Title: Local Group Dwarfs and the Cold Dark Matter Paradigm

Date: Jun 03, 2008 05:45 PM

URL: http://pirsa.org/08060143

Abstract:

Local Group Dwarfs and Dark Matter

Collaborators:
James Bullock (UCI)
Louis Strigari (Postdoc, UCI → Stanford)
Greg Martinez (Graduate student, UCI)

Manoj Kaplinghat
Center for Cosmology
Physics and Astronomy
UC Irvine

photo by Art Rosch

Properties of Dark Matter

Properties of Dark Matter

- *Damping length* λ_d : Mean-free path before kinetic decoupling.
  - Depends on interactions (scattering off of the plasma) and early universe cosmology.

Properties of Dark Matter

- *Damping length* λ_d : Mean-free path before kinetic decoupling.
  - Depends on interactions (scattering off of the plasma) and early universe cosmology.
- *Free-streaming length* λ_{fs}: Average distance traveled by a dark matter particle before it falls into a potential well.
  - Depends on mean speed after decoupling and early universe cosmology

Properties of Dark Matter

- *Damping length* λ_d : Mean-free path before kinetic decoupling.
  - Depends on interactions (scattering off of the plasma) and early universe cosmology.
- *Free-streaming length* λ_{fs}: Average distance traveled by a dark matter particle before it falls into a potential well.
  - Depends on mean speed after decoupling and early universe cosmology
- *"Average" phase-space density Q:* Mass density per unit volume in velocity space.
  - After "freeze-out" Q is constant
    - Q ~ mass density / v_{RMS}^3
    - density ~ $1/a^3$ while $v_{RMS} \sim 1/a$

Properties of Dark Matter

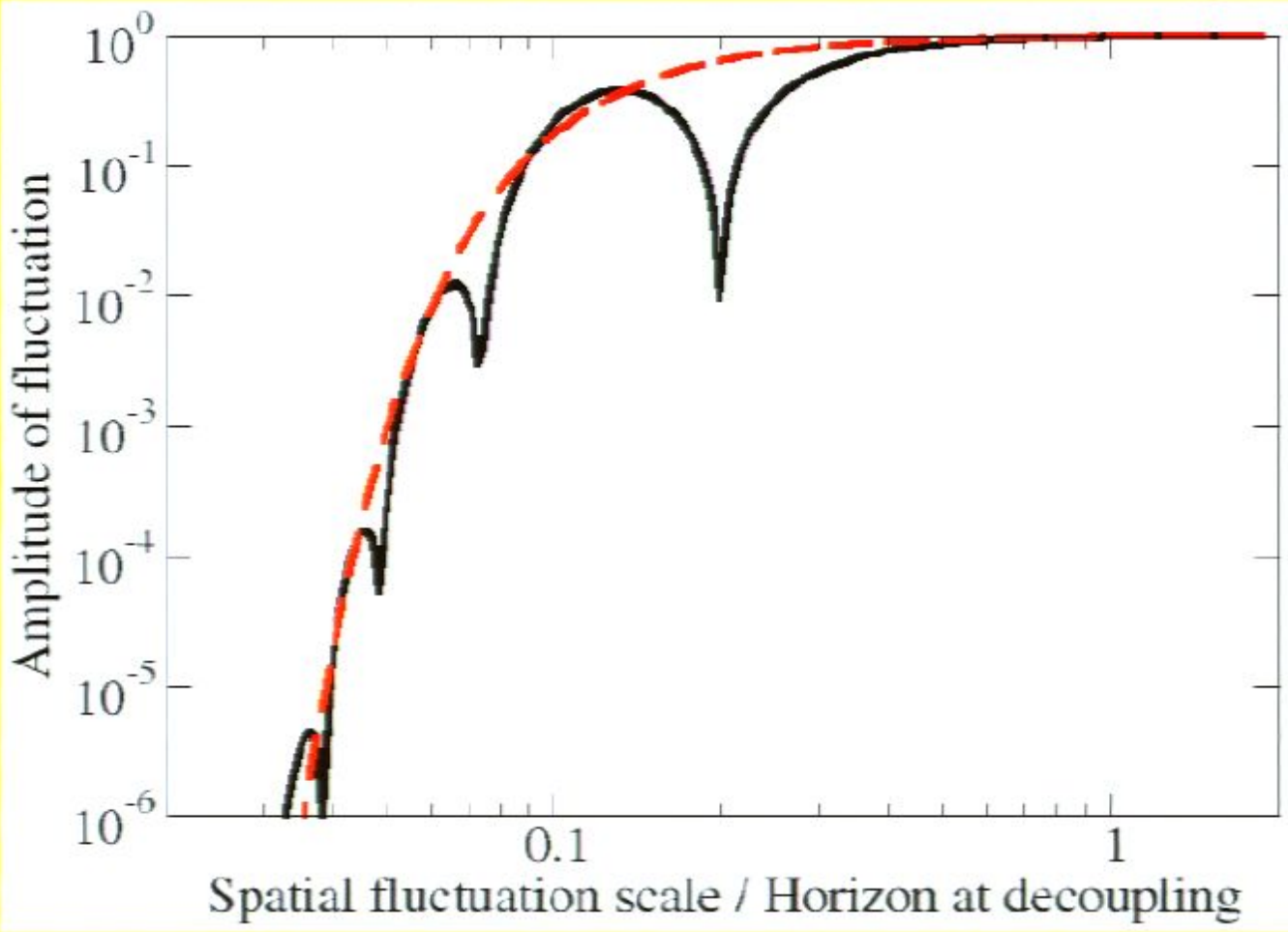
- *Damping length* λ_d : Mean-free path before kinetic decoupling.
  - Depends on interactions (scattering off of the plasma) and early universe cosmology.
- *Free-streaming length* λ_{fs}: Average distance traveled by a dark matter particle before it falls into a potential well.
  - Depends on mean speed after decoupling and early universe cosmology
- *"Average" phase-space density Q:* Mass density per unit volume in velocity space.
  - After "freeze-out" Q is constant
    - Q ~ mass density / v_{RMS}^3
    - density ~ $1/a^3$ while $v_{RMS} \sim 1/a$

Set by scatterings in the early universe

Set by annihilations in the early universe

Free-streaming and Damping: Power spectrum of fluctuations (Linear theory)

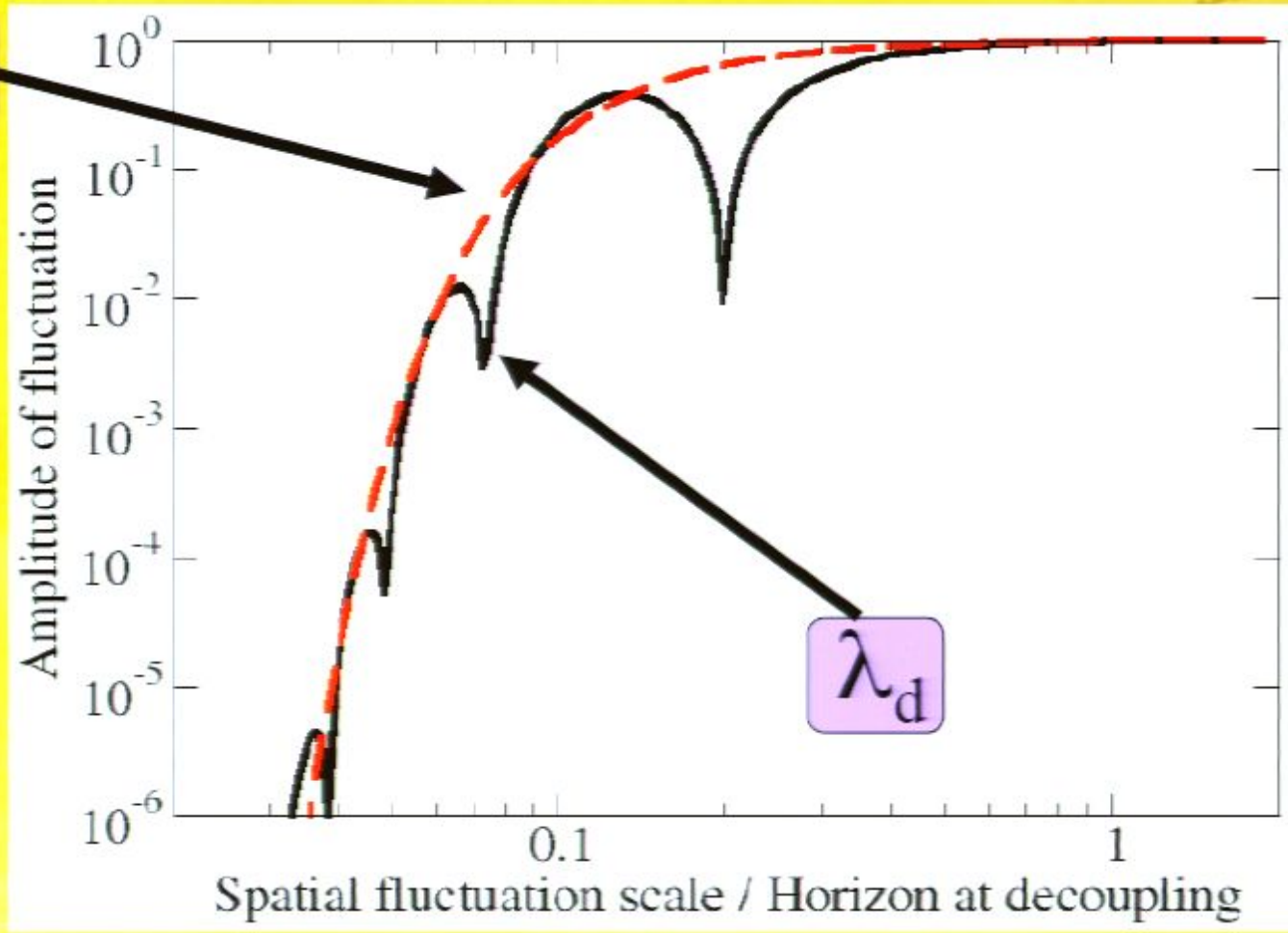
Perturbations are erased below the free-streaming and damping lengths



Hofmann, Schwarz and Stoecker 2001
Loeb and Zaldarriaga 2005
Bertschinger 2006

Free-streaming and Damping: Power spectrum of fluctuations (Linear theory)

Perturbations are erased below the free-streaming and damping lengths



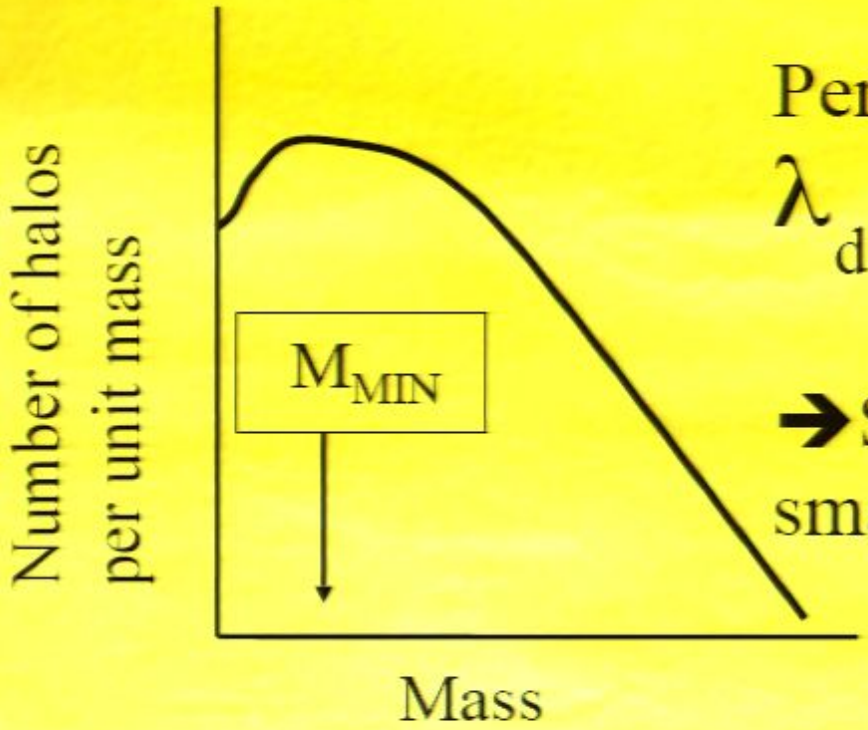
Hofmann, Schwarz and Stoecker 2001
Loeb and Zaldarriaga 2005
Bertschinger 2006

Free-streaming and Damping: Halos (non-linear effect)

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

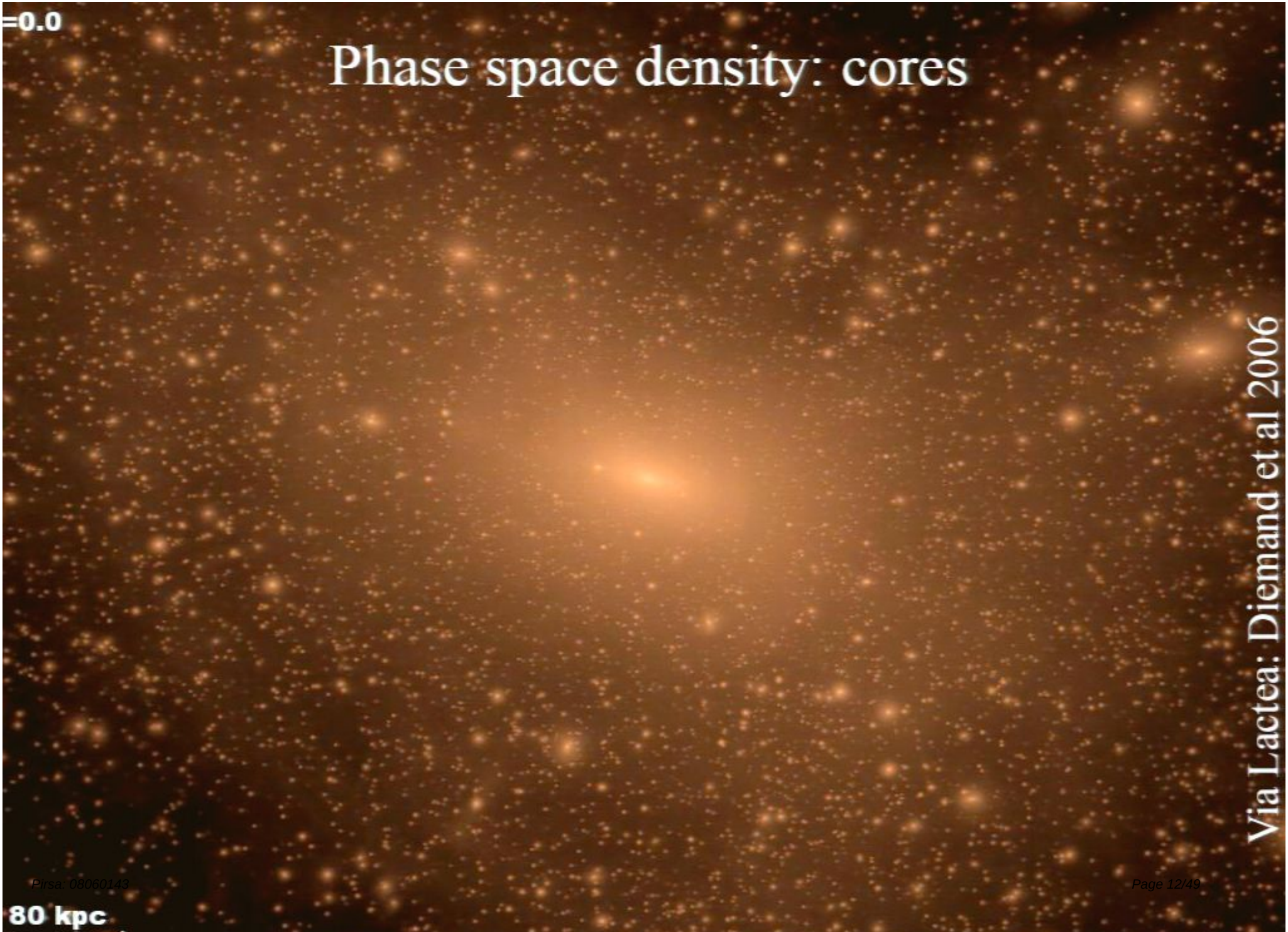
Free-streaming and Damping: Halos (non-linear effect)

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



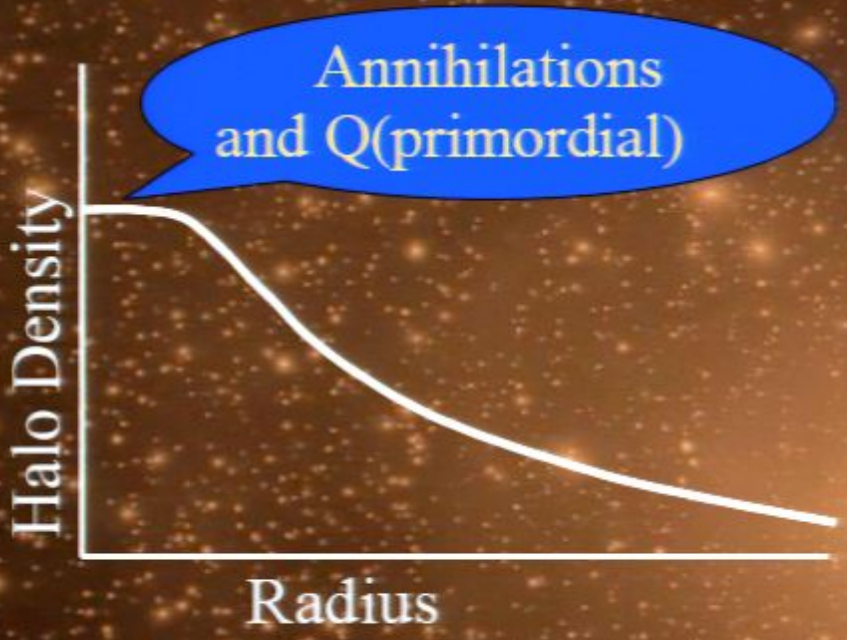
Perturbations erased below λ_d and λ_{fs}

➔Sets the mass of the smallest halos


=0.0
Phase space density: cores
Via Lactea: Diemand et al 2006
80 kpc

=0.0

Phase space density: cores



Cannot stuff particles without limit into the center of dark matter halos.

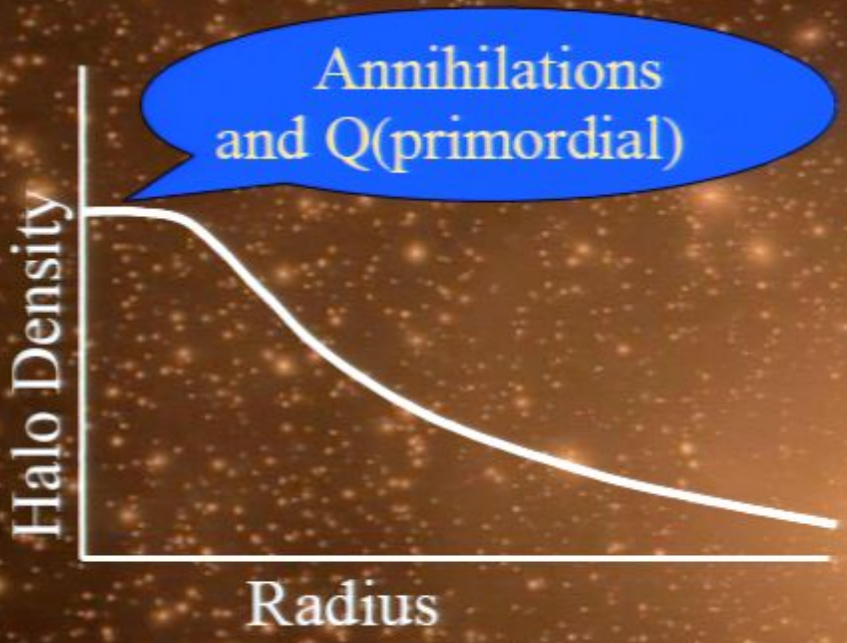
[Gunn and Tremaine 1979, Dalcanton and Hogan 2000, Dehnen 2005, Kaplinghat 2005, Martinez and Kaplinghat in prep]

Via Lactea: Diemand et al 2006

80 kpc

=0.0

Phase space density: cores

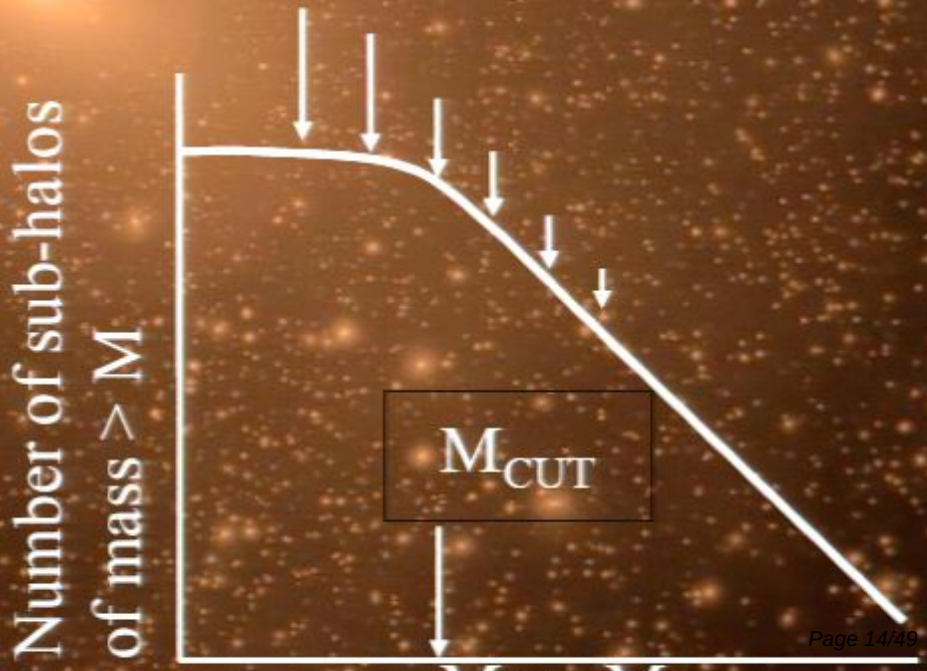


Cannot stuff particles without limit into the center of dark matter halos.

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

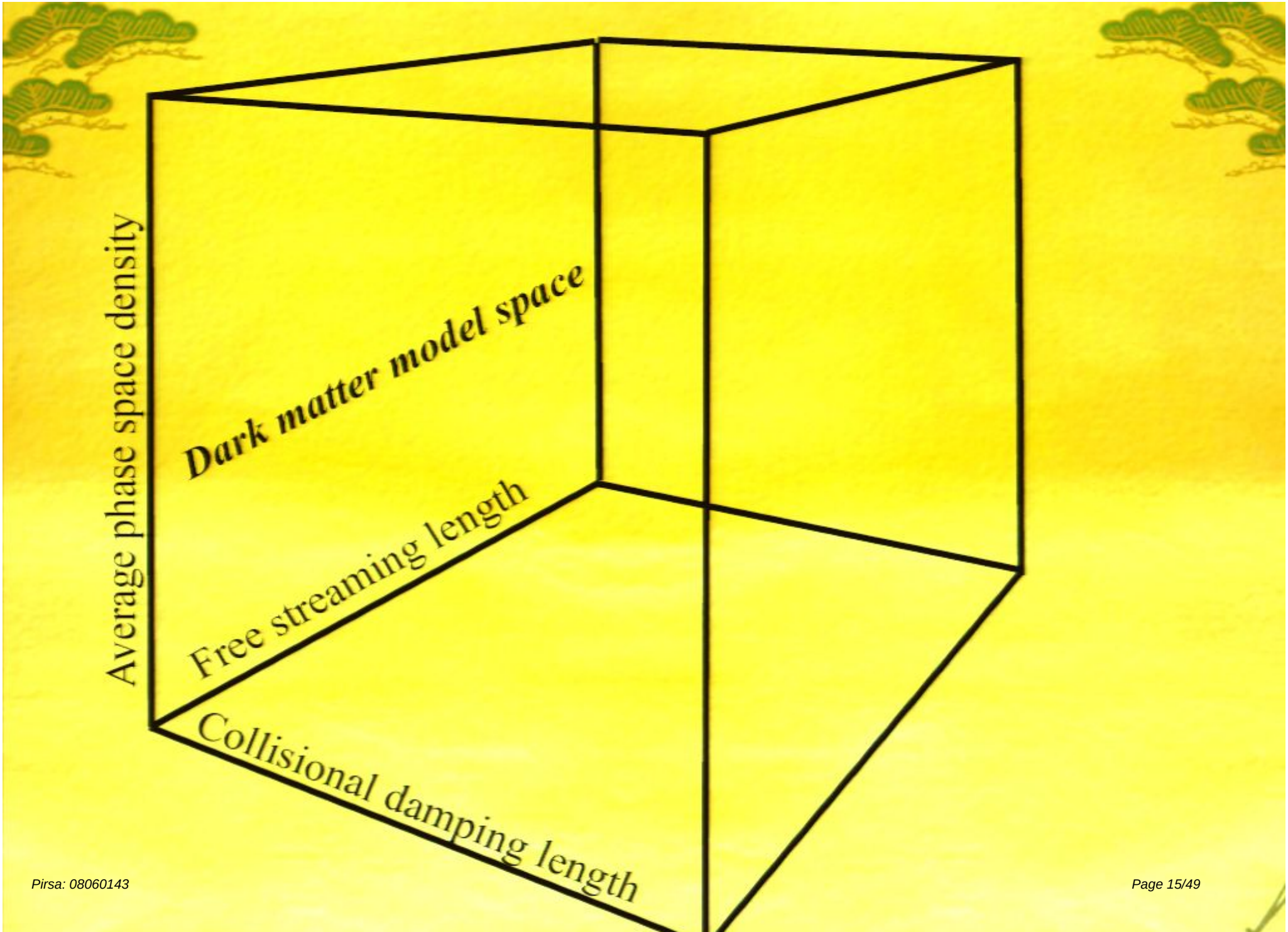
Halos with cores are more easily disrupted when accreted into a larger halo

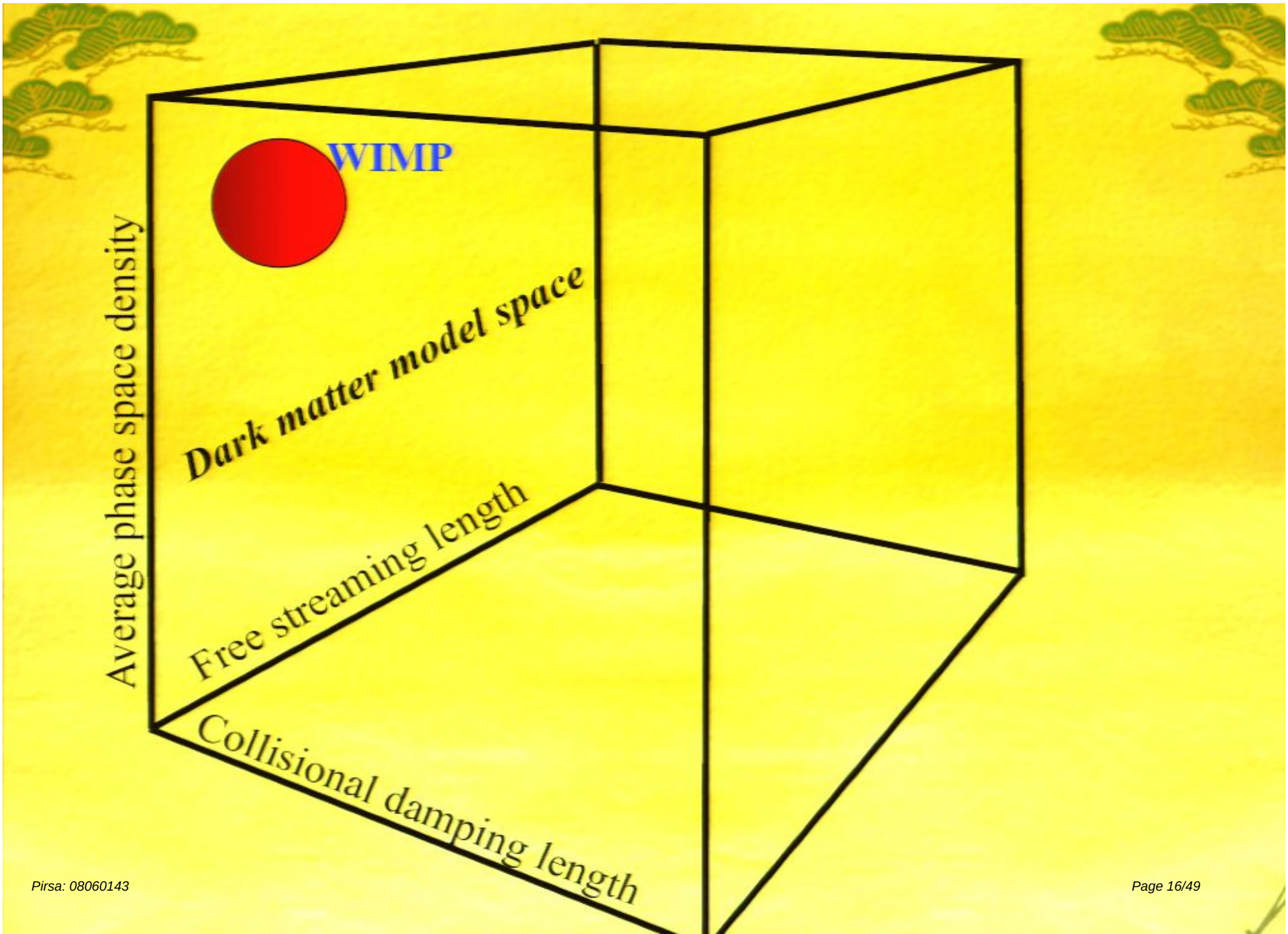
$M_{CUT} \sim M_{MIN}$?

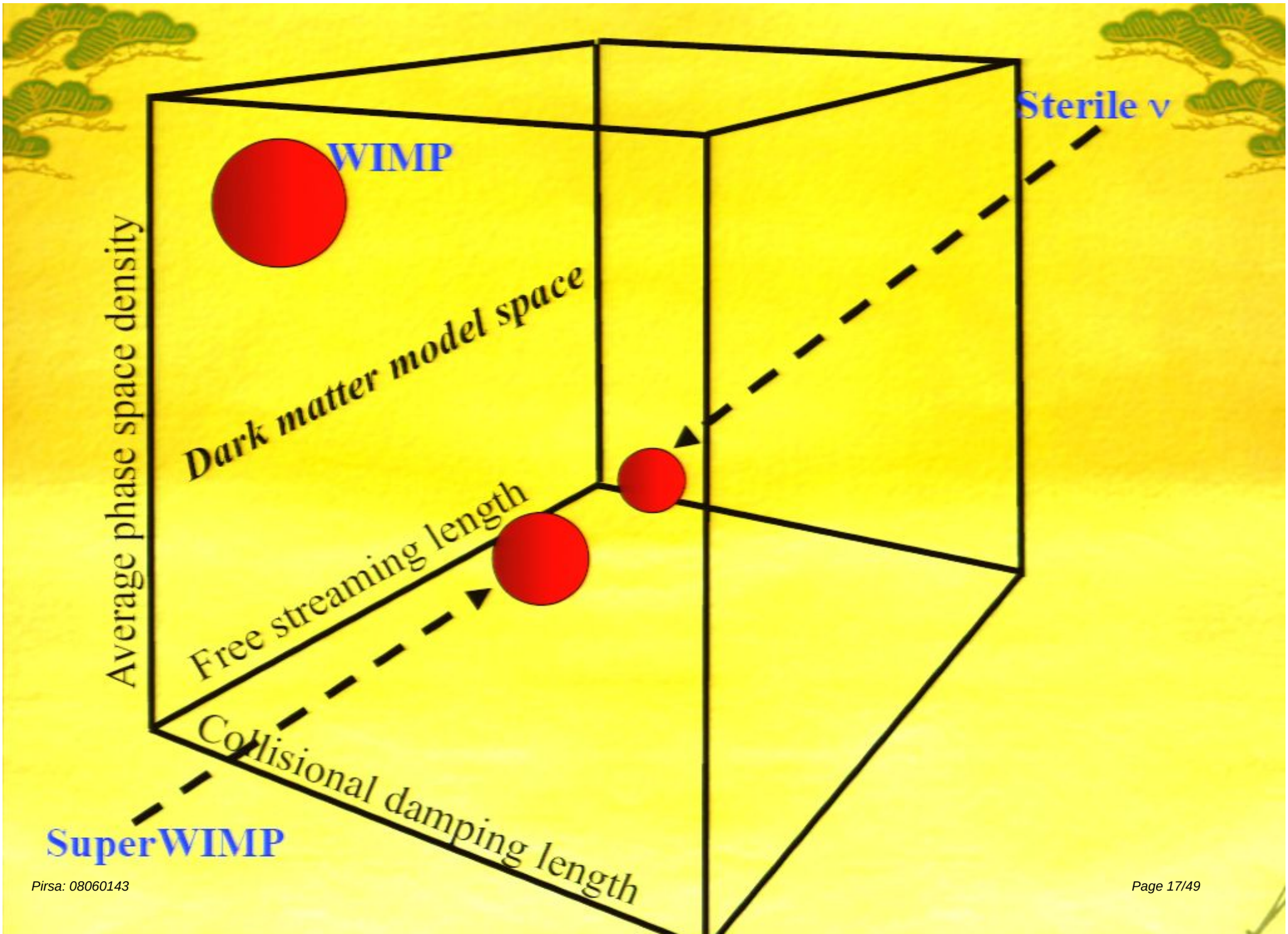


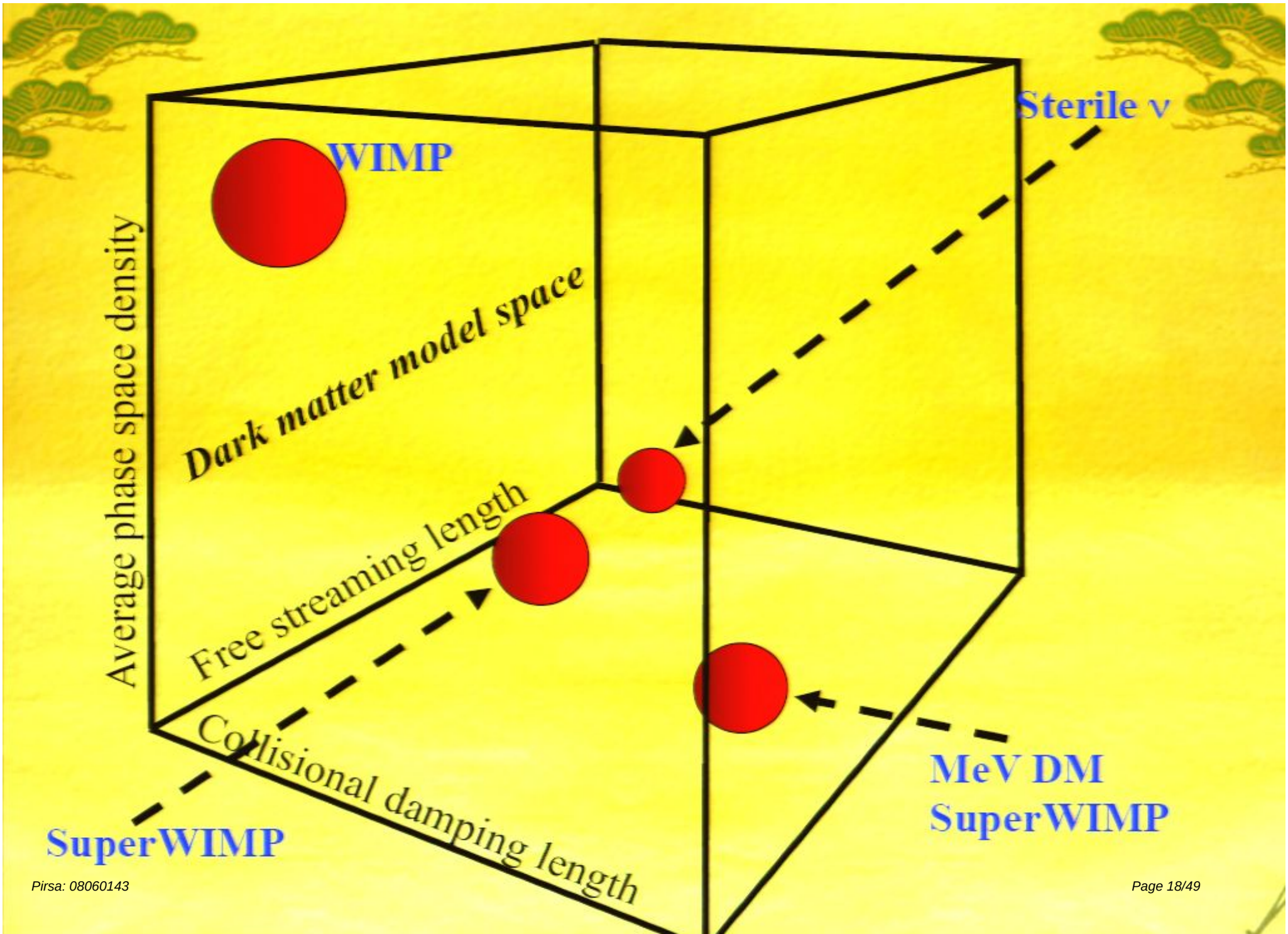
Via Lactea: Diemand et al 2006

80 kpc


Dark matter model space
Average phase space density
Free streaming length
Collisional damping length


WIMP
Dark matter model space
Average phase space density
Free streaming length
Collisional damping length


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

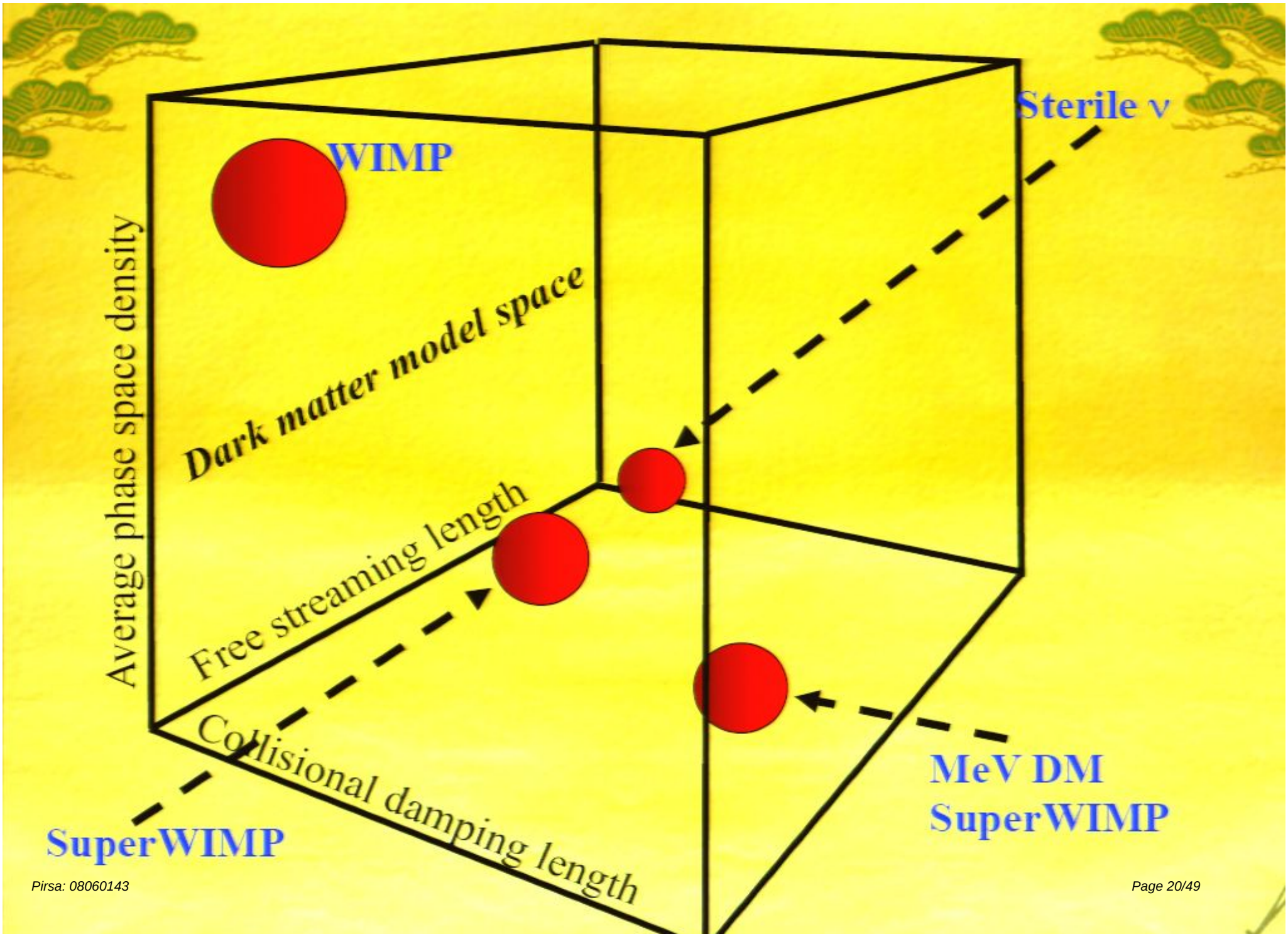

WIMP
Sterile ν
Dark matter model space
Average phase space density
Free streaming length
Collisional damping length
SuperWIMP
MeV DM
SuperWIMP

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 must be computed using numerical simulations.

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

- Size of core depends on the shape of the primordial momentum distribution function and not just on the average Q.


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

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 must be computed using numerical simulations.

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

- Size of core depends on the shape of the primordial momentum distribution function and not just on the average Q.

Review

- *Free-streaming and damping lengths:*
  - No perturbations on small scales (linear theory)
  - No halos below a minimum mass (non-linear effect)

- *Phase space density:*
  - Limits density in the center of halos (non-linear effect)
    - Makes small halos susceptible to disruption
    - Limits sub-structure in larger halos

Weak scale theories: warm to cold in SUSY

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

Weak scale theories: warm to cold in SUSY

- Neutralino is the LSP
  - Kinetic decoupling 10-100 MeV
  - Cold Dark Matter with large primordial phase space density
  - Minimum halo mass ~ earth mass (big spread)

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

Weak scale theories: warm to cold in SUSY

- Neutralino is the LSP
  - Kinetic decoupling 10-100 MeV
  - Cold Dark Matter with large primordial phase space density
  - Minimum halo mass ~ earth mass (big spread)

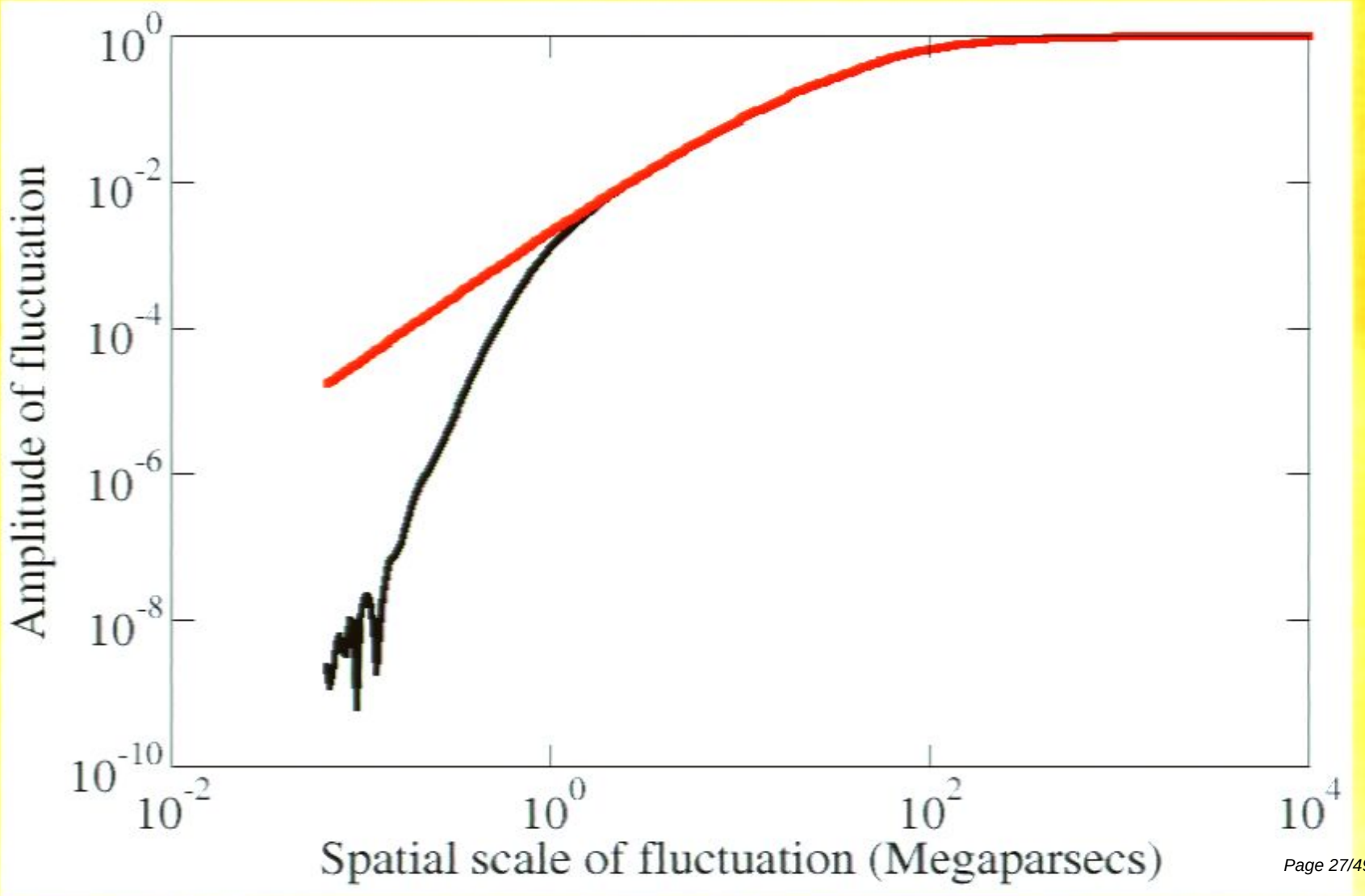
$$Q_{CDM} = 10^{14} \frac{M_\odot}{pc^3} \left(\frac{km}{s}\right)^{-3} \left(\frac{M}{100GeV}\right)^{3/2}$$

- Gravitino or axino LSP
  - Example: stau next-lightest-supersymmetric particle. stau decays to gravitino with lifetime ~ $1/(8\pi G M_{weak}{}^3)$ ~ month. [Feng, Rajaraman and Takayama, PRL 2003]
  - Example: axino LSP [Covi, Kim and Roszkowski, PRL 1999]
  - These particles could be warm (sliding scale) or a mix of warm and cold [Kaplinghat 2005, Cembranos et al 2005, Jedamzik, Lemoine, Moultaka 2005]
  - Minimum halos mass could be large enough to be ruled out by current observations. Many models have minimum mass around dwarf galaxy scale.
  - Small phase space density, Q (in the above) units ~ 1 (big spread)

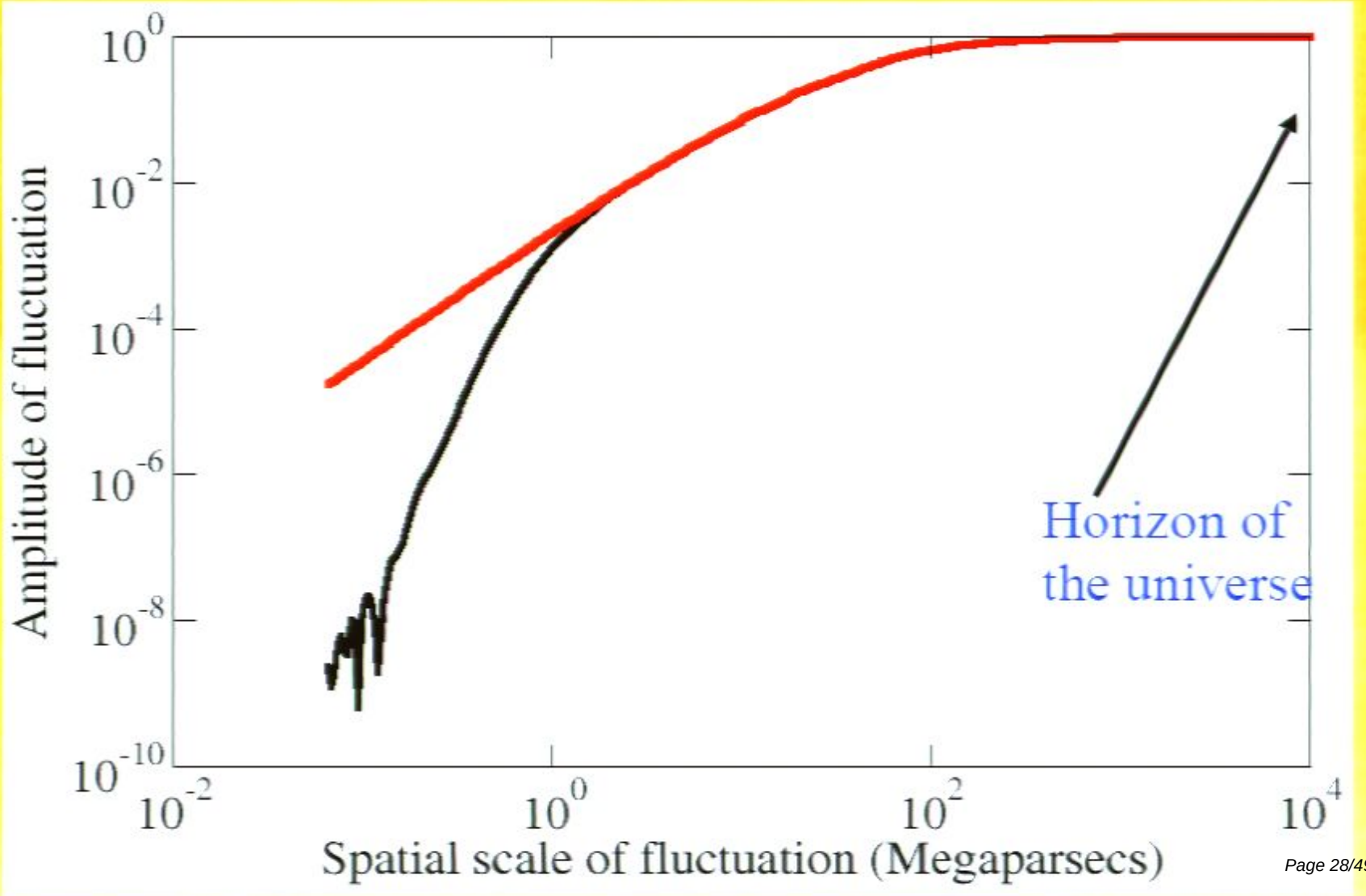
Distinguishing DM from decays and CDM

- 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

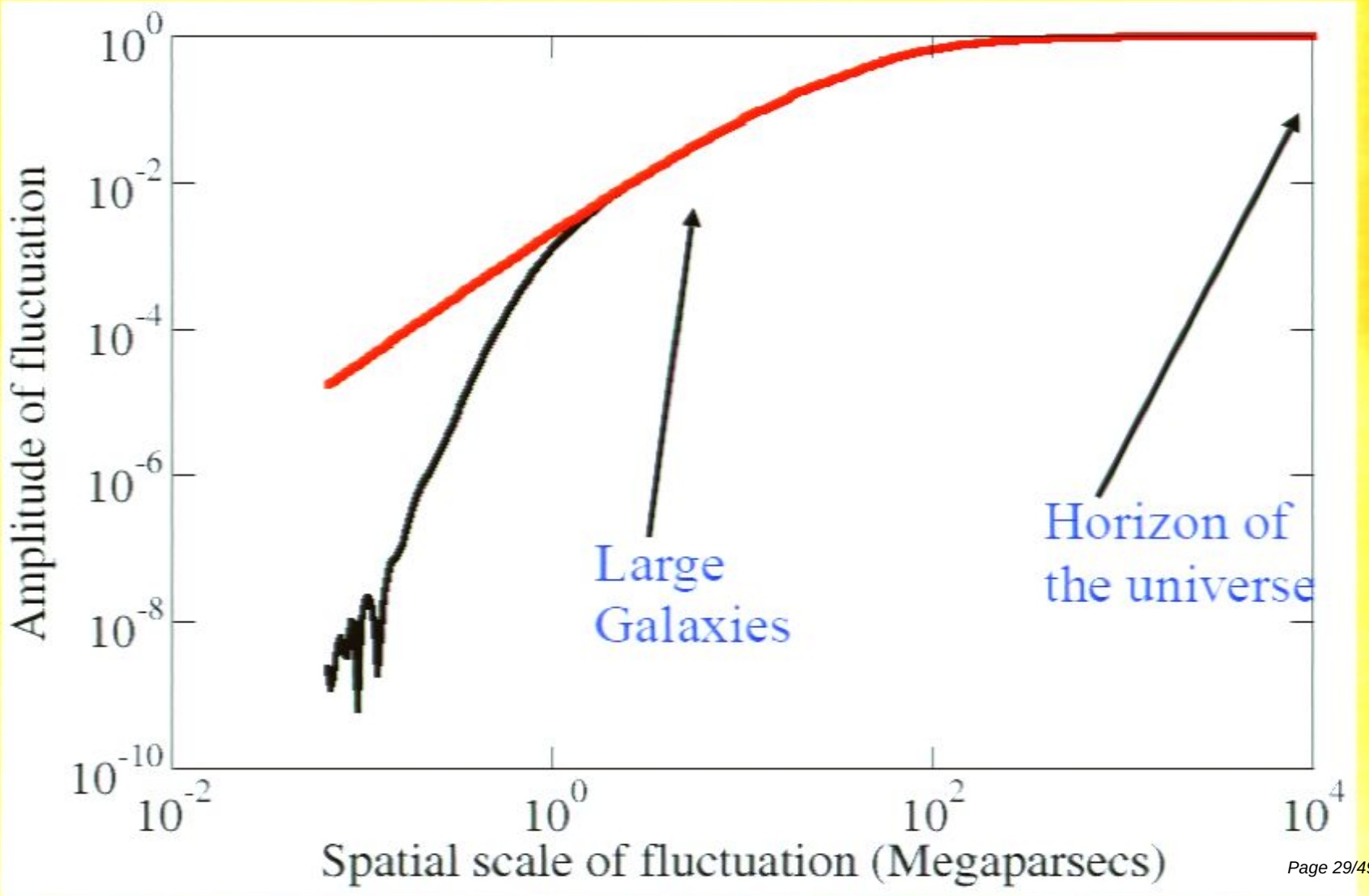
Power spectrum of fluctuations in DM from decays



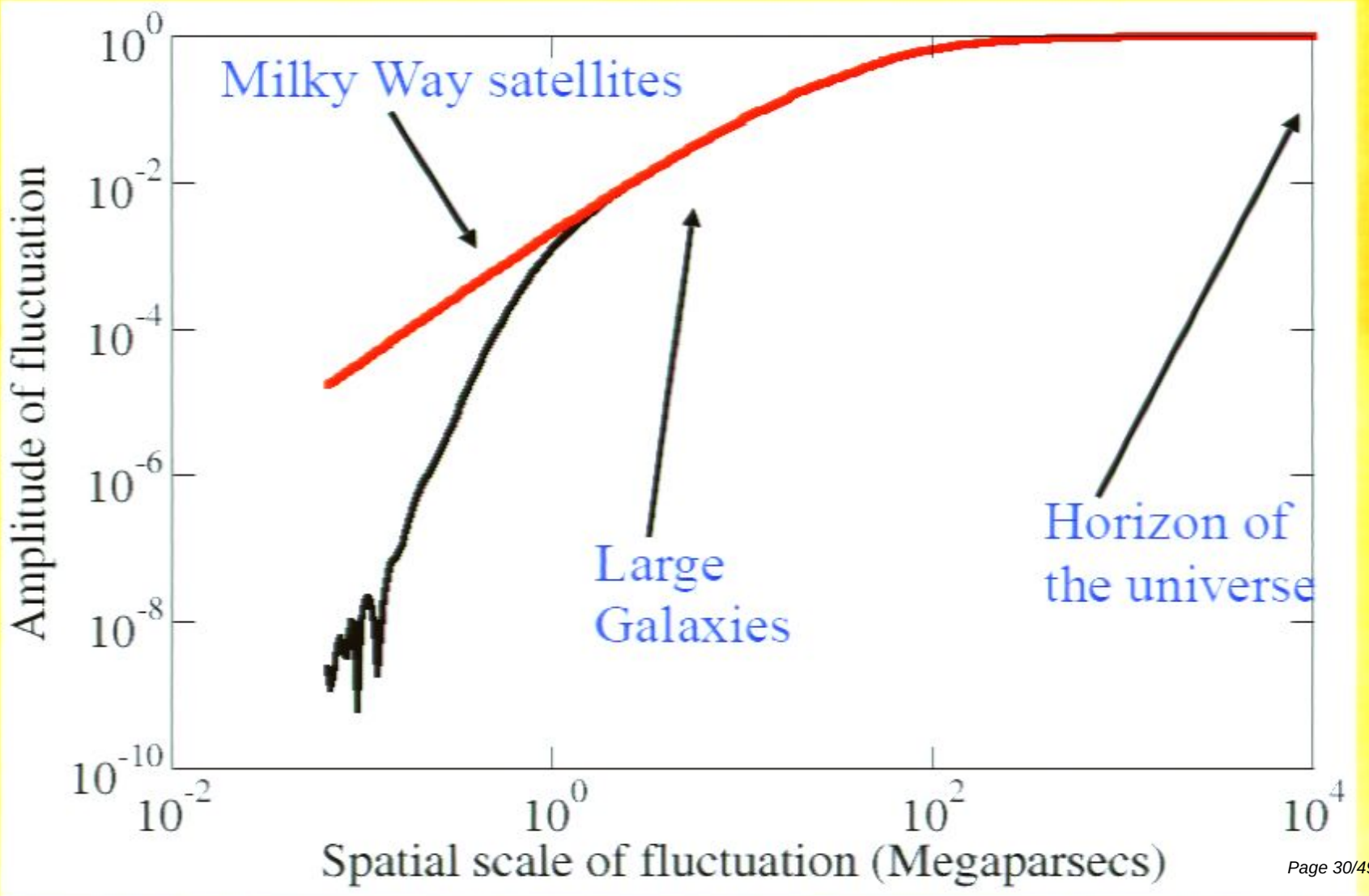
Power spectrum of fluctuations in DM from decays

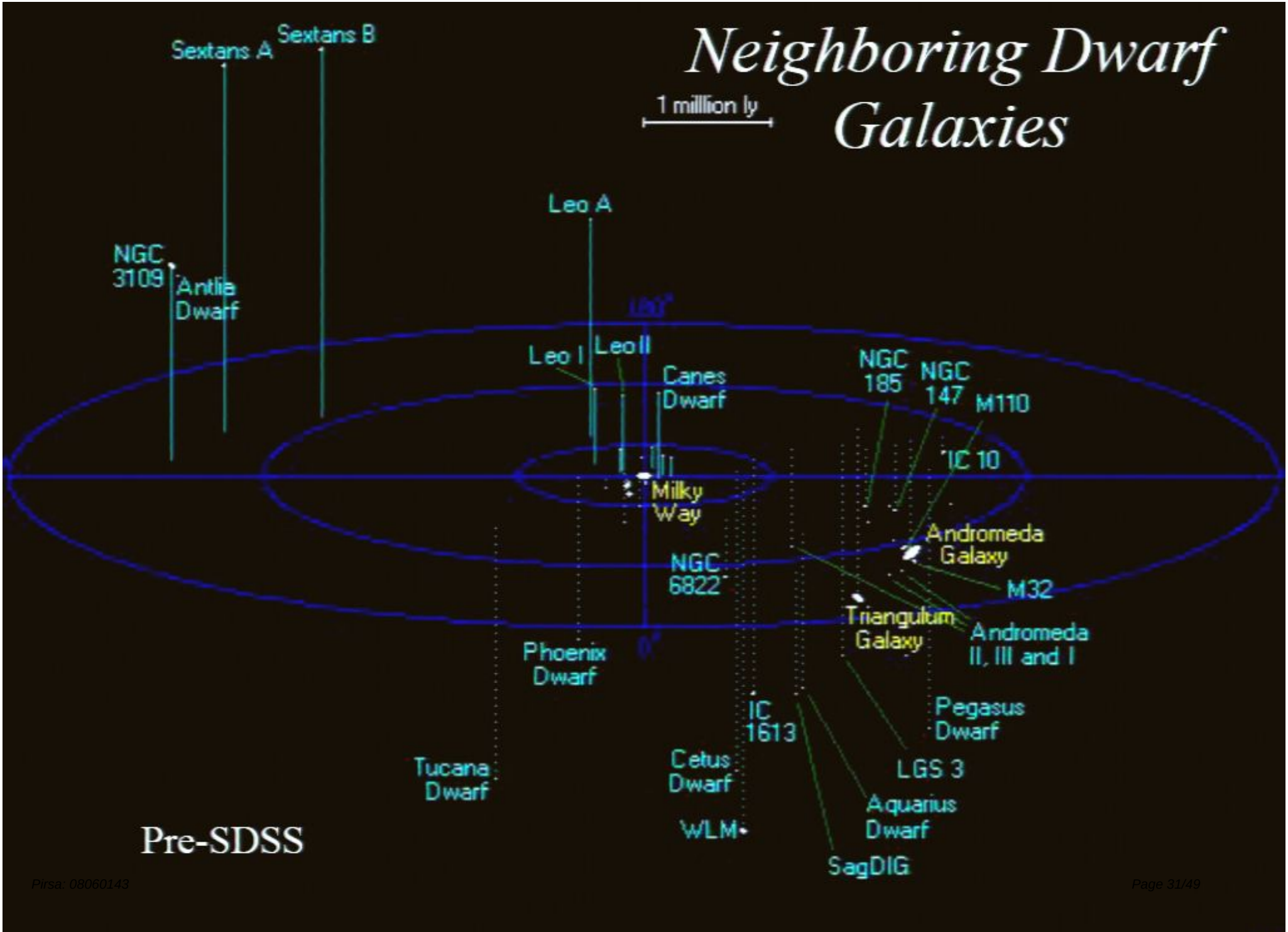


Power spectrum of fluctuations in DM from decays



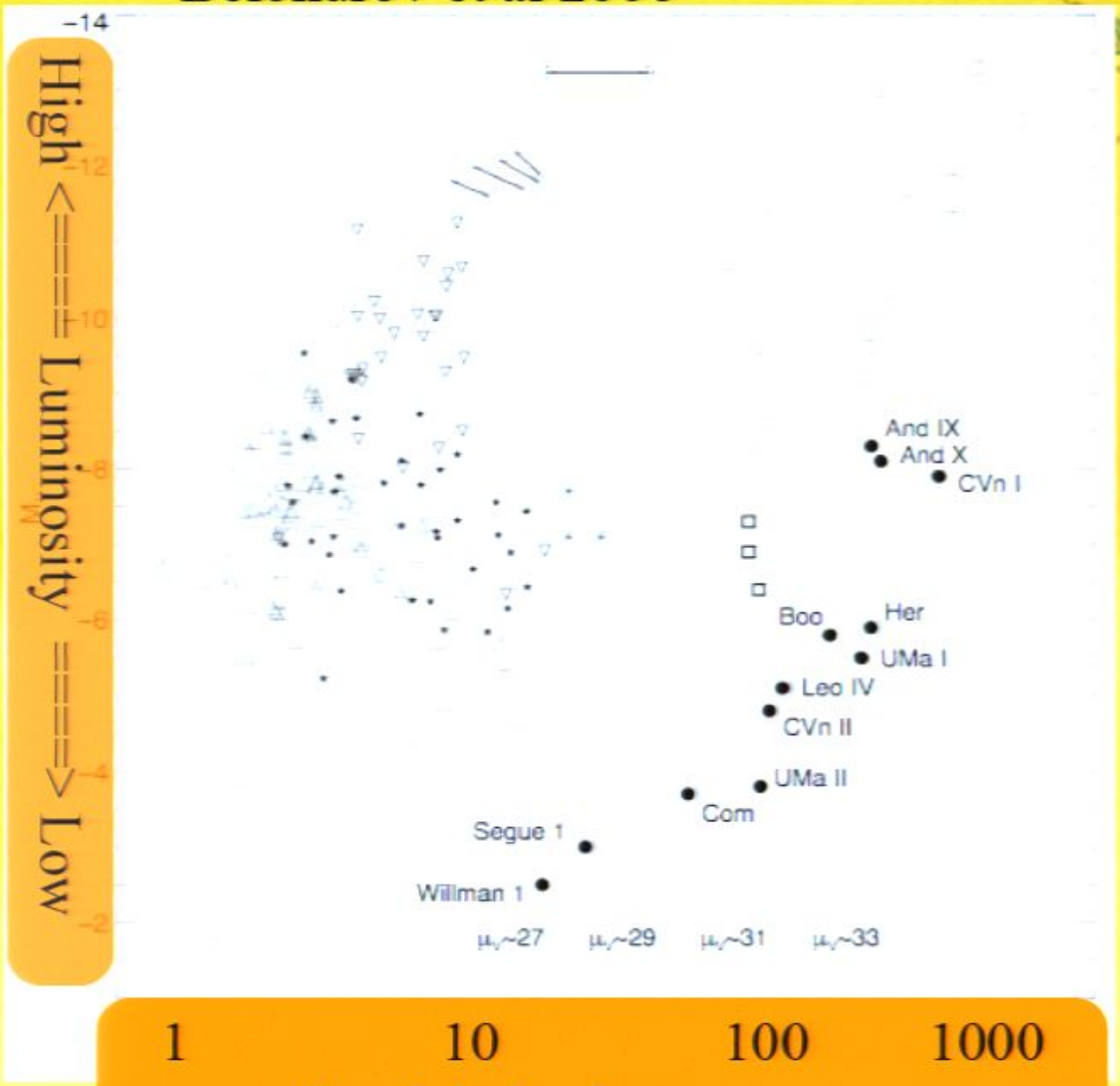
Power spectrum of fluctuations in DM from decays




Neighboring Dwarf Galaxies
1 million ly
Sextans A
Sextans B
Leo A
NGC 3109
Antlia Dwarf
Leo I
Leo II
Canes Dwarf
NGC 185
NGC 147
M110
IC 10
Milky Way
Andromeda Galaxy
NGC 6822
M32
Triangulum Galaxy
Andromeda II, III and I
Phoenix Dwarf
IC 1613
Pegasus Dwarf
Tucana Dwarf
Cetus Dwarf
LGS 3
Aquarius Dwarf
WLM
SagDIG
Pre-SDSS

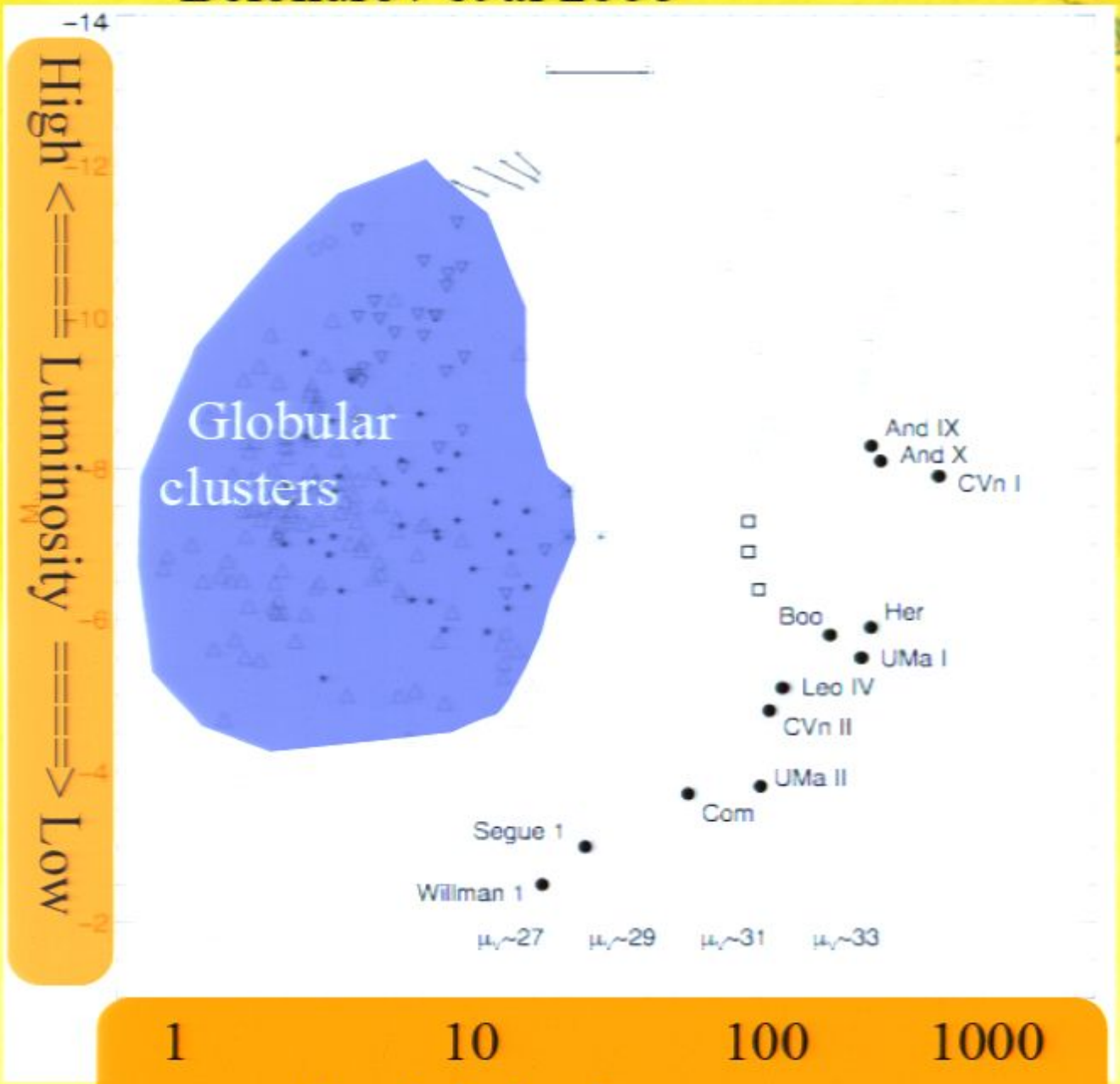
The newly discovered neighbors

Belokurov et al 2006



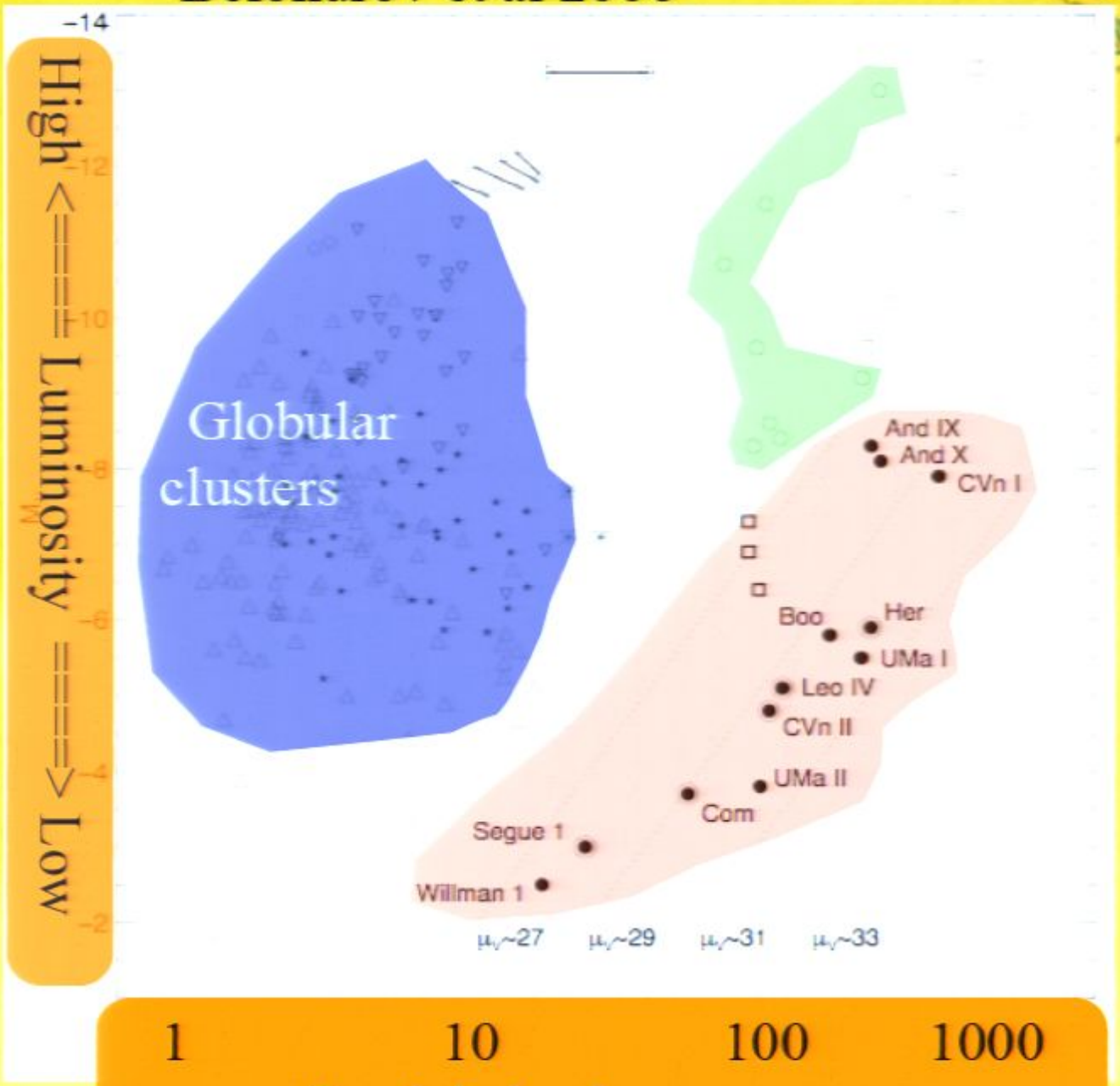
The newly discovered neighbors

Belokurov et al 2006



The newly discovered neighbors

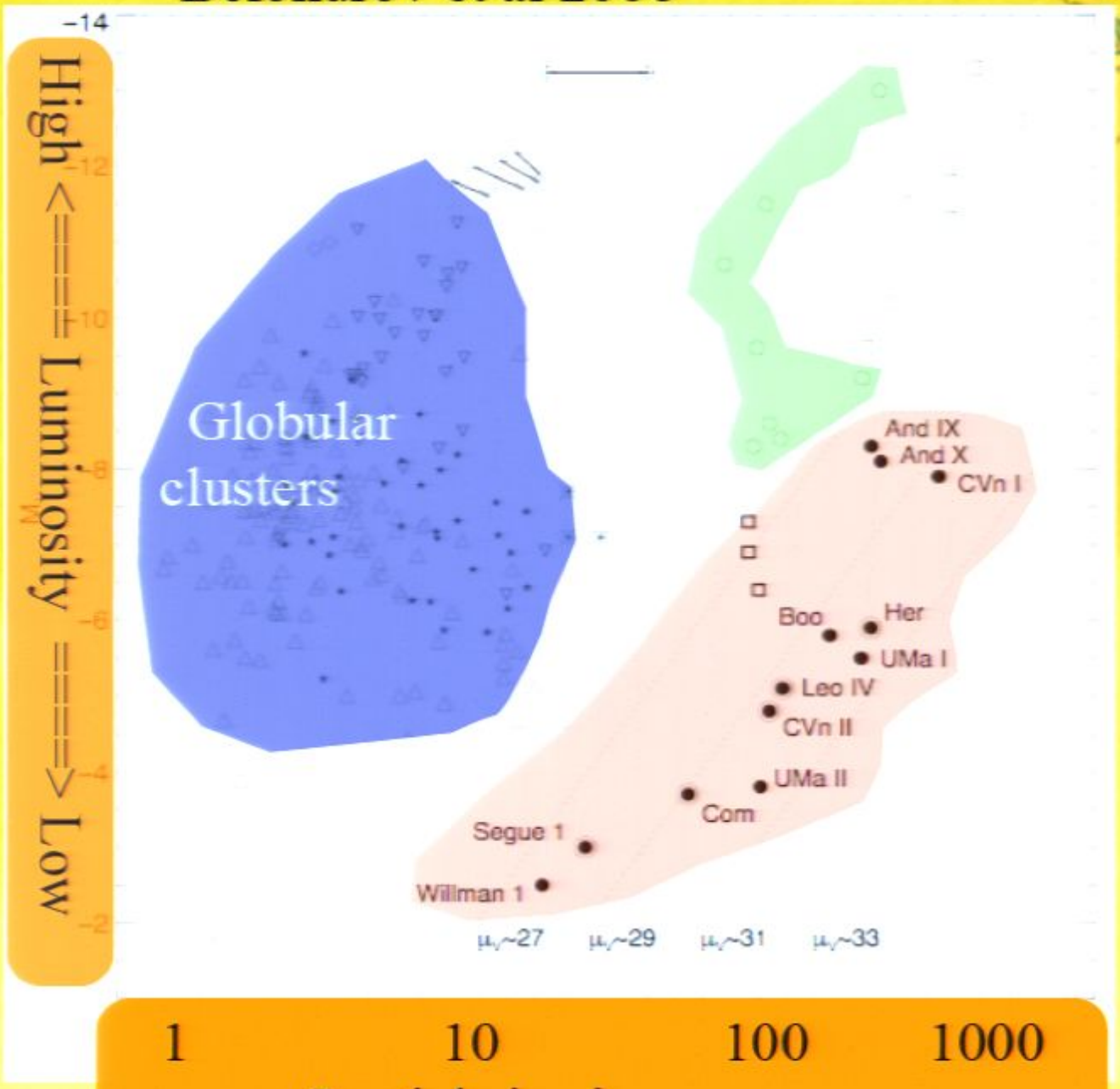
Belokurov et al 2006



The newly discovered neighbors

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

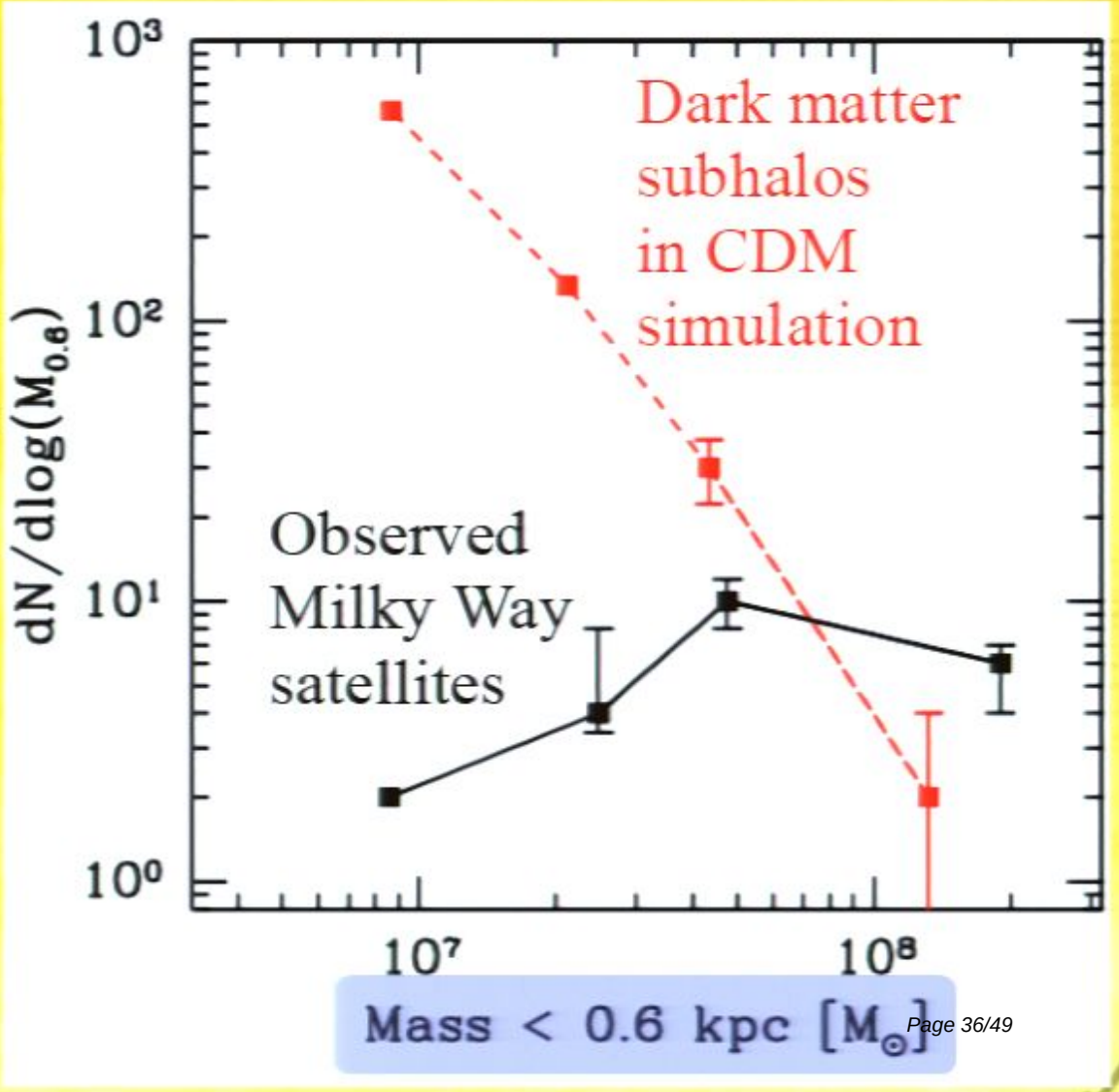
Belokurov et al 2006



Missing satellite problem

Klypin et al. 99; Moore et al. 99

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



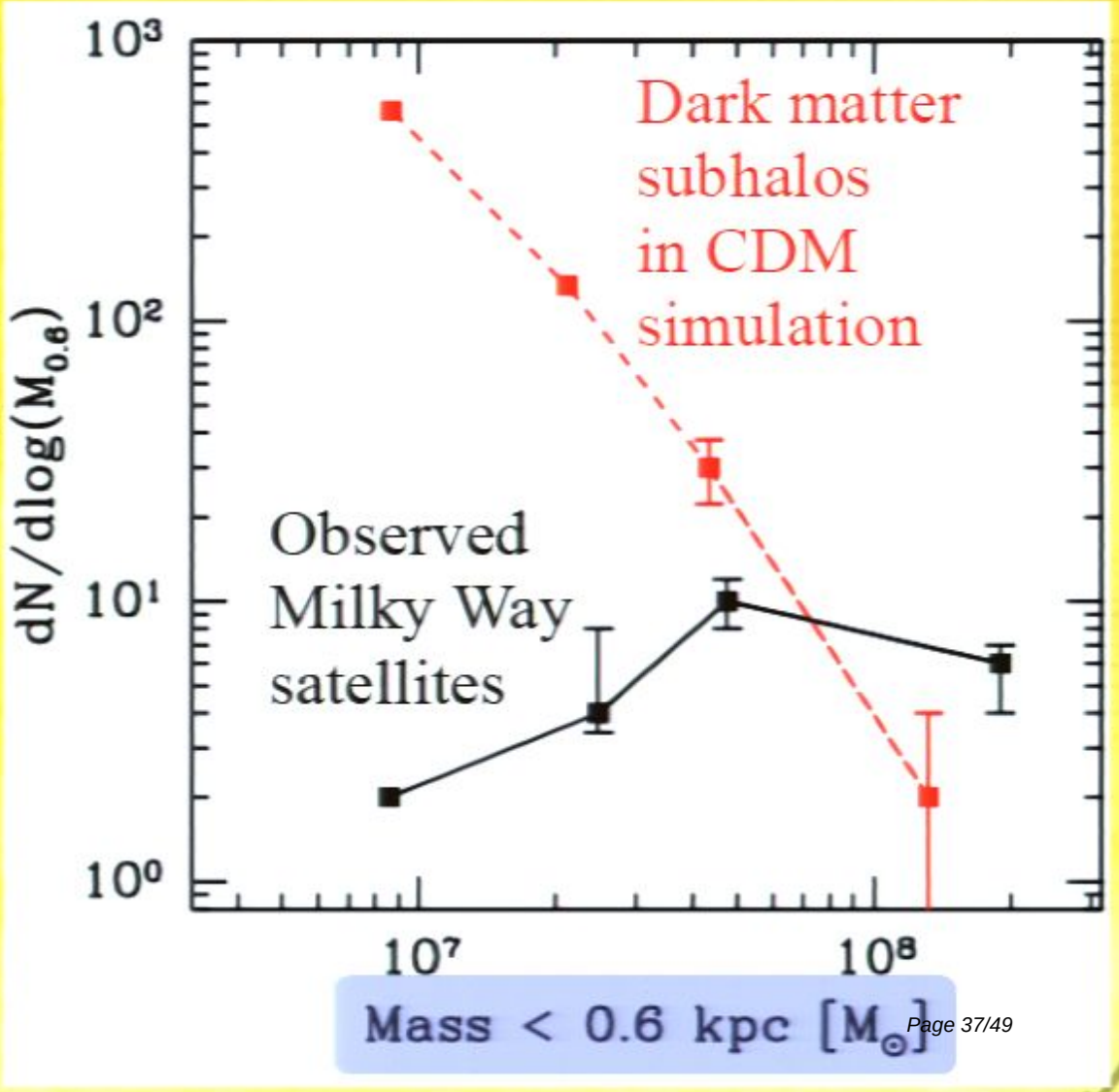
Strigari et al 07

Missing satellite problem

Klypin et al. 99; Moore et al. 99

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

Not all subhalos have to light up.
[Bullock et al 2000]
[Kravtsov, Gnedin and Klypin 2004]



Strigari et al 07

Testing the CDM paradigm

Testing the CDM paradigm

- How do we test the Cold Dark Matter paradigm and constrain Warm Dark Matter models?

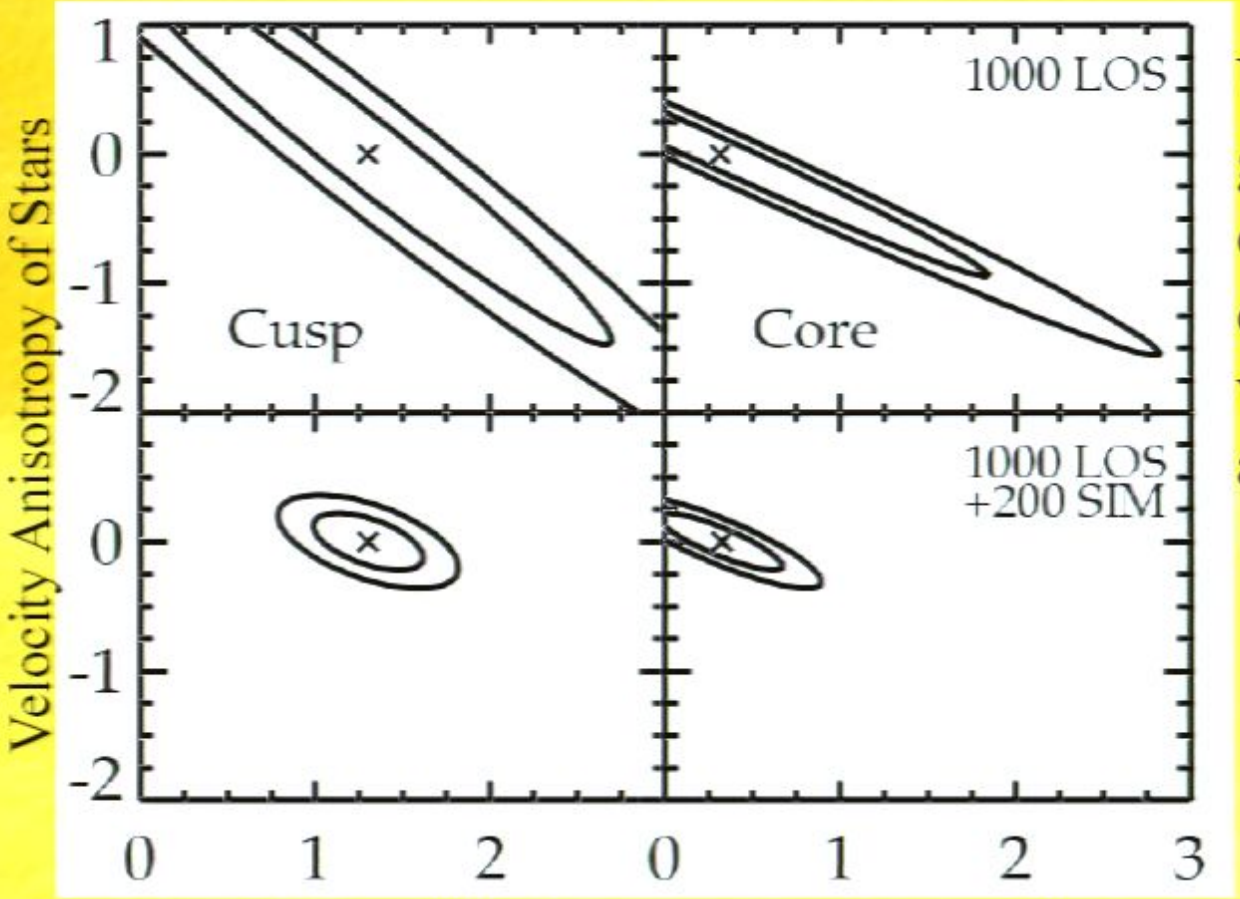
Testing the CDM paradigm

- How do we test the Cold Dark Matter paradigm and constrain Warm Dark Matter models?
- Best bet is probably to look at dwarf galaxies in the local neighborhood of Milky Way. Many dwarf galaxies are close by, about 100 kpc or closer.

Testing the CDM paradigm

- How do we test the Cold Dark Matter paradigm and constrain Warm Dark Matter models?
- Best bet is probably to look at dwarf galaxies in the local neighborhood of Milky Way. Many dwarf galaxies are close by, about 100 kpc or closer.
- Why Local Dwarf Galaxies?
  - Look for products of self-annihilation or decay of dark matter particles (GLAST, VERITAS, MAGIC, HESS, CHANDRA)
    - Close and dark matter dominated
    - Low intrinsic backgrounds
    - Good chance we will understand their spatial mass profile
  - Measure the dark matter halo density profile
    - Constrains Q and power spectrum
  - Census of dwarfs
    - Constrains power spectrum and Q

Measuring Density Profile: Solution

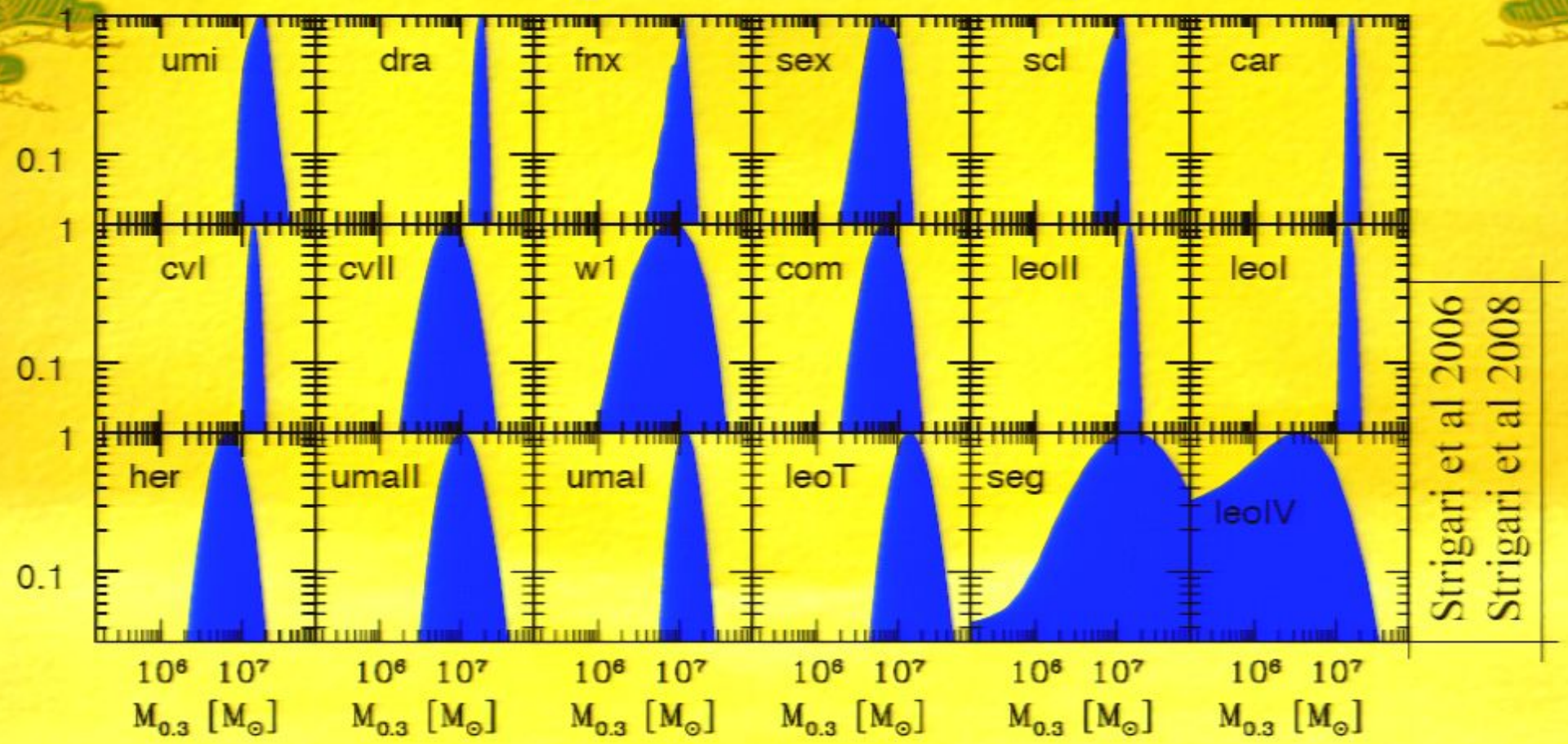


Log-slope of dark matter density profile

Strigari, Bullock and Kaplinghat, 2007

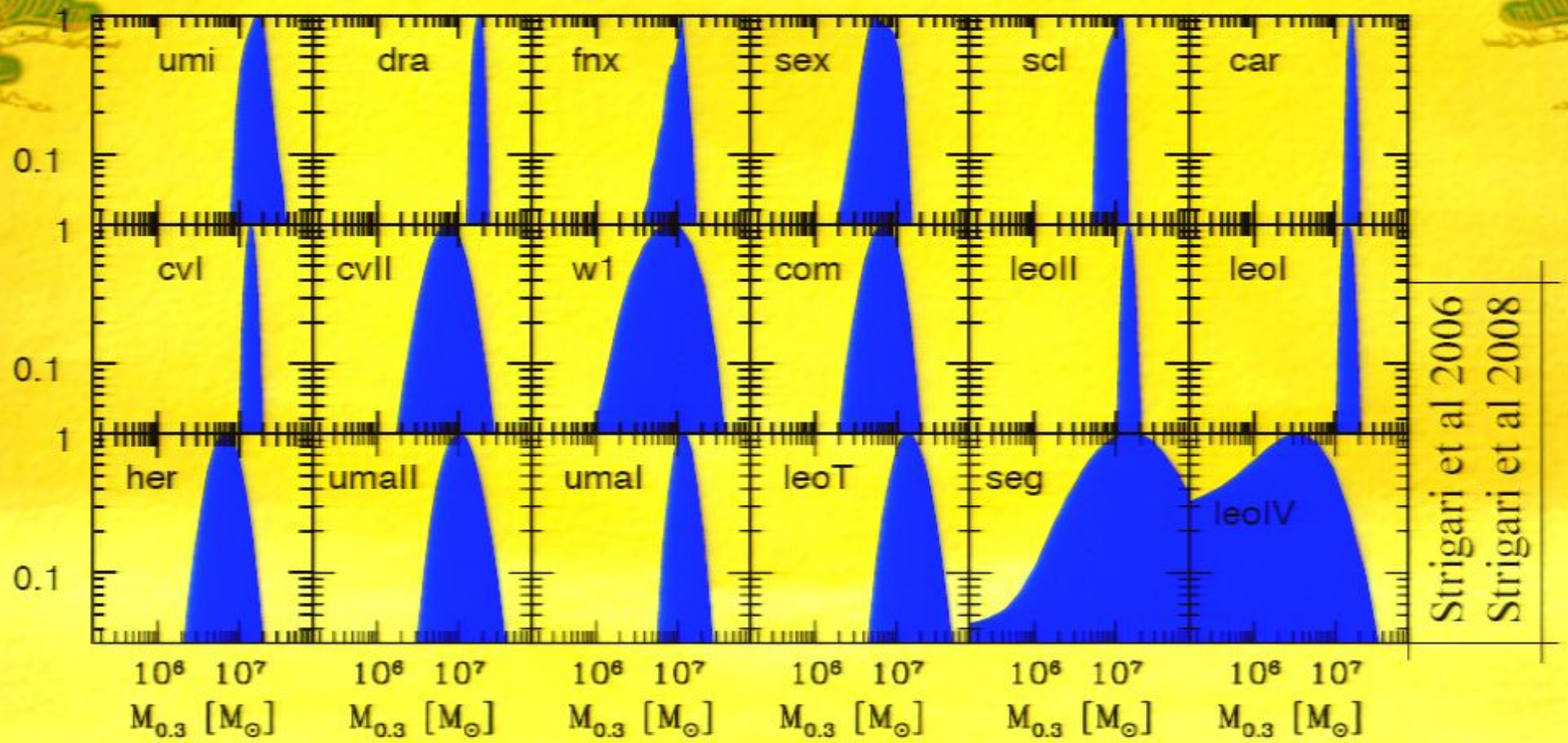
Use proper motions to get 3-d velocity dispersion. Breaks the degeneracy of slope with velocity dispersion anisotropy.

Measuring the masses of dwarfs



Current measurements **can** measure integrated mass within the stellar radius well

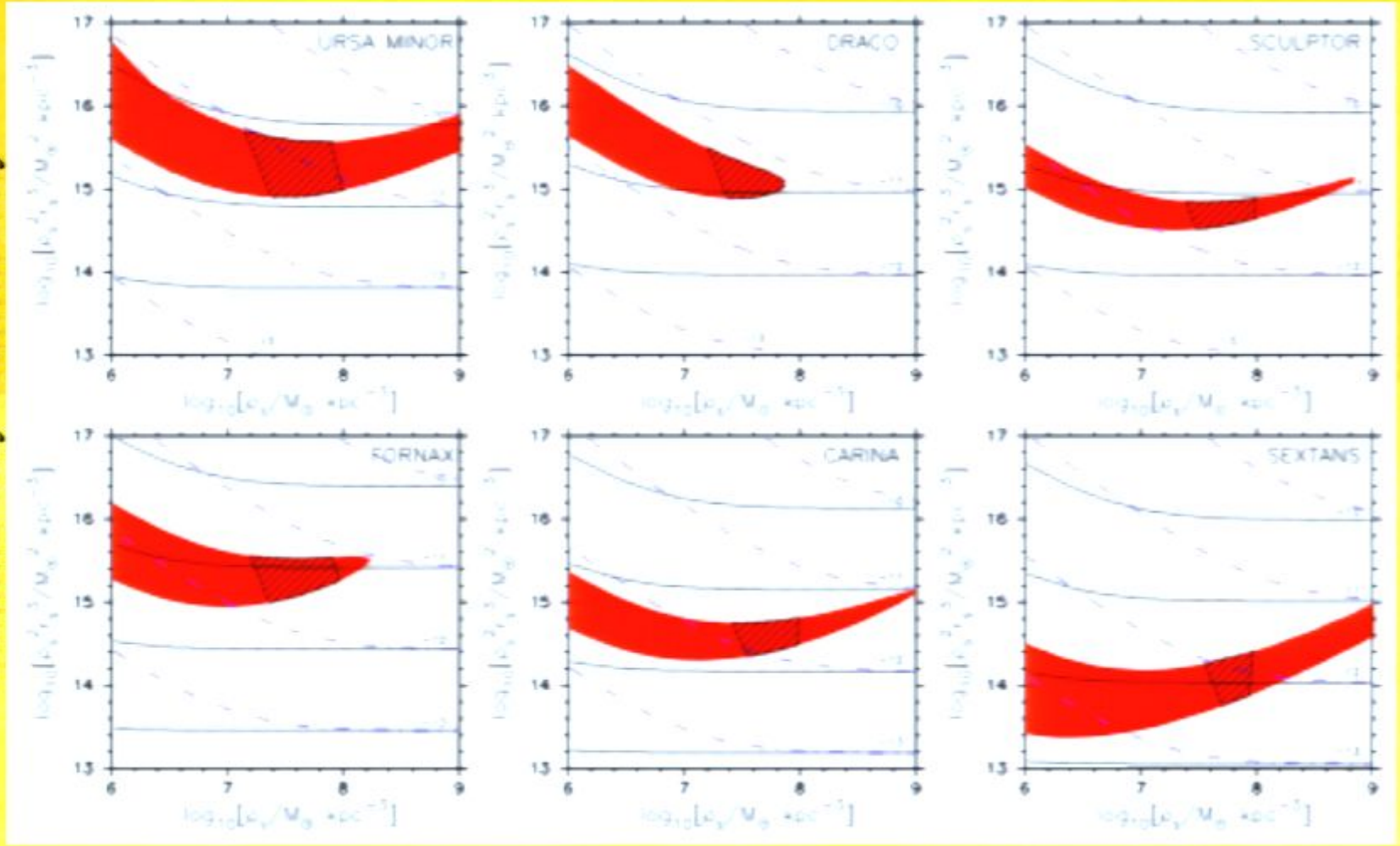
Measuring the masses of dwarfs



Current measurements **can** measure integrated mass within the stellar radius well

This mass can be reliably measured in simulations allowing robust comparison of theory and data

Indirect detection of dark matter: Annihilation products from the dwarfs



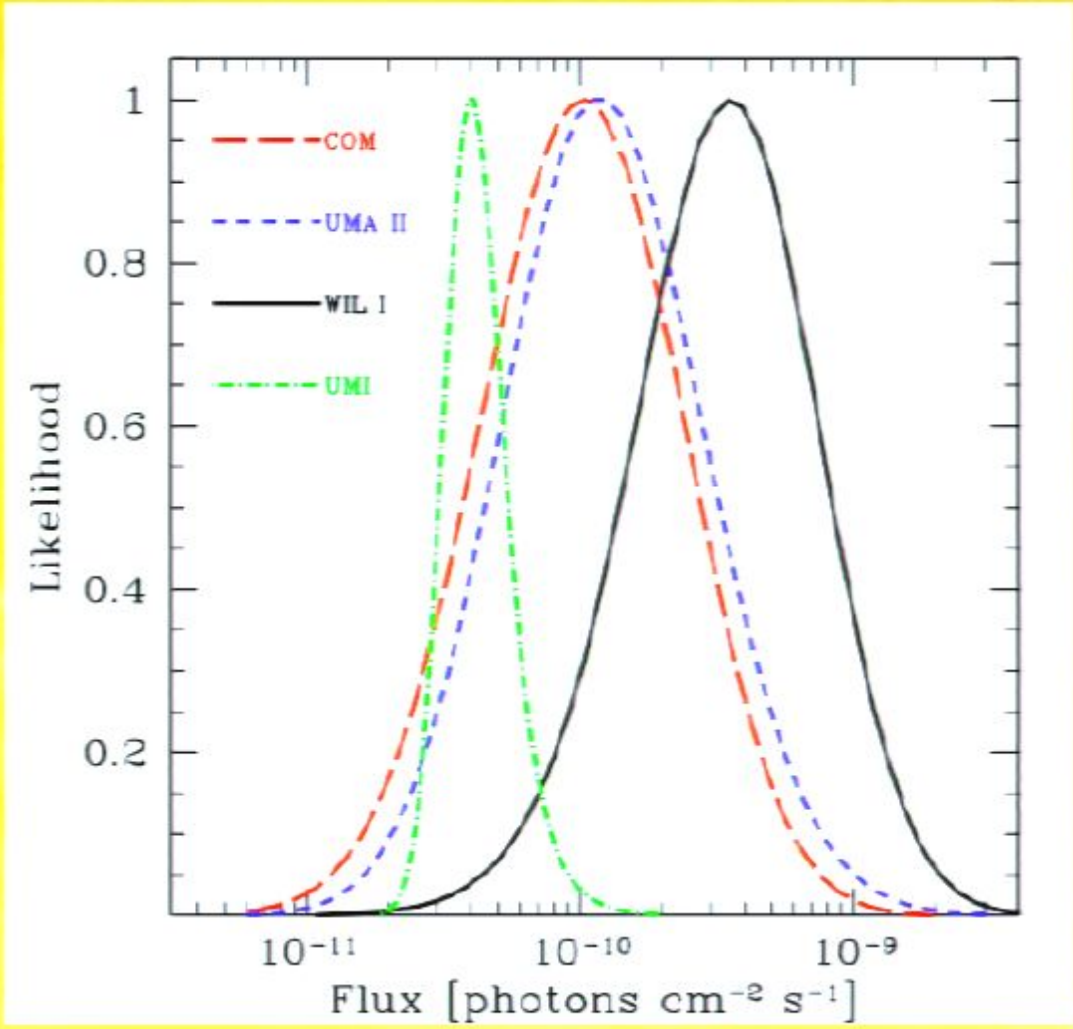
Gamma Ray Luminosity

Characteristic density

Strigari et al 2006

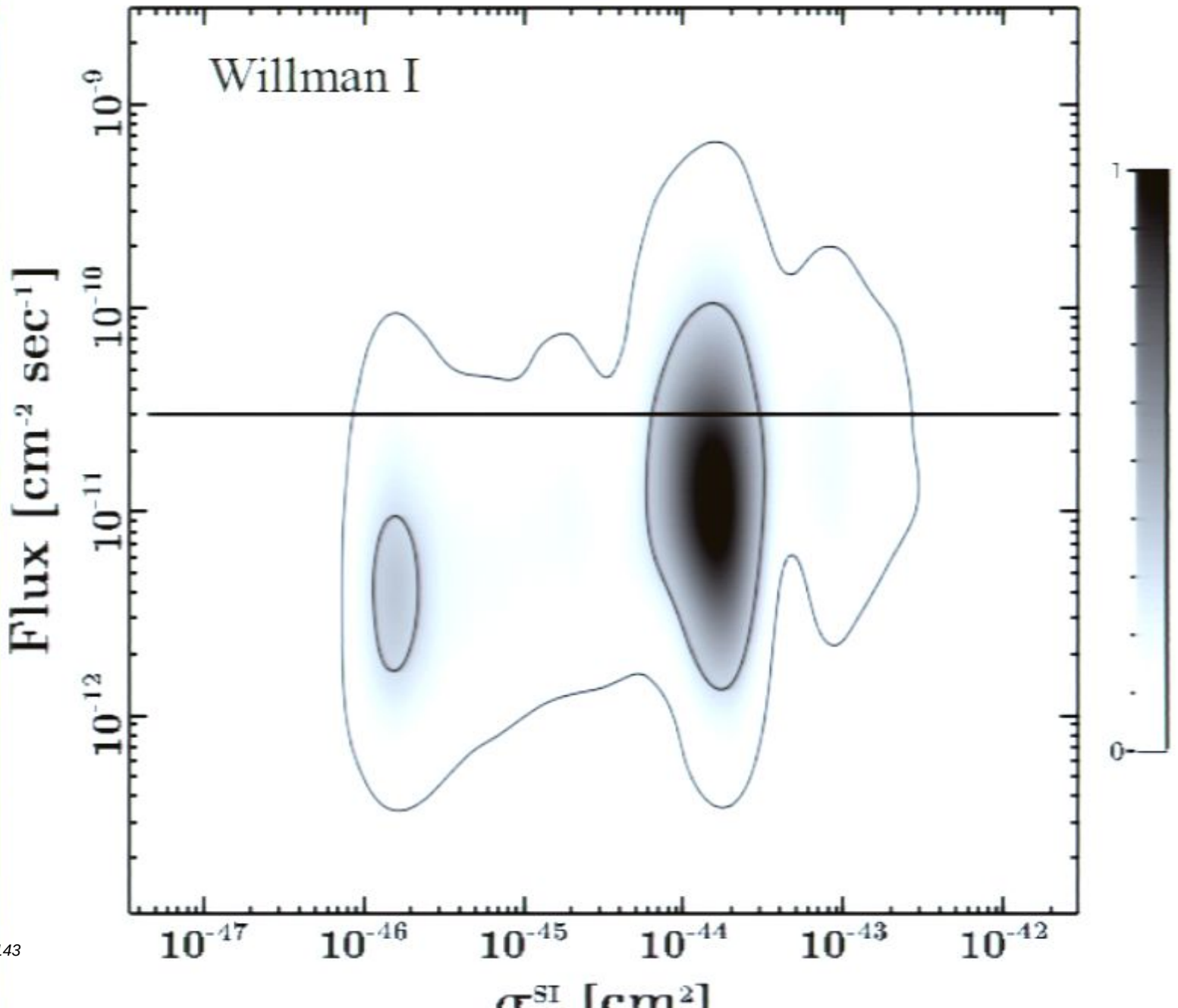
The new neighbors

- 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



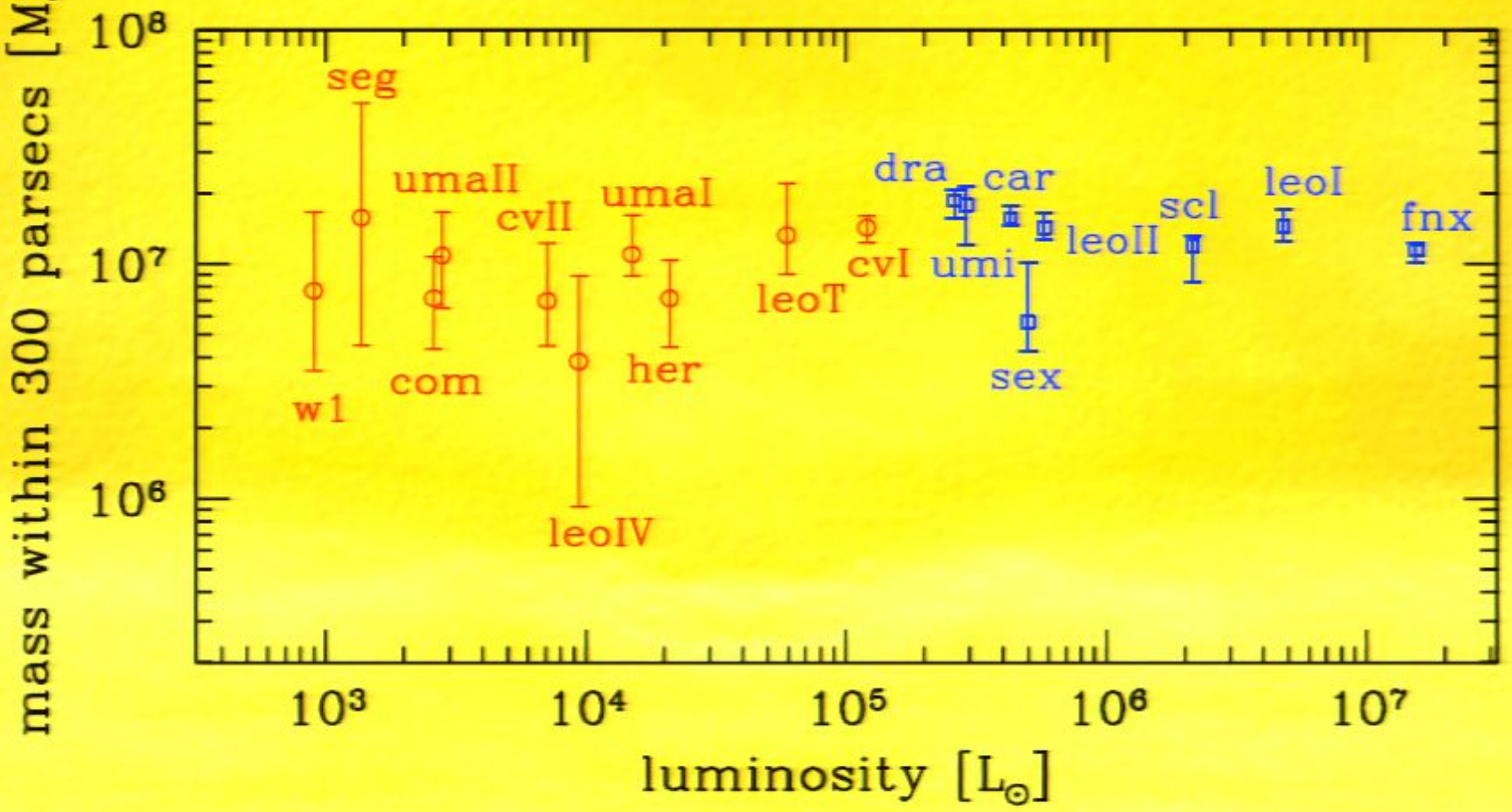
Strigari et al 2007

New Dwarf and WIMPs



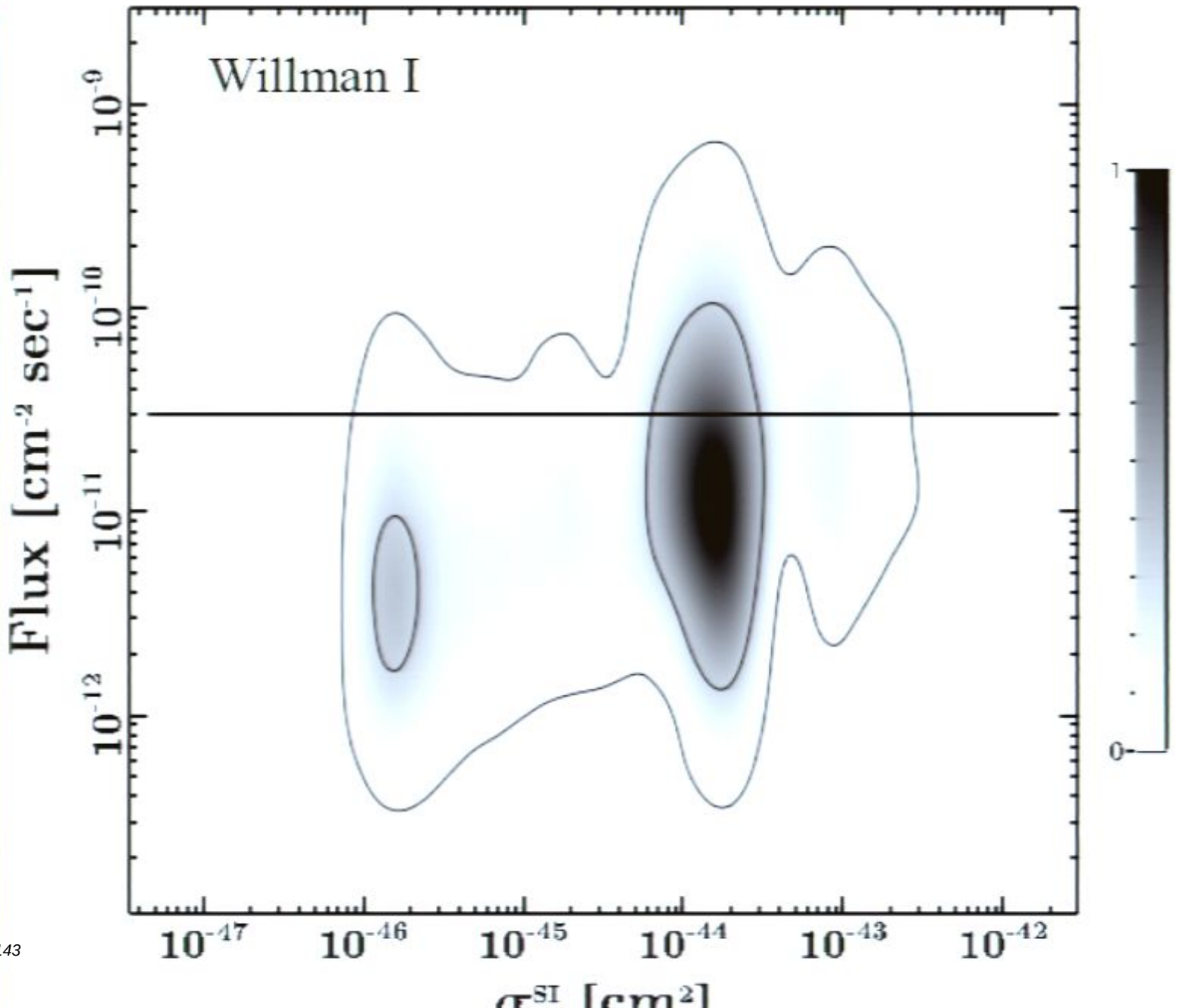
Martinez, Kaplinghat and Strigari 2008 in prep

A Common Mass



Strigari, Bullock, Kaplinghat, Geha, Simon, Willman 2008, will be posted very soon...

New Dwarf and WIMPs



Martinez, Kaplinghat and Strigari 2008 in prep