6 December 2013
XVI Roma Tre Topical Seminar on Subnuclear Physics:
'From the Higgs to Dark Matter'

Dark Matter:
evidences and basic properties,
from cosmology, astrophysics and particle physics searches

Marco Cirelli
(CNRS IPhT Saclay)

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erc NewDark

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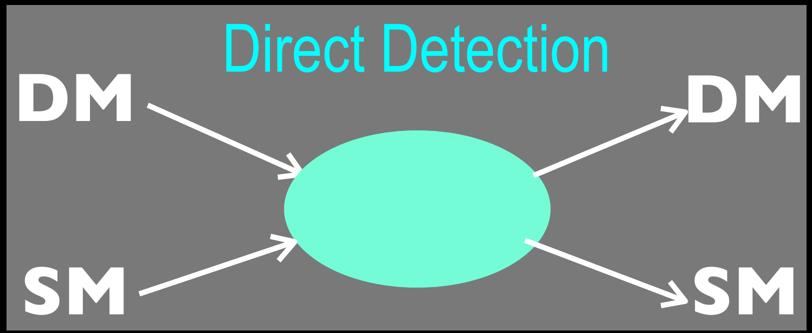

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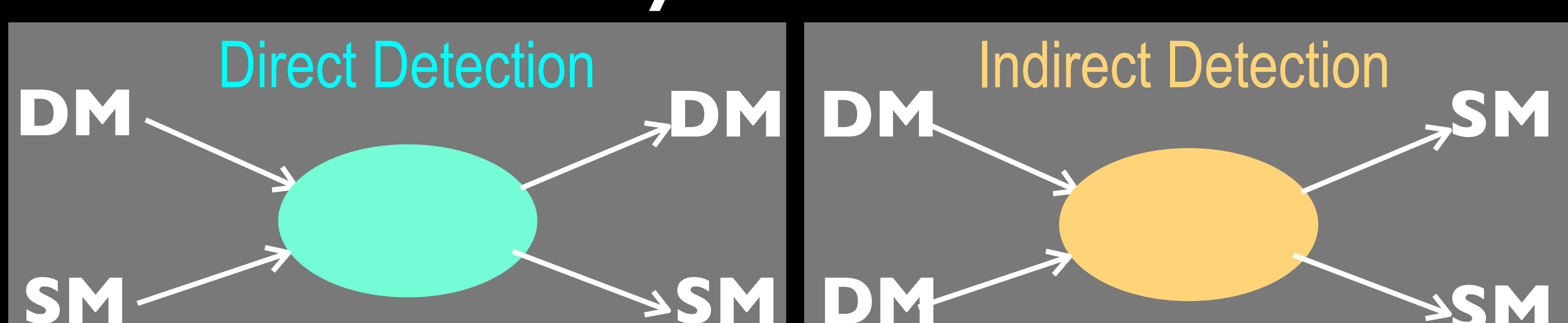

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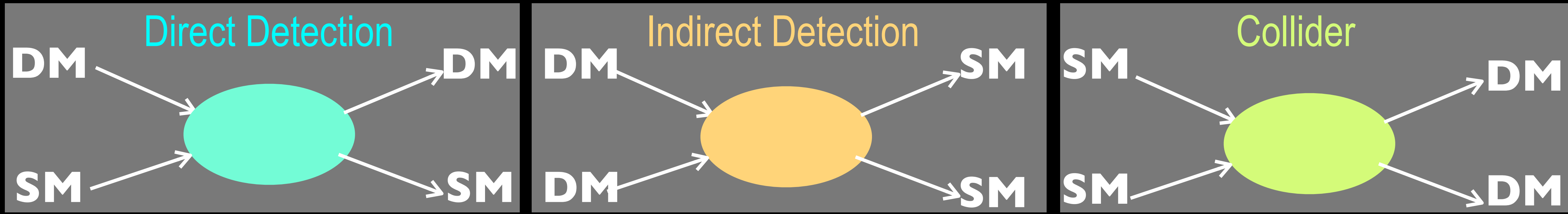
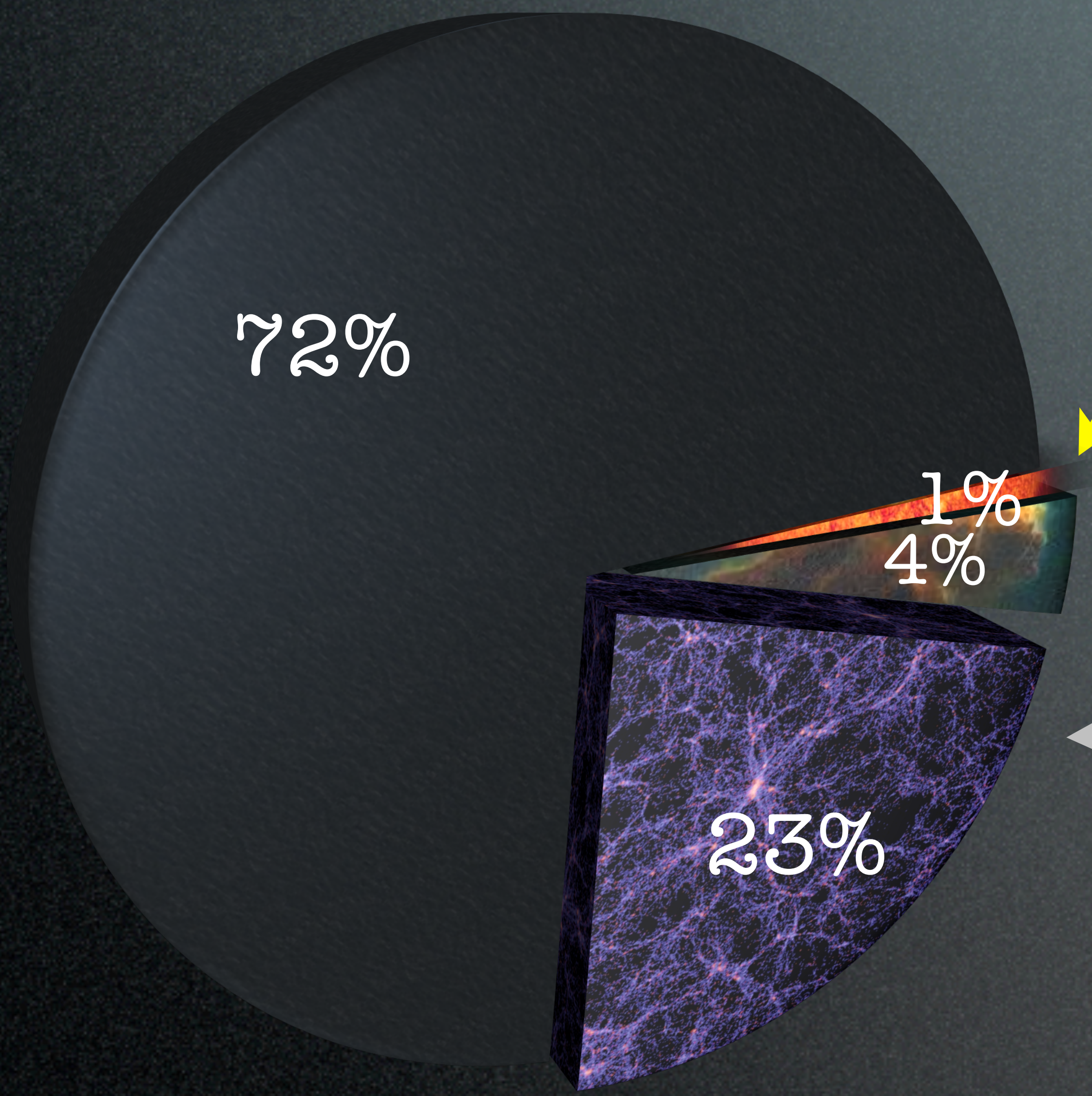


The cosmic inventory

Most of the Universe is Dark



$\Omega_{\rm lum} \sim 0.01$

$\Omega_{\rm b} \simeq 0.040 \pm 0.005$

-BBN
-CMB

$\Omega_{\rm DM} \sim 0.23$

$\Omega_{\rm de} \sim 0.72$

- CMB + SNIa
- CMB - DM
- acoustic peak in baryons

$\left(\Omega_x = \frac{\rho_x}{\rho_c};\ \text{CMB first peak} \Rightarrow \Omega_{\rm tot} = 1\ (\text{flat});\ \text{HST}\ h = 0.71 \pm 0.07\right)$

what's the difference
between DM and DE?

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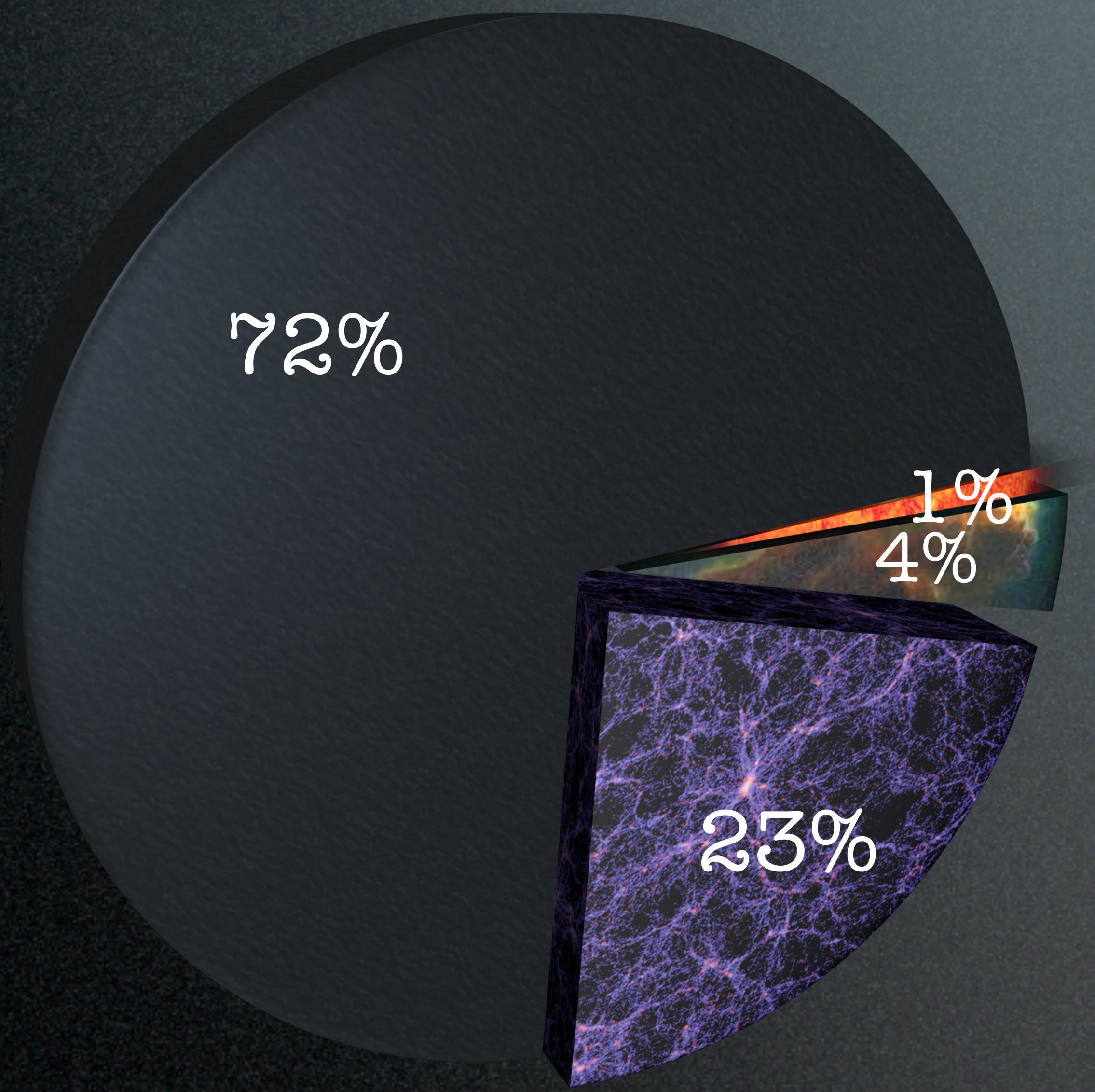

FAvgQ: what's the difference between DM and DE?

DM behaves like matter

- overall it dilutes as volume expands
- clusters gravitationally on small scales
- $w = P/\rho = 0$ (NR matter)
  (radiation has $w = -1/3$)

DE behaves like a constant

- it does not dilute
- does not cluster, it is prob homogeneous
- $w = P/\rho \simeq -1$
- pulls the acceleration, FRW eq. $\frac{\ddot{a}}{a} = -\frac{4\pi G_{\rm N}}{3}(1-3w)\rho$

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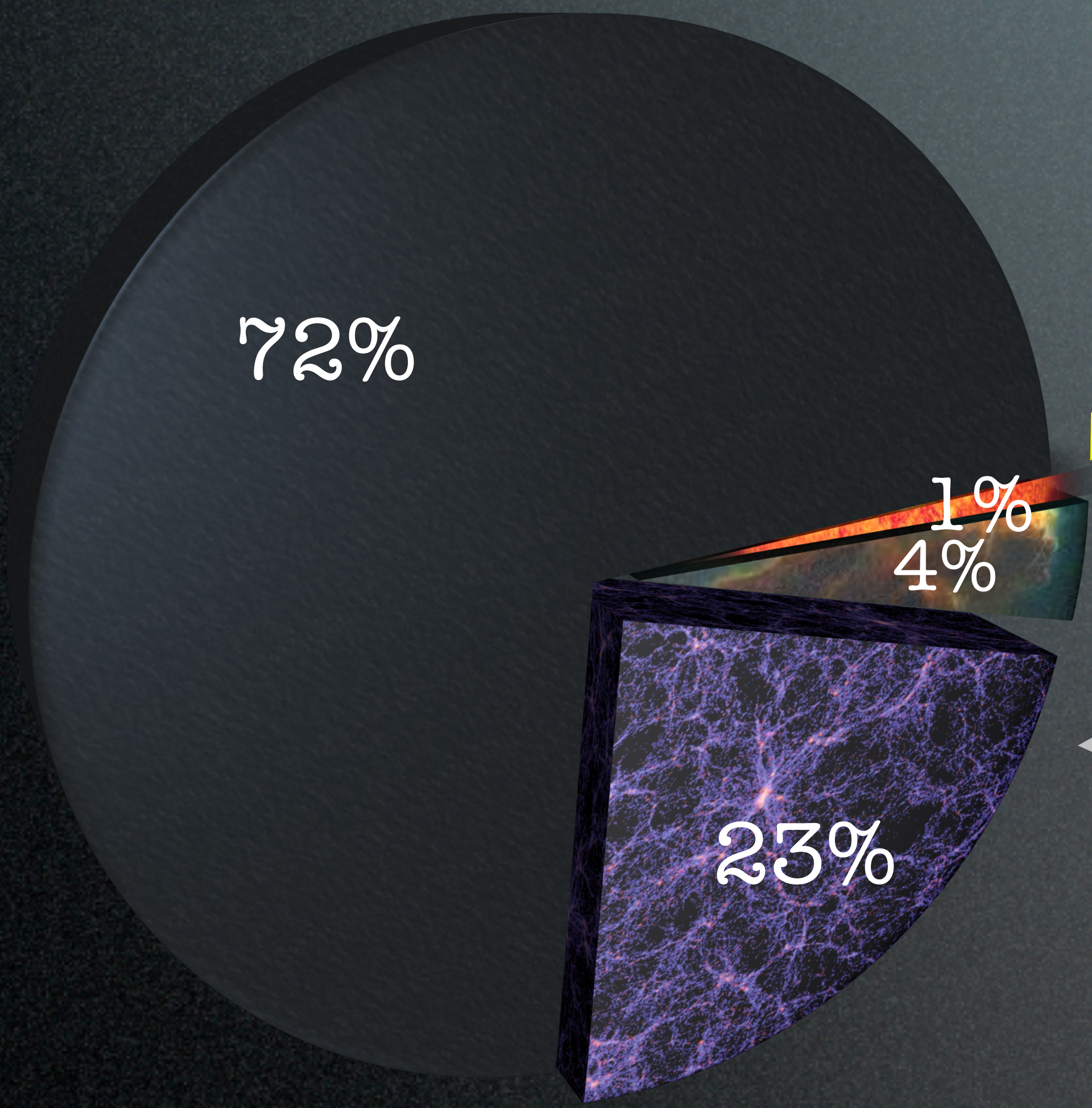

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particle physics $\cap$ cosmology

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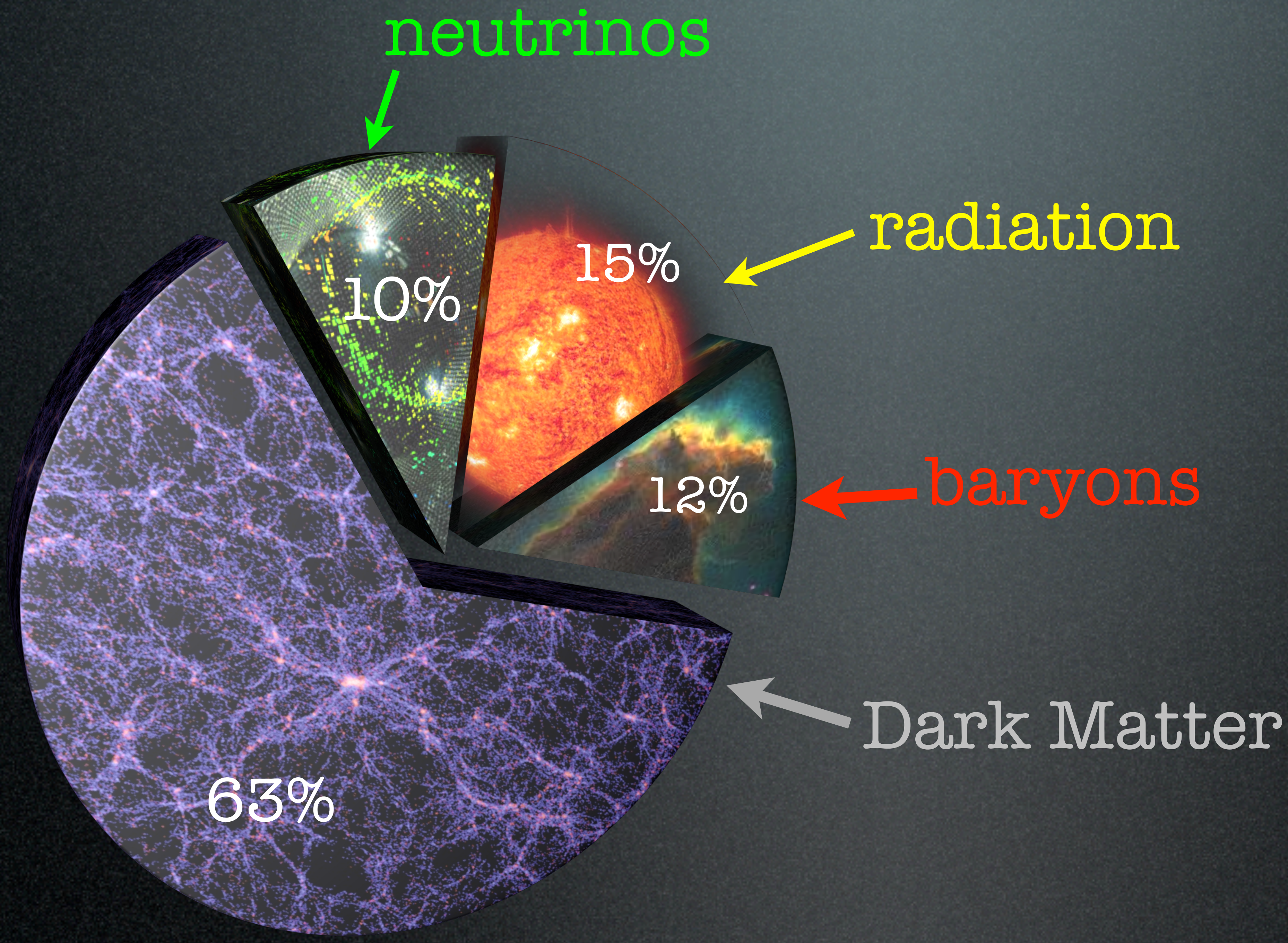


At the time of CMB formation (380 Ky)

How do we know that Dark Matter is out there?

The Evidence for DM

1) galaxy rotation curves

$$m\frac{v_c^2(r)}{r} = \frac{G_N m M(r)}{r^2}$$

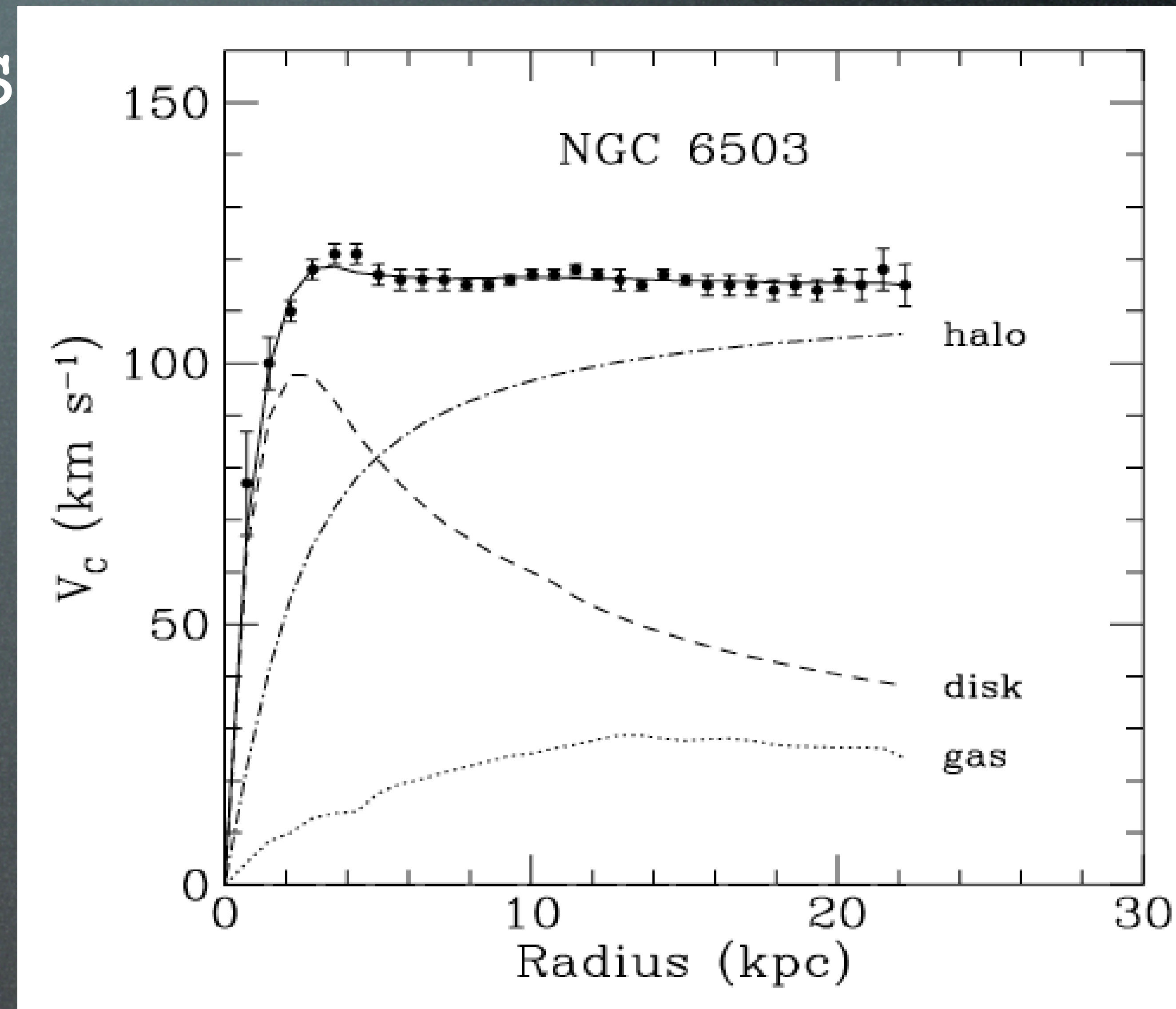
'centrifugal' 'centripetal'

$$v_c(r) = \sqrt{\frac{G_N M(r)}{r}}$$

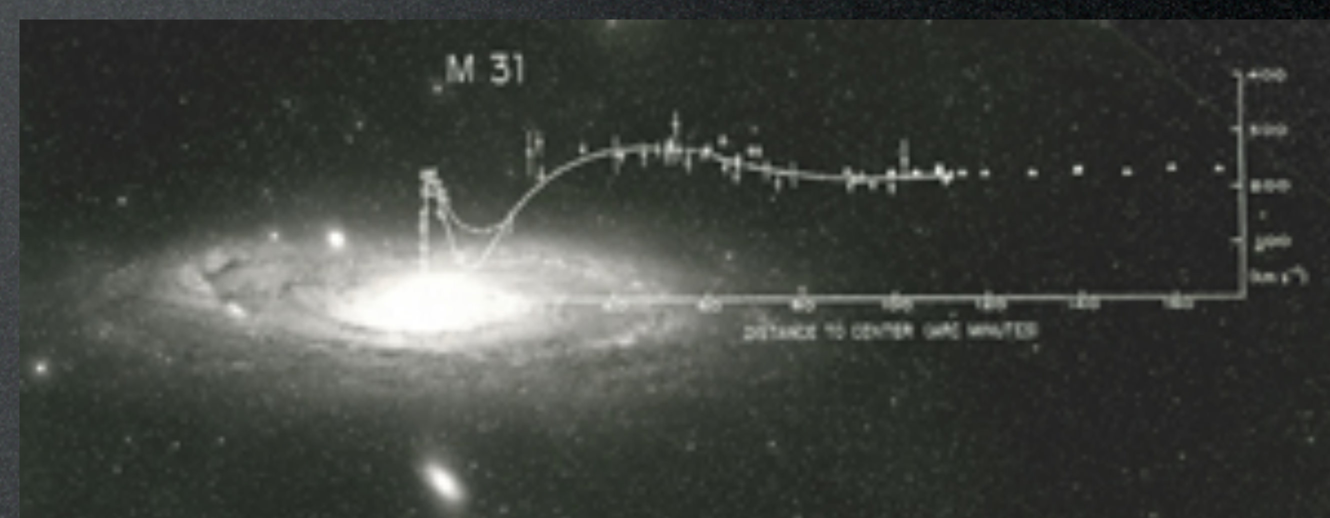
with $M(r) = 4\pi \int \rho(r)\, r^2 dr$

$$v_c(r) \sim \text{const} \Rightarrow \rho_M(r) \sim \frac{1}{r^2}$$

$$\Omega_\mathrm{M} \gtrsim 0.1$$



Begeman et al., MNRAS 249 (1991)



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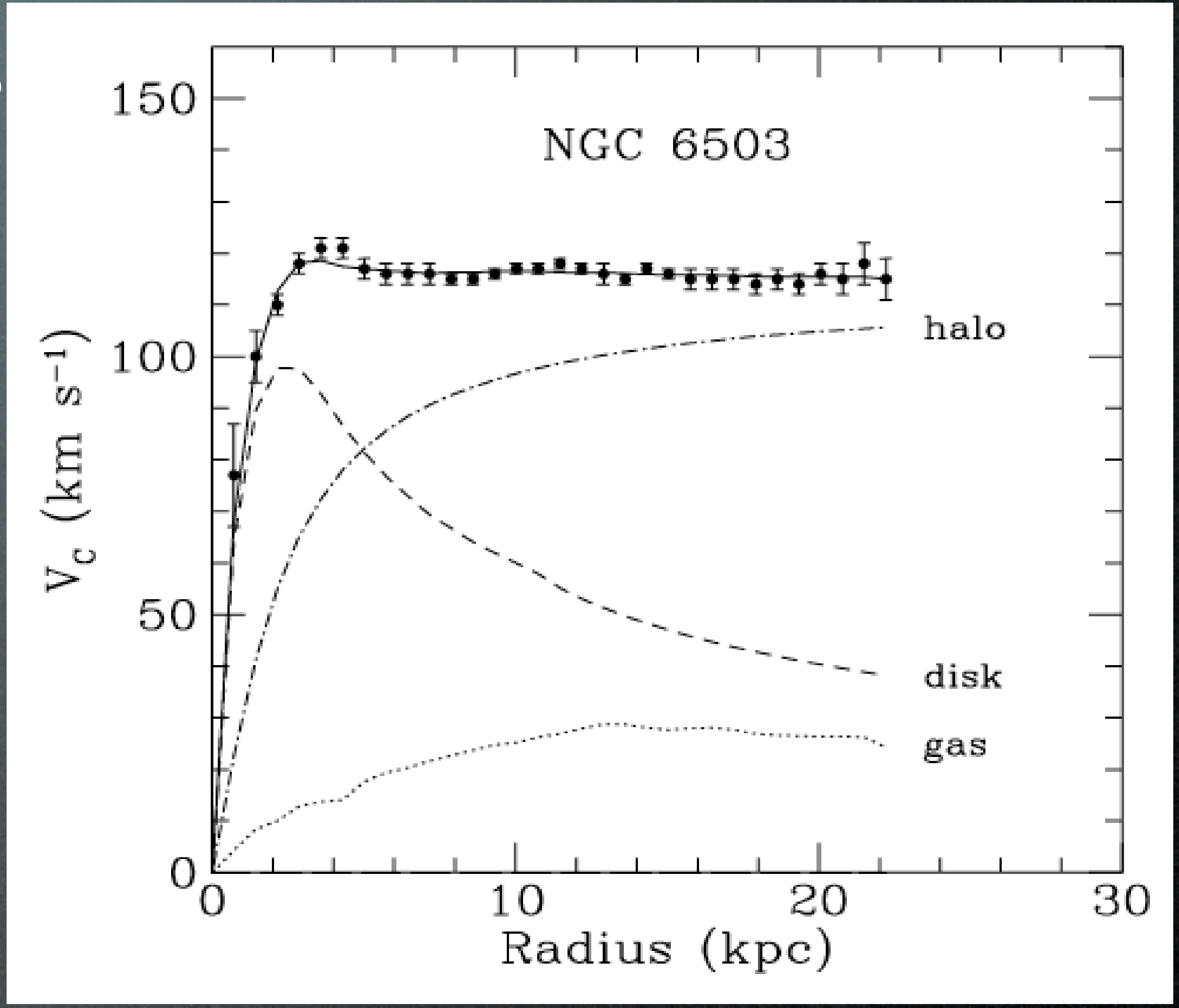

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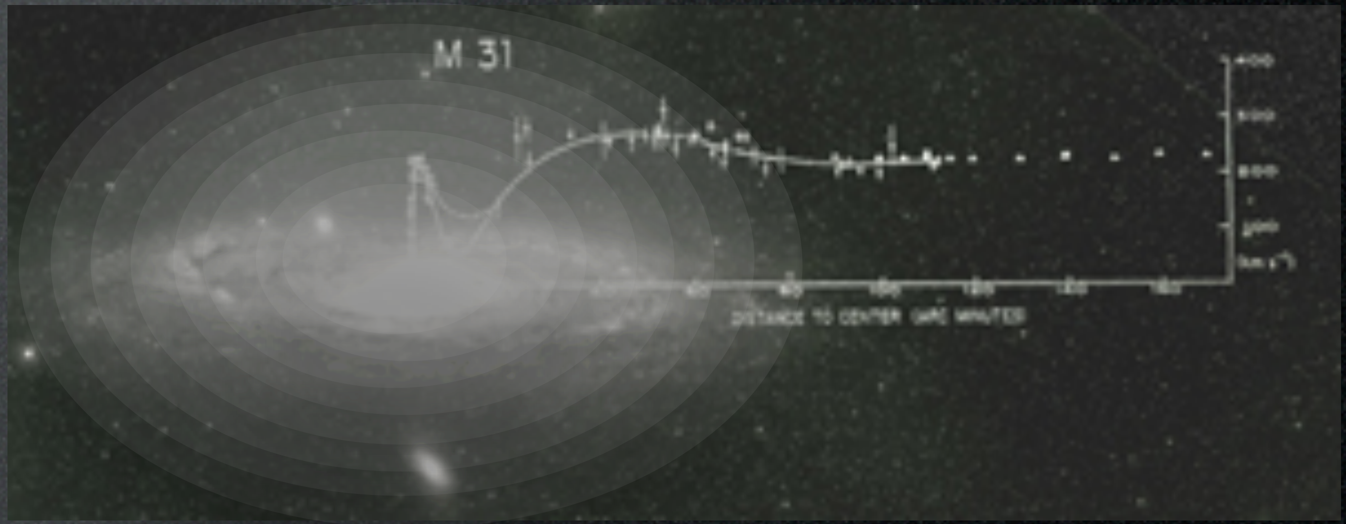

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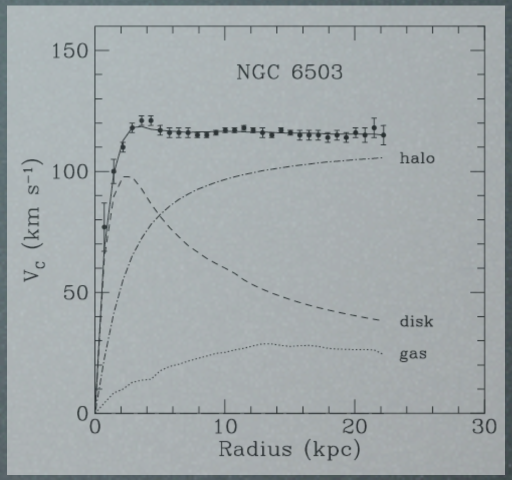

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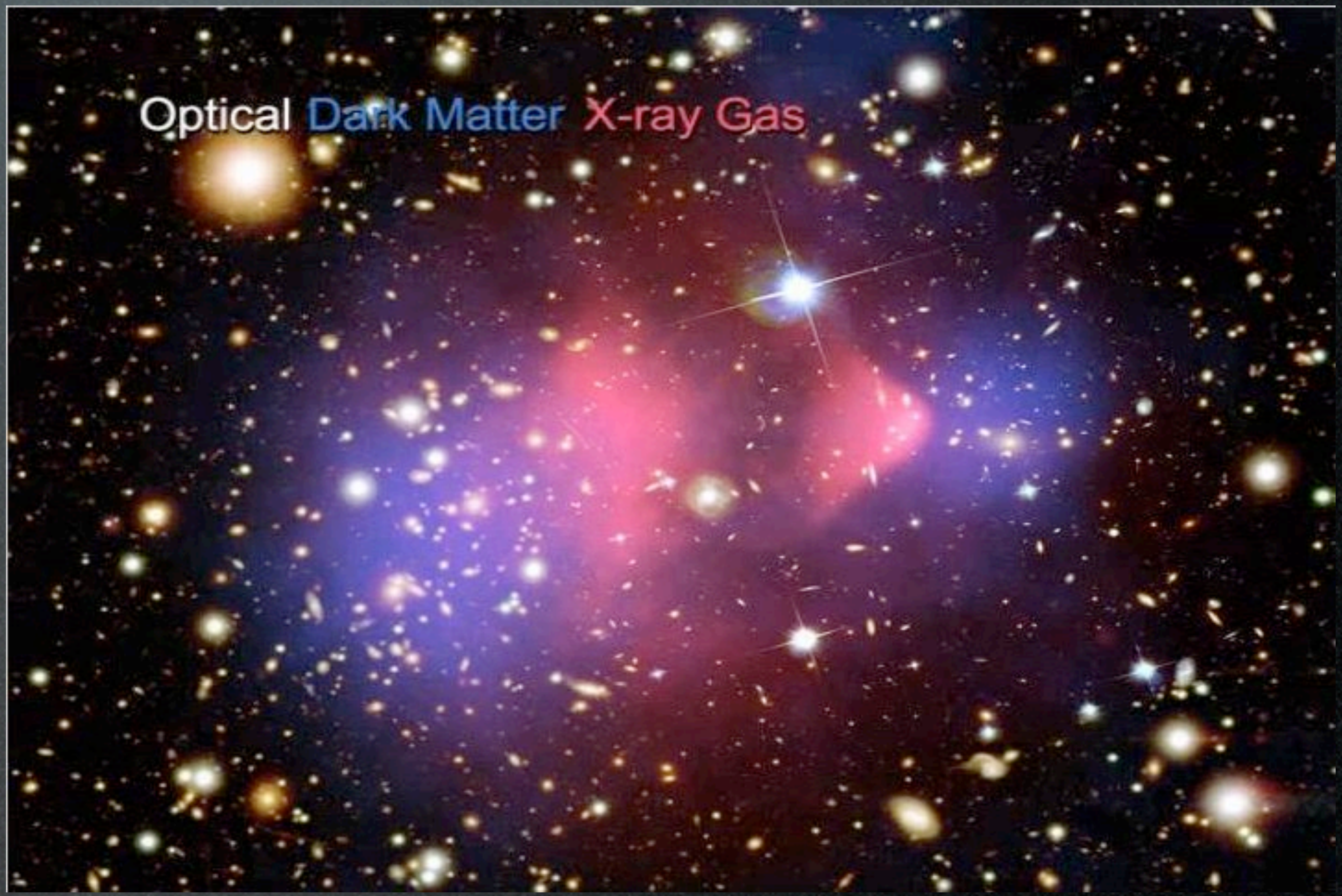
2) clusters of galaxies
- "rotation curves"
- gravitational lensing

$$\Omega_M \sim 0.2 \div 0.4$$



"bullet cluster" - NASA
astro-ph/0608247
[further developments]

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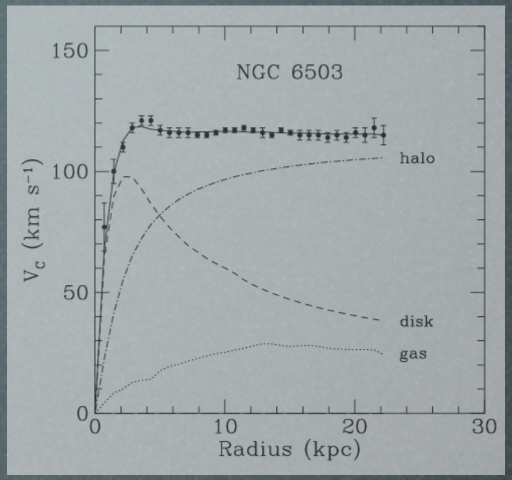

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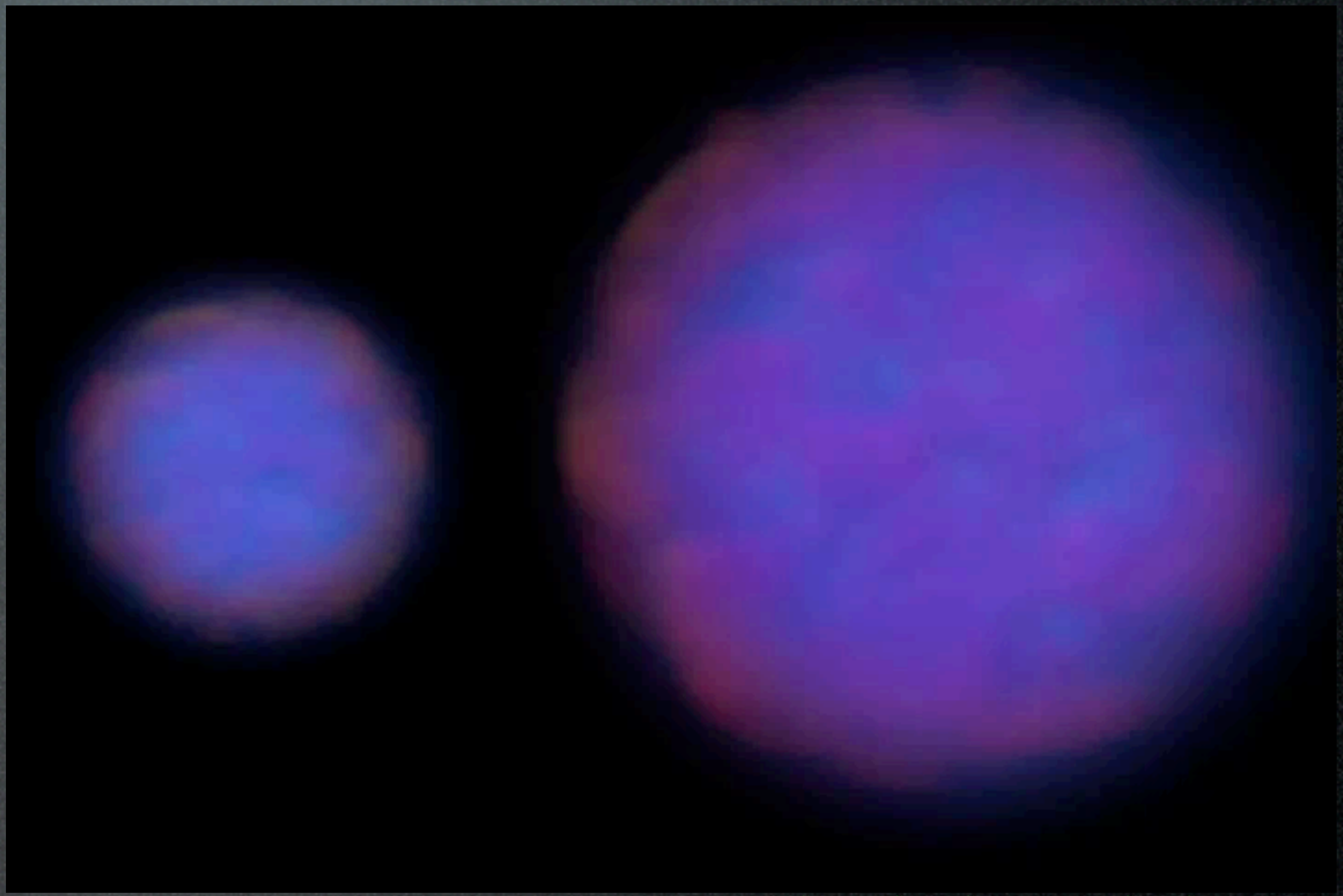

chandra.harvard.edu

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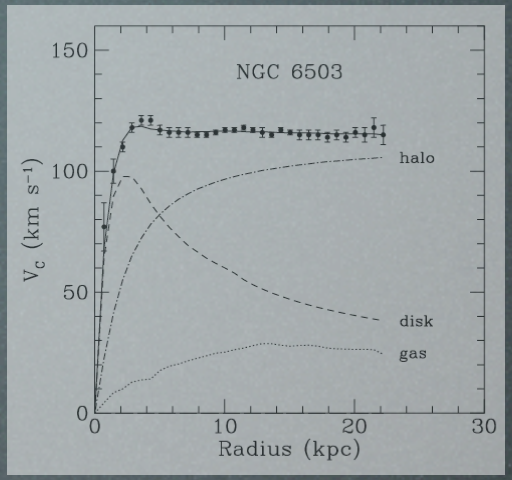

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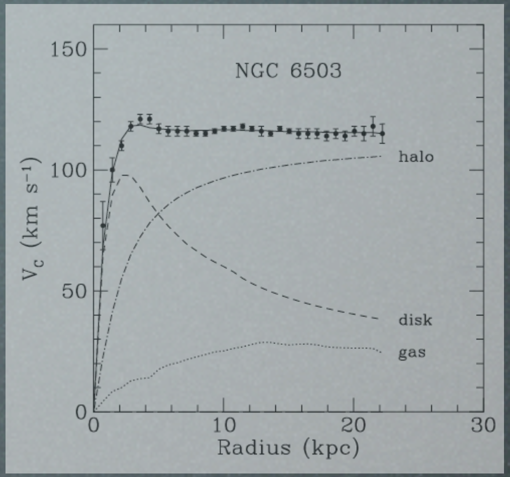

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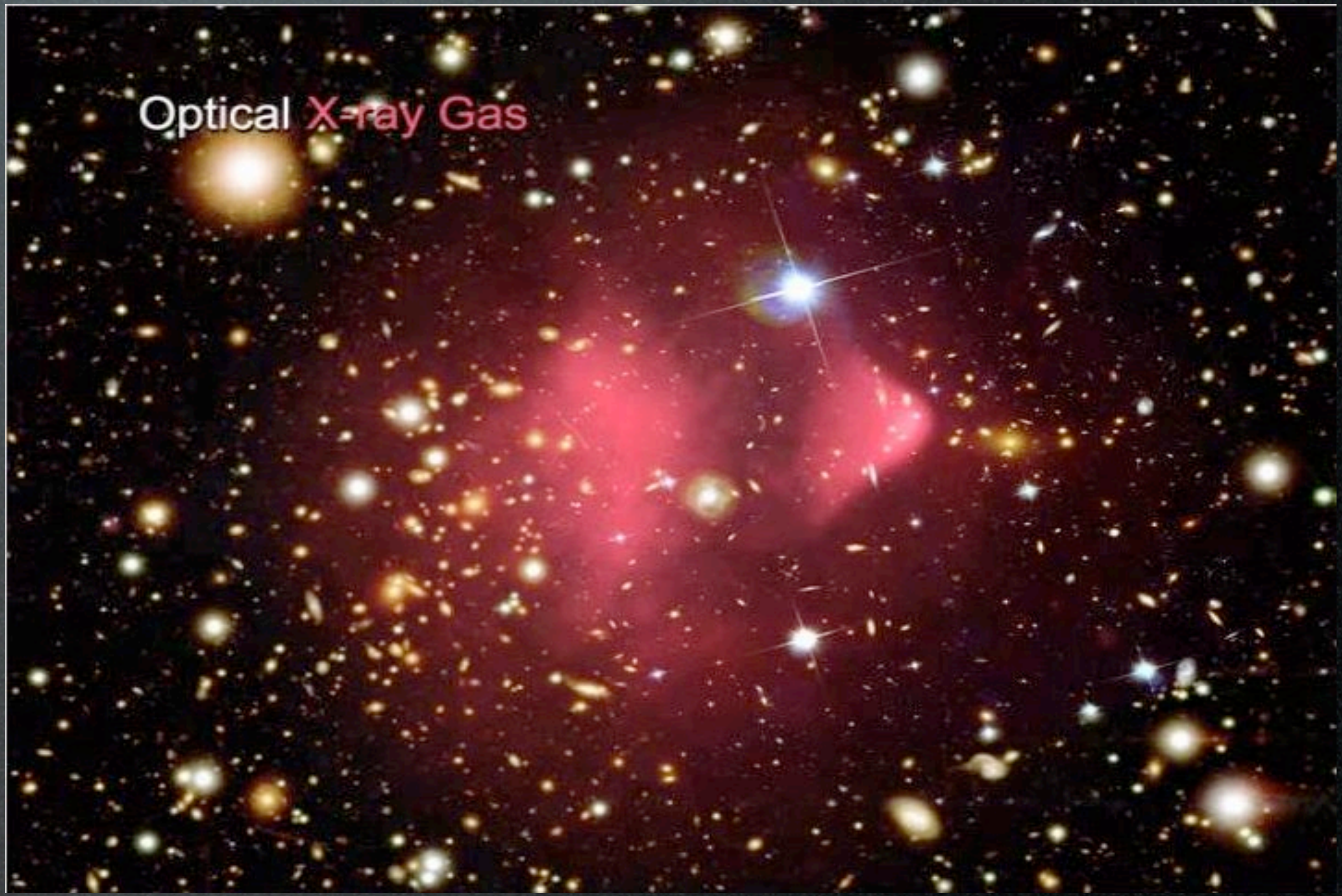

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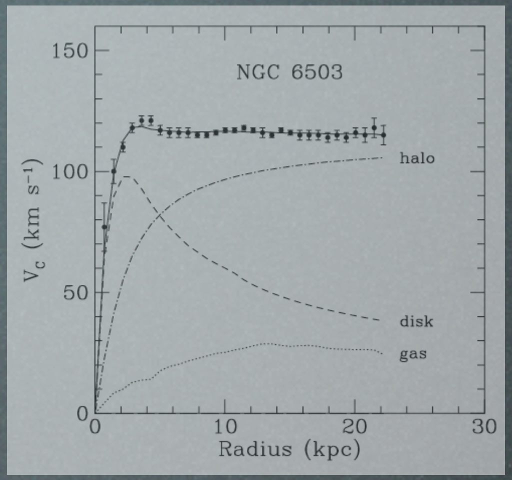

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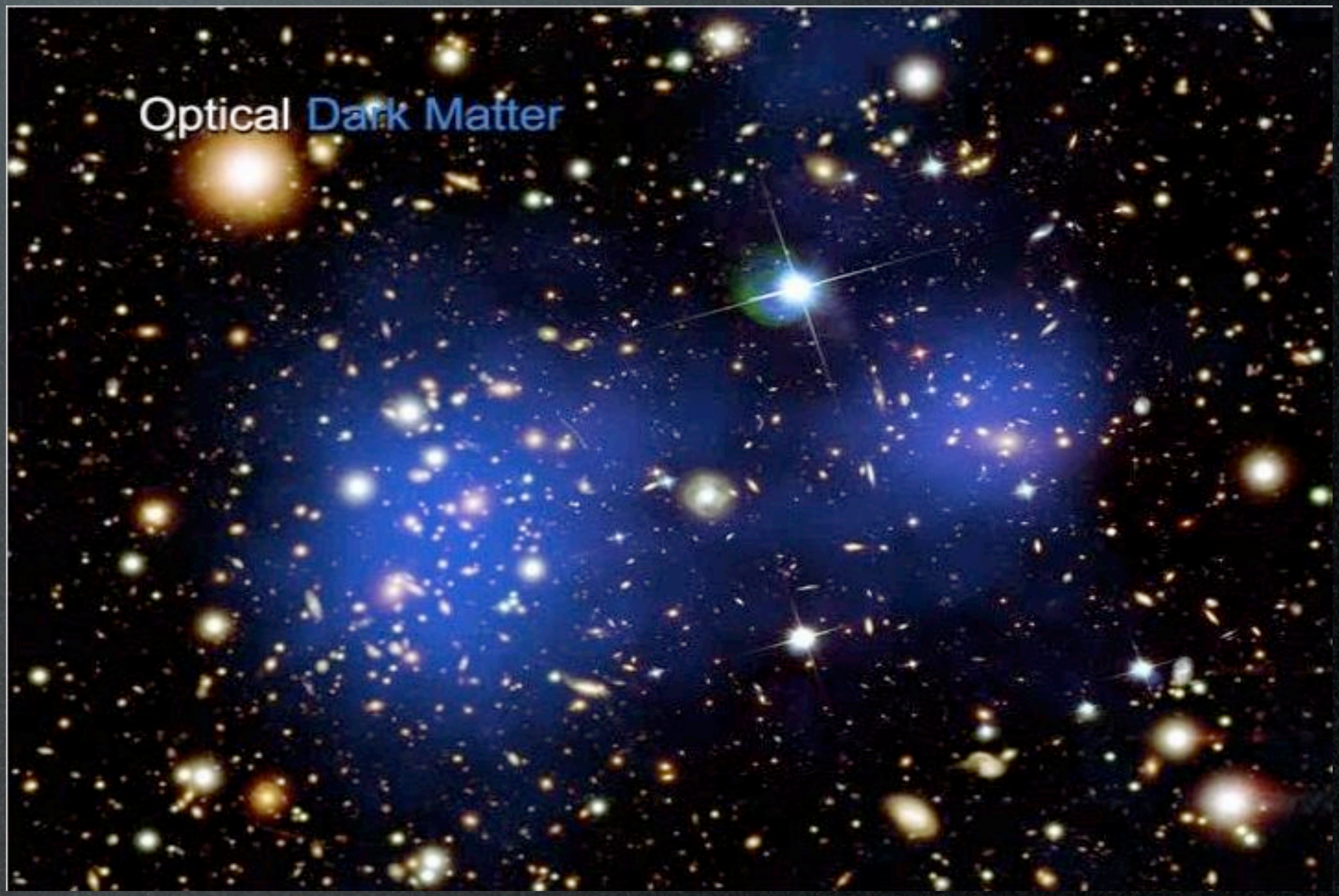

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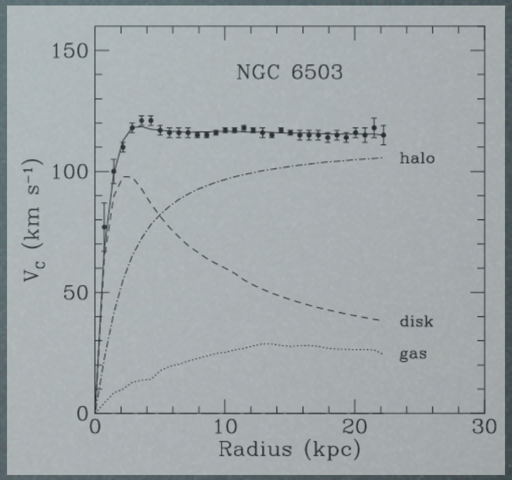

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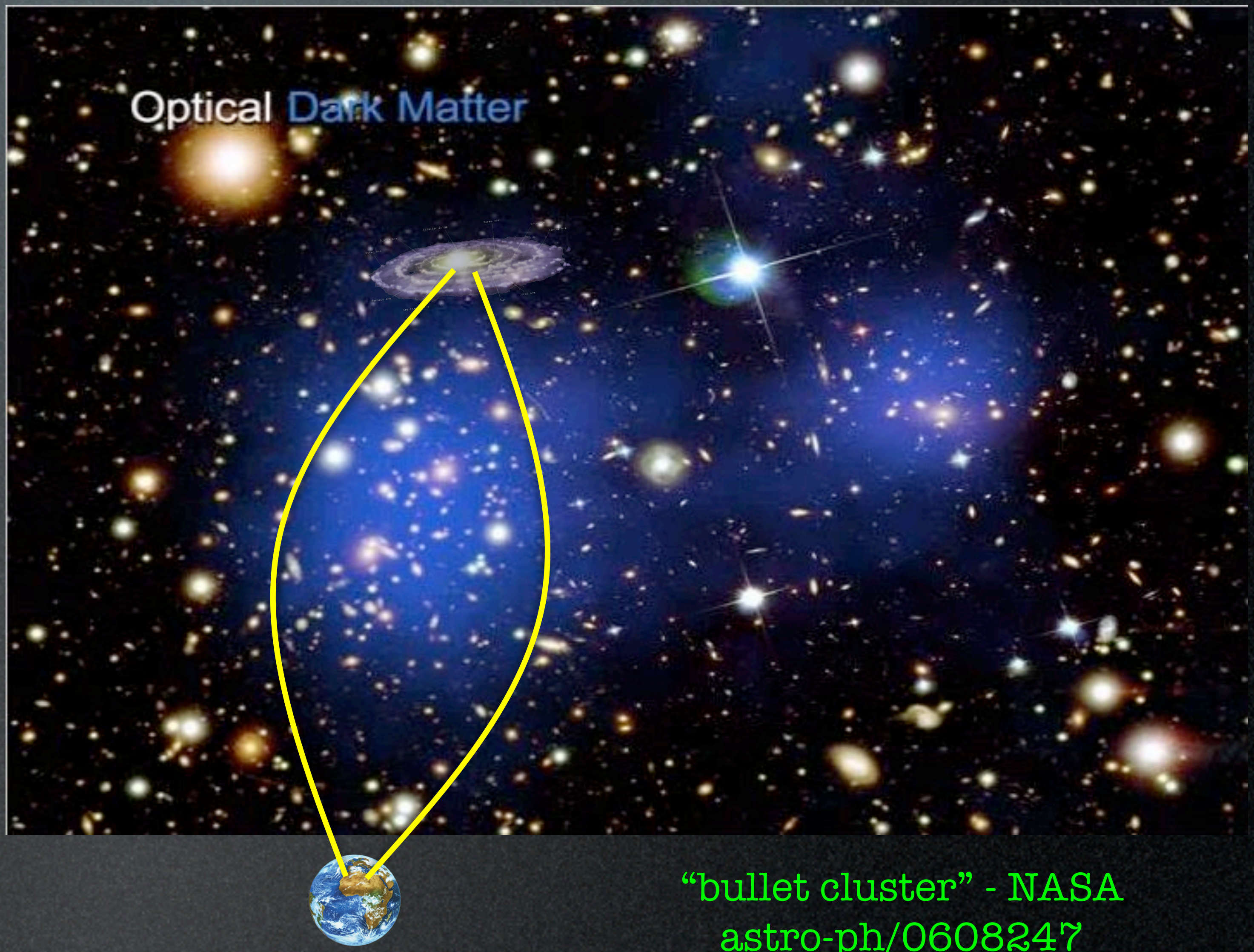

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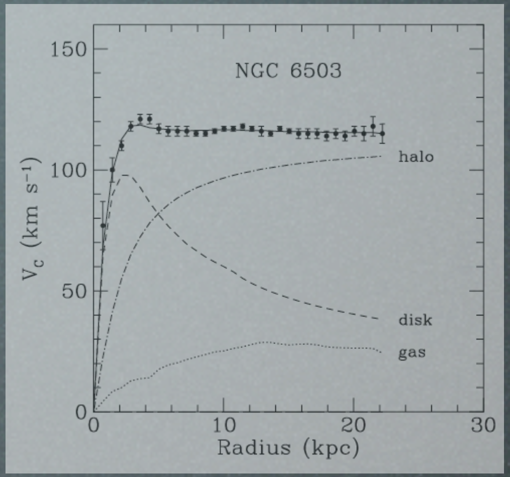

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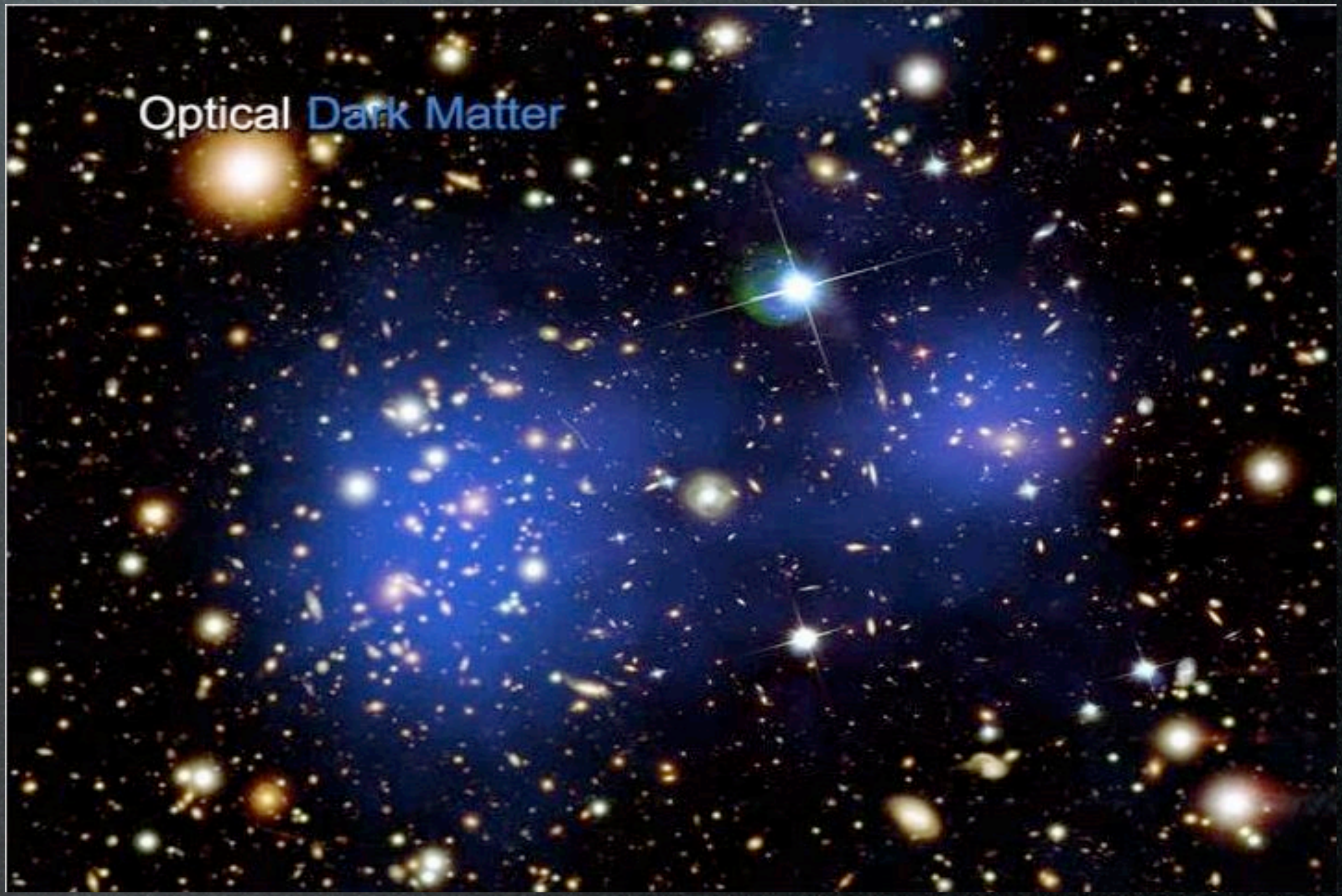

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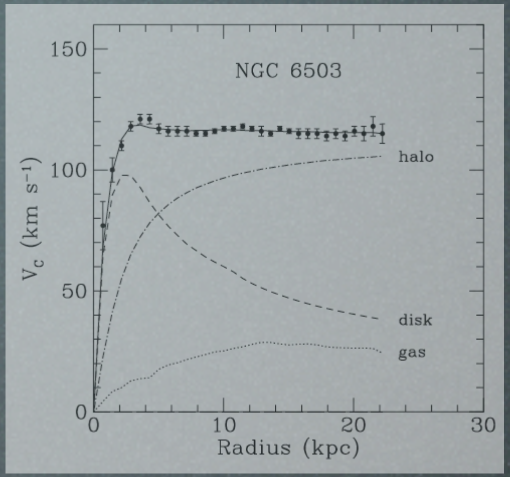

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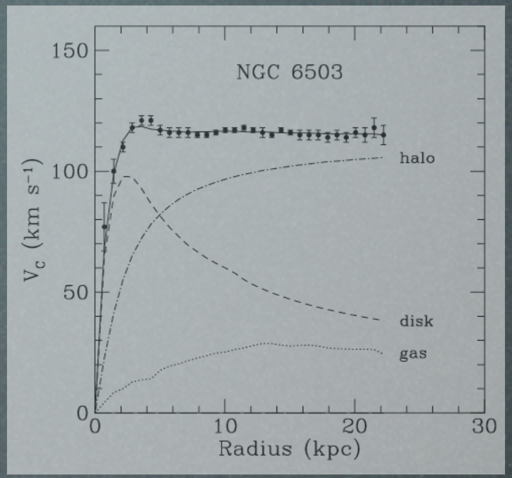

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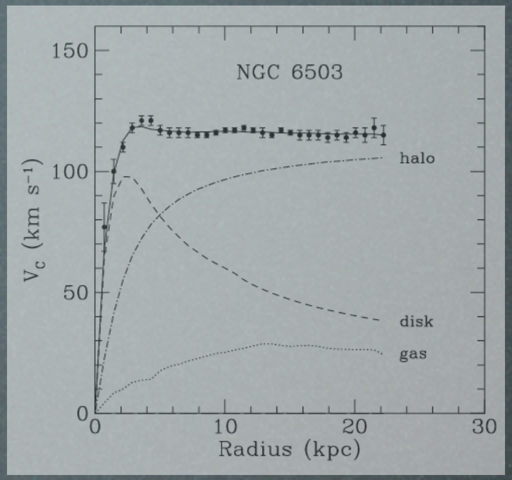

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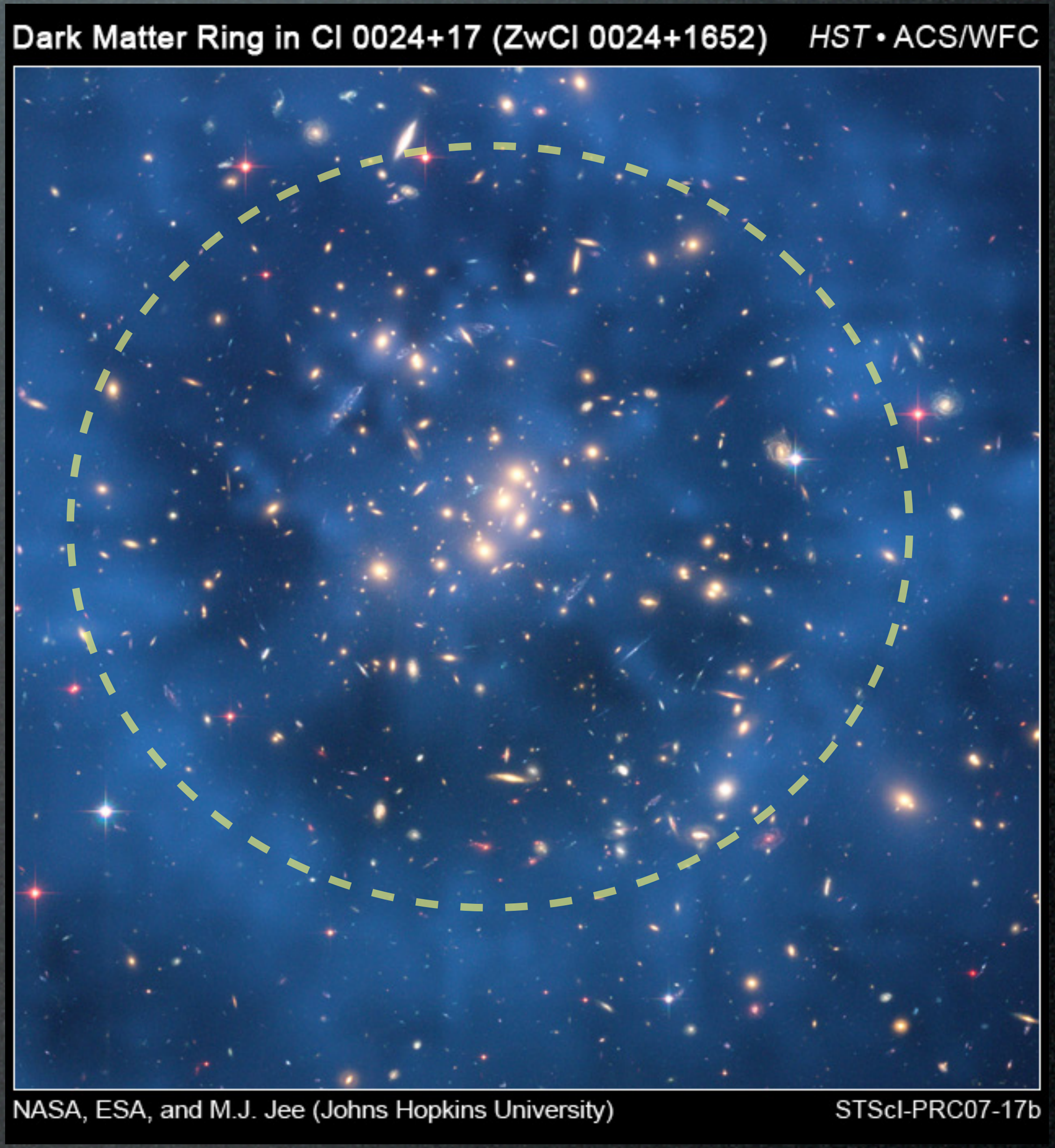

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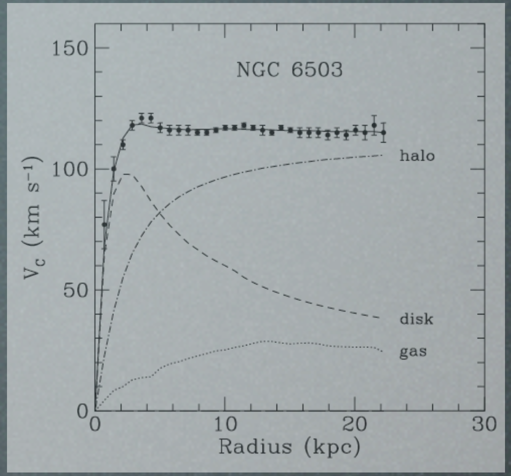

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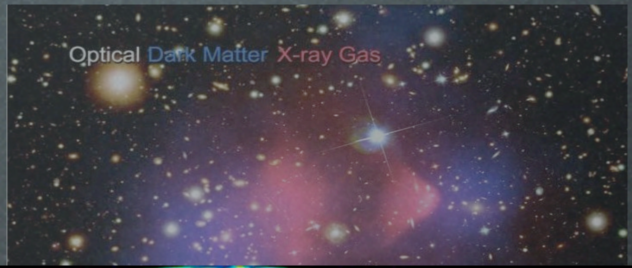

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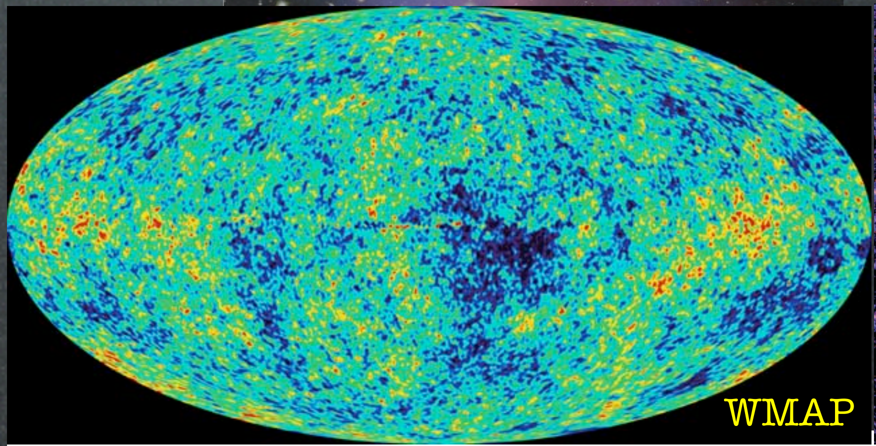
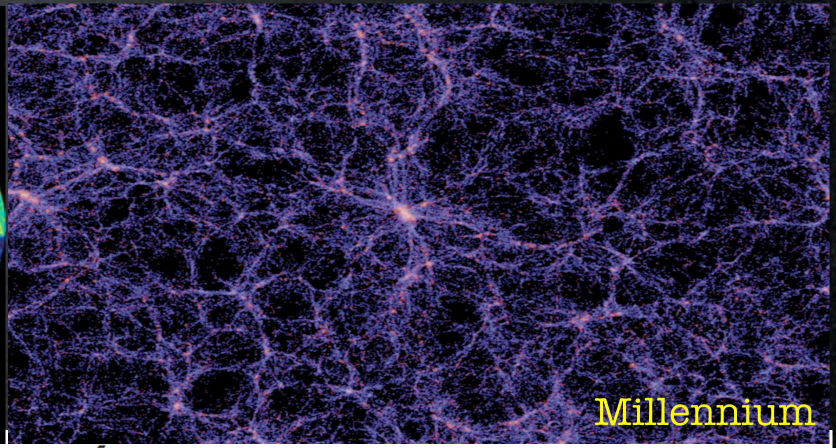
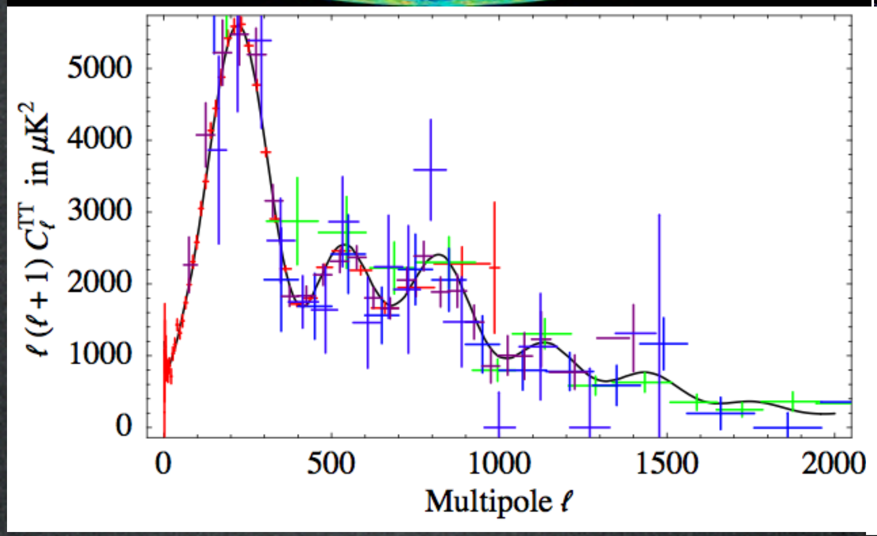
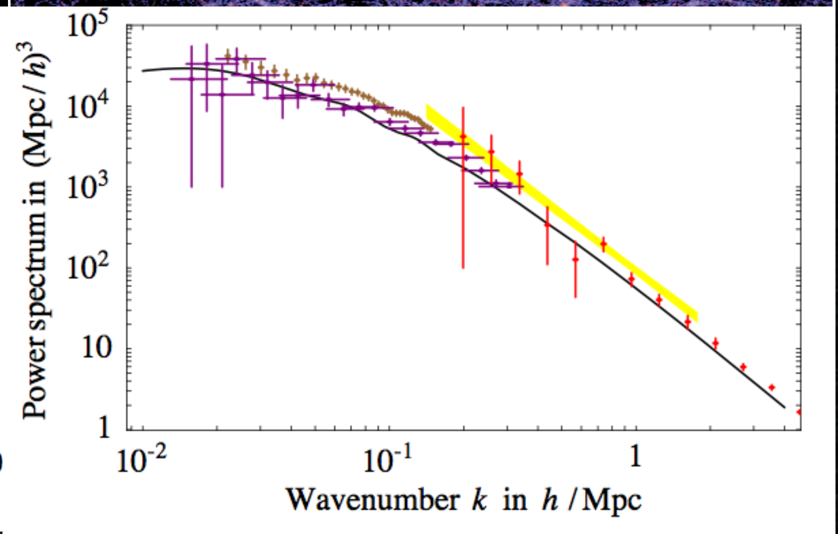
3) CMB+LSS(+SNIa:)









M.Cirelli and A.Strumia, astro-ph/0607086

DM N-body simulations

2 10^6 CDM particles, 43 Mpc cubic box

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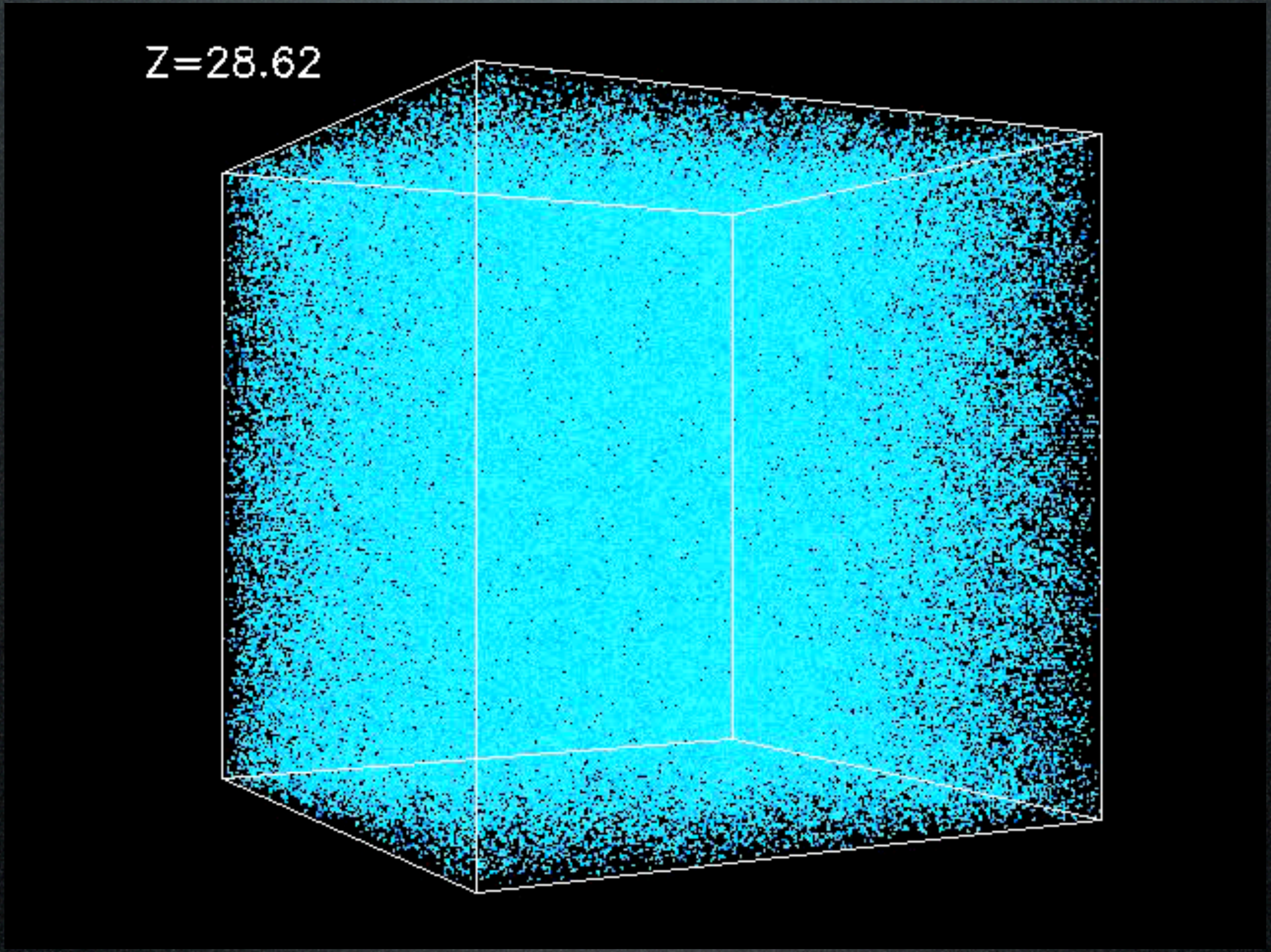

Andrey Kravtsov, cosmicweb.uchicago.edu

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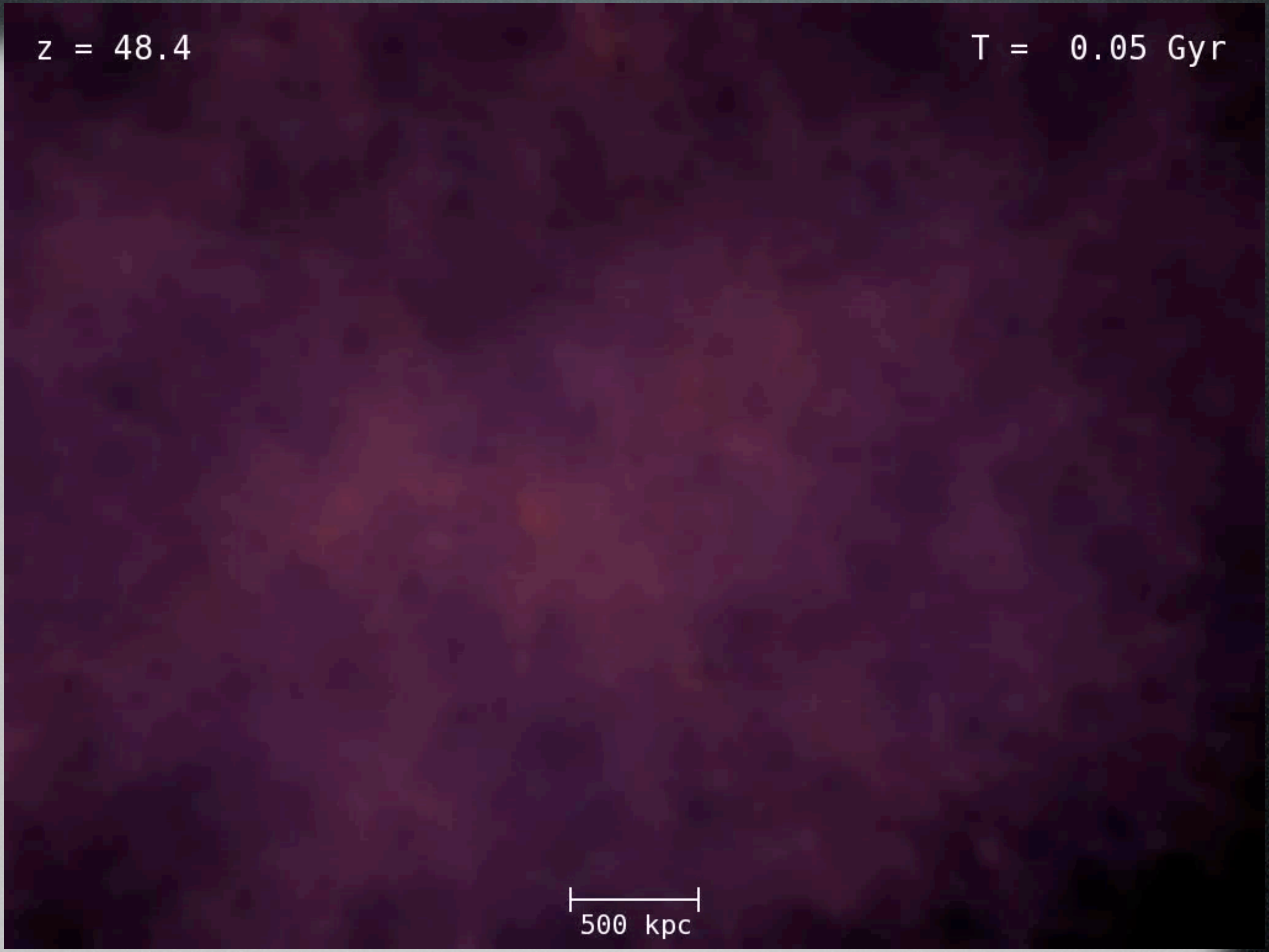
DM N-body simulations

Aquarius project of the VIRGO coll.:
1.5 10^9 CDM particles, single galactic halo

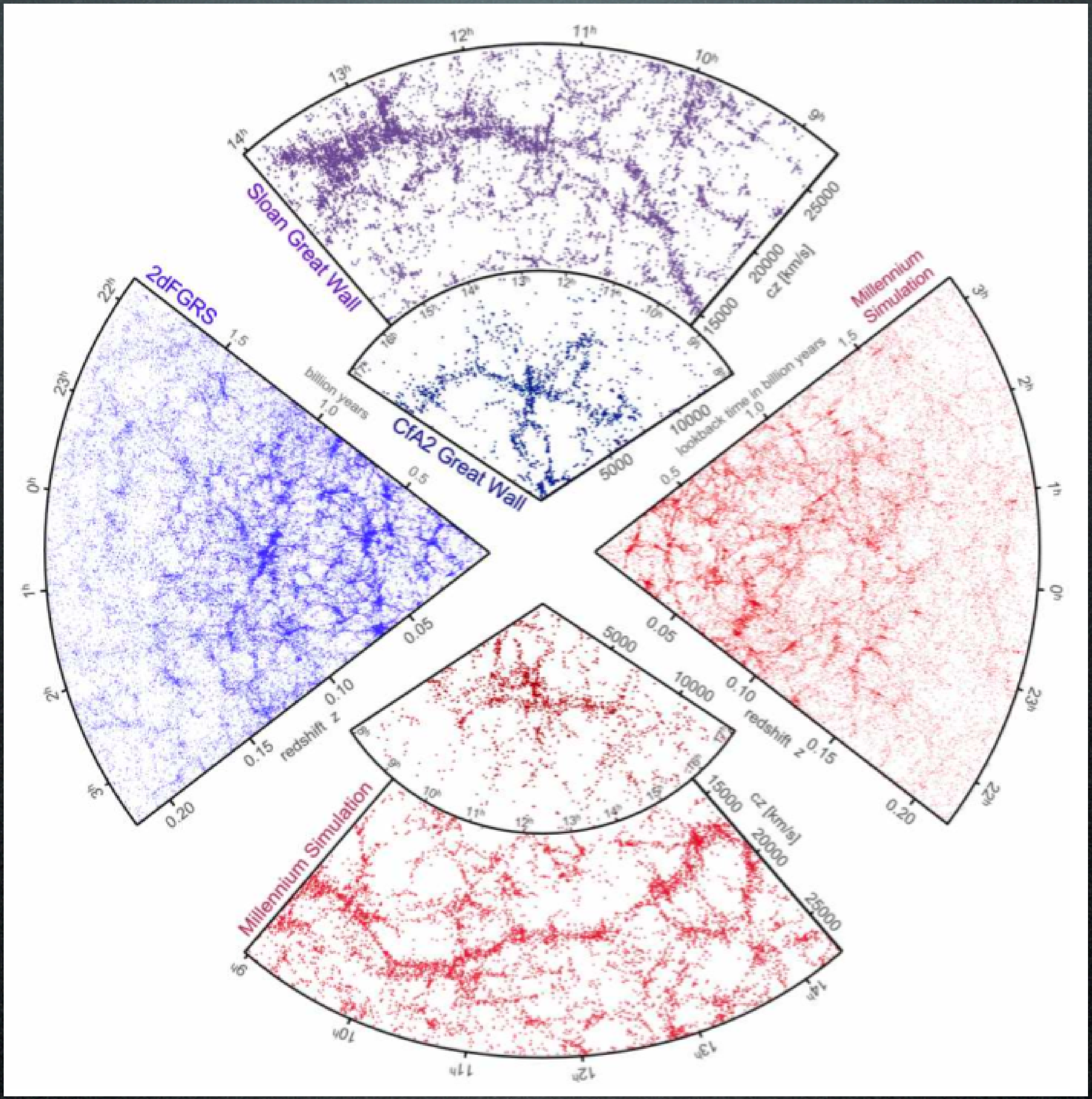


VIRGO coll., Aquarius project, www.mpa-garching.mpg.de/aquarius/ [back]

DM N-body simulations

2dF: 2.2 10^5 galaxies

SDSS: 10^6 galaxies,
2 billion lyr



Springel, Frenk, White, Nature 440 (2006)

Of course, you have to infer galaxies within the DM simulation

Millennium:
10^{10} particles,
500 h^{-1} Mpc

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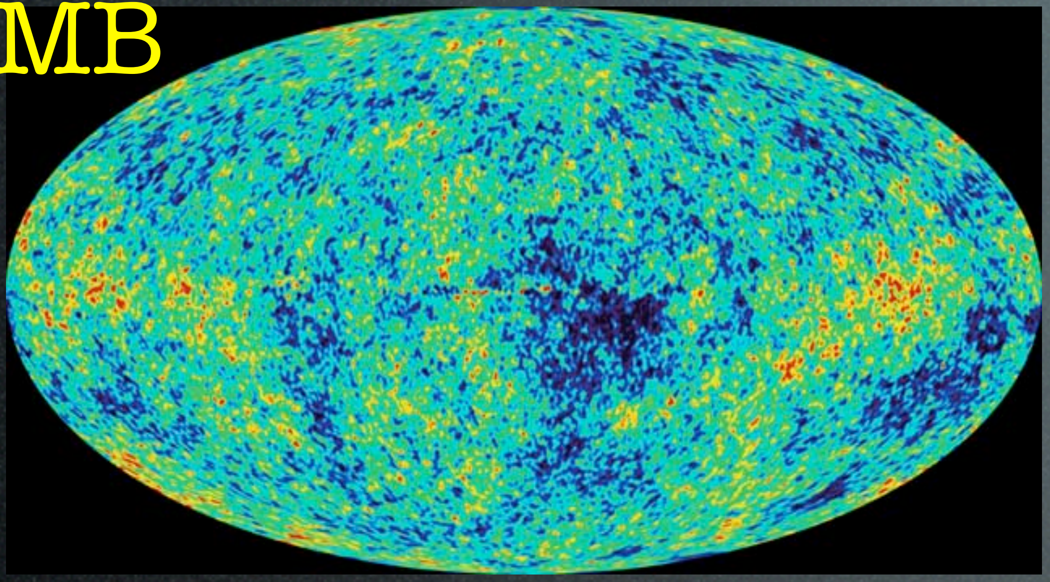
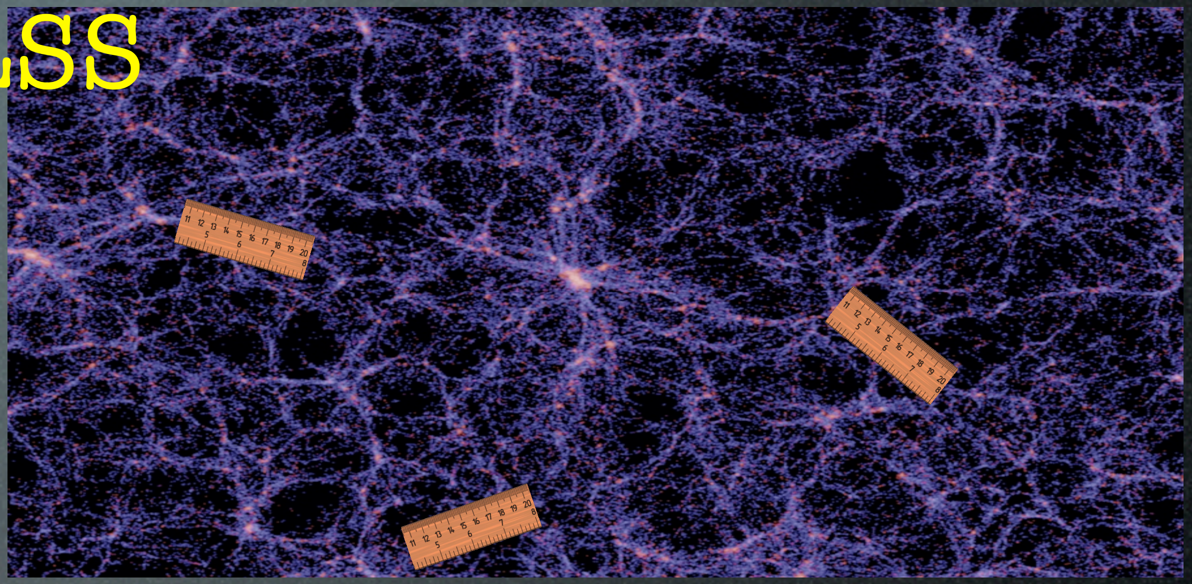
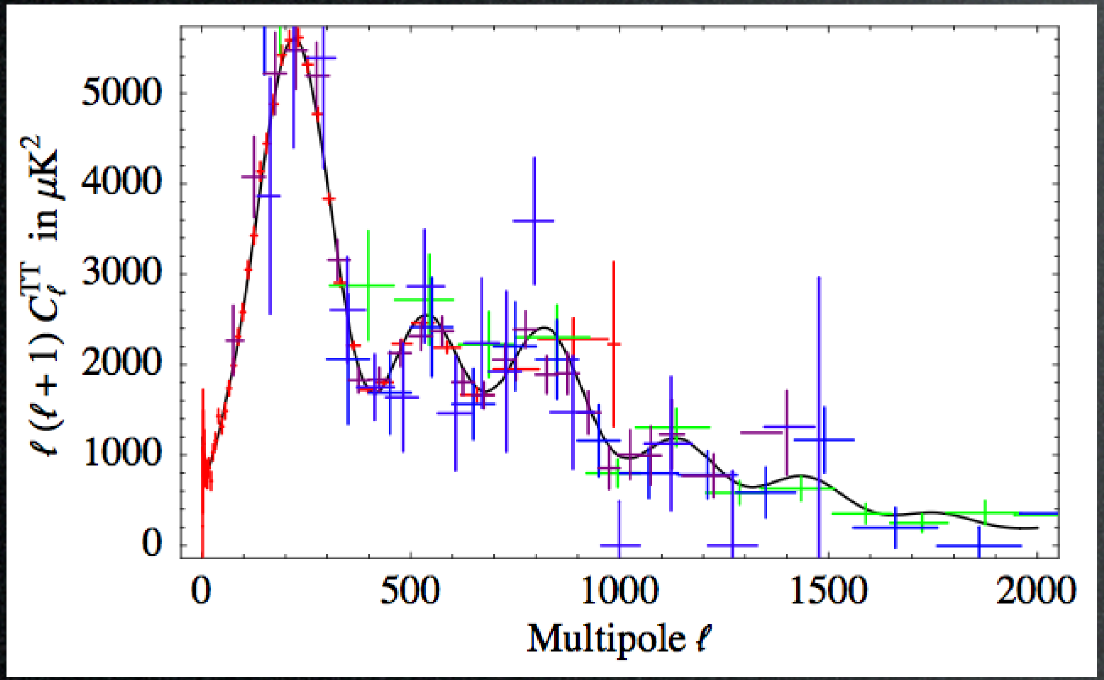
CMB & Large Scale Structure

CMB

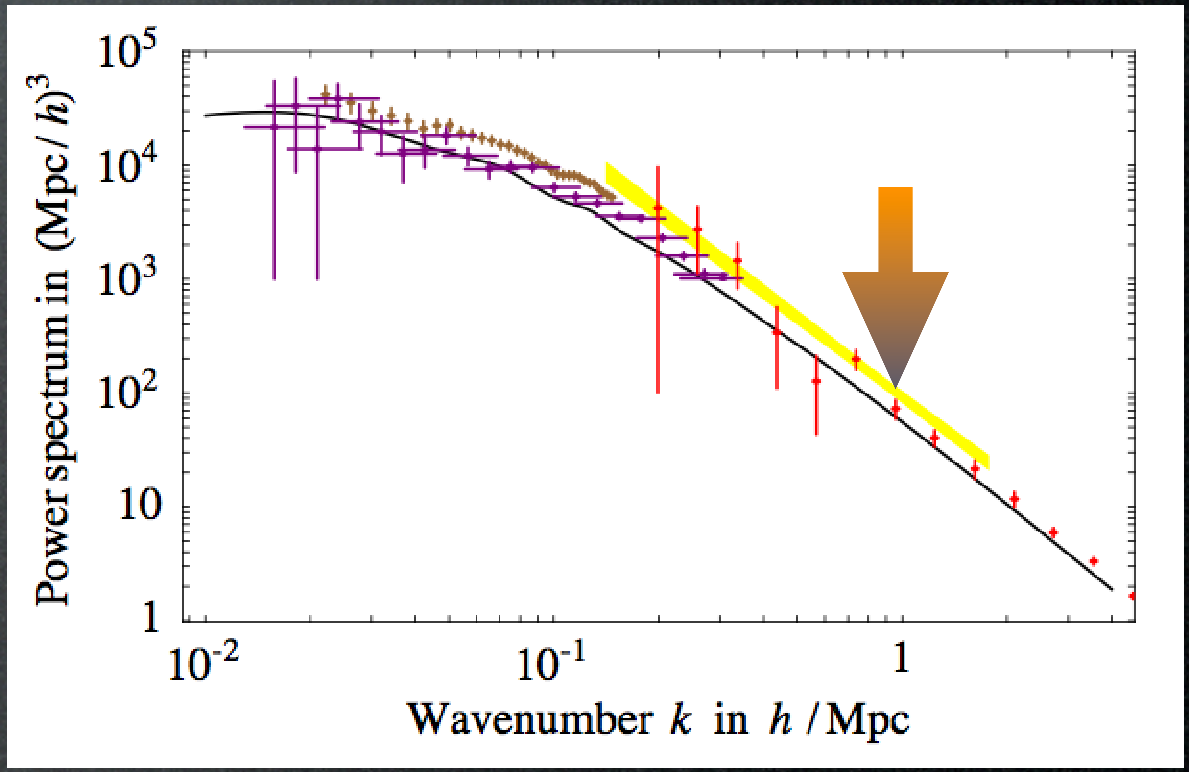


LSS



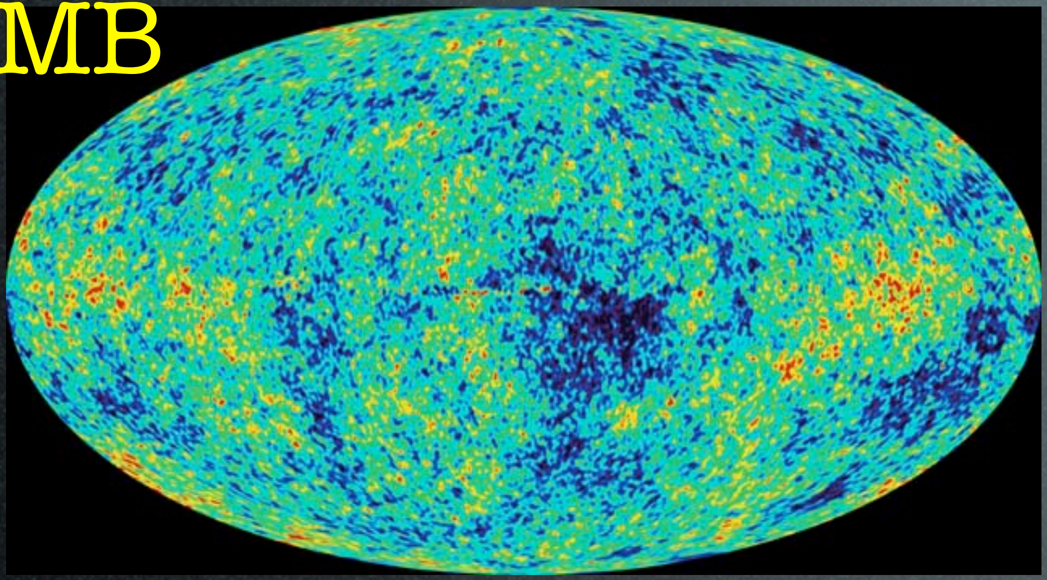


LSS matter power spectrum

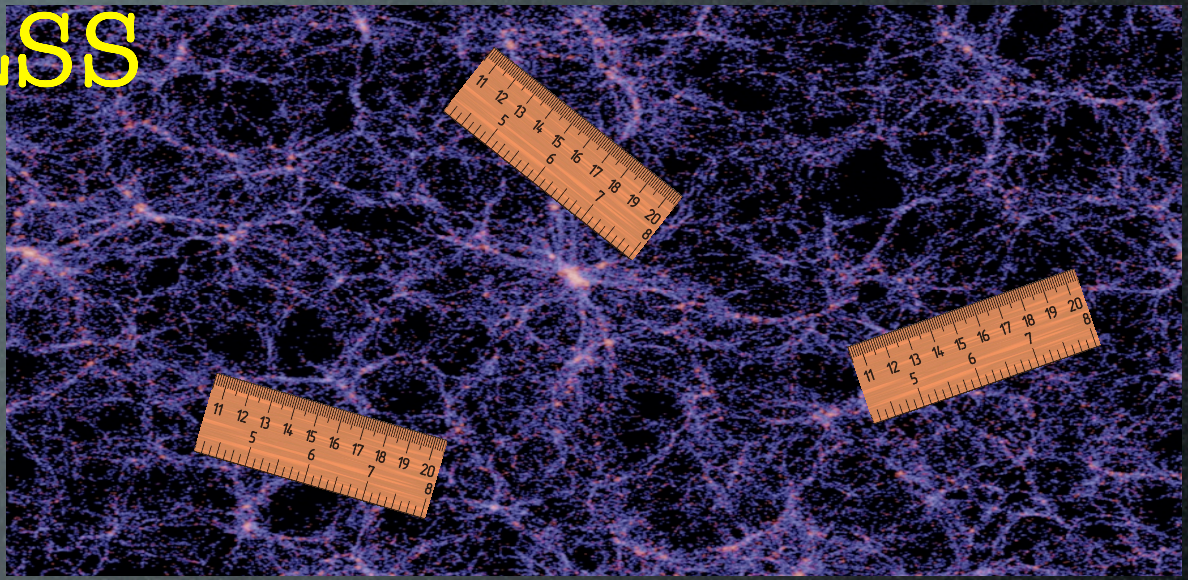


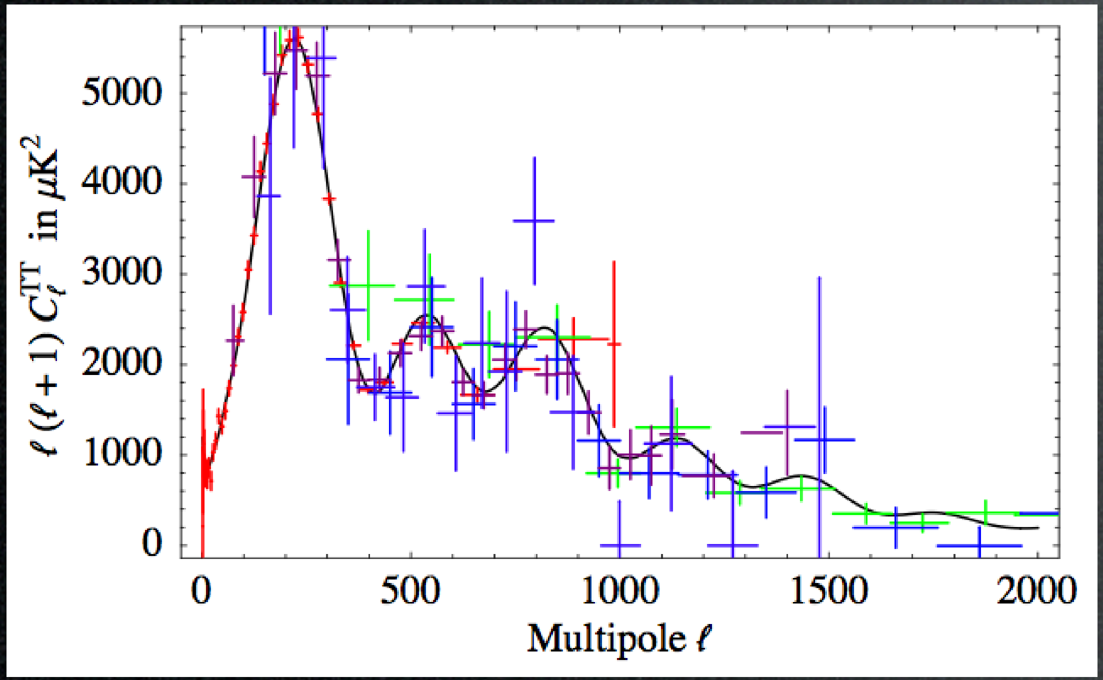
CMB & Large Scale Structure

CMB

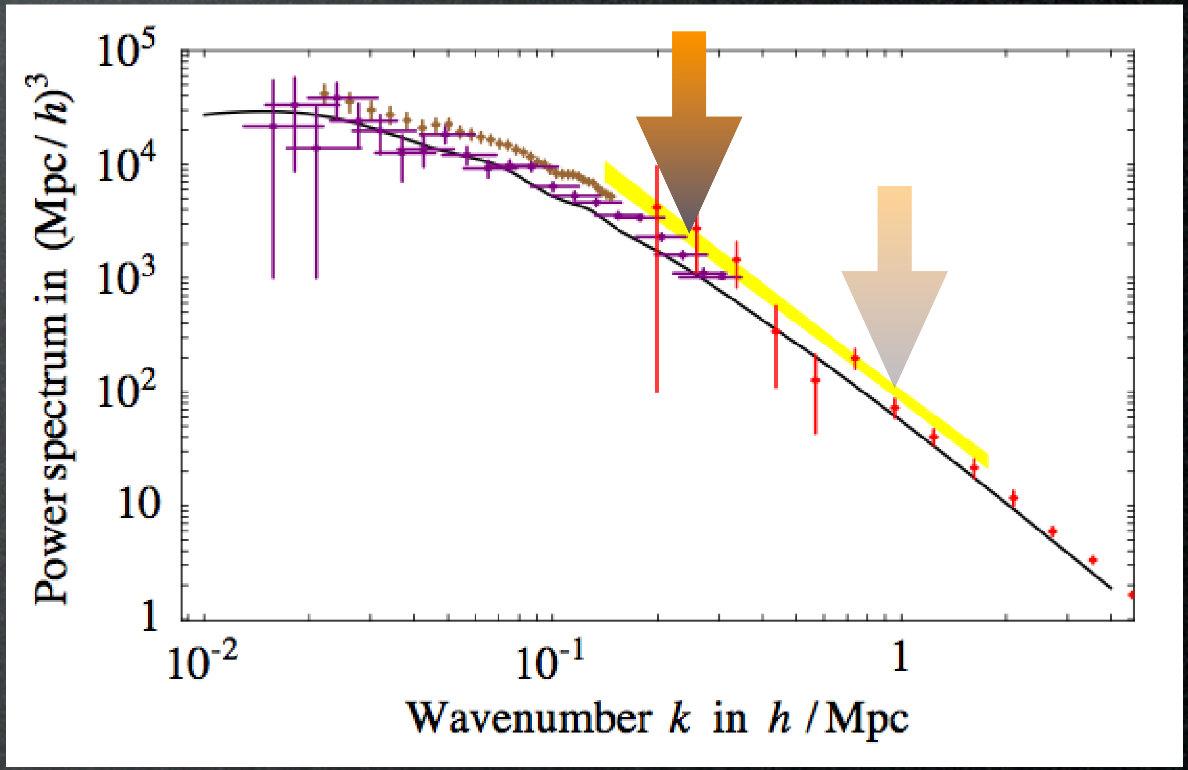


LSS



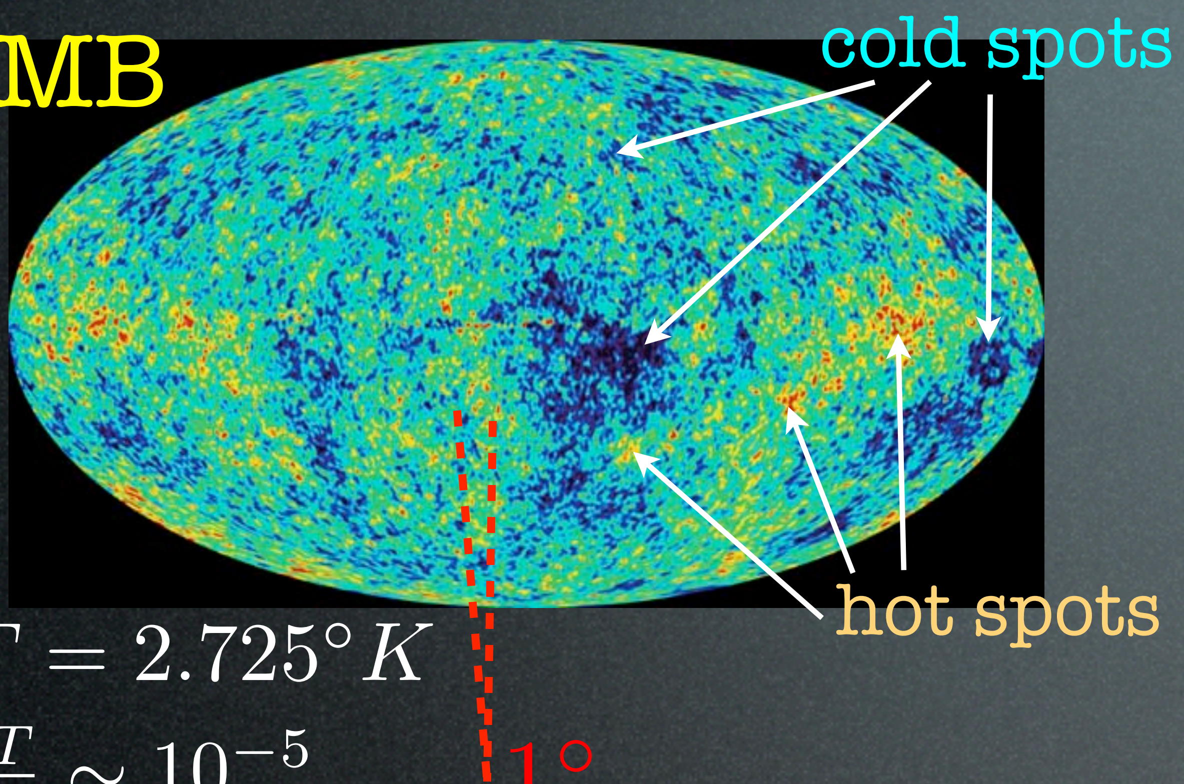


LSS matter power spectrum



CMB & Large Scale Structure

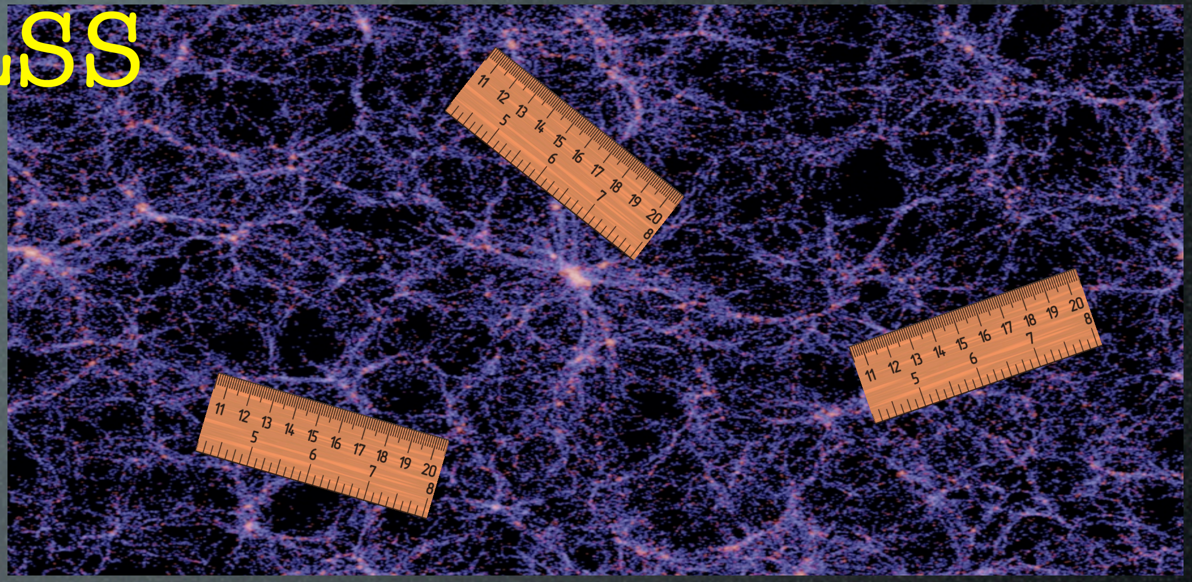
CMB



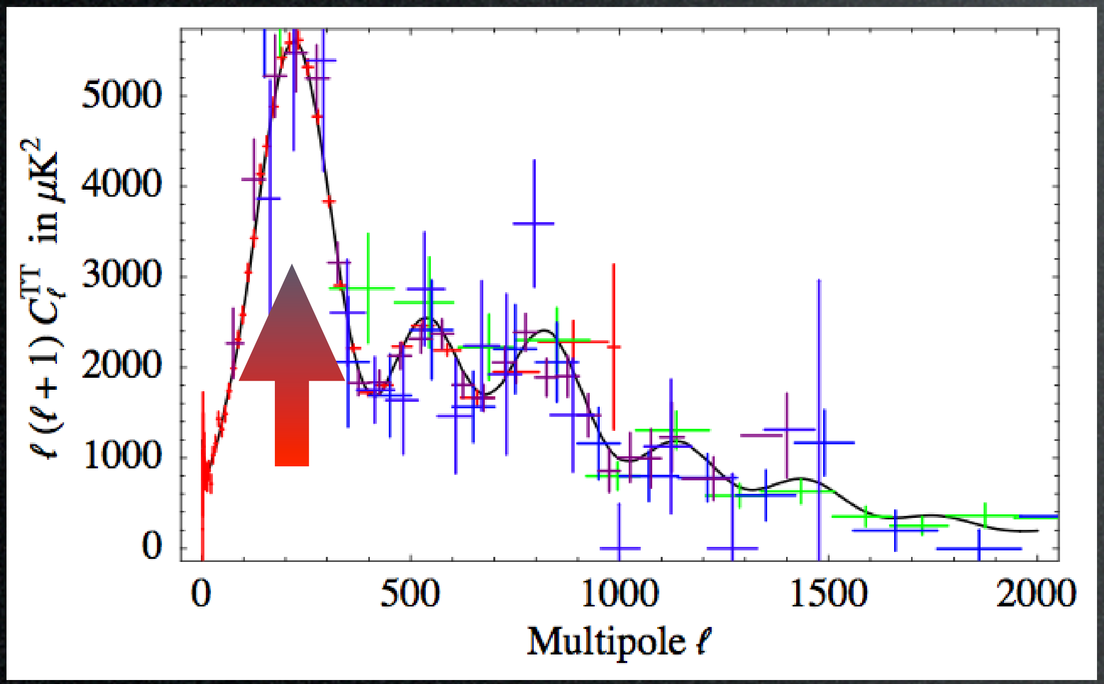
$T = 2.725^\circ K$

$\frac{\delta T}{T} \sim 10^{-5}$

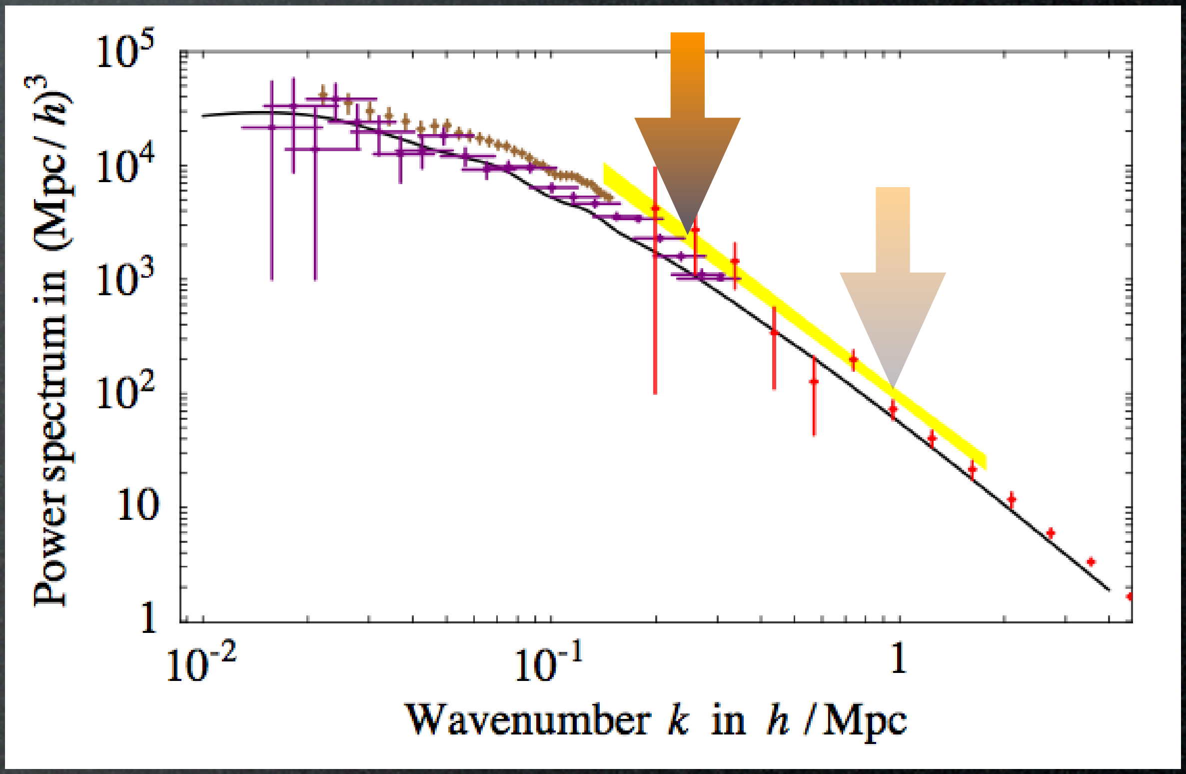
LSS



CMB spectrum

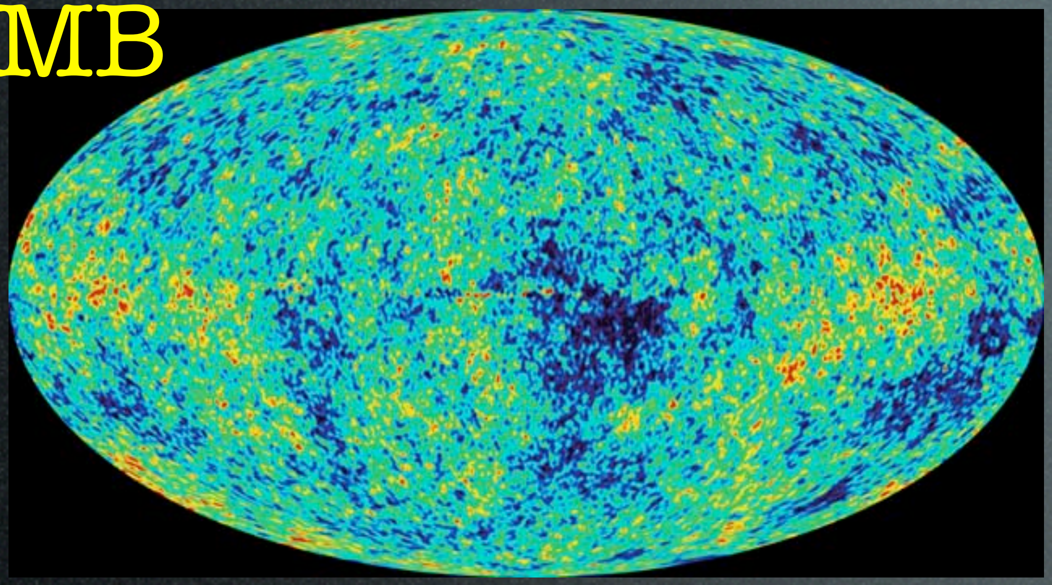


LSS matter power spectrum

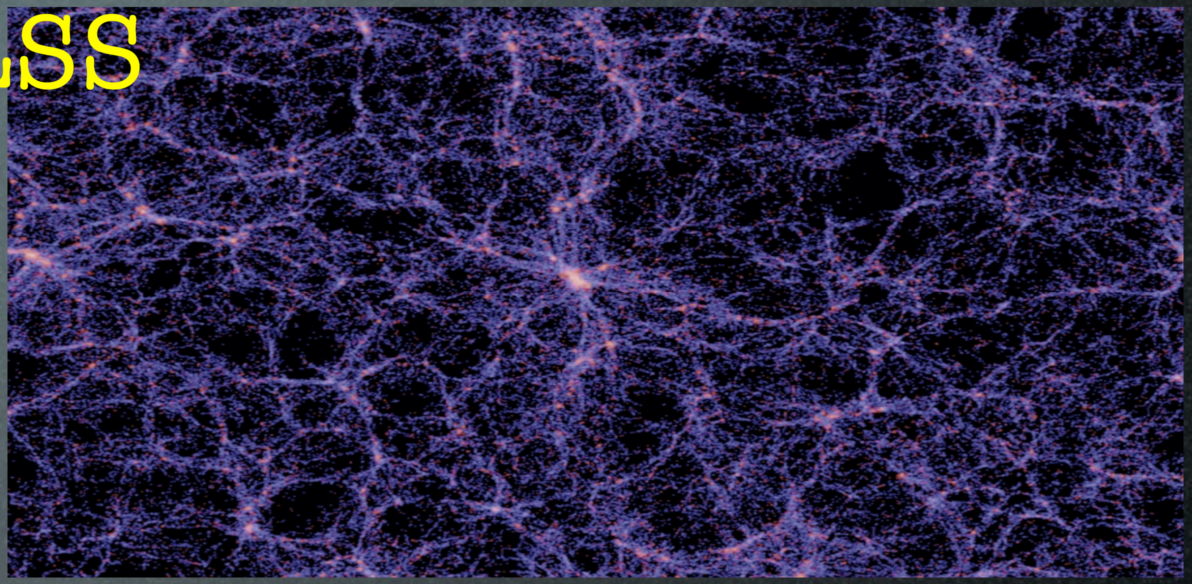


The Evidence for DM

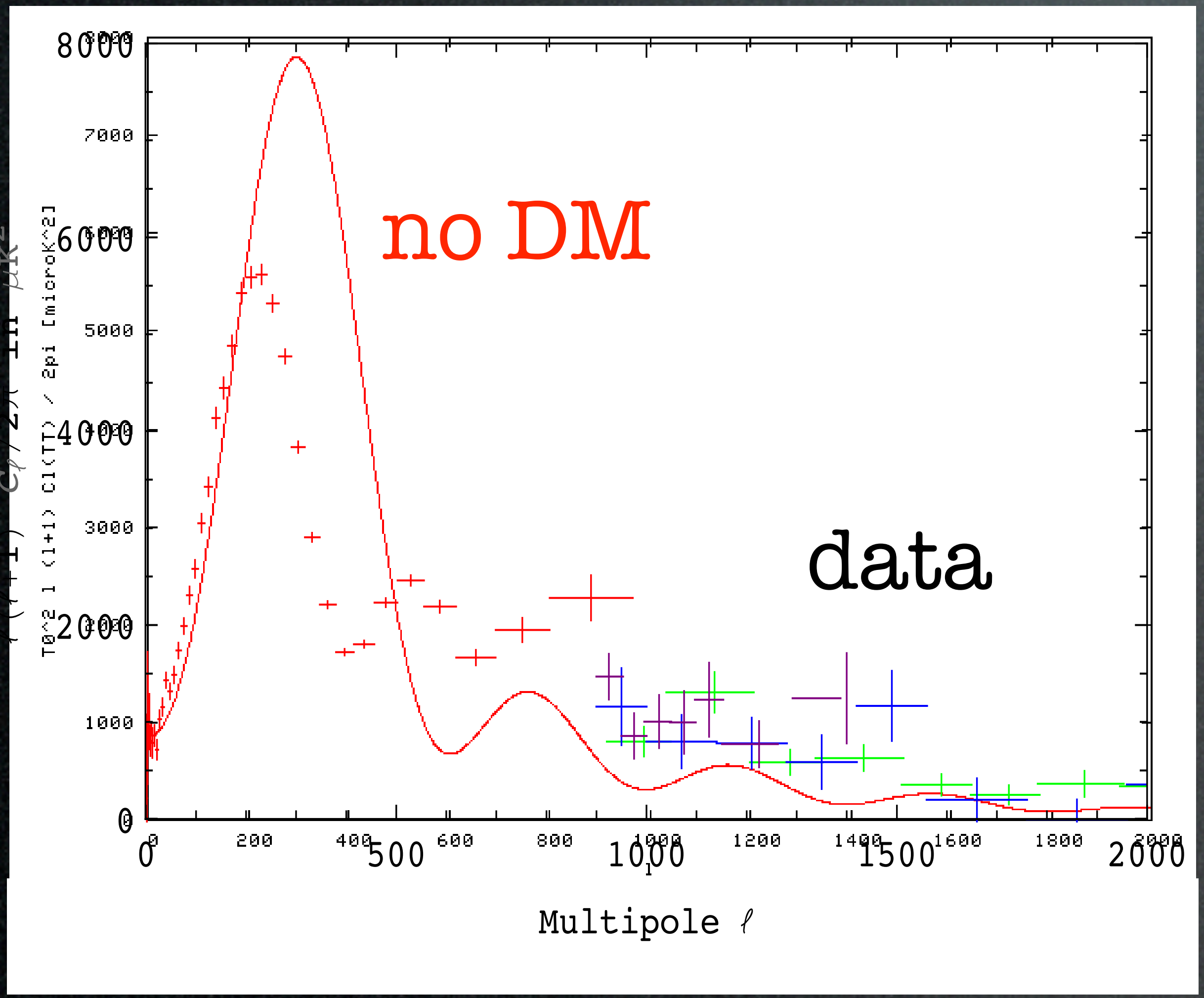
CMB



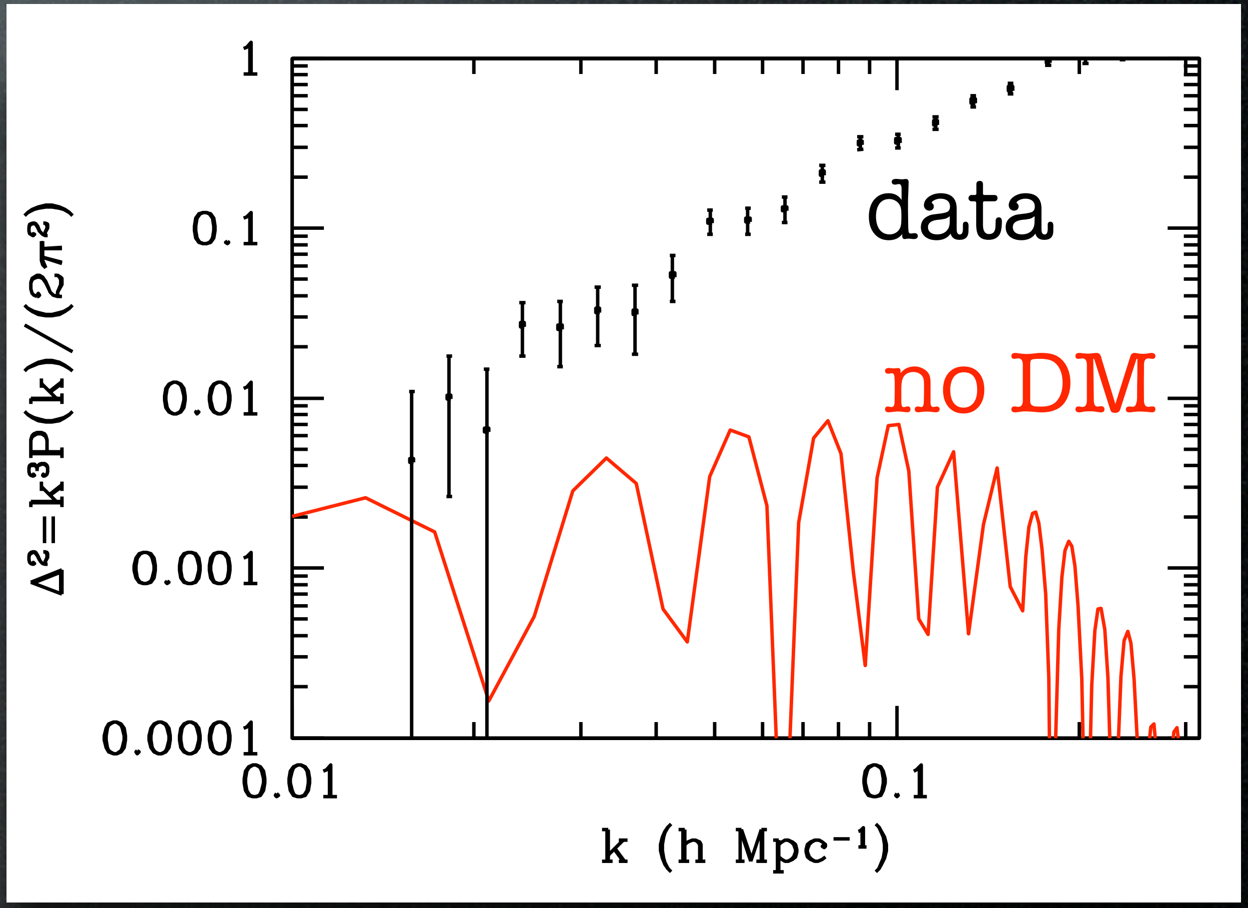
LSS



How would the power spectra be without DM? (and no other extra ingredient)



(in particular: no DM => no 3rd peak!)



(you need DM to gravitationally "catalyse" structure formation)


DETOUR

MOND? TeVeS?

Instead of adding matter, modify Newton or GR.

$$F = m\,a \longrightarrow F = m\,a \cdot \mu(a) \quad \text{with} \quad \mu(a) = \begin{cases} 1 & a > a_0 \\ a/a_0 & a \sim a_0 \end{cases}$$

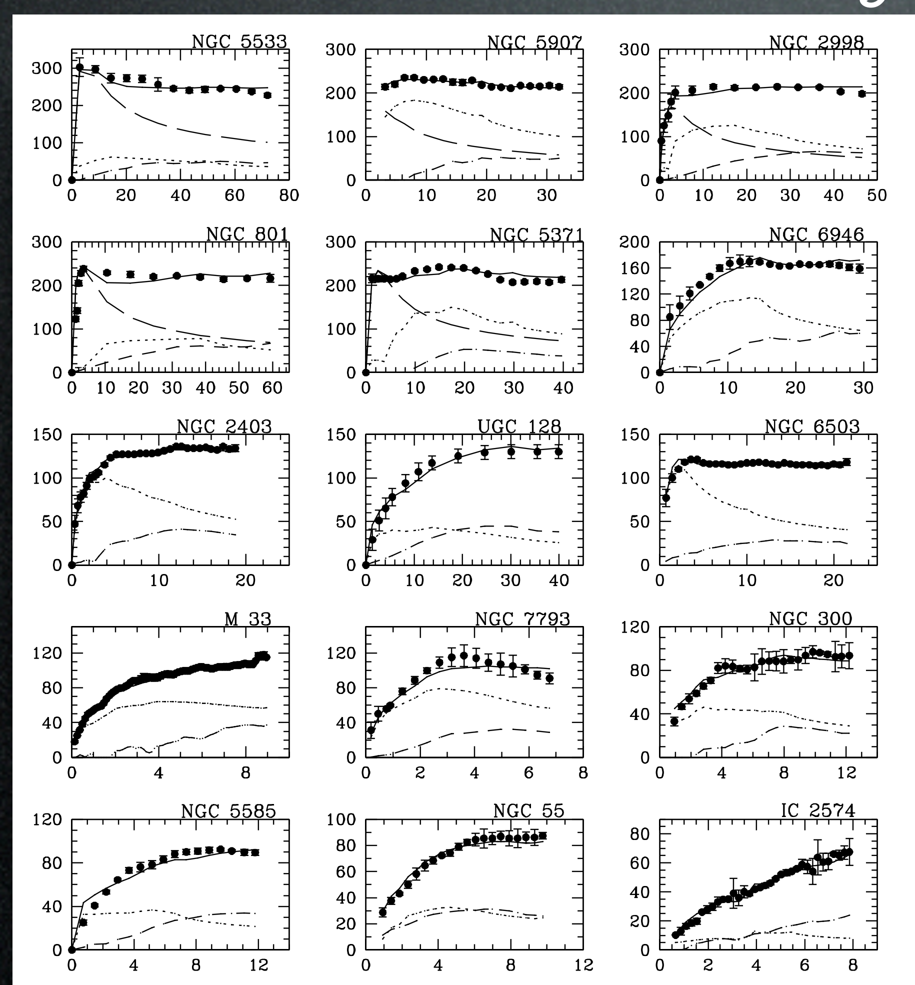
$$a_0 = 1.2 \cdot 10^{-10} m/s^2$$

$$F = m\frac{a^2}{a_0} = \frac{GMm}{r^2} \quad \Rightarrow \quad a = \frac{\sqrt{GMa_0}}{r} = \frac{v^2}{r} \quad \Rightarrow \quad v = (GMa_0)^{1/4} = \text{const}$$

force balance

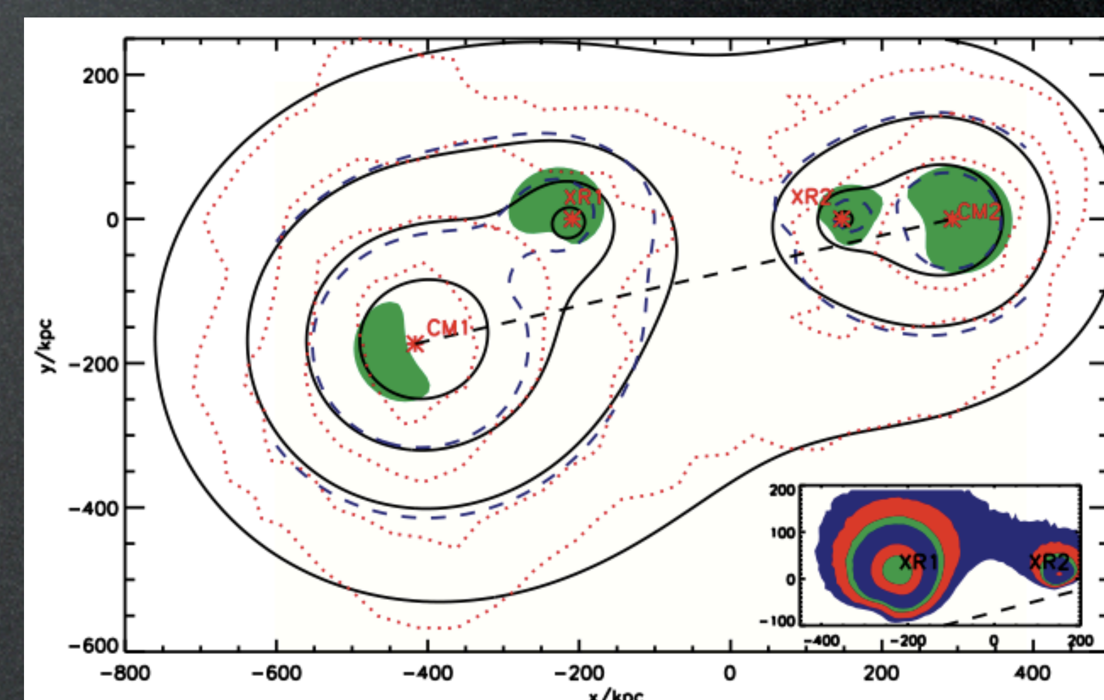
tangential acceleration

fits rotation curves very well



Sanders, McGaugh, Ann. Rev. AA, 2002

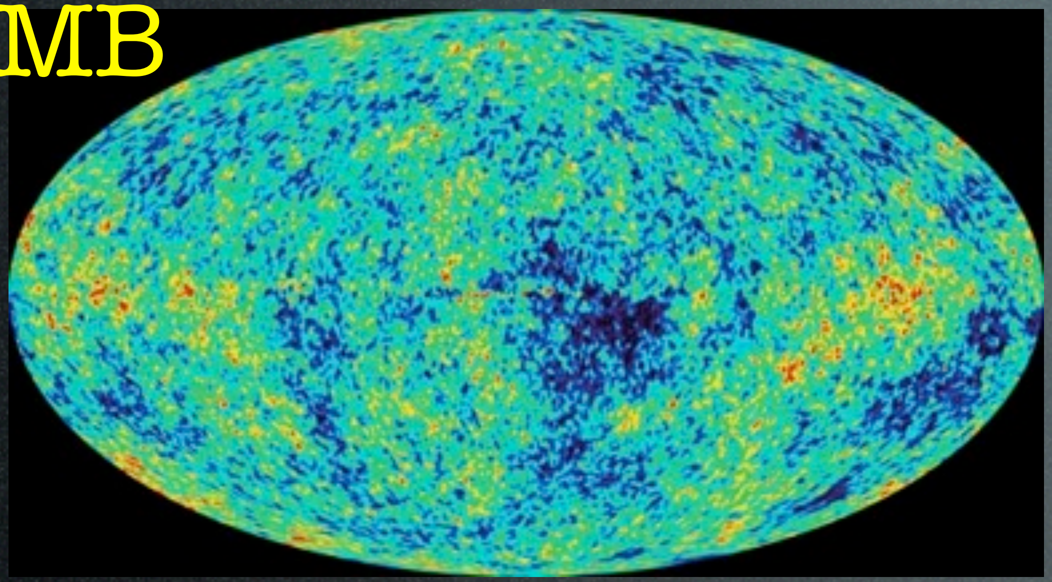
can fit (bullet) cluster if adding 2 eV neutrinos...



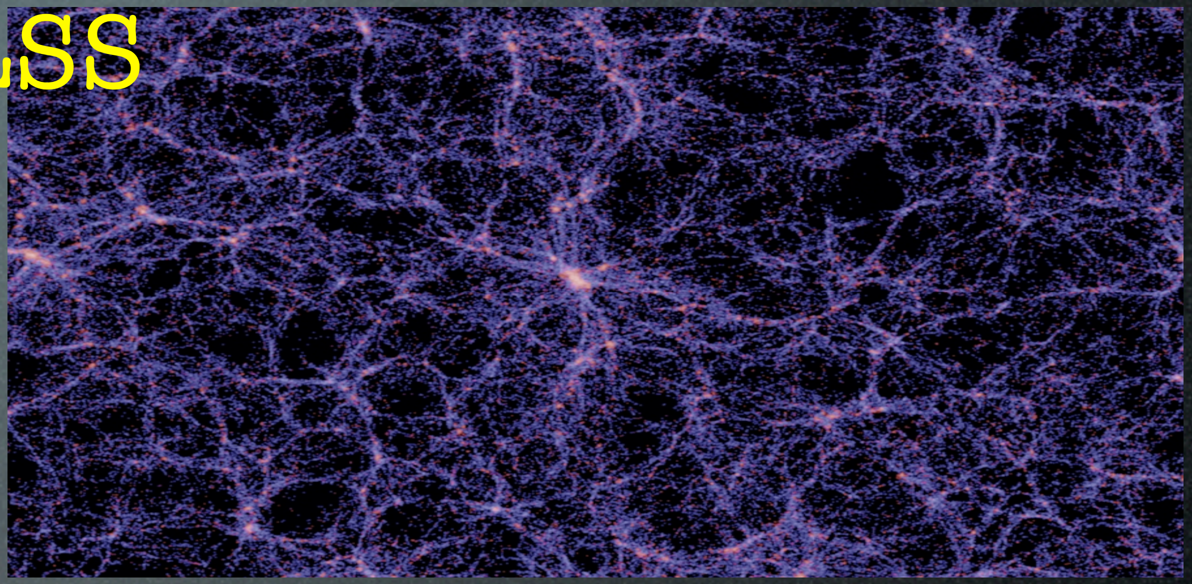
Angus et al., astro-ph/0609125

The Evidence for DM

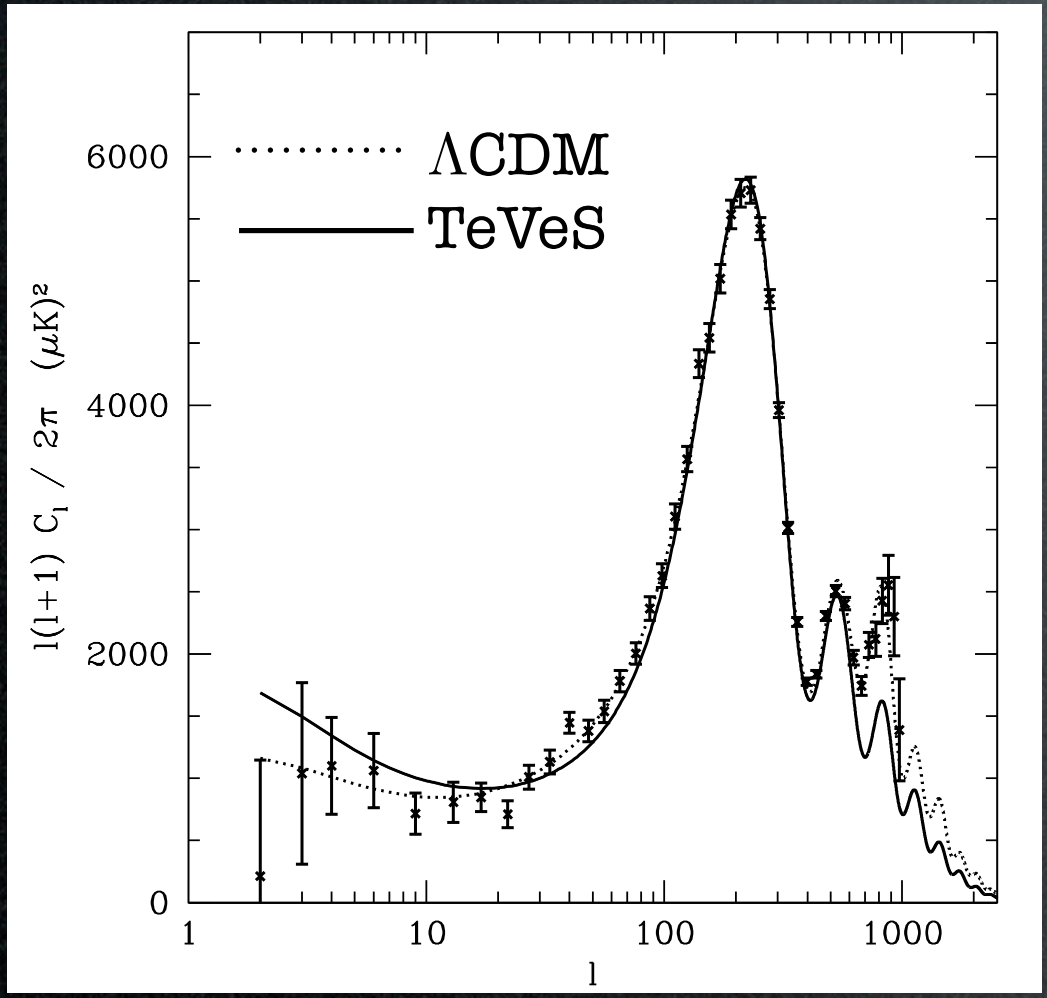
CMB



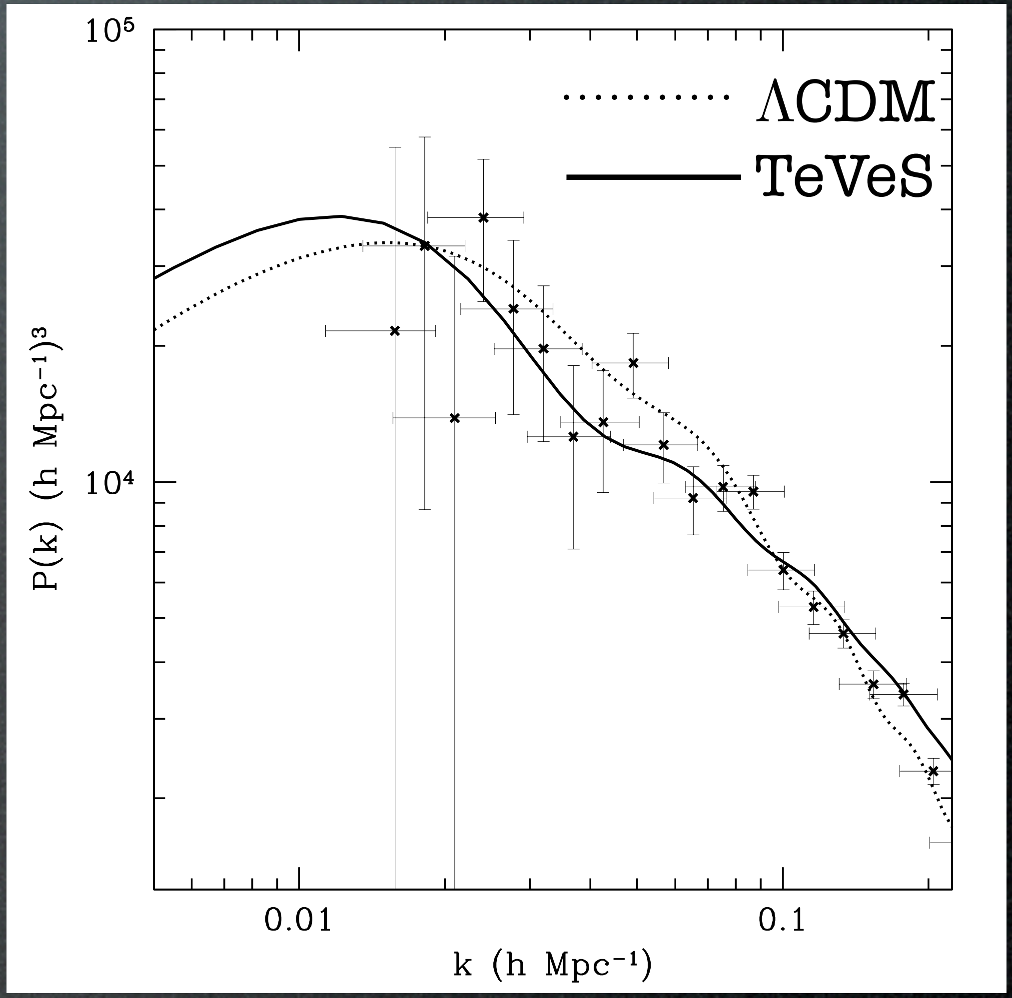
LSS



How would the power spectra be in MOND/TeVeS, without DM ?



C.Skordis, Review, 0903.3602



C.Skordis, Review, 0903.3602

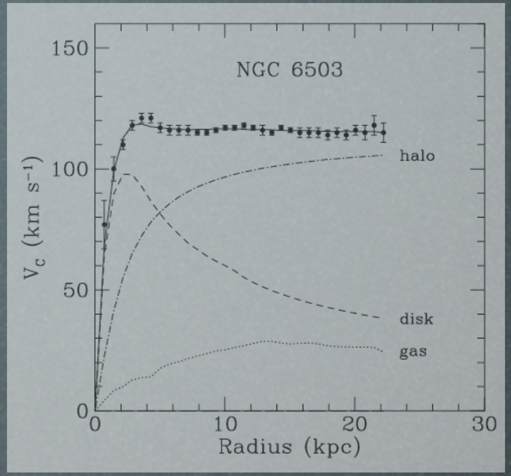
(in particular: no DM => no 3rd peak!)

(here you can make it)


DETOUR

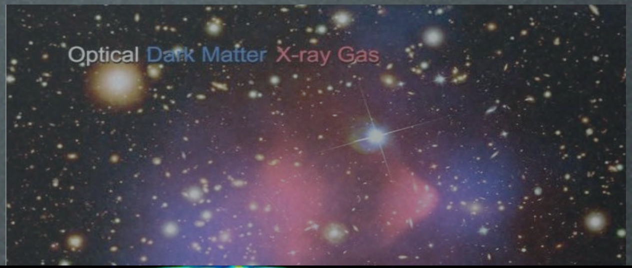
The Evidence for DM

1) galaxy rotation curves



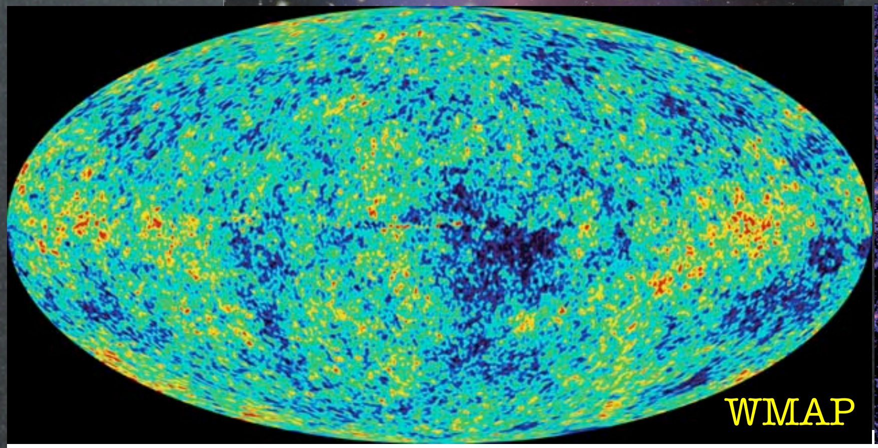
$\Omega_M \gtrsim 0.1$

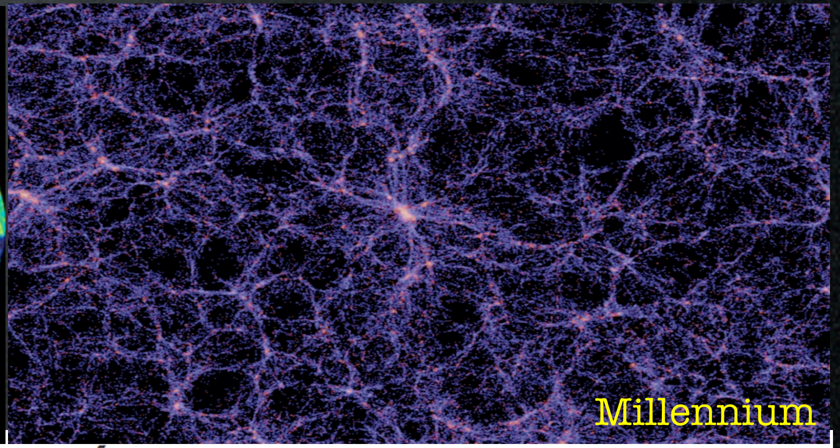
2) clusters of galaxies



$\Omega_M \sim 0.2 \div 0.4$

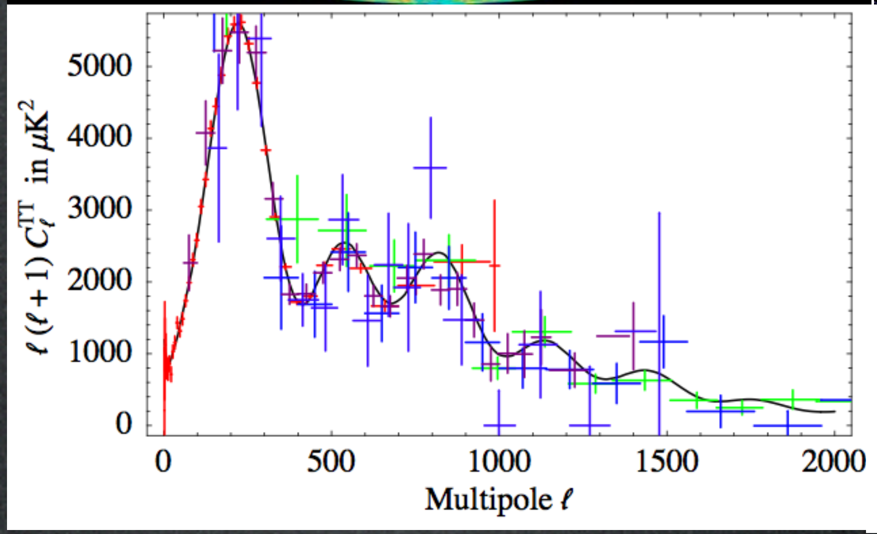
3) CMB+LSS(+SNIa:)

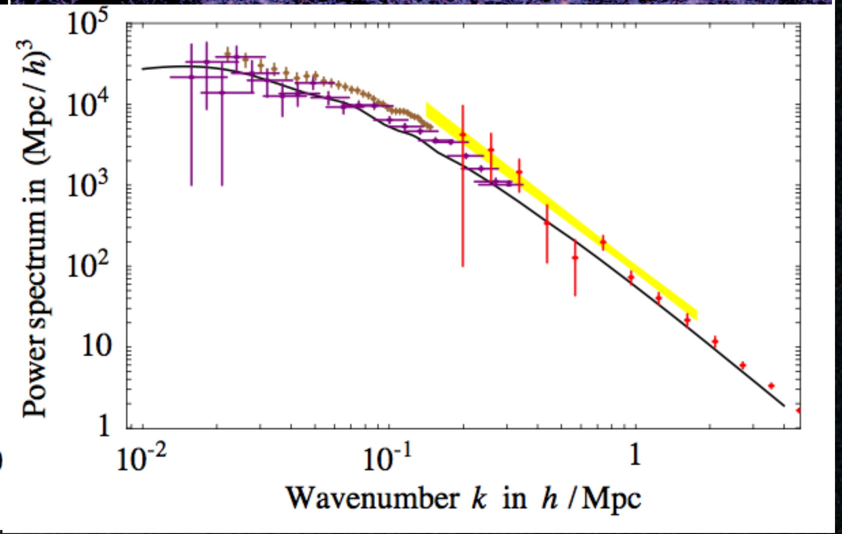




WMAP-3yr
ACbar
CBI
Boomerang
DASI
VSA

SDSS, 2dFRGS
LyA Forest Croft
LyA Forest SDSS





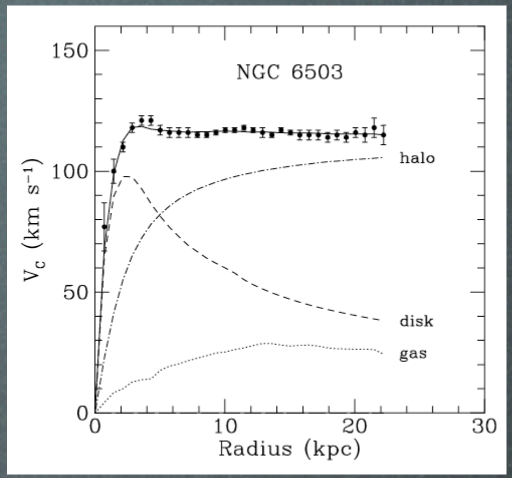
$\Omega_M \approx 0.275 \pm 0.02$

(spectra w/o DM)

M.Cirelli and A.Strumia, astro-ph/0607086

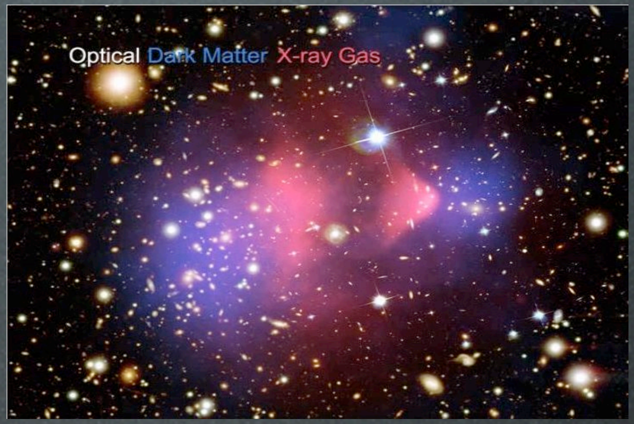
The Evidence for DM

1) galaxy rotation curves



$\Omega_M \gtrsim 0.1$

2) clusters of galaxies



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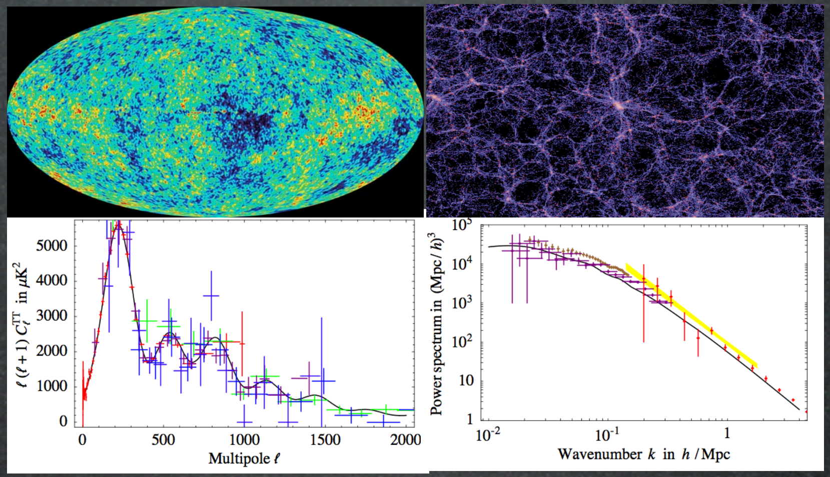

$\Omega_M \approx 0.275 \pm 0.02$

What is the DM??

It consists of a particle.

Permeates galactic haloes.

What do we know of the particle physics properties of Dark Matter?

DM can **NOT** be:

DM can **NOT** be:

an astro *je ne sais pas quoi*:

DM can **NOT** be:

an astro *je ne sais pas quoi*:

- neutrons

- gas

- Black Holes
- brown dwarves

DM can **NOT** be:

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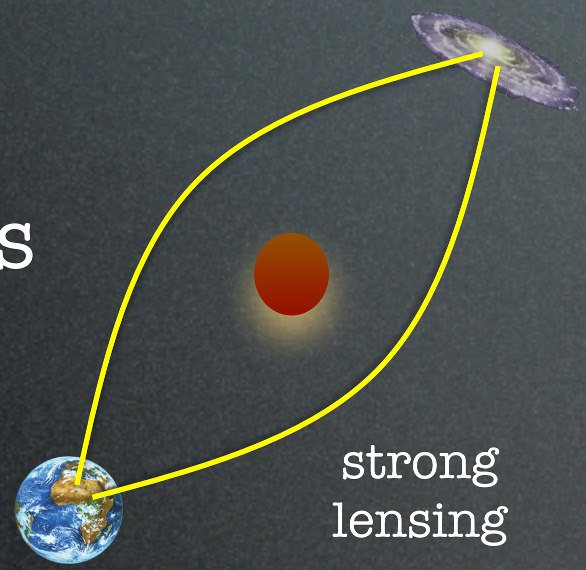
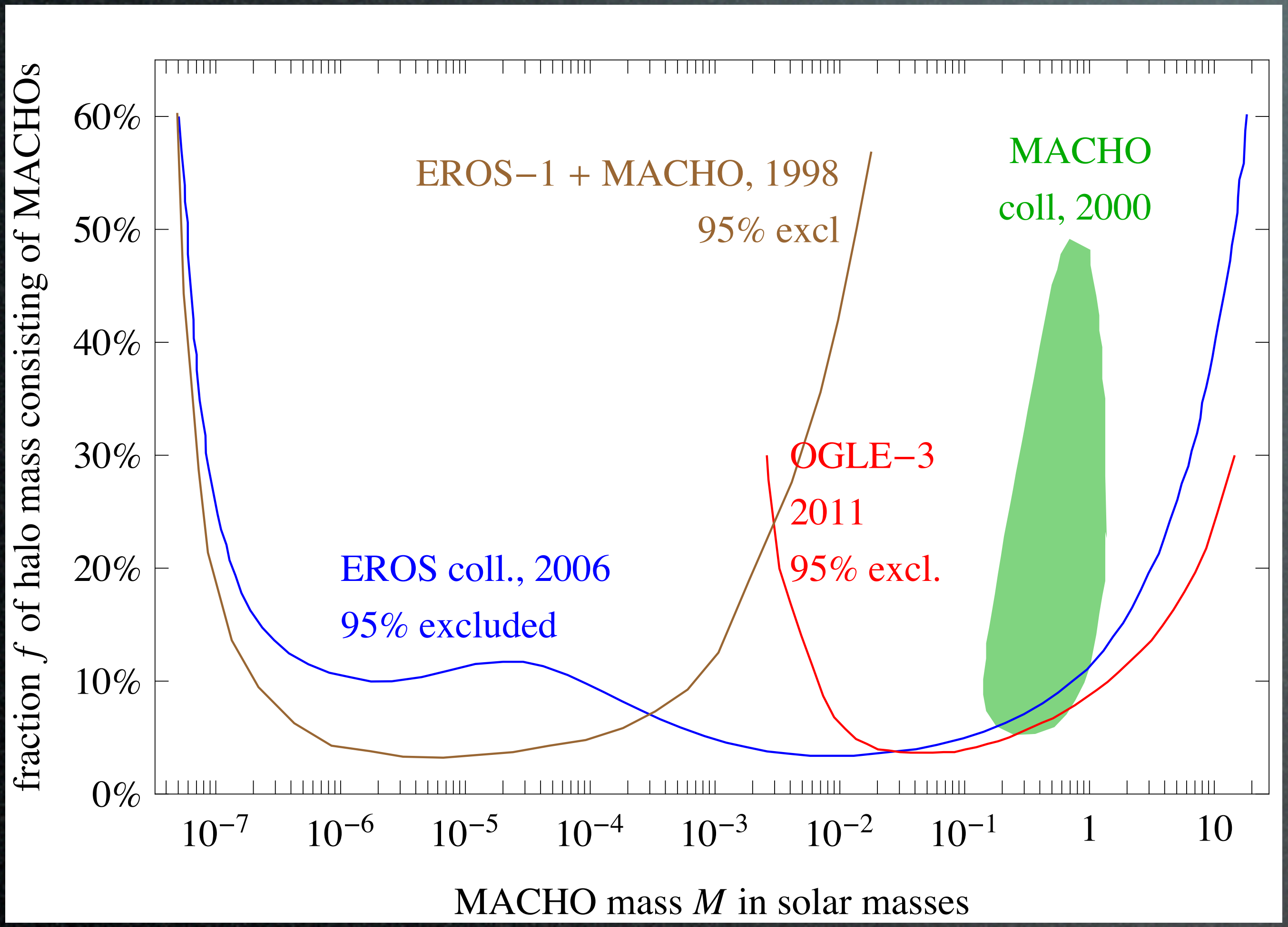


MACHOs or PBHs as DM



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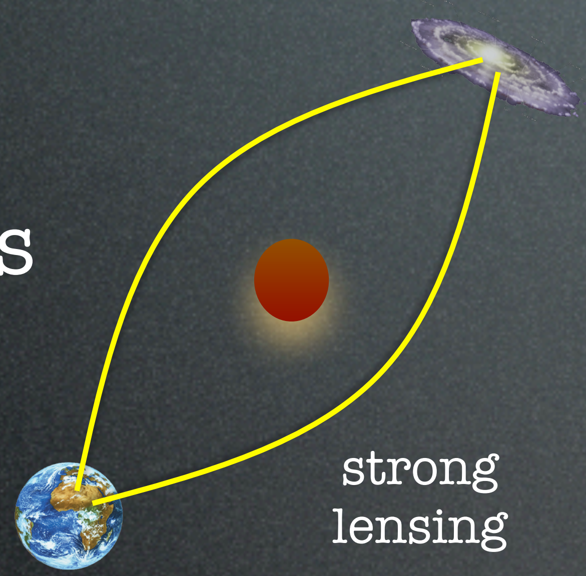

a baryon of the SM:

DM can **NOT** be:

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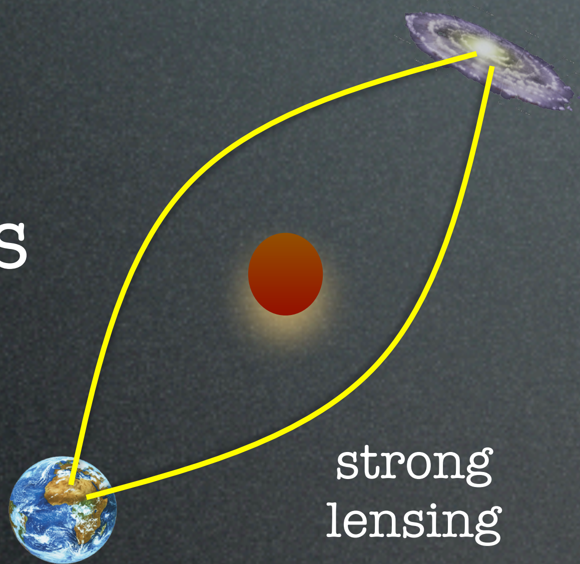
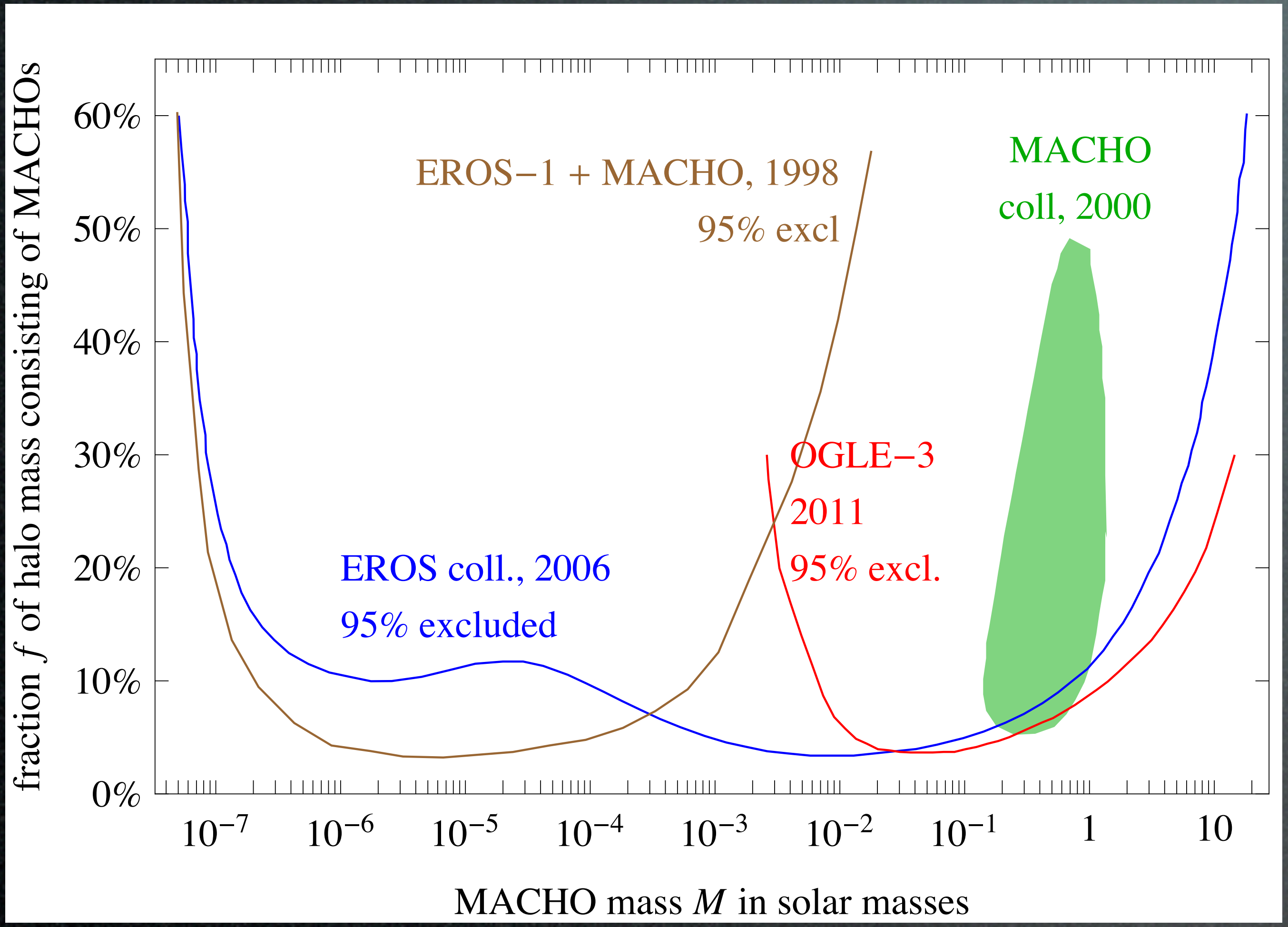
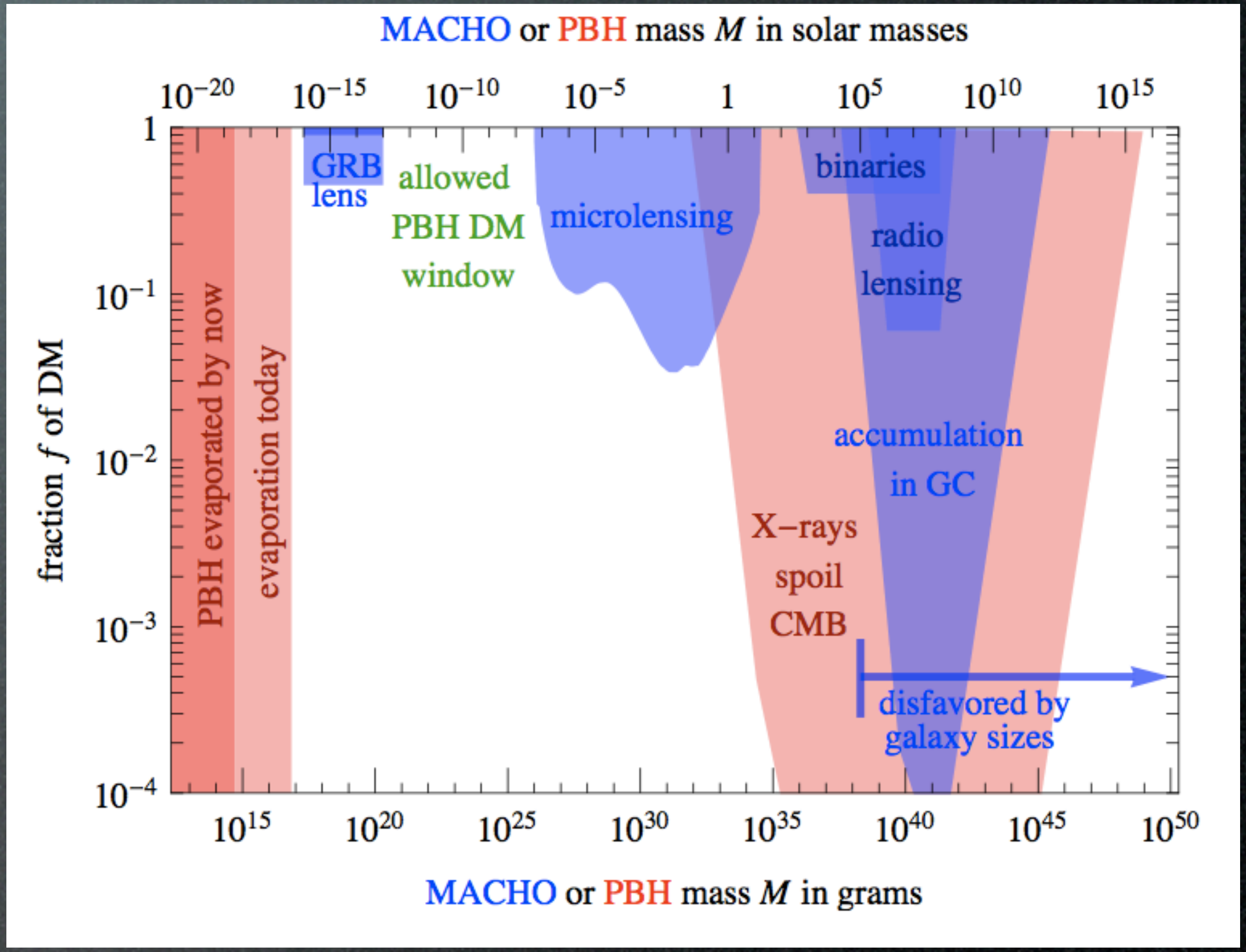


a ~~baryon of the SM~~:

- BBN computes the abundance of He in terms of primordial baryons: too much baryons => Universe full of Helium
- CMB says baryons are 4% max

MACHOs or PBHs as DM





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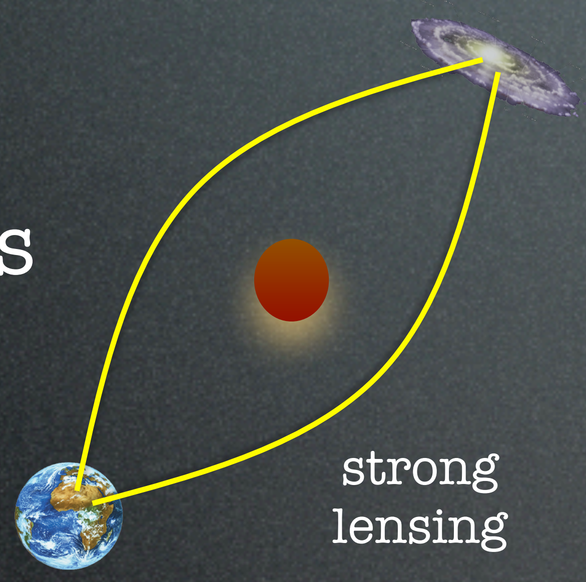

neutrinos:

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DM can **NOT** be:

an astro *je ne sais pas quoi*:

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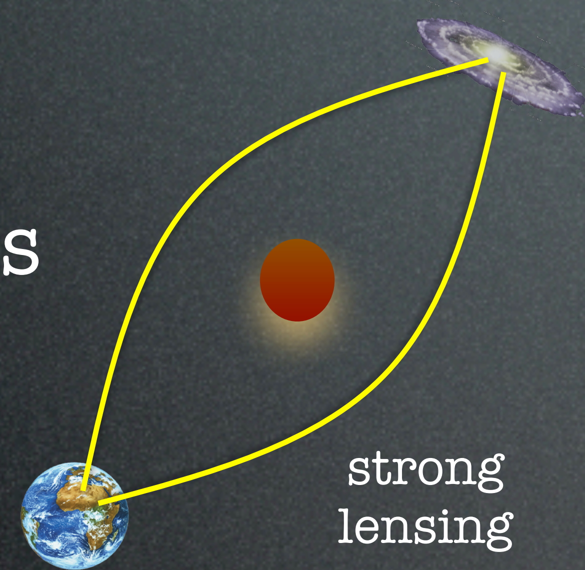
- ~~gas~~
- ~~Black Holes~~
- ~~brown dwarves~~



a ~~baryon of the SM~~:

- BBN computes the abundance of He in terms of primordial baryons: too much baryons => Universe full of Helium
- CMB says baryons are 4% max

~~neutrinos~~:

too light! $m_\nu \lesssim 1\,\mathrm{eV}$

do not have enough mass to act as gravitational attractors in galaxy collapse

(Neutrino) HDM in LSS

no HDM

$\sum m_\nu = 0$

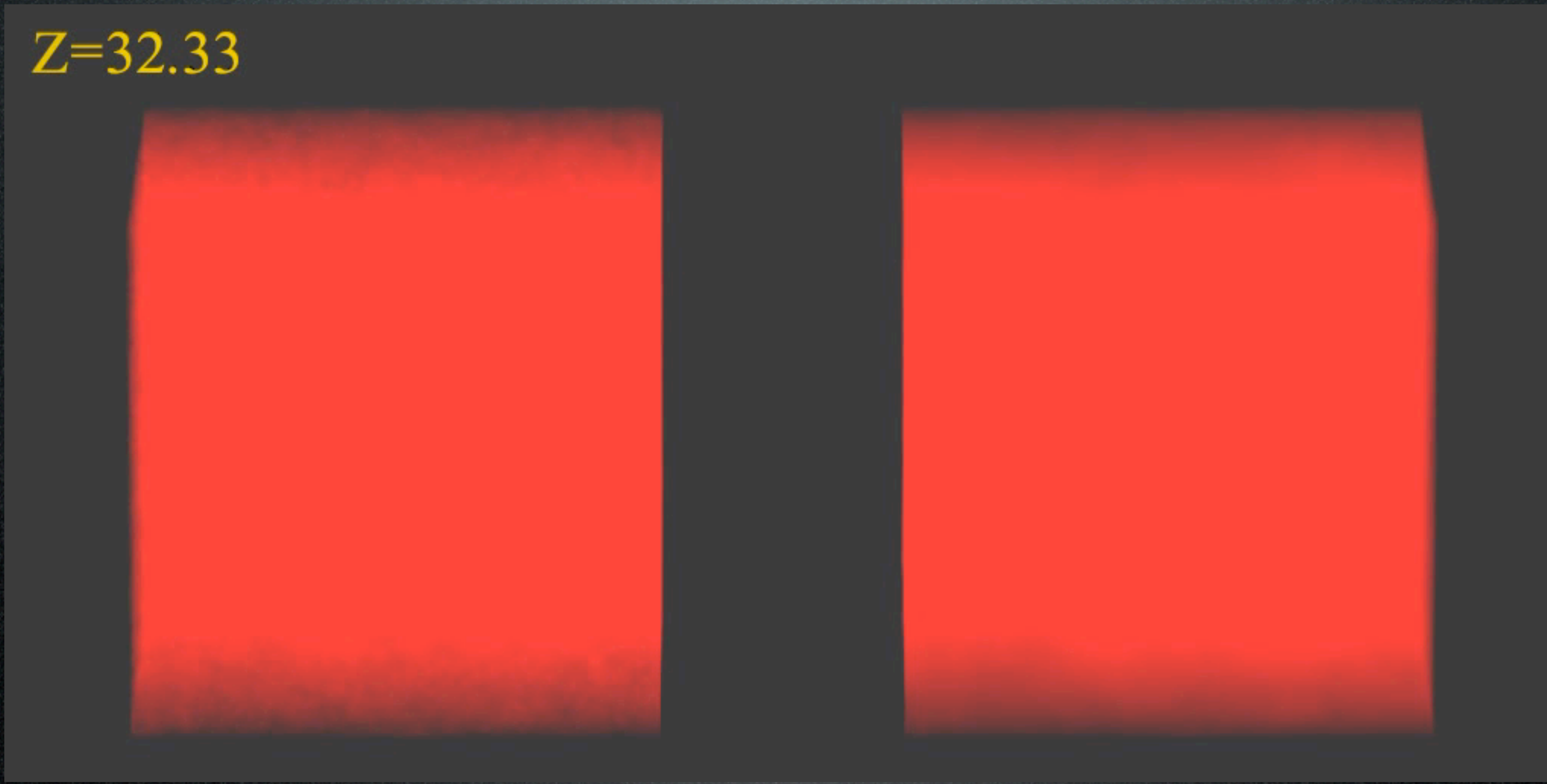
some HDM

$\sum m_\nu = 6.9$ eV

ΛCDM - Gadget2 - 768 Mpc^3

T.Haugboelle, S.Hannestad, Aarhus University

(Neutrino) HDM in LSS



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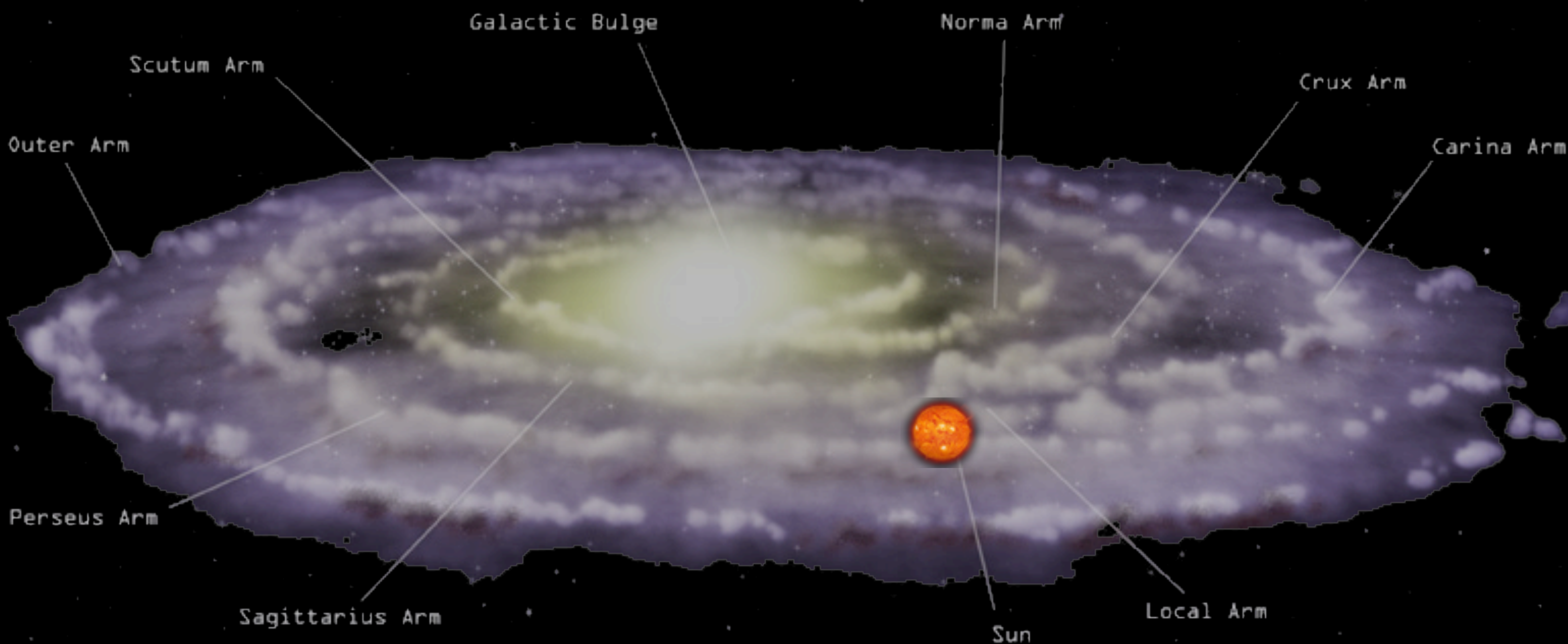
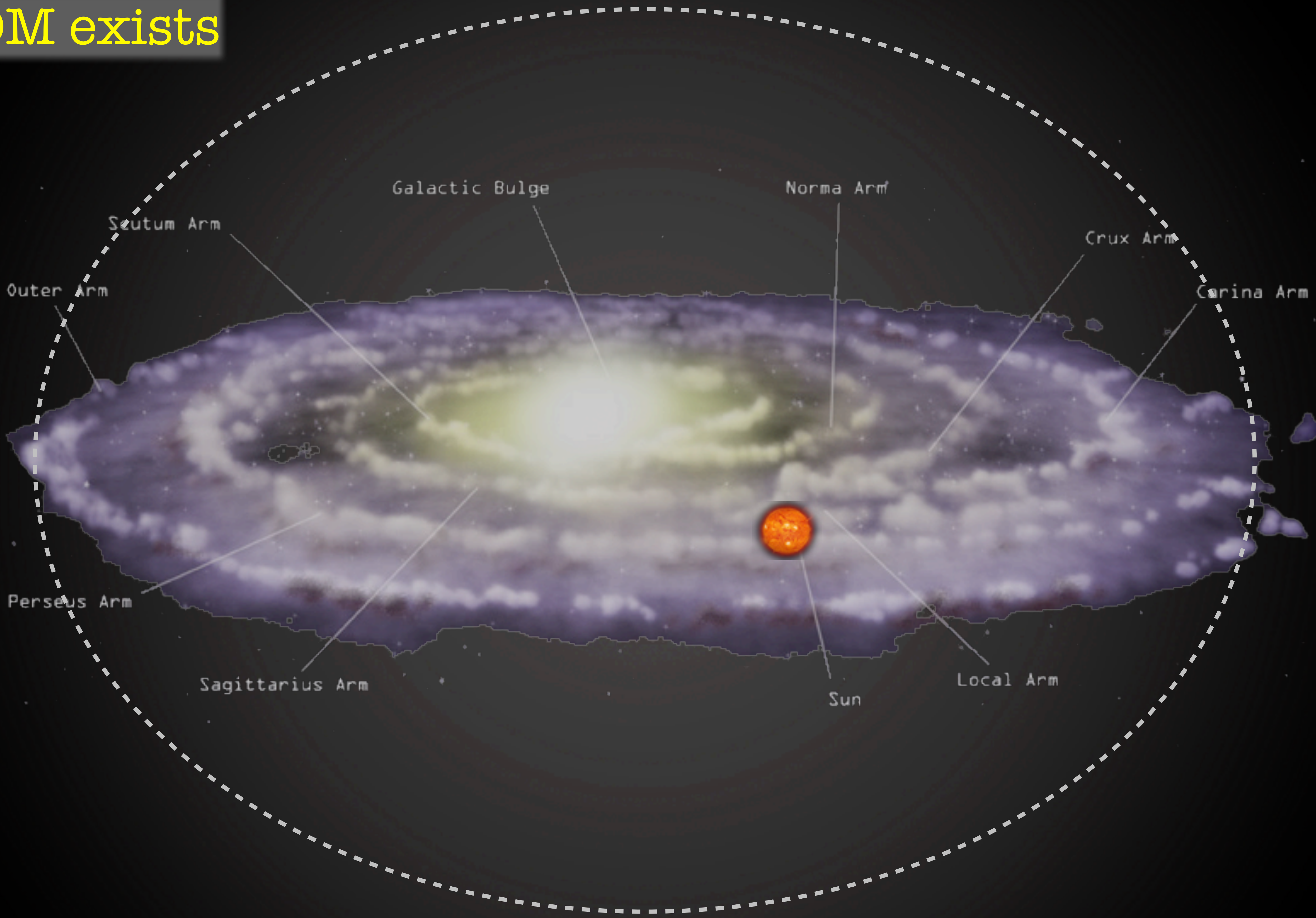
Recap: DM factsheet



Recap: DM factsheet

DM exists



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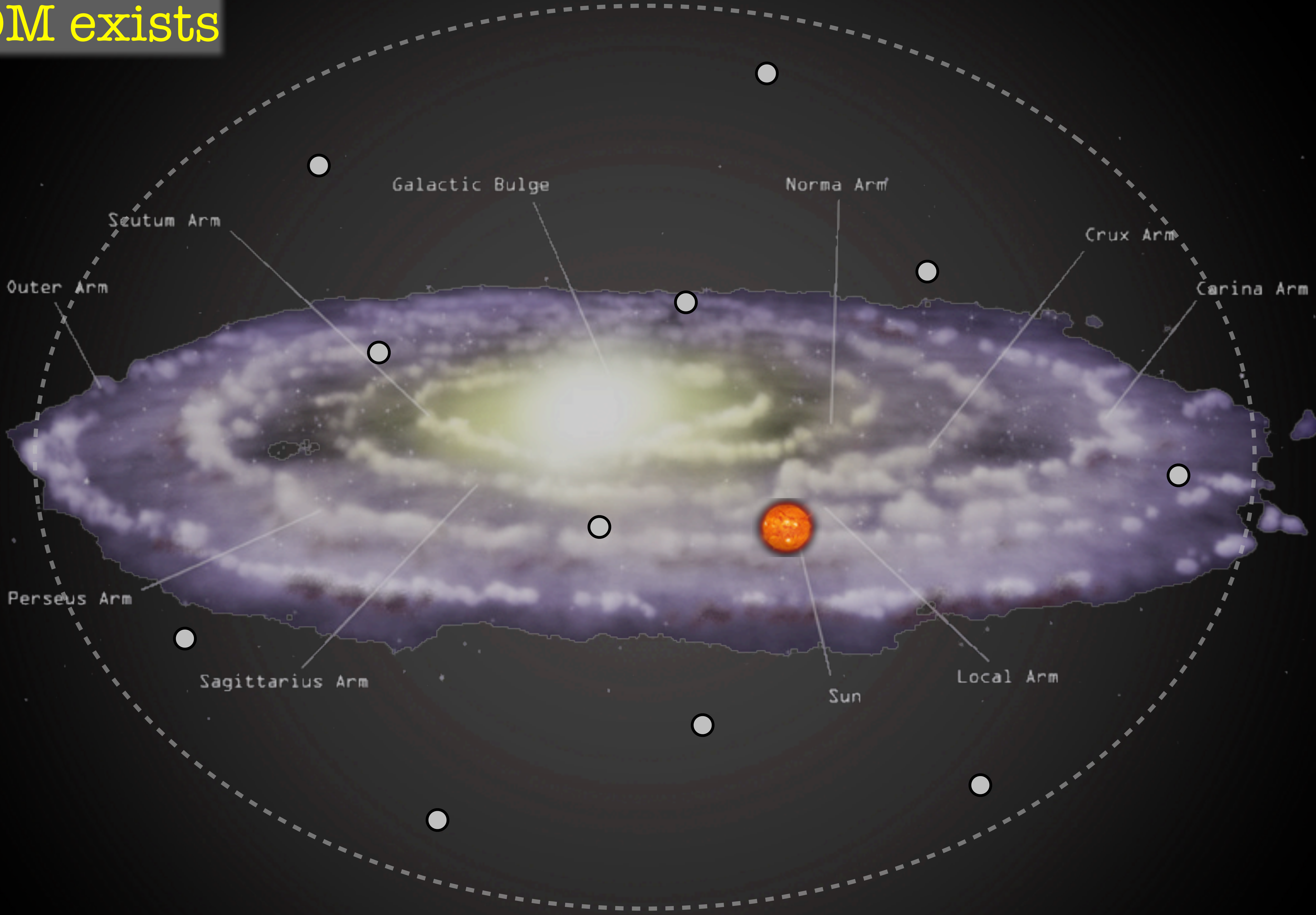

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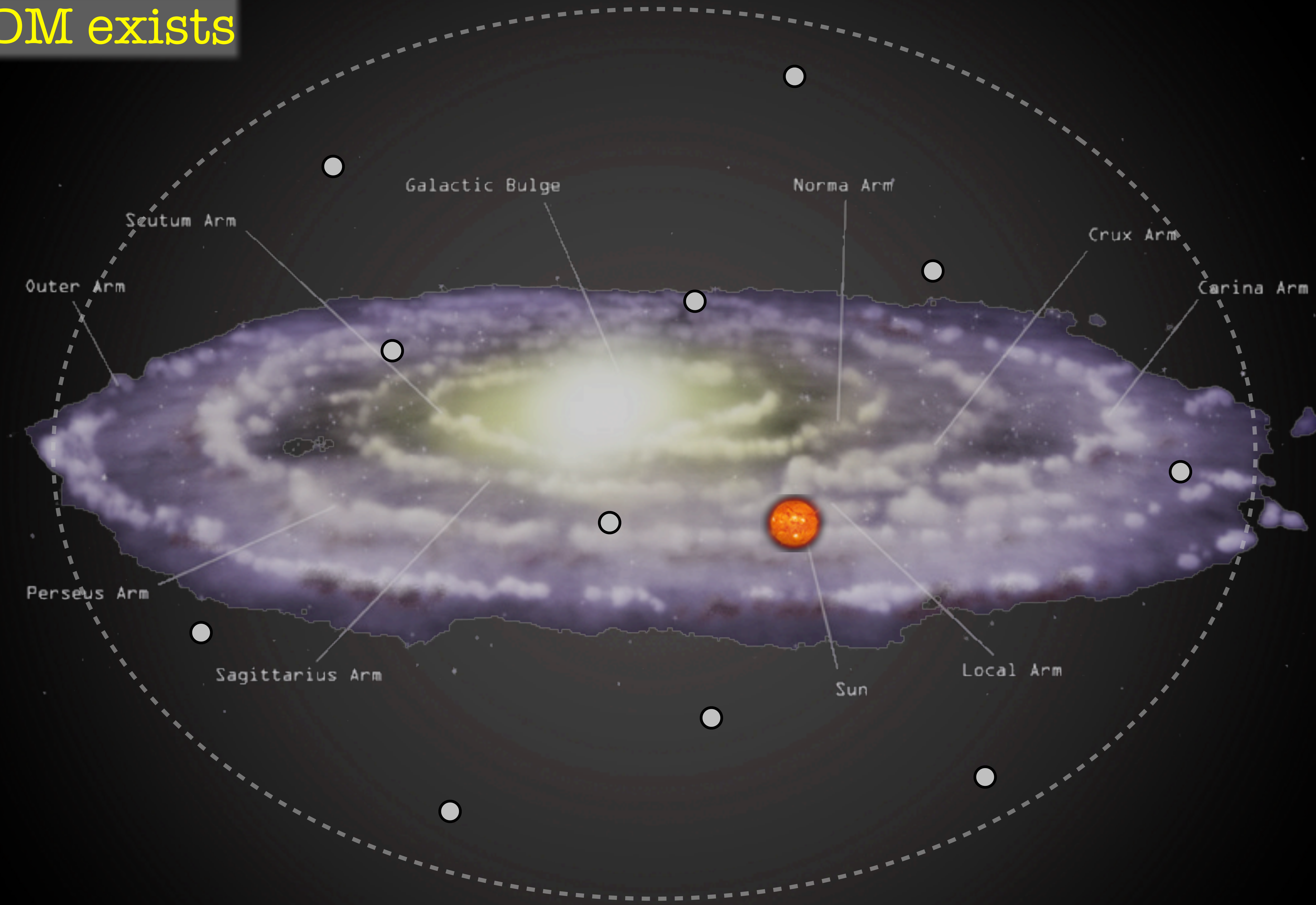

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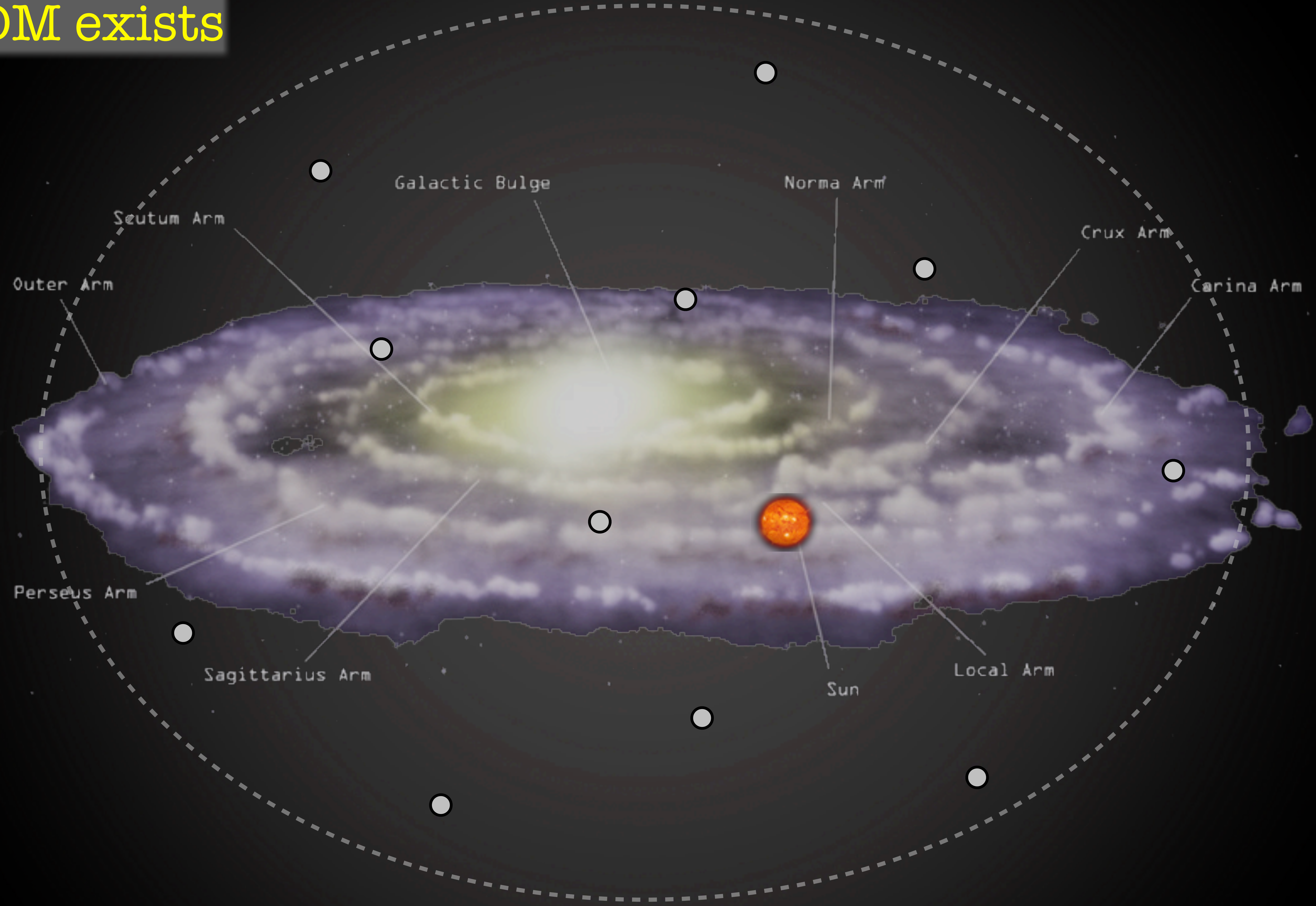

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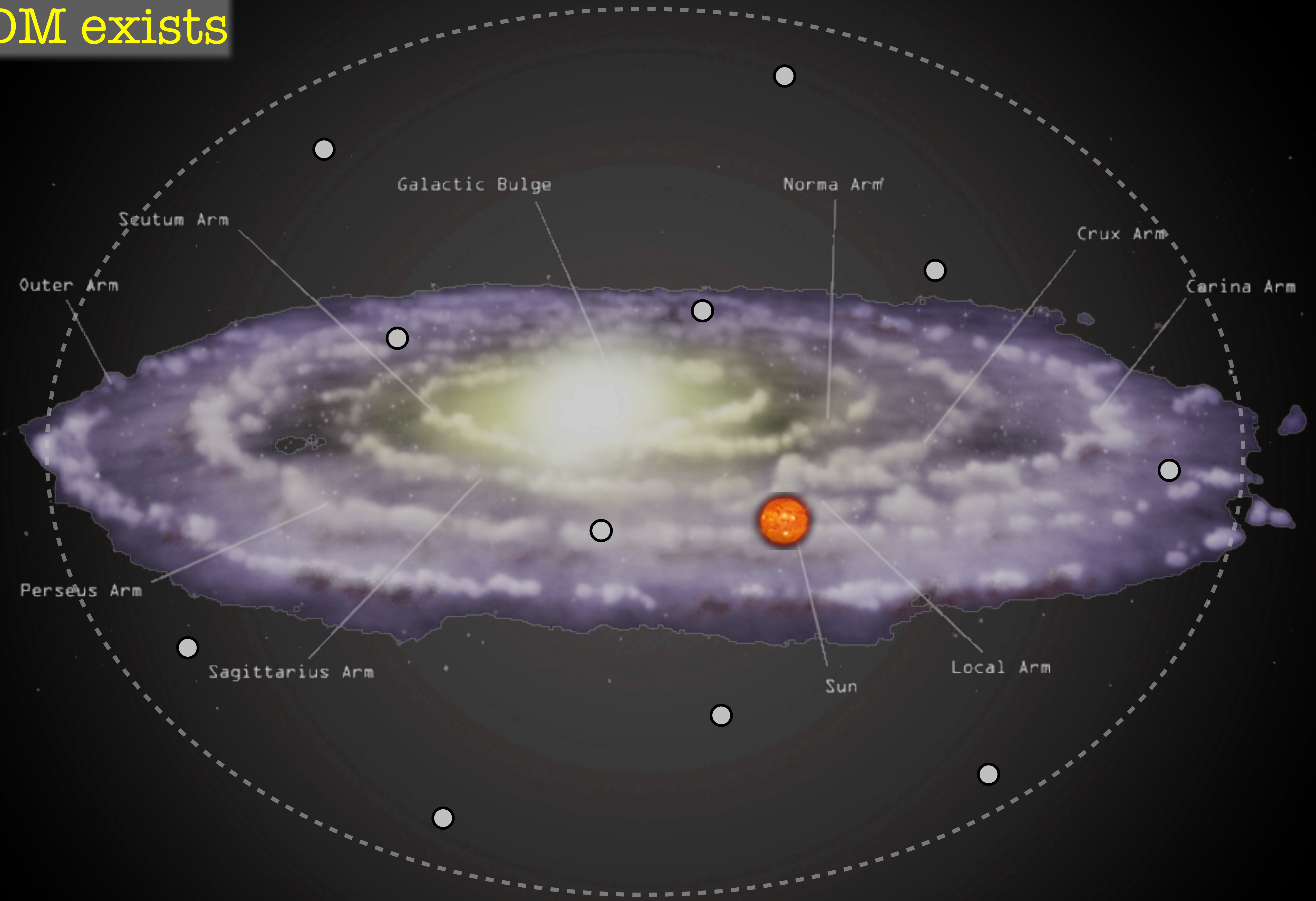

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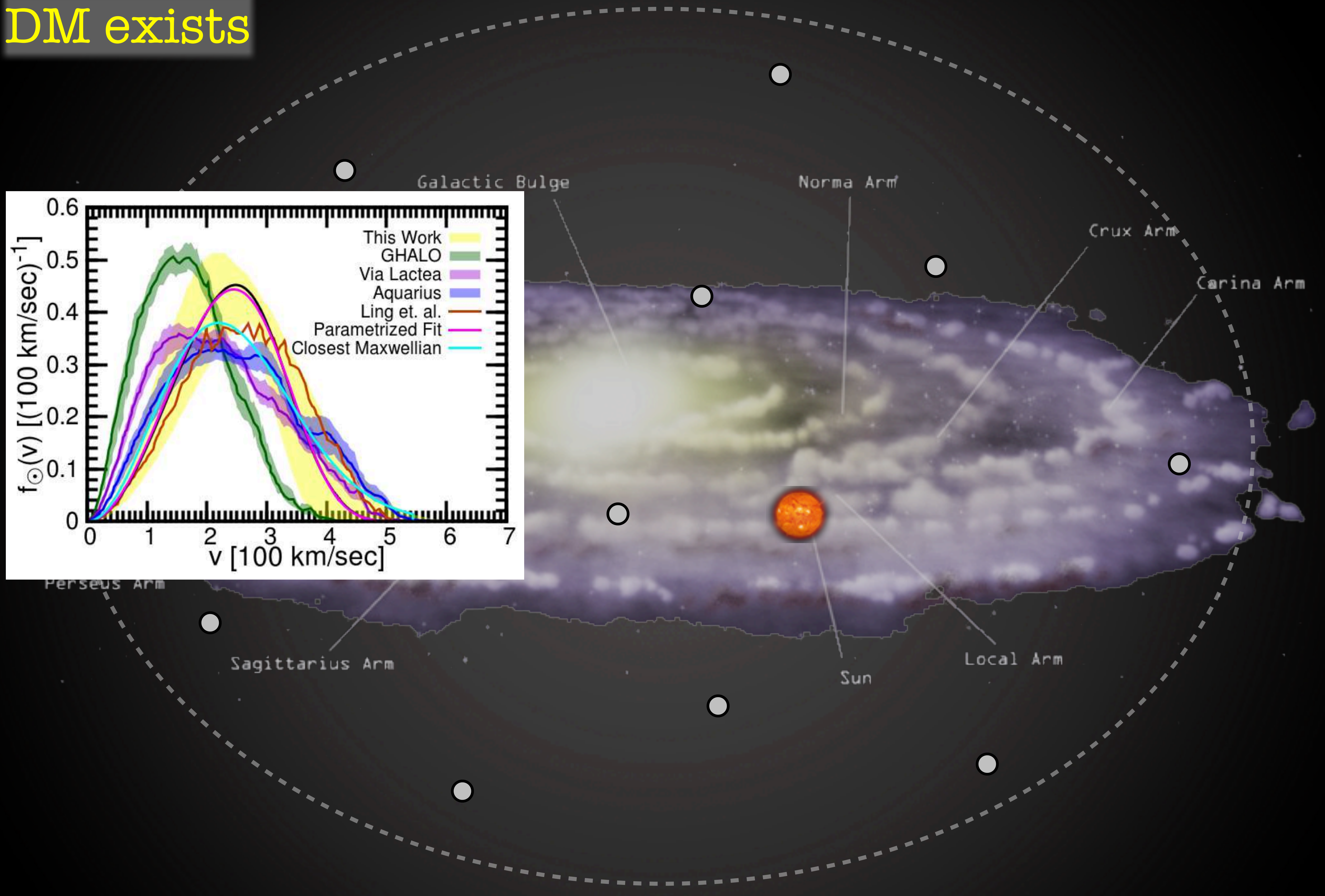

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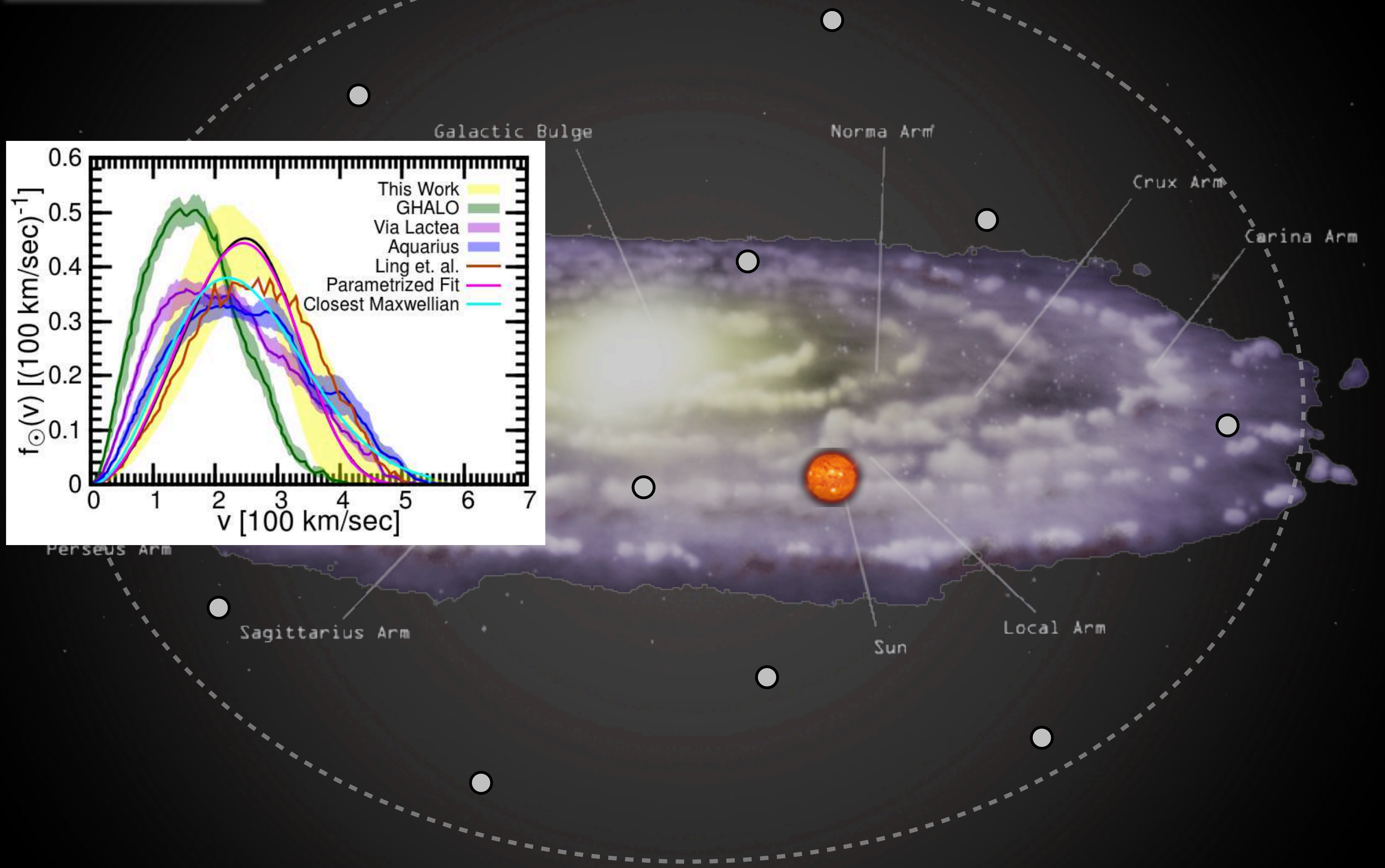

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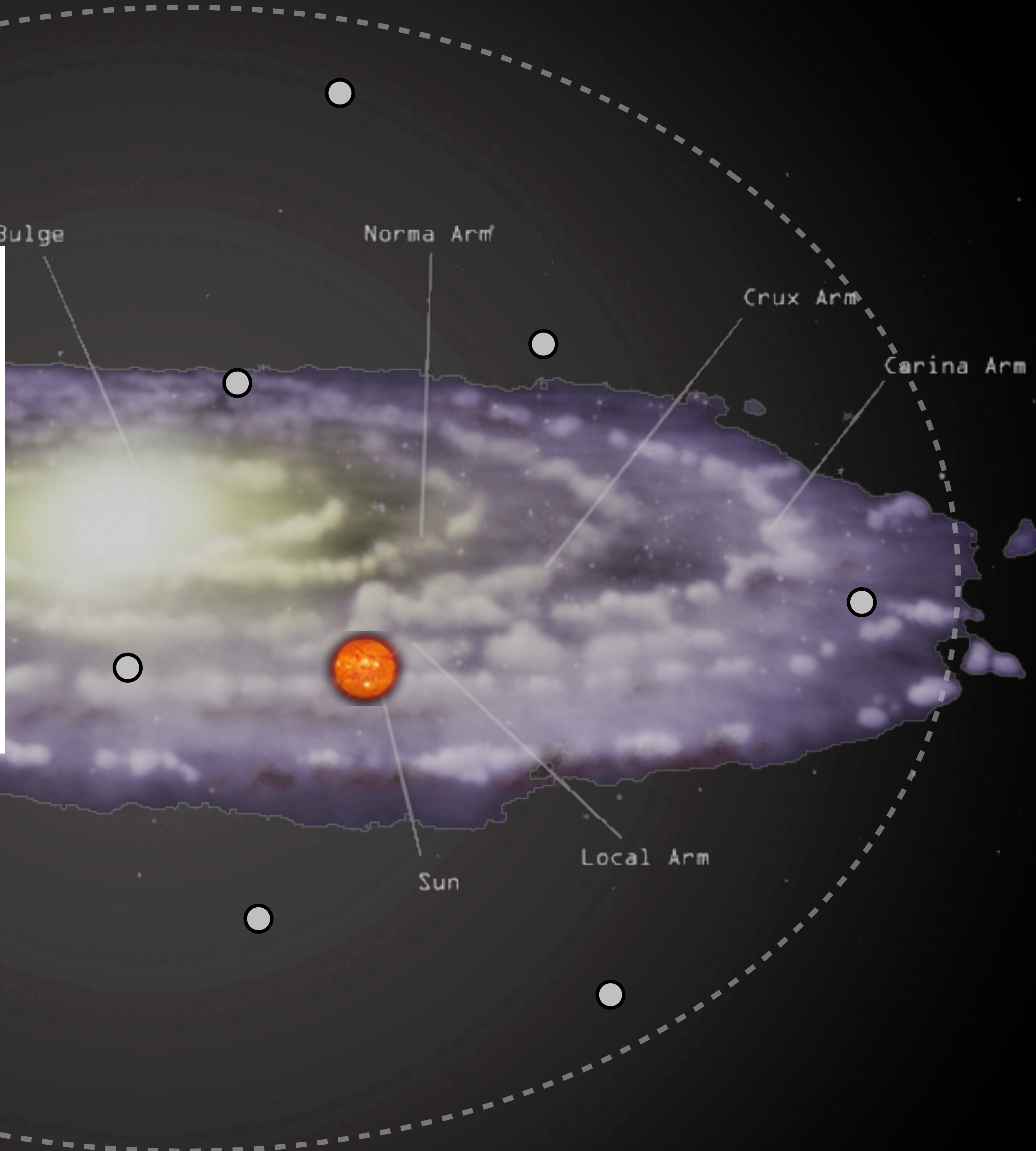
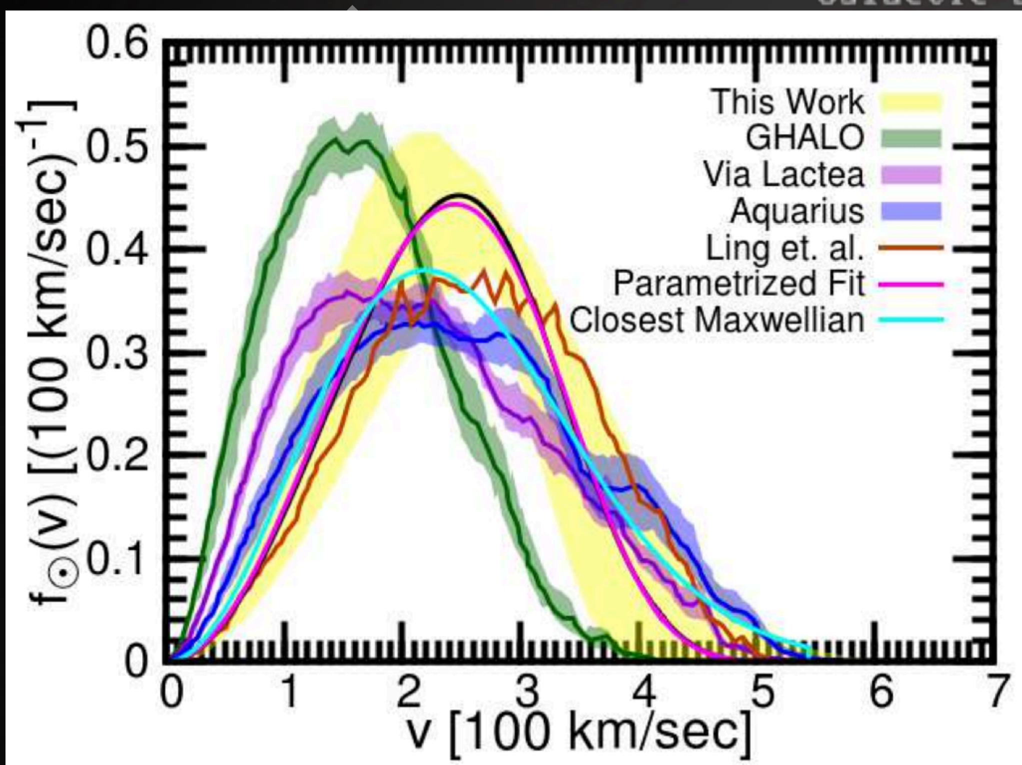
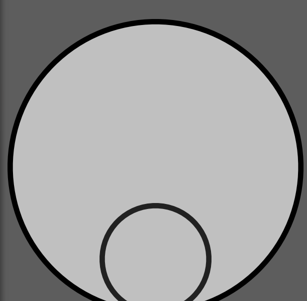




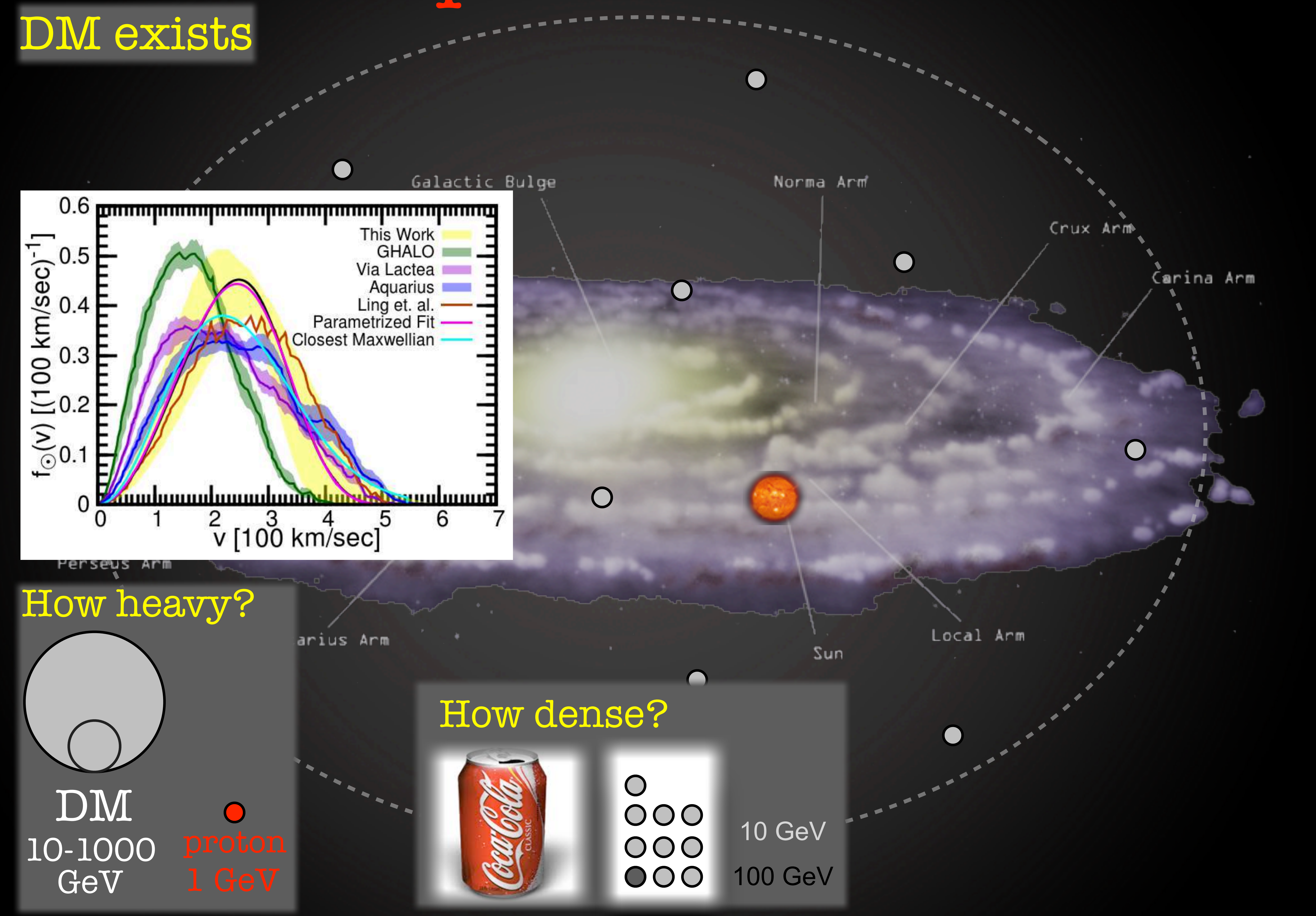
How heavy?



DM
10-1000 GeV

proton
1 GeV

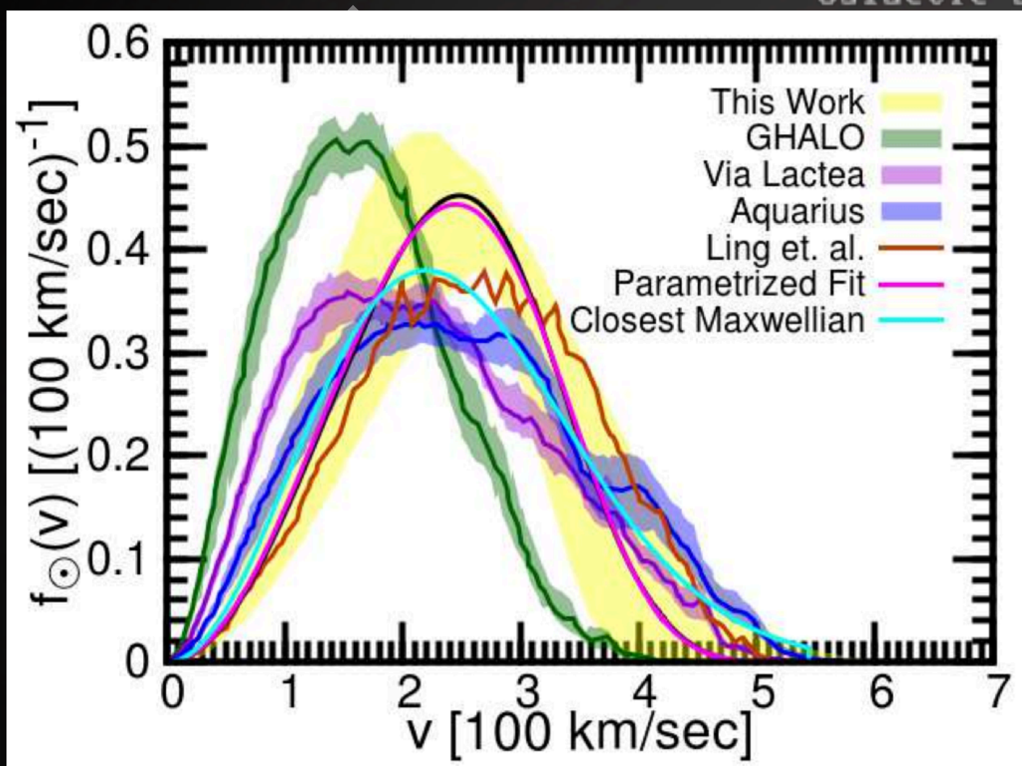
Recap: DM factsheet



Recap: DM factsheet

DM exists

They do not interact with normal matter nor with themselves, they fly freely thru matter



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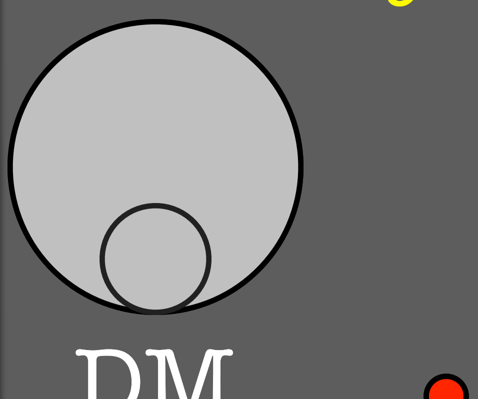
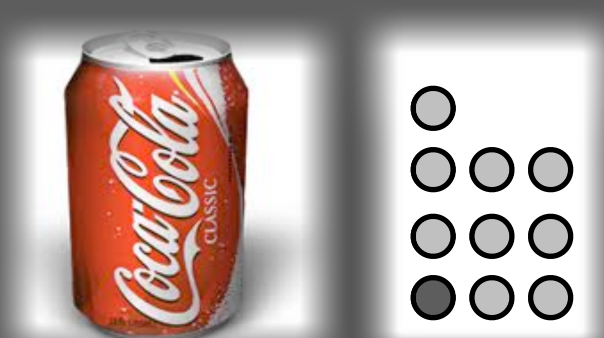


DM
10-1000
GeV

proton
1 GeV

How dense?

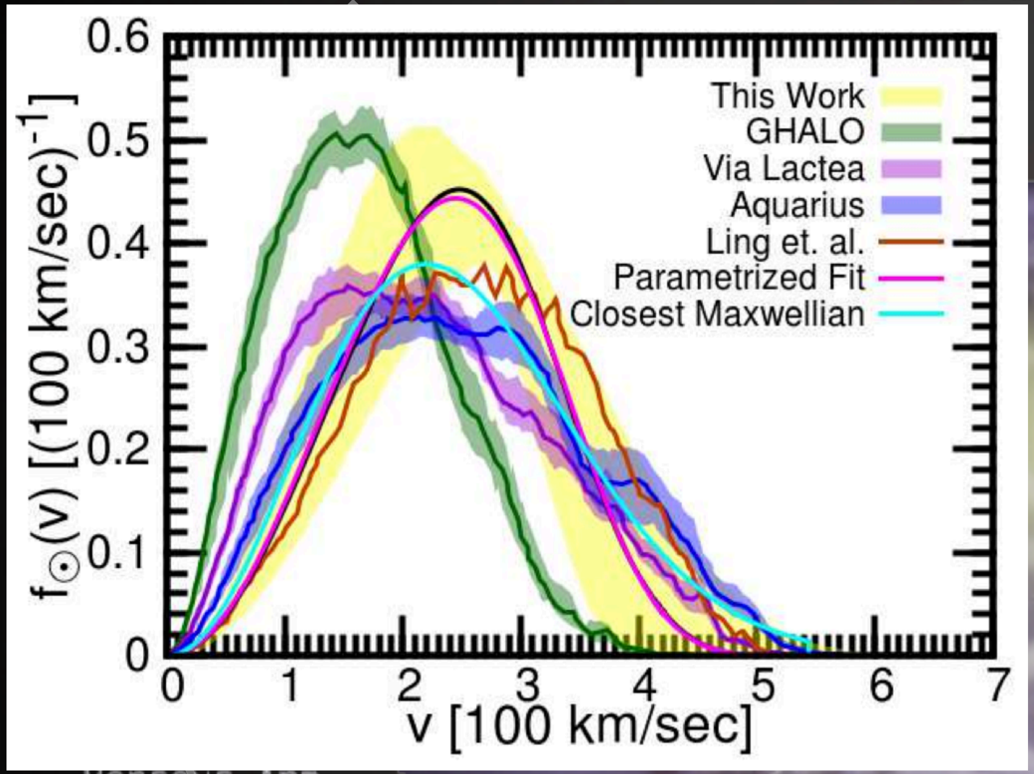


10 GeV

100 GeV

Recap: DM factsheet

DM exists



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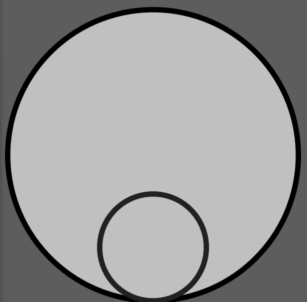

DM
10-1000 GeV

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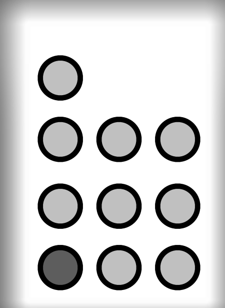

10 GeV

100 GeV

They interact a little little bit...

How was Dark Matter produced?

A thermal relic from the Early Universe

Consider a particle χ:

- subject to $\chi\bar{\chi} \rightarrow \ldots$
- ‘heavy’ (e.g. 100 GeV)
- ‘stable’
- in an expanding Universe
- symmetric abundance

A thermal relic from the Early Universe

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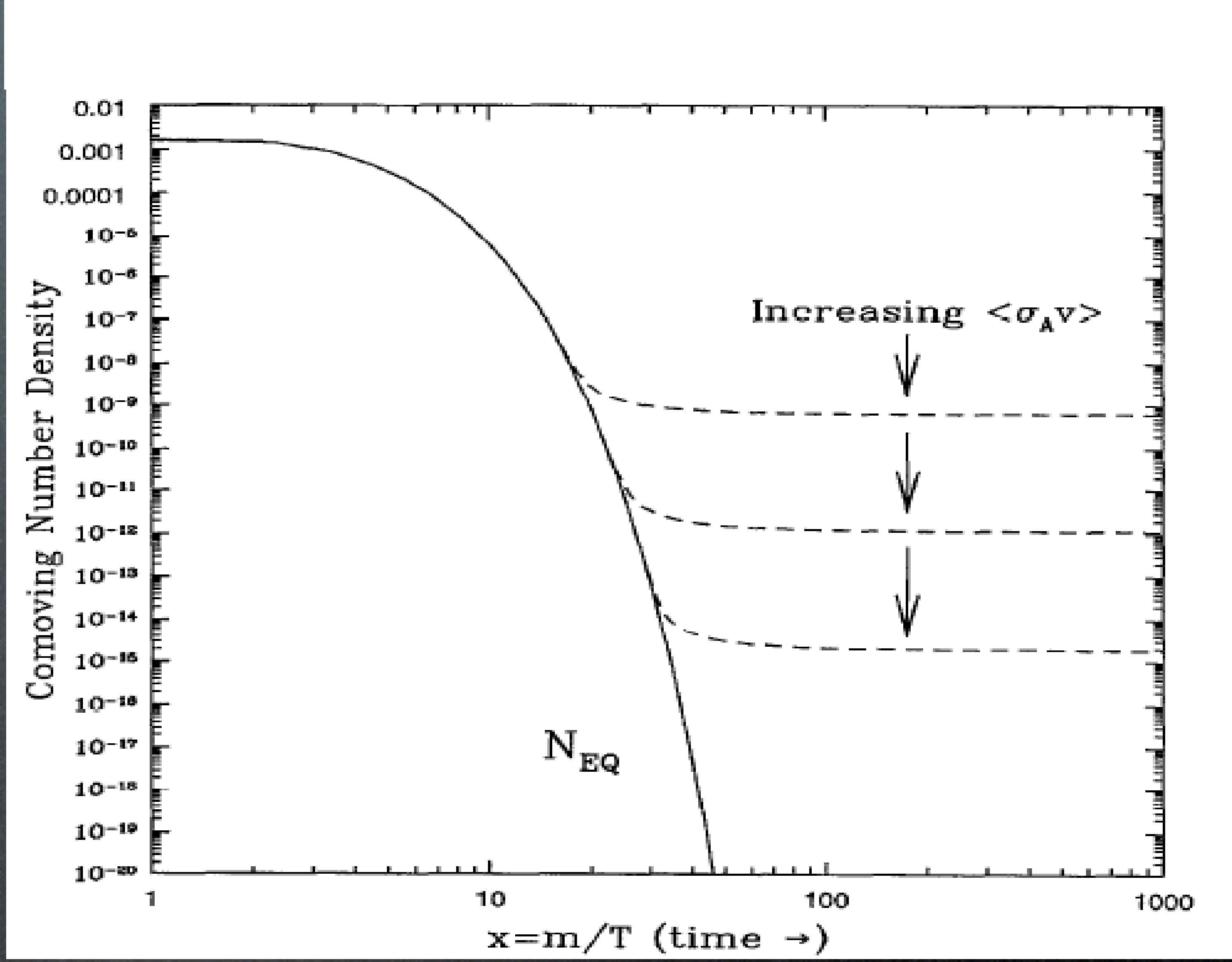

Kolb,Turner, The Early Universe, 1995

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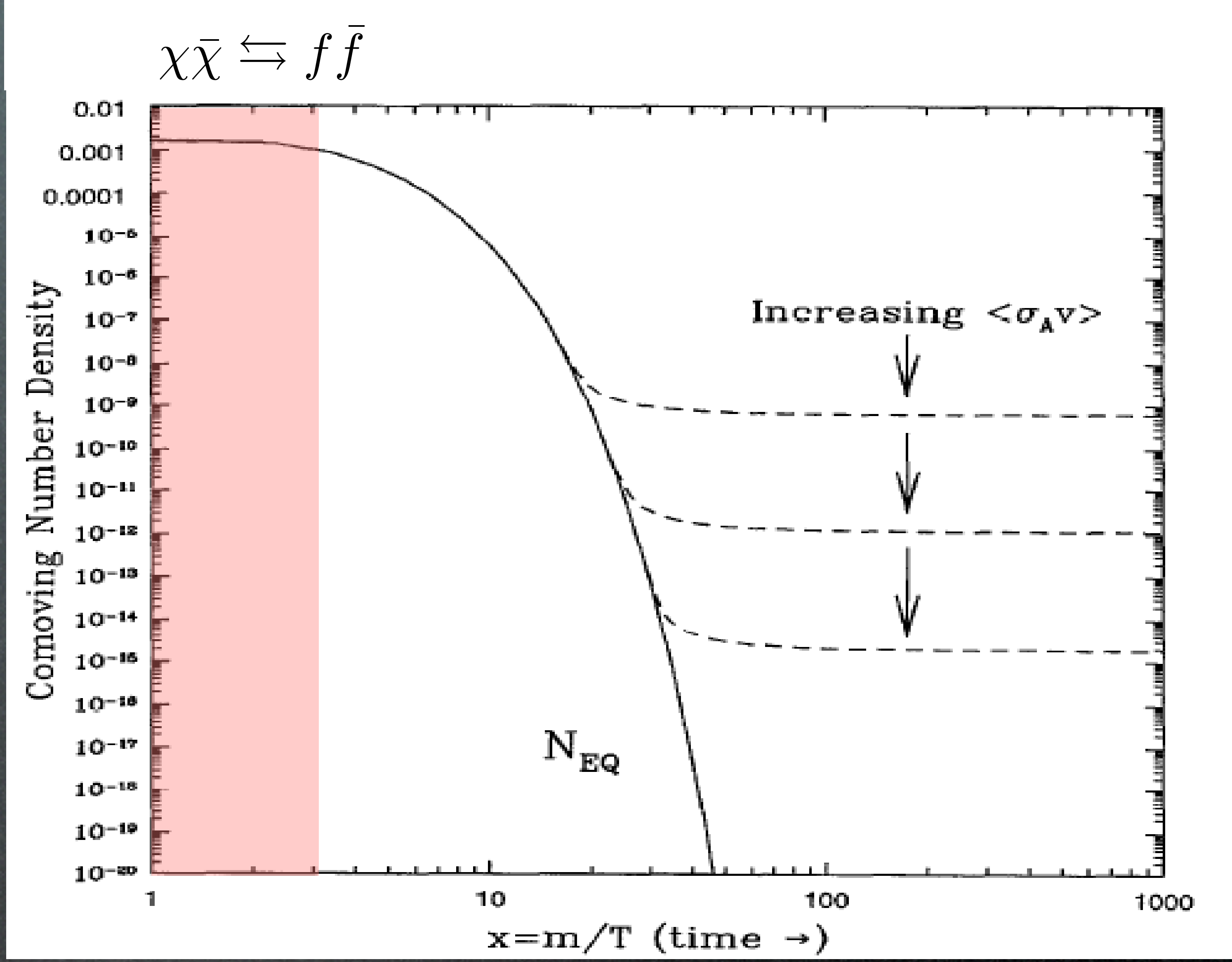

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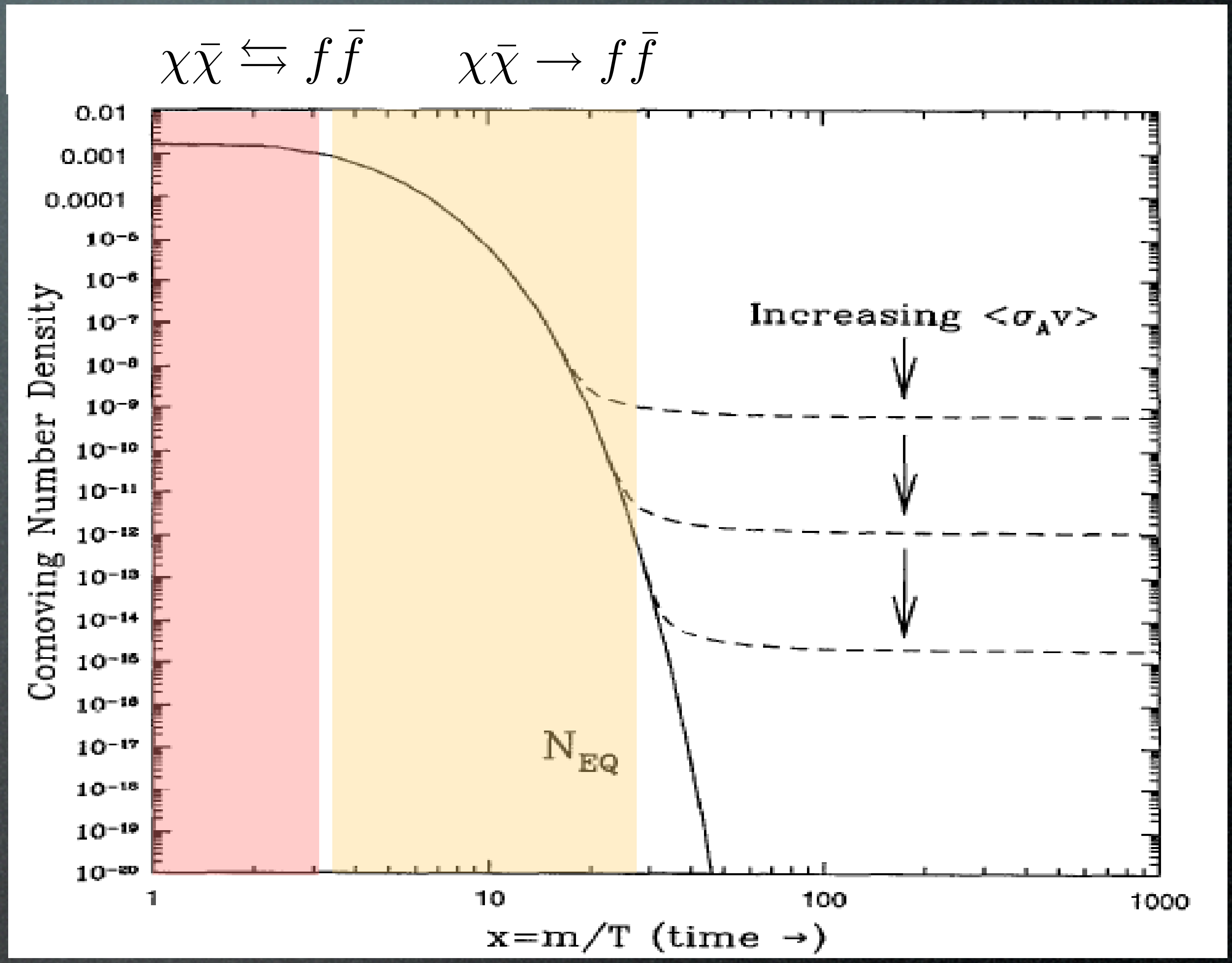

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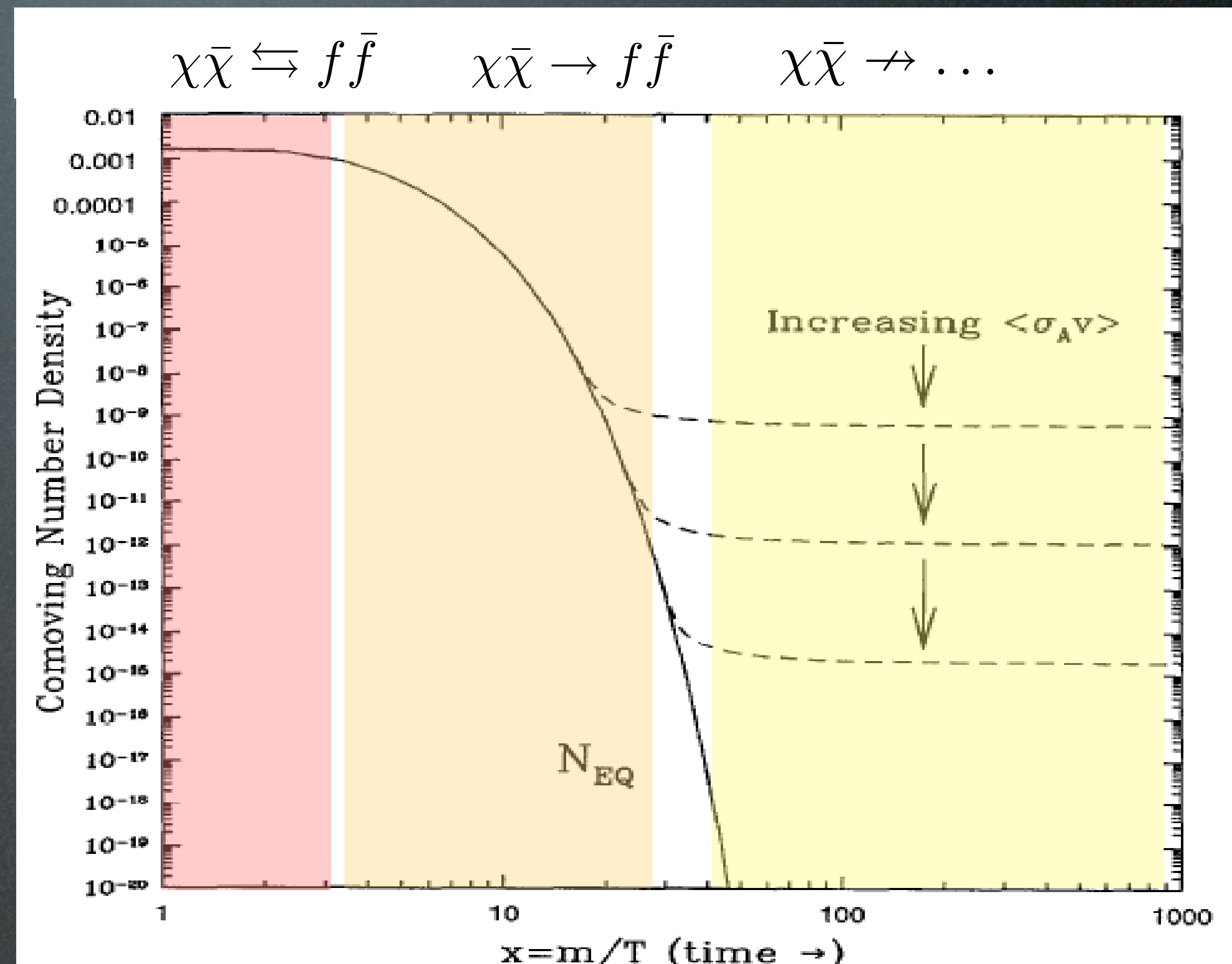

Kolb,Turner, The Early Universe, 1995

A thermal relic from the Early Universe

Boltzmann equation
in the Early Universe:

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma_{\mathrm{ann}} v \rangle}$$

Relic $\Omega_{\mathrm{DM}} \simeq 0.23$ for

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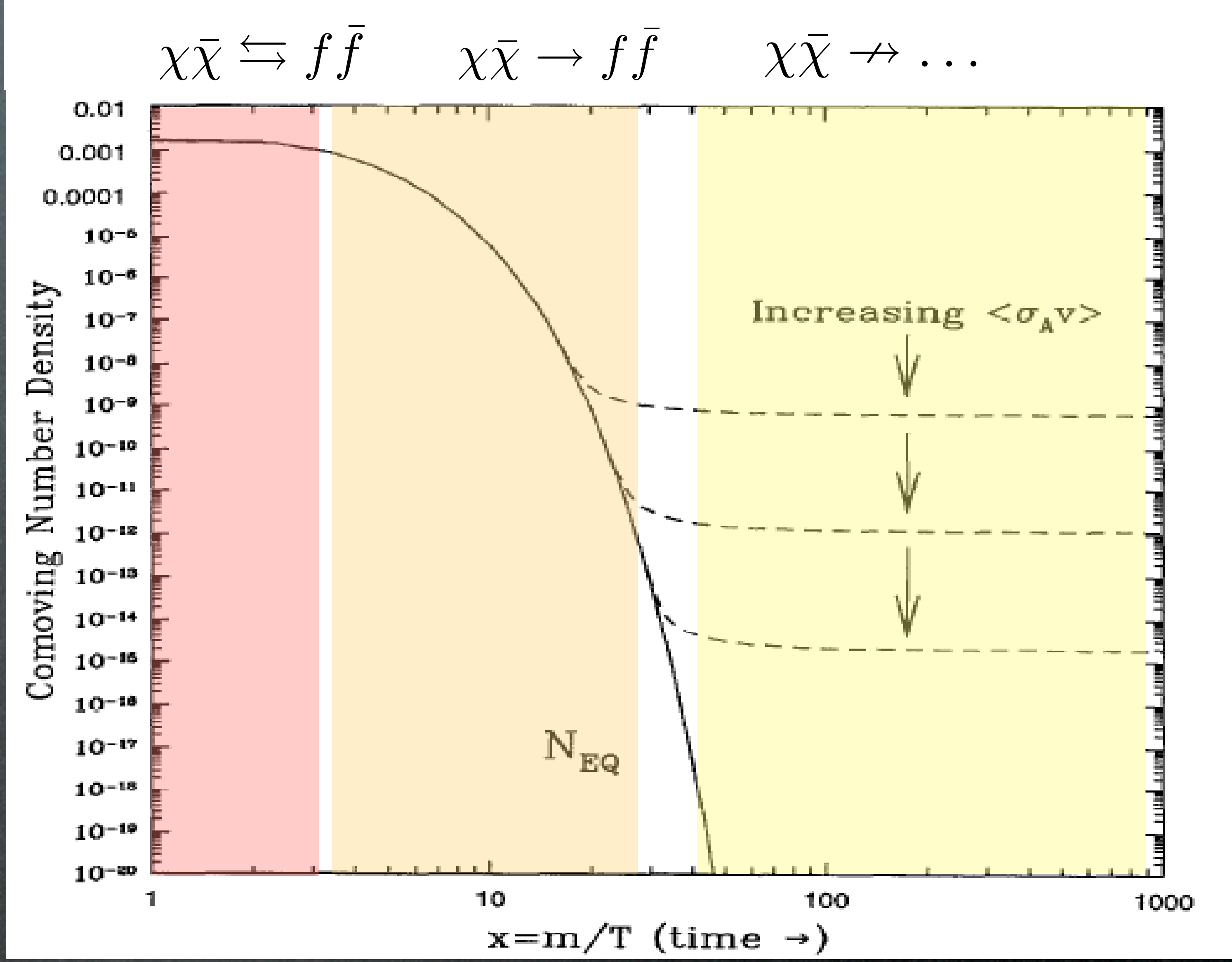

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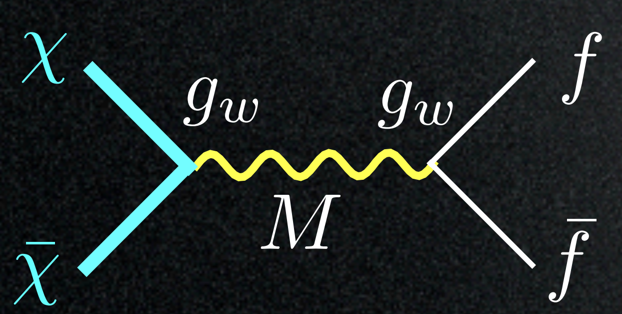

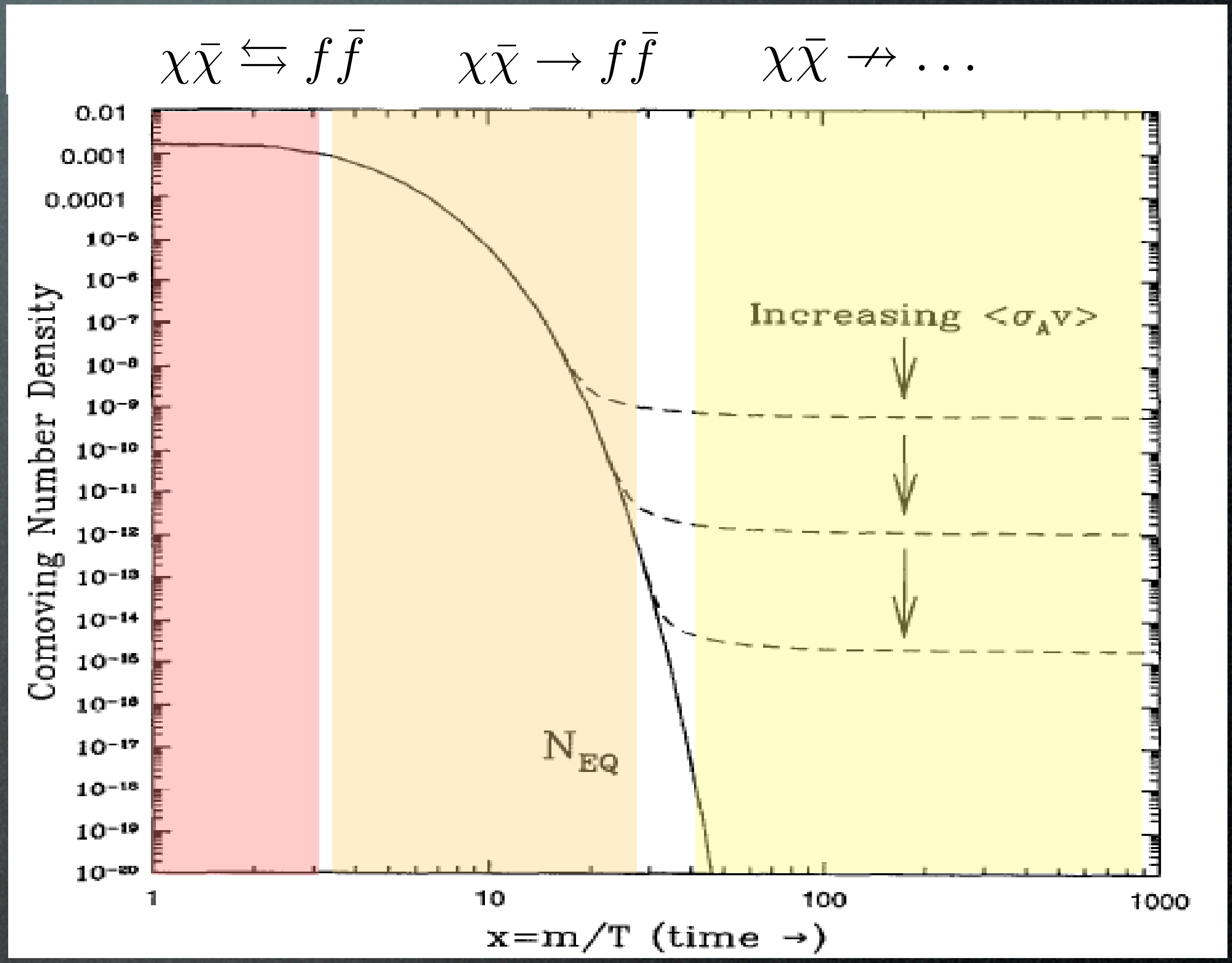

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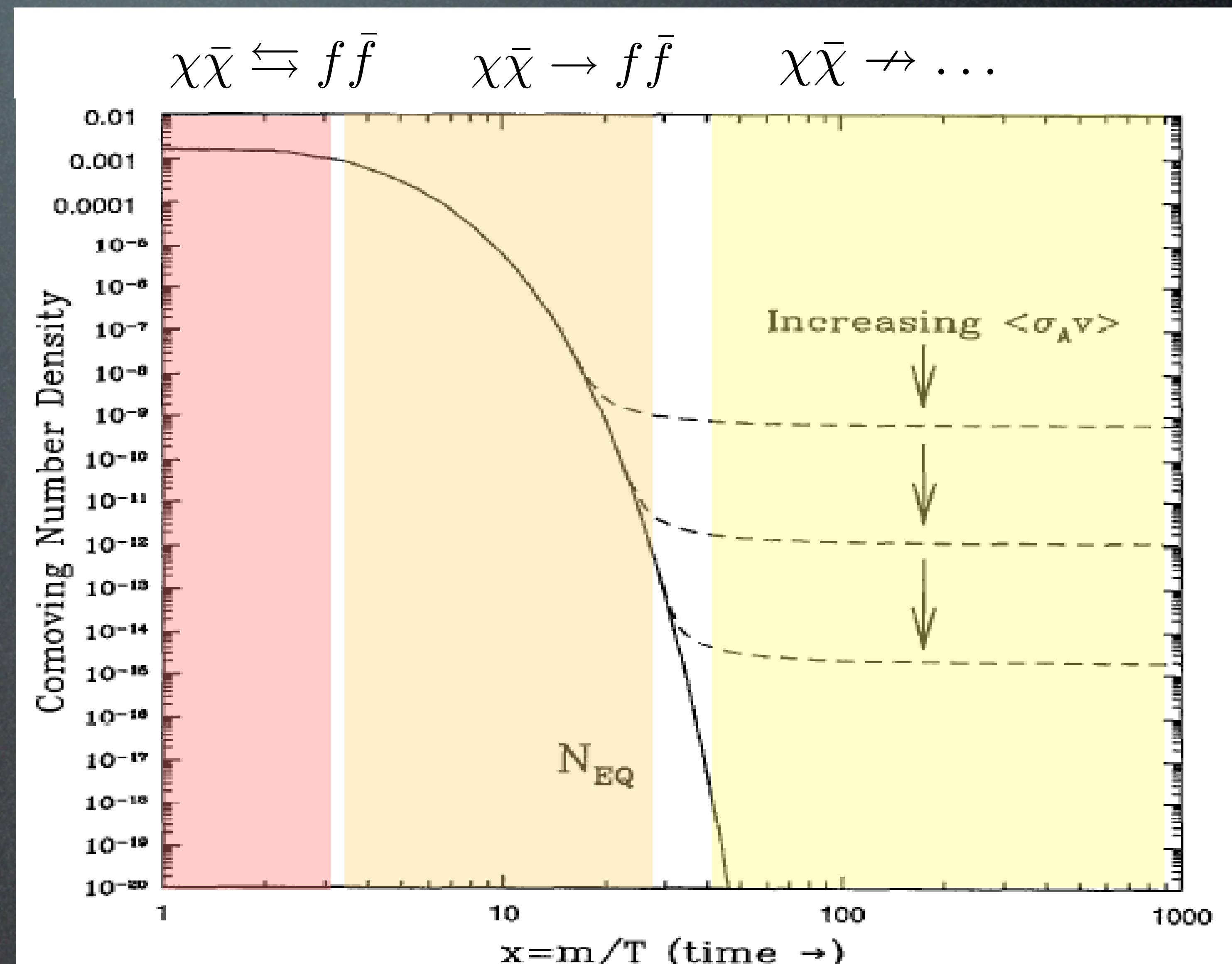

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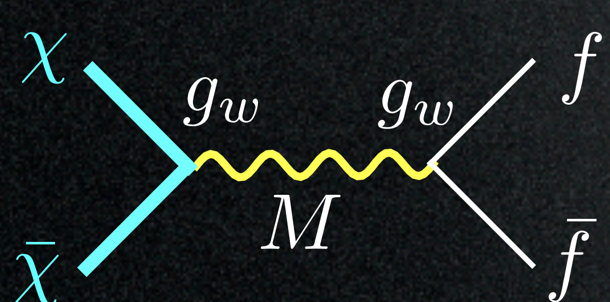

$$\langle \sigma_{\text{ann}} v \rangle \approx \frac{(g_w^2/4\pi)^2}{M^2} \approx 3 \cdot 10^{-26}\text{cm}^3/\text{sec}$$

WIMP *miracle!*

How do we search for Dark Matter?

DM detection

- direct detection
  Xenon, CDMS (Dama/Libra?)
- production at colliders
  LHC
- indirect
  - γ from annihil in galactic center or halo and from synchrotron emission
    Fermi, HESS, radio telescopes
  - e^+ from annihil in galactic halo or center
    PAMELA, ATIC, Fermi
  - $\bar{p}$ from annihil in galactic halo or center
  - $\bar{d}$ from annihil in galactic halo or center
    GAPS
  - $\nu, \bar{\nu}$ from annihil in massive bodies
    Icecube, Km3Net

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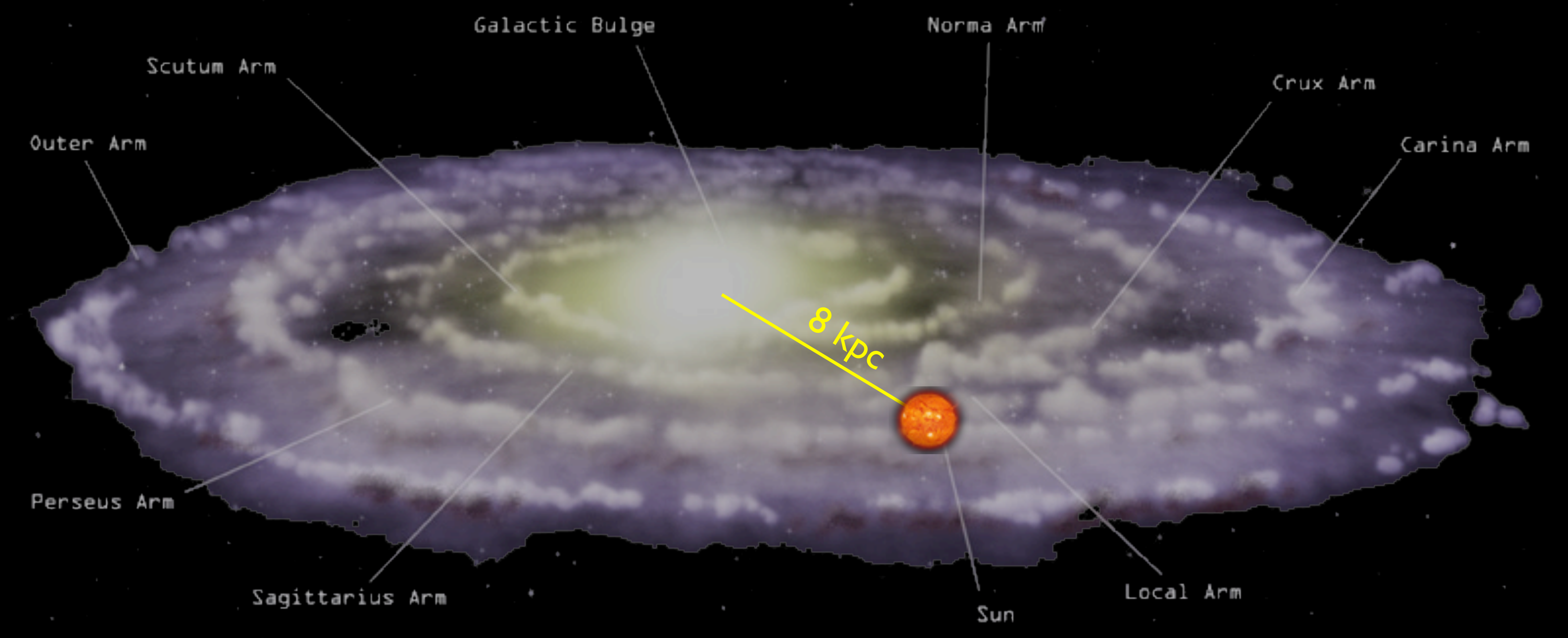
Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



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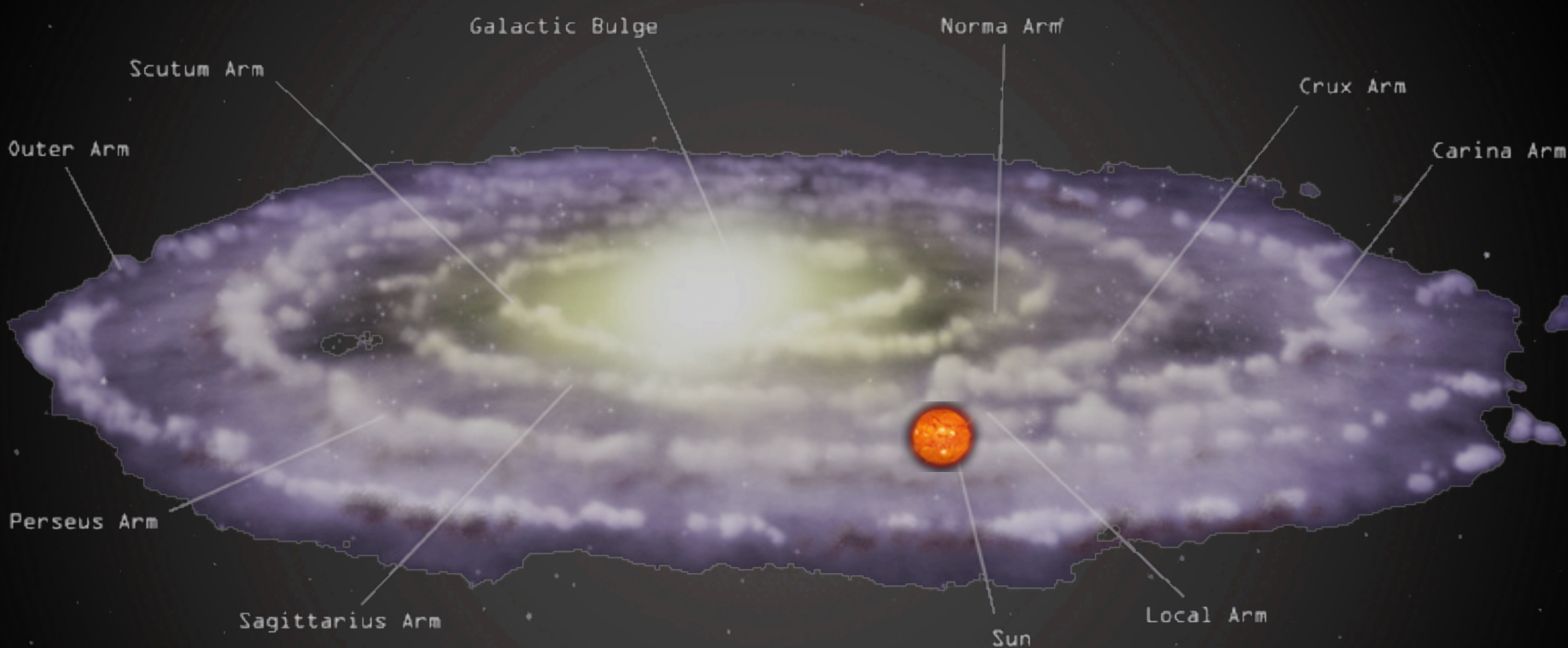

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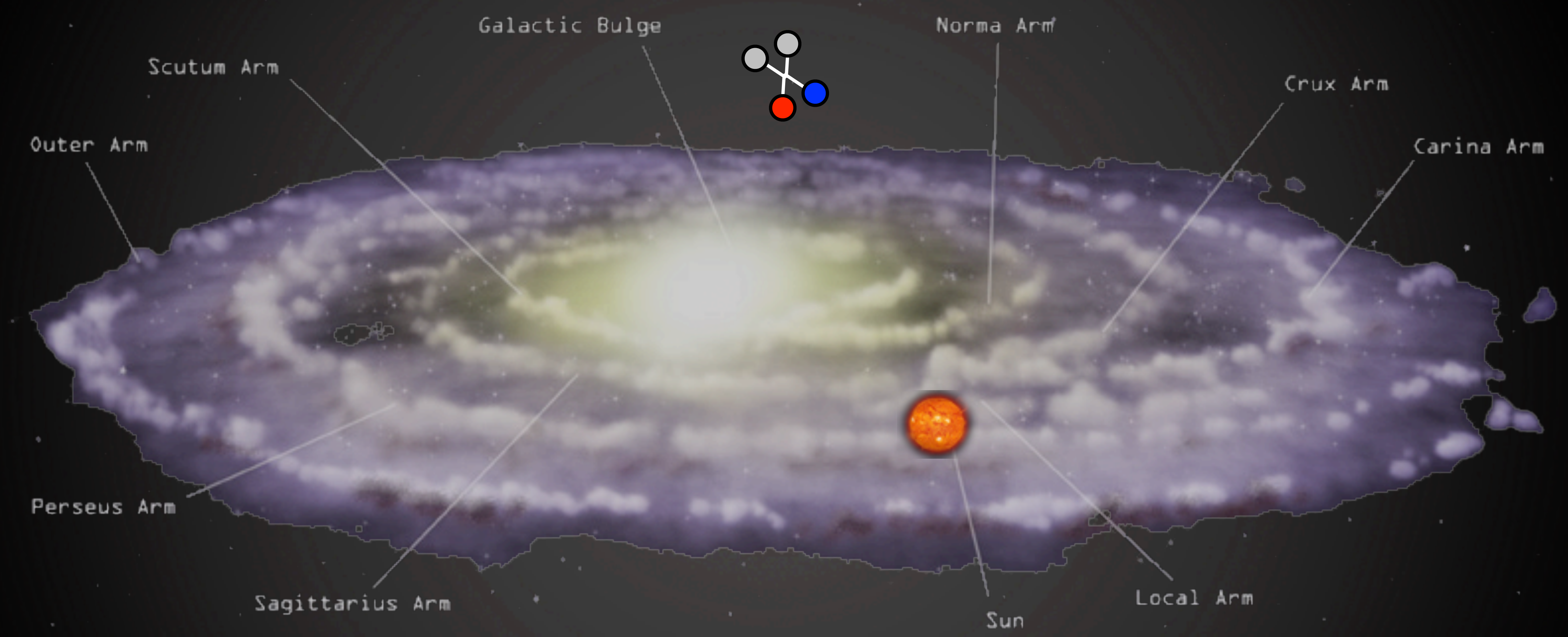

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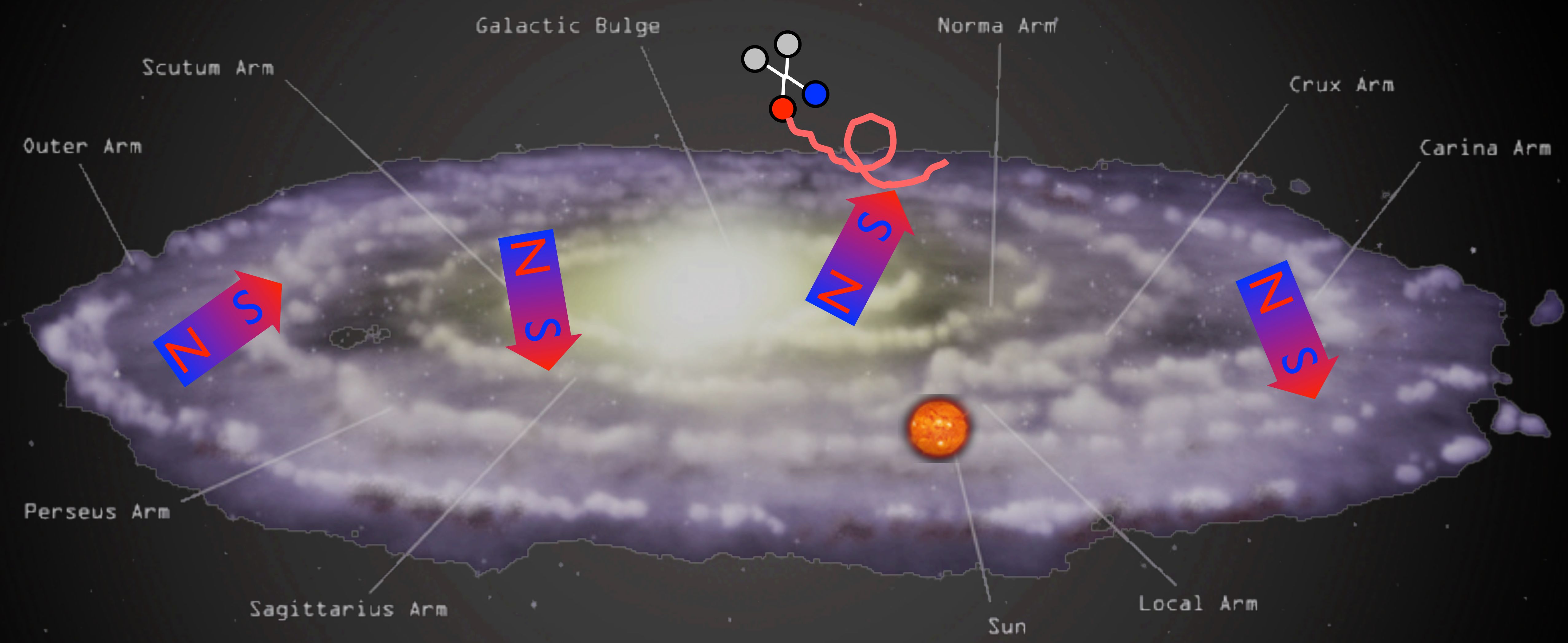

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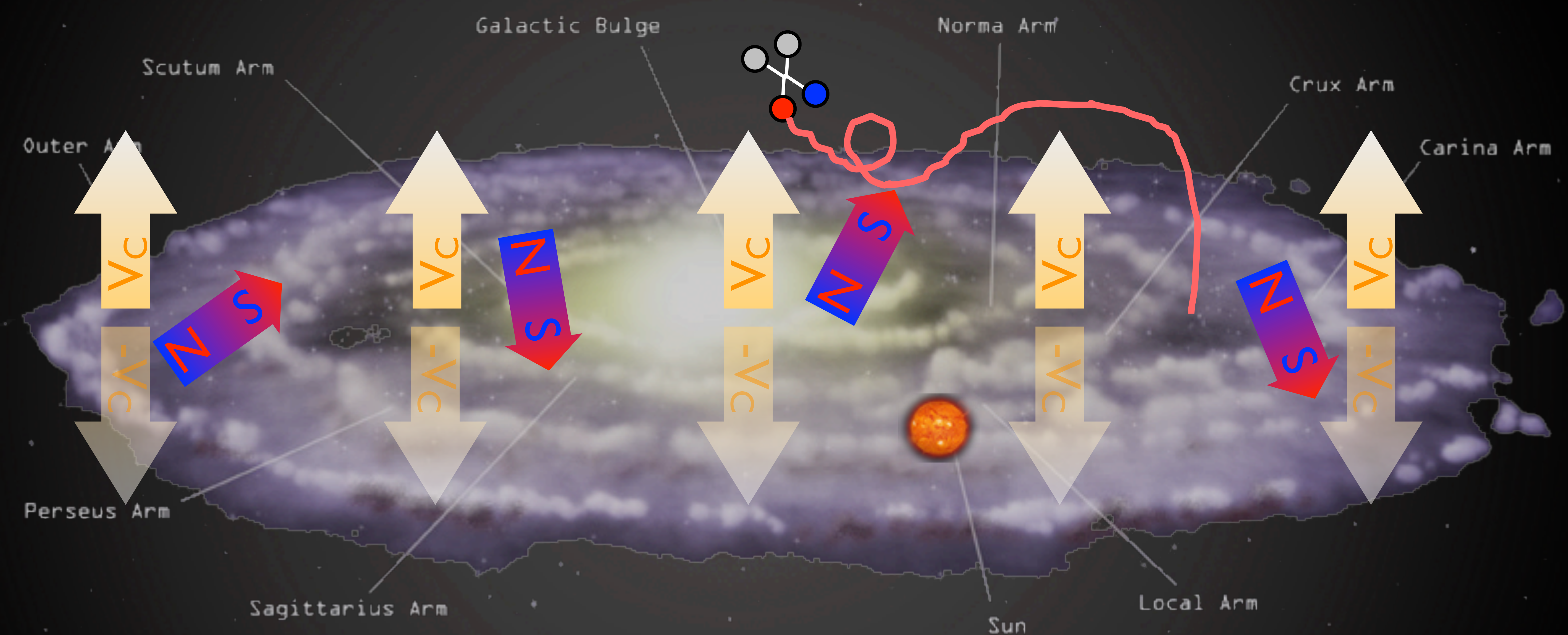

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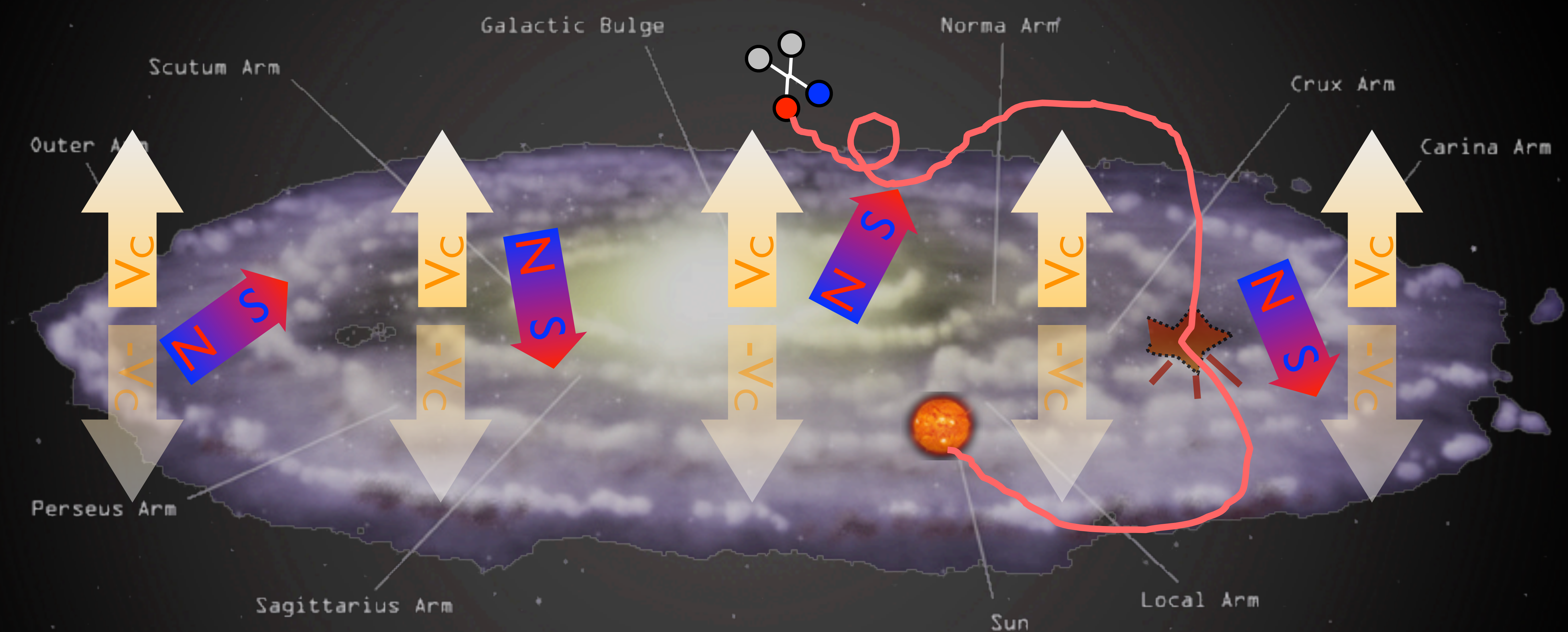
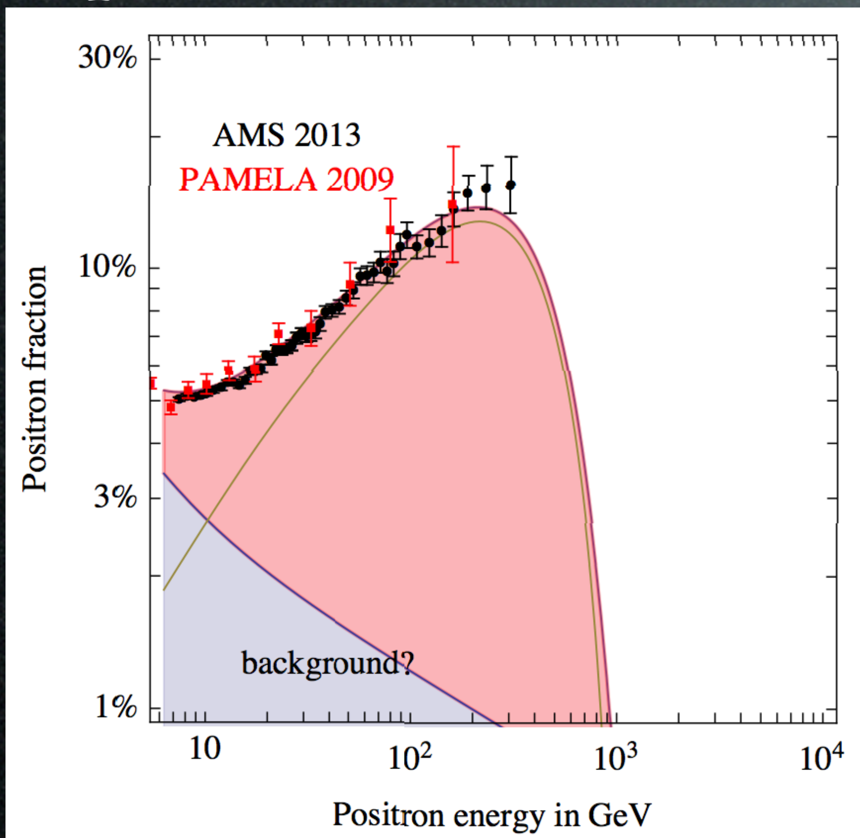
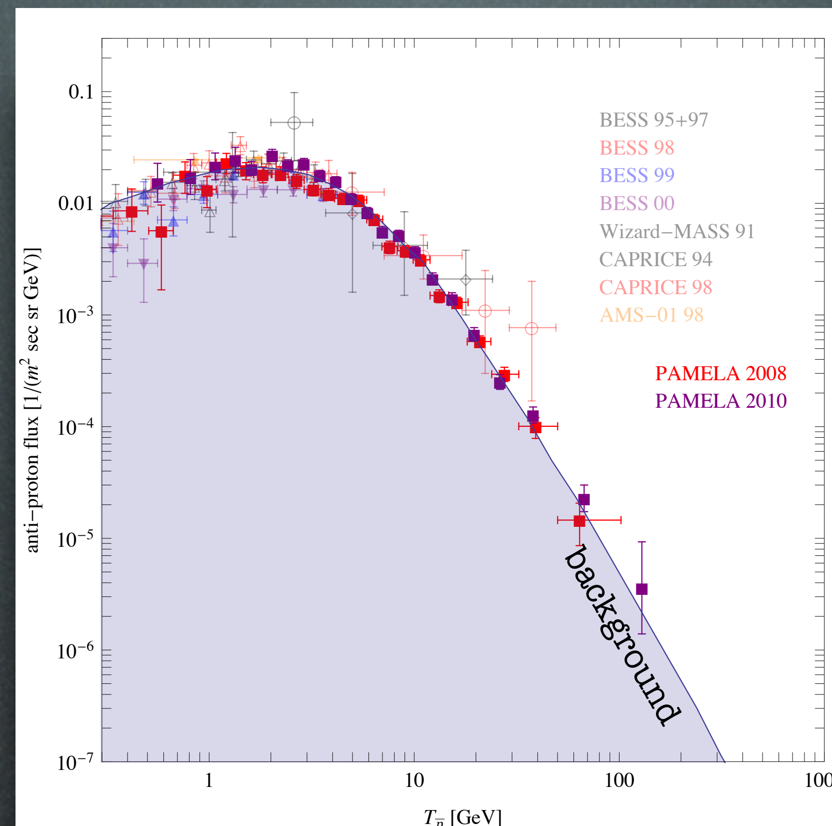


Results

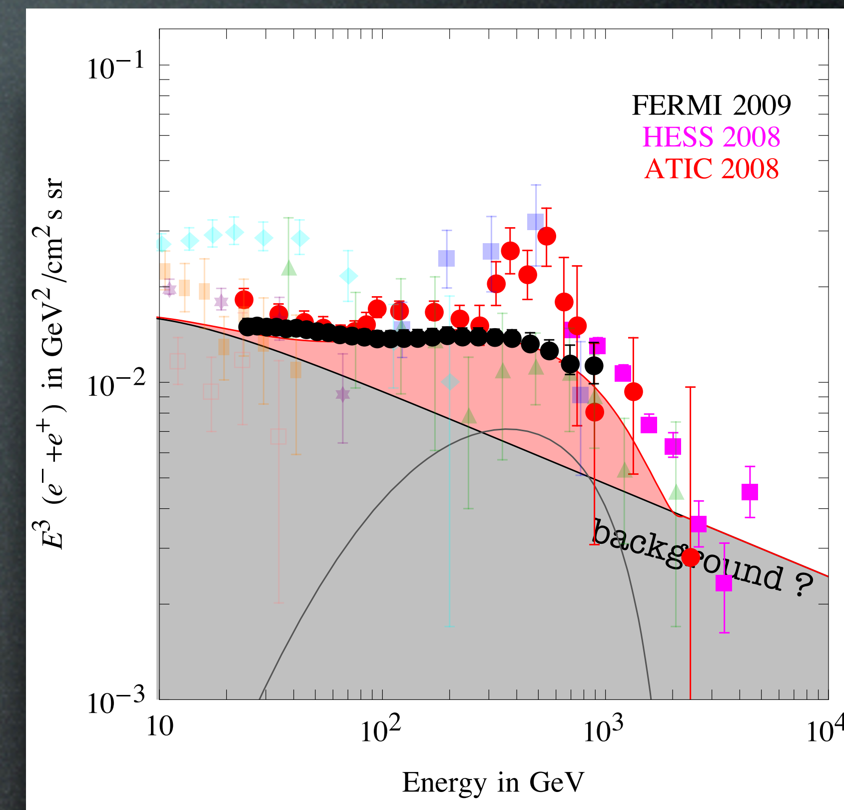
positron fraction



antiprotons



electrons + positrons



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YES: few TeV, leptophilic DM
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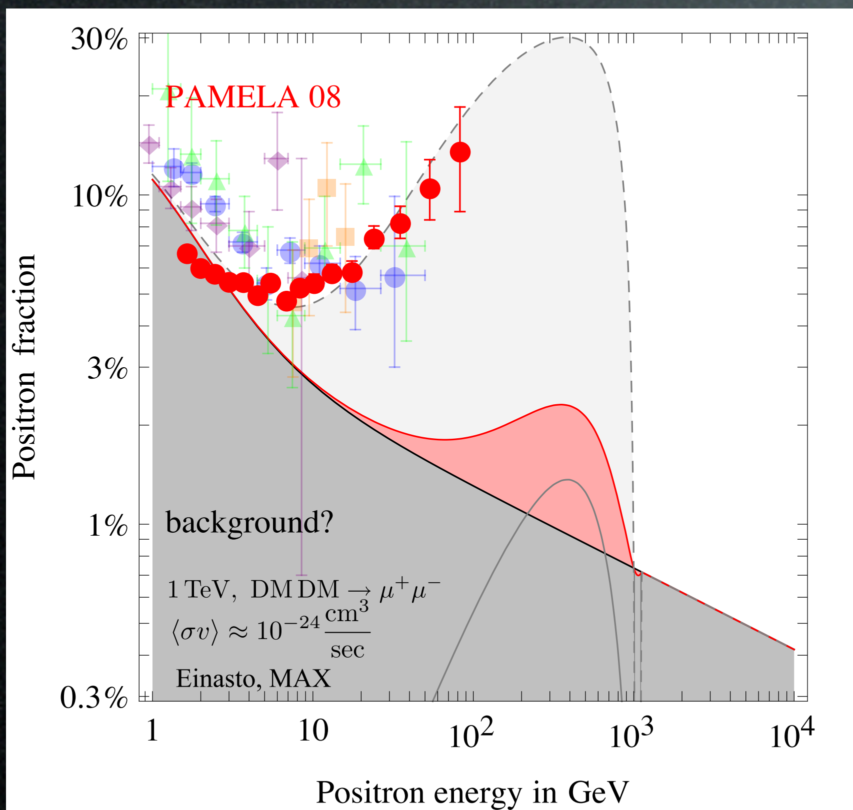

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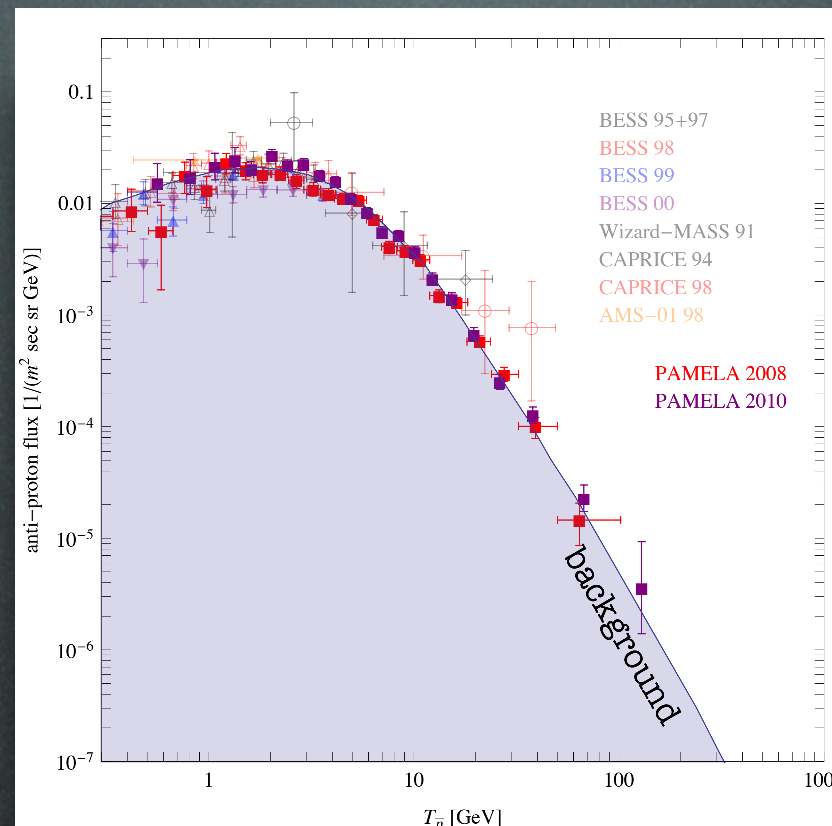

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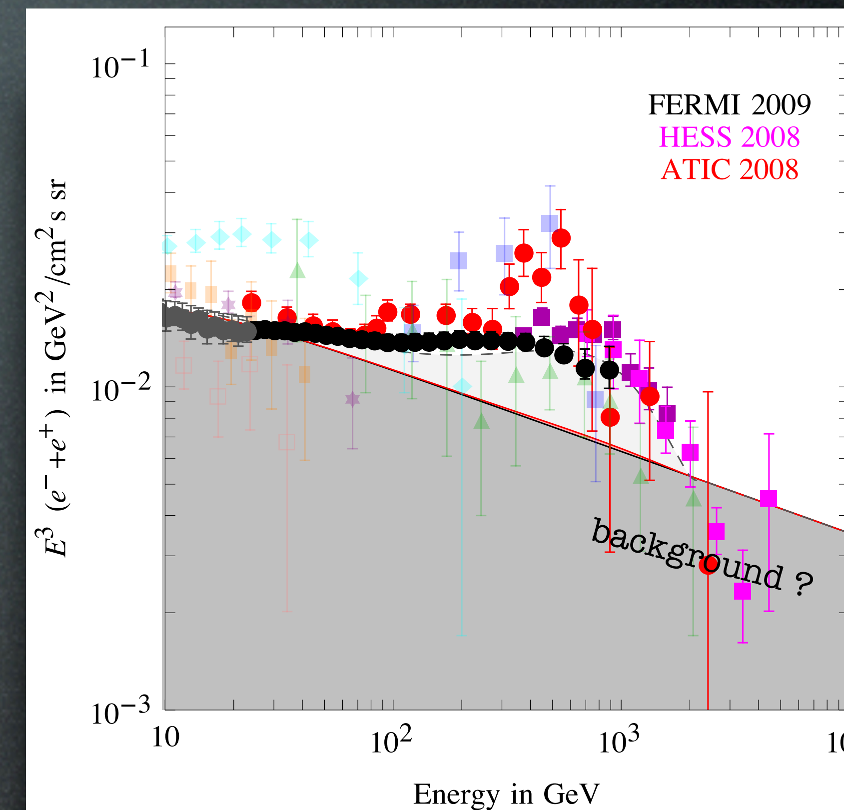

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NO: a formidable ‘background’ for future searches

Conclusions

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The 'era of data' is **now**.