Title: Central density profile of dark matter halos

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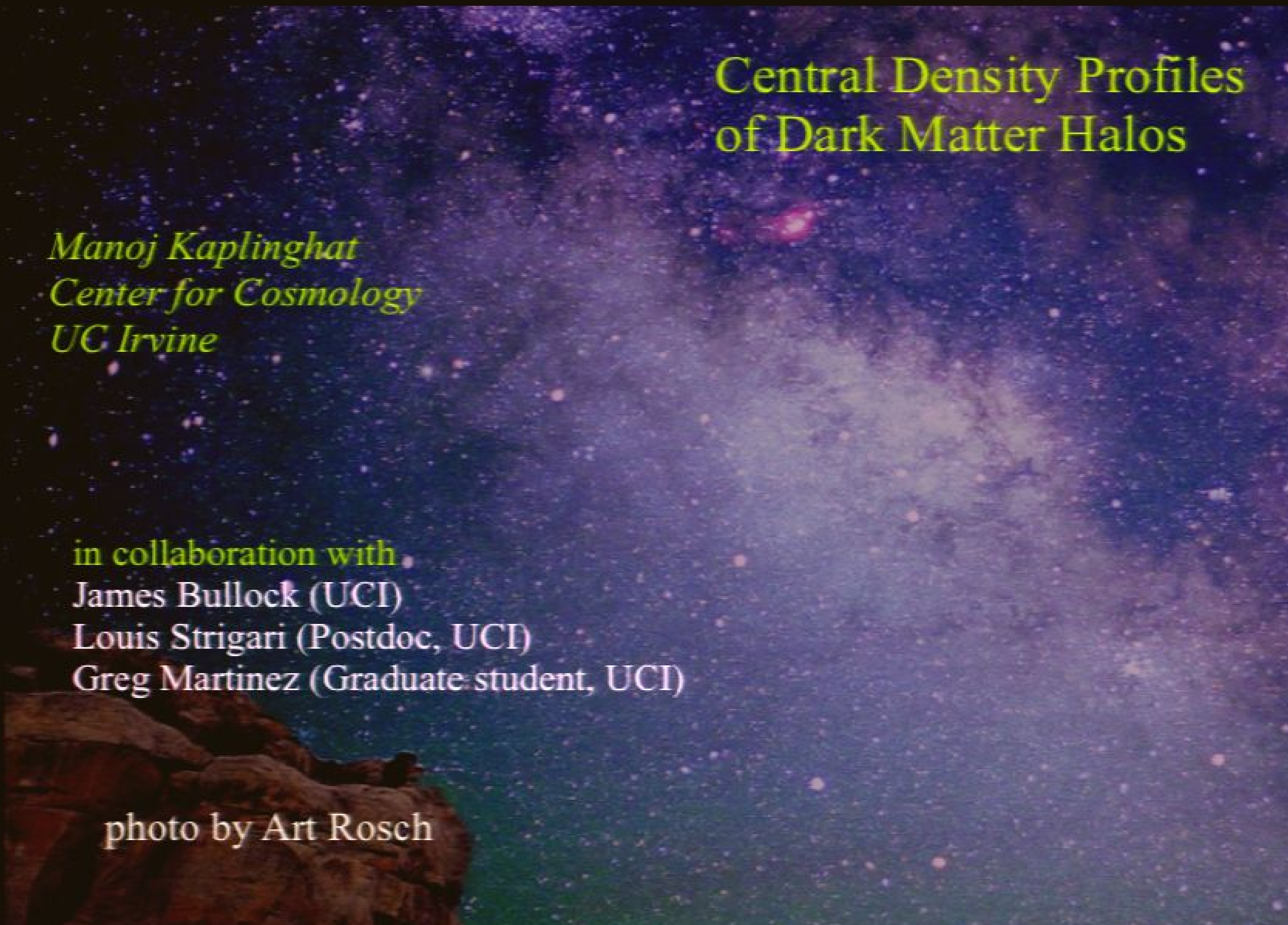
Abstract:



Central Density Profiles of Dark Matter Halos

Manoj Kaplinghat
Center for Cosmology
UC Irvine

in collaboration with
James Bullock (UCI)
Louis Strigari (Postdoc, UCI)
Greg Martinez (Graduate student, UCI)

photo by Art Rosch

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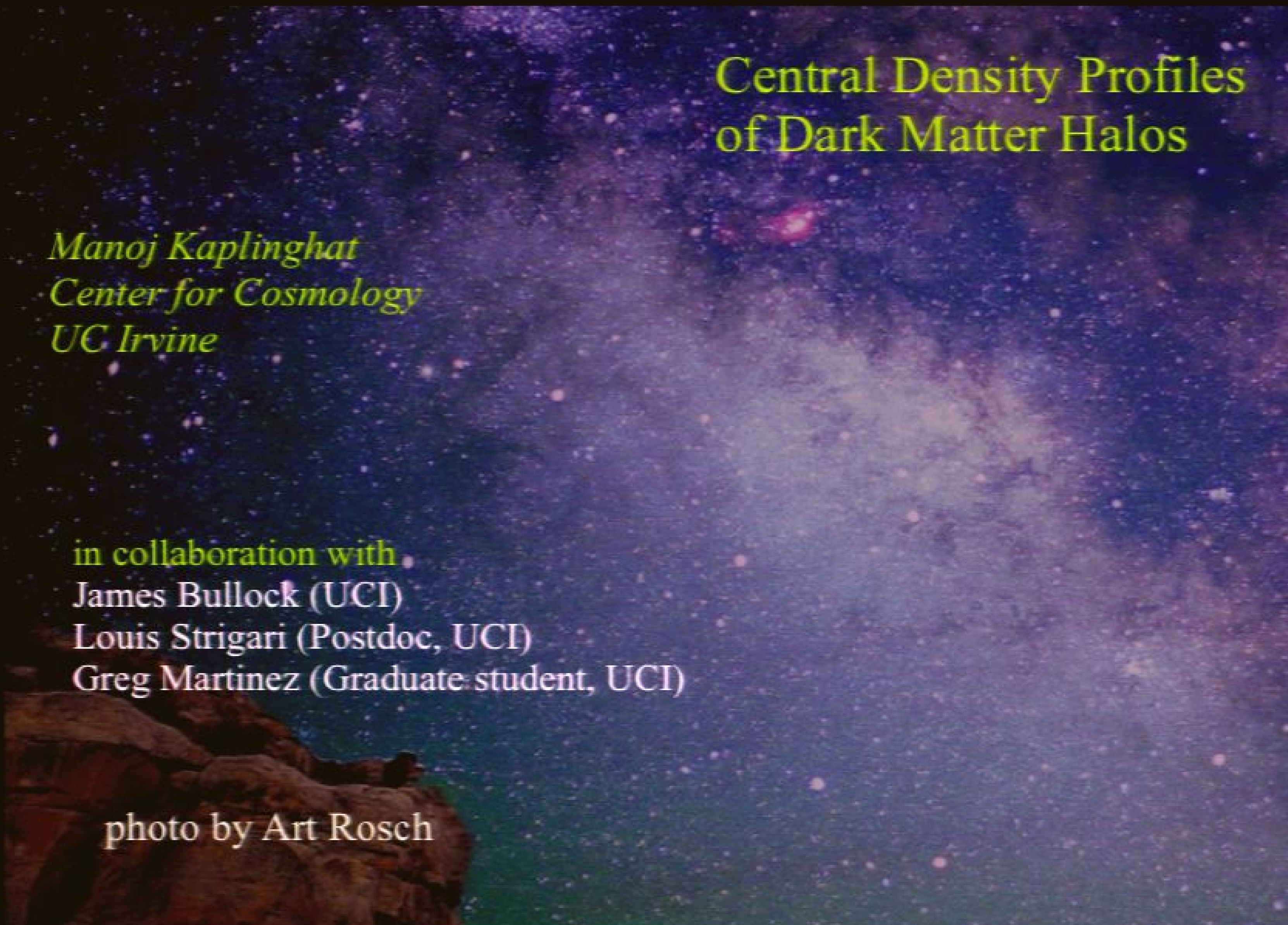

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Outline

- Dark matter model space
- Short summary of particle physics models
- Mapping early universe momentum distribution to halo structure
- Effect of baryons
- Aside: effect of substructure and (sub-sub...) on the flux of dark matter annihilation products

Properties of Dark Matter

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- *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} ~ $1/a$

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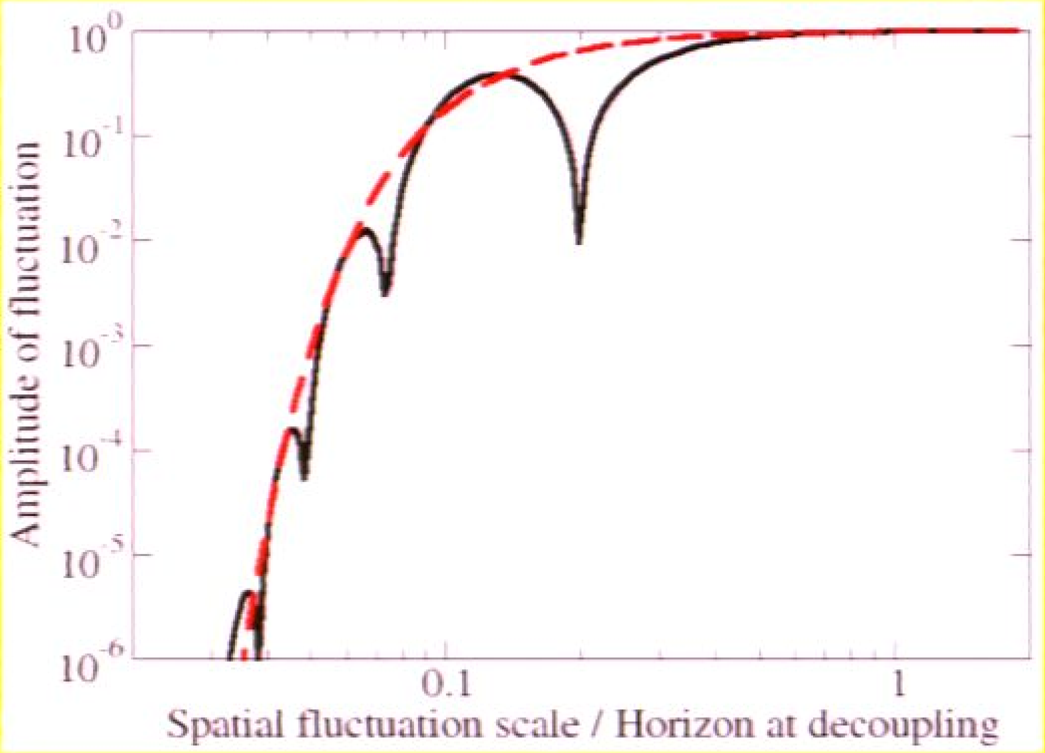
Set by scatterings in the early universe

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
Green, Hofmann and Schwarz 2004
Loeb and Zaldarriaga 2005
Bertschinger 2006

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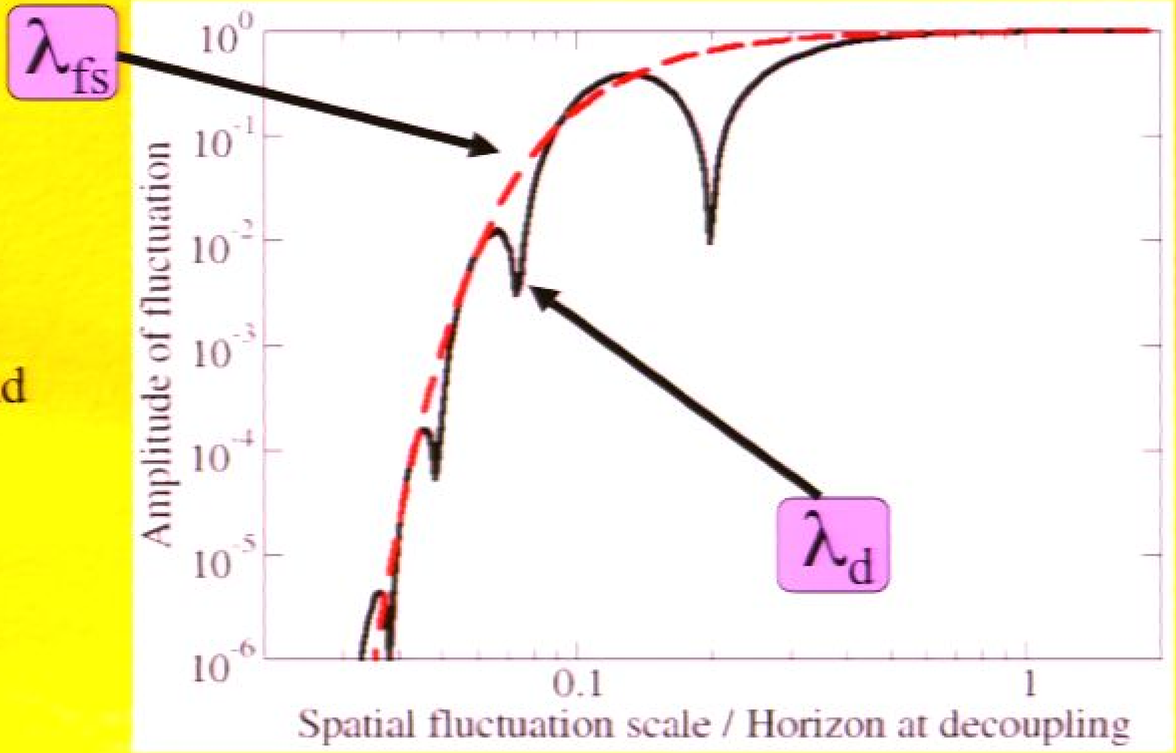

Hofmann, Schwarz and Stoecker 2001
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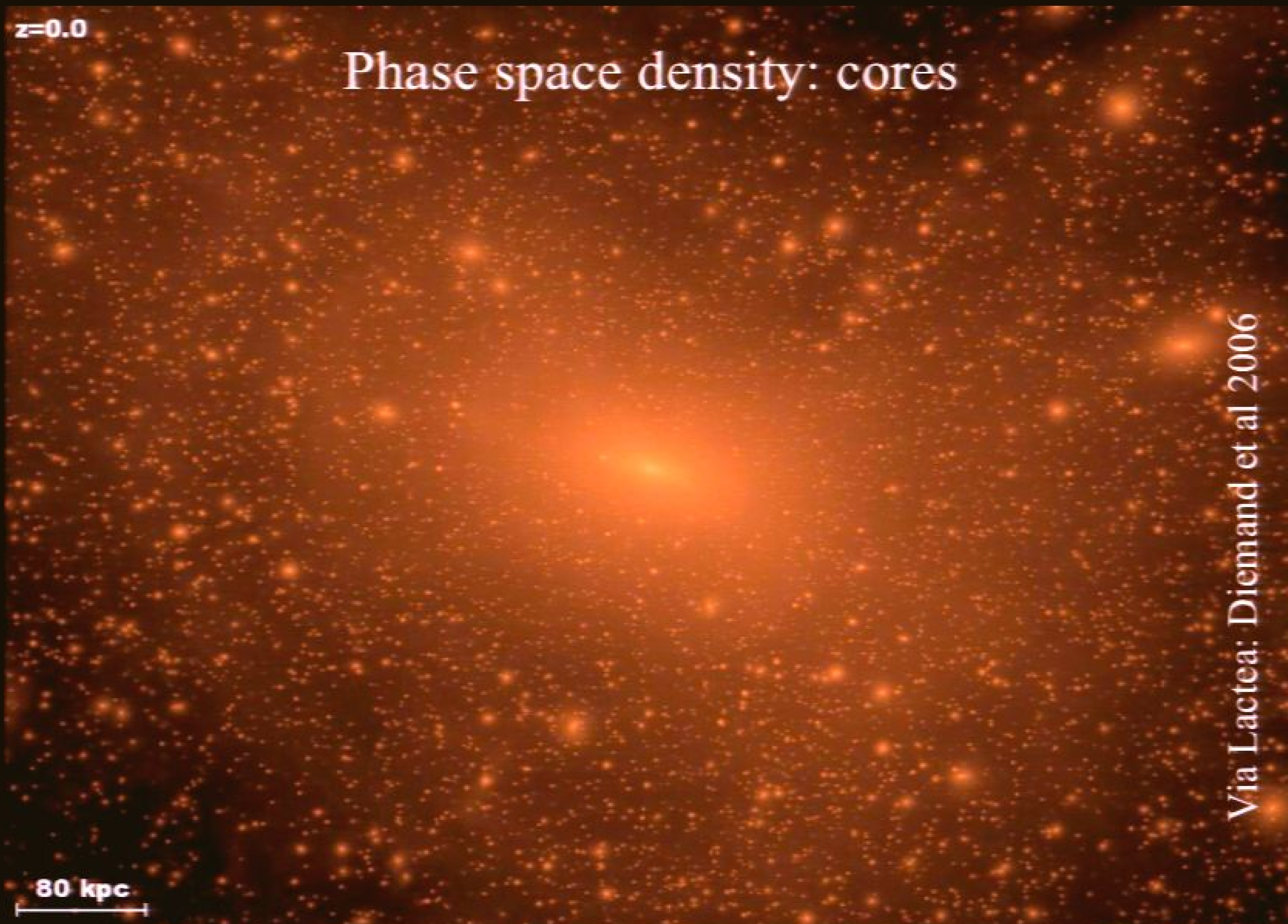
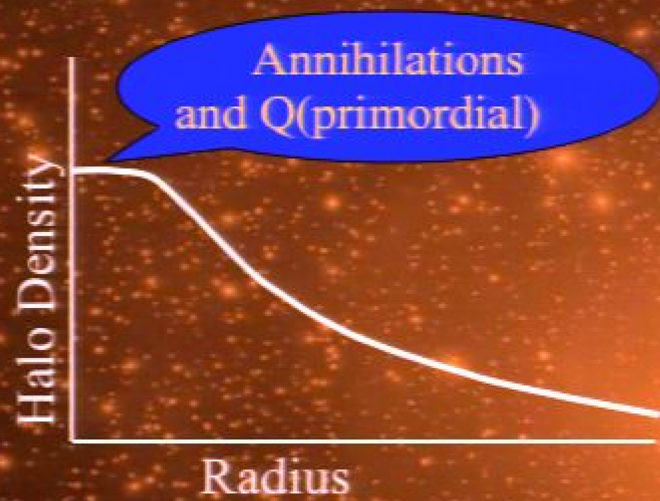
Free-streaming and Damping: Halos (non-linear effect)

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


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

z=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]

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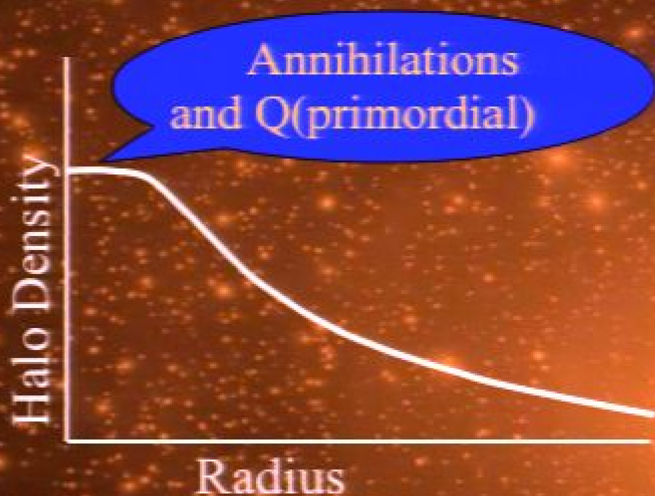

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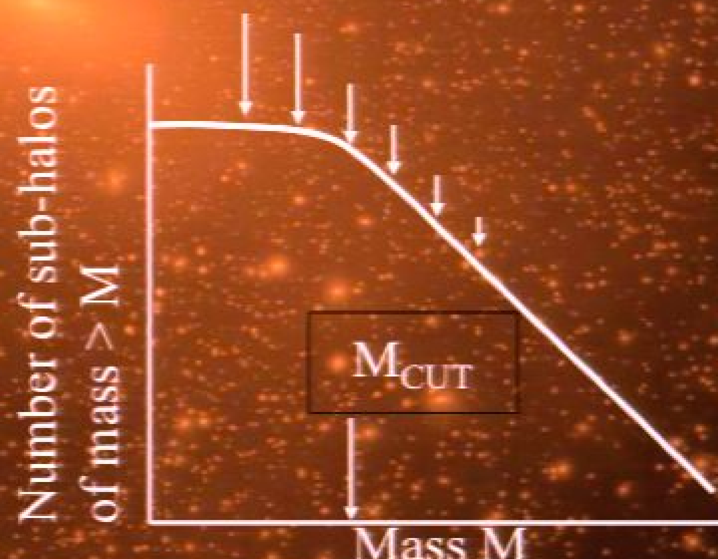
Halos with cores are more easily disrupted when accreted into a larger halo

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



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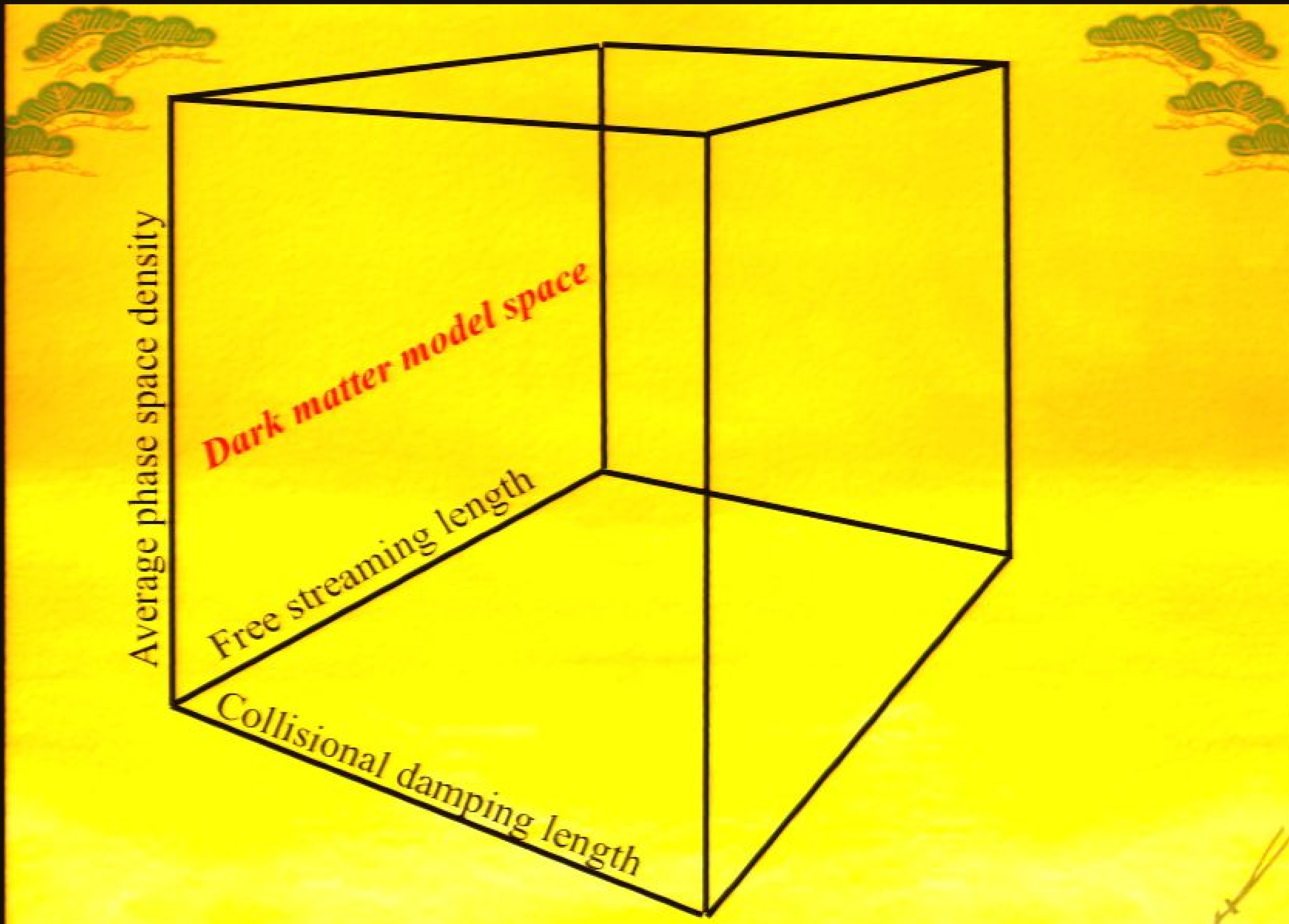
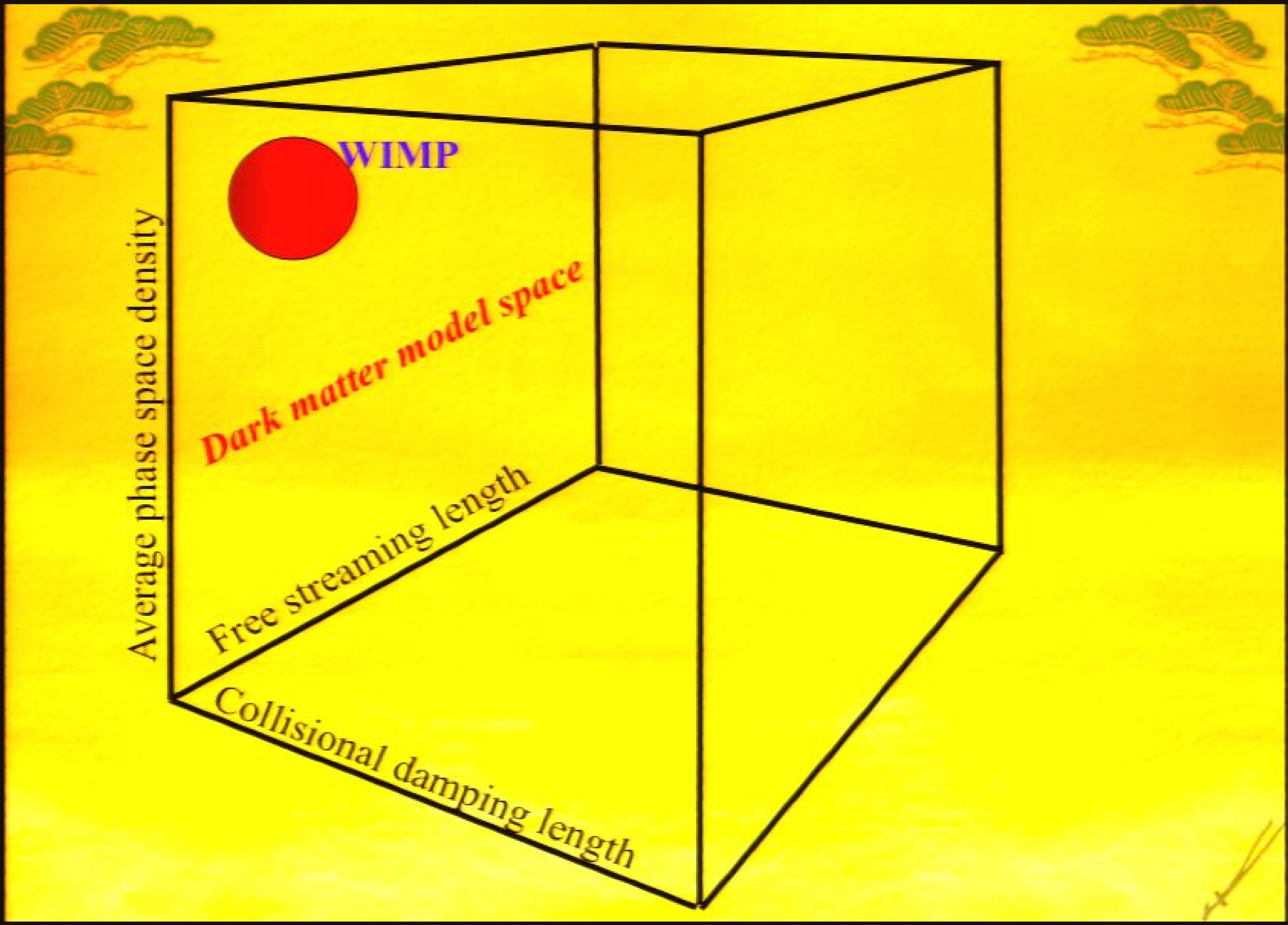

Dark matter model space
Average phase space density
Free streaming length
Collisional damping length


WIMP
Dark matter model space
Average phase space density
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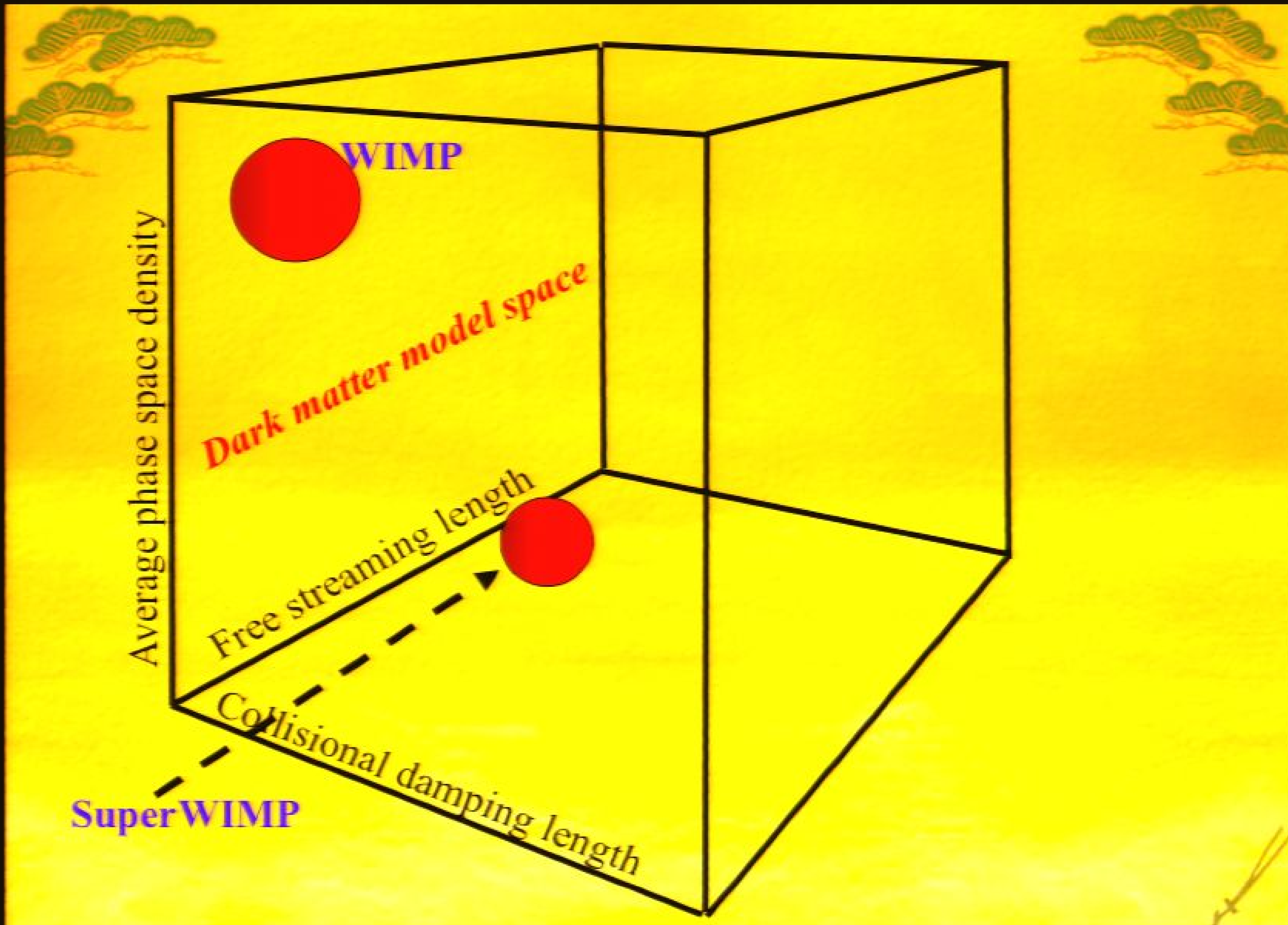
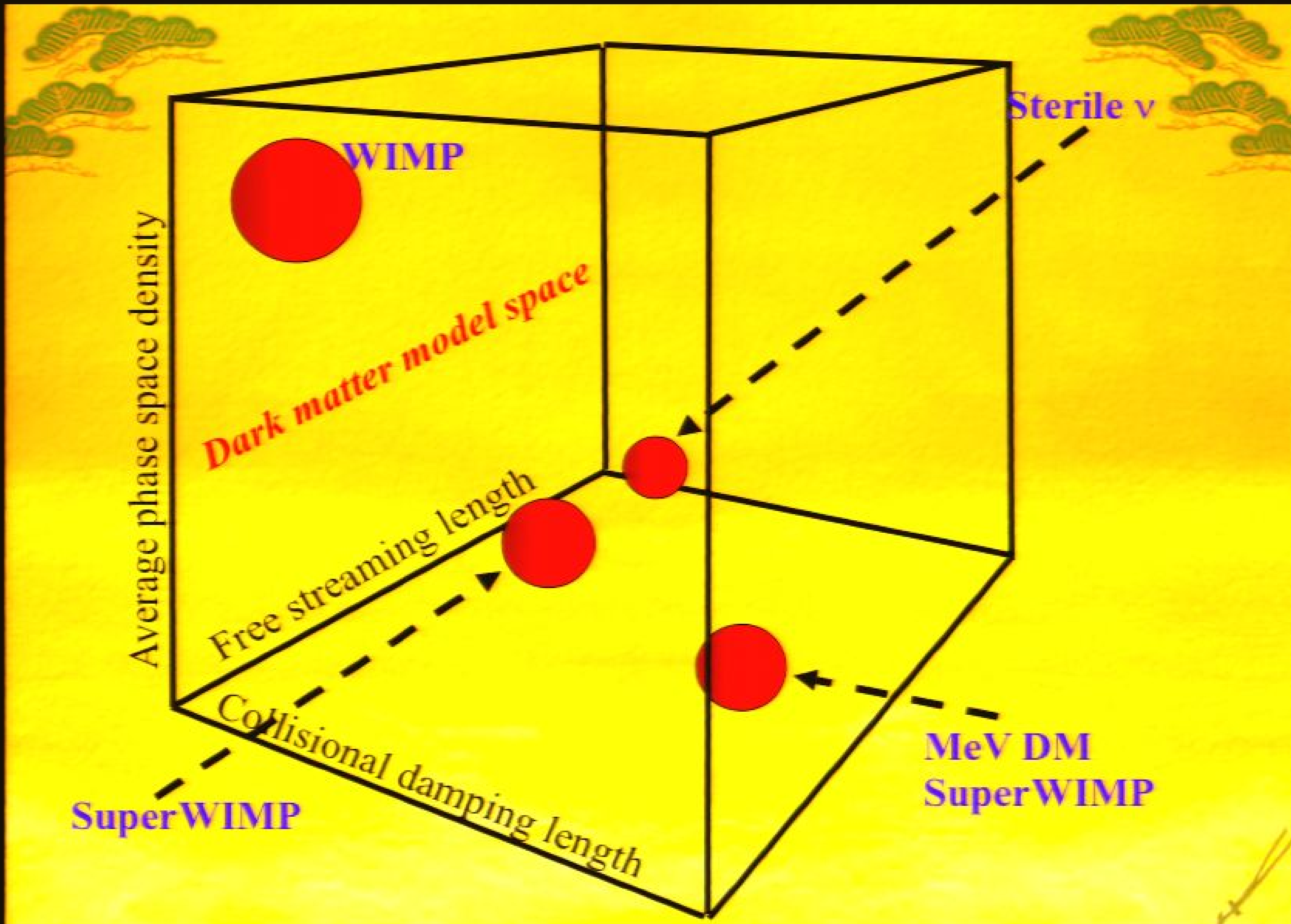

WIMP
Dark matter model space
Average phase space density
Free streaming length
Collisional damping length
SuperWIMP


Sterile ν
WIMP
Average phase space density
Dark matter model space
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 can 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 probably depends on the shape of the primordial momentum distribution function and not just on the average Q.

meta-CDM

Late decays will give rise to large phase space cores in dark matter halos while the power spectrum "looks like CDM"

Strigari, Kaplinghat and Bullock 2006

$$\begin{aligned} \mathrm{Free-streaming\quad scale} \quad &\propto \quad 1/Q^{1/3} \qquad (RD) \\ &\propto \quad 1/(Q\tau)^{1/3} \quad (MD) \end{aligned}$$

No free lunch though! Core size doesn't just depend on Q, but also on the primordial momentum distribution function.

Weak scale theories: warm to cold in SUSY

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

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)

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- 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

- Cosmology
  - Early Universe
    - Big Bang Nucleosynthesis
    - Cosmic Microwave Background black body
  - Late Universe
    - Small scale structure formation

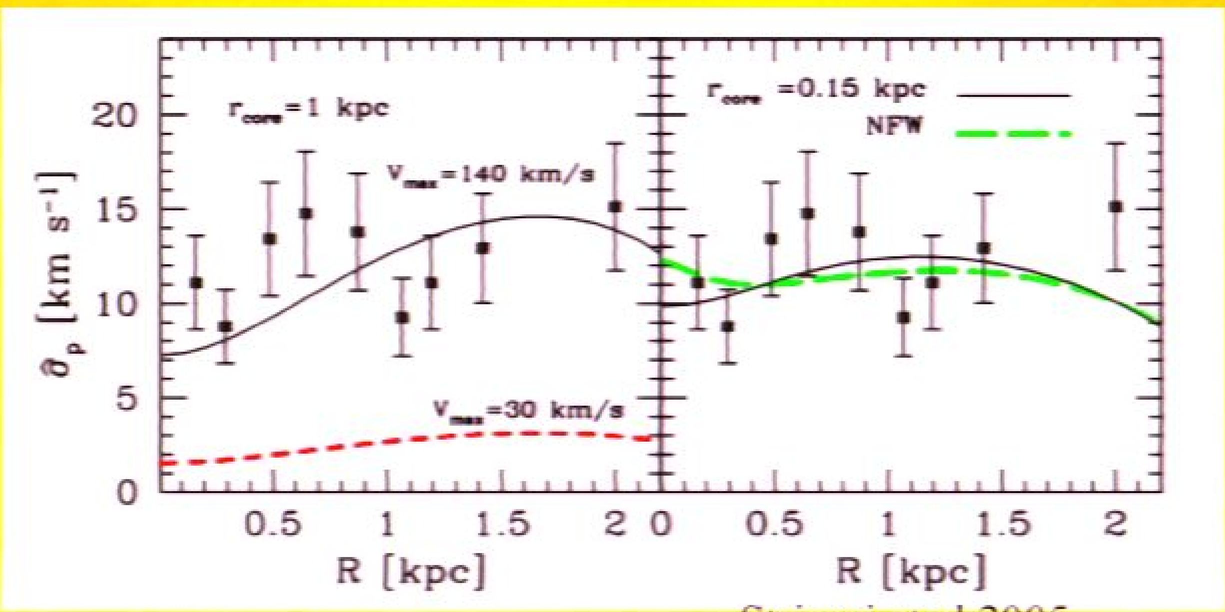
Testing the CDM paradigm

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
  - Census of dwarfs ("missing satellite problem")
    - Constrains power spectrum and Q
  - Measure the dark matter halo density profile
    - Constrains Q and power spectrum

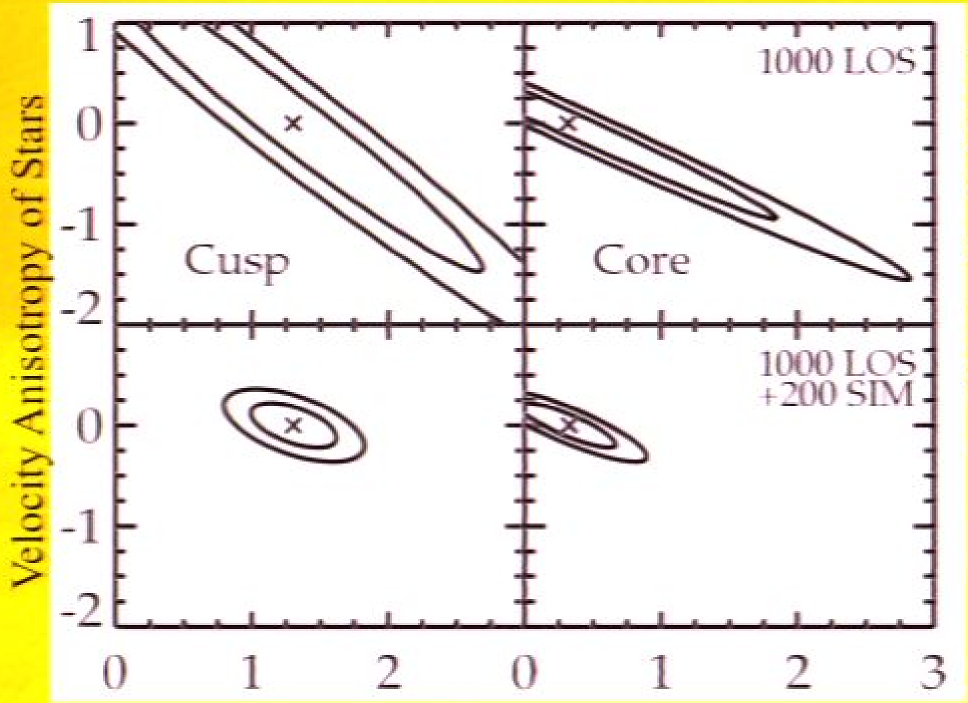
Measuring density profile: issues

Standard way to measure density profiles is to look at velocity dispersion of the stars in these dwarfs. Then fit to theory. However, there is a fundamental degeneracy with the velocity dispersion anisotropy of stars that prevents one from measuring the profile well.



Strigari et al 2005

Measuring Density Profile: solution

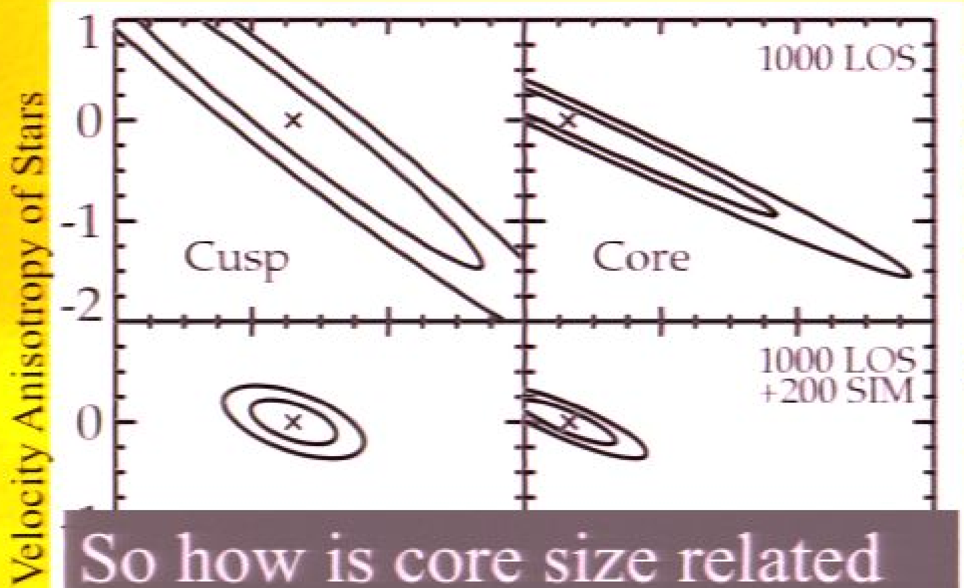


Log-slope of dark matter density profile

Strigari, Bullock and Kaplinghat, 2007

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

Measuring Density Profile: solution



So how is core size related to particle physics?

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Phase Space of Collisionless Systems

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  - 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]

Phase Space Constraint: DM from Decays

- For dark matter from decay –

$$f(v) \propto \frac{1}{v} \exp\left(-\frac{v^2}{v_0^2}\right)$$

Smaller the velocity earlier the decay

- 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"

Excess Mass Function

- Excess Mass function:
  - $D(f) \equiv \int_{F(x,v) > F} d^3x\, d^3v\, (F_c(x,v) - f)$
  - Mass in phase space cells with phase space density larger than f.
  - Mixing decreases D(f). Conserved otherwise.

Dehnen 2005

Mathur 1988

Tremaine, Henon, Lynden-Bell 1986

Mixing and Excess Mass Function

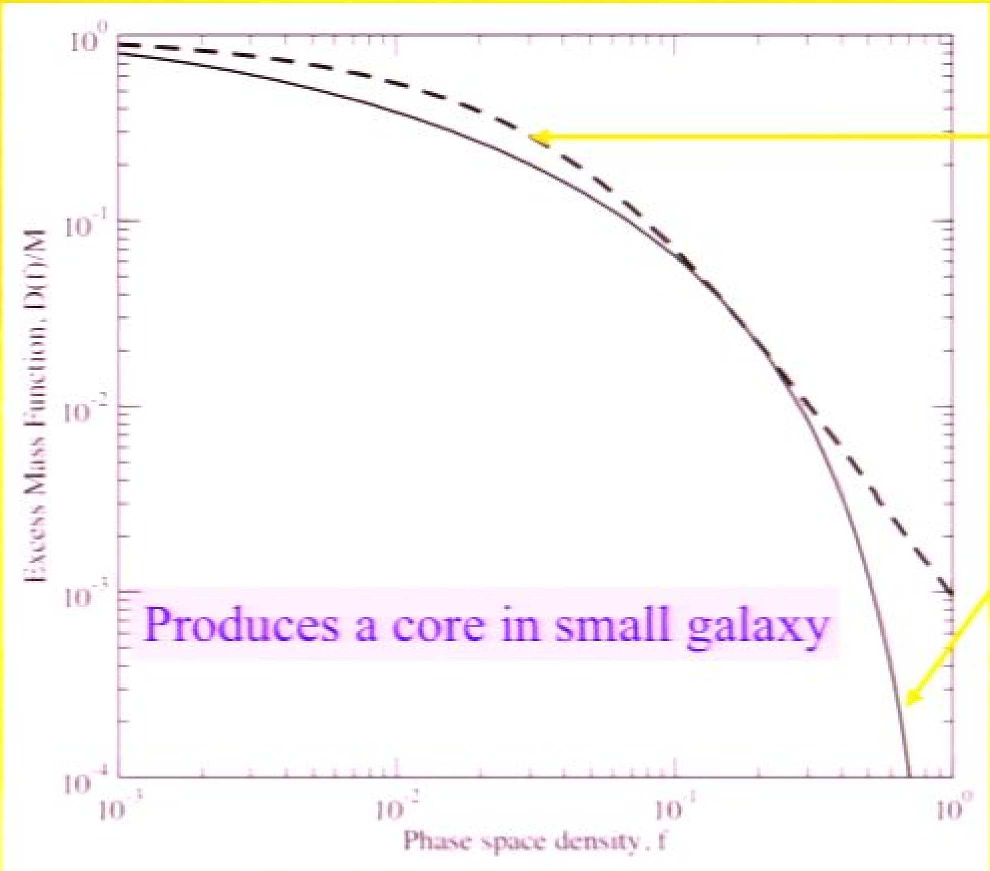
Green indicates $F_c(x,v) > f$ and orange indicates $F_c(x,v) < f$. When calculating D(f) only the green cells are counted.

Orange part not included in D(f) → Negative contribution from the orange part is included in D(f) → D(f) decreases

Entropy and Excess Mass Function

- Change in D(f) is related to change in entropy.
  - $\Delta S = -k_B \int_0^\infty \Delta D(f)\, df/f \geq 0$ for closed systems.
- The decrease of D(f) is a much stronger constraint.
- Gunn-Tremaine bound a special case

Constraints from the Excess Mass Function



For a distribution resulting from decays in the radiation dominated era.

For a halo with a uniform density core at the center

[Kaplinghat 2005]

Extended Gunn-Tremaine

- The arguments outlined provide not only a minimum measure of the core, but also the form of the density profile near the core.
- For thermal warm dark matter, the core must have an isotropic velocity dispersion and

$$\rho \sim 1 - (r/r_{\rm core})^2$$

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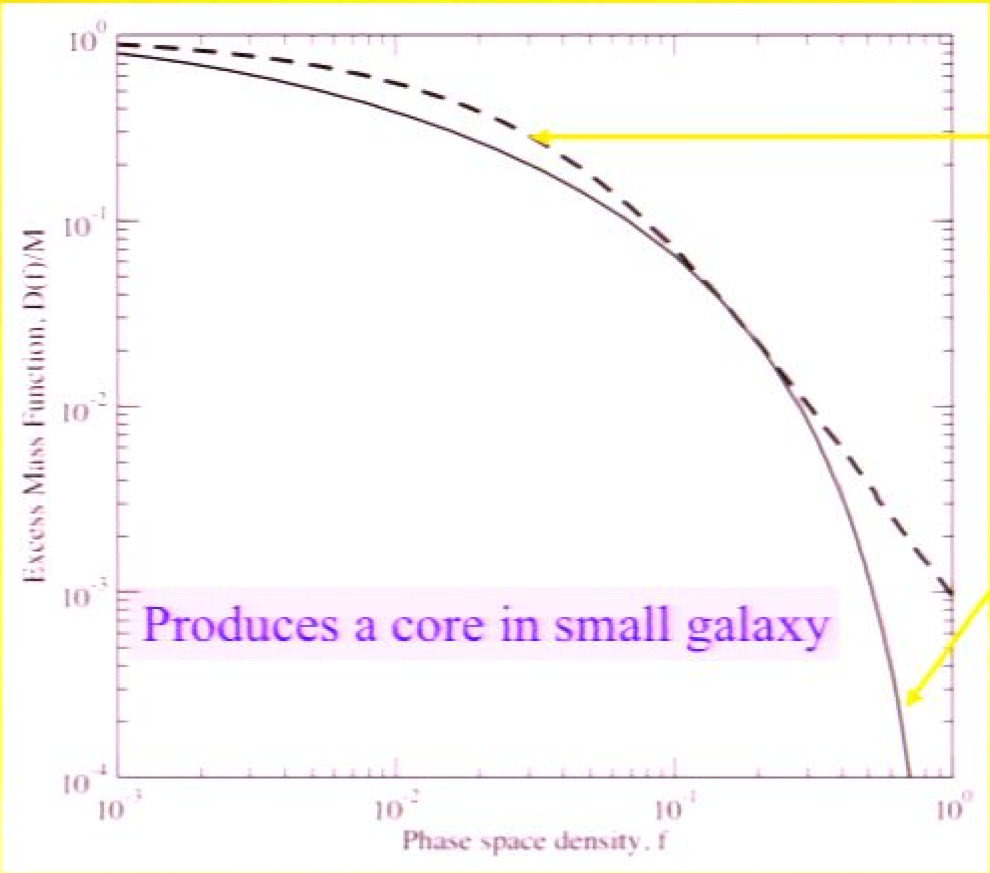

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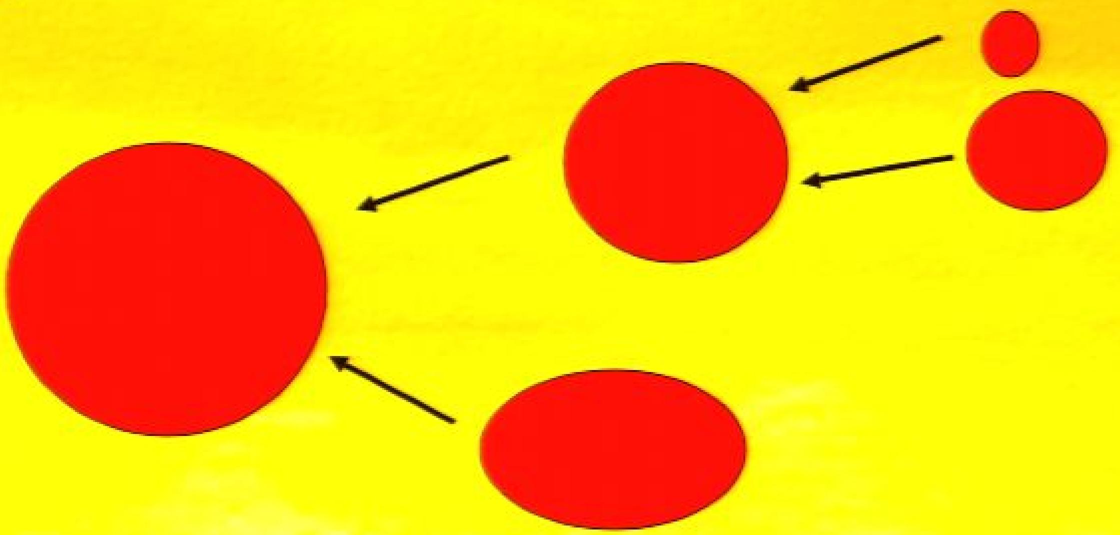
So what is the core size given a Q?

- This is a very hard question!
- The excess mass function (D(f)) argument only gives us the *minimum* size of the core.



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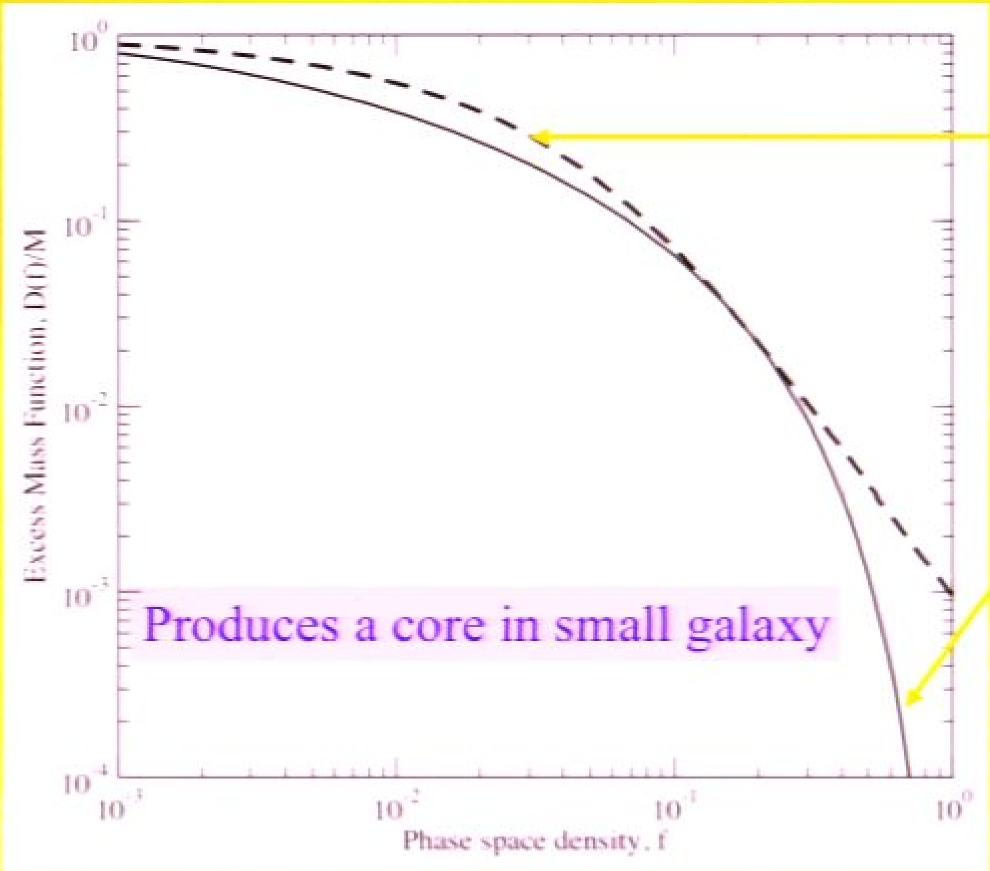

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What about baryons?

If the baryons dominate at the center after cooling, then the following applies.

$$\rho_{\rm core} \sim 1-(r/r_{\rm core})^{\delta}$$

$$\rho_{\rm cusp} \sim r^{-\alpha}$$

$$\rho_{\rm bary} \sim r^{-\alpha_b}$$

$$\delta_{\rm final} = \delta - \tfrac{1}{4}(\delta+3)\alpha_b \qquad ({\rm core} \rightarrow {\rm core})$$

$$\alpha_{\rm final} = \begin{cases} \tfrac{1}{4}(\delta+3)\alpha_b - \delta & ({\rm core} \rightarrow {\rm cusp}) \\ \alpha + \tfrac{3-\alpha}{4-\alpha}(\alpha_b-\alpha) & ({\rm cusp} \rightarrow {\rm cusp}). \end{cases}$$

Martinez and Kaplinghat, to appear soon

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Easily extended to the case of dark matter compressed by the presence of black holes

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No assumptions about adiabaticity.

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An aside related to density profile: Boost

Boost is not an arbitrary free parameter.

A self-similar hierarchy... $\Phi(M) = [1 + B(M, m_{\rm min})]\,\tilde{\Phi}(M)$

Depends on particle physics, early universe cosmology (including inflation) and late universe destruction

Strigari et al 2006

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$$\tilde{\Phi}(M) B(M, m_{\rm min}) =$$

$$A M^{\alpha} \int_{m_{\rm min}}^{qM} [1 + B(m, m_{\rm min})]\,\tilde{\Phi}(m)\,\frac{dm}{m^{1+\alpha}}$$

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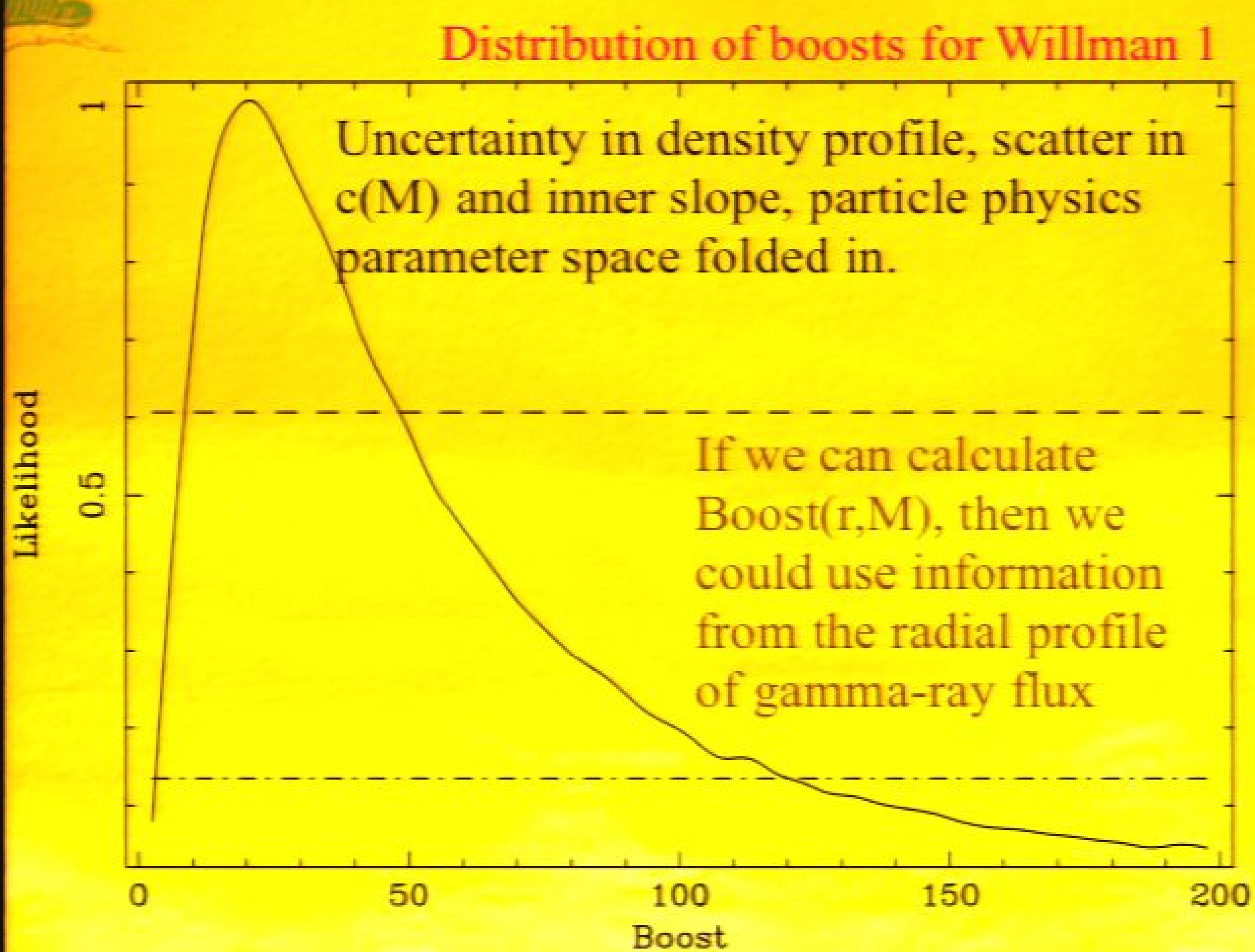
Strigari et al 2006

Can break the self-similar hypothesis and include minimum mass self-consistently in Markov Chain analysis.

Very preliminary, produced yesterday



27