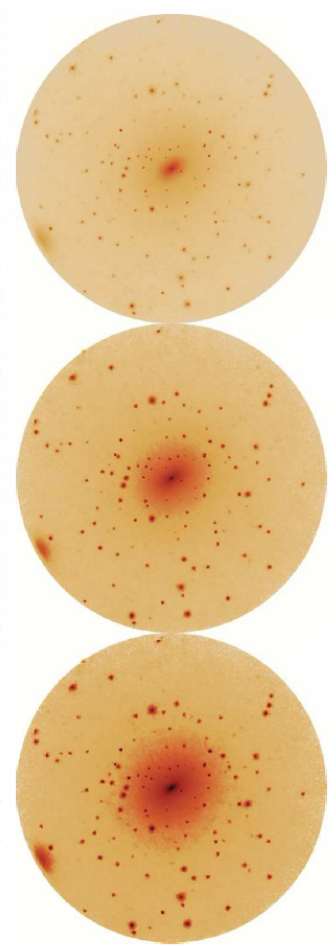
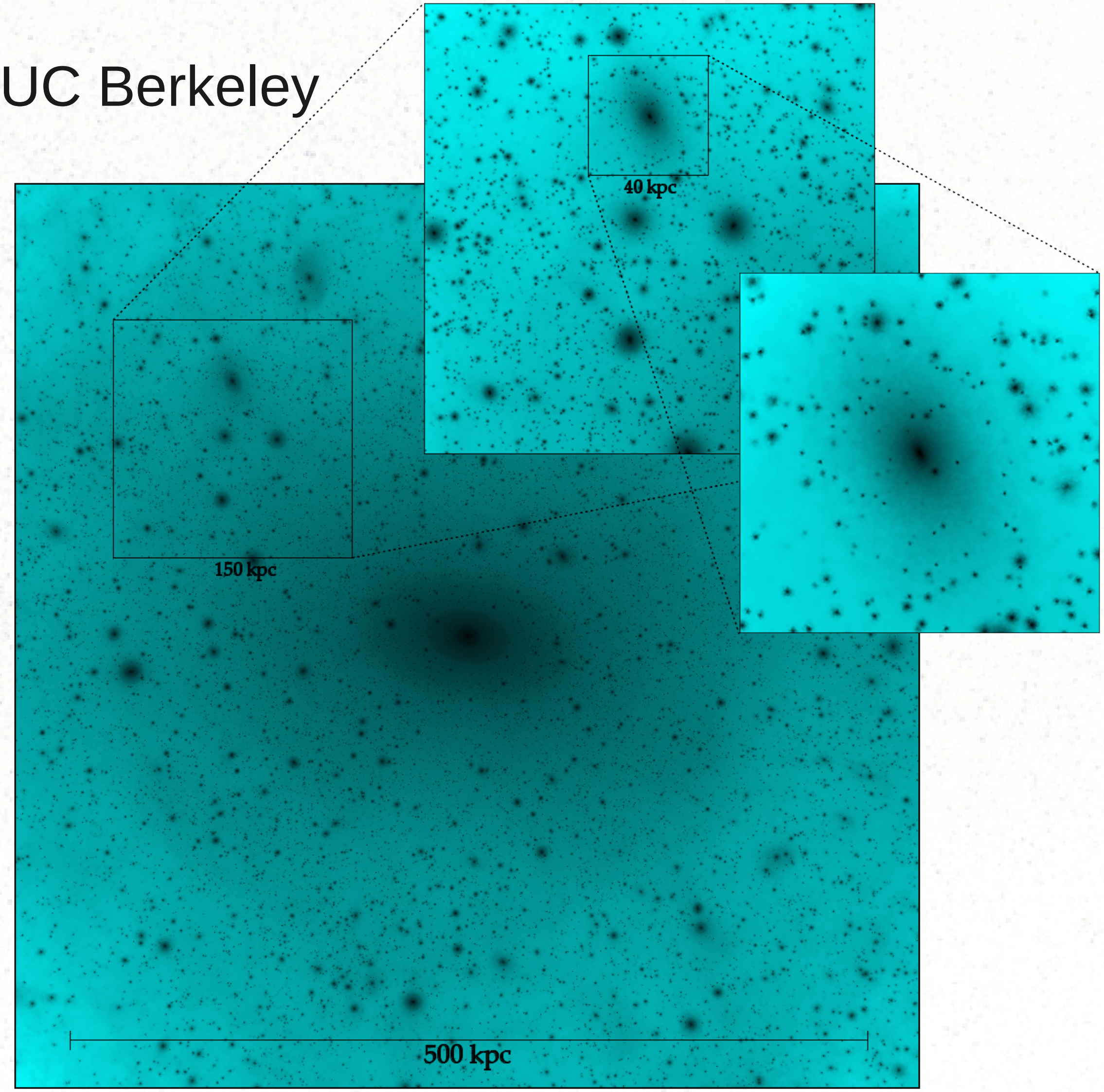
The annihilation boost factor from substructure

Michael Kuhlen, UC Berkeley

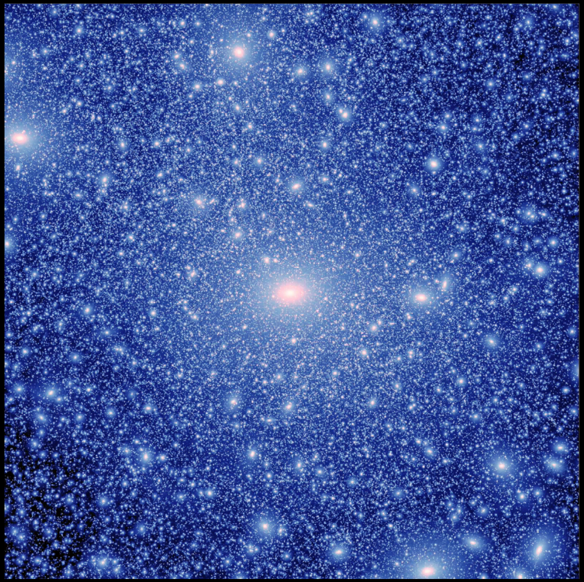


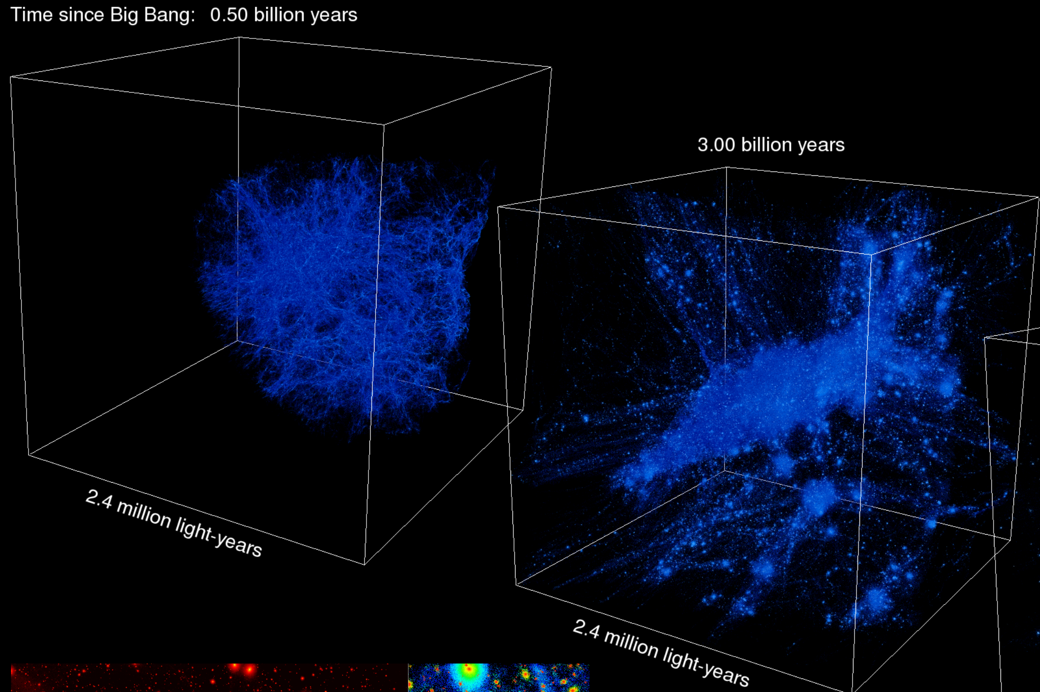


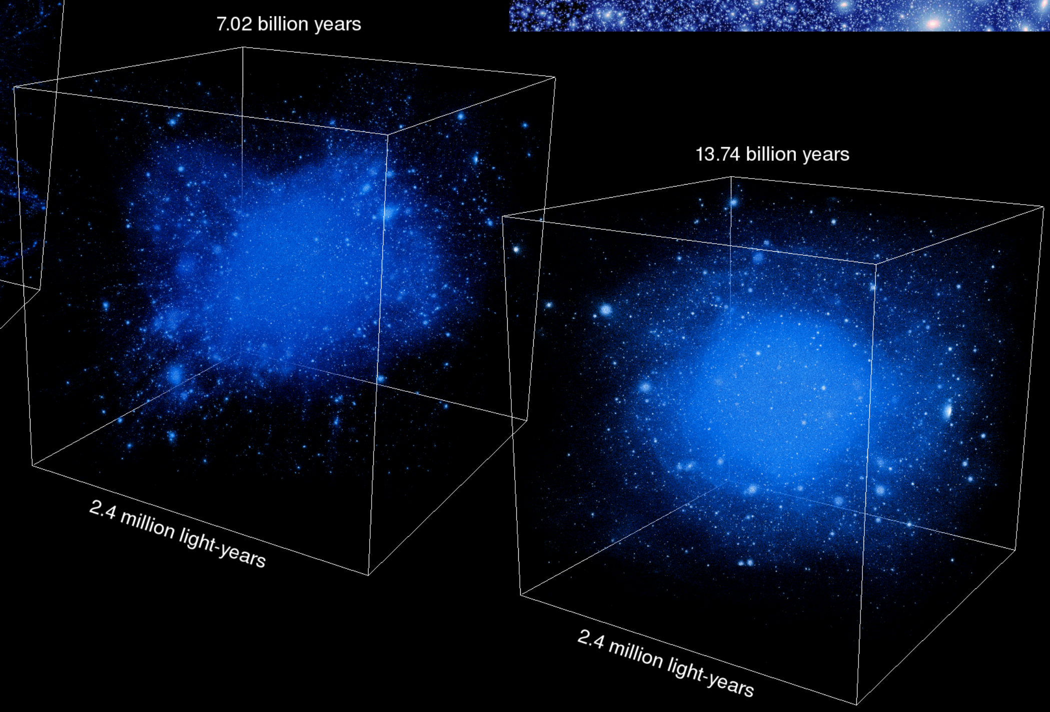
J. Diemand, P. Madau (and Via Lactea collaboration); B. Anderson; N. Dalal, Y. Lithwick

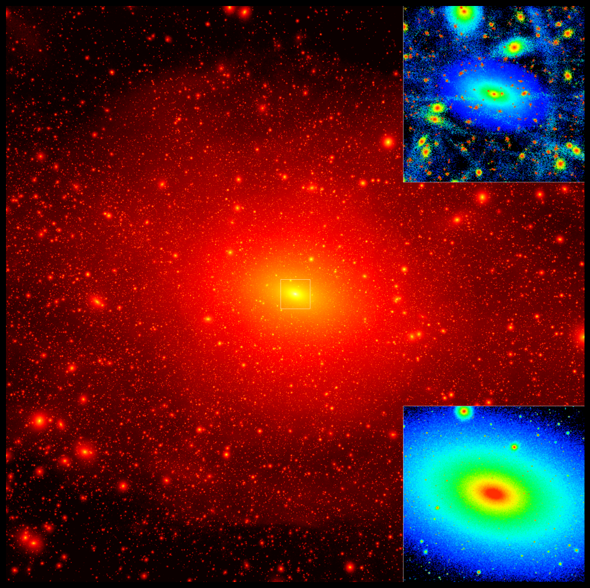
The Via Lactea Project

GHALO
Stadel et al. (2009)
2.1 billion particles, 1,000 $M_\odot$









VIA LACTEA II
Diemand, Kuhlen et al. 2008
1.1 billion particles, 4,000 $M_\odot$

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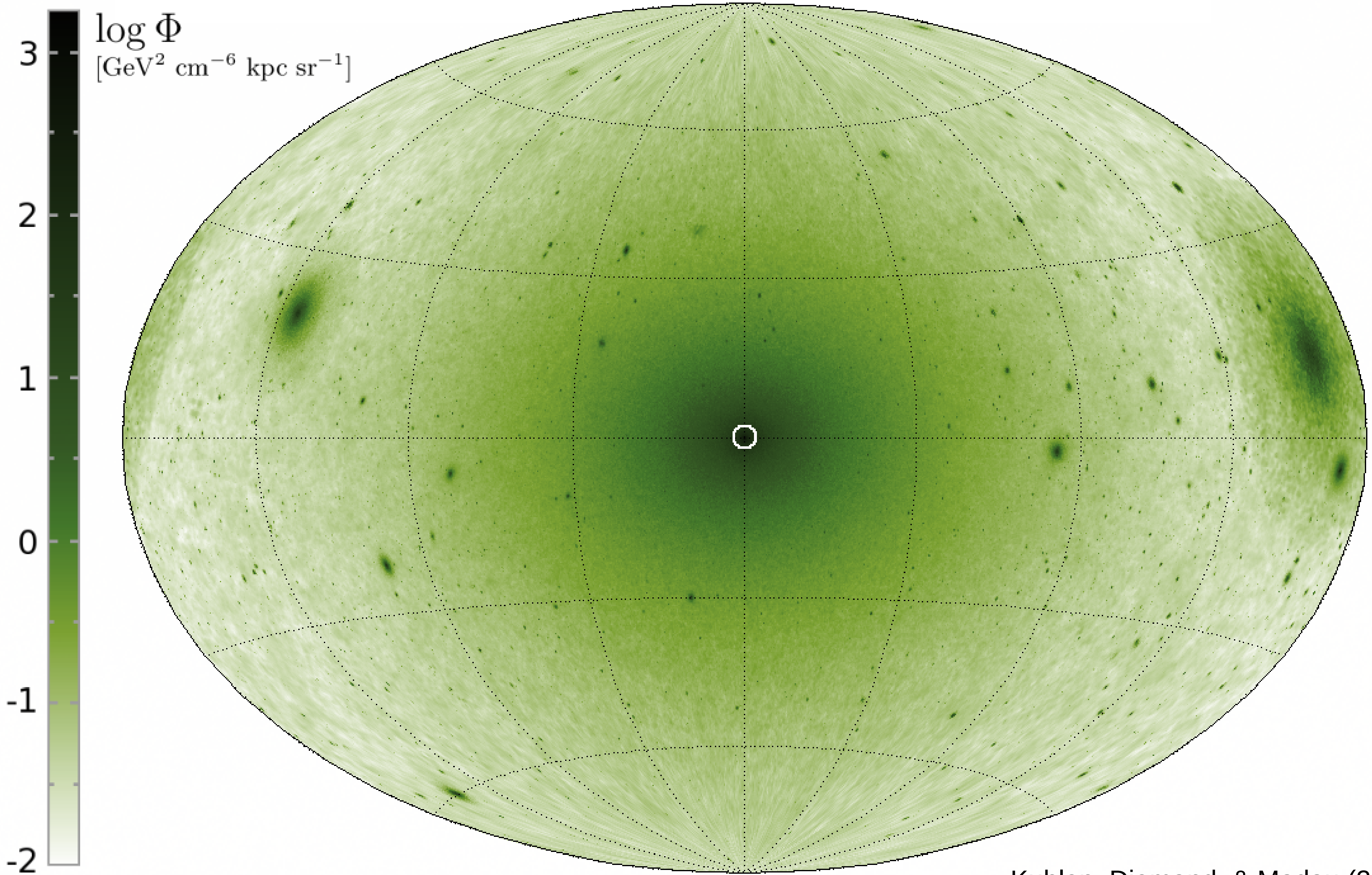
Subhalos as individual DM annihilation sources

$$N_\gamma = \left[\int_{\text{line of sight}} \rho^2_{\rm DM}\, dl(\psi)\right] \frac{\langle \sigma v \rangle}{2M^2_\chi} \left[\int_{E_{th}}^{M_\chi} \left(\frac{dN_\gamma}{dE}\right) A_{\rm eff}(E)dE\right] \frac{\Delta\Omega}{4\pi}\, \tau_{\rm exp}$$

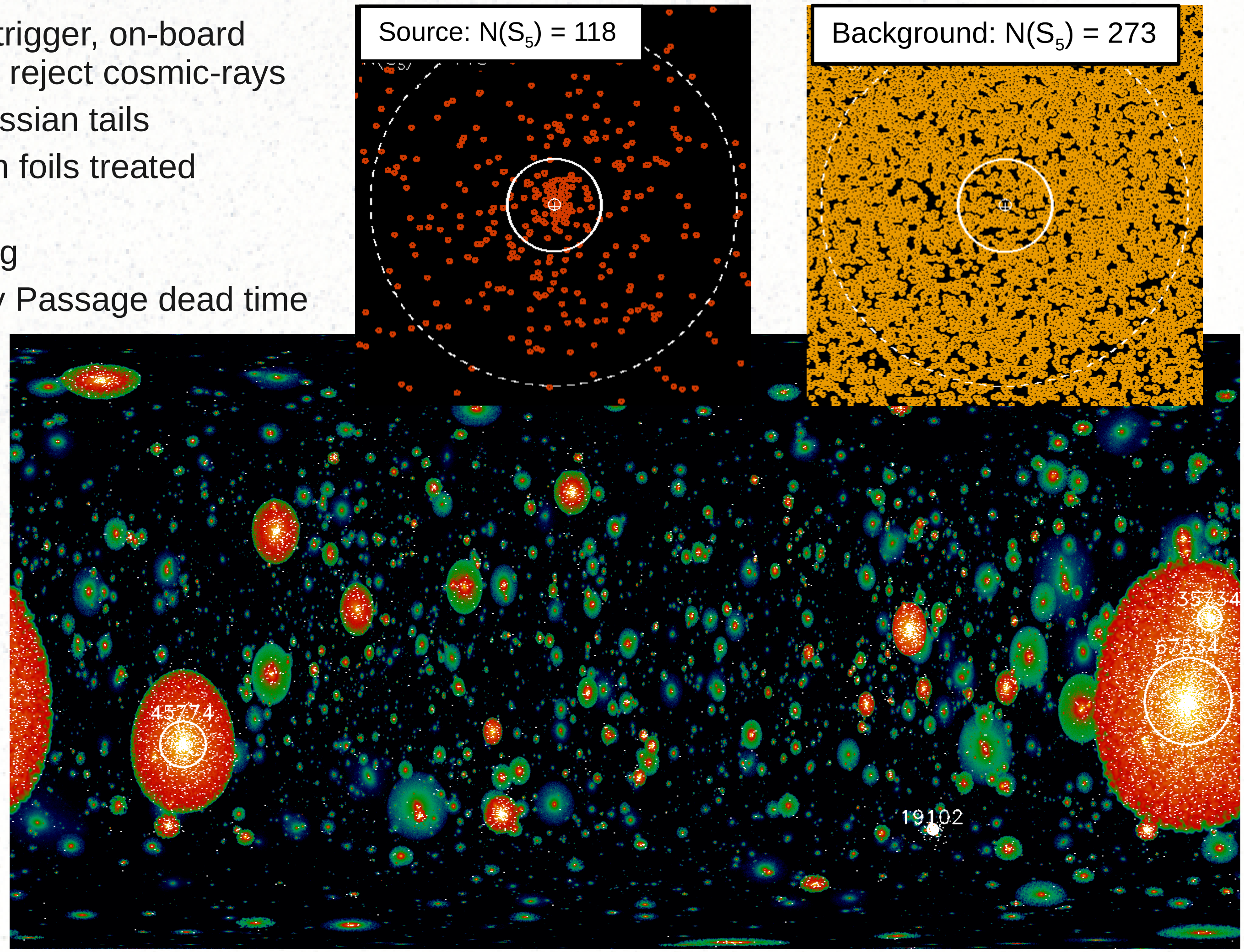


Kuhlen, Diemand, & Madau (2008)

Subhalos as individual DM annihilation sources

Fermi/LAT *GTOBSSIM* Monte-Carlo Simulation (with Brandon Anderson & Robert Johnson, SCIPP)

- LAT A_{eff} dependence on viewing angle and photon energy
- Selection effects: LAT trigger, on-board filter, offline analysis to reject cosmic-rays
- PSF includes non-Gaussian tails
- Thin and thick tungsten foils treated separately
- $\pm 35^{\circ}$ instrument rocking
- South Atlantic Anomaly Passage dead time



Energy-dependent ROI optimization

Calculate detection significance:

$$P = \sum_{i=k}^{\infty} \frac{\lambda^k e^{-\lambda}}{k!}$$

$$S = \sqrt{2}\ \mathrm{erf}^{-1}(1 - 2\mathrm{P})$$

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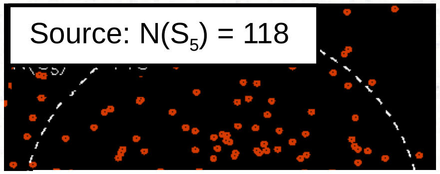
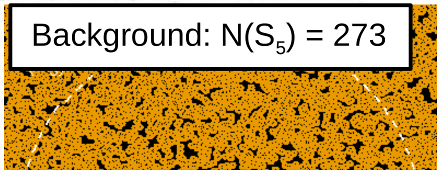
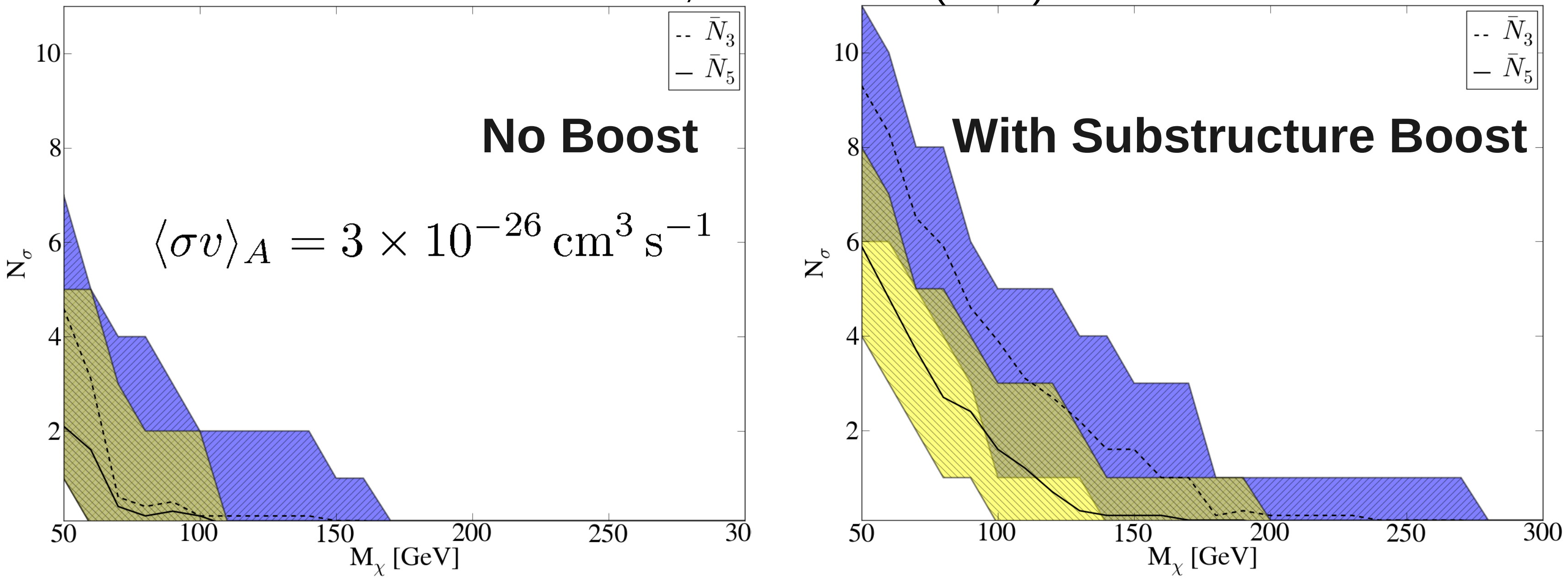
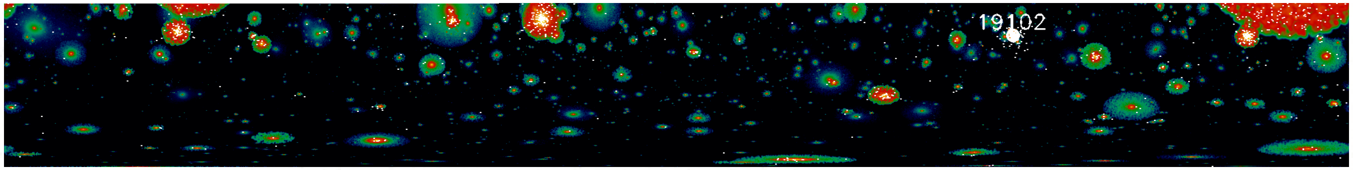




Anderson, Kuhlen et al. (2010)





Substructure “Boost Factor”

$$\langle \rho \rangle^2 \neq \langle \rho^2 \rangle$$

The term “Boost Factor” has been used in many ways, for example:

- Enhancement in total halo luminosity from NFW profile compared to a spherical tophat.
- Enhancement in total halo luminosity from substructure (and sub-substructure, etc.) compared to a smooth NFW density profile.
- Enhancement of local (8kpc) annihilation rate over (~0.3 GeV cm^{-3})^2.
- Enhancement of Galactic Center annihilation rate.
- Enhancement of the surface brightness of angularly resolved subhalos.

There is no one single “Boost Factor”!

The enhancement due to clumpy substructure depends on source location and/or its angular extent.

Substructure "Boost Factor"

$$\langle \rho \rangle^2 \neq \langle \rho^2 \rangle$$

Two ways to model

Subhalo modeling approach

- Subhalo mass (or V_{max}) function
- Radial distribution (tidal stripping)
- Concentration-mass relation (potentially also depends on radius)
- Integrate over contribution from subhalos and their sub-subhalos

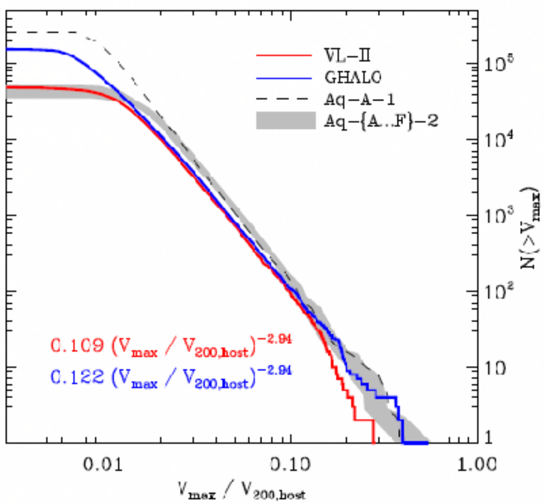
Density distribution approach

- Determine volumetric density distribution function as a function of radius.
- Fit log-normal + power law model.
- Integrate over distribution to get boost as a function of radius.

Substructure Boost: Subhalo Modeling Approach

Calibrate to numerical simulations.
Must extrapolate below resolution limit (“only” 12 orders of magnitude...)

Mass/V_{max} function:

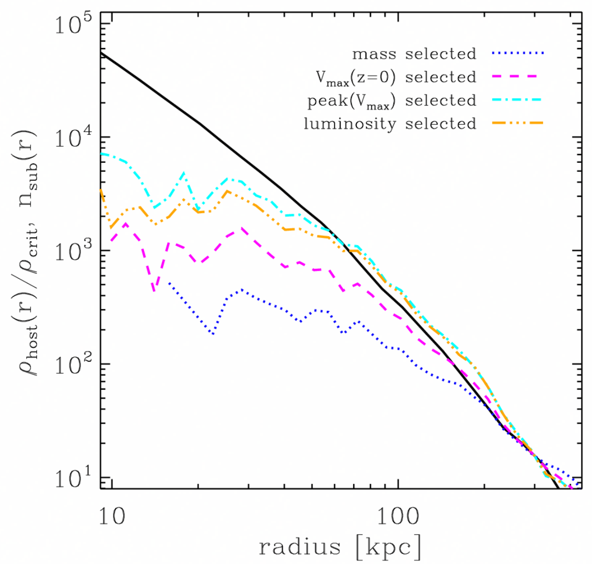


The subhalo mass function is steeply rising towards low masses.

$$\frac{dN}{dM} \sim M^{-\gamma} \quad \gamma \approx 1.9$$

$$N(>V_{\max}) \sim V_{\max}^{-\delta} \quad \delta \approx 3$$

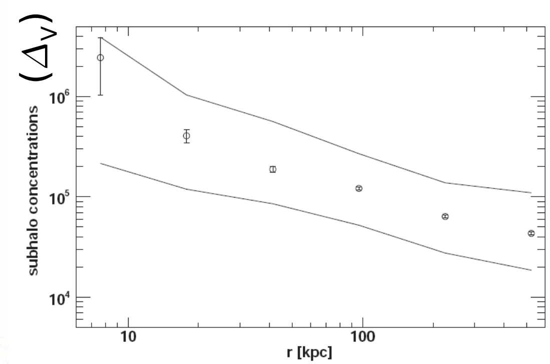
Radial Distribution:



The mass-selected distribution is “anti-biased” but a luminosity-selected sample less so.

Concentration:

$$L_{\rm ann} \sim \frac{M^2}{R^3}\frac{c^3}{f(c)^2}$$
$$\sim V_{\max}^3 \sqrt{\Delta_V}$$



$$\Delta_V = \langle \rho(<{\rm R}_{\rm V_{max}})\rangle / \rho_{\rm crit}$$

is a measure of subhalo concentration. It rises towards the center.

Substructure Boost: Subhalo Modeling Approach

The cumulative annihilation signal from all substructure results in a diffuse flux.

This is the boosted host halo signal as seen from the Sun, but it **does not have the same angular profile, even if $n_{sub}(r)$ follows $\rho_{host}(r)$**.

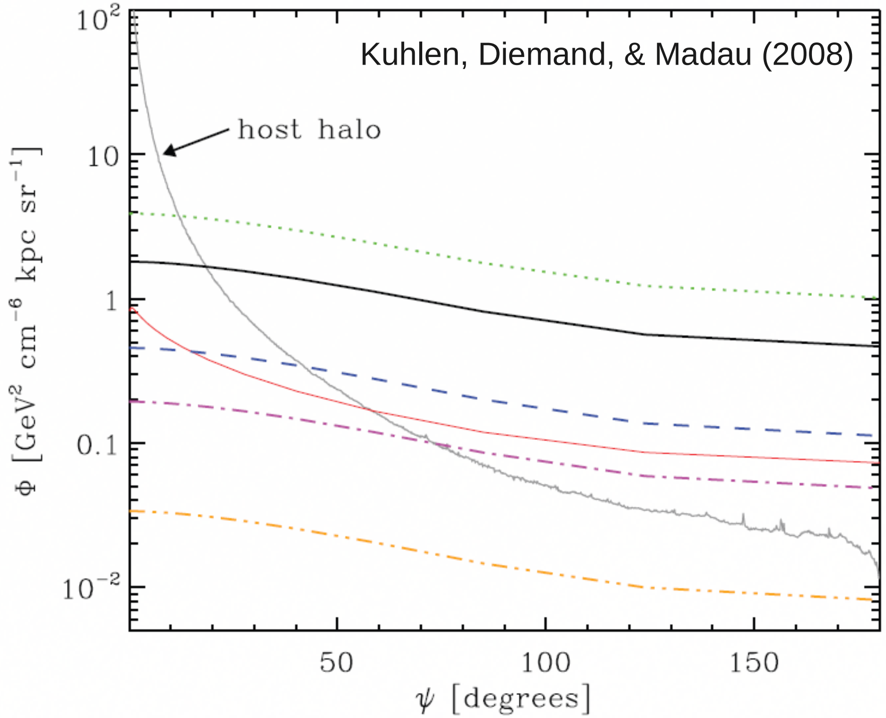
"We're not annihilating subhalos with each other."

- For the Galactic halo signal this results in a **reduced contrast between center and anti-center**. IceCube?
- For resolved individual subhalos (e.g. MW dwarf satellites) the substructure **preferentially boosts the outskirts** where the signal/noise is low.

Angular fluctuations are an interesting signal to be searched for (Siegal-Gaskins et al. 2008, Ando 2009)

Subhalo Mass Function Models

α	m_0 ($M_\odot$)	N_{tot}	M_{tot} ($M_\odot$)	f_{tot}	M_u ($M_\odot$)	f_u
2.0.........	10^{-6}	2.5×10^{16}	9.3×10^{11}	0.53	7.0×10^{11}	0.40
1.9.........	10^{-6}	9.2×10^{14}	3.2×10^{11}	0.19	1.2×10^{11}	0.070
1.8.........	10^{-6}	3.3×10^{13}	2.1×10^{11}	0.12	3.3×10^{10}	0.018
2.0.........	1	2.5×10^{10}	5.8×10^{11}	0.33	3.5×10^{11}	0.20
2.0.........	10^{-12}	2.5×10^{22}	1.3×10^{12}	0.73	1.0×10^{12}	0.60

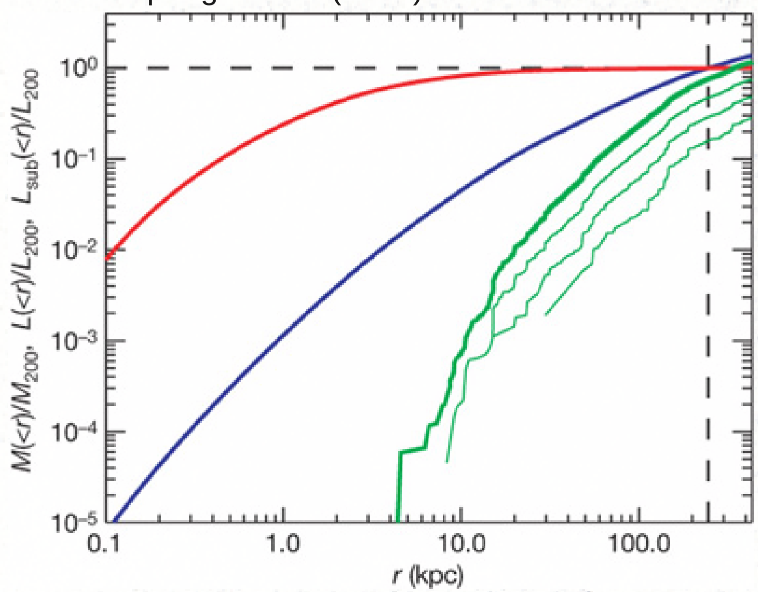


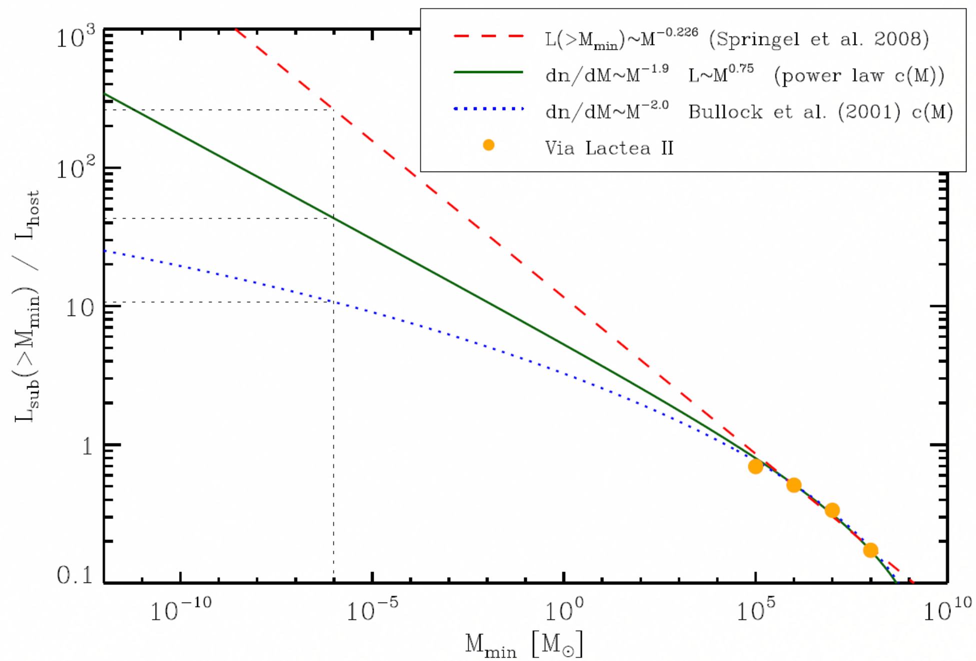
3) Substructure "Boost Factor"

Total Halo Luminosity Boost Factor

- **Only applicable to unresolved sources!**
- Important for the extragalactic gamma-ray background.

Springel et al. (2008)





$L(>M_{min}) \sim M_{min}^{-0.226}$

Total boost factor for $M_{min}=10^{-6}$ $M_\odot$ = 232!

Depends **critically** on what one assumes for the concentration-mass relation for subhalos below the simulations' resolution limit!

See also: Martinez, Bullock, Kaplinghat, Strigari, & Trotta (2010)

Recent Progress in Understanding The Origin of NFW

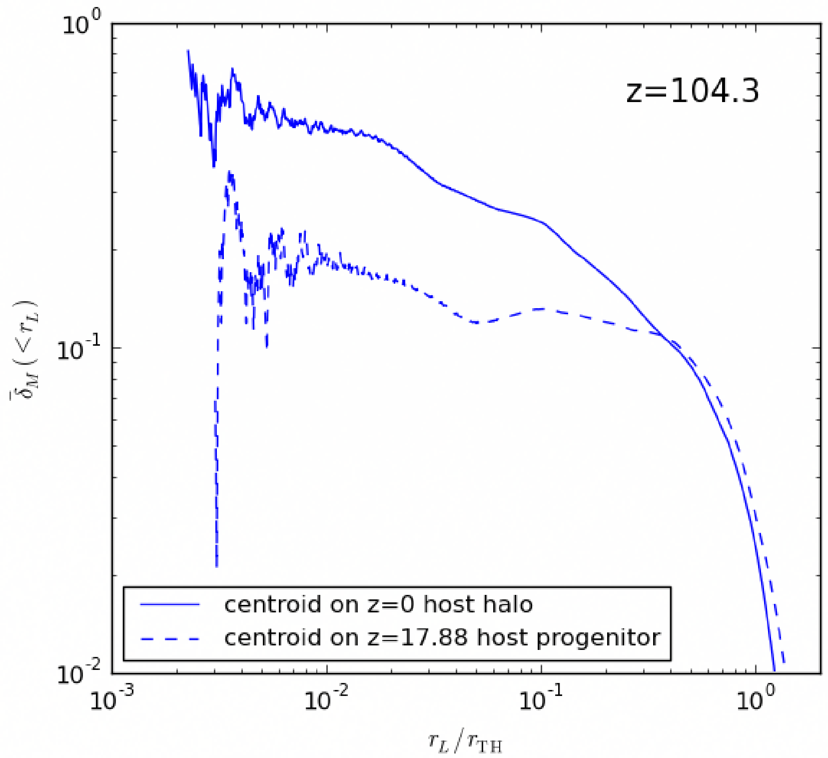
In Dalal, Lithwick, & Kuhlen (2011) we demonstrated that it's possible to predict the density profile of the collapsed halo from the initial linear density peak.

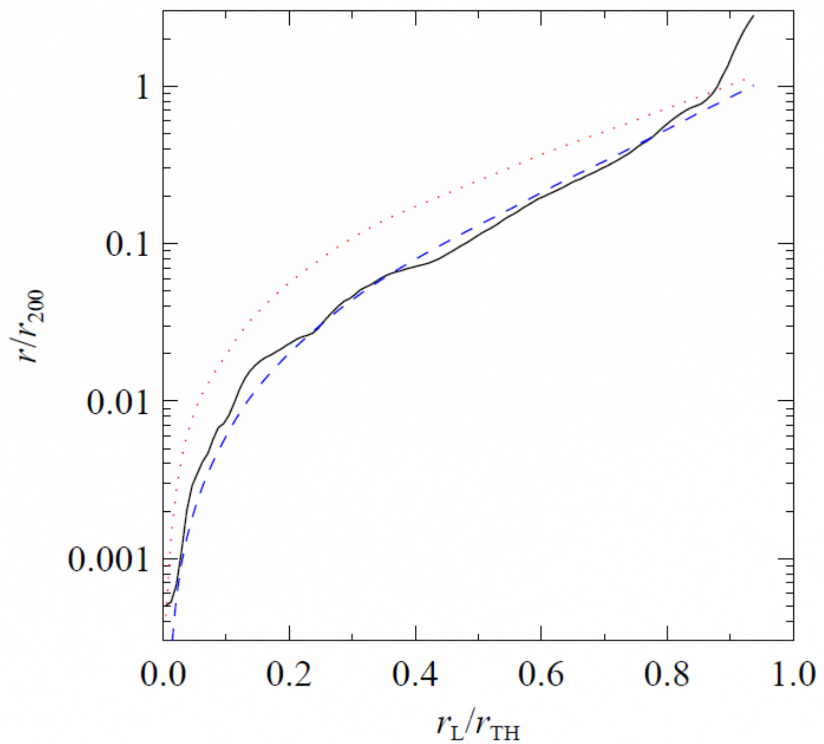
Initial peak profile

$$\bar{\delta}_{\mathrm{M}}(r) = \frac{\mathrm{M}(<r) - \overline{\mathrm{M}}(<r)}{\overline{\mathrm{M}}(<r)}$$

Can predict collapsed median shell radius, assuming only “adiabaticity” – the invariance of the radial action during collapse:

$$r_f \times M(<r_f) = r_{\mathrm{ta}} \times M(<r_{\mathrm{ta}})$$





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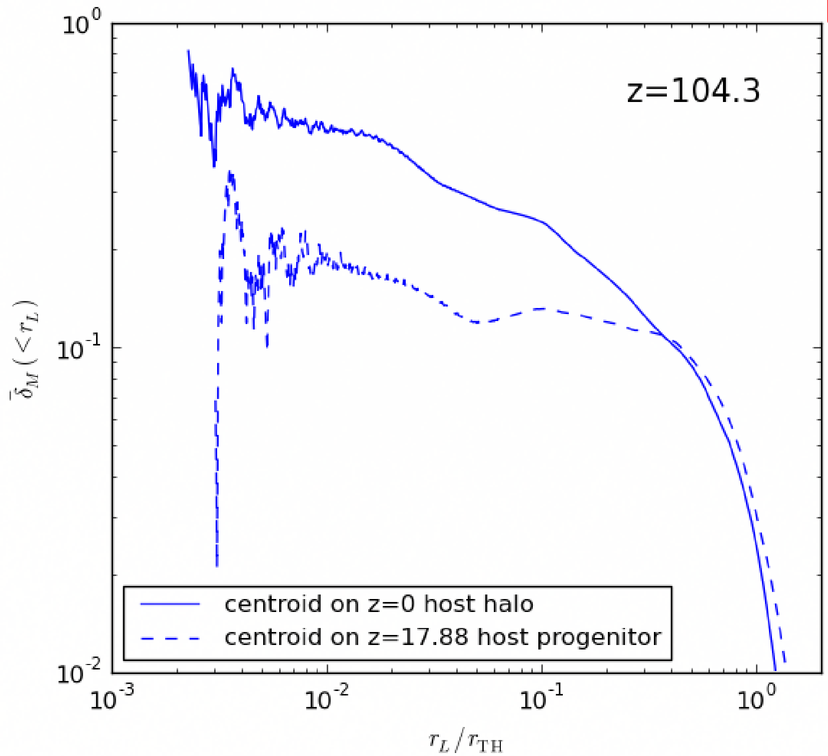
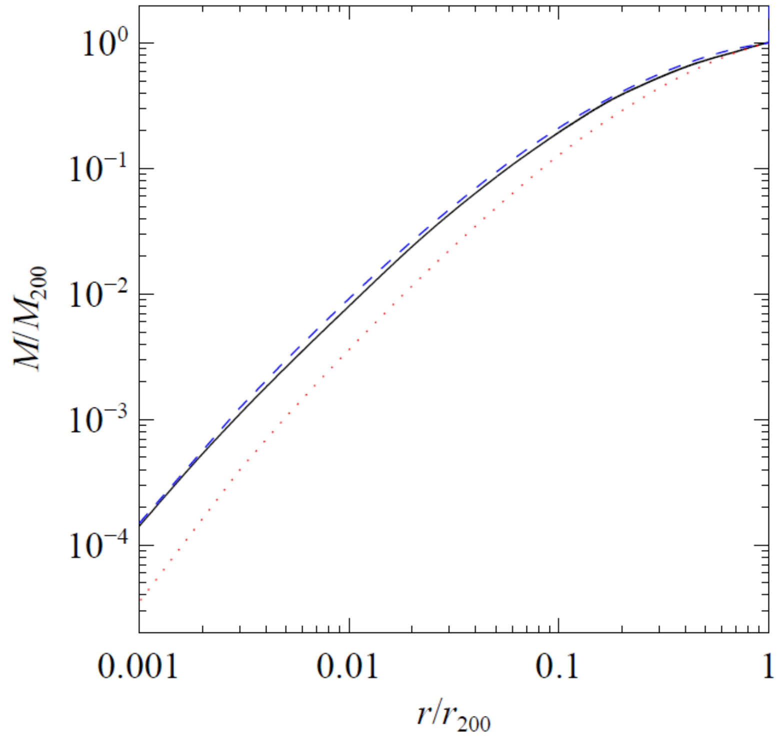
Initial peak profile

$$\bar{\delta}_{\rm M}(r) = \frac{{\rm M}(<r) - \overline{\rm M}(<r)}{\overline{\rm M}(<r)}$$

Making a simple assumption of $\rho_{\rm shell}$(r), the density profile deposited by a simple shell, the final collapsed halo density profile is given by this ODE:

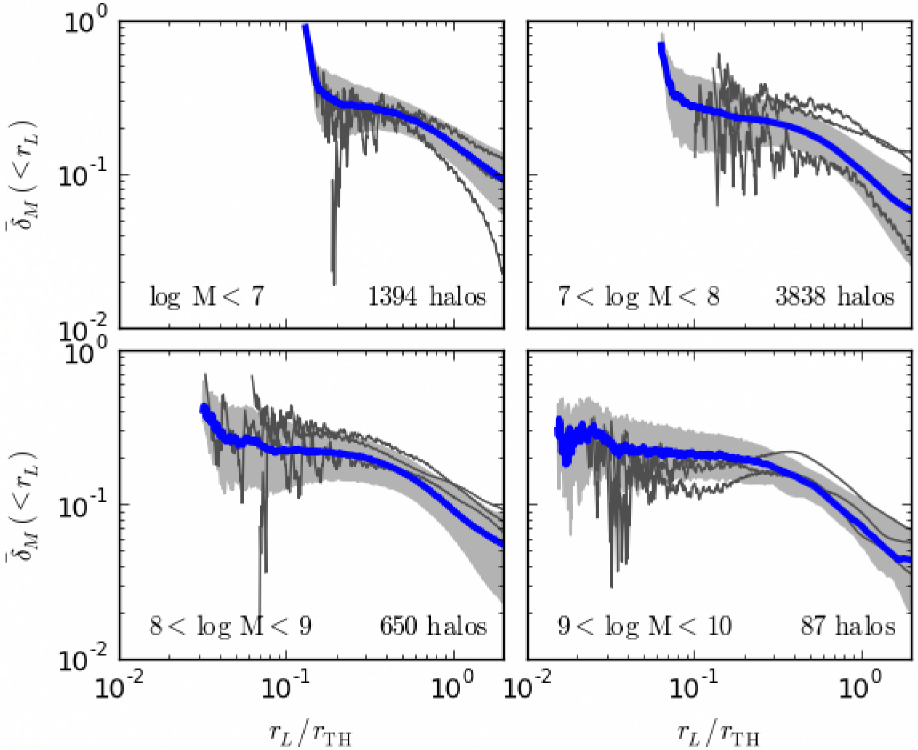
$$\frac{dM}{dr} = \frac{3M}{r}\frac{M - F^{-1}(Mr)}{M + F^{-1}(Mr)}$$



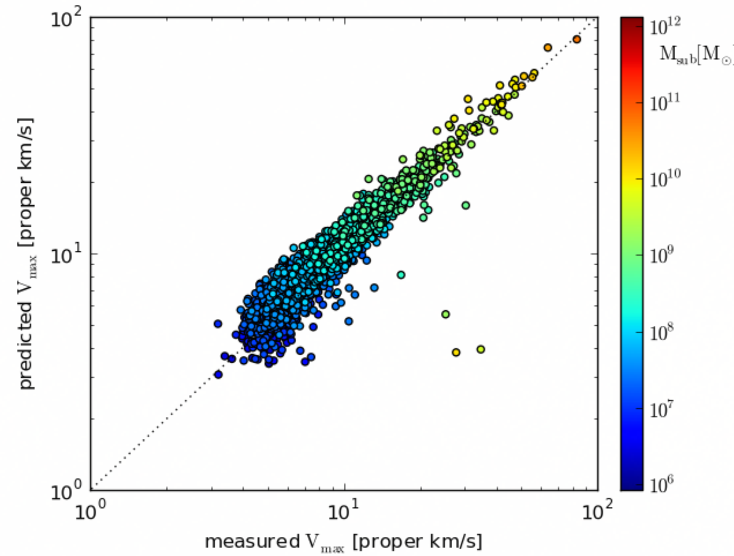


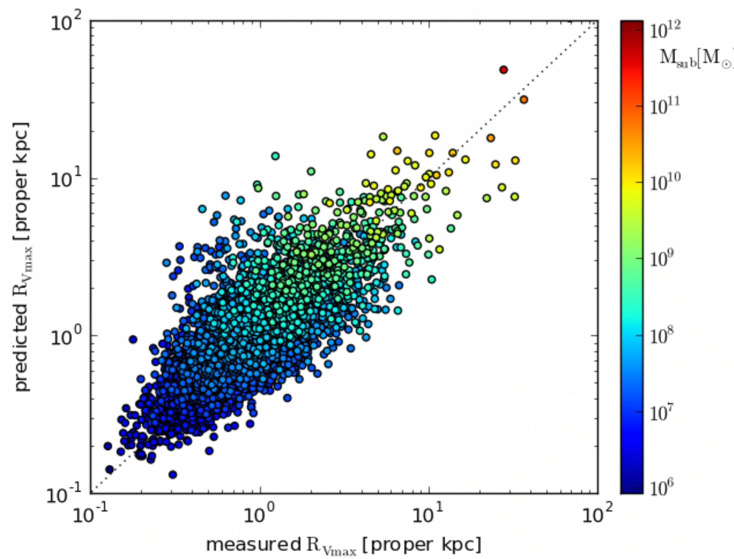
Recent Progress in Understanding The Origin of NFW

Initial peak profile for VL2 subhalos



Goal: extend this to masses below the simulations resolution limit and calculate a **concentration(mass) relation**.
Need: analytic prescription for initial peak profiles from Gaussian statistics for peaks-within-peaks, BBKS for sub-peaks.



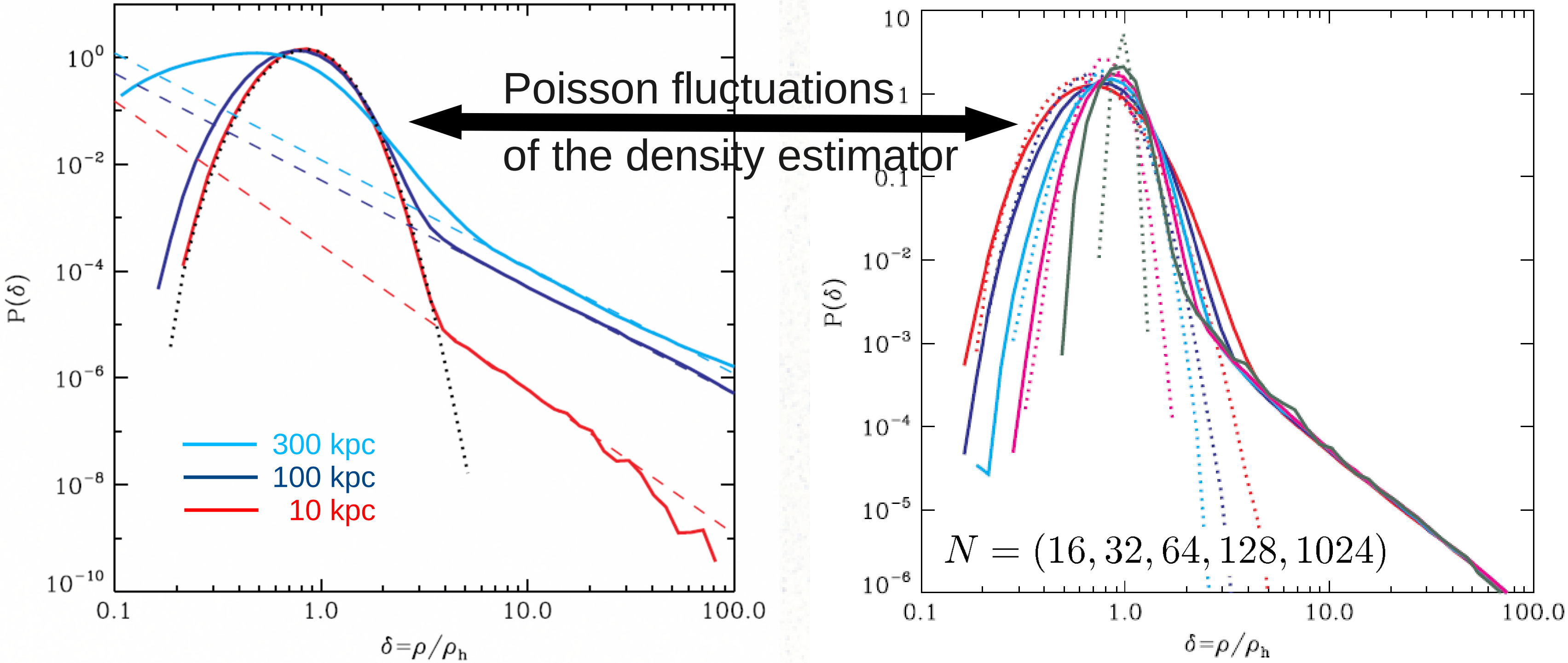


Kuhlen, Dalal, & Lithwick (in prep.)

Substructure Boost: Density Distribution Approach

Measure the PDF of ρ/ρ_{host} in the simulation.

It's fit well by a **log-normal** plus a **powerlaw** tail due to substructure.



$$P(\rho;r) = \frac{f_s}{\sqrt{2\pi\Delta^2}}\frac{1}{\rho}\exp\left\{-\frac{1}{2\Delta^2}\left[\ln\left(\frac{\rho}{\rho_h}e^{\Delta^2/2}\right)\right]^2\right\} + (1-f_s)\frac{1+\alpha(r)}{\rho_h}\Theta(\rho-\rho_h)\left(\frac{\rho}{\rho_h}\right)^{-(2+\alpha}},$$

$\alpha \approx 0.0 \pm 0.1$

$$\boxed{1 - f_s(r) = 7 \times 10^{-3}\left(\frac{\bar{\rho}(r)}{\bar{\rho}(r = 100\ \text{kpc})}\right)^{-0.26}}$$

Kamionkowski, Koushiappas & Kuhlen (2010)

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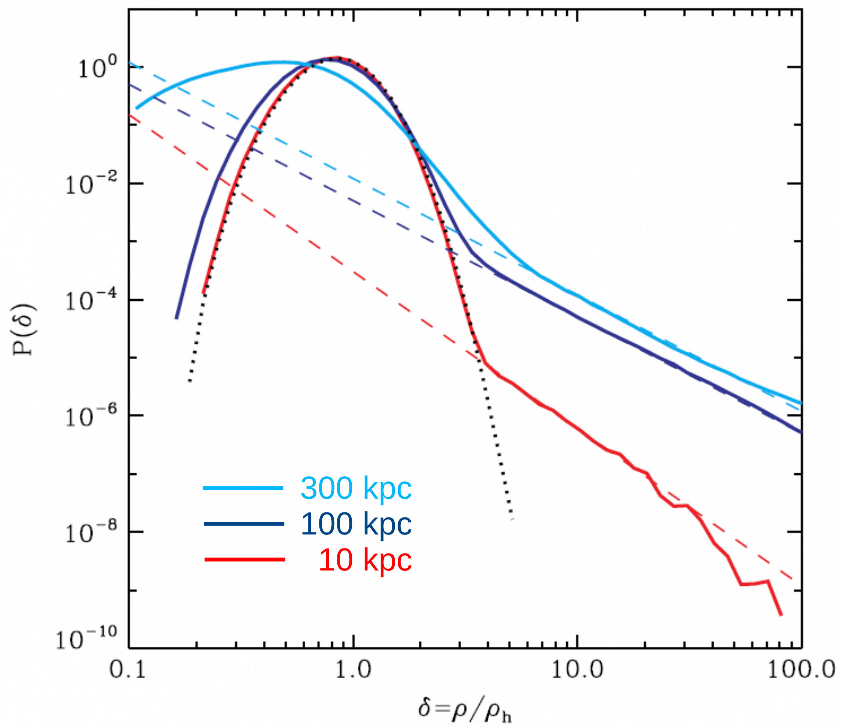

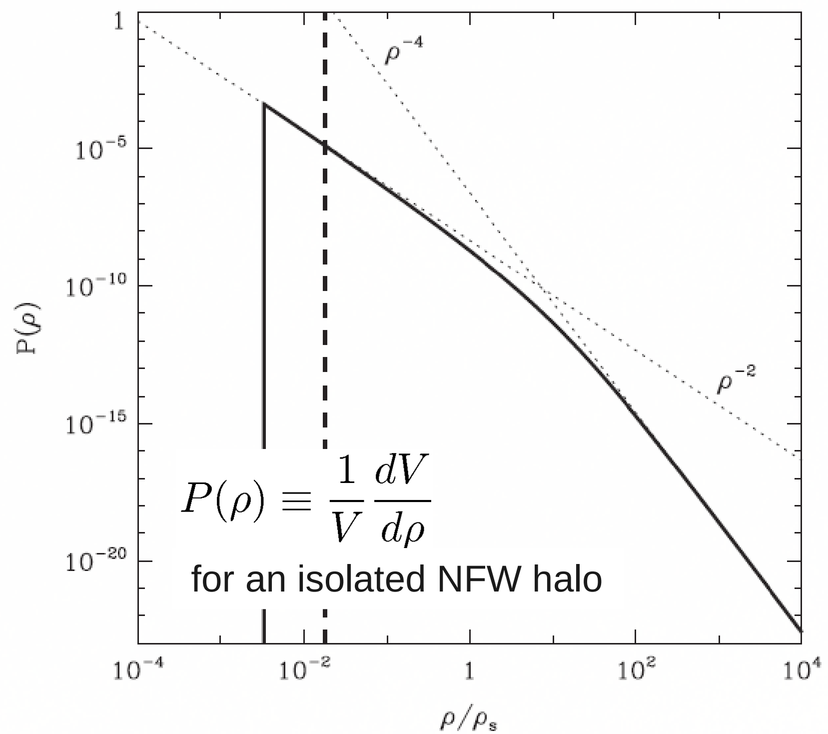

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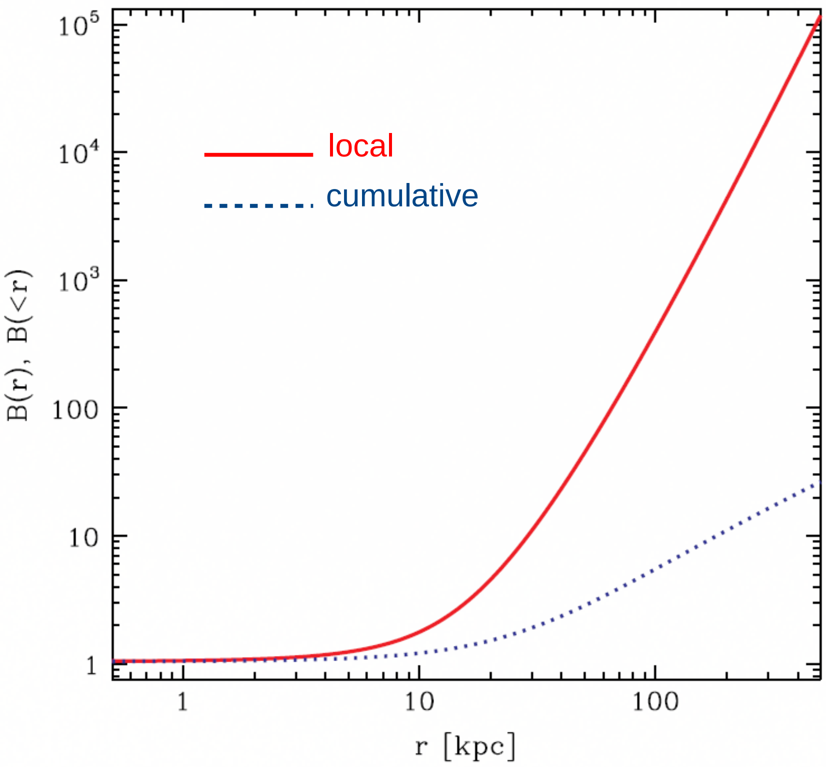
Use this distribution to calculate a boost factor as a function of radius.



$$B(r) = \frac{\int \rho^2 dV}{\int [\bar{\rho}(r)]^2 dV} = \int_0^{\rho_{\max}} P(\rho, r) \frac{\rho^2}{[\bar{\rho}(r)]^2} d\rho$$

$$B(r) = f_s e^{\Delta^2} + (1 - f_s) \frac{1 + \alpha}{1 - \alpha} \left[\left(\frac{\rho_{\max}}{\rho_h} \right)^{1-\alpha} - 1 \right].$$

Depends on ρ_{max}, which is set by the halo collapse epoch:

$$\rho_{\max} = 80\,\mathrm{GeV\,cm^{-3}} \left(\frac{z_c}{40} \right)^3 \left(\frac{c}{3.5} \right) \frac{f(3.5)}{f(c)}$$

[Here c is the **natal** concentration!]

The biggest uncertainty is in $f_s(r)$.

Kamionkowski, Koushiappas & Kuhlen (2010)

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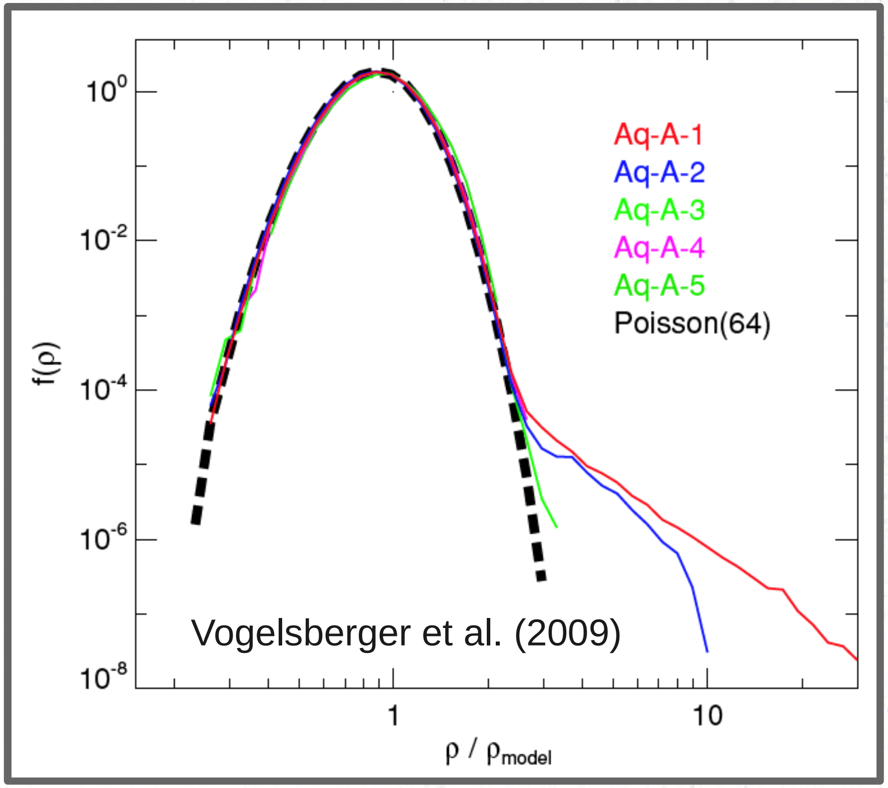

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Kamionkowski, Koushiappas & Kuhlen (2010)

Conclusions

- Abundant dark matter substructure can substantially boost the annihilation flux from external sources.
- The total luminosity boost factor critically depends on the extrapolation of the subhalo concentration-mass relation.
- Thanks to recent advances in our understanding of the origin of the DM halo density profile, it may soon be possible to put this c(M) relation on a firmer footing.
- Two completely independent approaches (subhalo- and $P(\delta)$-based) to calculating the boost factor give comparable results.
- There is not simply one substructure boost factor! It depends on location, signal type, and whether the source is angularly resolved.
- In particular, even a substantial total luminosity boost may not greatly enhance the detectability of a resolved source, if the boost applies mostly to the faint outskirts.
- The local (8 kpc) boost is unlikely to be larger than a few.