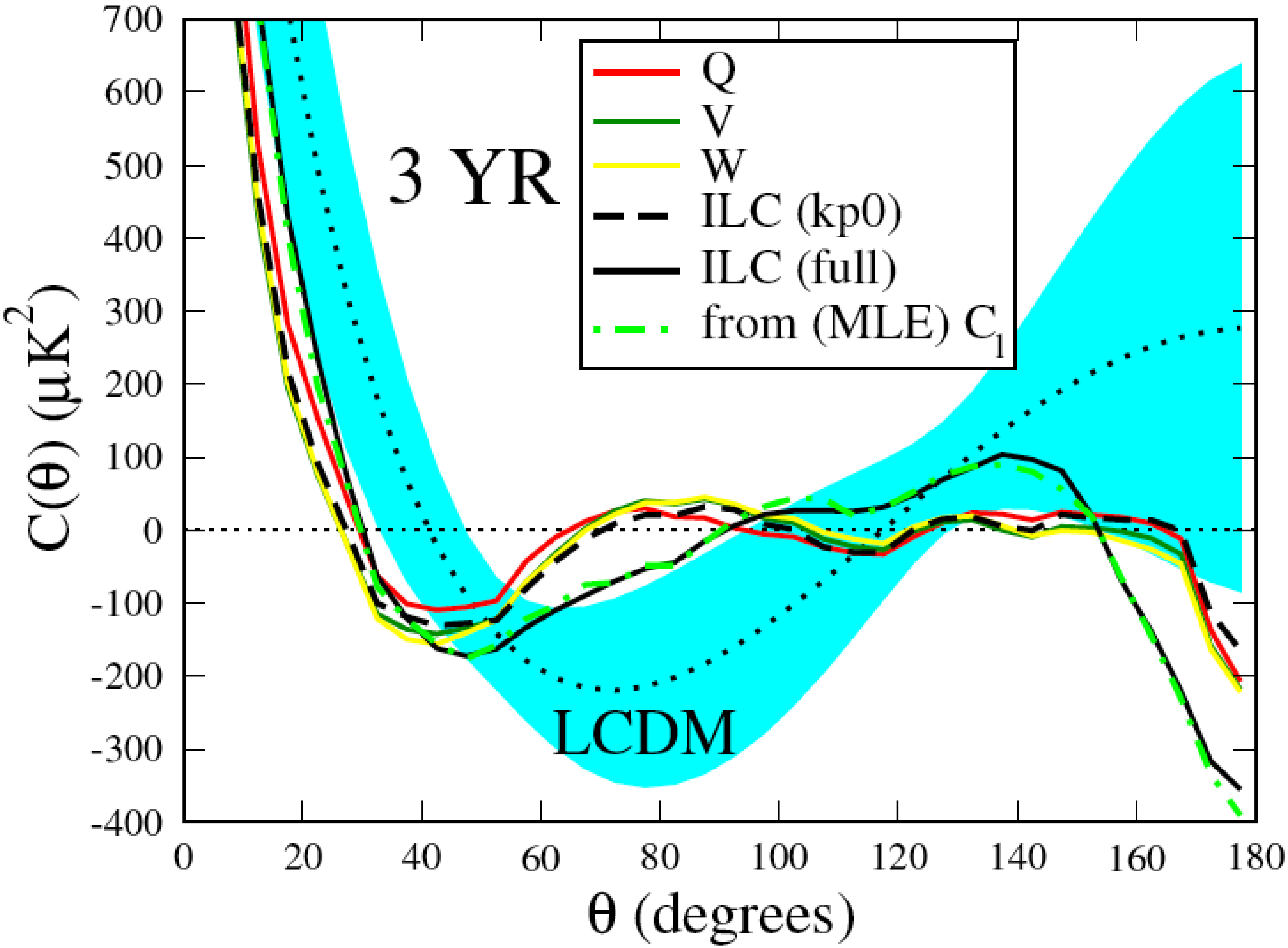
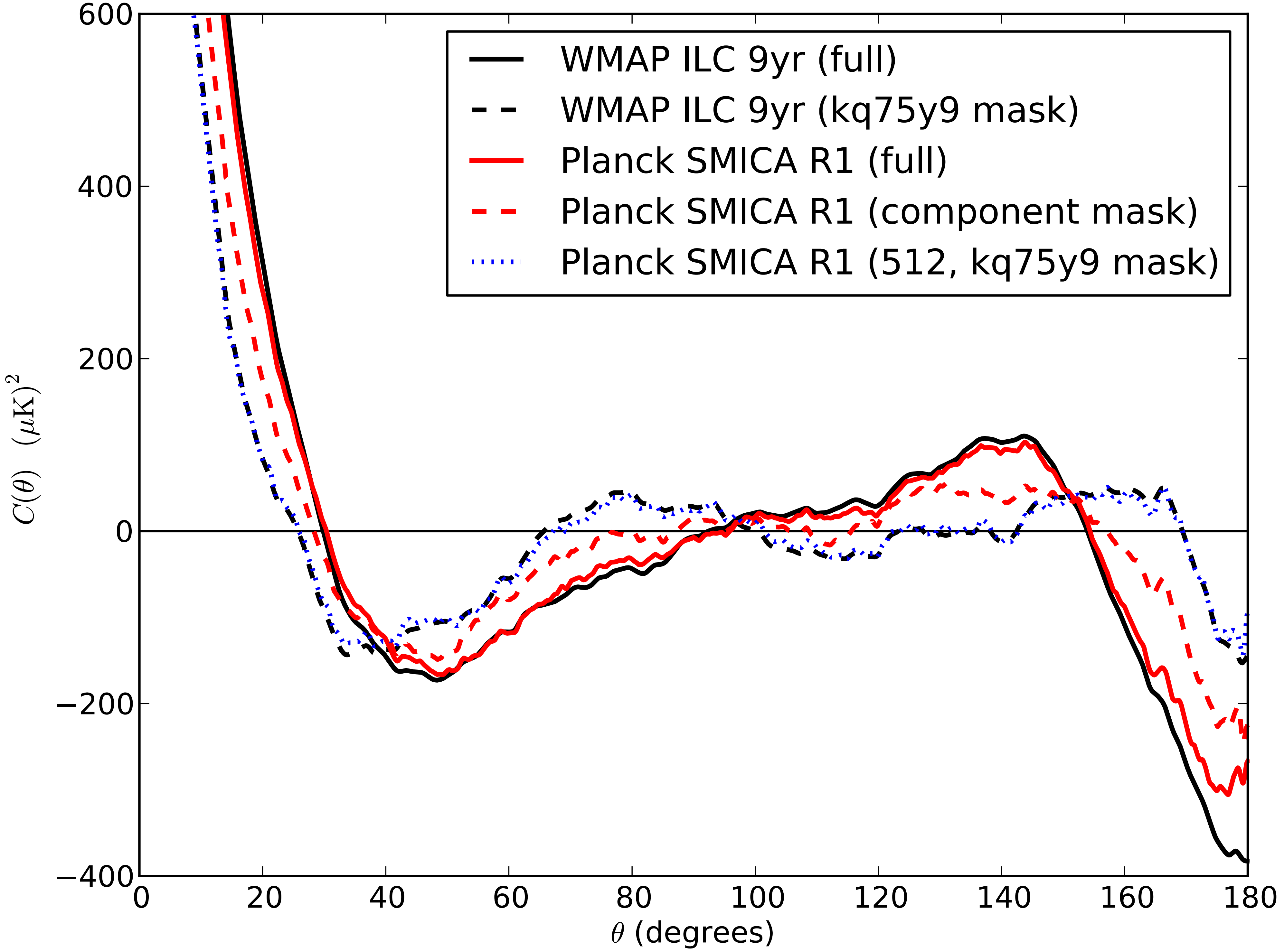
2015: The Spacetime Odyssey Continues

Stockholm, Sweden

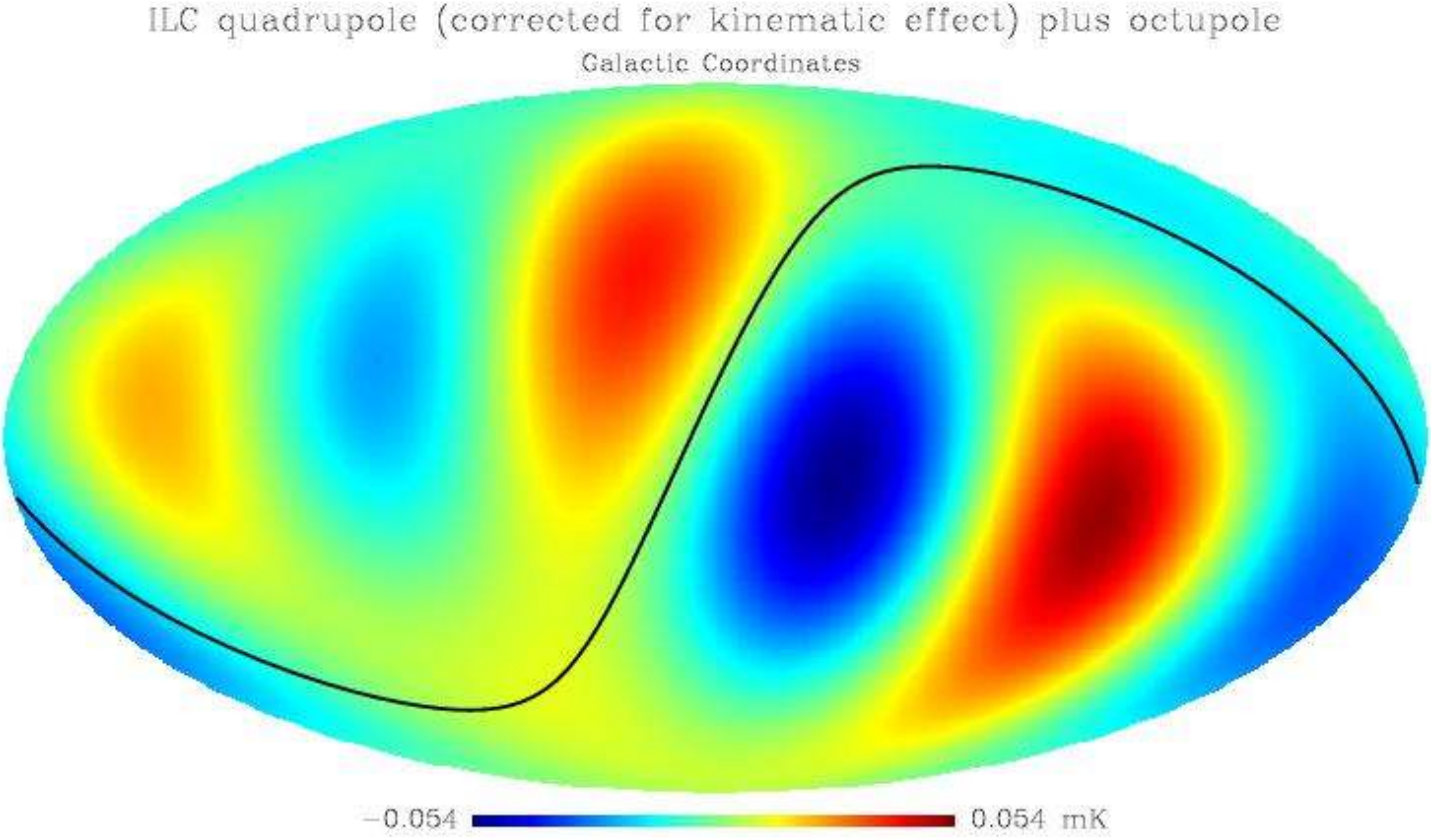
Two point angular correlation function -- WMAP3

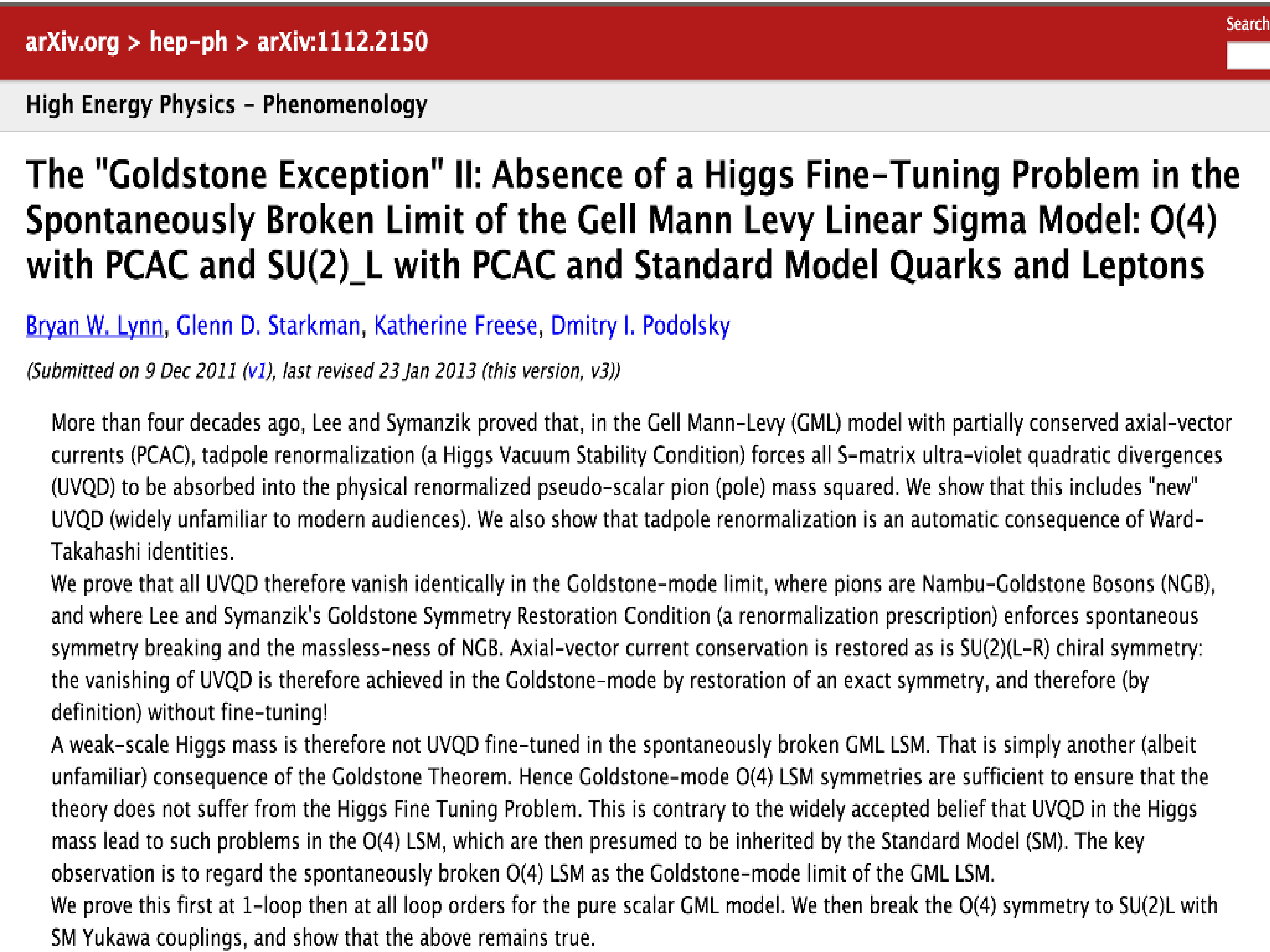


Did this change in Planck?



l=2&3 : The Map


ILC quadrupole (corrected for kinematic effect) plus octupole
Galactic Coordinates
−0.054
0.054 mK



High Energy Physics - Phenomenology

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

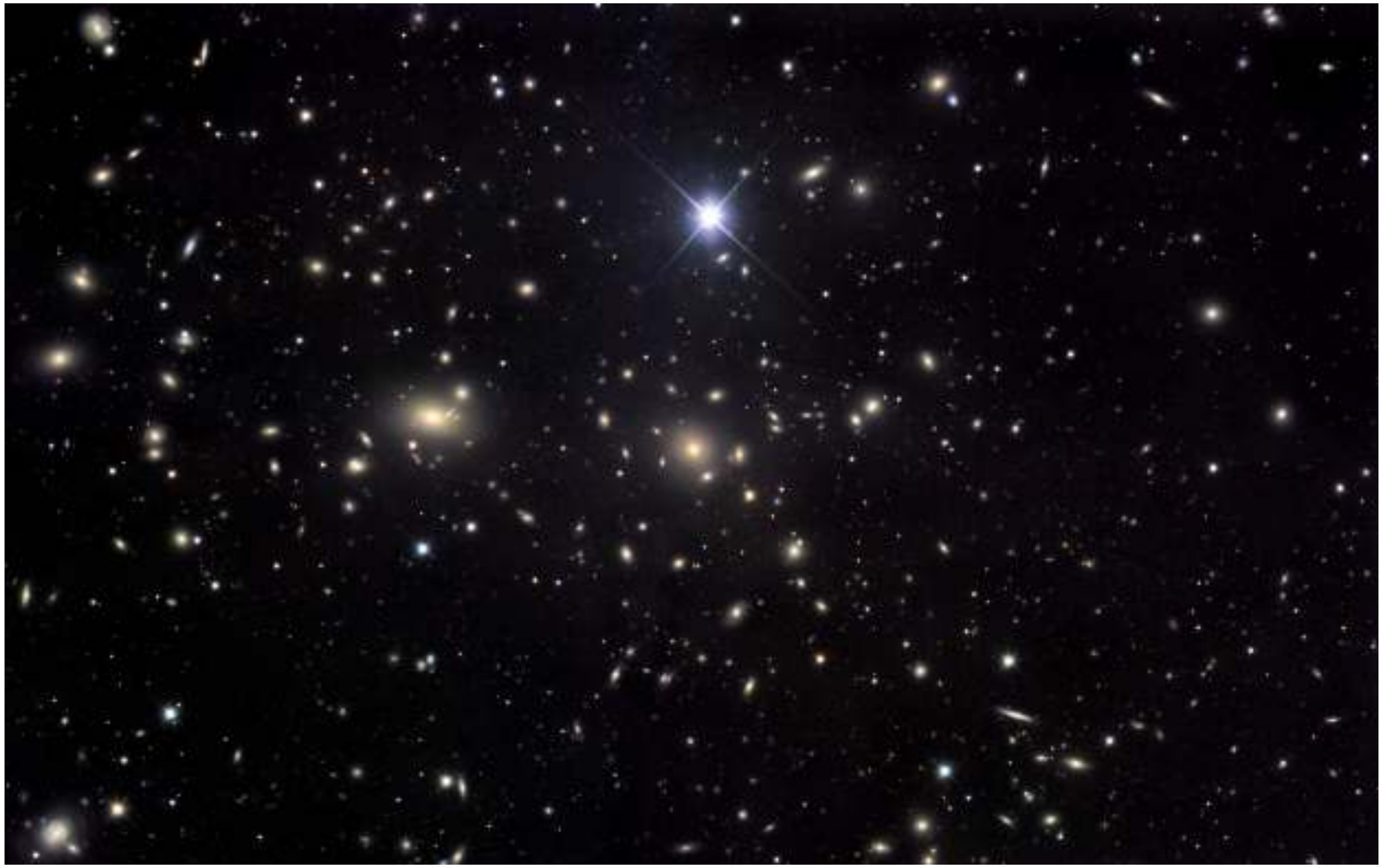
Collaborators: David Jacobs, Bryan Lynn, Amanda Weltman

ISORIGINS

Dark Matter: Evidence

Cluster Kinematics

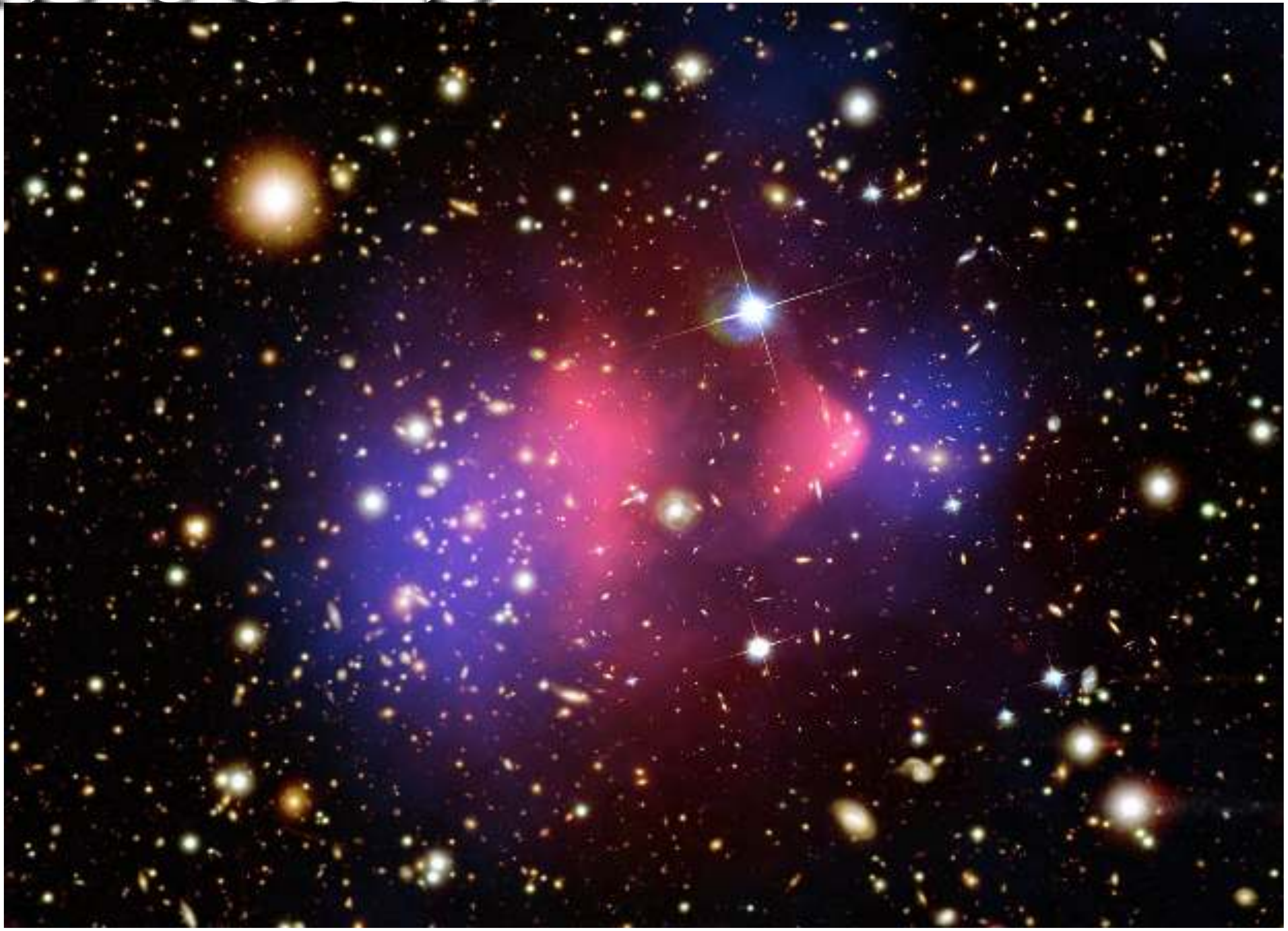
(Zwicky & the Coma cluster ~1933)



Coma cluster

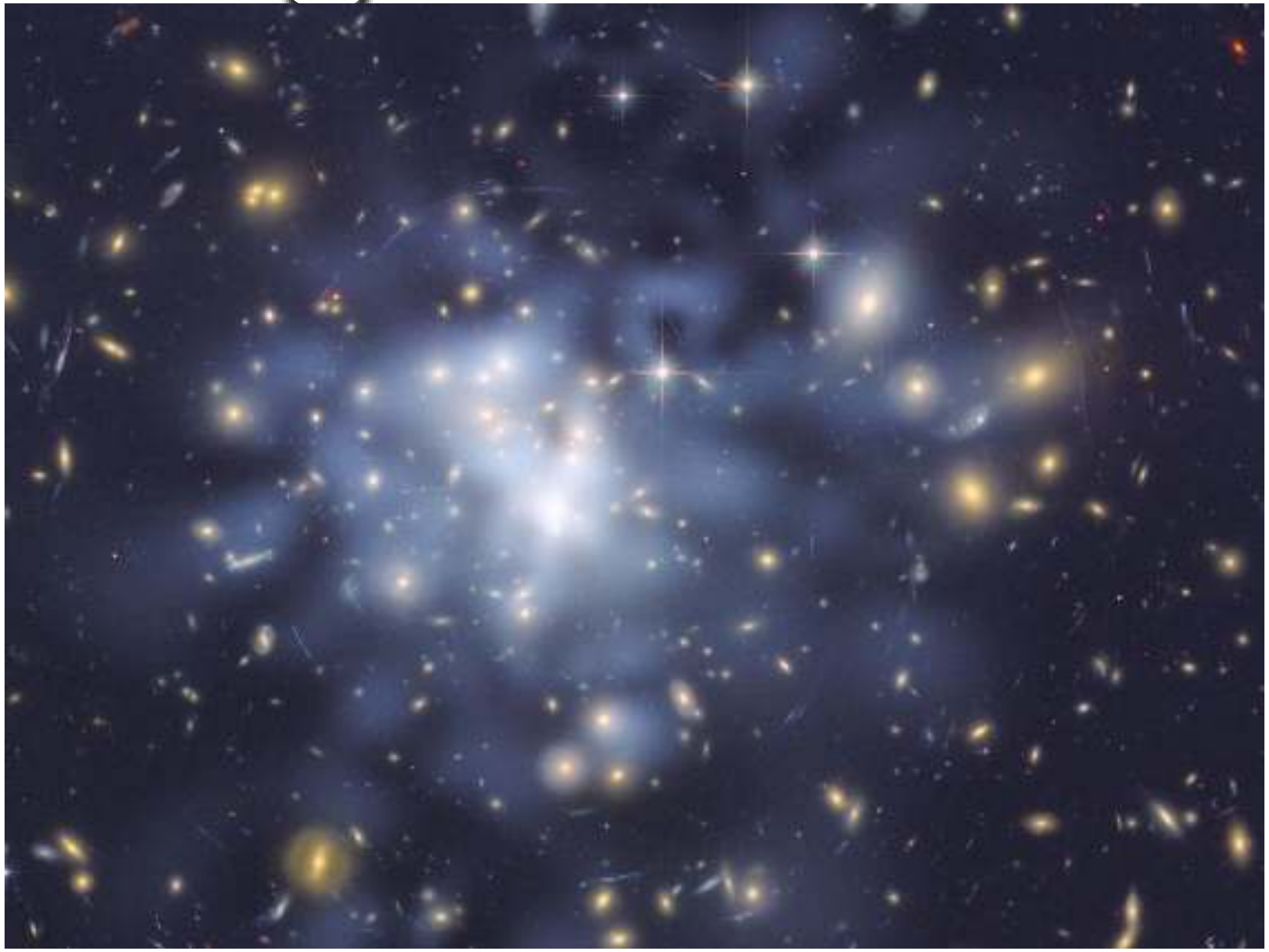
Image: Jim Misti (Misti Mountain Observatory)

Interacting Clusters



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

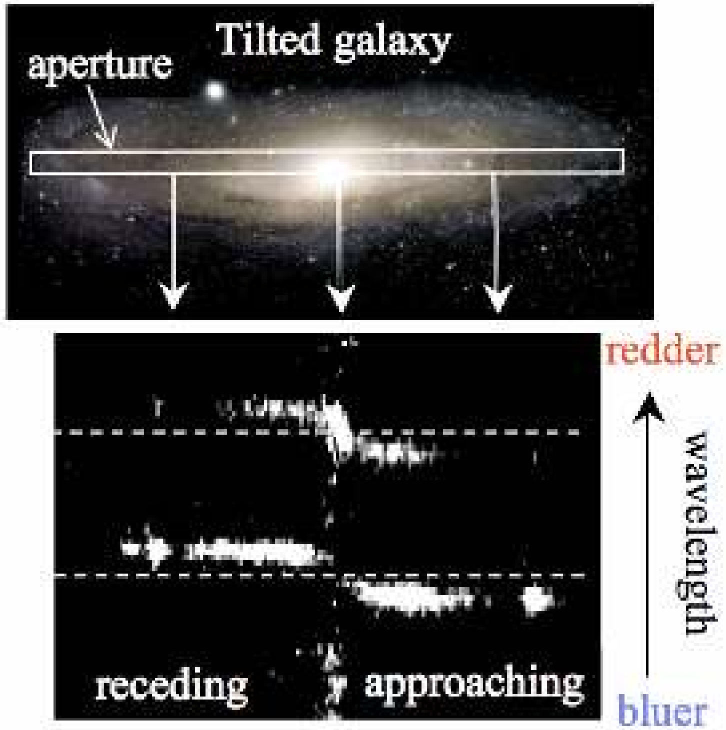
Gravitational Lensing



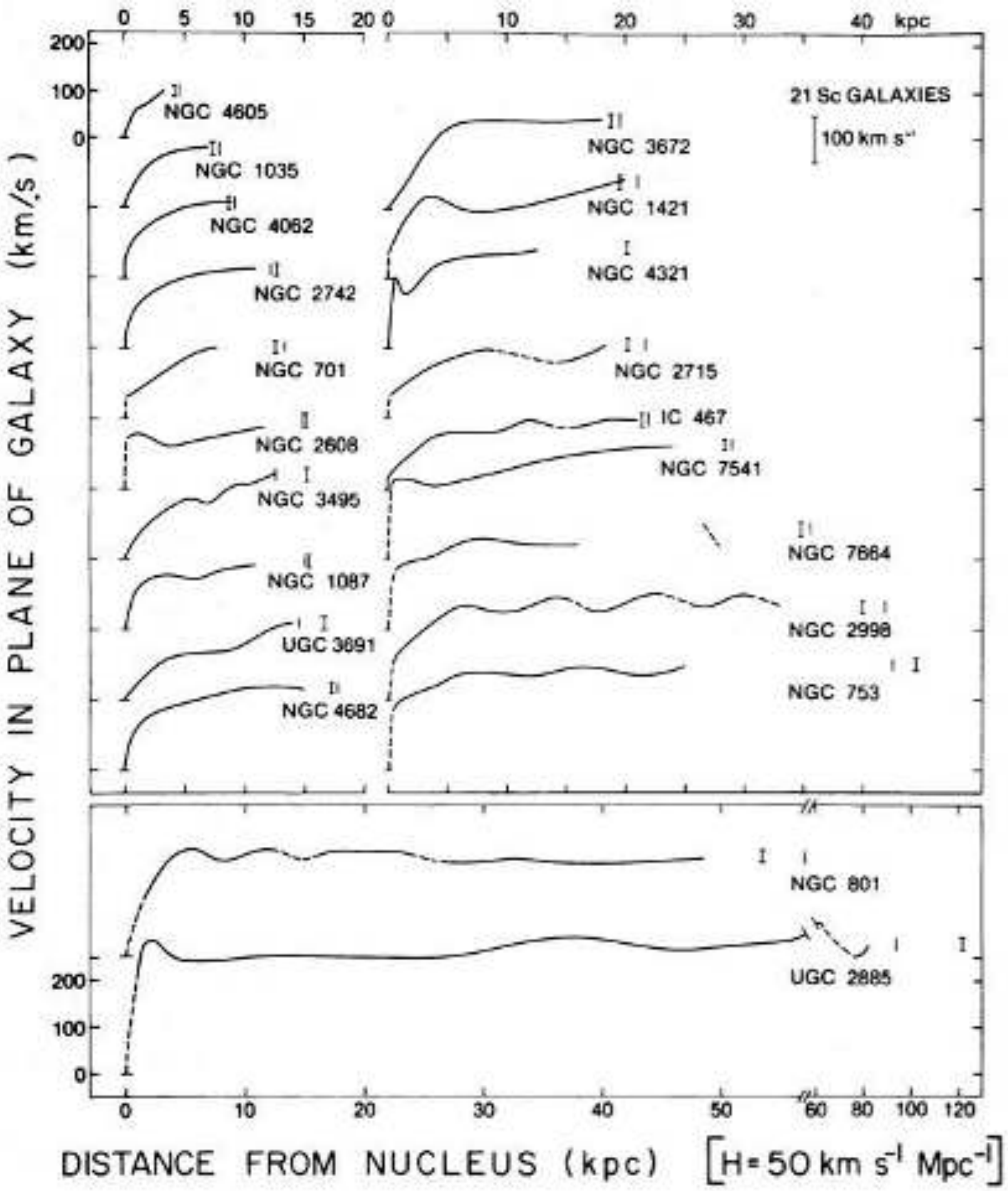
Cluster Abell 1689
Credit: NASA, ESA, and D. Coe (NASA/JPL)

Galactic Rotation Curves

Vera Rubin measuring galaxy rotation curves (~1970)

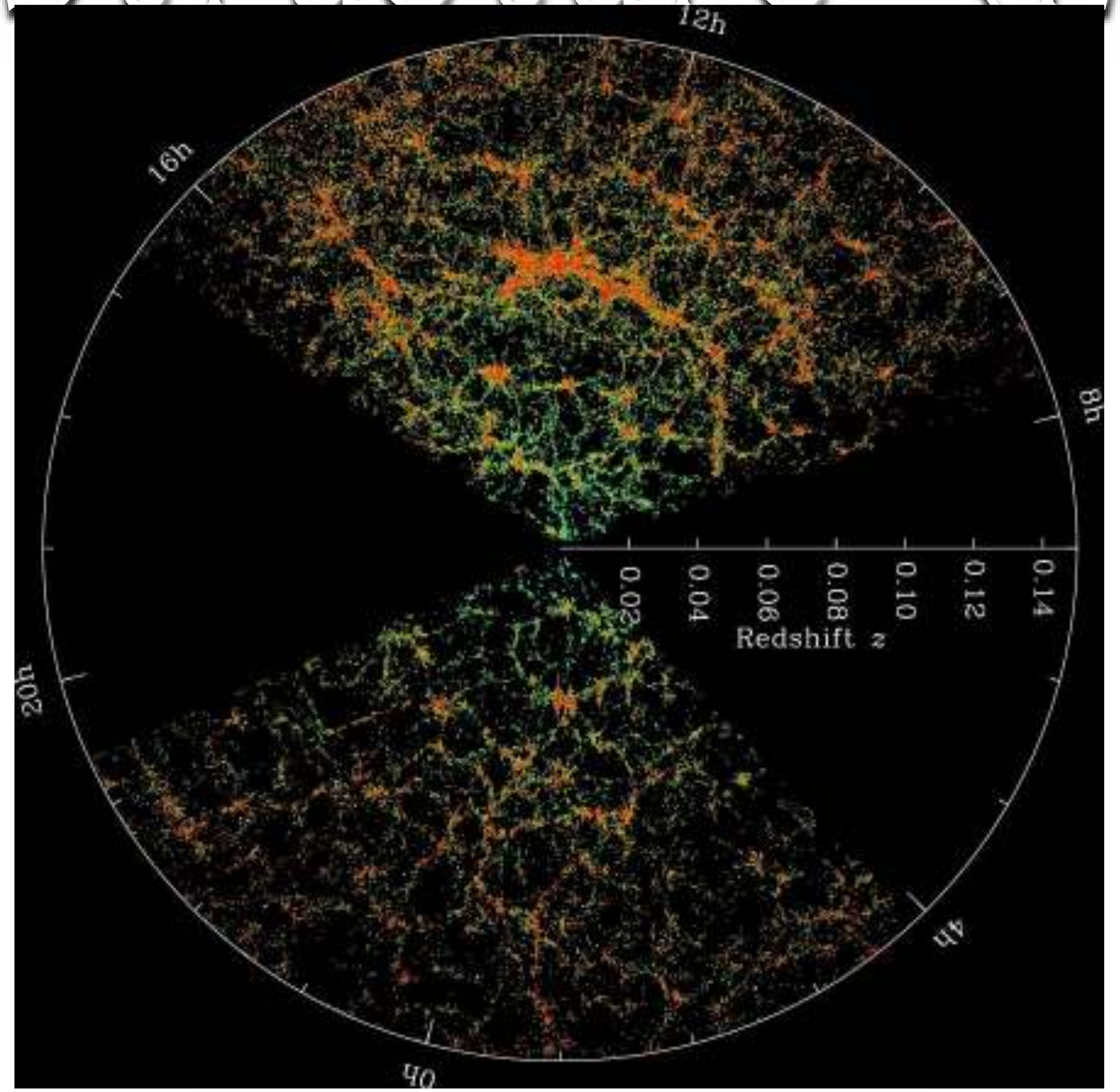


Resulting spectrum of light within aperture



Rubin, et al. (1980)

Growth of Large Scale Structure (LSS)



Sloan Digital Sky Survey

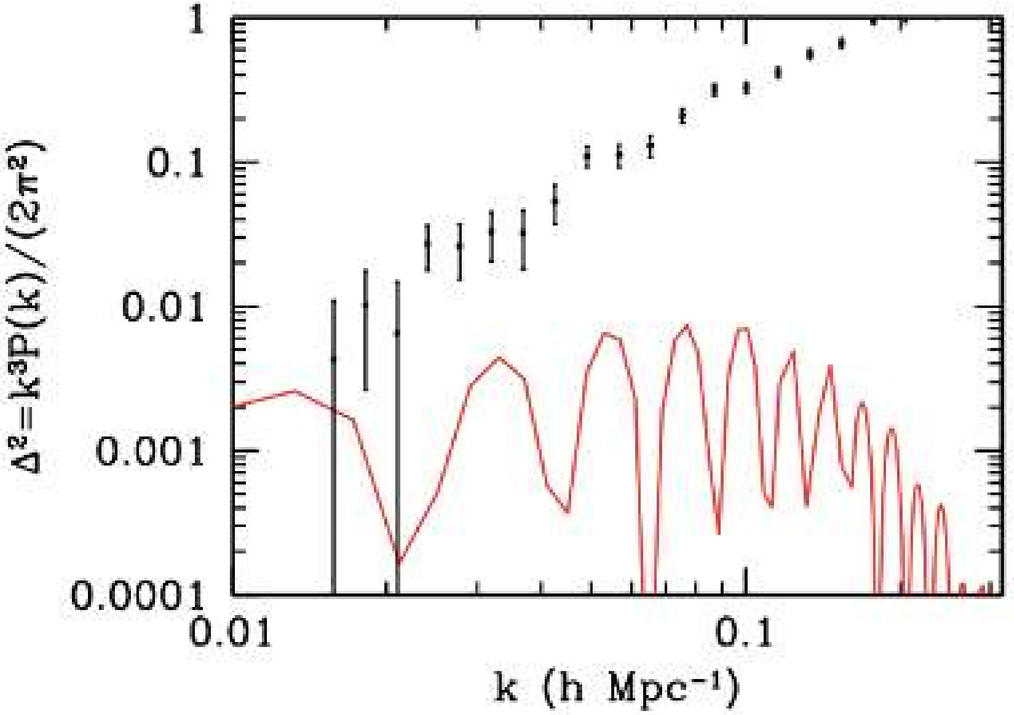


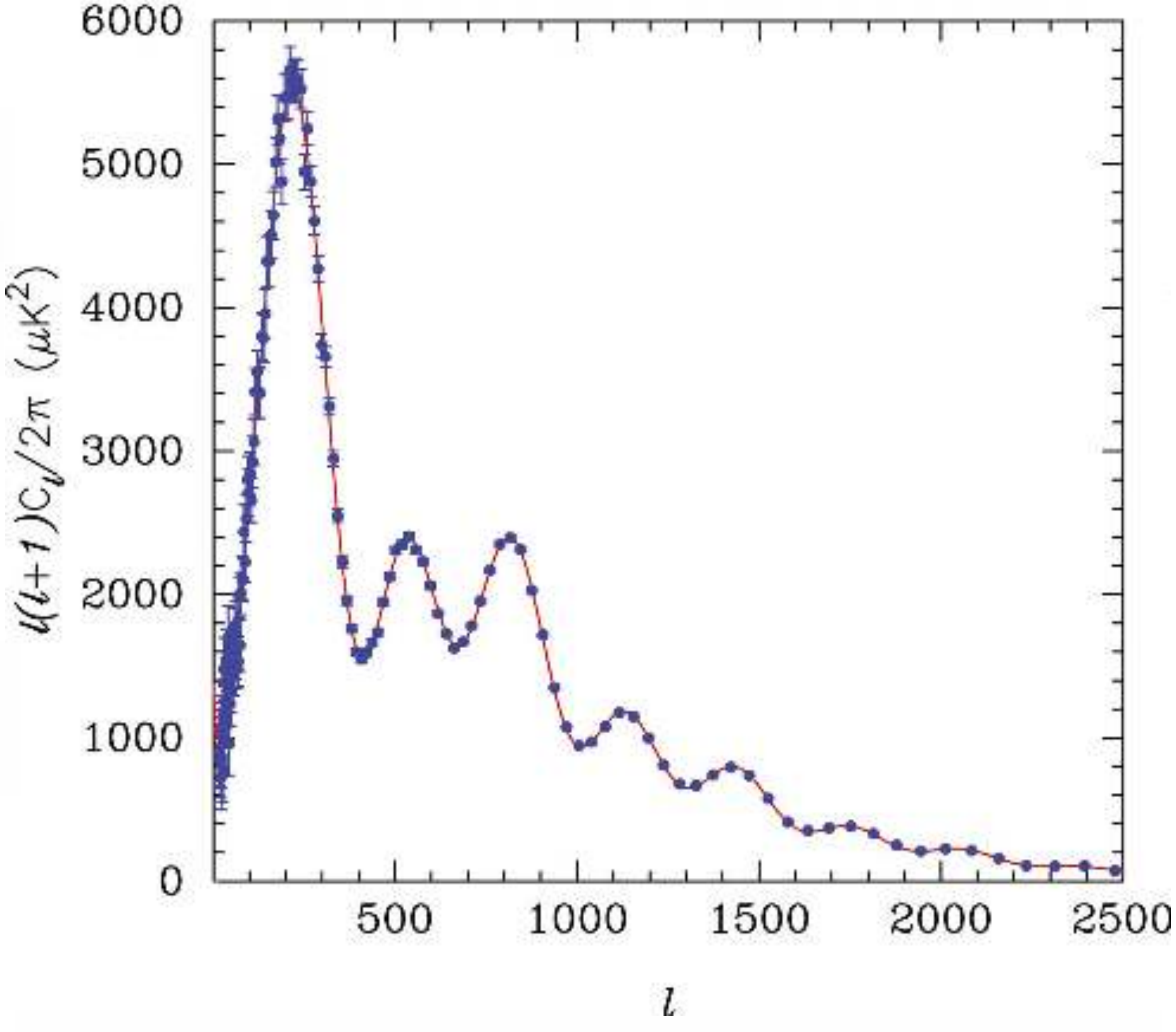
FIG. 1 (color online). Power spectrum of matter fluctuations in a theory without dark matter as compared to observations of the galaxy power spectrum. The observed spectrum [24] does not have the pronounced wiggles predicted by a baryon-only model, but it also has significantly higher power than does 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



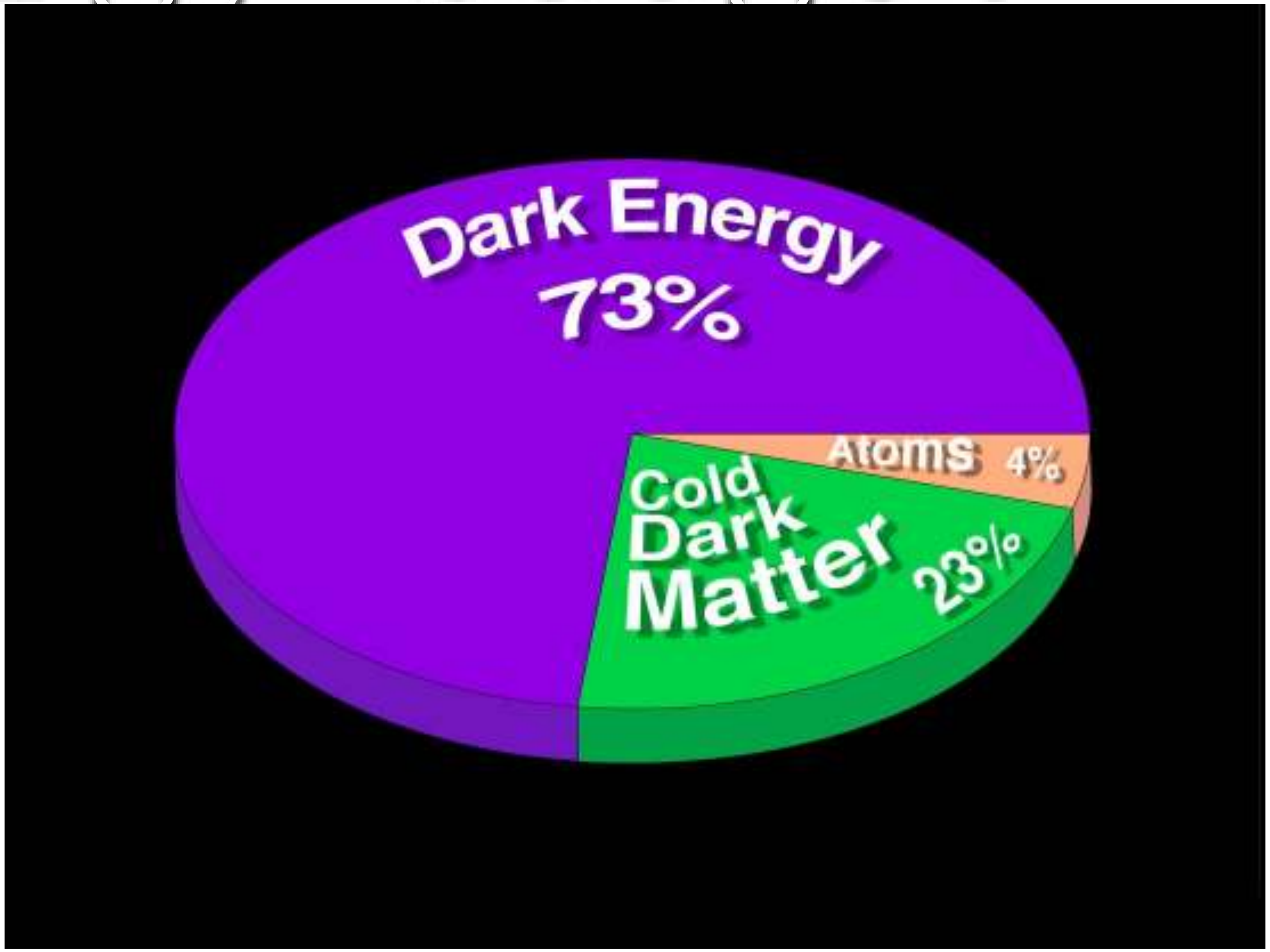
Plot: Planck Collaboration/ESA

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:

What do we really know about DM?

- Dark:

Dark Matter: Candidates

WIMPs

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

Other non-SM Dark-matter candidates

- Axions
- Exotica:
  - Eg. primordial blackholes

What do we really know about DM?

- “Dark”:

How could this be?

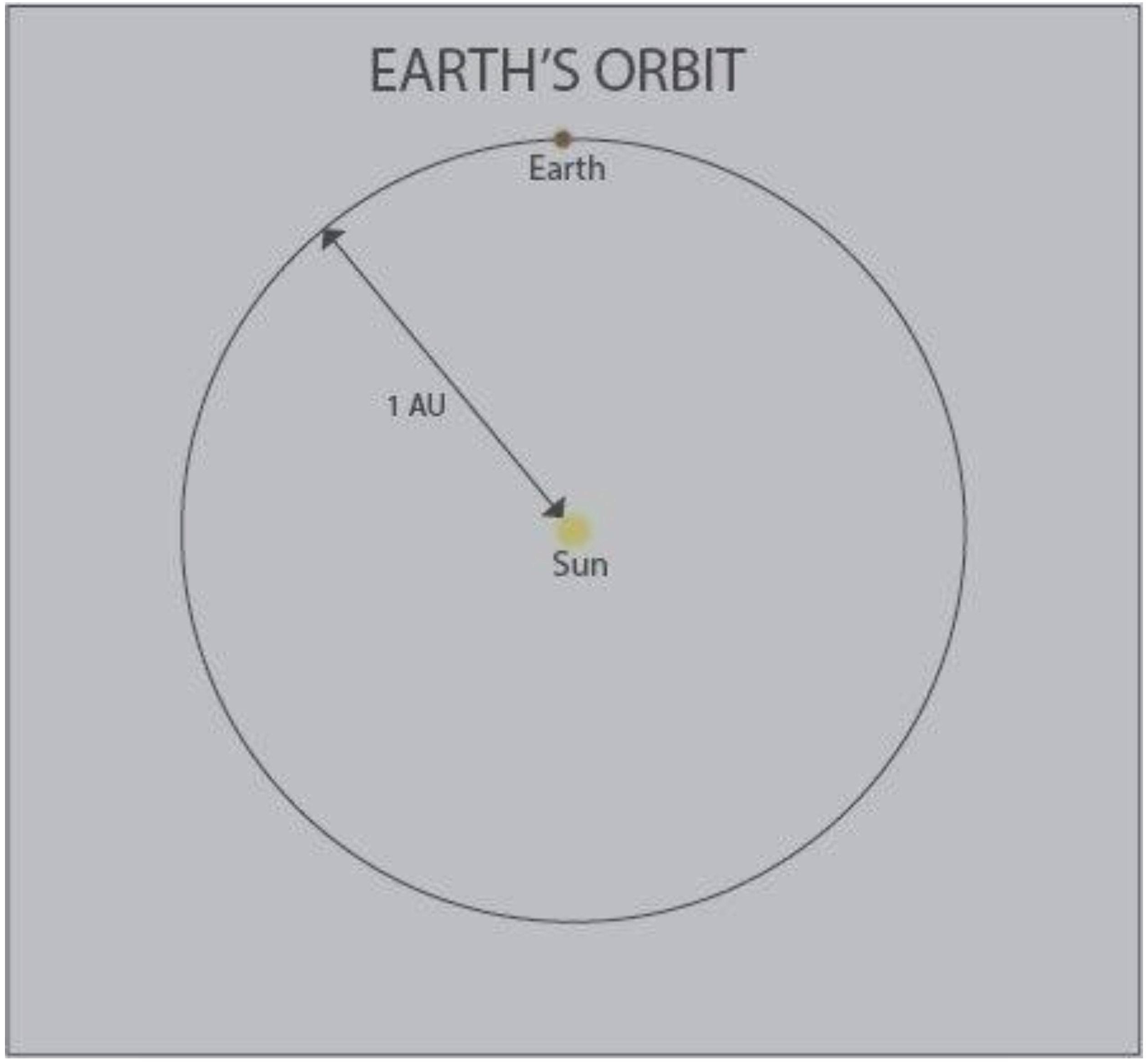
Interaction rates go as $\Gamma \sim n_X \sigma_X v$
$\sim (\sigma_X/m_X) \rho_X v$
Gravitational observations fix ρ_X
What matters is (σ_X/m_X) -- the “reduced cross-section”

DM can be low m low σ, or high & m not-so-low-σ !

MACROscopic Dark Matter

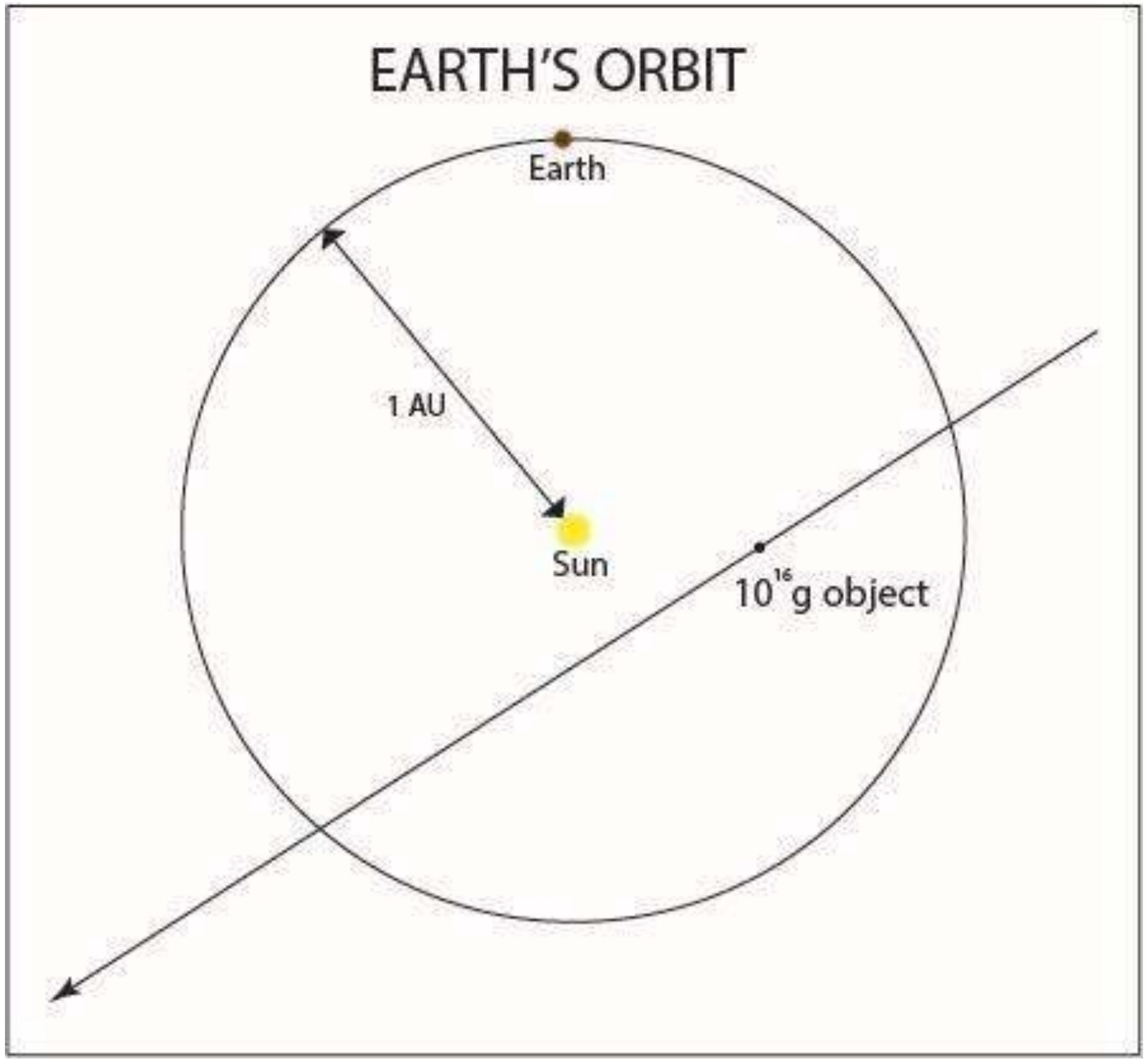
Average local dark matter de

10^{16} g of dark matter expected within th



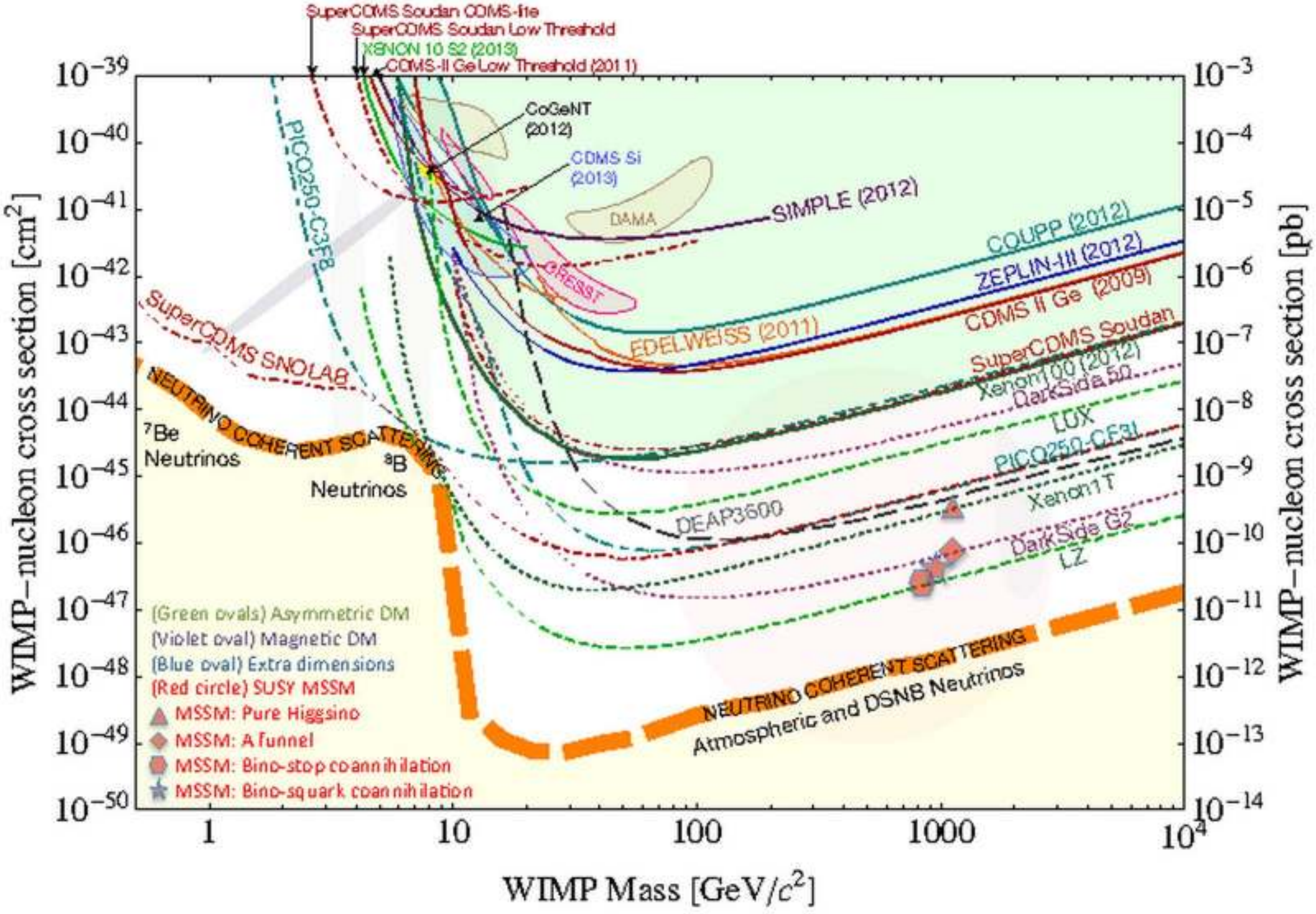
Here, a smooth distribution

Could this be the wrong picture?



Could this be the right picture?

What do we know about DM σ

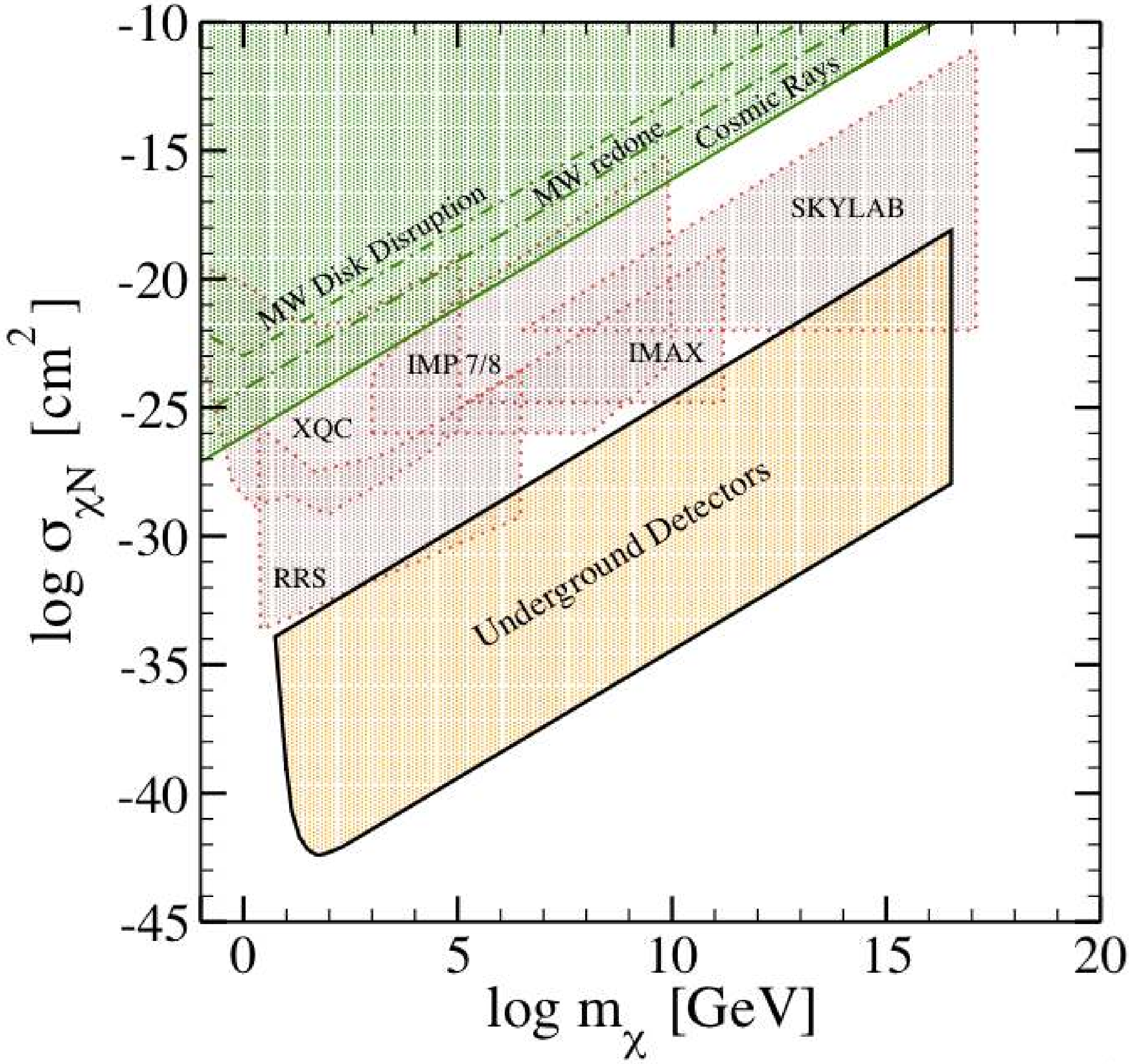


Planning the Future of U.S. Particle Physics (Snowmass 2013): Chapter 4: Cosmic Frontier

What do we know about DM σ?

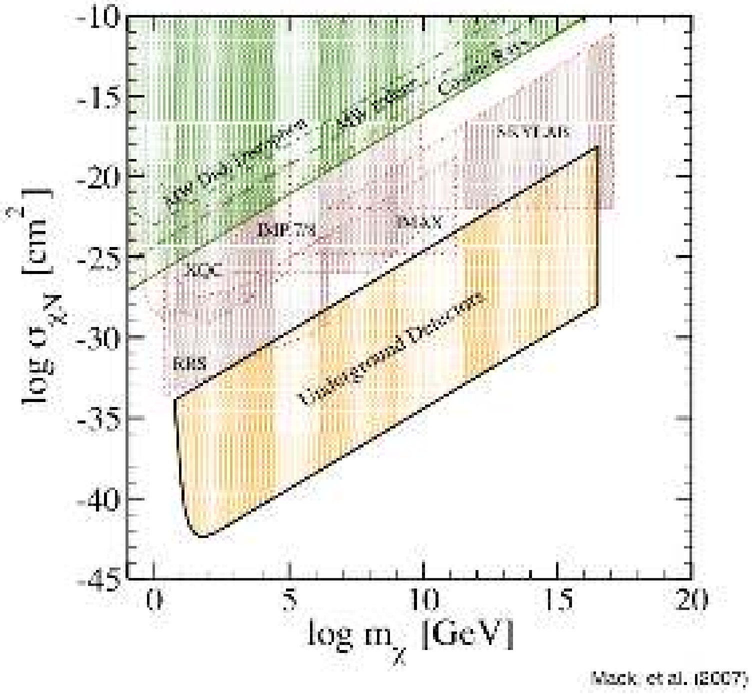
Strongly-interacting dark matter: GDS et al. (1990), …,
Mack et al. (2007)

More or less constrained up to ~ 10^{17} GeV

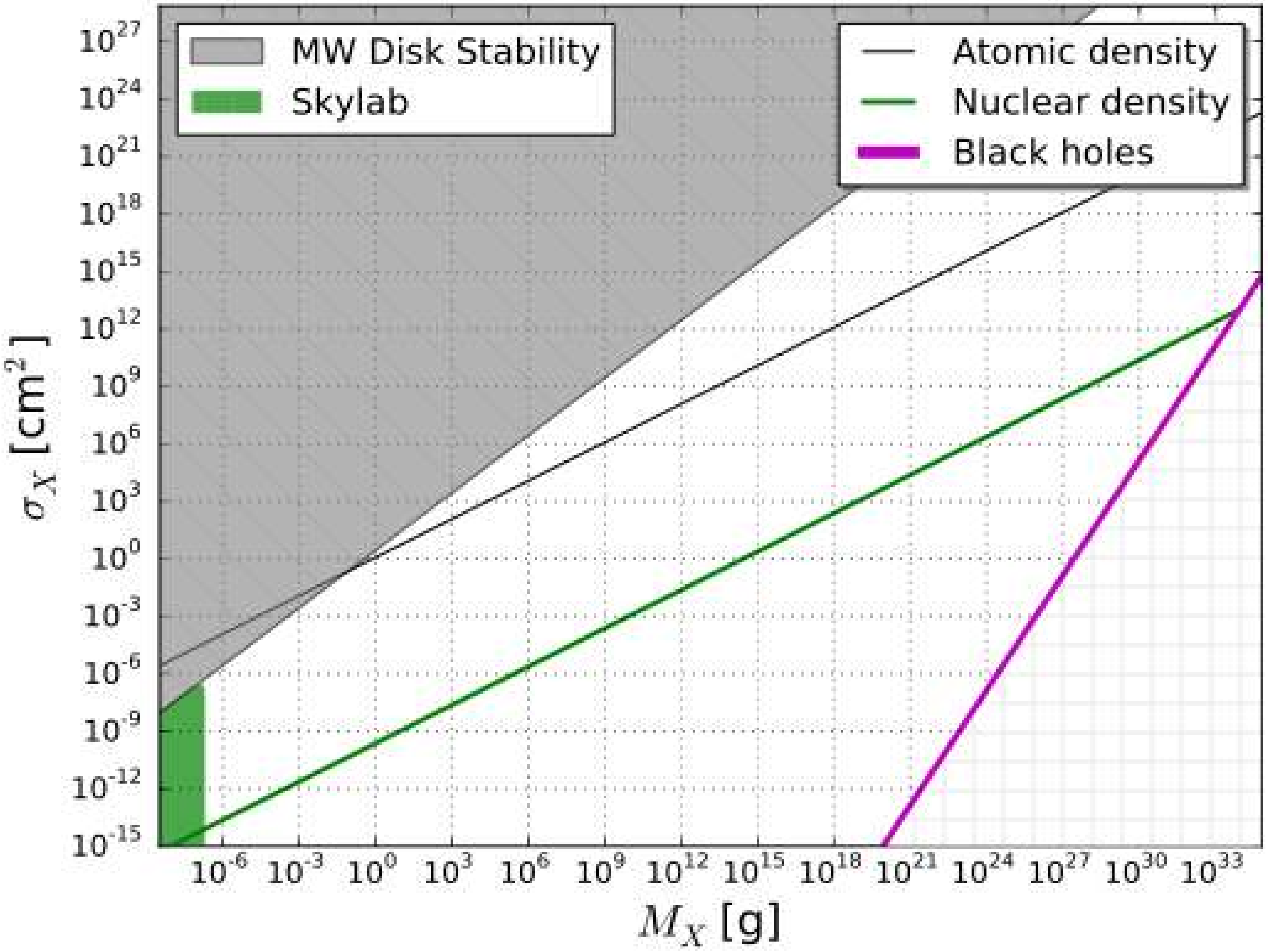


Mack, et al. (2007)

What about macros?



Mack et al. (2007)



Macros – what are they?

~~Ordinary Standard Model matter:~~

~~Stellar remnants – WD, NS, BH~~

Katie (as quoted by Paolo):

I HATE ~~M~~NACHOS

Macros – what are they?

~~Ordinary Standard Model matter:~~

~~Stellar remnants – WD, NS, BH~~ SBBN

Lesson: if DM is baryons it must be "hidden" before BBN

Macros – what are they?

In the Standard Model

- 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

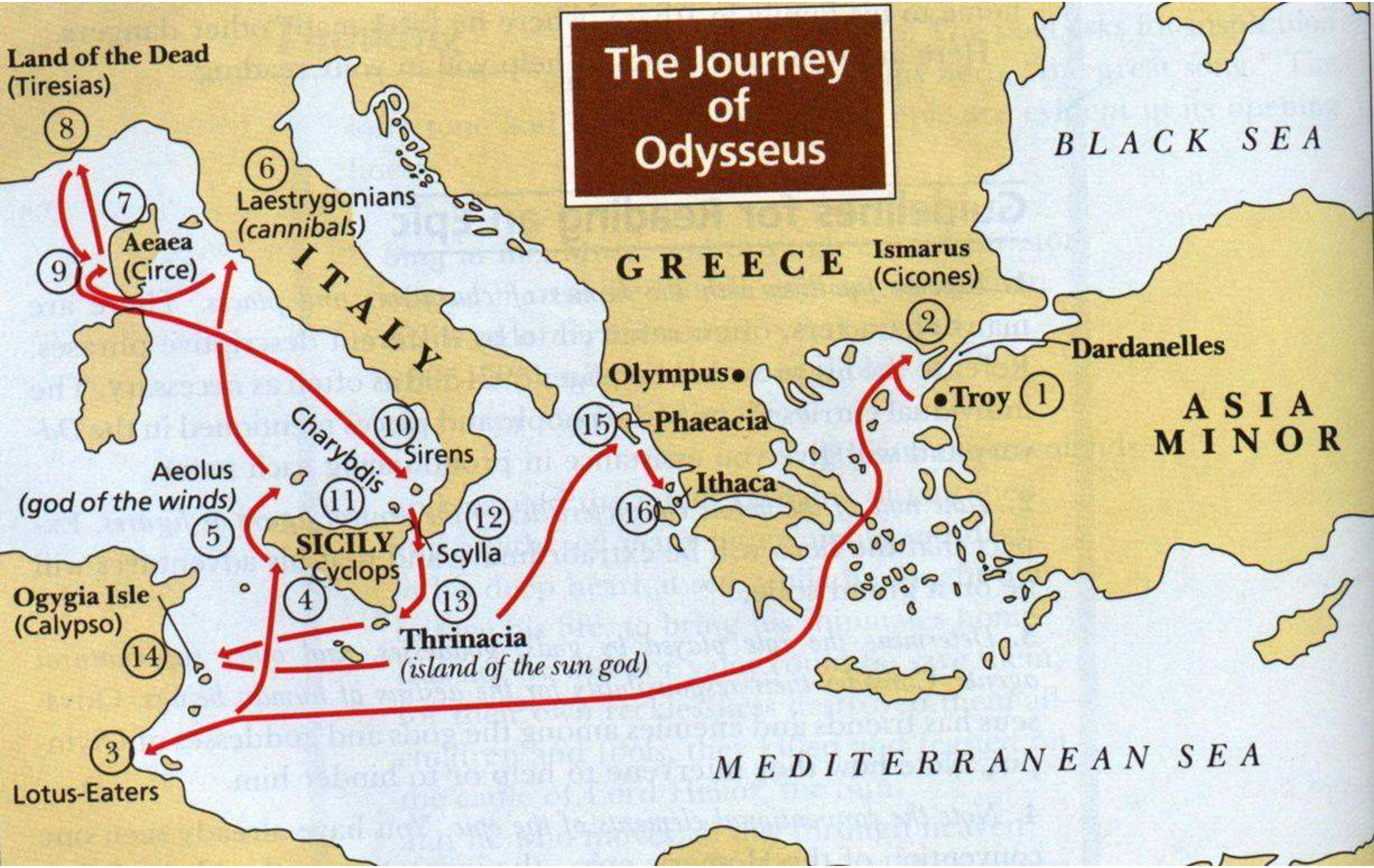
Strange Baryon Matter (Lynn et al.,1990)

Baryonic Colour Superconductors (+ axion) (Zhitnitsky, 2003)

Strange Chiral Liquid Drops (Lynn, 2010)

Other names: nuclearites, strangelets, quark nuggets, CCOs, CUDOs

Dark Matter may be a Standard Model phenomenon!


The Journey of Odysseus
Land of the Dead
(Tiresias)
8
7
Aeaea
(Circe)
9
6
Laestrygonians
(cannibals)
ITALY
GREECE
Ismarus
(Cicones)
2
Dardanelles
BLACK SEA
Olympus
Troy
1
ASIA MINOR
15
Phaeacia
Ithaca
16
10
Sirens
Charybdis
11
12
Scylla
Aeolus
(god of the winds)
5
SICILY
Cyclops
4
13
Ogygia Isle
(Calypso)
14
Thrinacia
(island of the sun god)
3
Lotus-Eaters
MEDITERRANEAN SEA

?

So… what’s allowed for Mac

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):

Model-*in*dependent 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

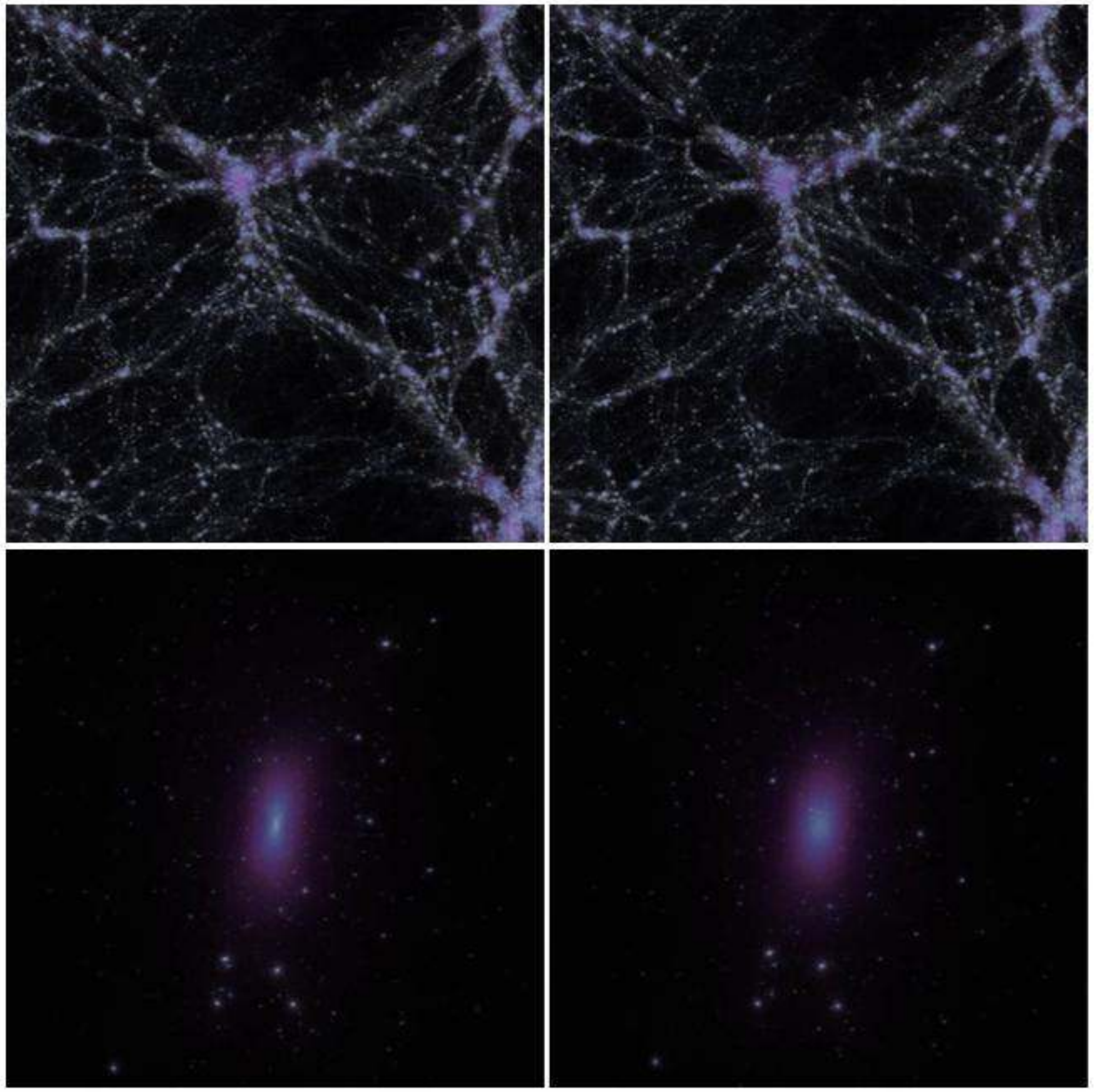
Macro-Macro Coupling

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)

Rocha et al. (2012)



Left – collision-less DM; Right – SIDM

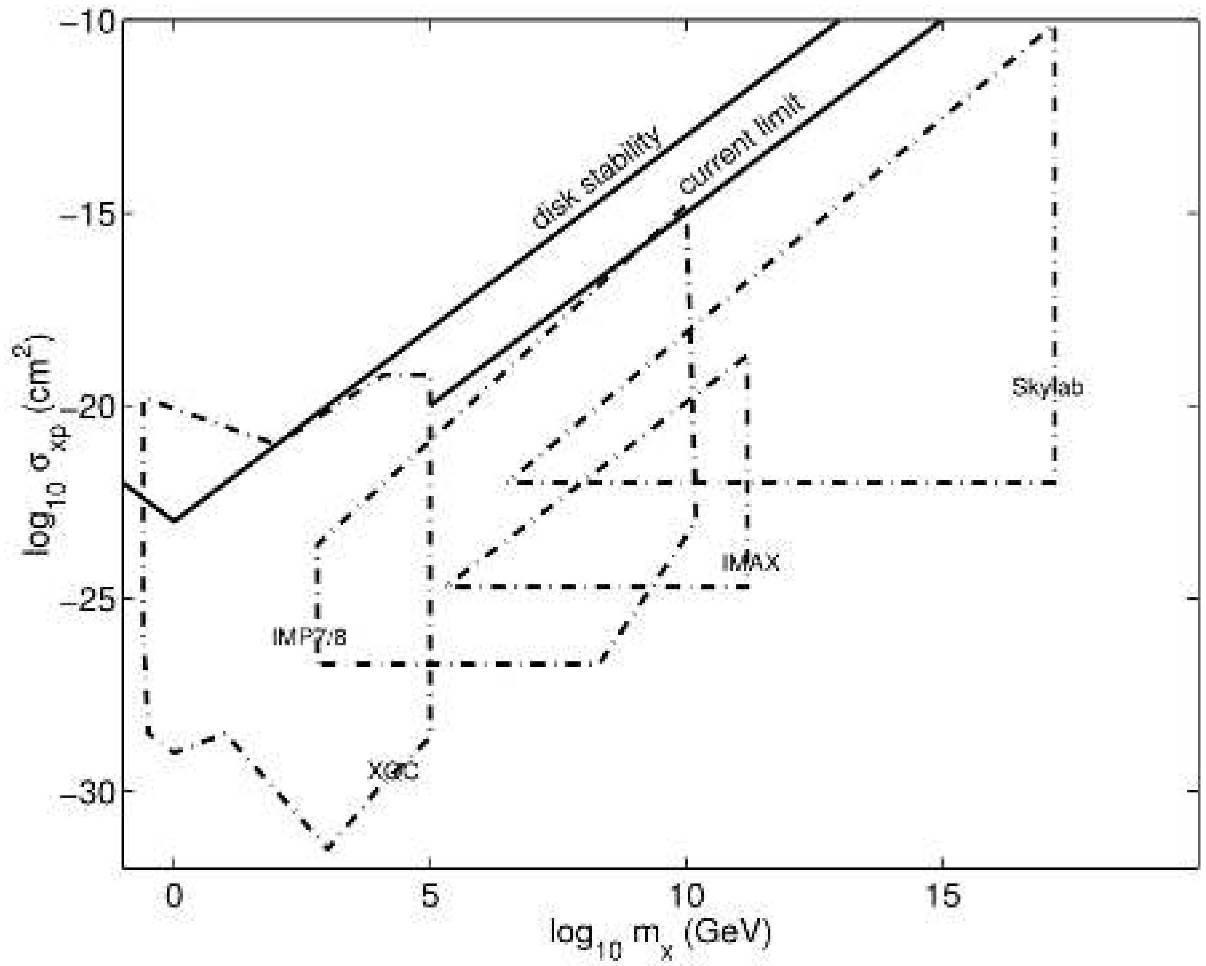
Macro-baryon Interactions

Cluster gas heating

Virial theorem implies 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



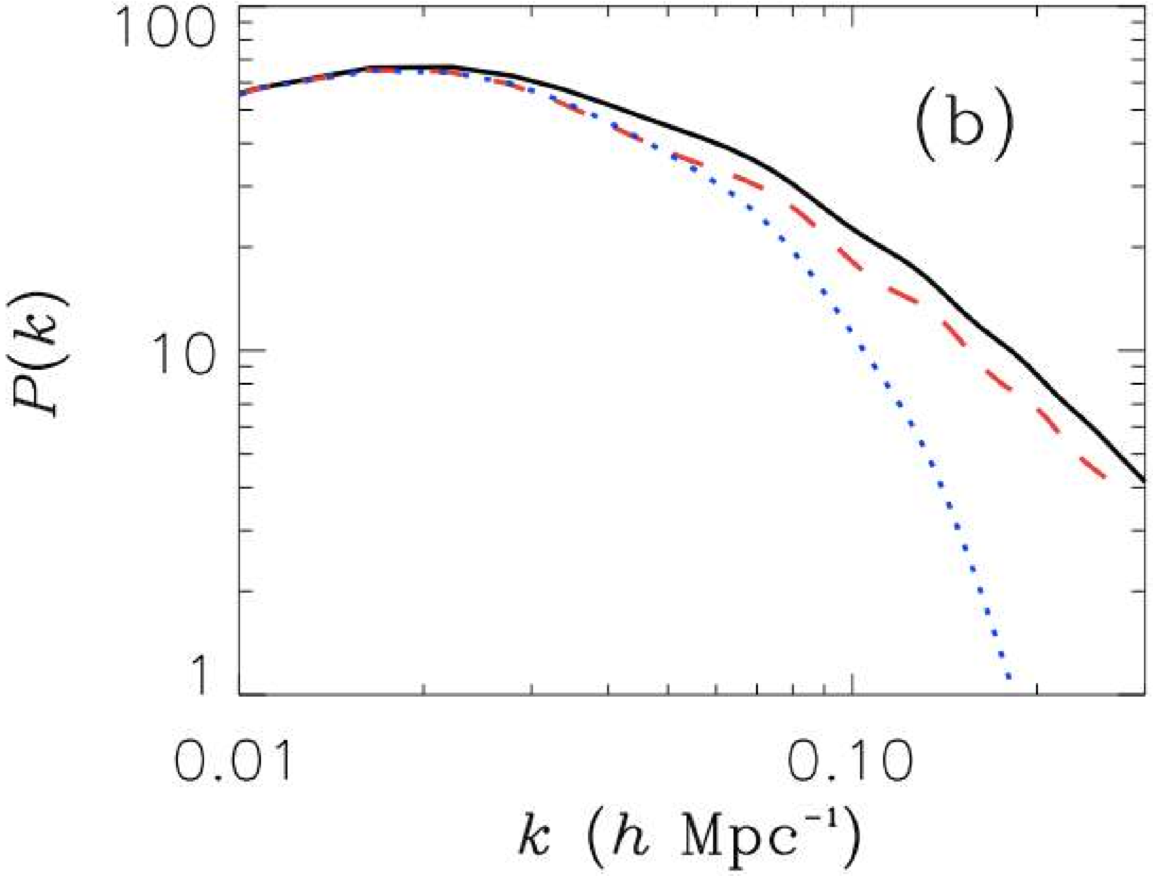
Chuzhoy and Nusser (2006)

Macro-baryon Interactions
Effects on large-scale structure

- DM-SM interactions would have caused extra 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~3) and found



Chen, et al. (2002)

Matter power spectrum

Model-*independent* constraints

Records left on earth

Macro-baryon Interactions

Resonant-bar Gravitational Wave Detectors

Passing gravitational waves might be 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. Jacobs, GDS, A. Weltman

Such detectors (at ~ 2K) can constrain nuclearite dark matter (Liu and Barish, 1988)

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: $m < \sim 10^{-5}$g for

Macro-baryon Interactions

Ancient Mica

Chemical etching reveals 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

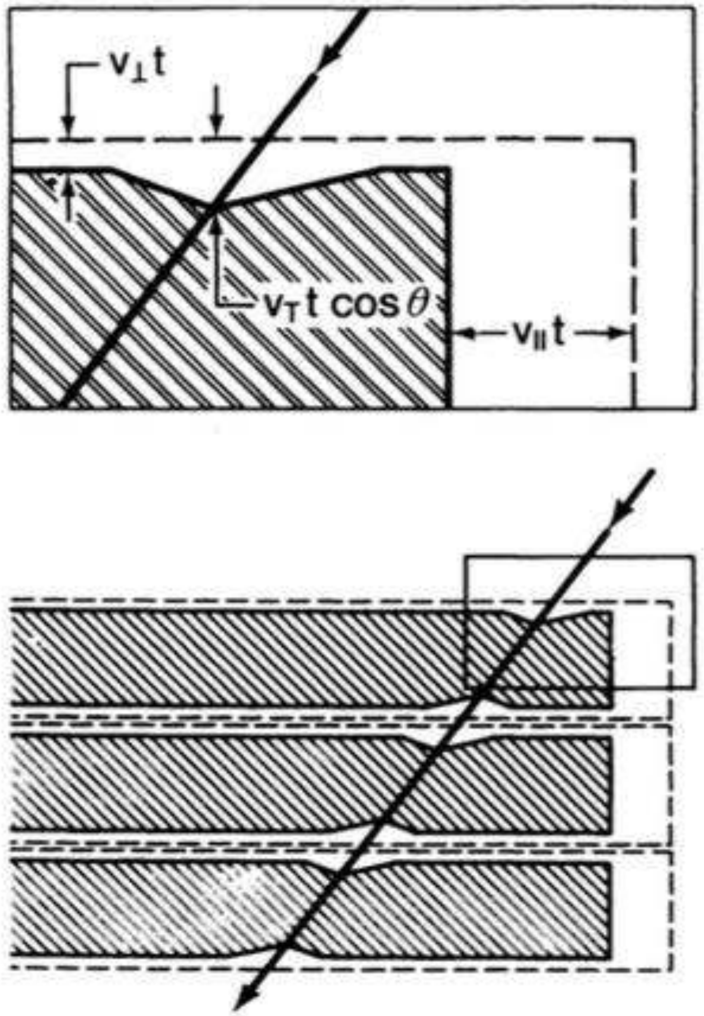
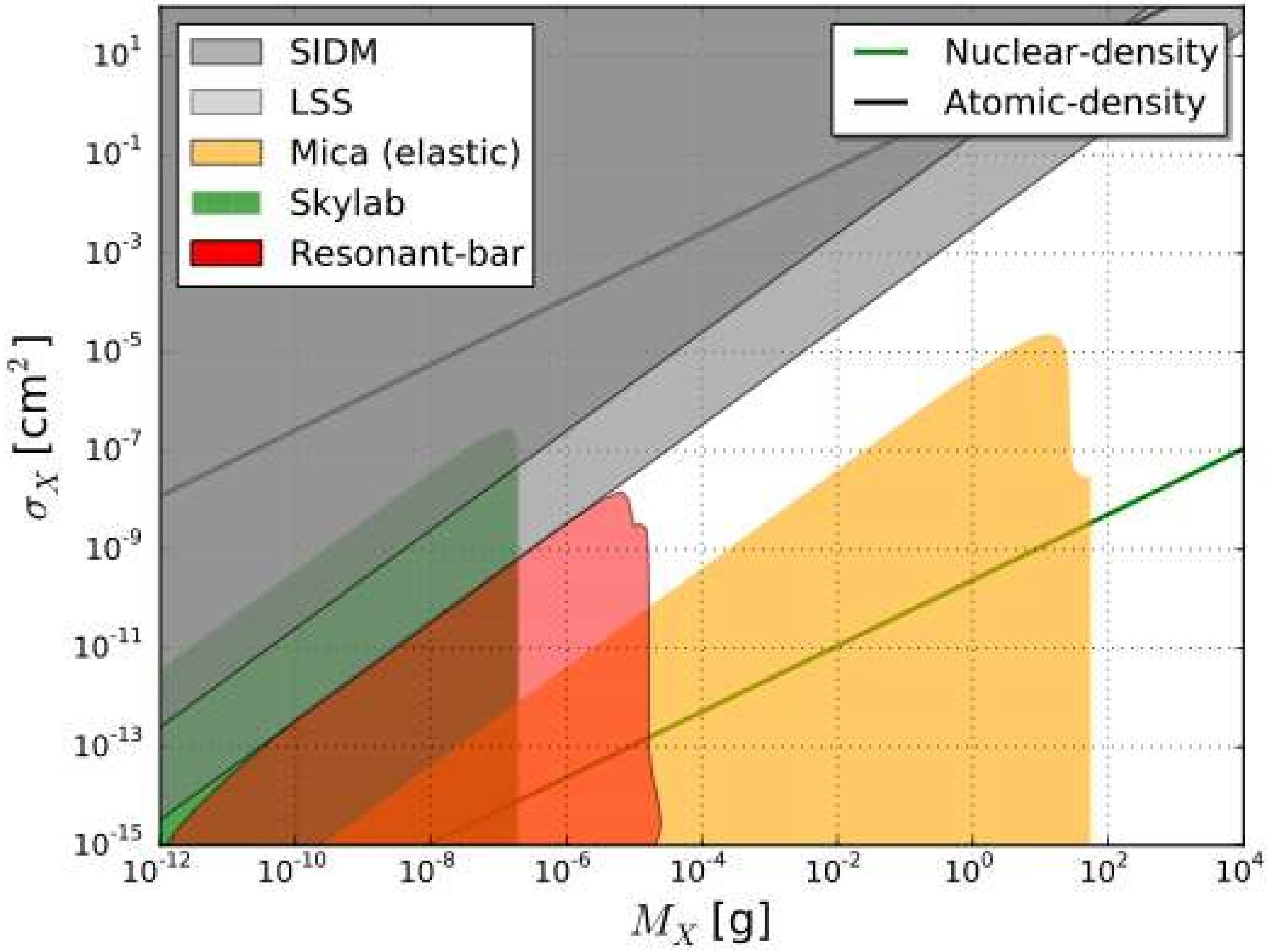


FIG. 2. Geometry of collinear etch pits along the trajectory of a hypothetical monopole-nucleus bound state in three sheets of mica that had been cleaved, etched, and superimposed for scanning.

Price and Salamon (1986)

Macro Constraints

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



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

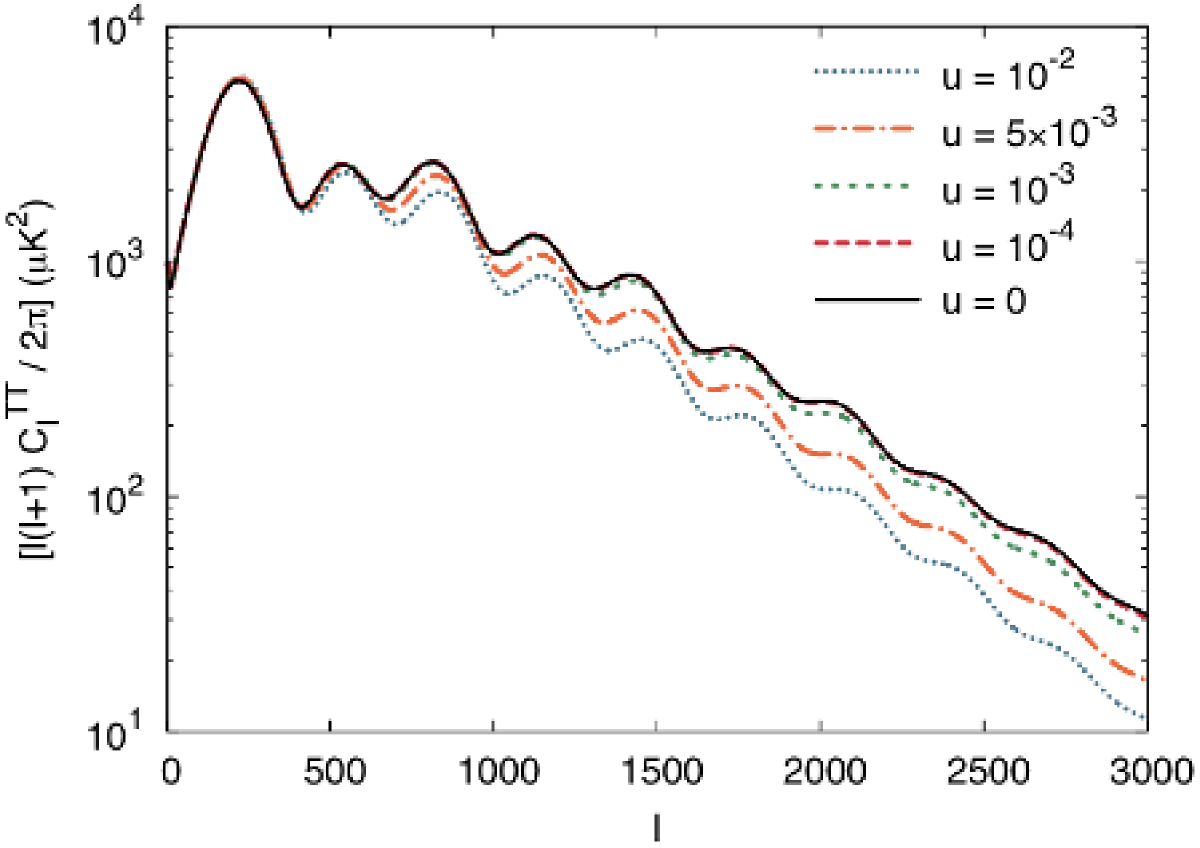
Macro-photon Interactions

Effects on large-scale structure

DM-photon interactions would also cause damping (Boehm et al. 2001, 2002, 2004)

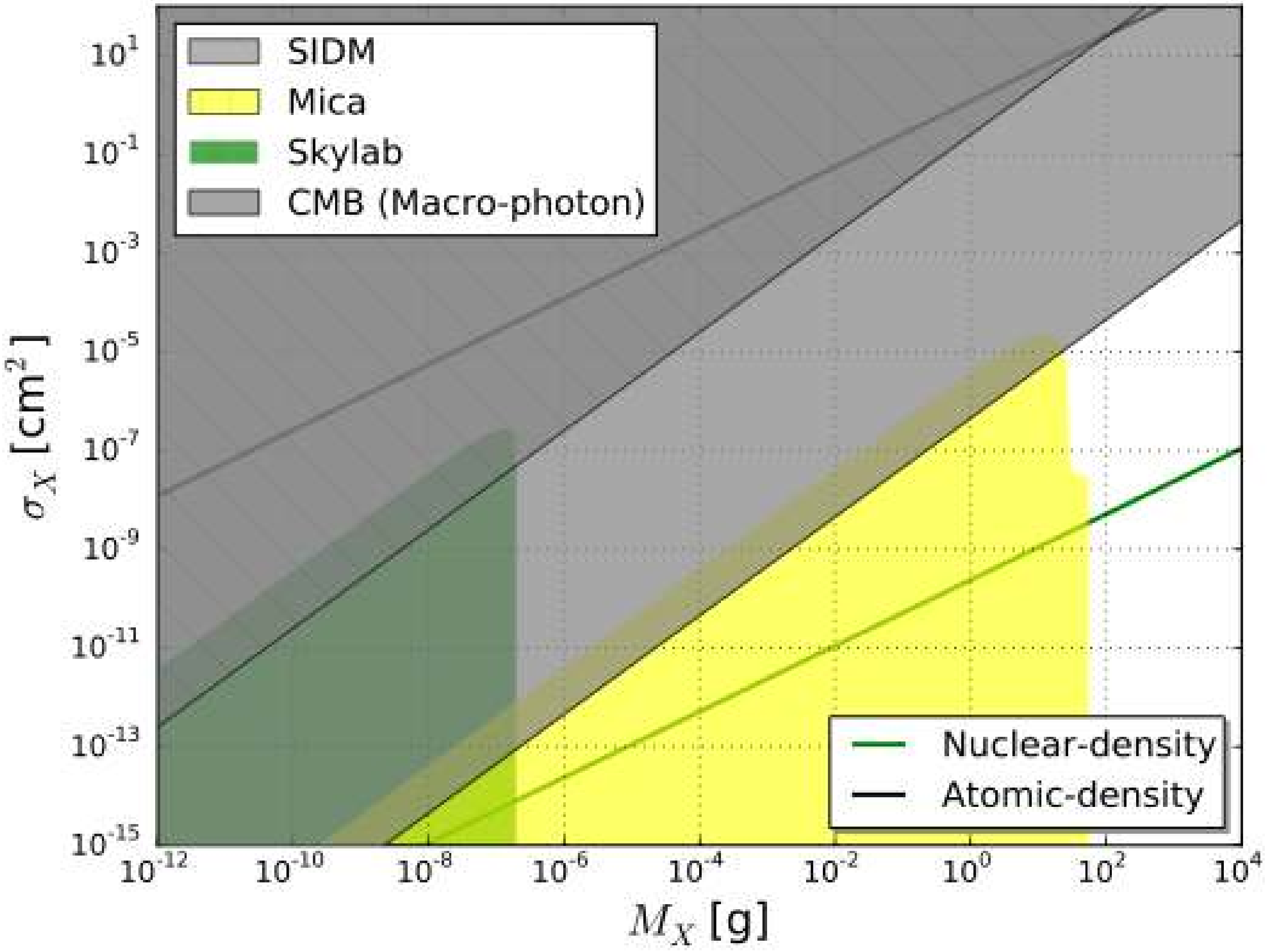
Wilkinson et al. (2014) used Planck CMB data to constrain DM-photon interactions to

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

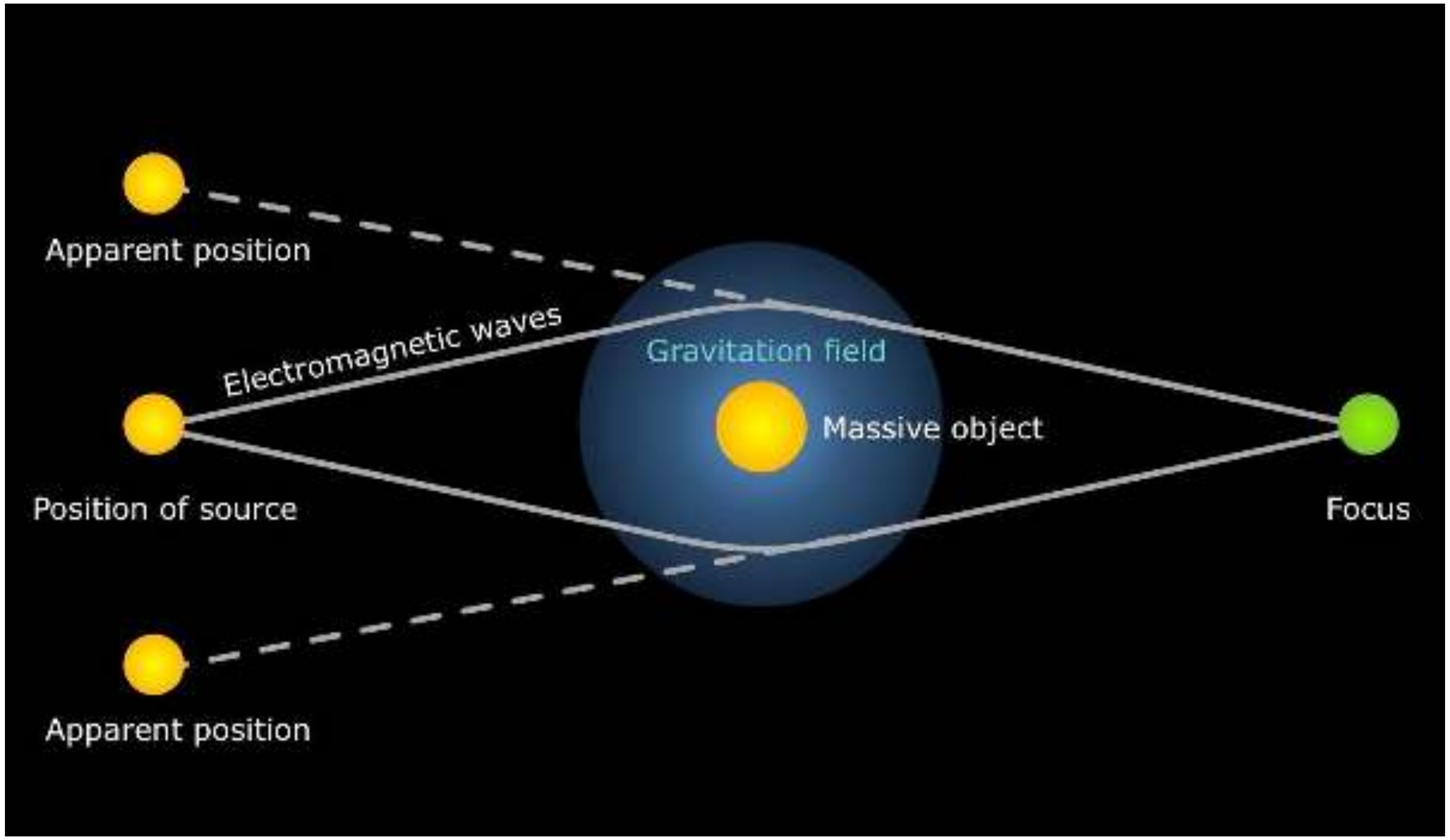


Image: GFDL

Gravitational Lensing

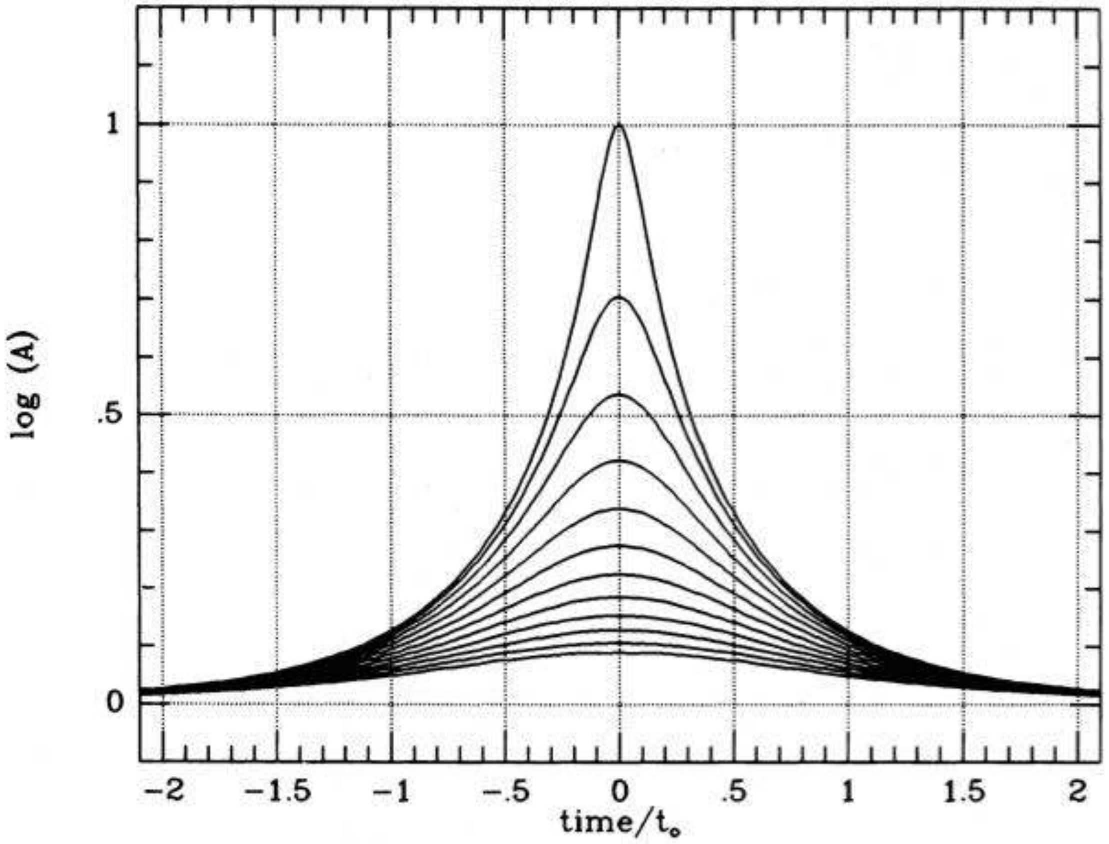
Microlensing

Allsman, et al. (2000) 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

4×10^{24} g < M < 6 ×



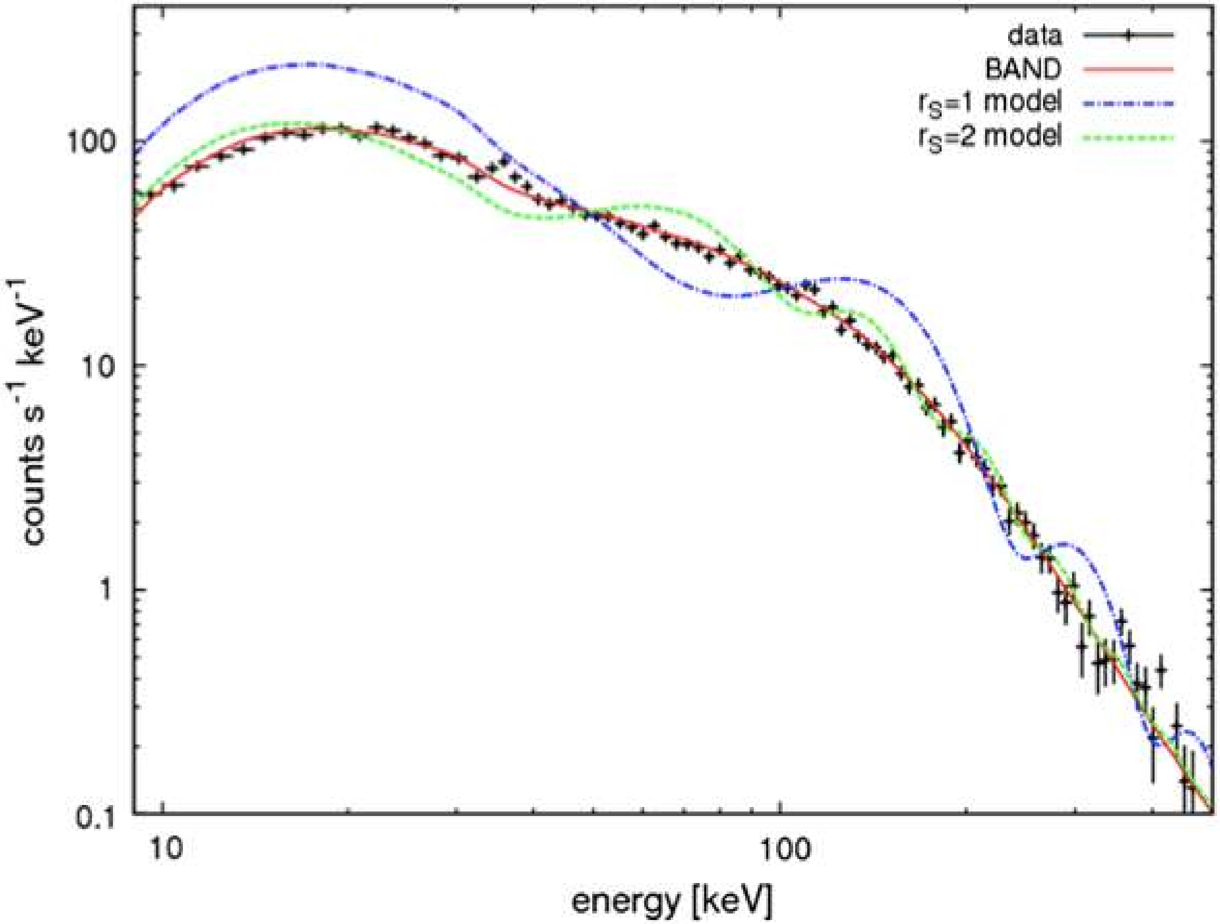
Paczynski (1986)

Gravitational Lensing

Femtolensing

Marani et al. (1998), used data the BATSE GRB experiment

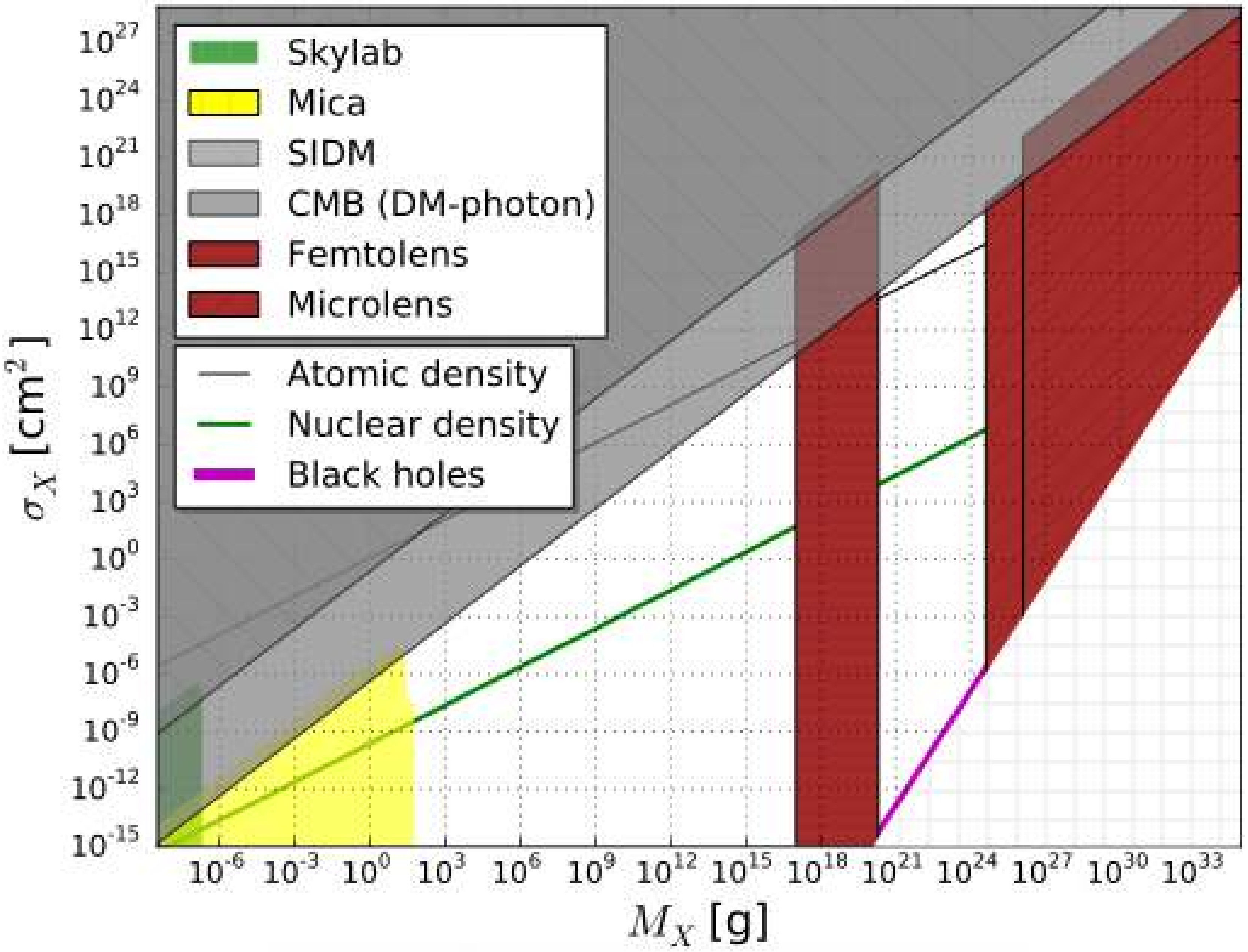
Barnacka et al. (2012) used GRB data from Fermi Combined, and exclude



Barnacka et al. (2012)

Model-independent Macro Constraints

(inclu



Jacobs, Starkman, Lynn (2014)

PHYSICAL REVIEW D
particles, fields, gravitation, and cosmology

Seismic search for strange quark nuggets

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

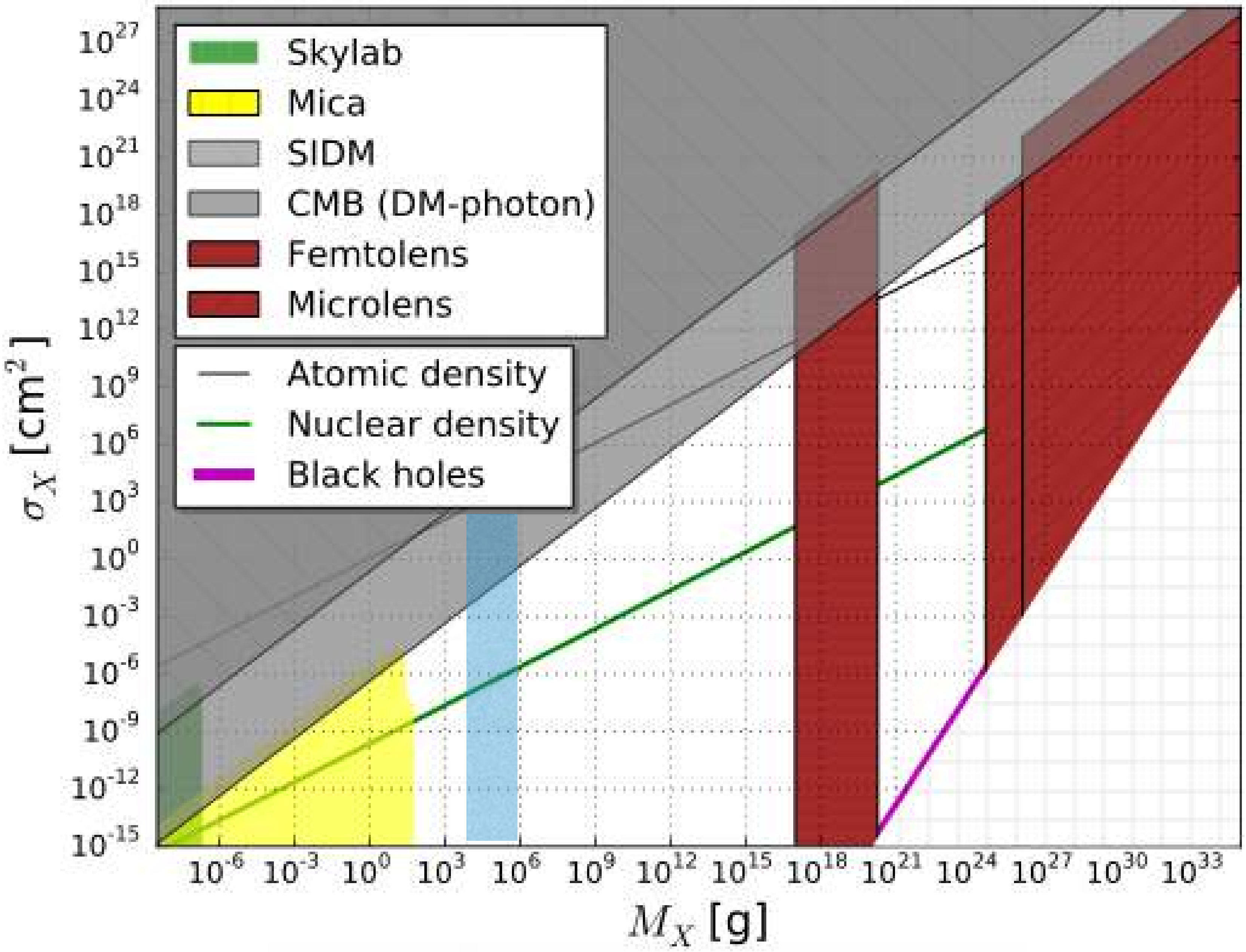
Phys. Rev. D **73**, 043511 – Published 17 February 2006

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

(incluc



Jacobs, Starkman, Lynn (2014)

Model-dependent constraints

Effects on BBN

Model-dependent constraints

Effects on BBN?

Helium mass fraction, X_4 (Aver et al. 2013)

G

If n and/or p can be absorbed by macros – change X_4

Theoretical uncertainties on Standard Model predications are relatively tiny so we must ensure $| X_4| <$

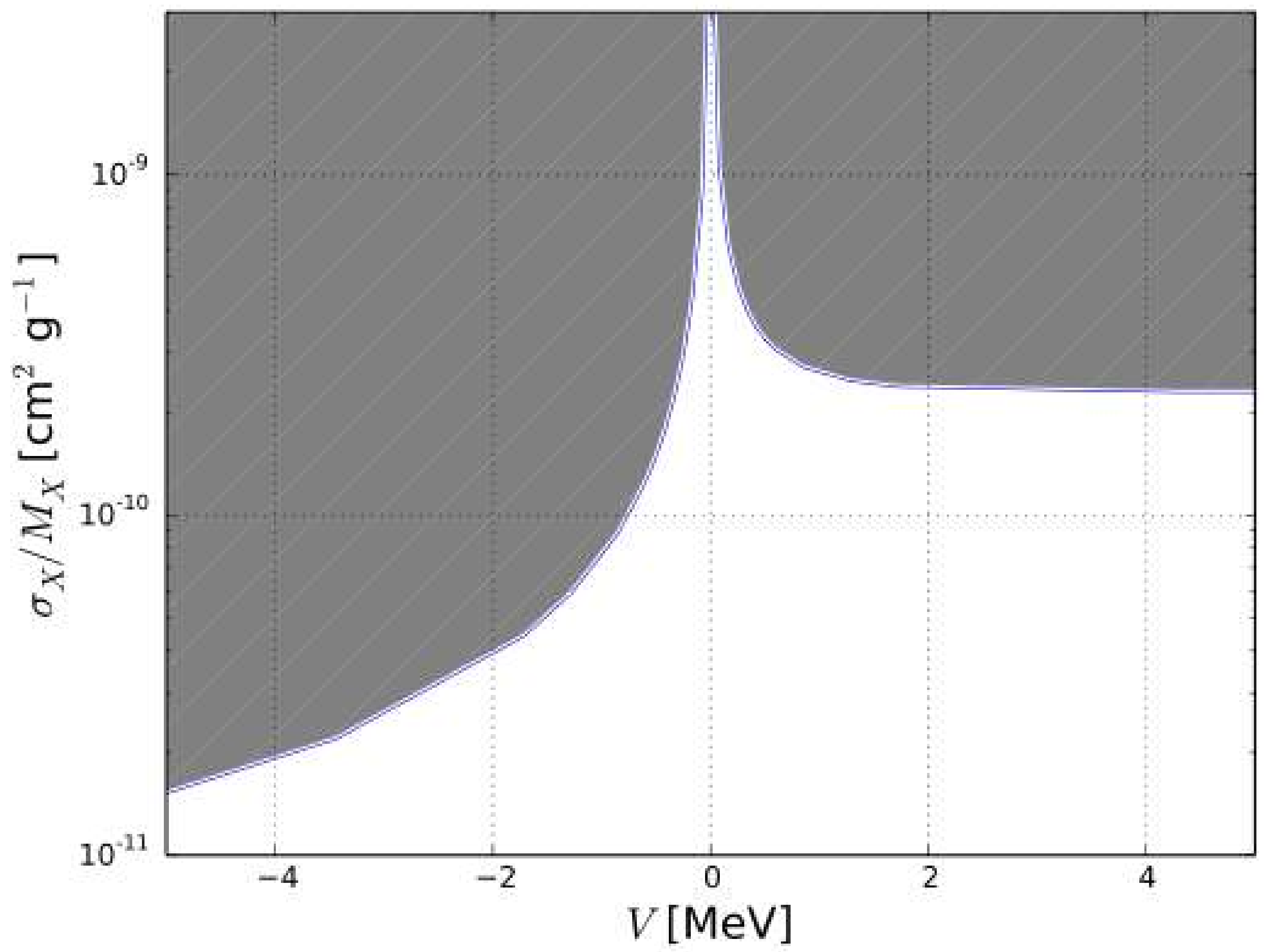
Model-dependent BBN constraints

- For surface potentials < 0.01 MeV

$$\frac{\sigma_{\rm X}}{M_{\rm X}} \lesssim 8 \times 10^{-11} \left| \frac{V(R_{\rm X})}{\rm MeV} \right|^{-1} \ {\rm cm}^2\ {\rm g}^{-1}$$

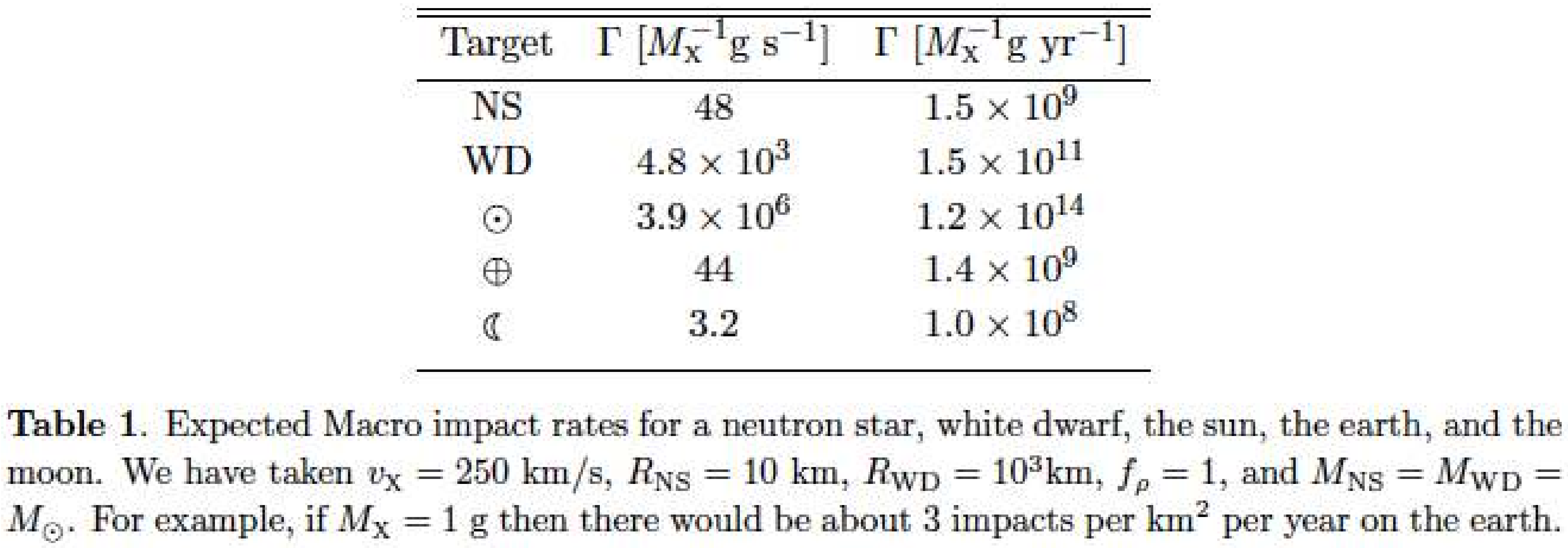
- For surface potentials > ~1 MeV,

$$\frac{\sigma_{\rm X}}{M_{\rm X}} \lesssim 2 \times 10^{-10}\ {\rm cm}^2\ {\rm g}^{-1}$$



Jacobs, Starkman, Lynn (2014)

Jacobs, GDS, Lynn (2014)

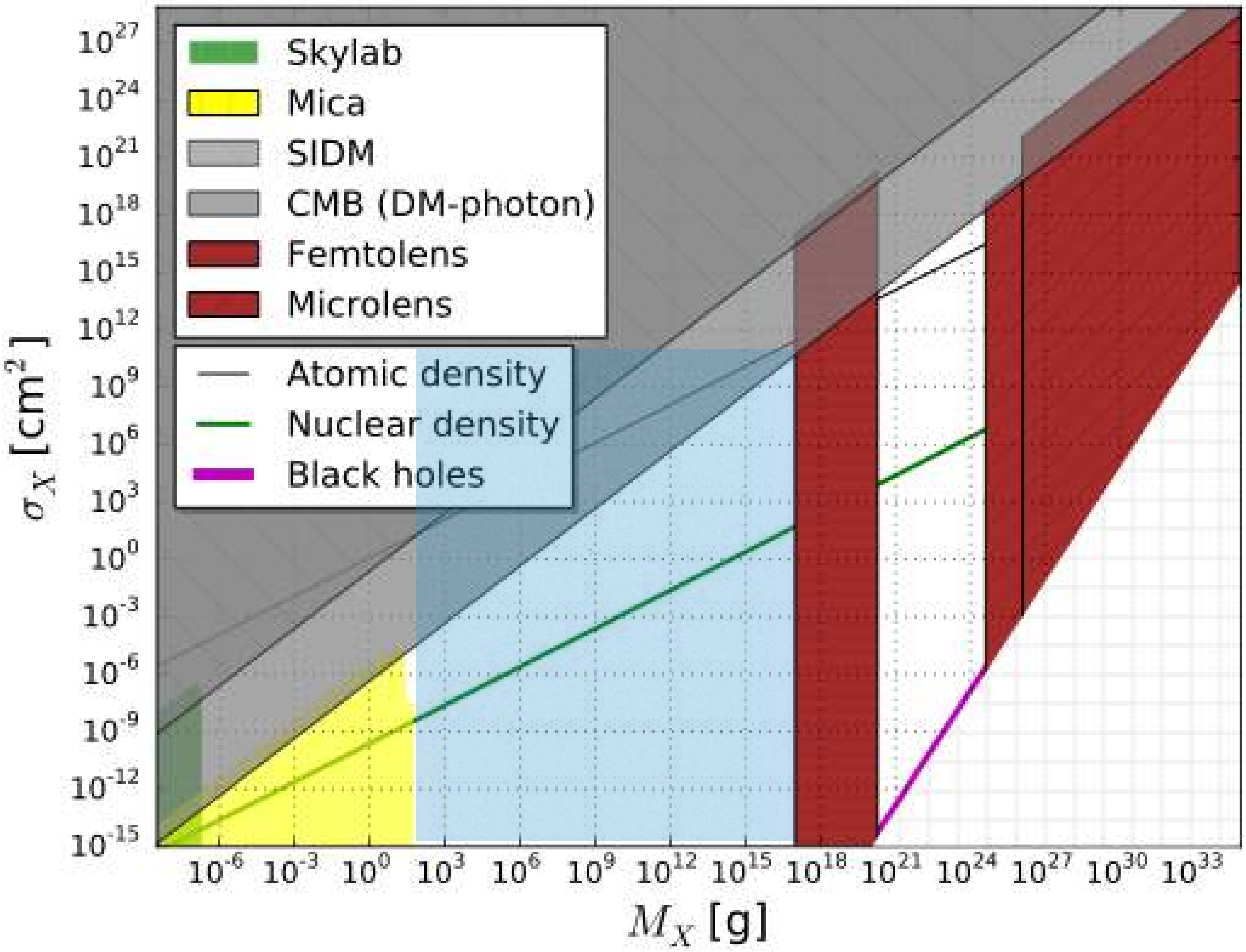


Target	Γ [M_X^{-1}g s^{-1}]	Γ [M_X^{-1}g yr^{-1}]
NS	48	1.5×10^9
WD	4.8×10^3	1.5×10^{11}
$\odot$	3.9×10^6	1.2×10^{14}
$\oplus$	44	1.4×10^9
☾	3.2	1.0×10^8

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, $R_{NS} = 10$ km, $R_{WD} = 10^3$km, $f_\rho = 1$, and $M_{NS} = M_{WD} = M_\odot$. For example, if $M_X = 1$ g then there would be about 3 impacts per km^2 per year on the earth.

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

$M_X > 10^{18}$g



Skylab
Mica
SIDM
CMB (DM-photon)
Femtolens
Microlens
Atomic density
Nuclear density
Black holes
σ_X [cm^2]
10^{27}
10^{24}
10^{21}
10^{18}
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
10^{0}
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
10^{21}
10^{24}
10^{27}
10^{30}
10^{33}
M_X [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)