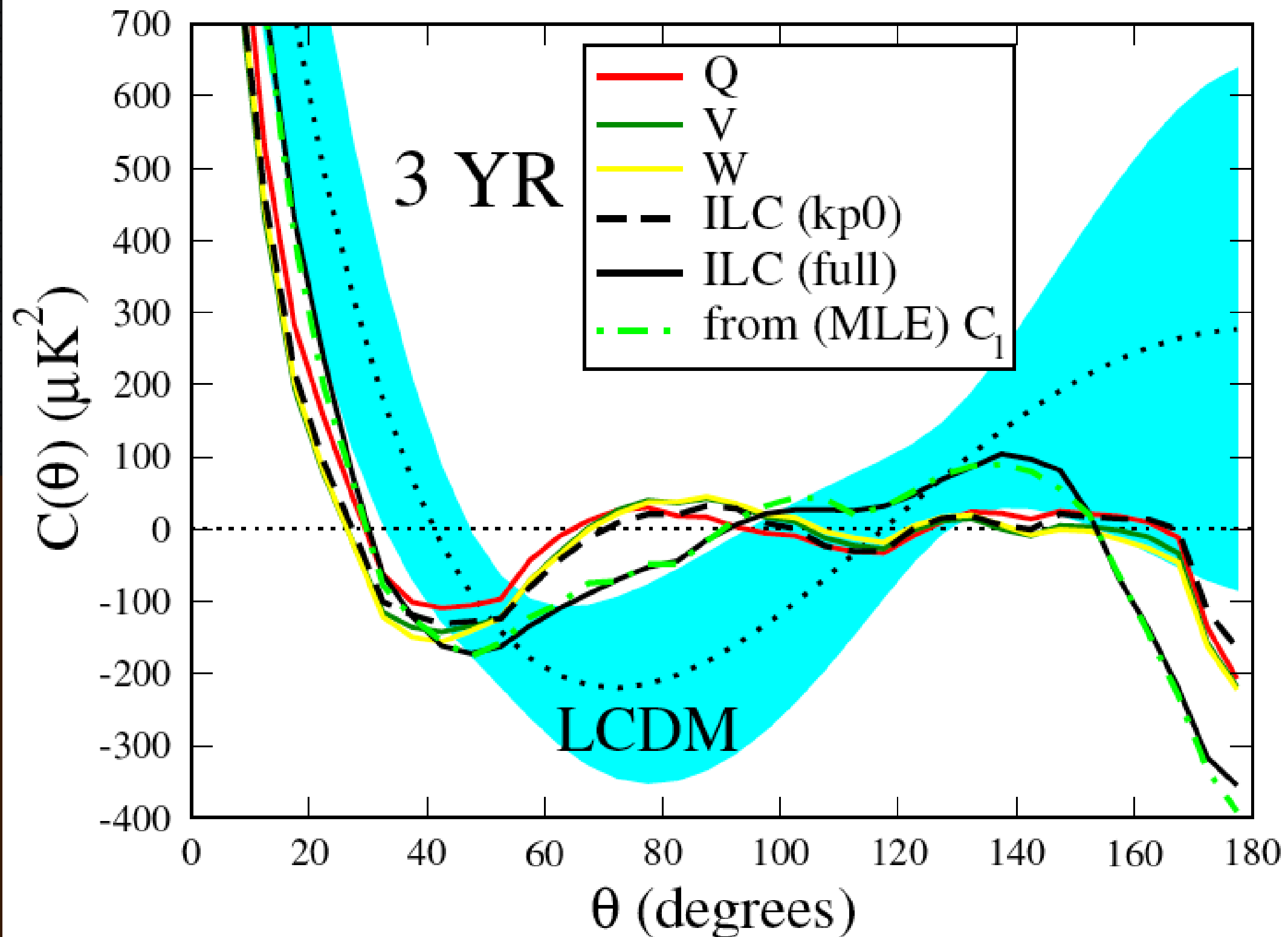
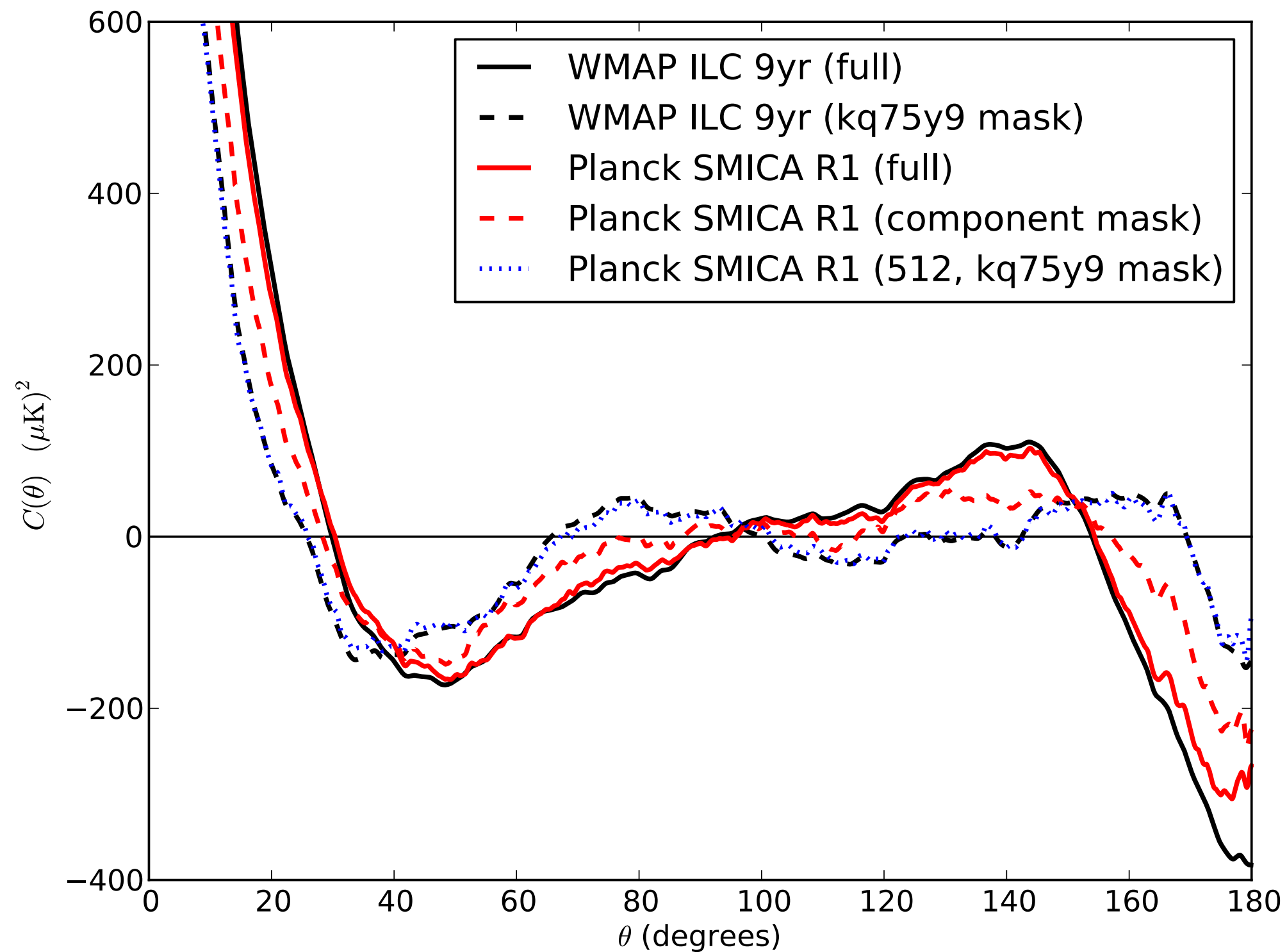


2015: The Spacetime Odyssey Continues
Stockholm, Sweden

Two point angular correlation function -- WMAP3

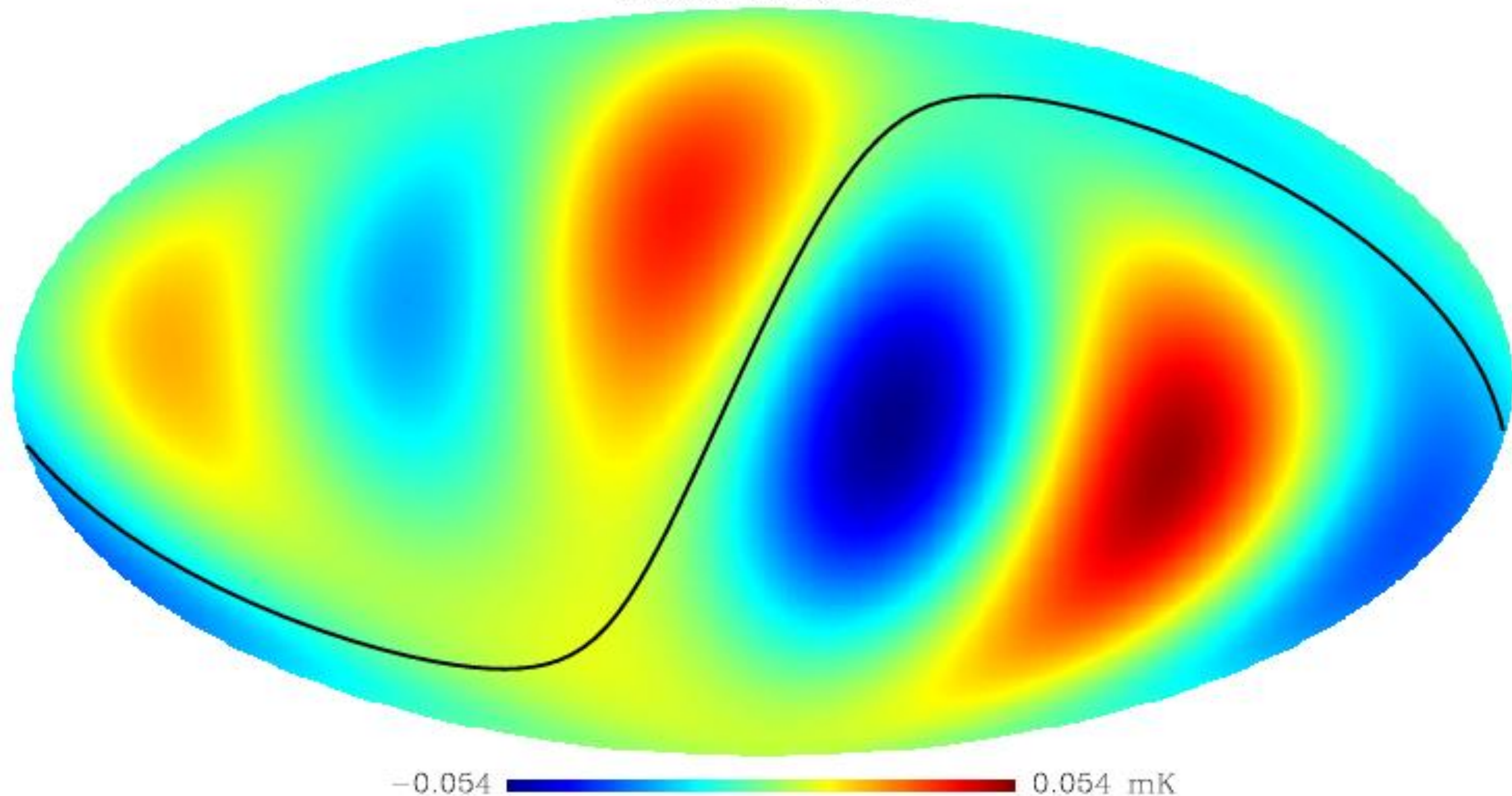


Did this change in Planck?



1=2&3 : The Map

ILC quadrupole (corrected for kinematic effect) plus octupole
Galactic Coordinates



The "Goldstone Exception" II: Absence of a Higgs Fine-Tuning Problem in the Spontaneously Broken Limit of the Gell Mann Levy Linear Sigma Model: $O(4)$ with PCAC and $SU(2)_L$ with PCAC and Standard Model Quarks and Leptons

[Bryan W. Lynn](#), [Glenn D. Starkman](#), [Katherine Freese](#), [Dmitry I. Podolsky](#)

(Submitted on 9 Dec 2011 (v1), last revised 23 Jan 2013 (this version, v3))

More than four decades ago, Lee and Symanzik proved that, in the Gell Mann–Levy (GML) model with partially conserved axial–vector currents (PCAC), tadpole renormalization (a Higgs Vacuum Stability Condition) forces all S–matrix ultra–violet quadratic divergences (UVQD) to be absorbed into the physical renormalized pseudo–scalar pion (pole) mass squared. We show that this includes "new" UVQD (widely unfamiliar to modern audiences). We also show that tadpole renormalization is an automatic consequence of Ward–Takahashi identities.

We prove that all UVQD therefore vanish identically in the Goldstone–mode limit, where pions are Nambu–Goldstone Bosons (NGB), and where Lee and Symanzik's Goldstone Symmetry Restoration Condition (a renormalization prescription) enforces spontaneous symmetry breaking and the massless–ness of NGB. Axial–vector current conservation is restored as is $SU(2)_{(L-R)}$ chiral symmetry: the vanishing of UVQD is therefore achieved in the Goldstone–mode by restoration of an exact symmetry, and therefore (by definition) without fine–tuning!

A weak–scale Higgs mass is therefore not UVQD fine–tuned in the spontaneously broken GML LSM. That is simply another (albeit unfamiliar) consequence of the Goldstone Theorem. Hence Goldstone–mode $O(4)$ LSM symmetries are sufficient to ensure that the theory does not suffer from the Higgs Fine Tuning Problem. This is contrary to the widely accepted belief that UVQD in the Higgs mass lead to such problems in the $O(4)$ LSM, which are then presumed to be inherited by the Standard Model (SM). The key observation is to regard the spontaneously broken $O(4)$ LSM as the Goldstone–mode limit of the GML LSM.

We prove this first at 1–loop then at all loop orders for the pure scalar GML model. We then break the $O(4)$ symmetry to $SU(2)_L$ with SM Yukawa couplings, and show that the above remains true.

Macro Dark Matter

Glenn Starkman

Dept. of Physics/CERCA/ISO

Case Western Reserve University

**2015: The Spacetime Odyssey Continues
Stockholm, Sweden**

Collaborators: David Jacobs, Bryan Lynn, Amanda Weltman

ISORIGINS

Dark Matter: Evidence

Cluster Kinematics

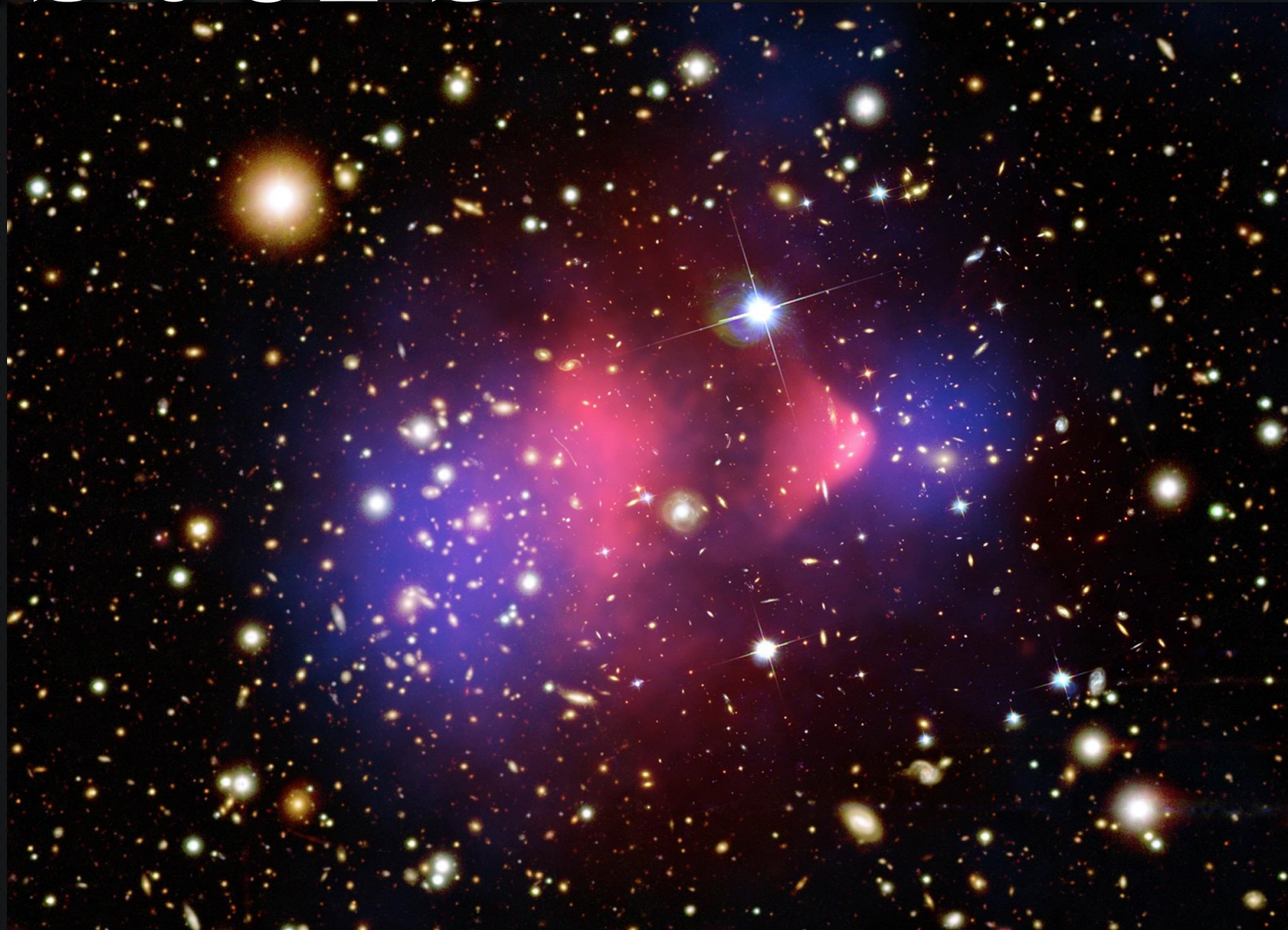
(Zwicky & the Coma cluster ~ 1933)



Coma cluster

Image: Jim Misti (Misti Mountain Observatory)

Interacting Clusters



The “Bullet” Cluster

Markevitch et al. (2005), Clowe et al. (2006)

Gravitational Lensing



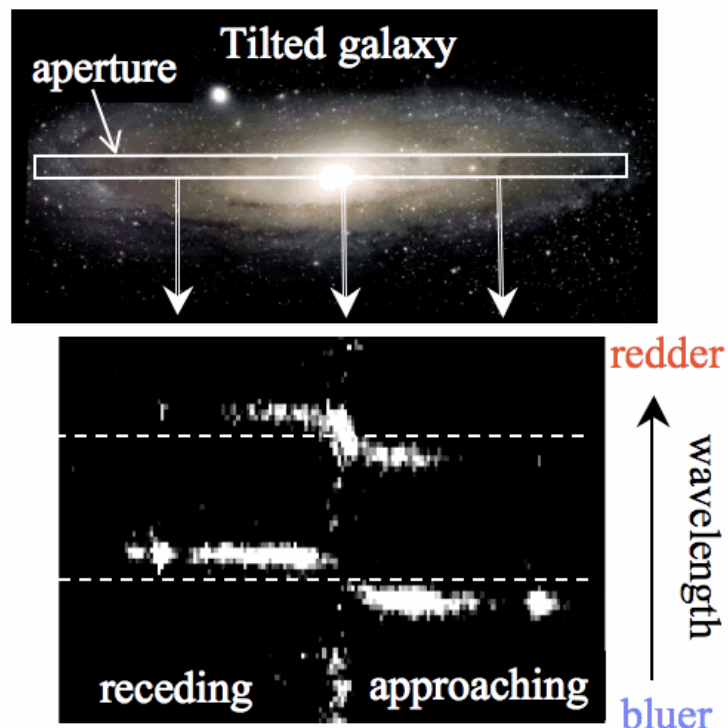
Cluster Abell 1689

Credit: NASA, ESA, and D. Coe (NASA/JPL)

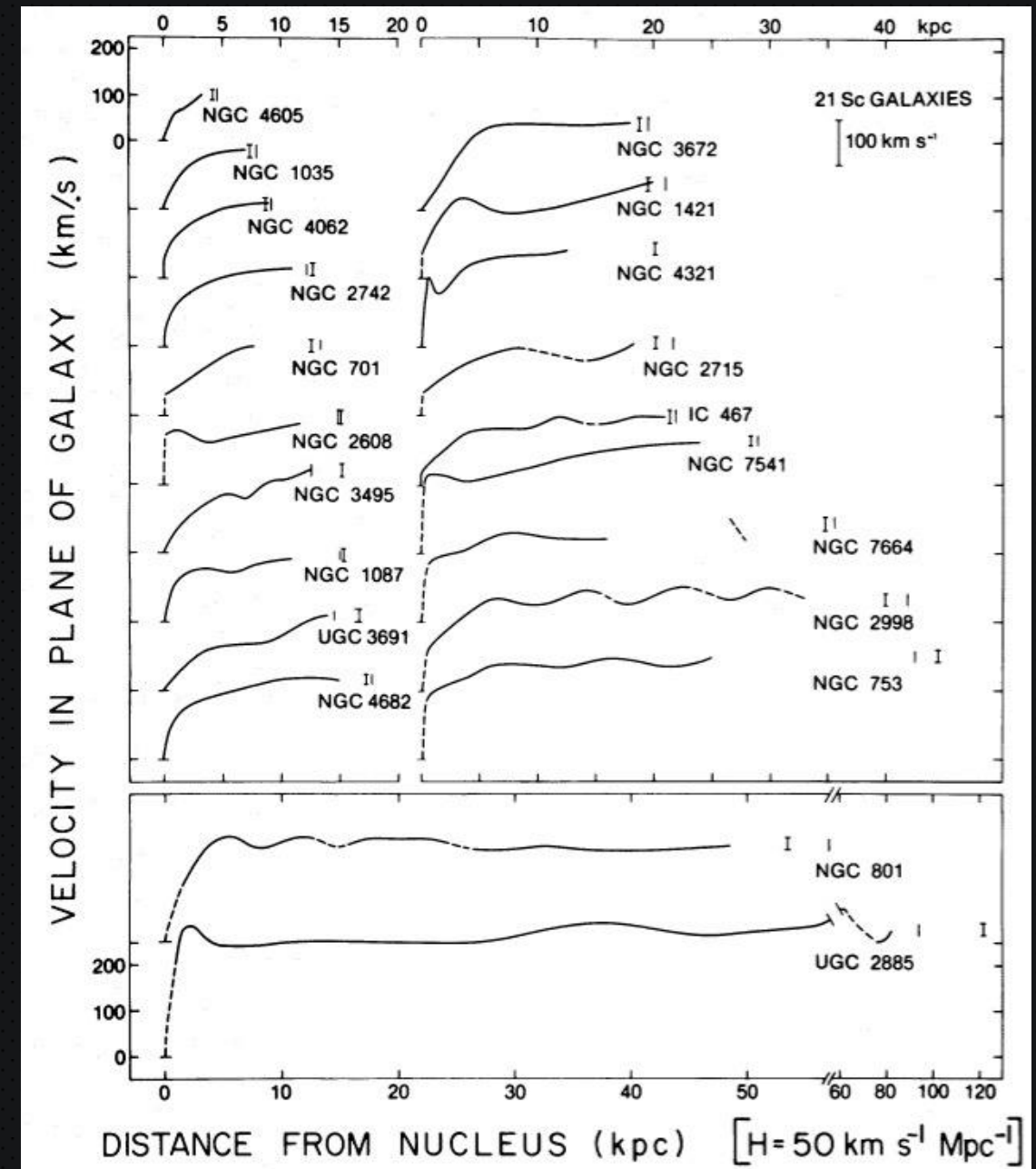
Galactic Rotation Curves



Vera Rubin measuring galaxy rotation curves (~1970)

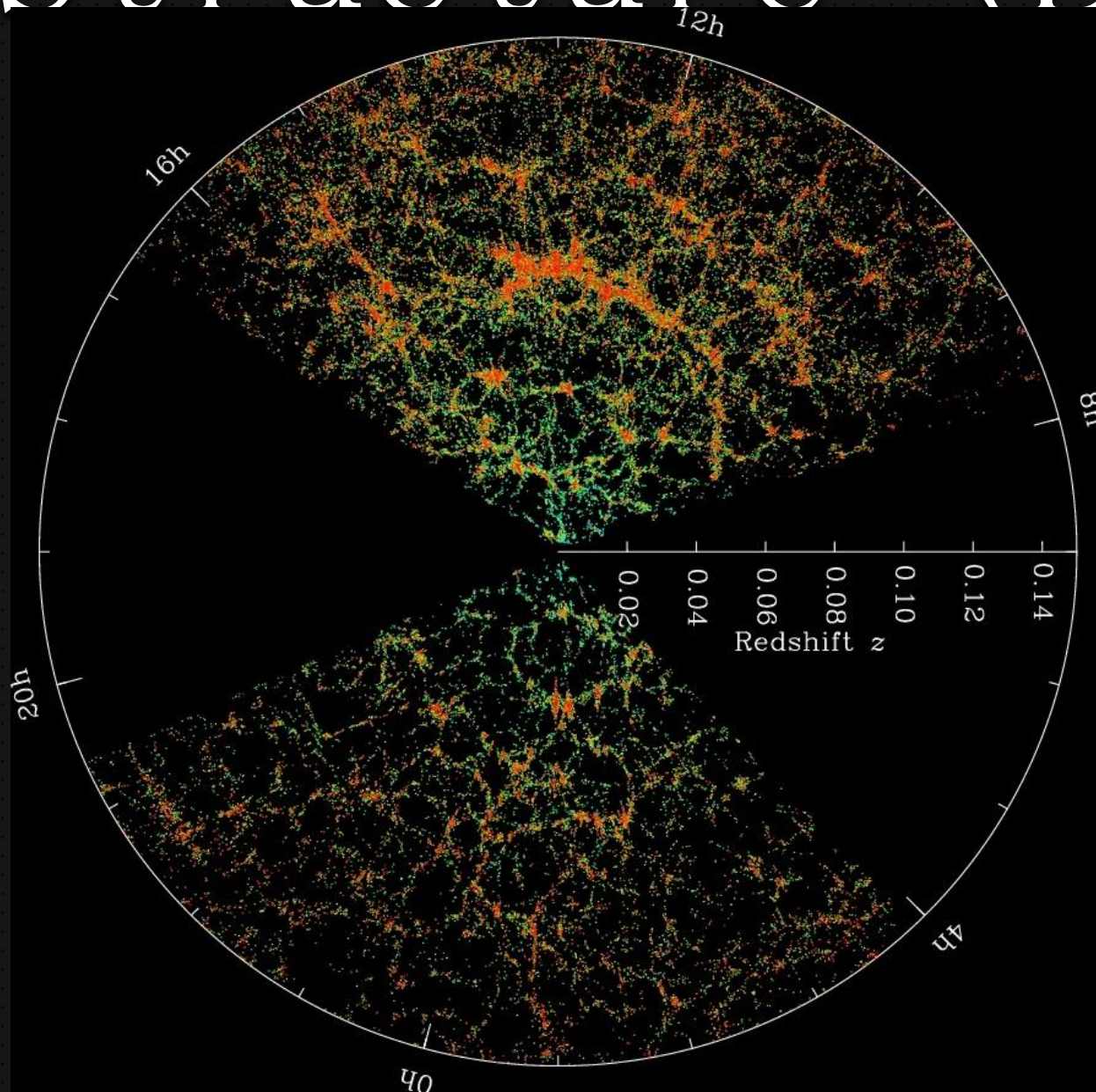


Resulting spectrum of light within aperture



Rubin, et al. (1980)

Growth of Large Scale Structure (LSS)



Sloan Digital Sky Survey

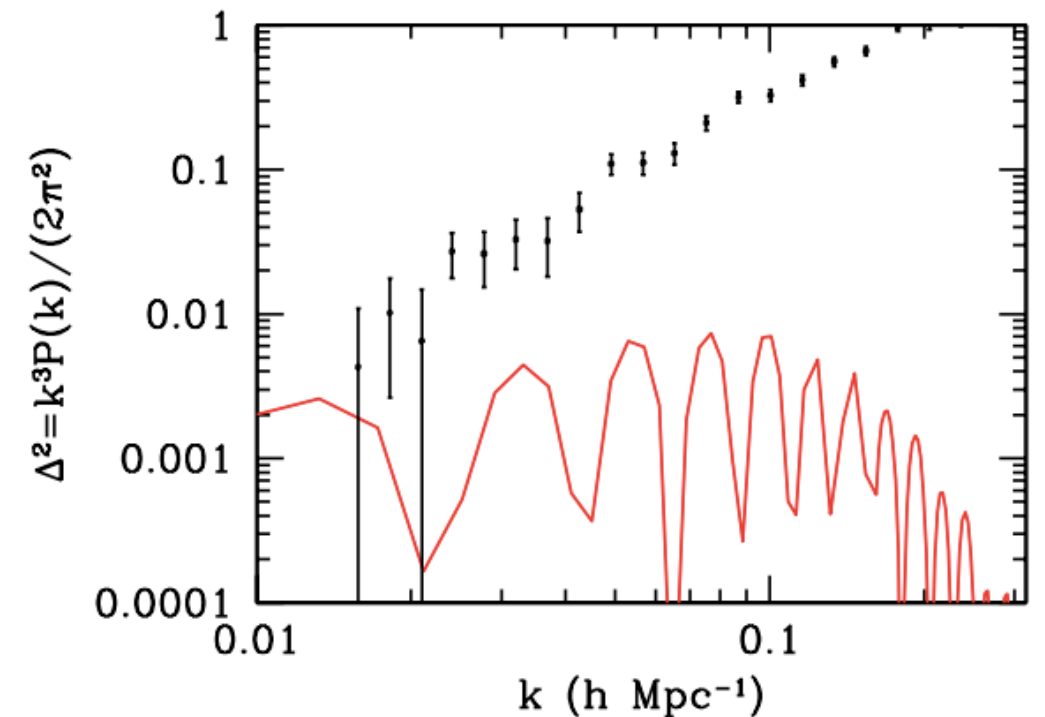
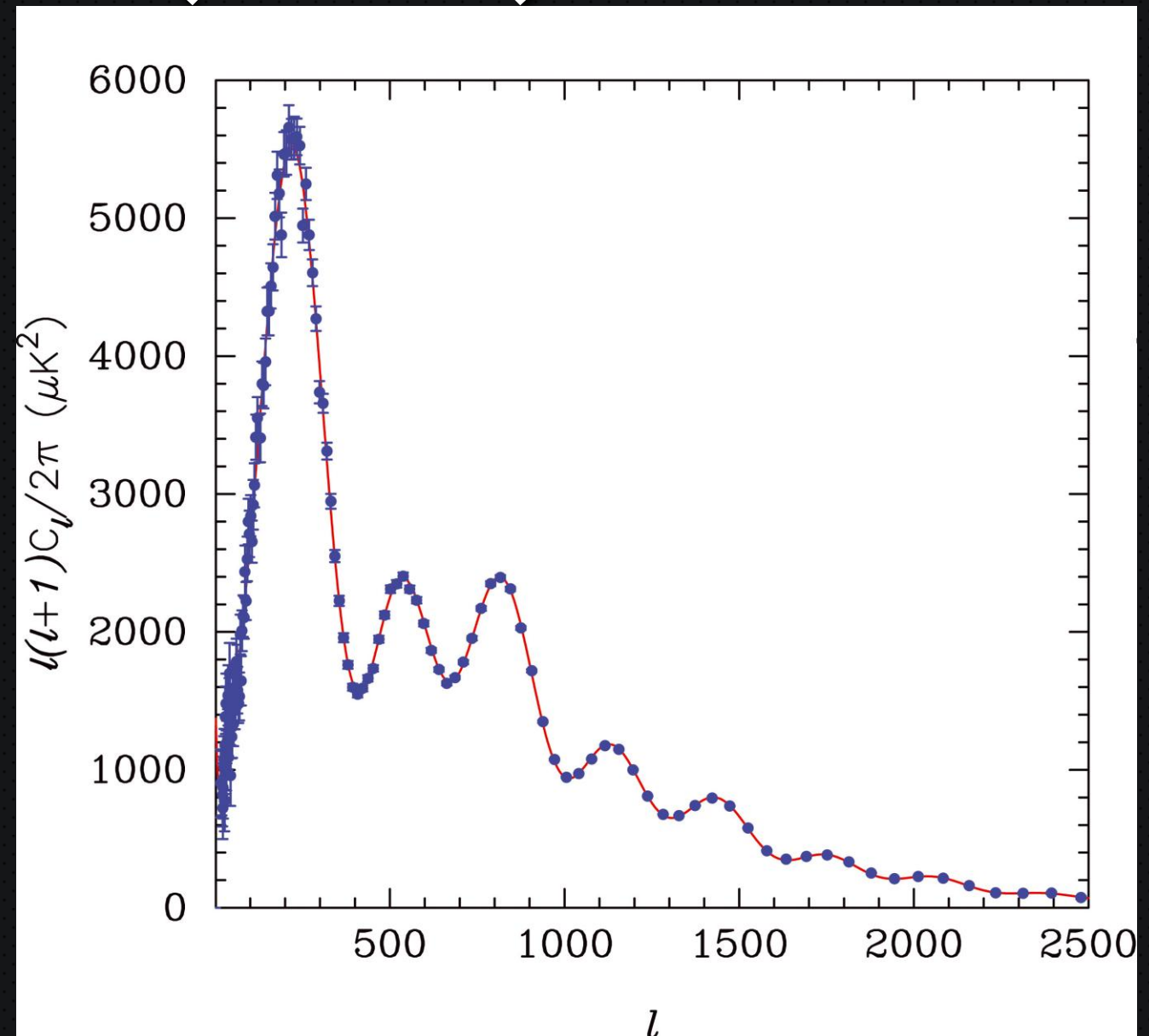


FIG. 1 (color online). Power spectrum of matter fluctuations in a theory without dark matter as compared to observations of the galaxy power spectrum. The observed spectrum [24] does not have the pronounced wiggles predicted by a baryon-only model, but it also has significantly higher power than does the model. In fact Δ^2 , which is a dimensionless measure of the clumping, never rises above one in a baryon-only model, so we would not expect to see any large structures (clusters, galaxies, people, etc.) in the Universe in such a model.

Dodelson & Ligouri (2006)

Cosmic Microwave Background (CMB)

- Power spectrum very well fit by the 6 (or 7) parameter flat LCDM model
- More information about baryons + DM from peaks

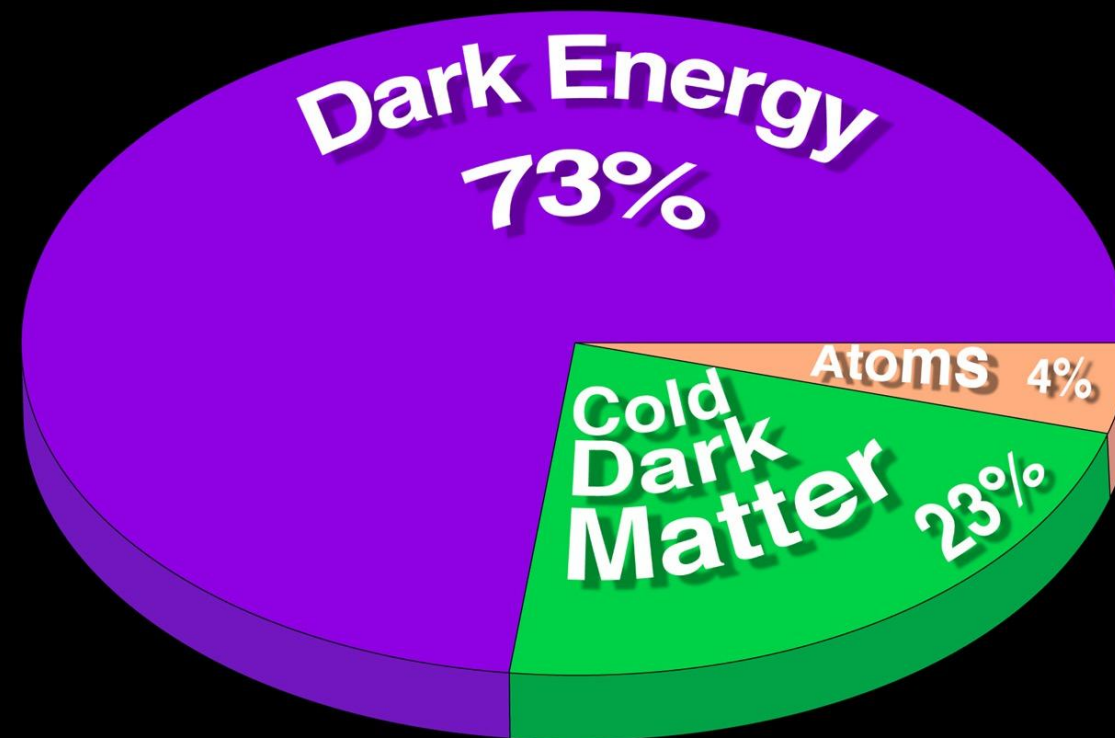


Plot: Planck Collaboration/ESA

Disclaimer:

*We could “just” modify the
theory of gravity!
(After all, GR has been
assumed.)*

Cosmological energy budget



Obligatory Pie Chart
Image: Jeff Filippini

What do we really know
about

Dark Matter?

- Matter:

- $n \propto (1+z)^{-3}$ (at least

- approximately,

- over a wide range of z)

What do we really know about DM?

- . Dark:

- . Does not emit, absorb or scatter much light

- . (or by implication much else in the SM)

Dark Matter:

Candidates

WIMPs

Motivations:

- “The WIMP miracle”
- Beyond the Standard Model desires
- esp. SUSY

*The non-discovery of WIMP-DM
and especially of any BSM
physics at the LHC
should de-privilege WIMPs
as the premiere DM*

Other non-SM Dark-matter candidates

- Axions

- Exotica:

- Eg. primordial blackholes

What do we really know
about DM?

- “Dark”:

- Does not automatically mean
 σ is small!

How could this be?

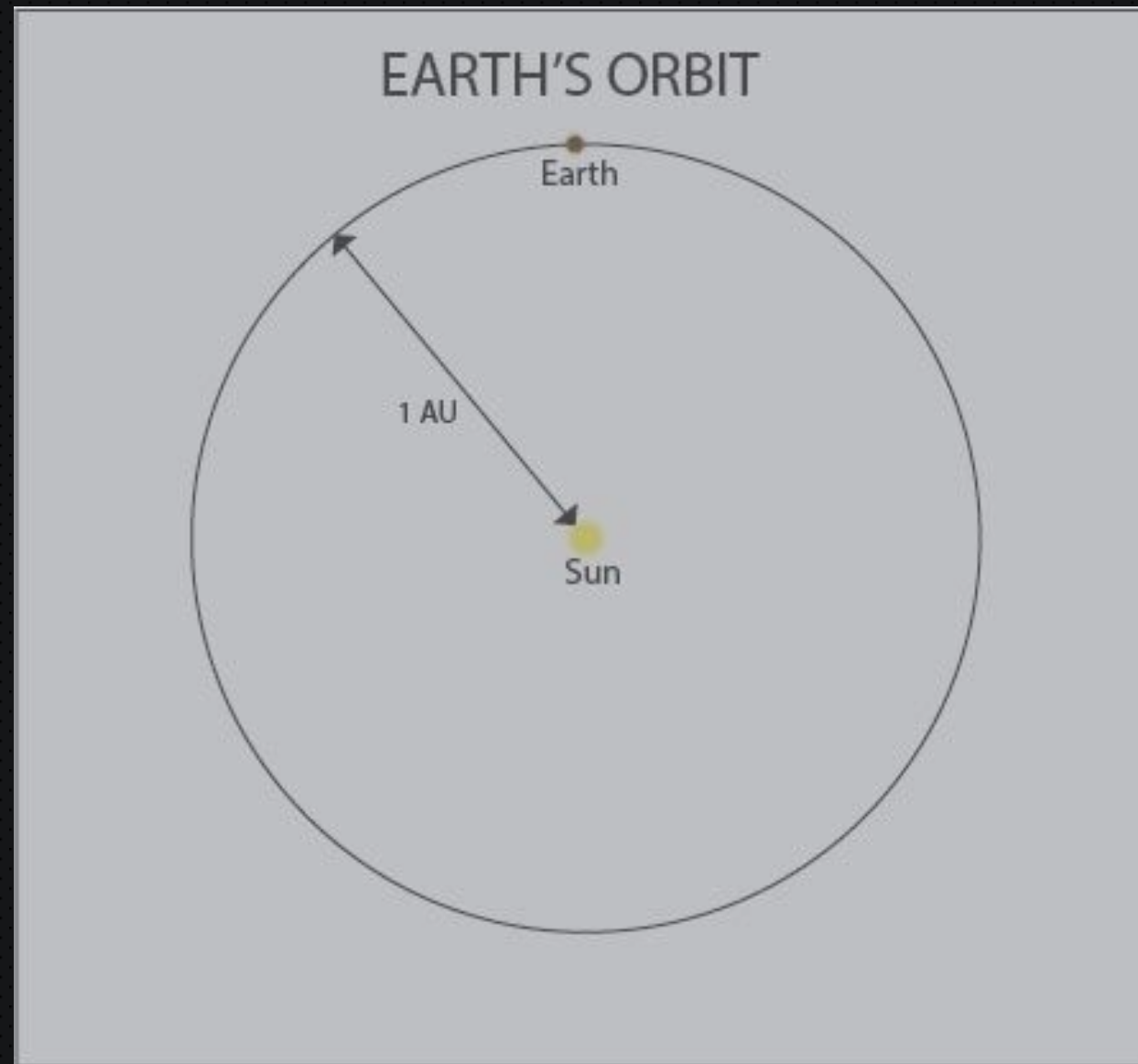
Interaction rates go as $\Gamma \sim n_X \sigma_X v$
 $\sim (\sigma_X/m_X) \rho_X v$

Gravitational observations fix ρ_X

What matters is (σ_X/m_X) -- the “reduced cross-section”
DM can be low m low σ , or high
& m not-so-low- σ !

MACROscopic Dark Matter

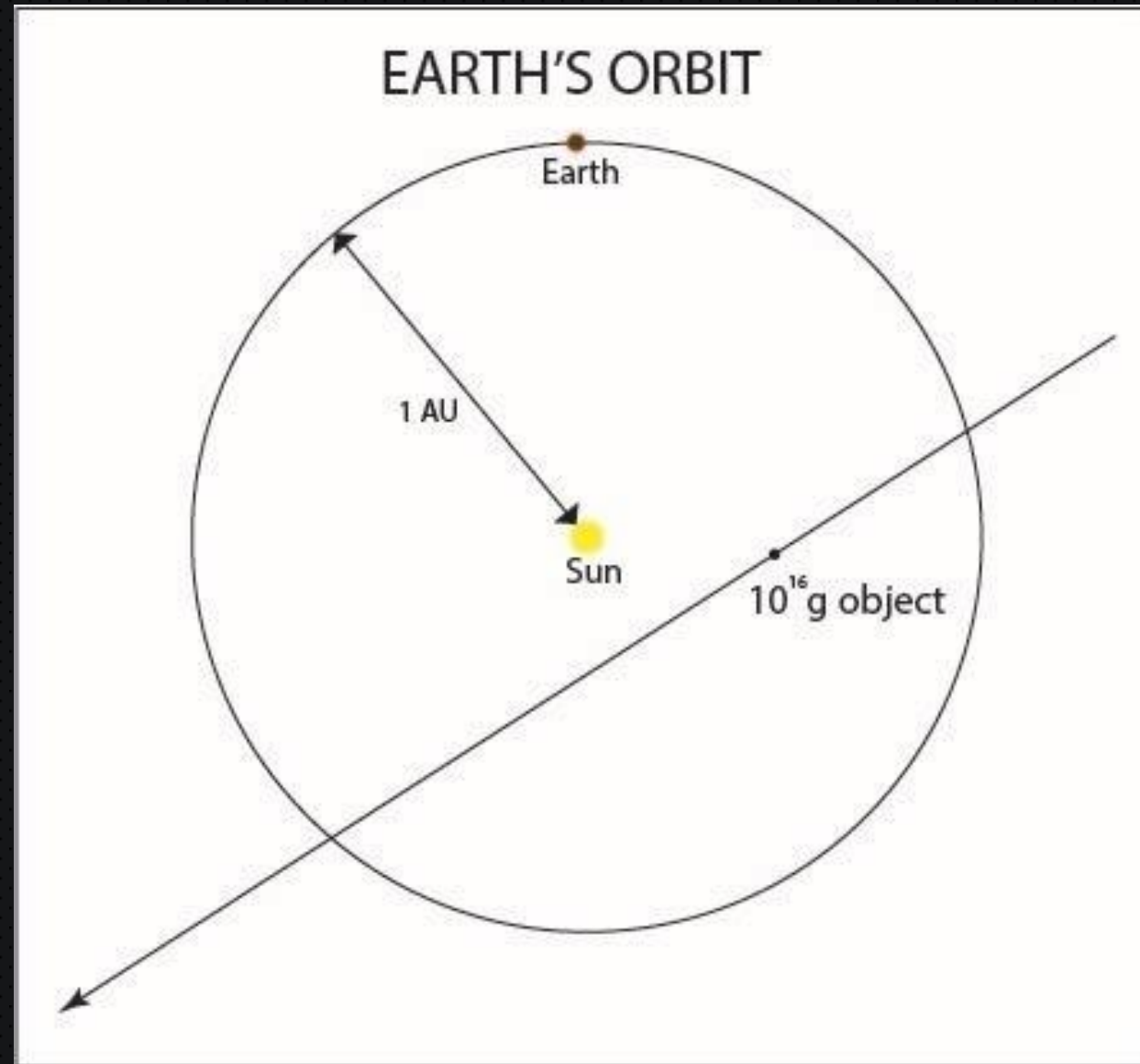
Average local dark matter density
 10^{16} g of dark matter expected within the



Here, a smooth distribution

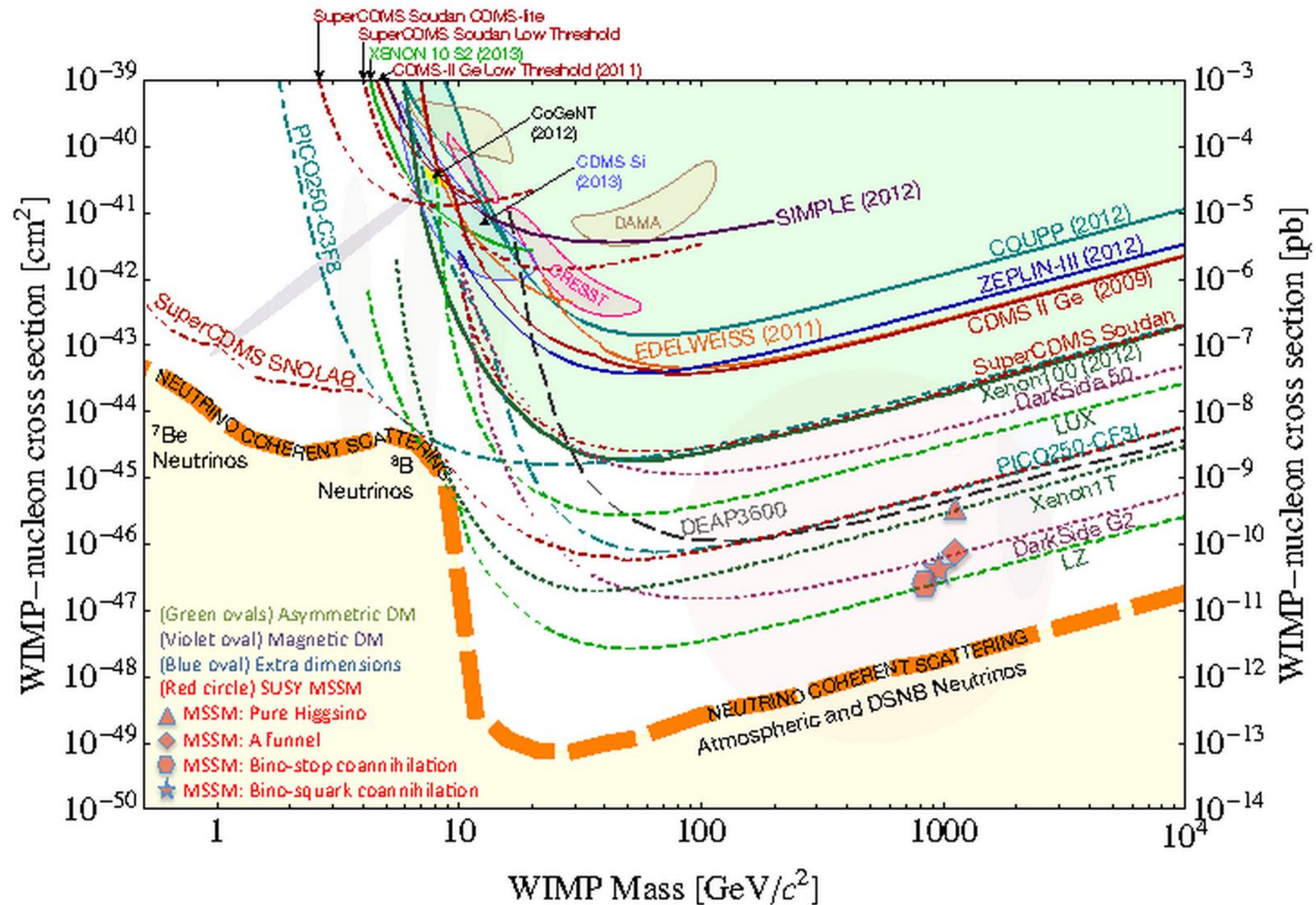
Could this be the wrong picture?

Average local dark matter density
 10^{16} g of dark matter expected within the



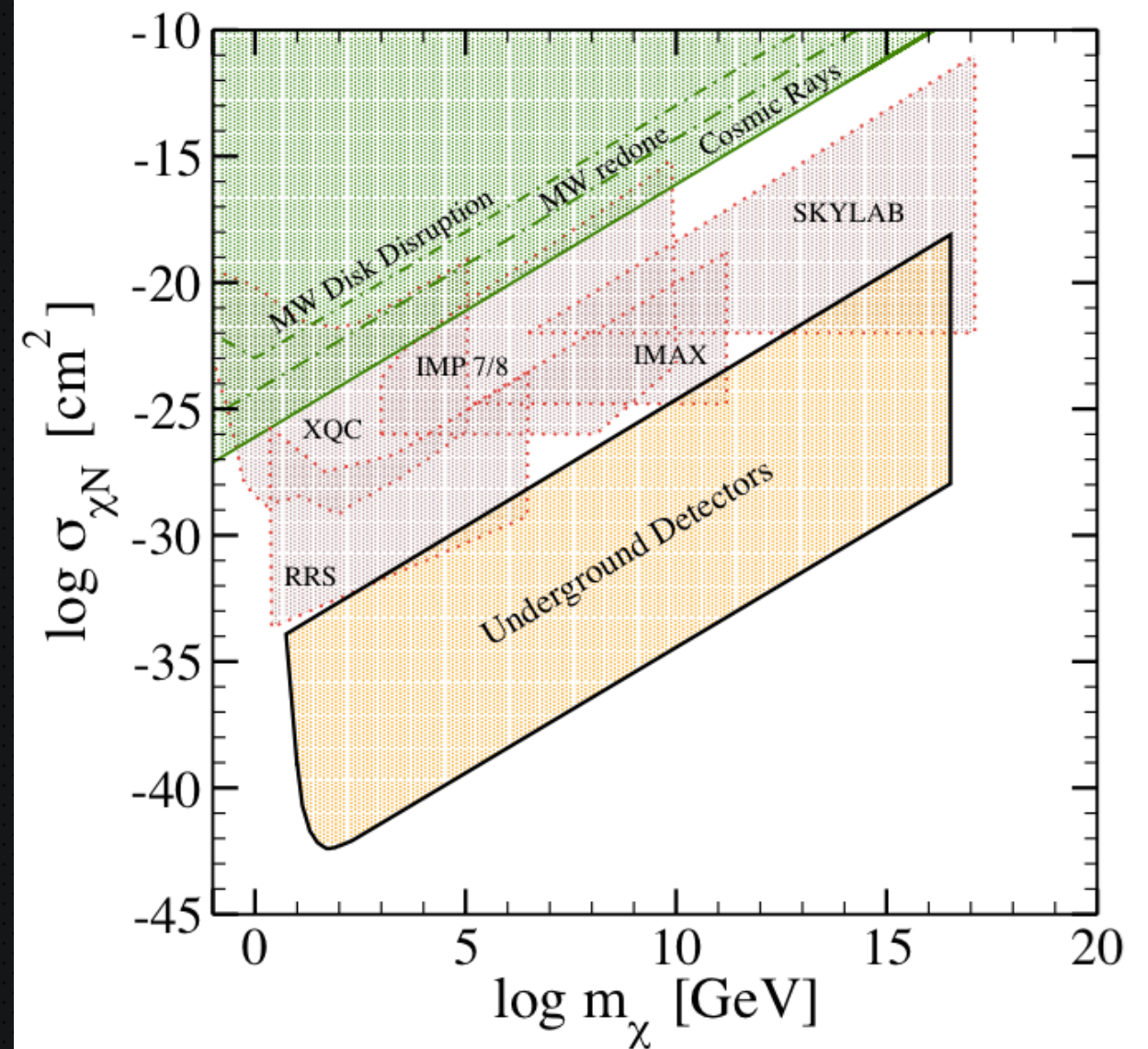
Could this be the right picture?

What do we know about DM



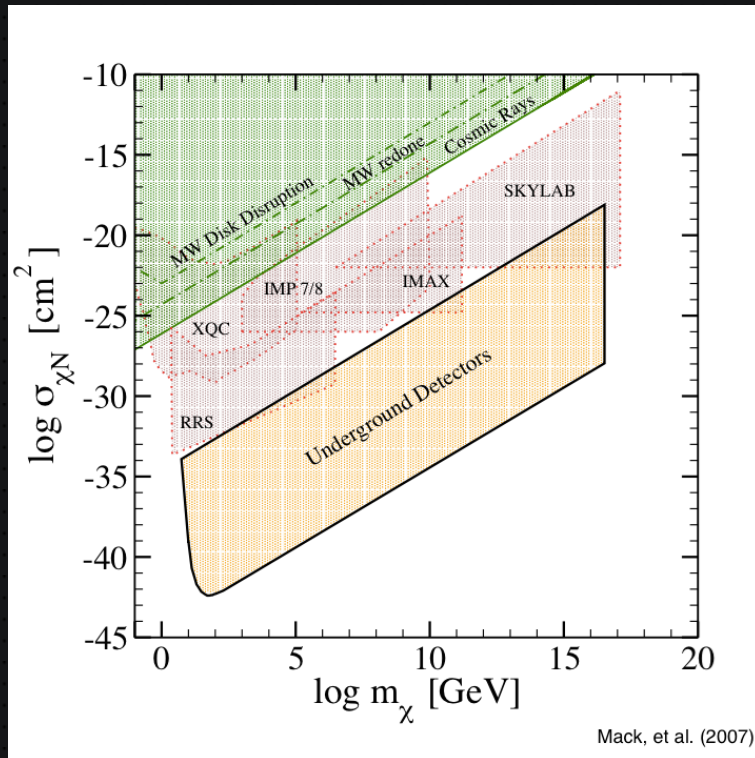
What do we know about DM σ ?

- Strongly-interacting dark matter: GDS et al. (1990), ..., Mack et al. (2007)
- More or less constrained up to $\sim 10^{17}$ GeV

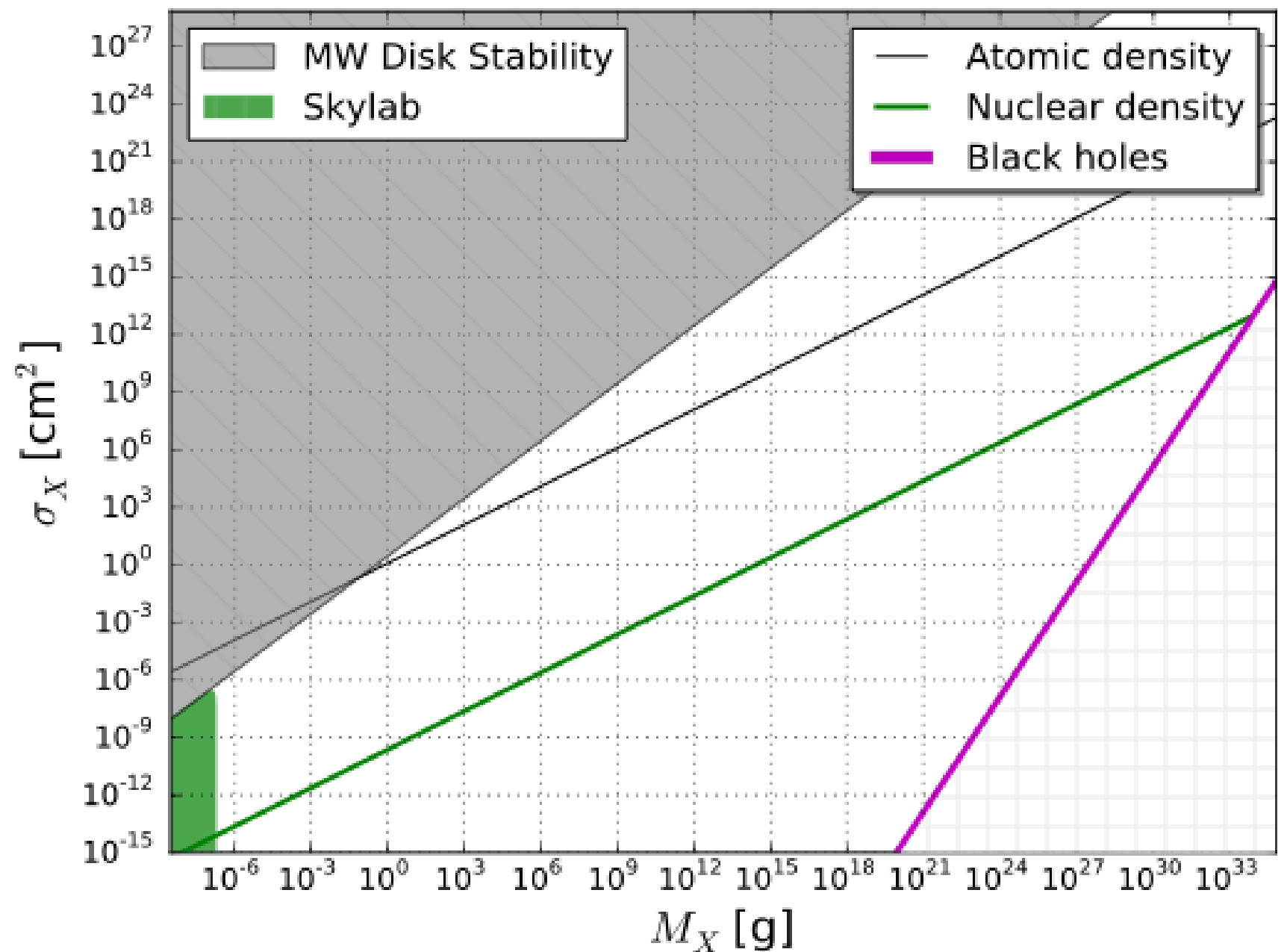


Mack, et al. (2007)

What about macros?



Mack et al. (2007)



Macros – what are they?

~~Ordinary Standard Model matter:~~

- ~~▪ Stellar remnants – WD, NS, BH~~
- ~~▪ Planets and other smaller~~

Katie (as quoted by Pao
lo):

I HATE ~~M~~ACHOS

Macros – what are they?

~~Ordinary Standard Model matter:~~

- ~~▪ Stellar remnants – WD, NS, BH~~
- ~~▪ Planets and other smaller~~

SBBN

Lesson: if DM is baryons it must be
“hidden” before BB

N

Macros – what are they?

In the Standard Model

- Quark nuggets, Witten (1984)
- Strange Baryon Matter (Lynn et al., 1990)
- Baryonic Colour Superconductors (+ axion)
(Zhitnitsky, 2003)
- Strange Chiral Liquid Drops (Lynn, 2010)
- Other names: nuclearites, strangelets, quark nuggets, CCO's, ...

Primordial Black Holes

BSM — e. g. SUSY Q-balls, topological defect
DM, ...

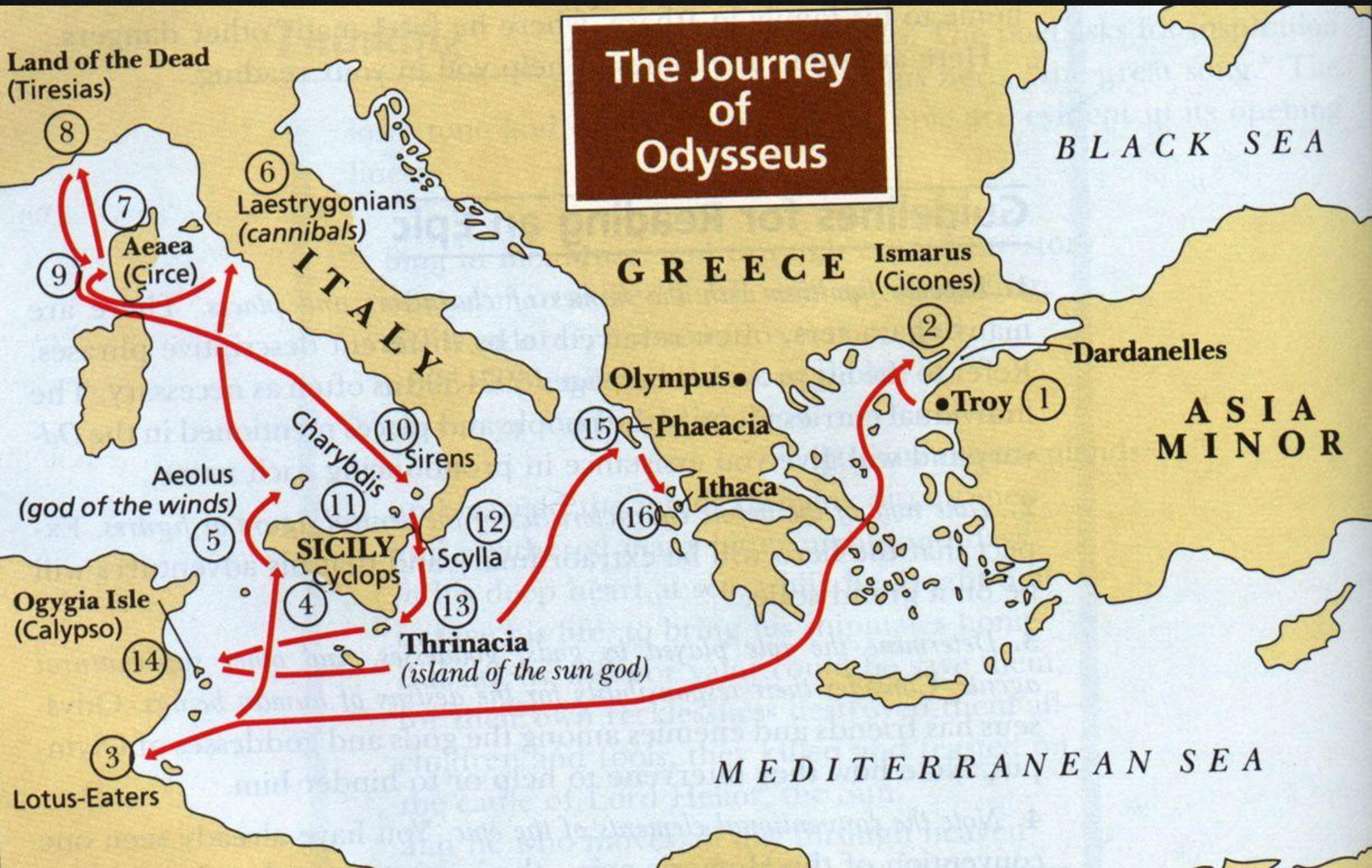
Macros – what are they?

In the Standard Model

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- Baryonic Colour Superconductors (+ axion) (Zhitnitsky, 2003)
- Strange Chiral Liquid Drops (Lynn, 2010)
- Other names: nuclearites, strangelets, quark nuggets, CCOs, CUDOs

Dark Matter may be a Standard Model phenomenon!

The Journey of Odysseus



So... what's allowed for Macroscopic

- A systematic probe of “macroscopic” dark matter candidates that scatter classically (geometrically) with matter
- Basic parameters: mass, cross section, charge, and some model-specific (e.g. elastic vs. inelastic scattering):

$$M_X, \quad \sigma_X \sim \pi R_X^2, \quad V(R_X) \sim eQ_X/R_X$$

Model-*i*ndependent constraints

- Elastic and inelastic coupling of
 - Macros to other Macros
 - Macros to baryons
 - Macros to photons
- Gravitational effects (lensing)

Model-*independent* constraints

Records left on the sky

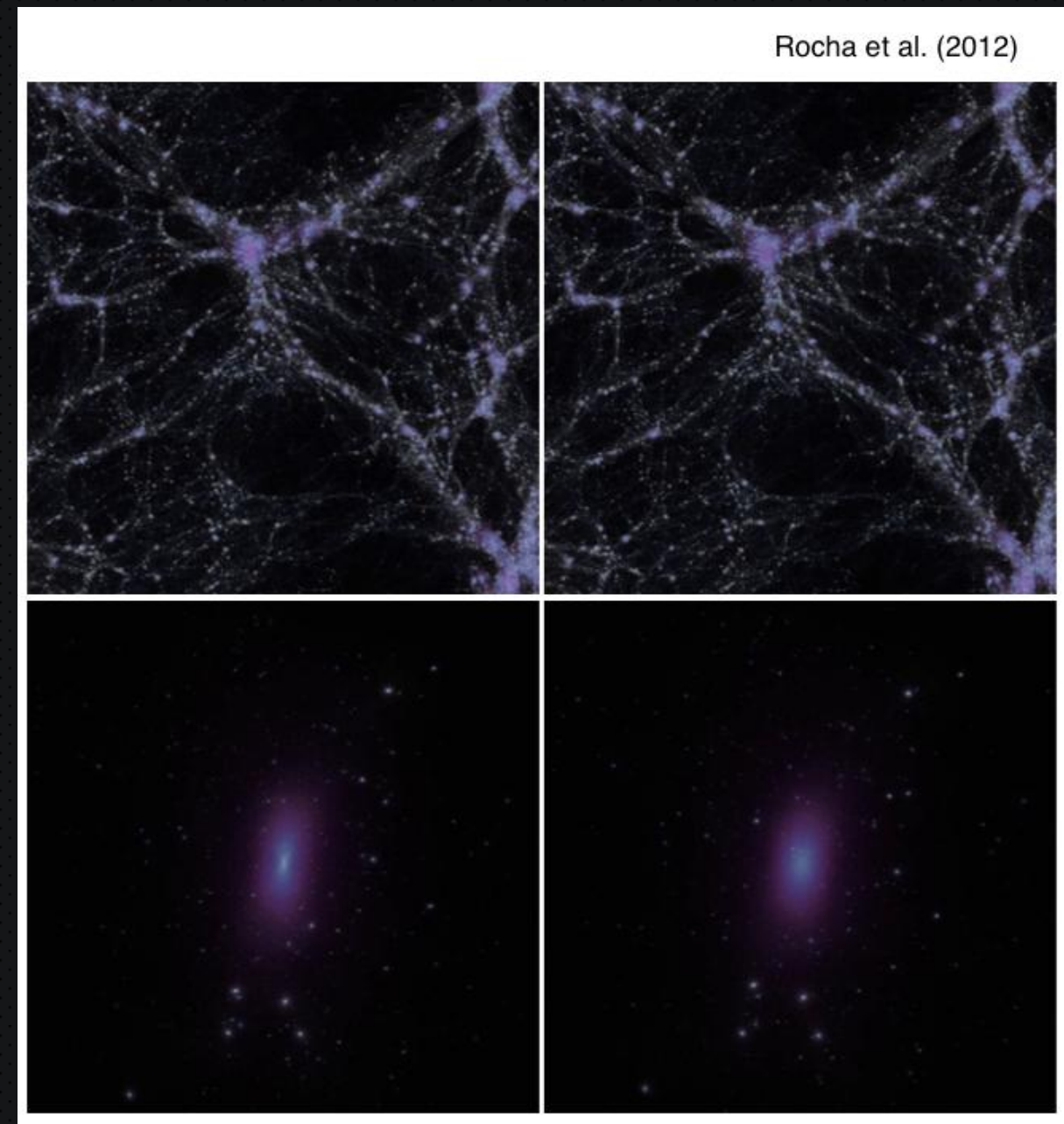
Macro-Macro Coupling

Self-interacting dark matter (SIDM)

- Spergel and Steinhardt (2000) (cusp-core issue)
- Simulations vs. obs:
e.g., Davé et al. (2000),
Randall et al. (2007),
Rocha et al. (2012)

$$(\sigma_X/m_X) < 0.25$$

cm^2/g



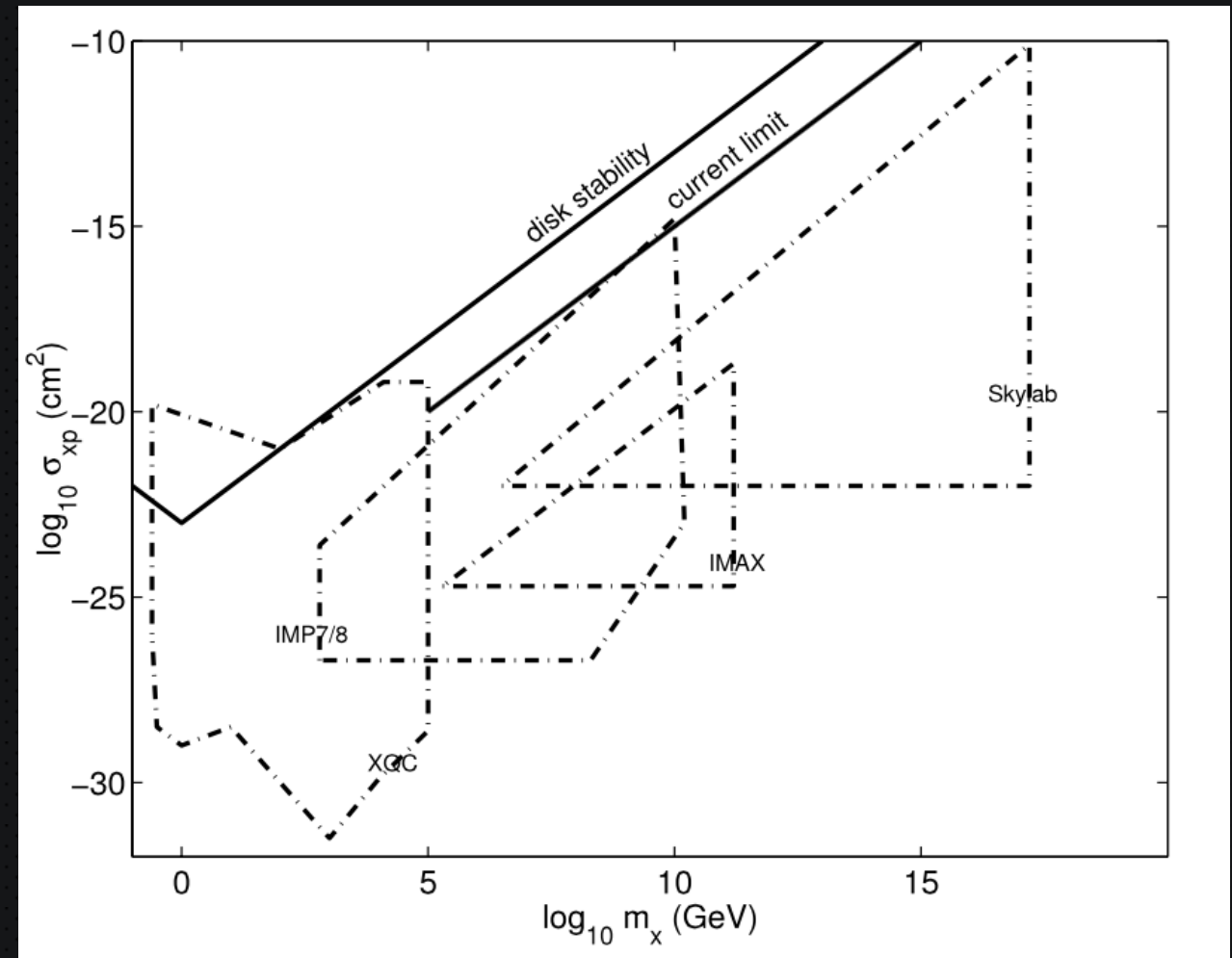
Left — collision-less DM; Right — SIDM

Macro-baryon Interactions

- Virial theorem implies
Cluster gas heating
DM particles and baryons
will have similar
velocities
- High mass of Macros
means energy transfer to
baryons in a collision,
implying gas heating
- Gas would be hottest at
center. Lack of this
observation implies

$$(\sigma_x/m_x) < 0.06$$

cm²/g



Chuzhoy and Nusser (2006)

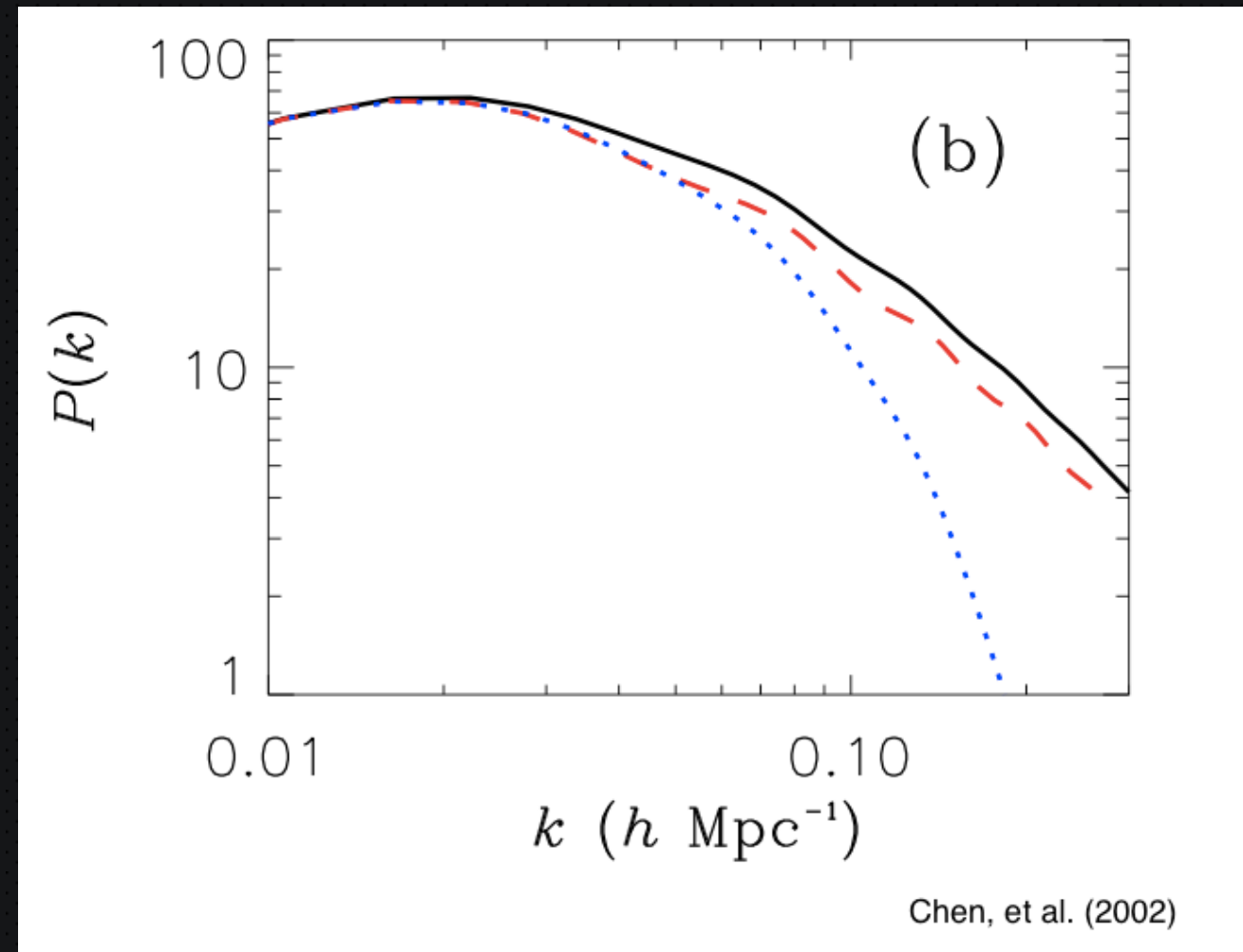
Macro-baryon Interactions

Effects on large-scale structure

collisional damping of acoustic oscillations of the baryon-photon plasma (Boehm et al. 2001, 2002, 2004)

- Chen et al. (2002) used CMB and LSS observations to constrain interaction
- Dvorkin et al. (2014) added Lyman-alpha observations ($z \sim 3$) and found

$$(\sigma_X/m_X) < 0.003 \text{ cm}^2/\text{g}$$



Matter power spectrum

Model-*independent* constraints

Records left on earth

Passing-baryon Interactions

gravitational
Resonant-bar Gravitational Wave

waves might be
Detectors

detected by

looking for

excitation of

normal modes of

aluminum cylinders

- If cold, these are also highly sensitivity to cosmic rays and exotic particles



Joseph Weber (~1960's)

Image: AIP Emilio Segrè Visual Archives

Resonant-bar Gravitational Wave Detectors

D. S. J. et al. (GDS-100), *Phys. Rev. D* **100**, 023504 (2019) (PRD in press)

- Null detection by the NAUTILUS & EXPLORER experiments rule out nuclearite dark matter candidates below 10^{-4}g
- Analysis can be generalized for macro dark matter: $m < \sim 10^{-5}\text{g}$ for $(\sigma_X/m_X) < \sim 0.001 \text{ cm}^2/\text{g}$

Macro-baryon Interactions

- Chemical etching reveals
Ancient Mica

lattice defects in
muscovite mica

- Old samples buried deep
(~3 km) underground makes
for a good exotic
particle detector (e.g.
monopoles and
nuclearites)
- Used by de Rujula and
Glashow (1984), Price
(1988) to rule out
nuclearite dark matter <
55g
- Generalizable to Macros

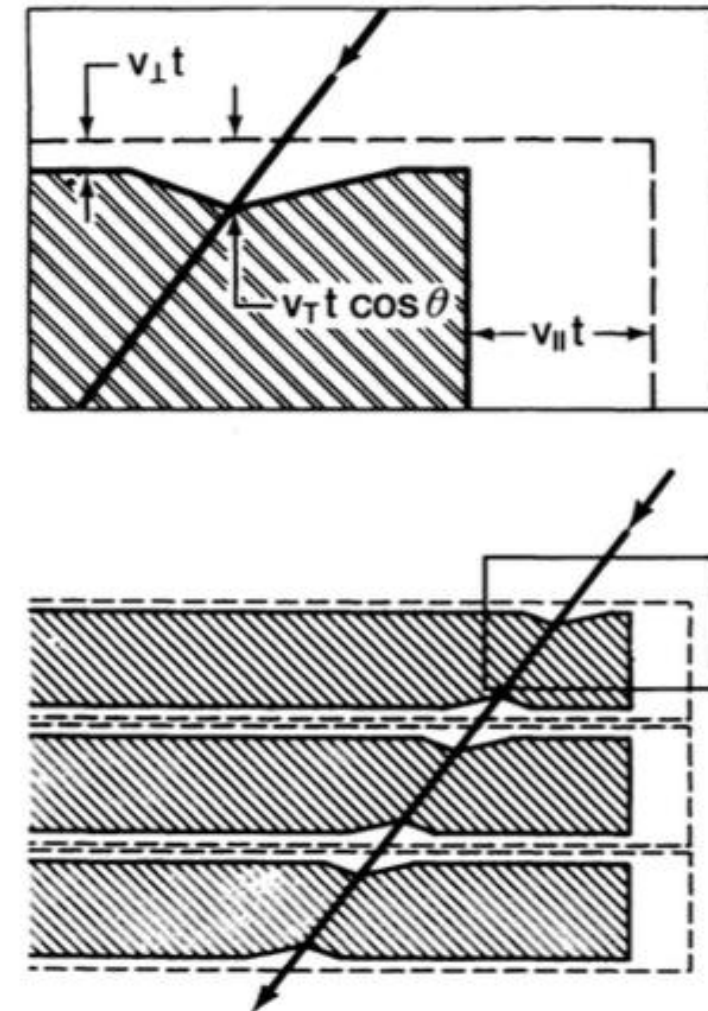
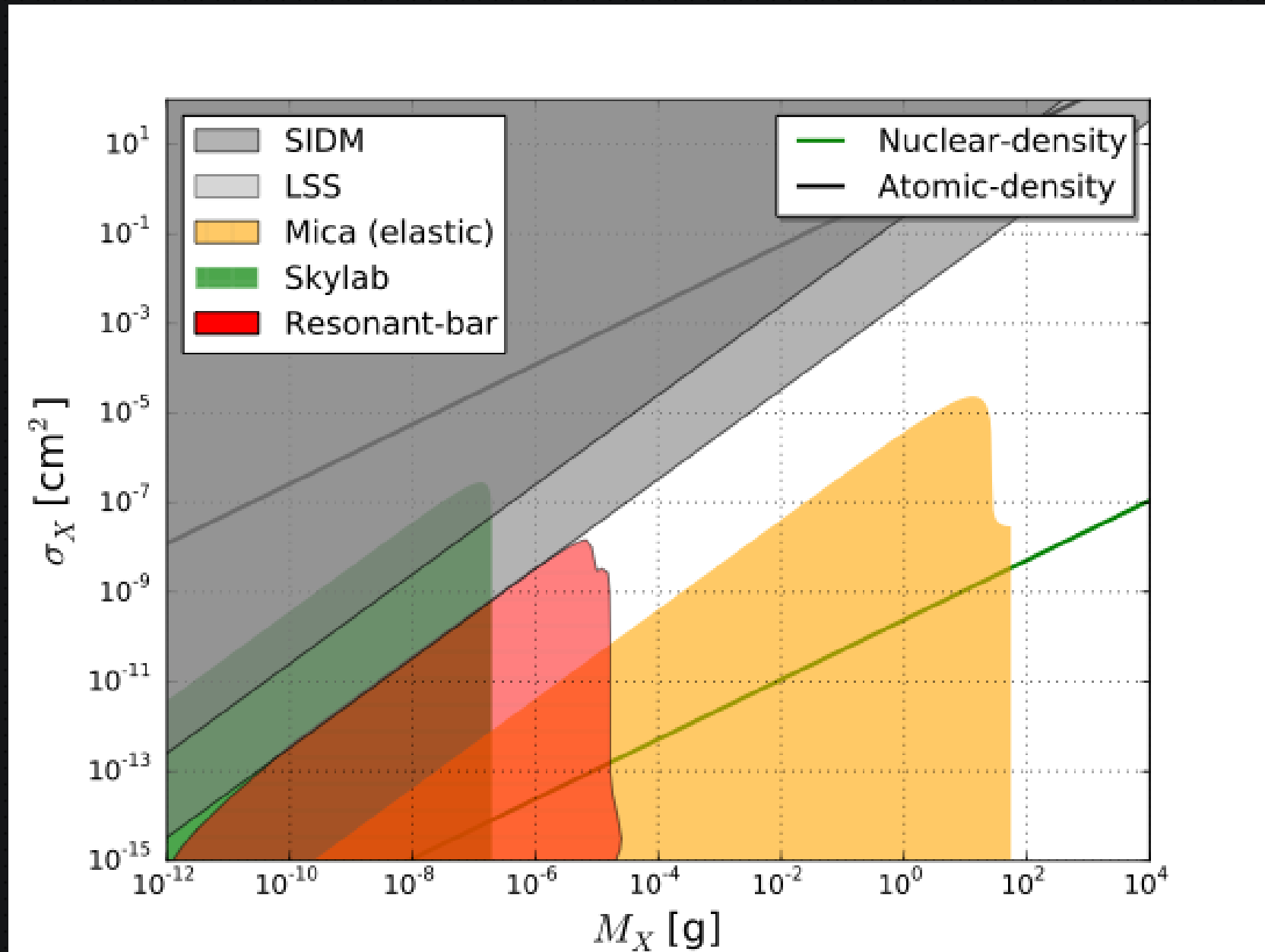


FIG. 2. Geometry of collinear etch pits along the trajectory of a hypothetical monopole-nucleus bound state in three sheets of mica that had been cleaved, etched, and superimposed for scanning.

Price and Salamon (1986)

Macro Constraints

(on *elastic* scattering w/ baryons and other
Macros)



Jacobs, Starkman, Lynn (2014); Jacobs, Starkman, Weltman (2014)

Macro-photon Interactions

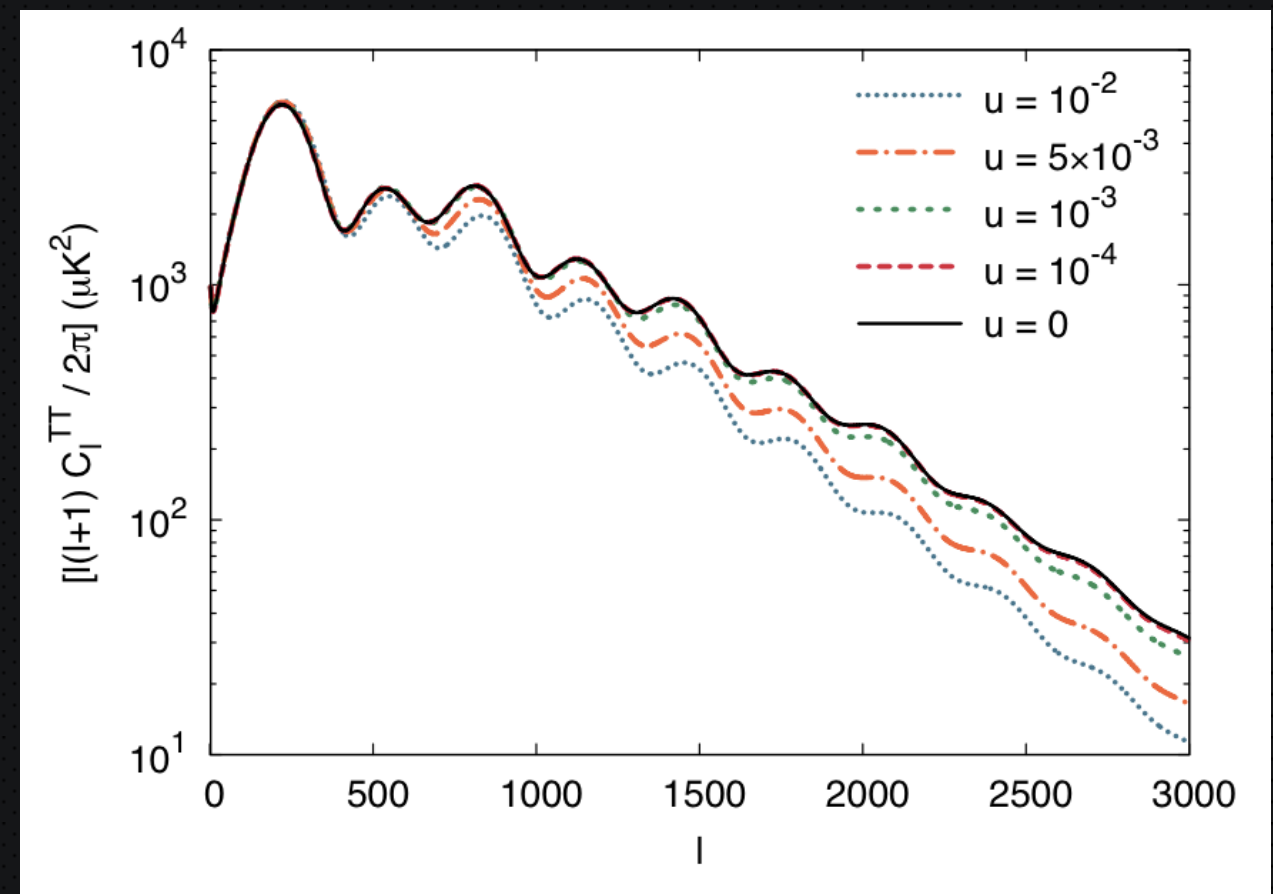
Effects on intermediate-scale structure

would also cause damping (Boehm et al. 2001, 2002, 2004)

- Wilkinson et al. (2014) used Planck CMB data to constrain DM-photon interactions to

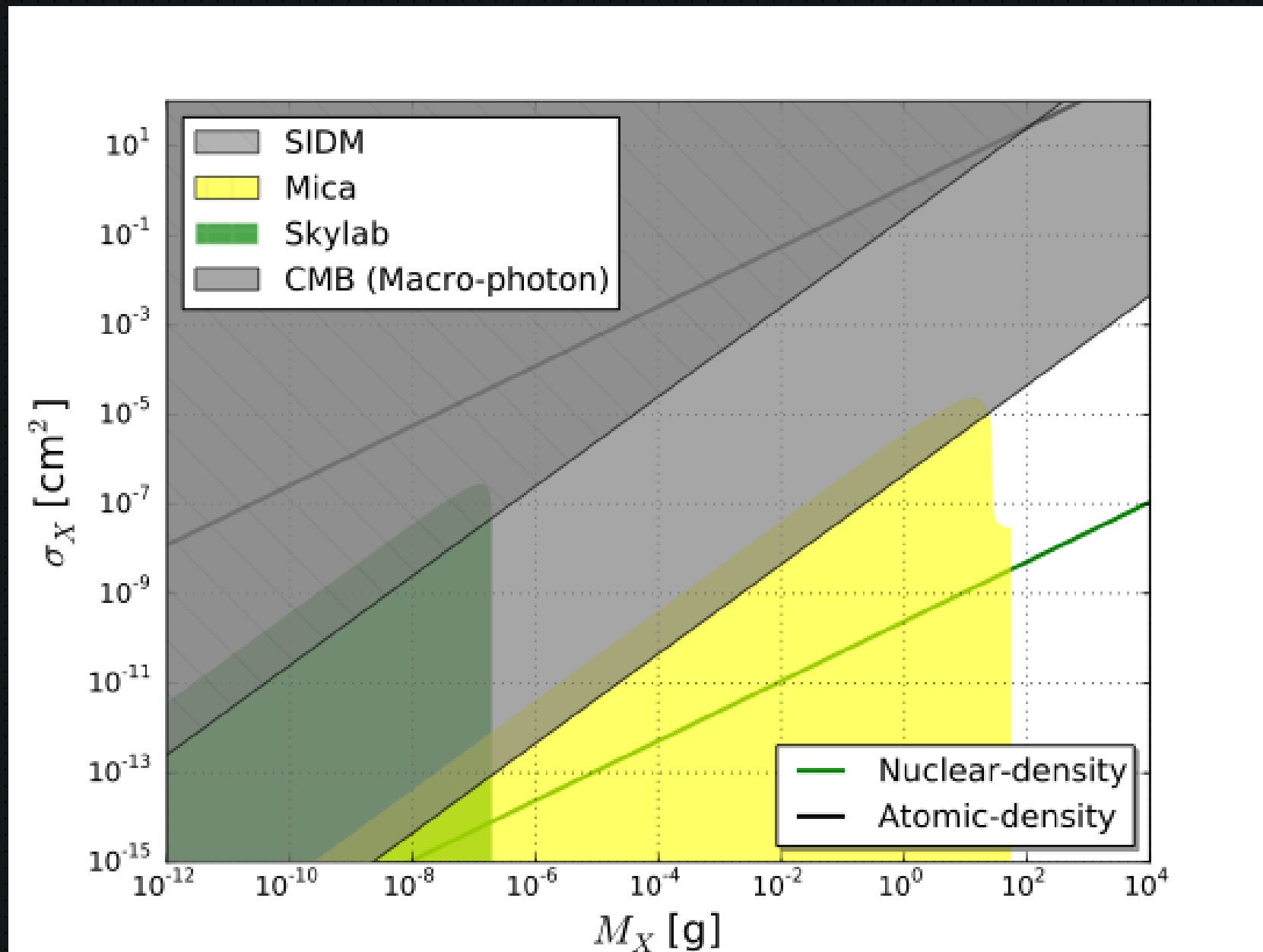
$$(\sigma_X/m_X) < 4.5 \times 10^{-7} \text{ cm}^2/\text{g}$$

- Applies to Macros, assuming thermal equilibrium with the plasma



Wilkinson et al. (2014)

Macro Constraints



Jacobs, Starkman, Lynn (2014)

Model-independent constraints

Gravitational effects

Gravitational Lensing

Flux amplification

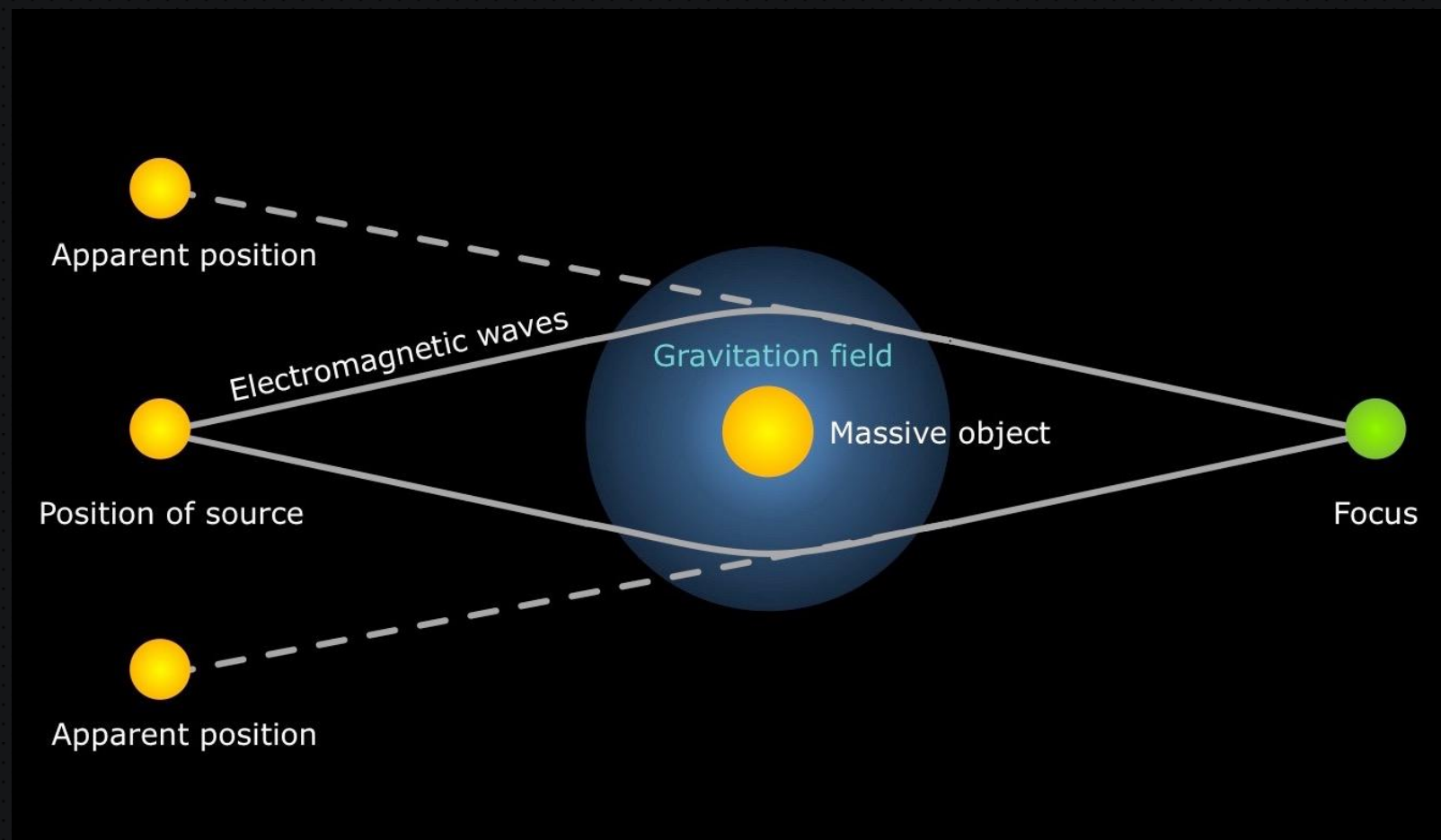


Image: GFDL

Gravitational Lensing

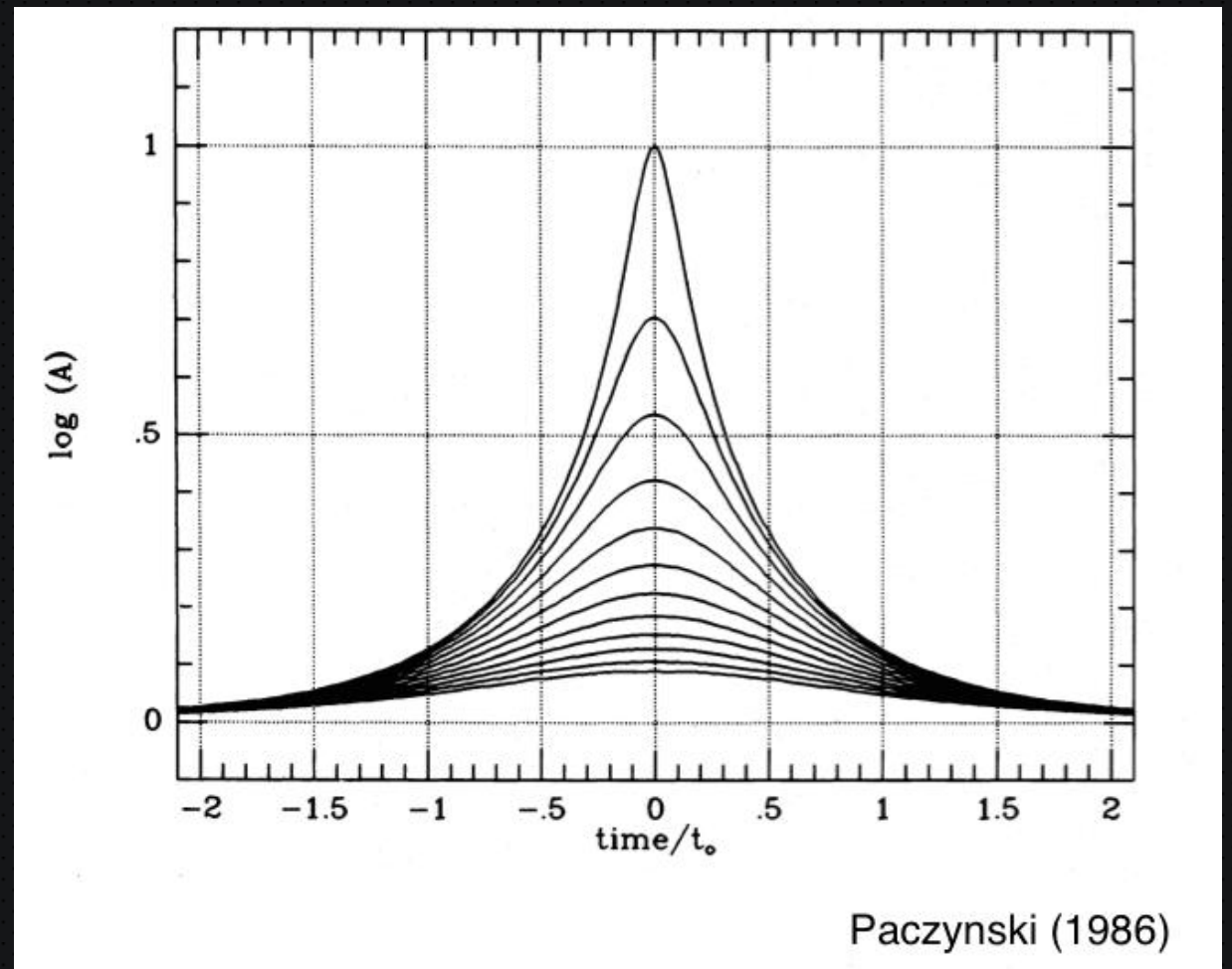
▪ Allsman, et al. (2000)
Microlensing
and Tisserand, et al.

(2006) monitored
sources in the Small
and Large Magellanic
Clouds

▪ Griest et al. (2013)
used sources in the
local solar
neighborhood

▪ Combined, they exclude

$$4 \times 10^{24} \text{ g} < M < 6 \times 10^{24} \text{ g}$$

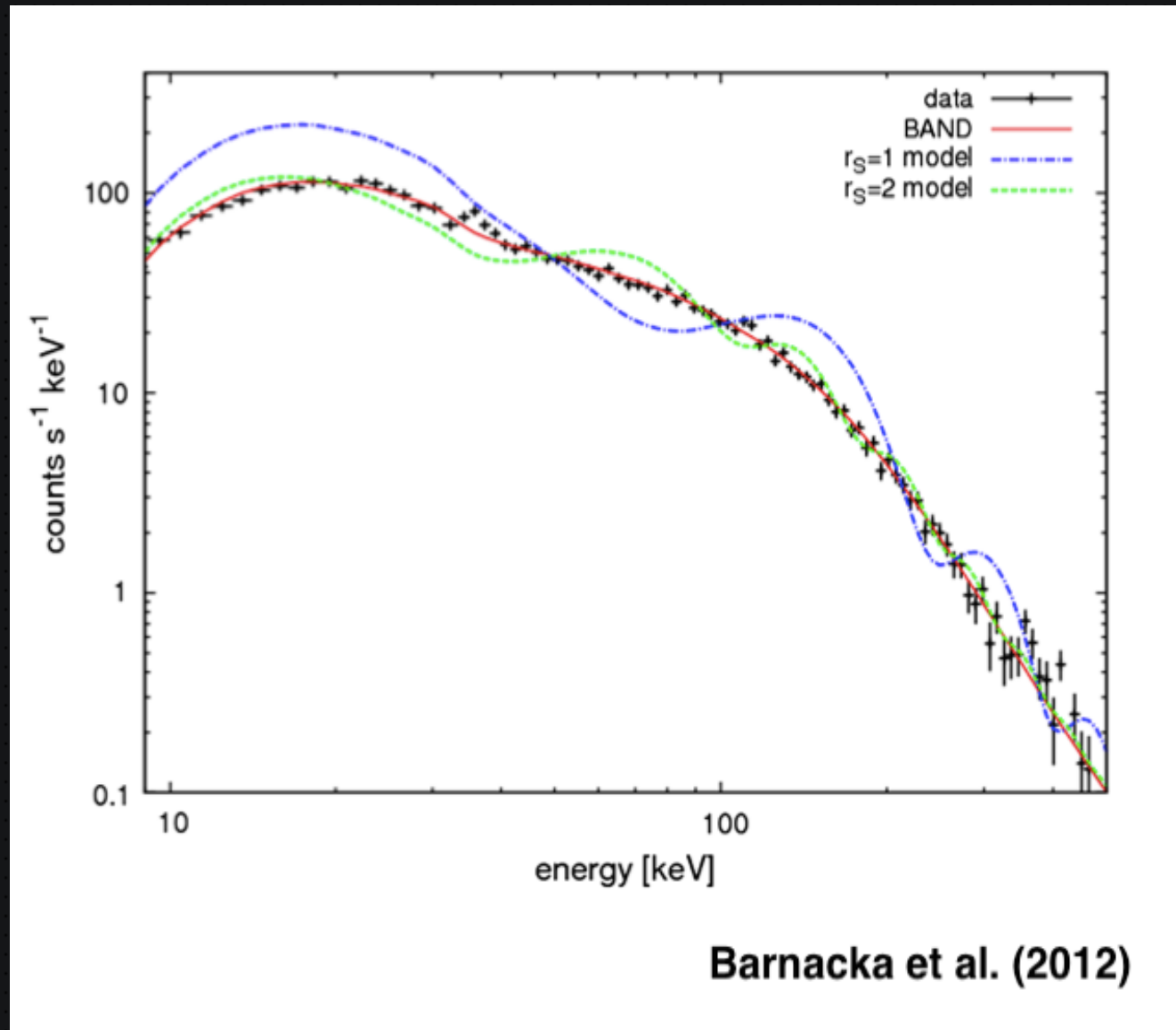


Gravitational Lensing

Femtolensing

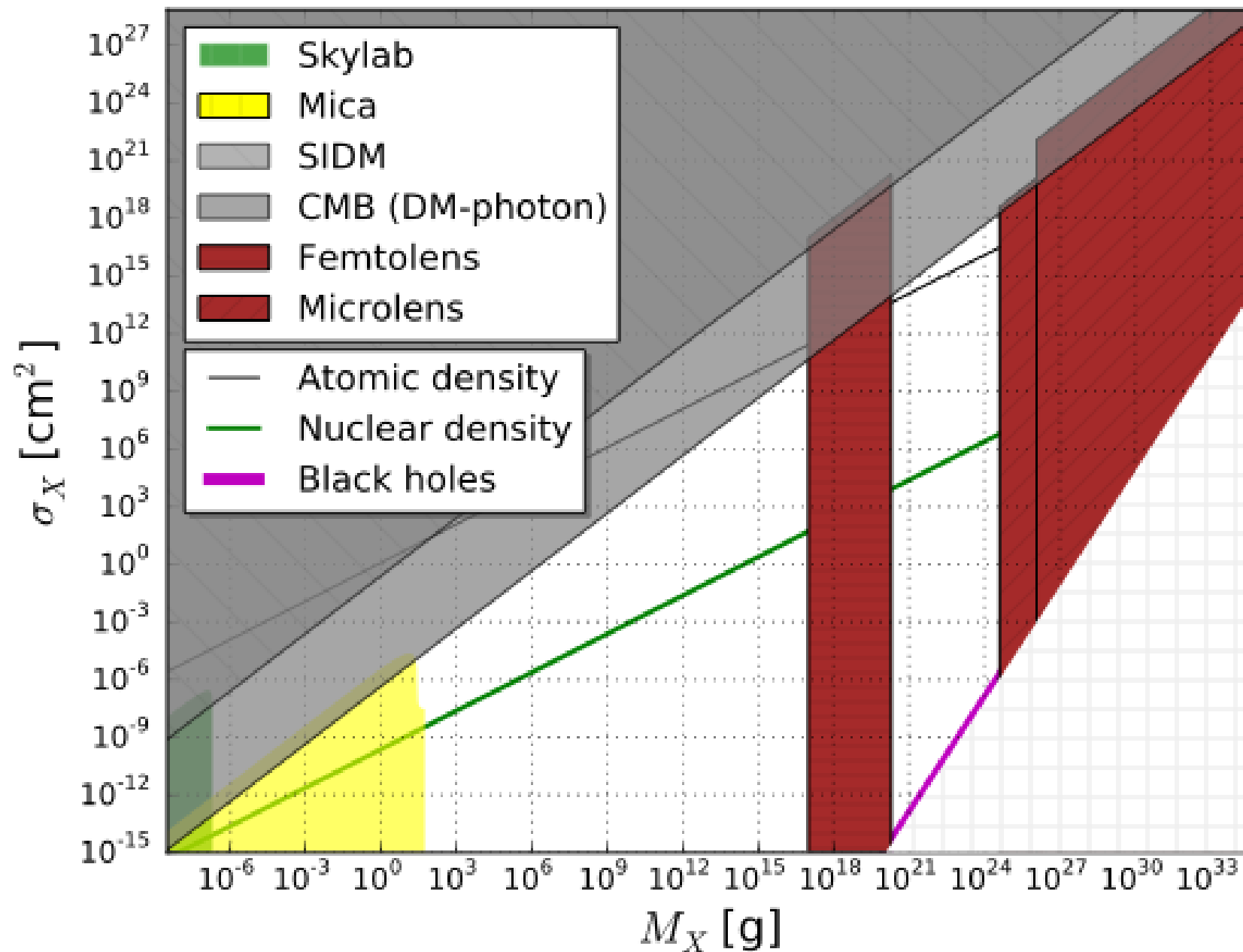
- Gould, A. (1992)
- Marani et al. (1998), used data the BATSE GRB experiment
- Barnacka et al. (2012) used GRB data from Fermi Combined, and exclude

$$10^{17} \text{g} < M_X < 10^{20} \text{g}$$



Model-independent Macro Constraints

(including)



Jacobs, Starkman, Lynn (2014)

Seismic search for strange quark nuggets

Eugene T. Herrin, Doris C. Rosenbaum, and Vigdor L. Teplitz

Phys. Rev. D **73**, 043511 – Published 17 February 2006

[Article](#)

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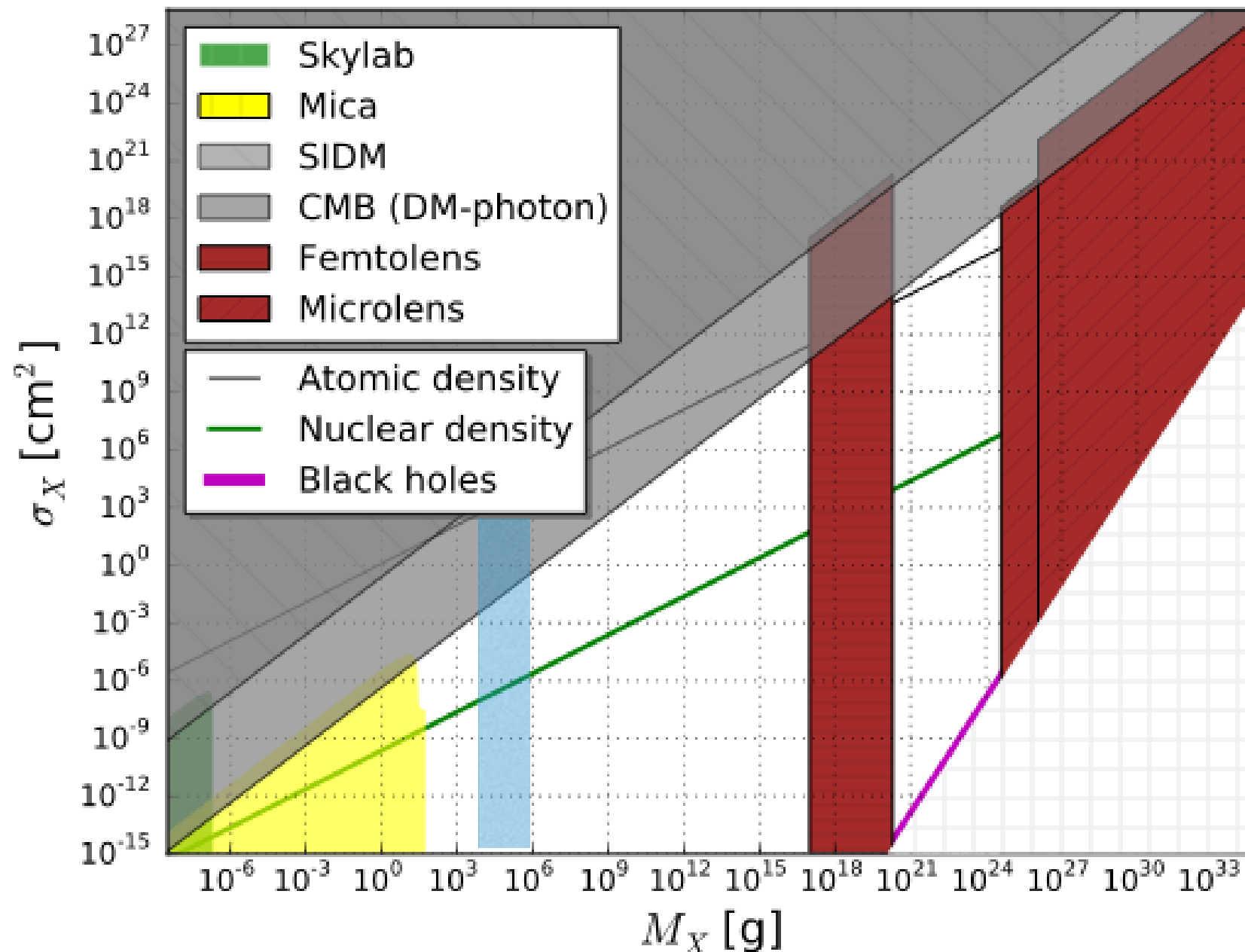


ABSTRACT

Bounds on masses and abundances of Strange Quark Nuggets (SQNs) are inferred from a seismic search on Earth. Potential SQN bounds from a possible seismic search on the Moon are reviewed and compared with Earth capabilities. Bounds are derived from the data taken by seismometers implanted on the Moon by the Apollo astronauts. We show that the Apollo data implies that the abundance of SQNs in the region of 10 kg to 1 ton must be at least an order of magnitude less than would saturate the dark matter in the solar neighborhood.

Model-independent Macro Constraints

(including)



Jacobs, Starkman, Lynn (2014)

Model-dependent constraints

Effects on BBN

Model-dependent constraints

Efficient macro BBN? $X_4 \approx 0.25 \pm 0.01$
(Aver et al. 2013)

- If n and/or p can be absorbed by macros ^G
– change X_4
- Theoretical uncertainties on Standard Model predictions are relatively tiny so we must ensure $|\Delta X_4| < 0.01$

Model-dependent BBN constraints

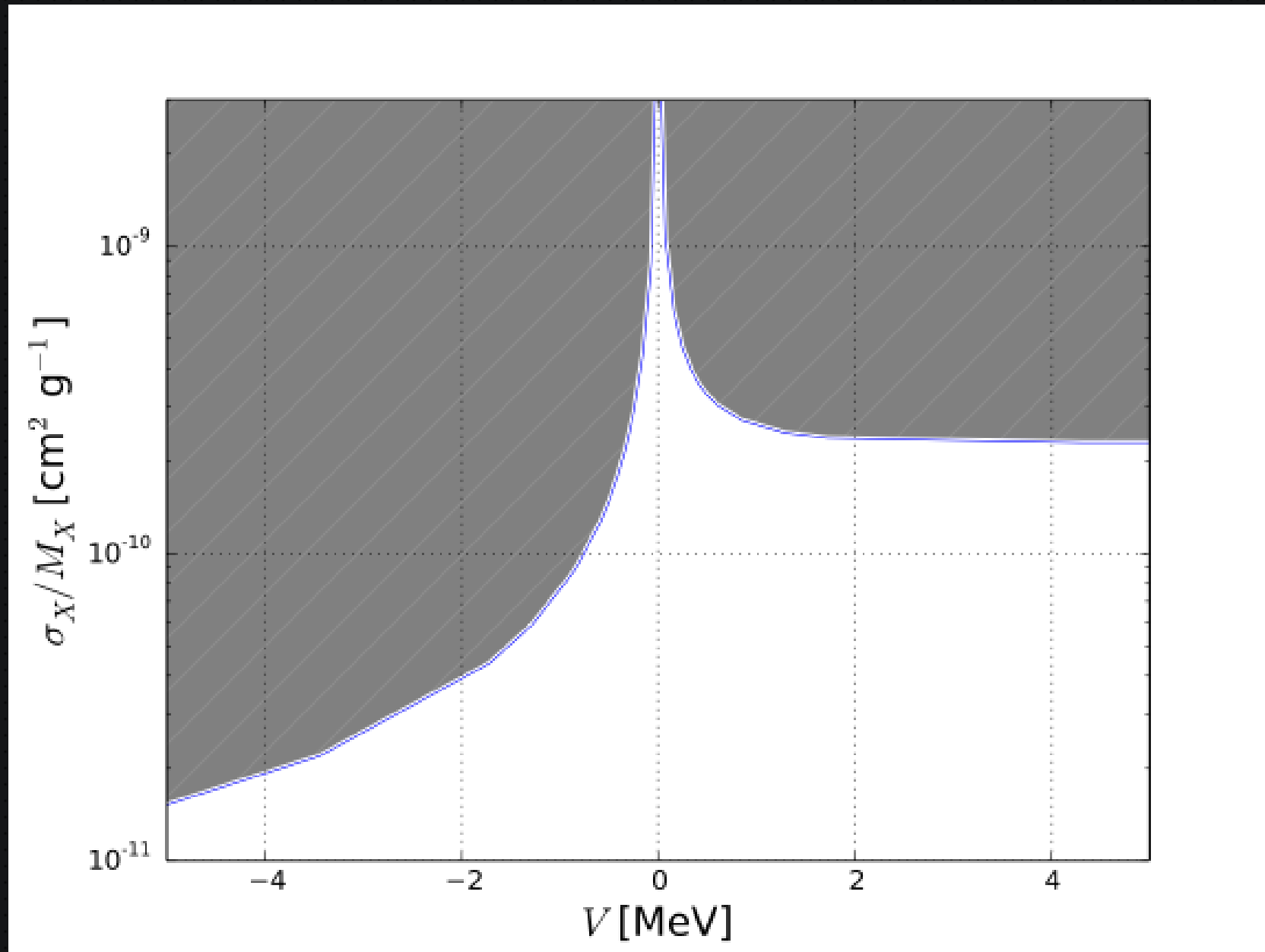
- For surface potentials < 0.01 MeV:

$$\frac{\sigma_x}{M_x} \lesssim 8 \times 10^{-11} \left| \frac{V(R_x)}{\text{MeV}} \right|^{-1} \text{cm}^2 \text{g}^{-1}$$

- For surface potentials $> \sim 1$ MeV, p

$$\frac{\sigma_x}{M_x} \lesssim 2 \times 10^{-10} \text{cm}^2 \text{g}^{-1}$$

Model-dependent BBN constraints



Jacobs, Starkman, Lynn (2014)

Model-dependent constraints:

Jacobs, GDS, Lynn (2014)

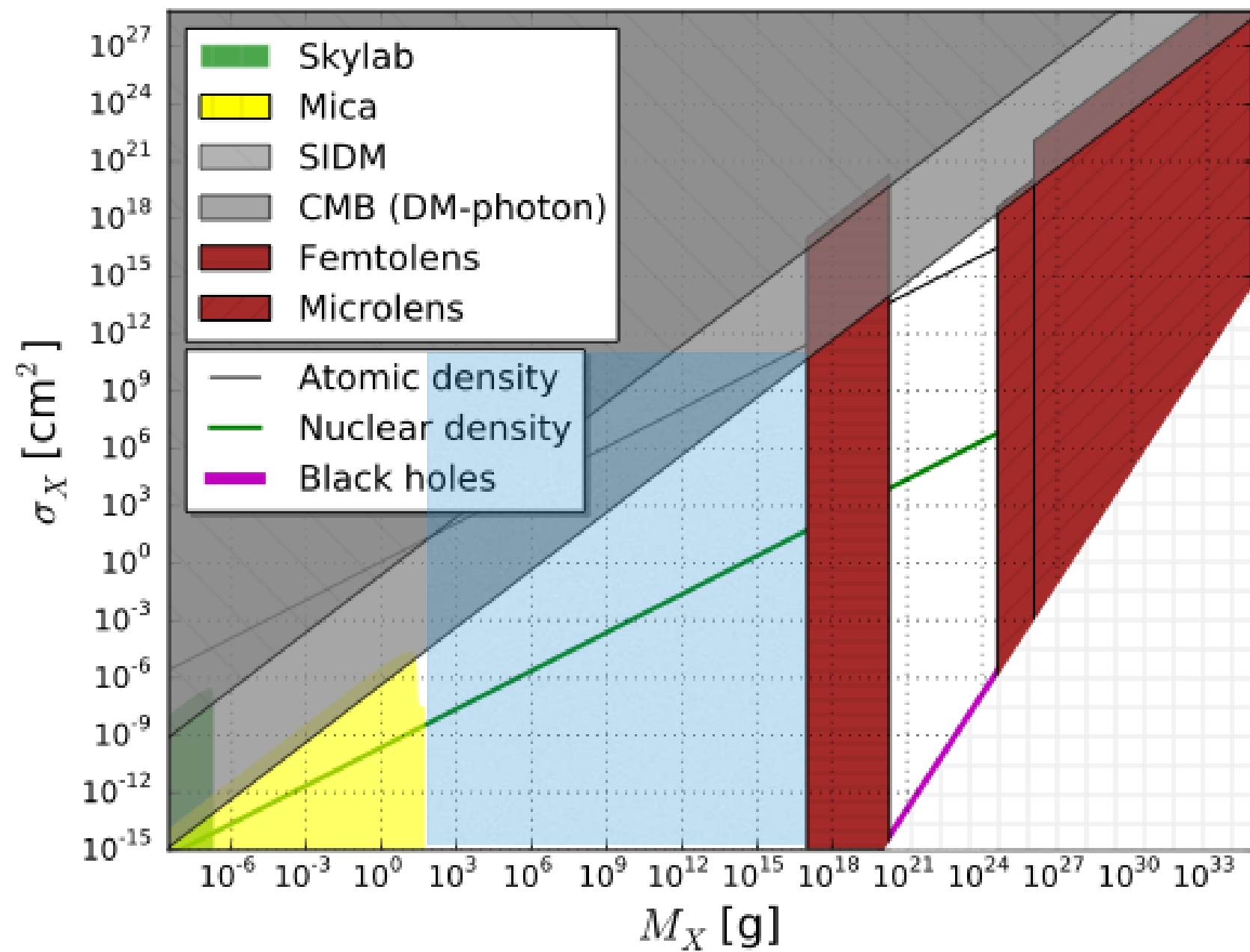
Continued solar existence

Target	$\Gamma [M_X^{-1} \text{g s}^{-1}]$	$\Gamma [M_X^{-1} \text{g yr}^{-1}]$
NS	48	1.5×10^9
WD	4.8×10^3	1.5×10^{11}
\odot	3.9×10^6	1.2×10^{14}
\oplus	44	1.4×10^9
ζ	3.2	1.0×10^8

Table 1. Expected Macro impact rates for a neutron star, white dwarf, the sun, the earth, and the moon. We have taken $v_X = 250$ km/s, $R_{\text{NS}} = 10$ km, $R_{\text{WD}} = 10^3$ km, $f_\rho = 1$, and $M_{\text{NS}} = M_{\text{WD}} = M_\odot$. For example, if $M_X = 1$ g then there would be about 3 impacts per km² per year on the earth.

- If the macro would “convert” ordinary matter, then solar stability probably requires

$$M_X > 10^{18} \text{g}$$



Conclusions

- Dark matter doesn't have to interact weakly if it's very massive. It might even arise within the Standard Model.
- Regardless of its nature, there are large unconstrained regions of macro dark matter parameter space. Much still needs to be done..
- There are many other potential probes: seismological (terrestrial and lunar), atmospheric and marine observations (light, sound)
- Such "strongly"-interacting dark matter candidates may be relevant to several outstanding issues in the current CDM paradigm (cusp vs. core, missing satellites,...) (but that idea may have a hard time with CMB constraints)