Petnica Summer Institute (PSI 2015)

The Dark Matter Problem

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References

http://arxiv.org/abs/1301.0952

(S. Profumo lectures, TASI'12)

http://indico.ictp.it/event/a14277/speakers

(P. Serpico lectures , ICTP'15)

http://arxiv.org/abs/1211.7090

(L. Strigari review, SLAC'12)

"Particle Dark Matter - Observations, Models and Searches"

(book edited by G. Bertone)

Evidences

In 1933 Zwicky bravely claimed the existence of unseen matter, dubbed "Dark Matter" (DM), in the Coma Cluster

Optical image of the Coma cluster

1000 galaxies within a radius of about 1 Mpc

Assuming dynamical equilibrium
(time averages well defined)

$$2\langle T\rangle = -\langle V\rangle$$

VIRIAL THEOREM

Galaxies as N point particles:

$$\langle T\rangle = N\frac{\langle m\rangle\langle v^2\rangle}{2}$$

$$\langle V\rangle = -\frac{N^2}{2}G_N\frac{\langle m\rangle^2}{\langle r\rangle}$$

$$\Rightarrow\ M_{tot}\simeq N\langle m\rangle\simeq\frac{2\langle v^2\rangle\langle r\rangle}{G_N}$$

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(time averages well defined)

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2 orders of magnitude for mass-to-light ratio of a galaxy in Coma cluster with respect to mass-to-light for stars observed in our solar local neighborhood !

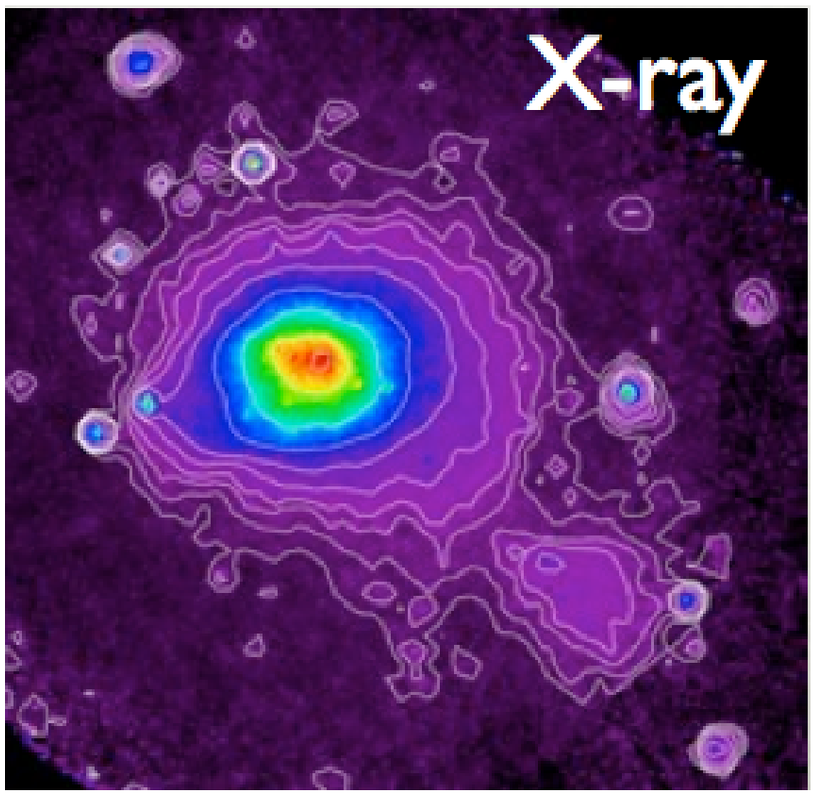
Modern proofs from clusters: X-rays !

Most baryonic mass is in the form of hot intercluster medium

temperature about $10^{7\text{-}8}$ K , bremsstrahlung emission from electrons in the ionized medium

X-ray luminosity → gas density map

X-ray spectra → temperature map, i.e. pressure maps.



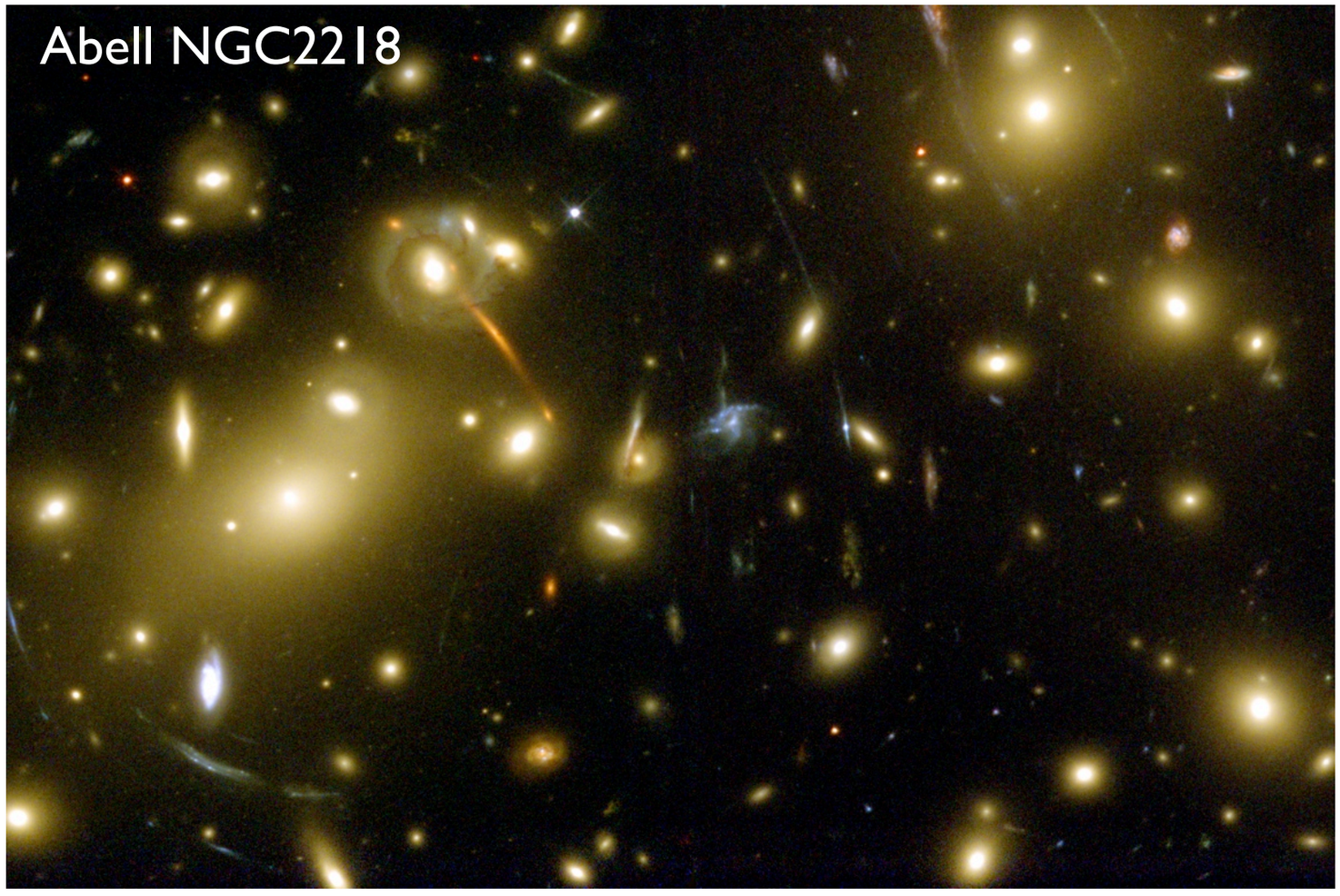
Coma galaxy cluster

Assuming spherical symmetry and hydrostatic equilibrium :

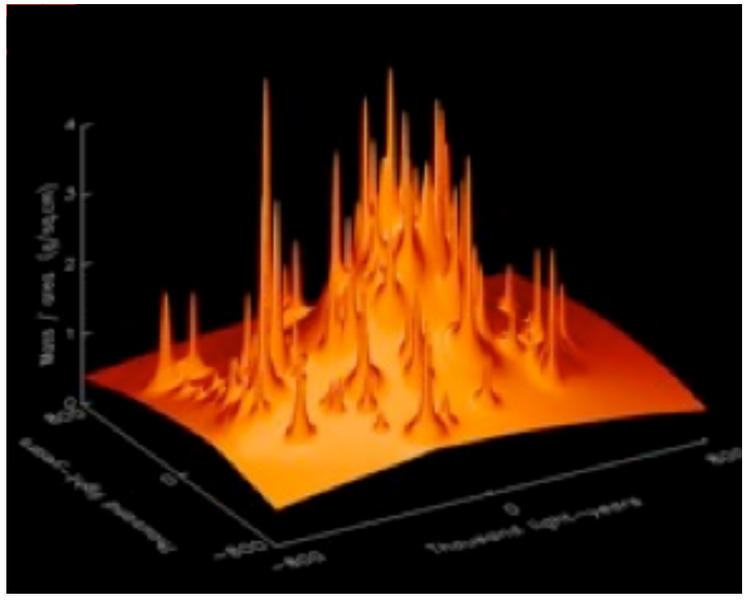
$$\frac{dP_g}{dr} = G_N \frac{M(<r)\rho_g}{r^2}$$

a factor ~ O(10) of more mass than the one in gas form it is inferred

Light from distant galaxies is "lensed" by the gravitational field of some massive objects along the line of sight ...



mass tomography of e.g. an intervining cluster through gravitational lensing



Presence of Dark Matter smoothly distributed in-between galaxies is required (actually dominating the total potential)

(Paraficz et al. '12)

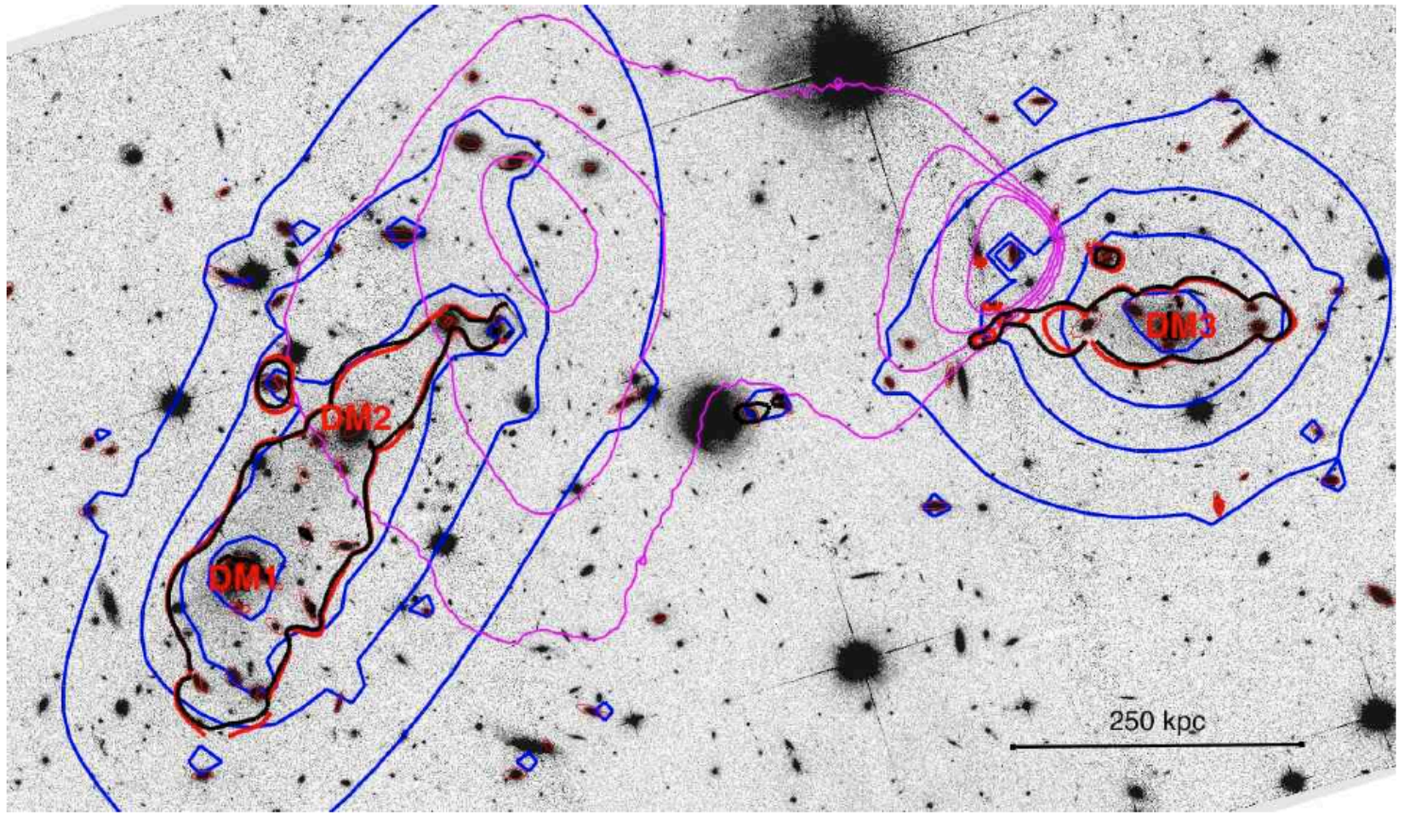
Color code :

X-ray image: magenta

Strong lensing map: blue

"The Bullet Cluster"

1E 0657-56

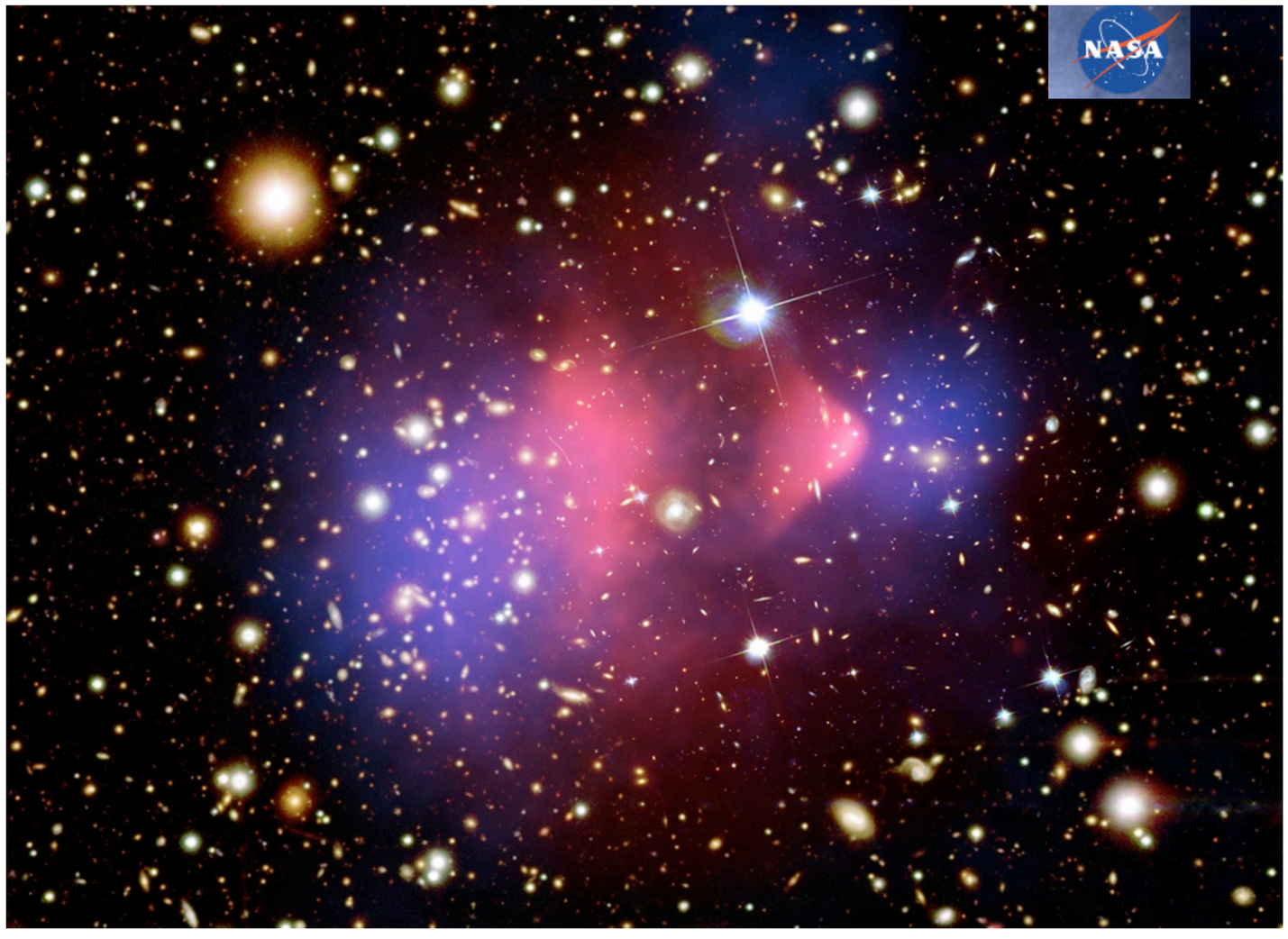


Color code:

X-ray image: pink

Optical: orange/white

Weak lensing map: blue



CHANDRA X-RAY OBSERVATORY

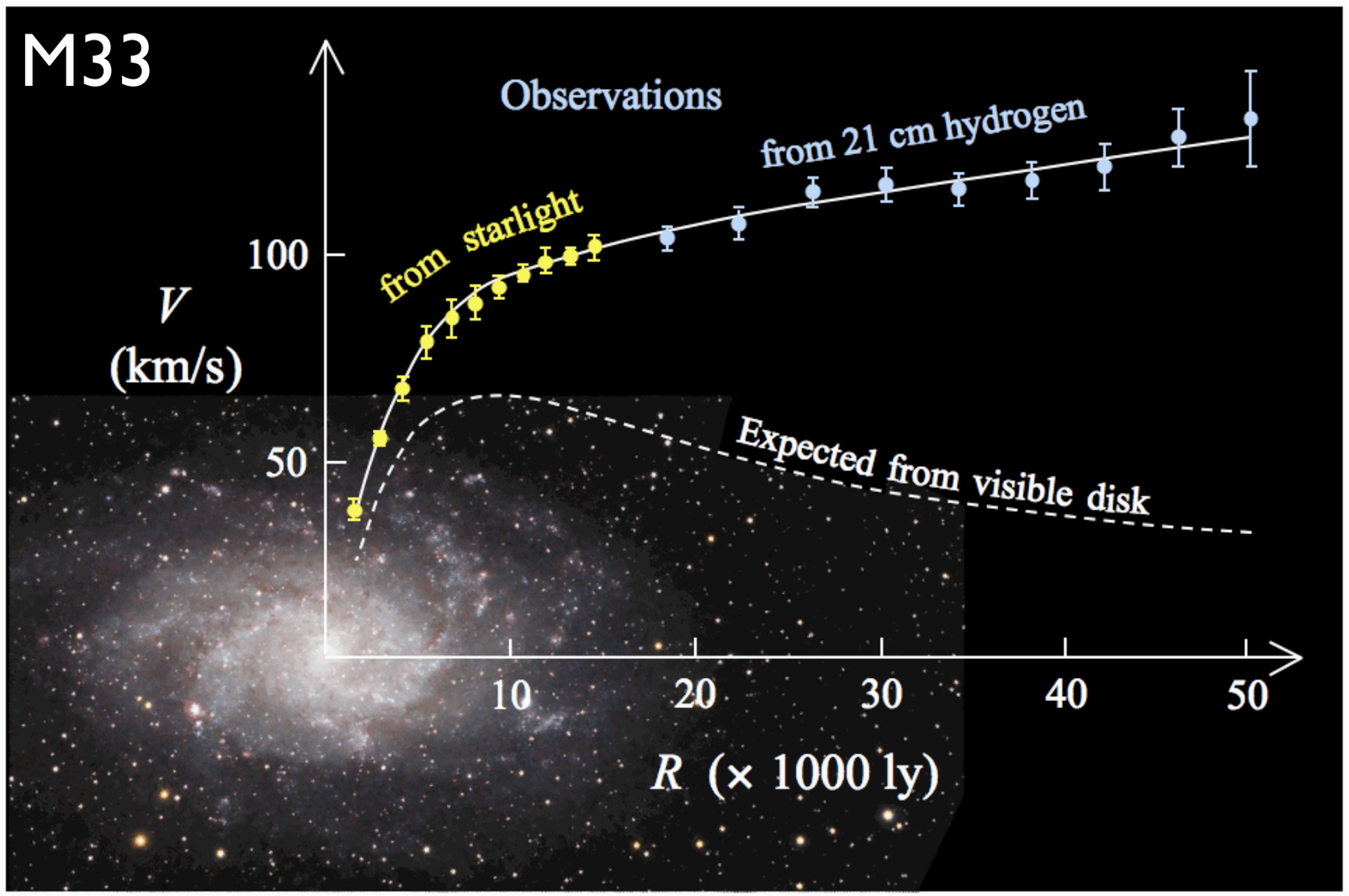
Image credit:

X-ray: NASA/CXC/CfA/M.Markevitch et al.;

Optical: NASA/STScI; Magellan/U.Arizona/ D.Clowe et al.;

Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

We have evidences of DM @ galactic scales (~ kpc)



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

Outside the visible mass scale one has :

$$M(<r) = M_{tot}$$

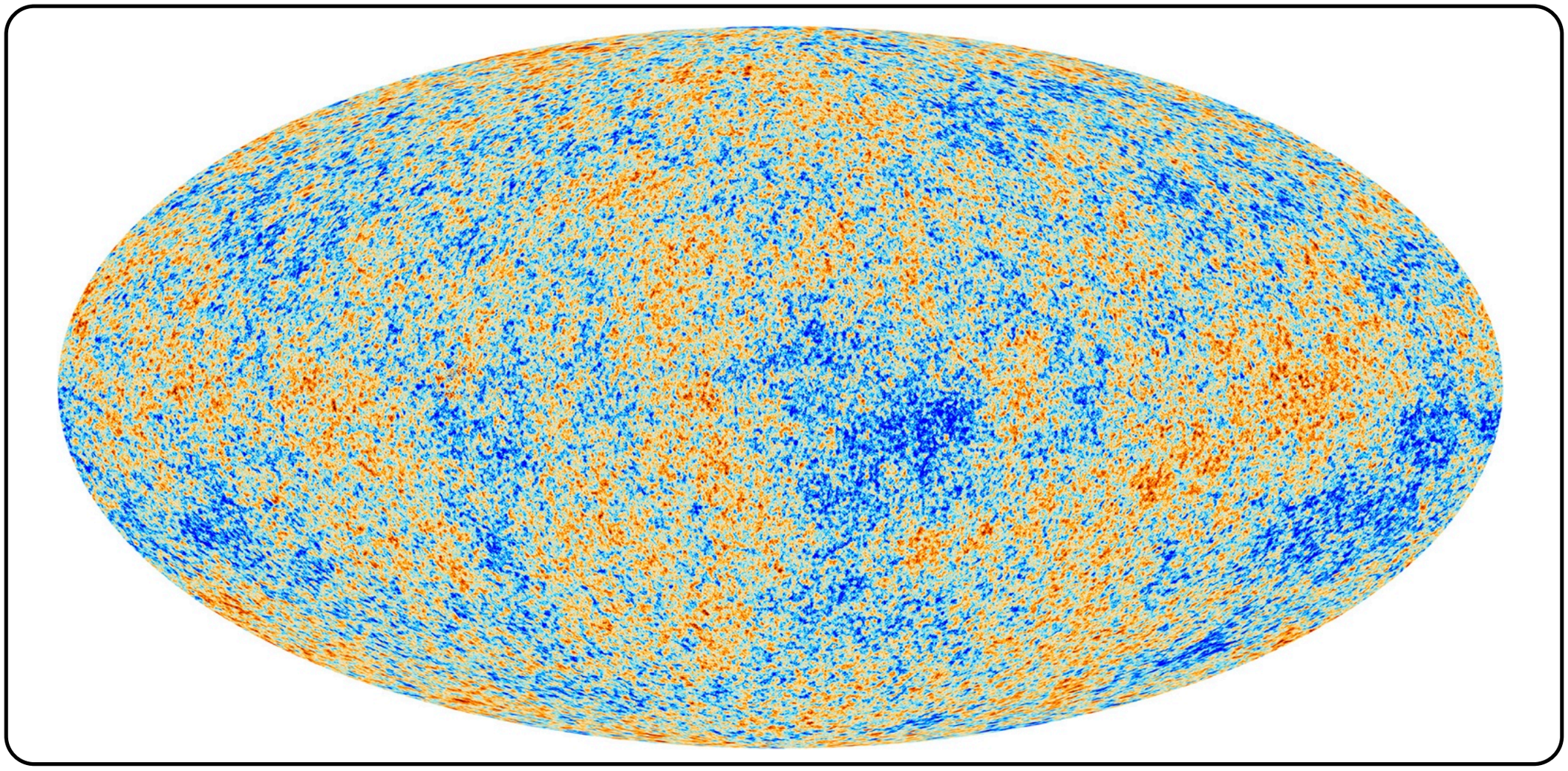
Keplerian fall-off expected, $v_c \sim r^{-1/2}$!

$$v_c = const. \;\Rightarrow\; M_{DM}(r) \propto r \;\Rightarrow\; \rho_{DM}(r) \propto r^{-2}$$

OK ... but why not a modification of Gravity laws ?

Cosmological probes can possibly answer to this question.

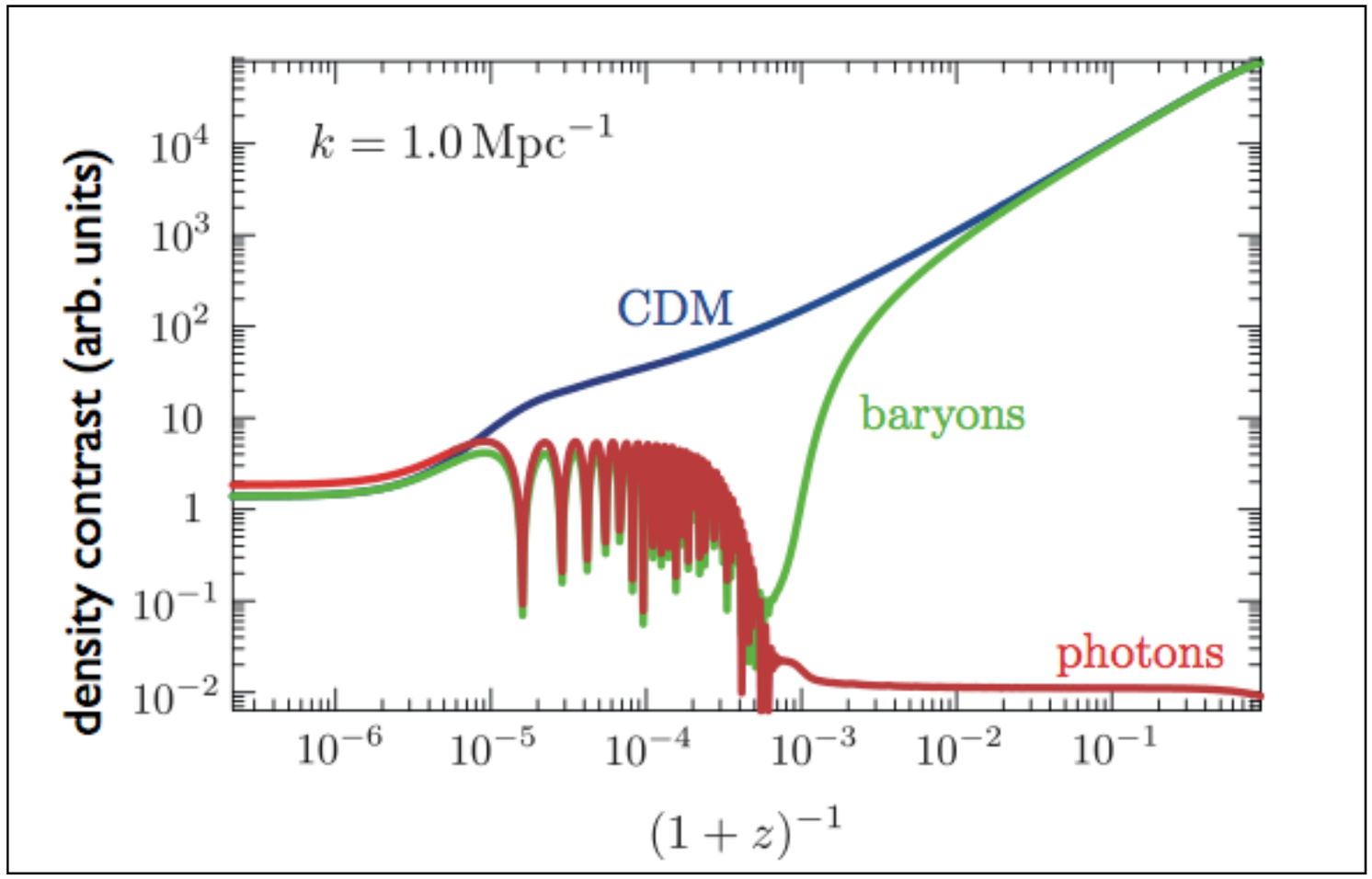
Baryons and photons were coupled before recombination,
380000 years after the Big Bang (13.7 billions of years ago).



At that time, they behaved as a single gas, sharing the same "perturbations",
which propagated like sound waves with amplitudes of the order of $O(10^{-5})$.

The collapsed structures we see nowadays are the result of the evolution of these perturbations in deep potential wells related to a lot of gravitating matter.

Looking closer @ the growth of structures :

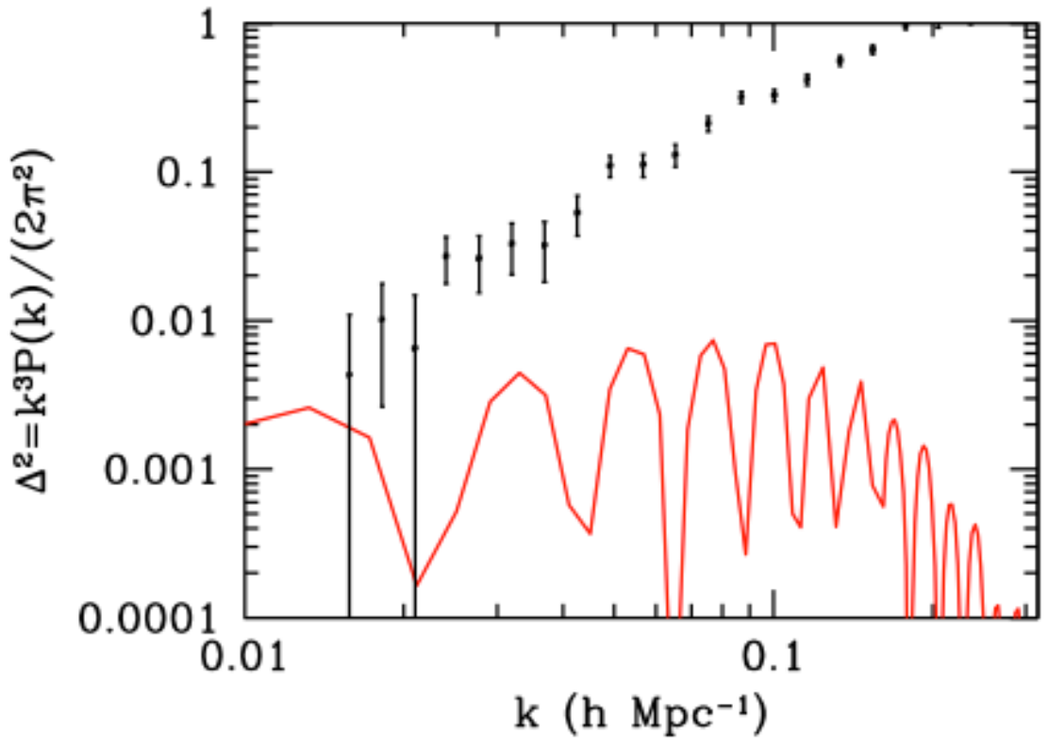


As far as barionic gas is ionized, it is coupled to radiation and oscillates: pressure prevents overdensities to grow.

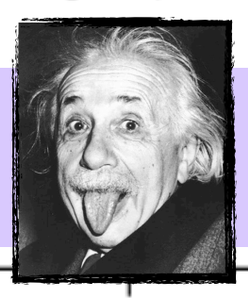
The uncoupled pressureless DM mode instead grows!

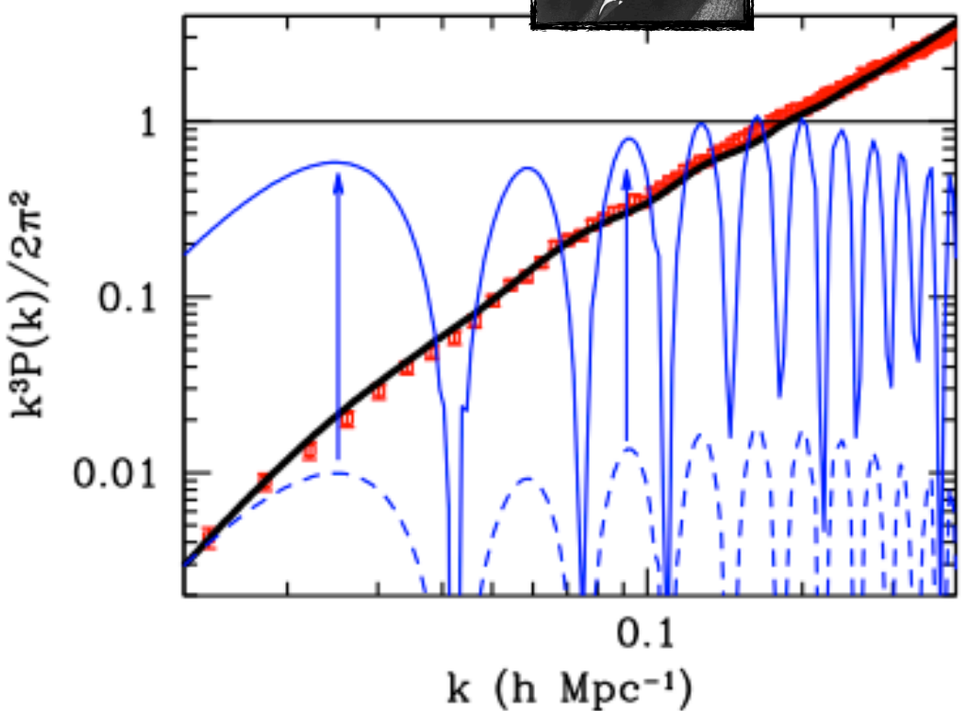
After recombination, baryons fall quickly in these DM deep potential wells: w/o DM they need much longer to reach the same level of density contrast!

What if only baryons were present in the game?



Non-linear structures absent!
Pattern of "clumpiness" complitely different!

What if we modify  in place of the DM component?



Models where one modifies GR do not allow easily for the "right growth" of structures

Precision Cosmology era points to DM existence.

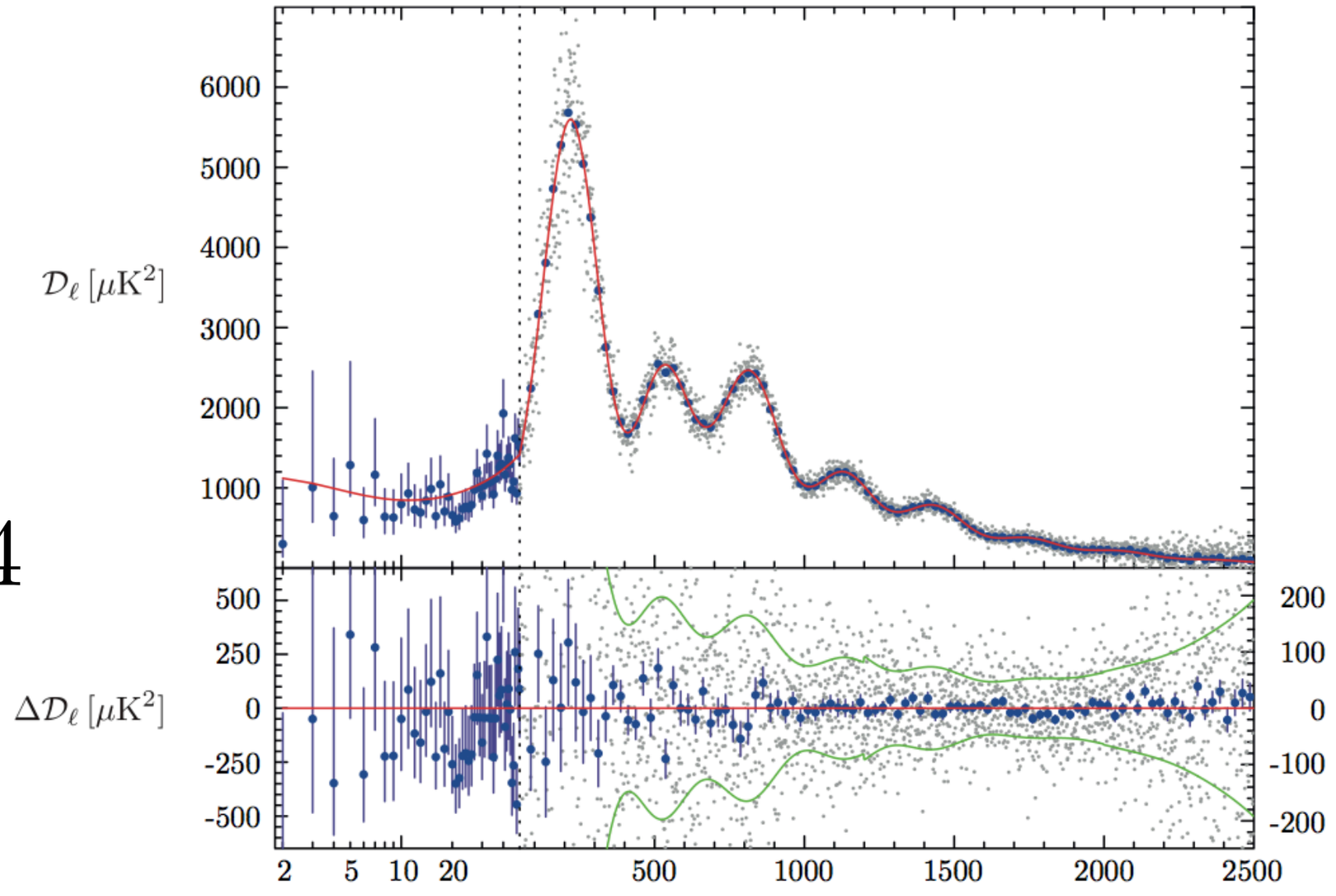
ΛCDM → assuming GR and a given set of constituents , we get access to how the total energy budget of the Universe is distributed within these components

$$\Omega_\Lambda \simeq 0.73$$

$$\Omega_M \simeq 0.27$$

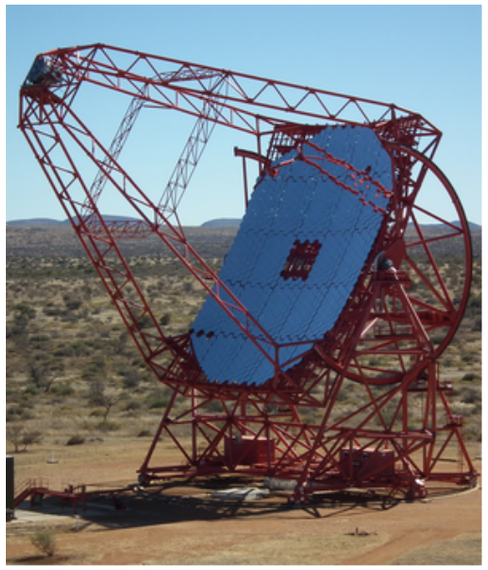
$$\Omega_b \simeq 0.04$$

in agreement with BBN



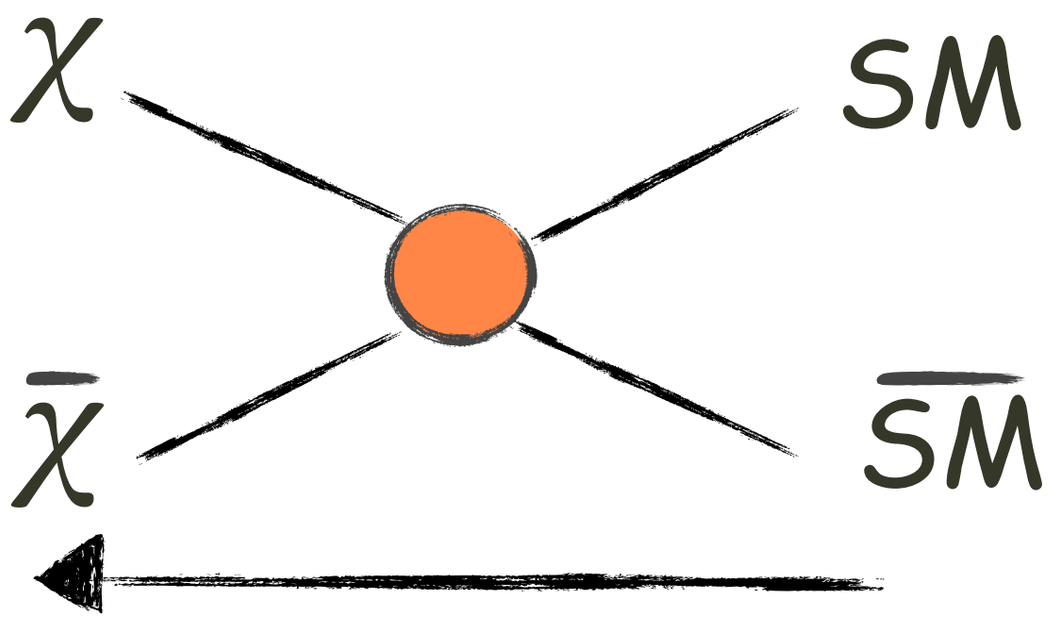
Dark Matter, as a pressureless fluid, dominates the Matter component of our Universe

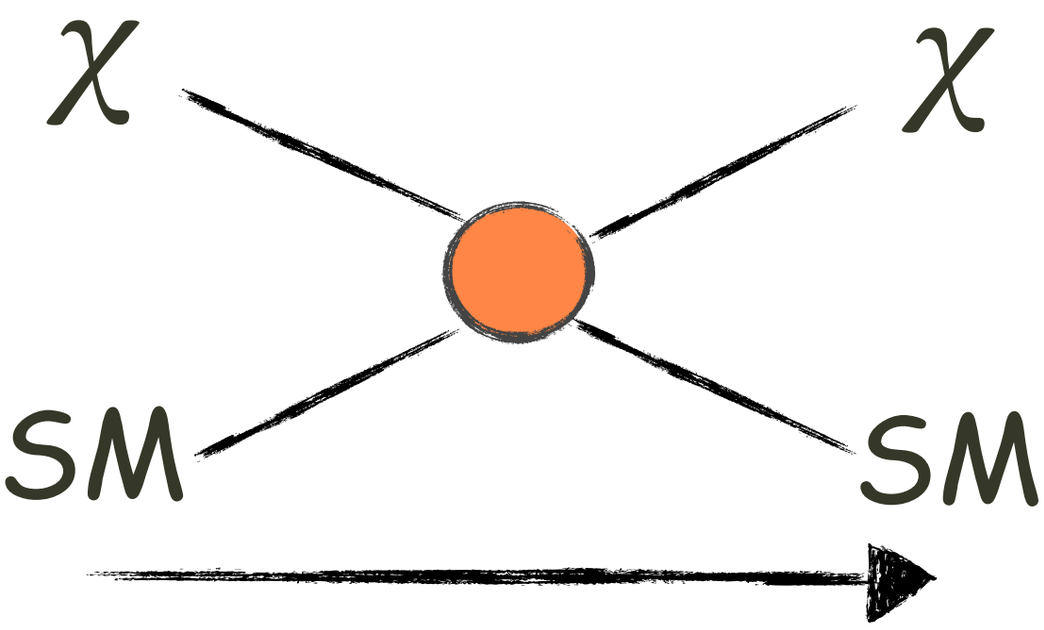
WIMP Detection Strategies

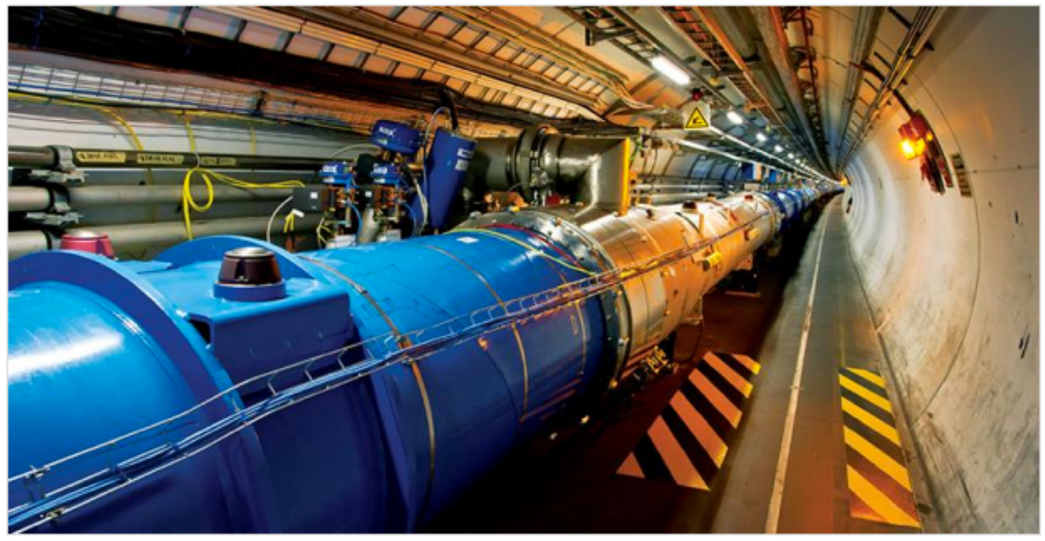


WARNING
model details
may be crucial x
detection success!

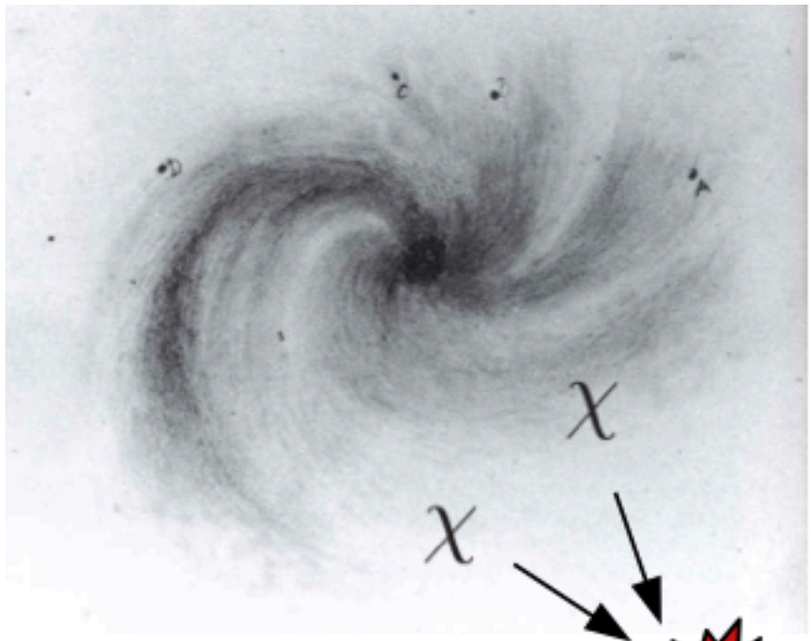
crossing symmetry







Indirect Searches for Dark Matter



γ

Gamma rays
- Very simple propagation (geodesics)
- Absorption negligible on Galactic scales
- Point towards their sources

$\bar{p},\ e^+,\ \ldots$

B-field

Charged cosmic rays
- Electrons/positrons, nuclei
- Propagation distorted by galactic magnetic fields
- Sizable energy losses & interactions

Today's dark matter **annihilation cross-section** is roughly given by

$$\langle \sigma v \rangle_{\rm tot} \sim 3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1}$$

Caveat: conditions during freeze-out are very different from today!

ν

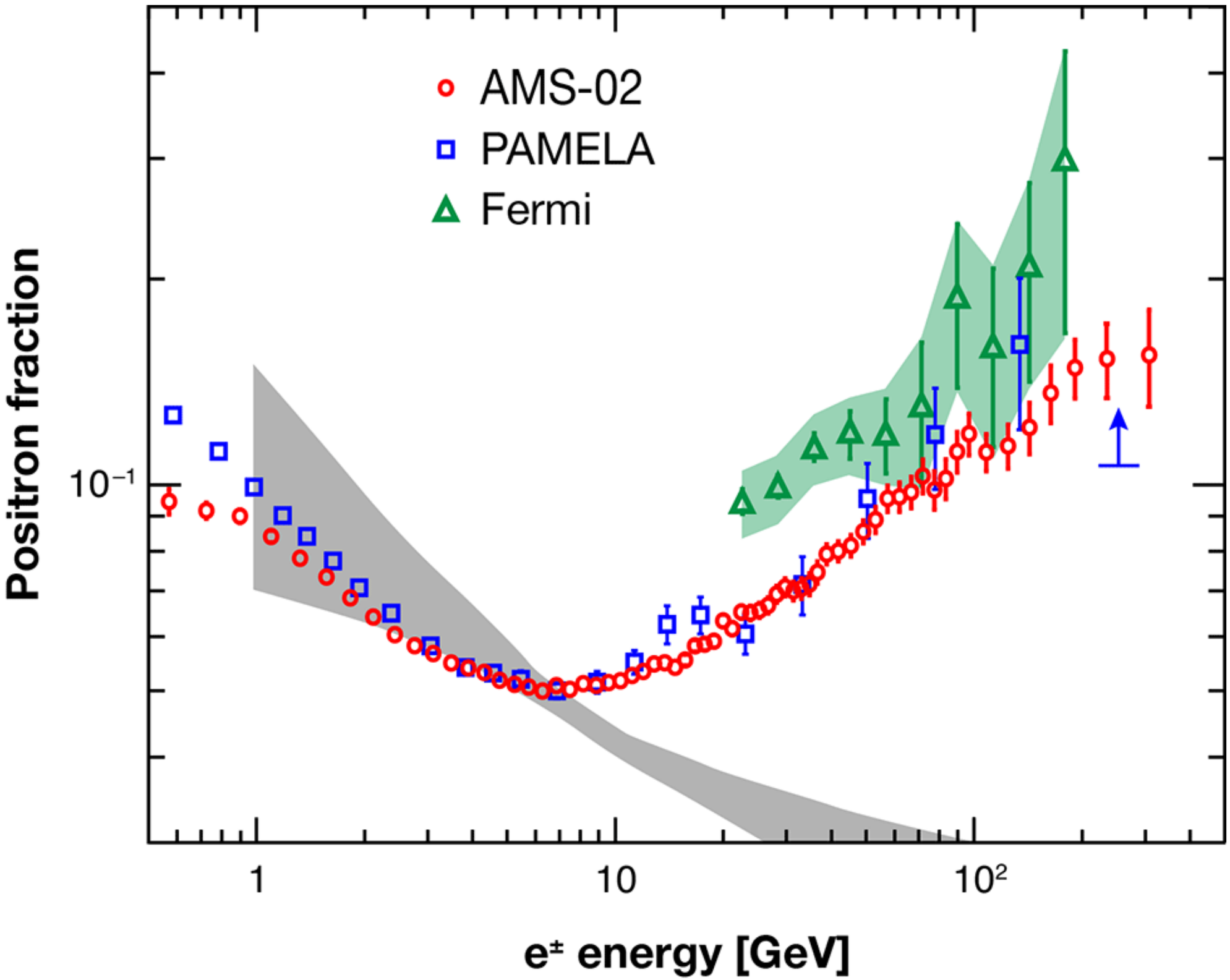
Neutrinos
- Simple propagation
- But: very hard to measure

Indirect searches are the most convincing probe for the "freeze-out" mechanism of WIMPs

from C.Weniger's talk

For example, people looked into positrons :

(wait for your cosmic-ray lecturer Daniele!)



Differential flux of γ s can be computed as :

$$\frac{d\Phi_\gamma}{d\Omega\, dE} = \mathcal{P}(m_{dm}) \cdot \mathcal{J}(\Delta\Omega)$$

(Bergstrom et al. '98)

(Cirelli et al. '12)

$$\mathcal{P}(m_{dm}) = \frac{1}{8\pi\, m_{dm}^2} \langle \sigma v \rangle \frac{dN_\gamma}{dE}$$

known x a given DM mass!

$$\mathcal{J}(\Delta\Omega) = \int_{l.o.s.} \rho^2(\ell(\Delta\Omega))\, d\ell$$

J-factors suggest us *where* it can be worth looking @!

Typical values : (S.Profumo-TASI '12)

MW Galactic Center : $J \sim 10^{23}$ GeV^2/cm^5

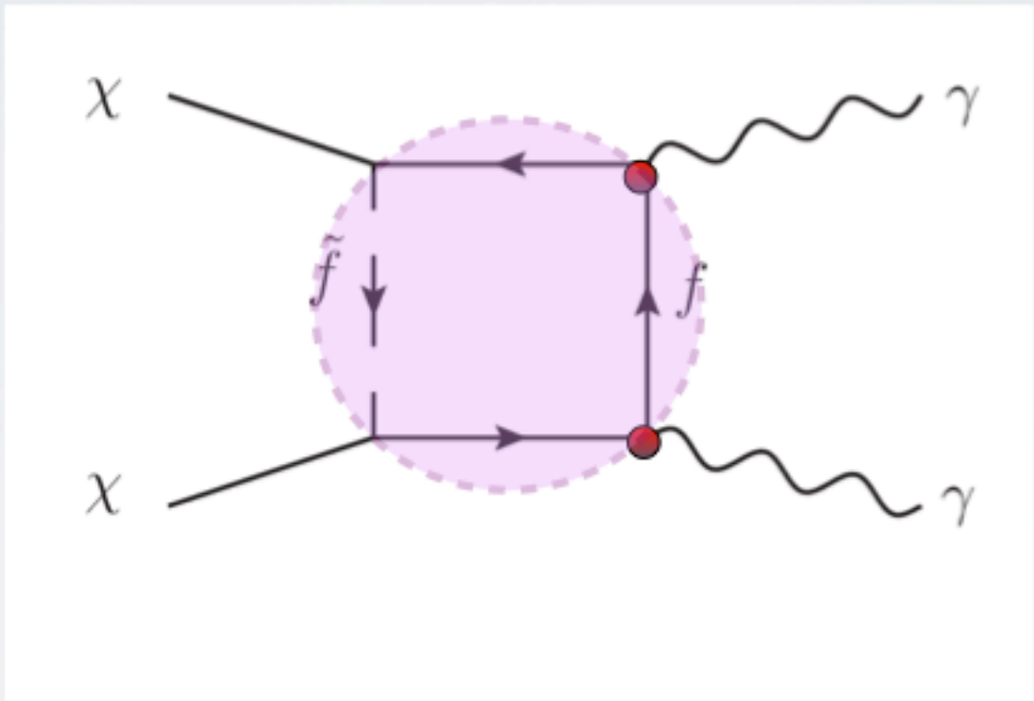
MW satellites : $J \sim 10^{19}$ GeV^2/cm^5

Local Cluster of Galaxies : $J \sim 10^{17}$ GeV^2/cm^5

Smoking gun for DM indirect searches?

- Line annihilation requires two-body final state channels containing at least one photon (for SM final states, $\gamma\gamma$, γZ, γH) yielding the spectrum

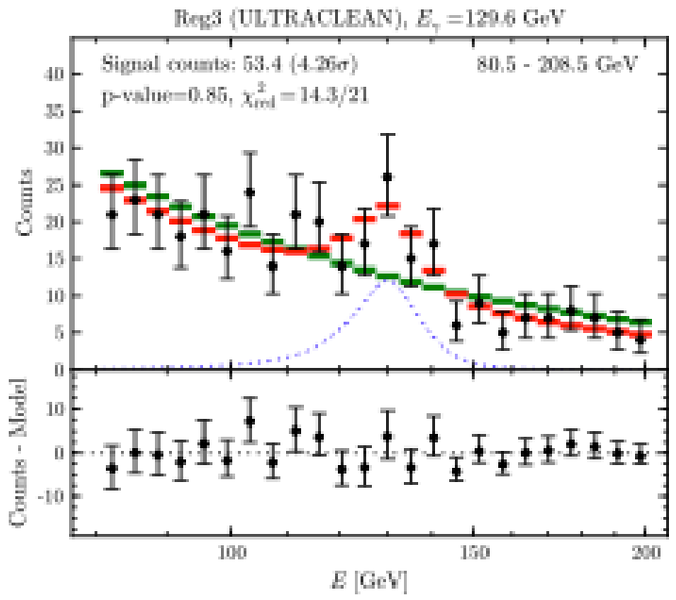
$$\frac{dN}{dE} \propto \delta(E - E_\gamma)\,, \quad E_\gamma \leq m_\chi$$



- This must be a loop-level process, suppressed with respect to the tree-level by $\alpha^2 \sim 10^{-4}$

- Usually it's theoretically difficult to produce line flux which is observable, while fulfilling bounds on continuum

from P.Serpico's lectures



Fermi 130 GeV γ-ray line? Weniger, 2012

Dream for any WIMP hunter ...

Updated search for spectral lines from Galactic dark matter interactions with pass 8 data from the Fermi Large Area Telescope

M. Ackermann (DESY, Zeuthen) , M. Ajello (Clemson U.) , A. Albert (SLAC & Stanford U., HEPL) , B. Anderson (Stockholm U. & Stockholm U., OKC) , W. B. Atwood (UC, Santa Cruz) , L. Baldini (INFN, Pisa & Pisa U. & SLAC & Stanford U., HEPL) , G. Barbiellini (INFN, Trieste & Trieste U.) , D. Bastieri (INFN, Padua & Padua U.) , R. Bellazzini (INFN, Pisa) , E. Bissaldi (INFN, Bari) *et al.* *Show all 120 authors*

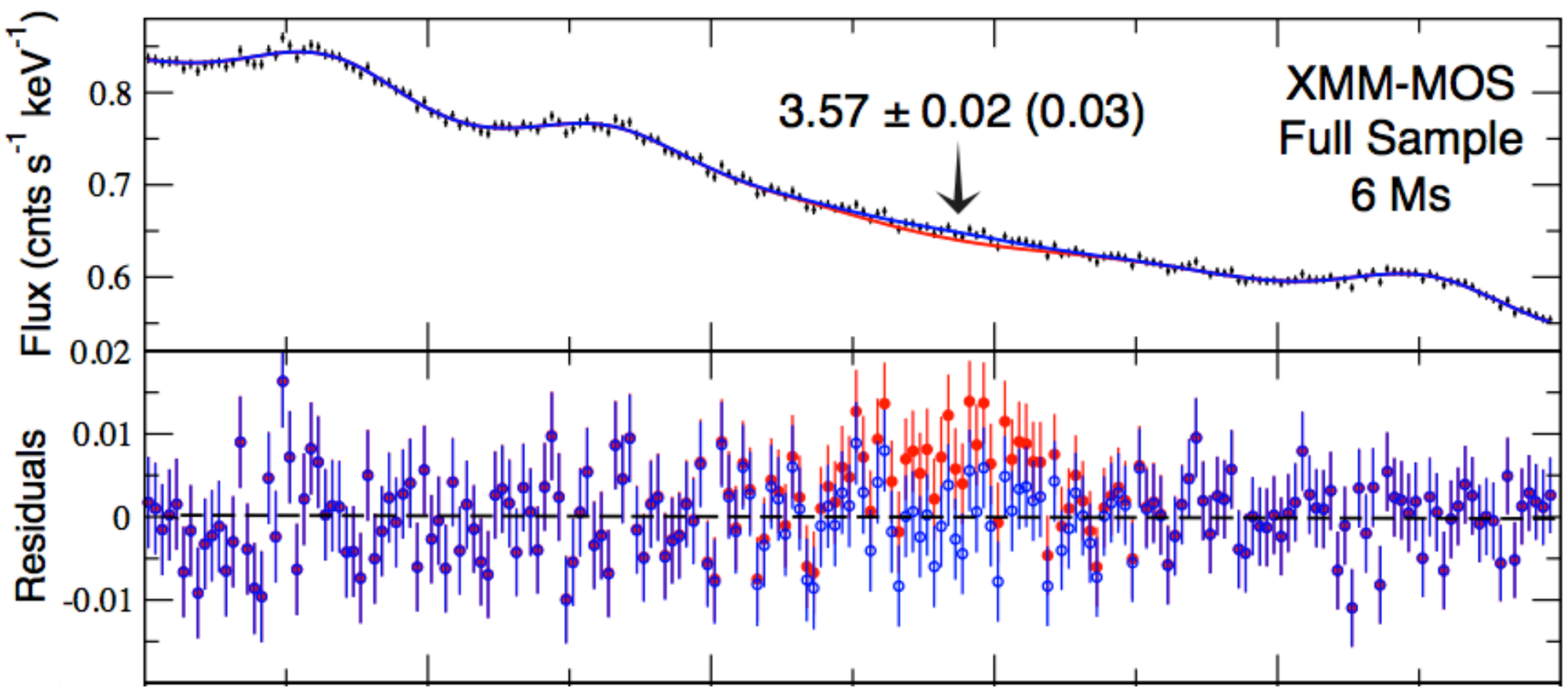
2015 - 19 pages

Phys.Rev. D91 (2015) 122002
(2015-06-22)
DOI: 10.1103/PhysRevD.91.122002

It seems it was only a statistical fluctuation

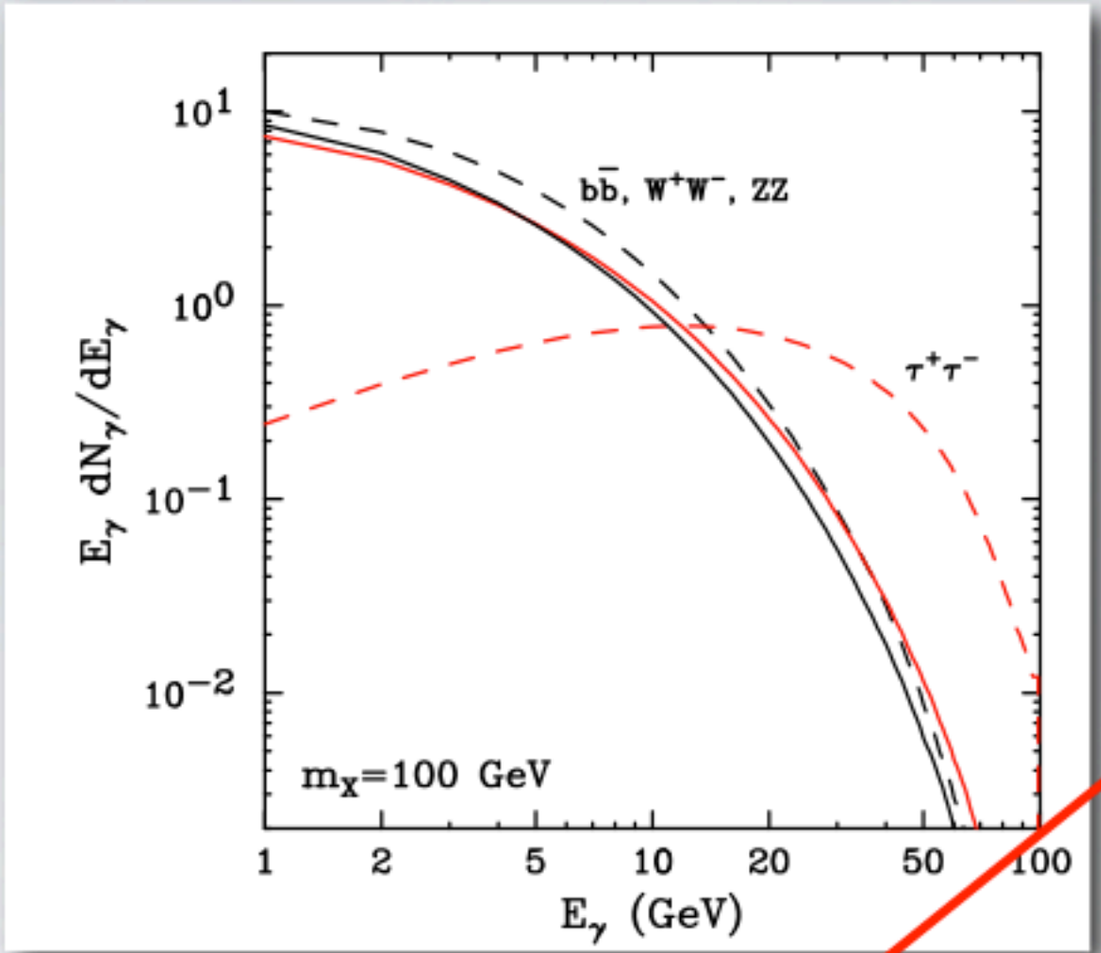
OUT OF THE WIMP WORLD

3.57 KeV line in Perseus and Coma Clusters ...



The diffuse spectral component

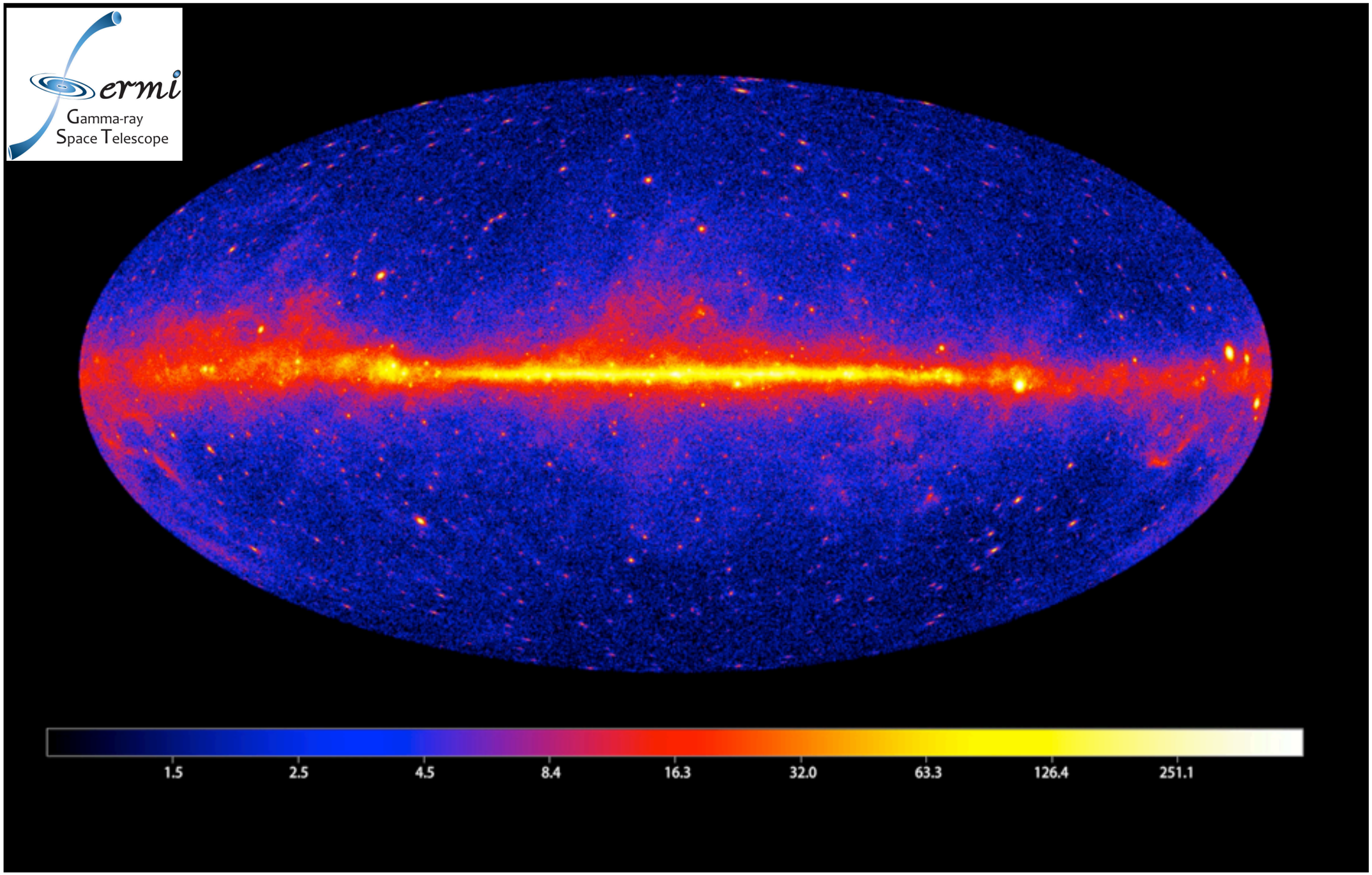
from P.Serpico's lectures



usually handled via e.g. PYTHIA incorporated in dedicated software

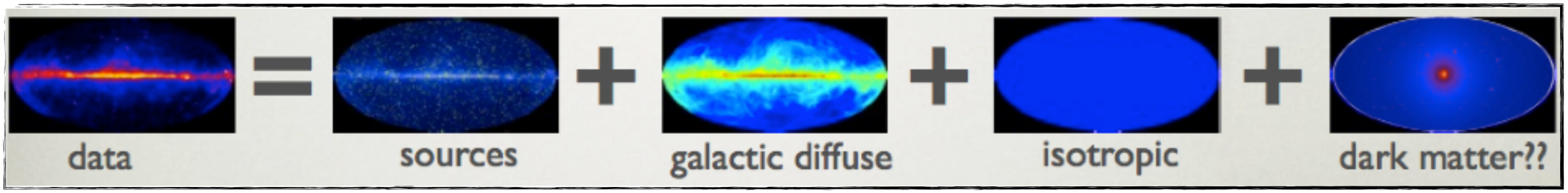
- ✓ whenever DM annihilates into quarks or gauge bosons, continuum photon spectrum is quasi-universal, as a result of decays/fragmentations
- ✓ Near the endpoints (~DM mass), or for leptonic final states, peculiarities may be present.
- ✓ Significant *secondary* (byproducts of electrons e-losses) gamma radiation may be emitted from electrons. Requires treatment as for charged particles, and astrophysical medium is important.

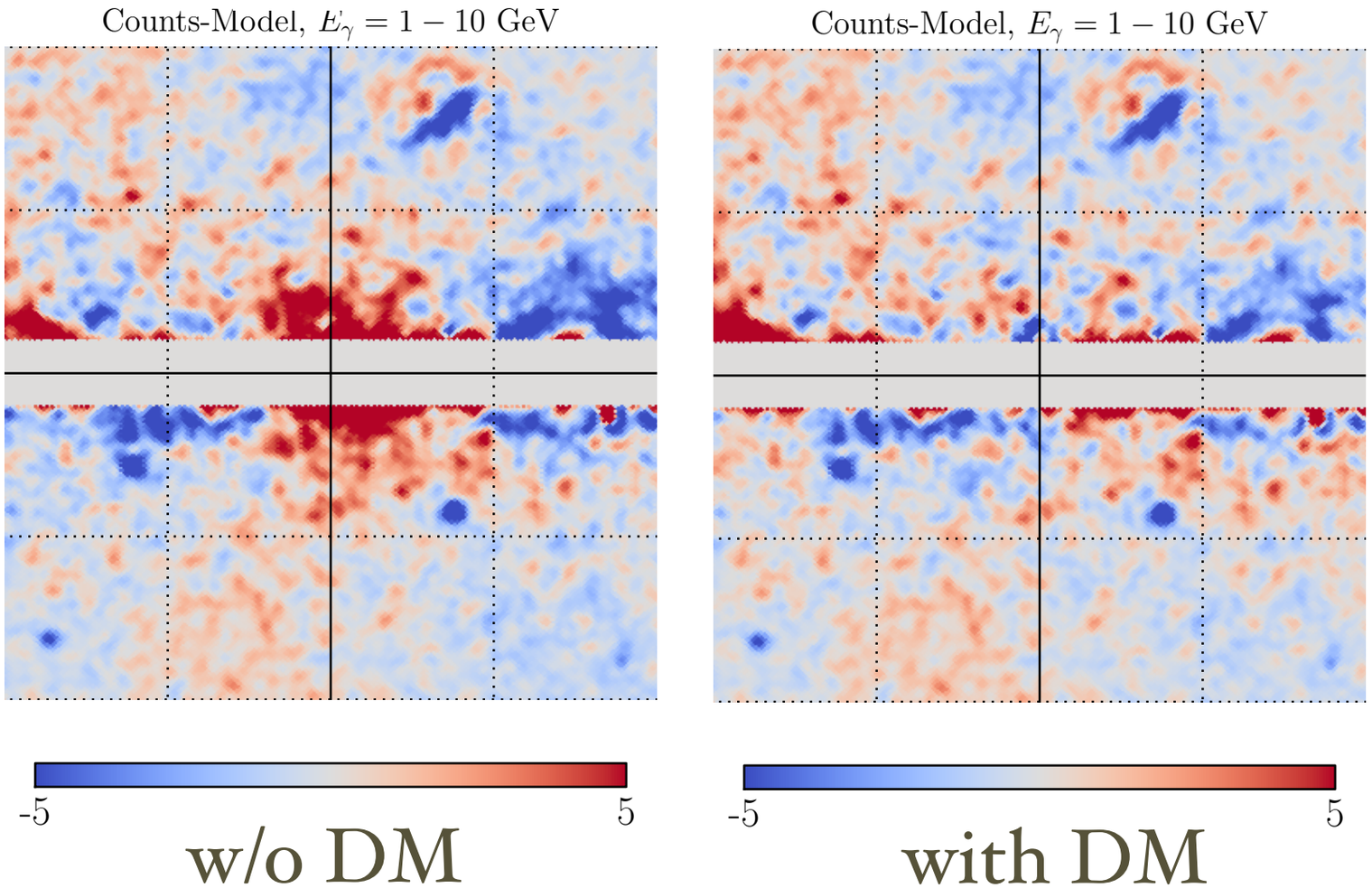
see e.g.: http://www.marcocirelli.net/PPPC4DMID.html

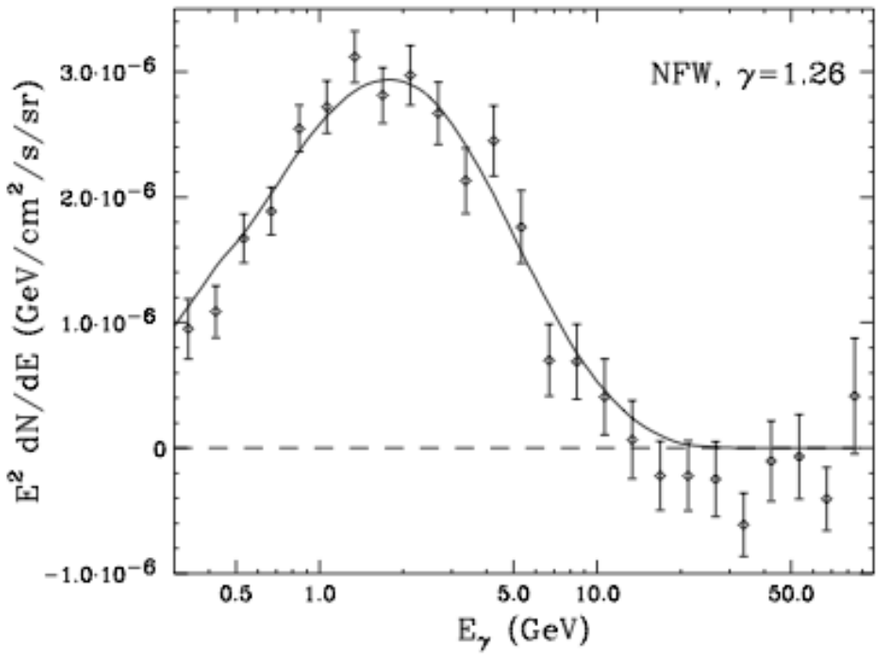


(http://www.nasa.gov/content/goddard/nasas-fermi-celebrates-five-years-in-space-enters-extended-mission/)

The GeV excess @ the Galactic Center







$b\bar{b}$ best fit for $m_{DM} \sim 35$ GeV

Have we "already" (2015-1933 ≃ 80) detected Dark Matter ?

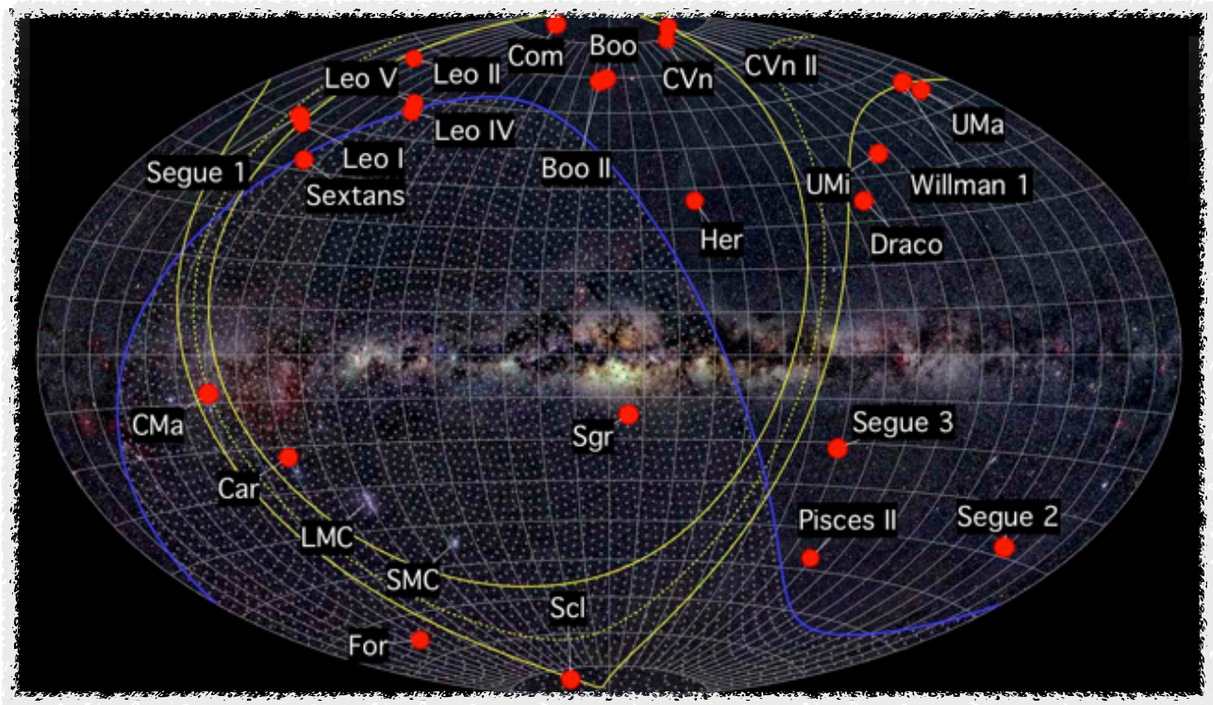
The Galactic Center is a rich astrophysical region ... stay tuned!

Dwarf spheroidal galaxies (dSphs) are ideal DM labs

$$\frac{M}{L} \sim 10^{2-3} \times \frac{M_\odot}{L_\odot}$$

very faint objects with
large mass-to-light ratio!

In particular, for Milky Way satellites:



high latitude position

suppressed gamma-ray flux
from standard processes

heliocentric distances
about 70 - 250 kpc

high
J-value

✓ photometry for stellar density profile , $I(R)$

✓ spectroscopy for line-of-sight kinematics , $\sigma_{los}(R)$

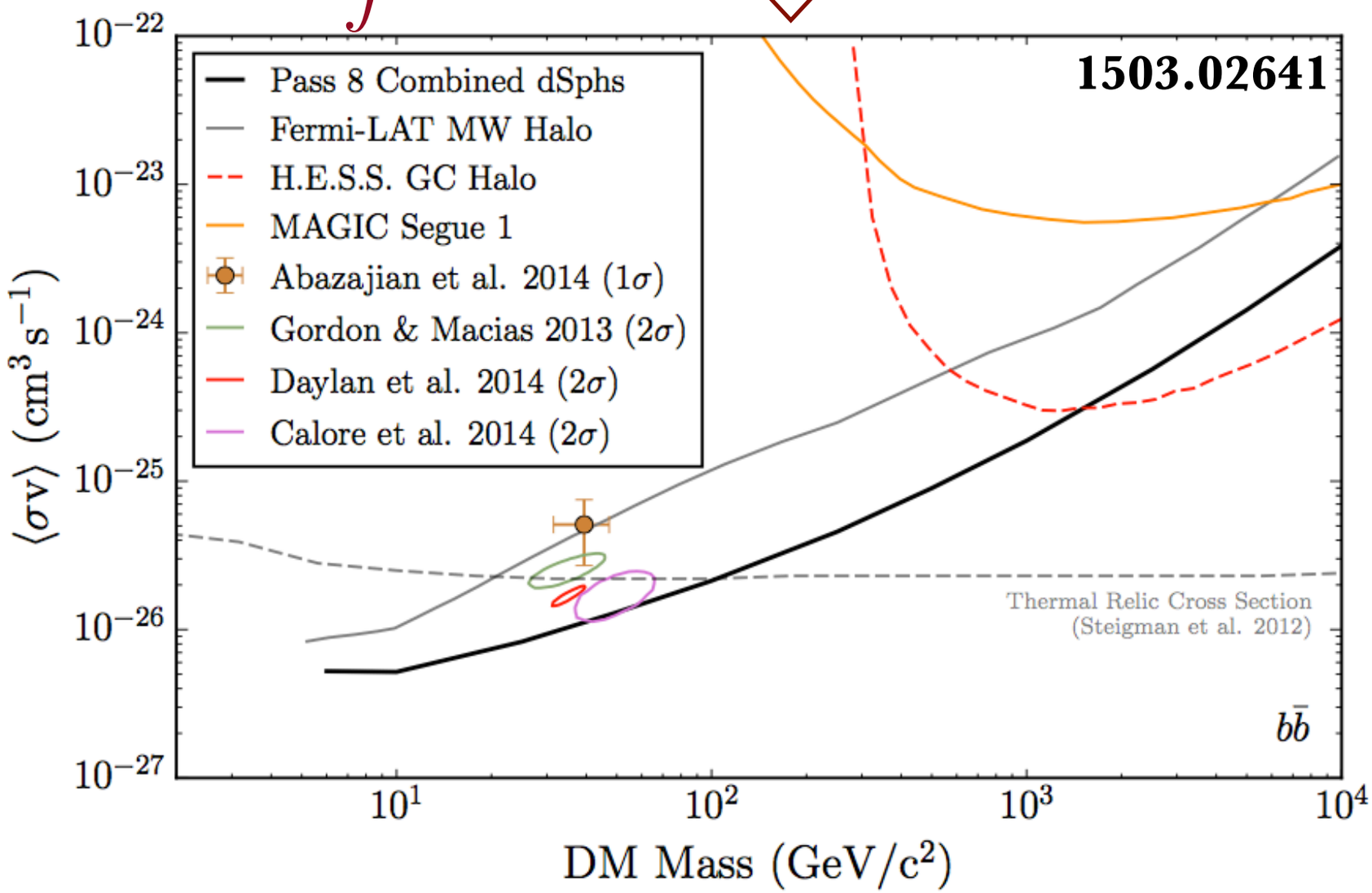
✗ full 3D kinematical knowledge , $\beta(r) \equiv 1 - \sigma_t^2(r)/\sigma_r^2(r)$

dSph ≡ collisionless spherical system in dynamical equilibrium

Spherical Jeans equation

$$\sigma_{los}(R) = f(I, \rho_\chi, \beta)$$

$$\int d\beta \; p(\beta)$$



A BIG "THANK YOU" to the organizers ...

... & especially THANKS TO YOU guys
(Even if I lost yesterday game!)