Title: Charged BBN and Dark Matter Models

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Abstract:


CBBN and Dark Matter Models
Collaborators:
James Bullock (UCI)
Arvind Rajaraman (UCI)
Louis Strigari (Postdoc, UCI)
Greg Martinez (Graduate student, UCI)
Quinn Minor (Graduate student, UCI)
Manoj Kaplinghat
Center for Cosmology
Physics and Astronomy
UC Irvine
photo by Art Rosch

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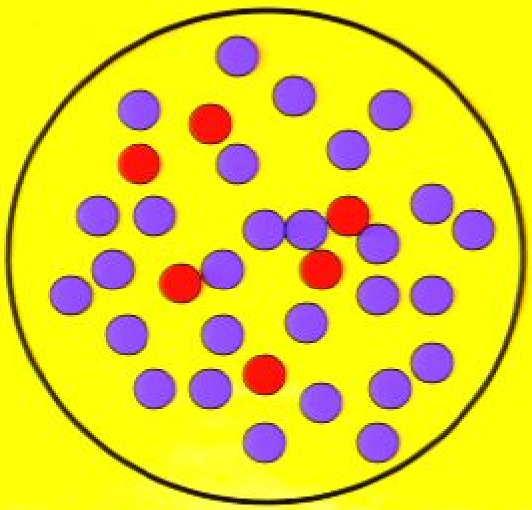

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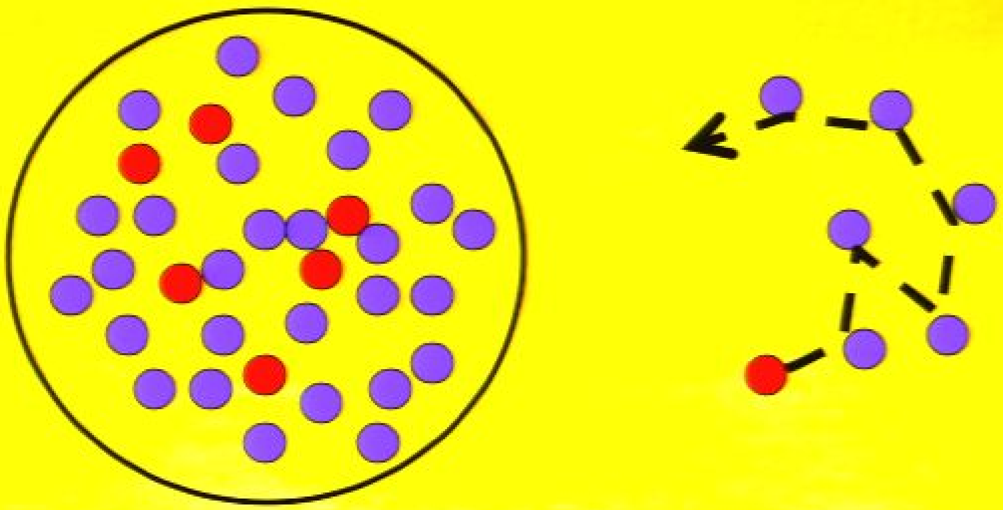

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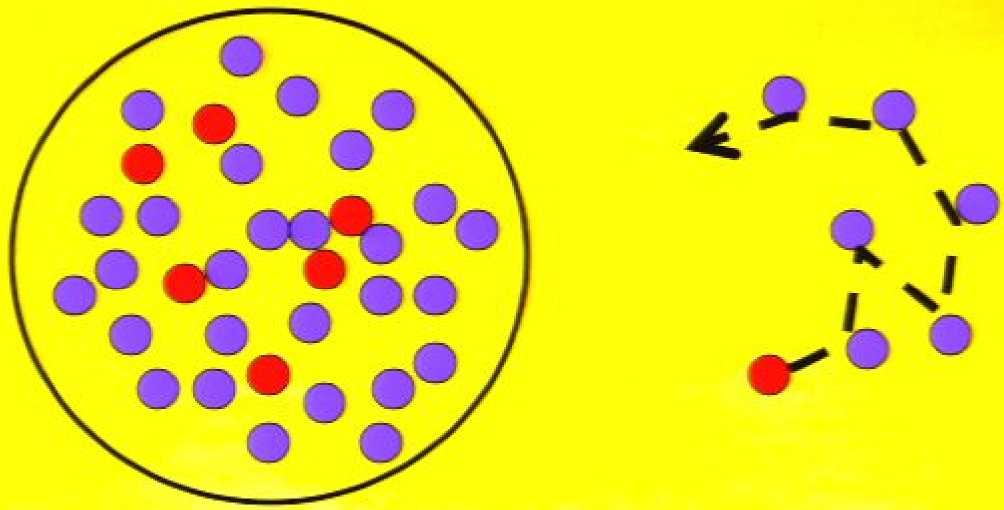

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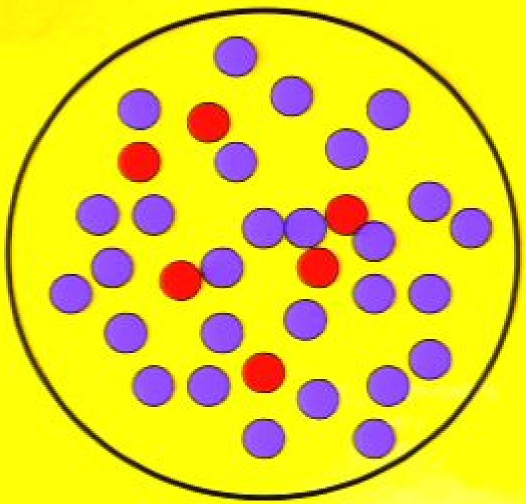

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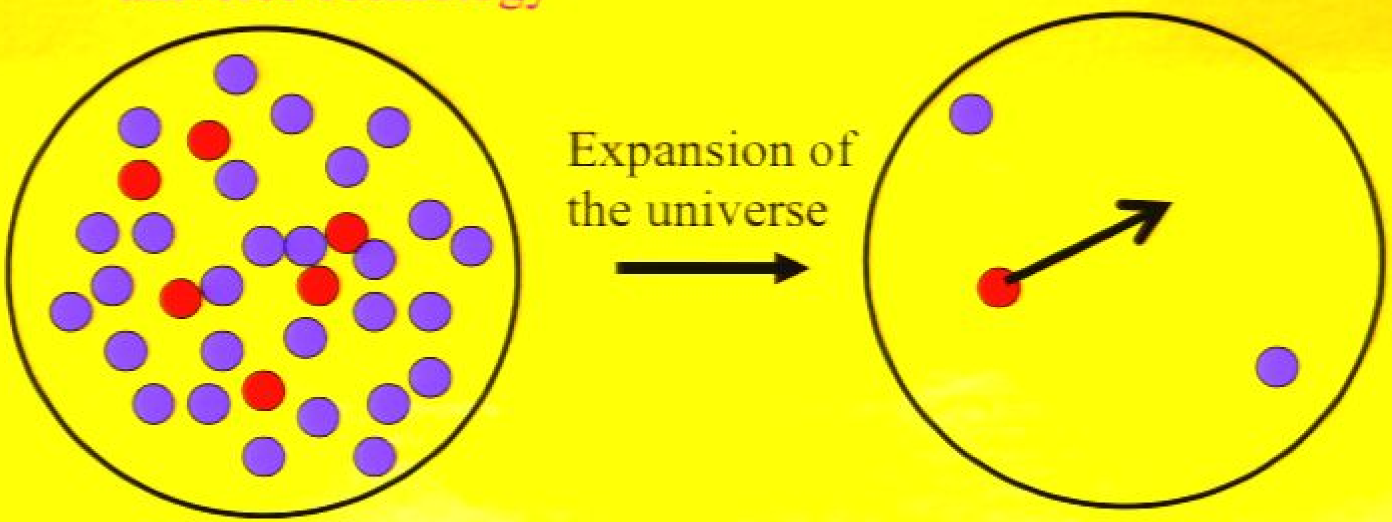

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    - Q ~ mass density / v_{RMS}^3
    - density ~ $1/a^3$ while v_{RMS} ~ $1/a$

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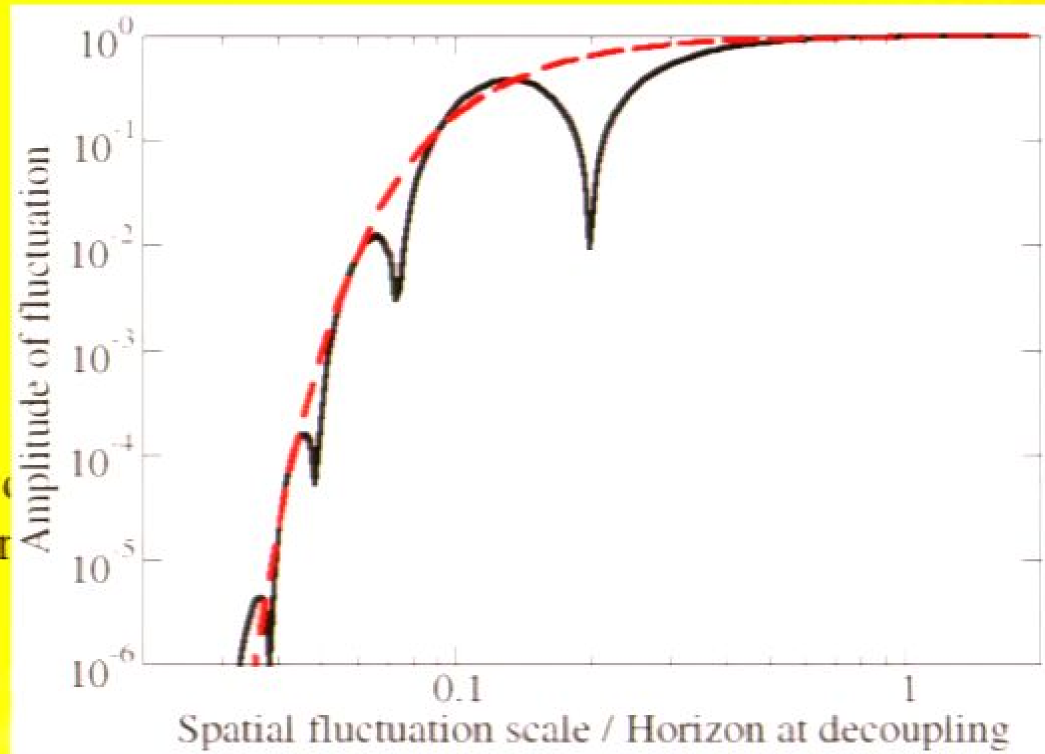
Set by annihilations in the early universe

Set by scatterings in the early universe

Free-streaming and Damping: Power spectrum of fluctuations

Perturbations are erased below the free-streaming and damping lengths

Shown to the right is the power spectrum of density fluctuations for a cold dark matter model



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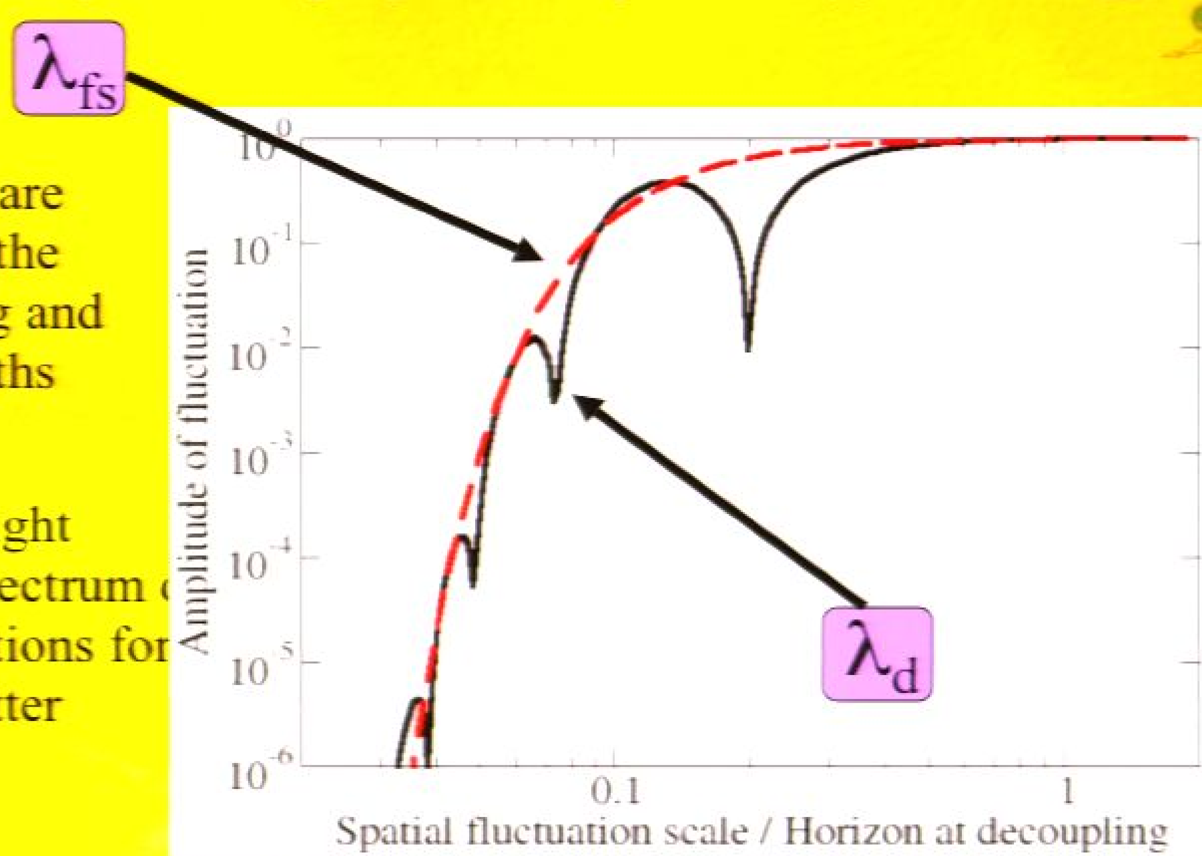

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Free-streaming and Damping: Halos

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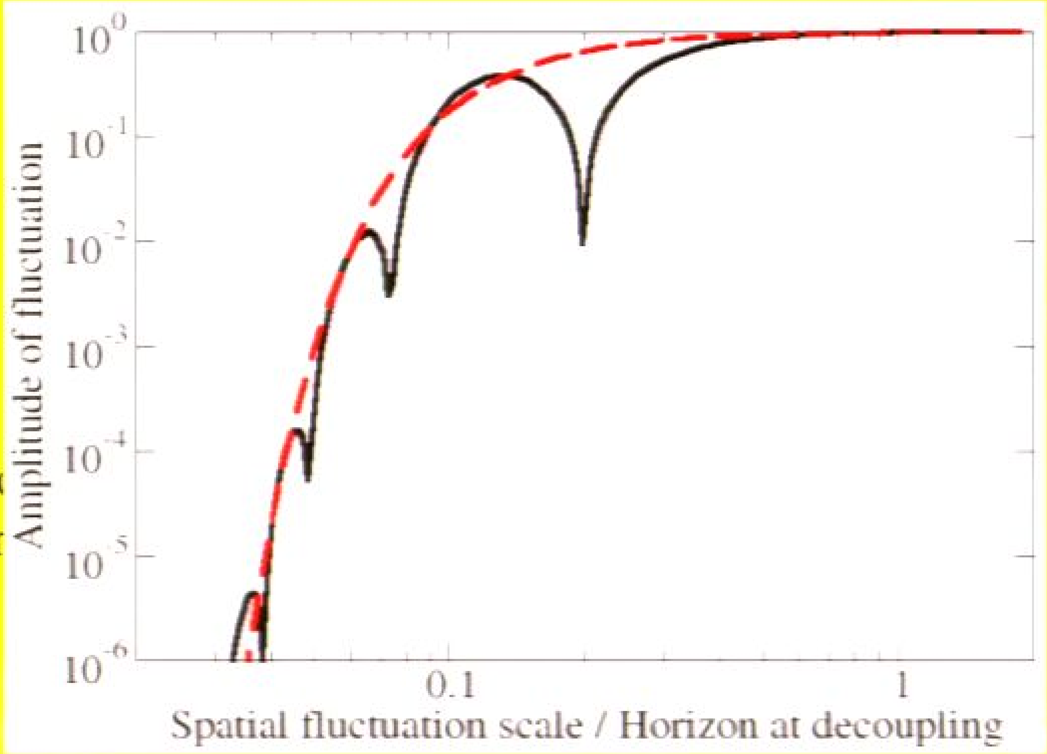

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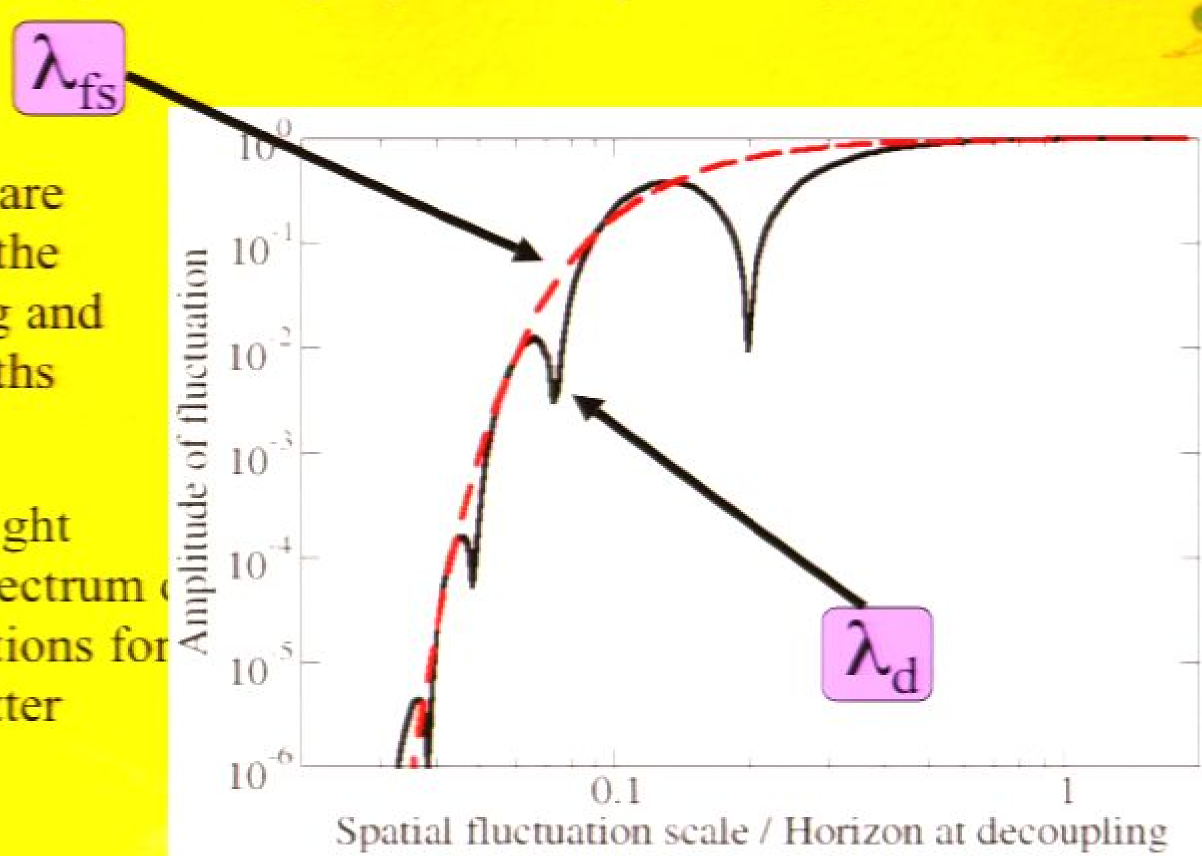

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Fluctuations grow through gravitational instability into dark matter halos. Galaxies form in these dark matter halos.

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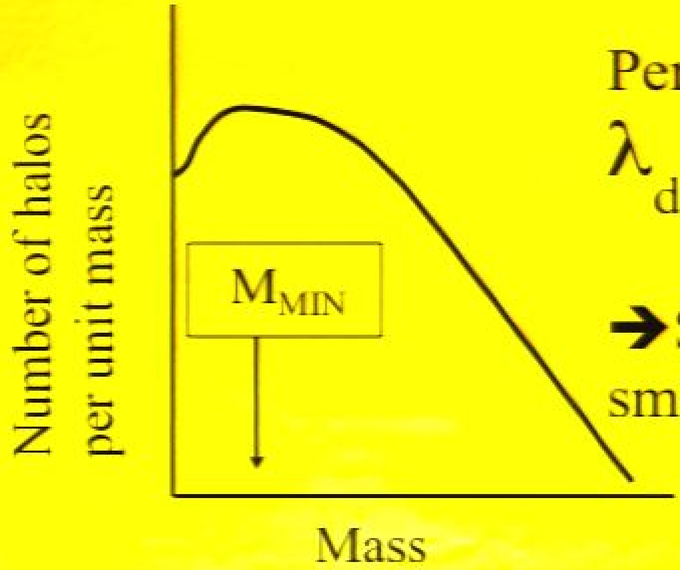

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Properties of Dark Matter

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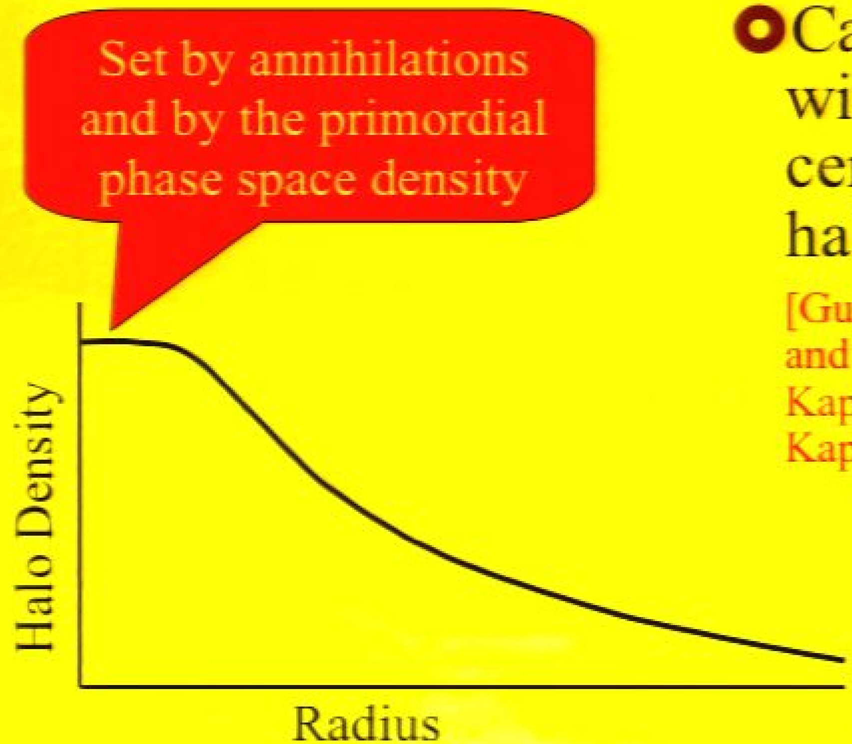
- *Free-streaming length λ_{fs}*: Average distance traveled by a dark matter particle before it falls into a potential well.
- *Phase-space density Q*
  - $Q \sim$ mass density / v_{RMS}^3

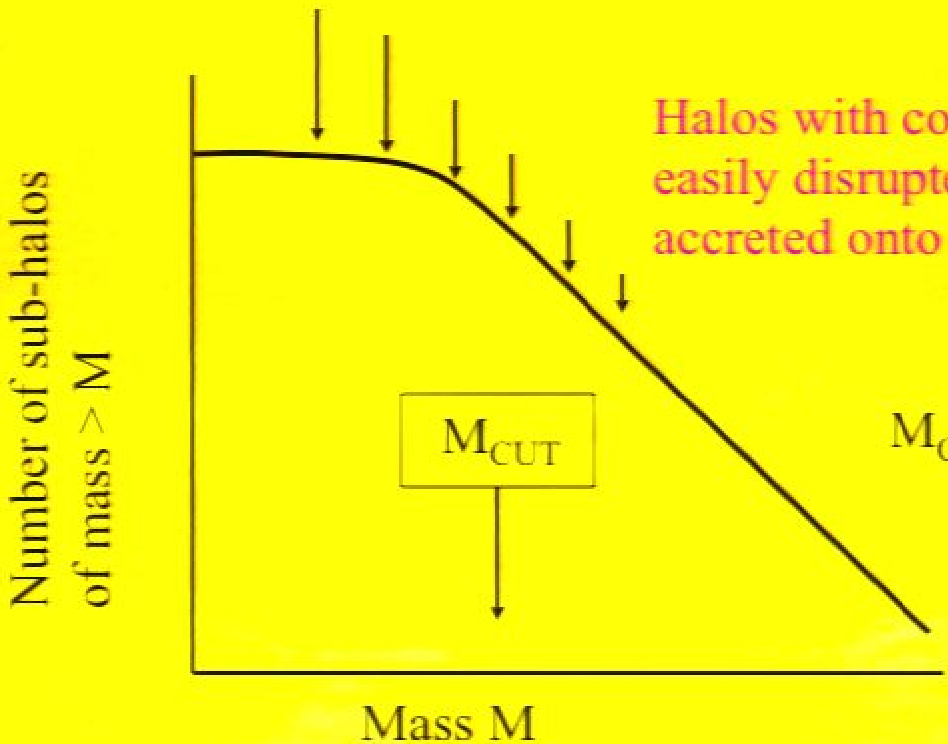
Phase space density: Cores



- Can't stuff particles without limit into the center of dark matter halos.

  [Gunn and Tremaine 1979, Dalcanton and Hogan 2000, Dehnen 2005, Kaplinghat 2005, Martinez and Kaplinghat in prep]

Phase space density: Substructure



Halos with cores are more easily disrupted when accreted onto the large halo

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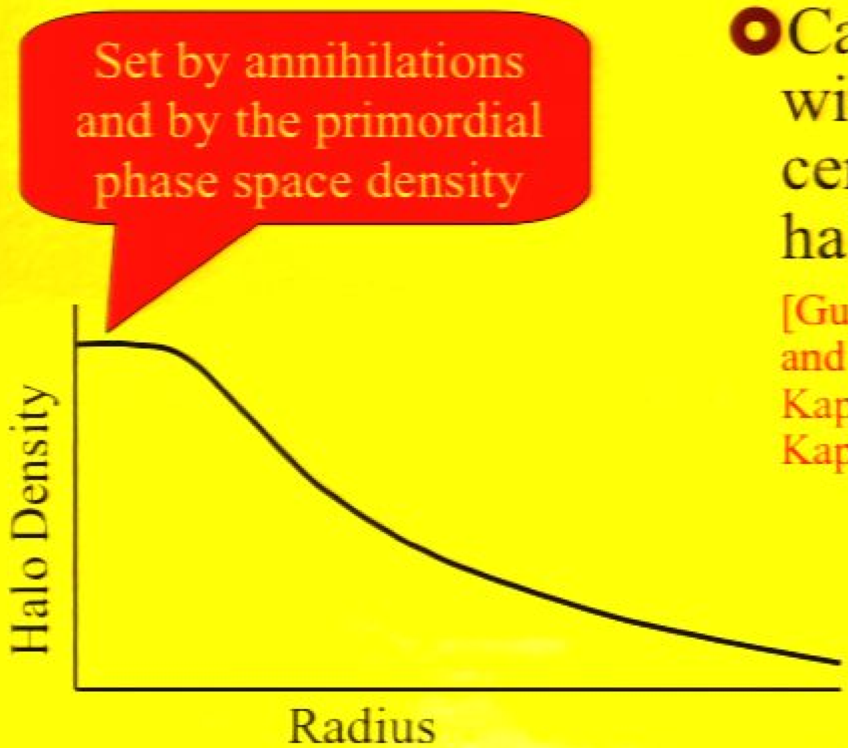

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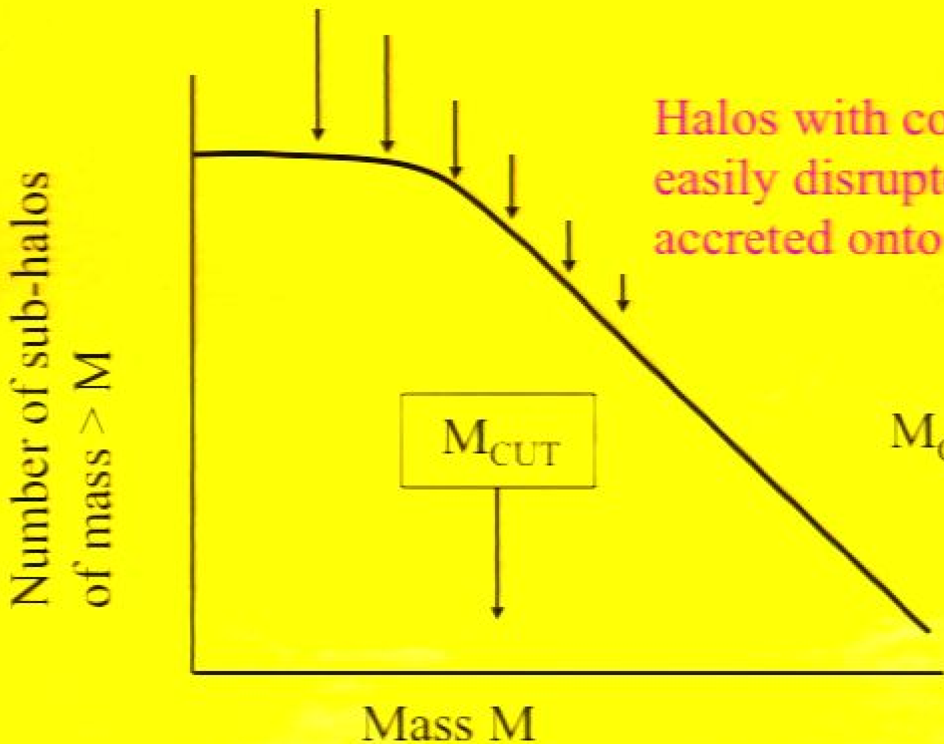

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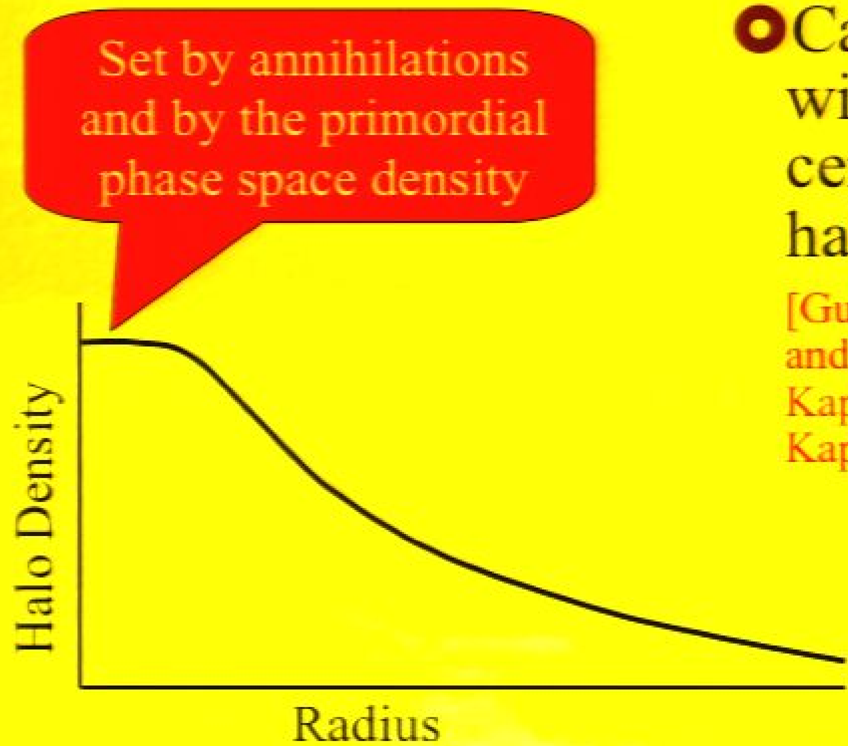

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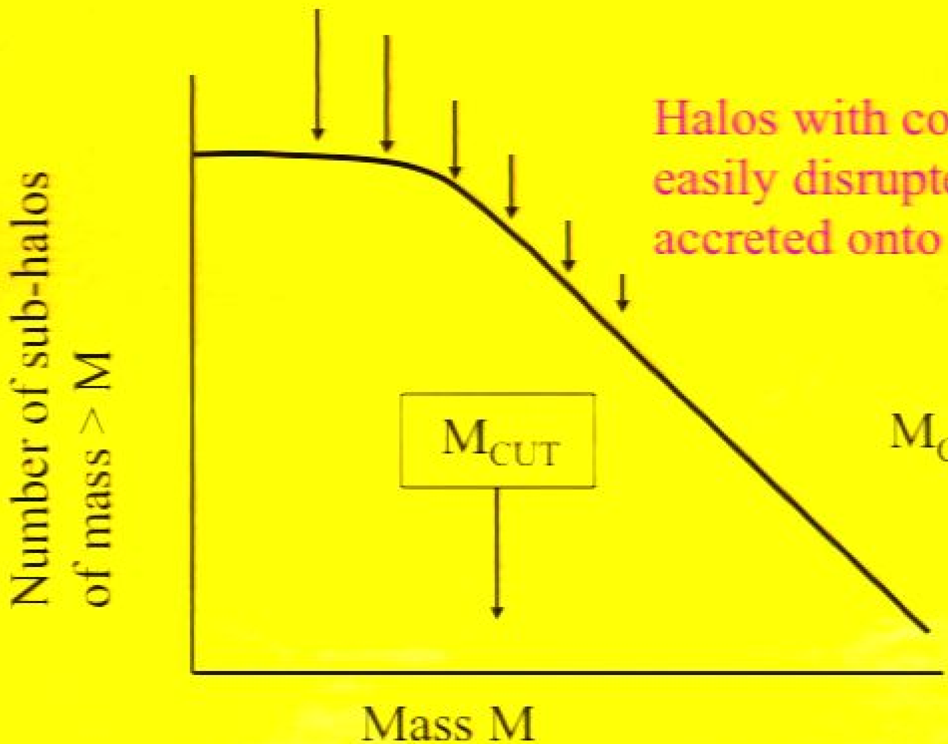

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Relation between Q and free-streaming

- The free-streaming scale and Q are related in many models of dark matter. For example,
  - Both are fixed by specifying the mass of a warm dark matter particle like the sterile neutrino.
  - Given the cut-off in the power spectrum, the size of cores in halos can be computed (using numerical simulations). [Kaplinghat 2005]

- This one-to-one relation can be broken, for example, in models where dark matter results from late decays [Strigari, Kaplinghat and Bullock 2007]

meta-CDM

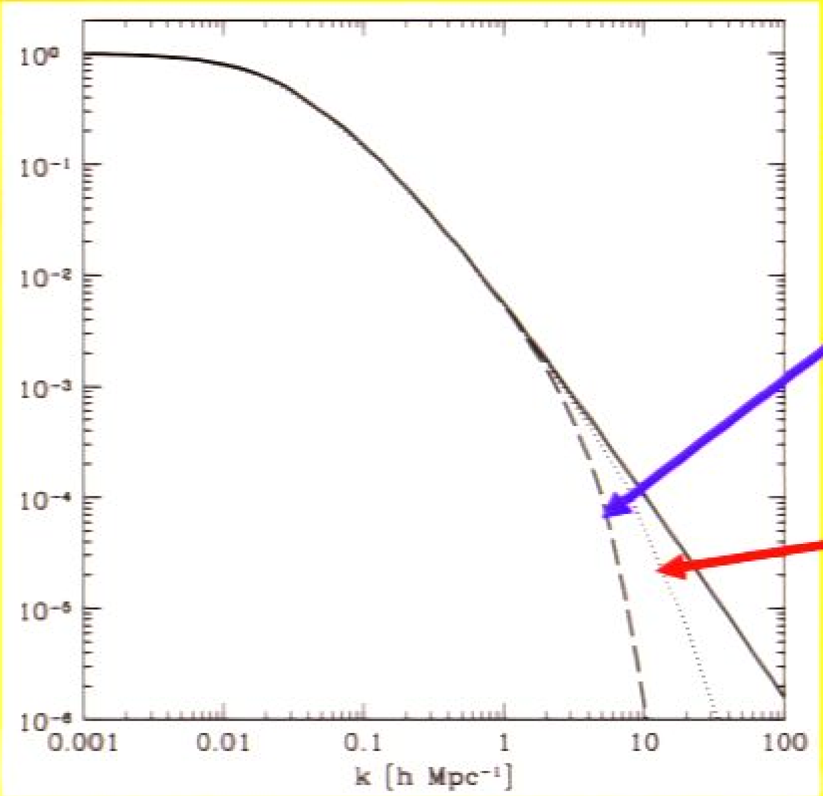
Late decays will give rise to large phase space cores in dark matter halos that have formed hierarchically!

$$c_s\eta \propto \frac{1}{Q^{1/3}} \quad \text{(RD)}$$

$$\propto \frac{1}{Q^{1/3}\tau^{1/3}} \quad \text{(MD)}$$

Strigari, Kaplinghat and Bullock 2006

meta-CDM Power Spectrum



For early decays (M^2_{pl}/M^3_{weak}):

cutoff scale ~ $Q^{-1/3}$

For late decays (10^5 yrs.):

cutoff scale given by

$0.2\ (\tau/10^{12}\ s)^{-1/3}\ (Q/10^{-6})^{-1/3}$ Mpc

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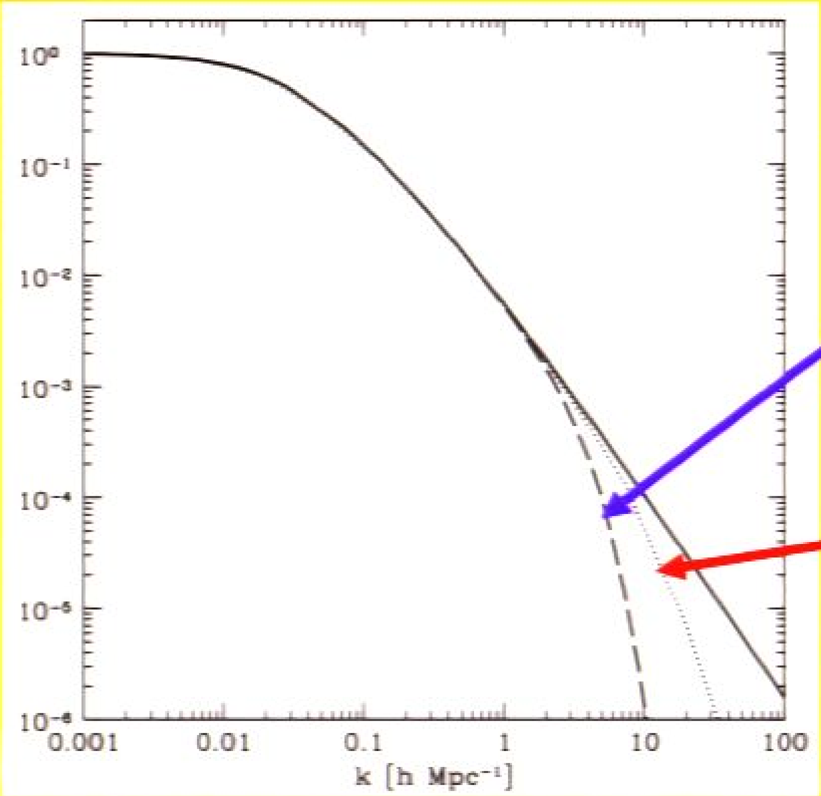

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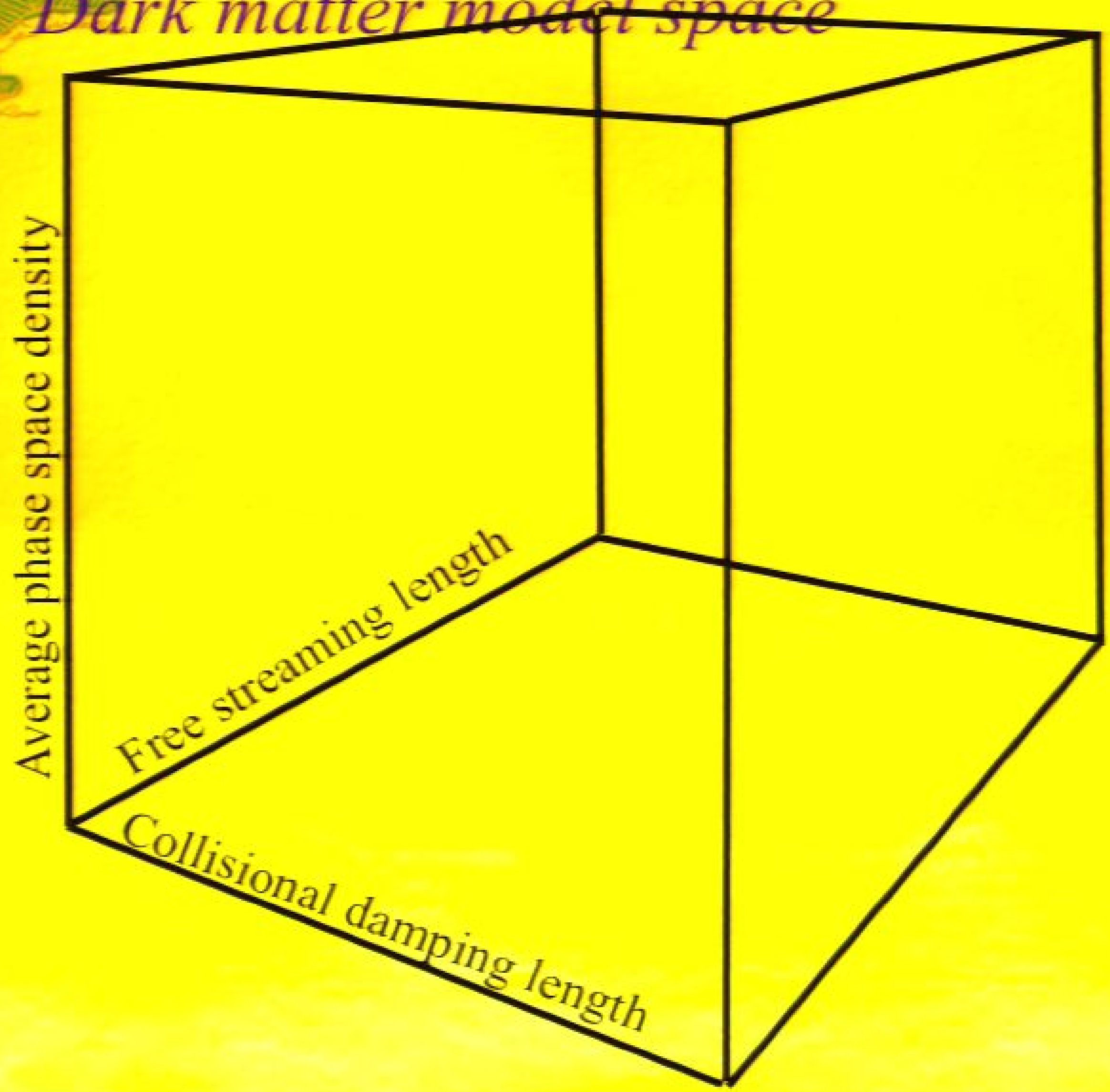
Dark matter model space



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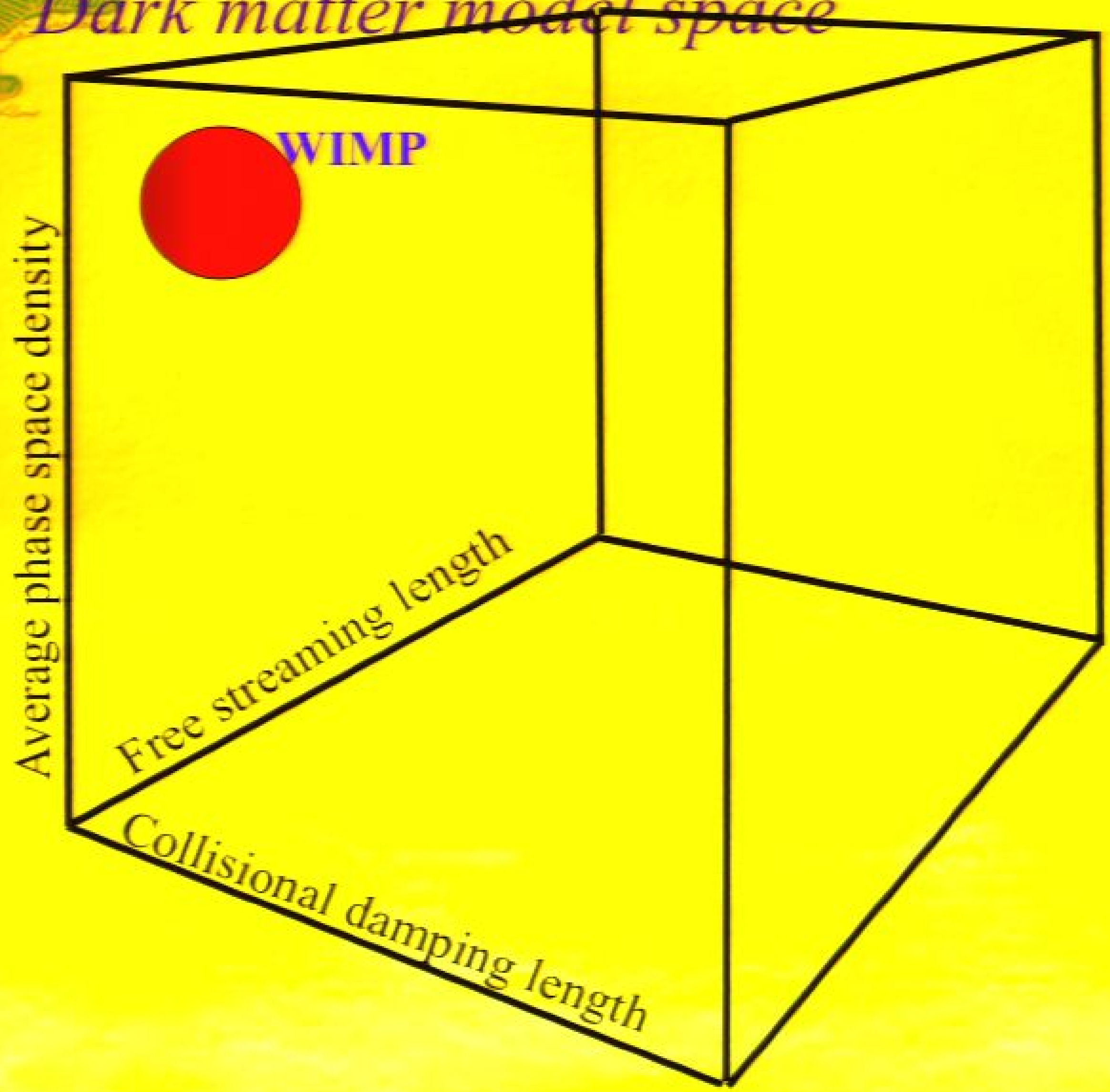

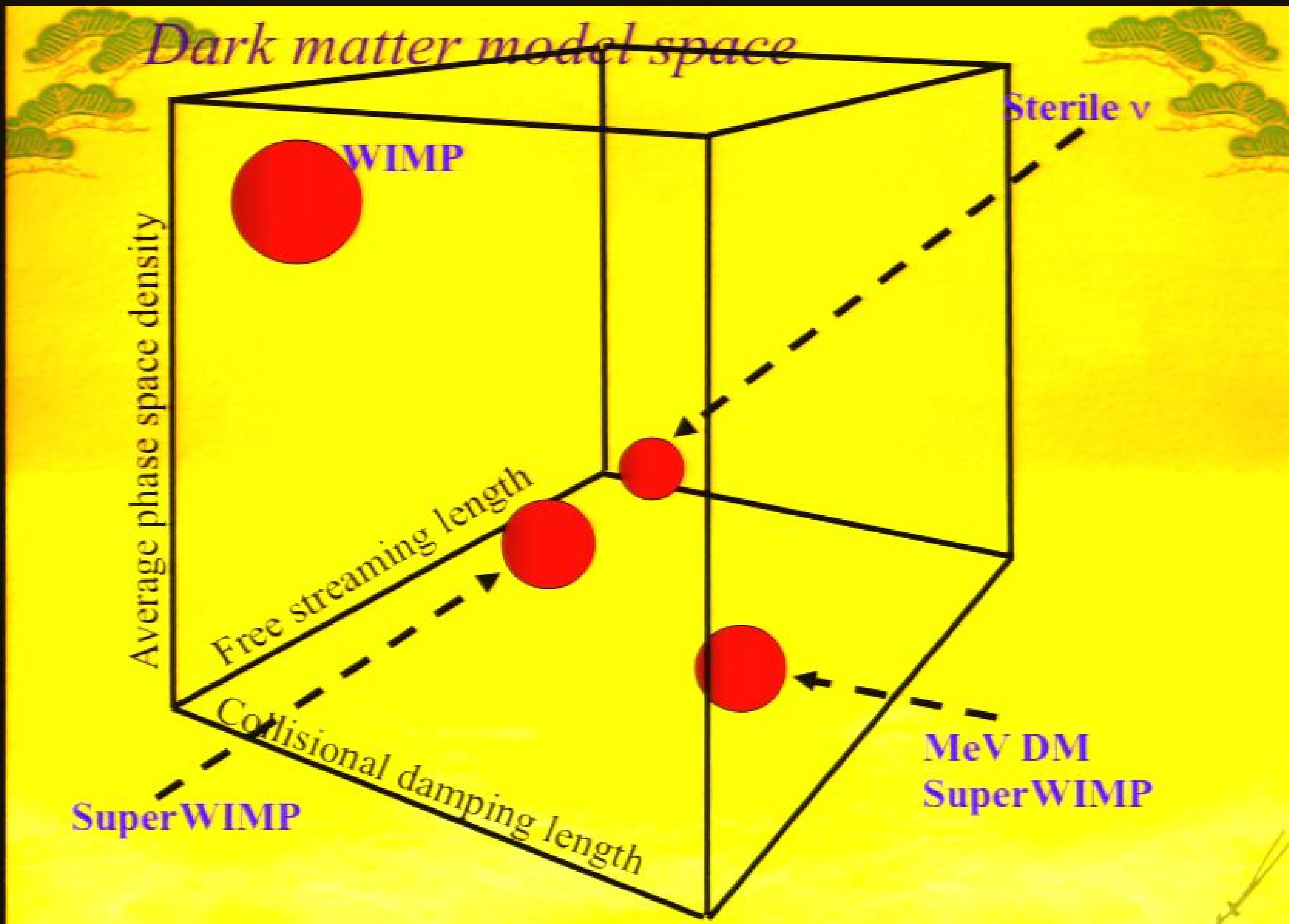
Dark matter model space
WIMP
Sterile ν
Average phase space density
Free streaming length
Collisional damping length
SuperWIMP
MeV DM
SuperWIMP

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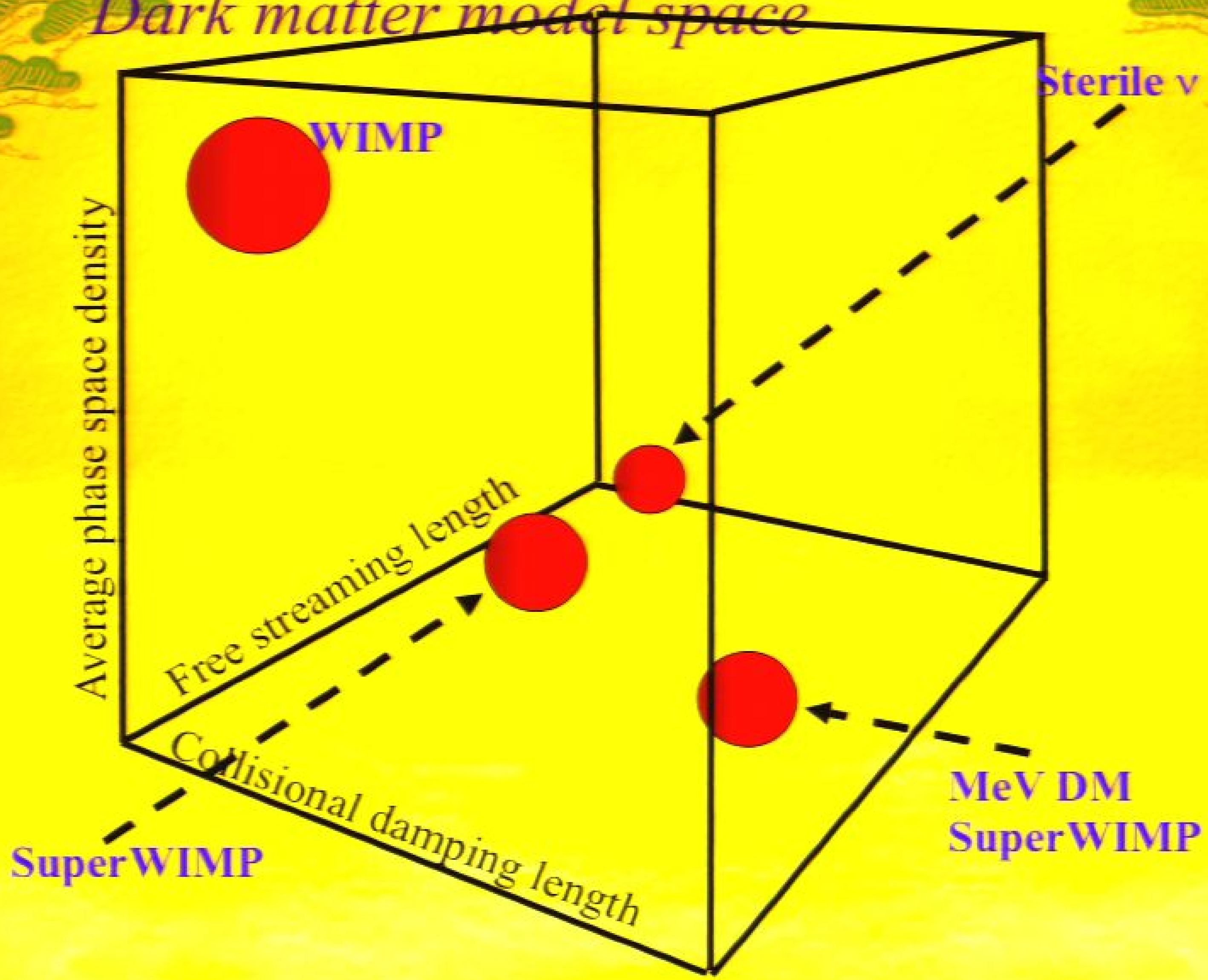


Review

- *Free-streaming and damping lengths:*
  - Truncates power on small scales
    - No perturbations on small scales
    - No halos below a minimum mass.

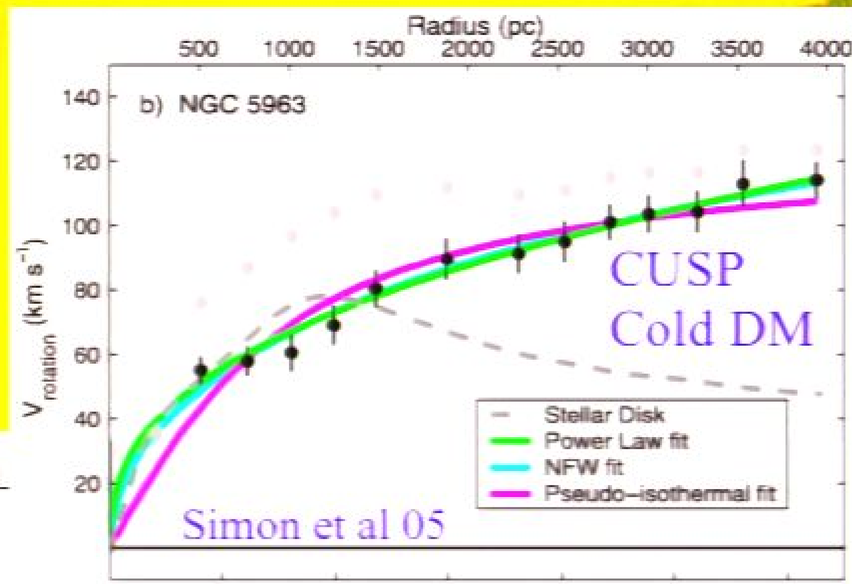
- *Phase space density:*
  - Limits density in the center of halos
    - Makes small halos susceptible to disruption
    - Limits sub-structure in larger halos..

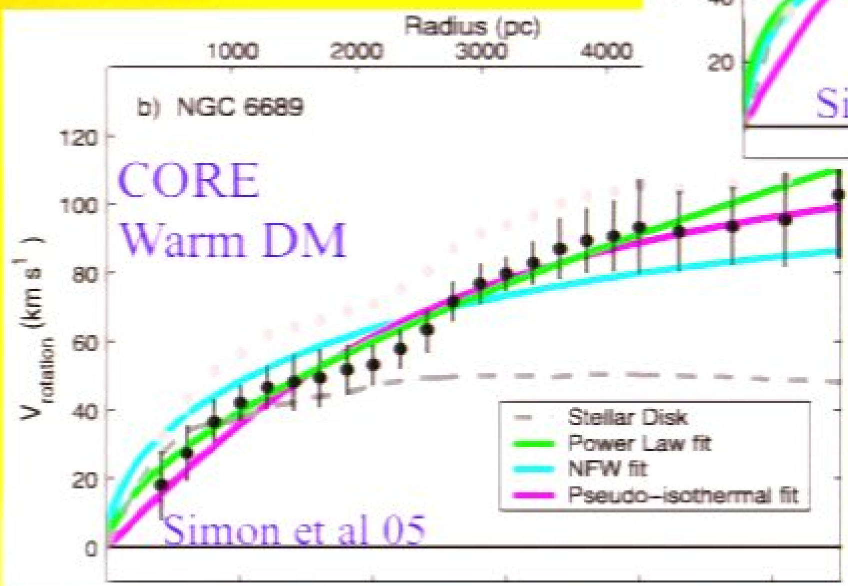
Cold or Warm?

- Cold dark matter (example: WIMP)
  - Decouples when non-relativistic
  - Small velocities today << mm/s
- "Warm" Dark Matter (example: SuperWIMP)
  - Large velocities today >> mm/s up to ~100 m/s
- Observations
  - Lyman-alpha forest: power spectrum of fluctuations cannot fall to half the CDM value on scales larger than about 10 kpc
  - Local group: Smallest mass halos less than 10^9 M_{sun}
  - *Problems for CDM on small scales?*

Cusp or Core?

Not as bad as old HI data suggested, but problem seems to persist for some galaxies with new high quality data





Missing satellite problem

Klypin et al. 99; Moore et al. 99

Simulation of Milky Way: Via Lactea [Diemand et al 2006]

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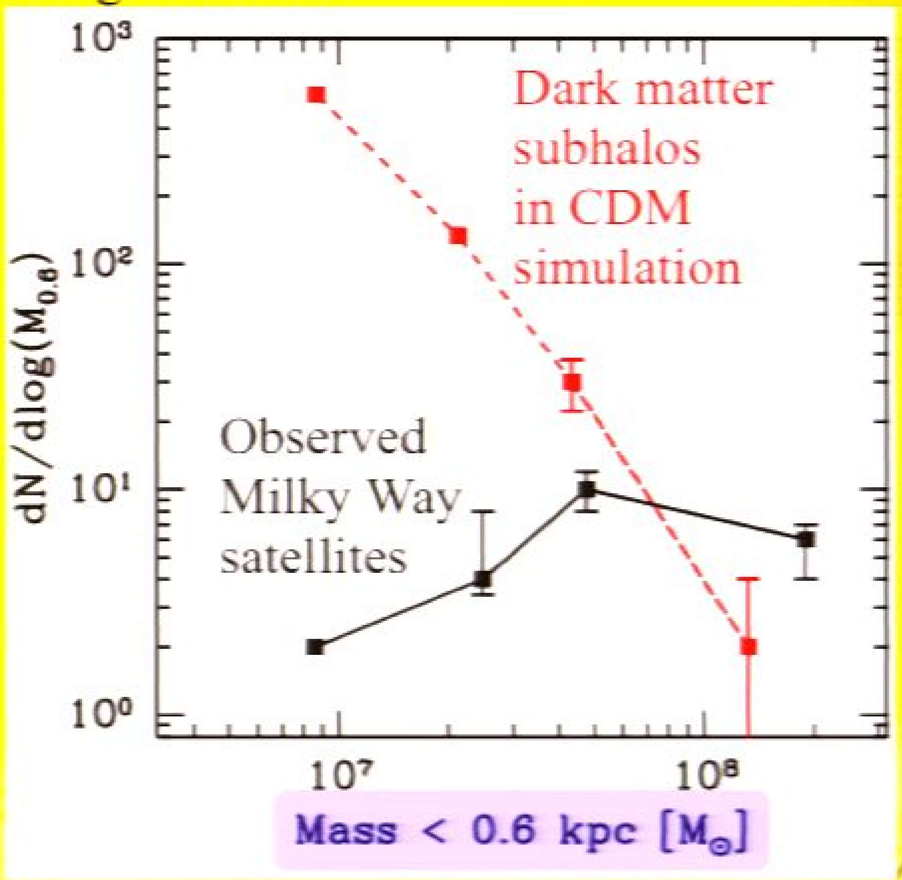

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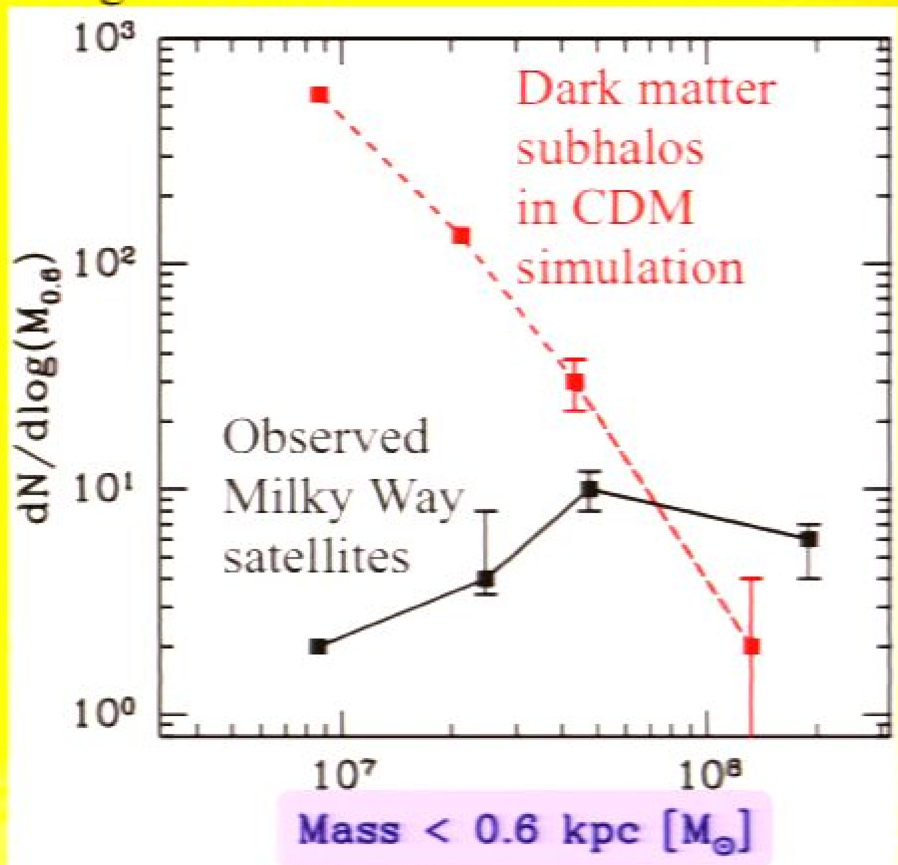

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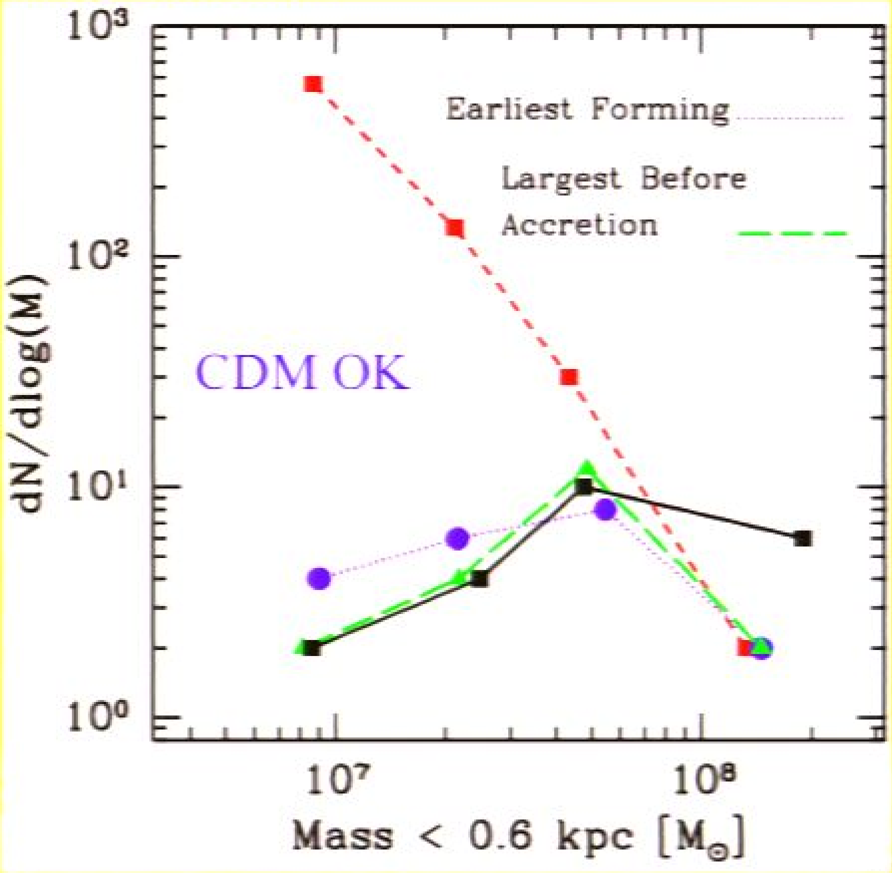
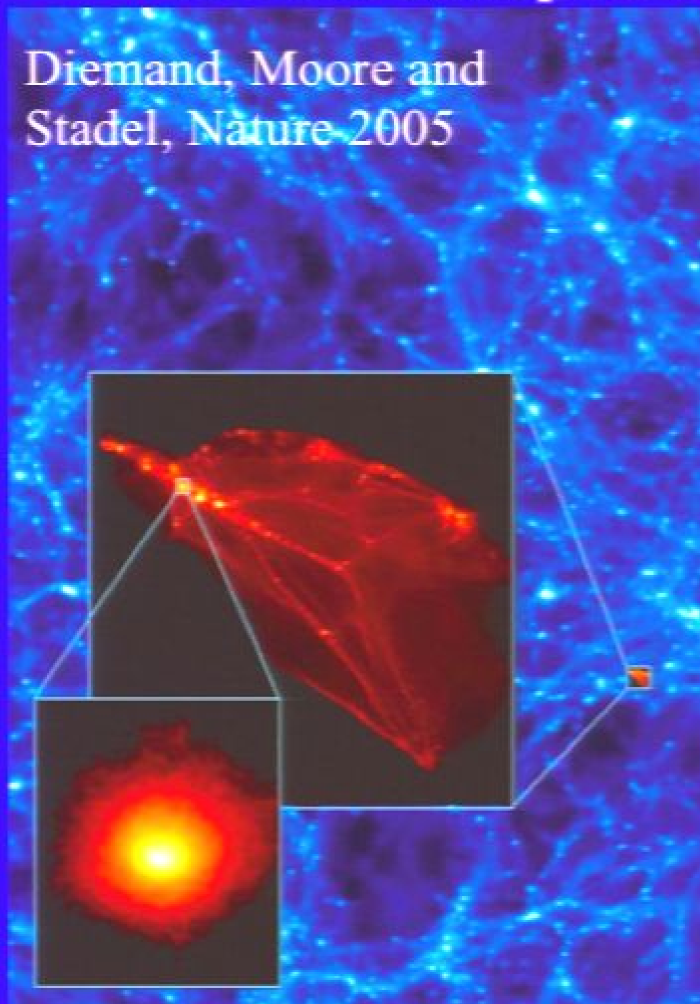


Cold Dark Matter: Theory

$$Q_{\mathrm{CDM}} = 10^{14} \frac{\mathrm{M}_\odot}{\mathrm{pc}^3} \left(\frac{\mathrm{km}}{\mathrm{s}}\right)^{-3} \left(\frac{\mathrm{M}}{100\mathrm{GeV}}\right)^{3/2}$$

Solved example: SUSY WIMP DM



- Decouples kinetically at temperatures $10^{11} - 10^{13}$ K
- Free-streaming length ~ parsec scale
- Smallest mass halos spread over a few orders of magnitude about the earth mass
- Puffy!

Abundance of Dark Matter from Decays

•WIMPs have the right abundance because of their weak interactions

WIMP

$\Gamma \sim M_w^3/m_{pl}^2$

Dark Matter

Abundance of Dark Matter from Decays

WIMP

$\downarrow$ $\Gamma \sim M_w^3 / m_{pl}^2$

Dark Matter

SuperWIMP

- WIMPs have the right abundance because of their weak interactions

- $\rho_{DM} = \rho_{WIMP}\ m_{DM}/m_{WIMP}$

- If $m_{DM} \sim m_{WIMP}$, then the dark matter abundance today is naturally in the correct range.

- Example: In super-gravity models, all super-partners have similar masses.

[Feng, Rajaraman and Takayama, PRL 2003]

The Case for Dark matter from Decays

- Theoretically compelling.
  - Strong theoretical hints that new physics (particles) may be lurking at the 100 GeV scale.
  - Weak cross-section and G_N naturally leads to the right dark matter abundance.
- Successful cosmological predictions on large (greater than about a Mpc) scales.
- Differences on small scales. May alleviate some "problems" with CDM.

Cosmological consequences: Early Universe

- Late entropy injection distorts CMB blackbody spectrum.

  [Feng, Su and Takayama, 2004: Austri and Roszkowski, 2004; Lamon and Durrer, 2005]

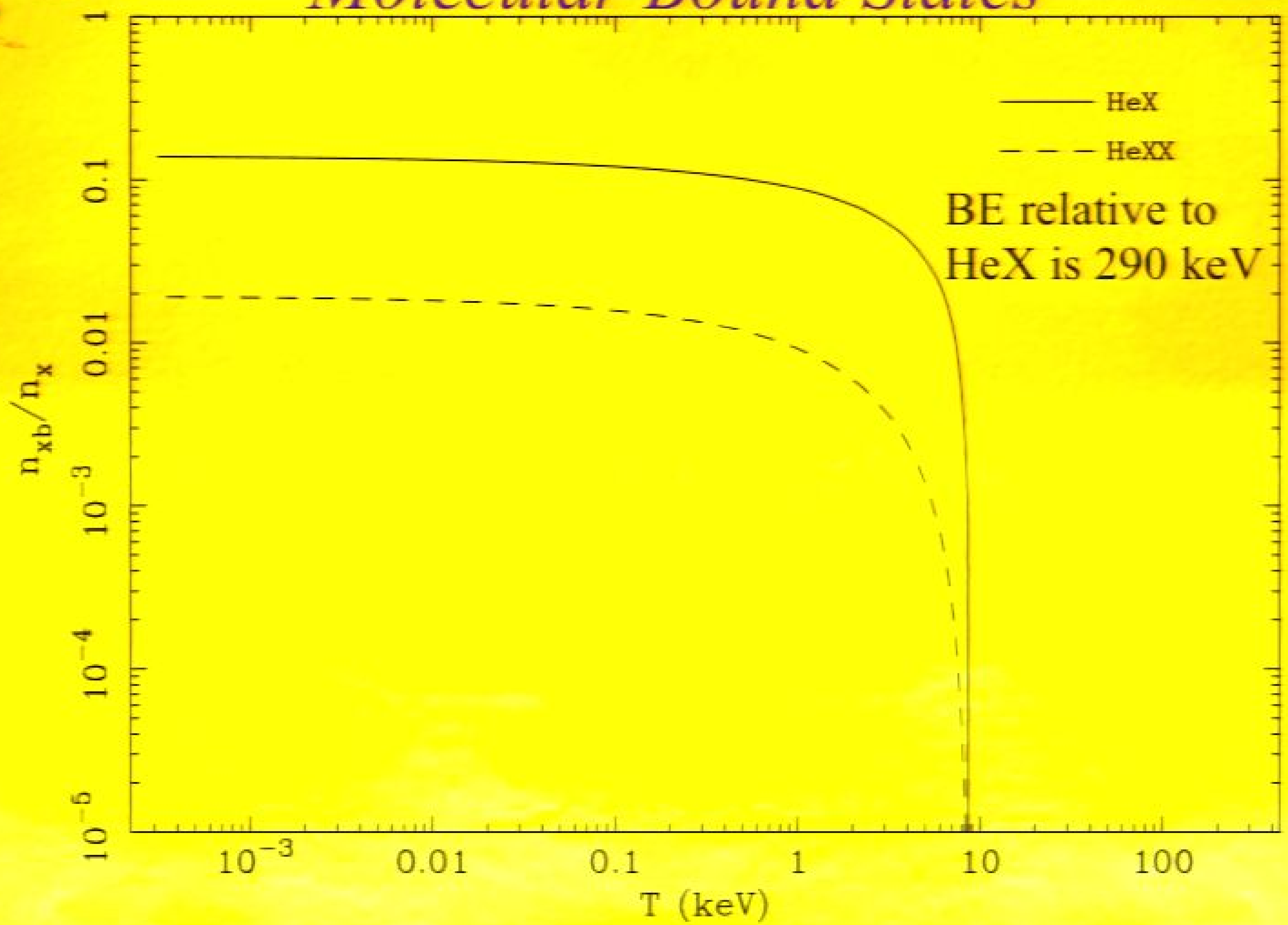
- Bound states of Helium-4 with charged NLSP

  [Pospelov 2006, Kohri and Takayama 2006, Kaplinghat and Rajaraman, 2006]

- Light element abundances affected. Can the Li7 and Li6 problems be solved?

  [Dimopoulos et al 1989: Kawasaki and Moroi 1995: Holtmann et al 1999: Jedamzik 2000: Feng, Rajaraman and Takayama, 2003: Jedamzik 2004: Ellis et al 2004: Jedamzik et al 2005: Cyburt et al 2006, Pradler and Steffen 2007]

Molecular Bound States



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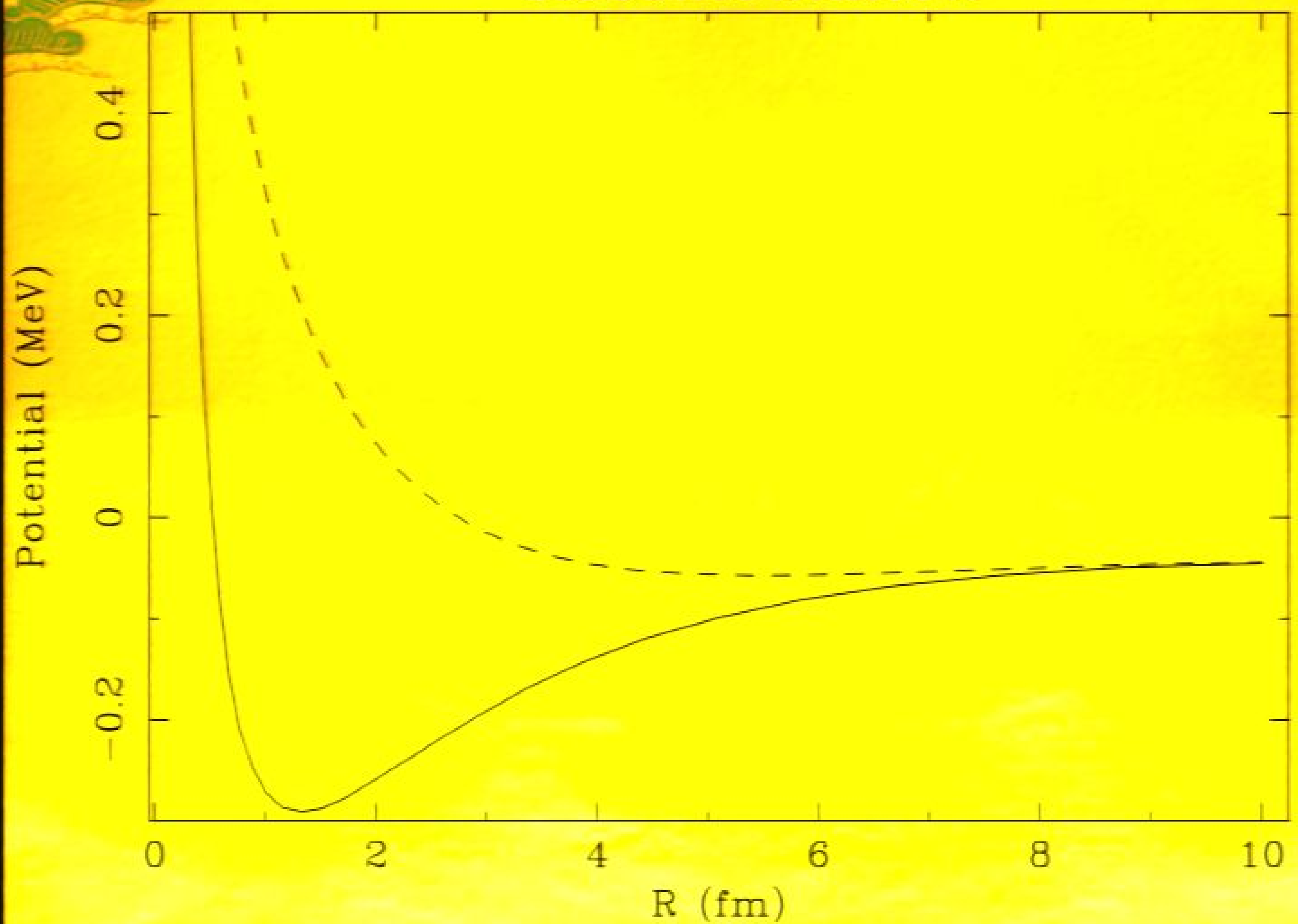

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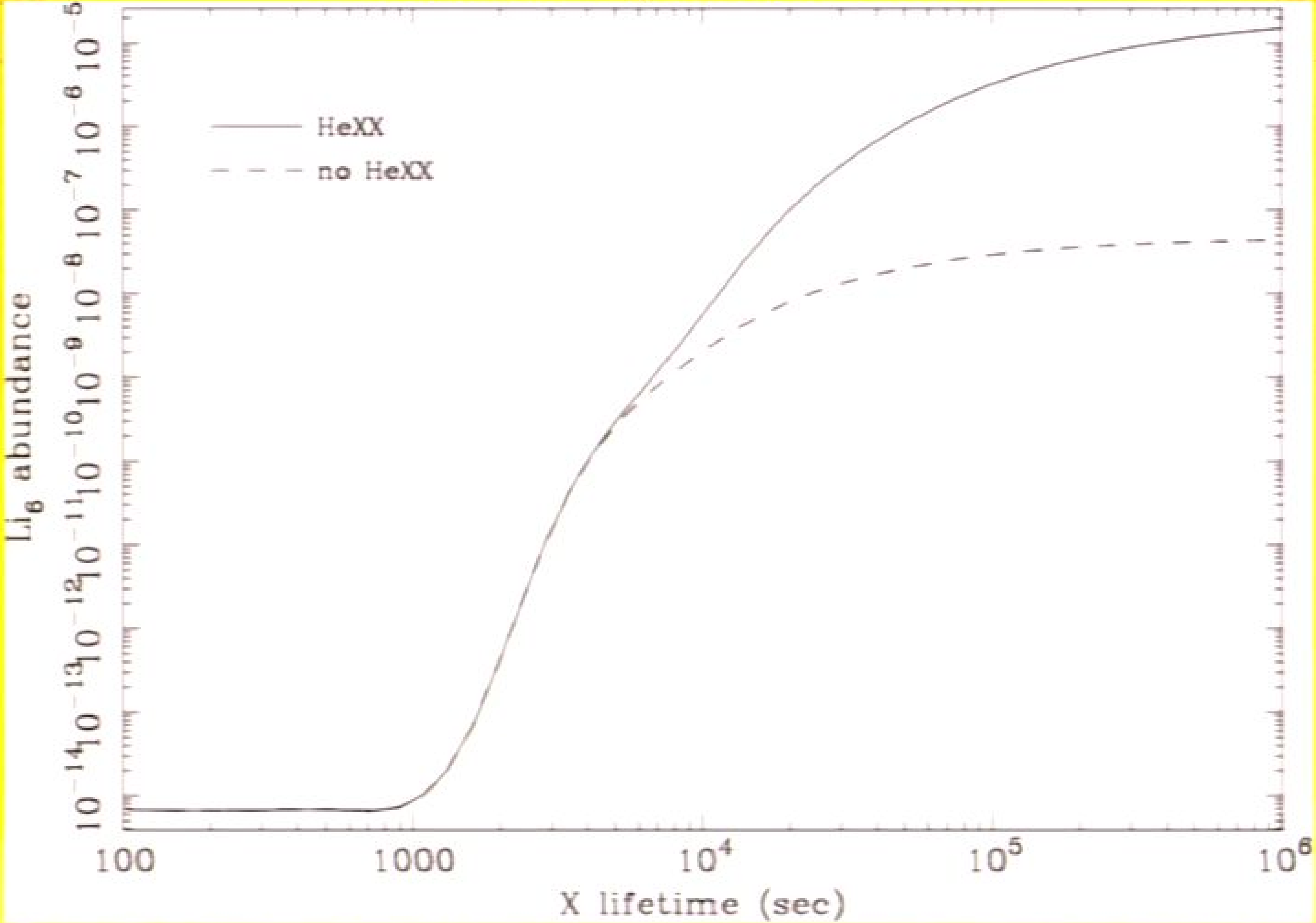

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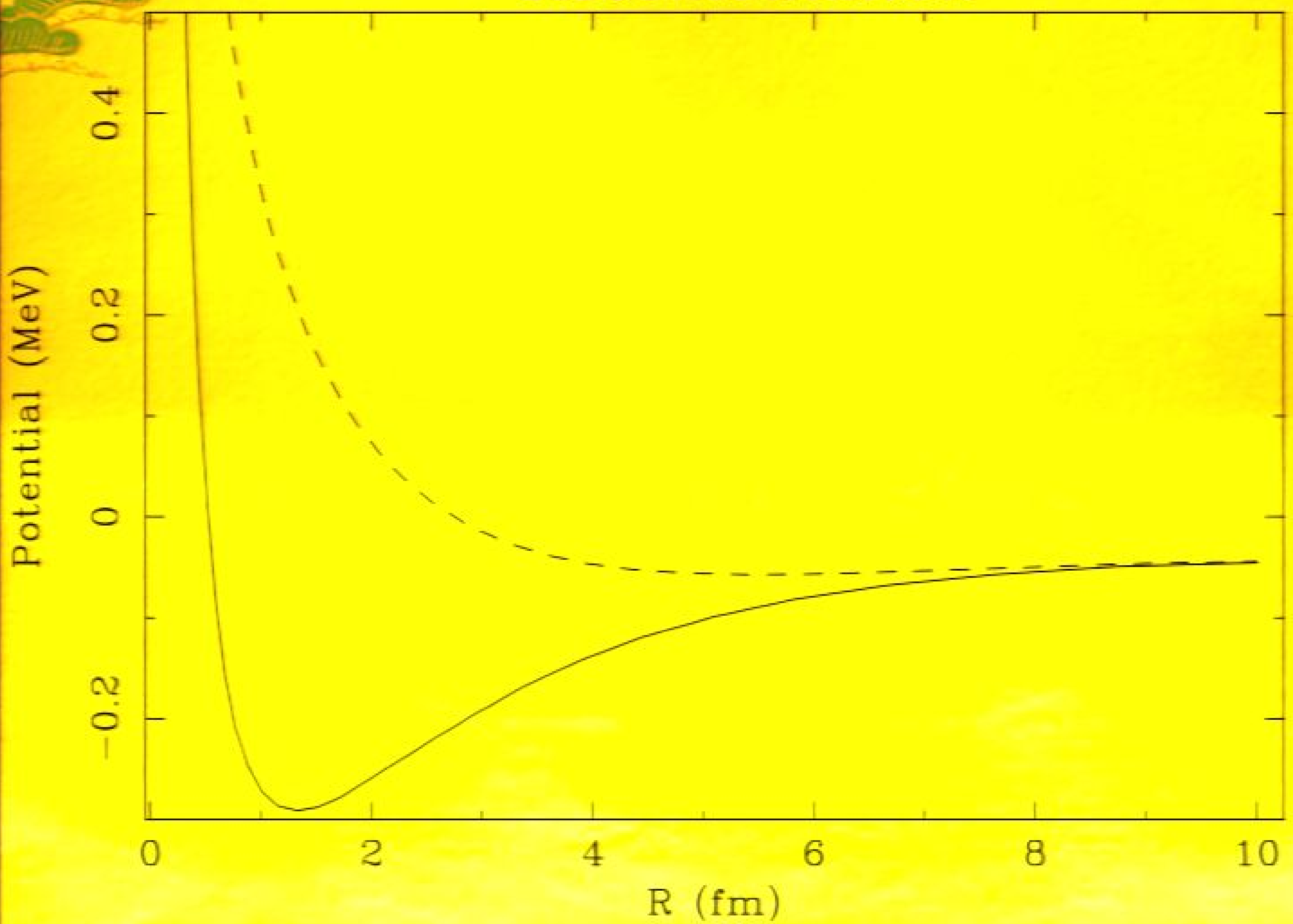

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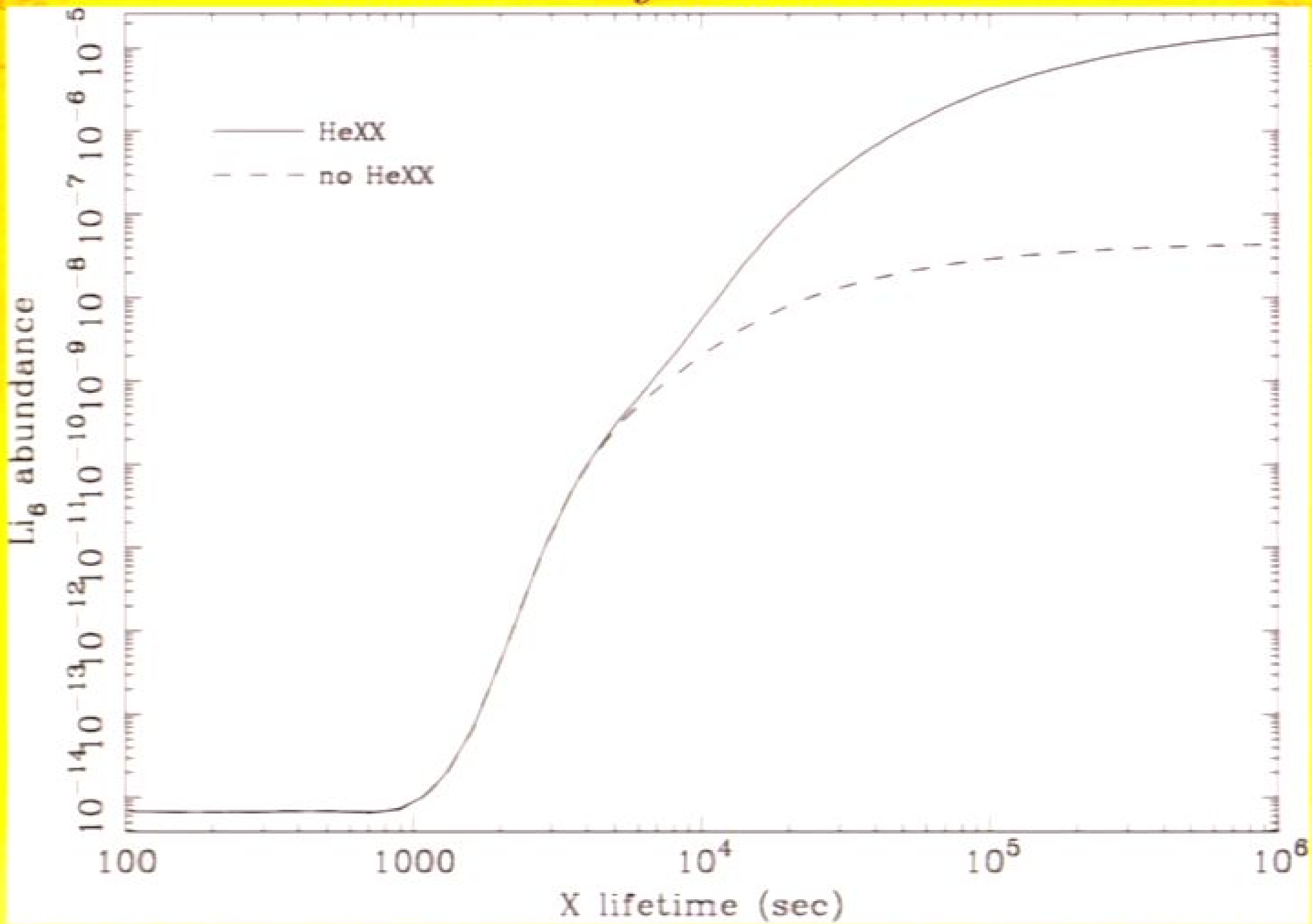

Cosmological consequences: Late Universe

- Growth of small scale structure modified [Kaplinghat 2005]
  - Lesser power on small scales
  - Smaller phase space density

$$Q = 10^{-3}\frac{\mathrm{M}_\odot}{\mathrm{pc}^3}\left(\frac{\mathrm{km}}{\mathrm{s}}\right)^{-3}\left(\frac{m}{p_{\mathrm{cm}}}\right)^3\left(\frac{10^{-7}}{a_{\mathrm{decay}}}\right)^3$$

- Observable?
  - Flat density cores in dwarf galaxies
  - Modified census of dwarf galaxies in Milky Way
- Super-WIMP parameter space [Cembranos et al 2005, Steffen 2006]

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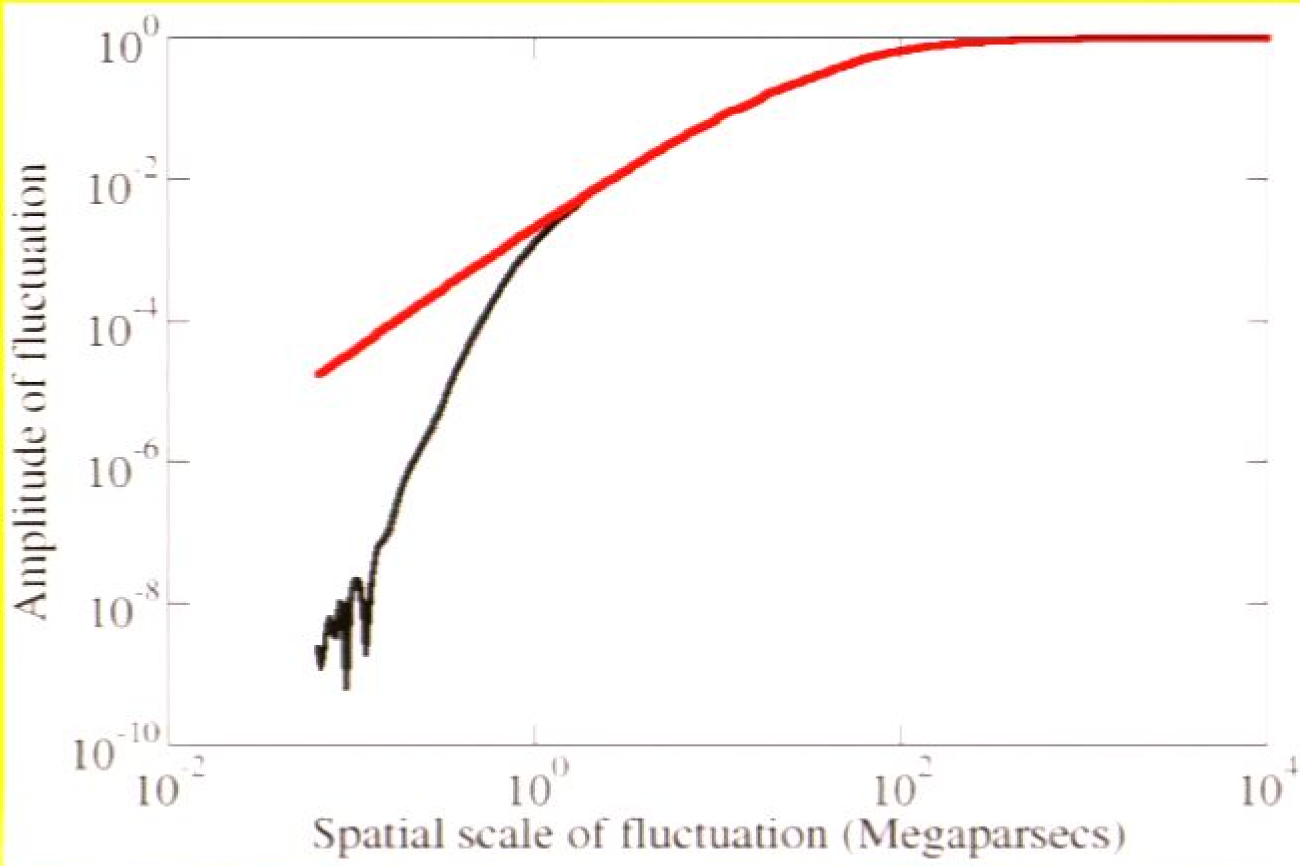

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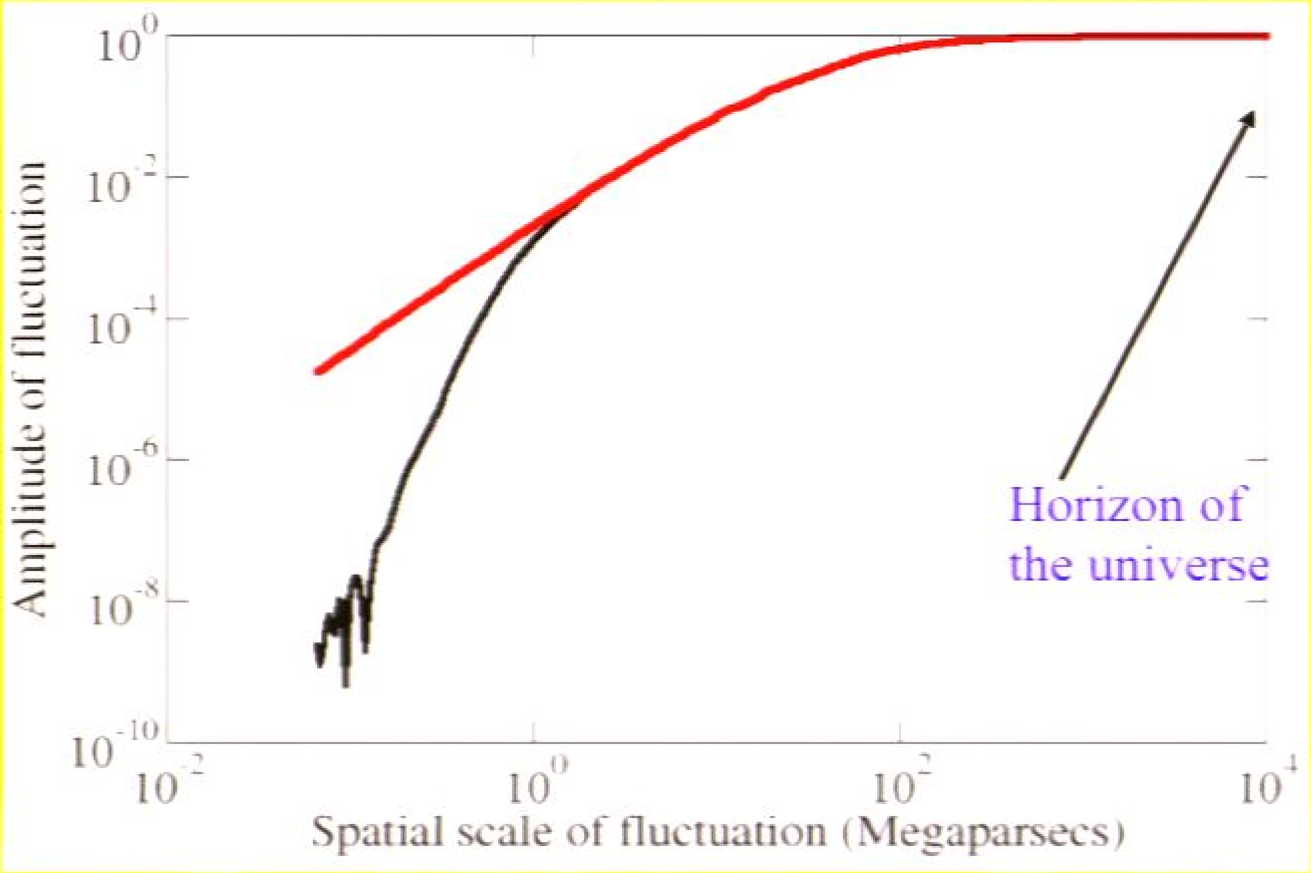

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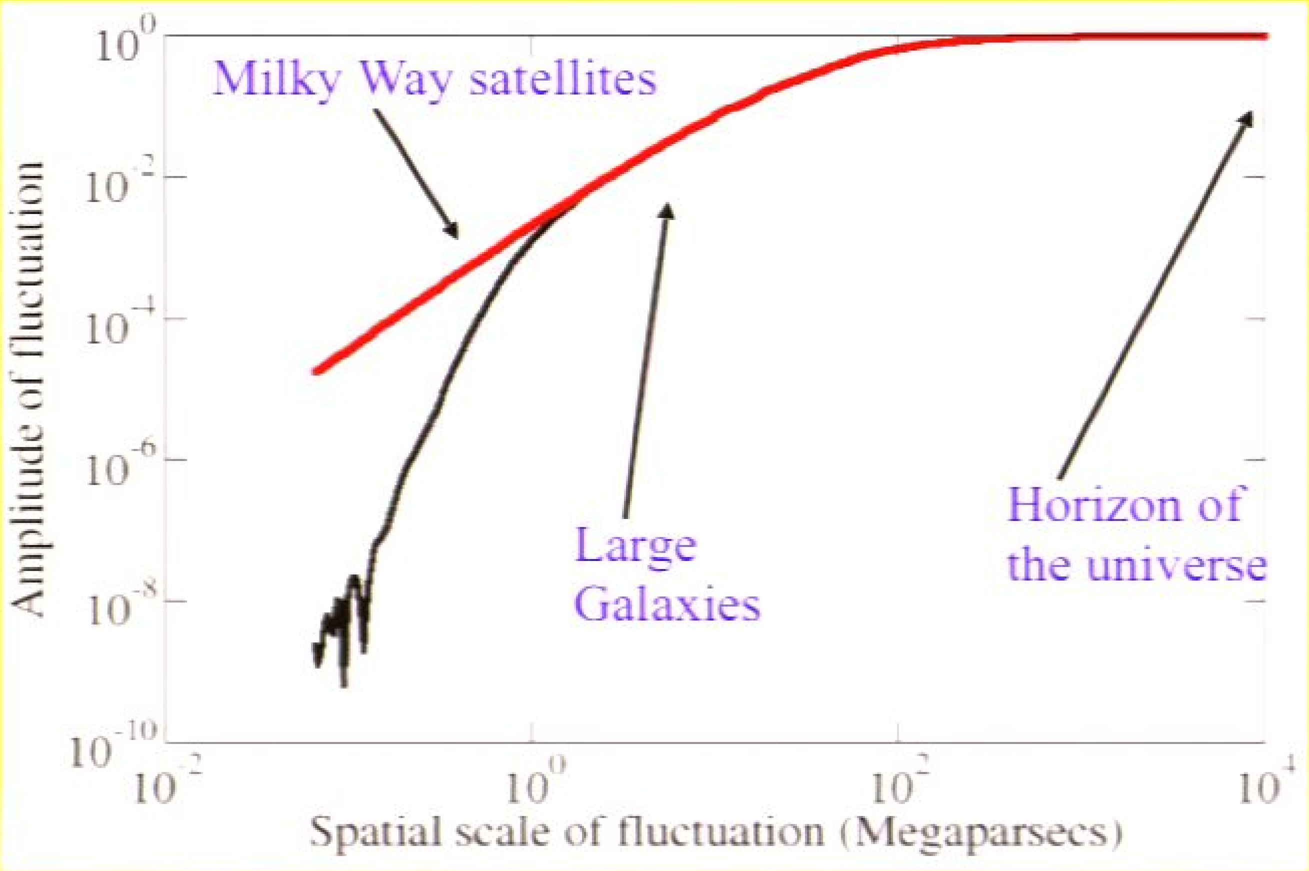

Phase Space of Collision-less Systems

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- Fine-grained phase space density F(x,y) conserved along the trajectory given by $\partial_t x = v$ and $\partial_t v = -\nabla \Phi$.
  - F_{max} conserved.
  - $M(f) = \int d^3x\, d^3v\, F(x,v)\, \Theta(F(x,v)-f)$ is conserved $\forall$ f. [Lynden-Bell, MNRAS 1967]

Gunn-Tremaine Bound

- Coarse-grained $F_c(x,v)$ *is not conserved.*
  - Cannot make statements about average Q.
  - However, maximum of F_c cannot exceed F_{max}
  - For Warm Dark Matter with Fermi-Dirac distribution $h^3 F_{max} = ½$ [Gunn and Tremaine, 1979]

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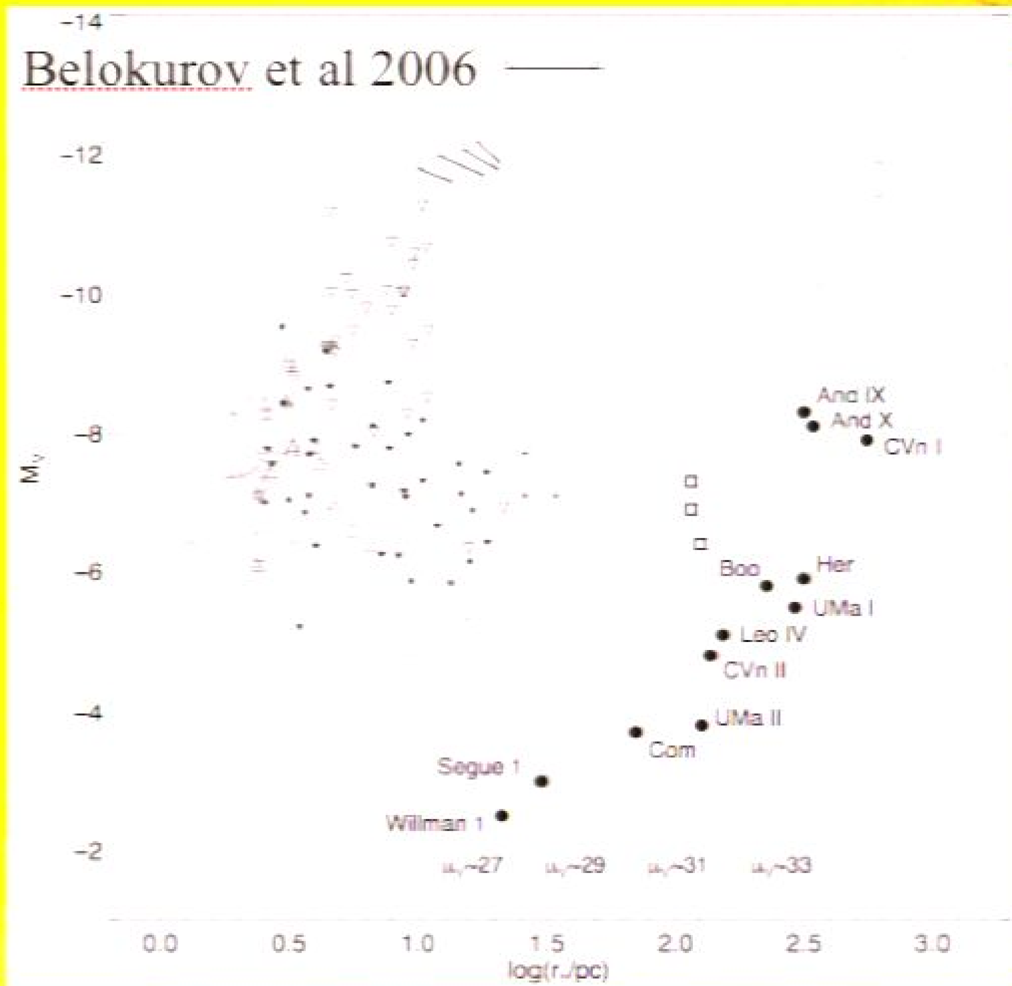
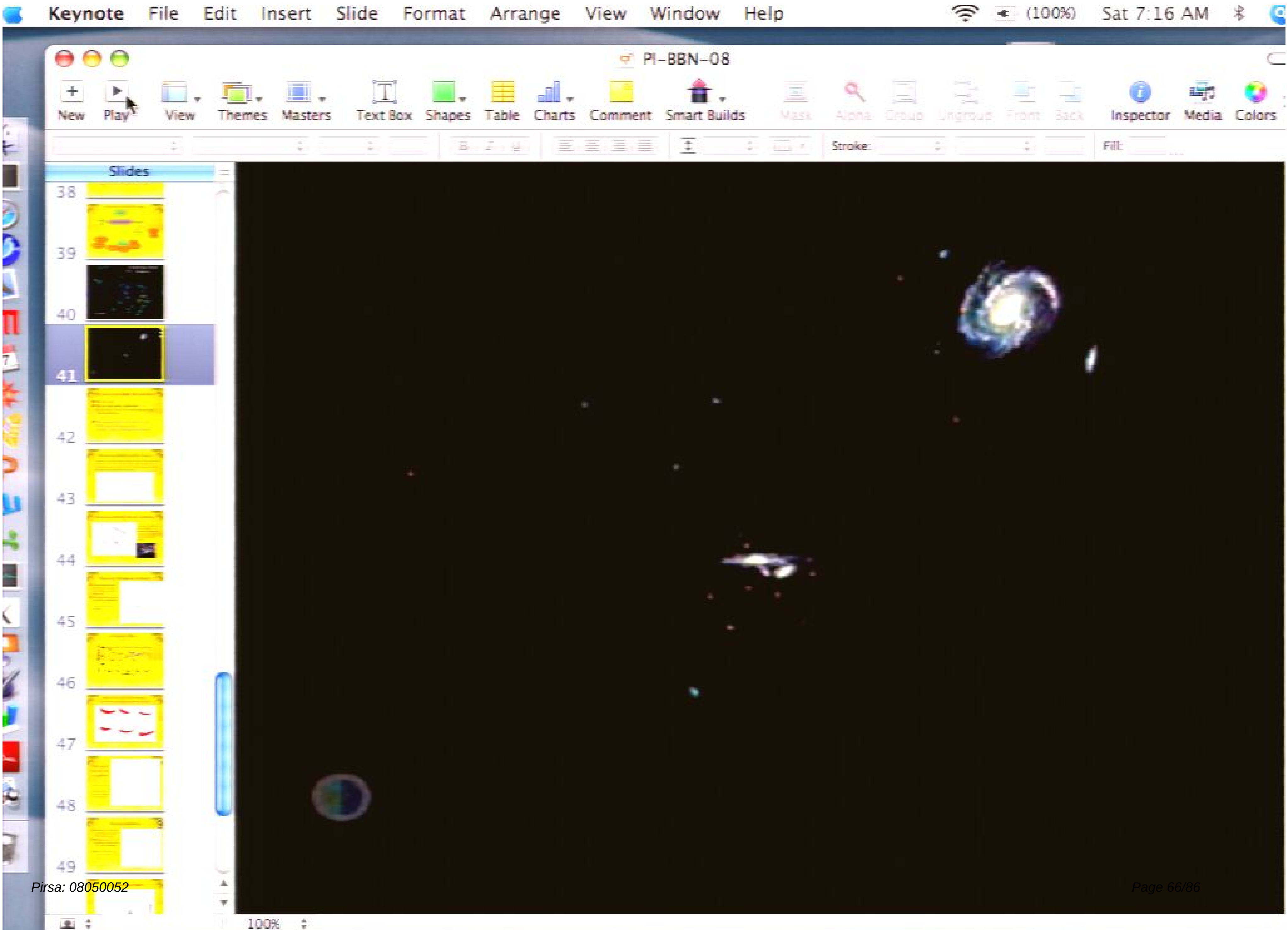
The newly discovered neighbors

Luminosity spans over four orders of magnitude from 1000 to 10 million solar luminosities

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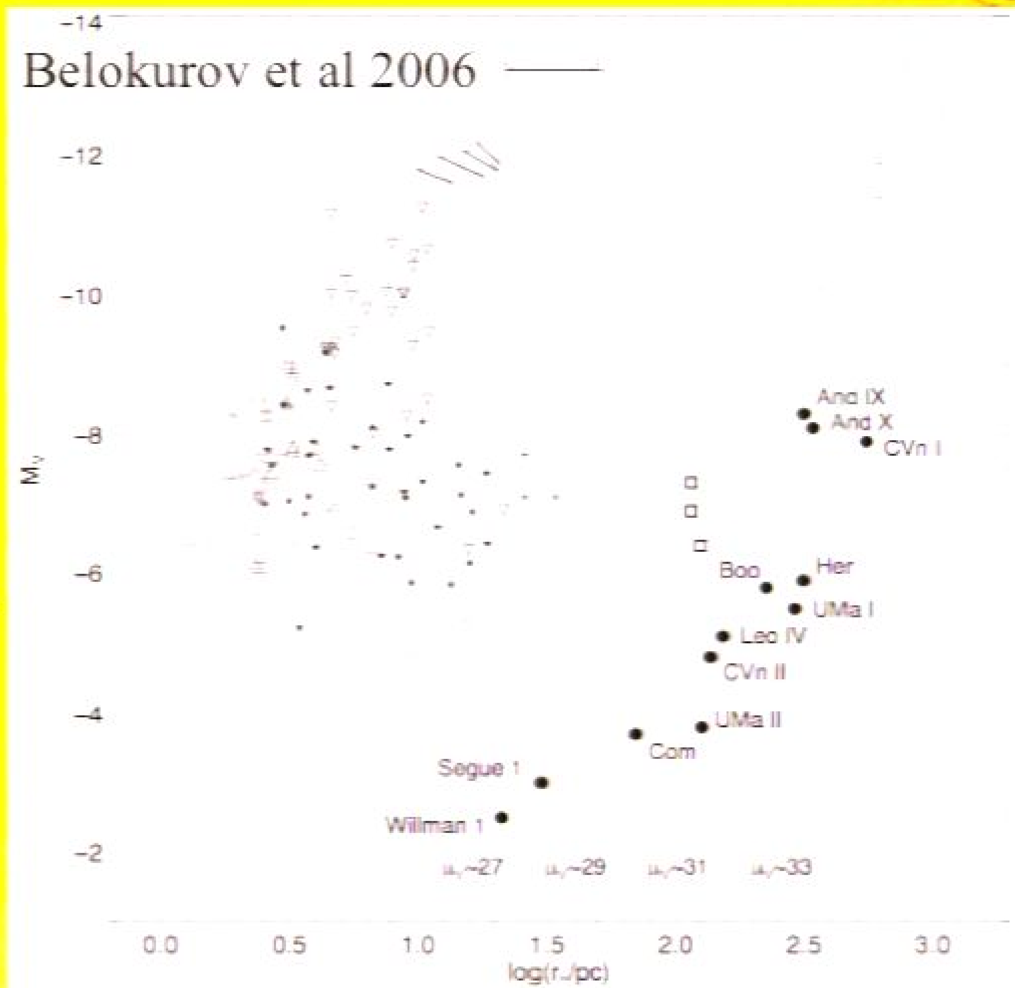
The newly discovered neighbors



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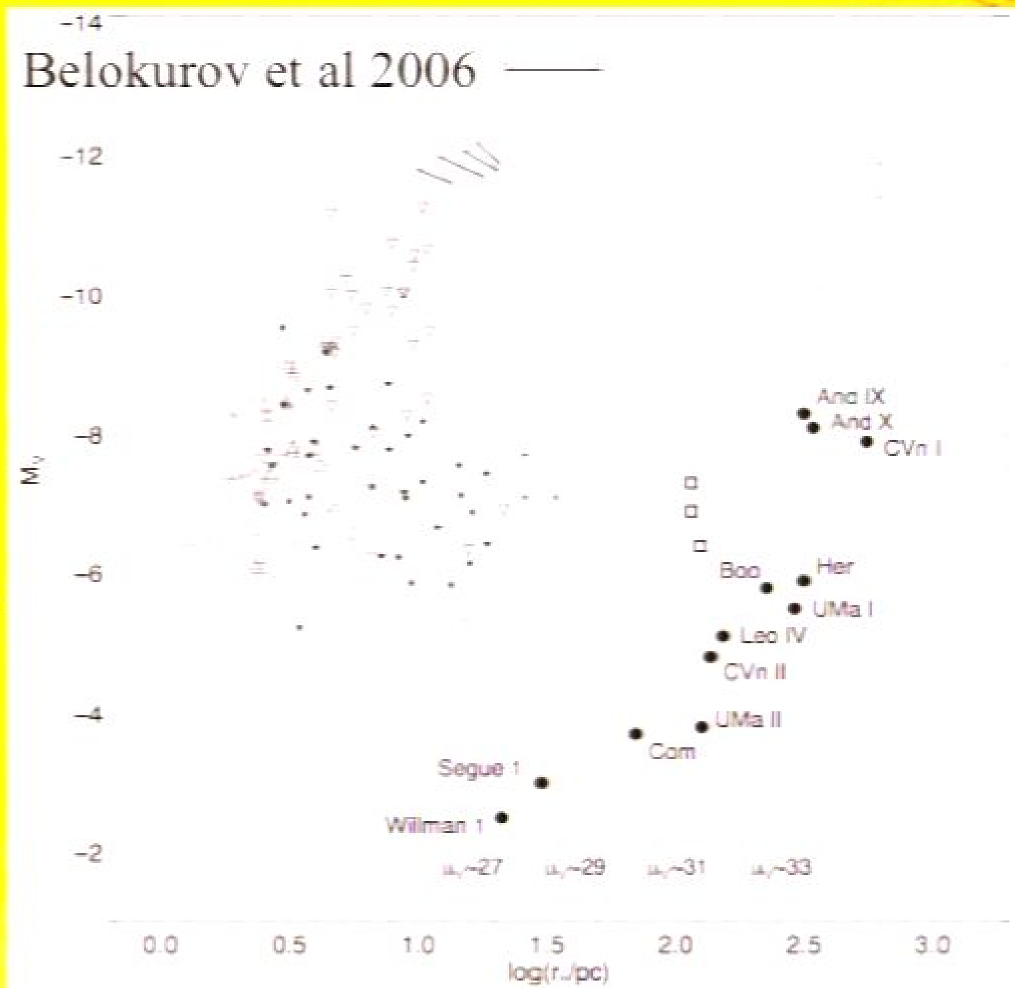
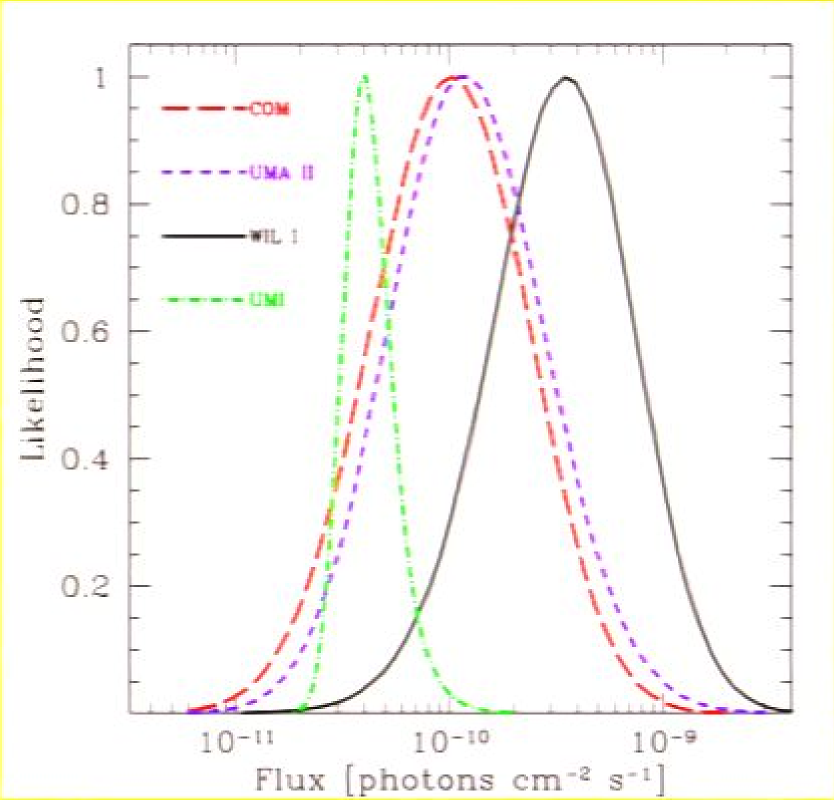


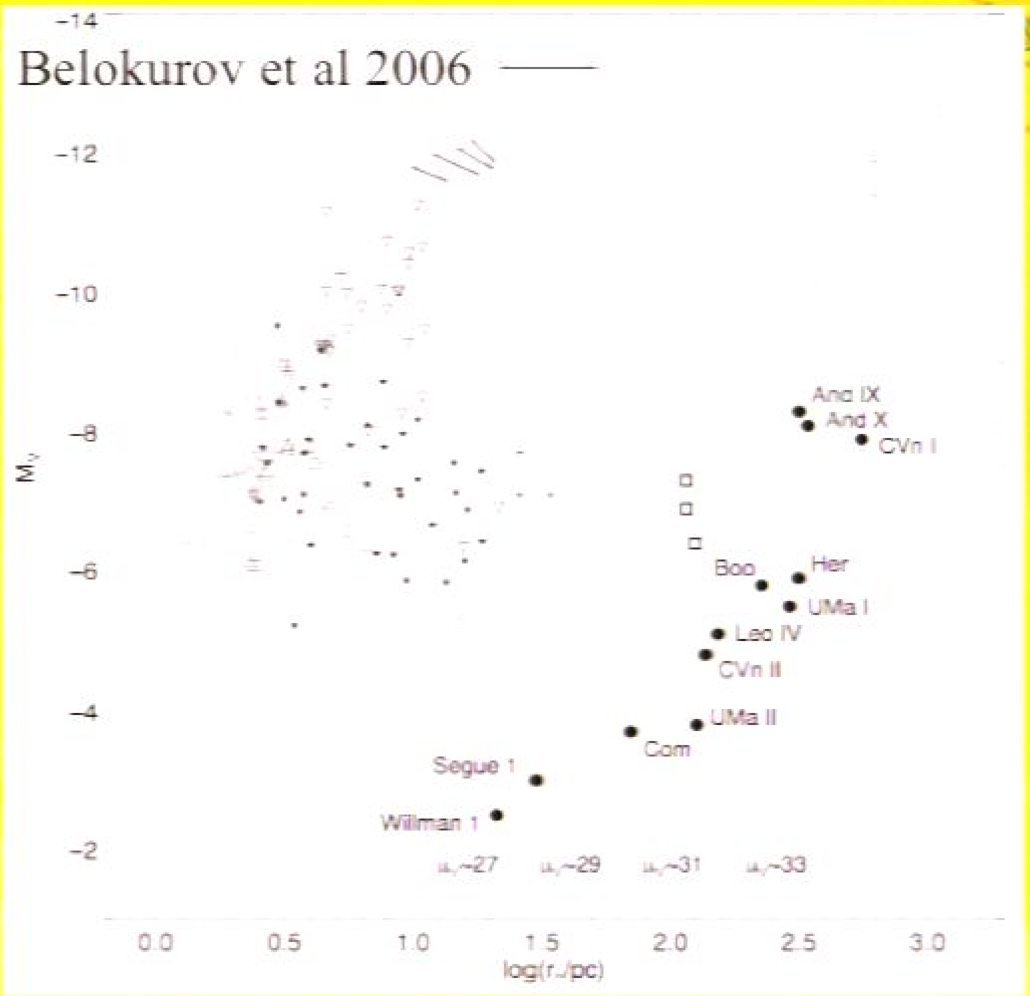
The new neighbors

- COM,WIL1,UM2 have very small luminosities ~ 1000 times the sun
- But they seem to be just as massive in dark matter as the more luminous ones!
- Make ideal targets for indirect detection of dark matter



Strigari et al 2007

The newly discovered neighbors



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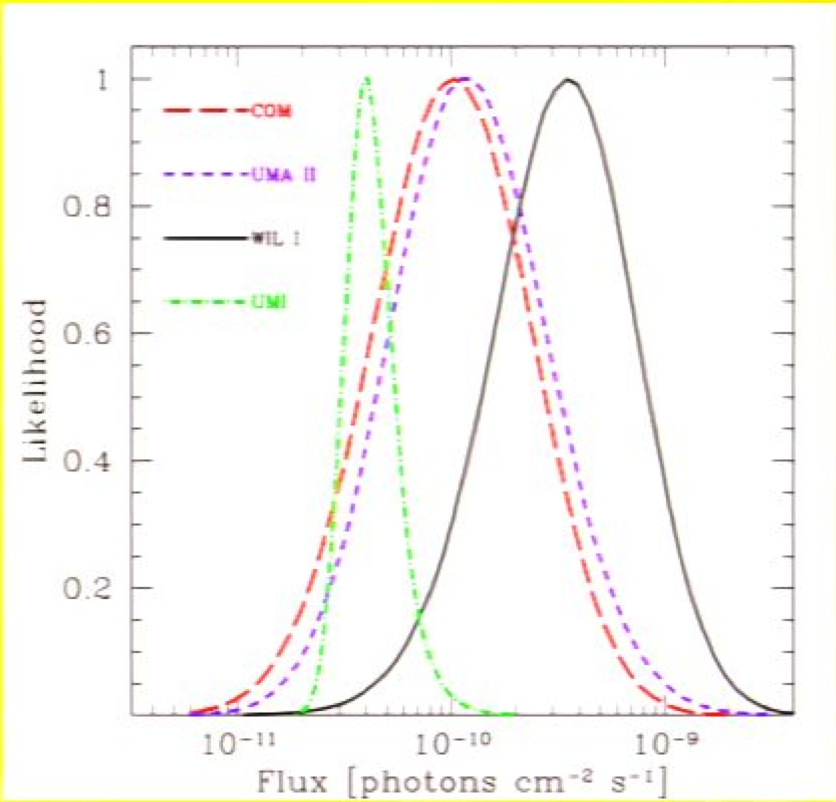
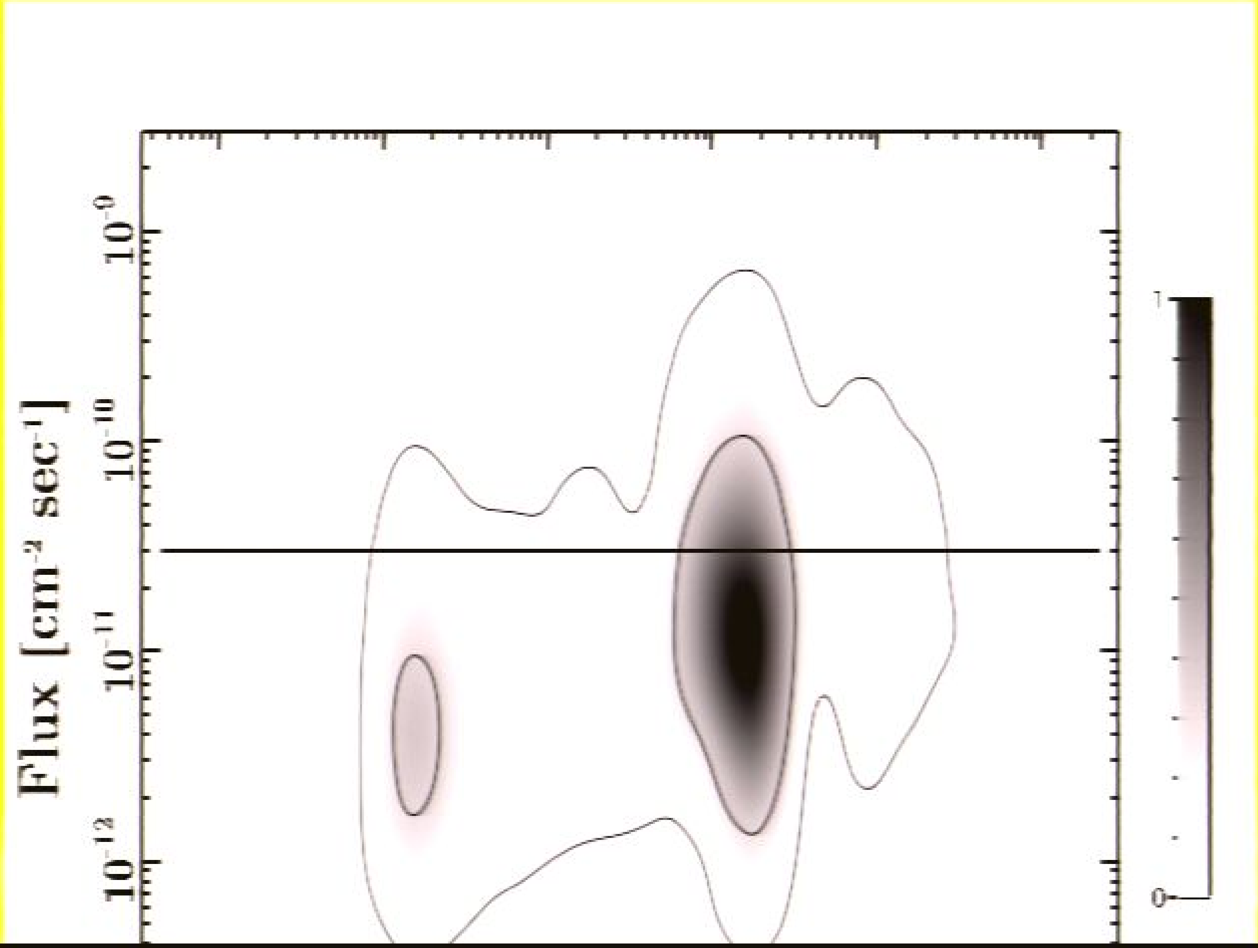


Strigari et al 2007

New Dwarf and WIMPs



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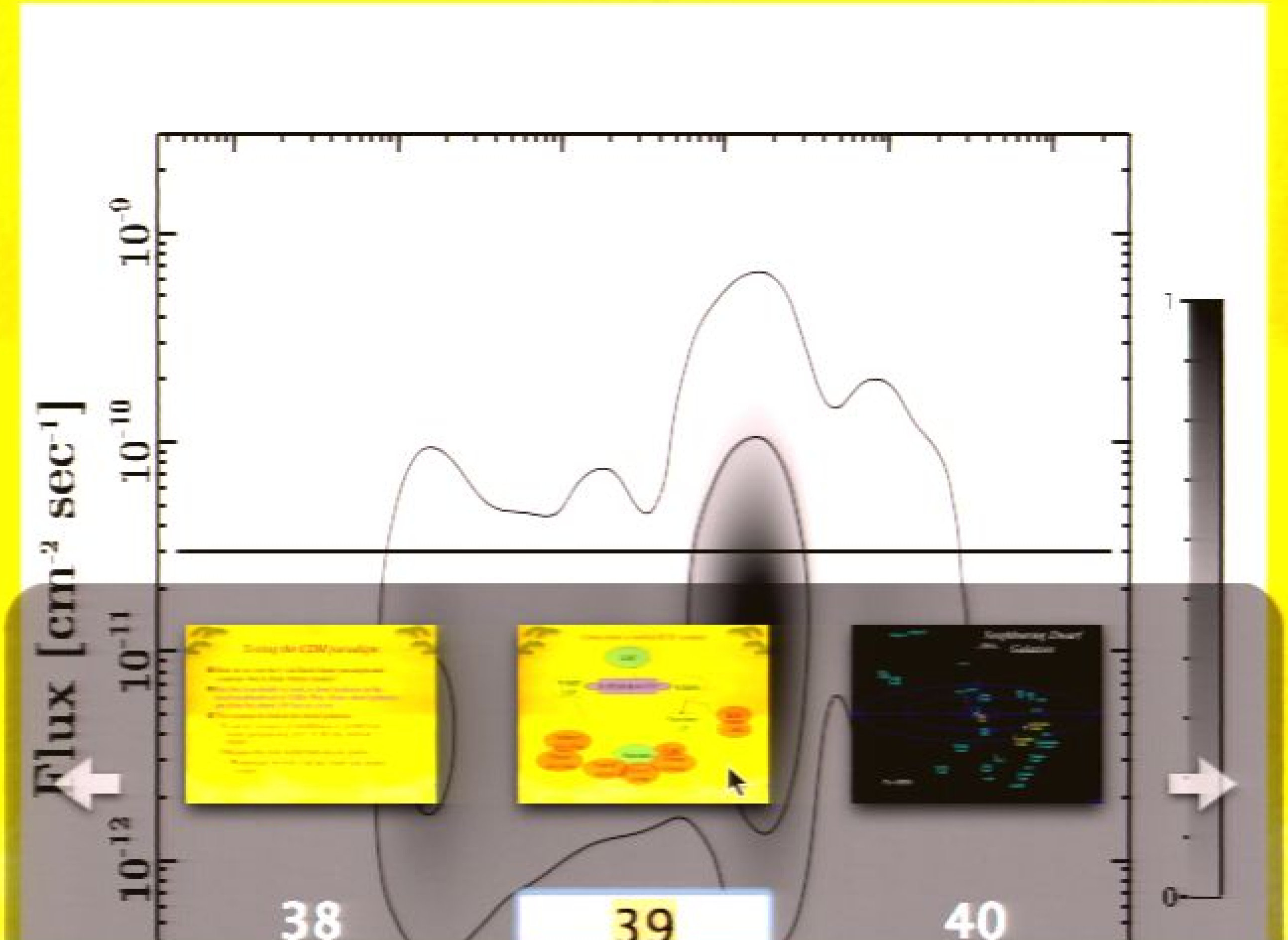

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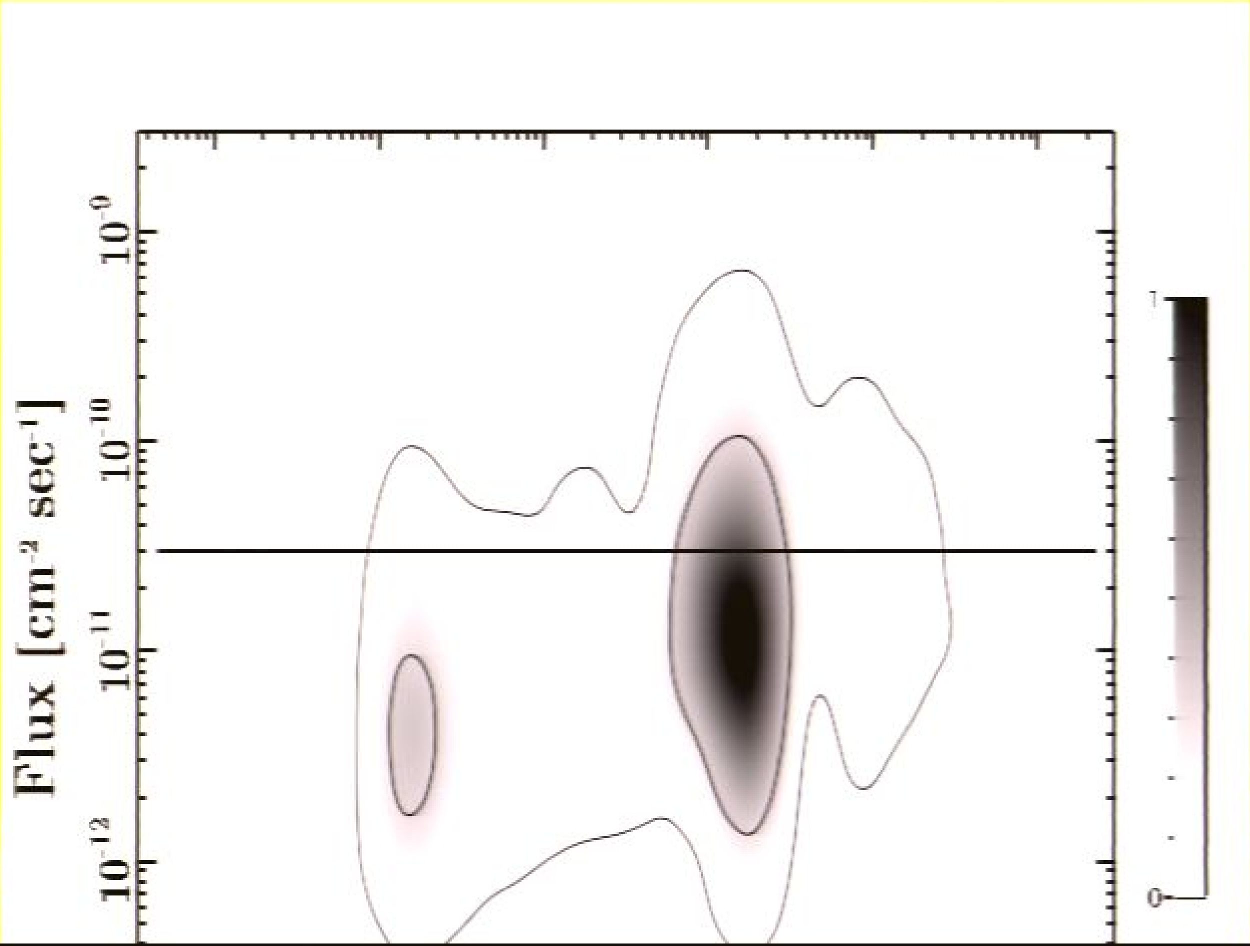
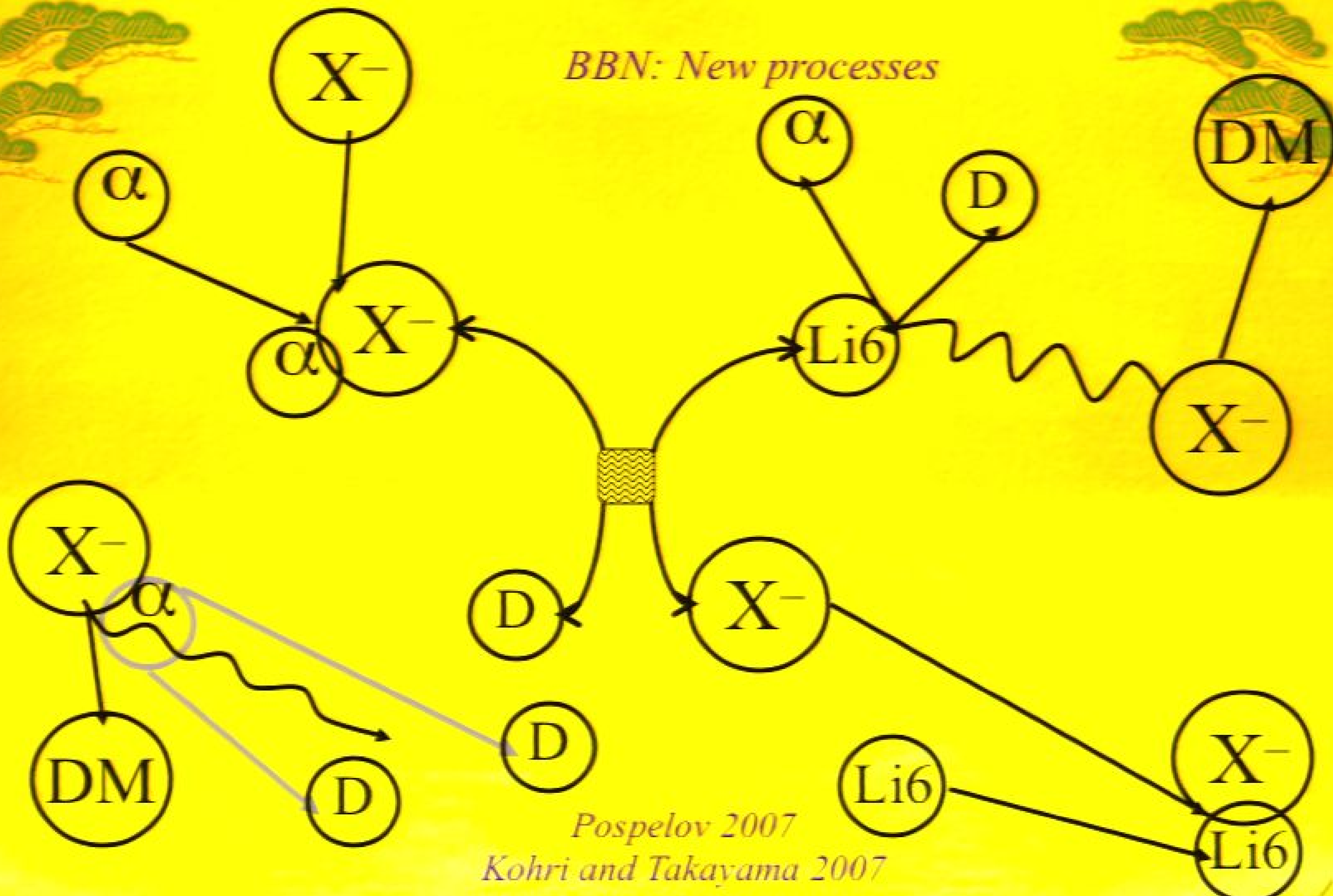


Looking ahead

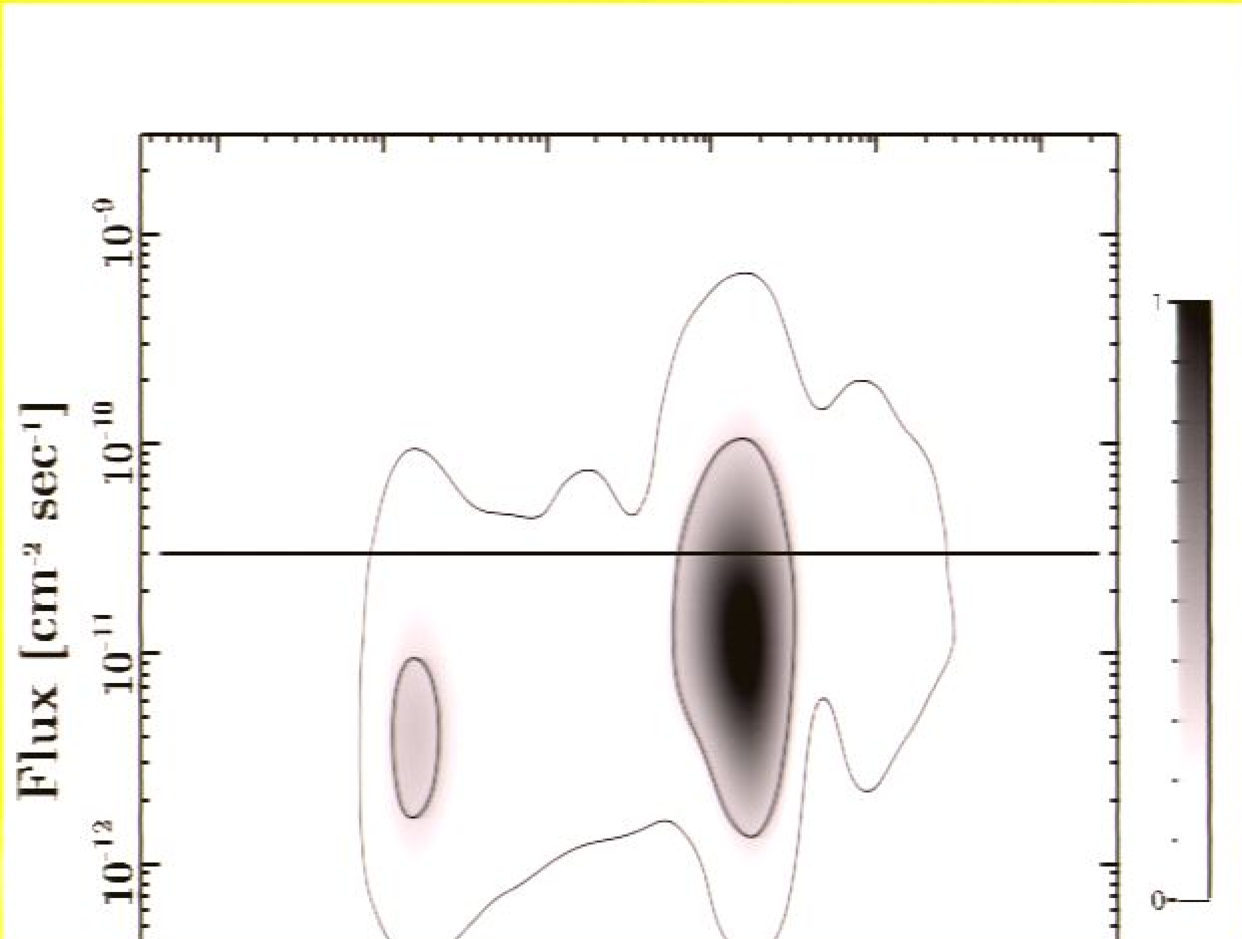
- GLAST will be launched early 2008
- Shortly after, LHC will turn on
- Direct detection experiments continue to scale up and innovate
- More dwarfs? (We hope!)
  - Better data on the existing dwarfs
  - Theory work to understand the systematics (binaries, tidal effects, triaxiality)
  - Connecting the mass distribution in dwarfs and their census to early universe and particle physics models

BBN: New processes

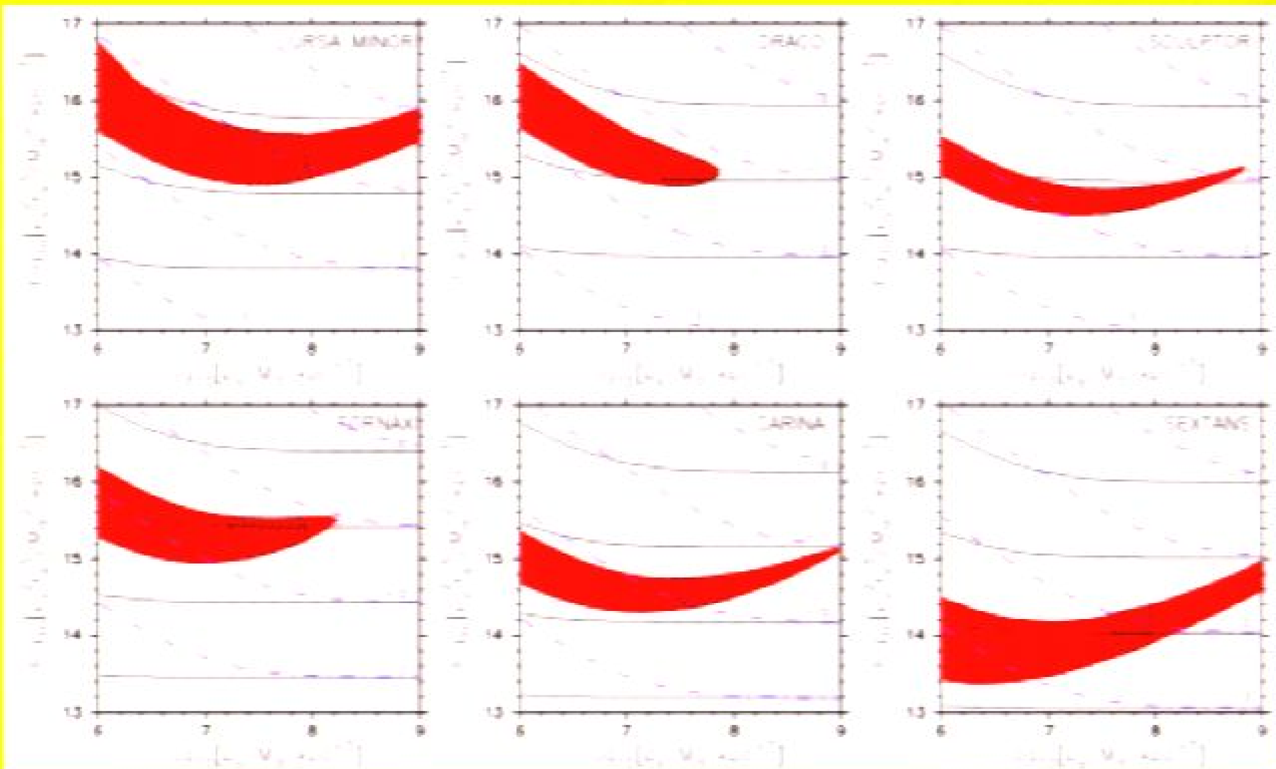


Pospelov 2007
Kohri and Takayama 2007
Kaplinghat and Rajaraman 2007

New Dwarf and WIMPs



Indirect detection of dark matter: Annihilation products from the dwarfs

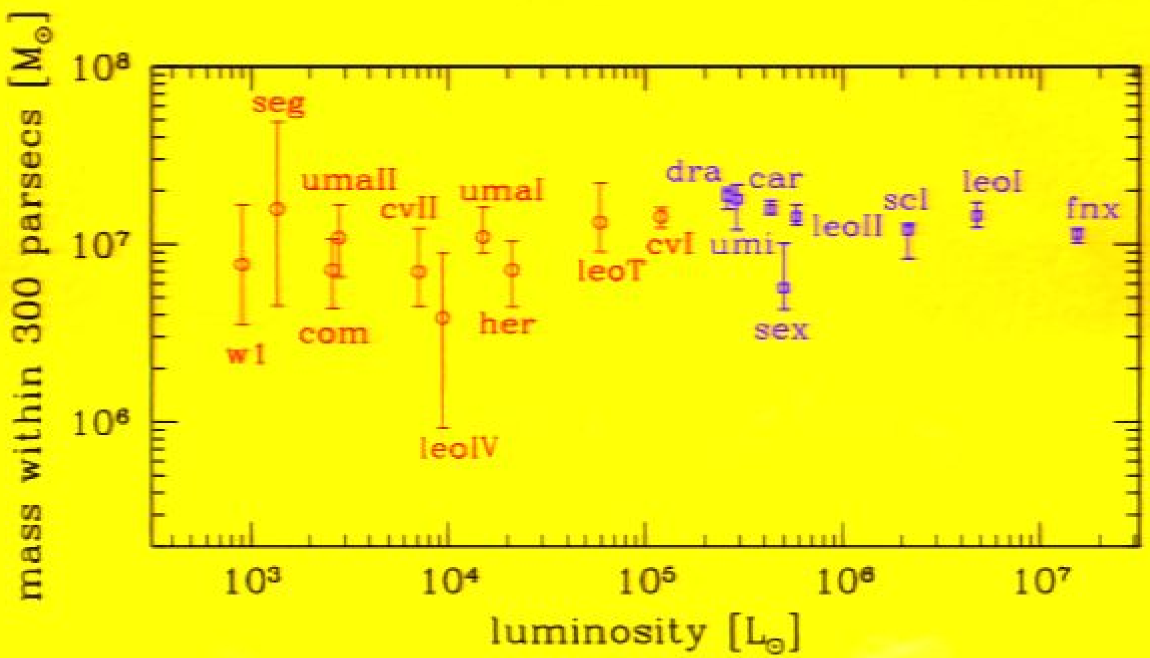


Luminosity

Characteristic density

Strigari et al 2006

A Common Mass



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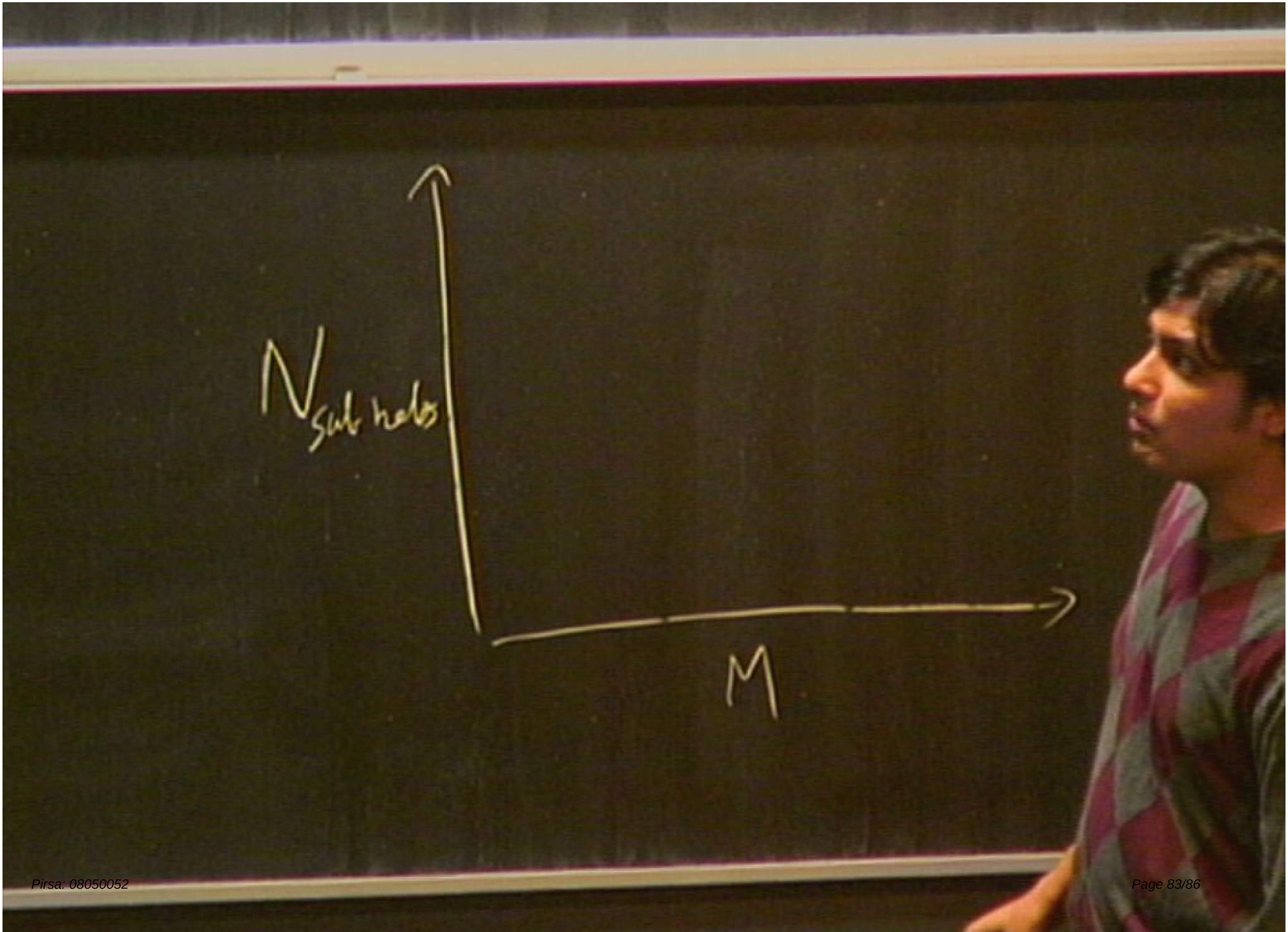
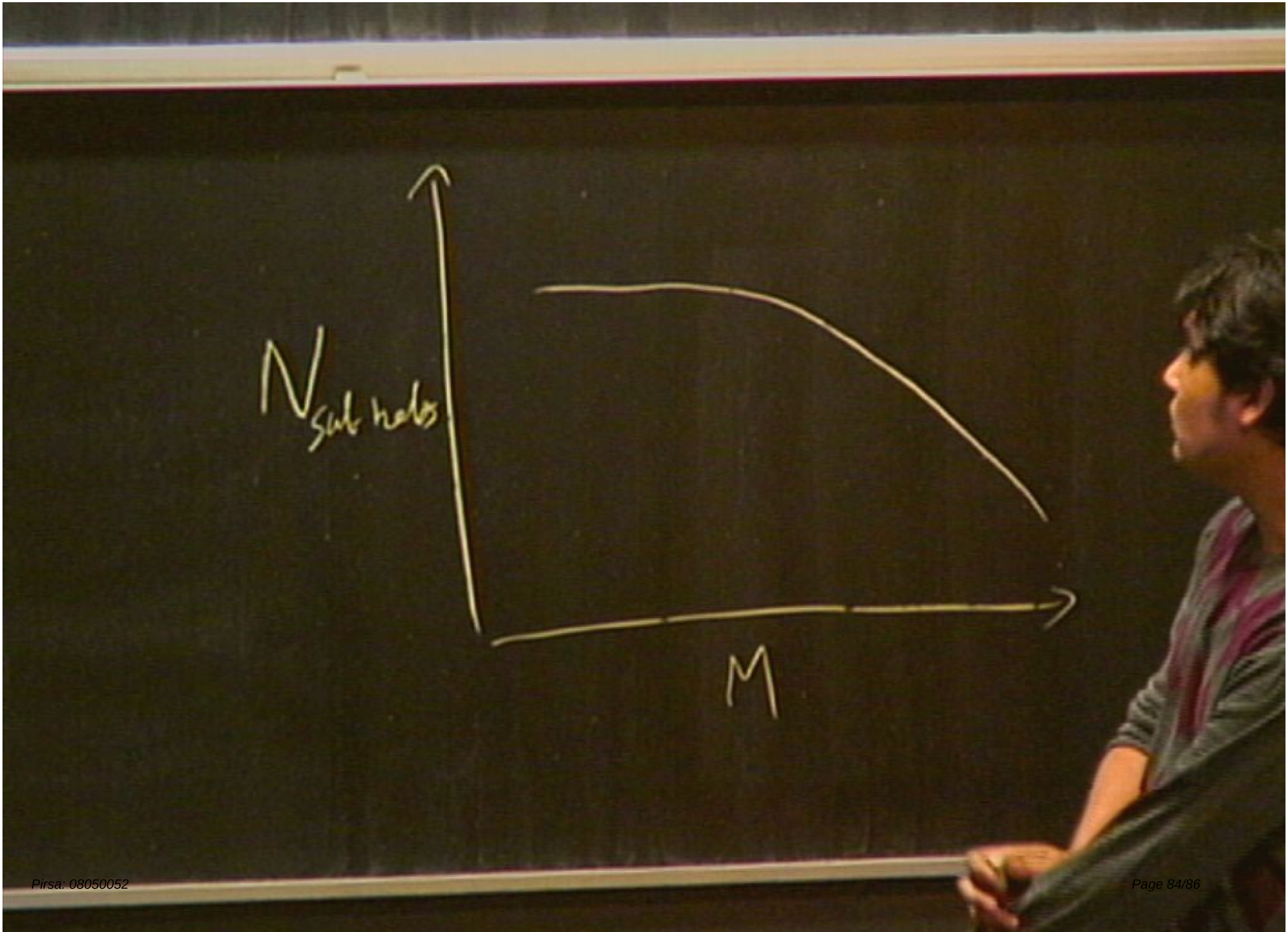


N sub halos
M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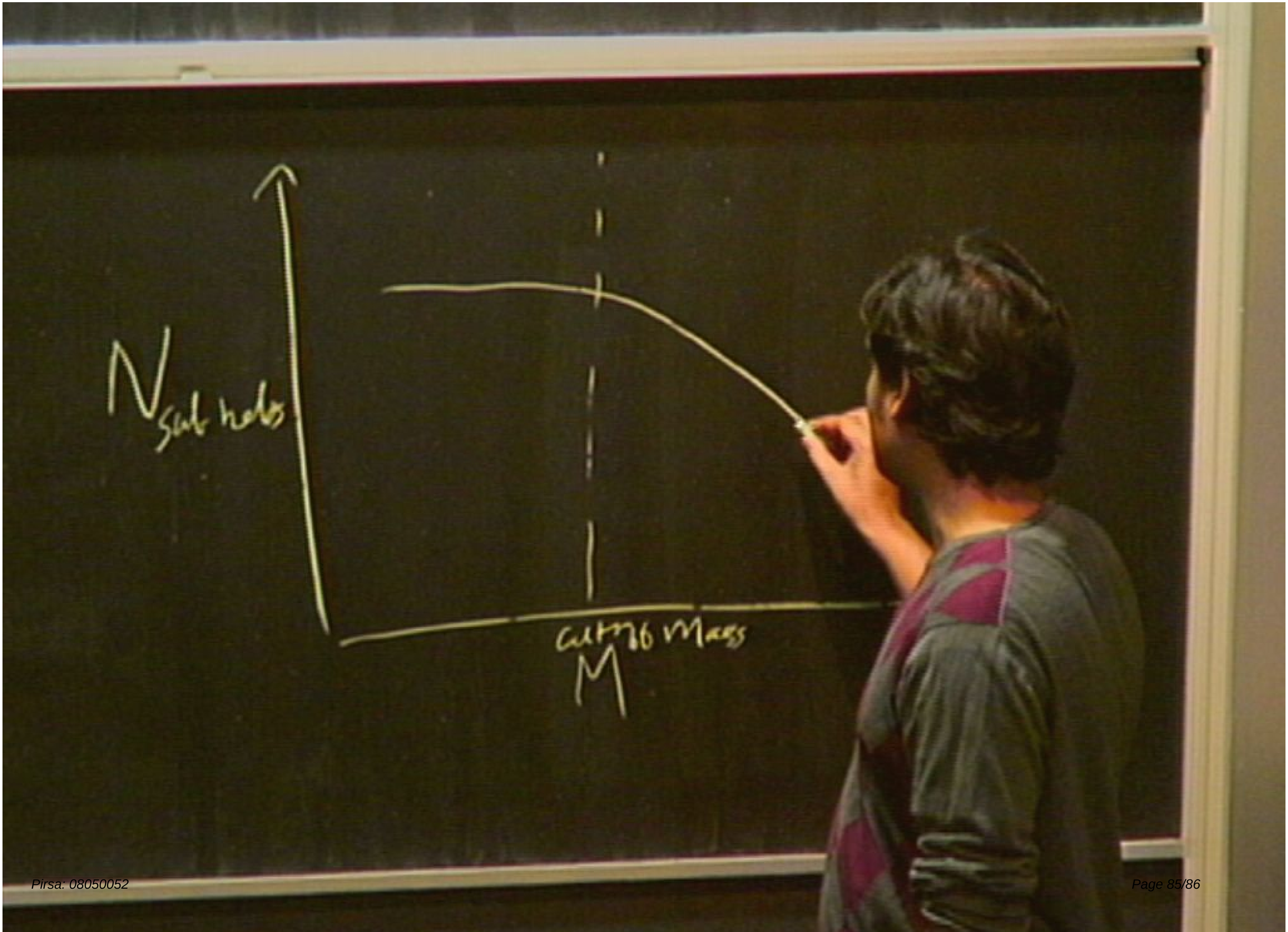
N
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Mass
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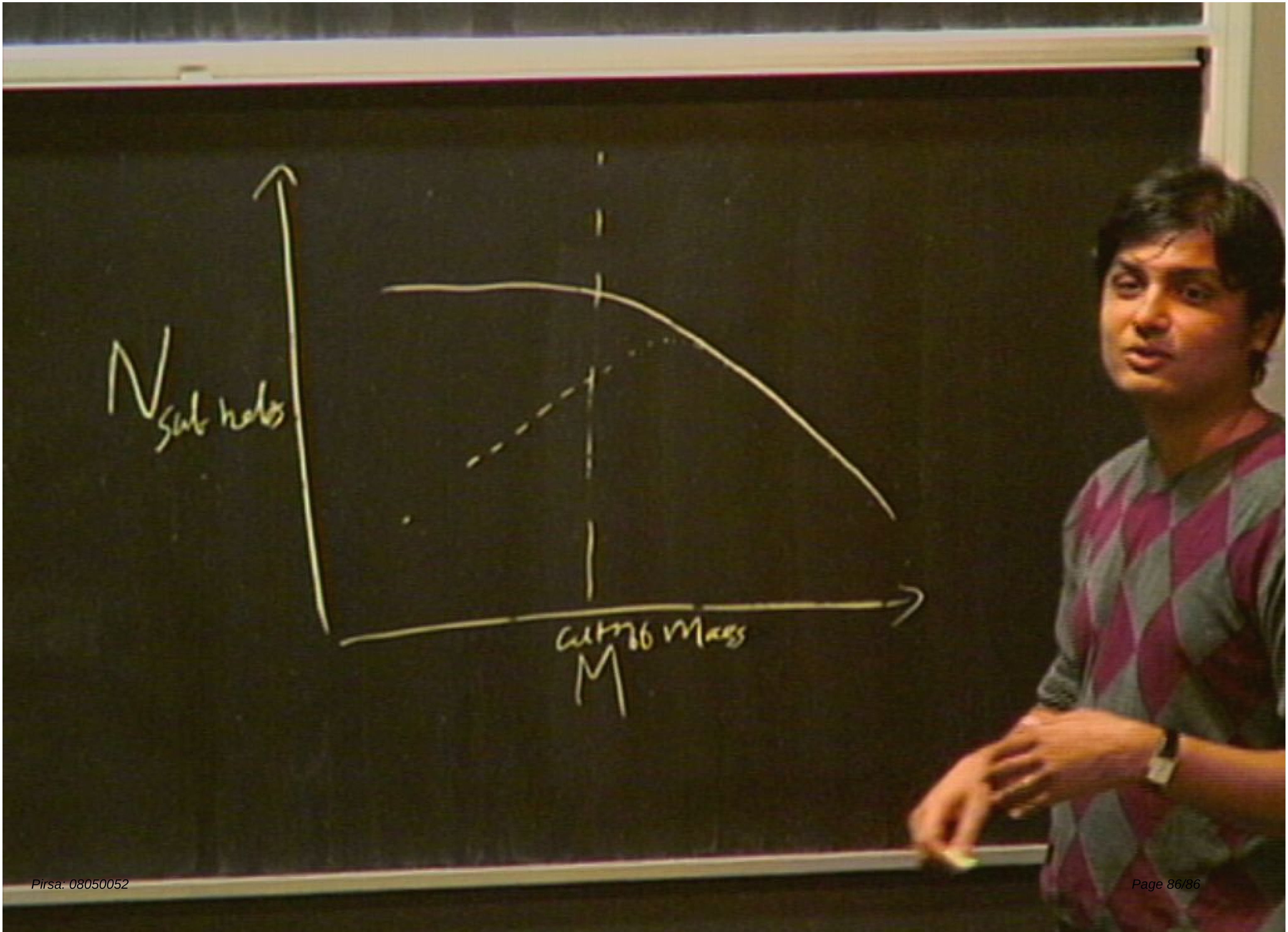
N sub halos
cutoff mass
M