

Title: Structure in the Phase Space and Dark Matter Astronomy

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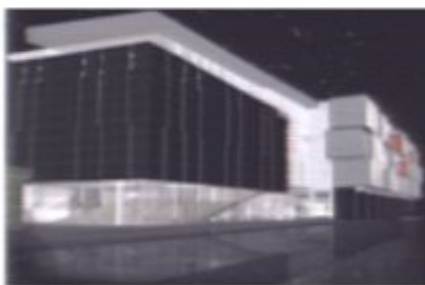
Abstract:




Unraveling Dark Matter
Perimeter Institute
September 23, 2011

Structure in the Phase Space and Dark Matter Astronomy

Niayesh Afshordi



PERIMETER  INSTITUTE FOR THEORETICAL PHYSICS

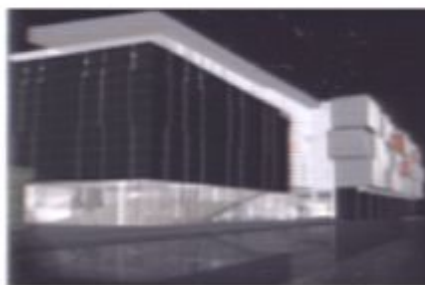




Unraveling Dark Matter
Perimeter Institute
September 23, 2011

**Triumph of
Modified Newtonian Dynamics
, and the *demise of*
Dark Matter paradigm**

Niayesh Afshordi



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Unraveling Dark Matter
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Structure in the Phase Space and Dark Matter Astronomy

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Outline

- Introduction: Cold Dark Matter (CDM)
- Why phase space of CDM haloes is hierarchical
- Bound Structures & CDM detection
- Future Prospects for dark matter astronomy

en.wikipedia.org/wiki/There_are_known_knowns

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Quoted from Persian literature

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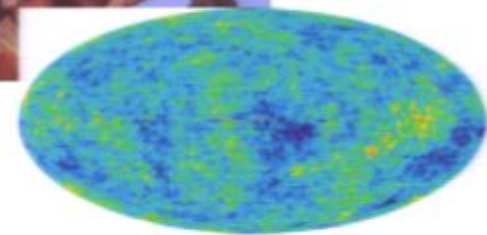
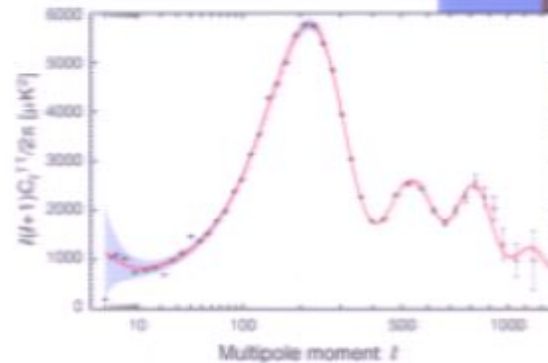
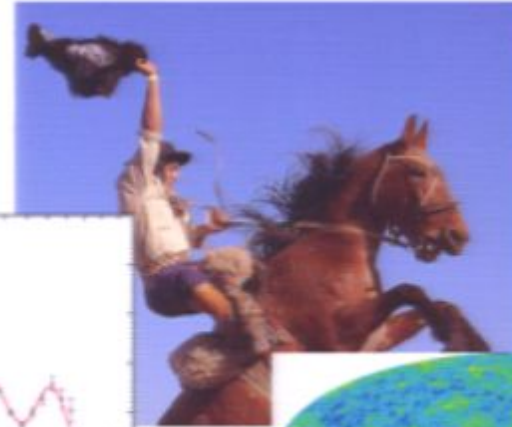
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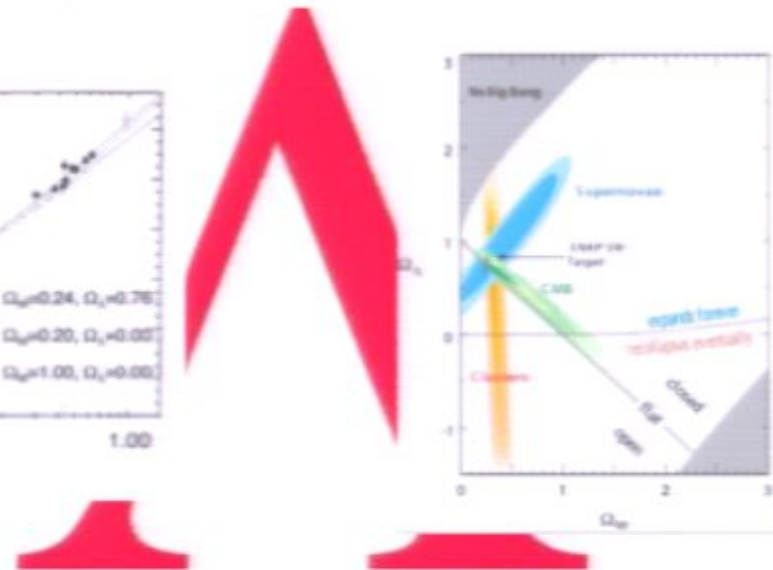
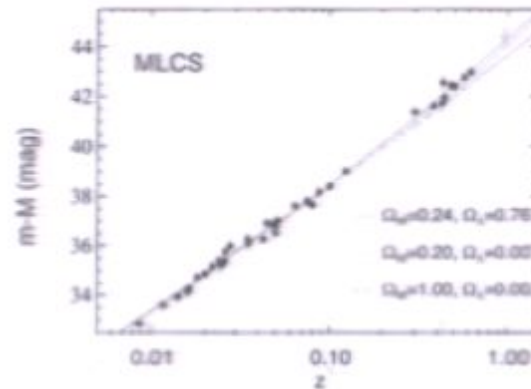
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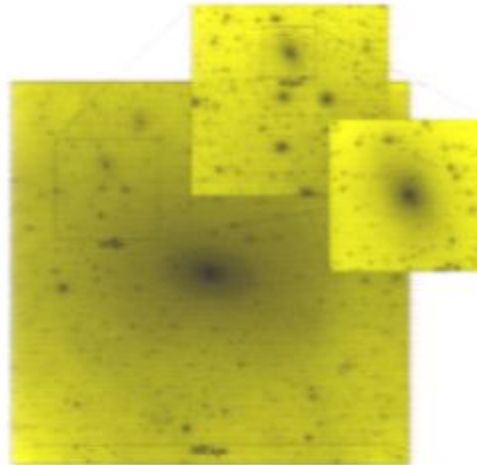
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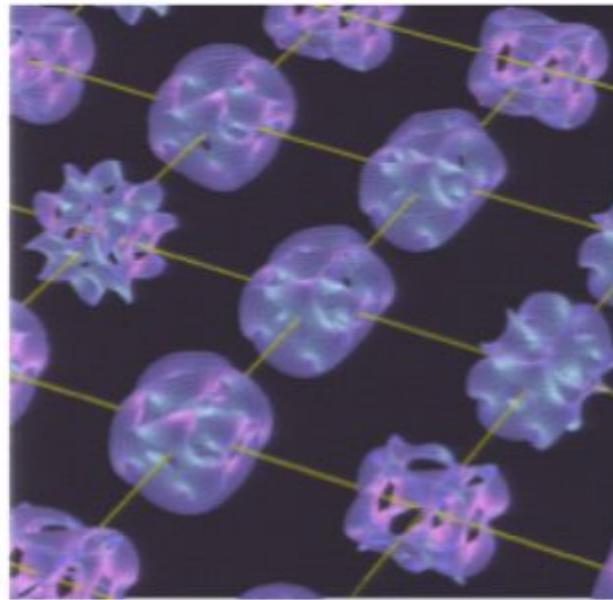
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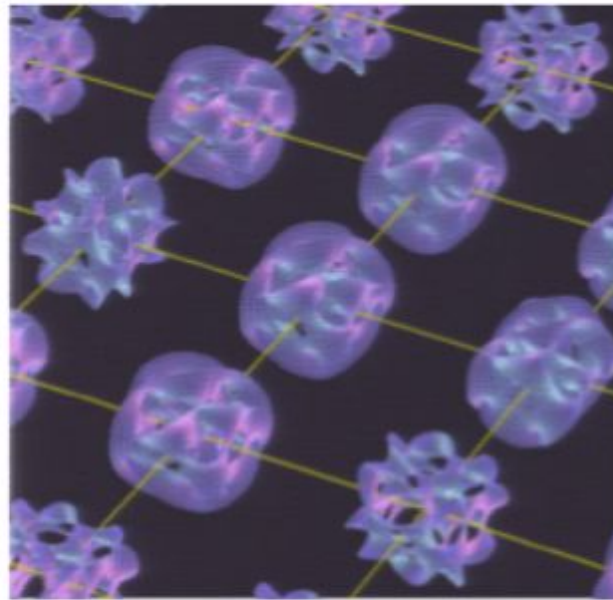
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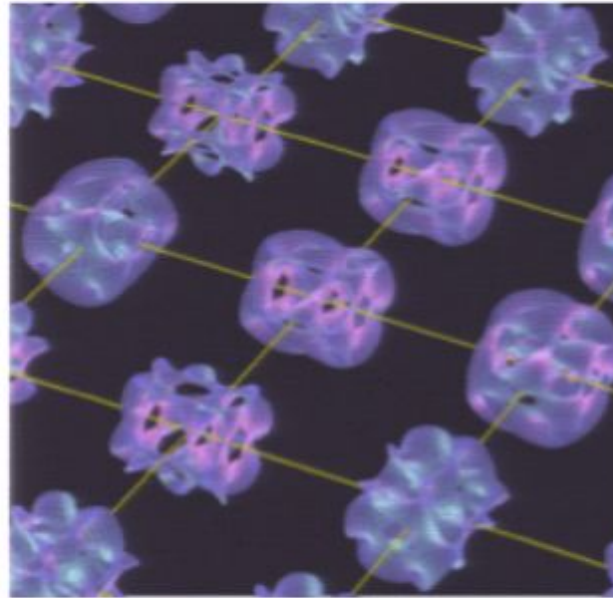
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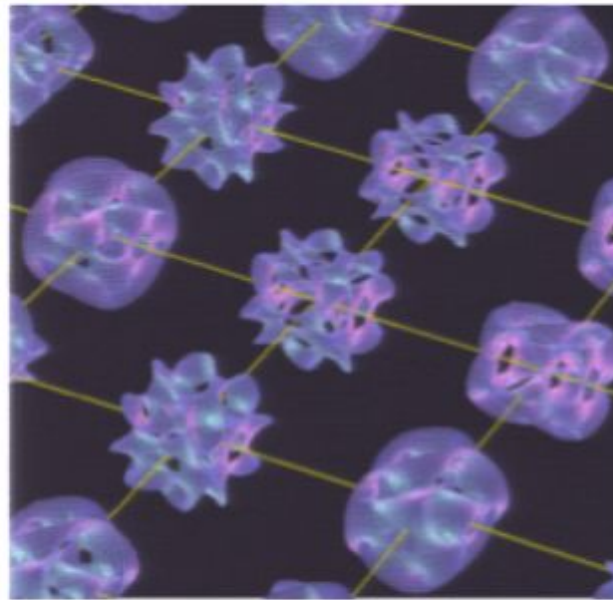
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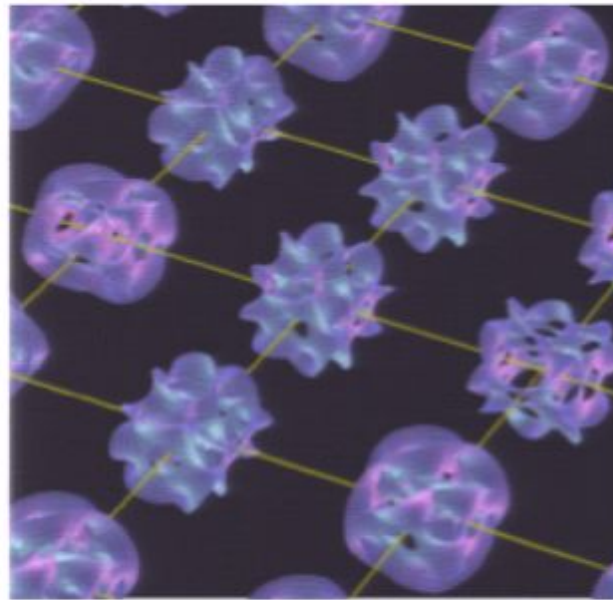
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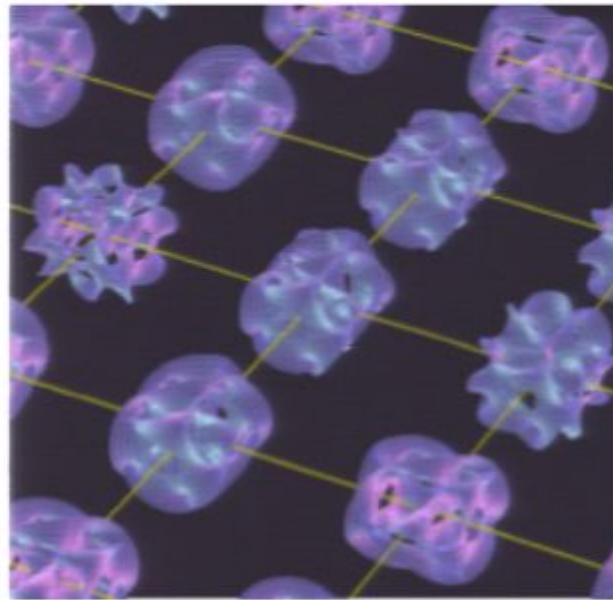
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Collaborators

- Roya Mohayaee (IAP, Paris)
- Ed Bertschinger (MIT)
- **Shant Baghram (Sharif U, Tehran → U-Waterloo)**
- Kathryn Zurek (U-Michigan)
- **Farbod Kamiab (U-Waterloo)**



- Hierarchical Phase Space Structure of Dark Matter Haloes: Tidal debris, Caustics, and Dark Matter annihilation (*NA, Mohayaee, Bertschinger*): [Phys.Rev.D79:083526,2009](#)
- Hierarchy in the Phase Space and Dark Matter Astronomy (*NA, Mohayaee, Bertschinger*): [Phys.Rev.D81:101301, 2010](#)
- Prospects for Detecting Dark Matter Halo Substructure with Pulsar Timing (*Baghram, NA, Zurek*): [Phys.Rev.D84:043511,2011](#)

Outline

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Dark Matter is Collisionless

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- Bullet Cluster

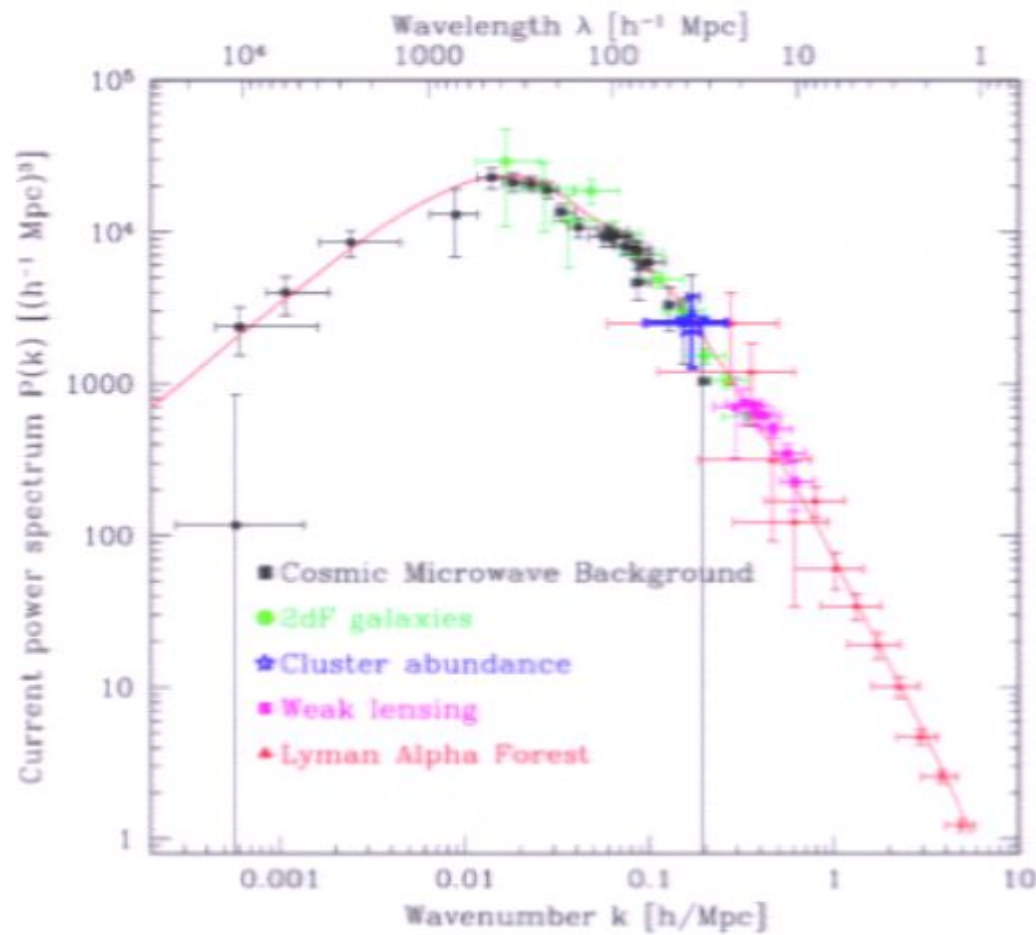


Baryons (X-ray)

Matter (lensing)

Dark Matter is Cold

Dark Matter is Cold



Indirect Detection

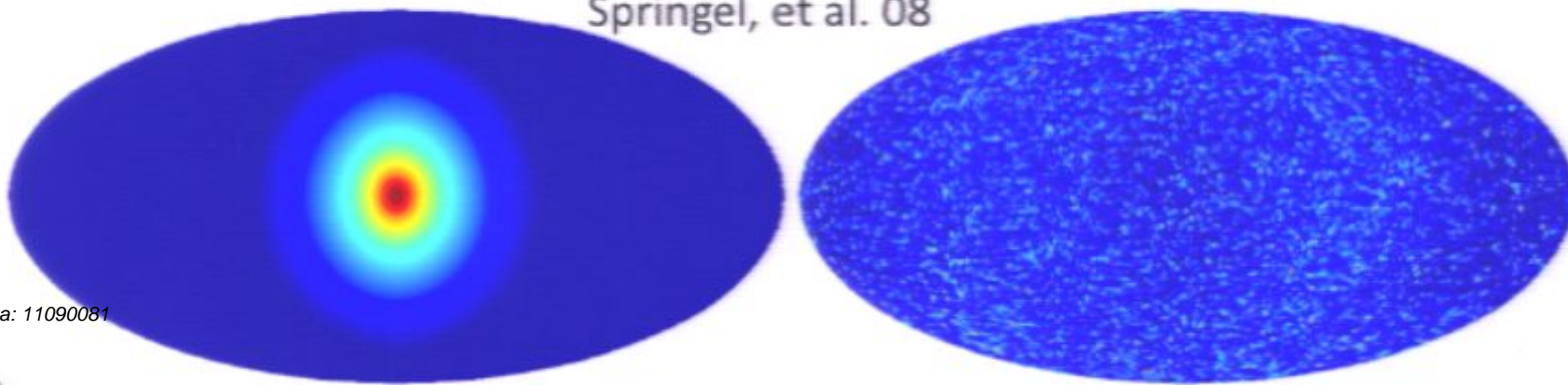
- Dark Matter can annihilate to
 - photons (*Fermi*)
 - electrons/positrons (*PAMELA/Fermi/WMAP...Planck*)
 - Neutrinos (*IceCube*)

$$\frac{dL_i}{dE_i} = \frac{\langle \sigma_{\text{ann}} v \rangle E_i}{2m_\chi^2} \frac{dB_i}{dE_i} \Phi \quad \Phi \equiv \int \rho^2(\mathbf{x}) d^3\mathbf{x}$$

smooth main halo emission (MainSm)

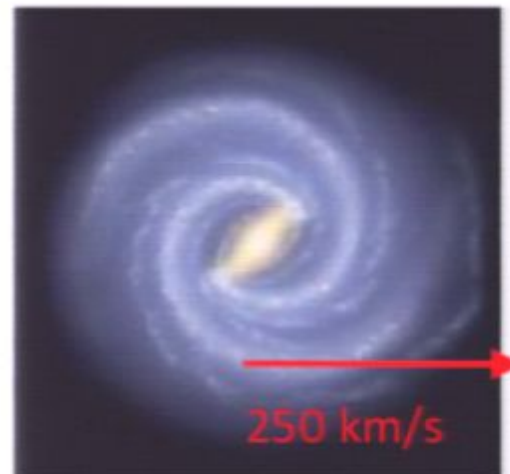
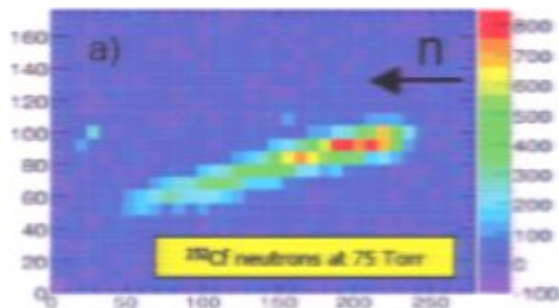
emission from resolved subhalos (SubSm+SubSub)

Springel, et al. 08



Directional DM detection

- Solar system is moving towards the Cygnus constellation in the Milky Way, at 250 km/s
- We should see a **DM wind coming from Cygnus**, which distinguishes it from any other background



WIMPs: from gravity to detection

- Gravitational evidence for DM comes from potential:
 $\int d^3x \rho(x)/|x-x'|$

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(e.g., Stiff, Widrow, & Frieman 2001)

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Hierarchy in the Phase space

- CDM is **really cold**
 - $\delta v_{\text{CDM}} \sim 10^{-11}c$

$$\begin{aligned} \langle \delta v_{\text{CDM}}^2 \rangle &\simeq \frac{3T_{D\chi}}{m_\chi} \left(\frac{T_{\text{CMB}}}{T_{D\chi}} \right)^2 \\ &\simeq (0.07 \text{ cm/s})^2 (1+z)^2 m_\chi^{-2} (\text{GeV}), \end{aligned}$$

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- At CDM freeze out:

$$f_{\text{CDM}} \sim (\bar{\rho}_{\text{CDM}}/m_\chi) \delta v_{\text{CDM}}^{-3} \sim 10^{-2} m_\chi^2 (\text{GeV}) (\text{cm/s})^{-3} (\text{cm})^{-3}$$

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- Within our Galaxy:

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!!??

Hierarchy in the Phase space

- CDM is **really cold**

- $\delta v_{\text{CDM}} \sim 10^{-11} \text{c}$

$$\langle \delta v_{\text{CDM}}^2 \rangle \simeq \frac{3T_{D\chi}}{m_\chi} \left(\frac{T_{\text{CMB}}}{T_{D\chi}} \right)^2$$

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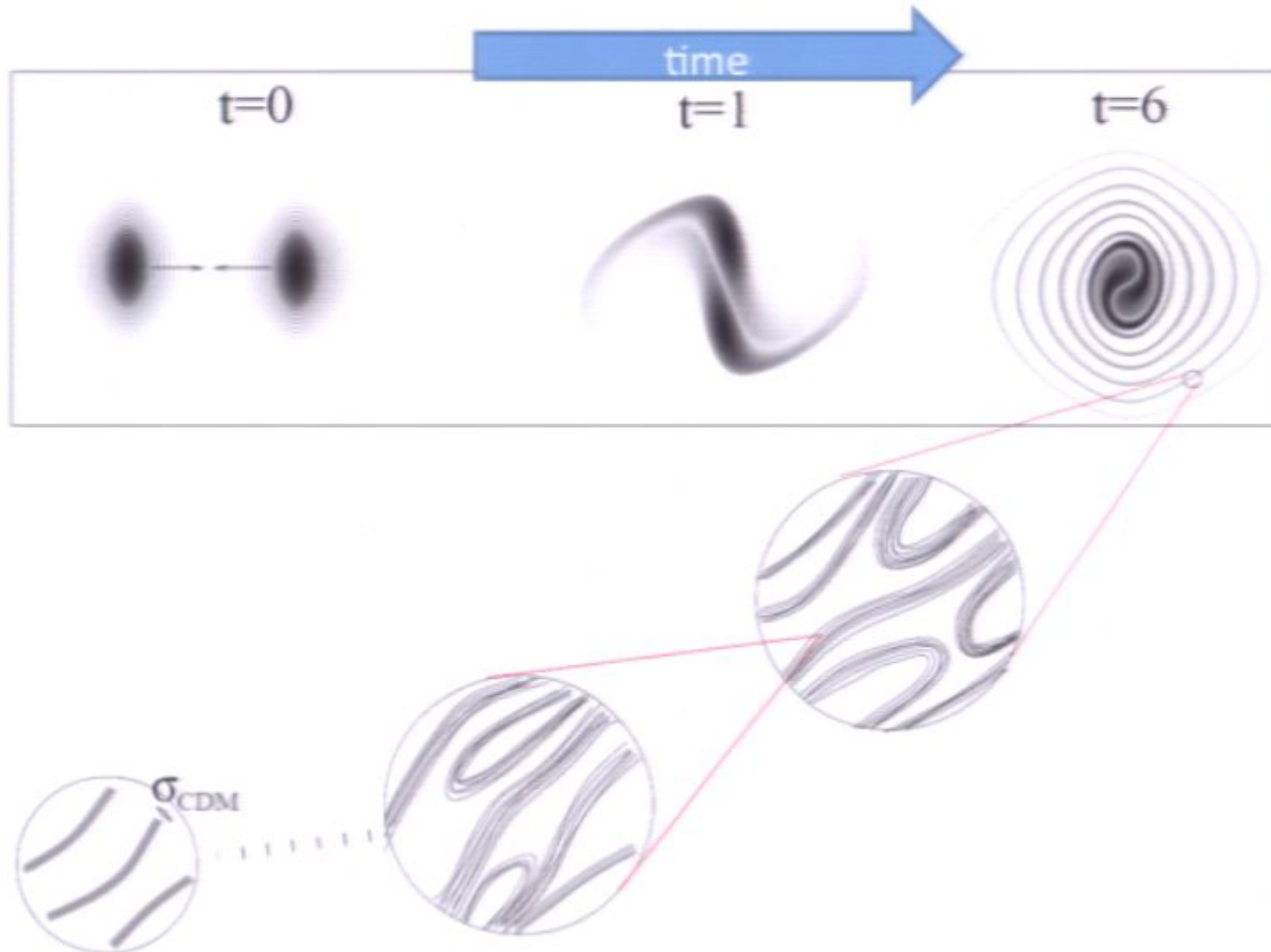
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→ Structures on all scales

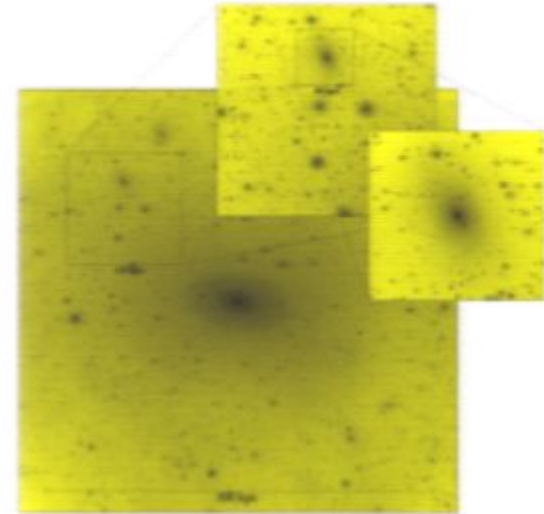
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Hierarchical Micro-Structure of the Phase Space



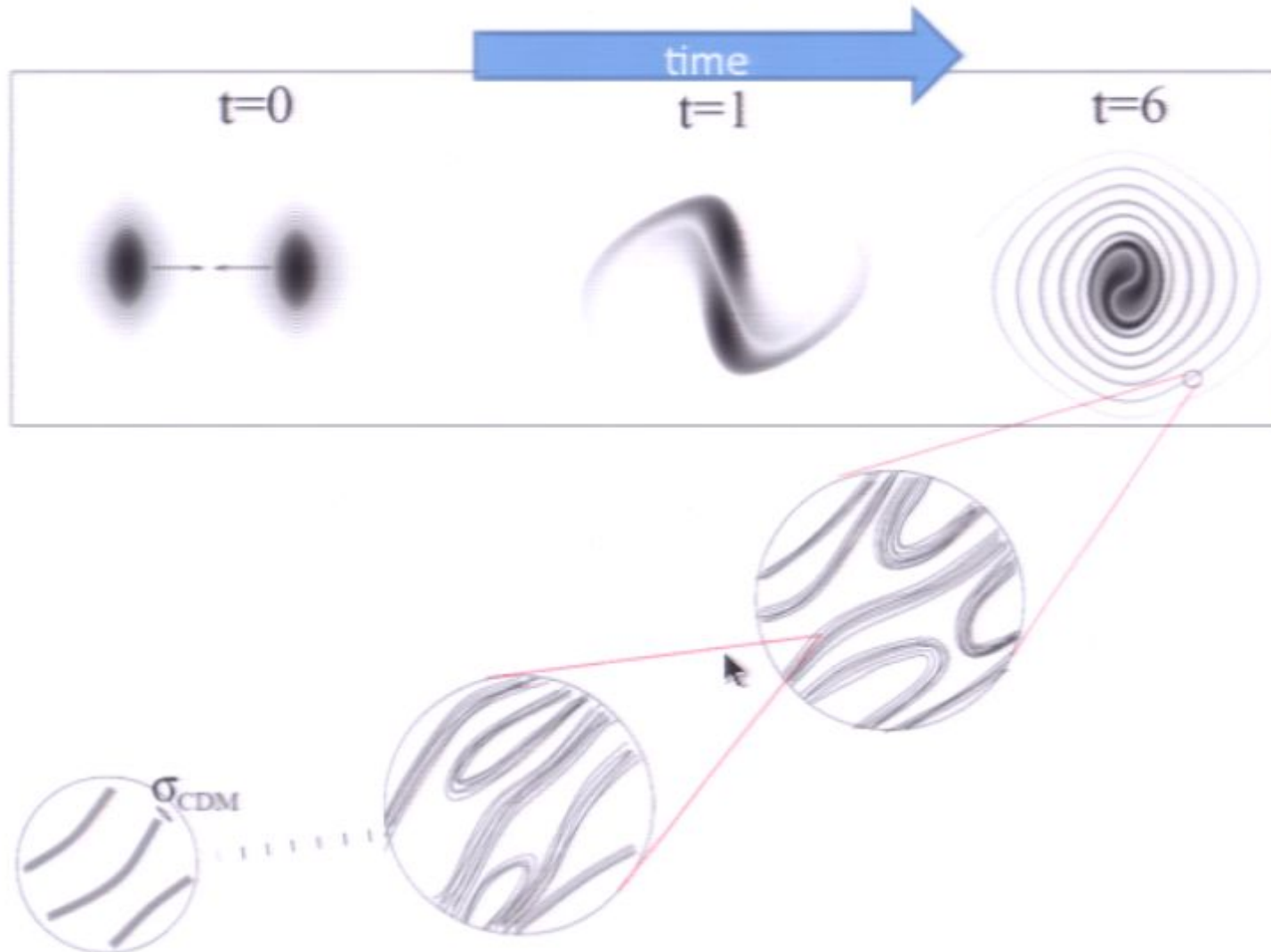
Three types of phase structures

- Bound sub-haloes (cluster in real/phase space)



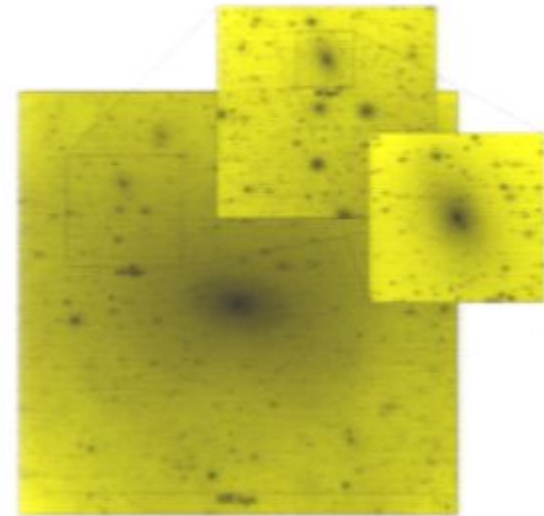
Kuhlen, Diemand, et al.

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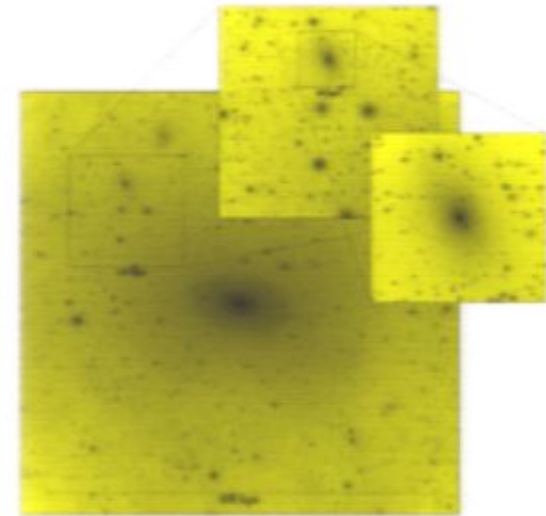
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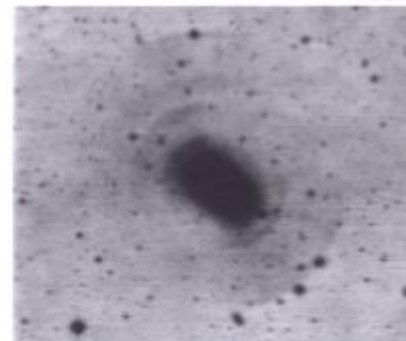
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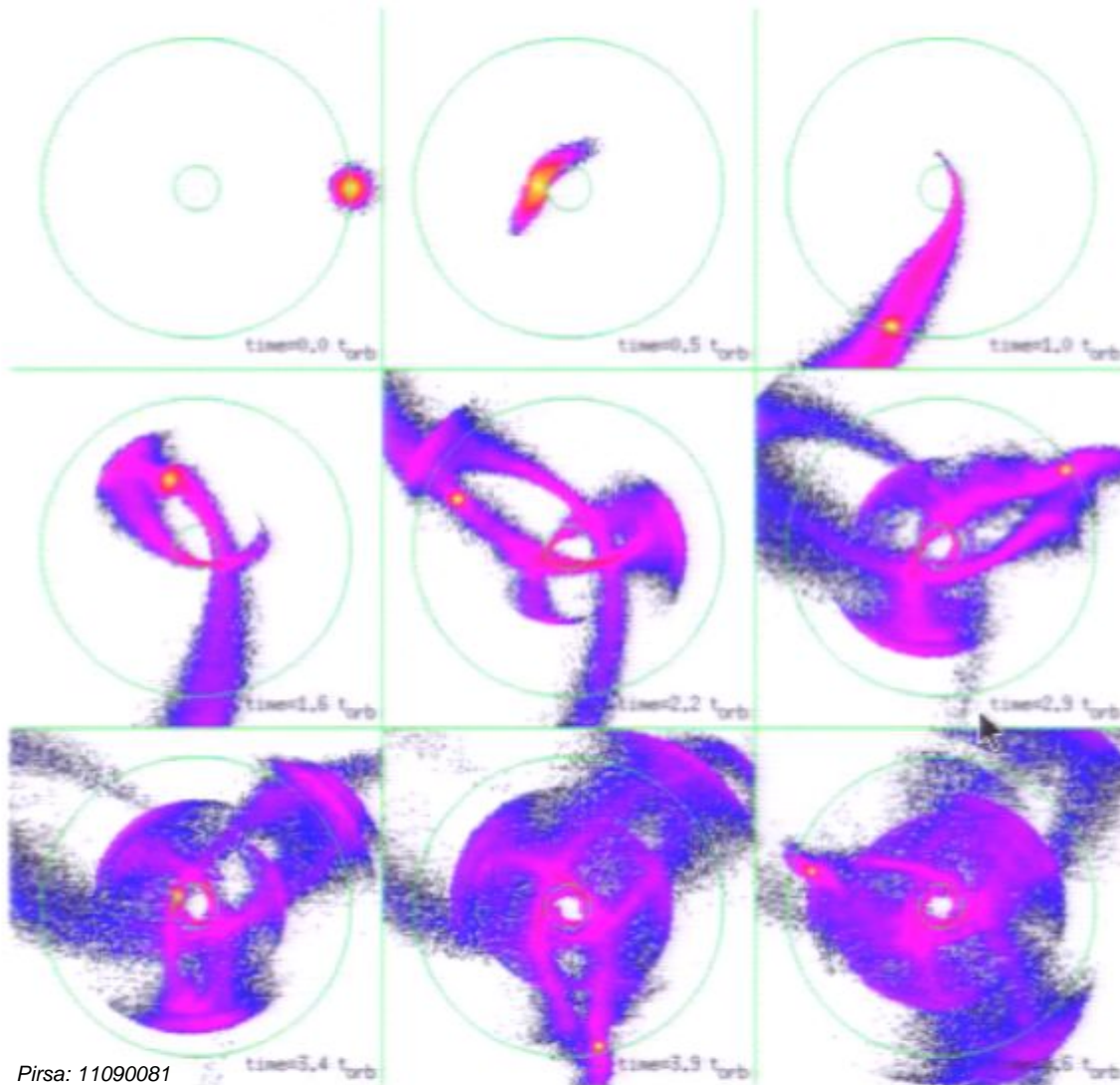


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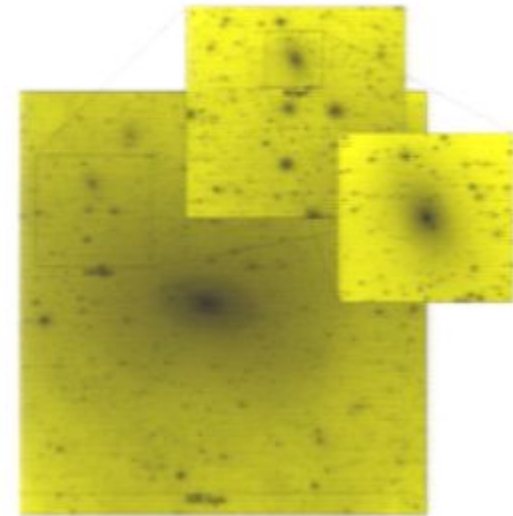


NGC 3923

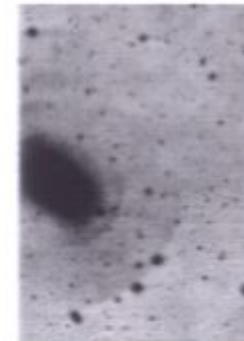
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Pirsa: 11090081



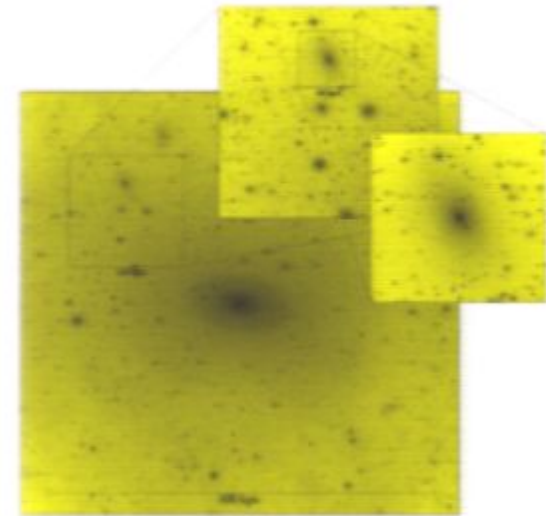
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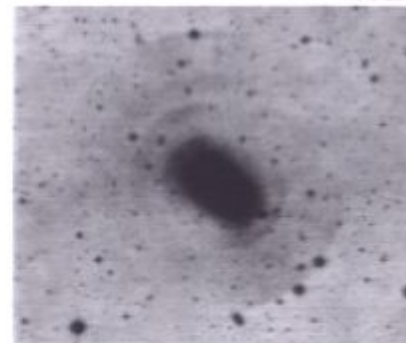
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Three types of phase structures

- Bound sub-haloes (cluster in real/phase space)
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- Fundamental discreteness



Kuhlen, Diemand, et al.



NGC 3923

→ *analogous to galaxy shot noise*

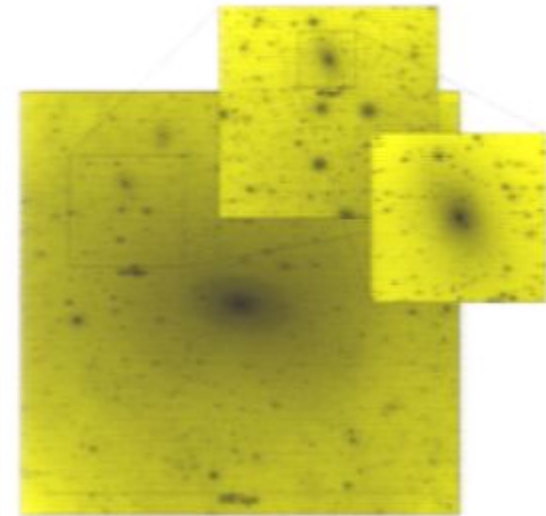
(NA, Mohayaee, Bertschinger 2009; Vogelsberger & White

2011)

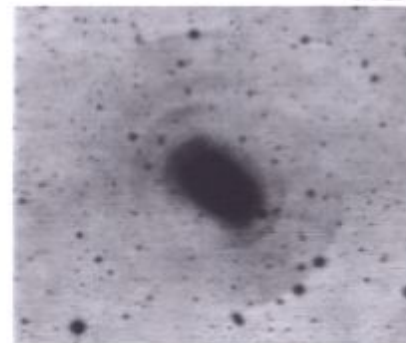
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Kuhlen, Diemand, et al.



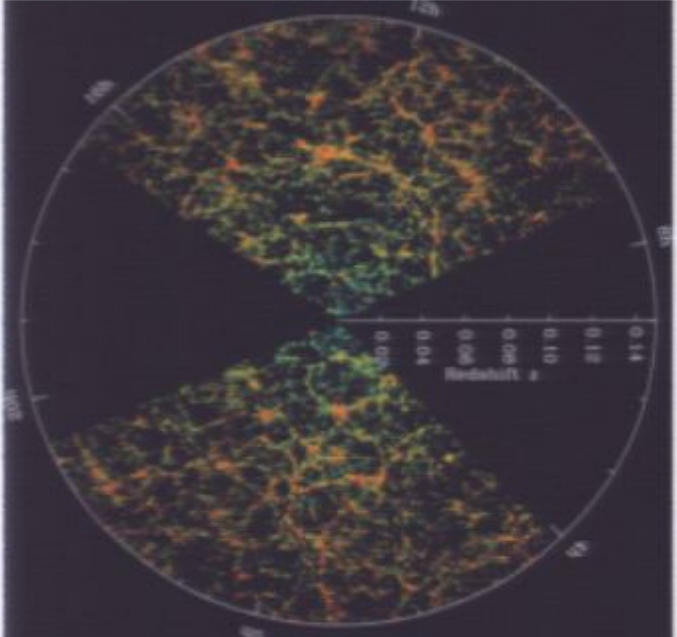
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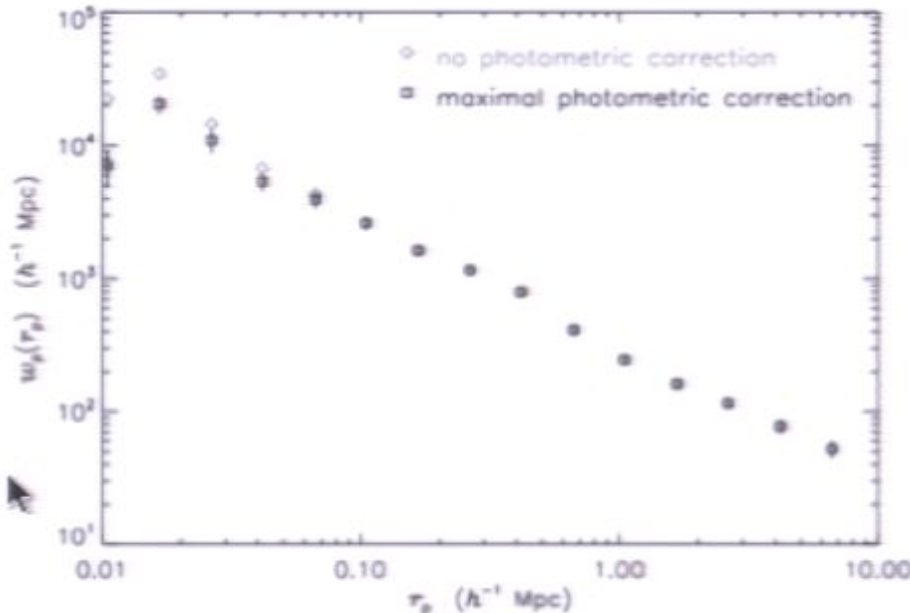
Correlation Functions quantify Hierarchy

- Large Scale Structure



SDSS

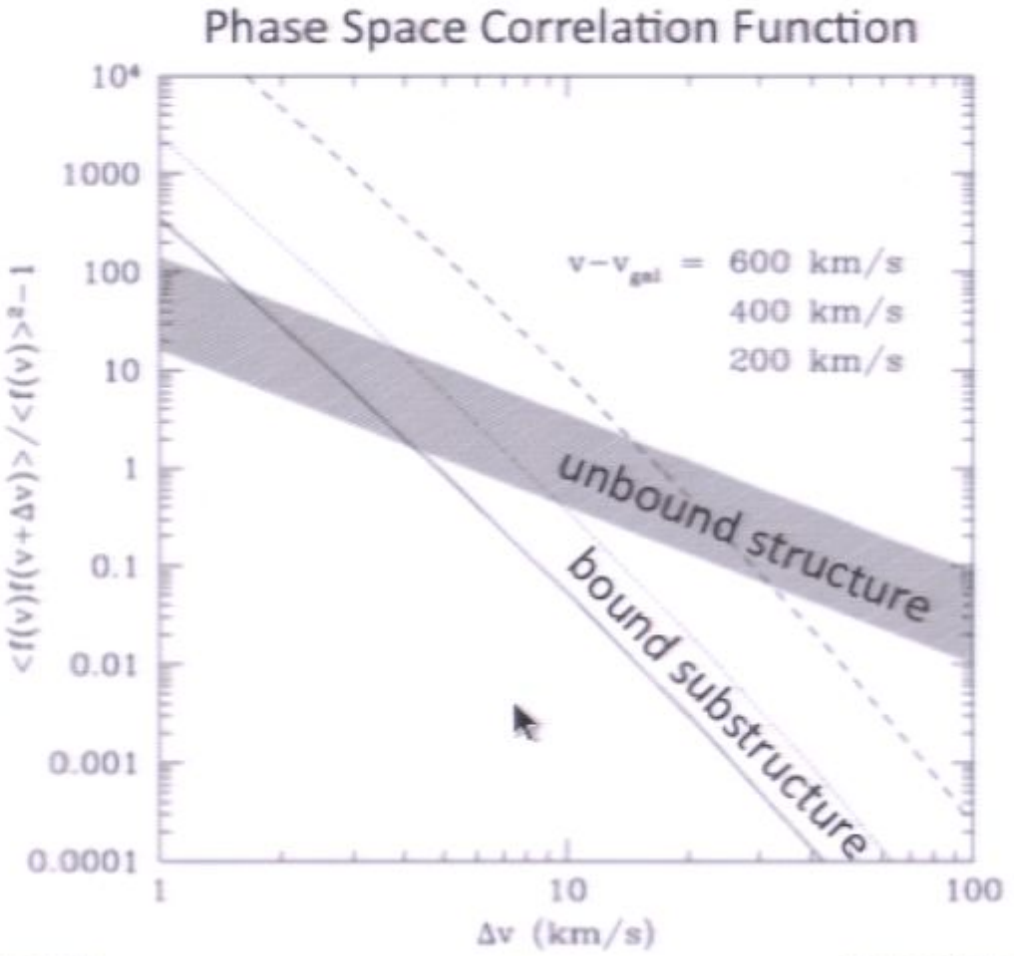
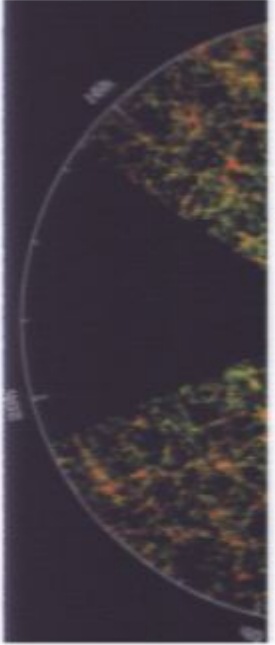
- Projected Correlation Function



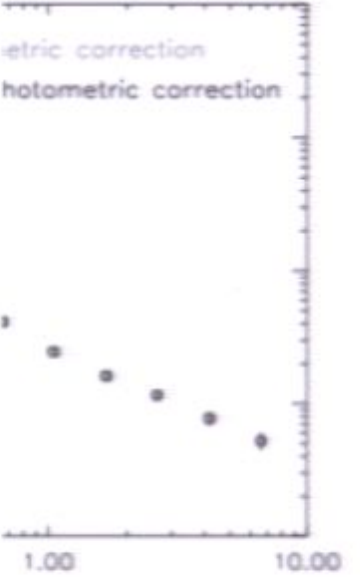
Masjedi, et al.

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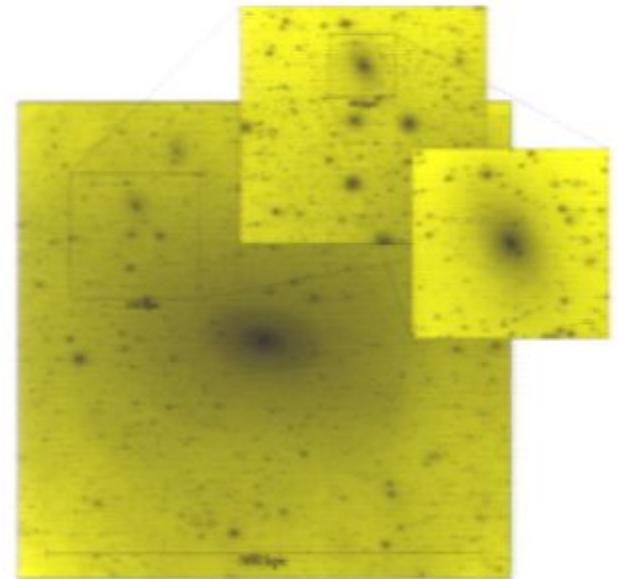


van der Marel, et al.

Outline

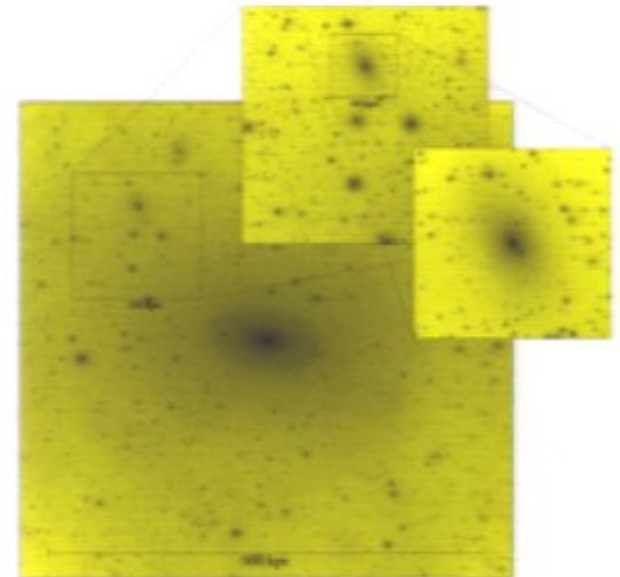
- Introduction: Cold Dark Matter (CDM)
- Why phase space of CDM haloes is hierarchical
- Bound Structures & CDM detection
- Future Prospects for dark matter astronomy

Bound Substructures



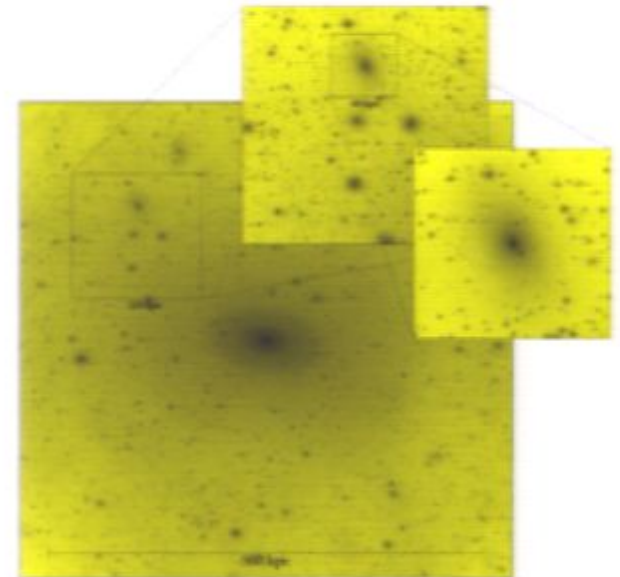
Bound Substructures

- Small sub-haloes become resilient to tidal stripping



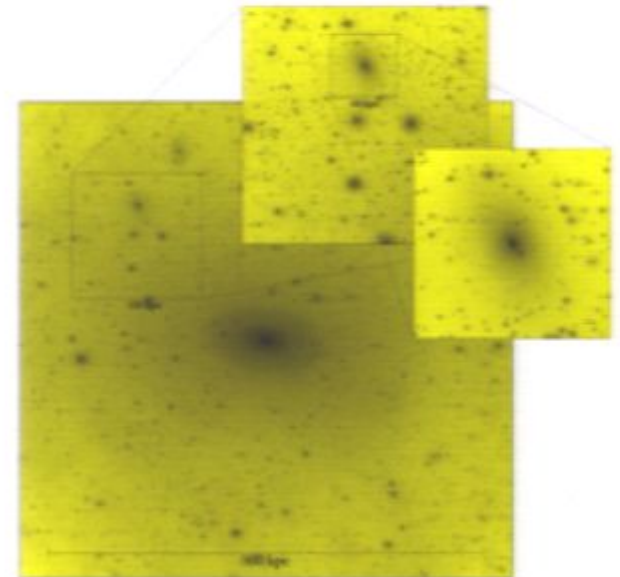
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of pairs at small physical separation remains constant (*Davis & Peebles 77*)



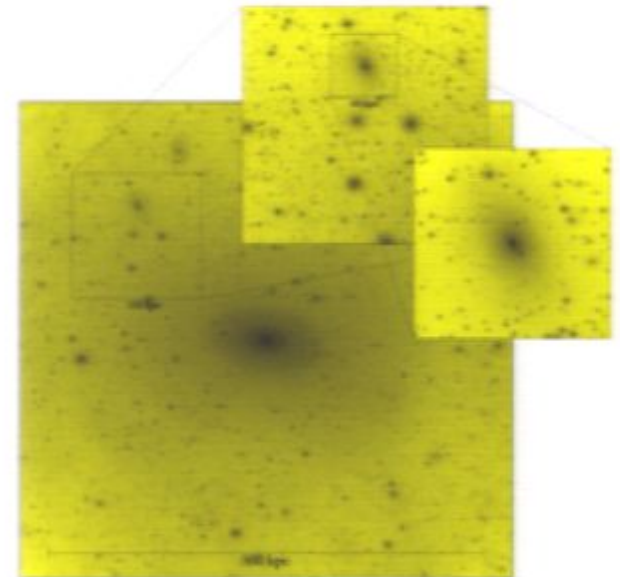
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Bound Substructures

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- Stable clustering hypothesis:
of pairs at small physical separation remains constant (*Davis & Peebles 77*)
- We extend this to the phase space
- Unlike the halo model, captures the **full hierarchy**: sub-haloes, sub-sub-haloes, etc. (*also much fewer parameters*)



Why Stable Clustering?

- Tidal Forces can only do **finite work** on tightly bound objects:

$$|\Delta v_i| < |\Delta x_i \int dt (\partial_i \partial_j \phi)| \lesssim |\Delta x_i| \int dt \nabla^2 \phi$$

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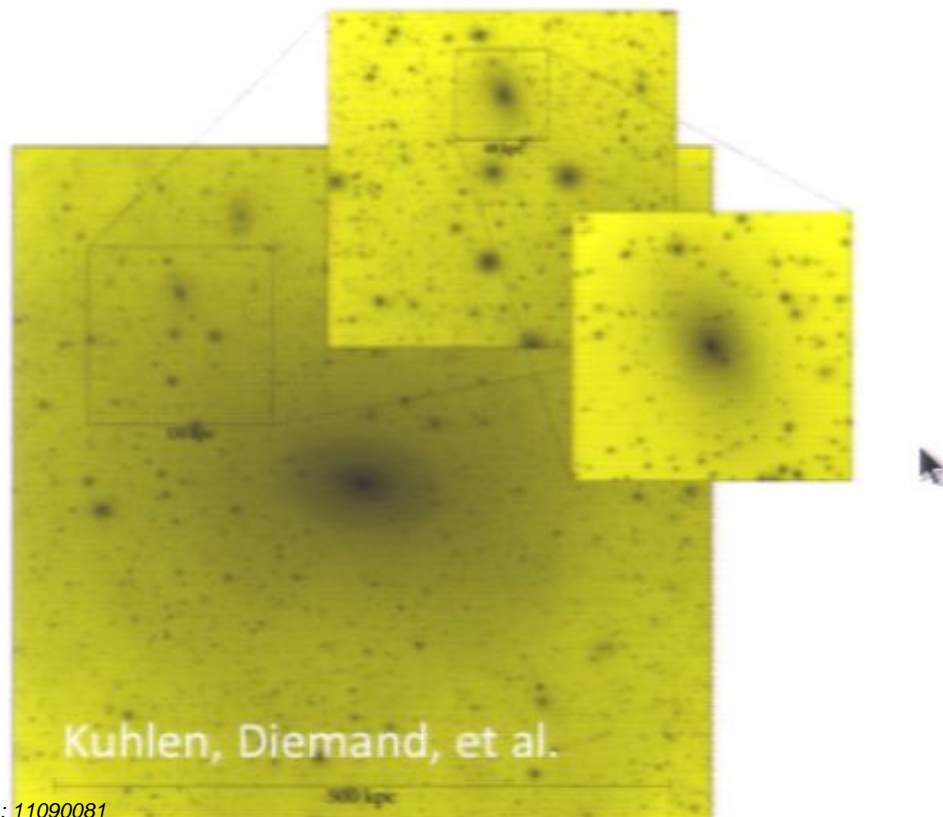
$$\frac{\partial f(E)}{\partial t} + \dot{E} \frac{\partial f(E)}{\partial E} = ??$$

in progress, with Farbod Kamiab



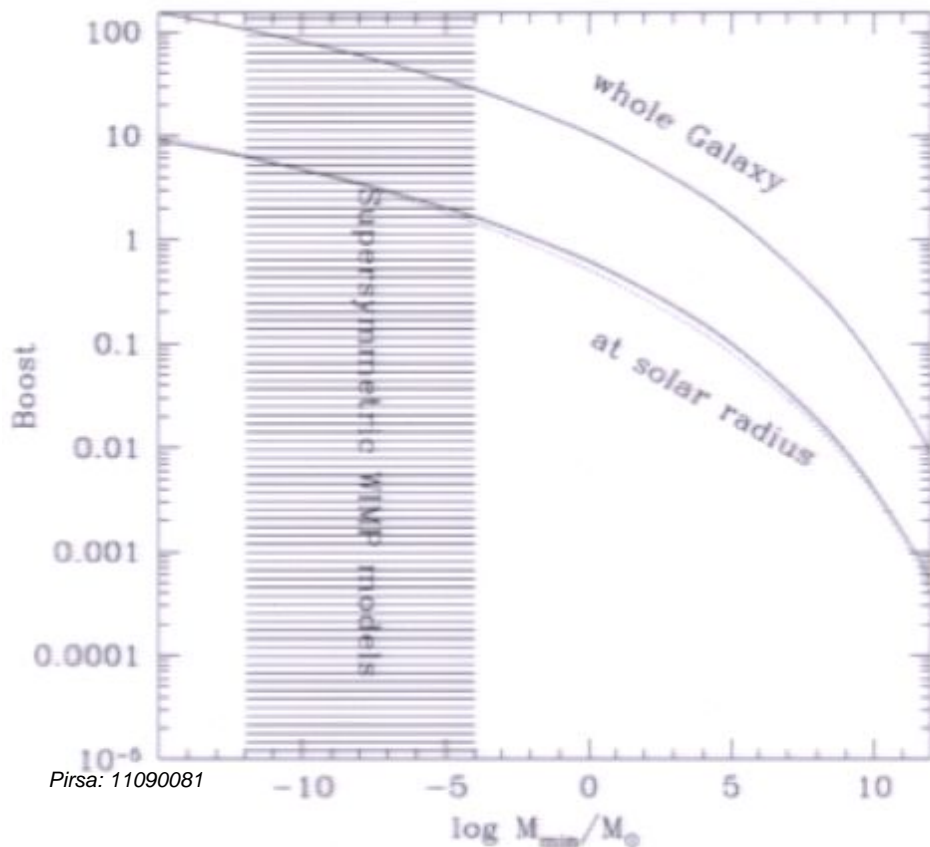
sub-haloes and stable clustering

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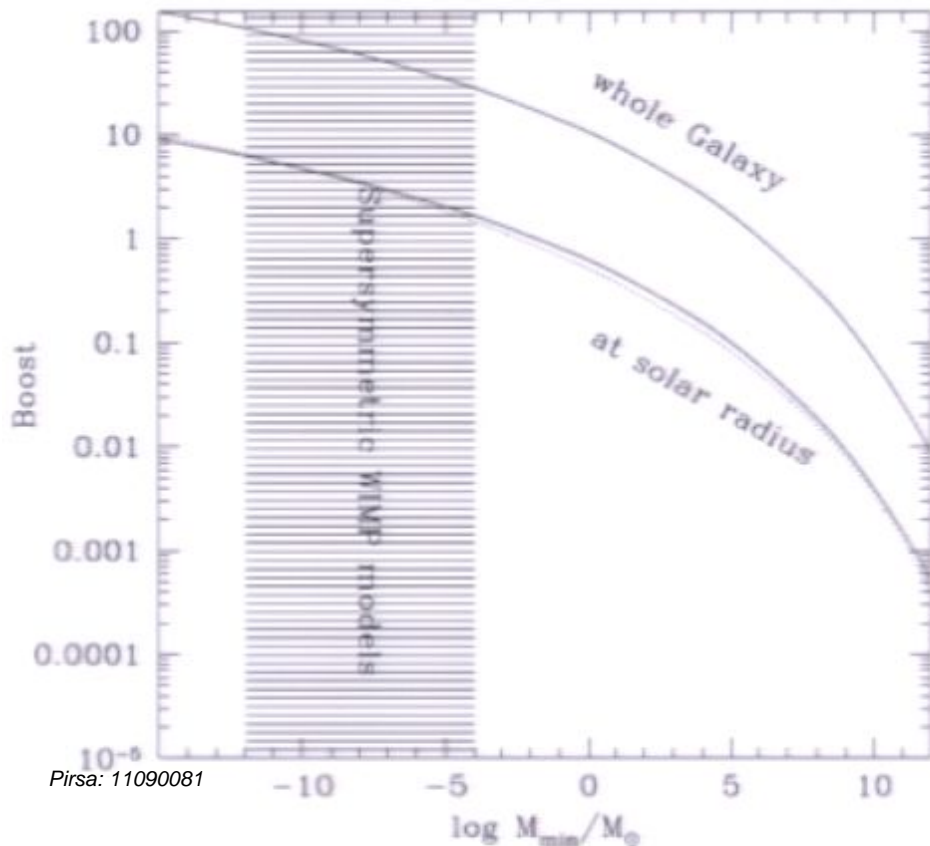
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NA, et al. 2010

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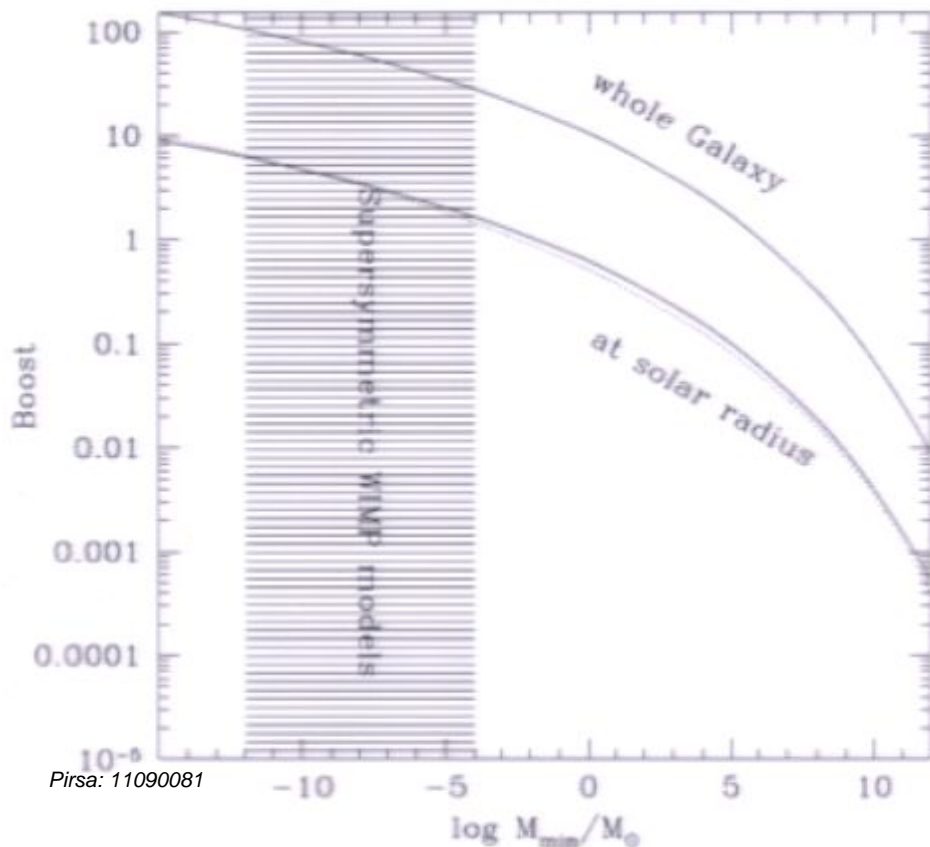


$$\mu \frac{8\pi^{1/2}}{9\delta_c^3} \left(\frac{\rho_{\text{halo}}(\mathbf{x})}{200\rho_{\text{crit},0}} \right)^{-1} \int_{M_{\min}}^{M_{\max}} M^{-2} d[M^2\sigma^3(M)]$$

NA, et al. 2010

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Pirsa: 11090081

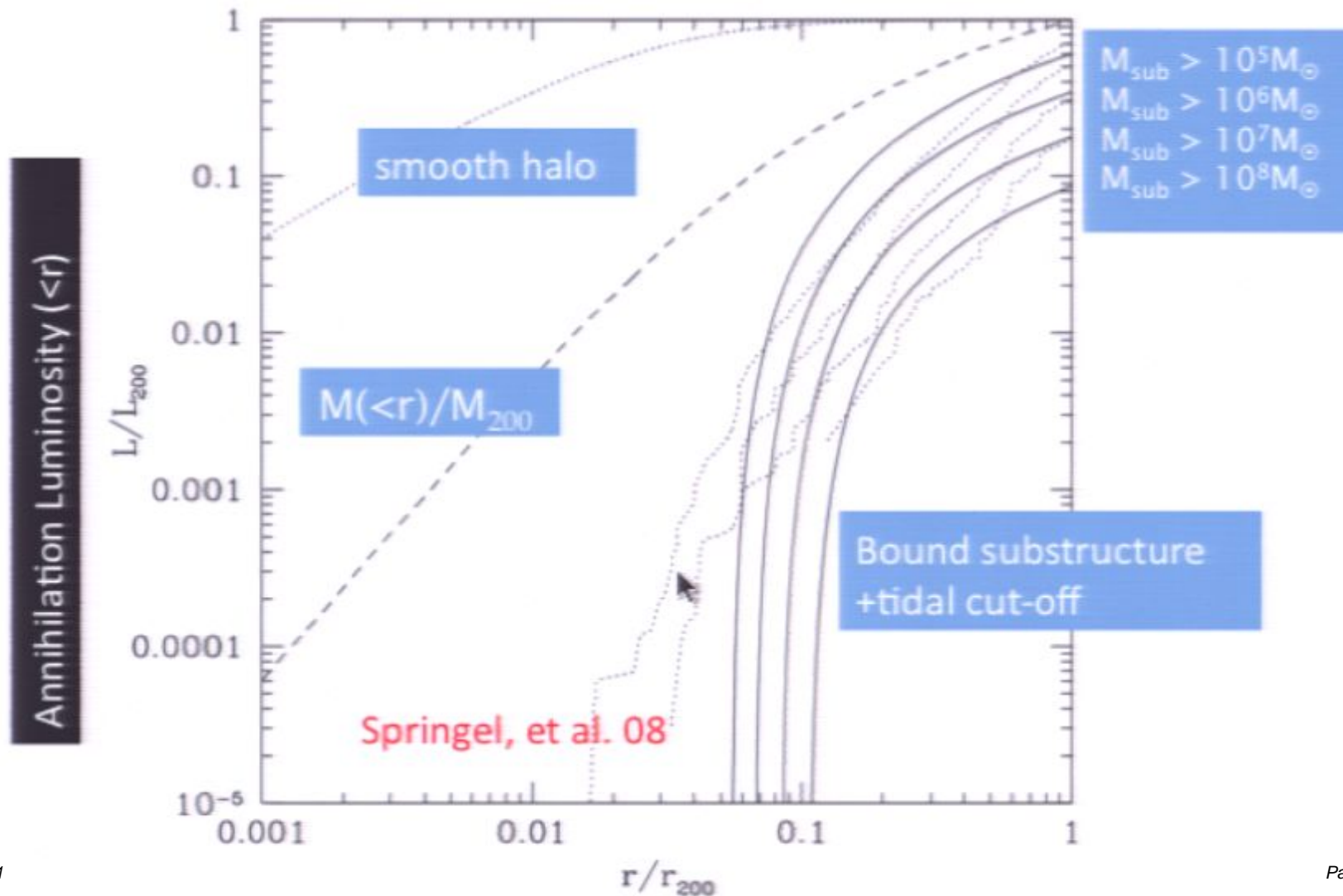
$$\delta \approx \frac{8\pi^{1/2}\mu}{9\delta_c^3} \left(\frac{\rho_{\text{halo}}(\mathbf{x})}{200\rho_{\text{crit},0}} \right)^{-1} \int_{M_{\text{min}}}^{M_{\text{max}}} M^{-2} d[M^2\sigma^3(M)]$$

0.03

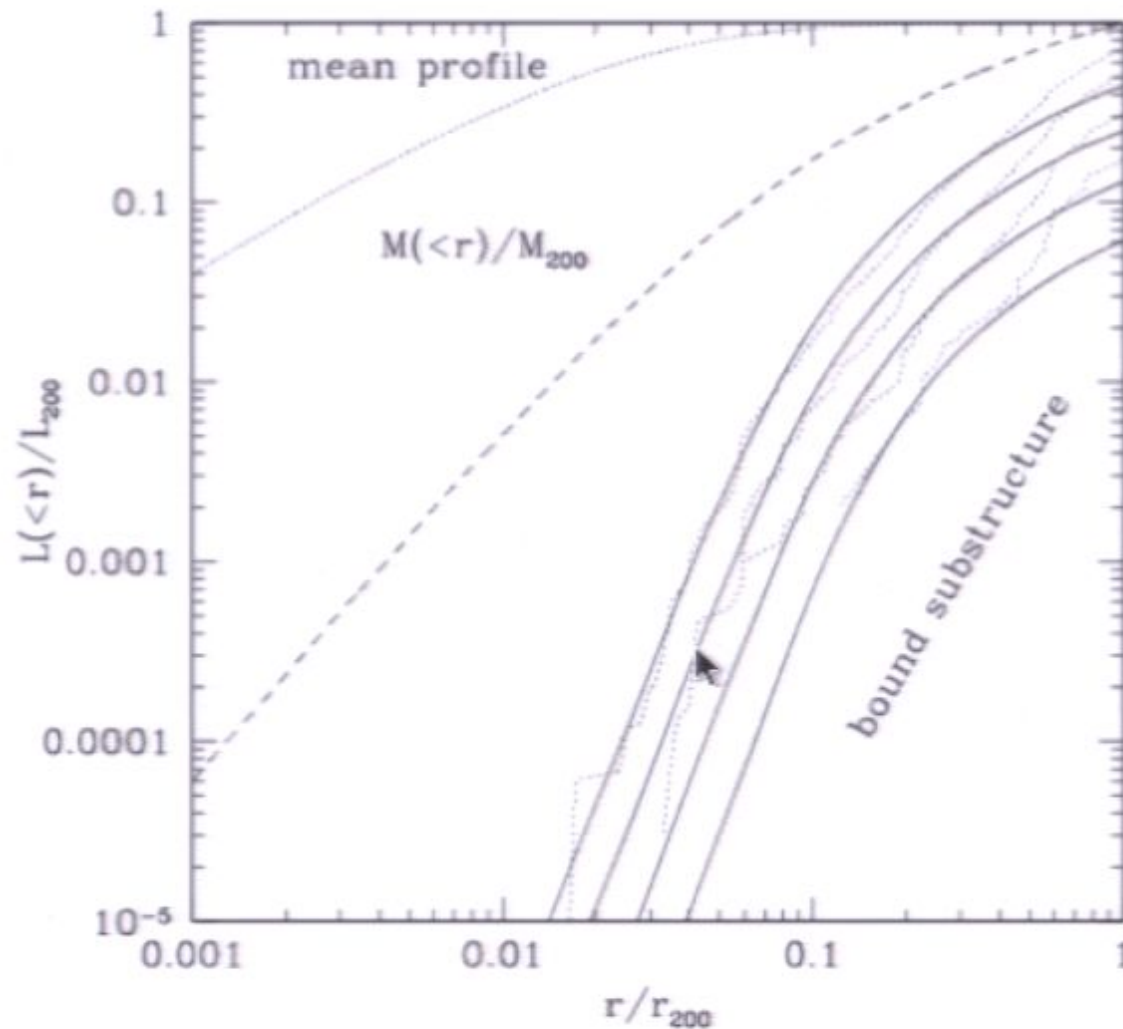
Standard deviation of linear overdensity on mass scale M

NA, et al. 2010

DM annihilation profile: stable clustering vs. simulations

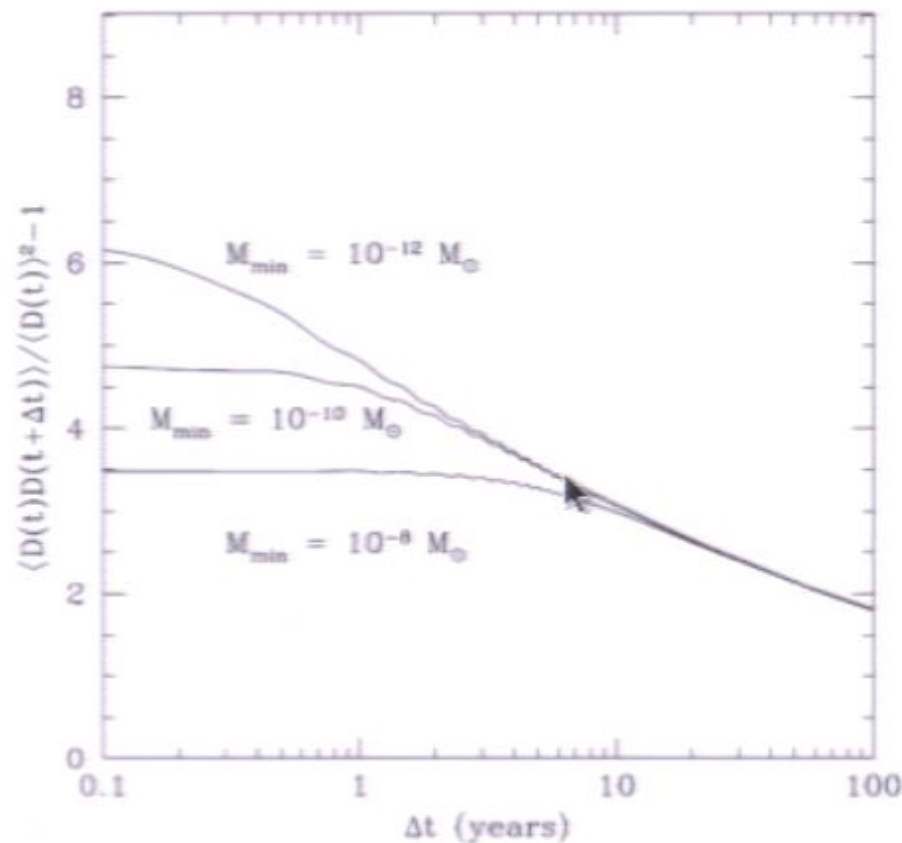


Massaging the tidal stripping prescription ...

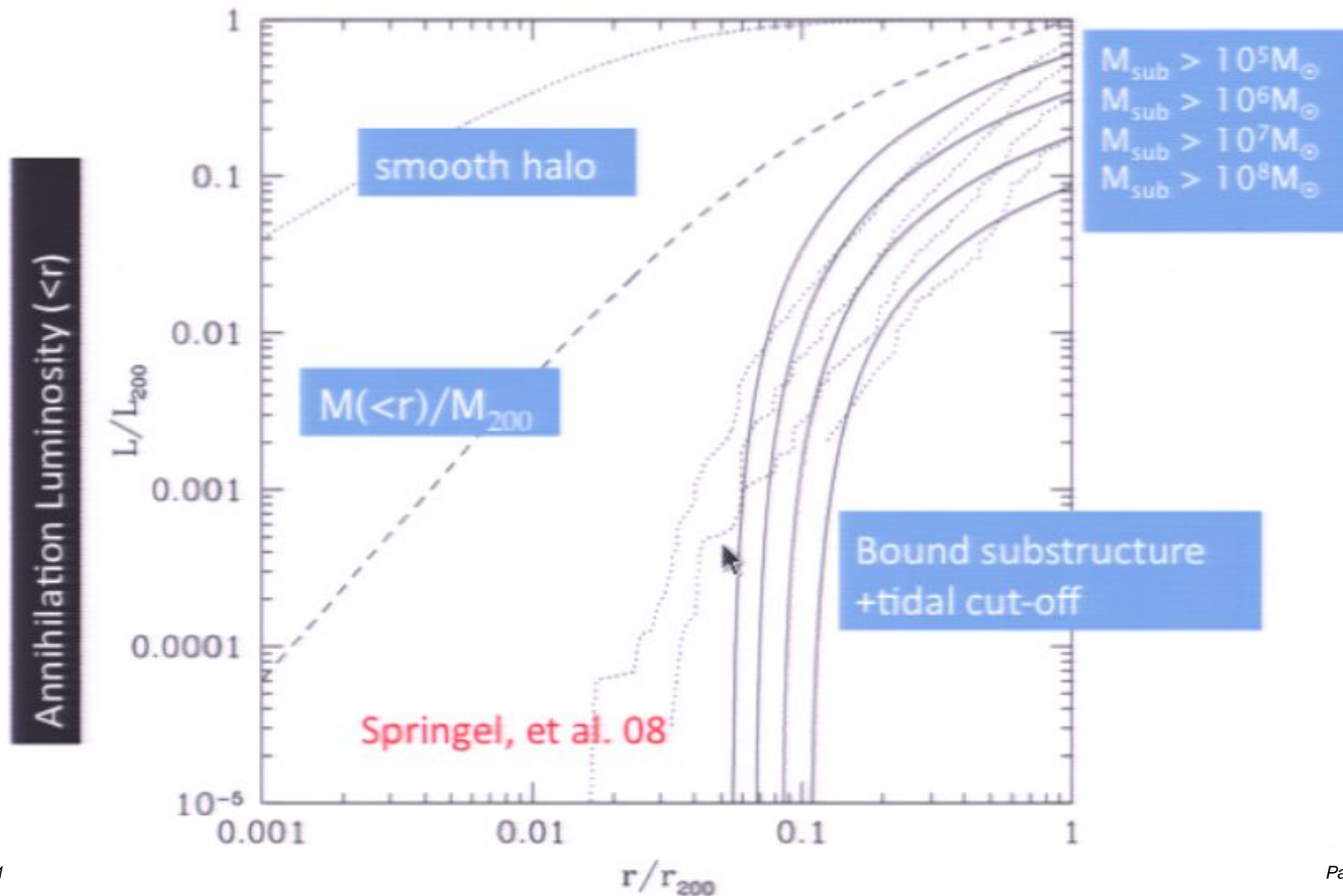


sub-haloes in Direct Detection!

- Temporal auto-correlation of DM detection in several years...

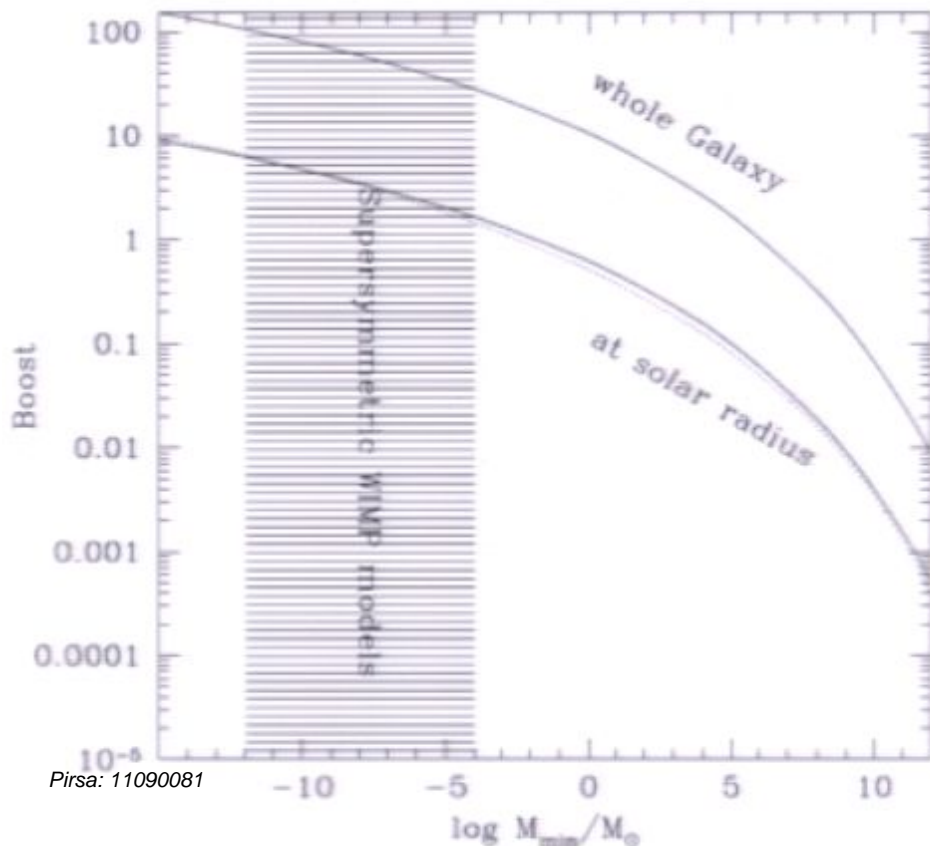


DM annihilation profile: stable clustering vs. simulations



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Pirsa: 11090081

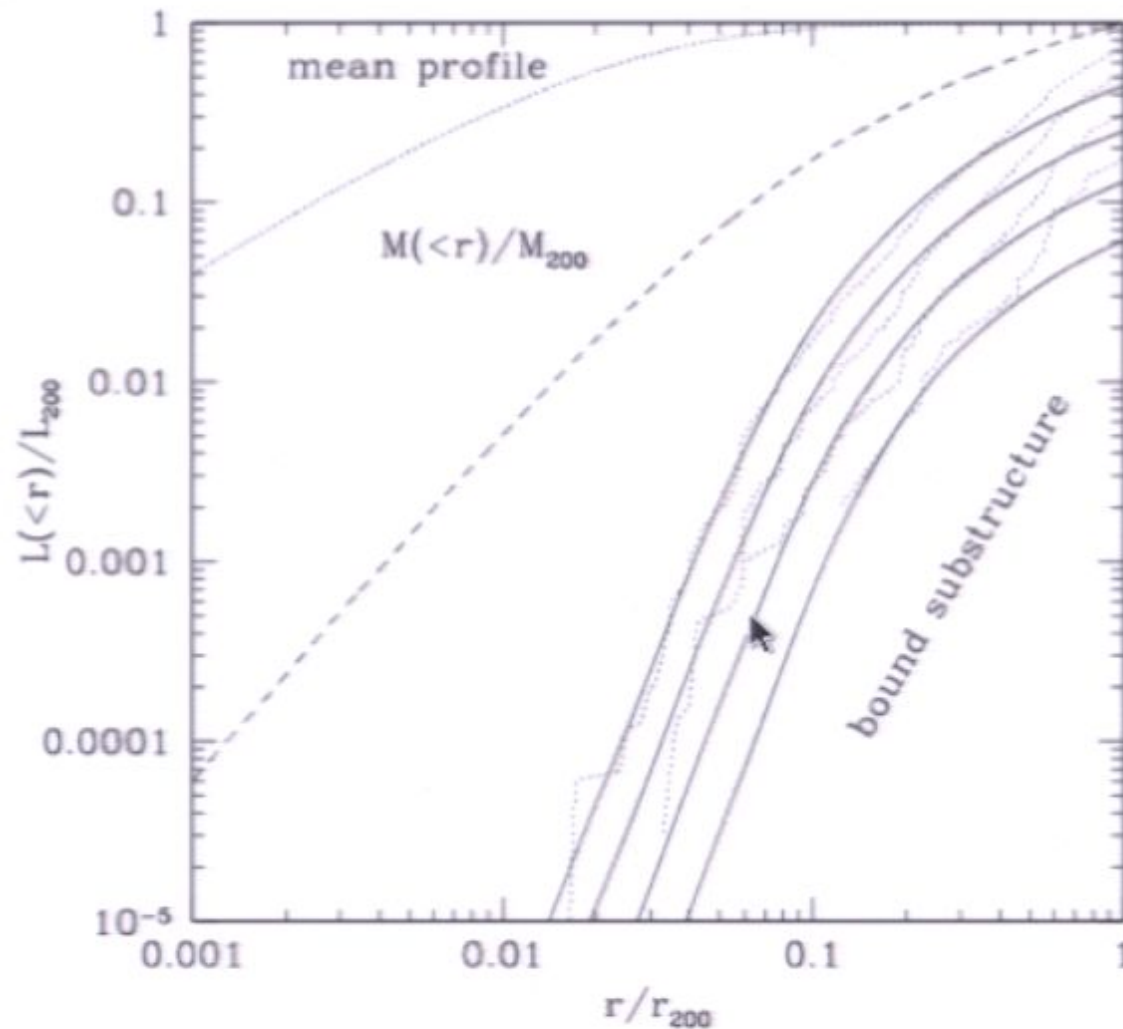
$$\sigma \approx \frac{8\pi^{1/2}\mu}{\delta_c^3} \left(\frac{\rho_{\text{halo}}(\mathbf{x})}{200\rho_{\text{crit},0}} \right)^{-1} \int_{M_{\text{min}}}^{M_{\text{max}}} M^{-2} d[M^2\sigma^3(M)]$$

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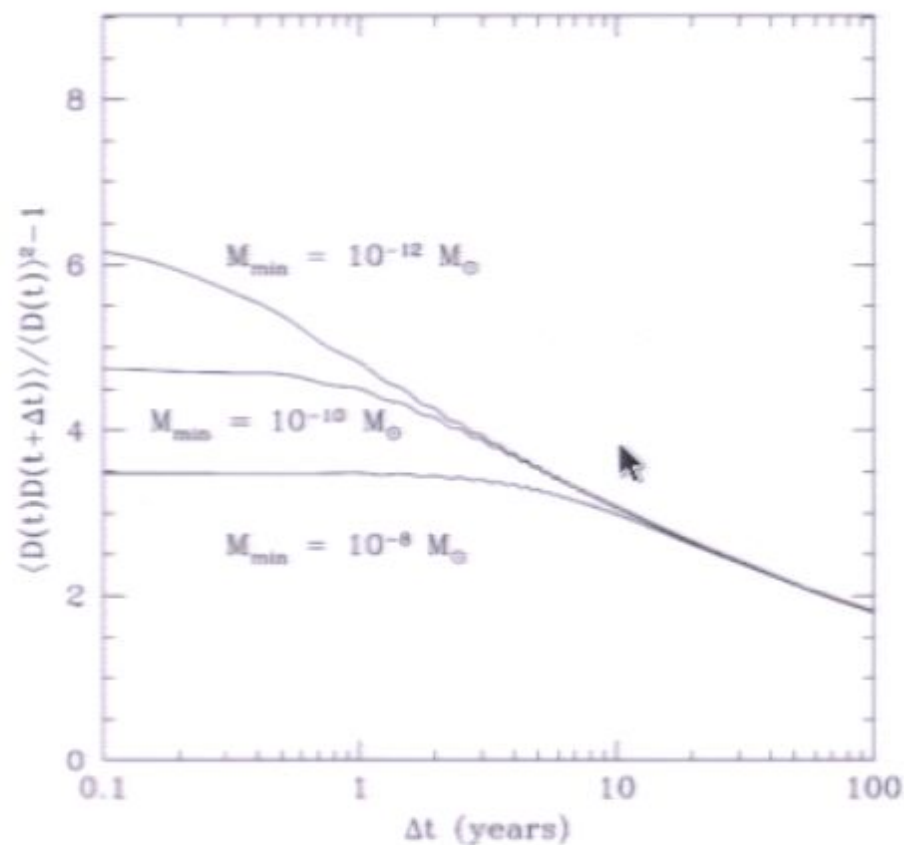
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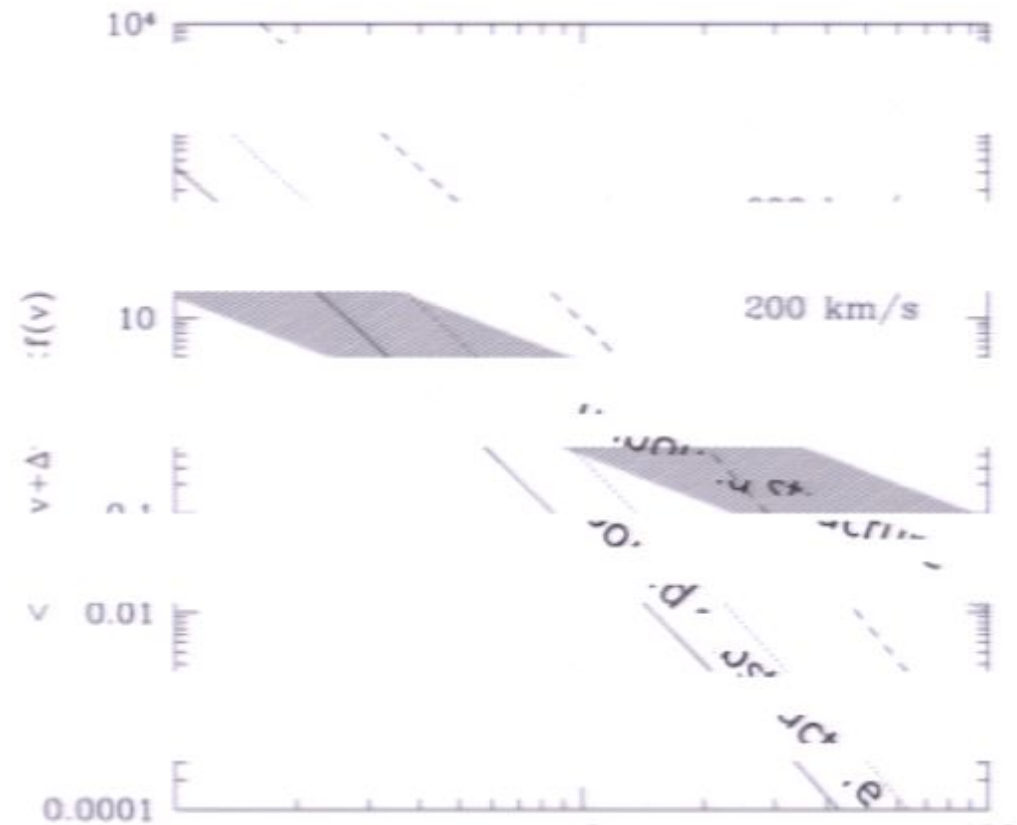
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Dark Matter Astronomy?

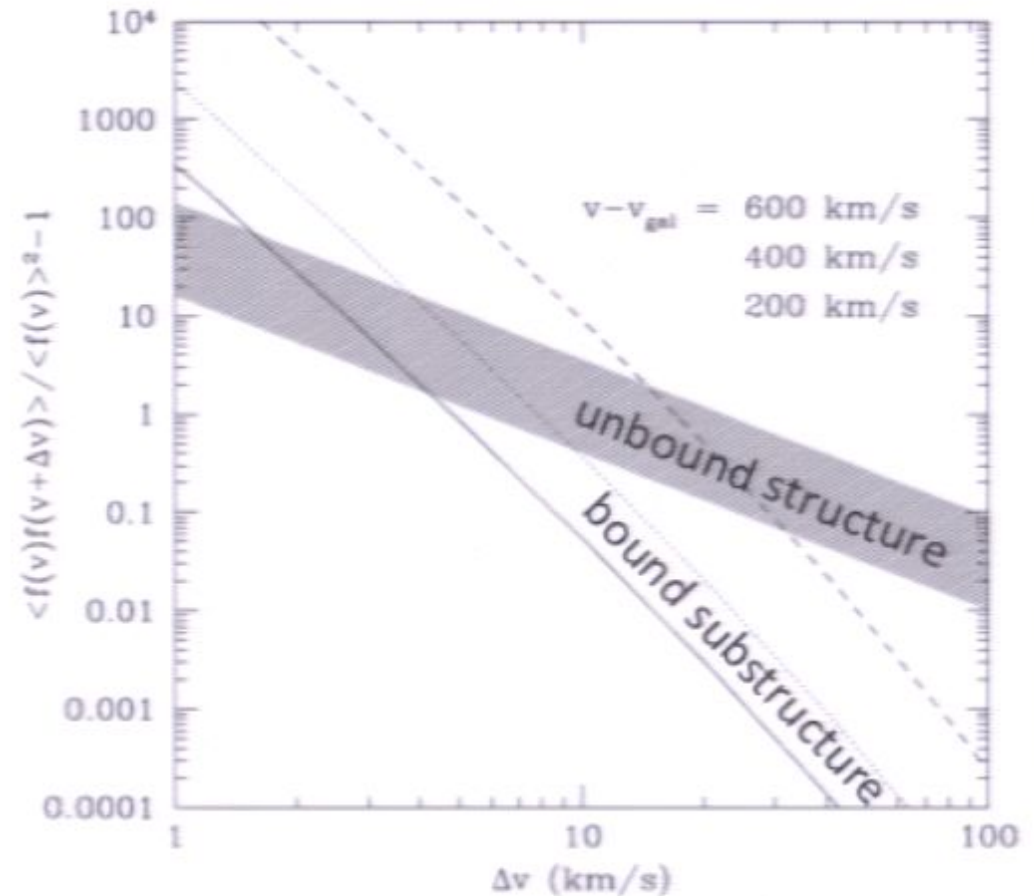
Dark Matter Astronomy?

- From bound subhaloes:
Boost = $O(1)$ = density variance @ solar radius
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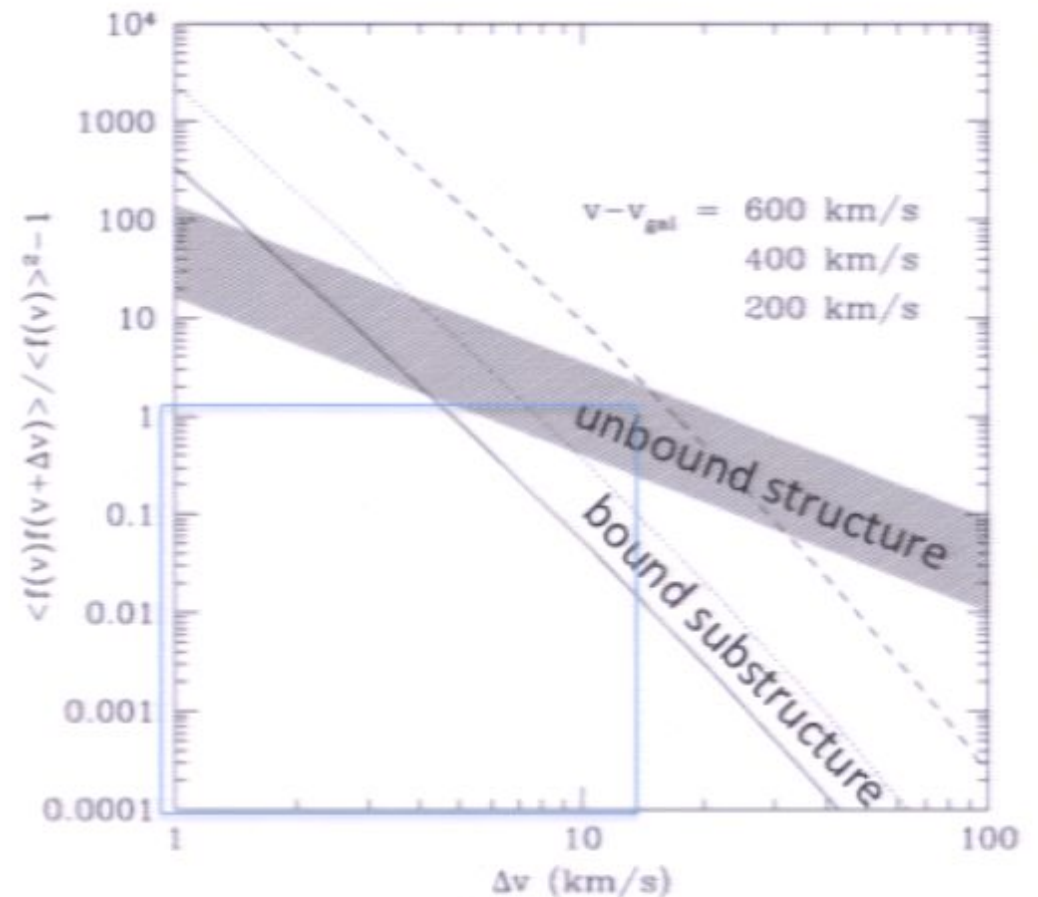
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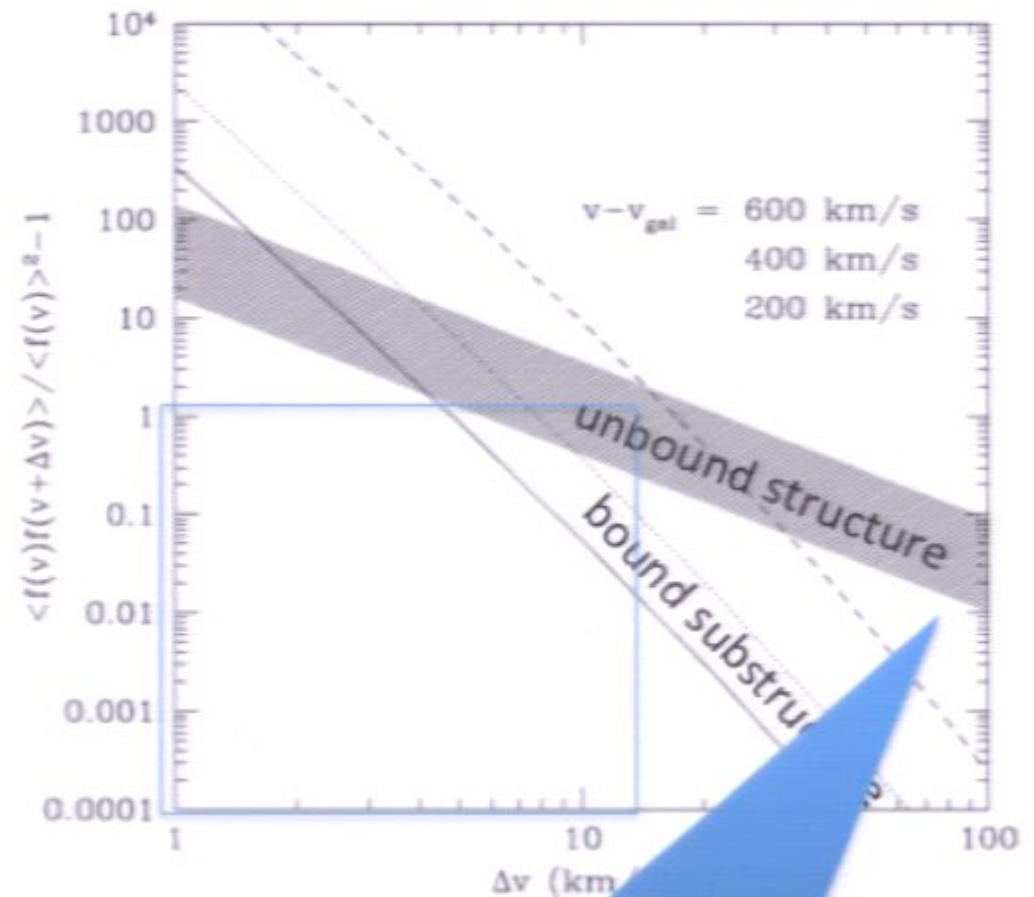
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- What about baryons?
 - They can enhance CDM structures through adiabatic contraction, or destroy them via gravitational collisions/heating
 - *Real haloes are almost certainly more complicated!*

Final Word

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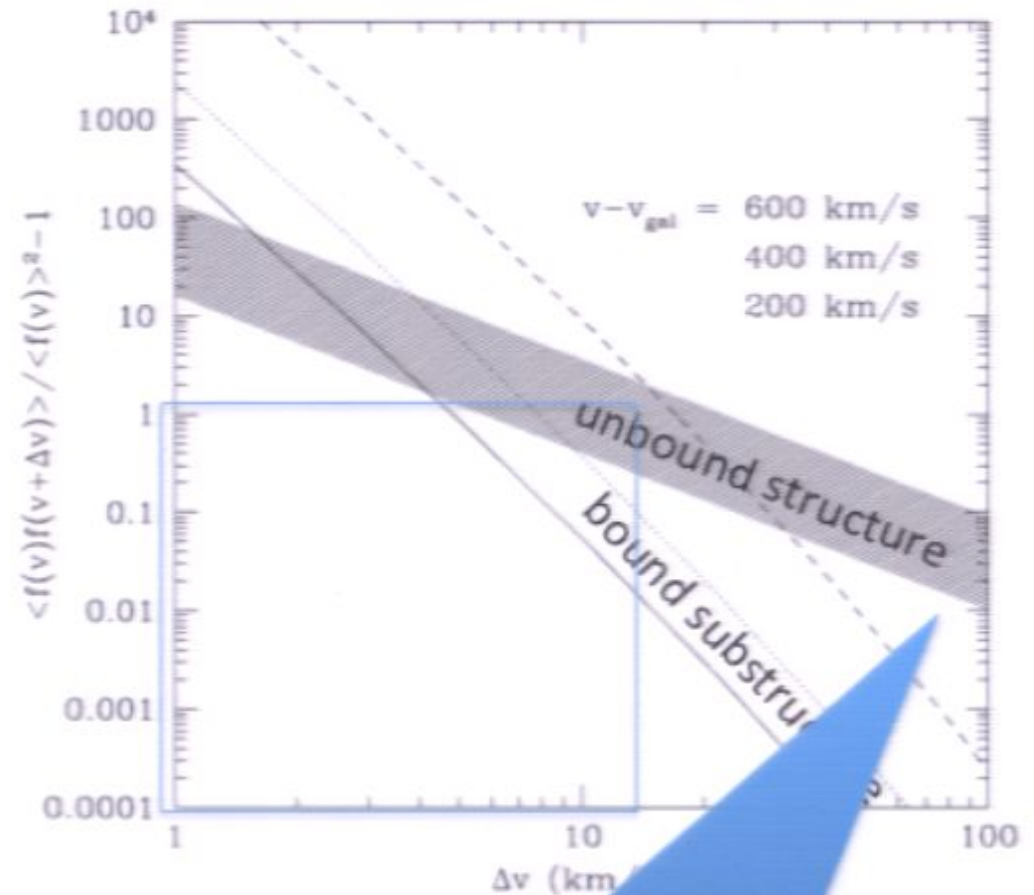
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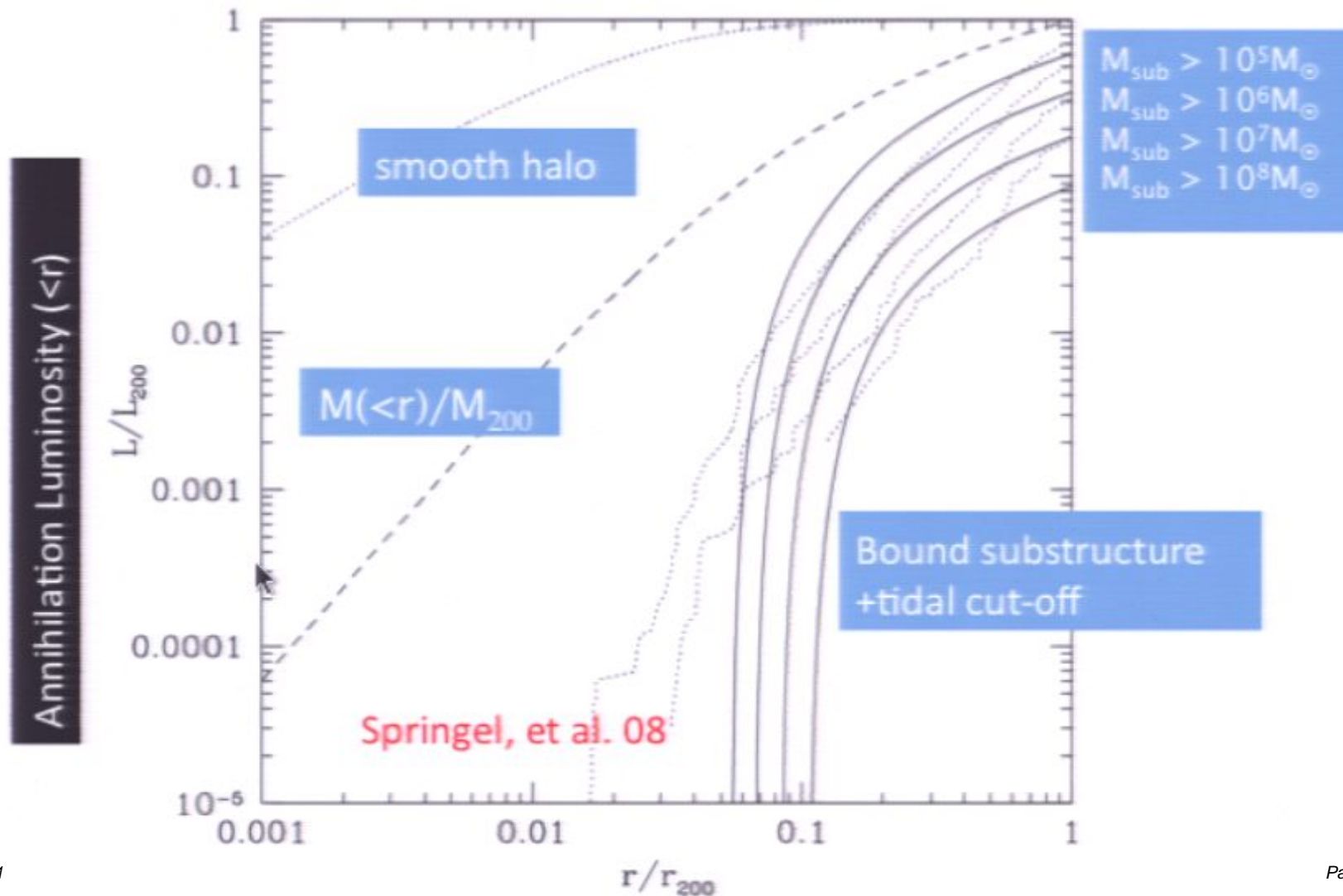
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- If/when we detect Dark Matter particles, **Dark Matter Astronomy** will be just around the corner

Dark Matter Astronomy?

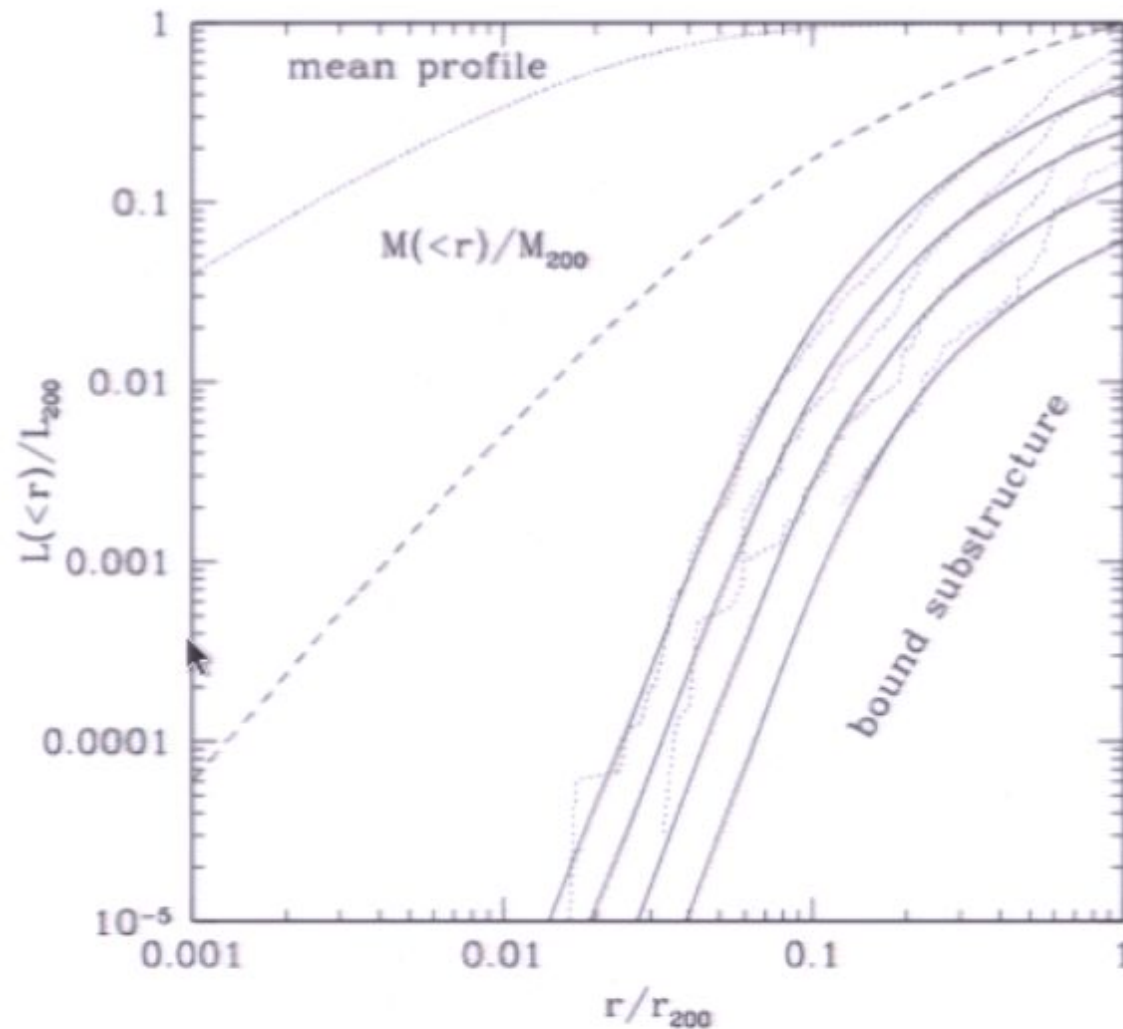
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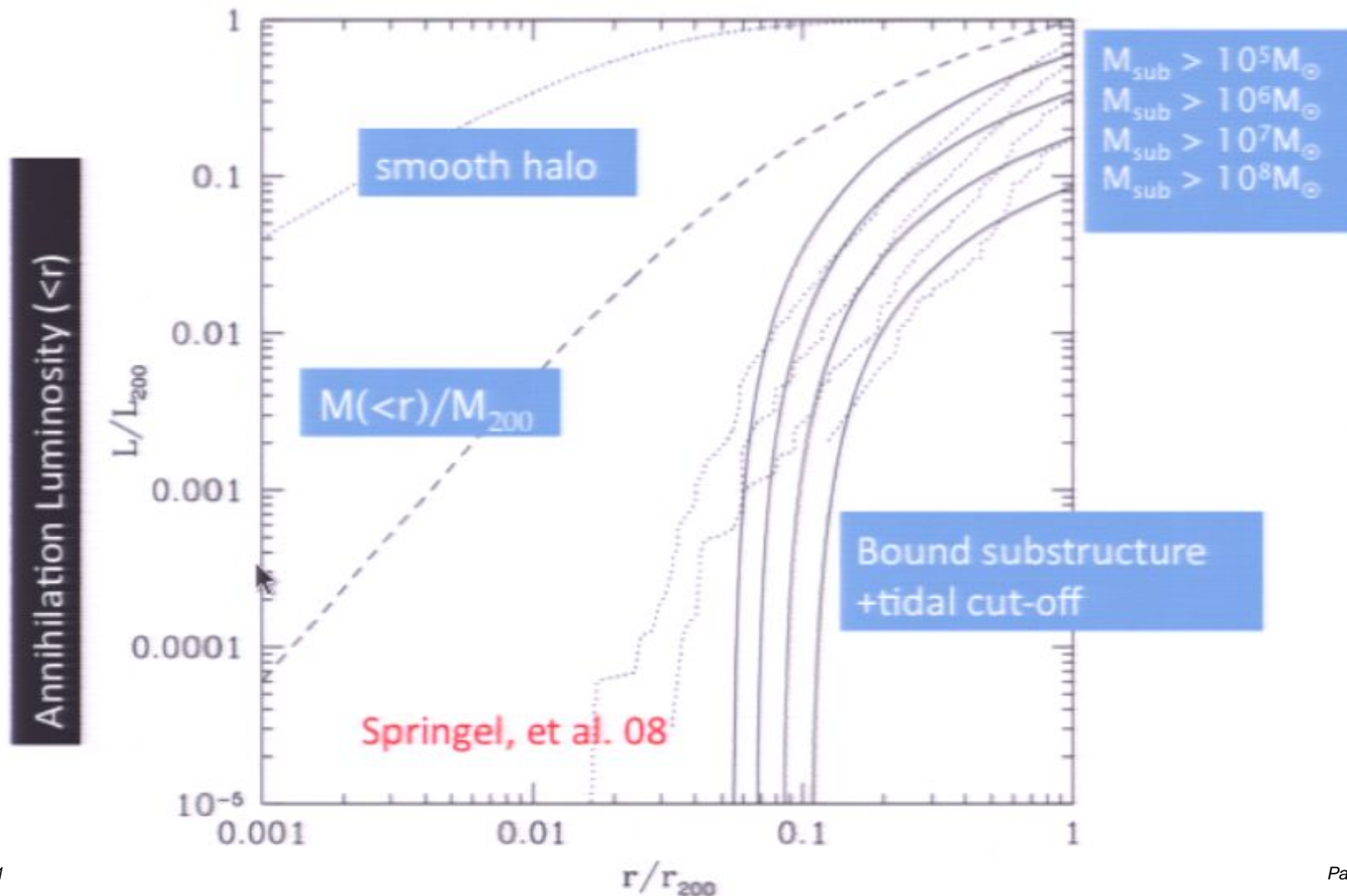
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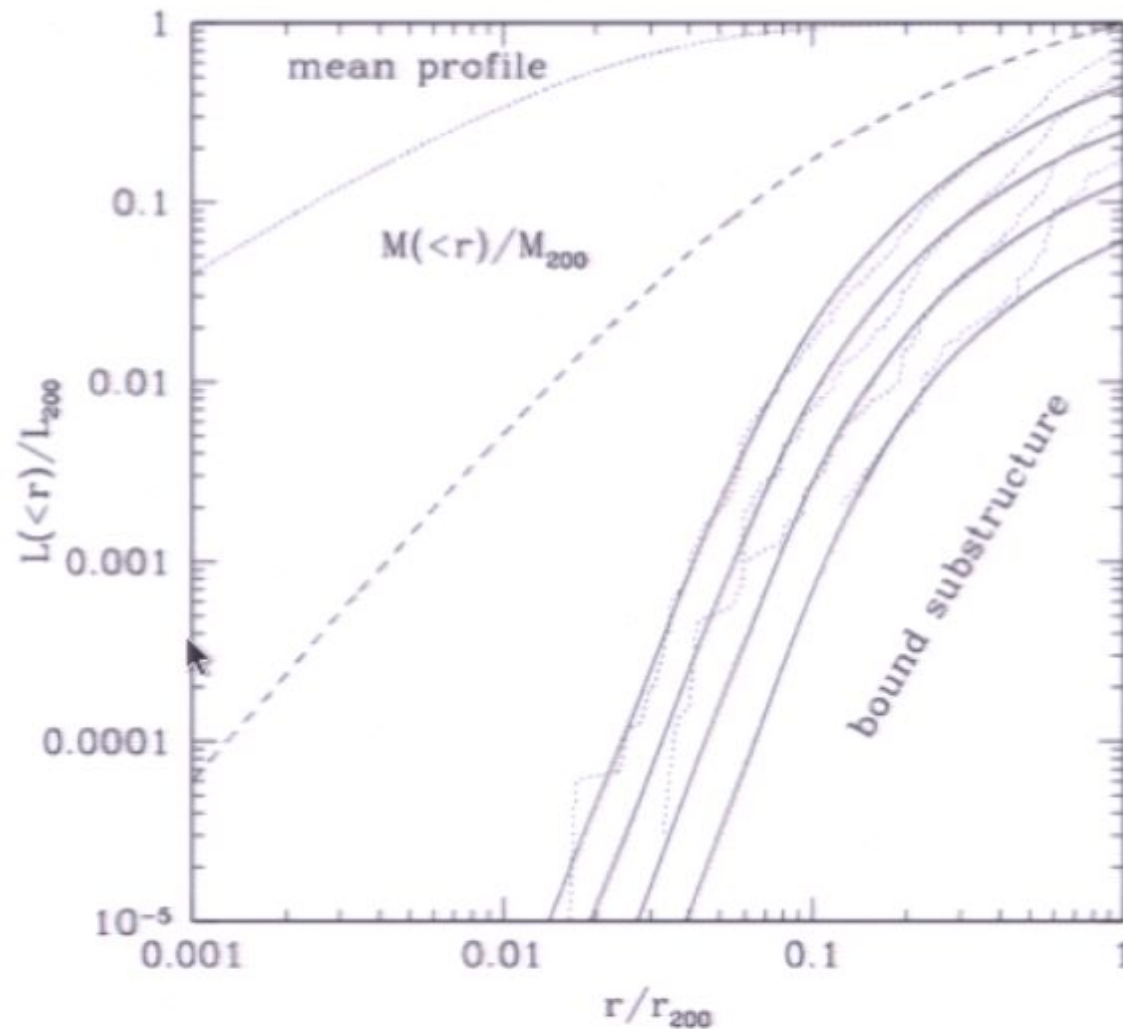
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