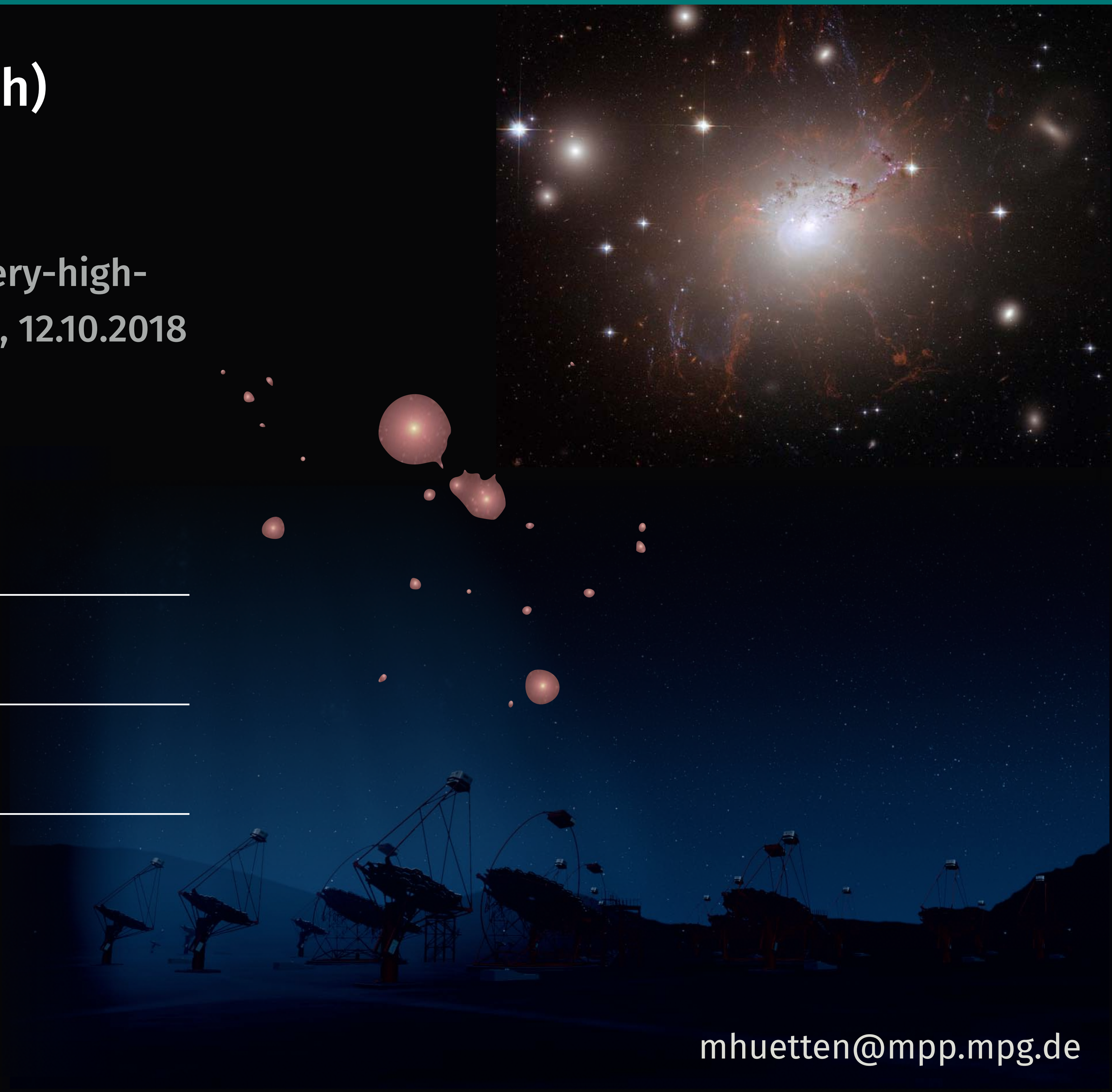
CTA as a γ-ray probe for dark matter structures: Searching for the smallest clumps & the largest clusters

Moritz Hütten (MPP Munich)
for the CTA consortium

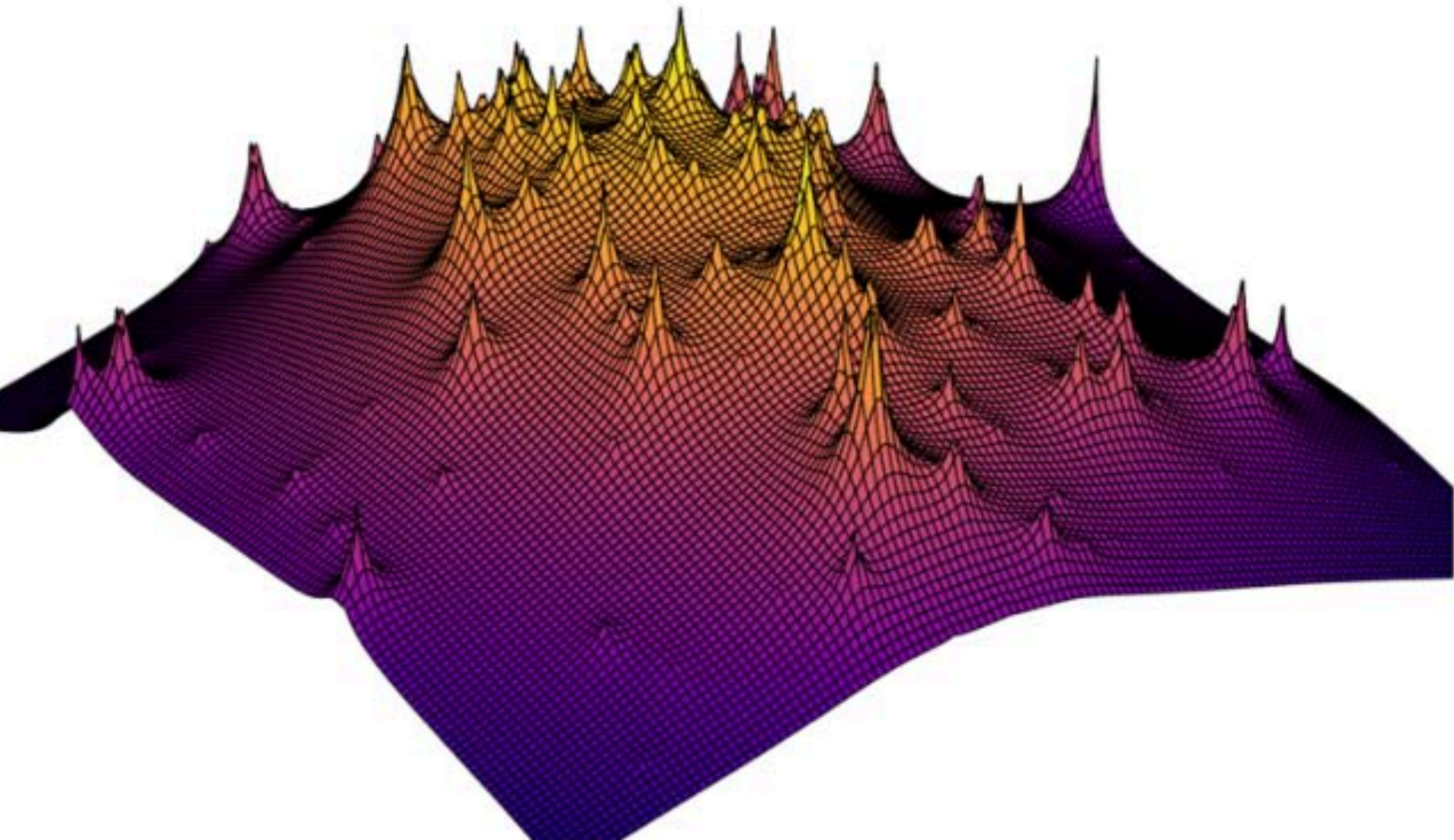
"The extreme Universe viewed in very-high-energy gamma rays 2018", La Palma, 12.10.2018

1. Introduction
2. Dark Galactic DM clumps
3. Galaxy clusters

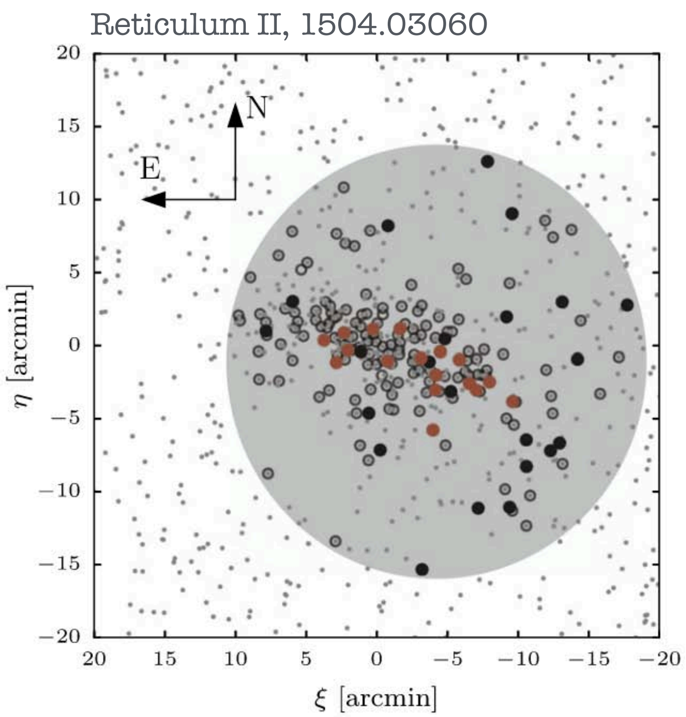


cta cherenkov telescope array
Max-Planck-Institut für Physik
mhuetten@mpp.mpg.de

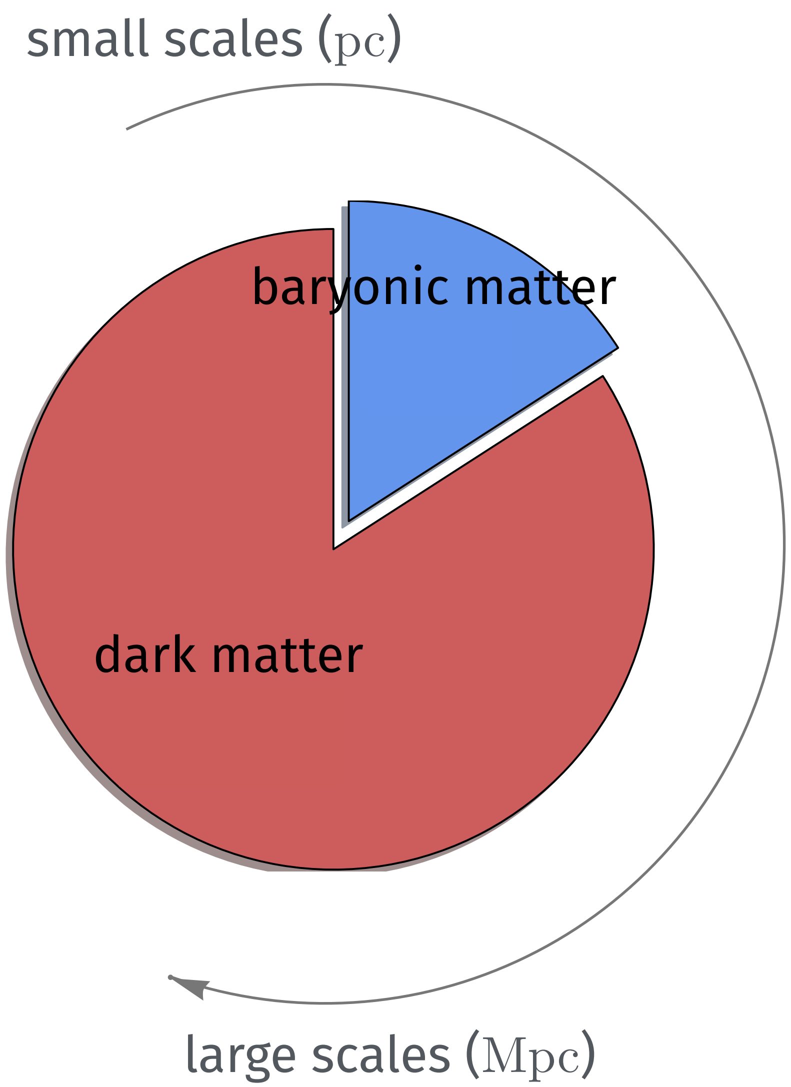
1. Introduction



Gravitational evidence for dark matter on all scales

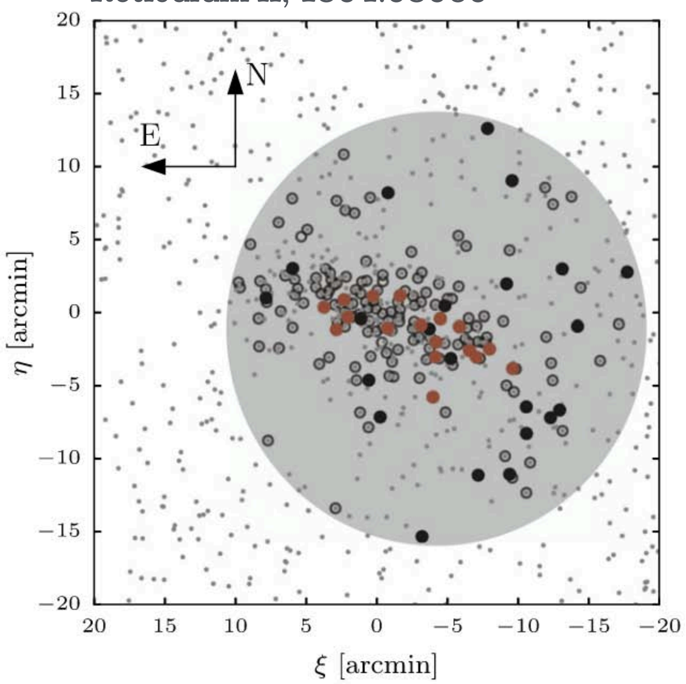


Dwarf galaxies



Gravitational evidence for dark matter on all scales

Reticulum II, 1504.03060



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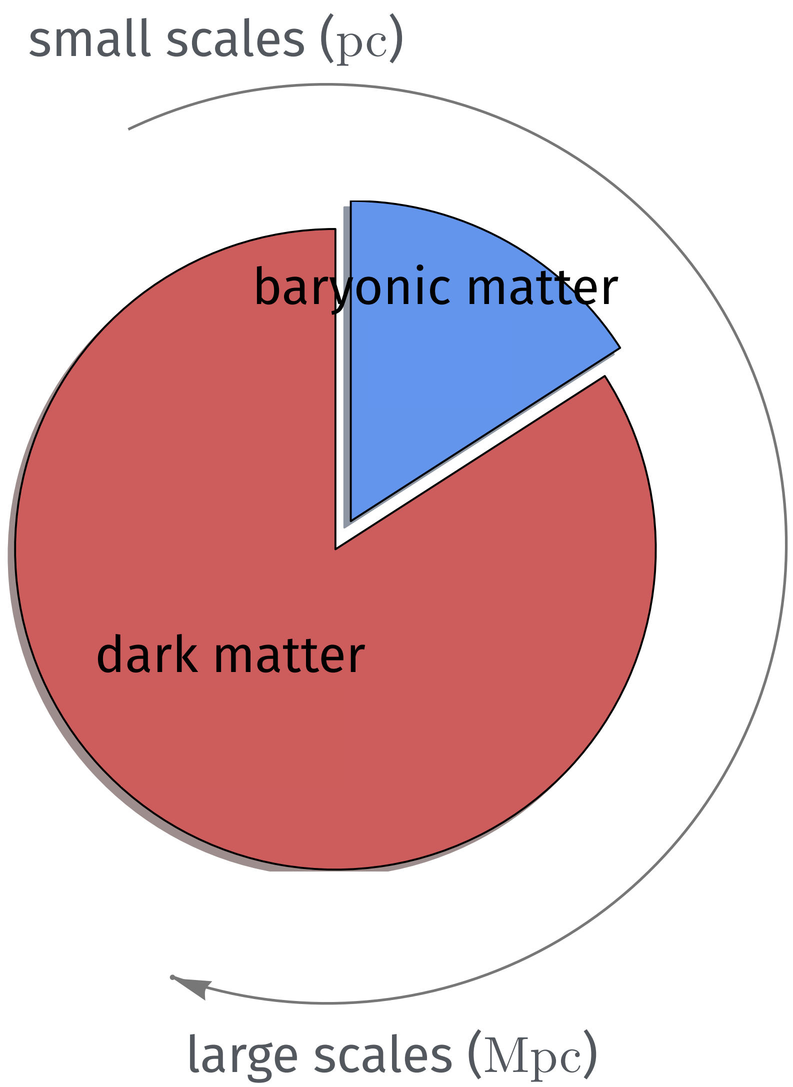
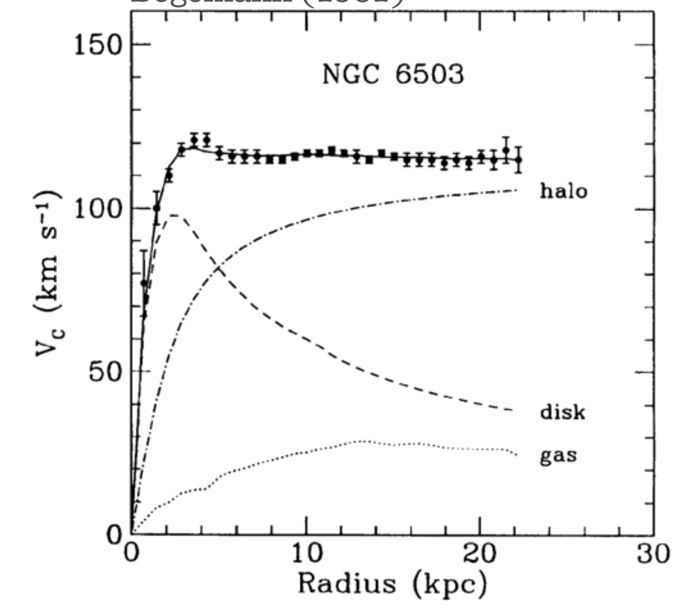


Begemann (1991)



Milky Way-like galaxies

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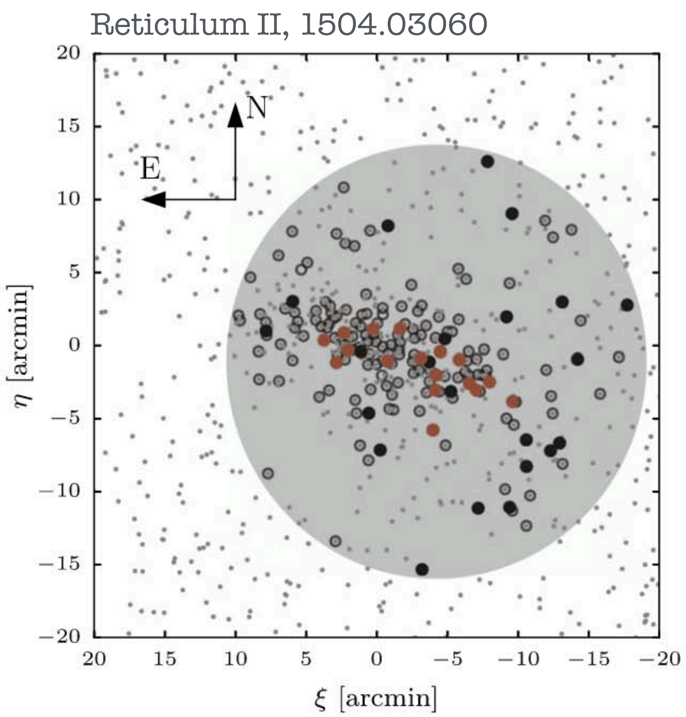
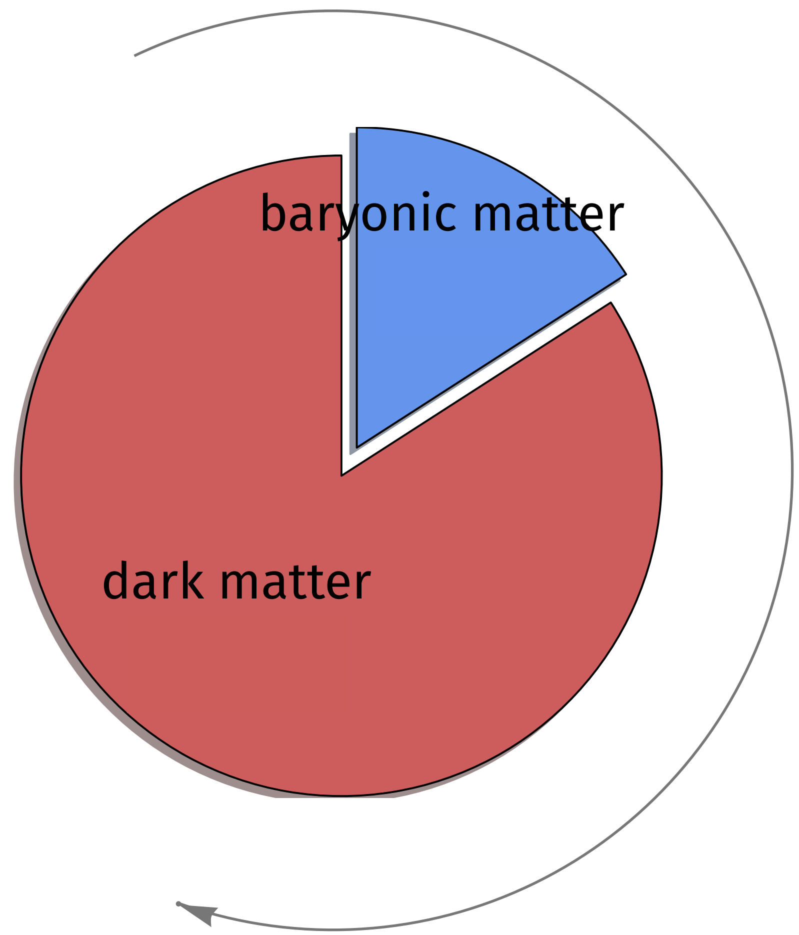
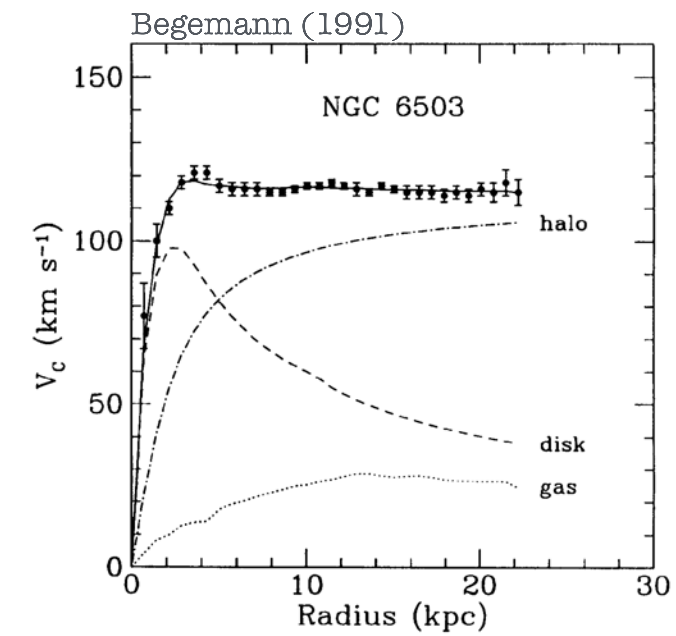


Dwarf galaxies

small scales (pc)



large scales (Mpc)



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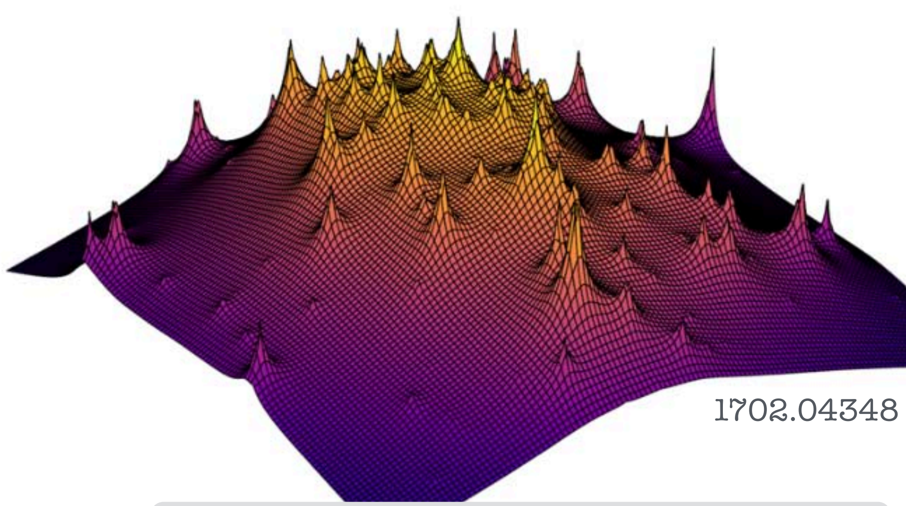

Galaxy cluster substructure

Gravitational evidence for dark matter on all scales

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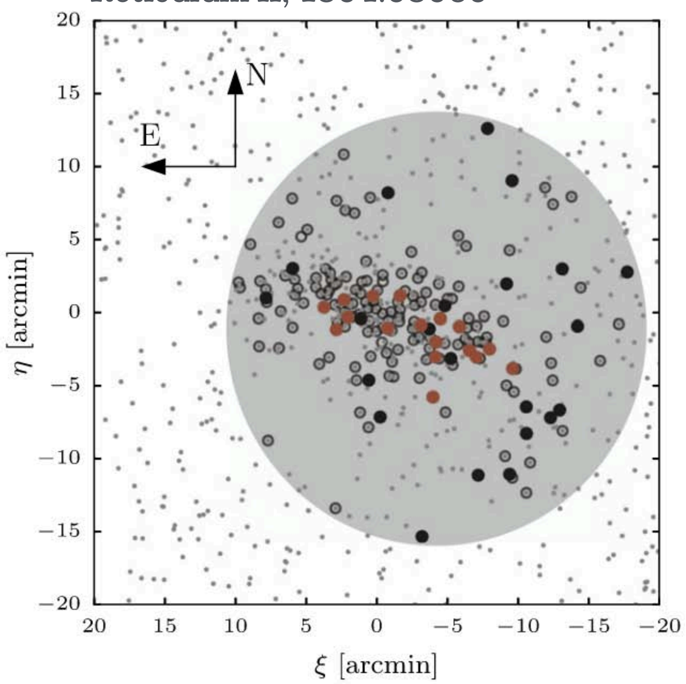

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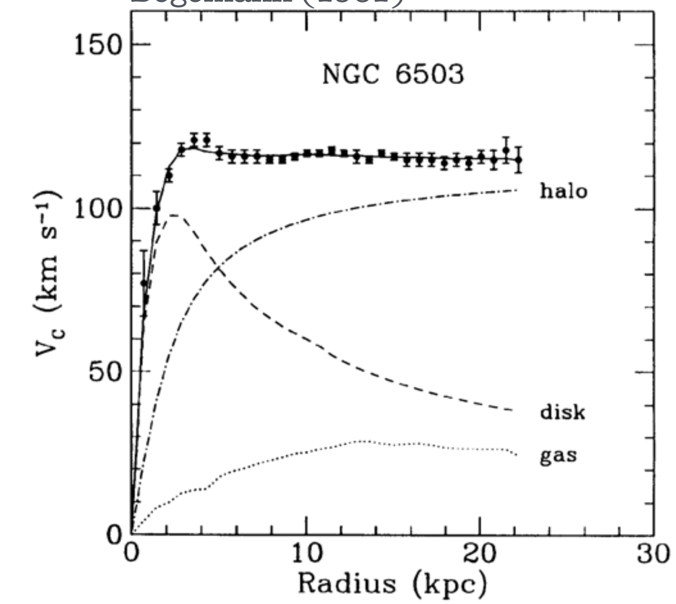

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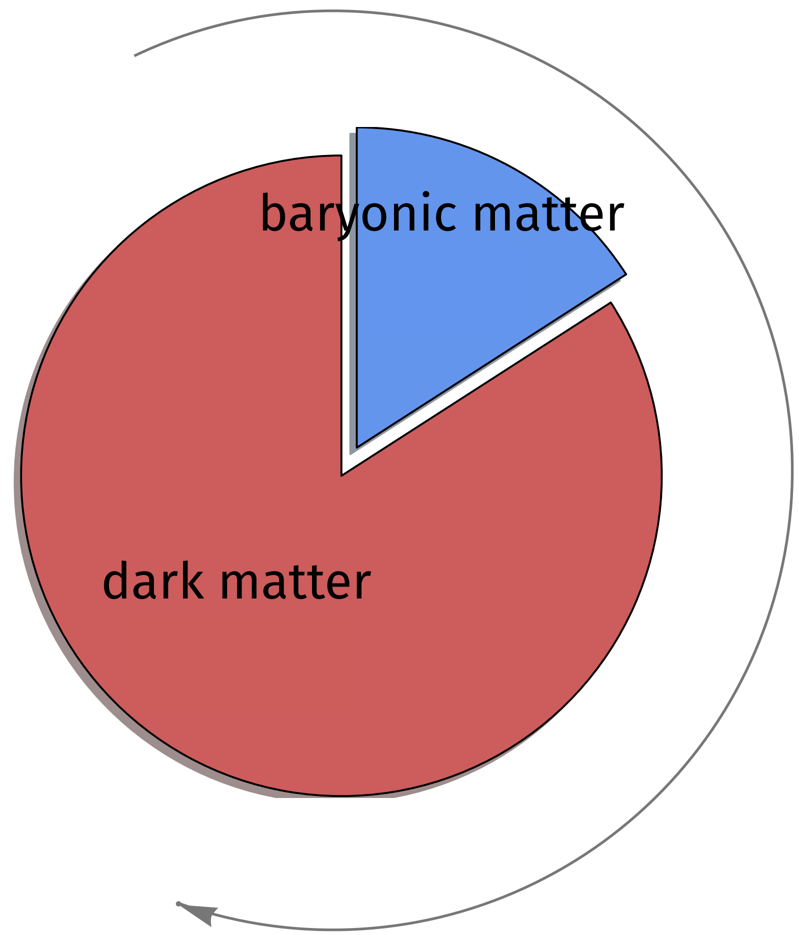

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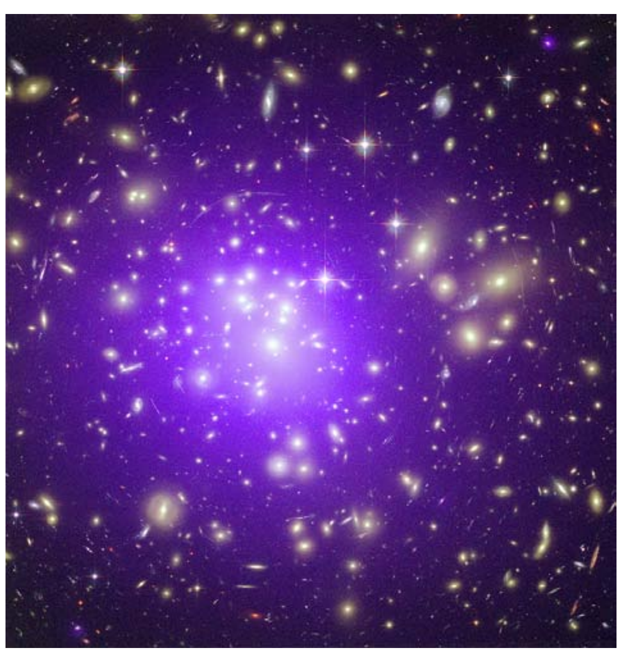
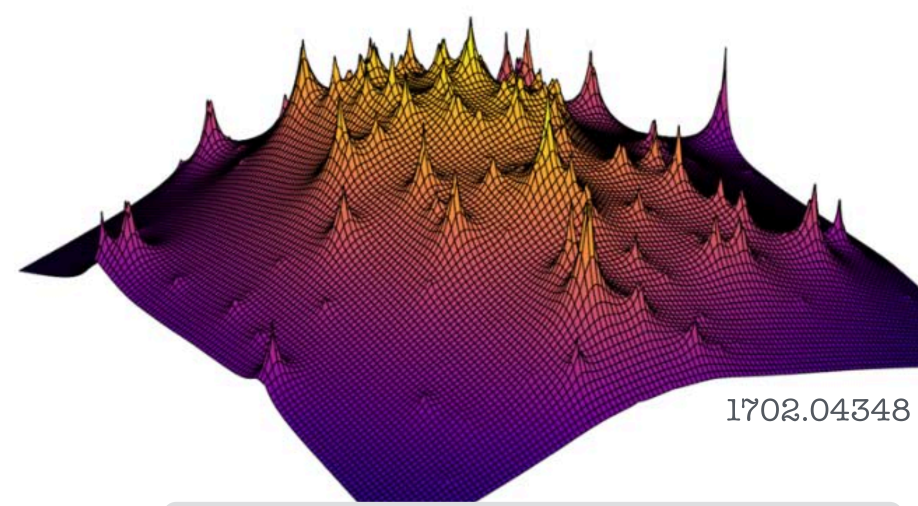
Galaxy clusters



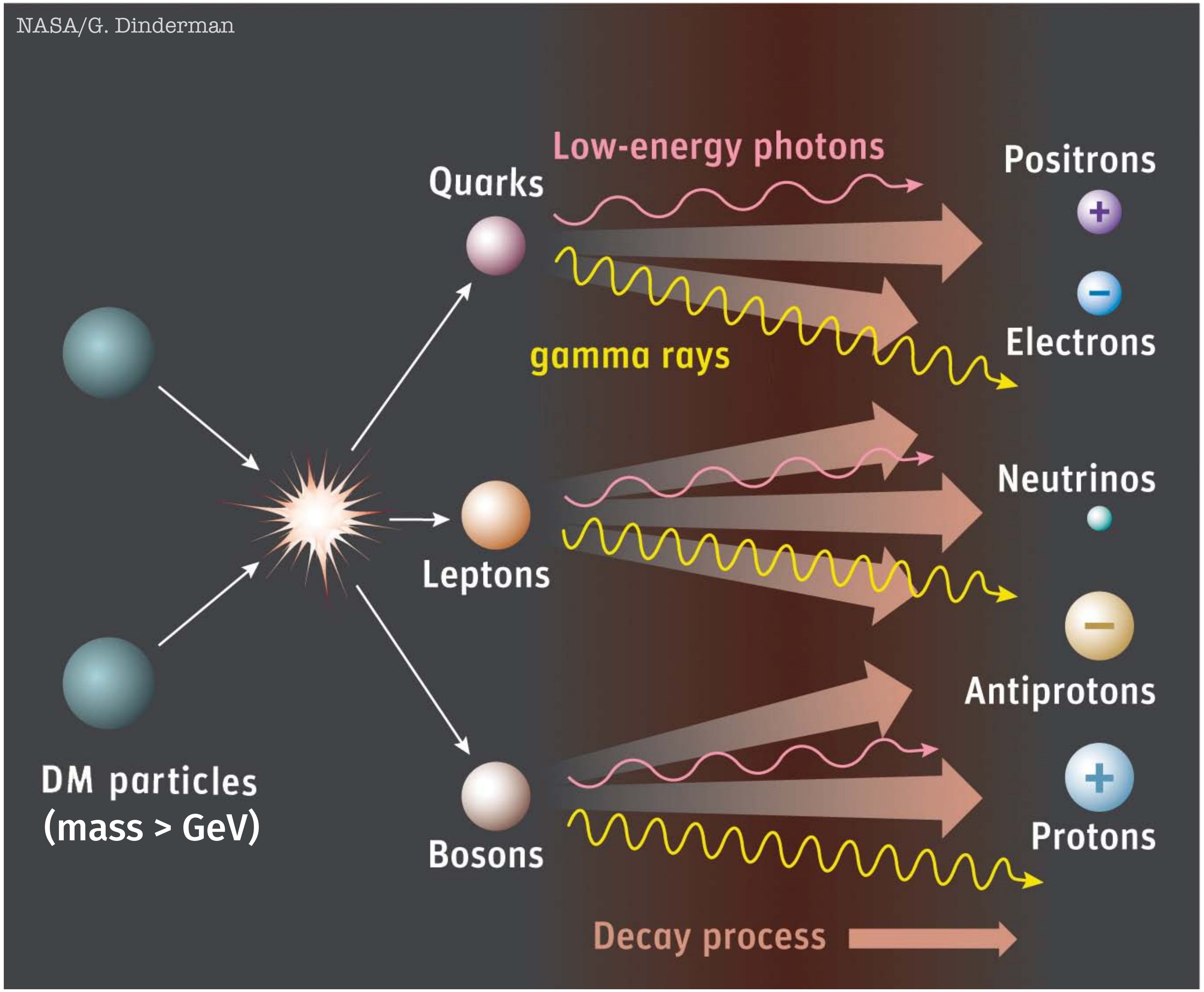
Chandra/HST image of Abell 1689



1702.04348

Galaxy cluster substructure

The dark matter ↔ γ-ray connection: indirect detection



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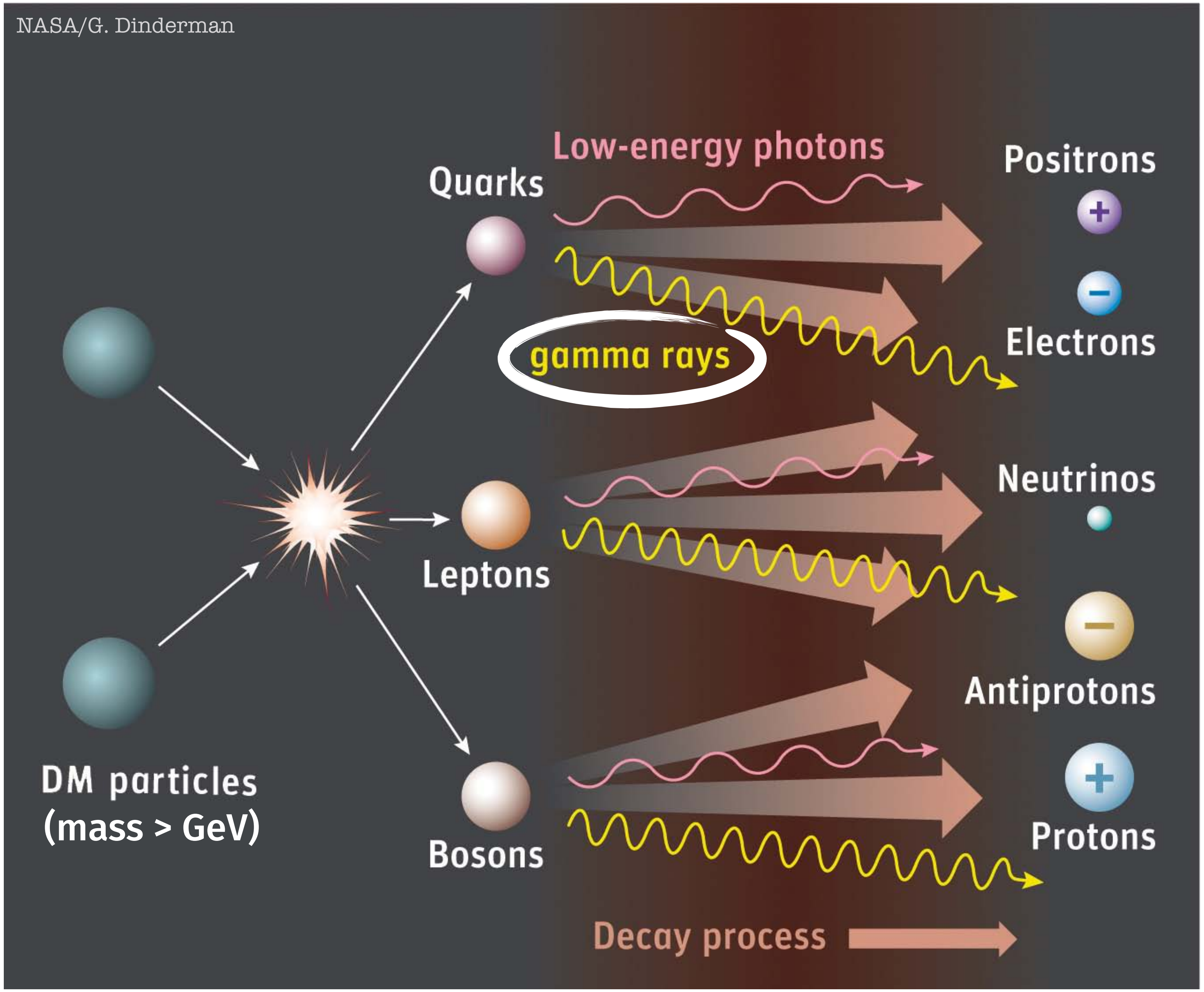

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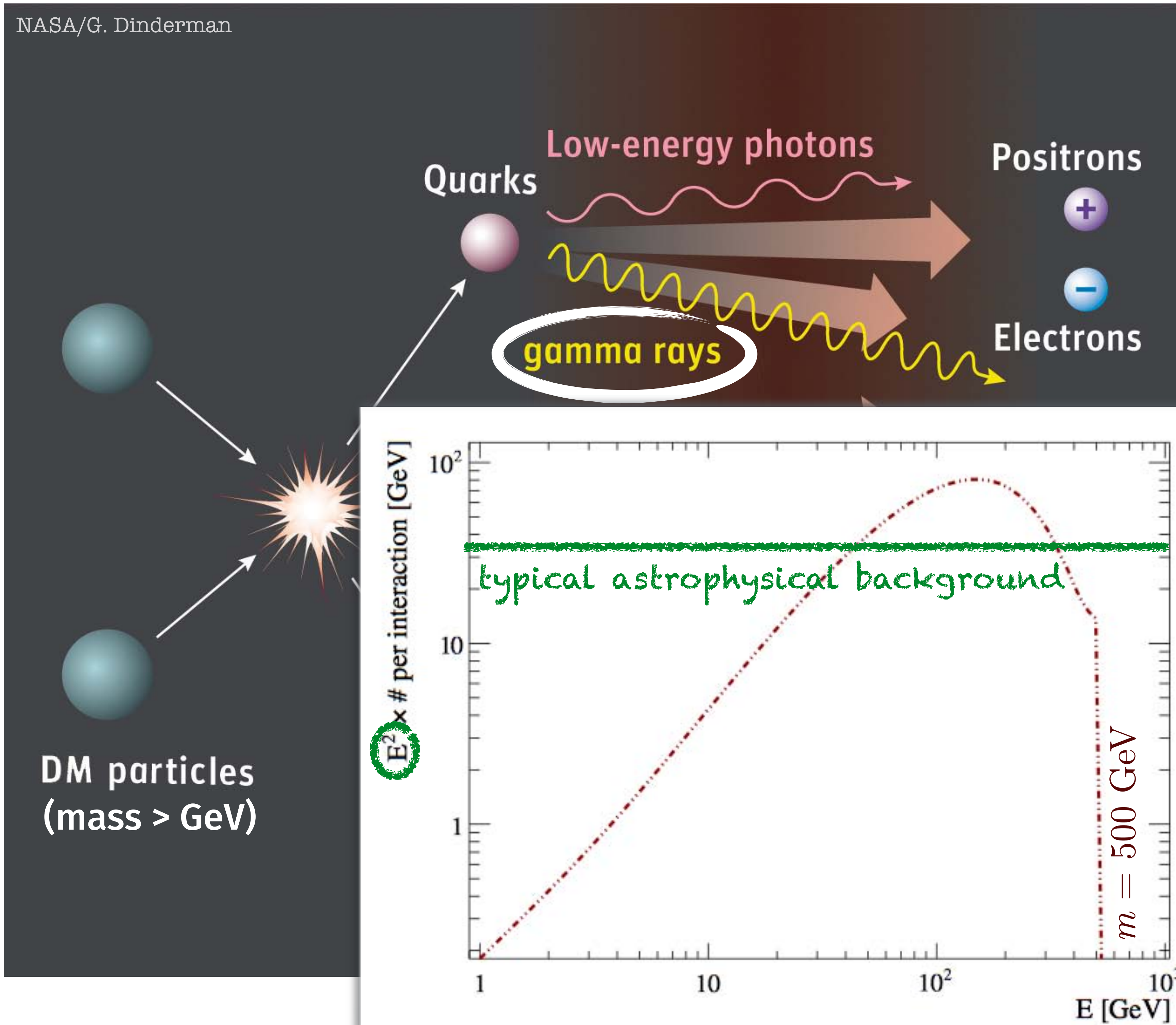
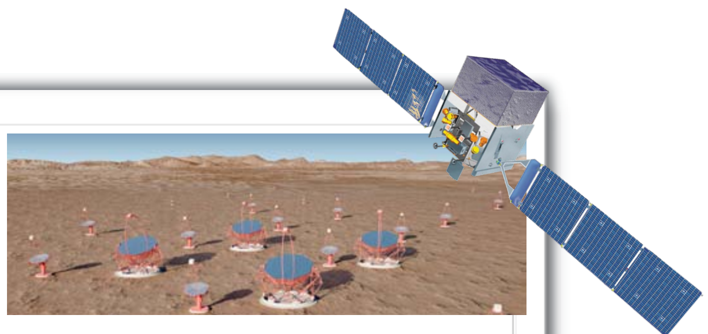


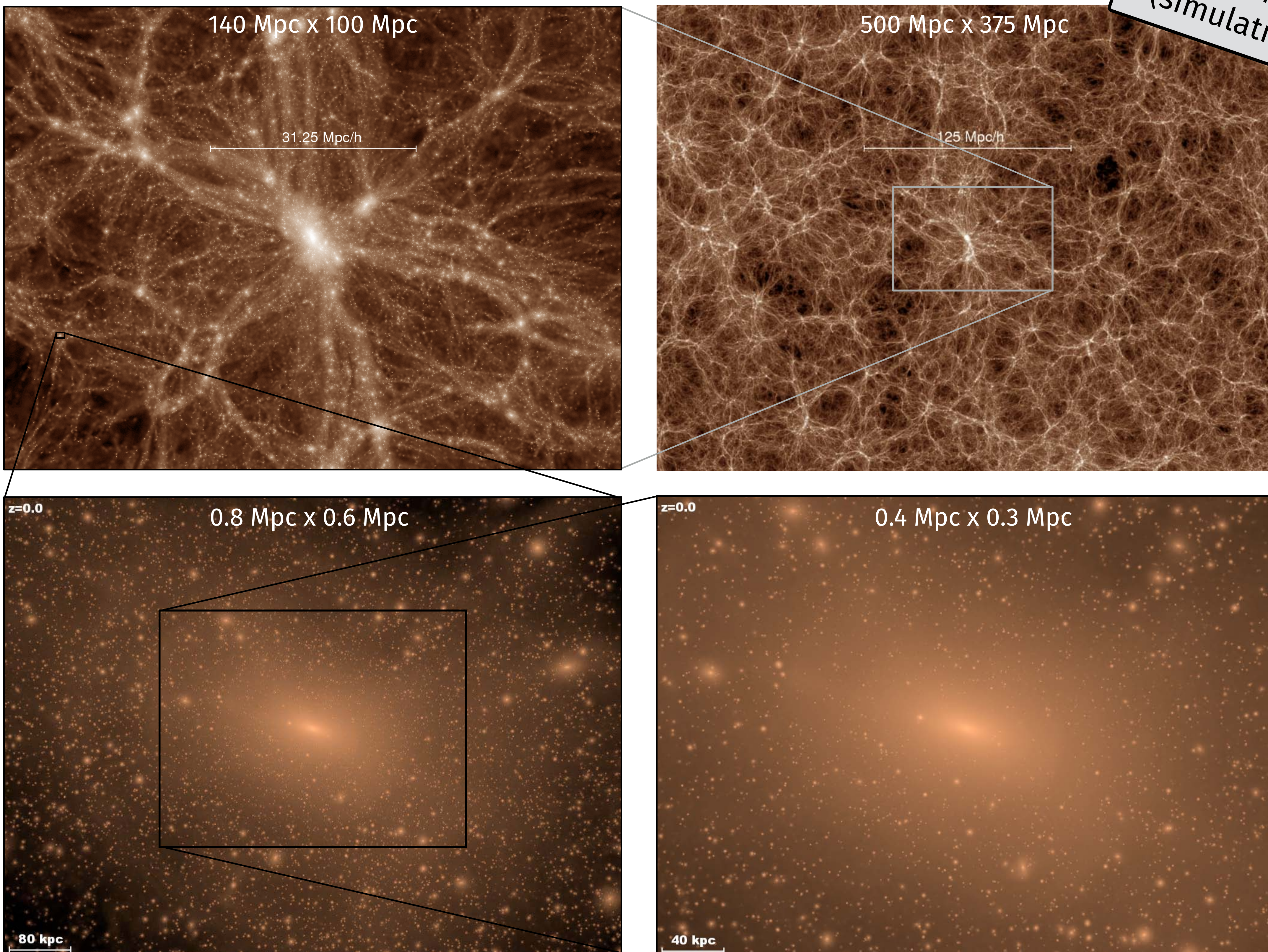


γ-rays:

+ straight to observer
+ no absorption in the Galaxy
- astrophysical background

Dark matter structures on all scales

DM density (simulation)

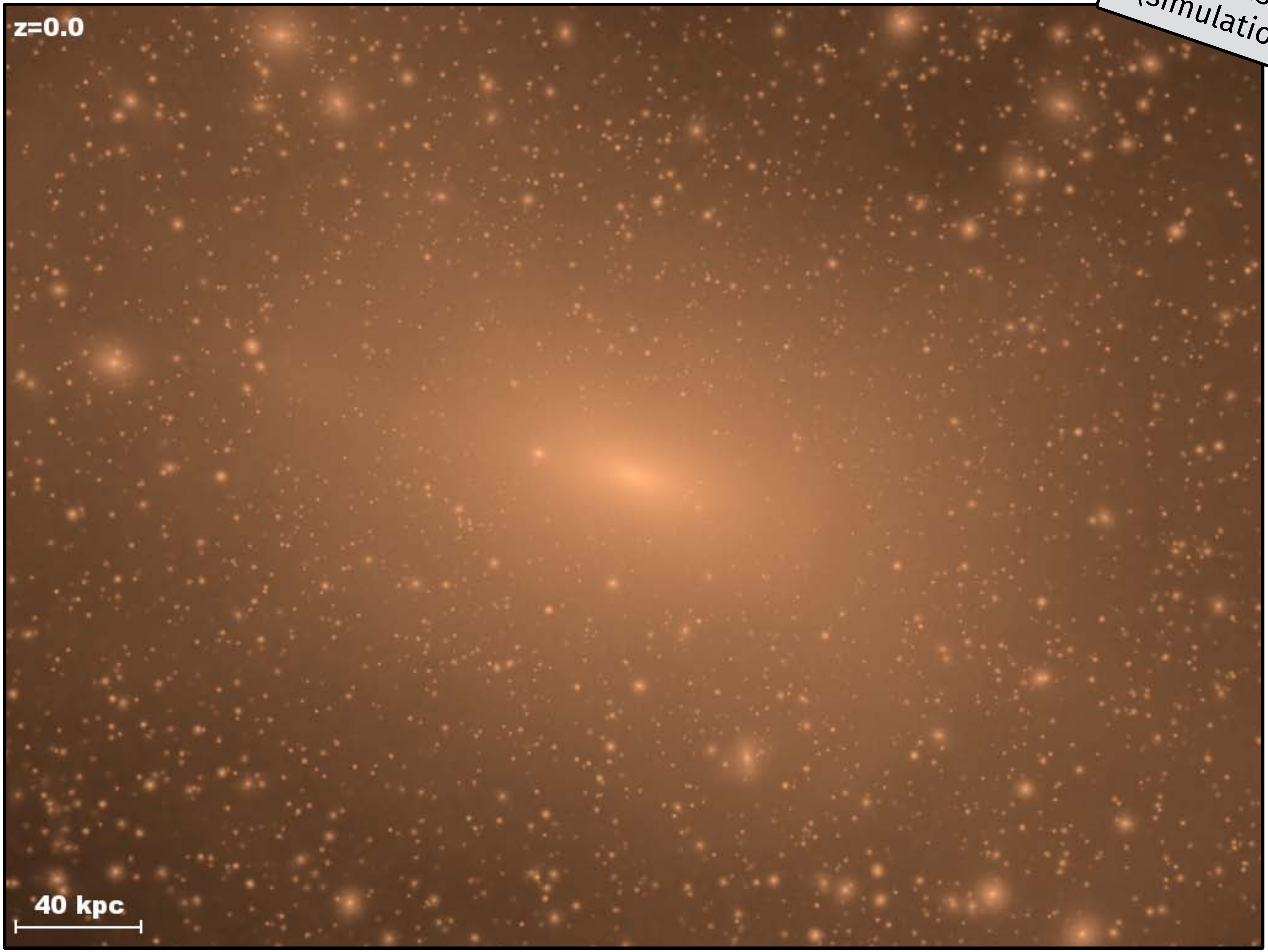


Springel et al. (2005)

Diemand, Kuhlen, Madau (2006)

color code:
brighter = denser

Dark matter structures on all scales



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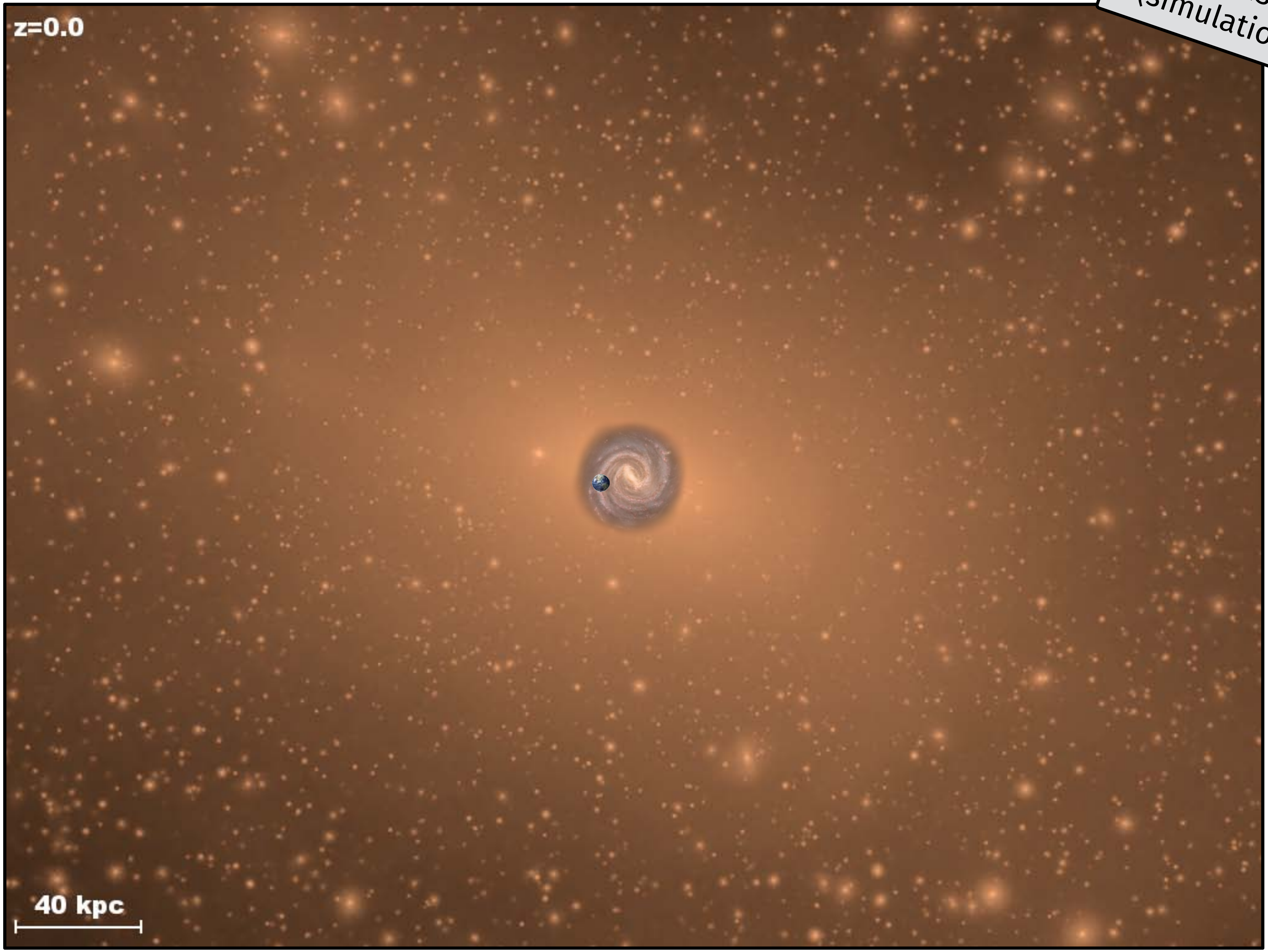

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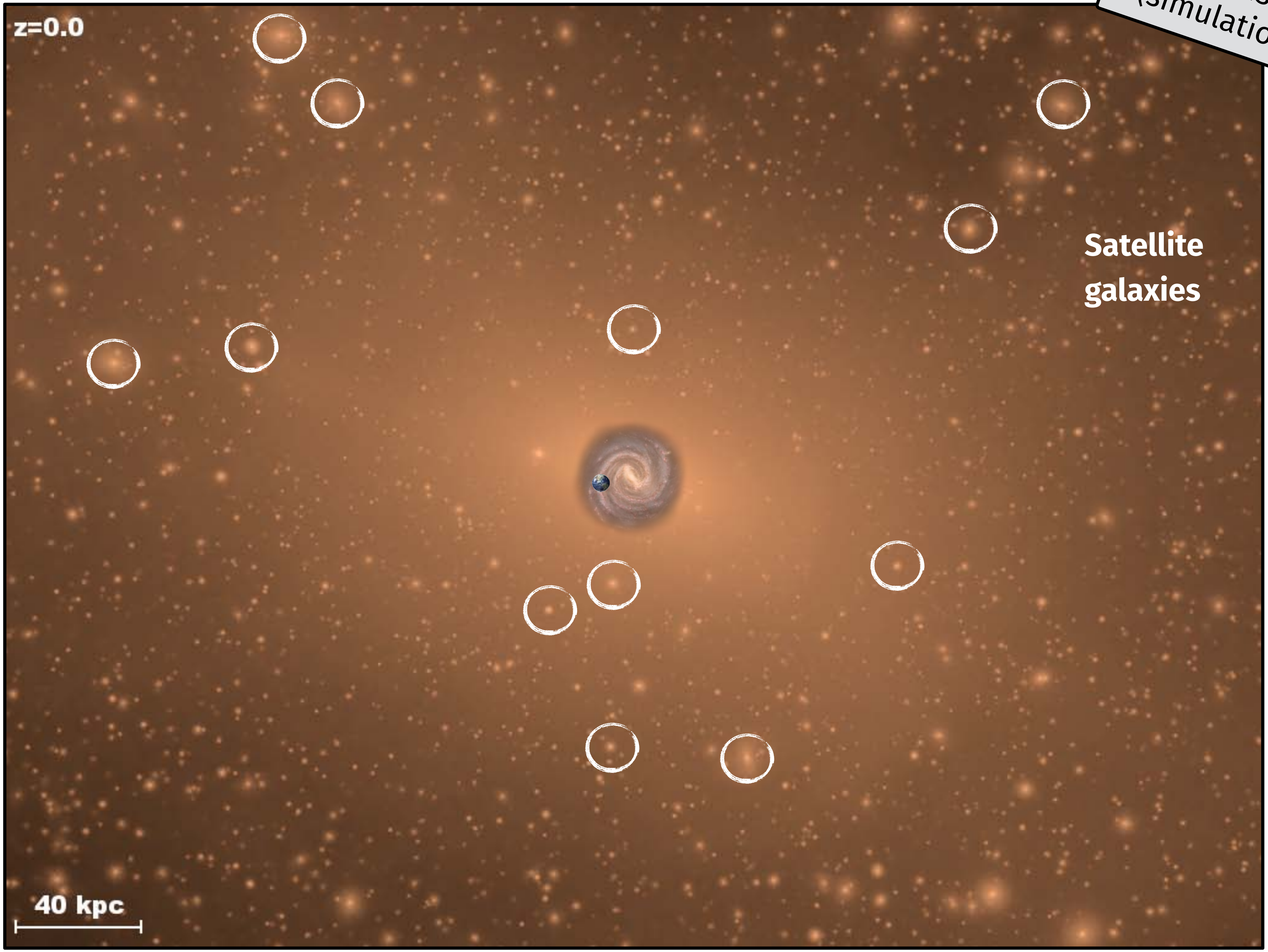

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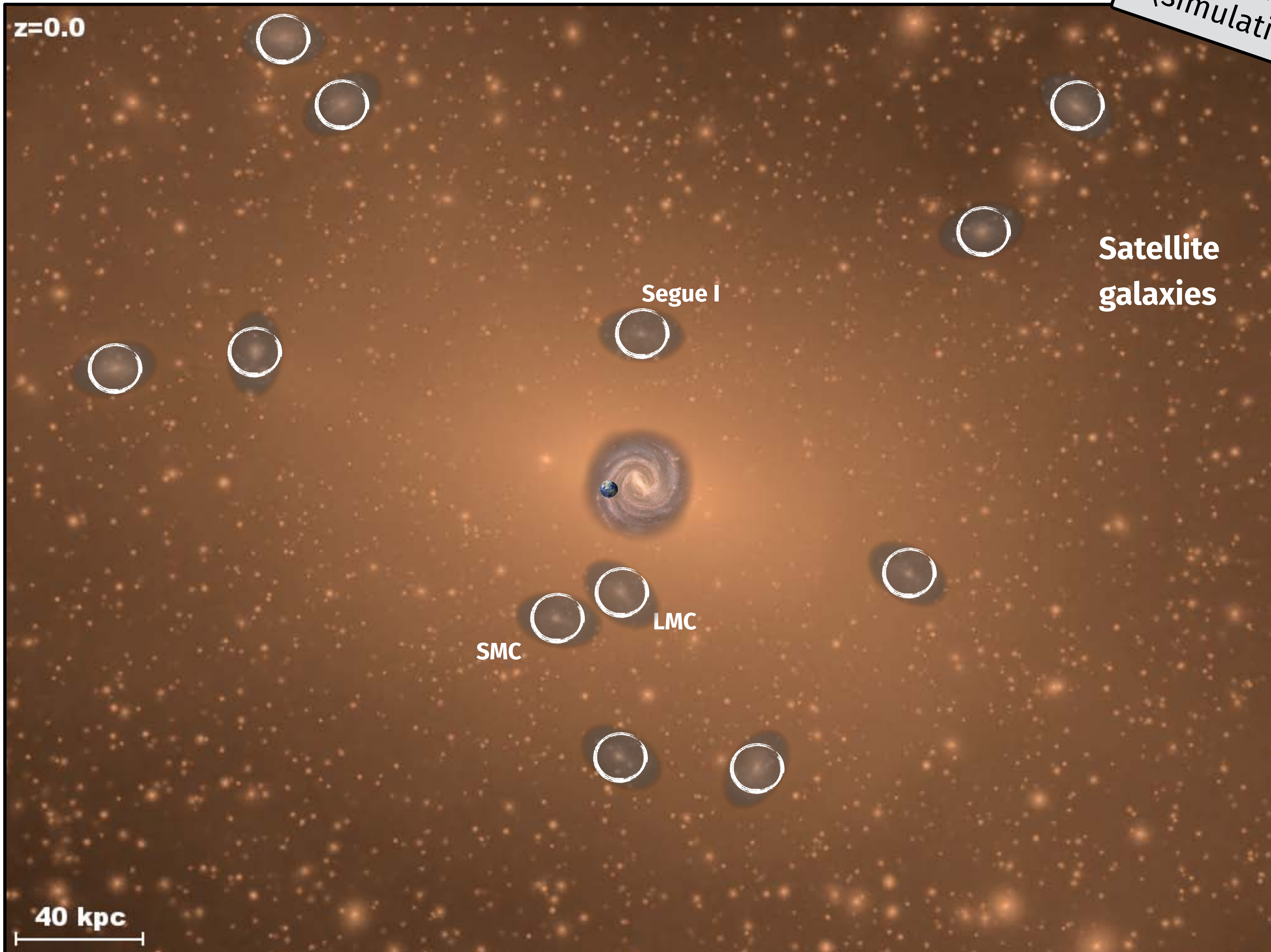

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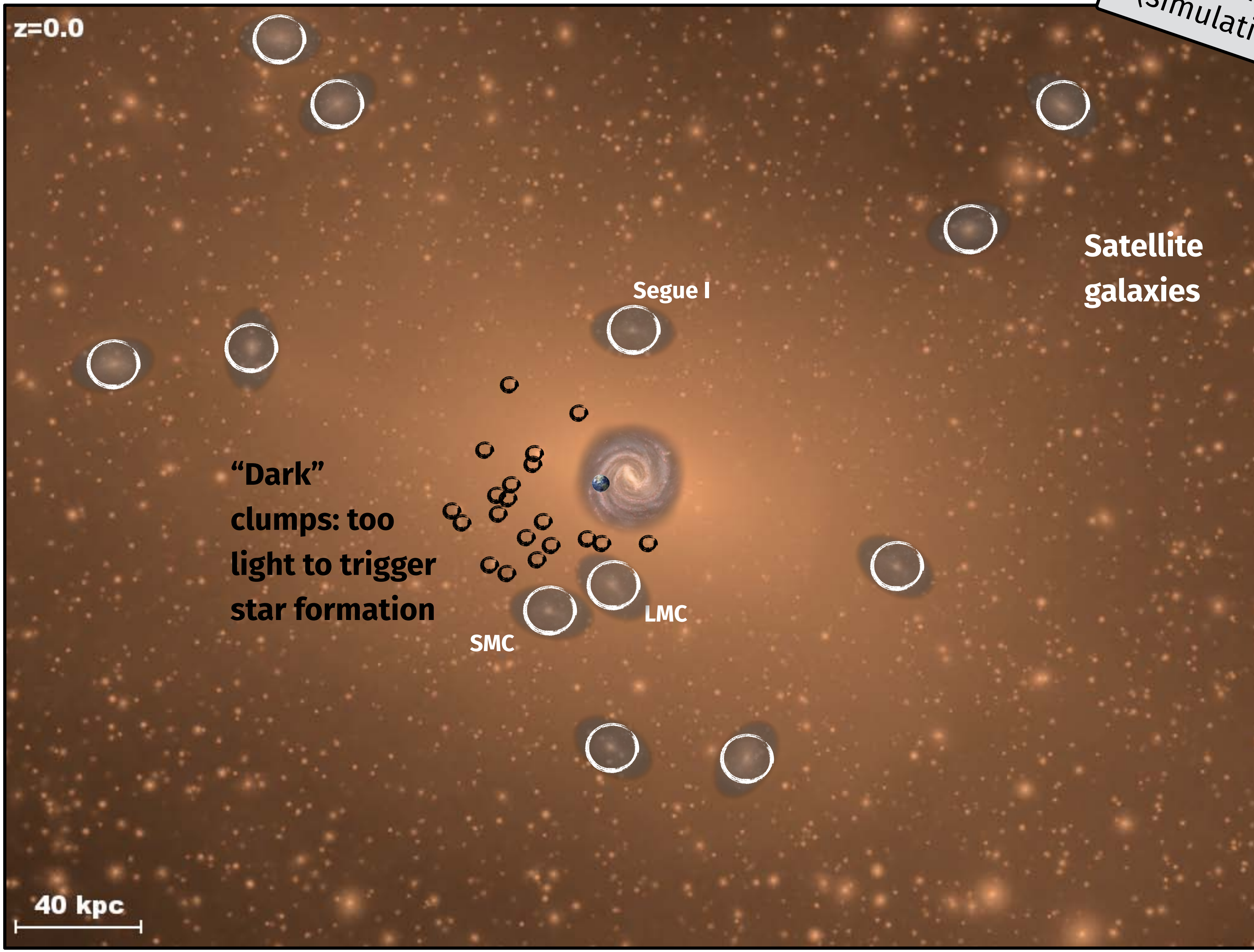

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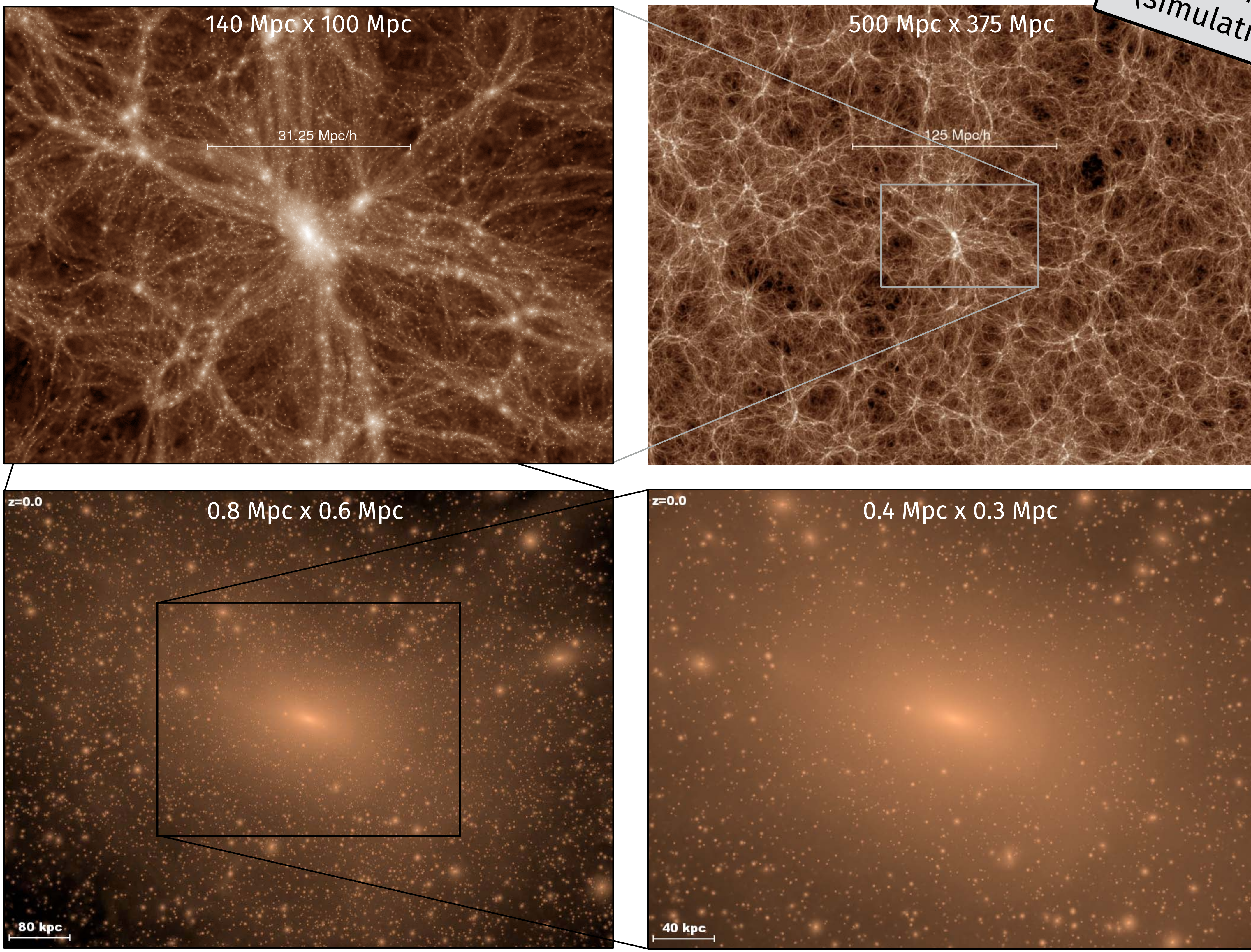

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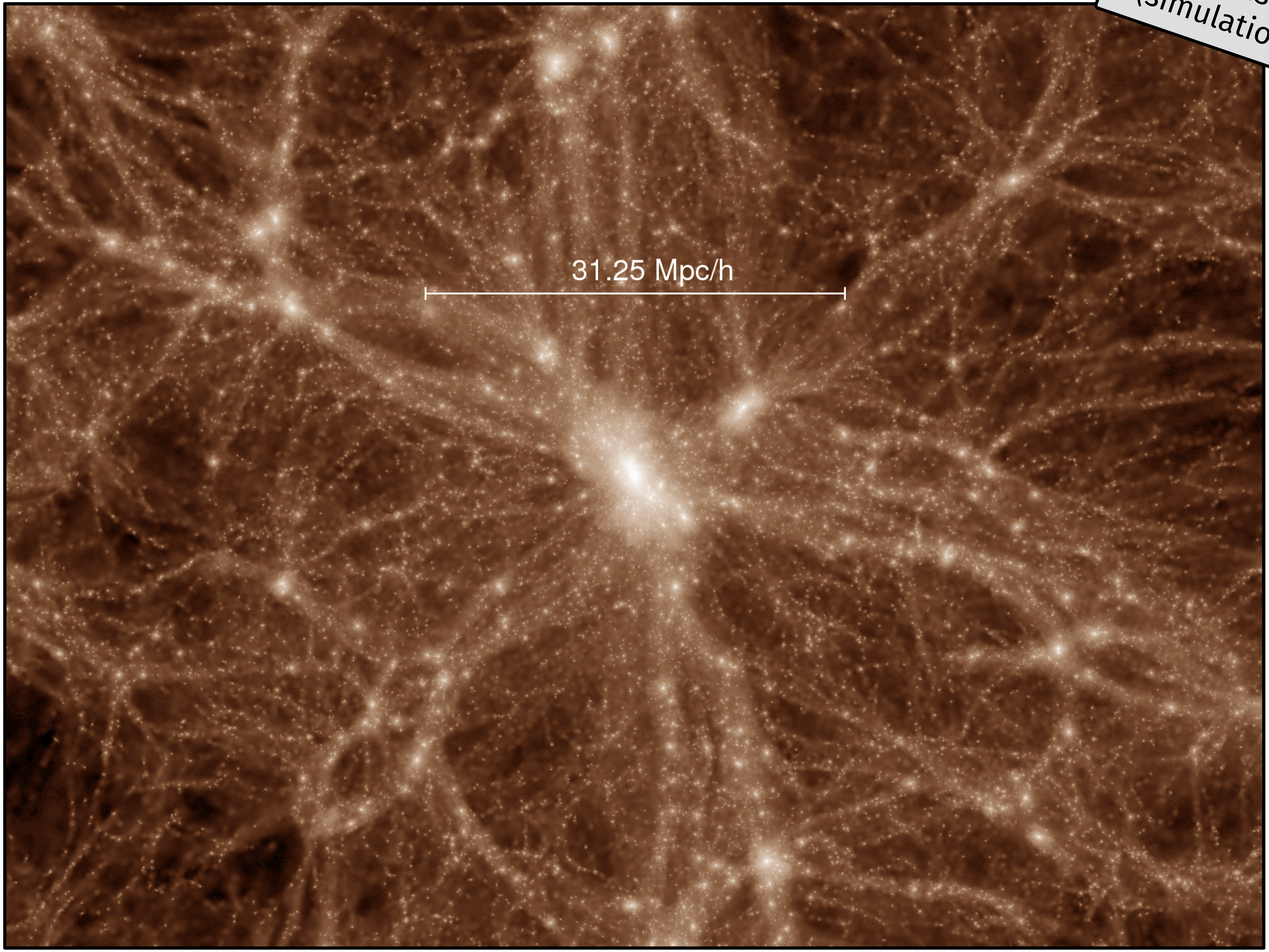

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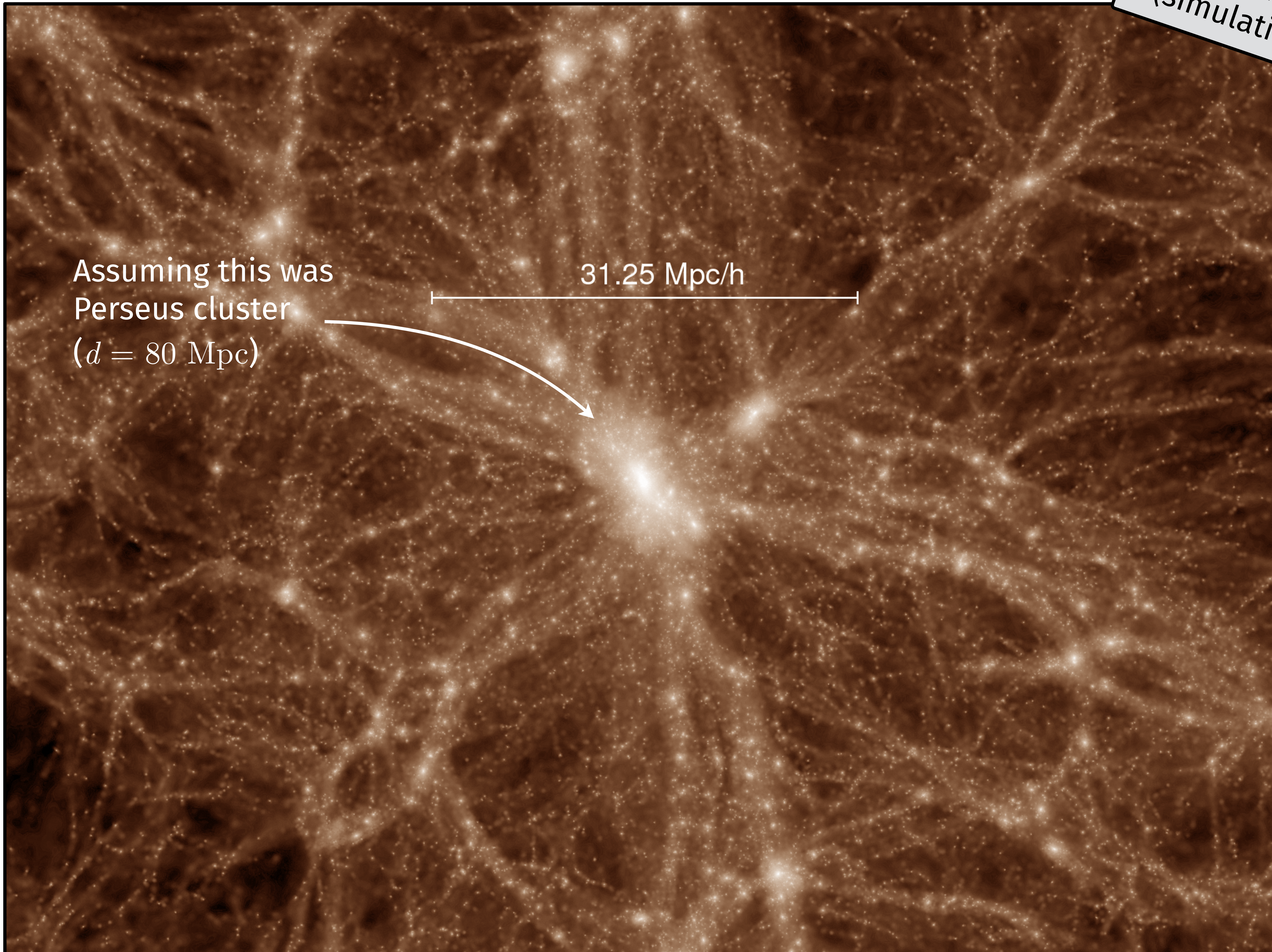

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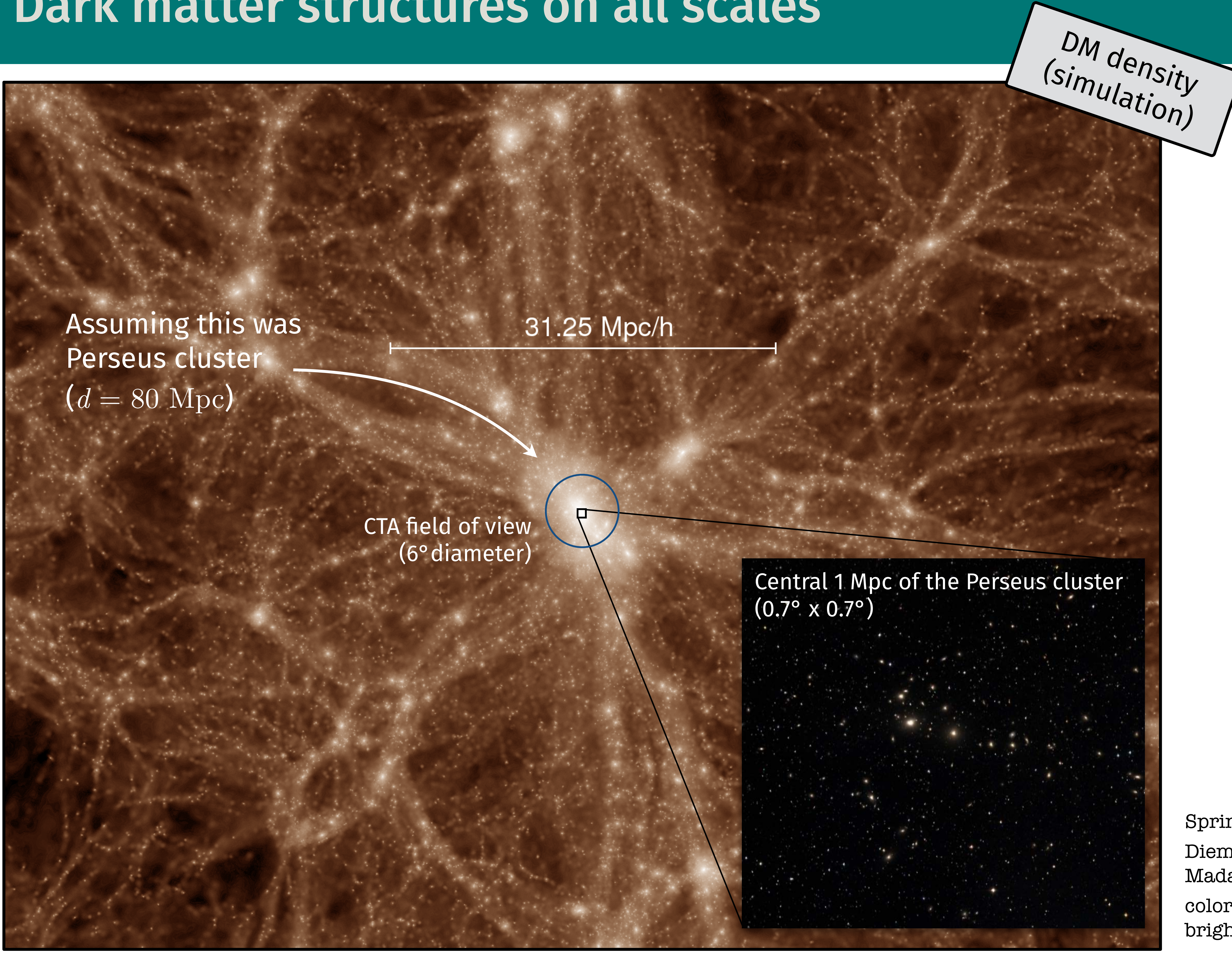

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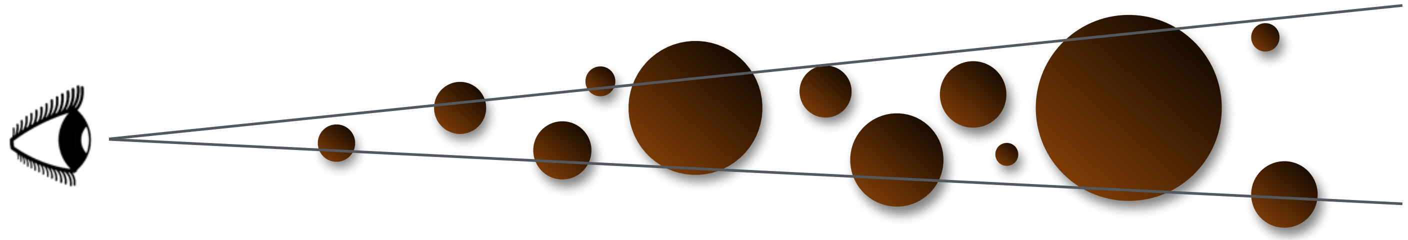
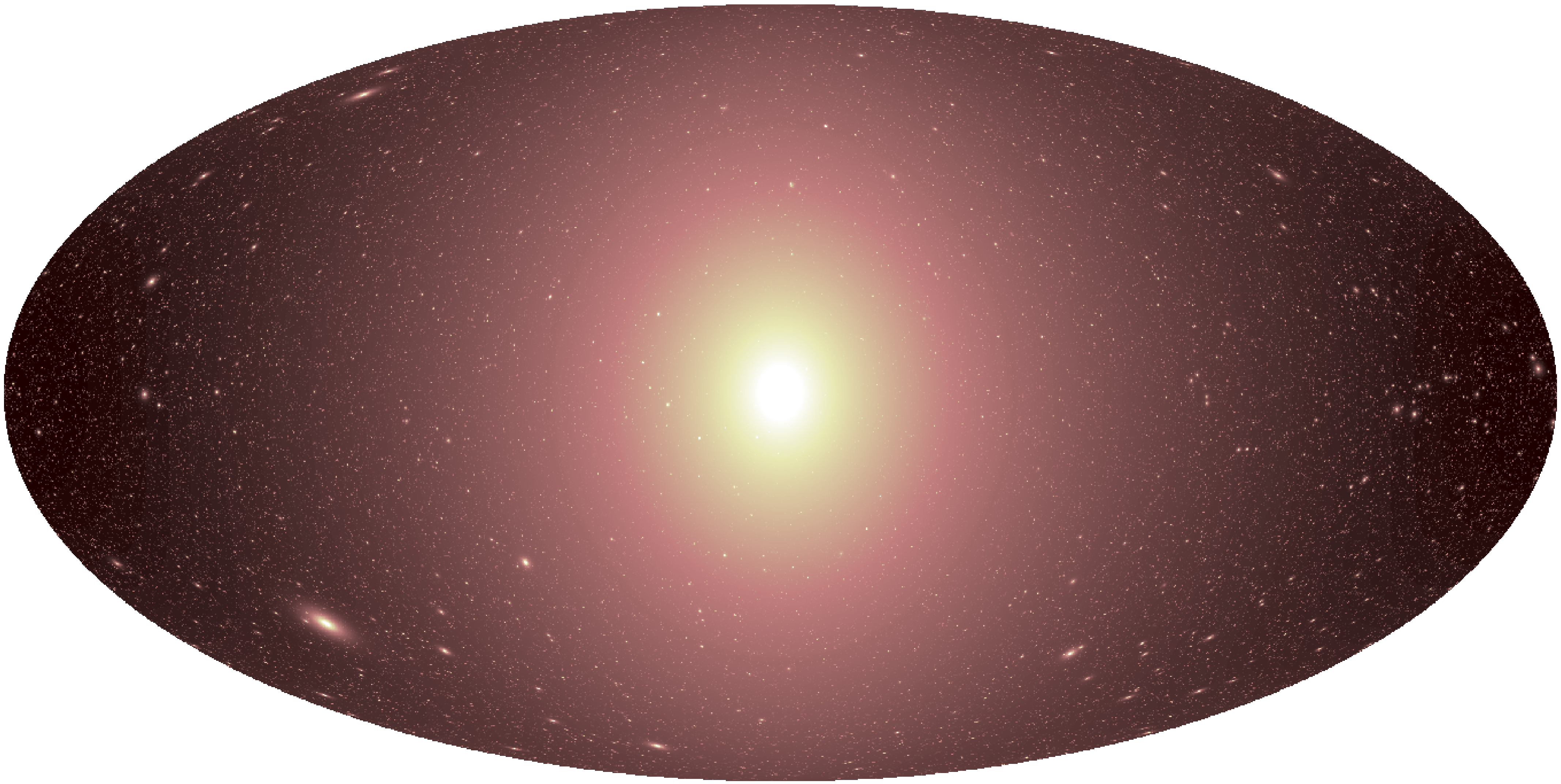
The dark matter sky seen from Earth (annihilation)





log (γ-ray intensity from DM annihilation), Galactic coordinates

synthetic map
calculated with CLUMPY
1806.08639

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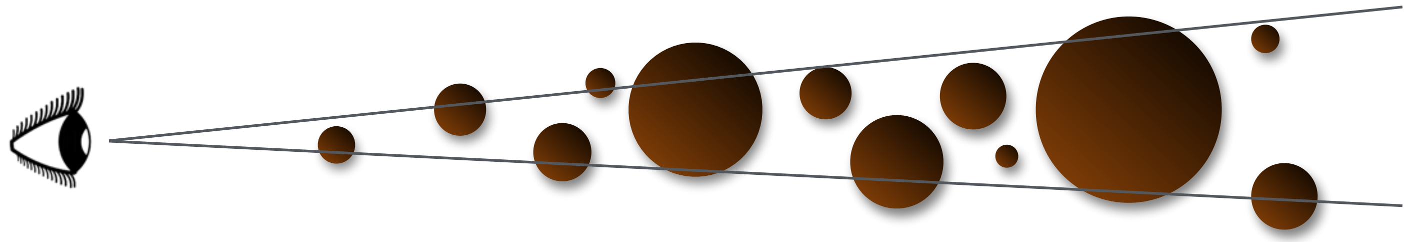

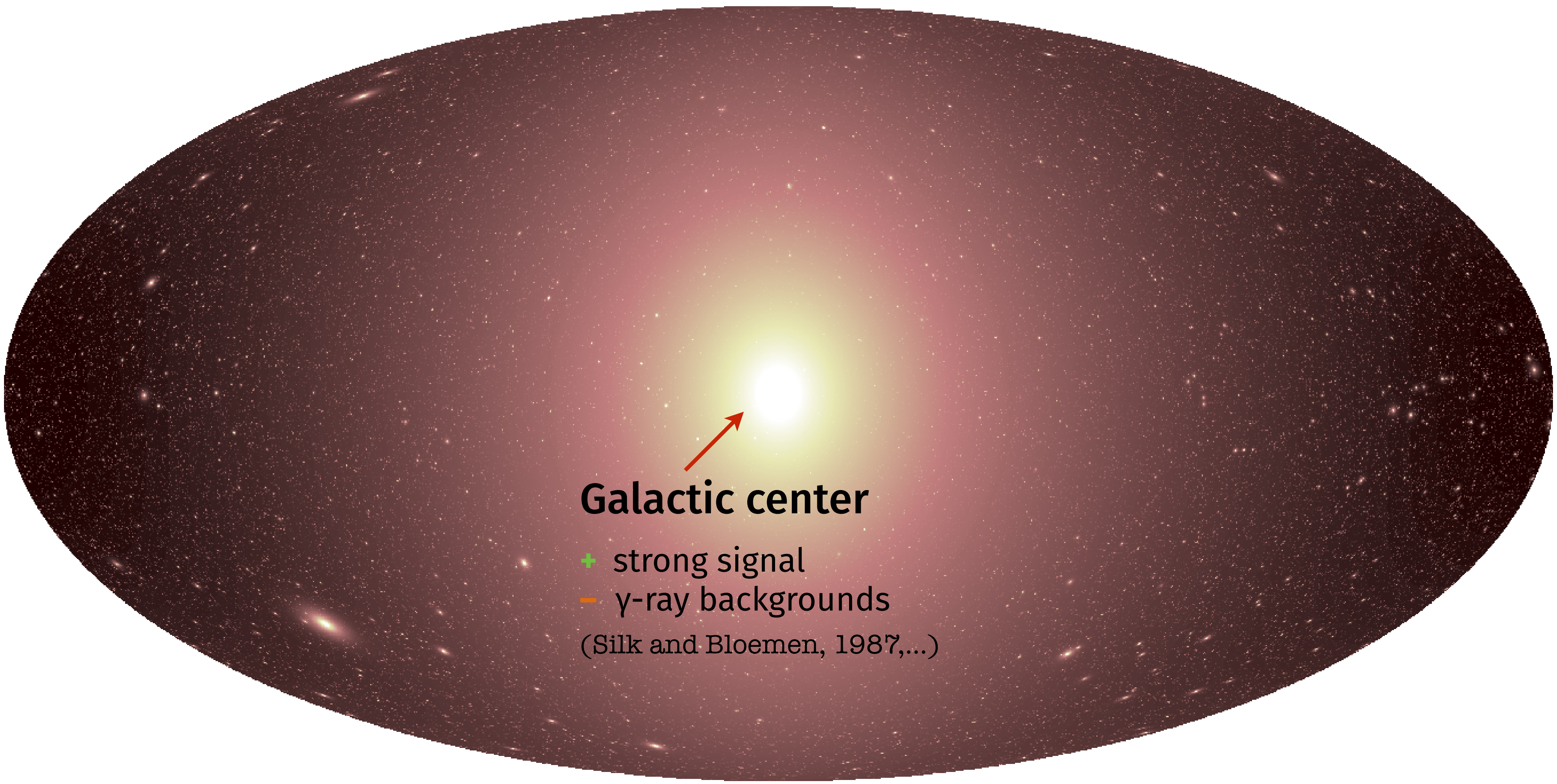

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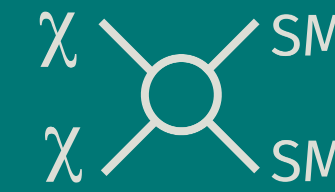

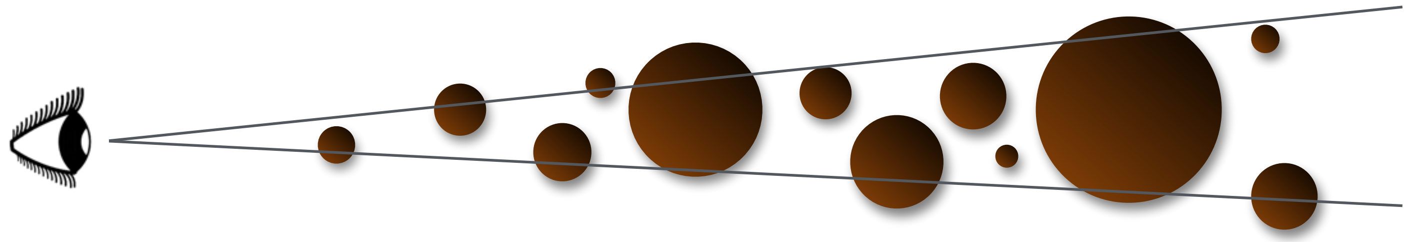

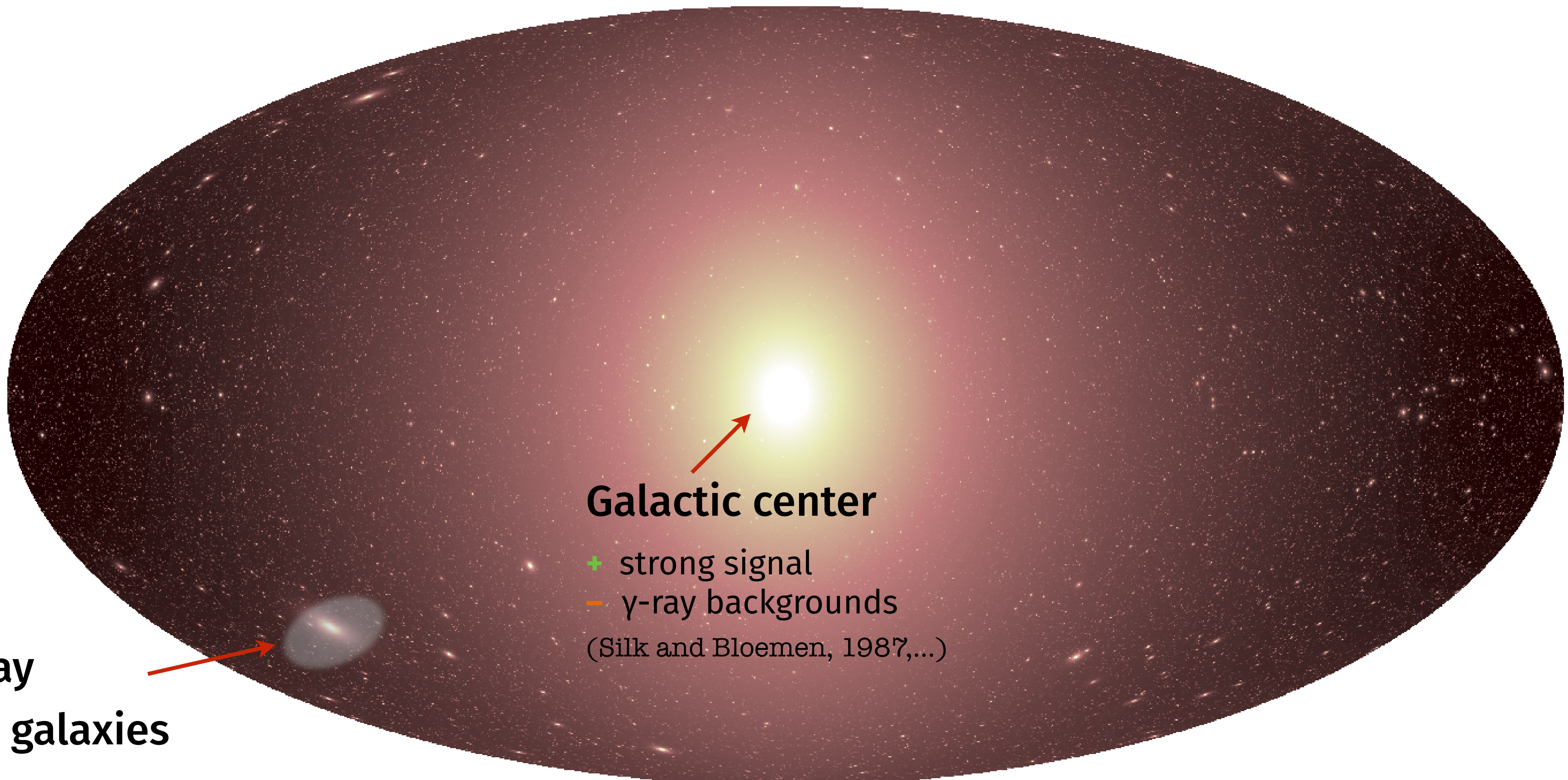

log (γ-ray intensity from DM annihilation), Galactic coordinates

Milky Way satellite galaxies

+ no background
– lower fluxes

1504.02048,
1408.0002,
...

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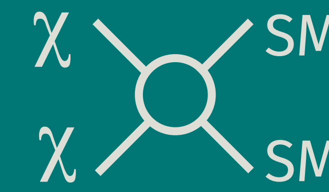
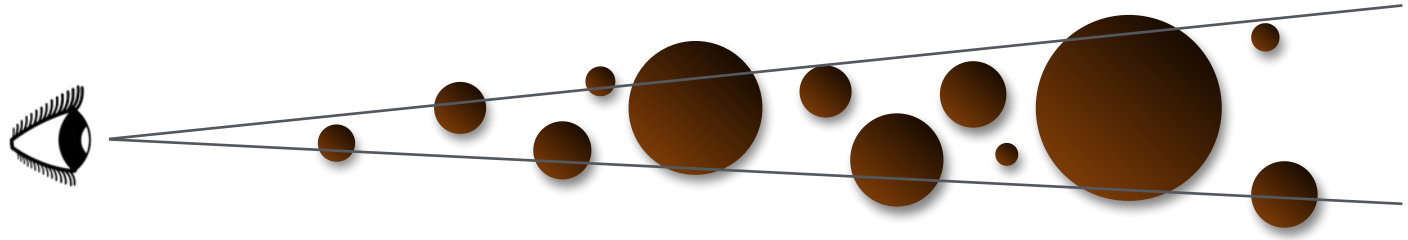
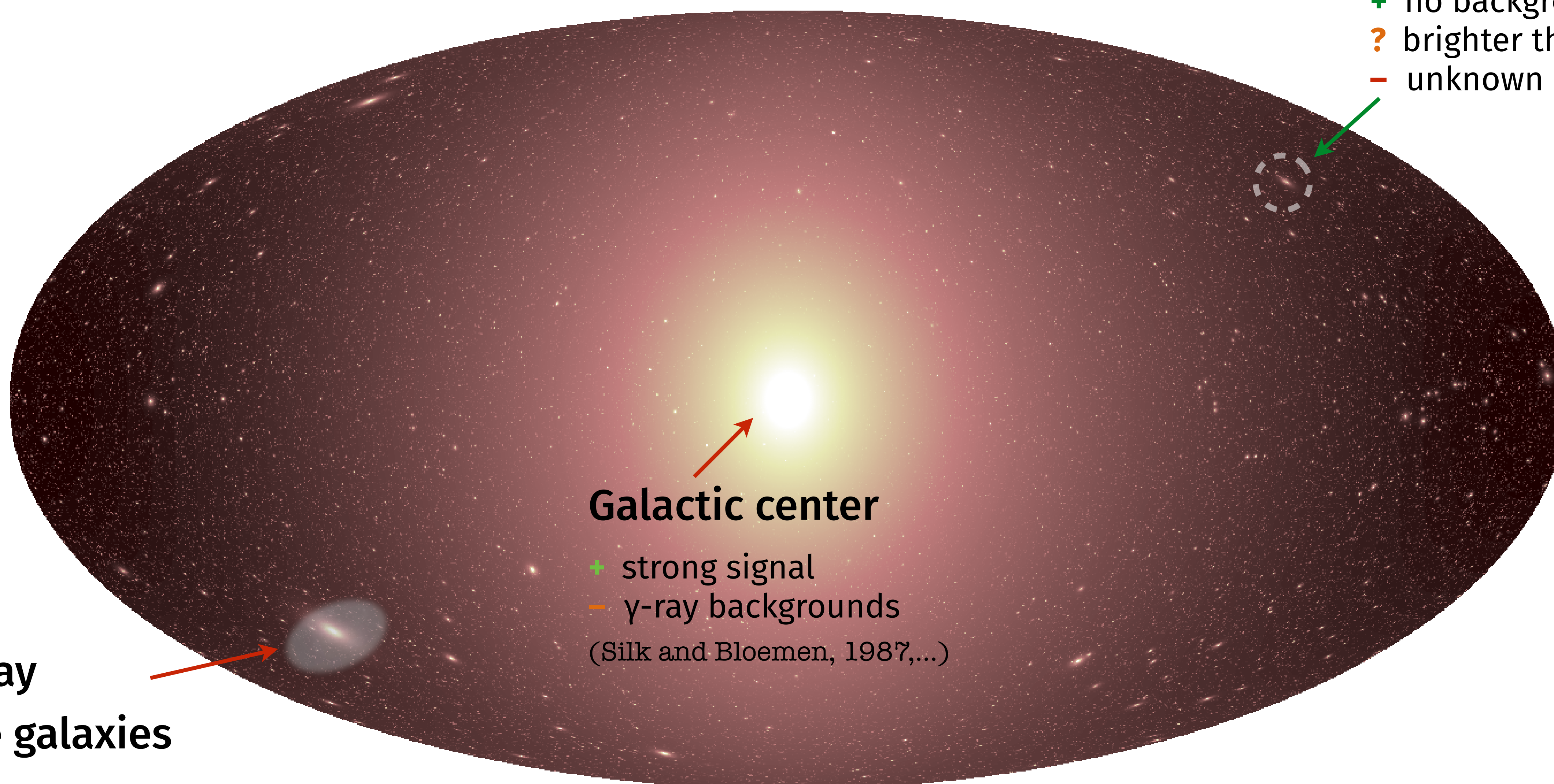




Dark clumps

- \+ no background
- ? brighter than satellites
- – unknown position



Galactic center

- \+ strong signal
- – γ-ray backgrounds

(Silk and Bloemen, 1987,...)

Milky Way satellite galaxies

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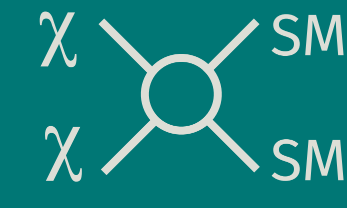

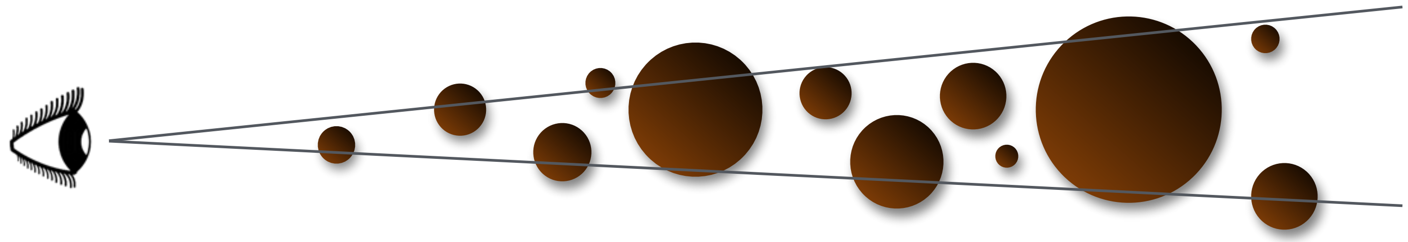

Galaxy clusters

- \+ massive DM targets
- – far away
- – γ-ray backgrounds

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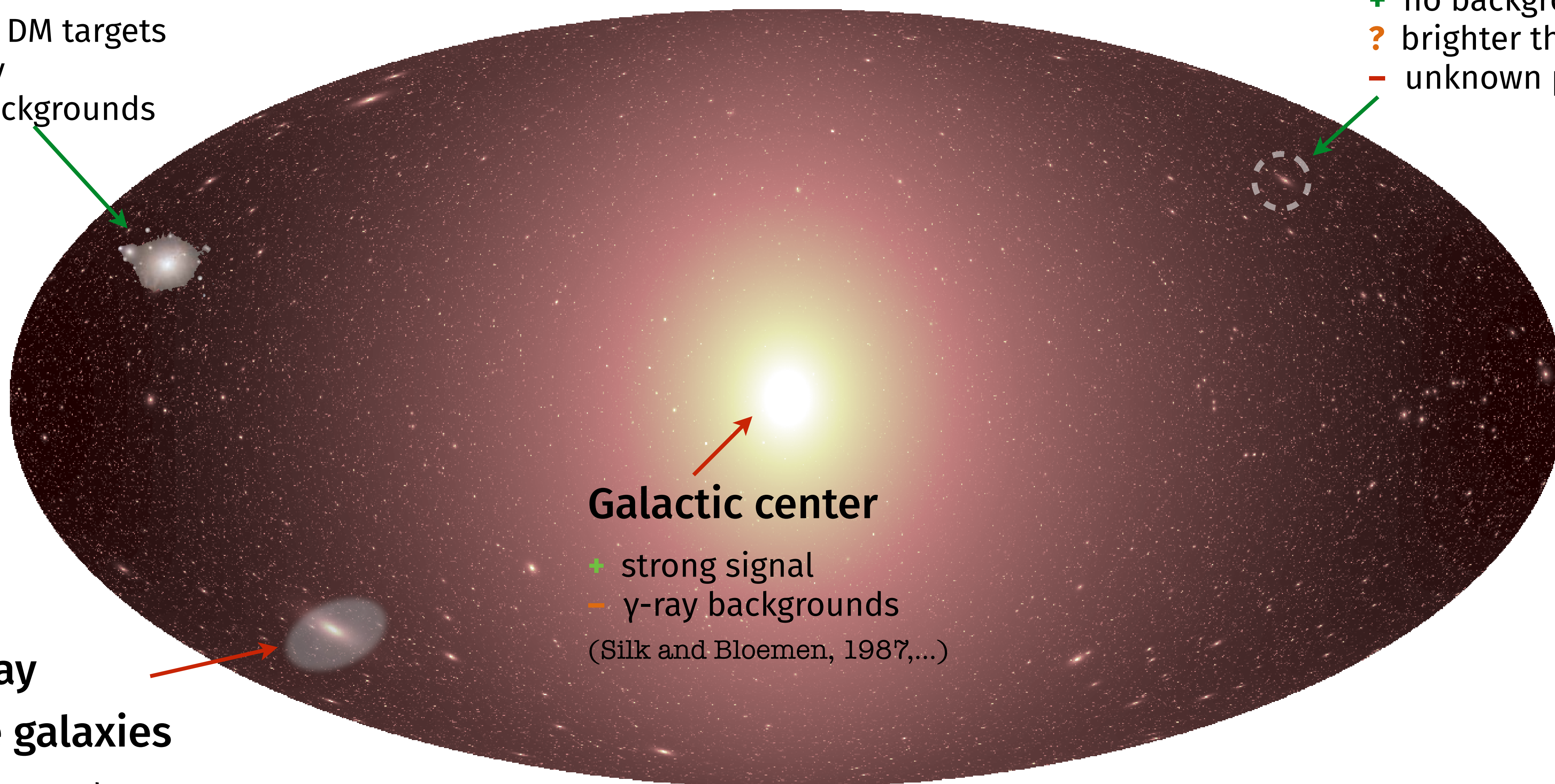

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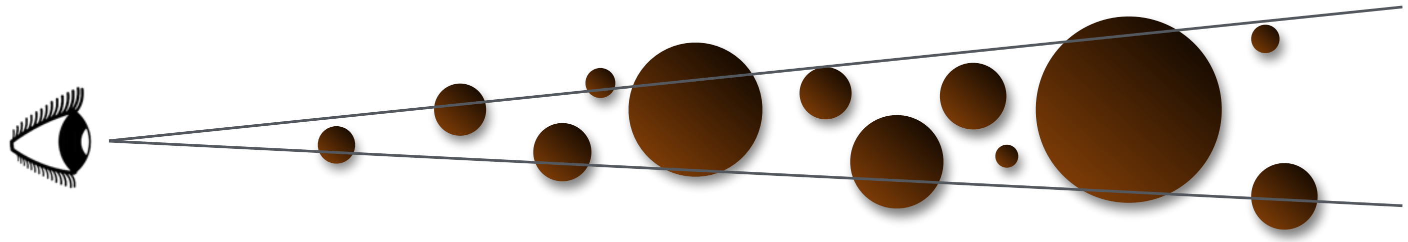
χ χ → SM SM



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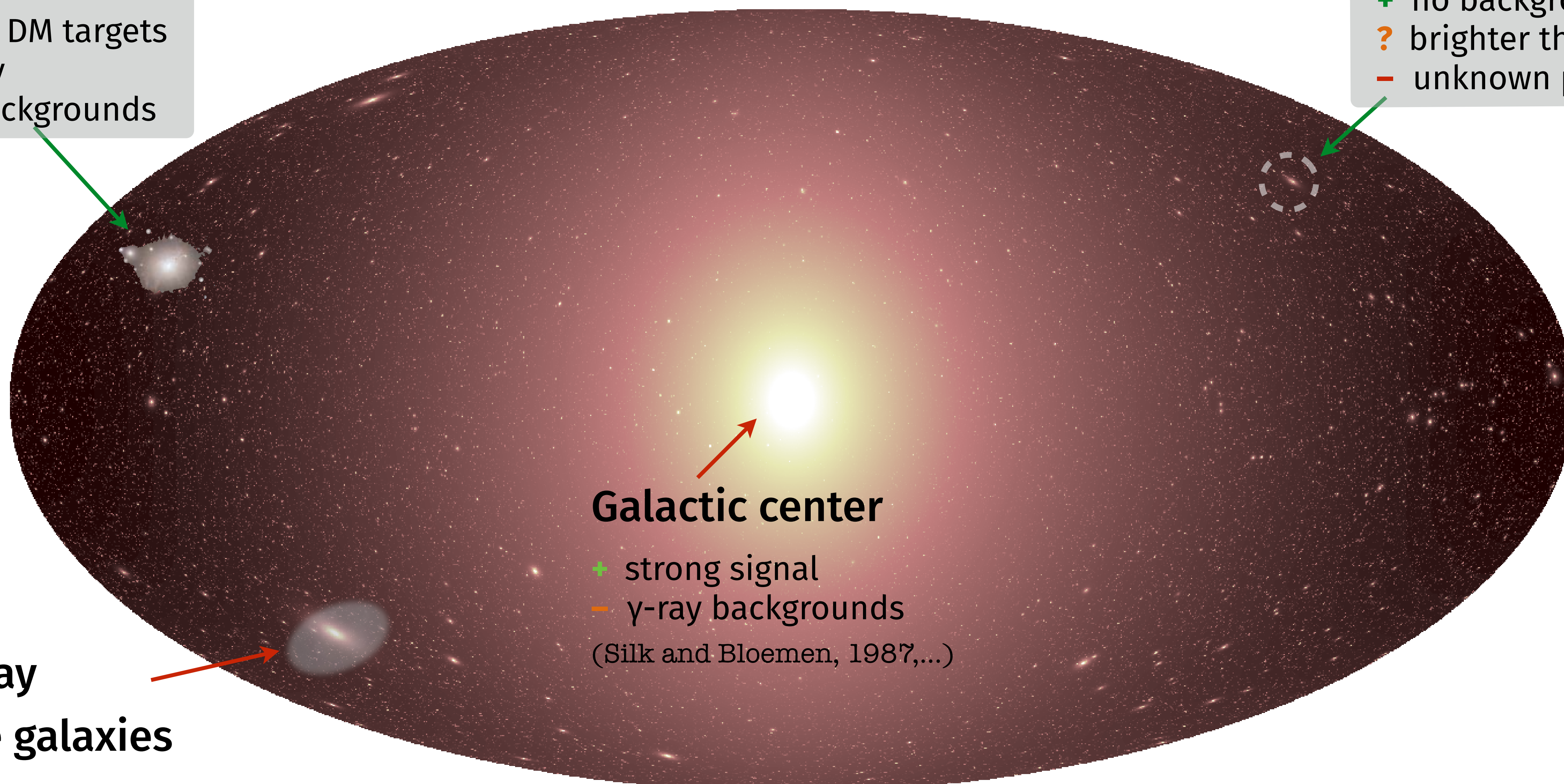

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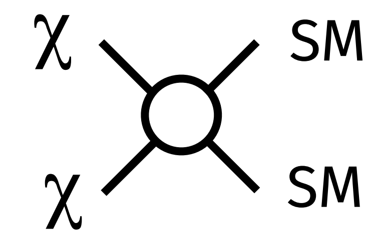
Dark matter clumpiness matters!

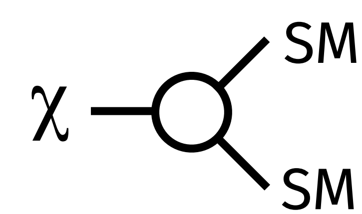
Annihilation

$$\frac{\mathrm{d}\Phi_\gamma^{\,\mathrm{ann.}}}{\mathrm{d}E_\gamma} = \frac{1}{4\pi}\,\frac{\langle\sigma v\rangle}{2m_\chi^2} \times \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \times \int_{\Delta\Omega}\int_{l.o.s.} \rho_{\mathrm{DM}}^2\,\mathrm{d}l\,\mathrm{d}\Omega$$



Decay

$$\frac{\mathrm{d}\Phi^{\,\mathrm{dec.}}}{\mathrm{d}E_\gamma} = \frac{1}{4\pi}\,\frac{1}{\tau_{\mathrm{DM}}\,m_\chi} \times \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \times \int_{\Delta\Omega}\int_{l.o.s.} \rho_{\mathrm{DM}}\mathrm{d}l\mathrm{d}\Omega$$



Dark matter clumpiness matters!

Flux searched for with γ-ray telescope 

Annihilation

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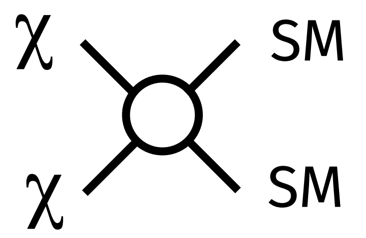

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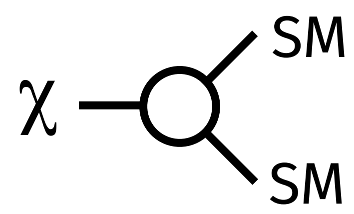
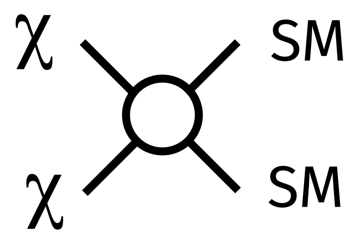


Dark matter clumpiness matters!

Secondary γ-rays after annihilation/decay

Annihilation

$$\frac{\mathrm{d}\Phi_\gamma^{\text{ann.}}}{\mathrm{d}E_\gamma} = \frac{1}{4\pi}\,\frac{\langle\sigma v\rangle}{2m_\chi^2} \times \boxed{\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}} \times \int_{\Delta\Omega}\int_{l.o.s.} \rho_{\mathrm{DM}}^2\,\mathrm{d}l\,\mathrm{d}\Omega$$



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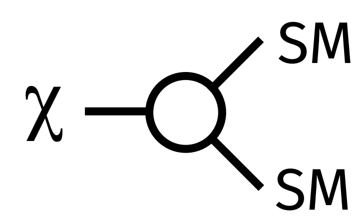

Dark matter clumpiness matters!

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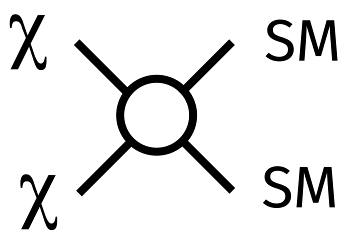

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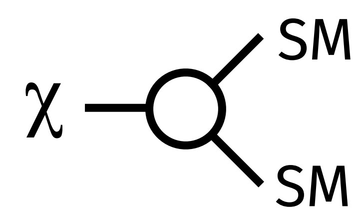


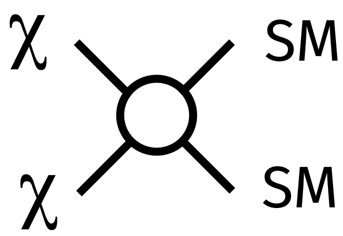
Unknown DM particle mass: parameter

Dark matter clumpiness matters!

Annihilation cross section

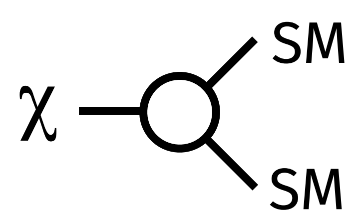
Annihilation

$$\frac{\mathrm{d}\Phi_{\gamma}^{\,\mathrm{ann.}}}{\mathrm{d}E_{\gamma}} = \frac{1}{4\pi}\,\frac{\langle\sigma v\rangle}{2m_{\chi}^{2}} \times \frac{\mathrm{d}N_{\gamma}}{\mathrm{d}E_{\gamma}} \times \int_{\Delta\Omega}\int_{l.o.s.} \rho_{\mathrm{DM}}^{2}\,\mathrm{d}l\,\mathrm{d}\Omega$$



Decay

$$\frac{\mathrm{d}\Phi^{\,\mathrm{dec.}}}{\mathrm{d}E_{\gamma}} = \frac{1}{4\pi}\,\frac{1}{\tau_{\mathrm{DM}}\,m_{\chi}} \times \frac{\mathrm{d}N_{\gamma}}{\mathrm{d}E_{\gamma}} \times \int_{\Delta\Omega}\int_{l.o.s.} \rho_{\mathrm{DM}}\mathrm{d}l\mathrm{d}\Omega$$

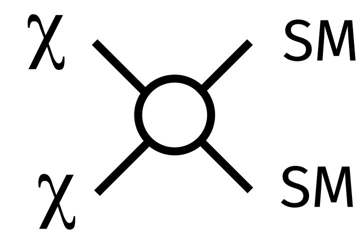


Particle lifetime

Dark matter clumpiness matters!

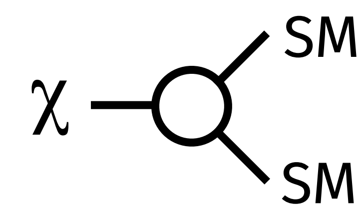
Annihilation

$$\frac{\mathrm{d}\Phi_\gamma^{\,\mathrm{ann.}}}{\mathrm{d}E_\gamma} = \frac{1}{4\pi}\,\frac{\langle\sigma v\rangle}{2m_\chi^2} \times \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \times \boxed{\int_{\Delta\Omega}\int_{l.o.s.} \rho_{\mathrm{DM}}^{2}\,\mathrm{d}l\,\mathrm{d}\Omega}$$



Decay

$$\frac{\mathrm{d}\Phi^{\,\mathrm{dec.}}}{\mathrm{d}E_\gamma} = \frac{1}{4\pi}\,\frac{1}{\tau_{\mathrm{DM}}\,m_\chi} \times \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \times \boxed{\int_{\Delta\Omega}\int_{l.o.s.} \rho_{\mathrm{DM}}\mathrm{d}l\mathrm{d}\Omega}$$

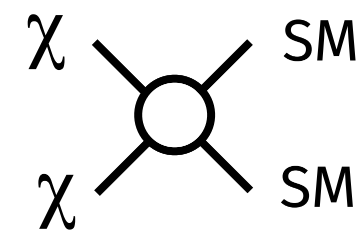


Density distribution

Dark matter clumpiness matters!

Annihilation

$$\frac{\mathrm{d}\Phi_\gamma^{\,\mathrm{ann.}}}{\mathrm{d}E_\gamma} = \frac{1}{4\pi}\,\frac{\langle\sigma v\rangle}{2m_\chi^2} \times \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \times \boxed{\int_{\Delta\Omega}\int_{l.o.s.} \rho_{\mathrm{DM}}^{2}\,\mathrm{d}l\,\mathrm{d}\Omega}$$



Decay

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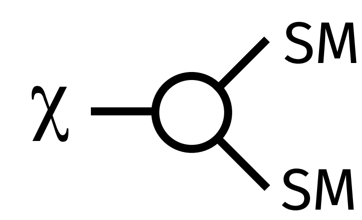
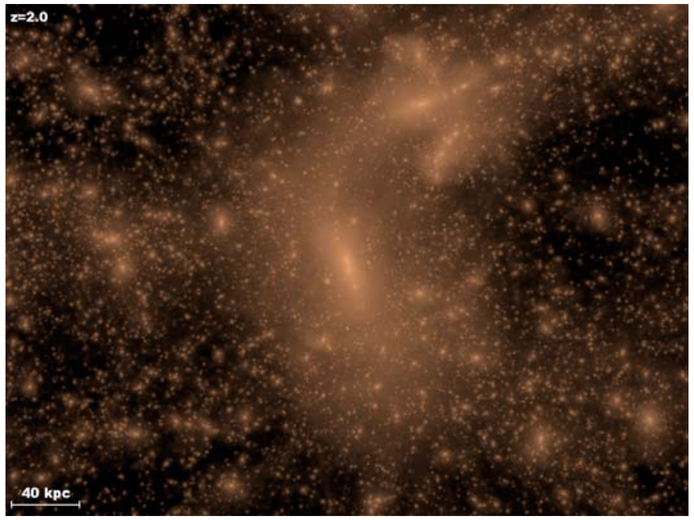


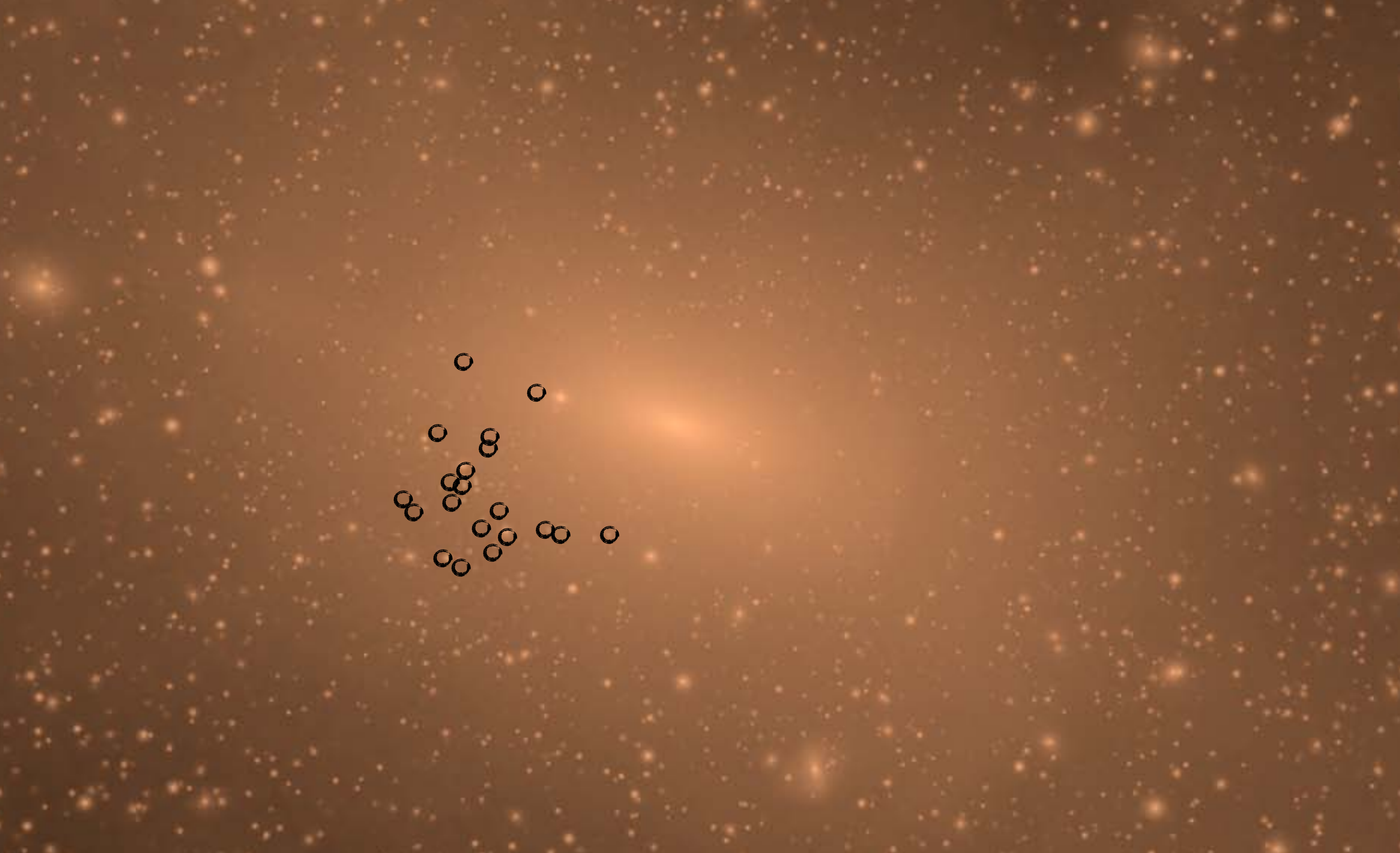
Density distribution



What density targets do we need for CTA?

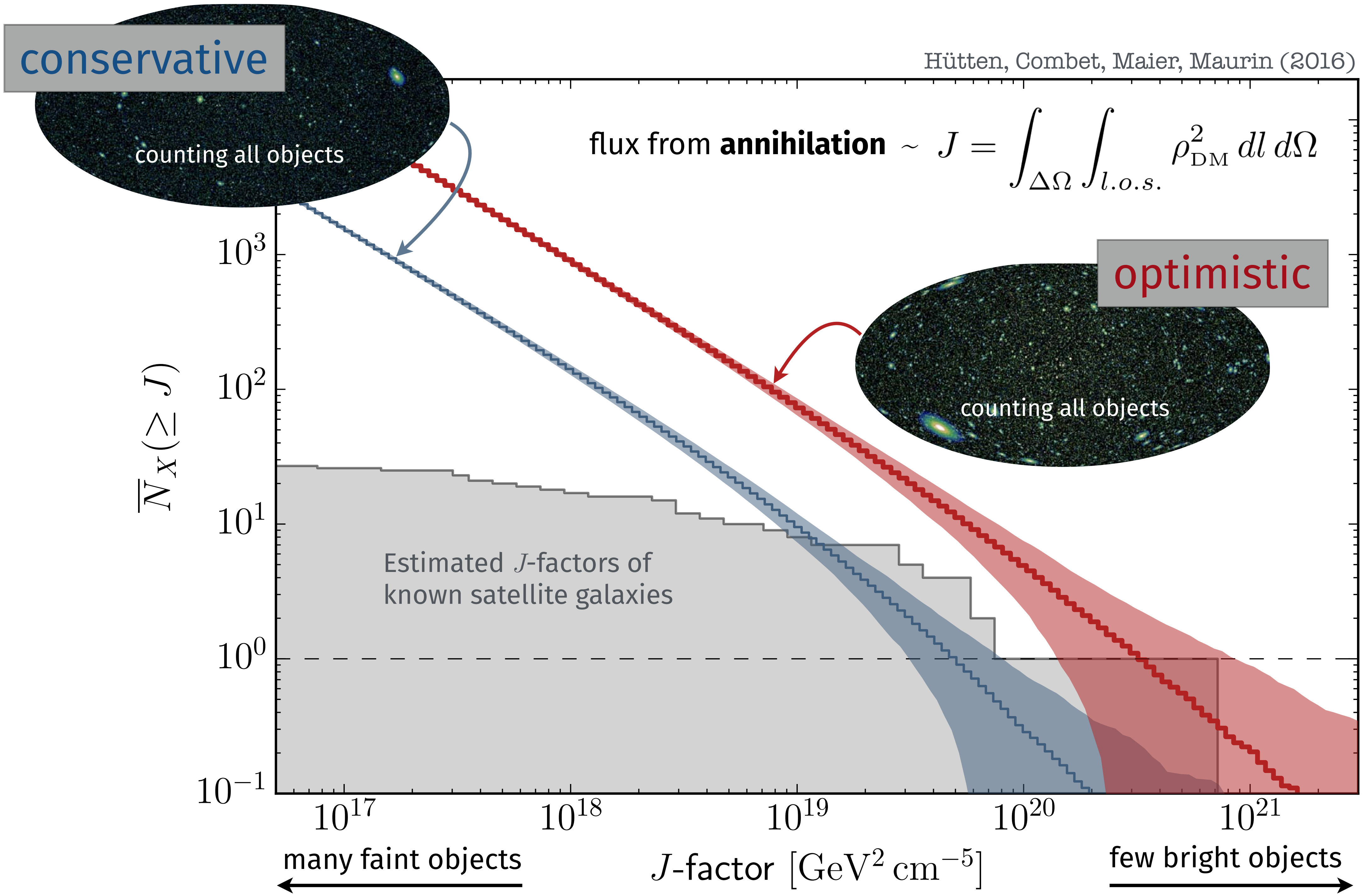
1. Bright: close and/or massive DM budget
2. Localized (“point-like”)
3. no astrophysical back-/foregrounds

2. Dark Galactic DM clumps

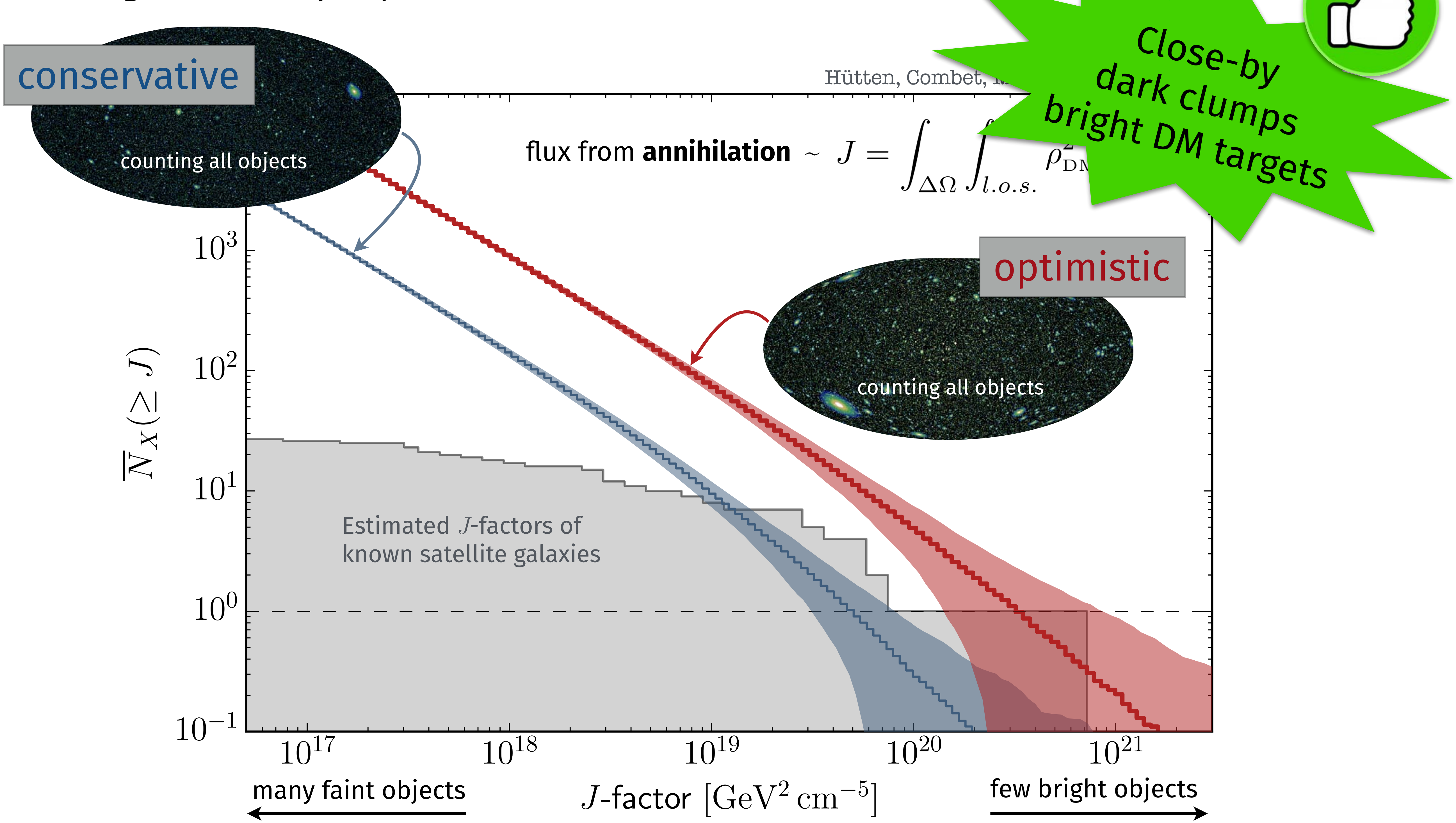


Dark clumps annihilation brightness

- Brightness in γ-rays (J-factor):

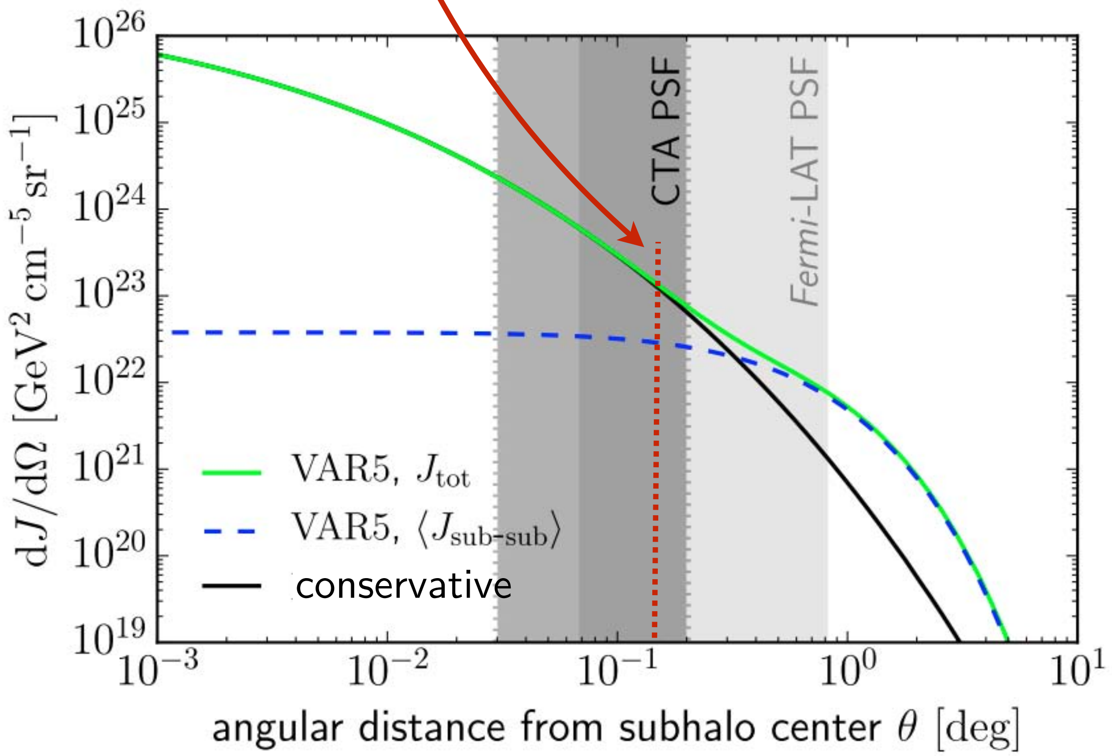


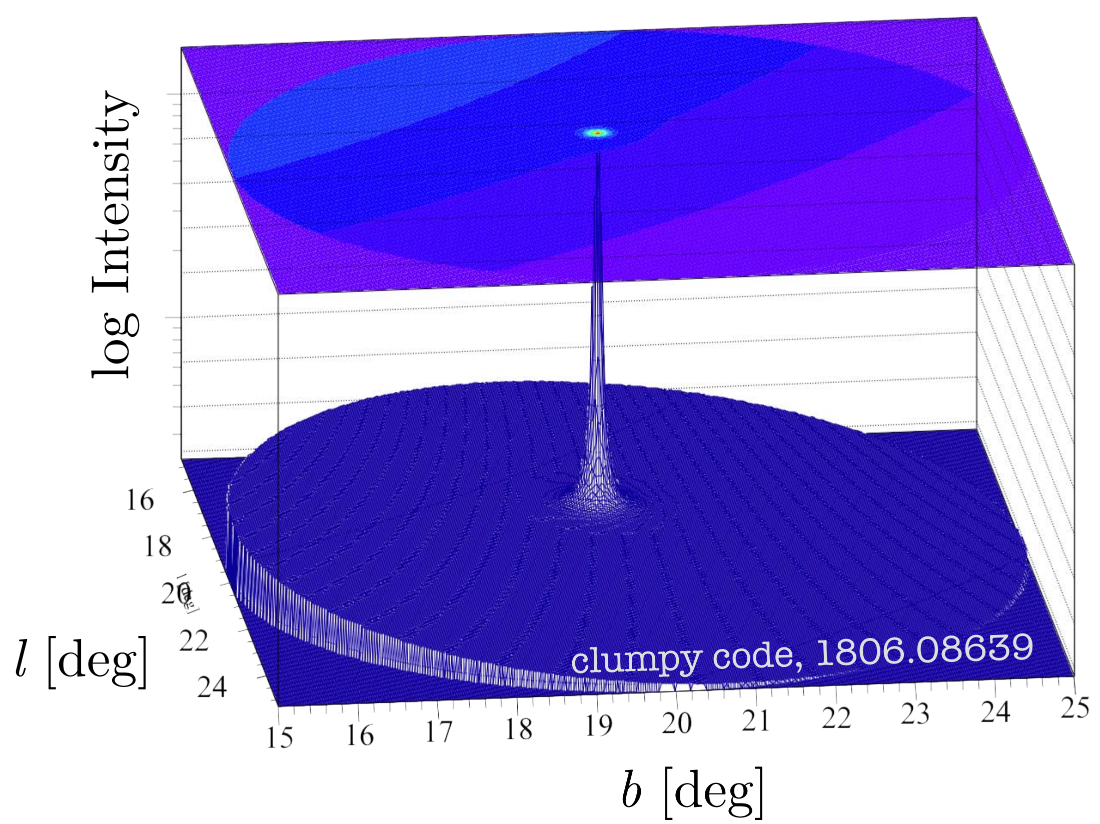
- Brightness in γ-rays (J-factor):



Dark clumps annihilation profiles

half-light
radius $\sim 0.14°$

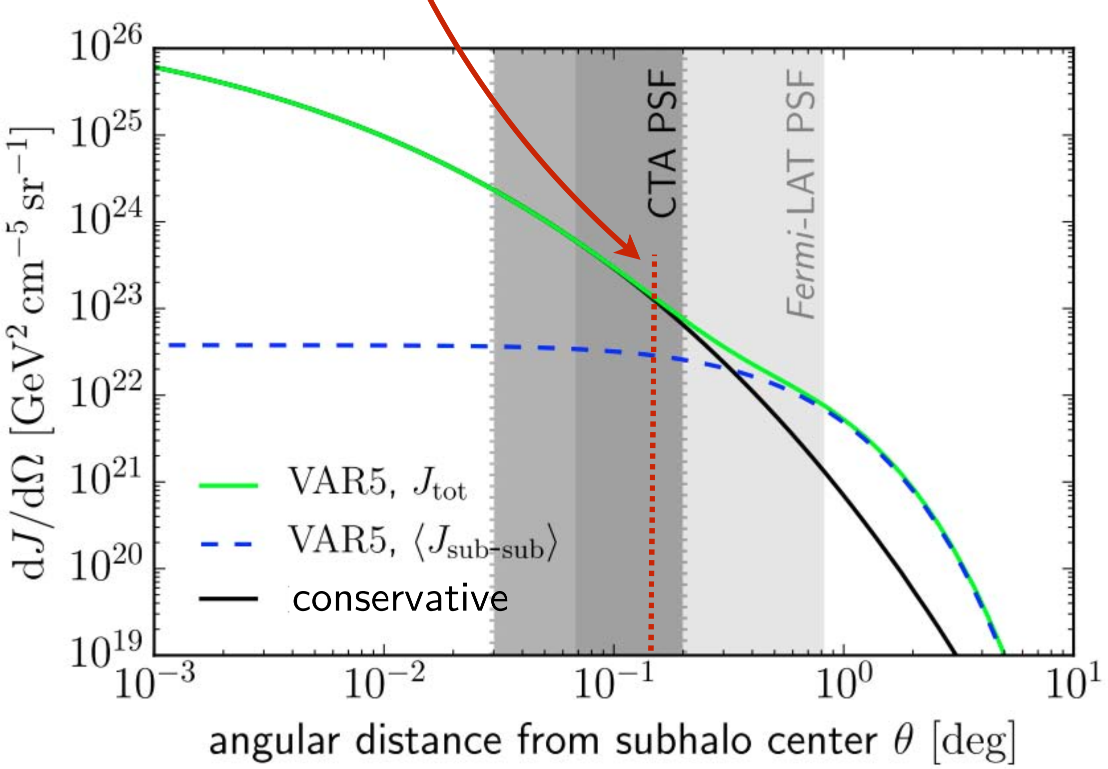


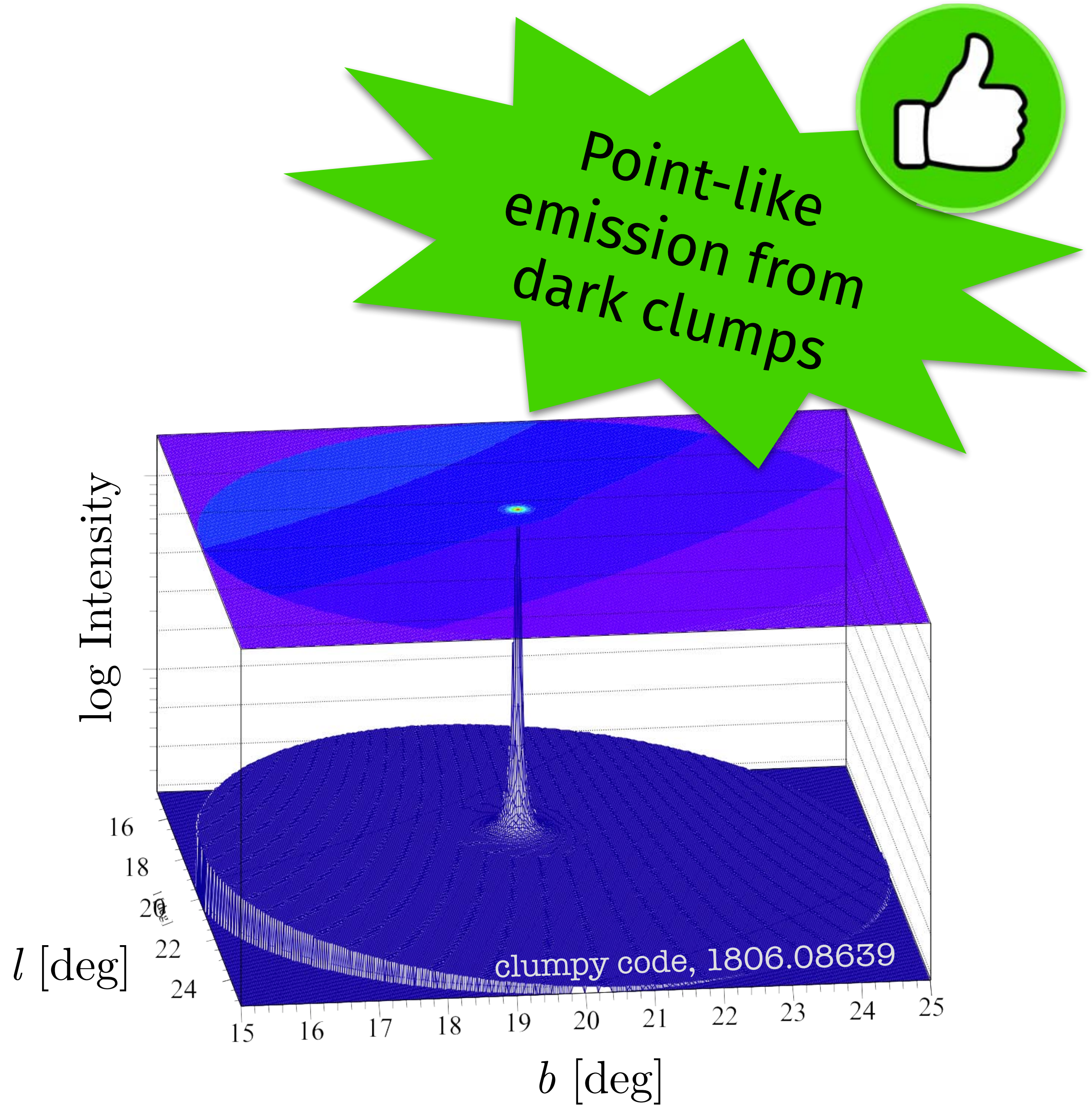


- Take advantage of CTA's excellent angular resolution

Dark clumps annihilation profiles

half-light radius $\sim 0.14°$



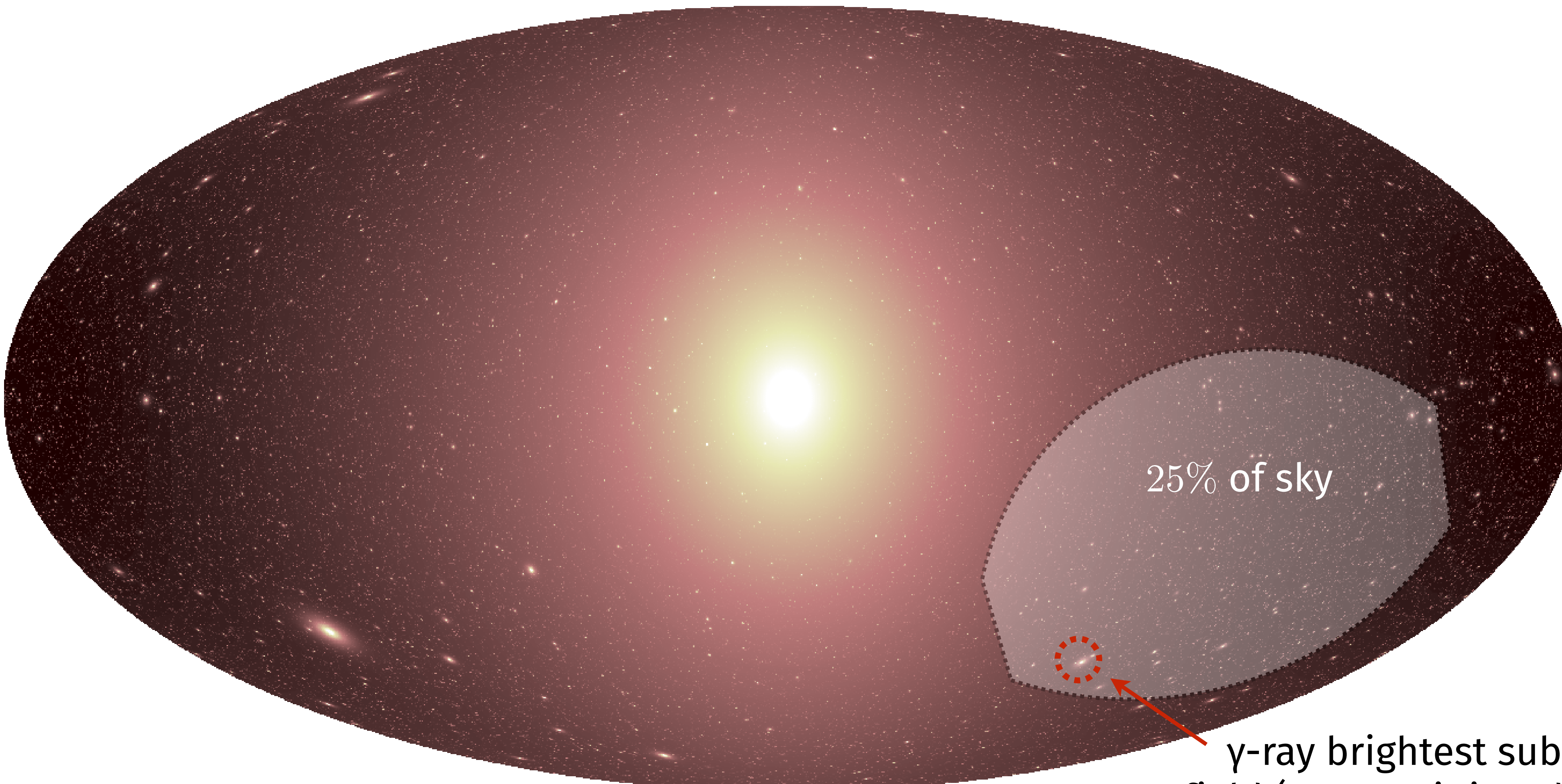


- Take advantage of CTA's excellent angular resolution

But how to find the dark clumps?

- In a survey:

  Observing 25% of the sky with 500 hours (extragalactic survey benchmark):



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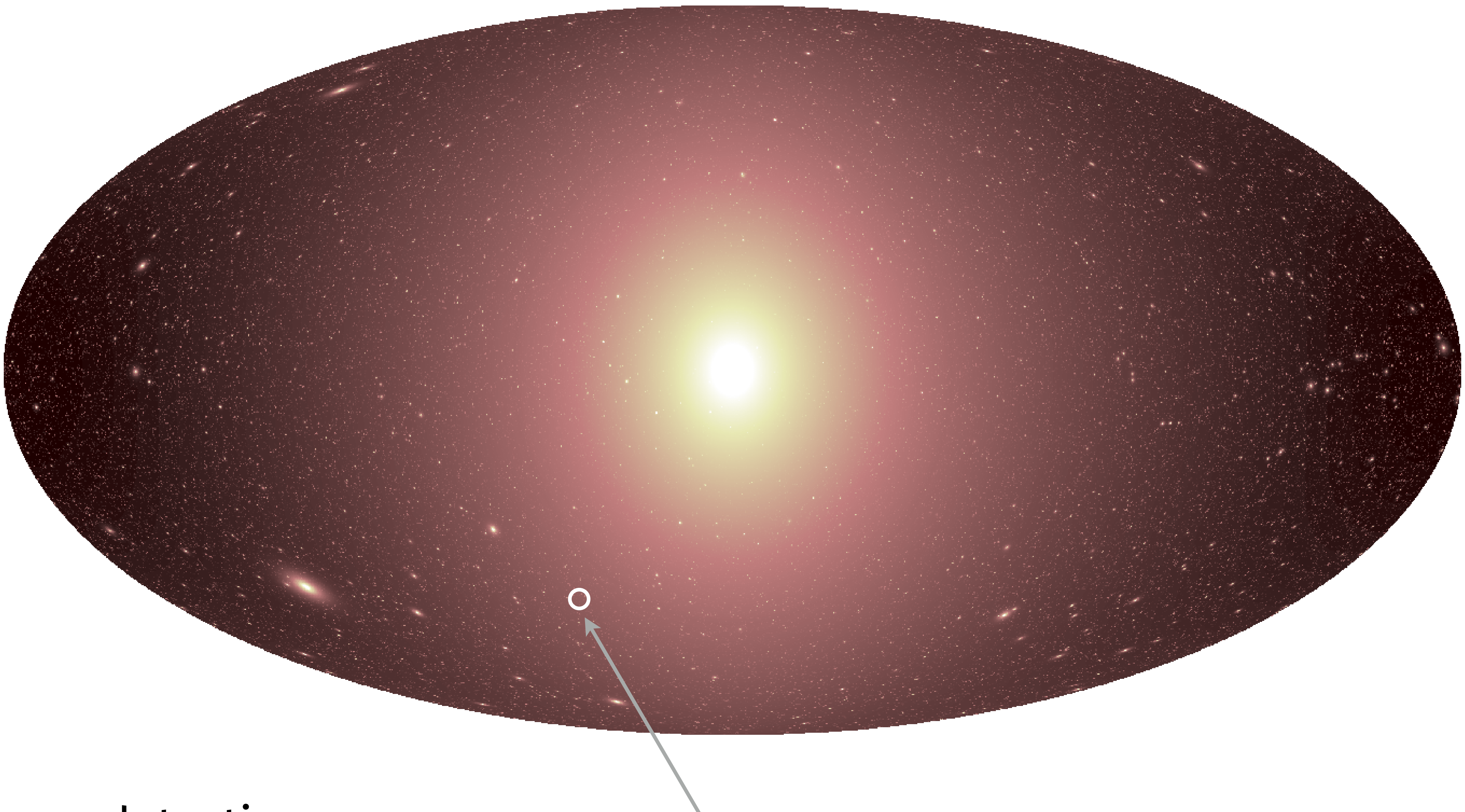
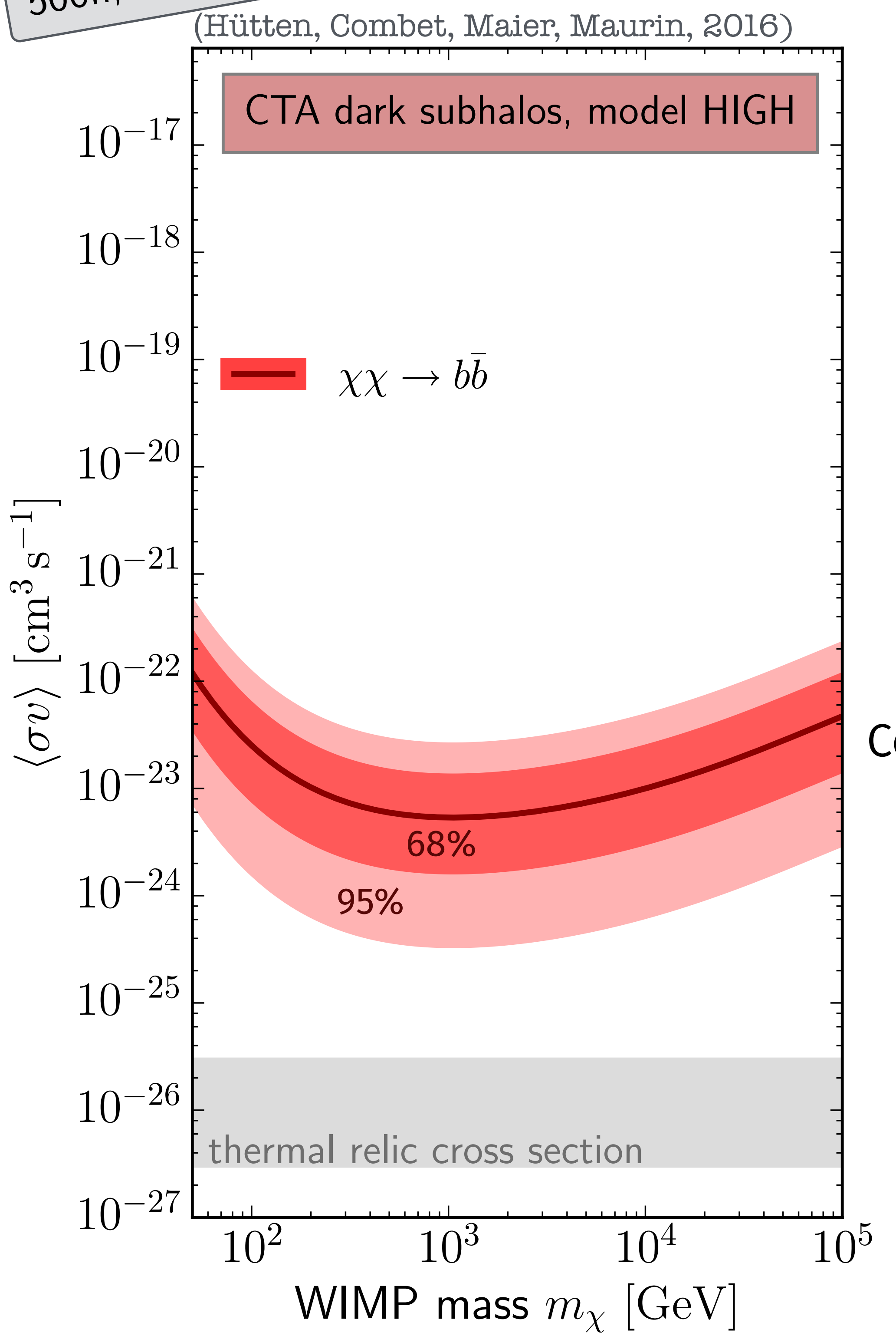


- Chance detection

Survey sensitivity based on CTA South (prod2-3)

500h, 95% C.L.

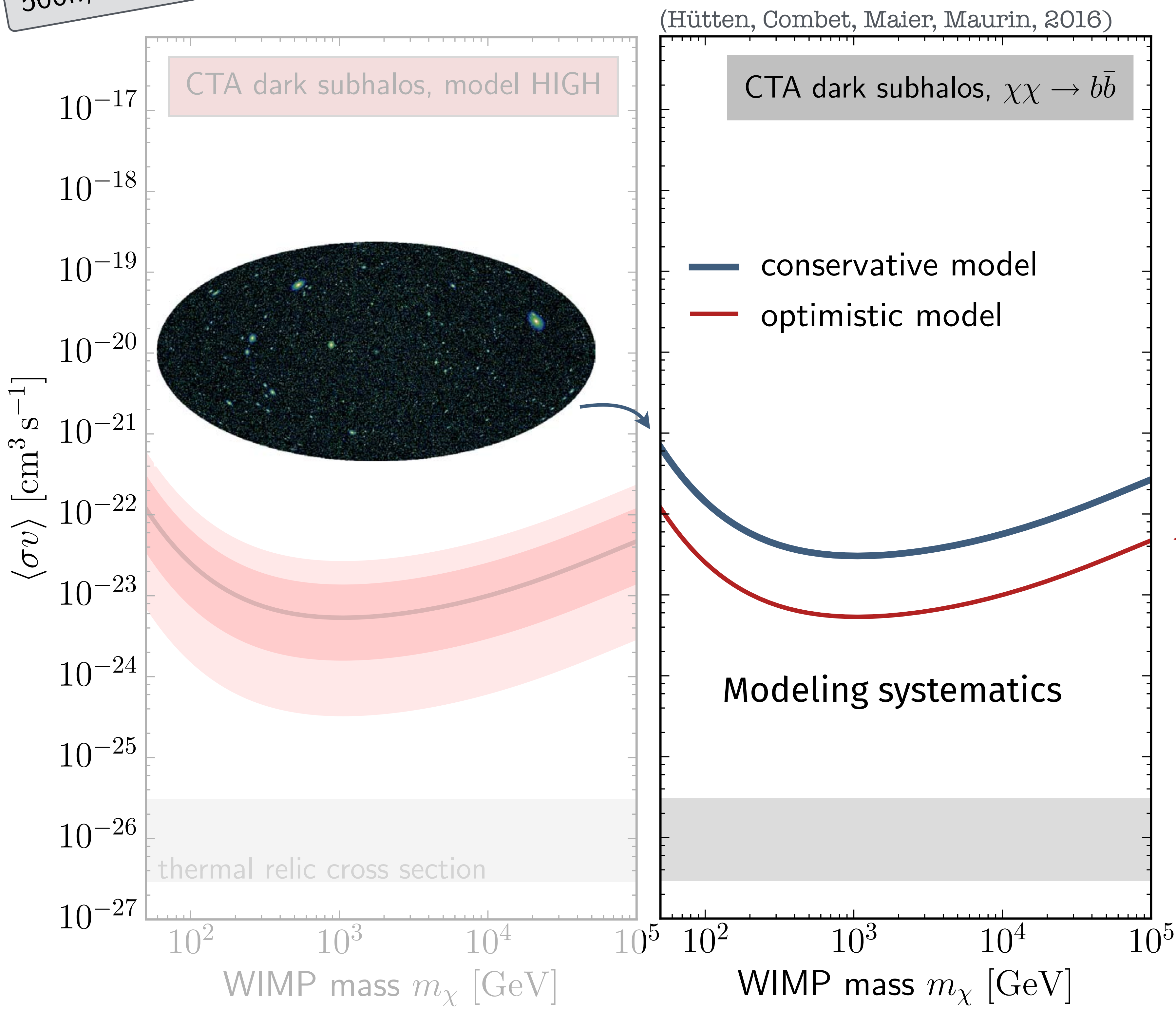


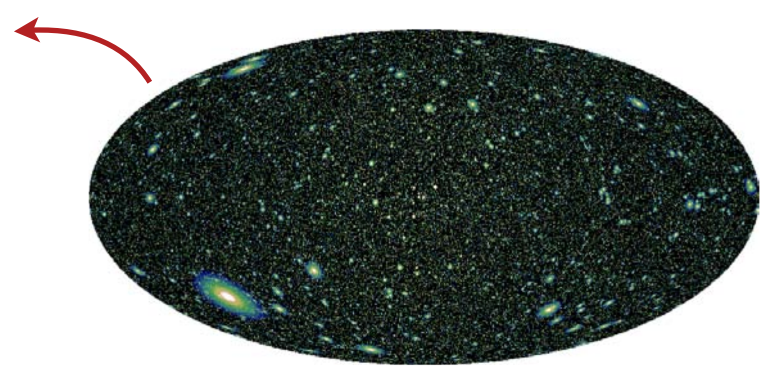
Cosmic variance

Survey sensitivity based on CTA South (prod2-3)

500h, 95% C.L.

(Hütten, Combet, Maier, Maurin, 2016)





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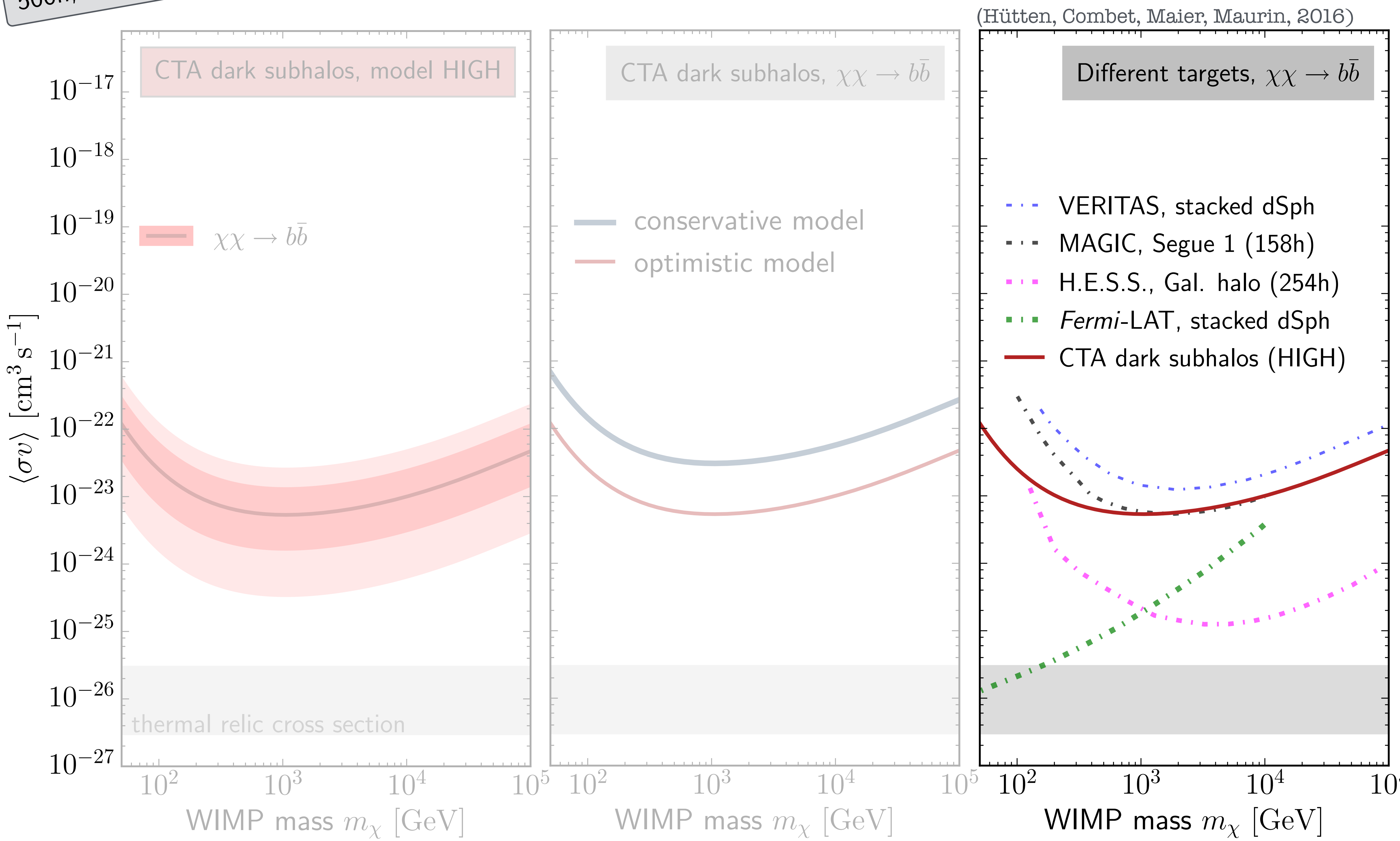

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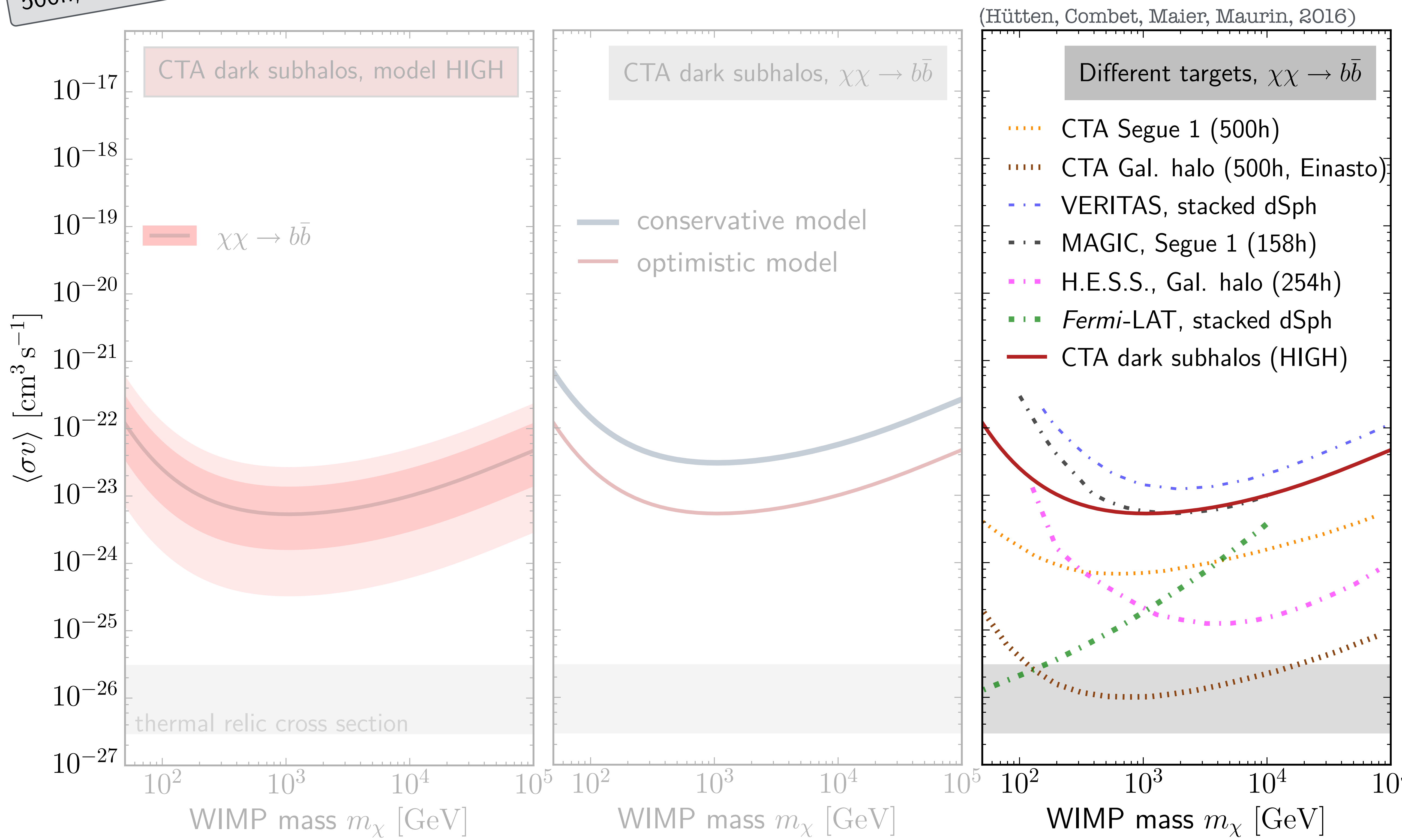

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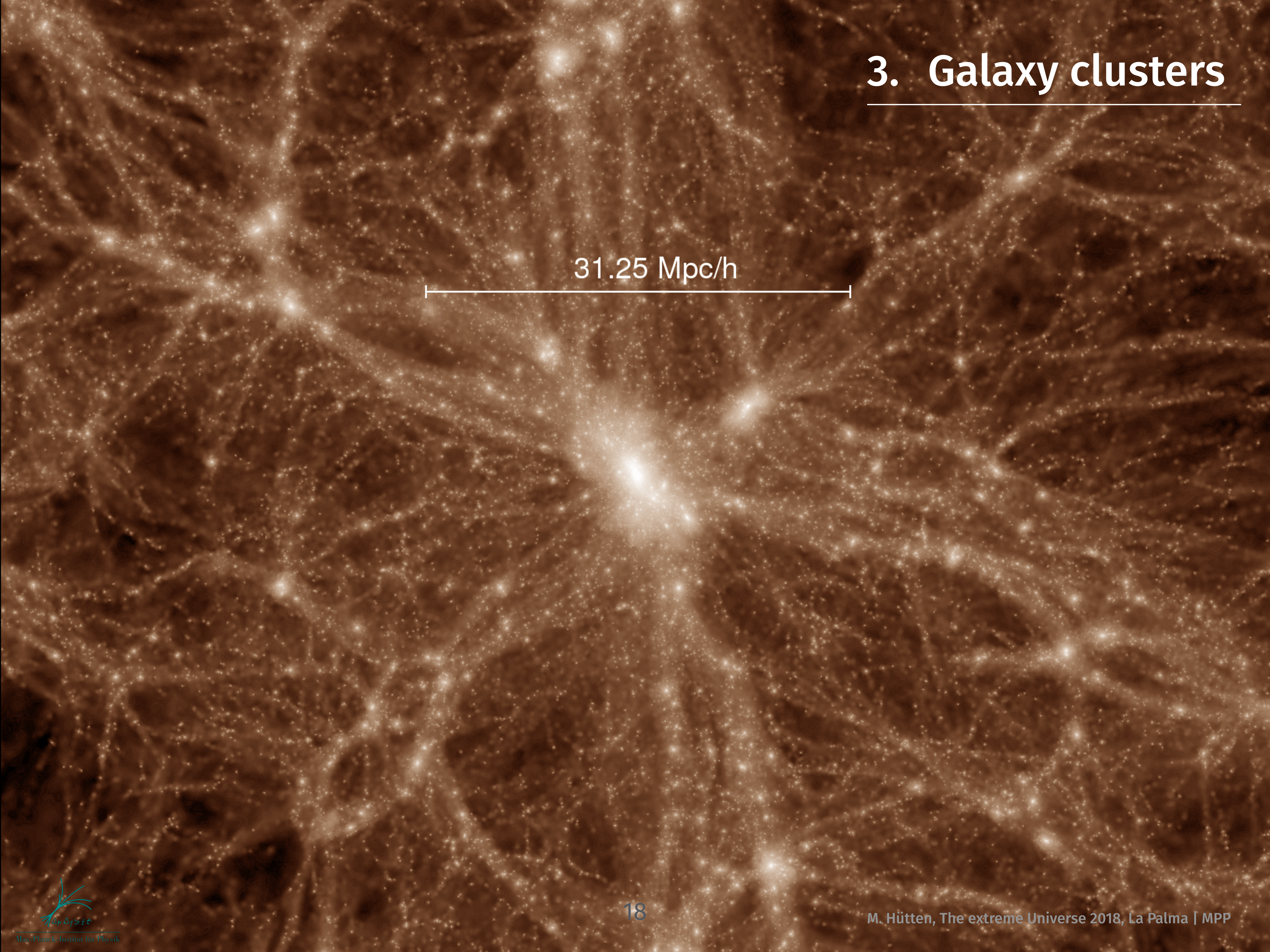
Chance detection probability: "Subhalo algebra"

1. Number of detectable objects rises linearly with $\Delta\Omega$: *geometry + isotropy*
2. Number of detectable objects rises with $\mathrm{sqrt}(T_{\mathrm{obs}})$: *instrument background*
3. Number of detectable objects rises inversely with sensitivity threshold $N_{\mathrm{objects}}(\geq F_{\mathrm{sens}}) \sim 1/F_{\mathrm{sens}}$: *subhalo source count distribution*

See Hütten et al. (2016), App. E, for details

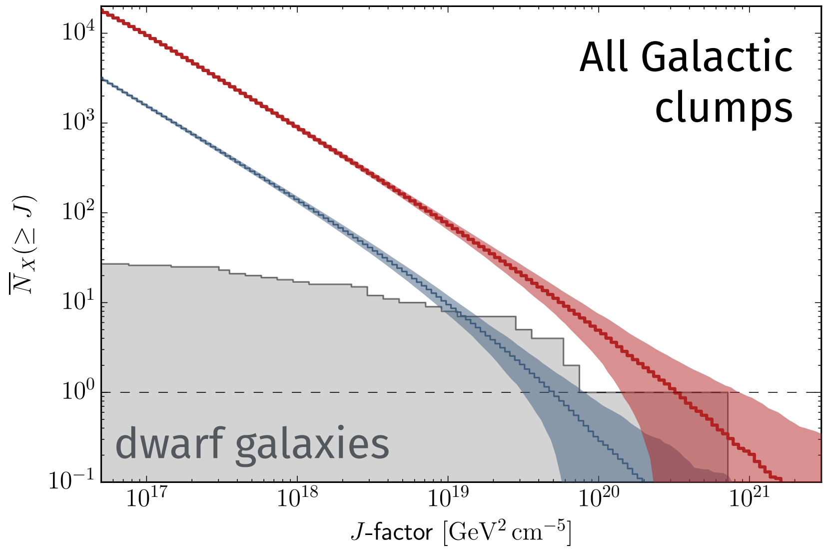
$\Delta\Omega$	N_{FOV}	$T_{\mathrm{obs}}/\mathrm{FOV}$	$<\sigma v>$	$\overline{N}_{\mathrm{spots}}(\geq 2\sigma)$
π	300	100 min	10^{-24} cm^3 s^{-1}	1
10^{-2}	1	100 min	10^{-24} cm^3 s^{-1}	$3 \cdot 10^{-3}$
10^{-2}	1	1000 min	10^{-24} cm^3 s^{-1}	$1 \cdot 10^{-2}$
10^{-2}	1	100 min	10^{-23} cm^3 s^{-1}	$3 \cdot 10^{-2}$

3. Galaxy clusters



The case of galaxy clusters: DM annihilation

Recall:



1104.3530

Cluster	B(< R_{vir})	Log$_{10}$ J$_T$ (GeV^{2}cm^{-5})	ψ_{90} (deg)	r$_{90}$/r$_s$	J$_{01}$/J$_T$	r$_{01}$/r$_s$	ψ_{r_s} (deg)	J$_{r_s}$/J$_T$	Rank$_{01}$	Rank$_{90}$
Perseus	34.0	17.73	1.22	4.24	0.037	0.14	0.29	0.19	3	5
Coma	51.6	17.84	1.41	4.08	0.028	0.29	0.34	0.20	4	4
Ophiuchus	54.0	17.89	1.38	3.89	0.028	0.28	0.36	0.21	2	3
Virgo	55.0	19.11	7.29	4.55	0.004	0.06	1.61	0.18	1	1
Fornax	39.9	18.17	2.97	5.11	0.013	0.17	0.58	0.16	5	2
NGC5813	34.8	17.33	1.36	5.69	0.035	0.42	0.24	0.14	7	7
NGC5846	36.1	17.51	1.59	5.54	0.028	0.35	0.29	0.15	6	6

Table 8. Same as table 7 but now including substructure. B(< R_{vir}) is the total boost within the virial radius of the object, as given by eq. (4.2). This table was computed assuming a PSF= 0.1°.

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The case of galaxy clusters: DM annihilation

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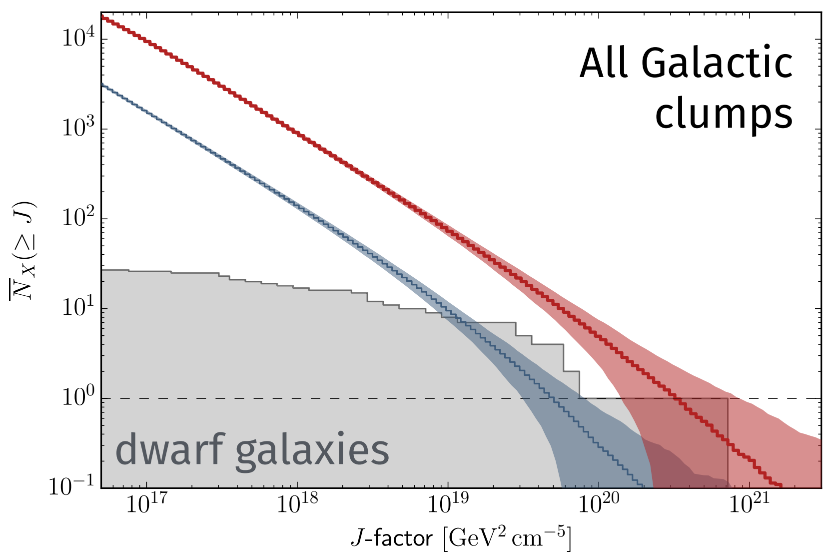

1104.3530

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- DM-annihilation brightness comparable to satellite galaxies

The case of galaxy clusters: DM annihilation

$\chi\chi \to$ SM SM

1104.3530

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- DM-annihilation brightness comparable to satellite galaxies
- Emission profiles more extended (typical half-light radii > 0.5°)

The case of galaxy clusters: DM annihilation

1104.3530

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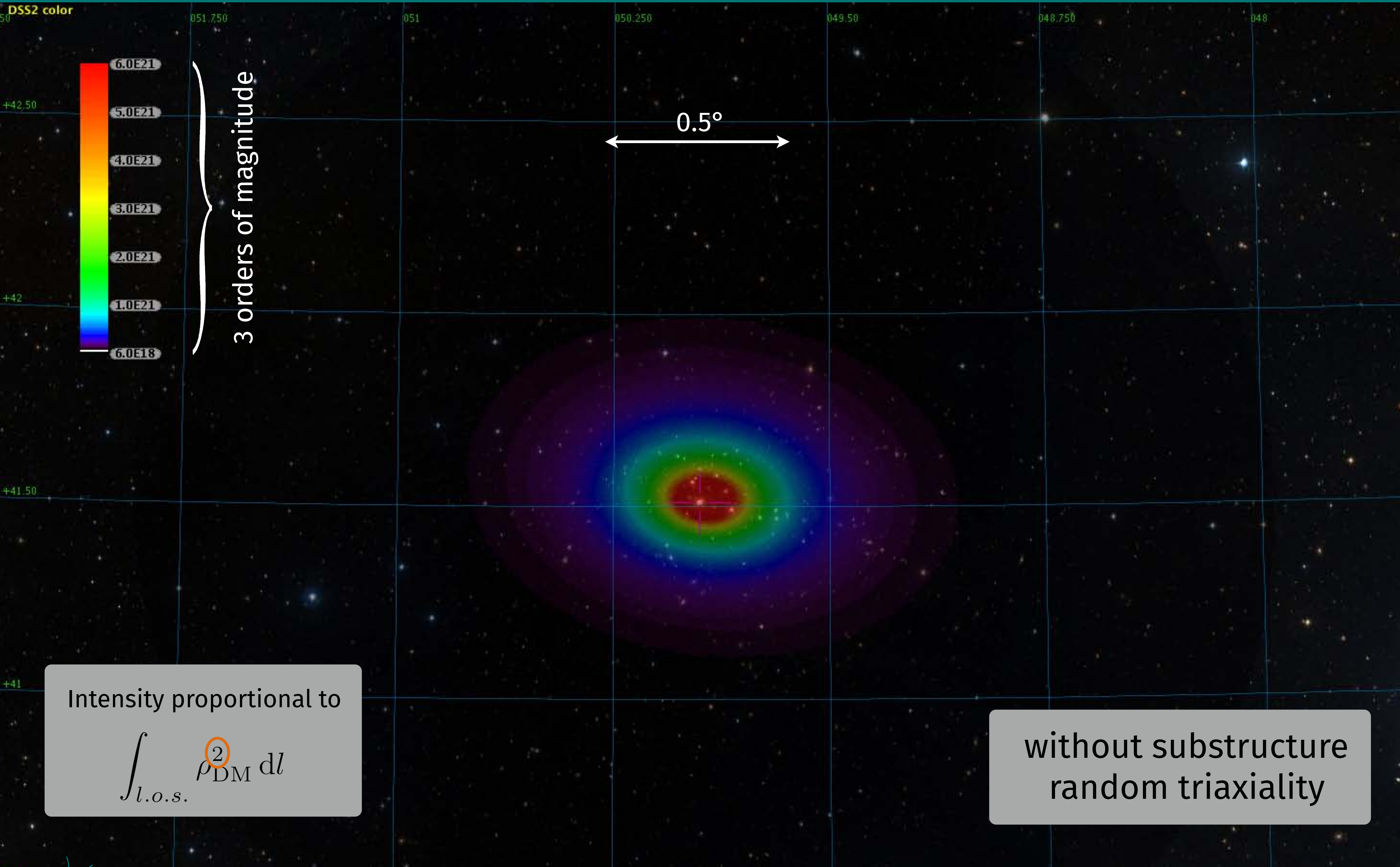
- DM-annihilation brightness comparable to satellite galaxies
- Emission profiles more extended (typical half-light radii > 0.5°)
- Astrophysical backgrounds:
  - γ-ray emitting galaxies (AGN, star-forming galaxies, CR interaction)
  - **Also expect diffuse emission from the inter-cluster medium (ICM)**

DM **annihilation** profile of the Perseus cluster

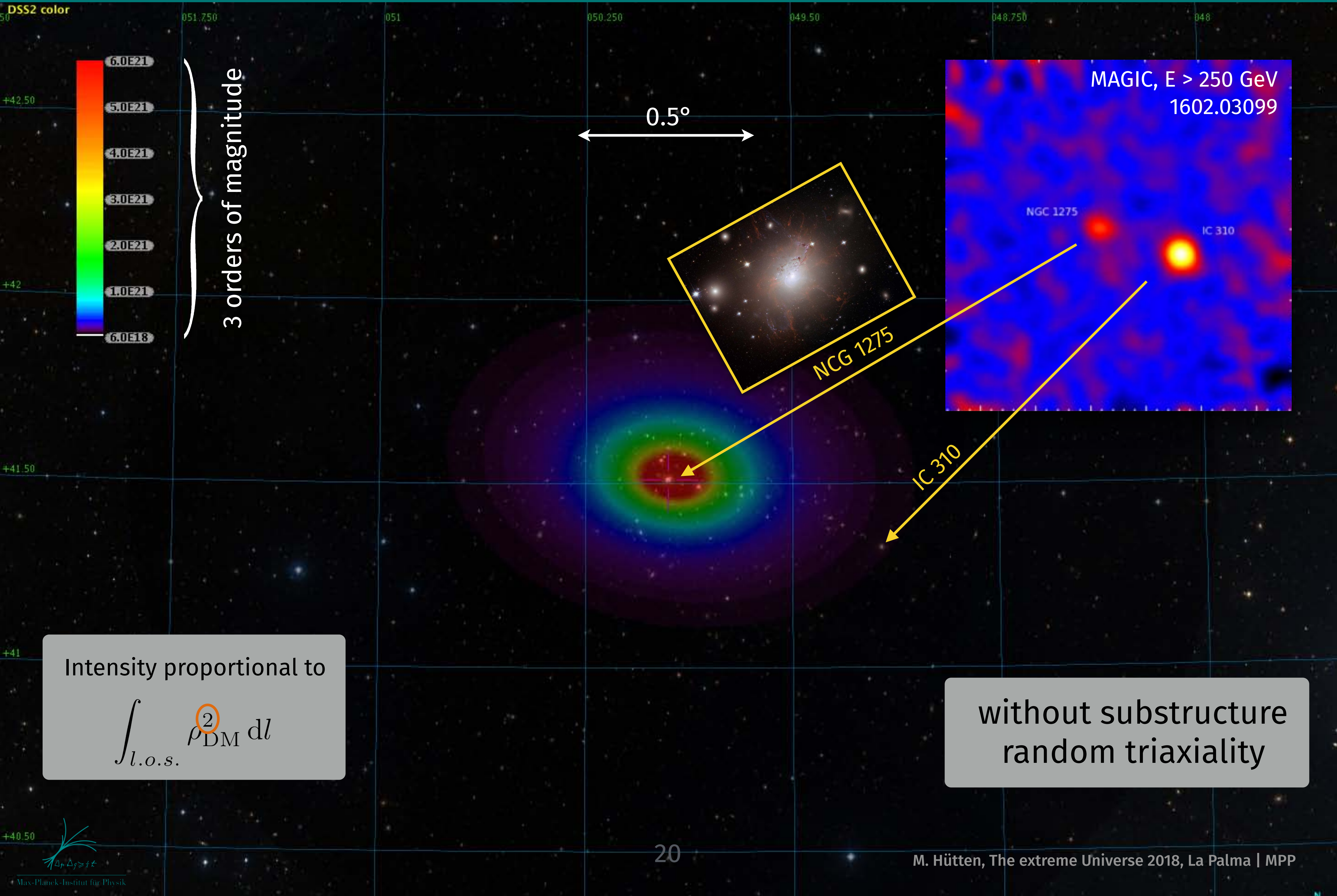


Intensity proportional to

$$\int_{l.o.s.} \rho_{\mathrm{DM}}^{2} \, \mathrm{d}l$$

without substructure
random triaxiality

DM **annihilation** profile of the Perseus cluster

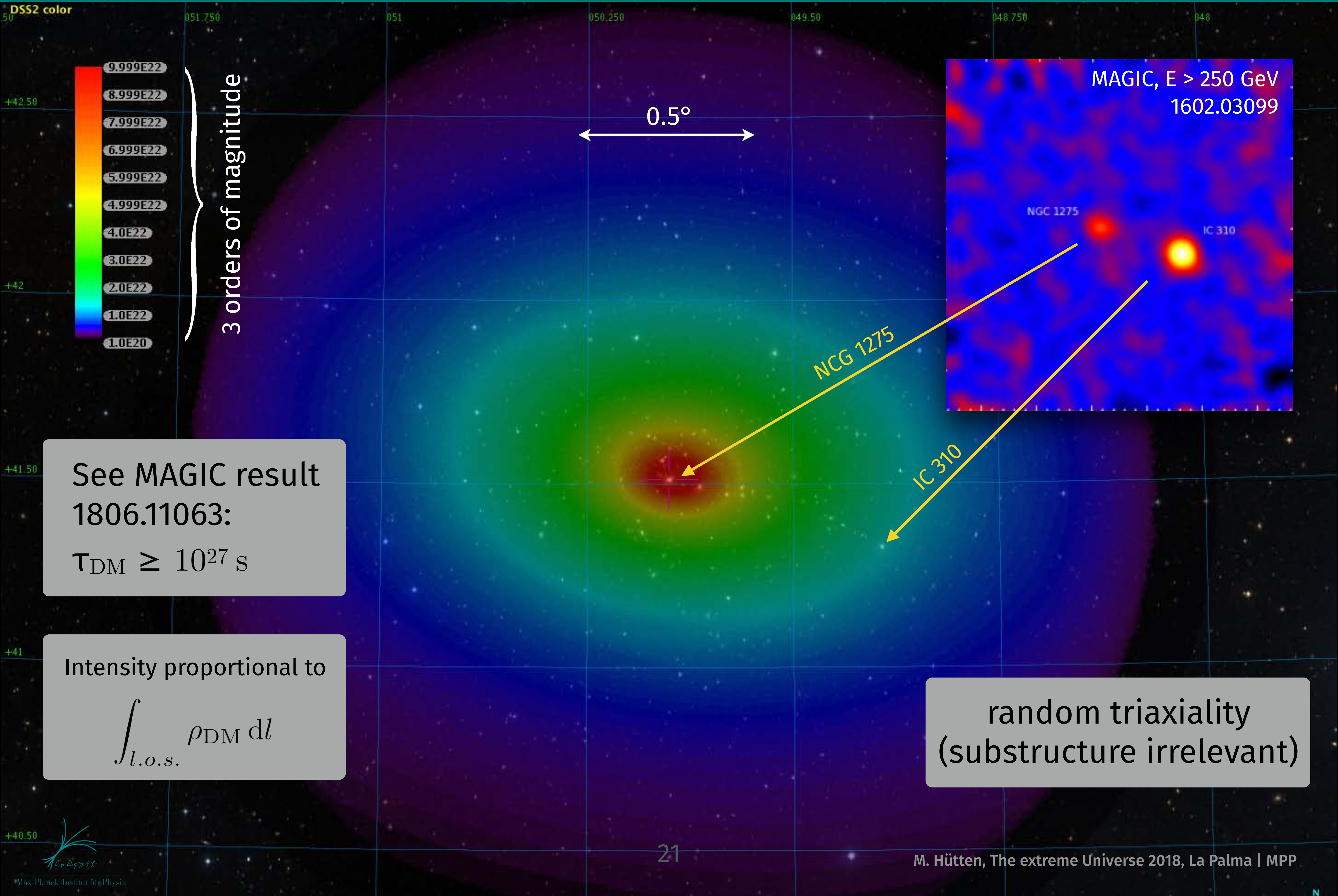


Intensity proportional to

$$\int_{l.o.s.} \rho_{\mathrm{DM}}^{2}\,\mathrm{d}l$$

without substructure
random triaxiality

DM **decay** profile of the Perseus cluster



See MAGIC result 1806.11063:

$\tau_{\rm DM} \geq 10^{27}$ s

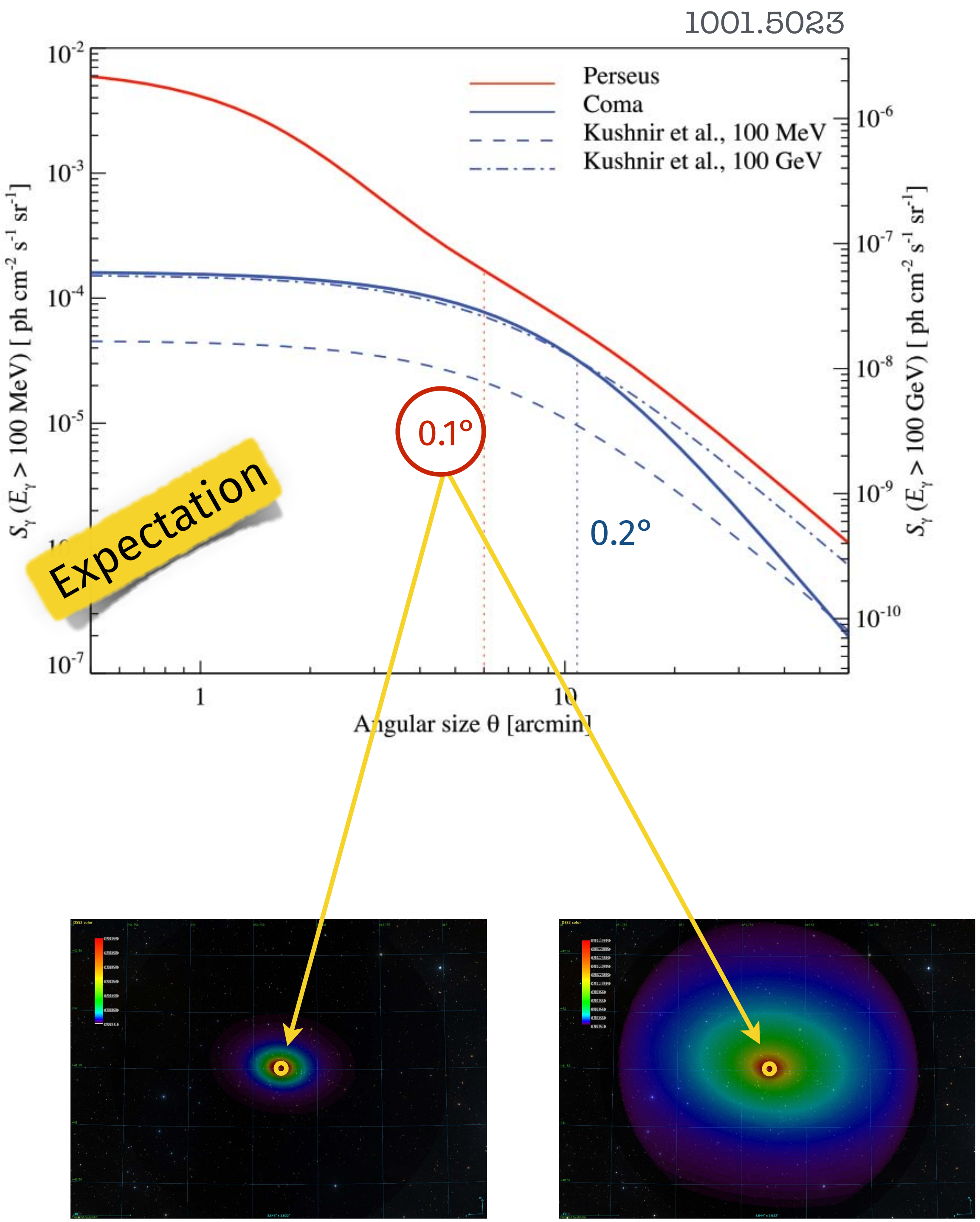
Intensity proportional to

$$\int_{l.o.s.} \rho_{\rm DM}\, dl$$

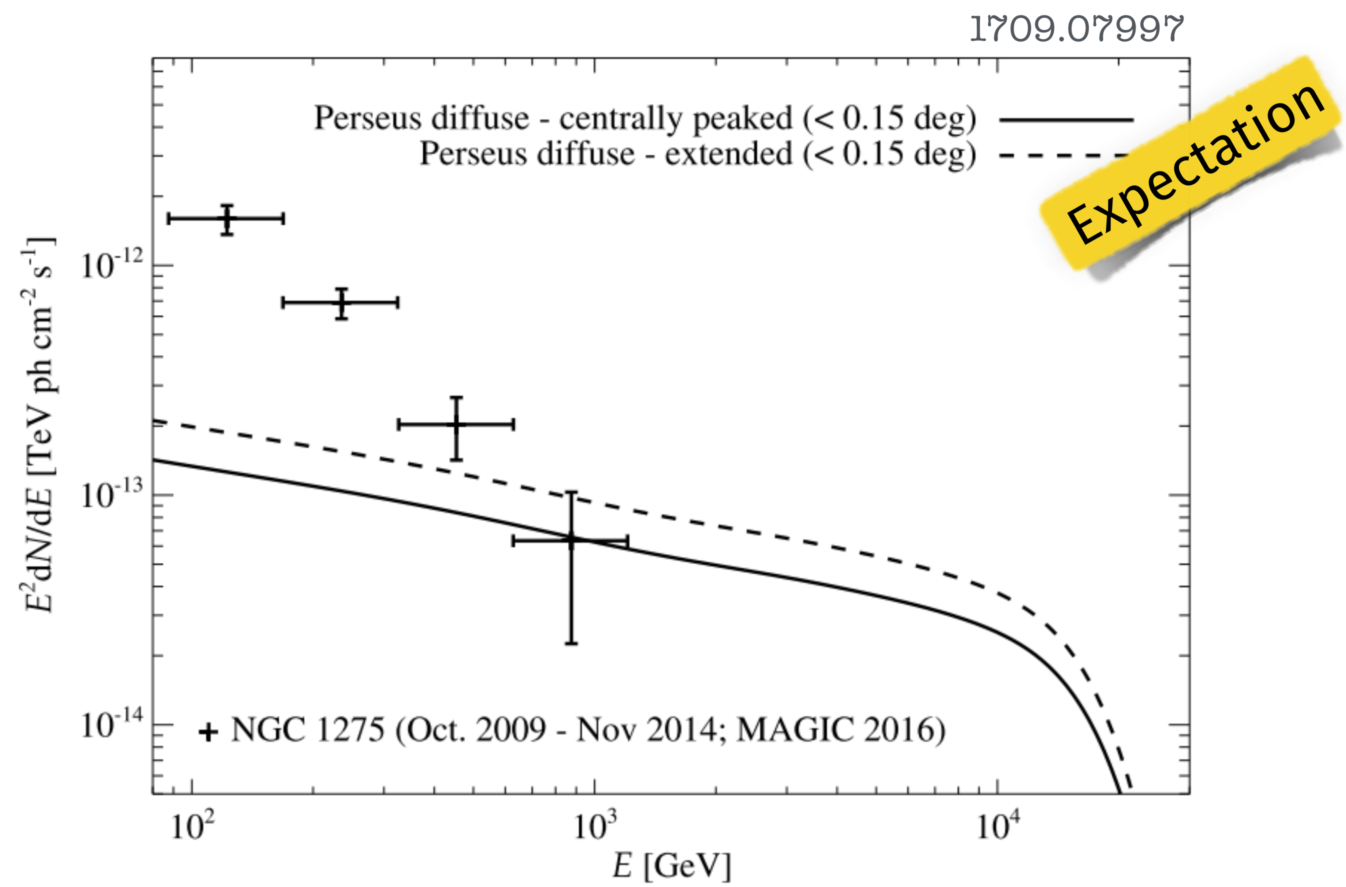
random triaxiality
(substructure irrelevant)

Cosmic-ray induced emission in the inter-cluster medium

Spatial profile



Spectral profile



- CTA's excellent angular resolution and energy range:

  disentangle the signals

- DM substructure extends annihilation profile

The CTA galaxy cluster working group (wg-phys-clusters)

- CTA galaxy cluster key science project: 300 hours allocated for CTA North
- Coordination:
  - Moritz Hütten (MPP Munich)
  - Judit Pérez-Romero, Miguel Sánchez-Conde (UAM Madrid)
- The team:

  R. Alfaro, G. Brunetti, S. Colafrancesco, C. Delgado, M. Doro, E. Fedorova, E. de Gouveia Dal Pino, S. Hernandez Cadena, M. Hütten, M. Lallena, S. Nuza, J. Pérez, O. Reimer, M. Sánchez-Conde, S. Zimmer

- Updated performance study on galaxy clusters in progress

Conclusions

- Hierarchical DM clustering:
  γ-ray clumps from annihilation/decay at various scales and distances
- Search for the **smallest clumps** in a TeV γ-ray survey with CTA
  (extragalactic key science project by-catch)
- Watch out for unidentified sources in the FOV: may be a Galactic DM clump
- Study the closest **galaxy clusters**:
  Perseus and Coma: Excellent observation conditions with CTA North
- Clusters: Constrain DM particle life times beyond $\tau_{\rm DM} > 10^{27}{\rm s} = 2 \cdot 10^9 \; t_{\rm Universe}$

CTA excellent probe for TeV dark matter particle physics
in various complementary targets

BACK UP

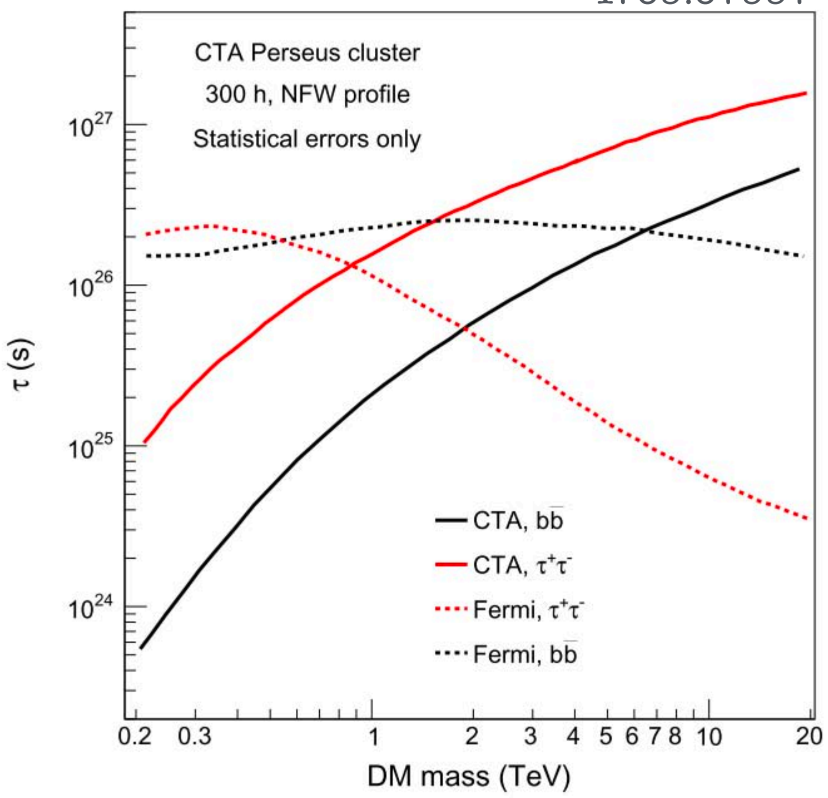
Perseus cluster also optimal target for DM **decay**

TABLE I: Ten brightest galaxy clusters (positions taken from the MCXC meta-catalogue [15]) in DM-decay for $\alpha_{int} = 0.1°$.

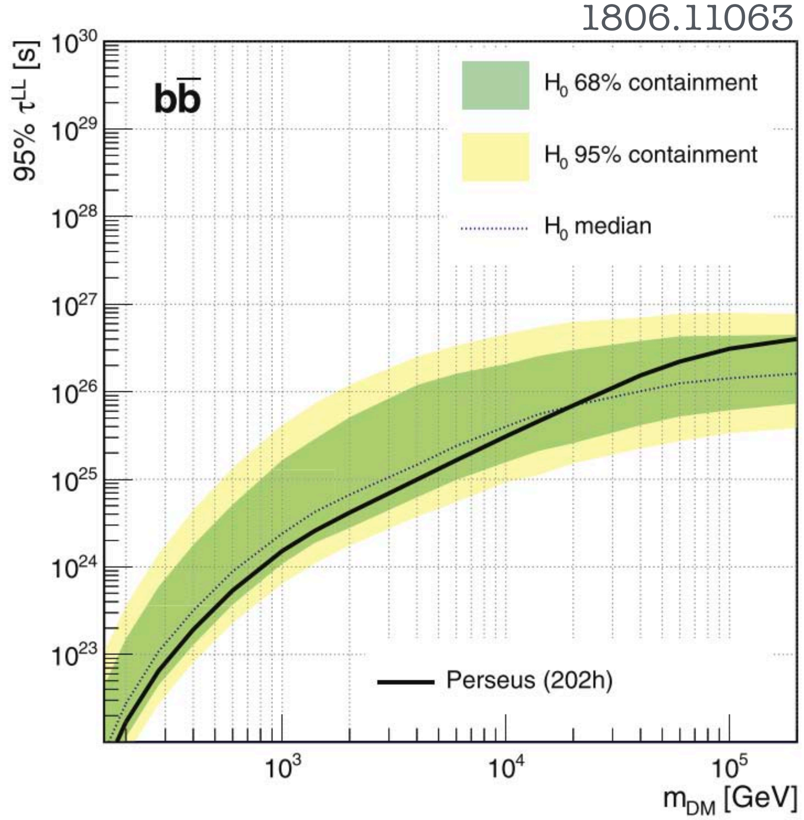
	Name	Index (MCXC)	l (deg)	b (deg)	d (Mpc)	α_s (deg)	$D(0.1°)$ ($M_\odot$ kpc^{-2})
Perseus =	A426	258	150.6	-13.3	75.0	0.44	$1.0 \cdot 10^4$
	Virgo	884	283.8	74.4	15.4	1.09	$1.0 \cdot 10^4$
	Coma	943	57.2	88.0	96.2	0.29	$7.3 \cdot 10^3$
	Ophiuchus	1304	0.6	9.3	116.	0.27	$7.3 \cdot 10^3$
	A3526	915	302.4	21.6	48.1	0.39	$6.8 \cdot 10^3$
	A3627	1231	325.3	-7.1	66.0	0.32	$6.5 \cdot 10^3$
	AWM7	224	146.3	-15.6	72.1	0.28	$5.7 \cdot 10^3$
	A1367	792	235.1	73.0	89.3	0.24	$5.4 \cdot 10^3$
	A3571	1048	316.3	28.6	160.	0.18	$5.4 \cdot 10^3$
	A2199	1249	62.9	43.7	124.	0.20	$5.1 \cdot 10^3$

1203.1164

1709.07997



1806.11063

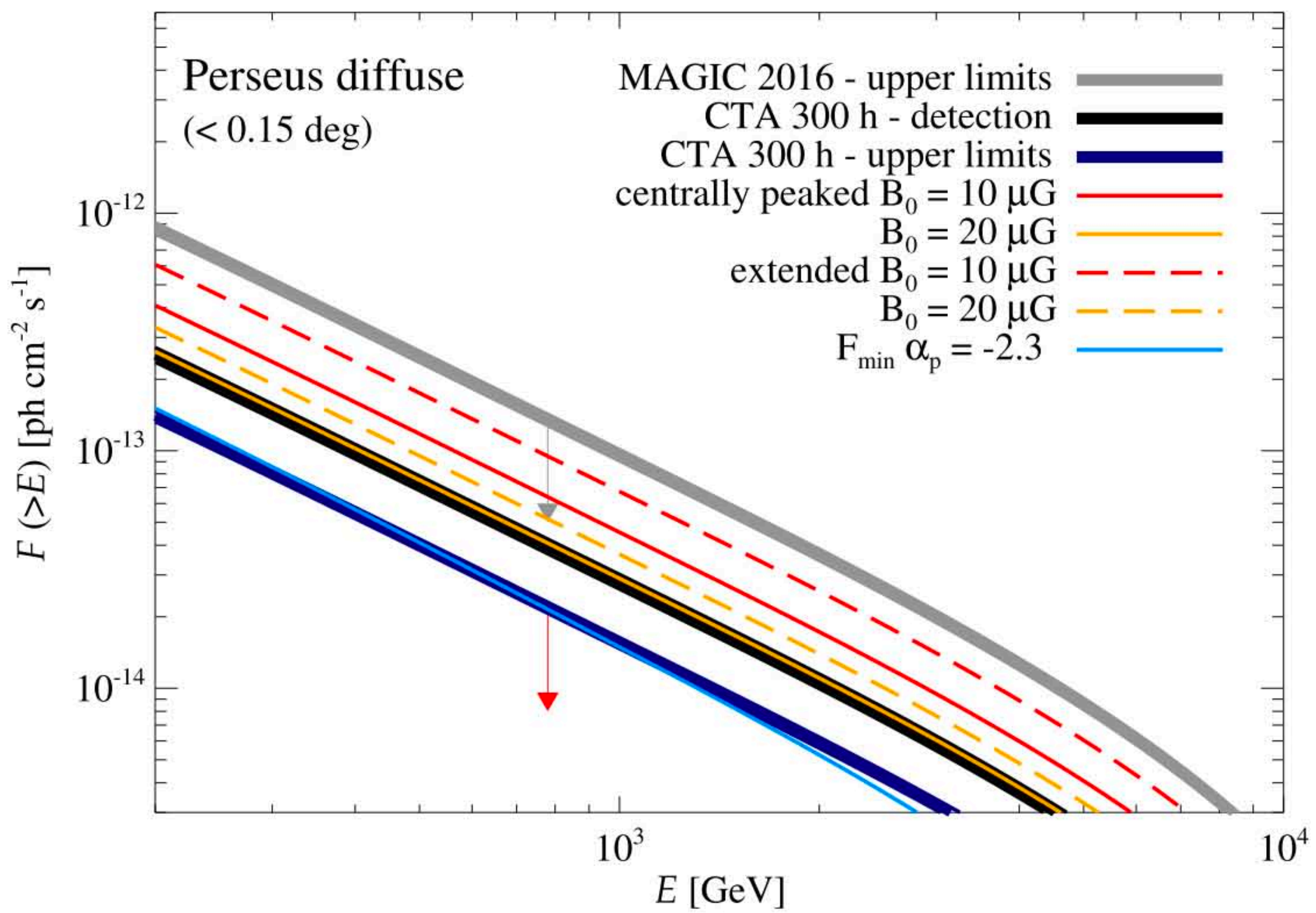


- Perseus region already extensively studied by MAGIC telescopes:
  0909.3267, 1009.2155, 1111.5544, 1310.8500, 1602.03099,

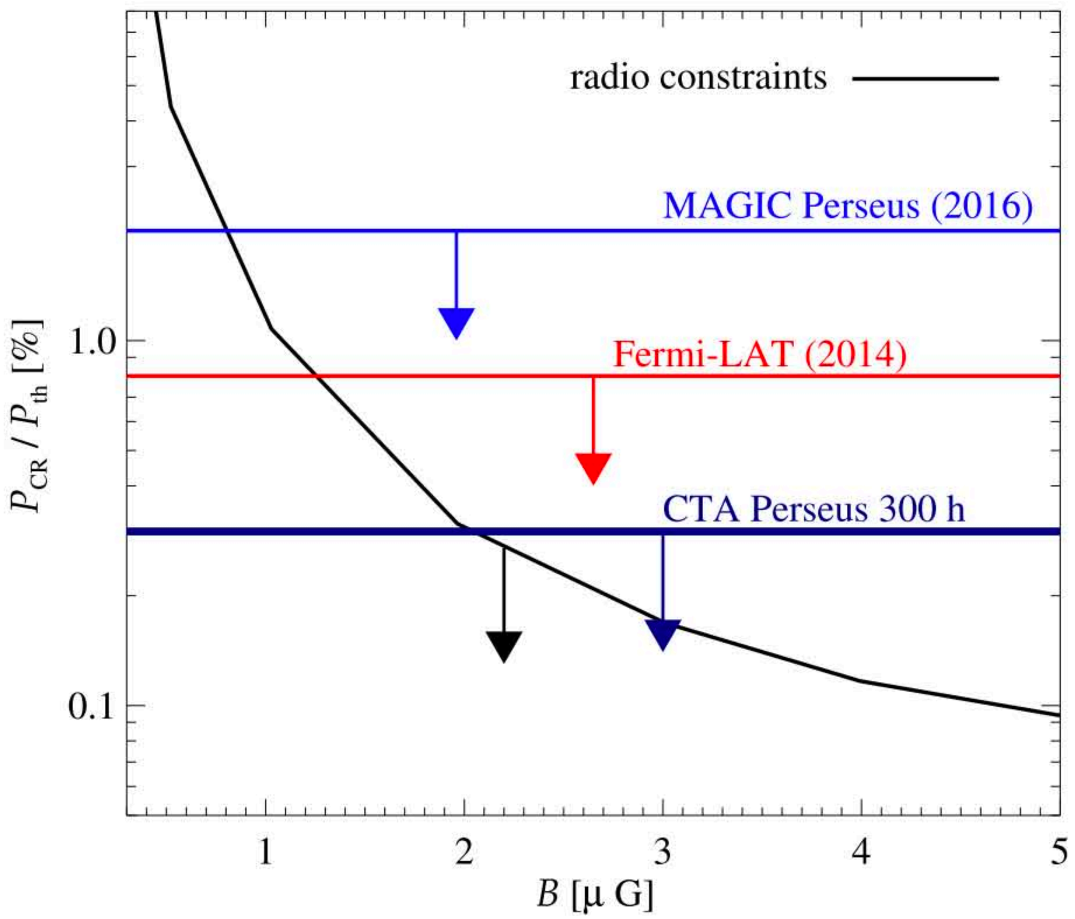
  1806.11063: $\tau_{DM} \geq 10^{27}$s

Astrophysical merits of Perseus cluster observations

1709.07997



1709.07997



Brightest Galactic DM clumps: Properties

- Average mass and distance (from 10^4 runs):

optimistic

Median properties of brightest subhalo within	*Fermi*-LAT scenario ($f_{sky} = 82.6\%$) $\theta_{int} = 0.1°$	$\theta_{int} = 0.8°$	CTA scenario ($f_{sky} = 25\%$) $\theta_{int} = 0.05°$	$\theta_{int} = 0.1°$
$\widetilde{D}^{\star}_{obs}$ [kpc]	7^{+10}_{-5}	8^{+11}_{-6}	7^{+10}_{-5}	8^{+12}_{-6}
$\log_{10}(\widetilde{m}^{\star}_{vir}/M_{\odot})$	$7.7^{+1.3}_{-1.5}$	$8.1^{+1.2}_{-1.6}$	$7.4^{+1.4}_{-1.4}$	$7.6^{+1.4}_{-1.5}$
$\log_{10}\left(\widetilde{J}^{\star}/\text{GeV}^2\,\text{cm}^{-5}\right)$	$20.3^{+0.4}_{-0.3}$	$20.7^{+0.4}_{-0.3}$	$19.7^{+0.3}_{-0.3}$	$19.9^{+0.4}_{-0.3}$

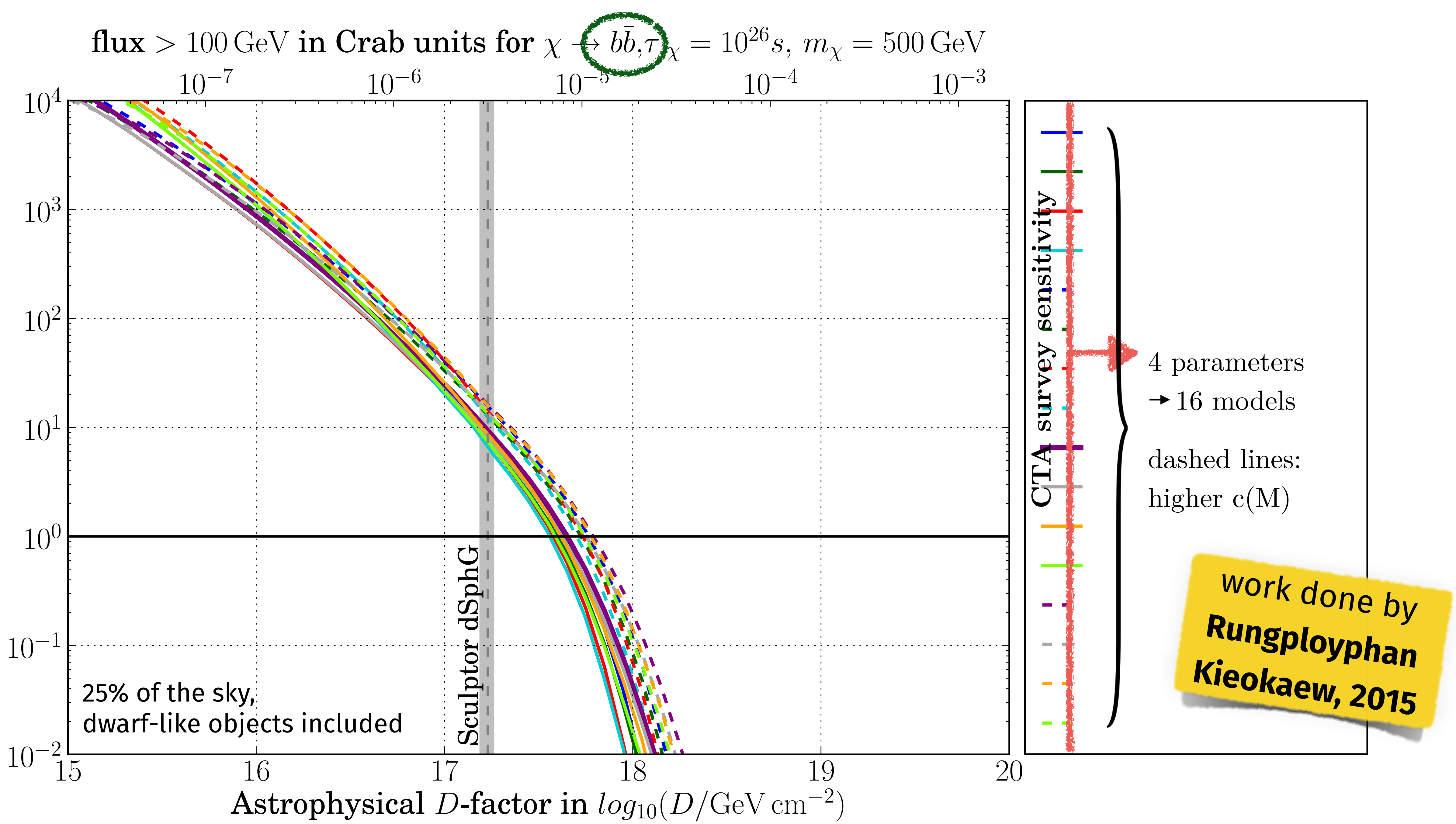
conservative

Median properties of brightest subhalo within	*Fermi*-LAT scenario ($f_{sky} = 82.6\%$) $\theta_{int} = 0.1°$	$\theta_{int} = 0.8°$	CTA scenario ($f_{sky} = 25\%$) $\theta_{int} = 0.05°$	$\theta_{int} = 0.1°$
$\widetilde{D}^{\star}_{obs}$ [kpc]	32^{+42}_{-23}	30^{+42}_{-22}	20^{+27}_{-15}	19^{+26}_{-14}
$\log_{10}(\widetilde{m}^{\star}_{vir}/M_{\odot})$	$8.7^{+0.9}_{-1.3}$	$8.6^{+0.9}_{-1.3}$	$8.7^{+0.8}_{-1.4}$	$8.7^{+0.9}_{-1.4}$
$\log_{10}\left(\widetilde{J}^{\star}/\text{GeV}^2\,\text{cm}^{-5}\right)$	$18.9^{+0.3}_{-0.2}$	$19.1^{+0.3}_{-0.3}$	$19.4^{+0.3}_{-0.3}$	$19.8^{+0.4}_{-0.3}$

Dark clumps decay brightness

Number of subhalos brighter than a given flux/ *J*-factor:

$$\frac{d\Phi_\gamma^{\text{ann.}}}{dE_\gamma} \sim \int_{\Delta\Omega}\int_{l.o.s.} \rho_{\text{DM}}\, dl\, d\Omega$$



Max-Planck-Institut für Physik