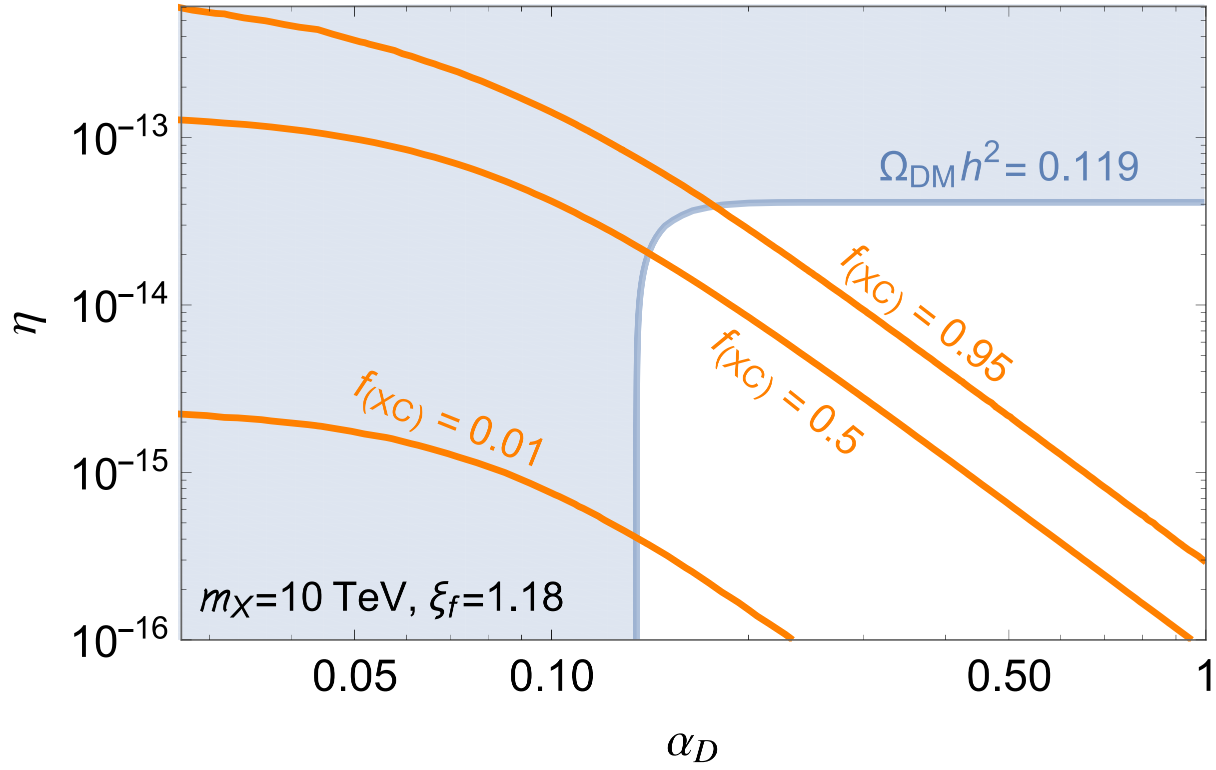
Ask me about caveats!

back to $X, \bar{X}, C$

Asymmetric Relic Abundance

- For a symmetric freeze-out: as the DM annihilates both populations are getting depleted
- For an asymmetric freeze-out, one of the populations (say X) will always be available: this type of freeze-out is much more efficient.
- There are two regimes:
  A. Freeze-out before the asymmetric population matters: regular freeze-out
  B. Freeze-out when the asymmetry matters: mostly determined by the initial asymmetry



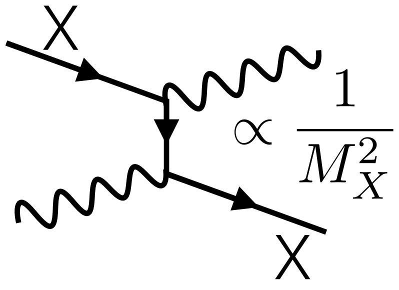


Structure Formation

- In the Early Universe the dark sector is populated by: Dark Radiation, Xs, Cs

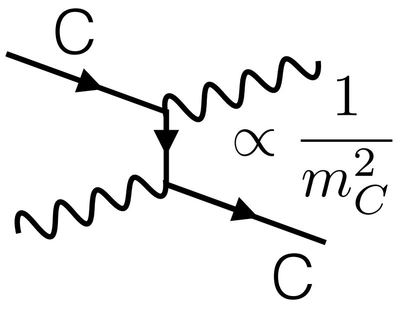
Dark radiation might erase structure!!!

- The Xs are too heavy to efficiently interact with dark radiation.



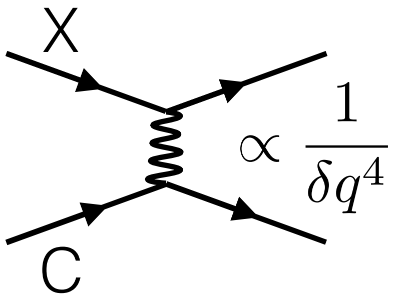
$\propto \frac{1}{M_X^2}$

- However, the Cs are light enough to get pushed around by the radiation.

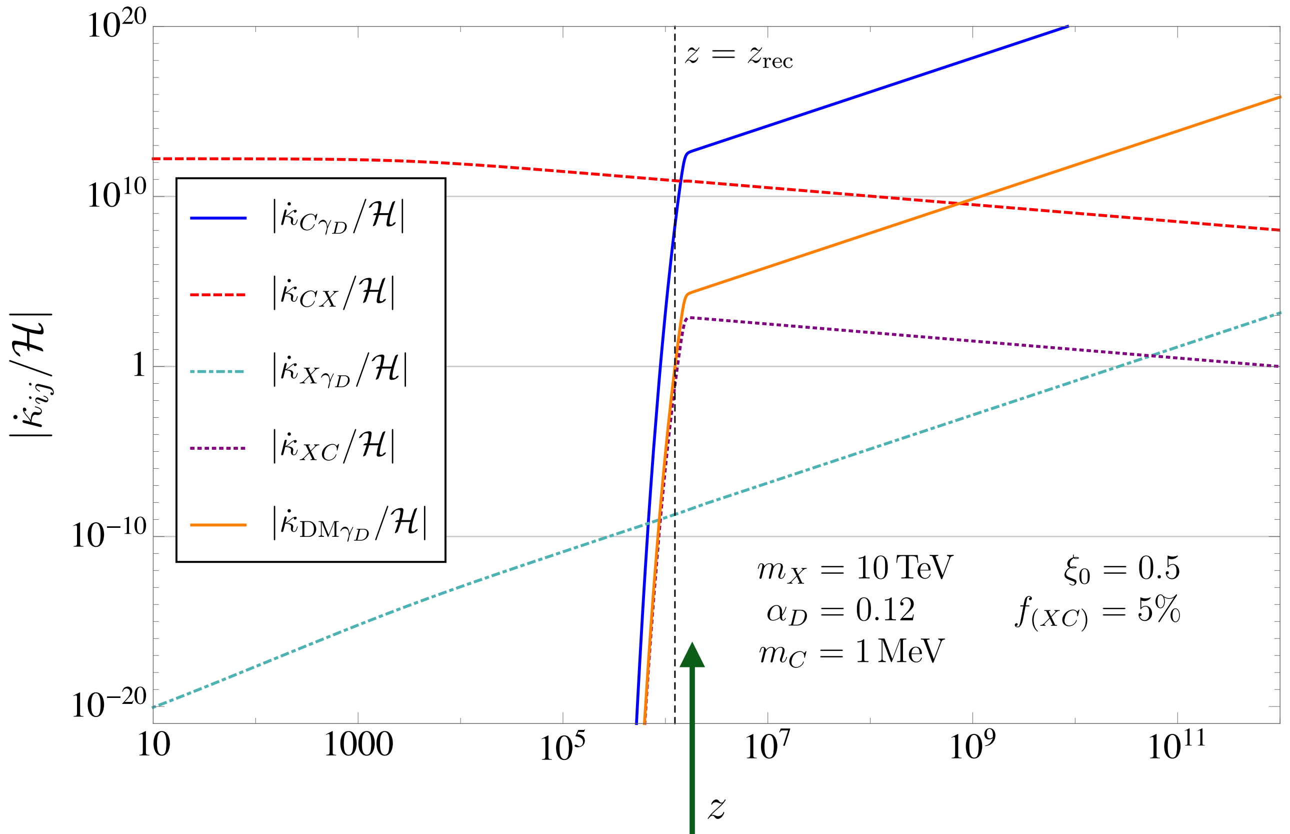


$\propto \frac{1}{m_C^2}$

- Cs interact strongly enough to recouple the Xs to the radiation. This is why we call this model Dark Catalysis.

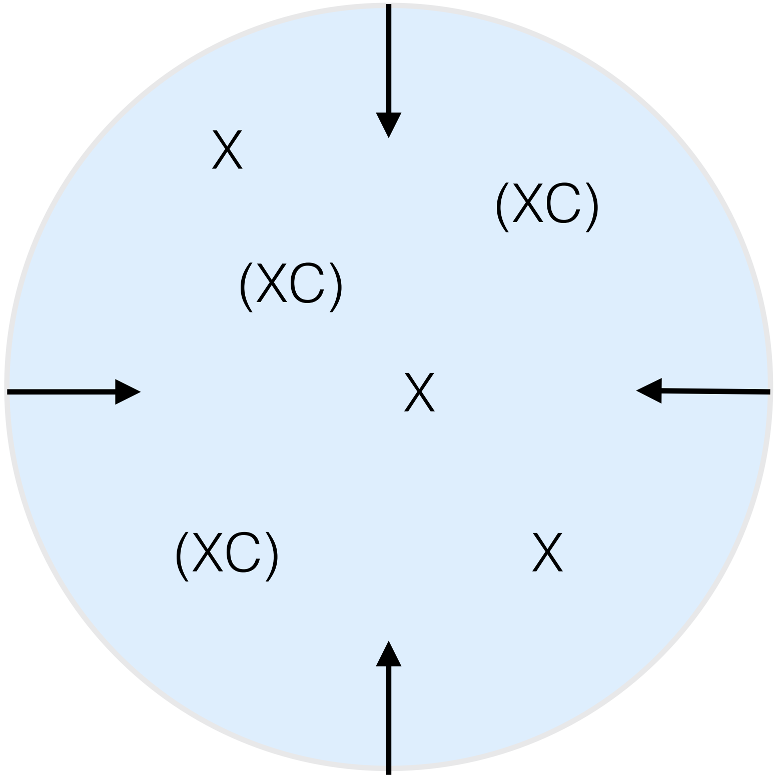


$\propto \frac{1}{\delta q^4}$

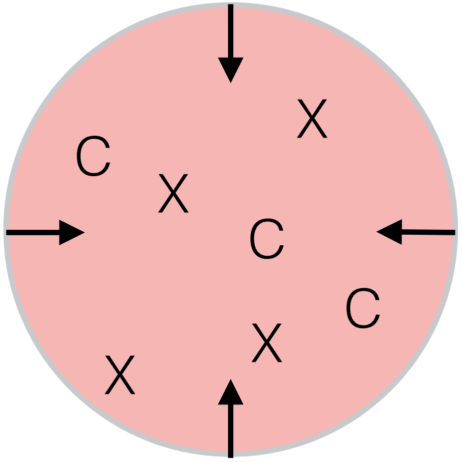


Recombination can save us!

Dissipative Dynamics I



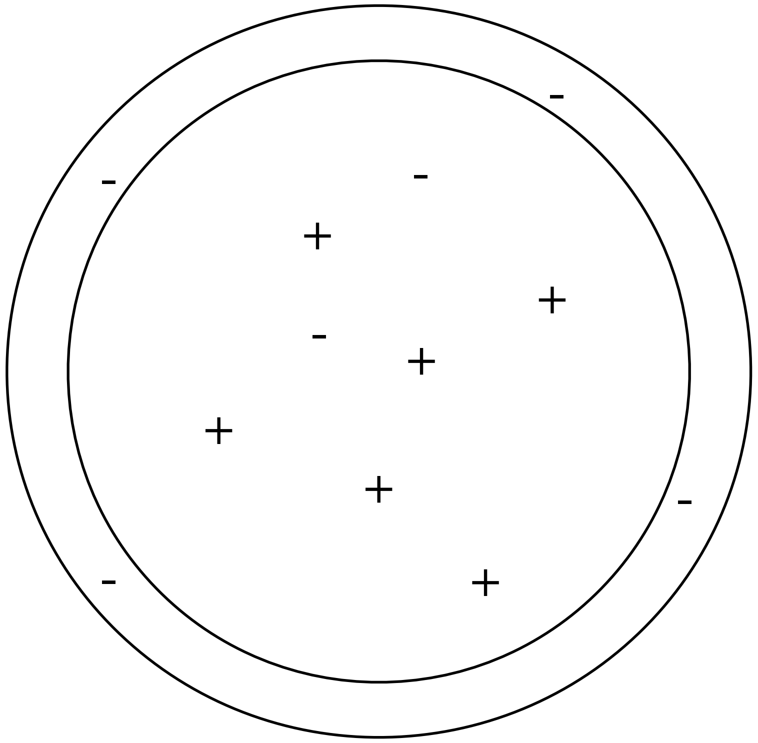
- Typically, at the beginning of galaxy formation the Cs are only in the bound states (XC).



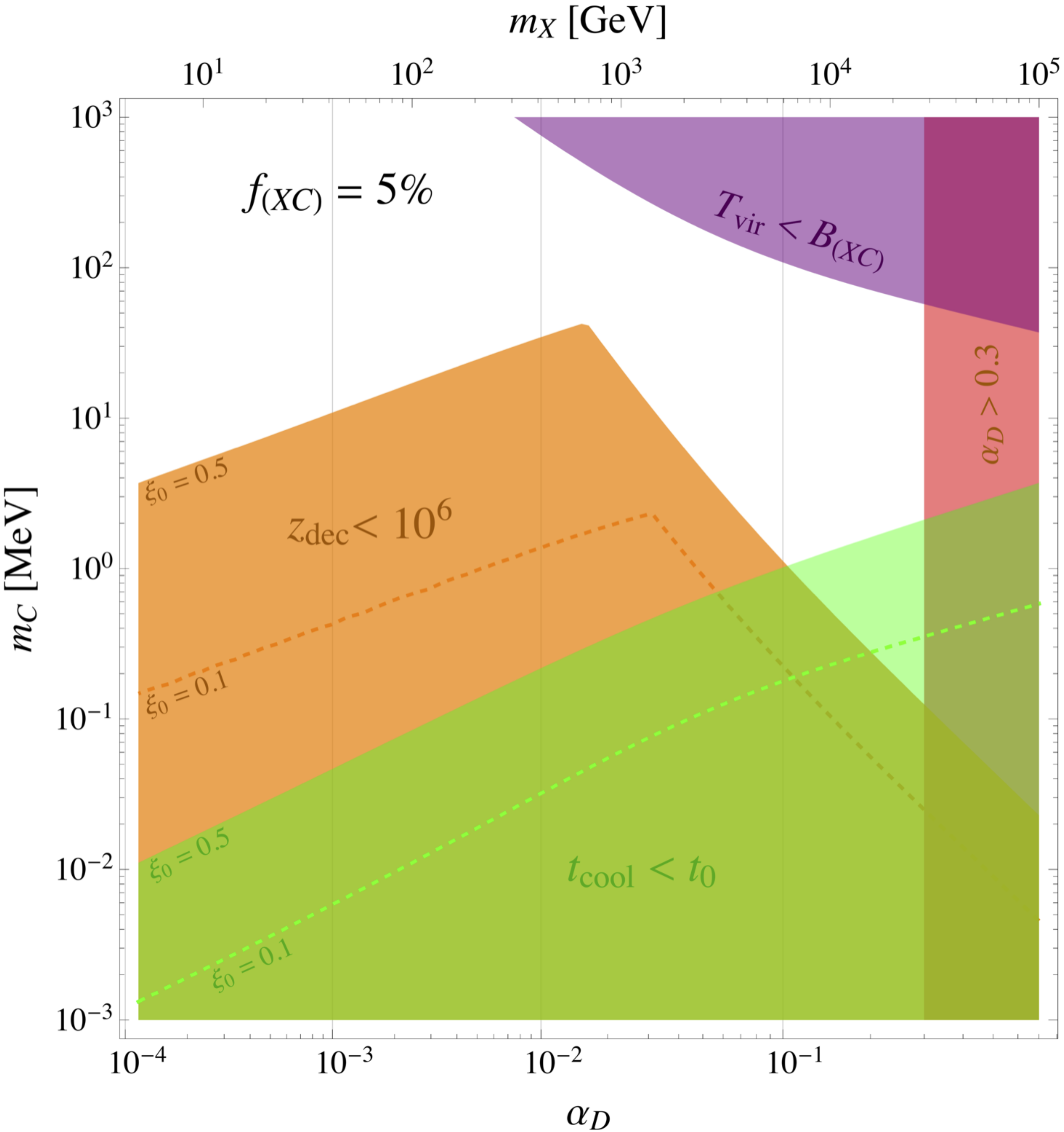
- As the gas falls into the galaxy, it heats up and re-ionizes.

Dissipative Dynamics III

- We need to make sure that:
  1. Not all Xs are in kinetic equilibrium with Cs: otherwise all of dark matter flattens.
  2. The virial temperature is high enough to ionize the (XC) bound state.
  3. We treat possible large scale electric fields correctly.
  4. Are there plasma instabilities?



Structure Formation Constraints

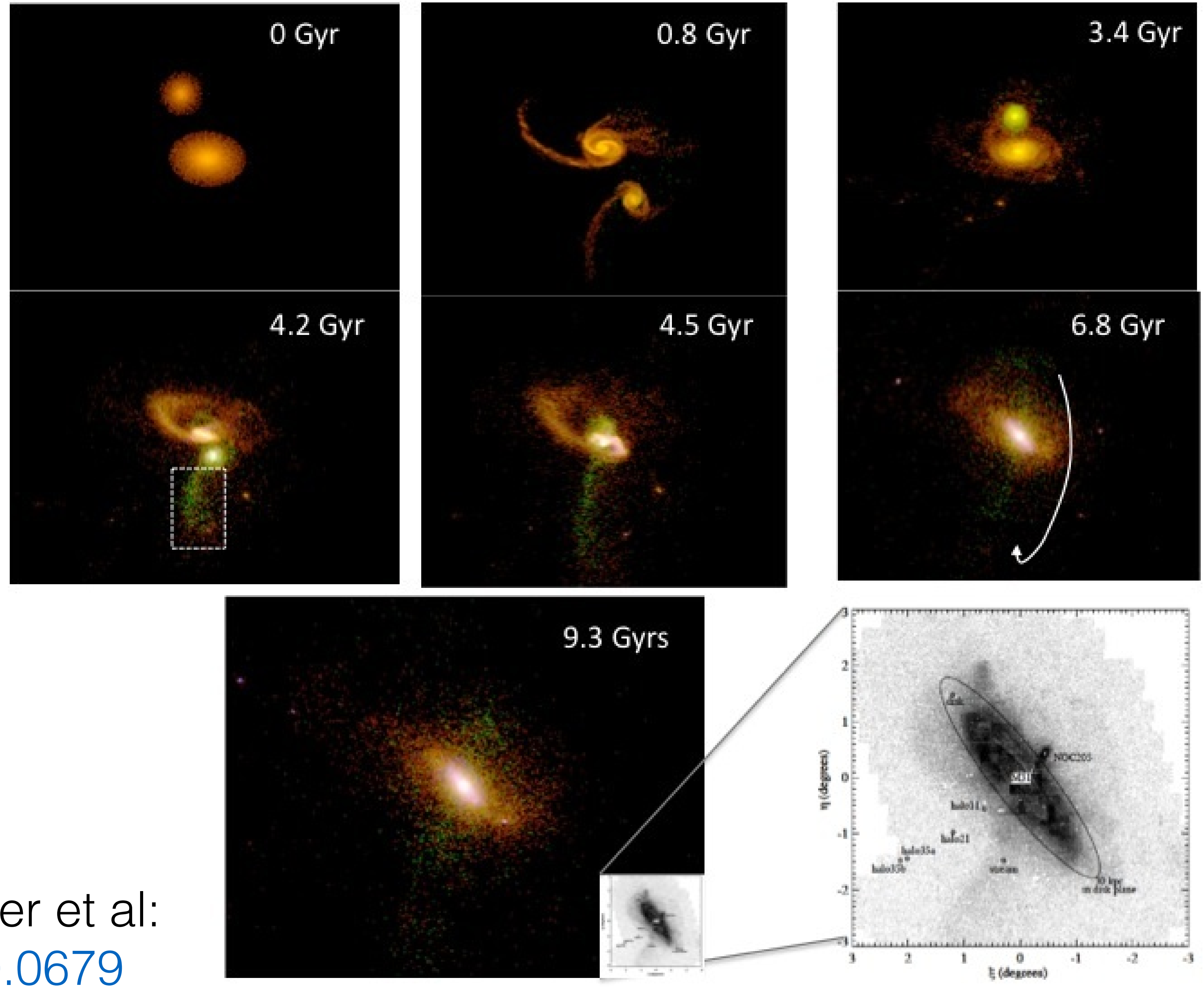


Next Iteration:

Use three fermions!

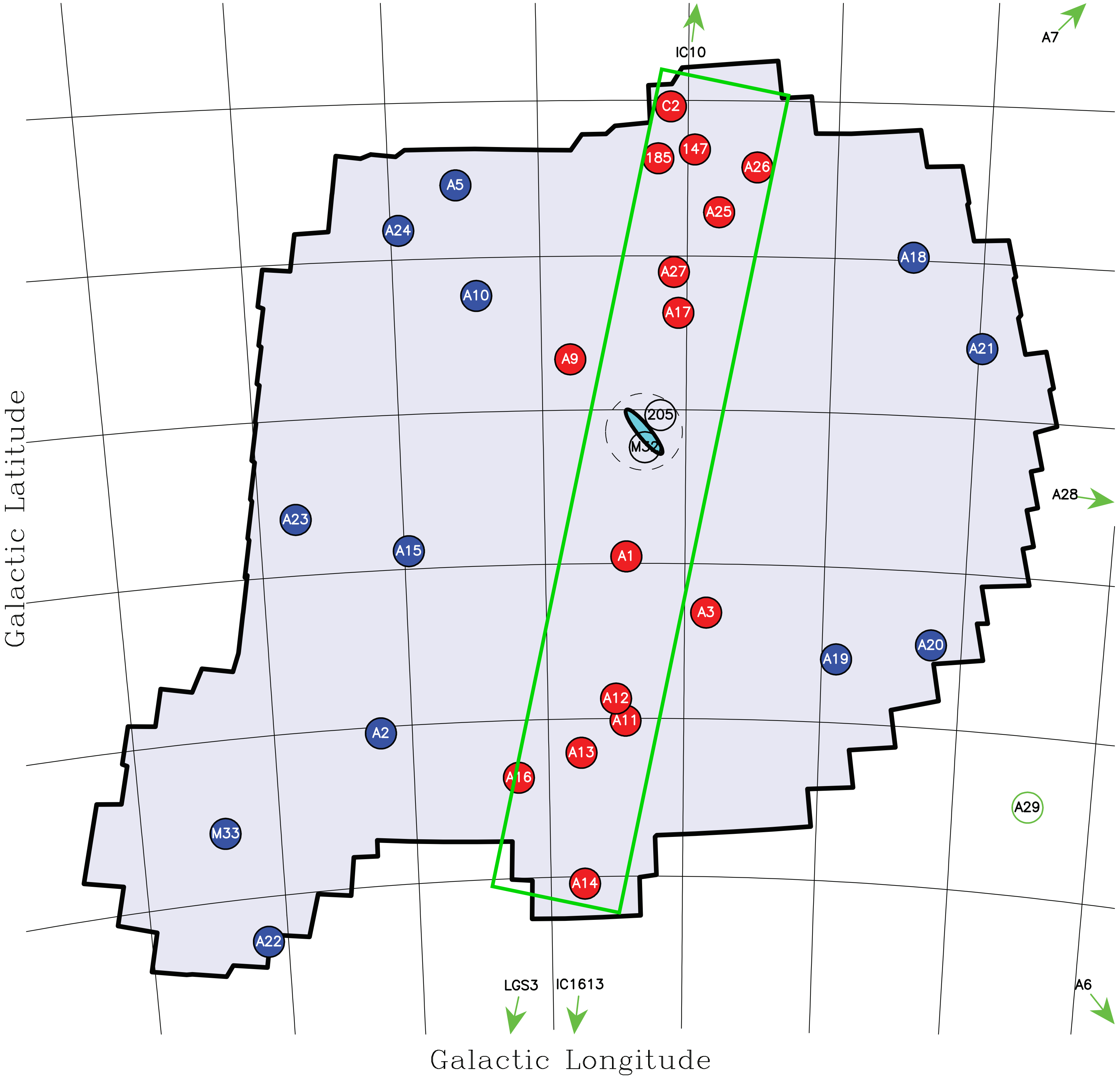
And now for something completely different…

2010: Formation of Andromeda as a merger of two galaxies reproduces many properties of the galaxy



Hammer et al: 1010.0679

2013: Andromeda Plane of Satellites



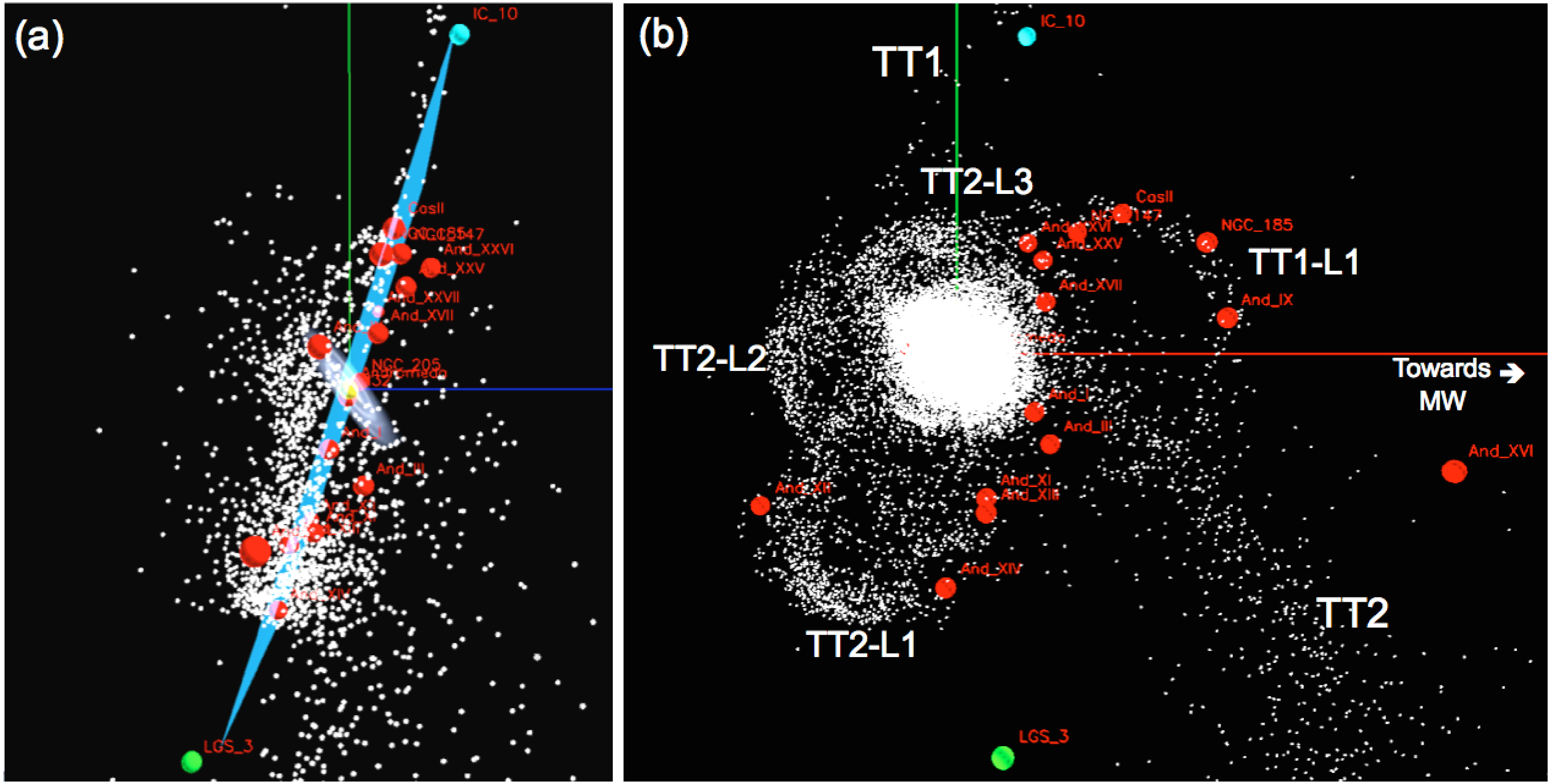
R=400kpc

w=14kpc

sig = 4.1σ

Ibata et al
1301.0446

2013: Merger history predicts streams that might form into TDGs

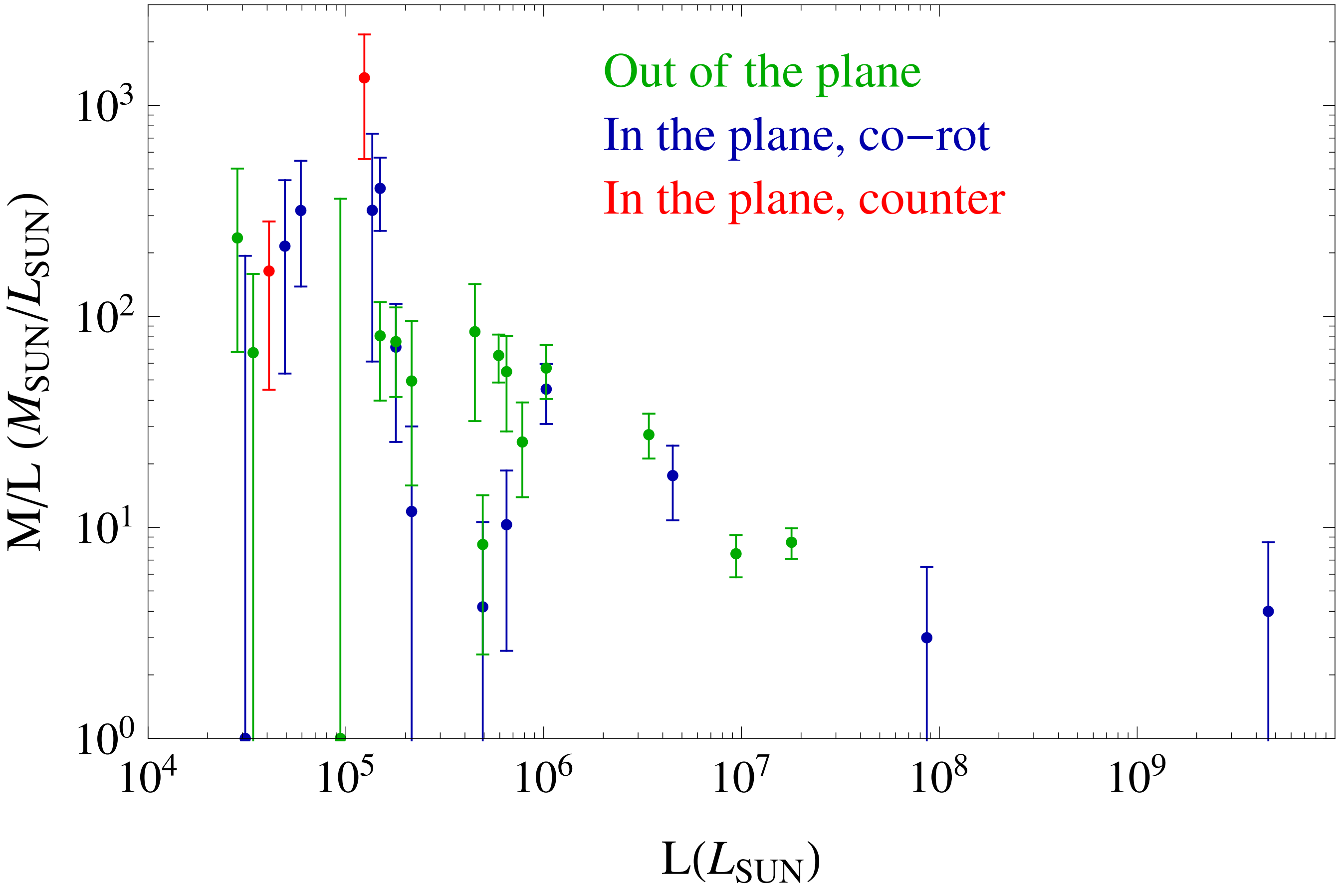


Hammer et al: 1303.1817

Too much Mass/Light

1303.1817 : “If TDGs are progenitors of many dSph in both MW and M31 outskirts, it leads to an absence of dark-matter (DM) in galaxies that are being thought to be the most DM — dominated systems. Clearly the above ballistic exercise has to be discarded if the dark matter (DM) content of dSphs is large (Strigari et al. 2008) as inferred from their large velocity dispersions”

dSph	$M/L(1)$	$M/L(2)$	$M/L(3)$
And I	21 ± 5	–	18 ± 7
And III	14 ± 12	–	45 ± 14
And IX	88^{+167}_{-88}	–	404 ± 150
And XI	78^{+183}_{-78}	216^{+115}_{-87}	215 ± 162
And XII	77^{+176}_{-77}	0^{+194}	0^{+194}
And XIV	63 ± 55	–	71 ± 46
And XVI	39^{+79}_{-39}	–	$4.2^{+6.4}_{-4.2}$
And XVII	–	–	12^{+16}_{-12}
And XXV	–	$10.3^{+7.0}_{-6.7}$	10 ± 8
And XXVI	–	325^{+243}_{-225}	318 ± 179
Cass II	–	308^{+269}_{-219}	318 ± 257
NGC 147	3 ± 0.5	–	–
NGC 185	4 ± 0.5	–	–



Data from: 1204.1562, 1302.6590

Proposed Solutions

- Maybe the satellites are not in equilibrium, and the dynamically measured mass is incorrect. Satellites are often tidally disrupted. Some of the gas may have been stripped as they pass close: 1405.2071
- MOND predicts large apparent M/L ratios: 1301.0822
- Mirror Dark Matter: 1306.1305
- Double Disk Dark Matter!

Dark Disk Helps

- There is a significant amount of dark matter with the same distribution as baryons. So whatever the baryons do, DDDM is likely to do as well.
- Moreover, dissipative dark matter may be colder, lees prone to evaporation:

$$\sigma^2_{dm} \leq \sigma^2_{bar}$$

- And clumpy: easily forming seeds of future dwarf spheroidals:

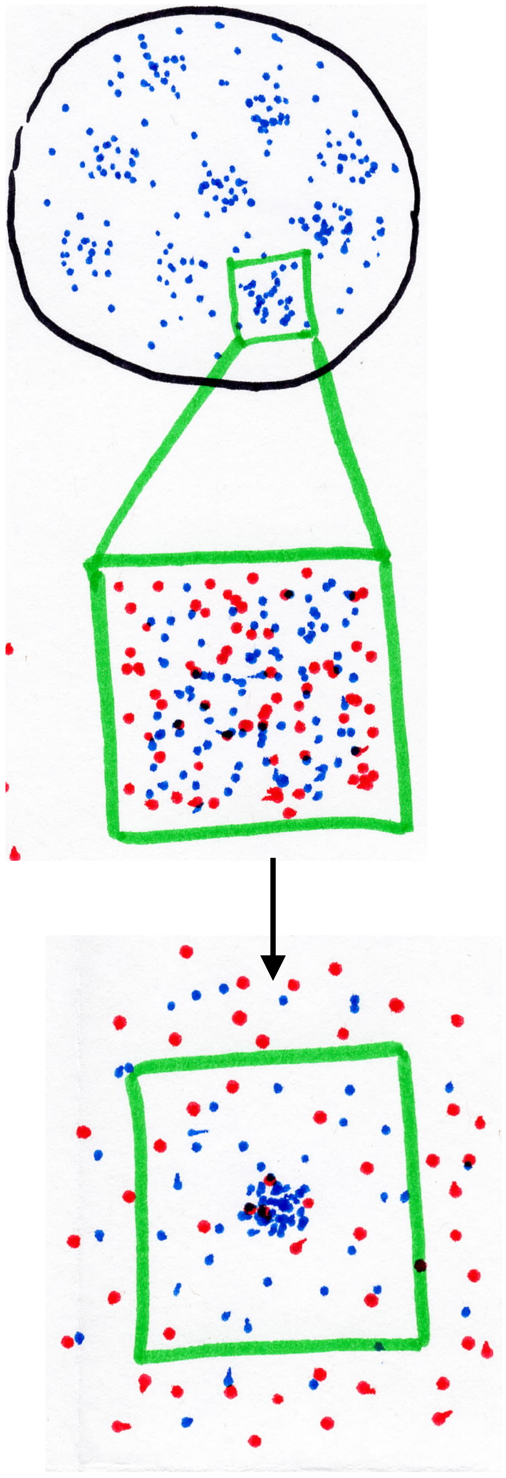
$$\Sigma_{dm}(1/k_-)^2 \approx 10^7 M_\odot$$

Analytic Results?

Unfortunately, it is hard to make any reasonable analytical predictions:

1. Gravitational systems are unstable: without additional effects, the final state is always a black hole.
2. One cannot treat the two components (baryons, DM) separately and only a small amount of leakage between the components can change the result.
3. The initial conditions do not correspond to an equilibrium.
4. Even the mean field potential is time dependent.

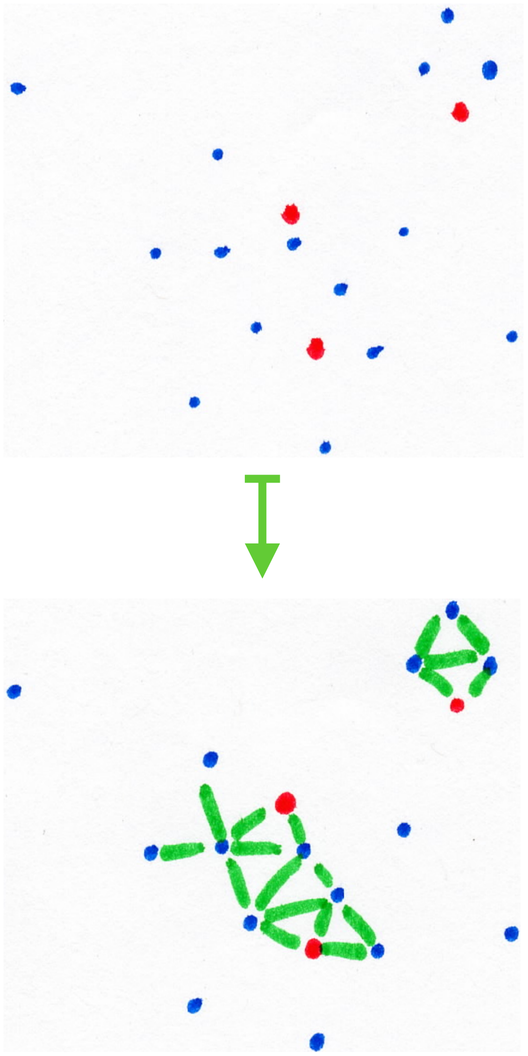
The “Experimental” Setup I

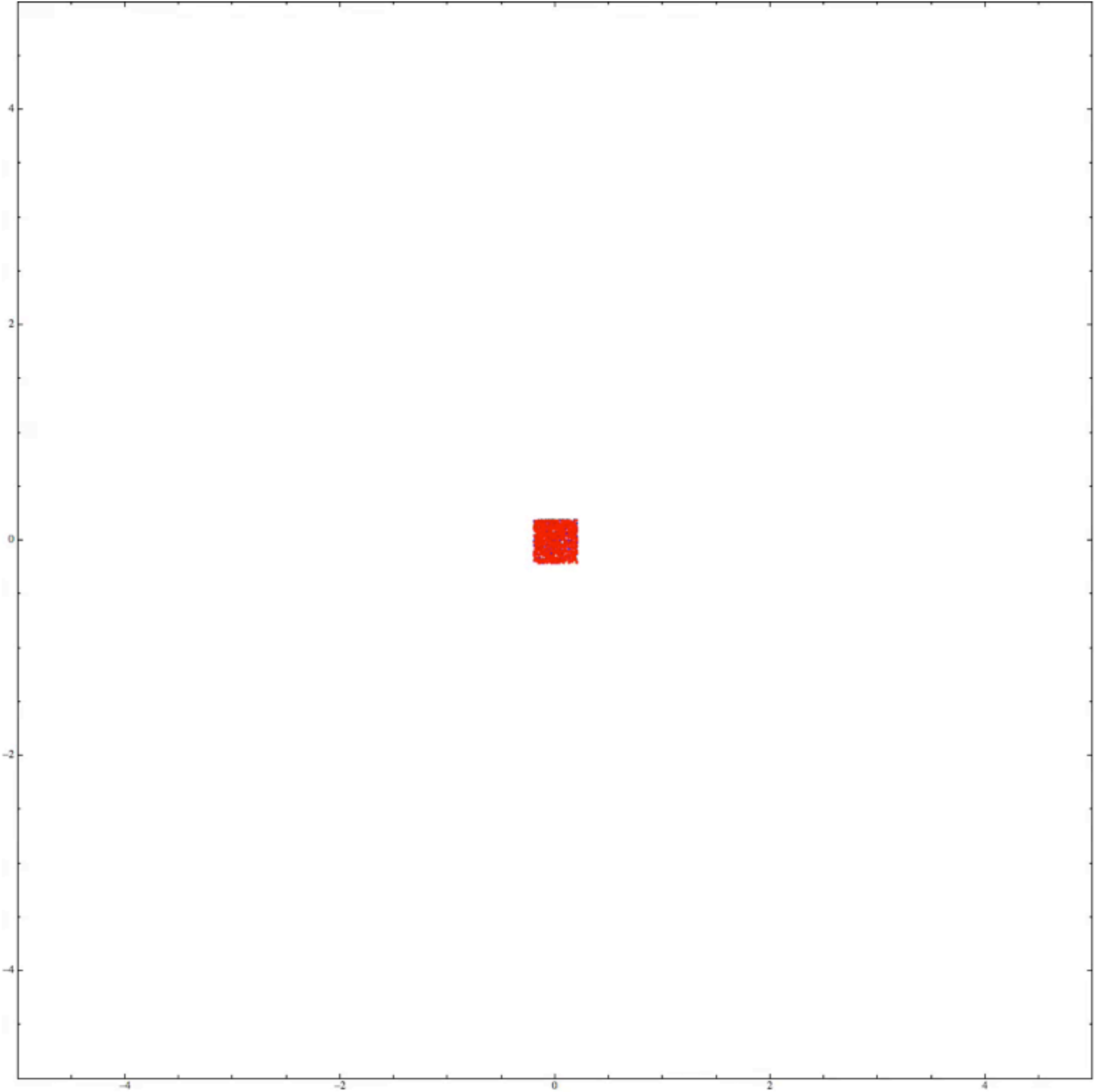


1. Take patches the size of Toomre instabilities in the disk: those are likely to form objects anyway.
2. Take a single patch from the smaller of the two progenitor galaxies.
3. Isolate this patch from the rest of the galaxy.
4. Let it evolve long enough to reach an equilibrium.

The “Experimental” Setup II

5. Find clusters of particles with a Friends of Friends algorithm.
6. Determine binding energies of each particle with respect to these clusters to determine the final number of bound particles.
7. Determine the final baryon to DM ratio.
8. Repeat to build up statistics and sample parameters.

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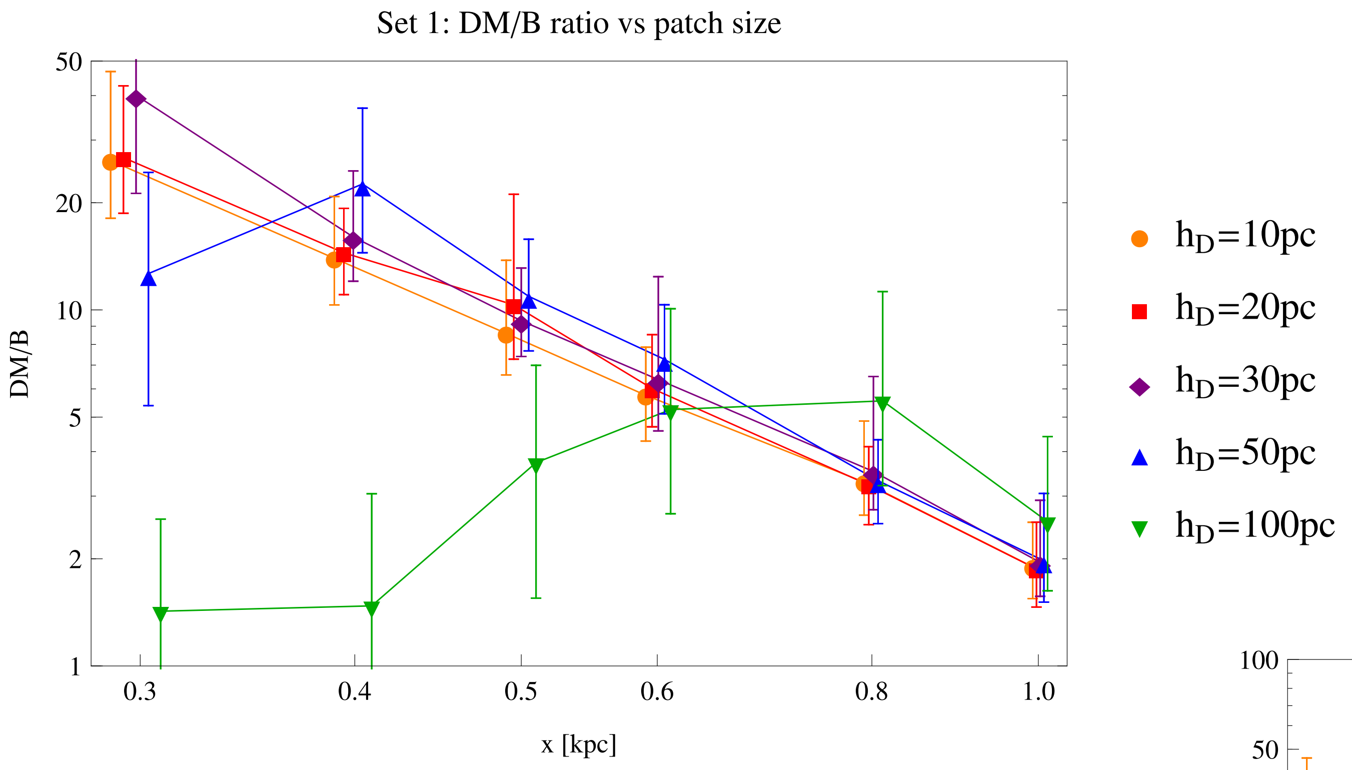
-2
-4
-4
-2
0
2
4

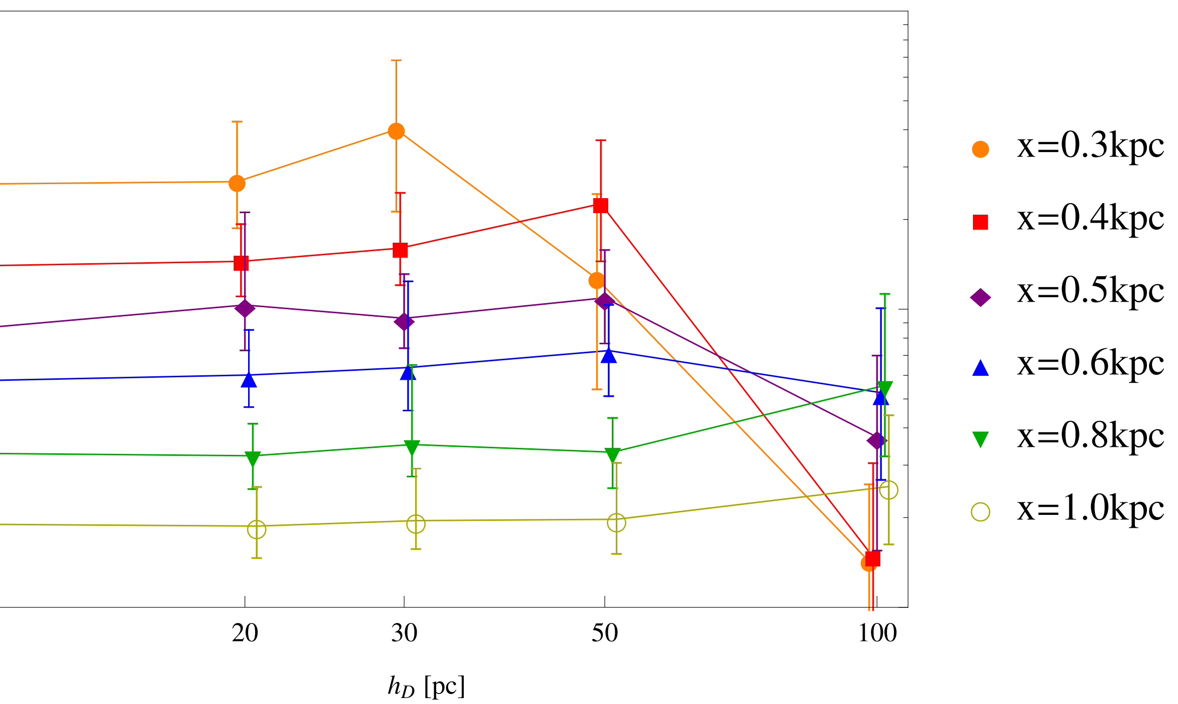
Benchmark Set: Results I

$$R = 4\text{kpc}, N = 1024, \Sigma_{dm} = 10^7 M_\odot/\text{kpc}^2, \Sigma_{bar} = 5{\times}10^7 M_\odot/\text{kpc}^2, h_B = 180\text{kpc/Gyr}$$

Set 1: DM/B ratio vs patch size

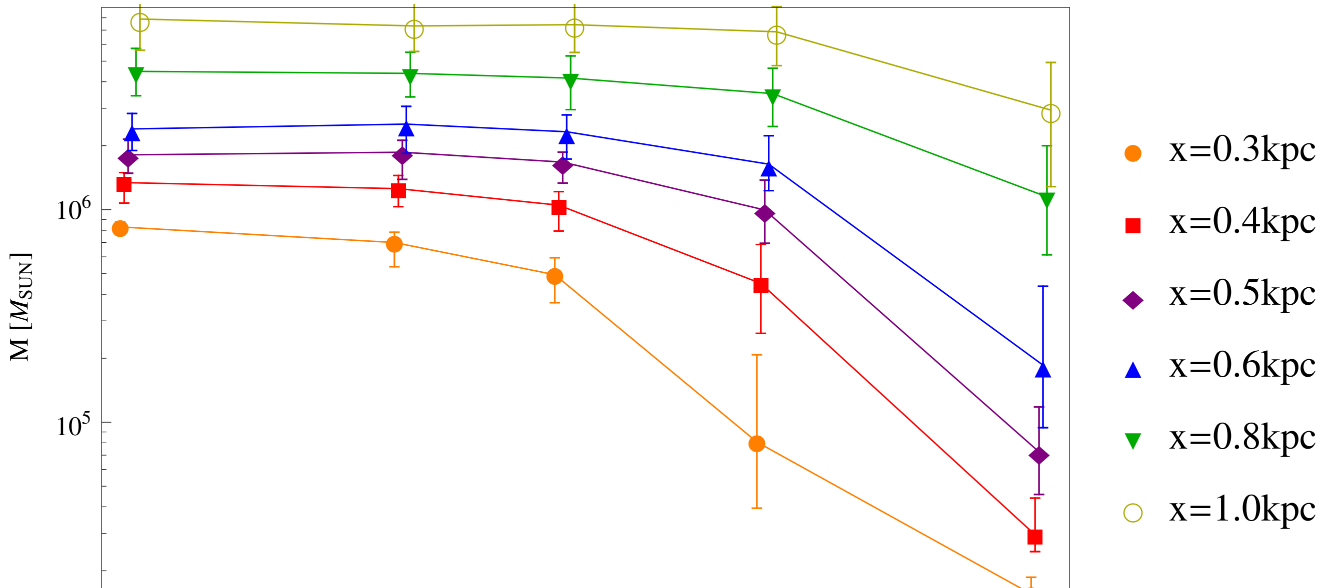


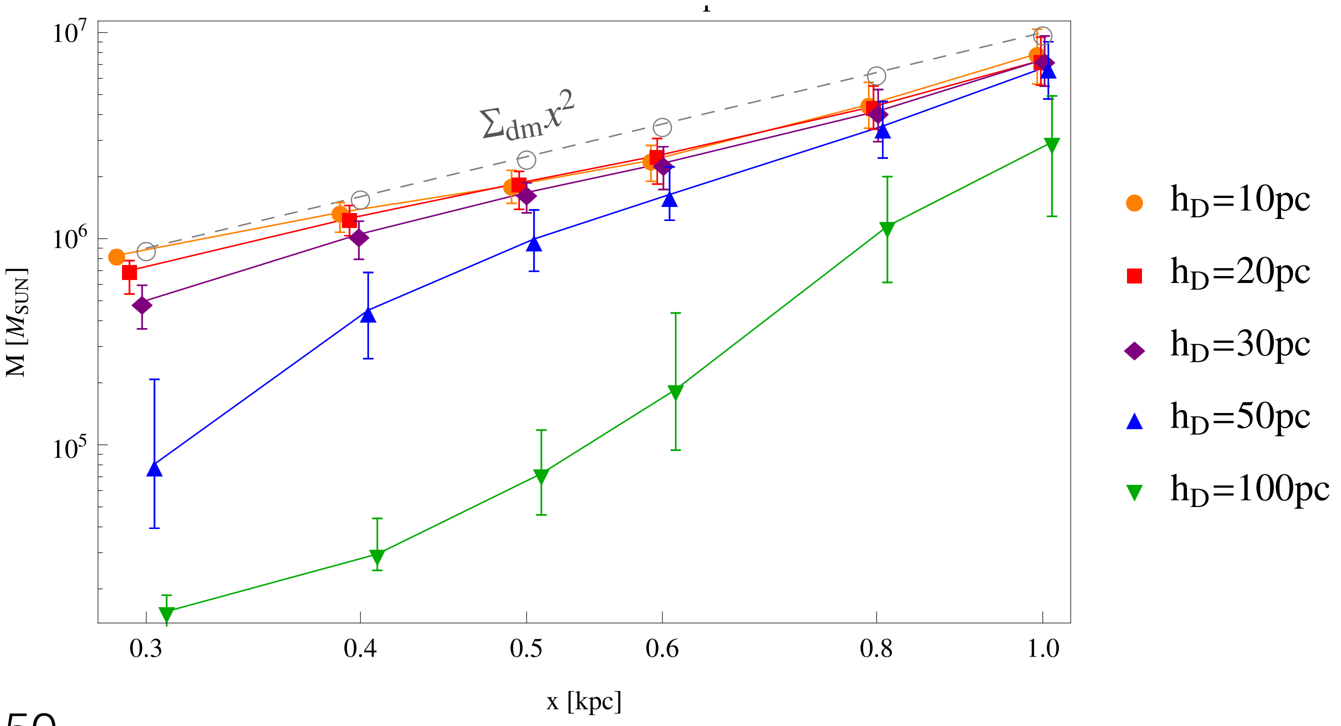
Set 1: DM/B ratio vs disk thickness



Benchmark Set: Results II

$$R = 4\text{kpc}, N = 1024, \Sigma_{dm} = 10^7 M_\odot/\text{kpc}^2, \Sigma_{bar} = 5\times10^7 M_\odot/\text{kpc}^2, h_B = 180\text{kpc/Gyr}$$


Set 1: Total Bound Mass vs disk thickness



Limitations

- We use small number of particles
- We only simulate a small patch rather than the entire merger.
- We pretend that baryons and dissipative dark matter can be simulated as non-interacting. In reality hydrodynamics is important to get TDGs right.
- Our initial state is highly idealized, both components start out as smooth.

Future Work

- All of the previous complaints can be addressed by using a more sophisticated software.
- Once we modify any of the available programs to include hydrodynamics of the Dissipative Dark Matter, we can do great things:
  1. Look at structure formation in the early Universe.
  2. Check the DDM distribution in a galaxy.
  3. Follow a merger that formed Andromeda and check our results.

Potential Signals

- Formation of disks: star and gas kinematics in our neighborhood,
- More detailed tests of dark matter morphology such as overcooling, fragmentation, point sources.
- Galactic DM halo ellipticity measurements
- Non-standard filament formation
- Shapes of dwarf galaxies, from drag, heating and formation
- Diffuse galaxies from heating inside galaxy clusters
- Number of effective degrees of freedom
- Direct detection: co-rotating disks lead to higher density, lower relative velocity and different peak in annual modulation.
- Planes of tidal dwarf galaxies in Milky Way and Andromeda

Conclusions

- Dissipative DM is **fun**: many signals, complicated/rich phenomenology, can solve anomalies — sometimes there are **surprises**.
- Pretty cheap, particle contents wise.
- It’s okay to **complicate** the DM sector: “if the **simple** approach **does not work**, take the complicated one”. (perhaps a more general life lesson)
- It would be great to work on **full cosmological simulations** of this theory.

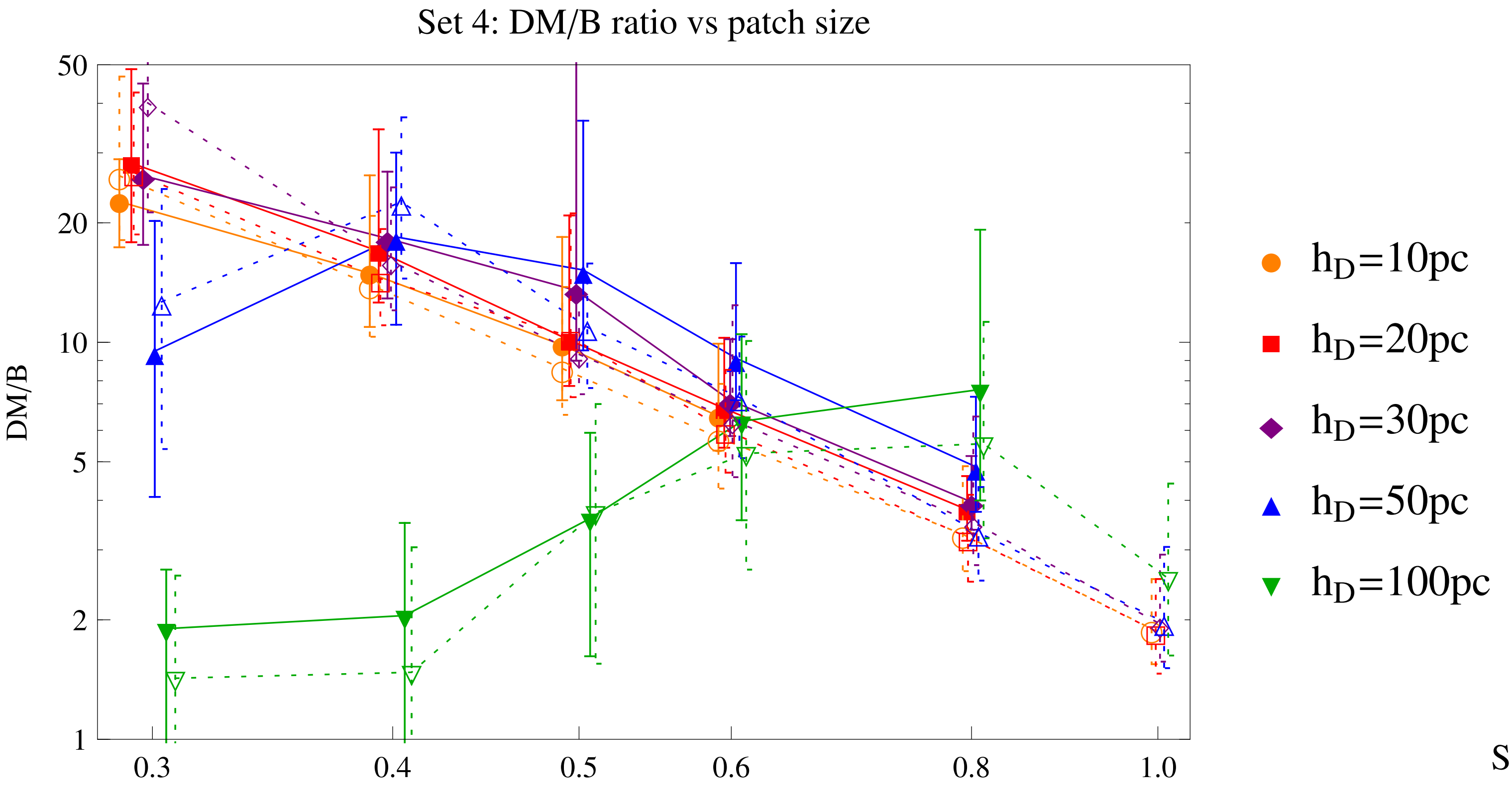
Back-up

Fixed Mass Set: Motivation

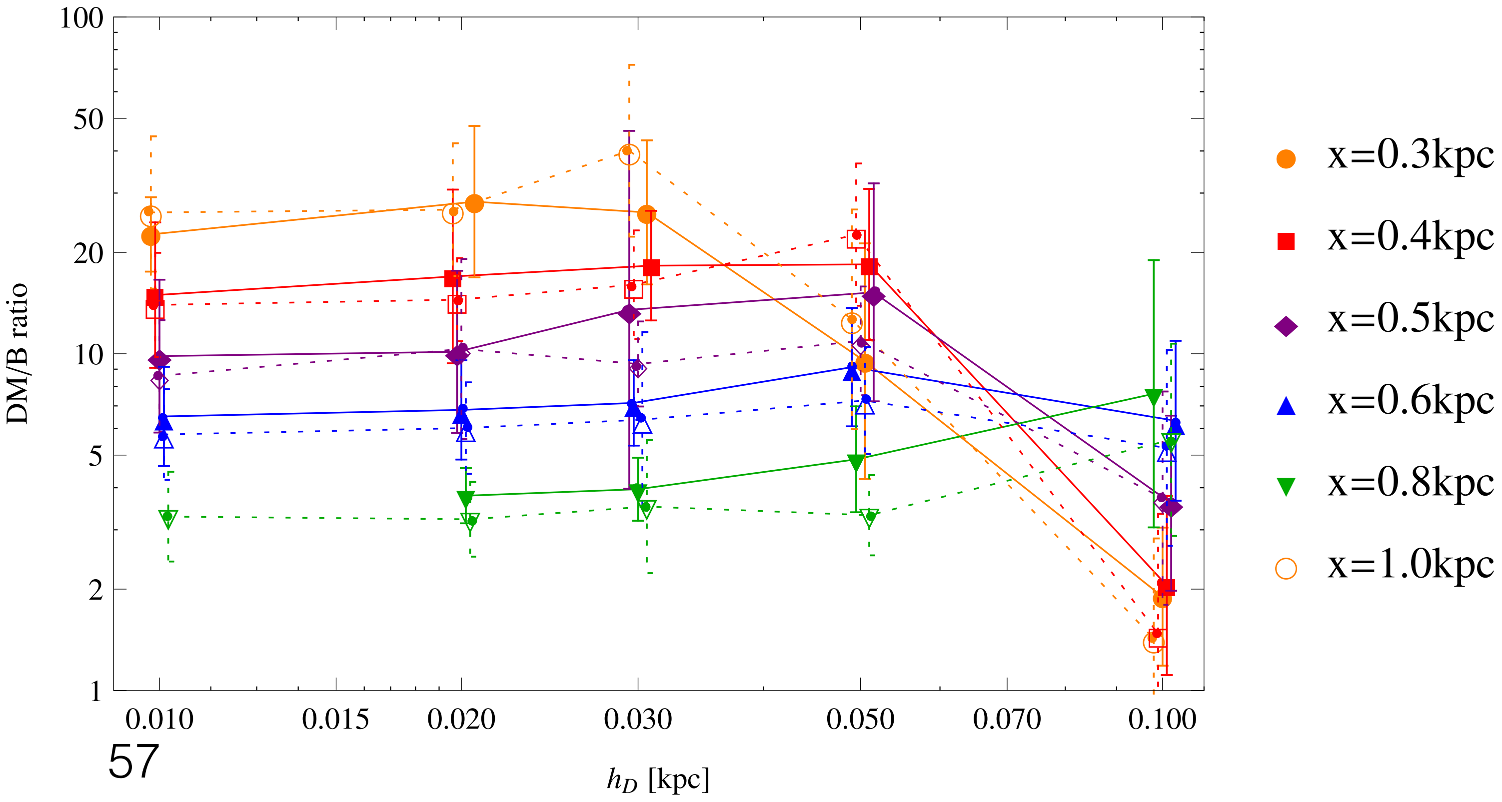
- A lot of previous results appear to strongly depend on the size of the patch.
- Keeping fixed number of particles implies different particle masses — potential source of systematic effects.
- We run another set for which each simulation has exactly the same particle mass:

$x[kpc]$	N(Extended Run)	N(Fixed Mass Run)
0.3	1024	540
0.4	1024	960
0.5	1024	1500
0.6	1024	2160
0.8	1024	3840

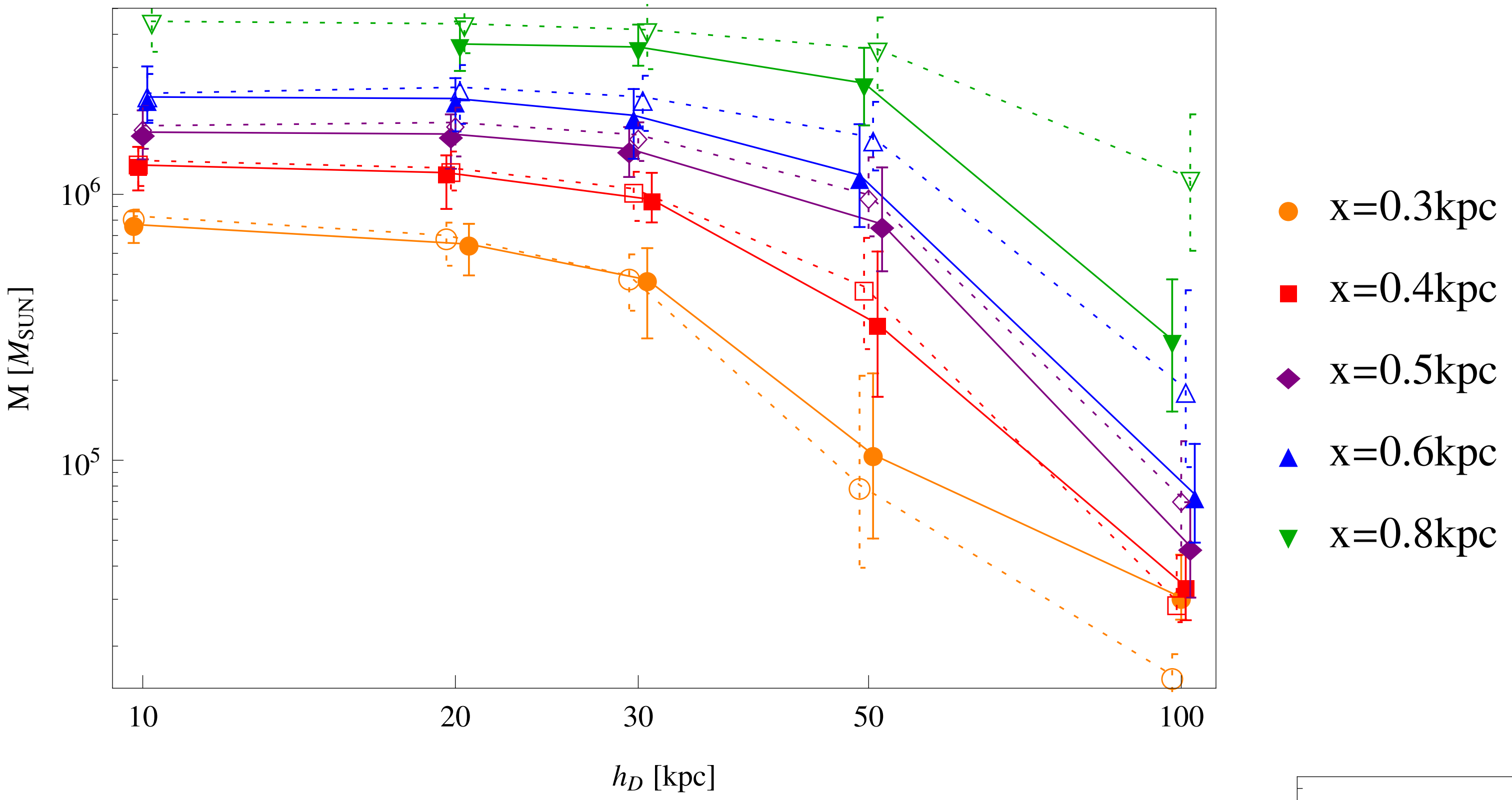
Fixed Mass Set: Results I

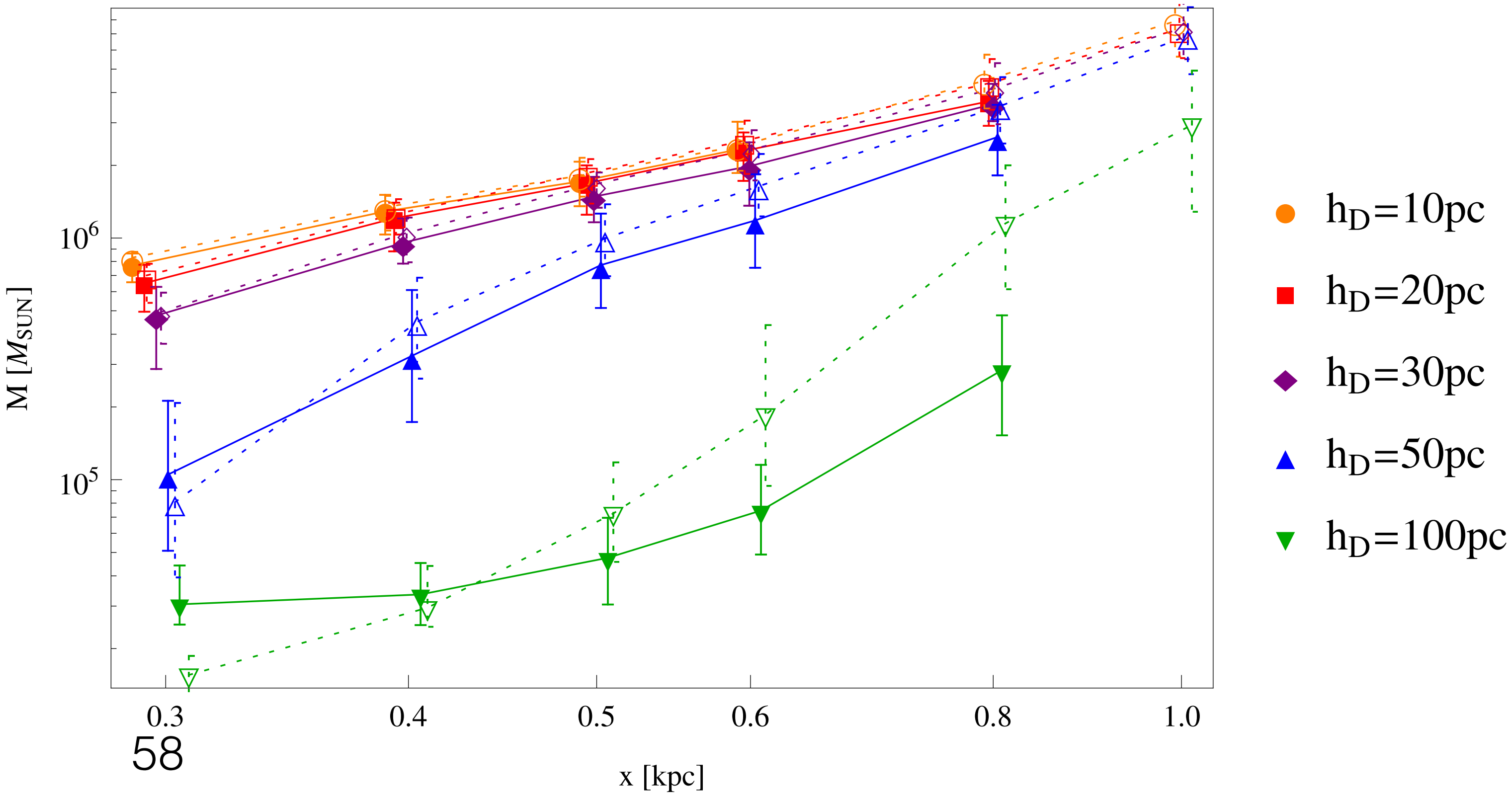


Set 4: DM/B ratio vs disk thickness



Fixed Mass Set: Results II


Set 4: Total Bound Mass vs disk thickness


Set 4: Total Bound Mass vs patch size