CTA Dark Matter searches in **dwarf galaxies, dark halos,** and **galaxy clusters**

MORITZ HÜTTEN (MPP Munich)
On behalf of the CTA consortium, with input from
J. Pérez-Romero, J. Coronado-Blázquez, A. Morselli, F. Saturni,
and the dSph & cluster task-force groups

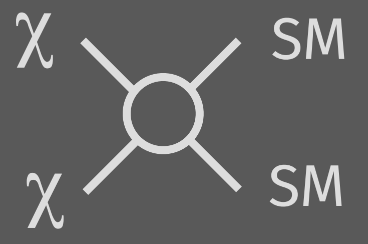
Symposium "Dark Matter Searches in the 2020s" Kashiwa, 13.11.2019

γ-ray searches: hunt for DM clumps!

Nagisa's & Gabi's talks

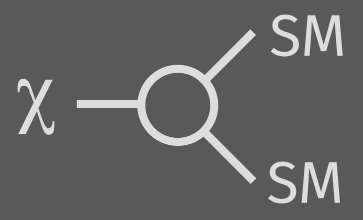
Annihilation

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



Decay

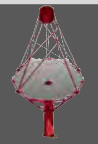
$$\frac{\mathrm{d}\Phi^{\,\mathrm{dec.}}}{\mathrm{d}E_\gamma} = \frac{1}{4\pi}\,\frac{1}{\tau_{\mathrm{DM}}\,m_\chi} \times \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \times \int_{\Delta\Omega}\int_{l.o.s.} \rho_{\mathrm{DM}}\mathrm{d}l\mathrm{d}\Omega$$



γ-ray searches: hunt for DM clumps!

Nagisa's & Gabi's talks

Flux searched for with γ-ray telescope



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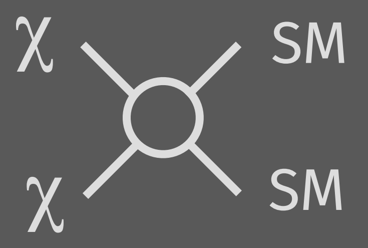

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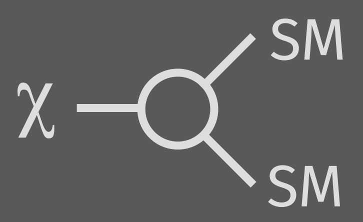


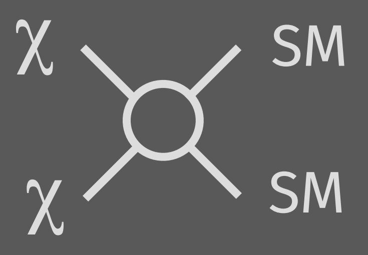
γ-ray searches: hunt for DM clumps!

Nagisa's & Gabi's talks

Secondary γ-rays after annihilation/decay

Annihilation

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



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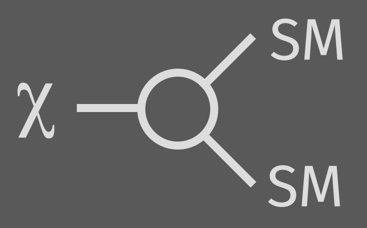
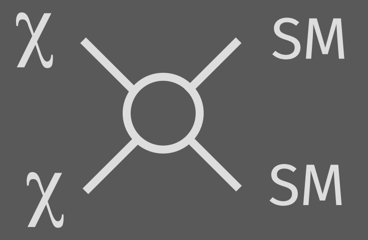


γ-ray searches: hunt for DM clumps!

Nagisa's & Gabi's talks

Annihilation

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



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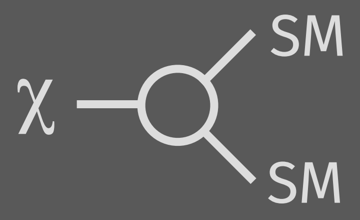

Unknown DM particle mass: parameter

γ-ray searches: hunt for DM clumps!

Nagisa's & Gabi's talks

Annihilation cross section

Annihilation

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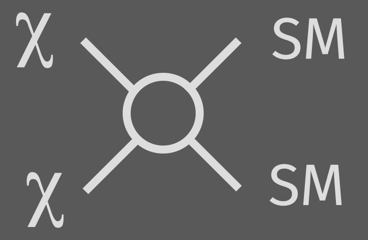

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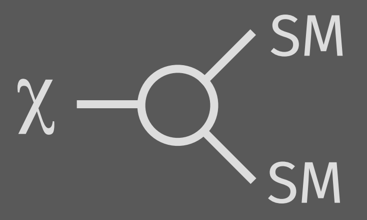

Particle lifetime

γ-ray searches: hunt for DM clumps!

Nagisa's & Gabi's talks

Annihilation

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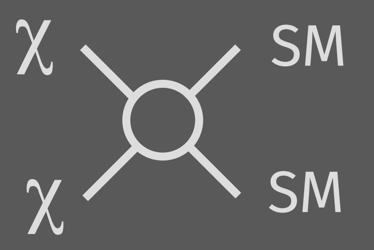

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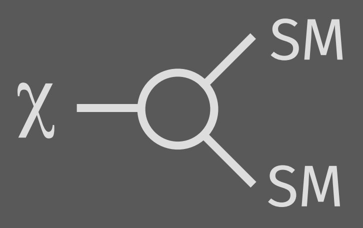

Density distribution & distance

γ-ray searches: hunt for DM clumps!

Nagisa's & Gabi's talks

Annihilation

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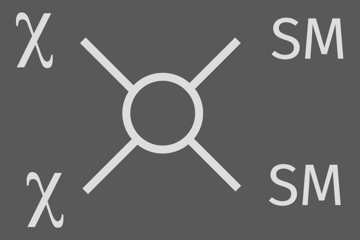

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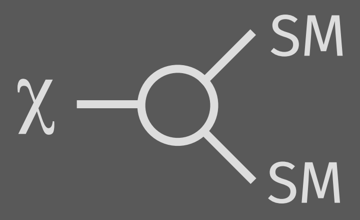
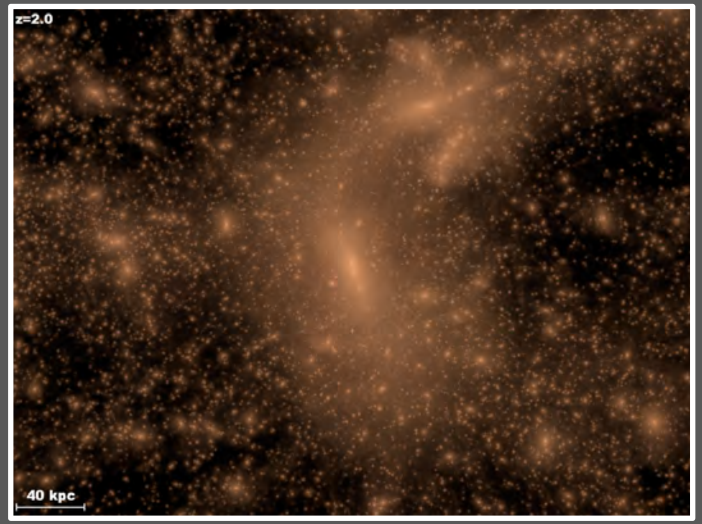


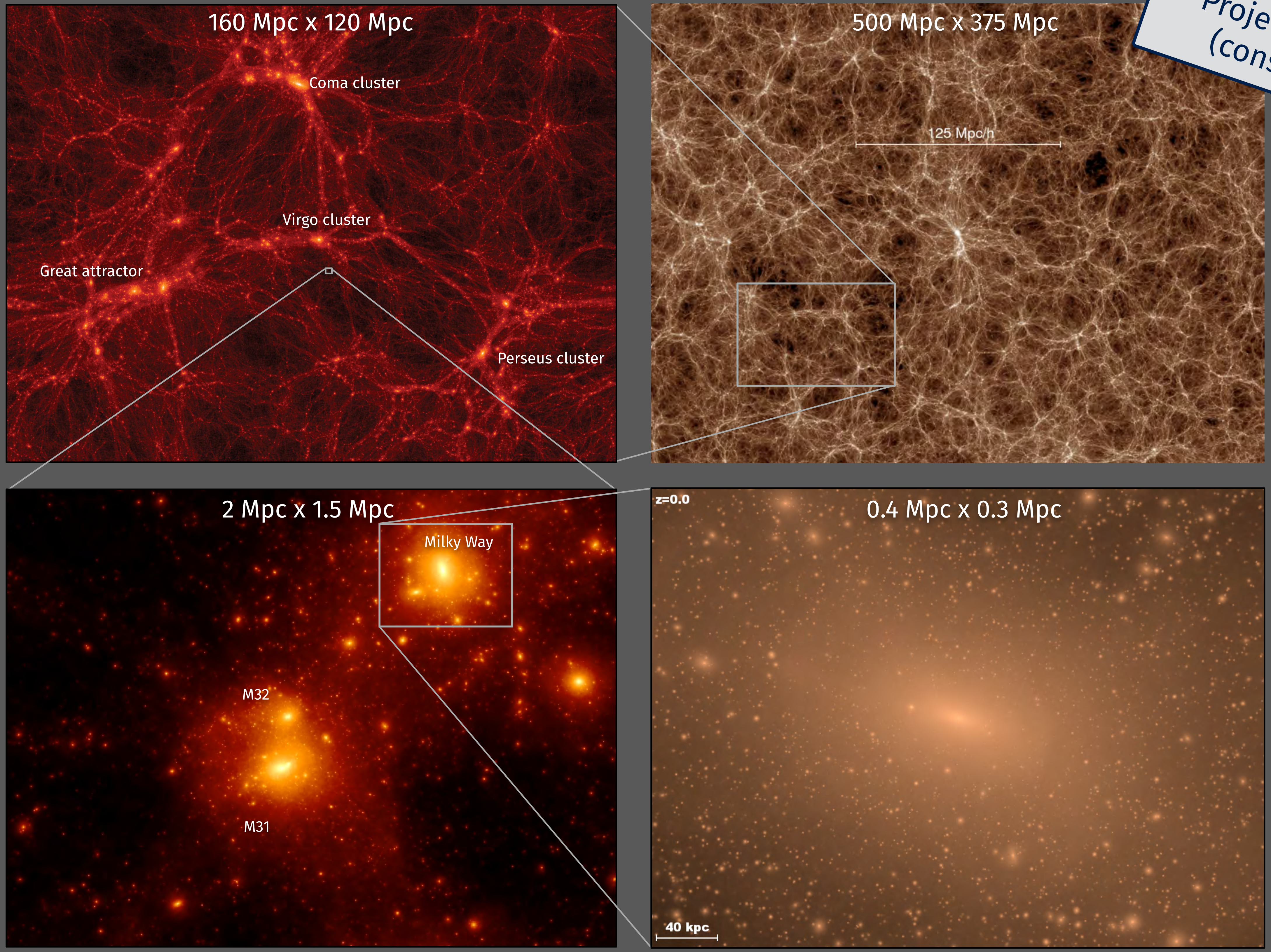
Density distribution & distance



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

Dark matter structures on all scales



Projected DM square density (constrained) simulations

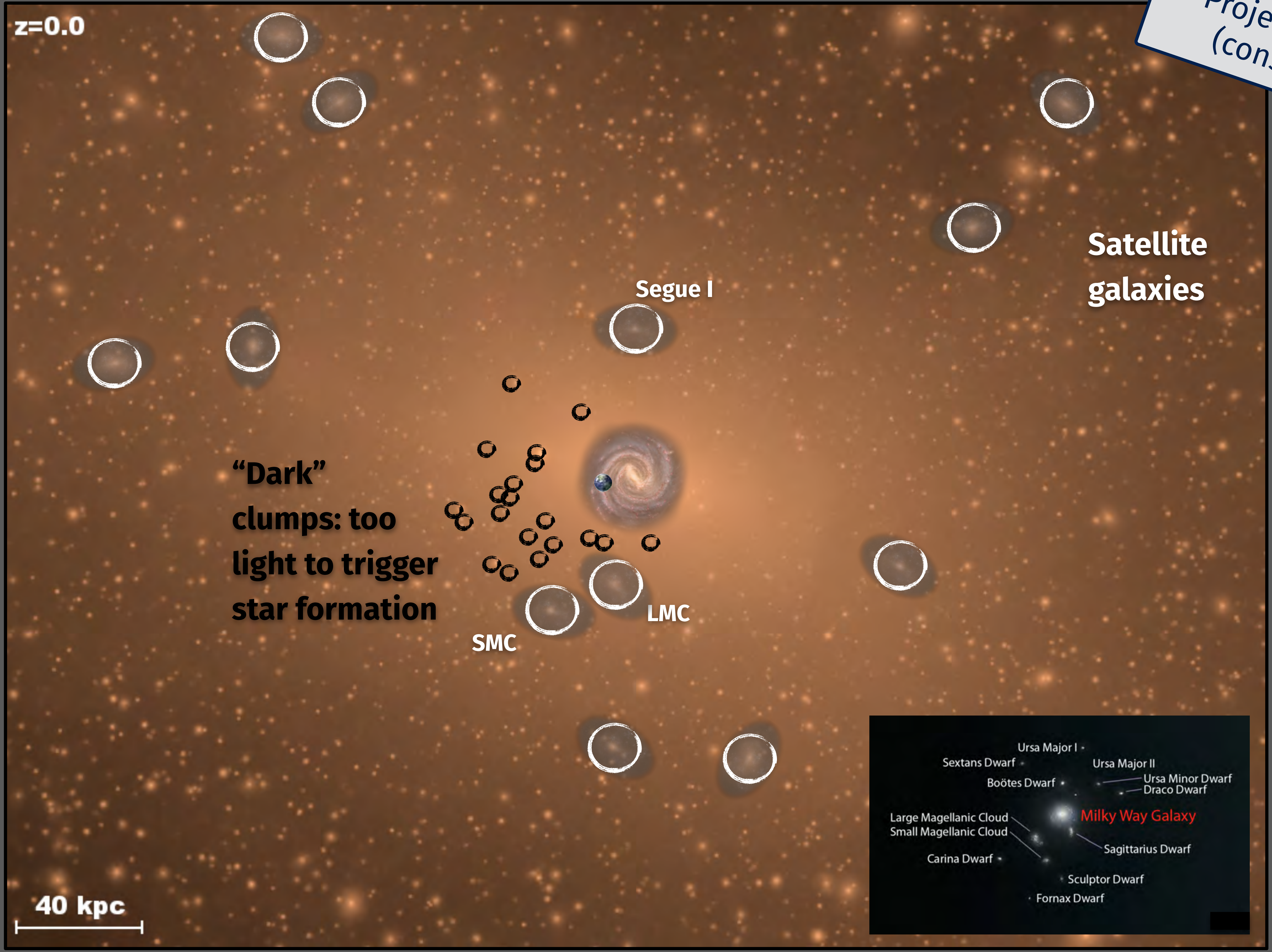
Springel et al. (2005), Millenium simulations

Gottlöber et al. (2010), CLUE simulations

Diemand, Kuhlen, Madau (2006), Via Lactea simulations

color code: brighter = denser

Dark matter structures on all scales



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color code: brighter = denser

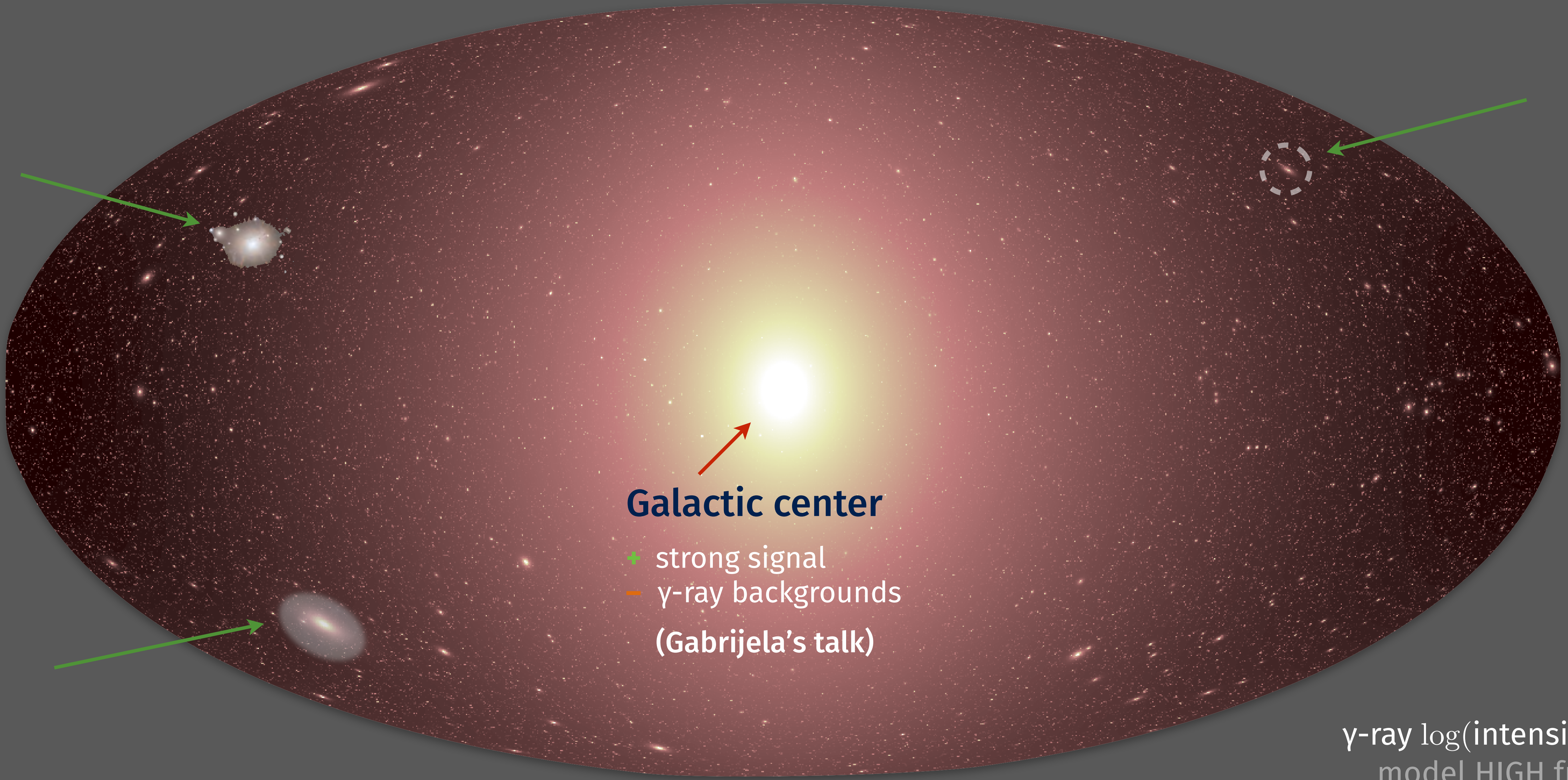
The dark matter γ-ray sky from Earth

Galaxy clusters

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

Dark clumps

+ no background
? brighter than satellites
– unknown position



Galactic center

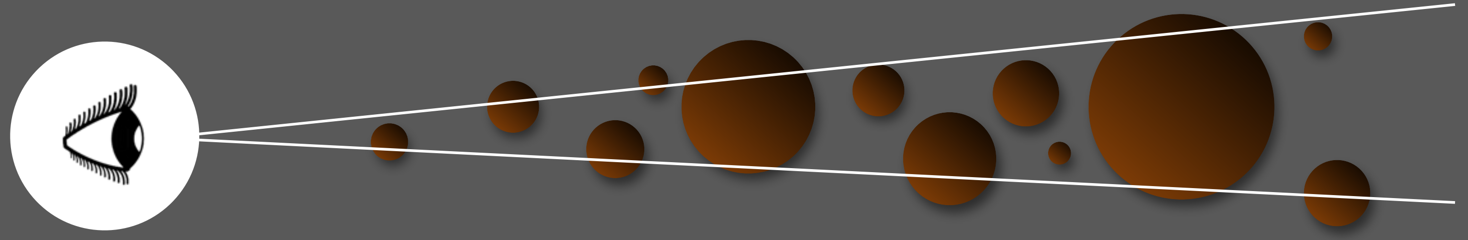
+ strong signal
– γ-ray backgrounds

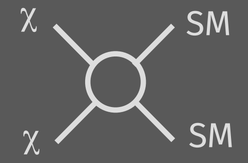
(Gabrijela's talk)

Milky Way satellite galaxies

+ no background
– lower fluxes

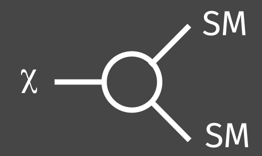
γ-ray $\log$(intensity) from DM *annihilation*,
model HIGH from MH et al., 1606.04898



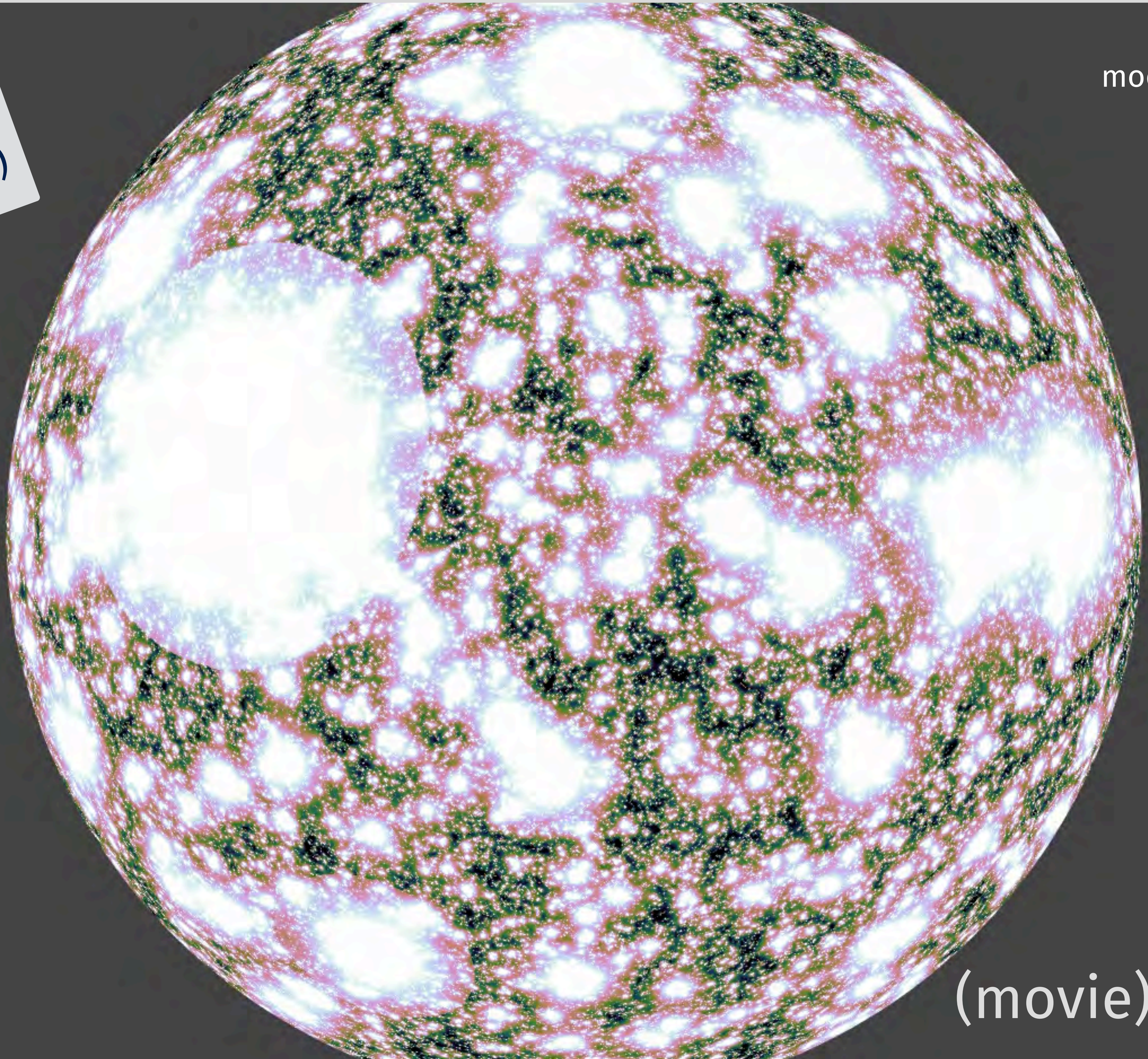


The dark matter γ-ray sky from Earth

γ-ray $\log(\text{intensity})$ from DM *decay*,
model Phat-ELVIS from MH et al., 1904.10935



Galactic Center excluded
(Galactic substructure only)

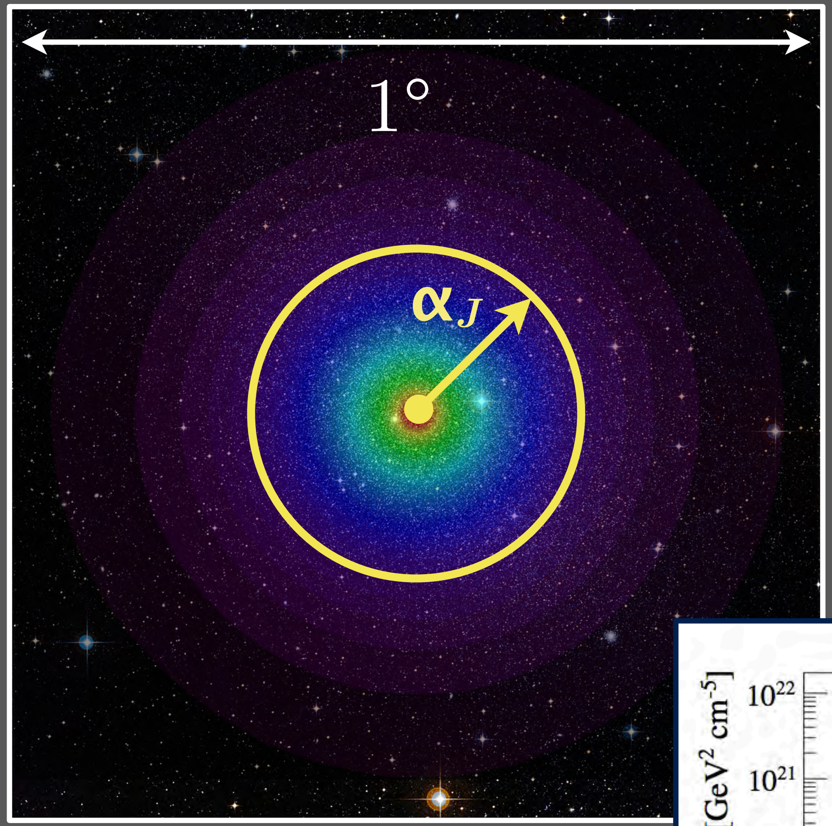


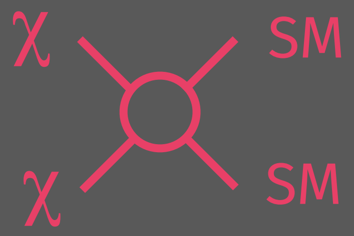
(movie)

Made with CLUMPY

Dwarf Spheroidal Galaxies (dSphs)

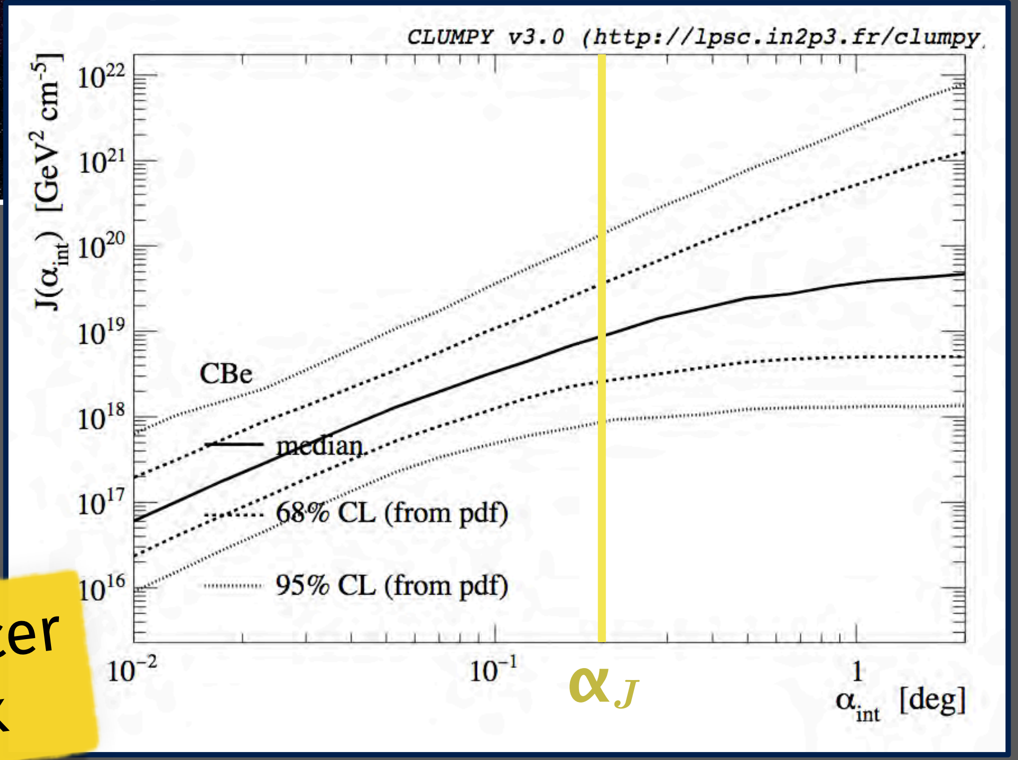
dSphs: γ-rays from DM





Signal $\sim \int_{l.o.s.} \rho^2_{\mathrm{DM}}\, \mathrm{d}l$

F. Saturni for the dSph task force

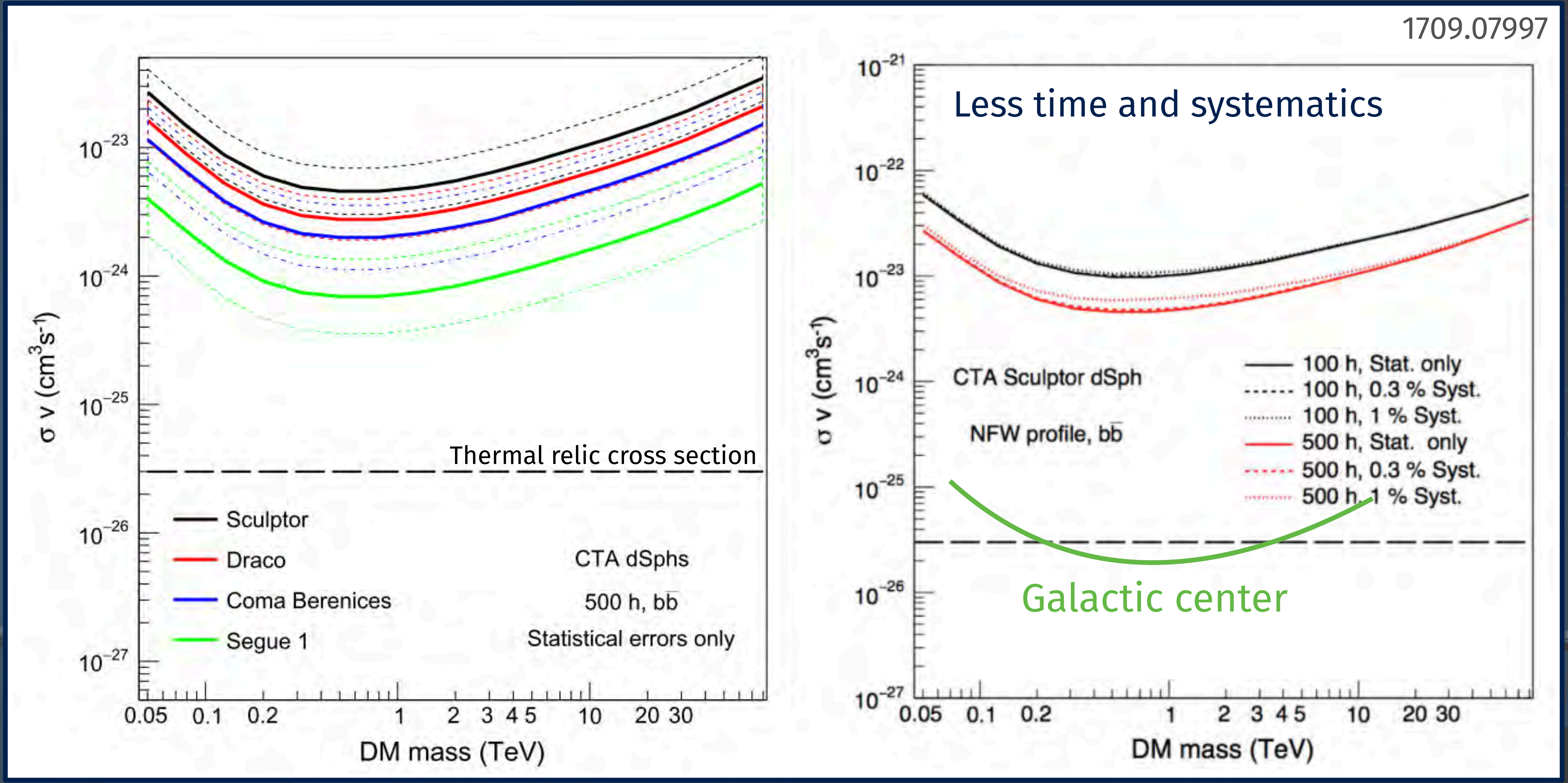


Jeans analysis of tracer stars: Nagisa's talk

J-factor values from 1504.02048

	α_J	Log $J(\alpha_J)$ (GeV² cm⁻⁵)
Coma Berenices	0.20°	$19.2^{+0.6}_{-0.5}$
Ursa Minor	0.49°	$19.1^{+0.1}_{-0.1}$
Draco	0.28°	$18.9^{+0.3}_{-0.1}$
Ret II	0.08°	$18.7^{+0.6}_{-0.5}$
Sculptor	0.38°	$18.6^{+0.1}_{-0.1}$
Segue 1	???	???

dSphs: CTA sensitivity to DM annihilation



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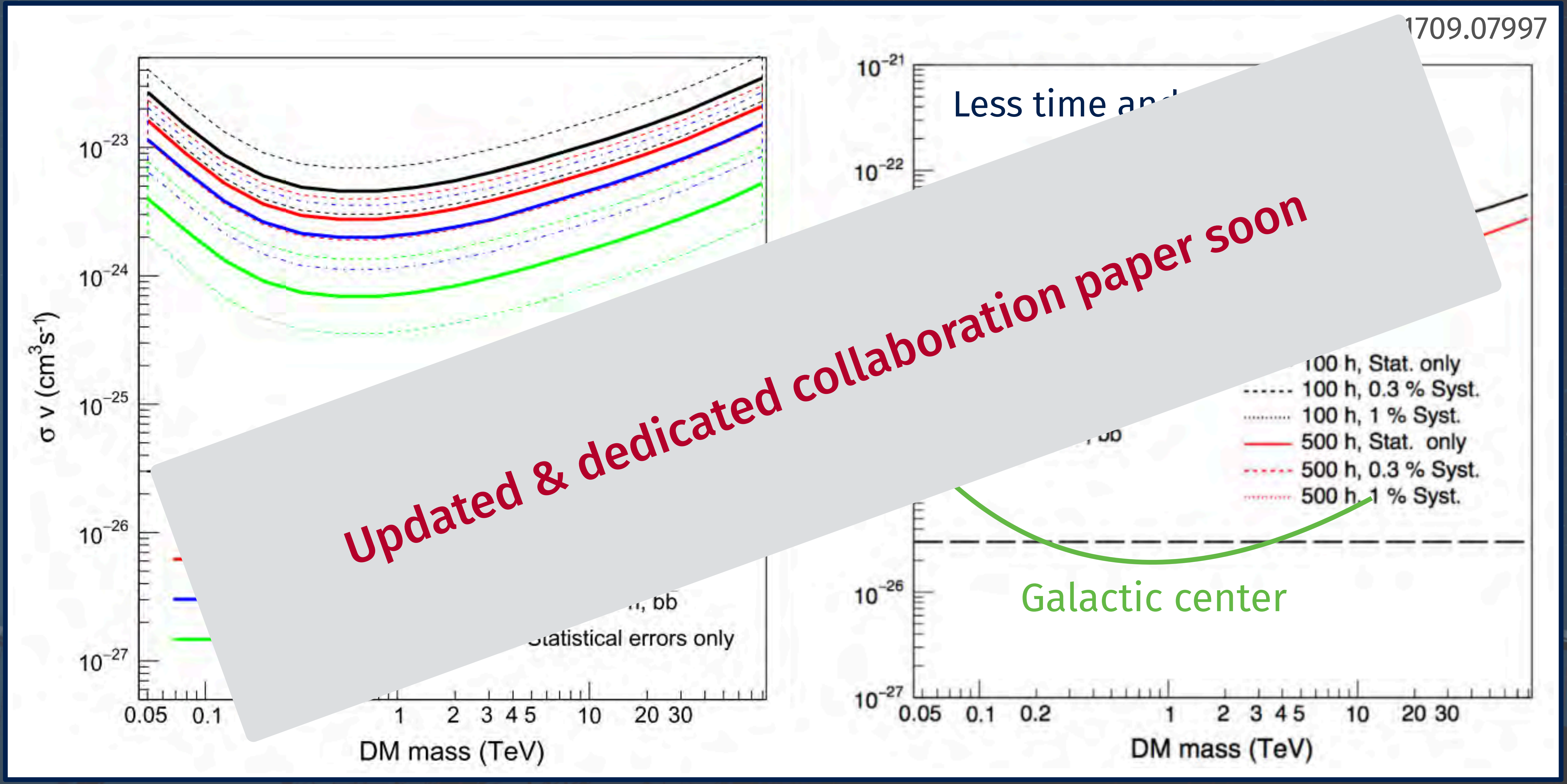
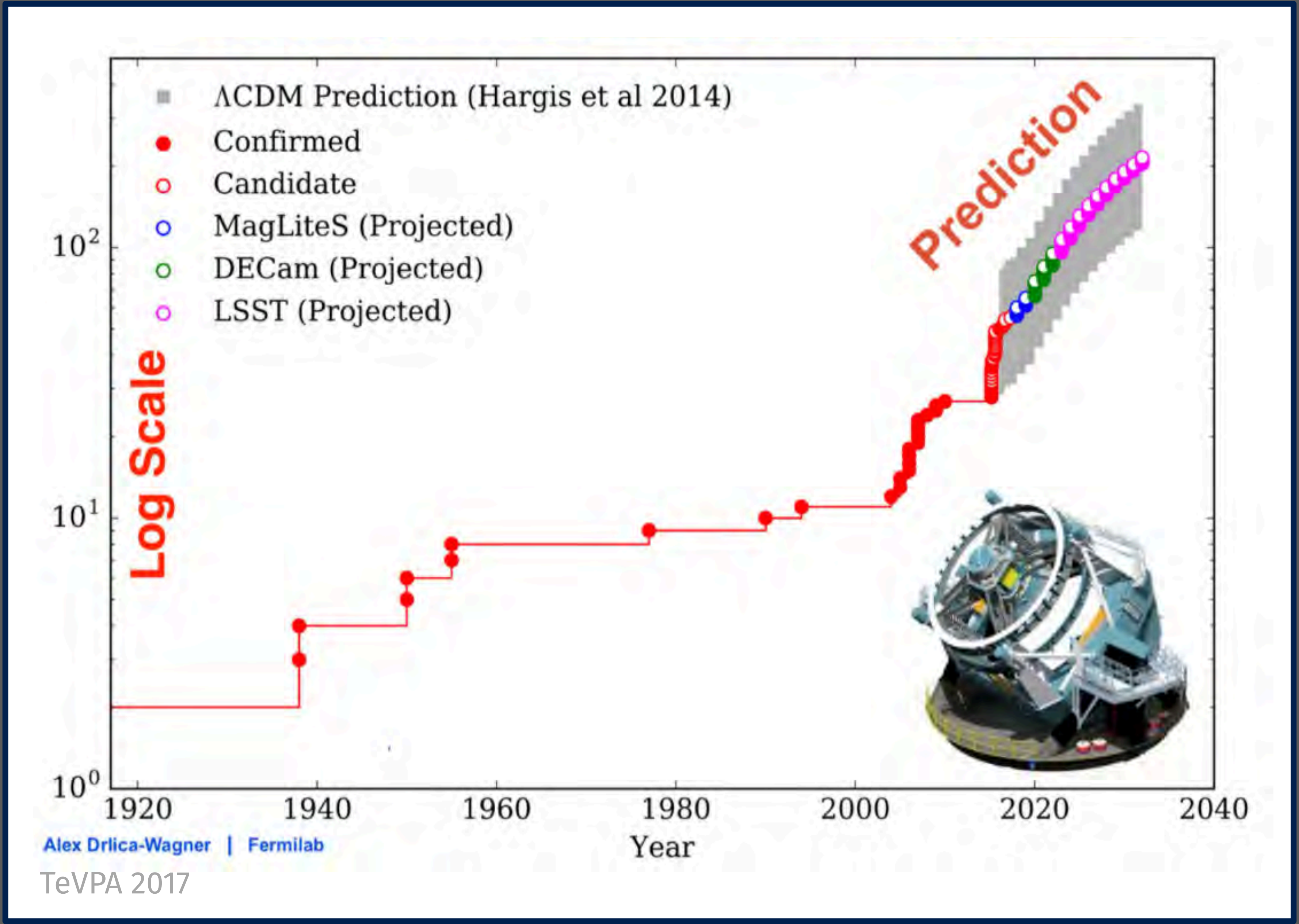


dSphs: More to be discovered in the future

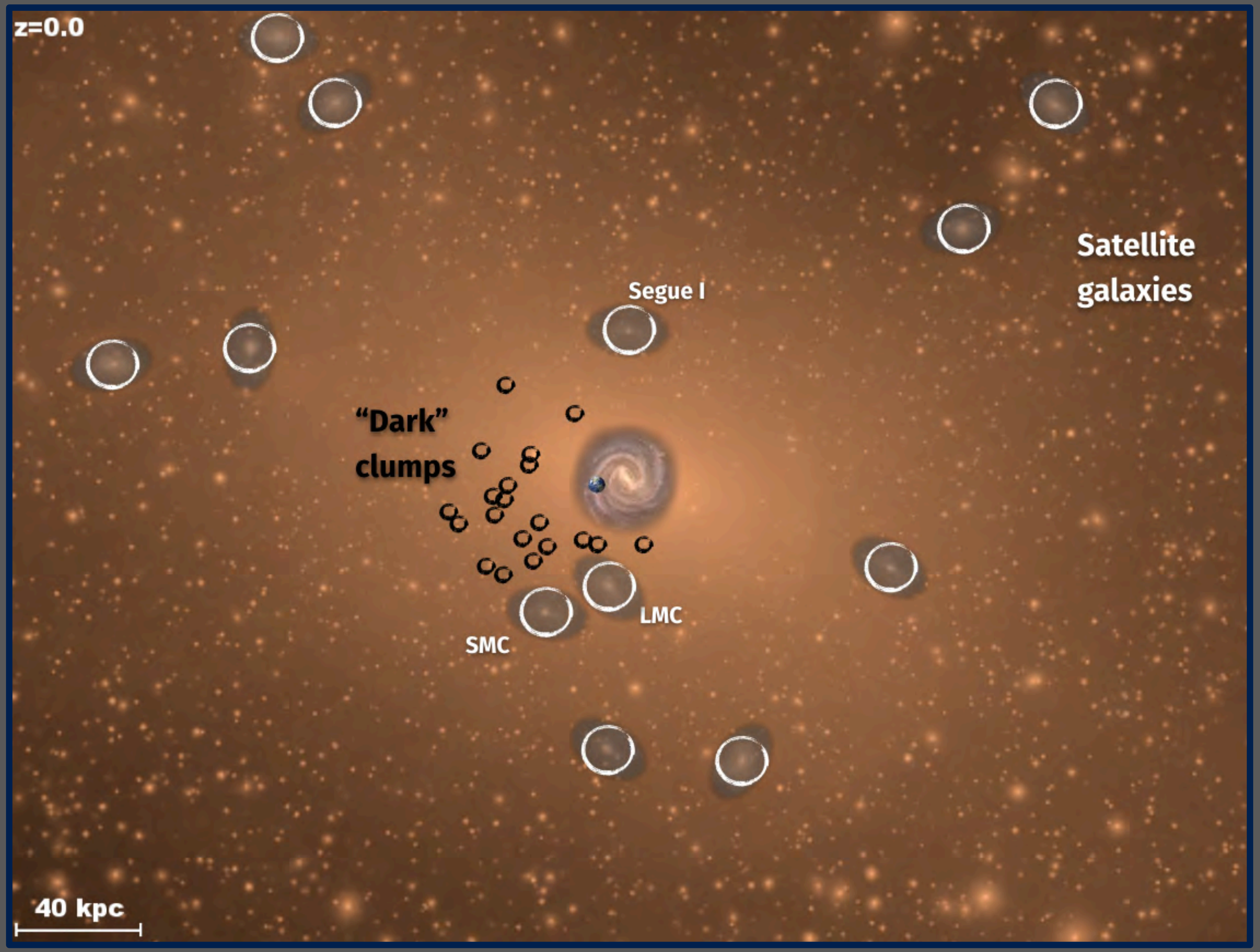


Can't wait for LSST...

Dark subhalos

Simulating the DM γ-ray sky with CLUMPY, MH et al., 1806.08639

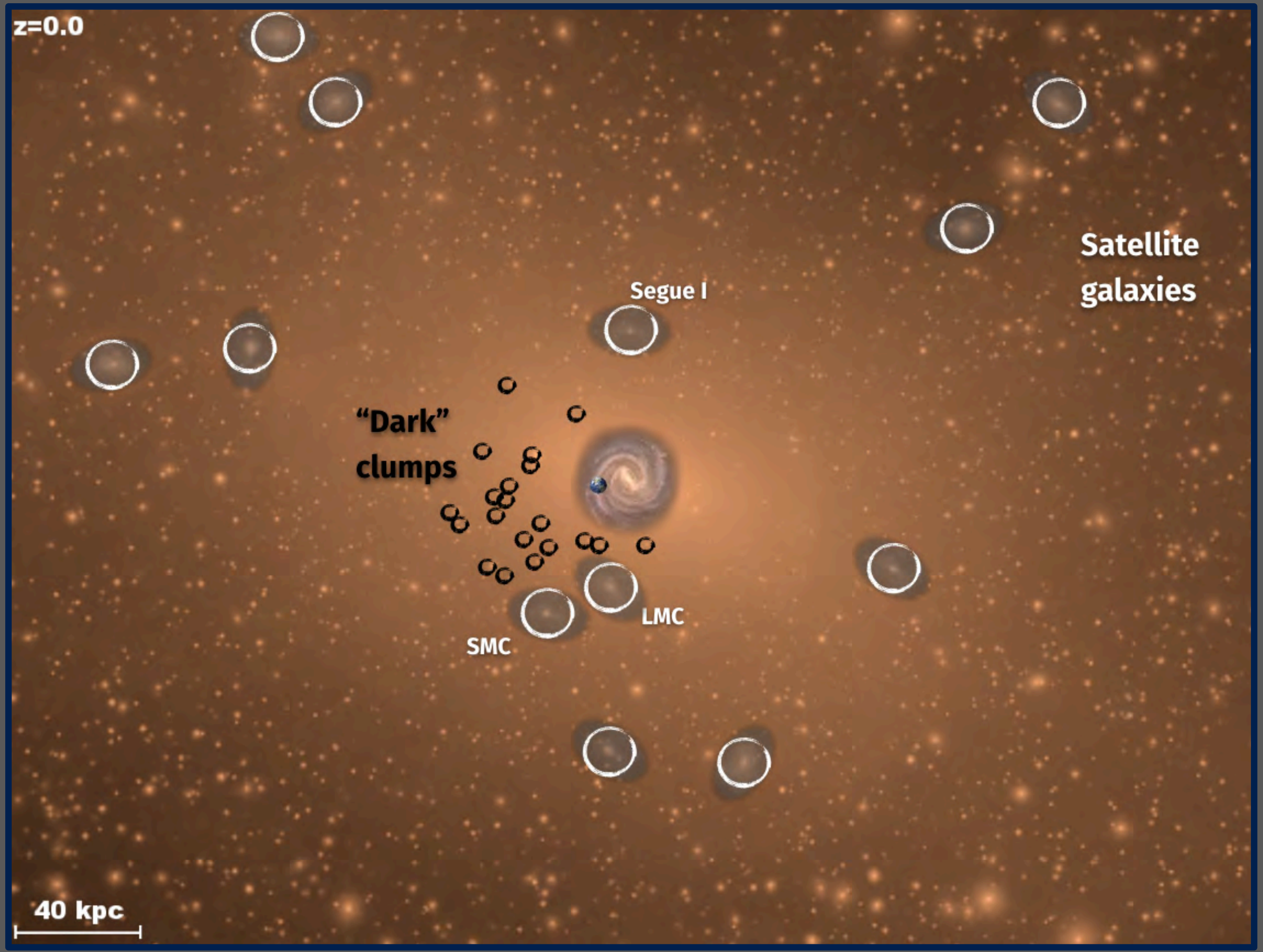
Dark subhalos



Dark subhalos

- Many DM clumps in the Milky DM halo too light ($m_{\mathrm{DM}} \lesssim 10^7\ \mathrm{M}_\odot$) to trigger star formation:

  “optically dark”



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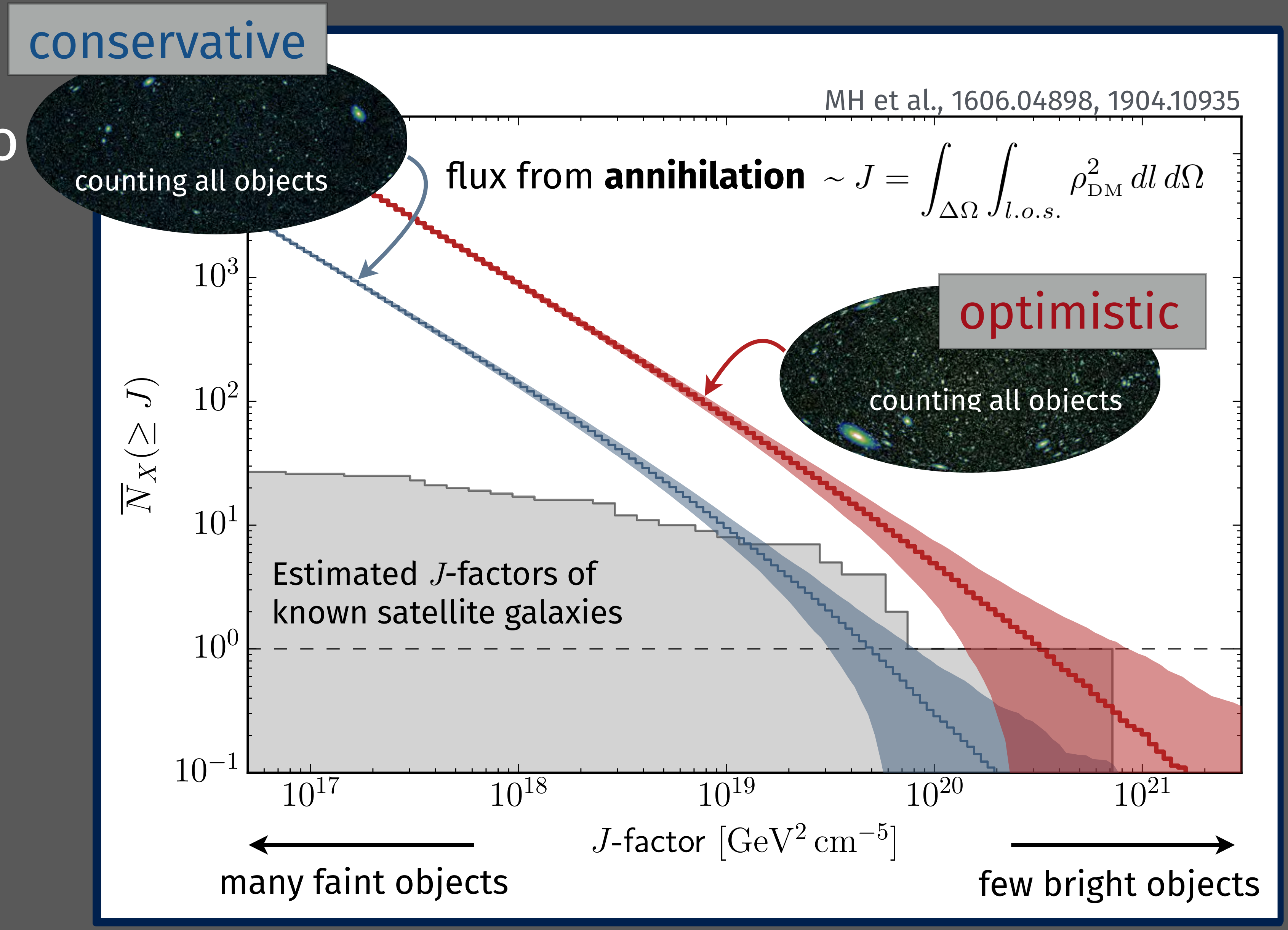

Dark subhalos

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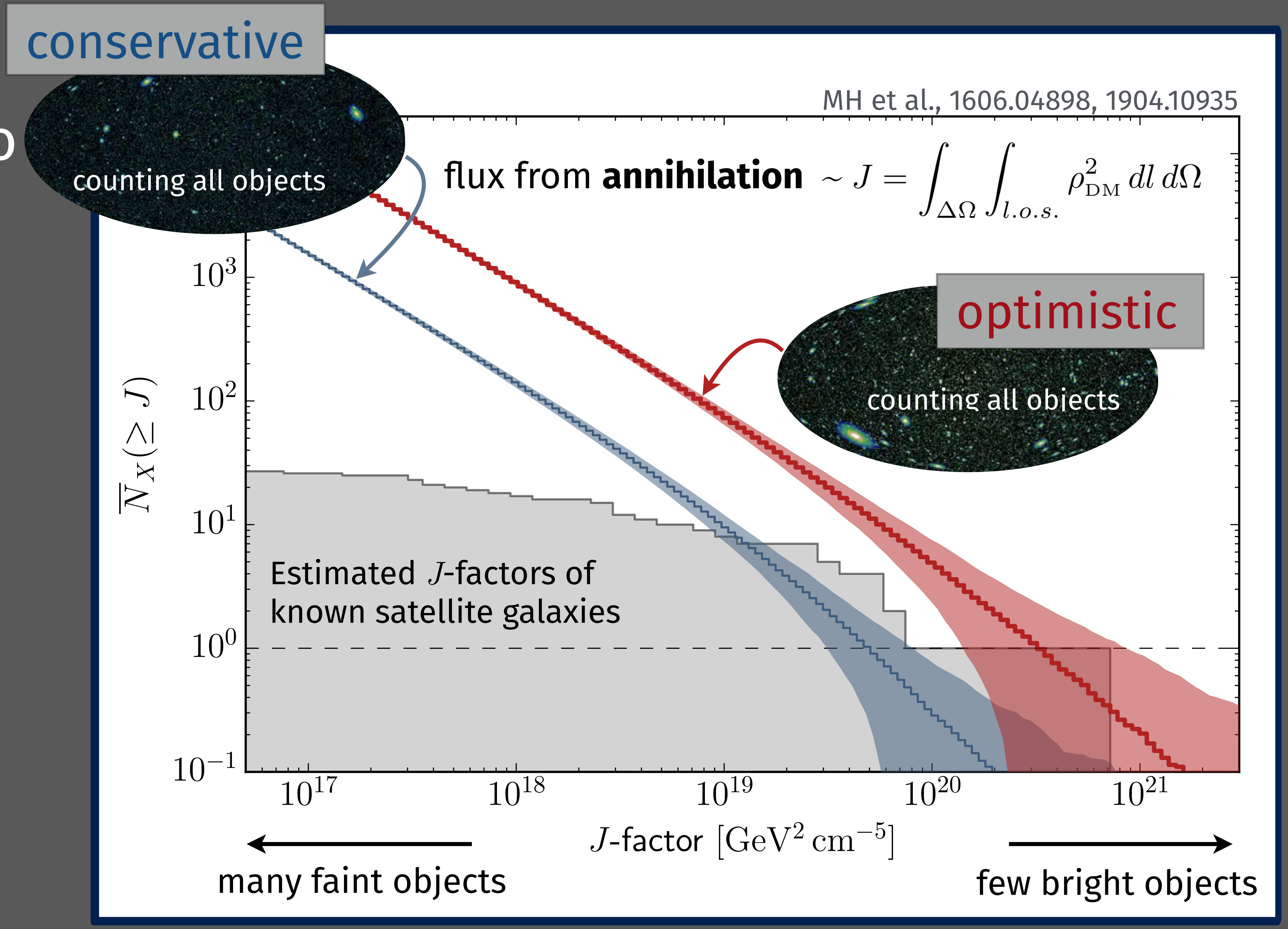
  "optically dark"

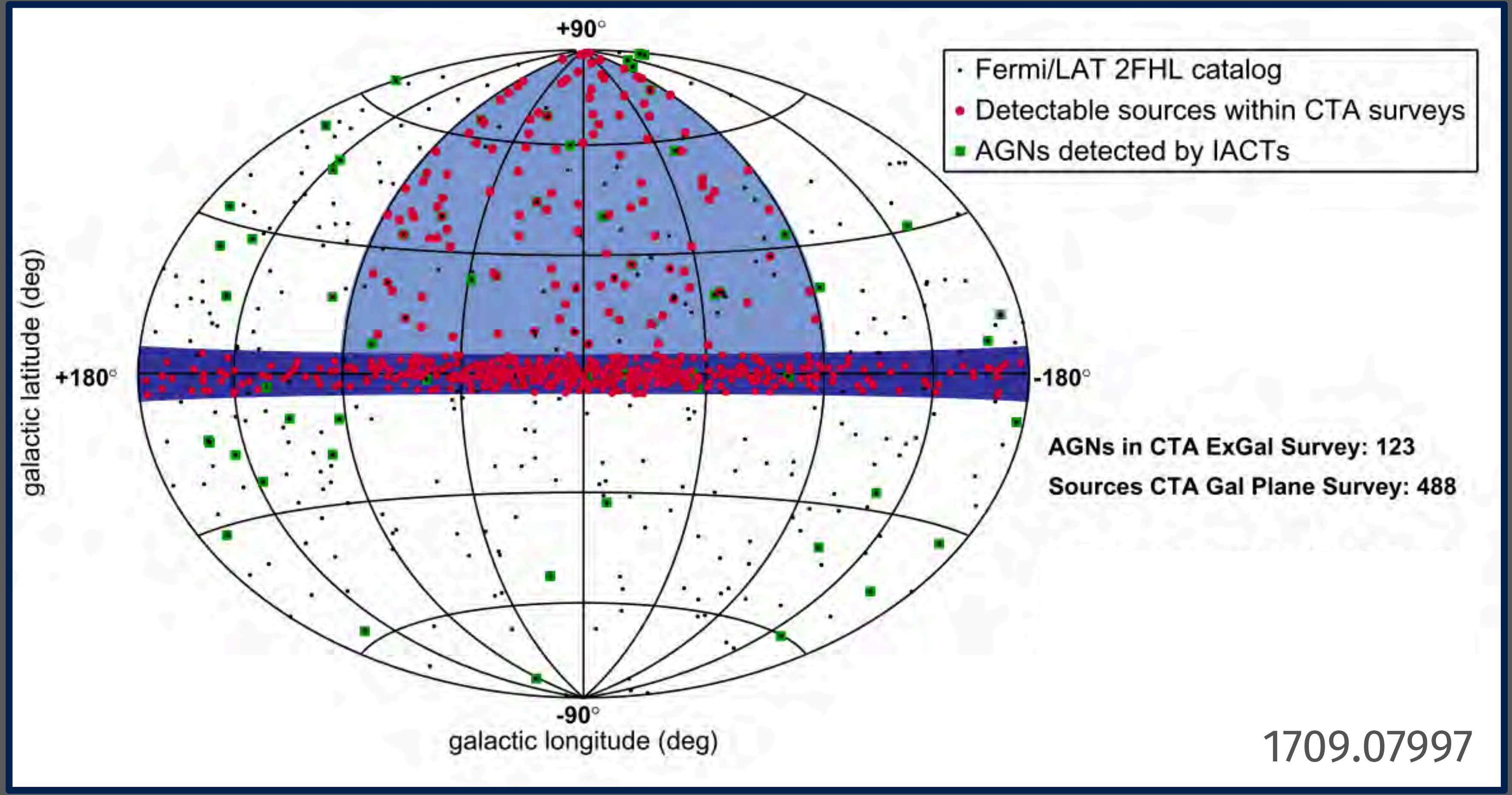
- ~ 33% of objects in γ-ray surveys (Fermi-LAT) unidentified: may have already found DM signal from subhalos? (1111.3514, 1111.2613, 1205.4825, 1504.02087,1601.06781, 1906.11896, ...)
  - Follow-up observation with CTA

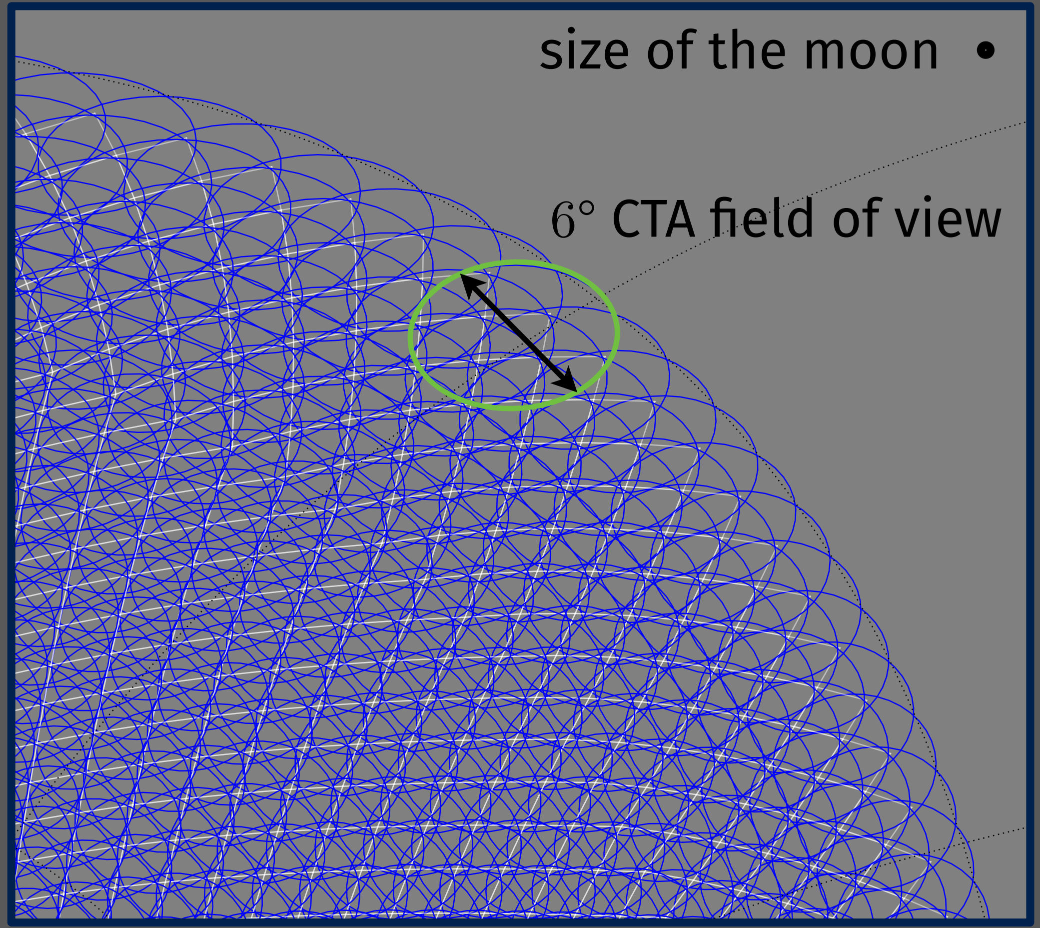


How to find dark subhalos with CTA?

1. CTA extragalactic sky survey

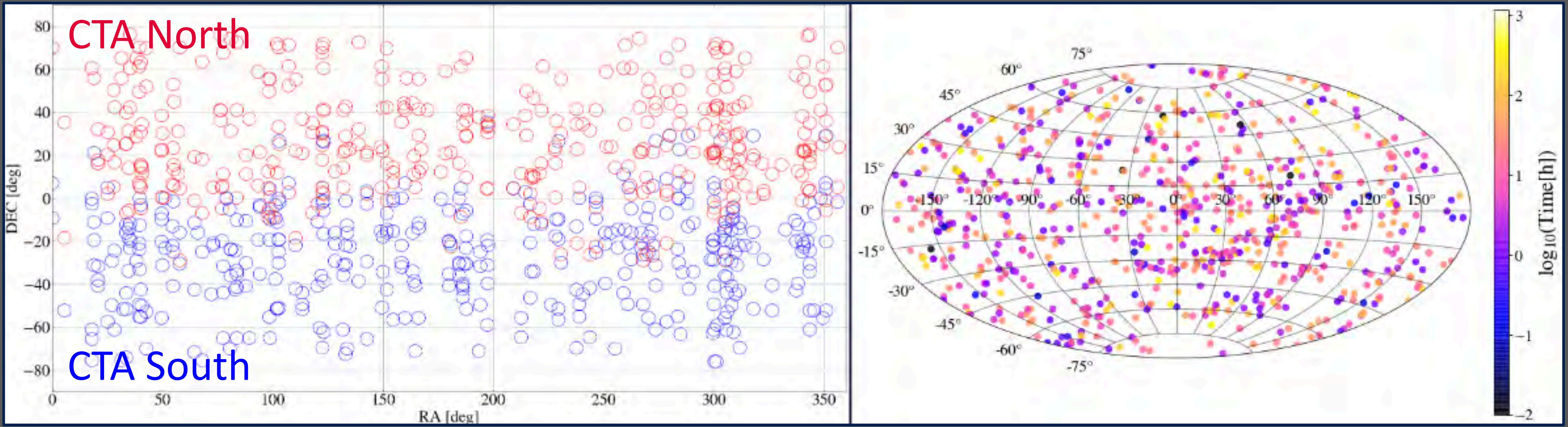
- $1000\mathrm{h}$ to raster $\sim 25\%$ of the sky outside the Galactic plane ($\sim 3\mathrm{h}$ on-axis exposure on each point in the sky)
- Complete within first 10 years of operation





How to find dark subhalos with CTA?

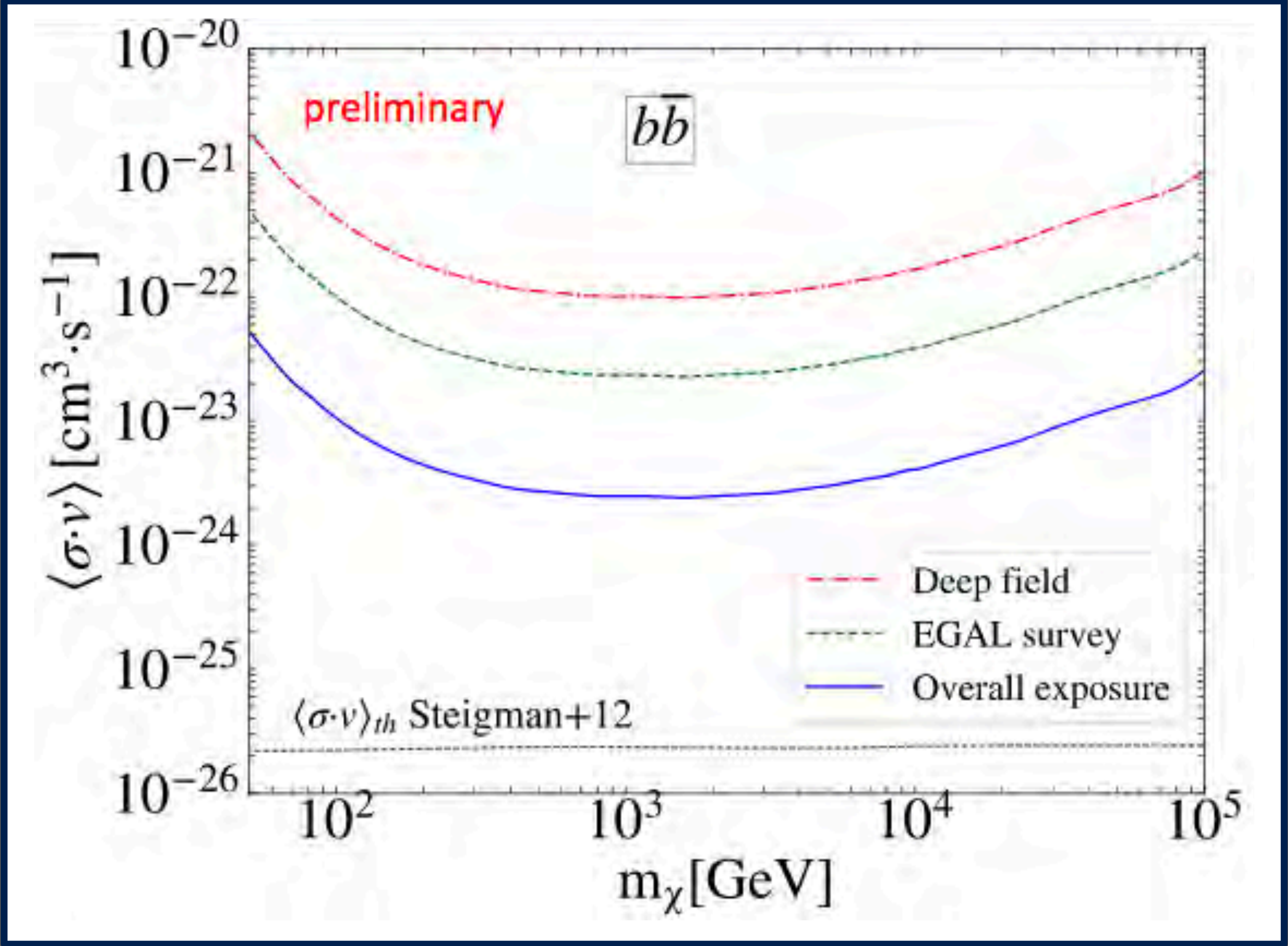
2. Serendipitous discovery in all CTA data (first 10 years, $\sim 2\times10^4$ h data)

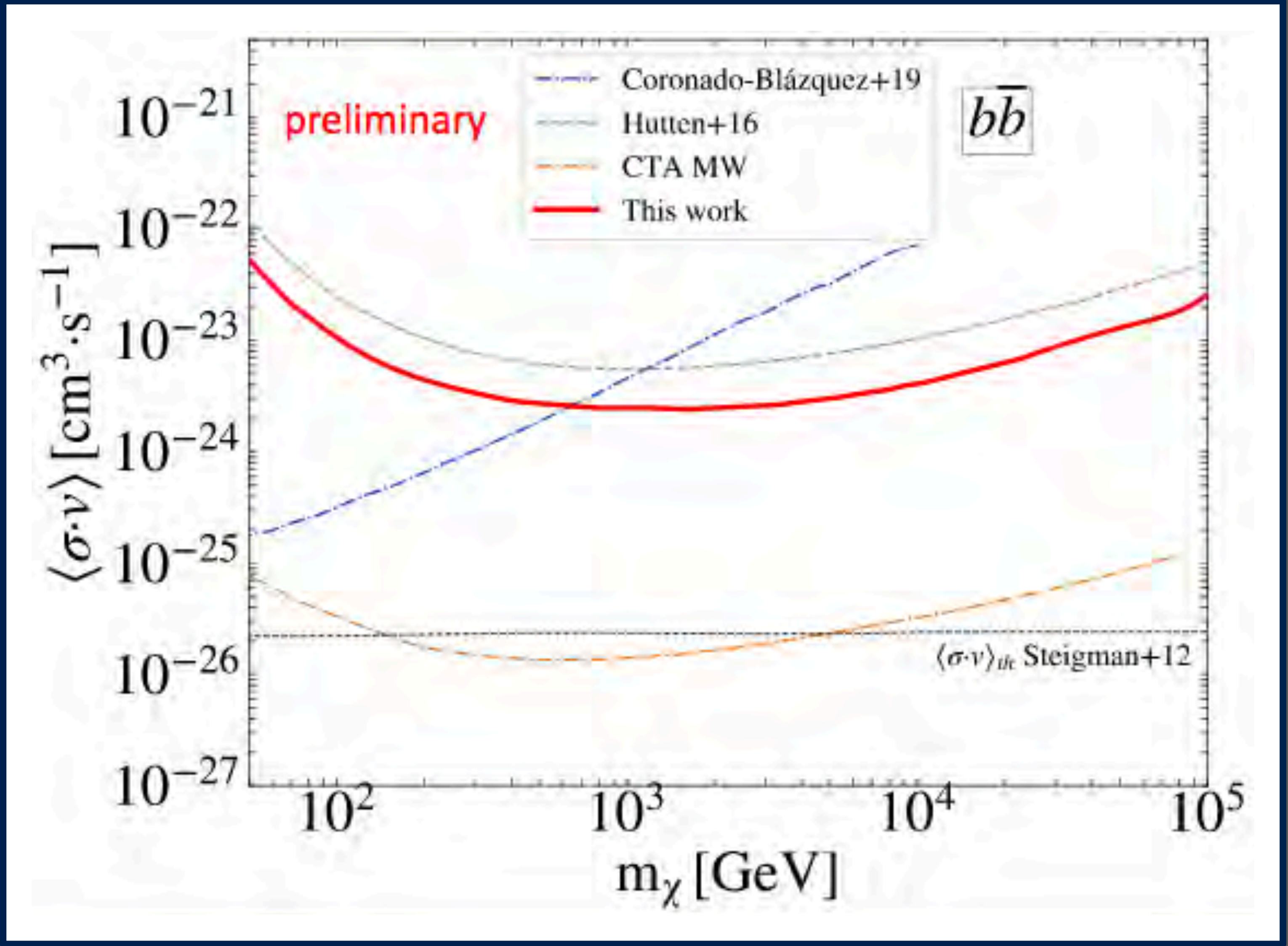


J. Coronado-Blázquez, M. Sánchez-Conde, M. Doro, A. Aguirre-Santaella (in preparation)

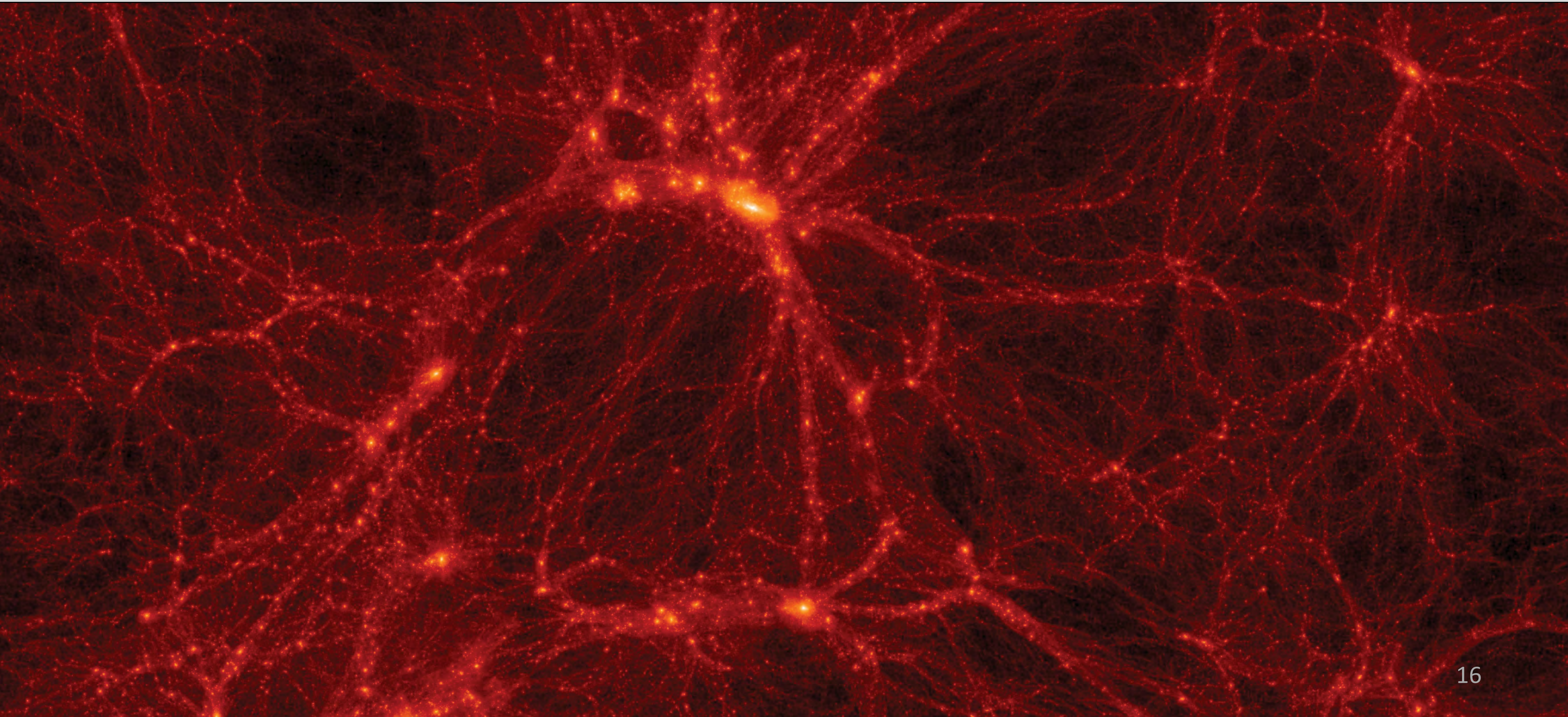
CTA sensitivity to dark subhalos

J. Coronado-Blázquez, M. Sánchez-Conde, M. Doro, A. Aguirre-Santaella (in preparation), see also 1606.04898

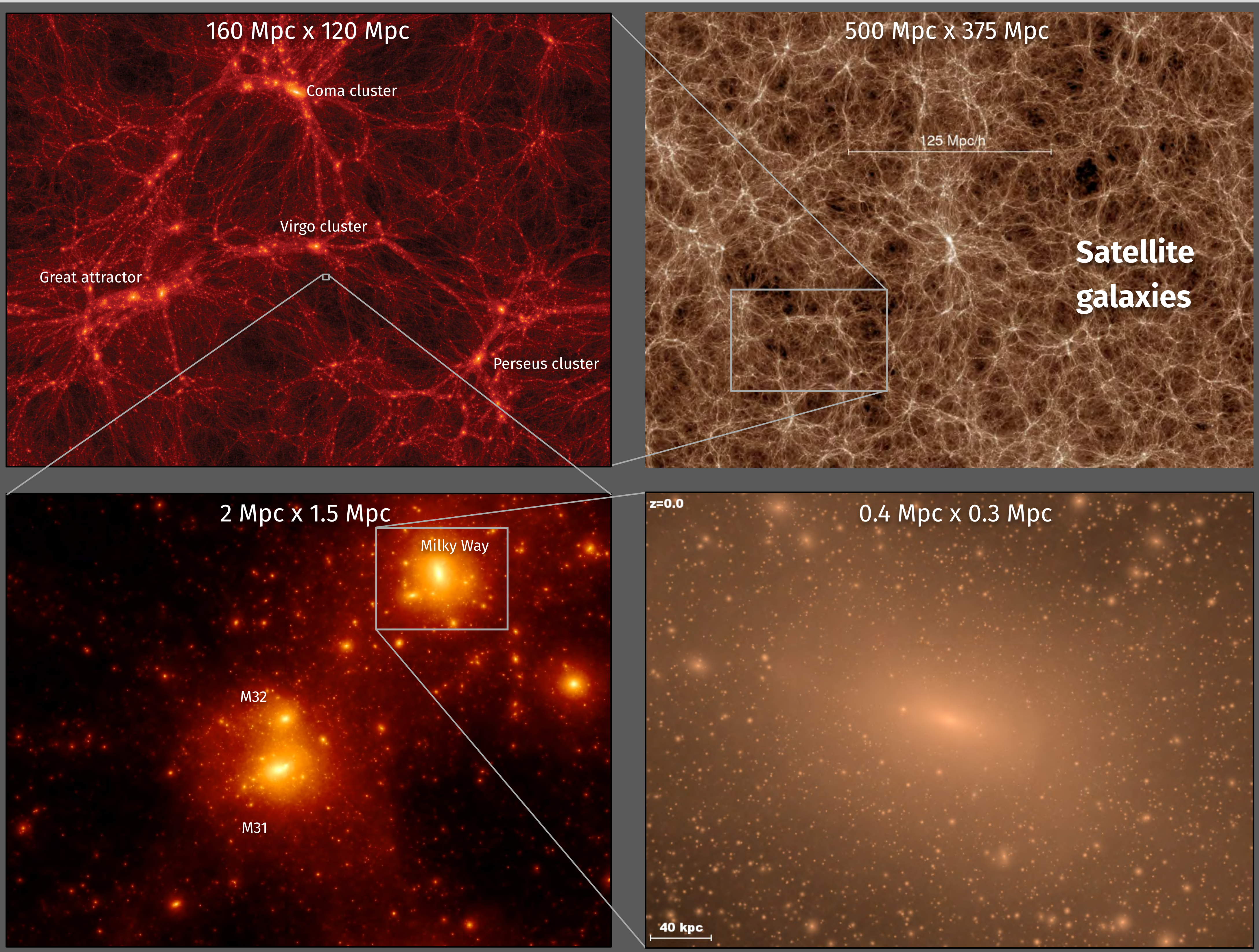




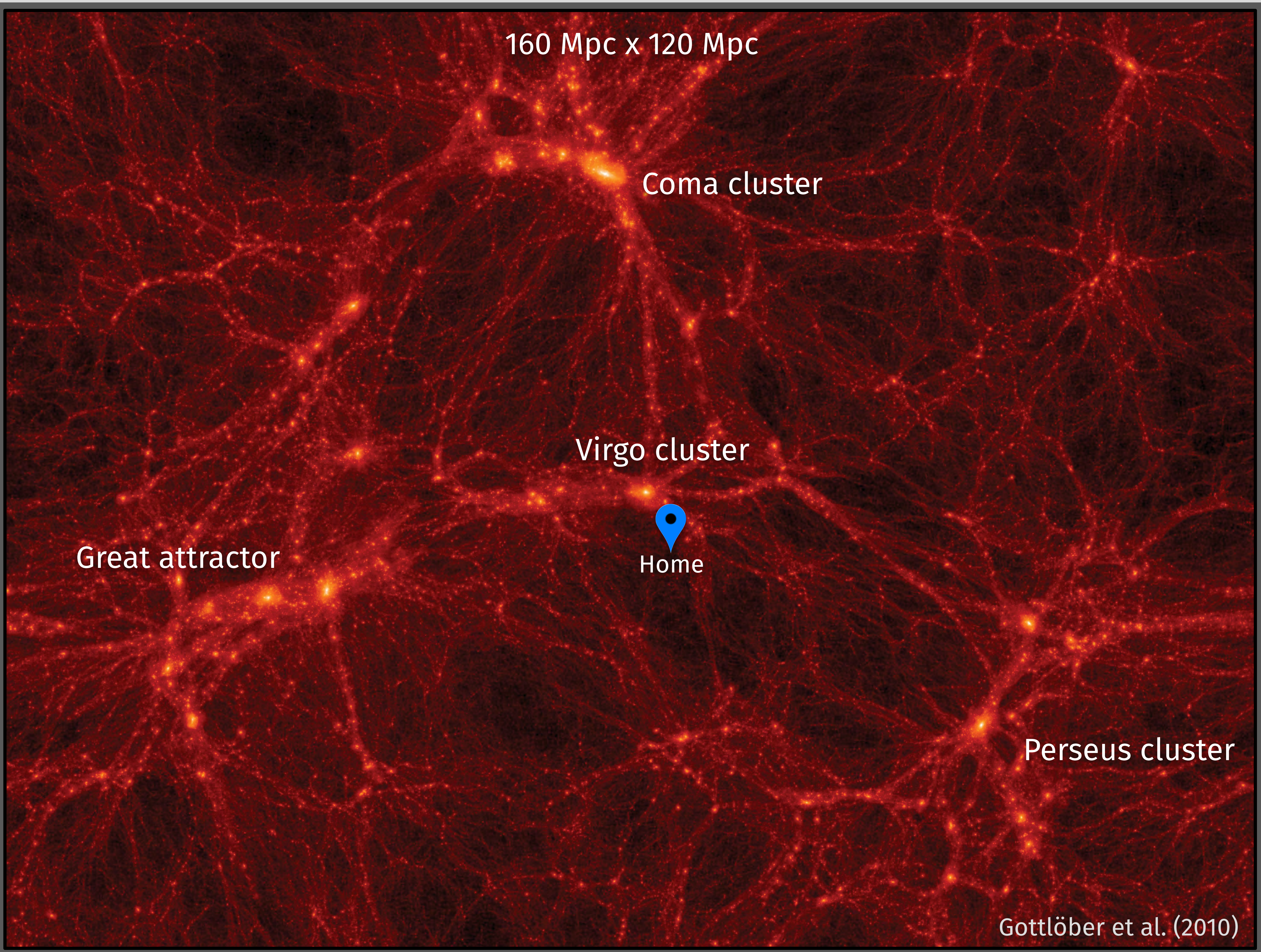
Galaxy clusters



The case of galaxy clusters



The case of galaxy clusters



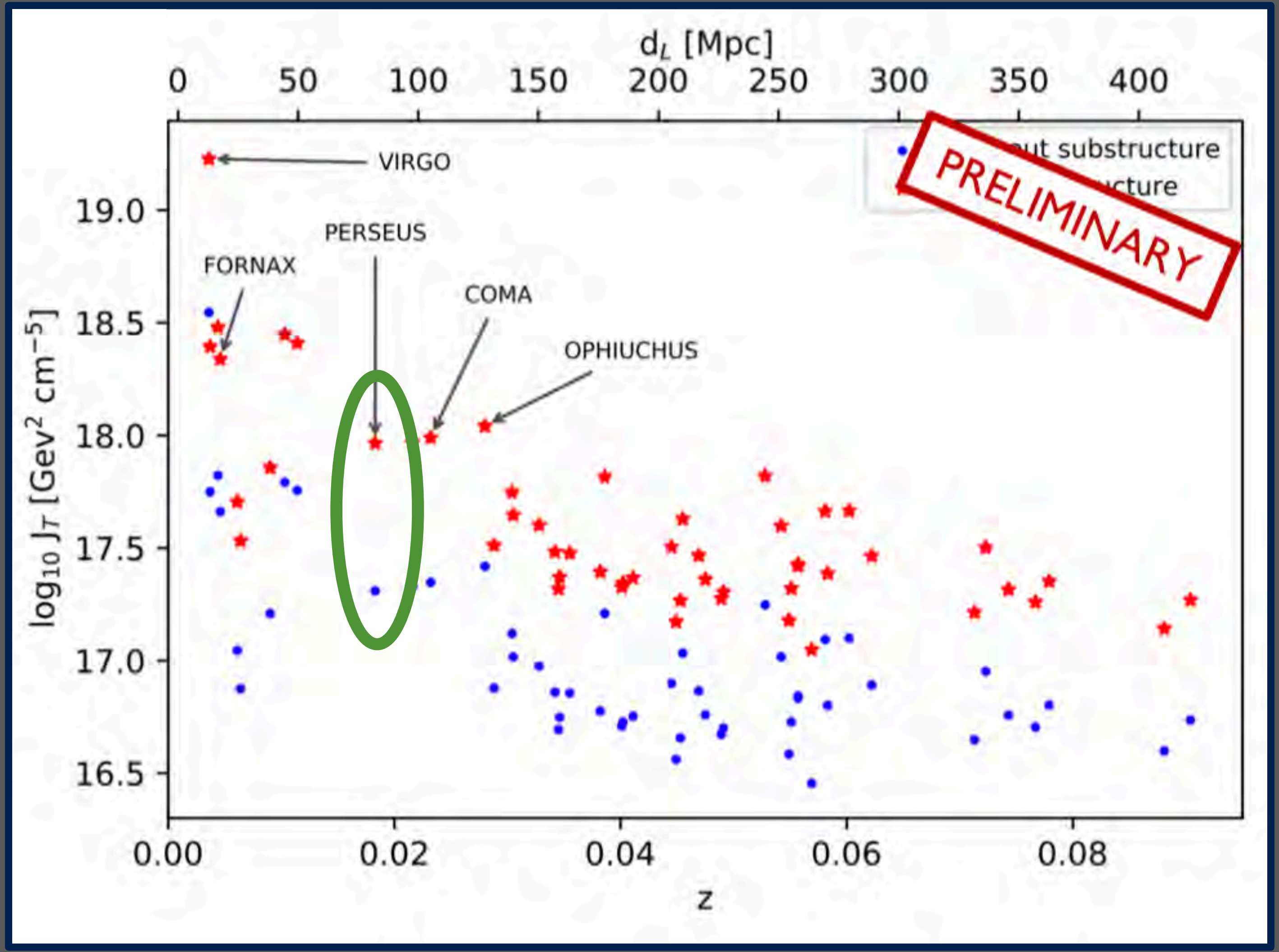
- Biggest DM clumps in the Universe:

  $m_{\rm DM} \gtrsim 10^{14} - 10^{15}\ {\rm M}_\odot$

- However, $\gtrsim 100$ times more distant than dSphs and Galactic DM.

The case of galaxy clusters

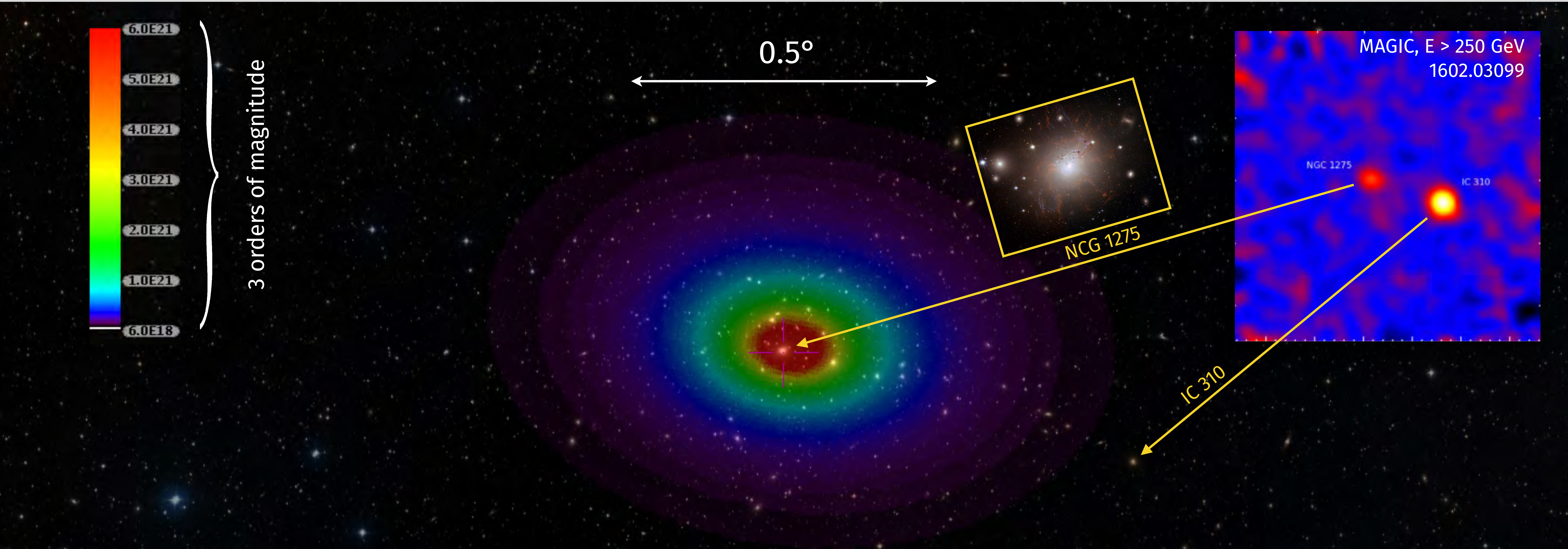
- DM-annihilation γ-ray fluxes comparable to dSph galaxies
- Emission profiles more extended (typical half-light radii $> 0.5°$)
- Astrophysical backgrounds:
  - γ-ray emitting galaxies (AGN, star-forming galaxies, cosmic-ray interaction)
  - Also expect diffuse emission from the inter-cluster medium



J. Pérez-Romero for the galaxy cluster task force

CTA key science project: Observe Perseus galaxy cluster for 300h

Perseus cluster: DM annihilation signal

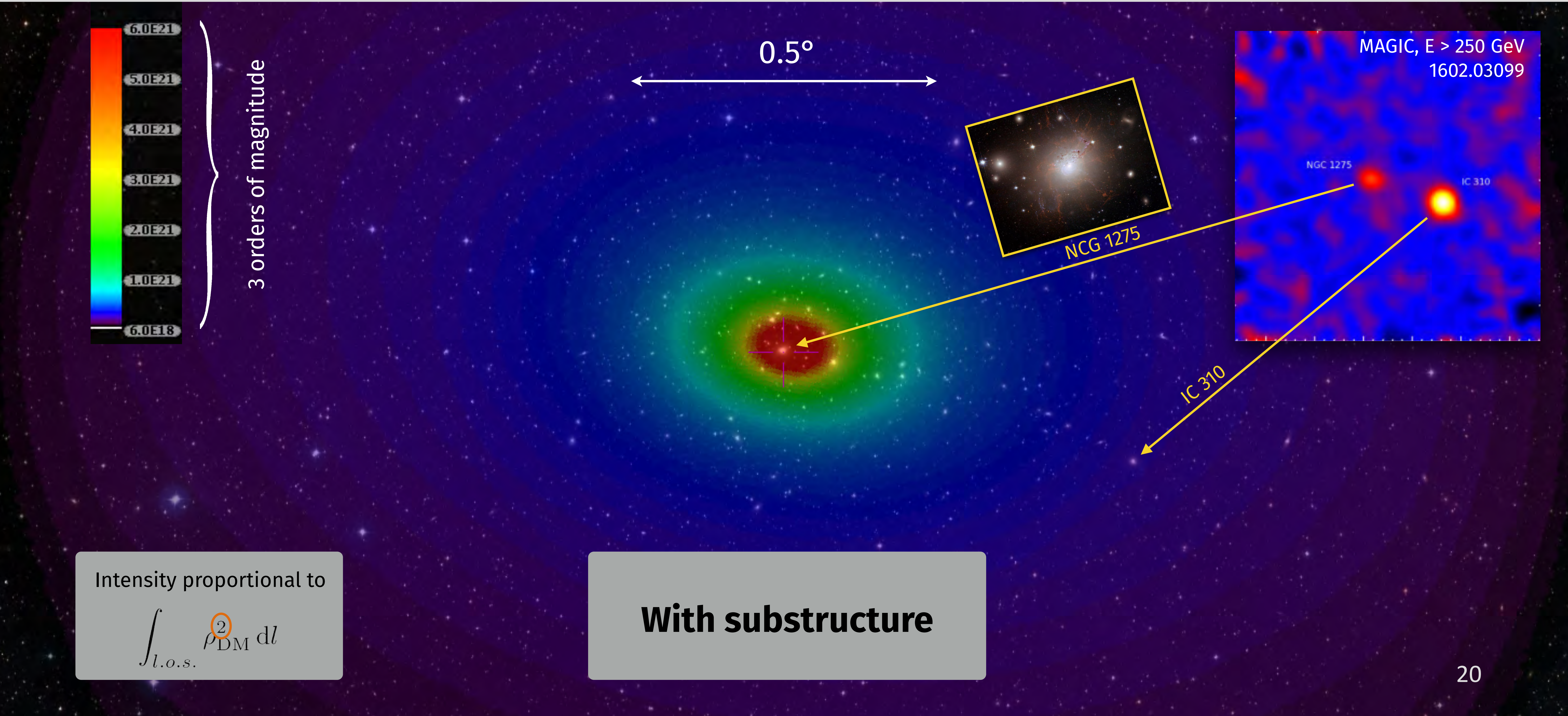


Intensity proportional to

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

without substructure
random triaxiality

Perseus cluster: DM annihilation signal

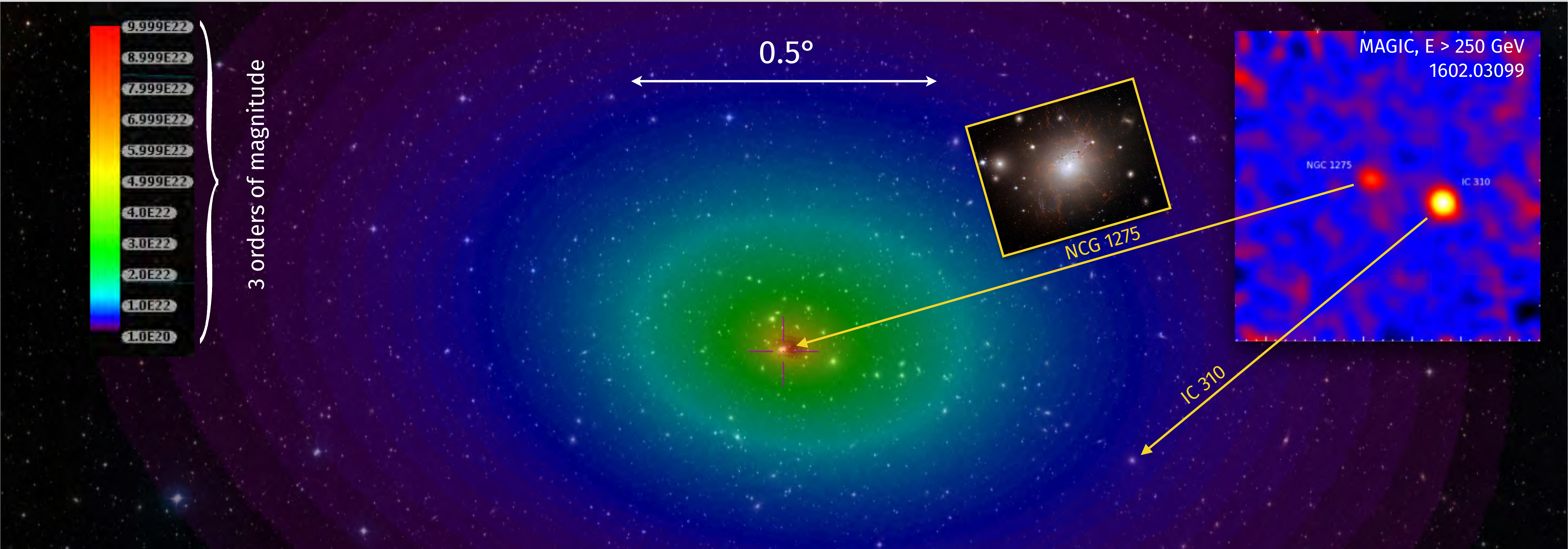


Intensity proportional to

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

With substructure

Perseus cluster: DM decay signal



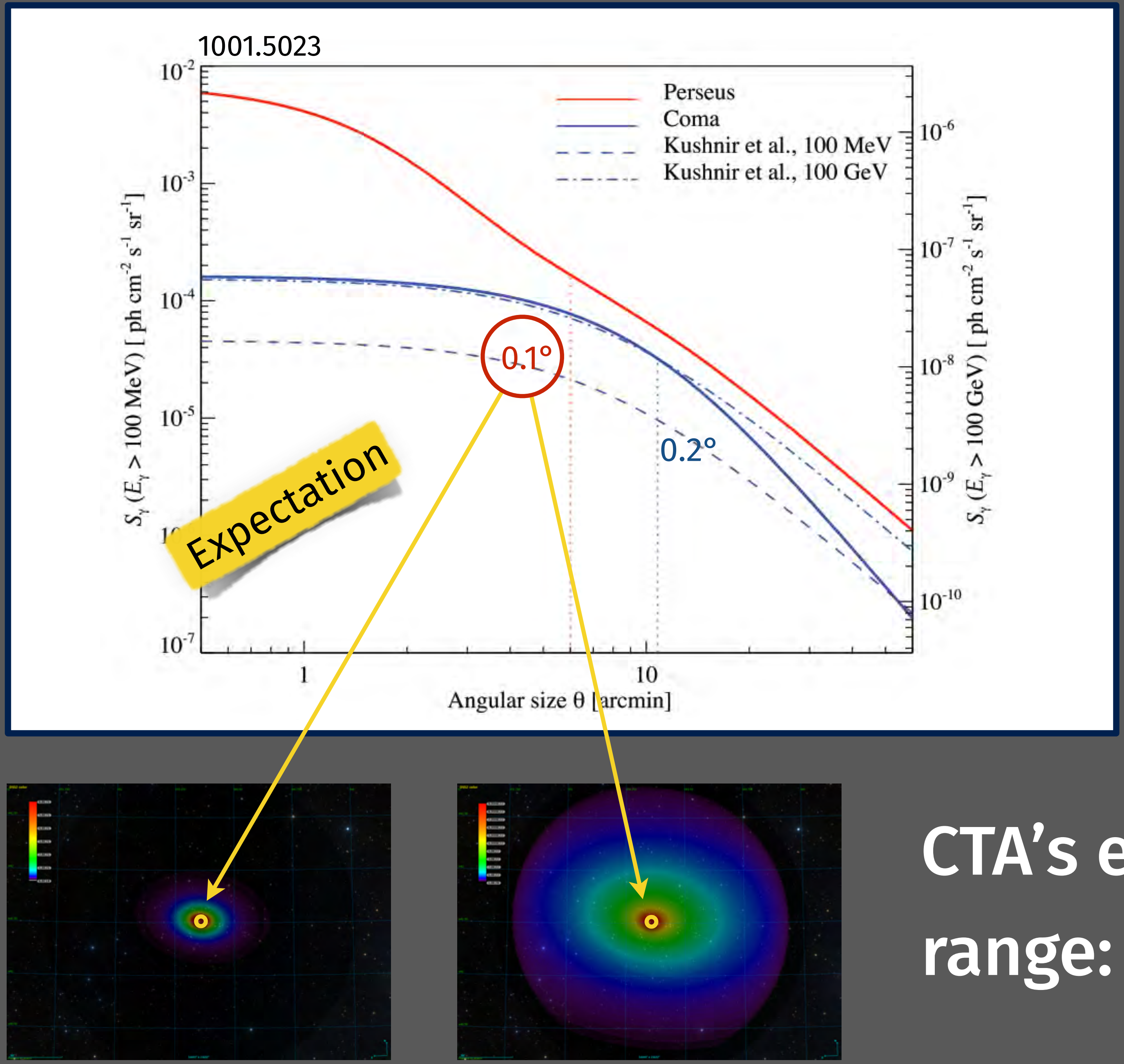
Intensity proportional to

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

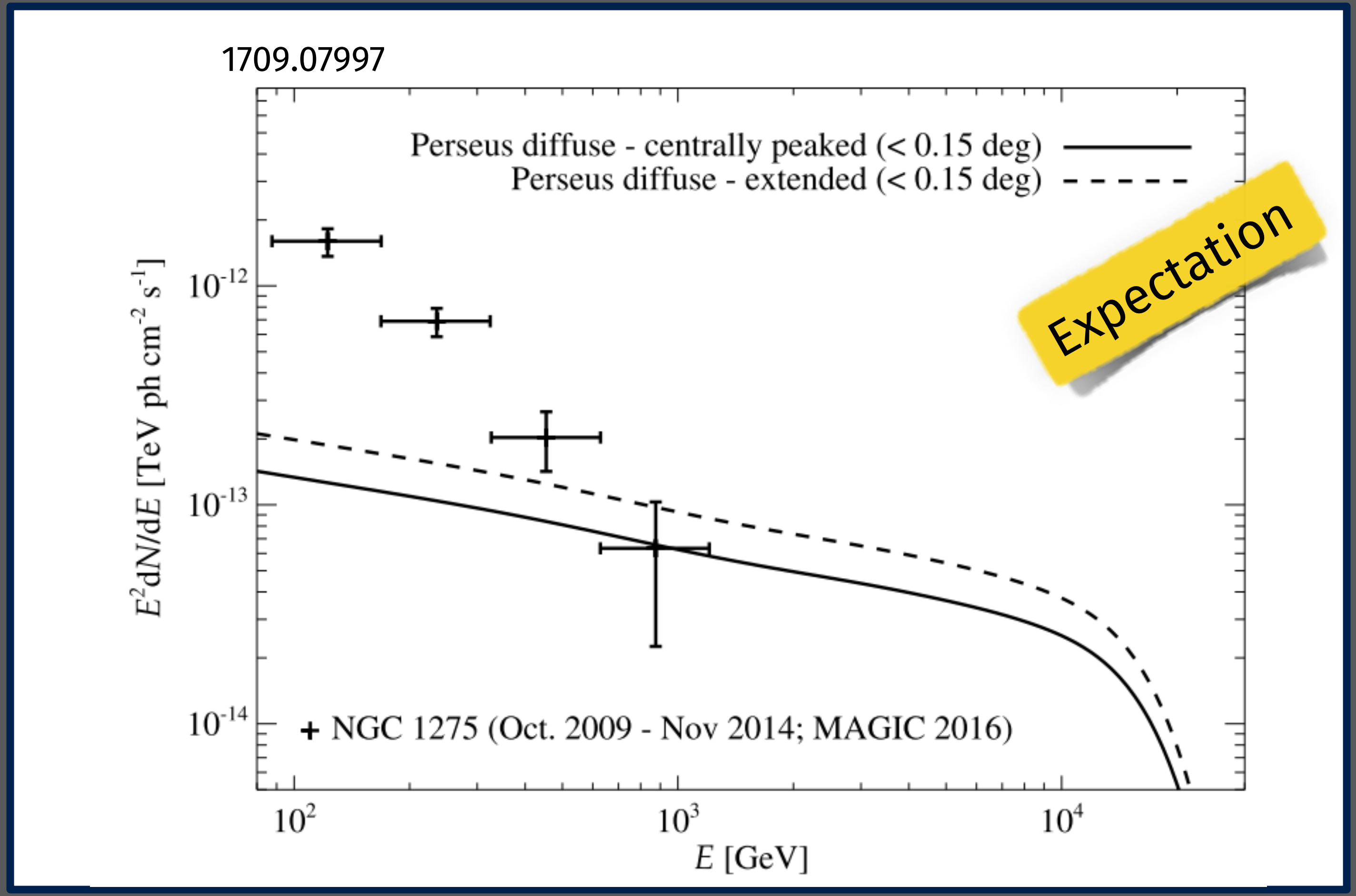
Decay

DM and astrophysical emission in clusters

Spatial profile

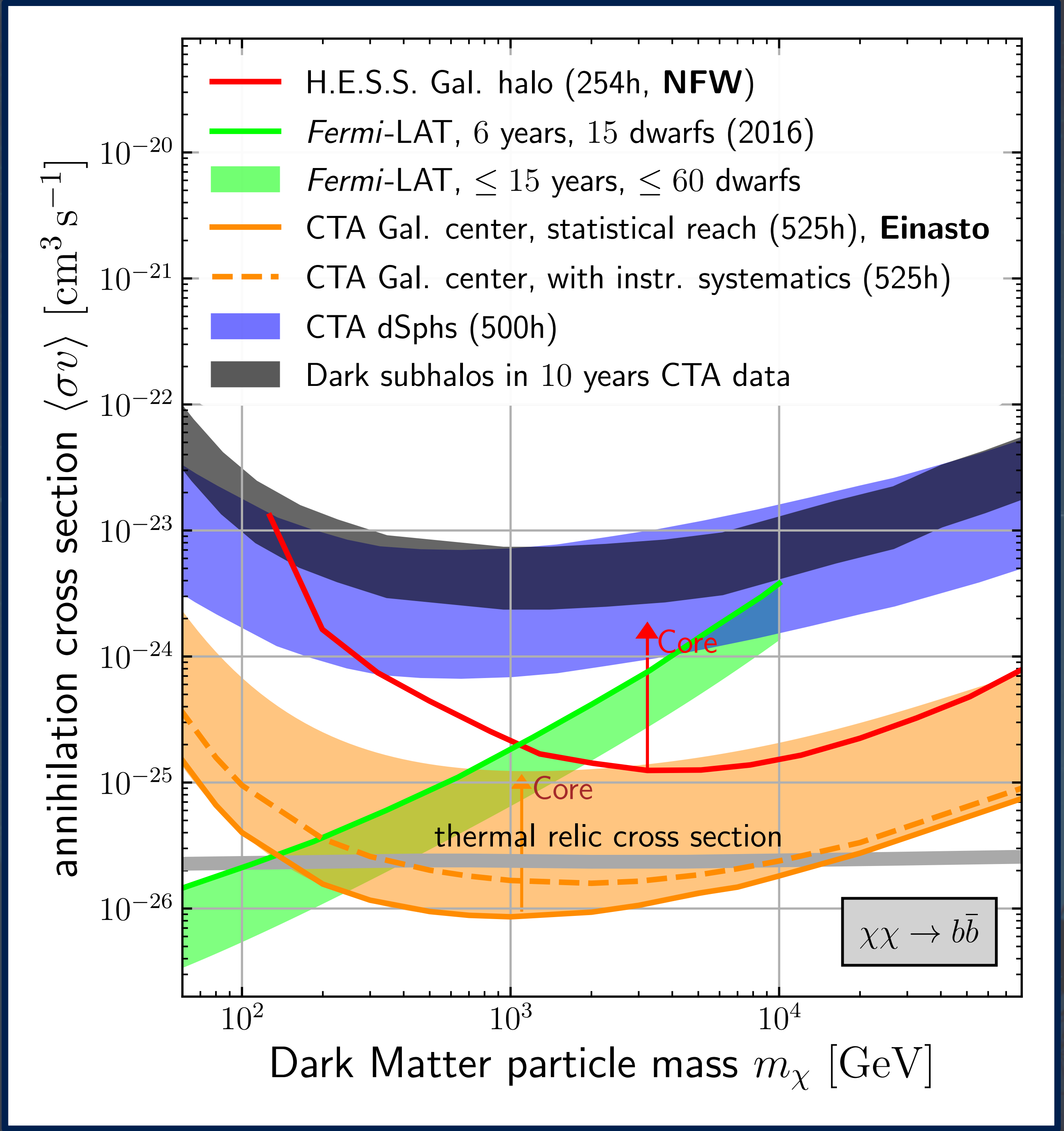


Spectral profile

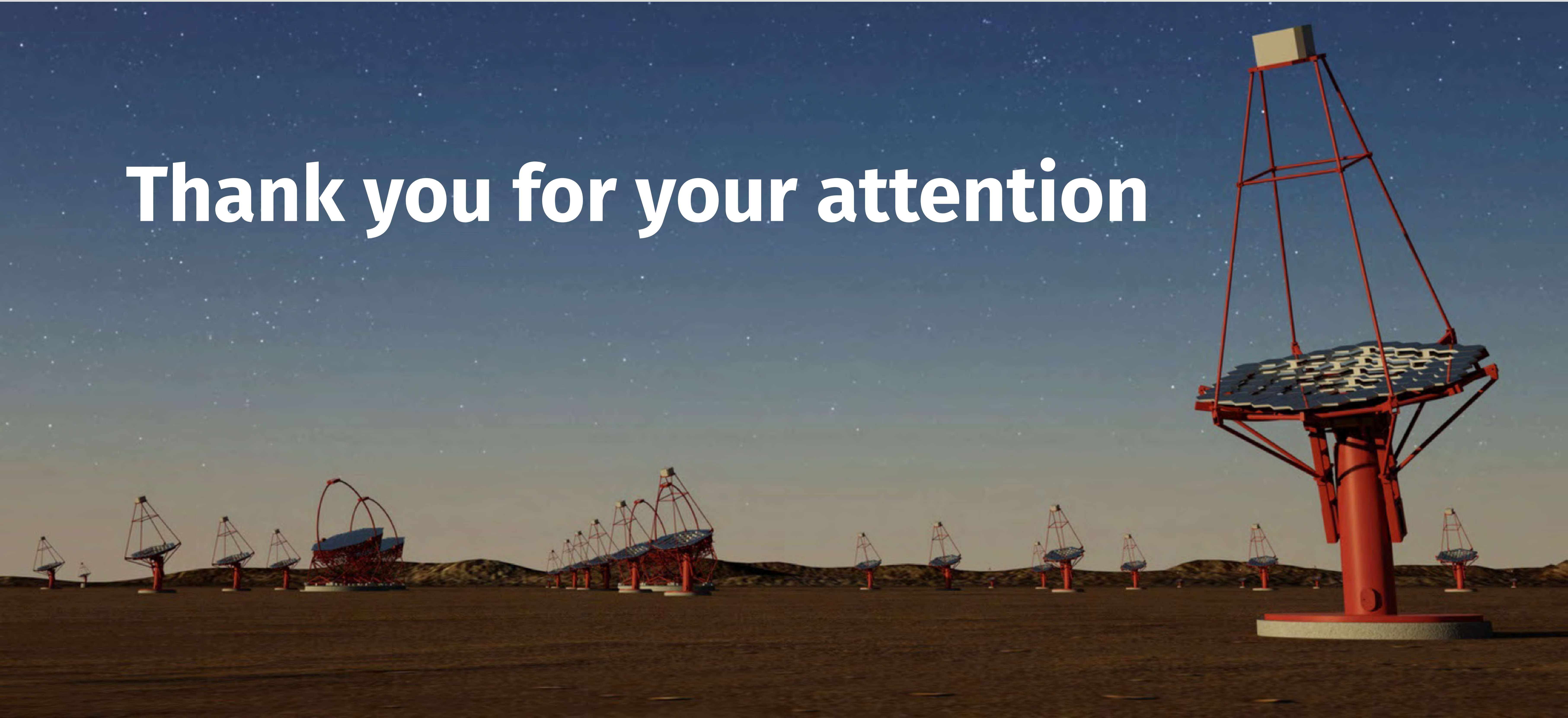


CTA's excellent angular resolution and energy range: disentangle the signals

Summary



- Probe various astrophysical regions for WIMP annihilation: *Galactic center, dwarf galaxies, dark subhalos, galaxy clusters*
- Unique sensitivity for $m_\chi \gtrsim 1$ TeV WIMPs
- Complementary uncertainties in different targets: **Detection**: Galactic center, **Identification**: dwarf galaxies
- Crucial to control deep-exposure instrument systematics and *J*-factors for particle physics implications


Thank you for your attention

dSphs: CTA observation strategy

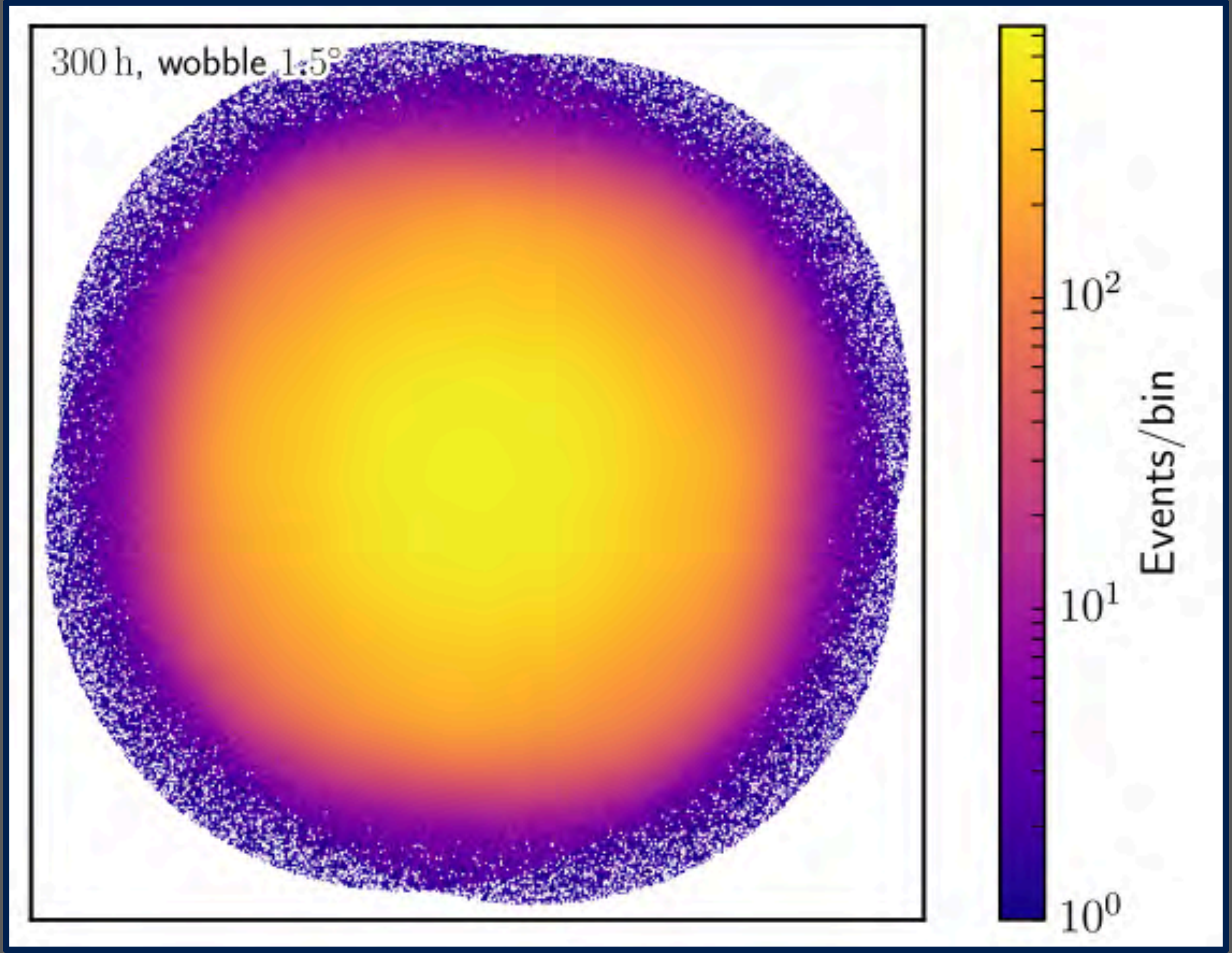
- First 3 years: Focus on best dwarf only
- Next 7 years: In case of strong signal at GC, use dSph to confirm signal in clean environment

Year	1	2	3	4	5	6	7	8	9	10
Galactic halo	175 h	175 h	175 h							
Best dSph	100 h	100 h	100 h							
				in case of detection at GC, large σv						
Best dSph				150 h	150 h	150 h	150 h	150 h	150 h	150 h
Galactic halo				100 h	100 h	100 h	100 h	100 h	100 h	100 h
				in case of detection at GC, small σv						
Galactic halo				100 h	100 h	100 h	100 h	100 h	100 h	100 h
				in case of no detection at GC						
Best Target				100 h	100 h	100 h	100 h	100 h	100 h	100 h

1709.07997

How to find dark subhalos with CTA?

3. Dedicated deep-exposure observation on dark field



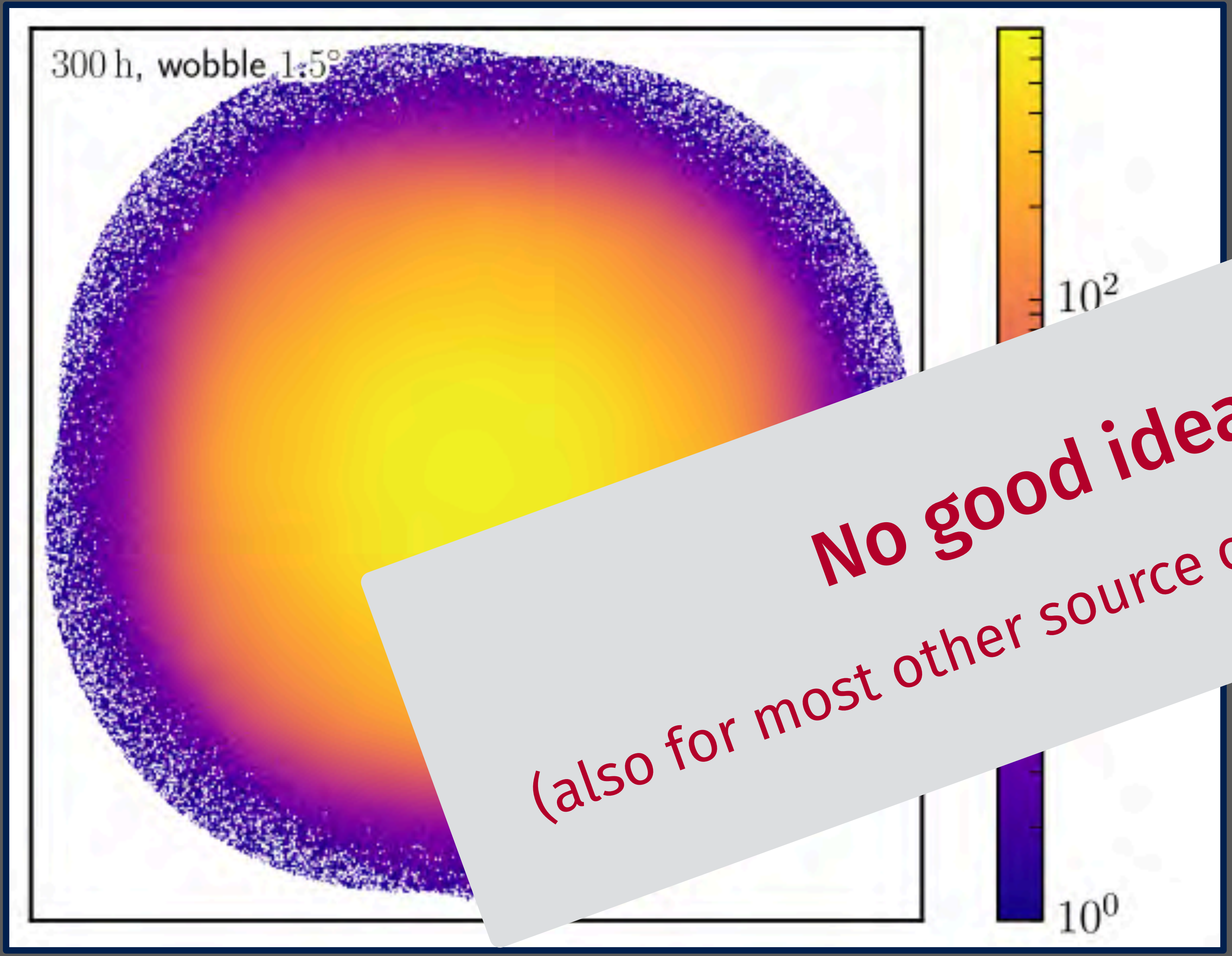
"Subhalo algebra": (details see 1606.04898)

1. Number of 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, $\sim 1/F_{\mathrm{sens}}$: *subhalo source count distribution*

- **For constant total observation time, number of detectable objects rises with** $\mathrm{sqrt}(\Delta\Omega)$

How to find dark subhalos with CTA?

3. Dedicated deep-exposure observation on dark field



“Subhalo alge… …e 1606.04898)

1. N… with $\Delta\Omega$:

…jects rises with

…ment background

…ber of detectable objects rises inversely with sensitivity threshold, $\sim 1/F_{\rm sens}$: *subhalo source count distribution*

- **For constant total observation time, number of detectable objects rises with** $\mathrm{sqrt}(\Delta\Omega)$

No good idea for DM subhalos

(also for most other source classes, see 1208.5686 and 1606.04898)

CTA sensitivity to dark subhalos

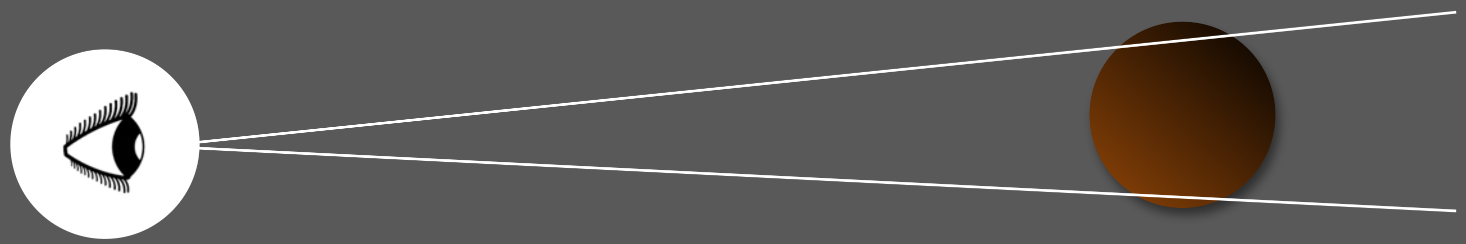
Dependent on many factors:

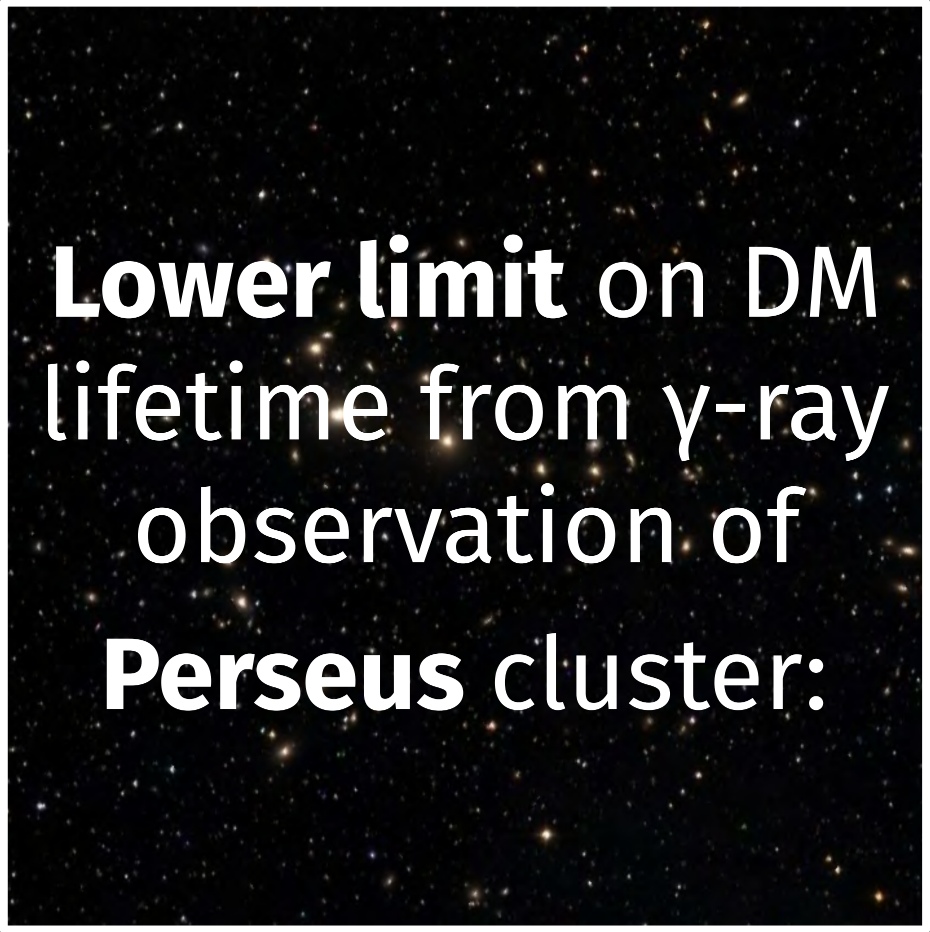
- Observation strategy
- Total observation time
- Search with CTA North or CTA South
- Off-axis acceptance
- Parallel vs. divergent pointing (1501.02586, 1508.06197)

- Search region in the sky: other sources in the field of view
- Expected DM subhalo population (1606.04898, 1904.10935, 1906.11896,...)

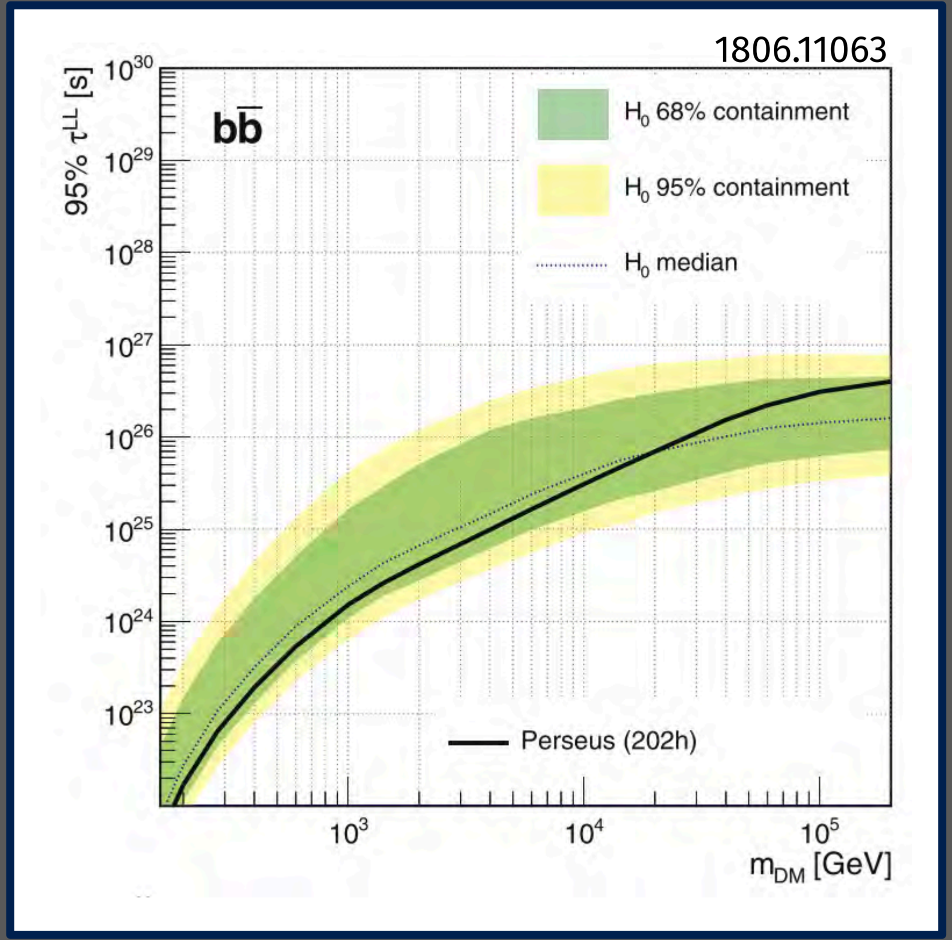
Probe DM lifetime in galaxy clusters

- Huge integrated mass (up to $10^{15}\ \mathrm{M}_\odot$)
- Probe $\tau_{\mathrm{DM}} > 10^{27}\ \mathrm{s} = 2 \cdot 10^9\ t_{\mathrm{Universe}}$





MAGIC measured



CTA expected