Title: A New look at Dark Matter in the Universe

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Abstract: The best studied class of dark matter candidates in Supersymmetric theories is the WIMP, Weakly Interacting Massive Particles, which makes cold dark matter. There is a well-motivated alternative to the WIMP -- dark matter populated by decays of WIMPs. This dark matter from decays is closer in spirit to warm dark matter. They can be distinguished from cold dark matter by observations of structure on scales smaller than about a megaparsec, where cold dark matter models seem to face difficulty. Big Bang Nucleosynthesis predictions are also modified in interesting ways.

A New Look at Dark Matter in the Universe

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Collaborators

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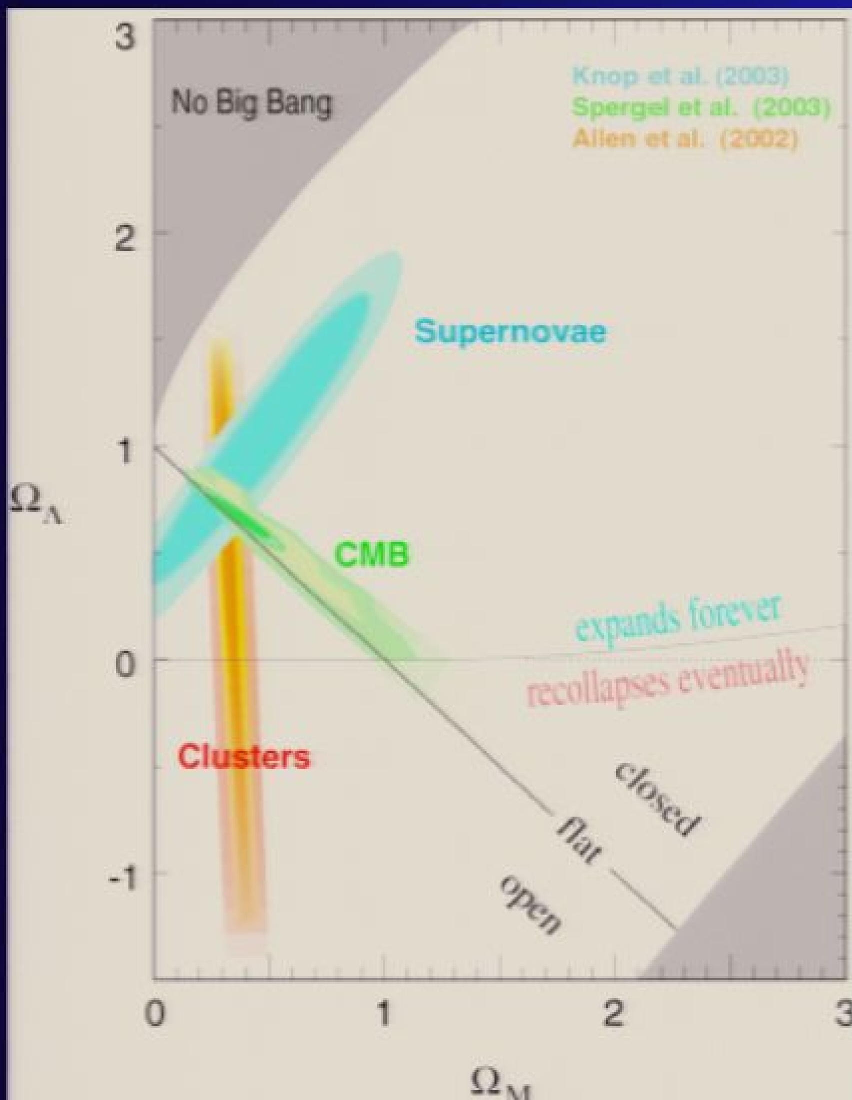
Dark Matter in the Universe



BBN

+

CMB

The Case for Dark Matter

- Zwicky (1933) noted that the velocity dispersion of galaxies in the Coma cluster implied a gravitational mass for the cluster well in excess of the implied luminous mass.
- Gravitational lensing by clusters of galaxies suggested by Zwicky (1937).
- Rubin and Ford (1970) on the Andromeda galaxy : "*Beyond R=4 kpc, the total mass of the galaxy increases approximately linearly out to R=14 kpc, and more slowly thereafter.*"

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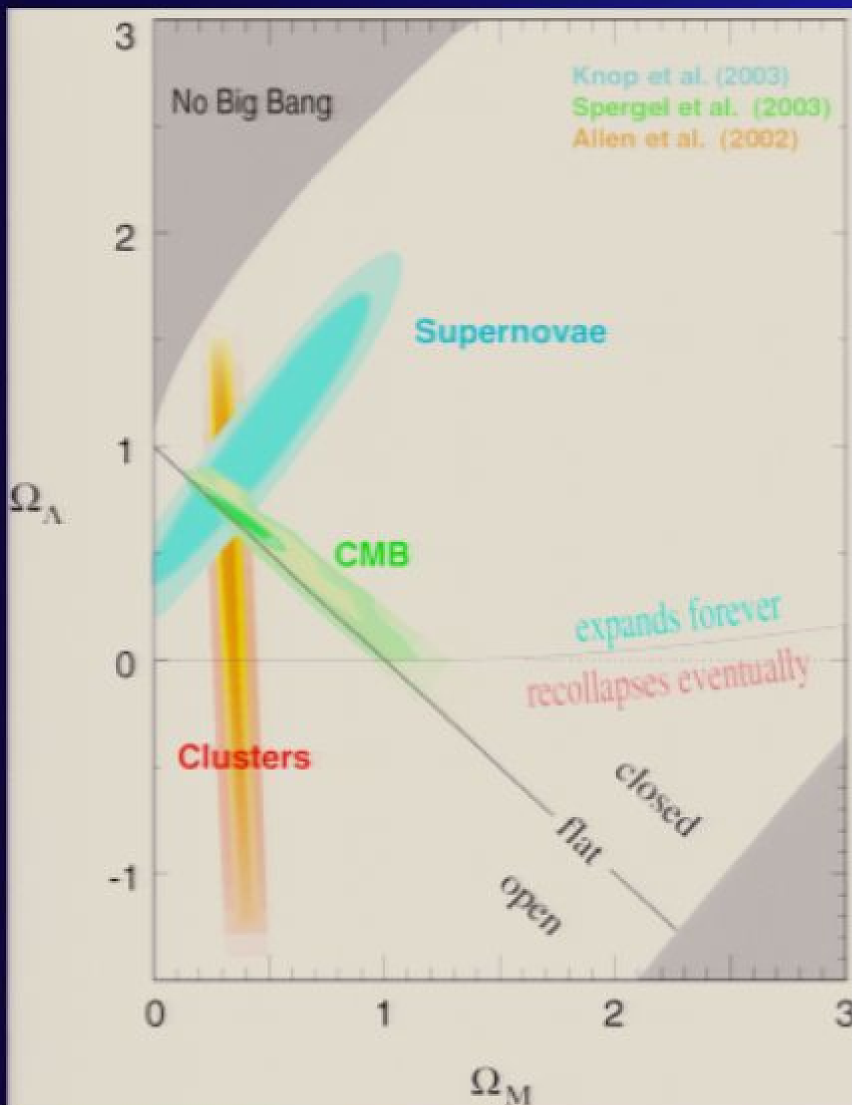

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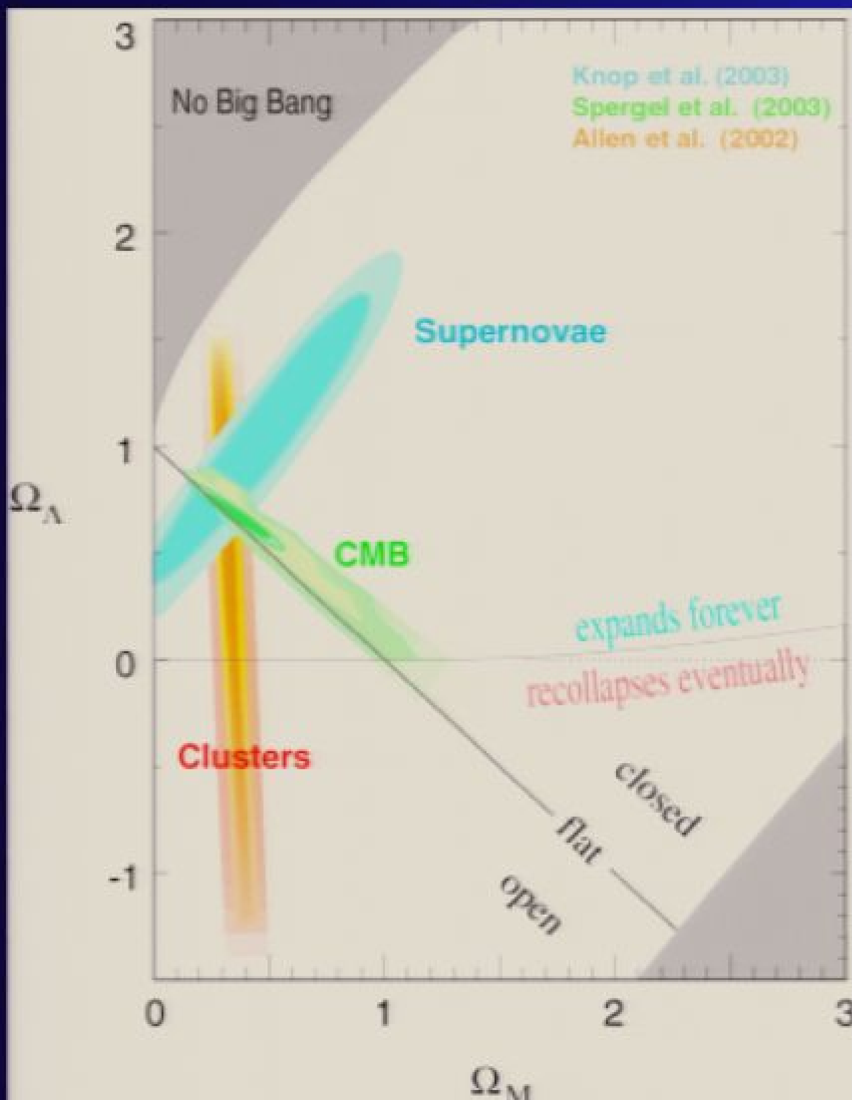

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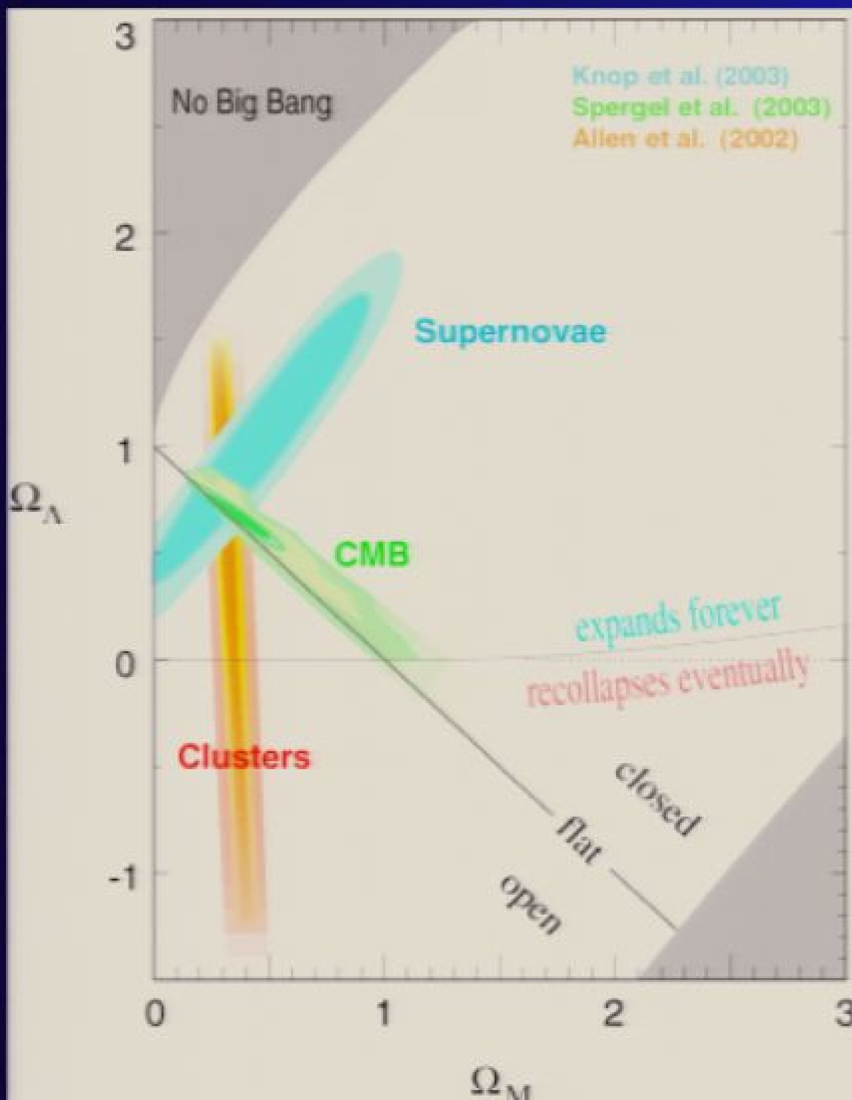

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→

30% Matter
70% Vacuum
4% Baryons

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

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  [Navarro et al MNRAS 2004; Diemand et al, MNRAS 2004]
- The "concentration" of the halos is set by the mean dark matter density of the universe "when the halo collapsed".

Dark Matter Particles from Decay

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  [Feng, Rajaraman and Takayama, PRL 2003]

- Example: sneutrino NLSP. sneutrino decays to gravitino with a lifetime $\sim 1/(8\pi G M_{weak}^3) \sim$ month.

Abundance of Dark Matter from Early Decays

WIMP

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

Dark Matter

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

Recap

- Weak scale mass gravitinos
- Natural in supergravity and extra-dimension theories
- Not completely cold
- Not thermal (unlike the gravitino considered as dark matter by Pagels and Primack, 1982)

The Case for Dark matter from Early 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.

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Same as CDM
[Peebles 1982, Bond & Szalay 1983
Blumenthal, Faber, Primack & Rees 1984,
Davis, Efstathiou, Frenk & White 1985]

Distinguishing from WIMPs

- Accelerator searches
  - Look for signatures of long-lived charged particles at LHC [Hamaguchi et al 2004, Feng and Smith 2004]
- Cosmology
  - Early Universe
    - Big Bang Nucleosynthesis
    - Cosmic Microwave Background black body
  - Late Universe
    - Small scale structure formation

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- Bound states of Helium-4 with charged NLSP
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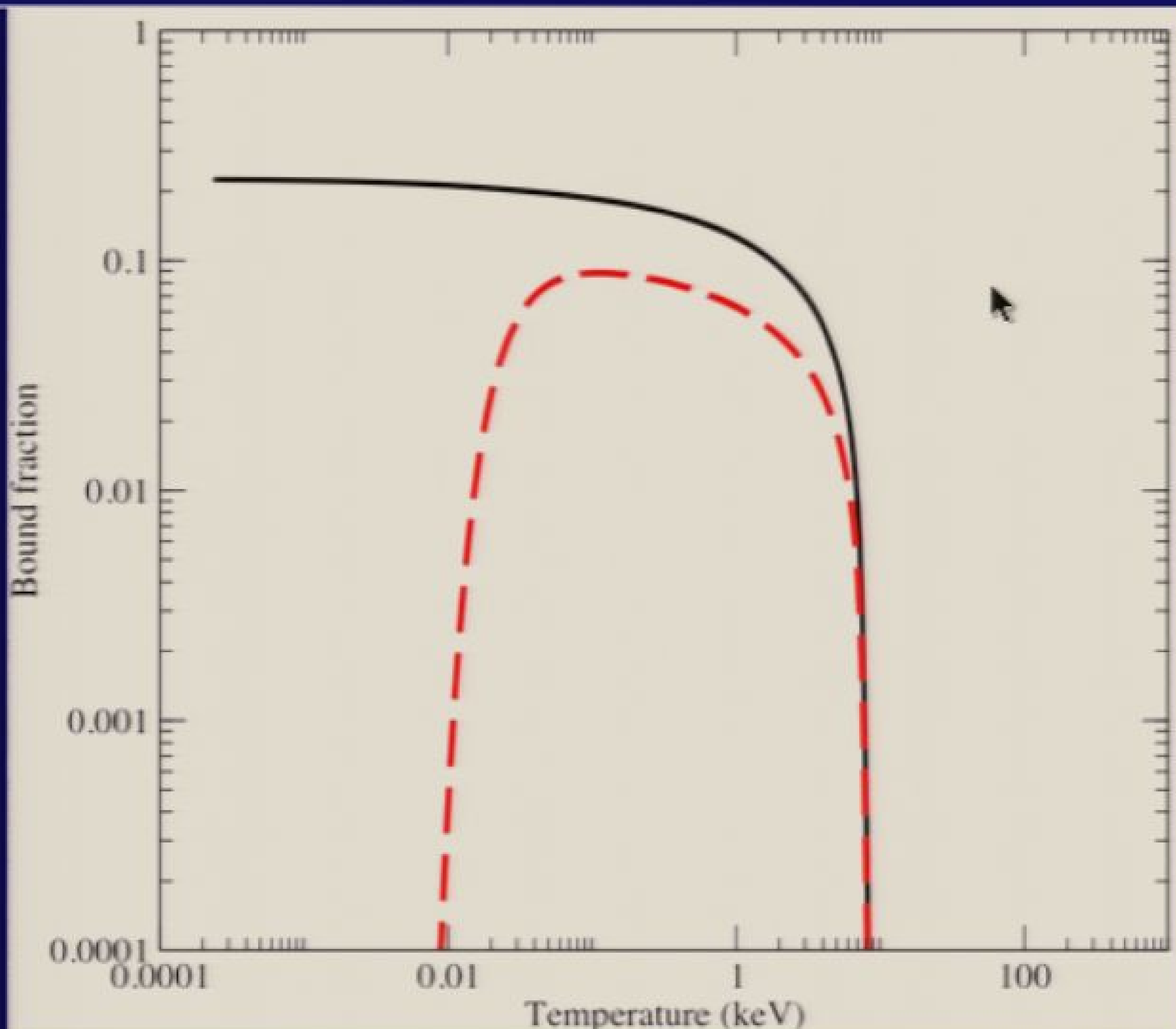
BBN with negatively charged dark matter

- Atoms!
- He4 is the electron.
- Charged NLSP is the proton.

- Binding energy = 0.3 MeV
- "Bohr radius" = 3.6 fm

- When does "recombination" happen?

Recombination



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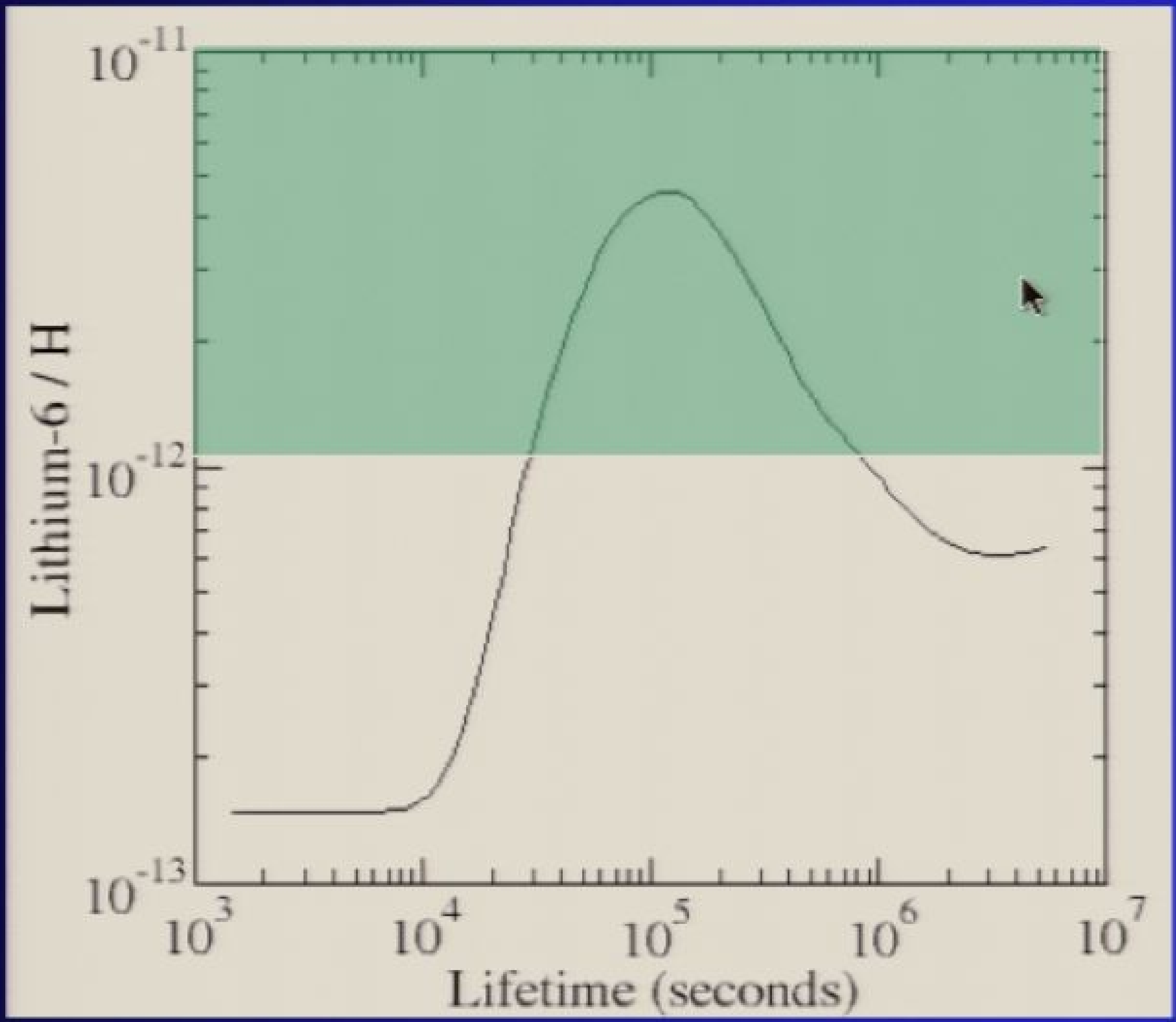
- *Include energy loss and destruction by non-thermal photons*

Li^6 abundance



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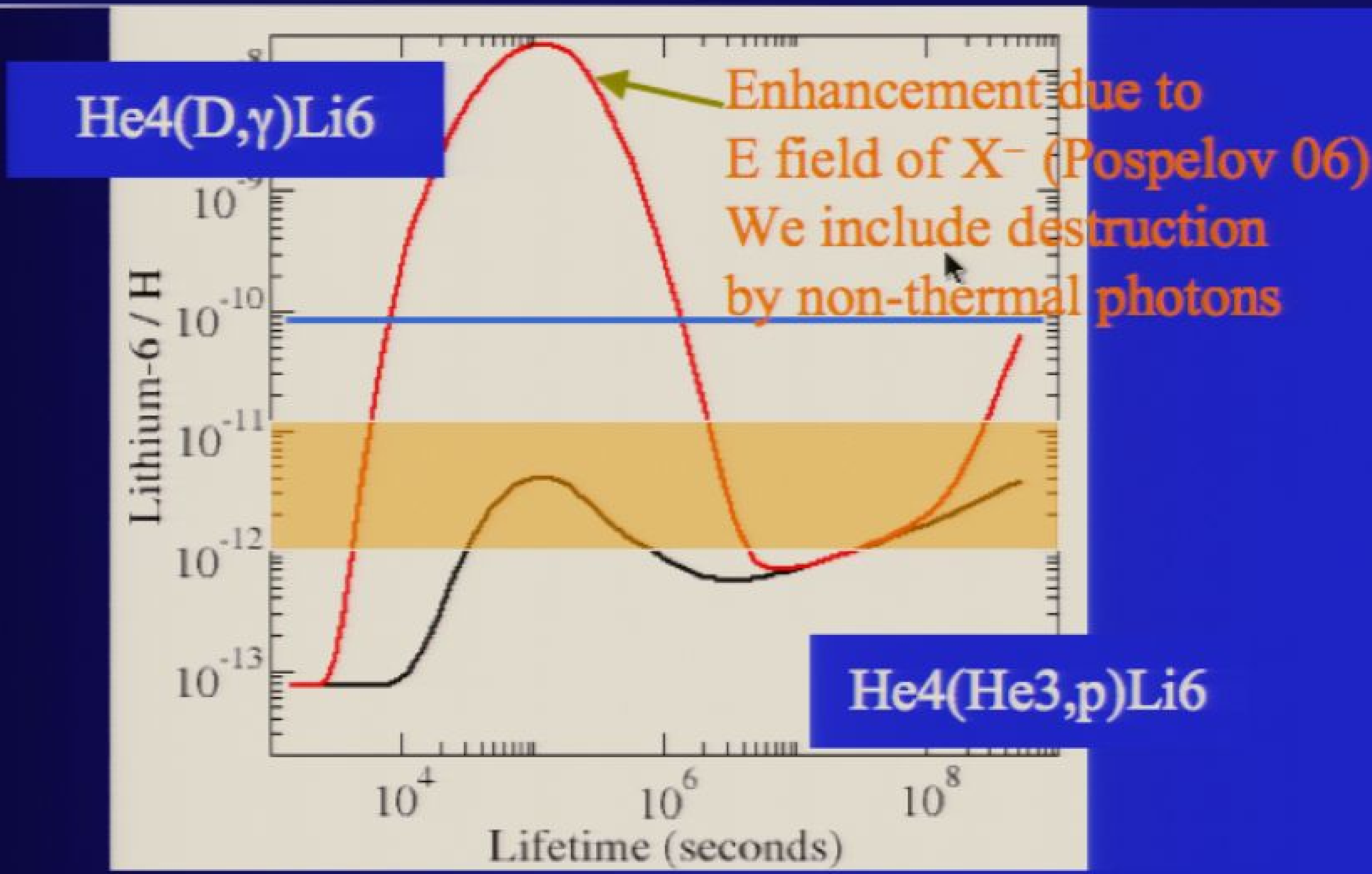

Work in progress

Cosmological consequences: Late Universe

- Growth of small scale structure modified [Kaplinghat 2005]
  - Larger free streaming scale
    - Produces lesser power on small scales; cuts off the power spectrum like warm dark matter models
  - Smaller phase space density
    - Creates lower concentration (less dense) halos and perhaps those with *observable* flat density cores *even though the phase space density does not have a FD form*

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

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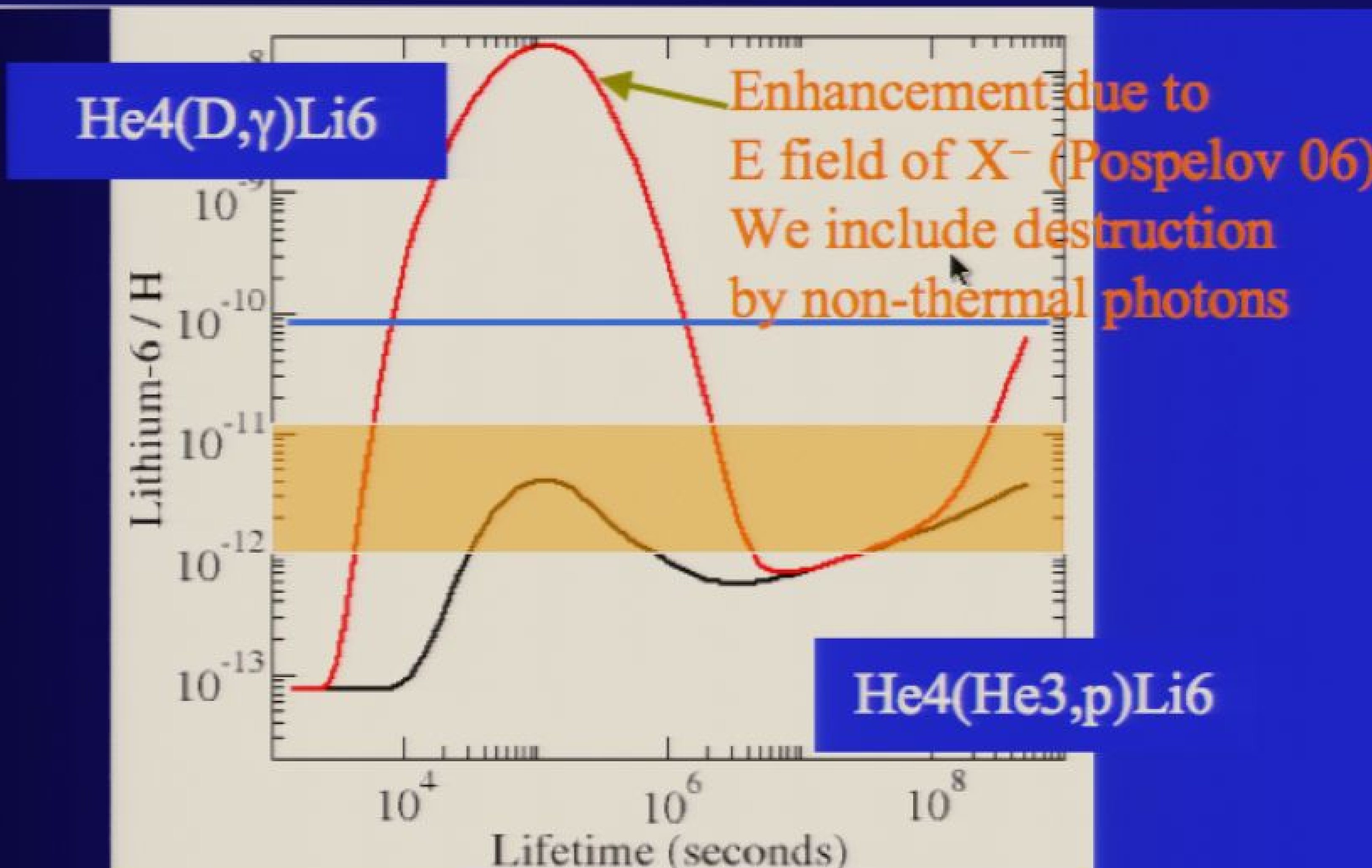

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Small-scale structures

- Lesser power on small scales means less substructure on small scales.
- Lower concentration or cored small mass halos are more easily destroyed.
- Lower concentration small mass halos are more consistent with 2-d rotation curves.
- Constant density cores in small galaxies? Need more accurate velocity dispersion and rotation velocity measurements.

Phenomenological Parameter Space

- Two parameter family of models…

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- For a slepton decaying to a gravitino, we have

$$Q = 2.1\times 10^{-3}(2p_{\mathrm{cm}}/M)^3(M/\mathrm{TeV})^{4.5}\mathrm{M}_\odot/\mathrm{pc}^3/(\mathrm{km/s})^3$$

- *For neutral decays in radiation dominated regime, parameter space is effectively one dimensional*

Kinematics of Early Universe Decay: 0

- Decay during *radiation dominated era* of heavy charged or neutral particle at rest. The resulting phase space distribution for the daughter dark matter particle (in terms of its comoving momentum) is

$$f(q,a) \propto \frac{q_0}{q} \exp\left(\frac{-q^2}{q_0^2}\right) \quad \text{for} \quad q < a p_{\text{cm}}$$

$q = a \times$ physical momentum

$= a_{\text{born}} \times p_{\text{CM}}$

Kinematics of Early Universe Decay: 1

- Relative density perturbation of decaying matter is unaffected if the decay is non-relativistic.

- Perturbation to the phase space density of the dark matter is (schematic):

$$\delta f_0(q,a,k) = \delta f_0^{(a)}(q,a,k) - f(q,a)\frac{h(k,q/p\mathrm{cm})}{2} j_0(k\omega_q)$$

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Free-streaming Suppression

- The relevant scale that controls the suppression of the power spectrum is not the standard free-streaming scale defined as $\lambda_{fs} = \int^{EQ} dt\, v(t)/a(t)$

$$\lambda_{\text{fs}} = 7\,\text{kpc}/Q^{1/3} \times \left[2\log\left(\frac{1+z_{\text{decay}}}{3125}\right) - \log(1+\sqrt{1+(p_{\text{cm}}/M)^2})\right]$$

- The suppression of the power spectrum is primarily controlled by the phase space density Q for decays deep in the radiation dominated era.

Free-streaming Scale

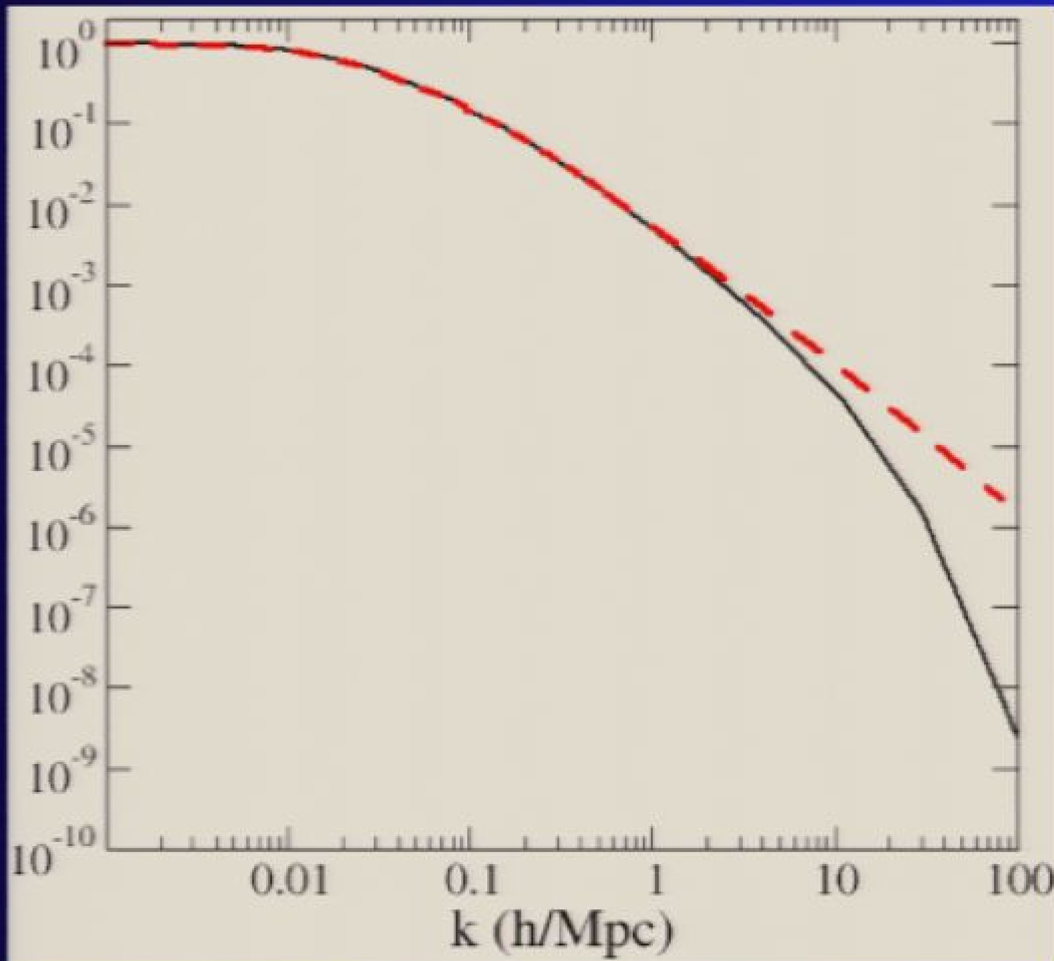
- Neglecting the decay, the solution is just free-streaming.

$$\delta\rho(a_0,k) = (2\pi^2)^{-1} a_0^{-4} \int_0^{a_0} da \int_0^{\infty} dq\, \epsilon q^3 \frac{df_0}{dq} \left[-\dot{\phi} j_0(k\omega_q) + \frac{\epsilon}{q} k\psi j_1(k\omega_q) \right]$$

- Here ω_q stands for $\omega_q(a_0,a) = \omega_q(a_0,0)-\omega_q(a,0)$, the comoving distance travelled by the dark matter particle.
- No contribution to the integral when $k\omega_q(a,0) \gg 1$
- Analogous to the massive neutrino case

Bond, Efstathiou and Silk 1980; Bond and Szalay 1983
Brandenberger, Kaiser, Turok 1987

Free Streaming: Power Spectrum Cut-off



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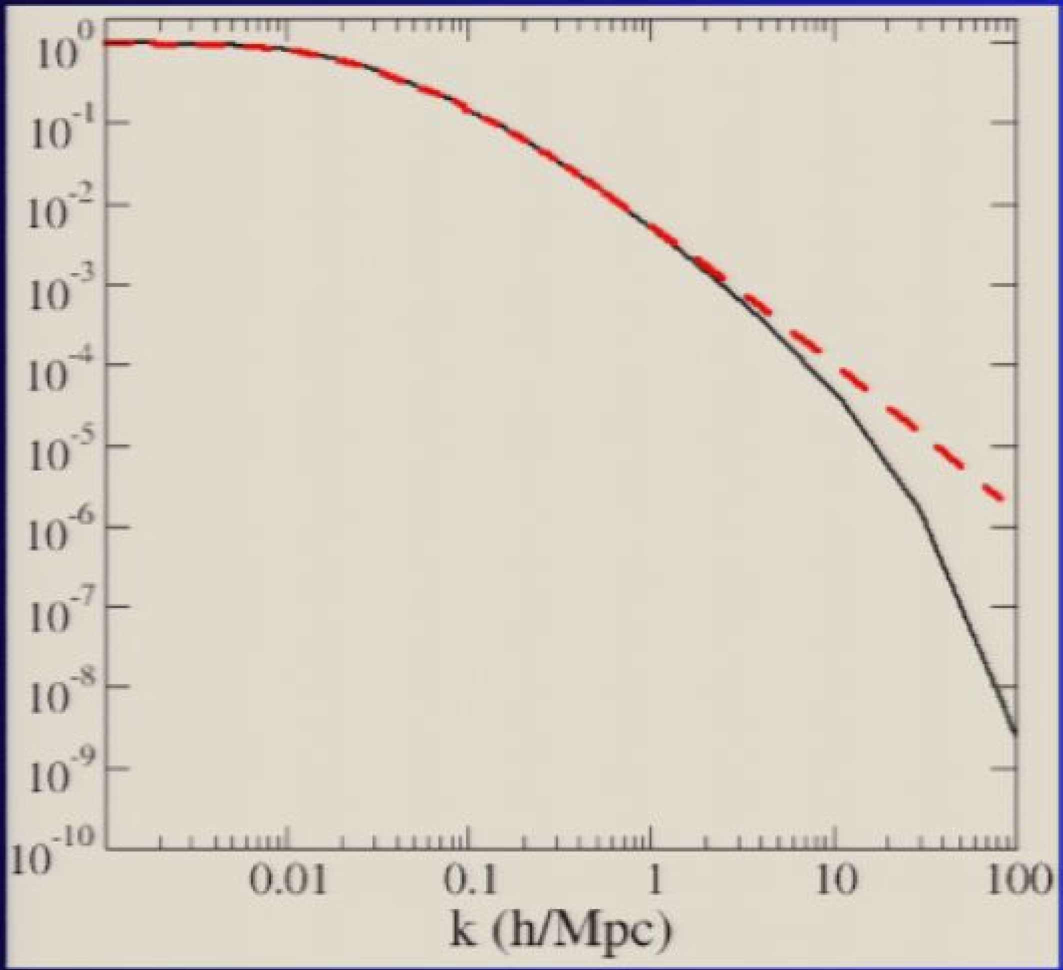

$k_{enter}(t=\tau)$
$= 0.7$ h/Mpc

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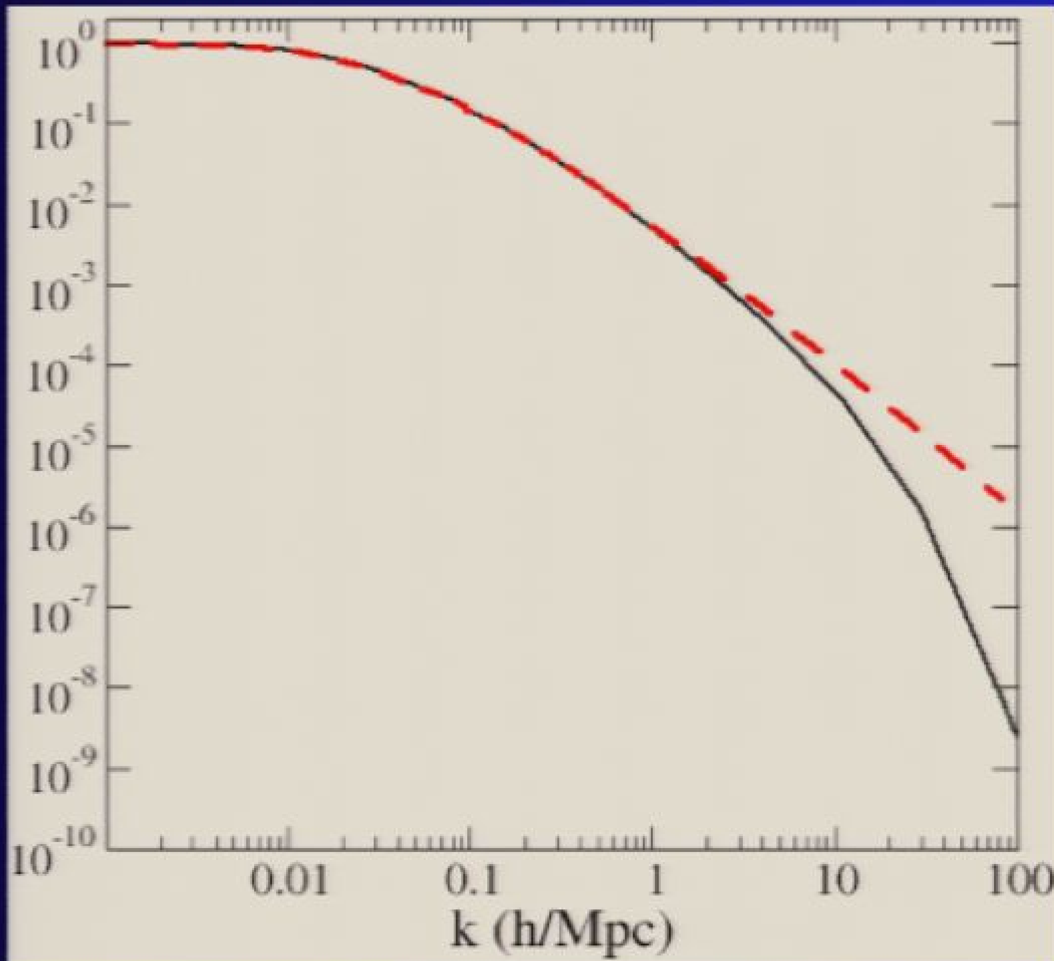

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$k_c = 12$ h/Mpc

Phase Space of Collision-less Systems

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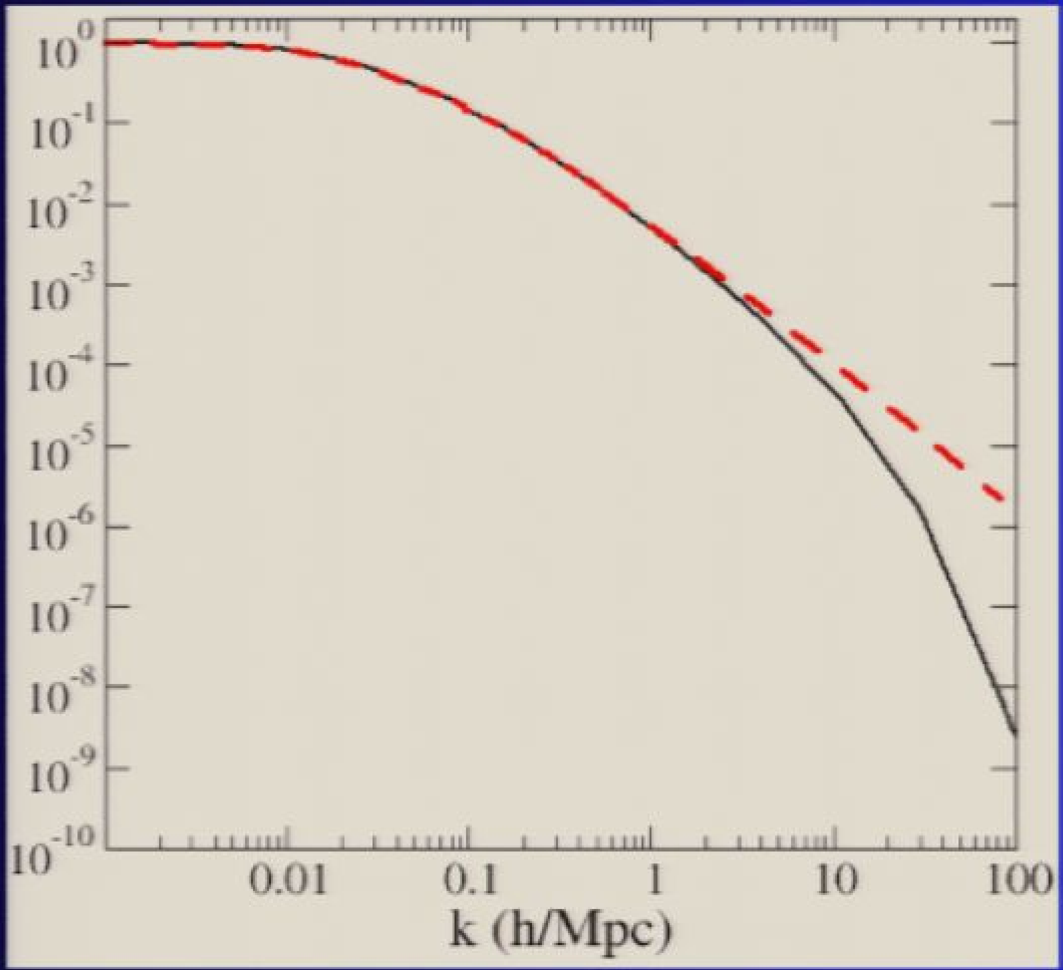

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- $D/Dt\, F(x,v) = 0$ for collision-less system.
  - Phase space density conserved along the trajectory given by $\partial_t x = v$ and $\partial_t v = -\nabla \Phi$.
  - F_{max} conserved.
  - $M(f) = \int d^3x\, d^3v\, F(x,v)\, \Theta(F(x,v)-f)$ is conserved $\forall$ f.

[Lynden-Bell, MNRAS 1967]

Gunn-Tremaine Bound

- Coarse-grained $F_c(x,v)$ does not have to obey the Vlasov equation.
- $\mathrm{Max}(F_c)$ less than or equal to F_{max}
- For Warm Dark Matter with Fermi-D irac distribution $h^3 F_{max} = \frac{1}{2}$ [Gunn and Tremaine, 1979]

Phase Space Constraint: DM from Decays

- For dark matter from decay –

$$f(q,a) \propto \frac{q_0}{q} \exp\left(\frac{-q^2}{q_0^2}\right) \theta(a p_{cm} - q)$$

- Phase space density can be large for particles from very early decay. However, number of such particles is small. To quantify this effect I will use the "Excess mass function" [Dehnen, 2005]

Excess Mass Function

- "Coarse-graining": Micro-cells → Macro-cells

  [Lynden-Bell MNRAS 1967]

- $F_c(x,y)$ is the coarse-grained distribution function.
- Excess Mass function:

  $$D(f) \equiv \int d^3x\, d^3v\, (F_c(x,v) - f)\, \Theta(F_c(x,v) - f)$$

- Mixing always decreases D(f).

  [Tremaine, Henon, Lynden-Bell, 1986, S. Mathur 1988, W. Dehnen 2005]

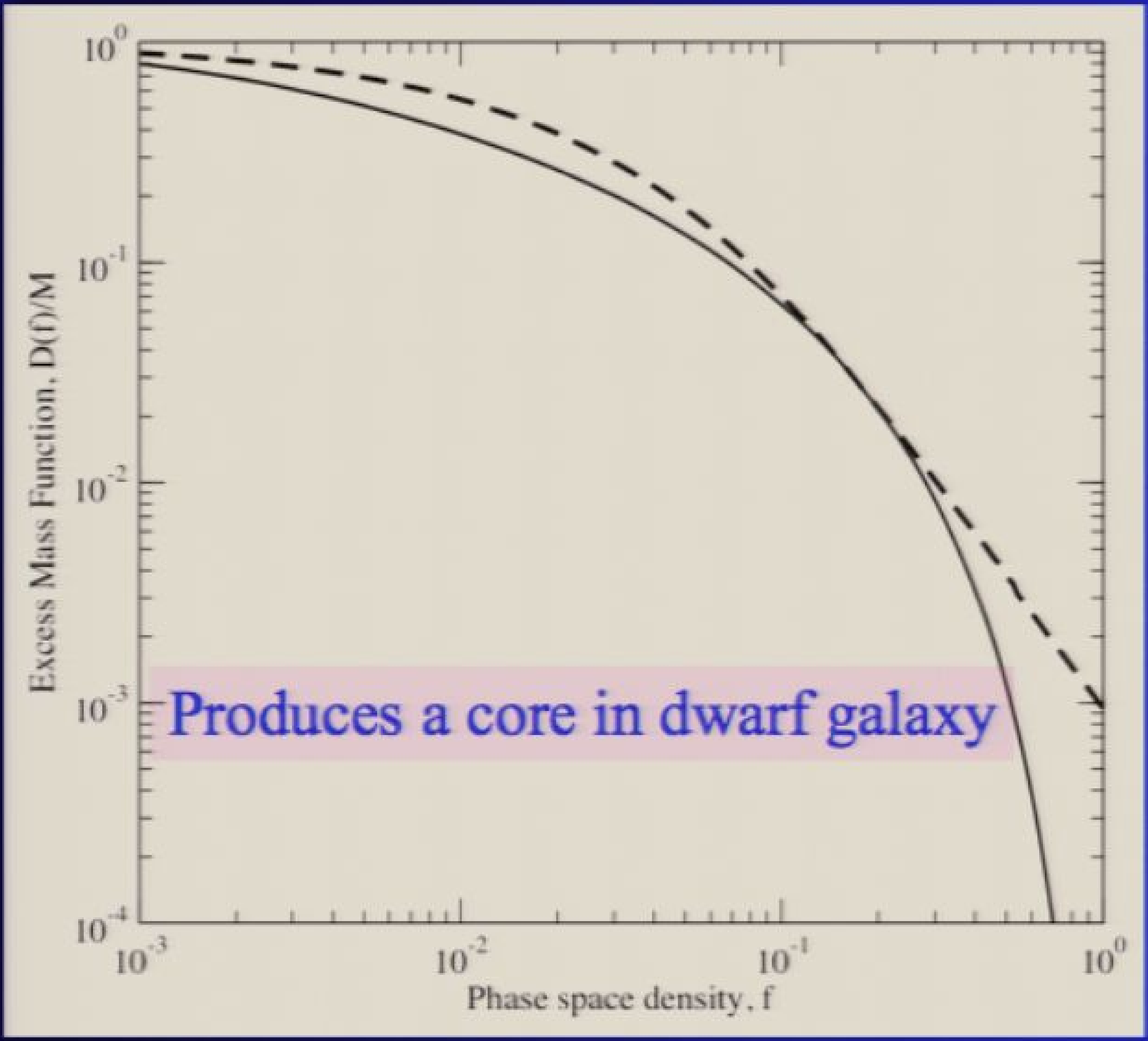
- D(f) is conserved in the absence of mixing.

Entropy and Excess Mass Function

- $\Delta S = -k_B \int_0^\infty \Delta D(f)\, df/f \geq 0$ for closed systems.

- The decrease of D(f) (typically) is a much stronger constraint.

Constraints from the Excess Mass Function



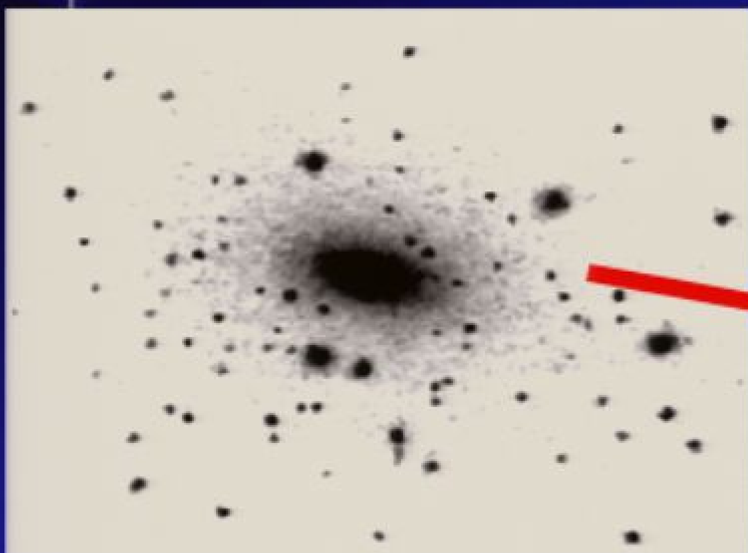
Truncated King Profile with Mass

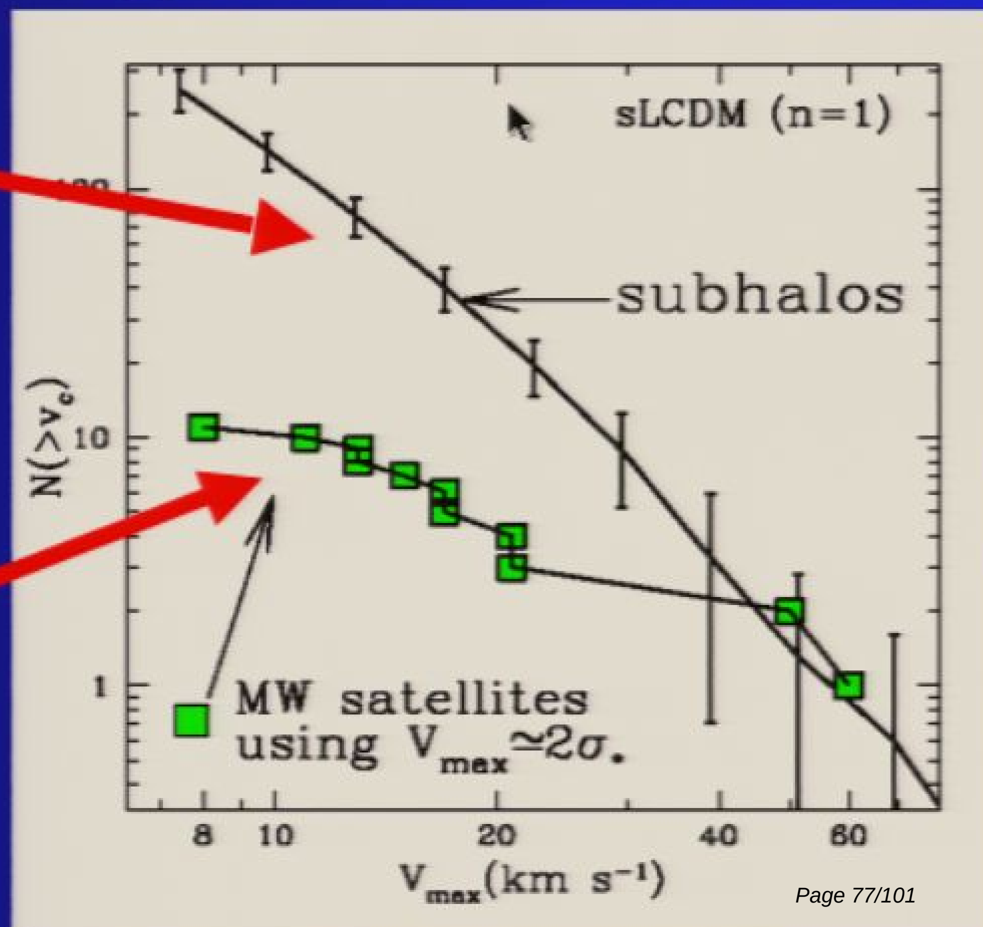
Mass = $2 \times 10^7 M_\odot$

$Q_{prim} = 2x\ 10^{-5}$

LCDM Missing satellite problem

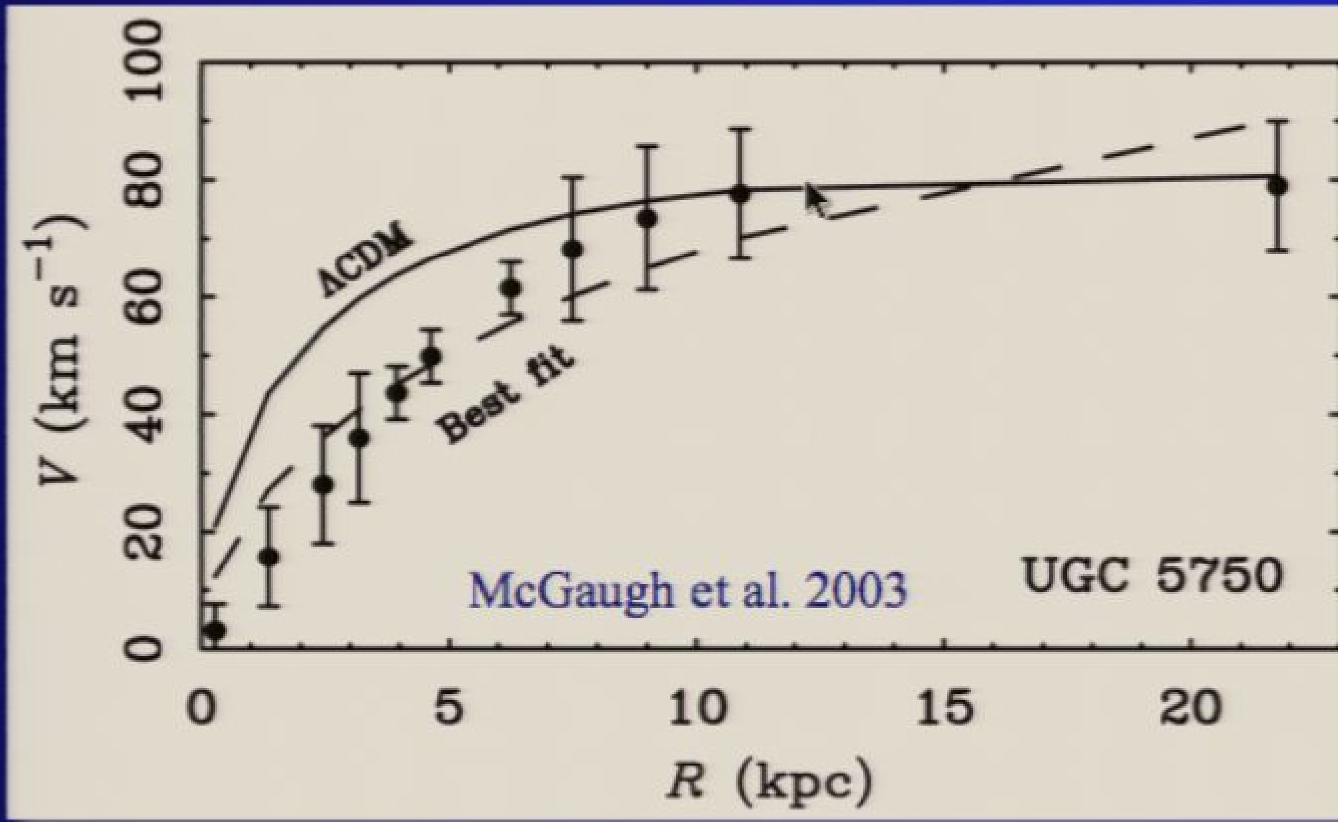
Klypin et al. 99; Moore et al. 99





Cusp crisis for CDM

High-resolution H-alpha rotation curves. Not as bad as old HI data suggested, but problem seems to persist for some galaxies. Similarly for 2D data (Simon et al. 05)



Reionization and Small Scale Power

- The universe was fully reionized by a redshift of 6.

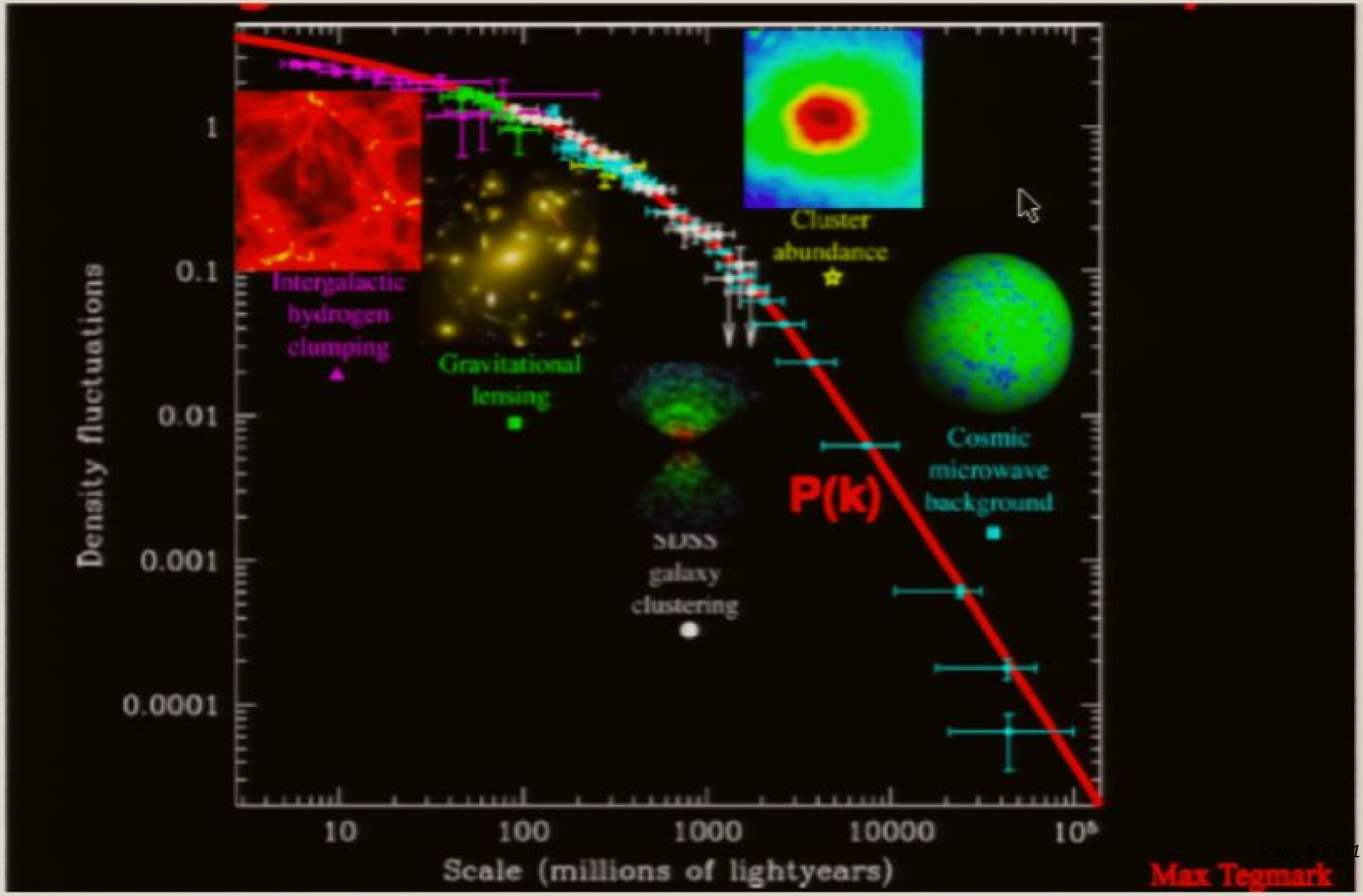
  Becker et al 2001

- The universe may have been fully reionized all the way to a redshift of ~ 10 or higher.

  Spergel et al 2006

Power Spectrum

Large-Scales: looks like CDM + Dark Energy



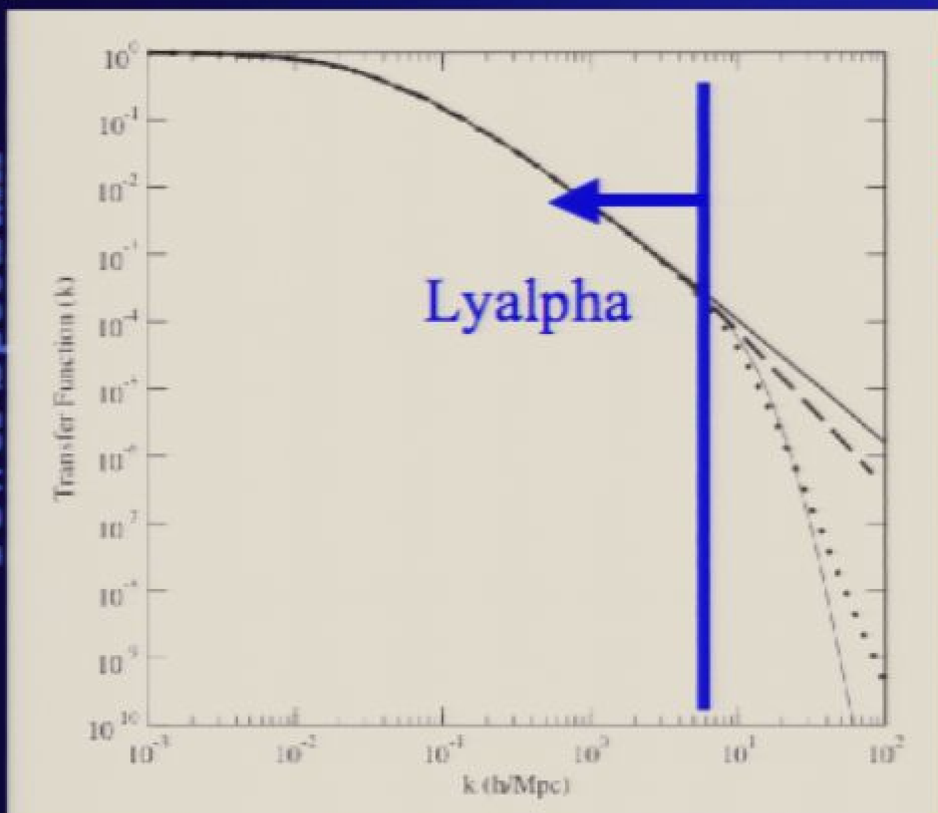
Lyman-α forest constraints

- Constraints on warm dark matter particle mass may be applied to the WDM models.
- Set σ(M) for warm dark matter == σ(M) for dark matter from early decays.

- Narayan et al 2000 claim $m_{WDM} > 750$ eV
  - => $Q > 10^{-4}$
- Viel et al 2005 claim $m_{WDM} > 550$ eV
  - => $Q > 5 \times 10^{-5}$
- New data and analysis. Seljak et al 2006; Viel et al 2006

Dark Matter from Early Decays

Power Spectrum



Models which give Q values needed for large cores are in marginal conflict with Ly-α power spectrum

Is the relation between power spectrum suppression and Q fixed?

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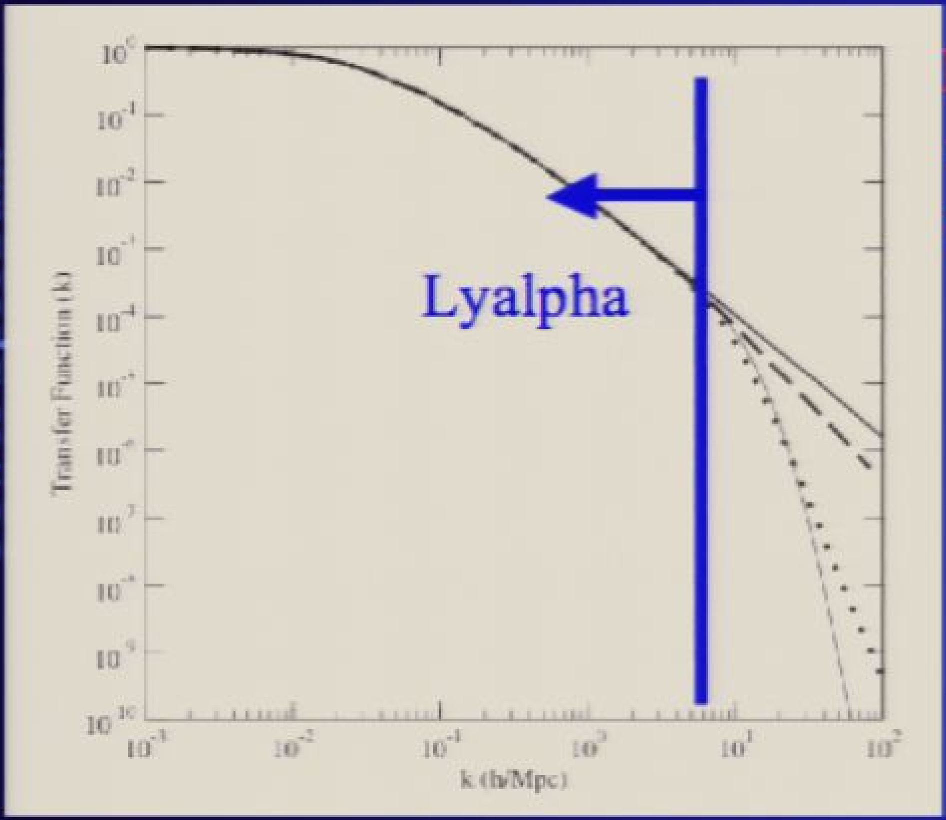


Models which give Q values needed for large cores are in marginal conflict with Ly-α power spectrum

Is the relation between power spectrum suppression and Q fixed?

Free-streaming: Reprise

- Closed set of equations including DDM and DM?

$$\delta T^{\nu}_{\mu;\nu} = 0$$

- We need isotropic and anisotropic perturbations to the pressure.

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

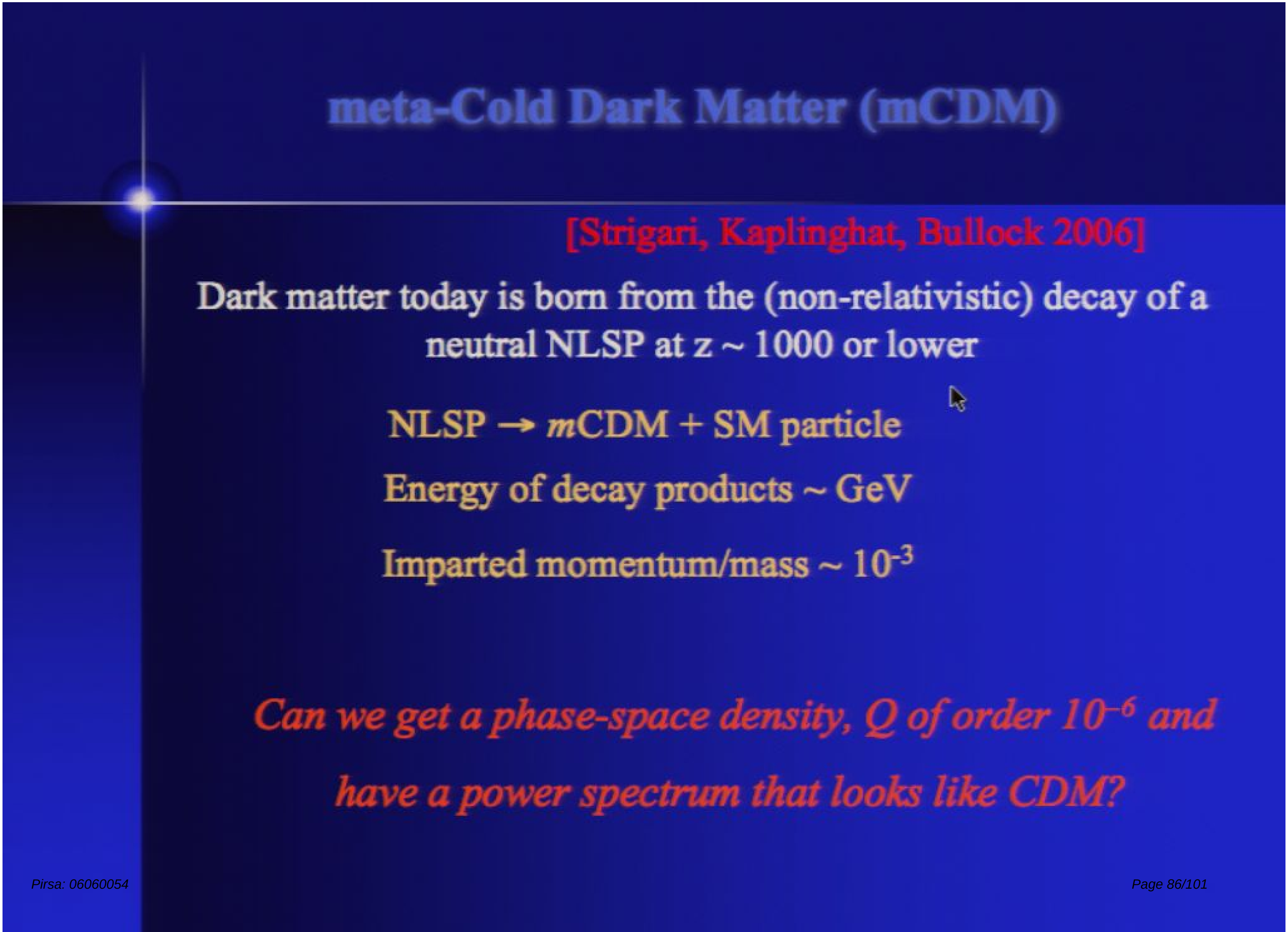
$$\propto \quad \frac{1}{Q^{1/3}\tau^{1/3}} \qquad \mathrm{(MD)}$$

PS cut-off

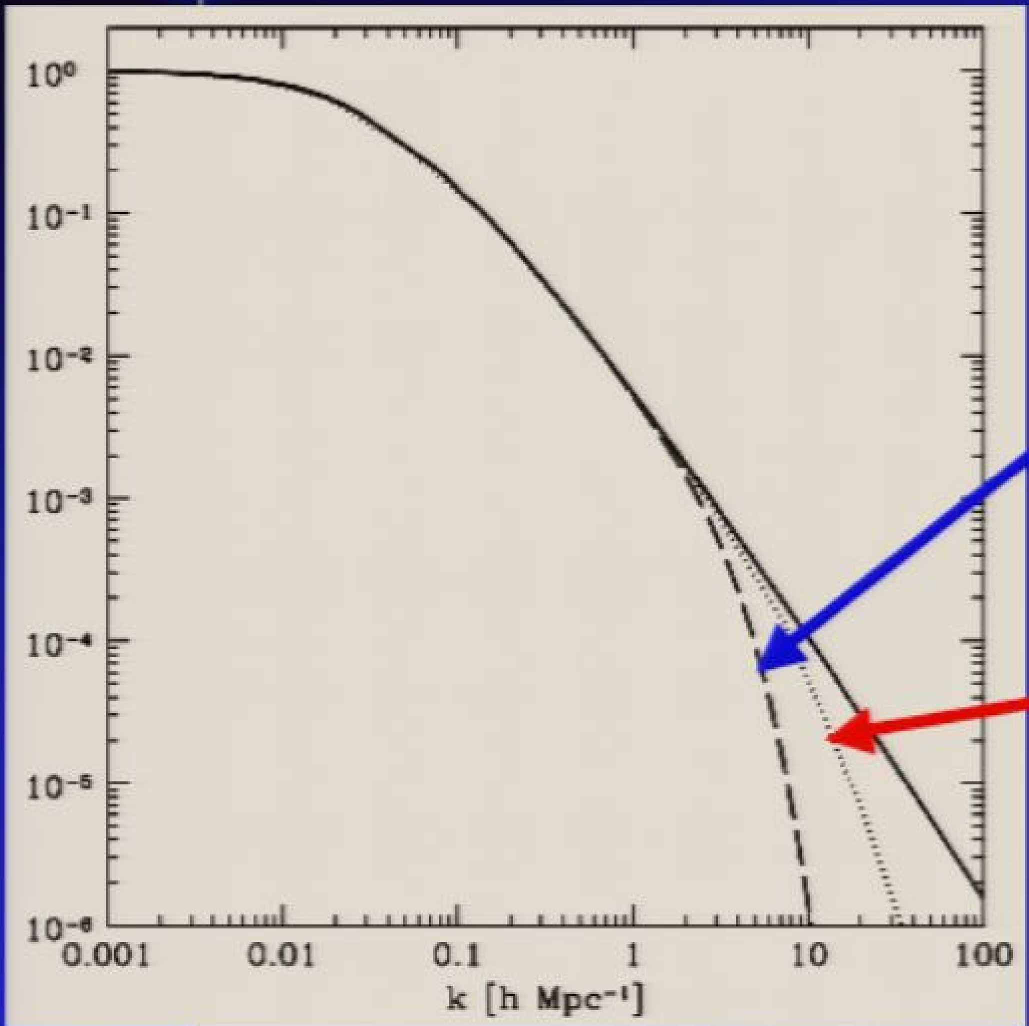
Core

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

Strigari, Kaplinghat and Bullock 2006


meta-Cold Dark Matter (mCDM)
[Strigari, Kaplinghat, Bullock 2006]
Dark matter today is born from the (non-relativistic) decay of a neutral NLSP at z ~ 1000 or lower
NLSP → mCDM + SM particle
Energy of decay products ~ GeV
Imparted momentum/mass ~ 10-3
Can we get a phase-space density, Q of order 10-6 and have a power spectrum that looks like CDM?

meta-CDM Power Spectrum



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

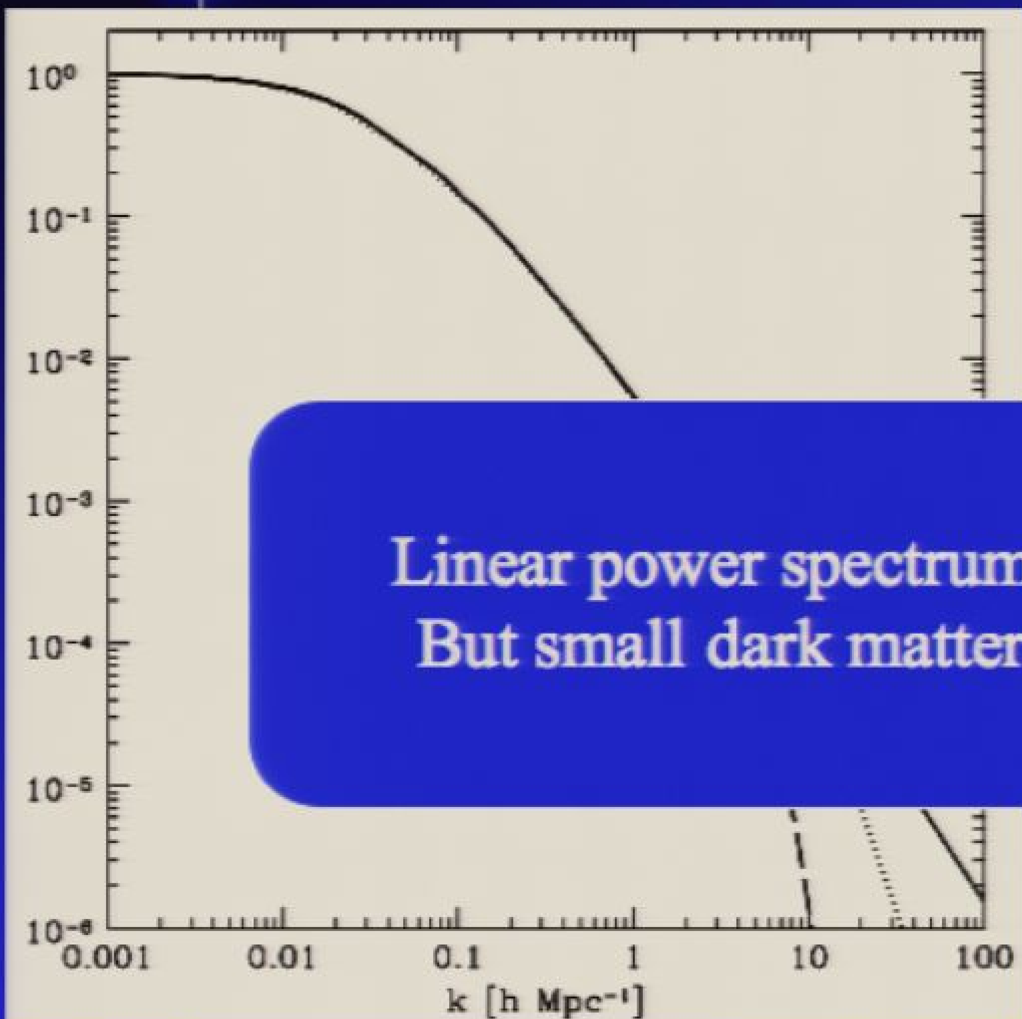
cutoff scale ~ $Q^{-1/3}$

For late decays (10^5 yrs.):

cutoff scale given by

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

meta-CDM Power Spectrum



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

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

Linear power spectrum like that of CDM.
But small dark matter halos have cores!

yrs.):

by

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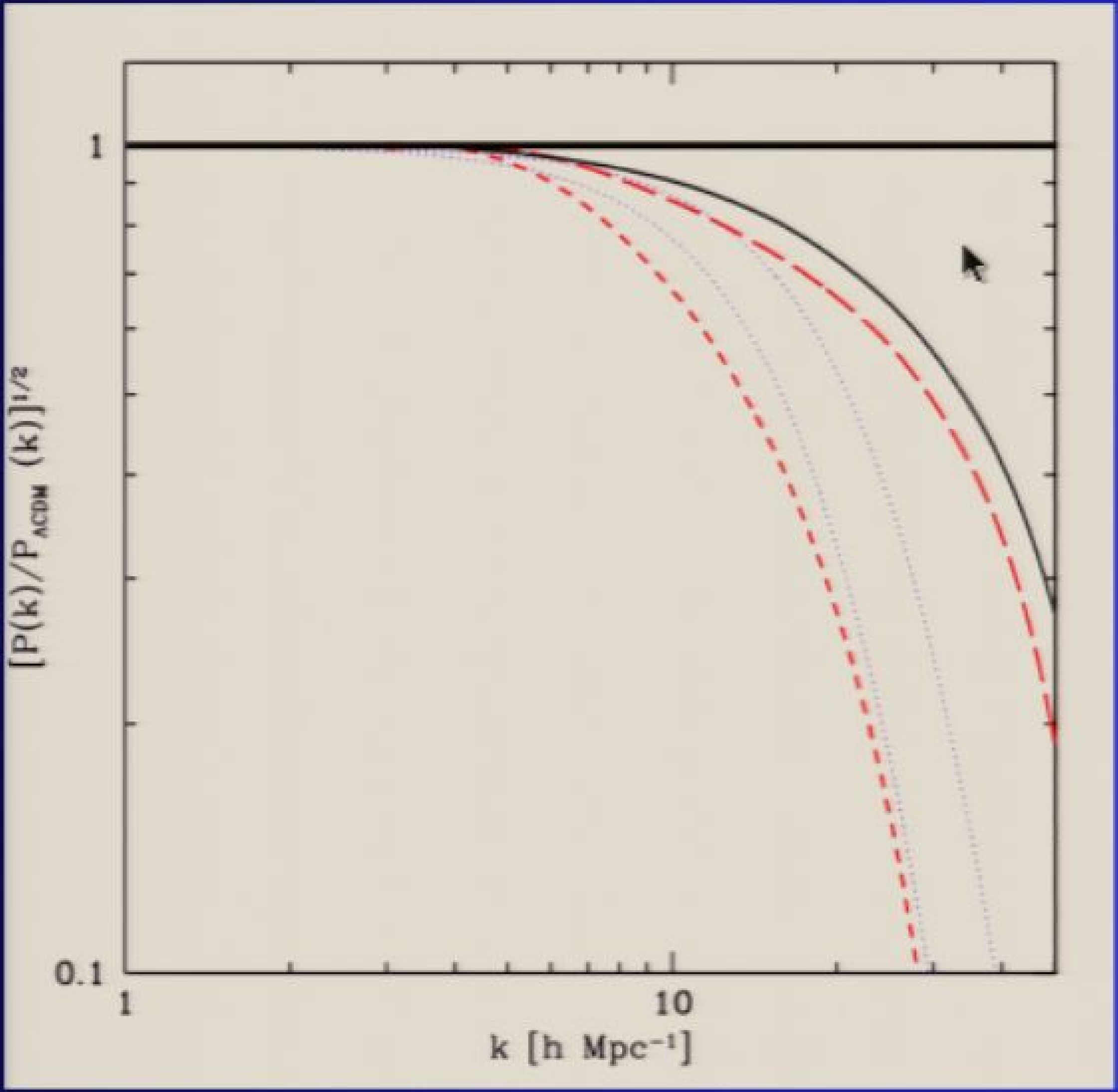
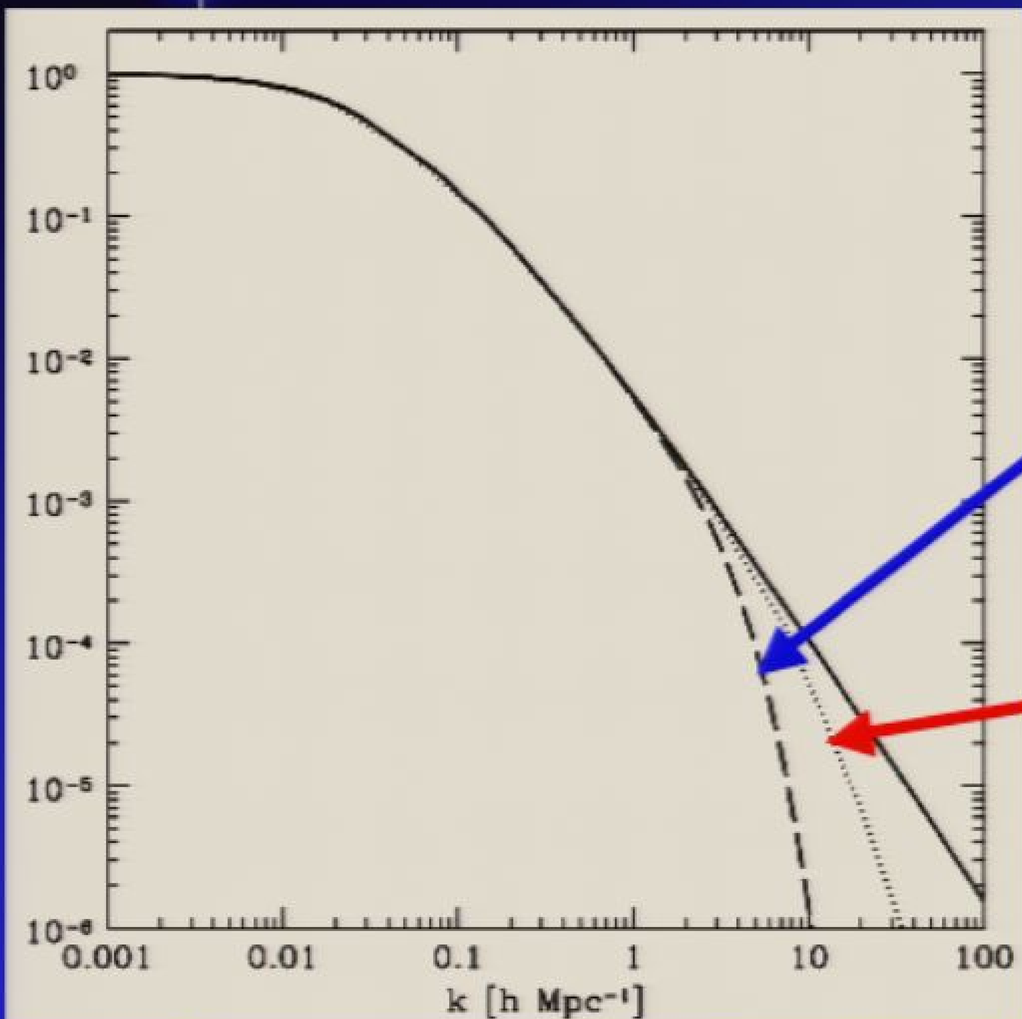
mCDM power spectrum



meta-CDM Power Spectrum



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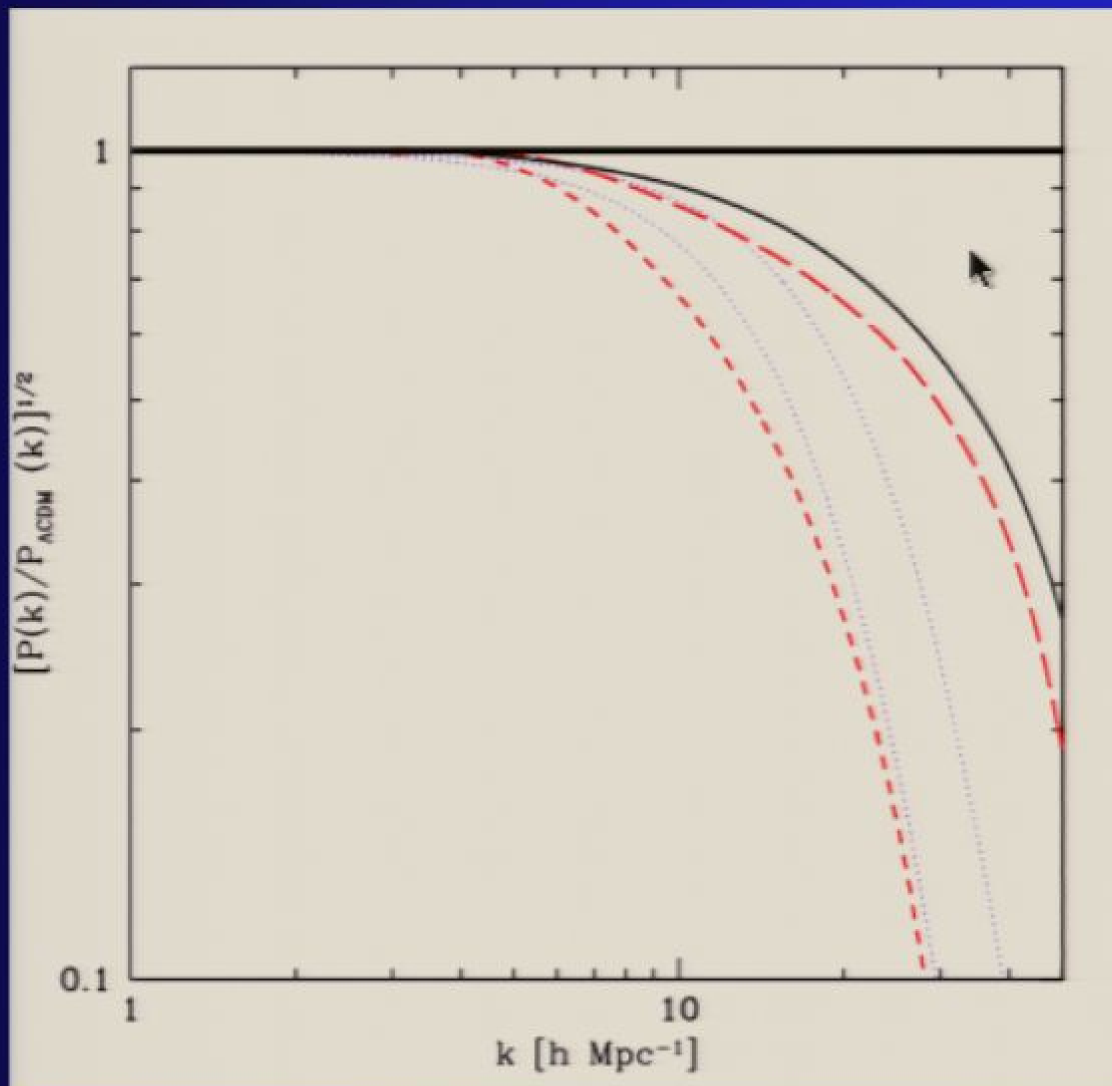

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[Strigari, Kaplinghat, Bullock 2006]

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NLSP → meta-CDM + SM particle

Energy of decay products ~ GeV

Imparted momentum/mass ~ 10^{-3}

Phase-Space density

$$Q \approx 10^{-24} \left(\frac{m}{p_{cm} a_{decay}} \right)^3 M_{sun} pc^{-3} (km/s)^{-3}$$

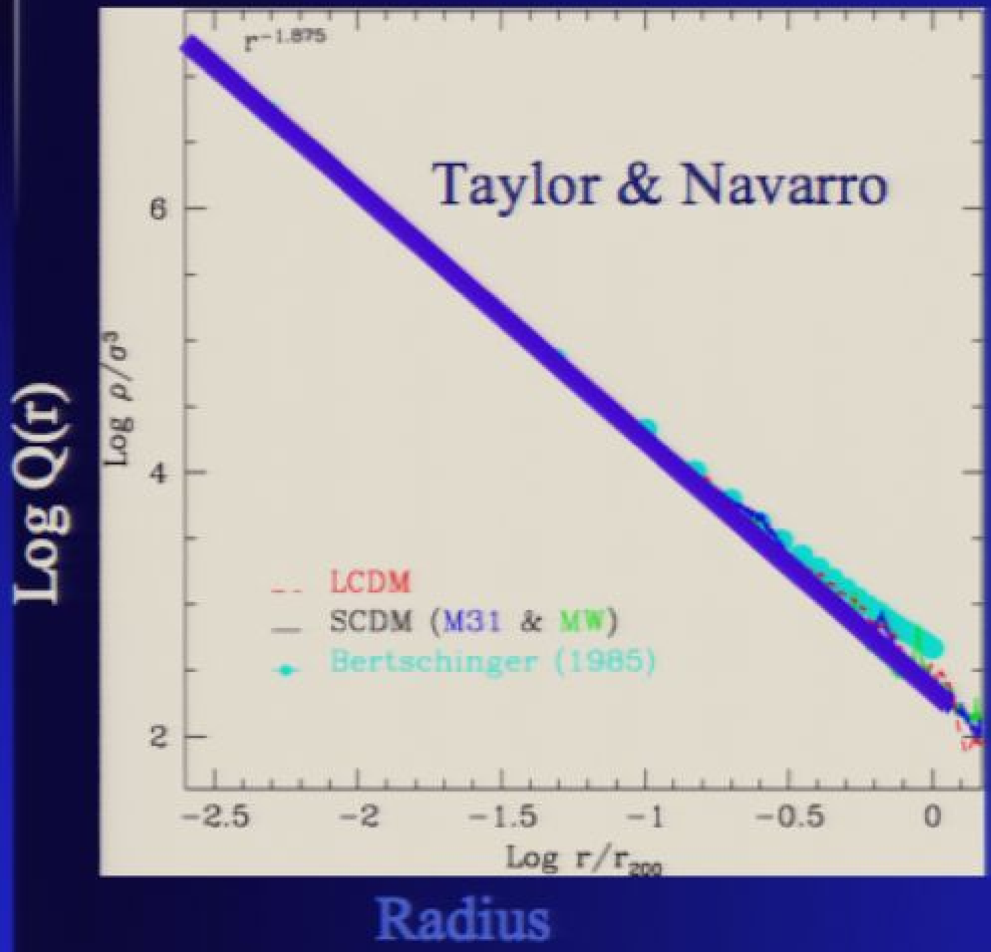
Meta-Cold Dark Matter

From Dictionary.com:

meta- or *met-*
/pref./

1.
   1. ***Later in time*** : metestrus.
   2. At a later stage of development: metanephros.
2. Situated behind: metacarpus.
3.
   1. ***Change; transformation***: metachromatism.
   2. ***Alternation***: metagenesis.
4.
   1. ***Beyond; transcending; more comprehensive***: metalinguistics.
   2. At a higher state of development: metazoan.
5. ***Having undergone metamorphosis***: metasomatic.
6.
   1. Derivative or related chemical substance: metaprotein.
   2. Of or relating to one of three possible isomers of a benzene ring with two attached chemical groups, in which the carbon atoms with attached groups are separated by one unsubstituted carbon atom: meta-dibromobenzene.

Phase-space Density in CDM Simulations

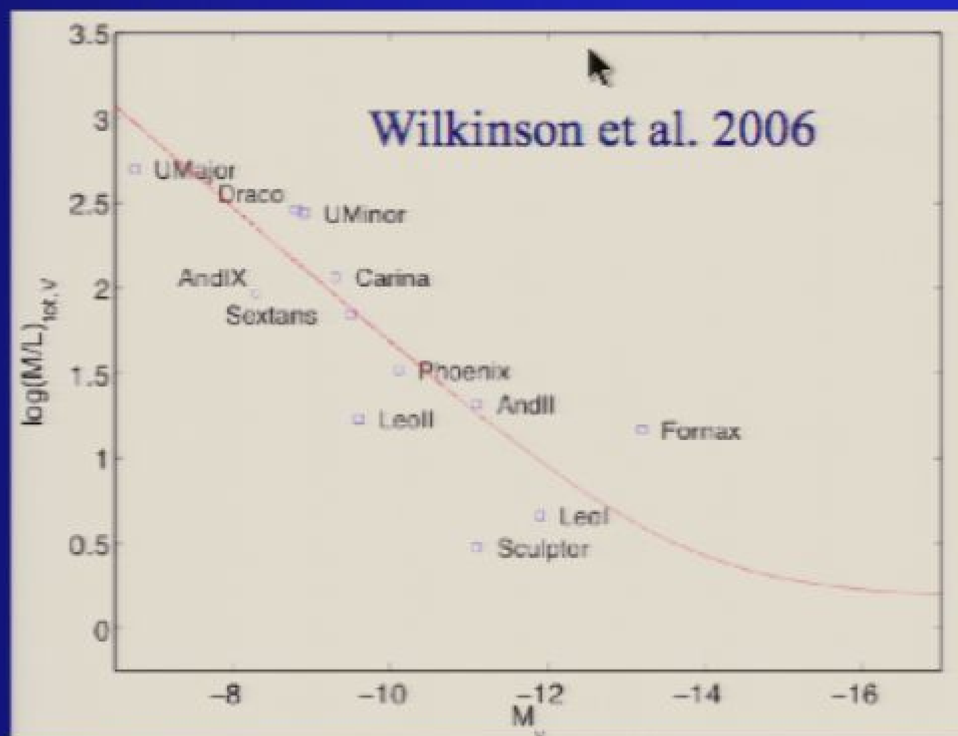


Q rises as a power-law with decreasing radius

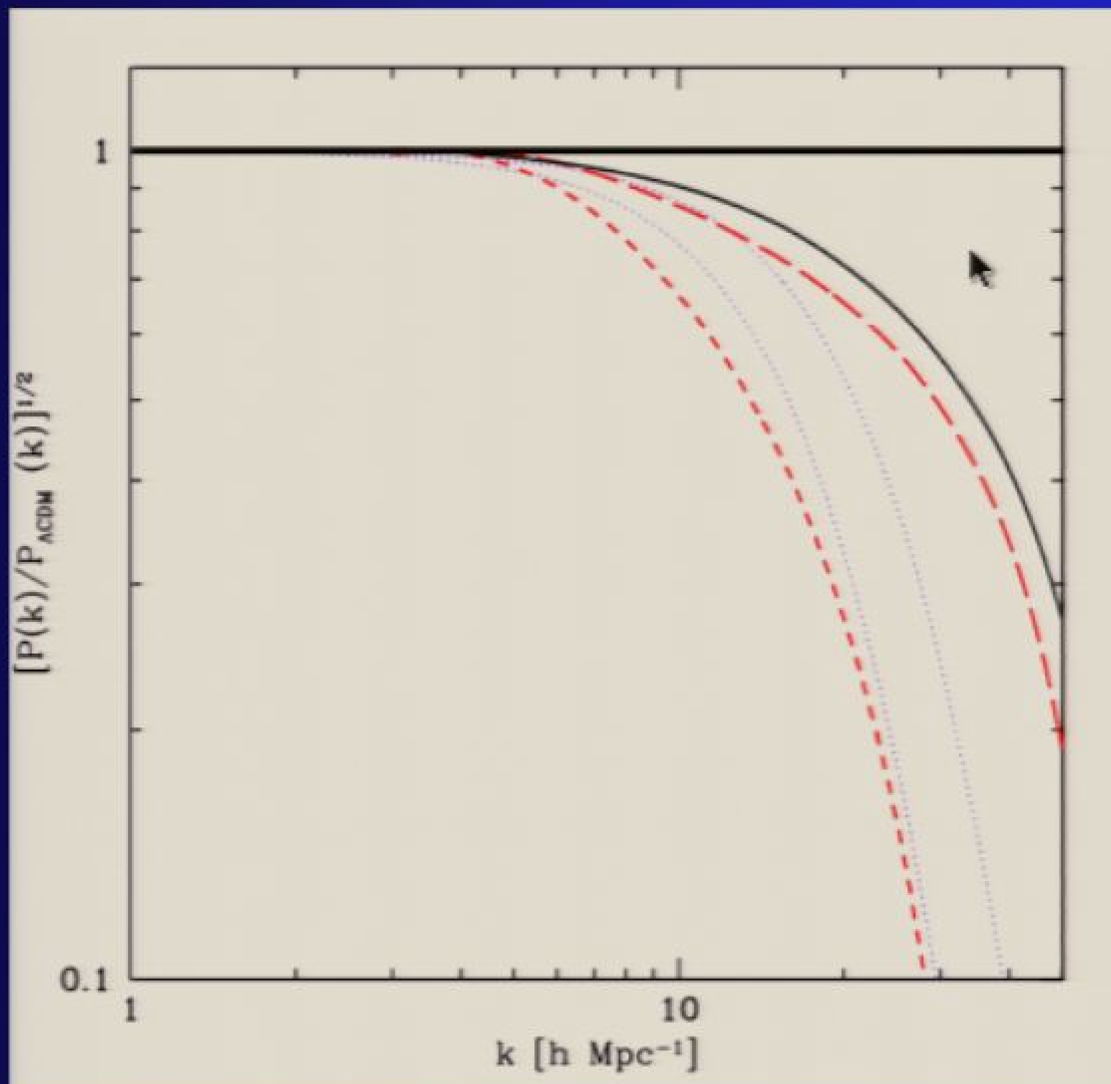
There is no hint of a phase-space maximum, but this is not a surprise

Dwarf Spheroidals

11+2 dwarf galaxies observed to reside within 300 kpc of the Milky Way



mCDM power spectrum



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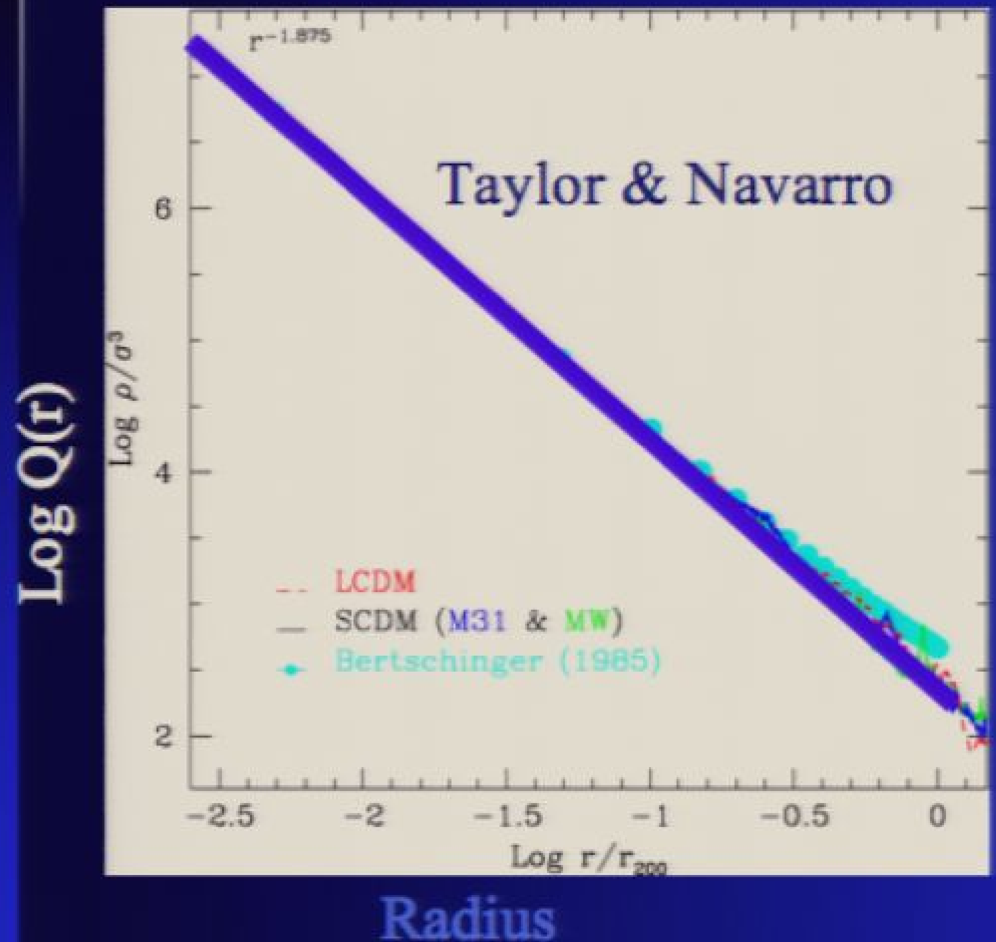

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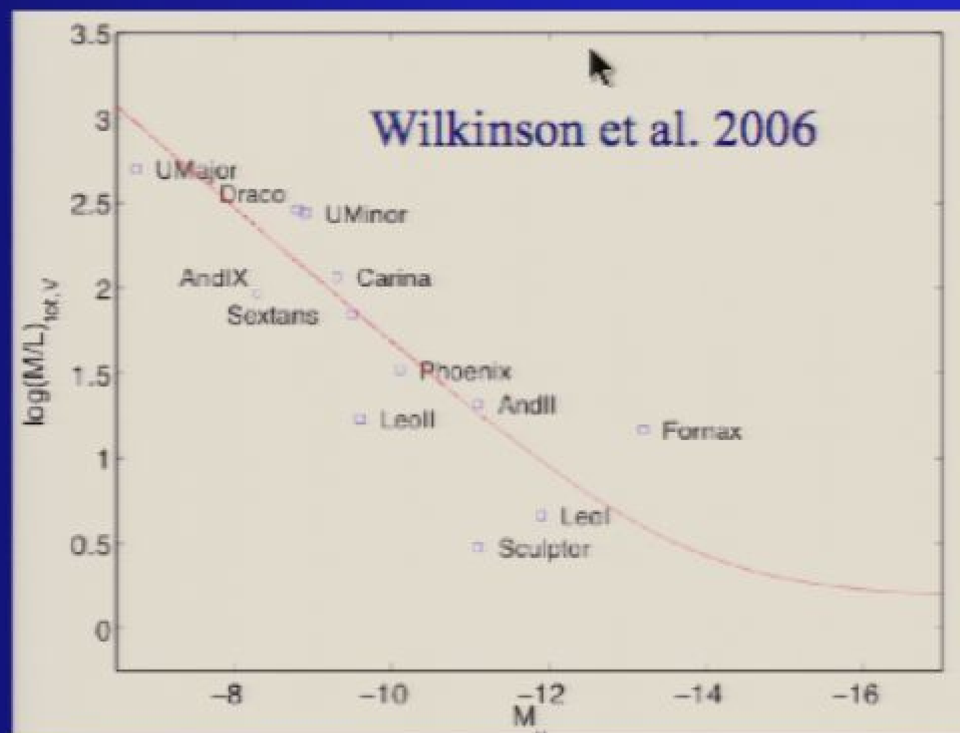
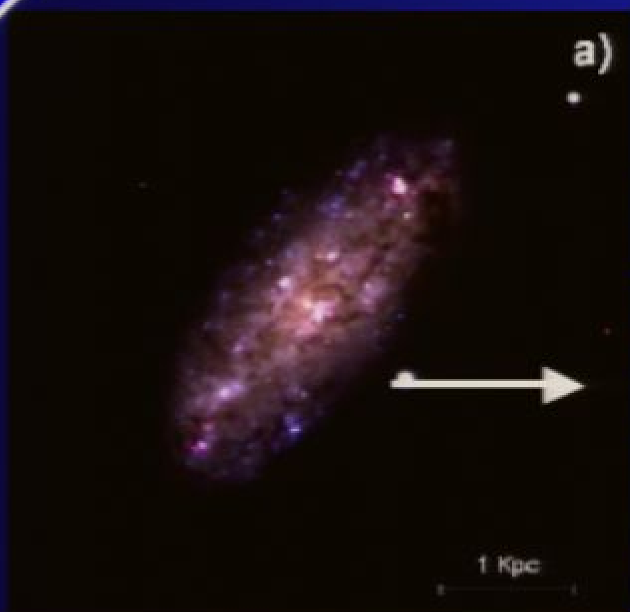
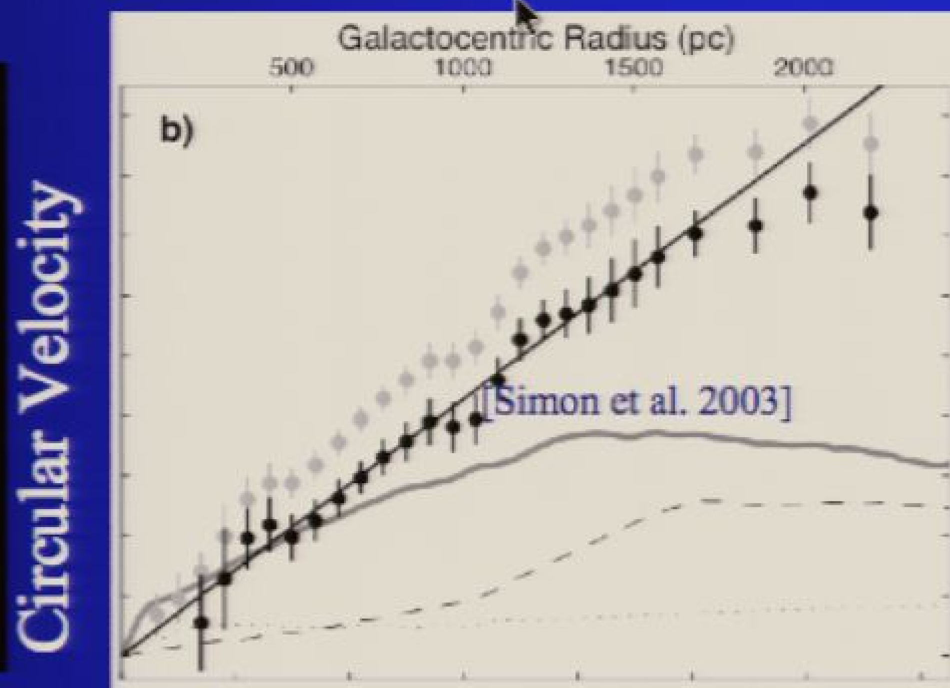


Low Mass Spirals

Averaging over all the galaxies in the Simon et al. 2005 sample, we can infer $Q \sim 10^{-6}$

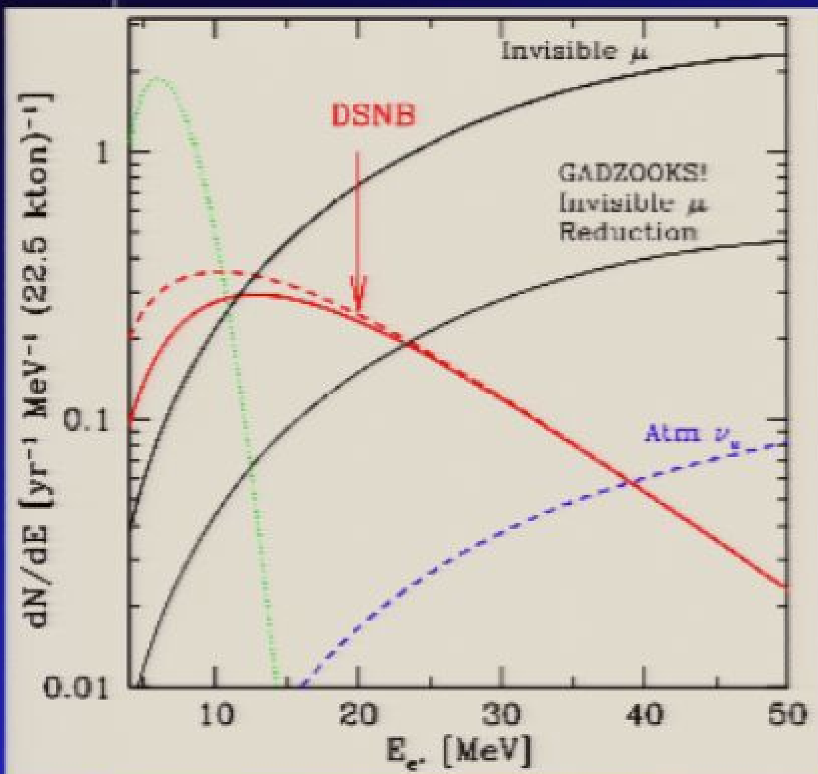




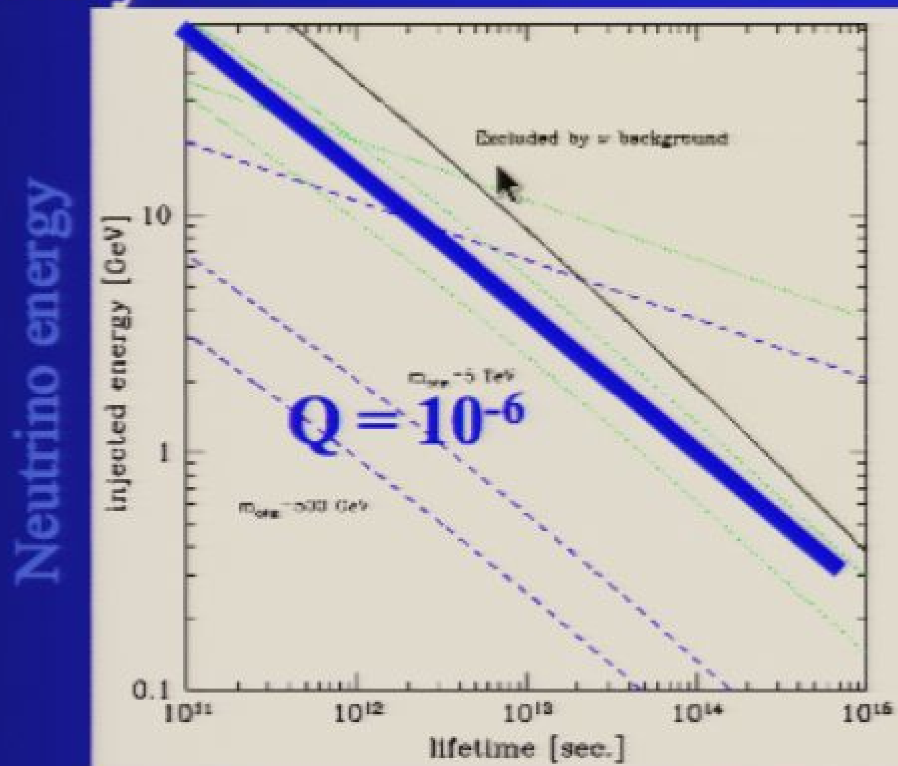
Strigari etal 2006

meta-CDM at Super-Kamiokande?

Preliminary!



Neutrino Energy Spectrum



lifetime

Summary

Rich phenomenology of dark matter from decays

WIMP

↓ $\Gamma \sim M_w^3/m_{pl}^2$

Dark Matter

<u>Constraints</u>

Free-streaming cut-off

Phase space limits

Adequate reionization

Non-linear small scale structure

CMB black body

BBN

<u>Probes</u>

LHC, BBN, CMB,

Weak lensing, Reionization,

21 cm, Ly-α forest, …