Gamma-ray background anisotropy from Galactic dark matter substructure

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Ando, arXiv:0903.4685 [astro-ph.CO]

1. Introduction

Dark matter annihilation and substructure

- Dark matter: 80% of matter content of the Universe; known to be nonbaryonic
- Candidate: Weakly Interacting Massive Particle (WIMP), e.g., supersymmetric neutralino
  - WIMP mass is around GeV–TeV scale

Two important features:

✓ WIMPs may annihilate into gamma rays

✓ WIMPs may form substructure with scales down to ~ Earth mass

Where to look for annihilation signature

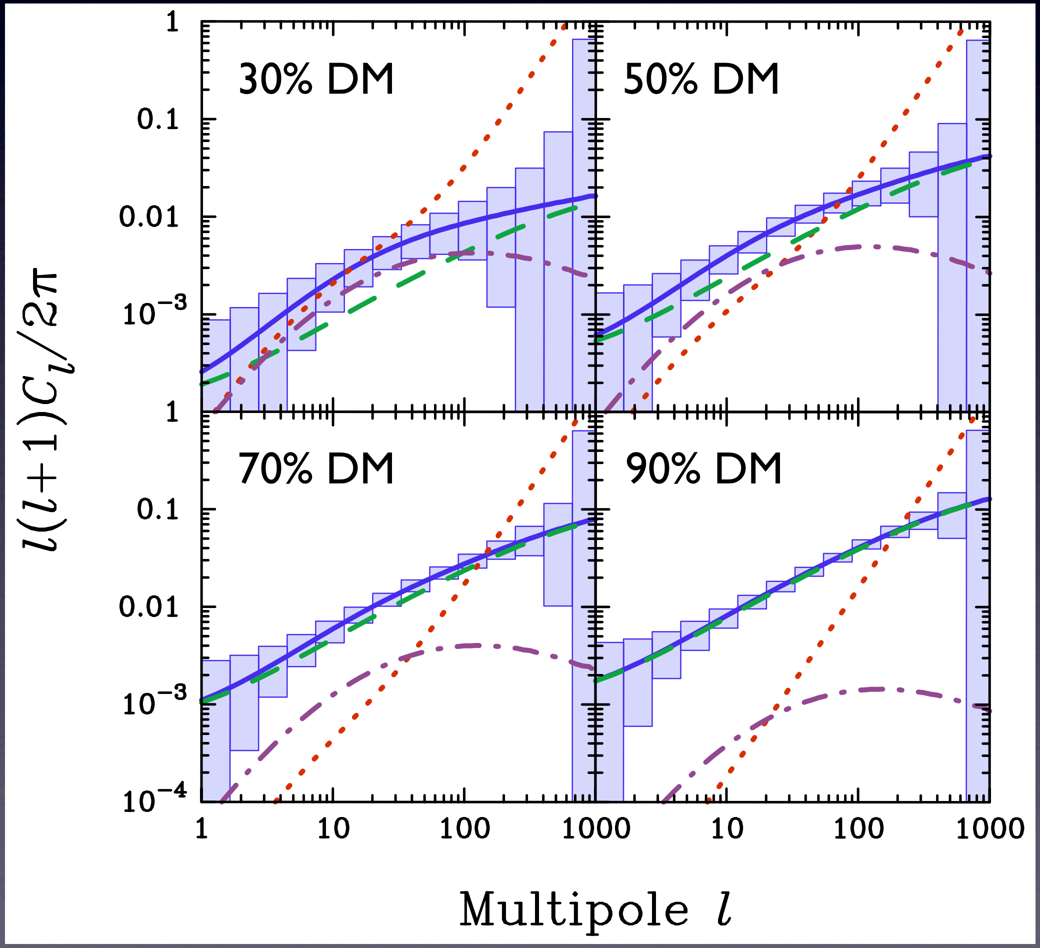
- Galactic center
- Nearby dwarf galaxies
- Nearby subhalos
- Diffuse background radiation
- Etc.

Dark matter substructure seen by simulations
e.g., Diemand, Kuhlen, Madau, *Astrophys. J.* **657**, 262 (2007)

Gamma-ray background anisotropy

- Most DM halos/subhalos are individually dim
- But they all give contribution to the diffuse gamma-ray background

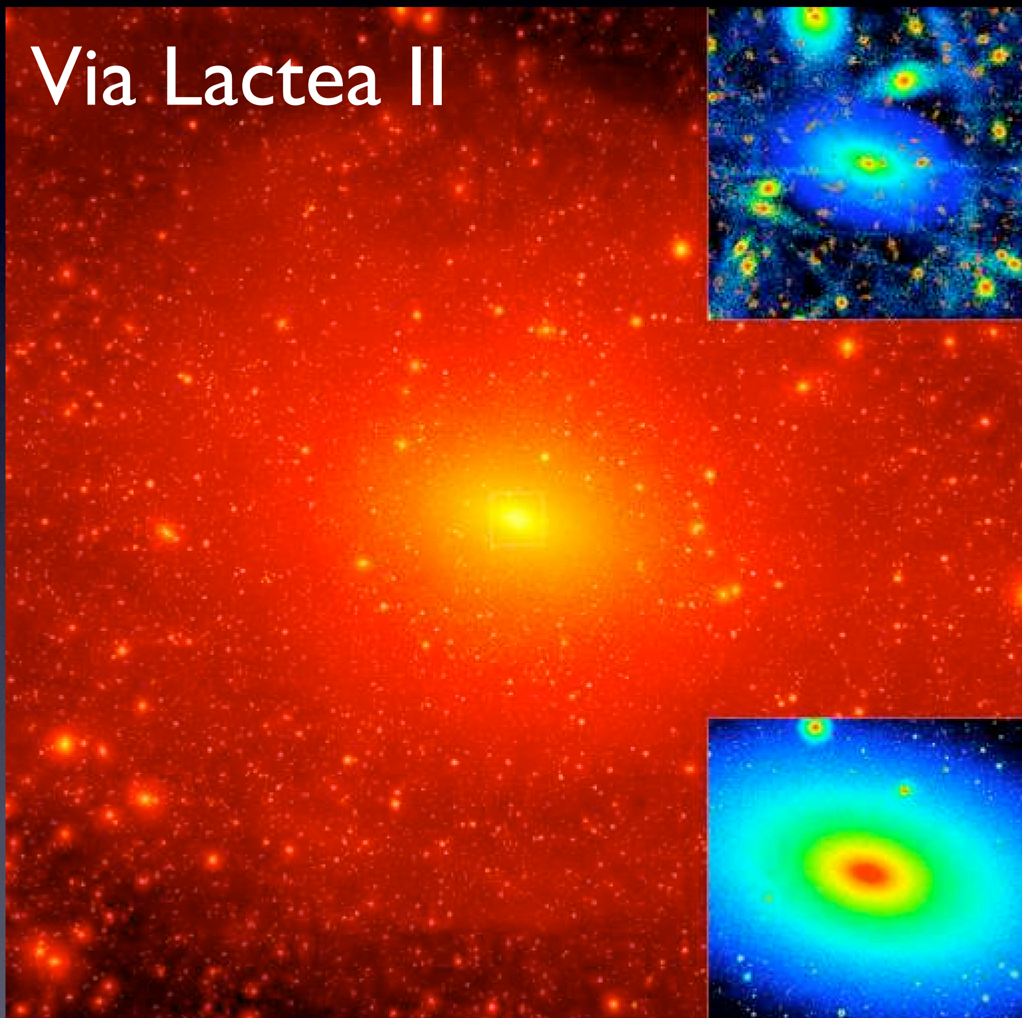
- We might see characteristic signature in the angular power spectrum
  - This was done by Ando & Komatsu (2006) followed by several people
  - DM component can excel in angular power spectrum even if they are subdominant in flux
  - These studies focused on extragalactic DM halos



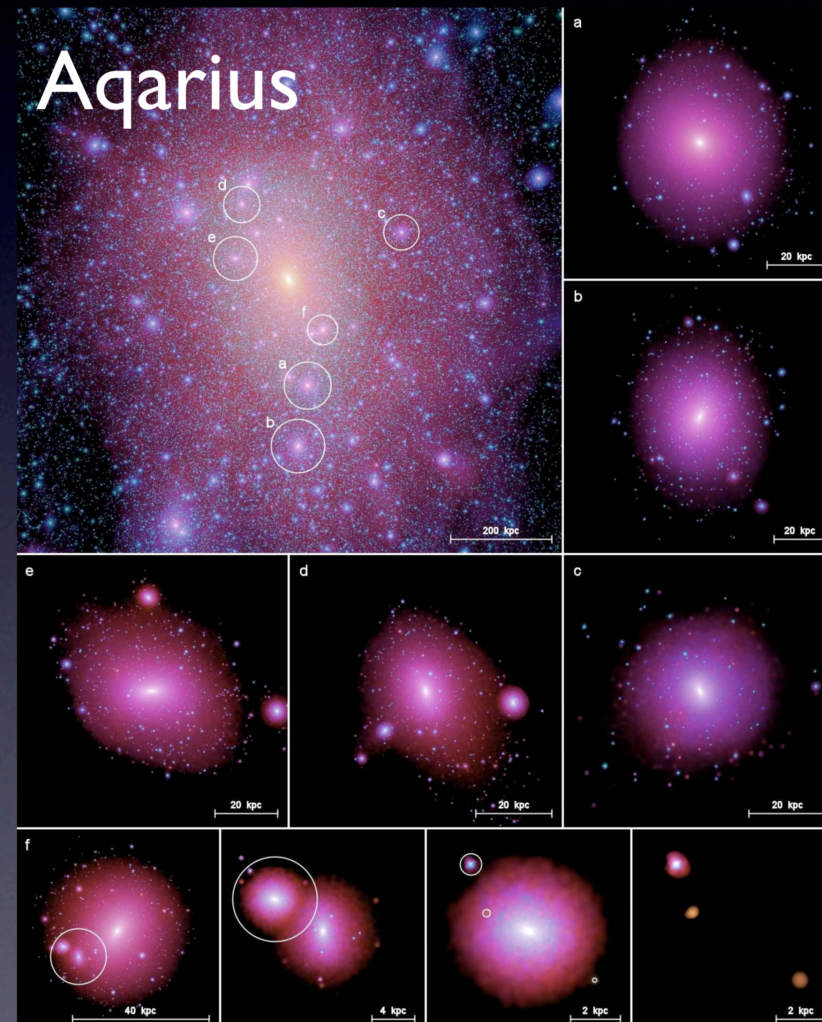
Ando et al., *Phys. Rev. D* **75**, 063519 (2007)

Galactic dark matter substructure

- There is an increasing interest in Milky Way substructure...

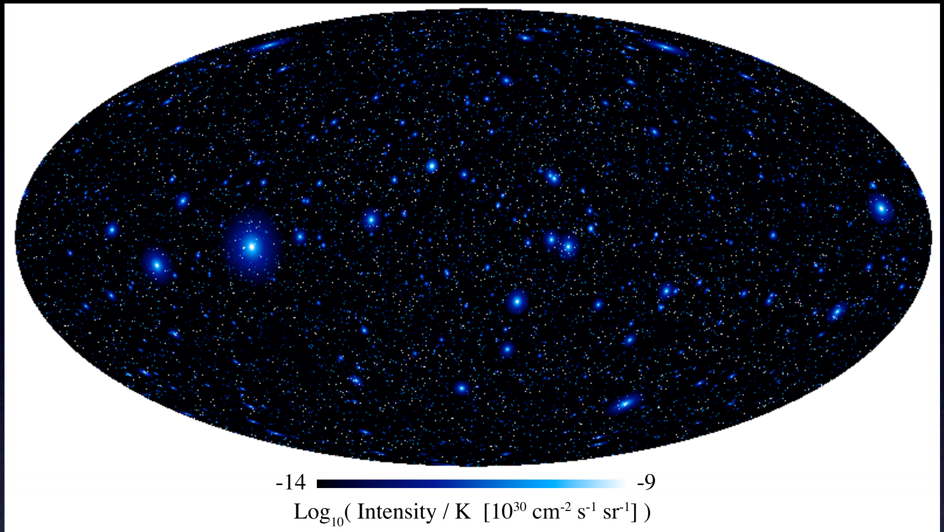


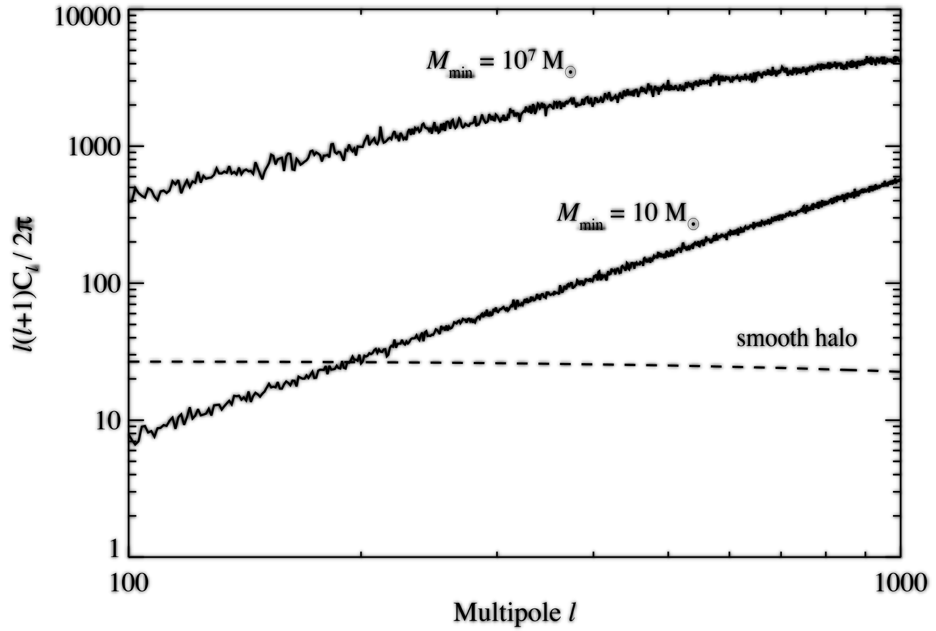
Diemand et al., *Nature* **454**, 735 (2008)



Springel et al., *MNRAS* **391**, 1685 (2008)

Anisotropy from MW subhalos





Siegal-Gaskins, *JCAP* **10**, 40 (2008)

- Angular power spectrum from MW subhalos has been studied using simulated gamma-ray map

  Siegal-Gaskins (2008); Fornasa et al. (2009)

- Subhalo anisotropies are characteristic and large
- But how do we extract physics information from data?
  - It's hard to do that by this approach
- We do need analytic approach!

Approach in this work

Angular power spectrum, C_l

Approach in this work

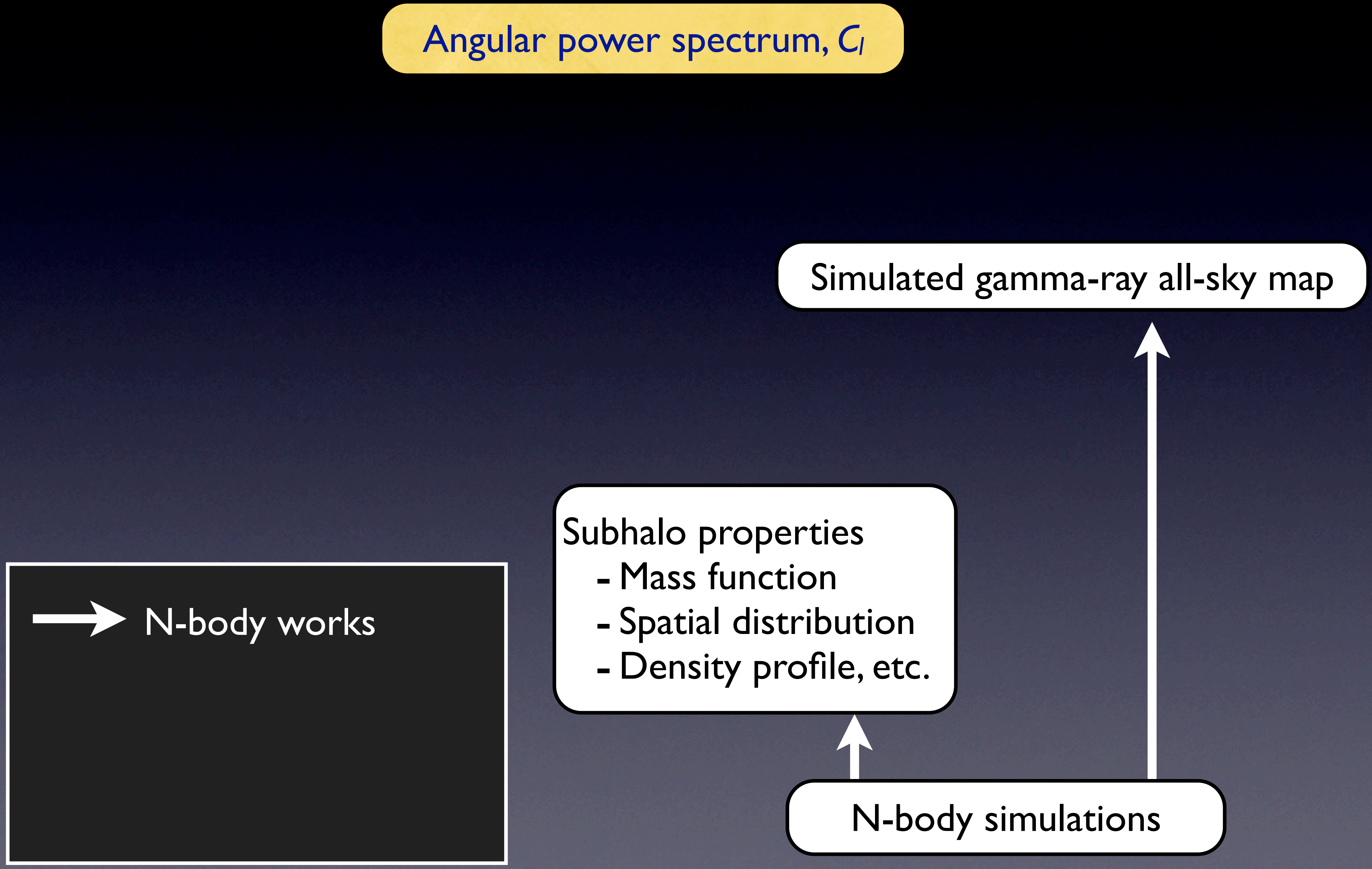
Angular power spectrum, C_l

Subhalo properties
- Mass function
- Spatial distribution
- Density profile, etc.

N-body simulations

→ N-body works

Approach in this work



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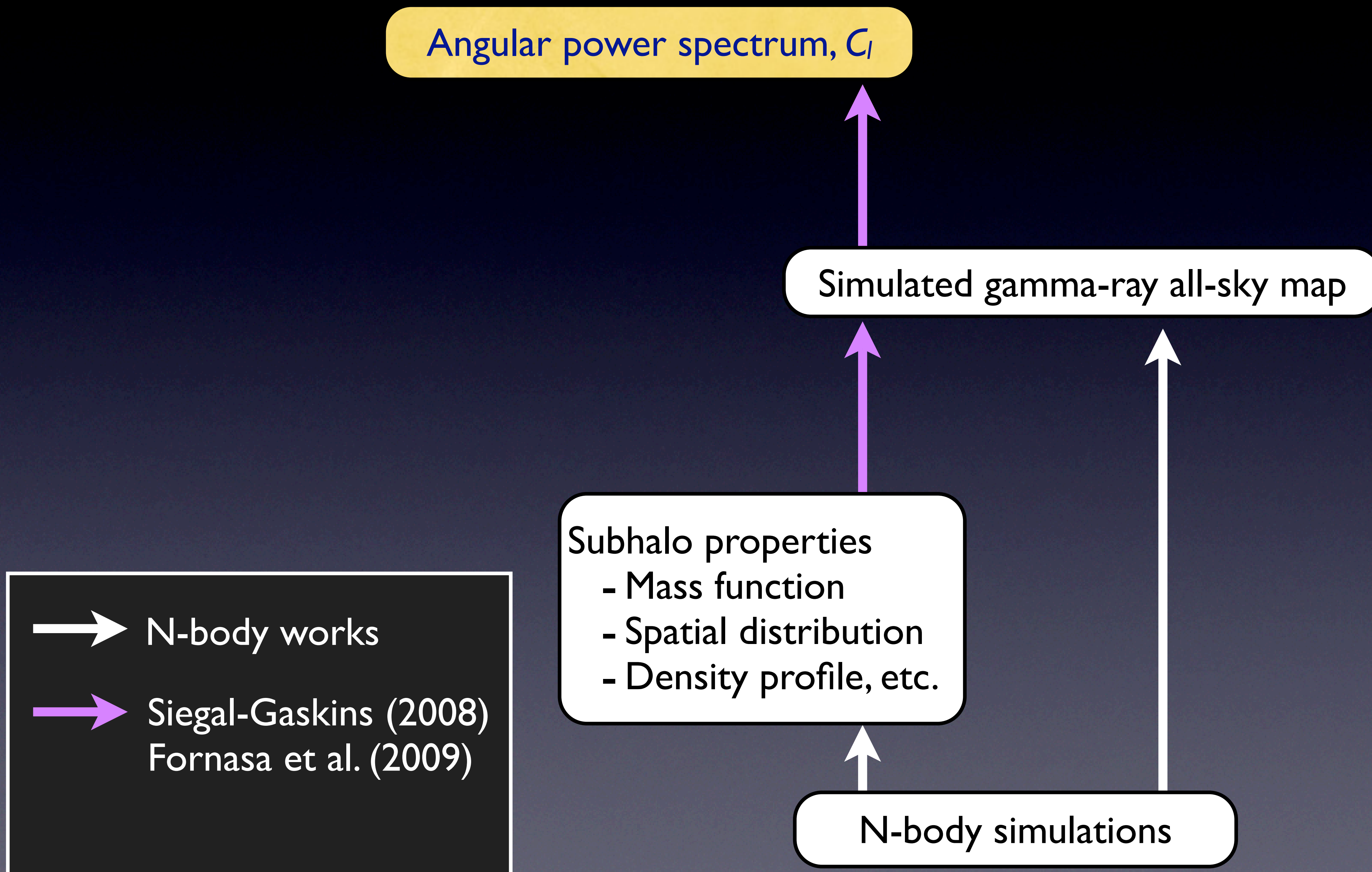

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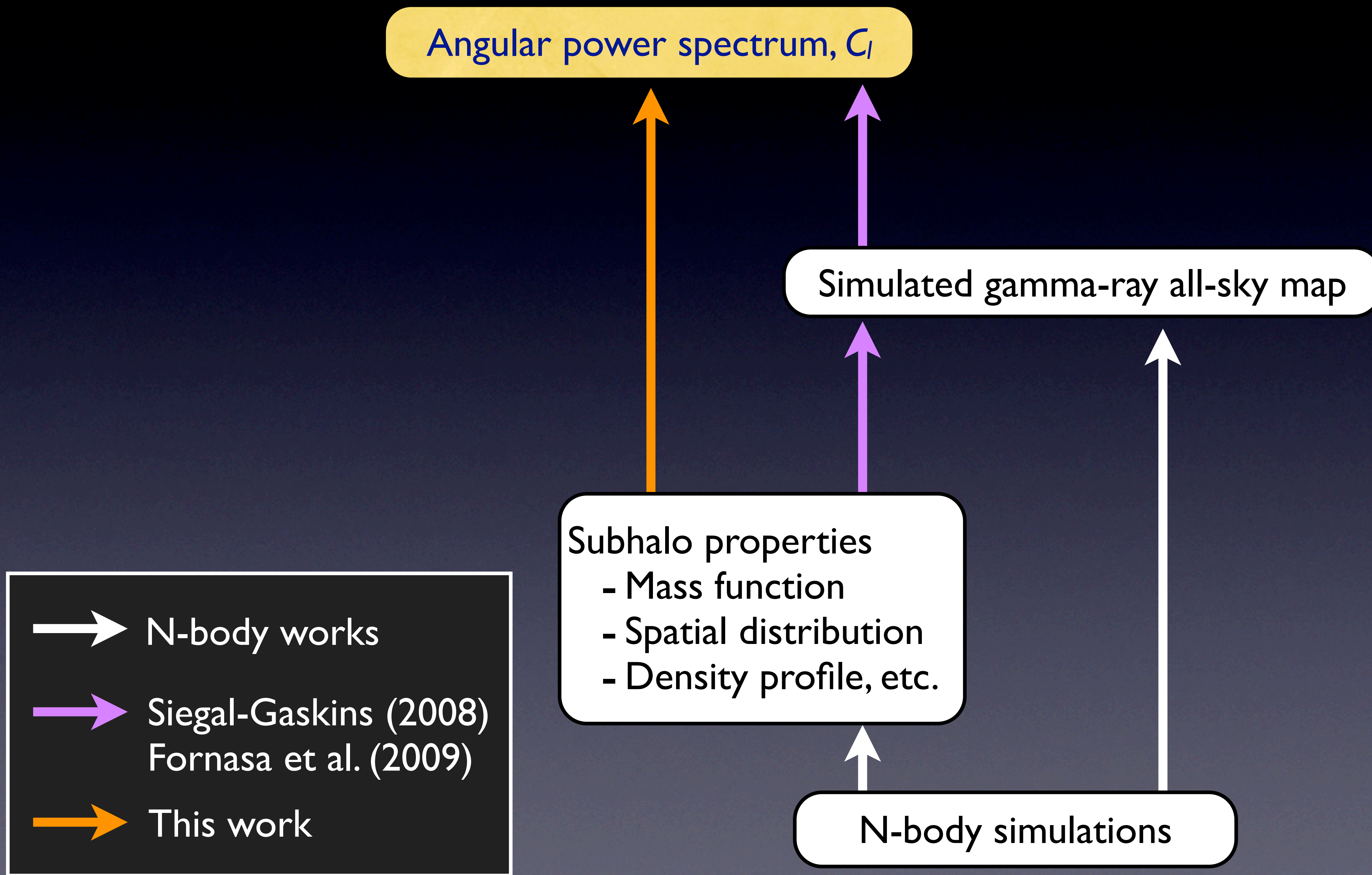

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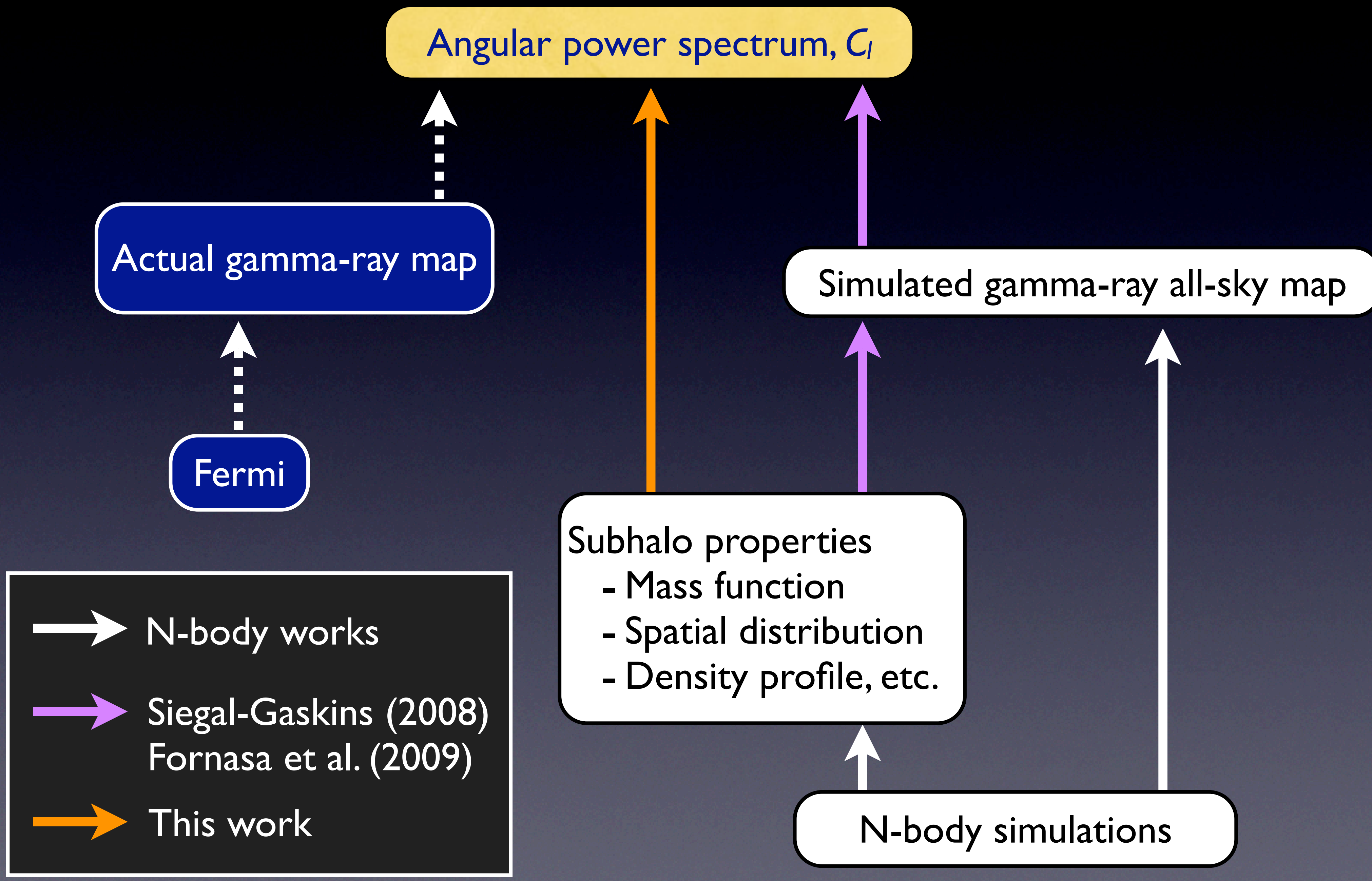

2. Formulation

Halo model

Seljak 2000; Cooray & Sheth 2002

- Analytic prescription to get matter/galaxy power spectrum including nonlinear regime

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  1. Distribute halo *seeds* following linear matter power spectrum

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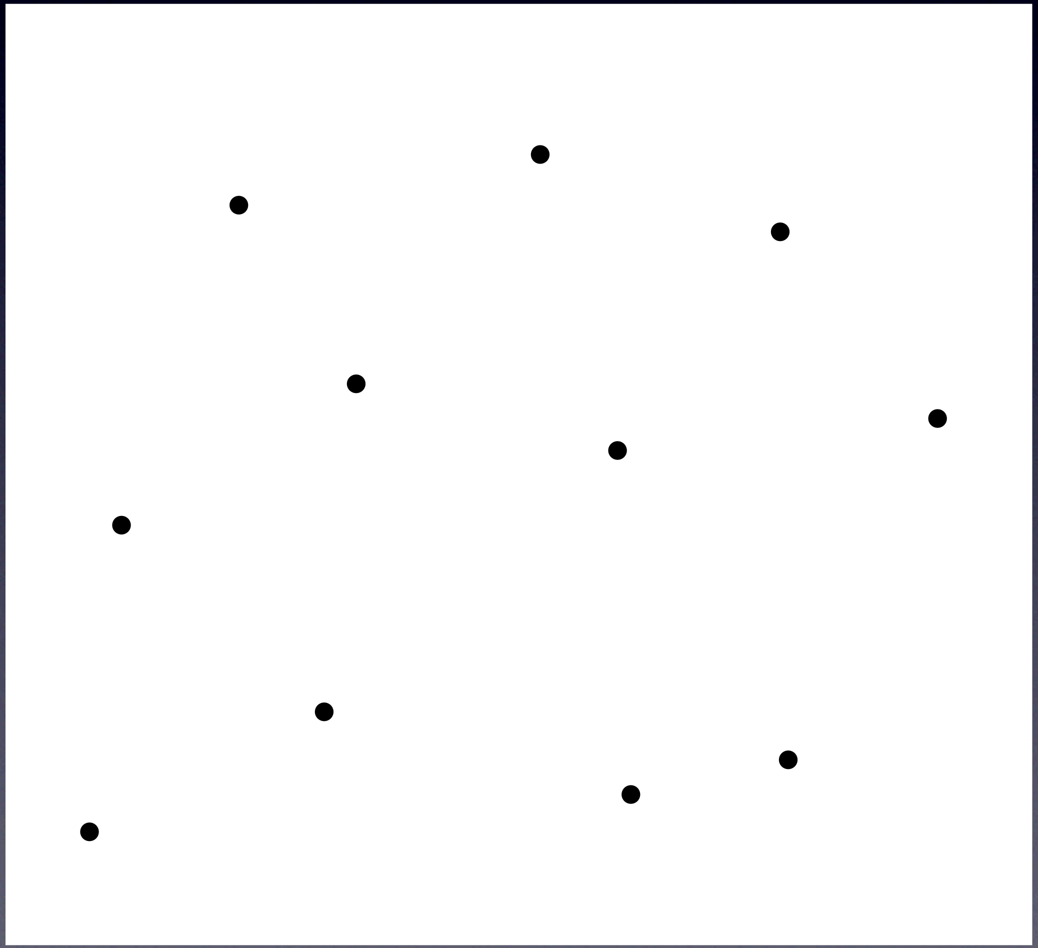

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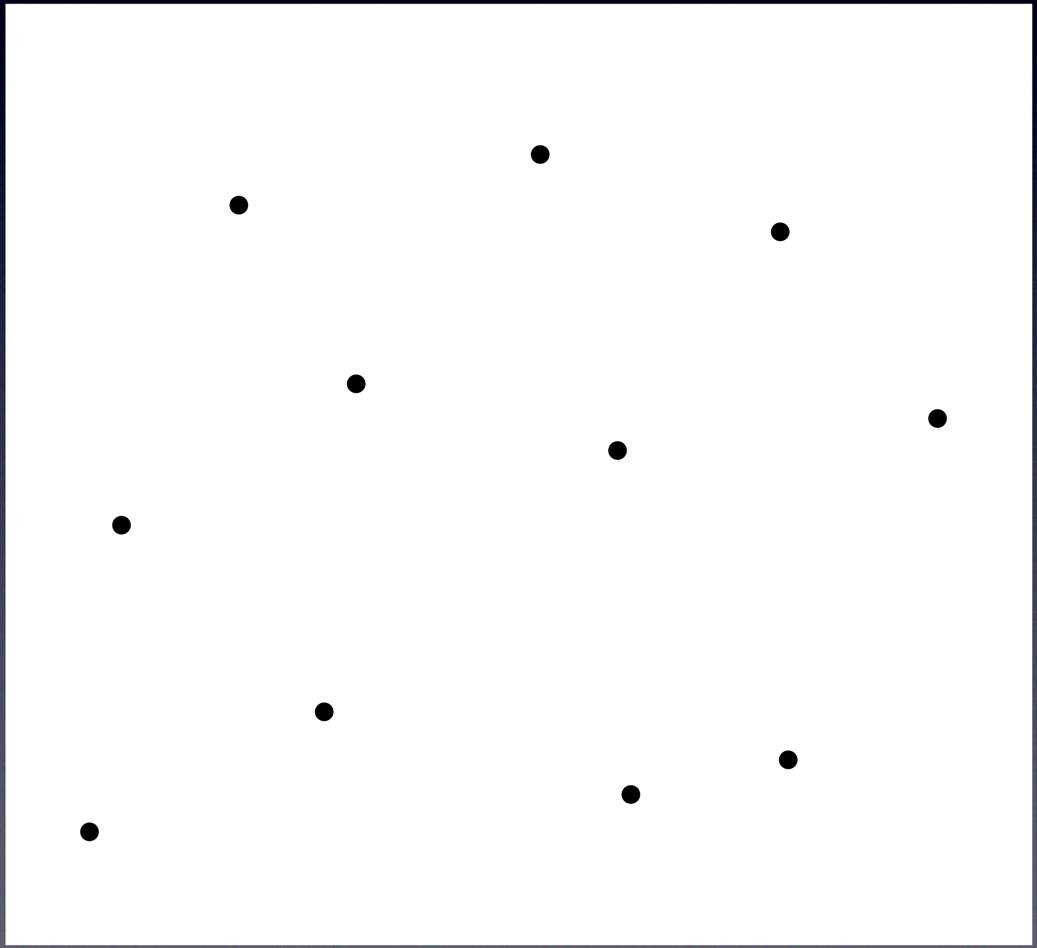

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  1. Distribute halo *seeds* following linear matter power spectrum
  2. Surround each halo by NFW density profile

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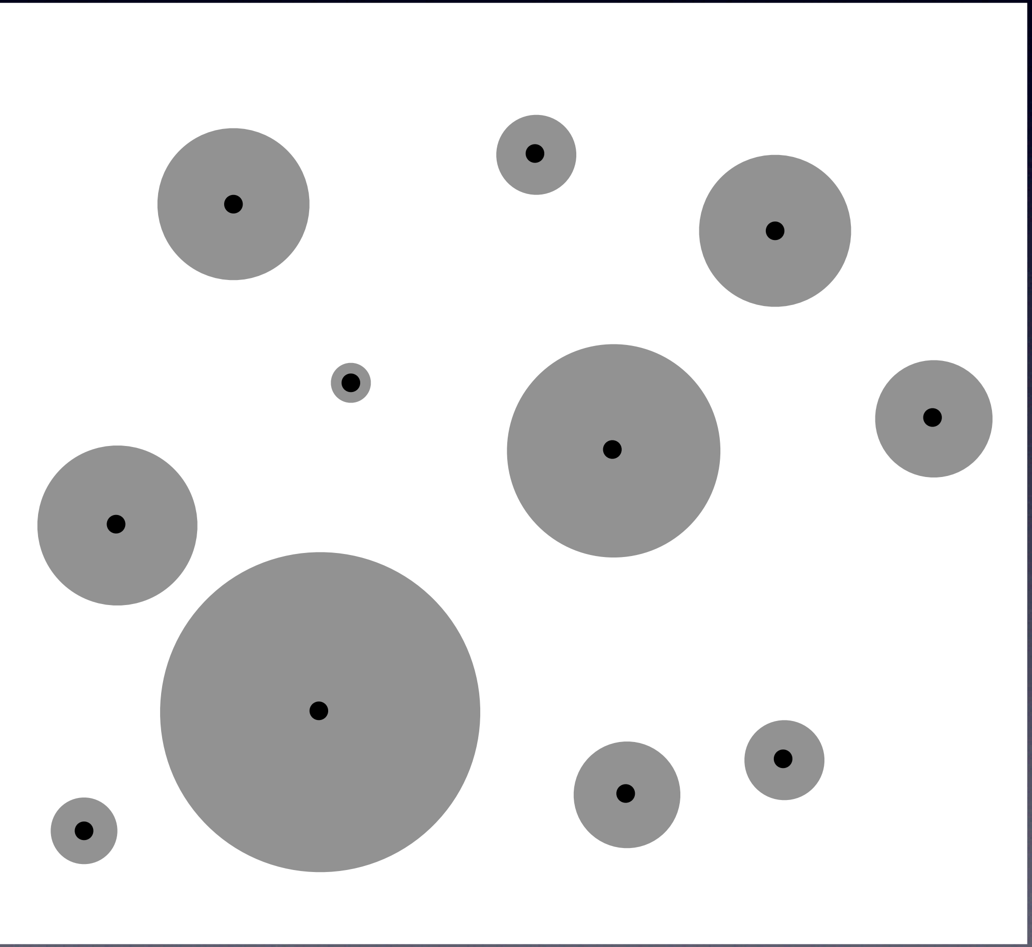

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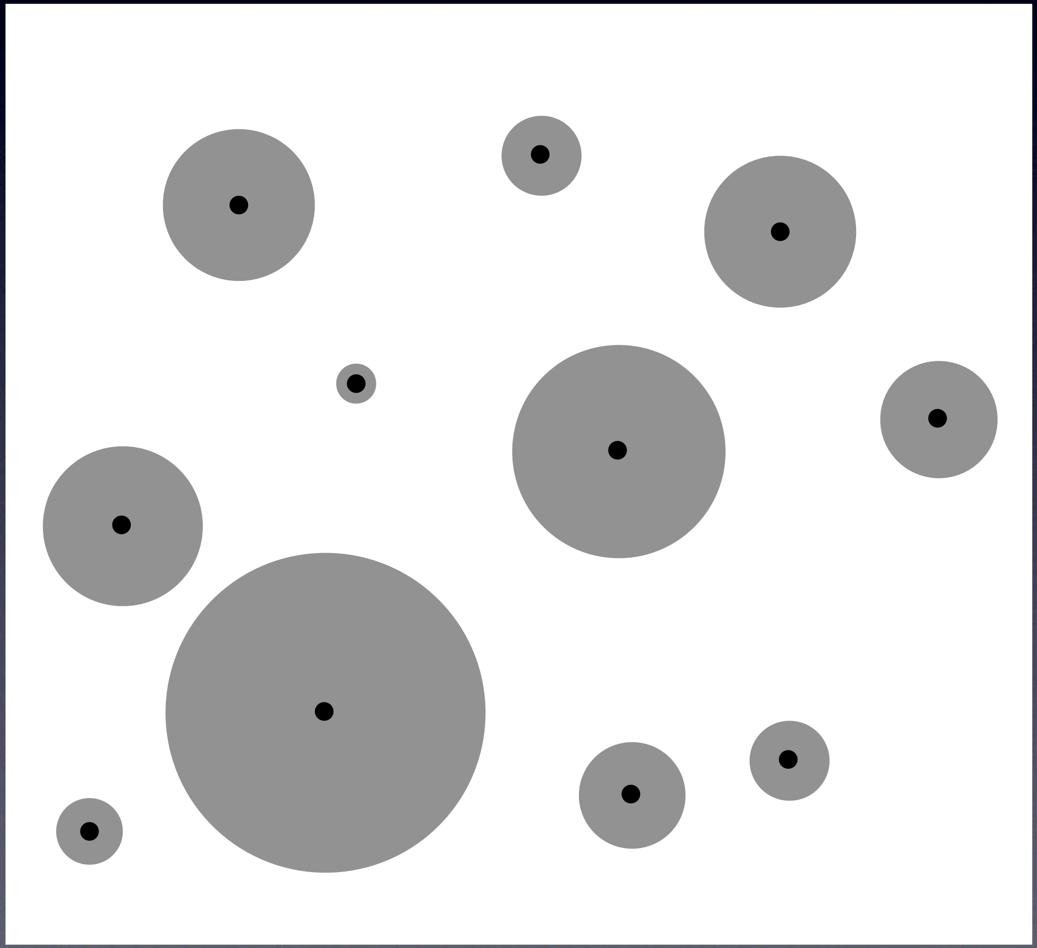

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  1. Distribute halo *seeds* following linear matter power spectrum
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  3. Evaluate $\langle\delta(\mathbf{x})\delta(\mathbf{y})\rangle$ as a function of $r = |\mathbf{x}-\mathbf{y}|$

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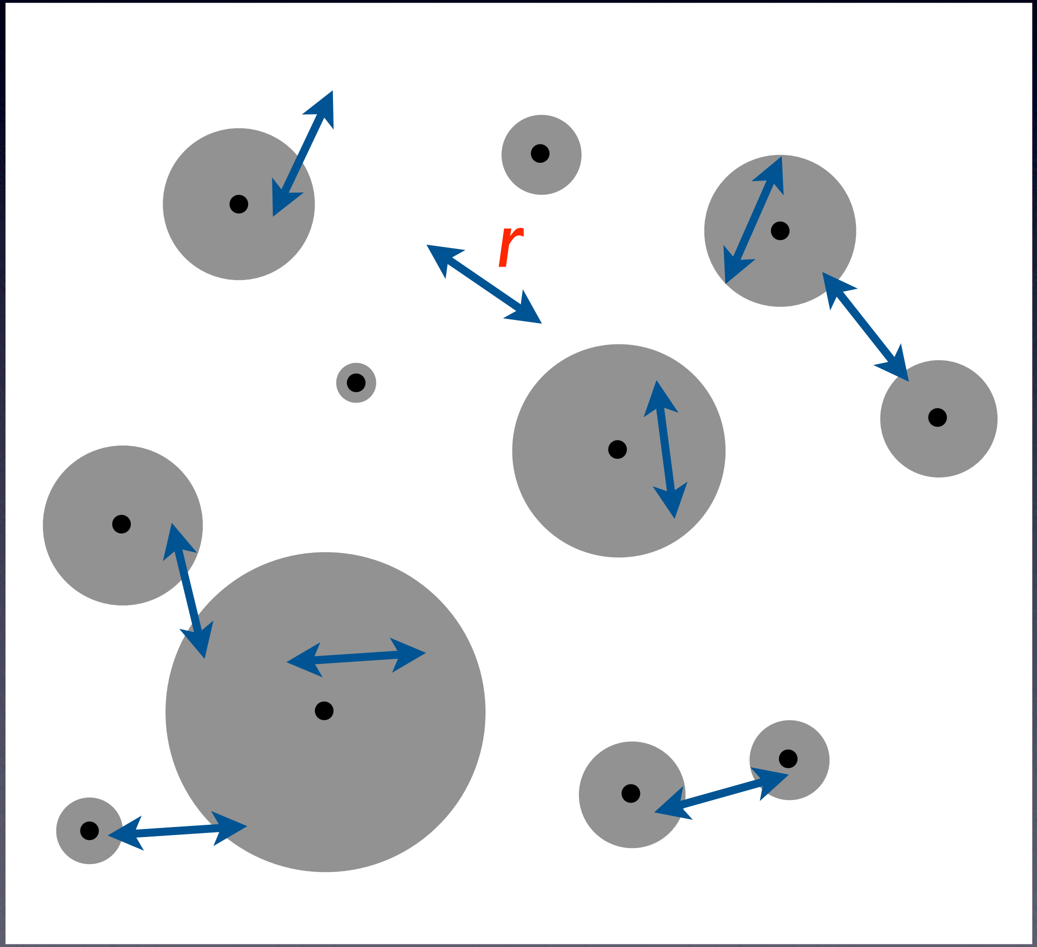

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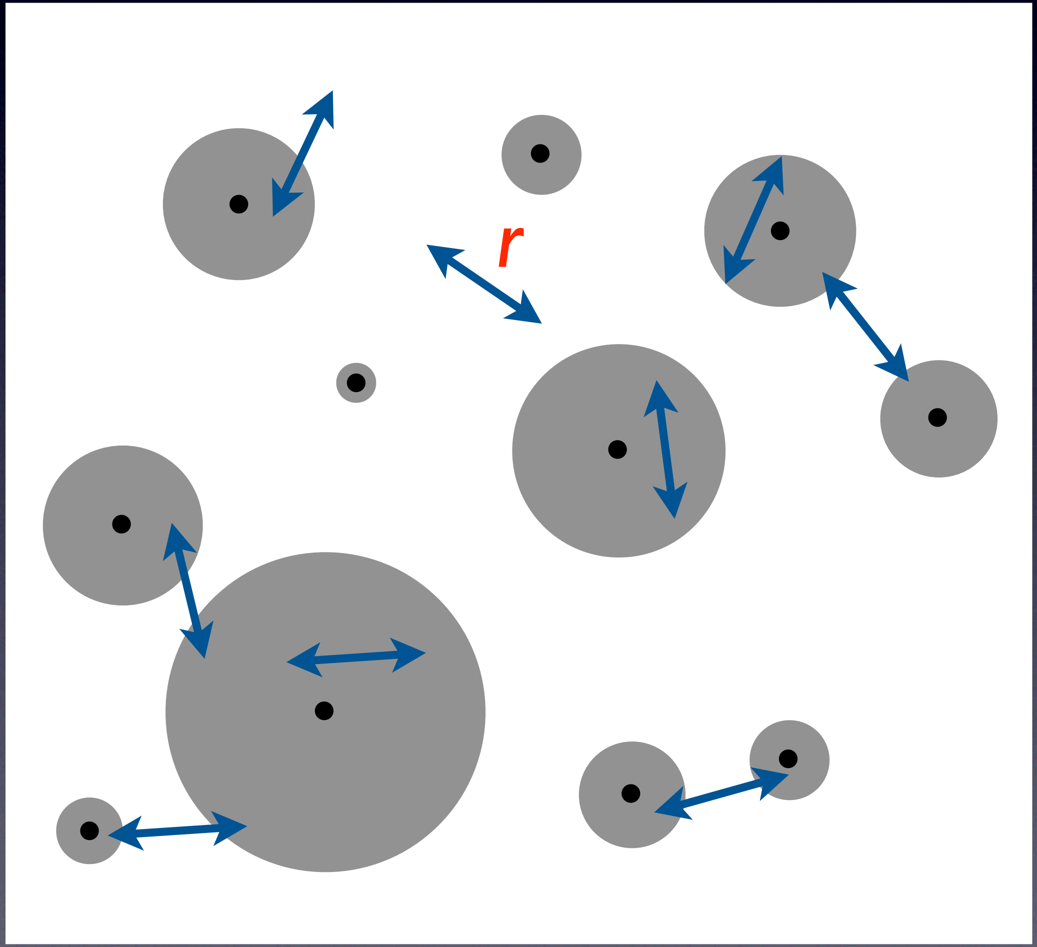

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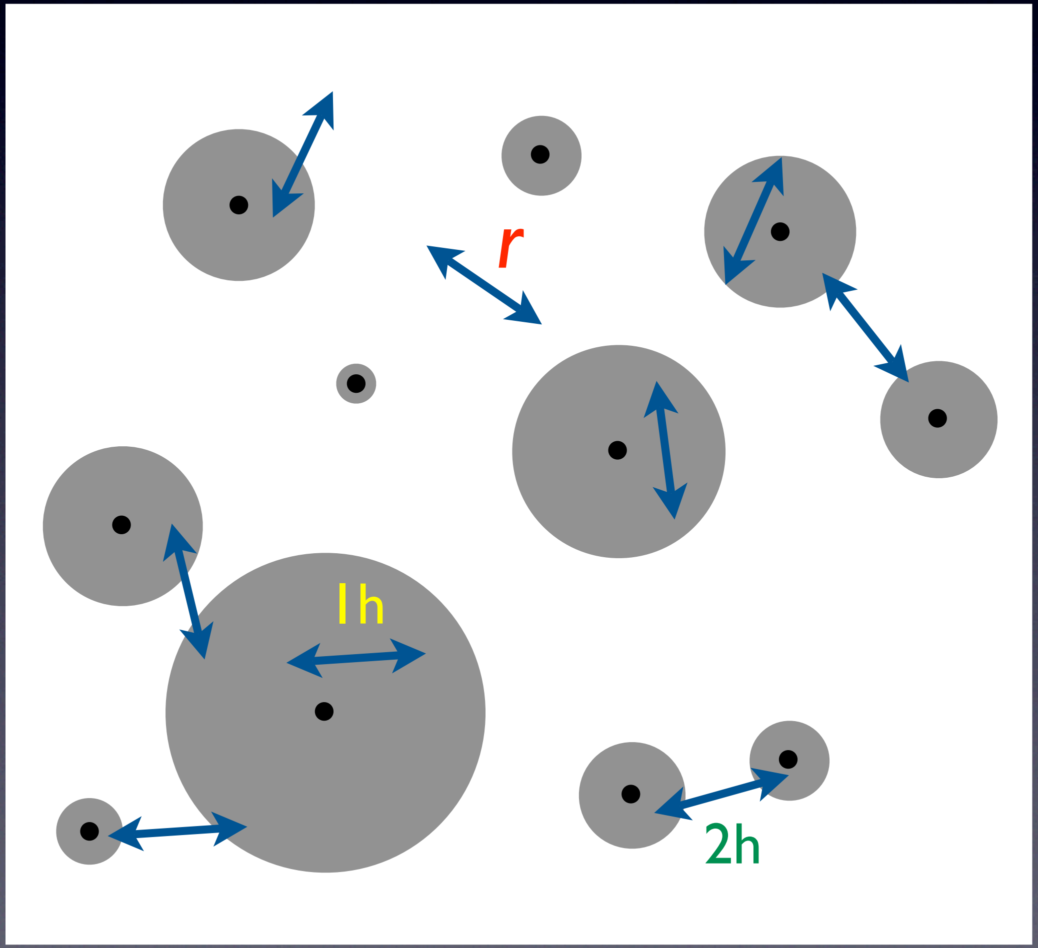

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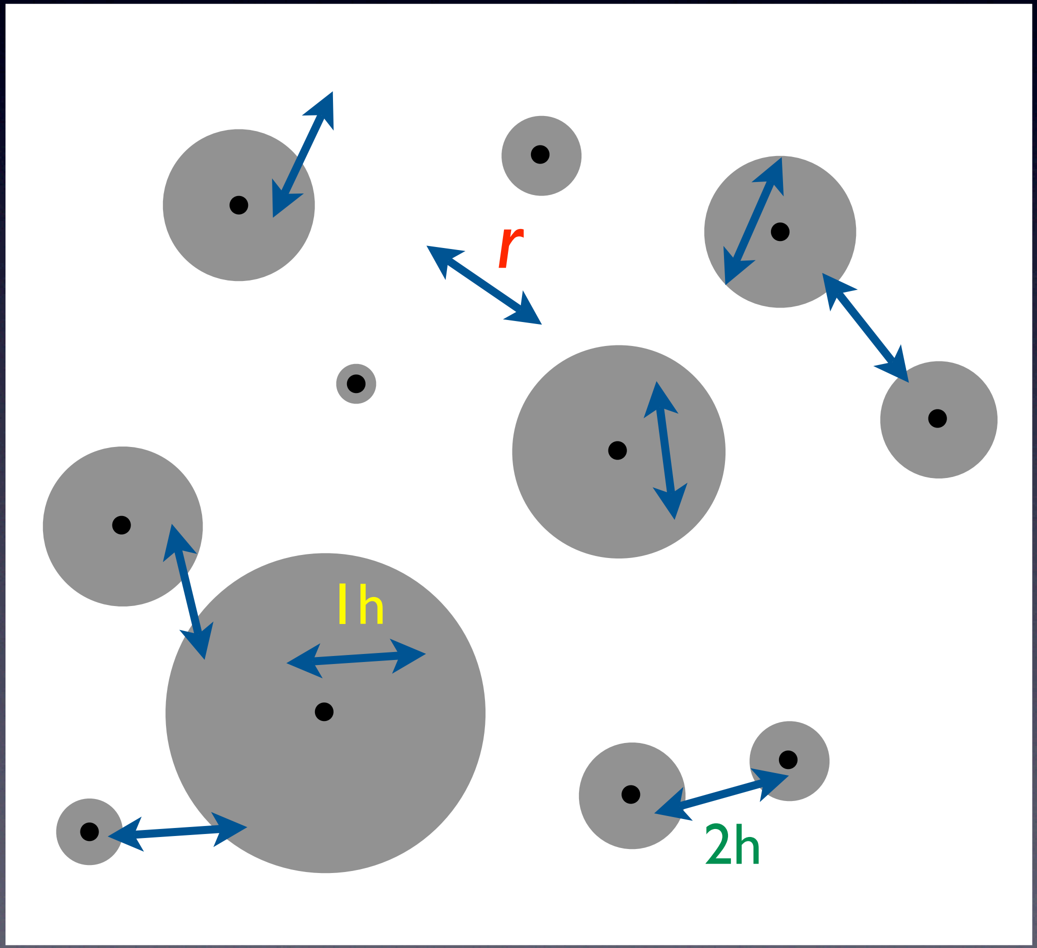

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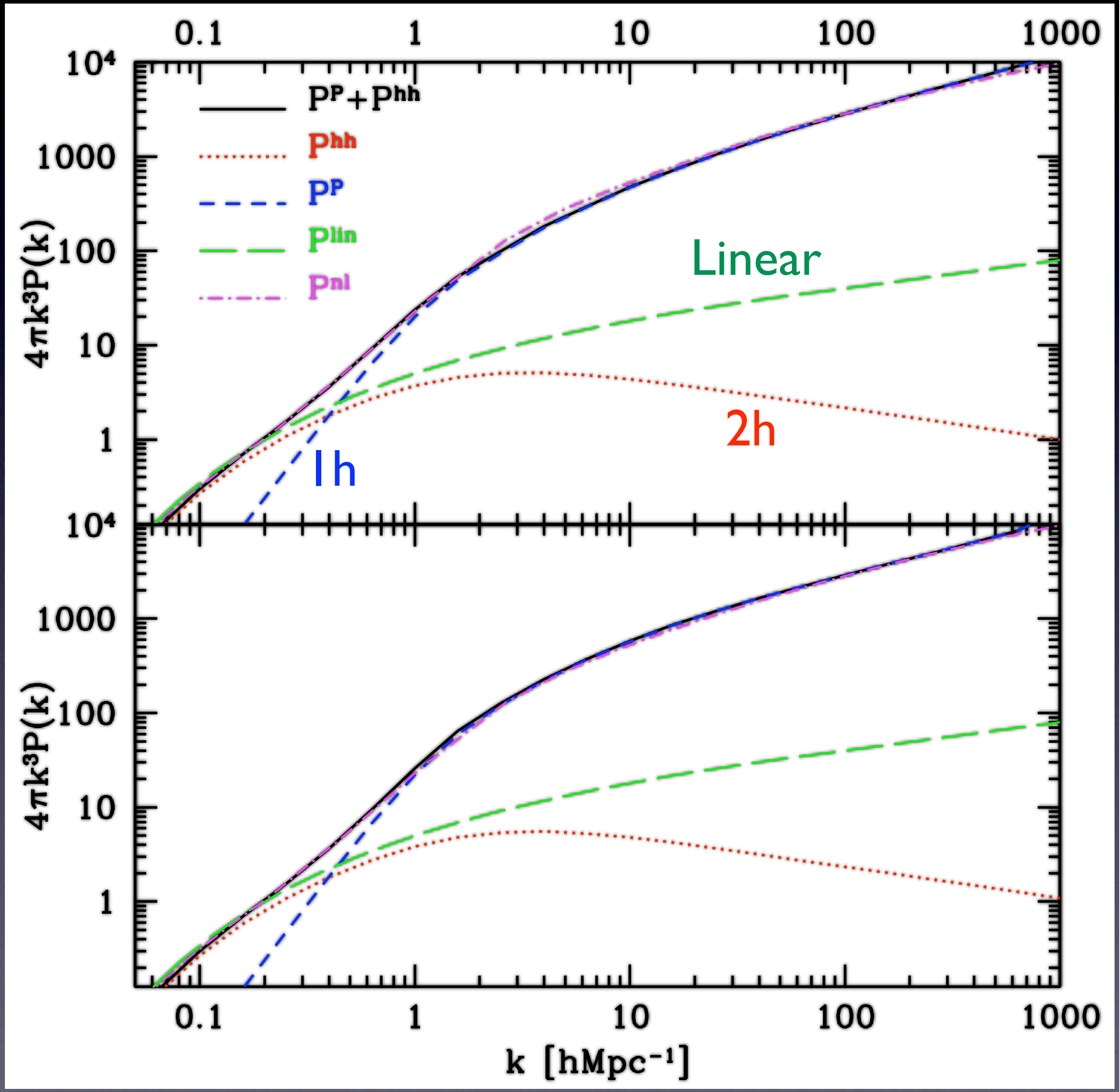
   There are 1-halo and 2-halo terms

4. Go to Fourier space to get $P(k)$

Power spectrum by halo model

Seljak., *MNRAS* **318**, 203 (2000)



- Halo model provides good fit to the nonlinear power spectrum
- 1-halo term dominates at small scales (large *k*)

Apply halo model to DM subhalos

	DM power spectrum	Gamma-ray background anisotropy
Seed distribution	Follows linear spectrum	Distribution given in simulations
Correlating quantity	ρ	$L \propto \rho^2$
Density profile of each halo/subhalo	NFW	Truncated NFW

Angular power spectrum: Formulae

$$C_\ell = C_\ell^{\rm 1sh} + C_\ell^{\rm 2sh}$$

$$C_\ell^{\rm 1sh} = \frac{1}{16\pi^2 \overline{\langle I \rangle}^2} \int dL L^2 \int ds \frac{ds}{s^2} \frac{d\bar{n}_{\rm sh}(s,L)}{dL} \left| \tilde{u}\left(\frac{\ell}{s}, M\right)\right|^2$$

$$C_\ell^{\rm 2sh} = \frac{1+\xi_{\rm sh}}{4\pi \overline{\langle I \rangle}^2} \int d\hat{\mathbf{n}}_1 \int d\hat{\mathbf{n}}_2 \langle I(\hat{\mathbf{n}}_1)\rangle \langle I(\hat{\mathbf{n}}_2)\rangle P_\ell(\hat{\mathbf{n}}_1 \cdot \hat{\mathbf{n}}_2)$$

Angular power spectrum: Formulae

$$C_\ell = C_\ell^{1\mathrm{sh}} + C_\ell^{2\mathrm{sh}}$$

Luminosity function

$$C_\ell^{1\mathrm{sh}} = \frac{1}{16\pi^2 \overline{\langle I \rangle}^2} \int dL L^2 \int ds \frac{ds}{s^2} \boxed{\frac{d\bar{n}_{\mathrm{sh}}(s, L)}{dL}} \left| \tilde{u}\left(\frac{\ell}{s}, M\right)\right|^2$$

$$C_\ell^{2\mathrm{sh}} = \frac{1+\xi_{\mathrm{sh}}}{4\pi \overline{\langle I \rangle}^2} \int d\hat{\mathbf{n}}_1 \int d\hat{\mathbf{n}}_2 \langle I(\hat{\mathbf{n}}_1)\rangle \langle I(\hat{\mathbf{n}}_2)\rangle P_\ell(\hat{\mathbf{n}}_1 \cdot \hat{\mathbf{n}}_2)$$

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Fourier transform of luminosity profile

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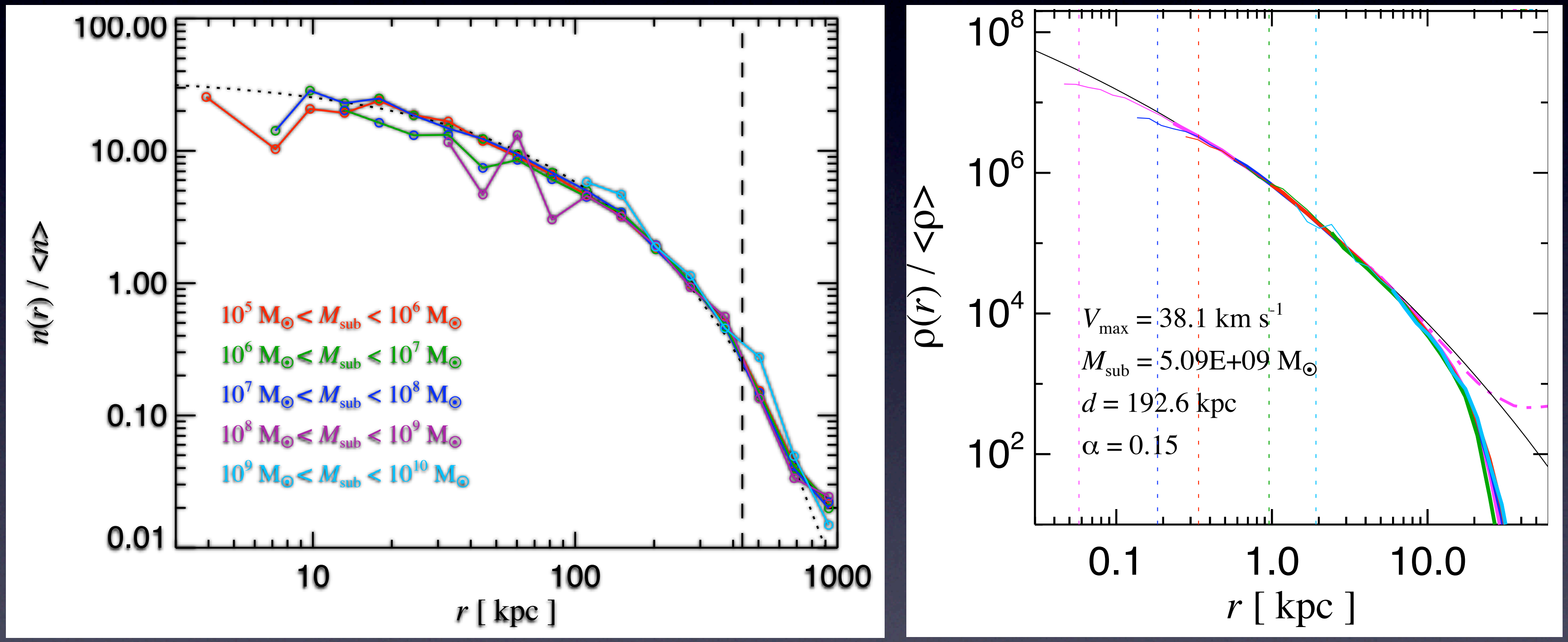
This 2sh term only depends on subhalo distribution within the host

3. Subhalo models

Distribution, density profile, and particle physics parameters

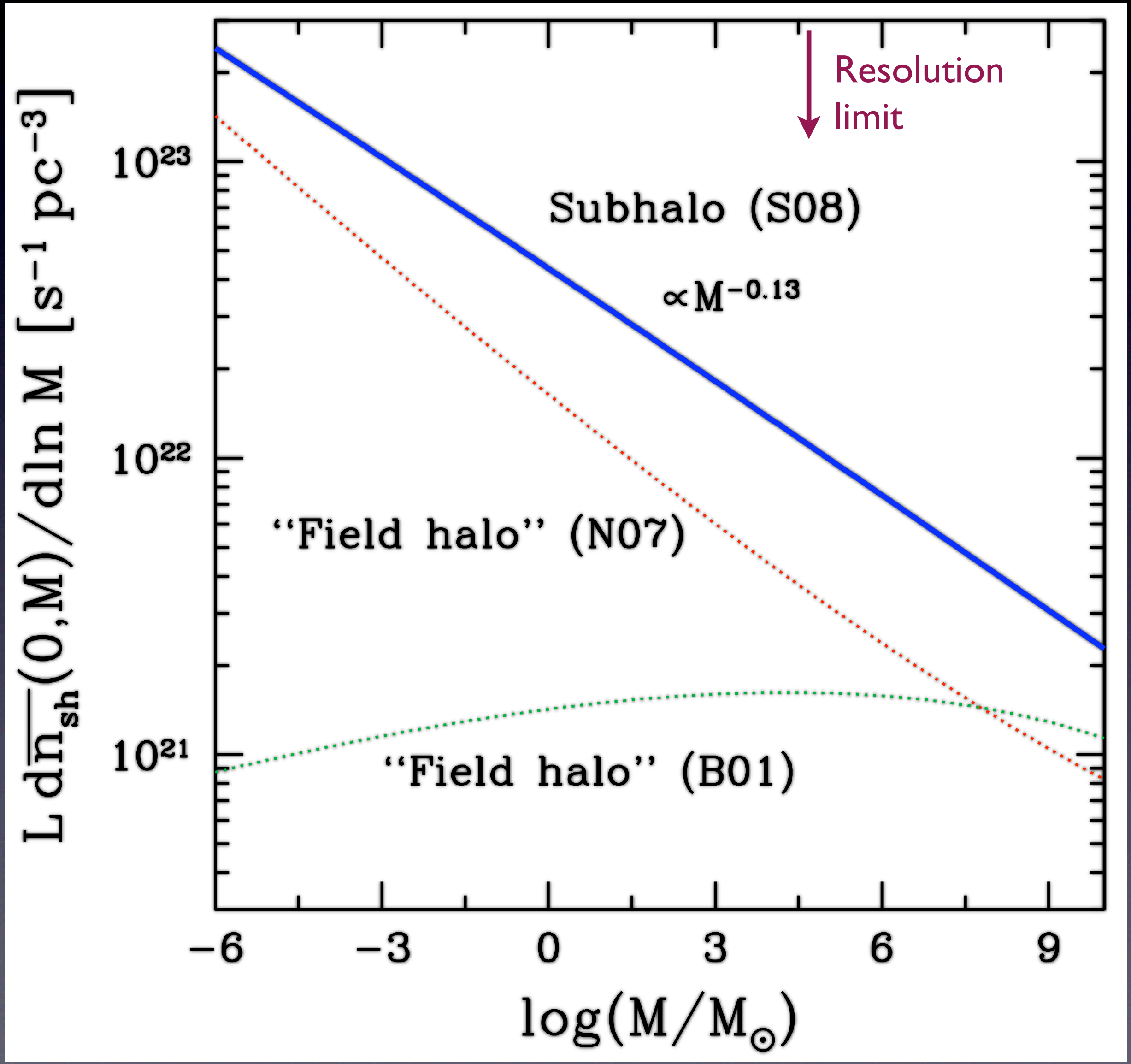
- Follows Springel et al. (2008) for distribution and density profile of subhalos



- Use "canonical" particle physics parameters

$$\langle \sigma v \rangle = 3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}, \quad m_\chi = 100\,\mathrm{GeV}$$

Luminosity-weighted mass function



- Mass function is $M^{-1.9}$
- According to Springel et al. prescription, $L \propto M^{0.77}$
- Smaller subhalos contribute more to the gamma-ray intensity
- Subhalos are much more luminous than field halos of the same mass

Angular power spectrum: Formulae

$$C_\ell = C_\ell^{1\mathrm{sh}} + C_\ell^{2\mathrm{sh}}$$

Luminosity function

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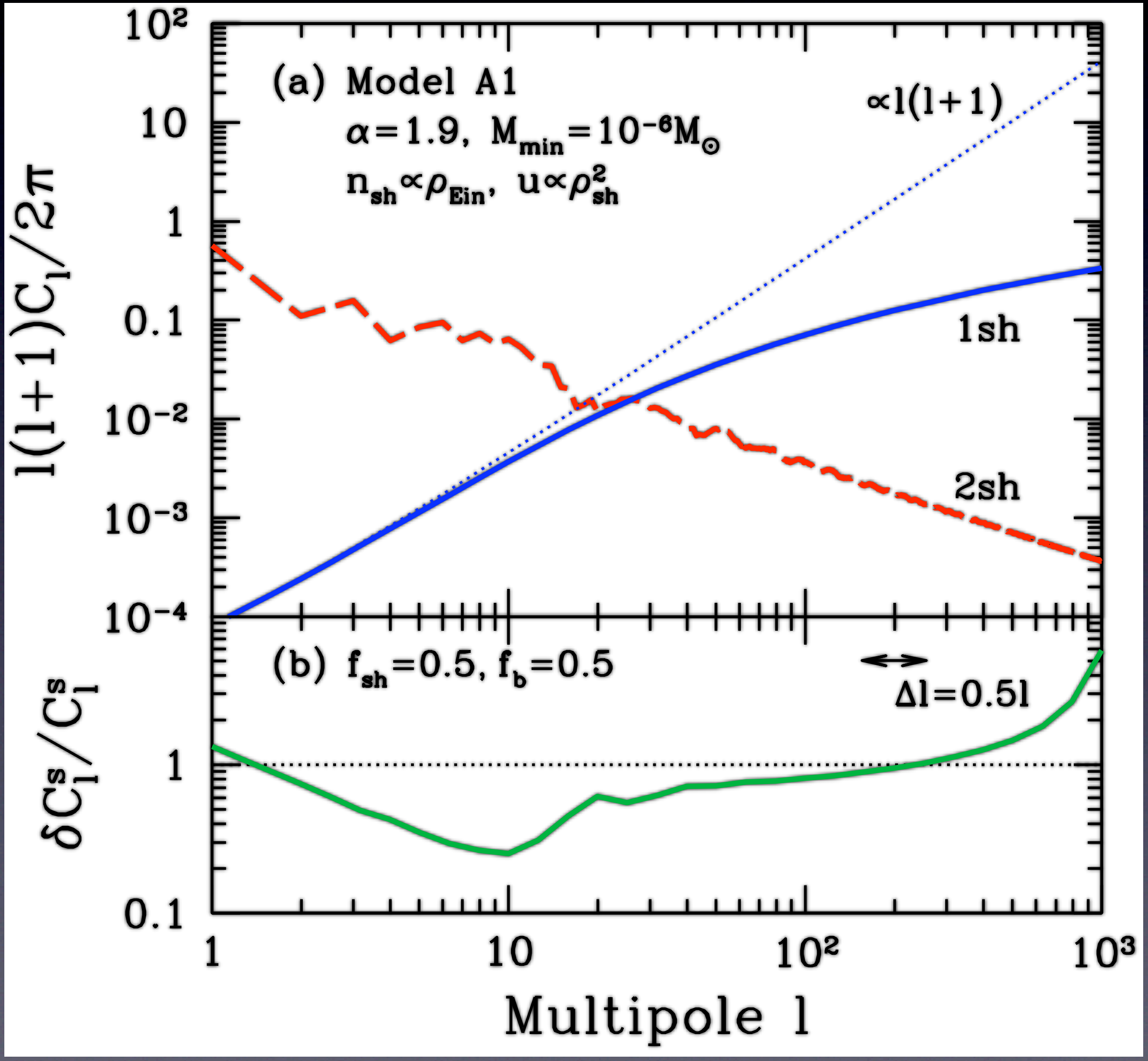
4. Results

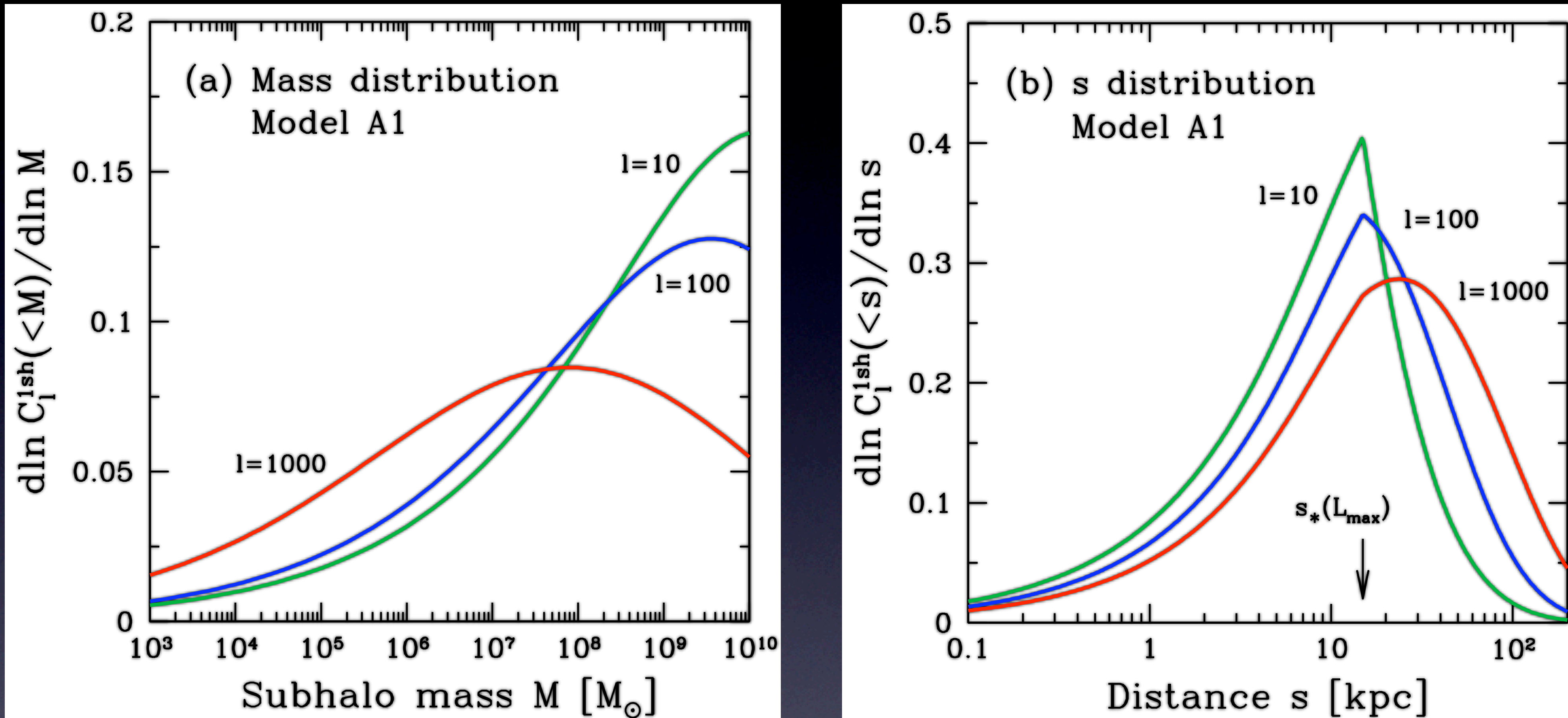
Angular power spectrum

Ando, arXiv:0903.4685 [astro-ph.CO]



- $M_{min} = 10^{-6}\, M_{sun}$
- 1sh term dominates at smaller scales
- Fermi's angular resolution corresponds to $l \sim 1000$
- Deviation from shot-noise is due to spatial extention of subhalos

Contributions from mass, radius range



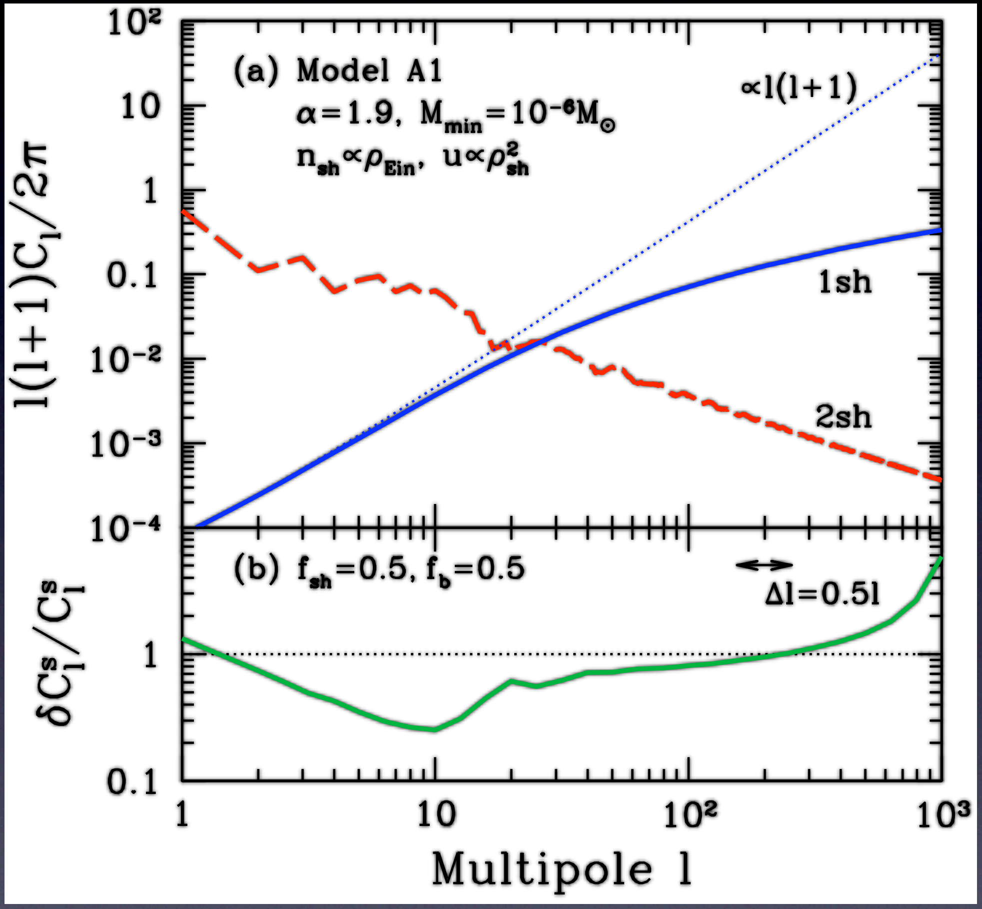
Typical subhalo extension:

$$\delta\theta_s = \frac{r_s(\langle M\rangle)}{\langle s\rangle} = \begin{cases} 6.6^\circ & (\ell = 10) \\ 3.9^\circ & (\ell = 100) \\ 1.9^\circ & (\ell = 1000) \end{cases}$$

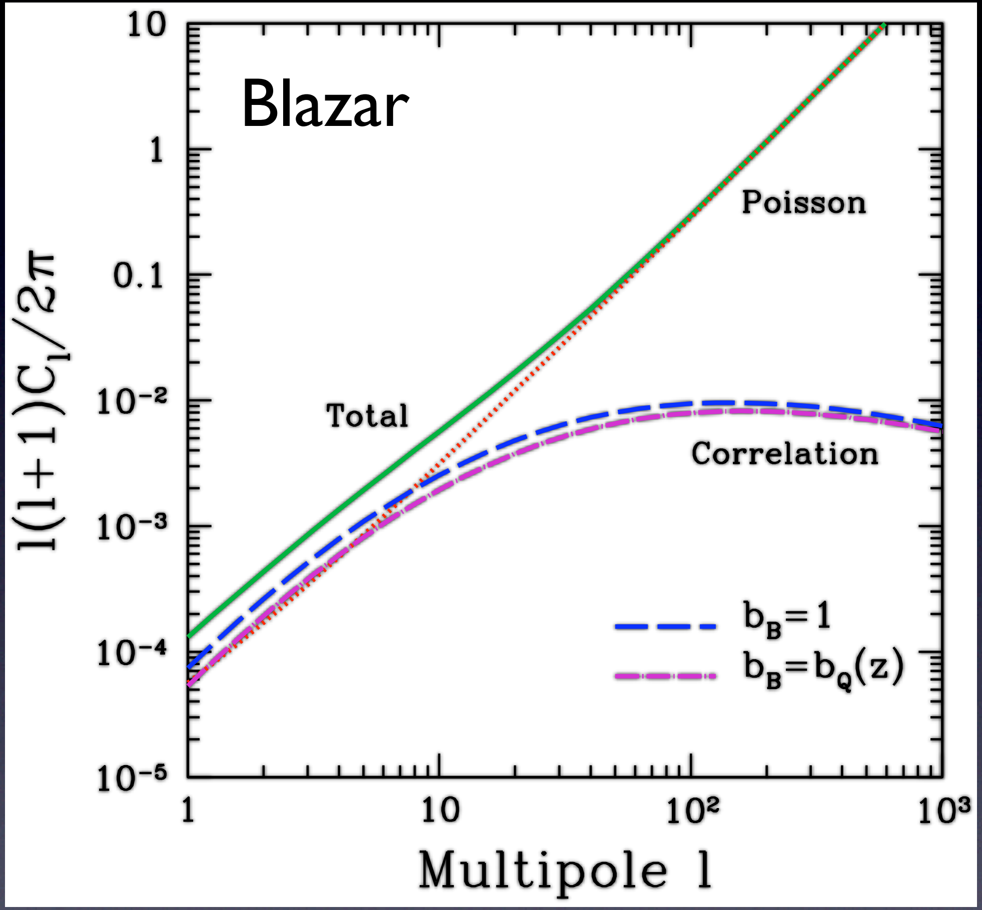
They are extended for Fermi

Detectability

Ando, arXiv:0903.4685 [astro-ph.CO]



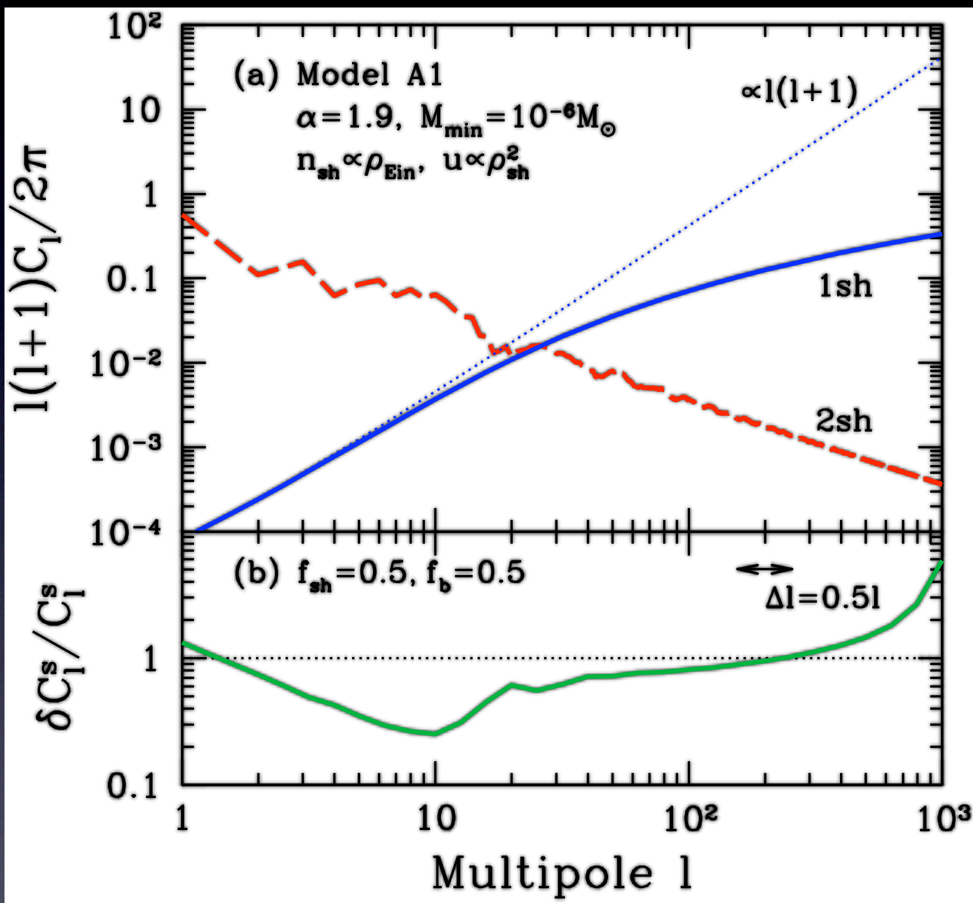
Ando et al., *Phys. Rev. D* **75**, 063519 (2007)

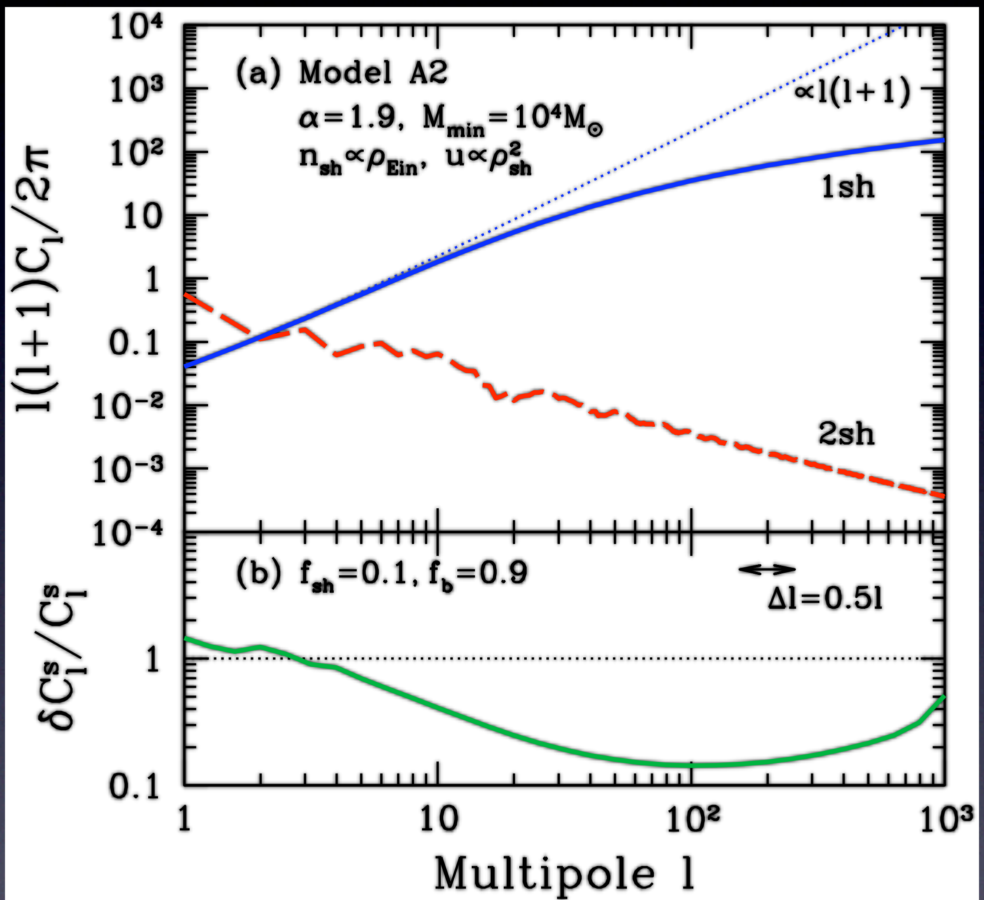


- Consider blazar (Poisson-like power spectrum) as background
- Good chance to detect dark matter if 50:50 mixture

Dependence on minimum mass

Ando, arXiv:0903.4685 [astro-ph.CO]

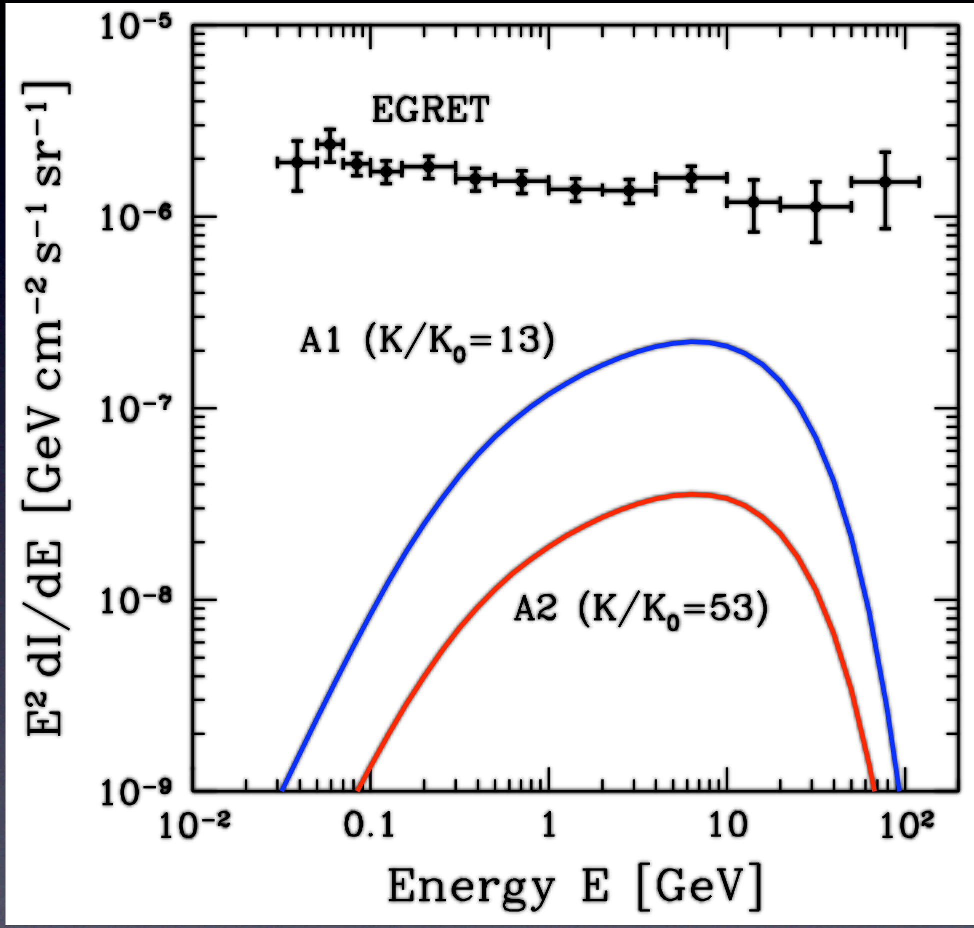




- If $M_{\rm min} = 10^4\, M_{\rm sun}$, we get larger anisotropies
- Even with 10%, dark matter component can be easily detected

Parameters for anisotropy detection

	A1	A2
I_{sh} / I_{obs}	0.24	0.038
Boost	13	53
Associated N_{sh}	0.64	4.0



- Even the subhalo contribution is subdominant in the mean intensity, it can excel in the anisotropy
- This could provide stronger probe of subhalos than detection as single gamma-ray sources

5. Conclusions

- We developed analytic approach to compute the angular power spectrum of the gamma-ray background from dark matter substructure
    - Enabling to extract physics information directly

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- Anisotropy might be stronger probe of subhalos than detection as individual gamma-ray sources