Stefano Profumo

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What is the Dark Matter?

TRIUMF, Vancouver, BC

Thursday February 7, 2019

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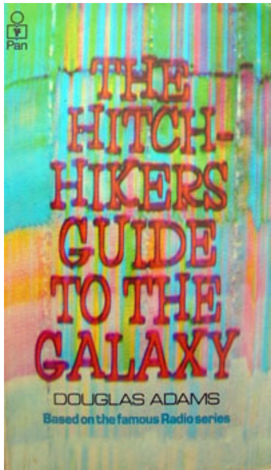
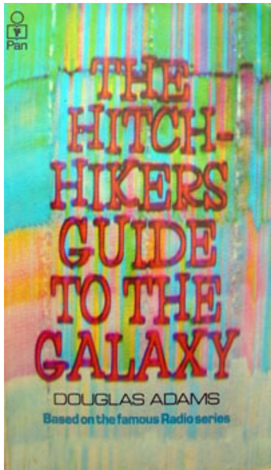
“Answer to the Ultimate Question of Life, the Universe, and Everything”



Certainly the correct answer, real question is: in which units

42

"Answer to the Ultimate Question of Life, the Universe, and Everything"



Stefano Profumo

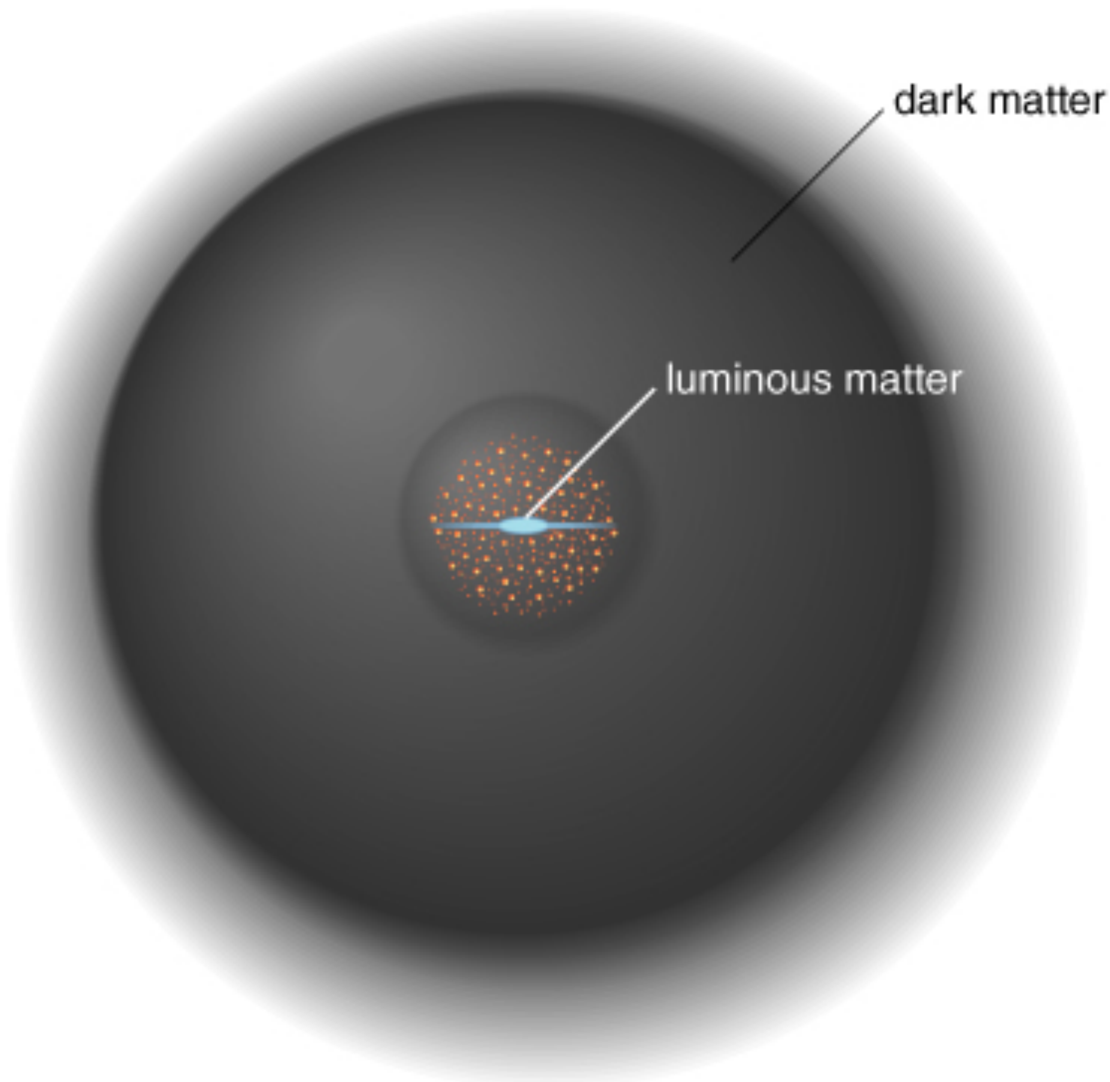
Santa Cruz Institute for Particle Physics
University of California, Santa Cruz

What is the Dark Matter?*

**Disclaimer: this question will not be answered in this talk*

University of California, Santa Cruz

Thursday January 10, 2019


dark matter
luminous matter

5/6

(and we need it all!)

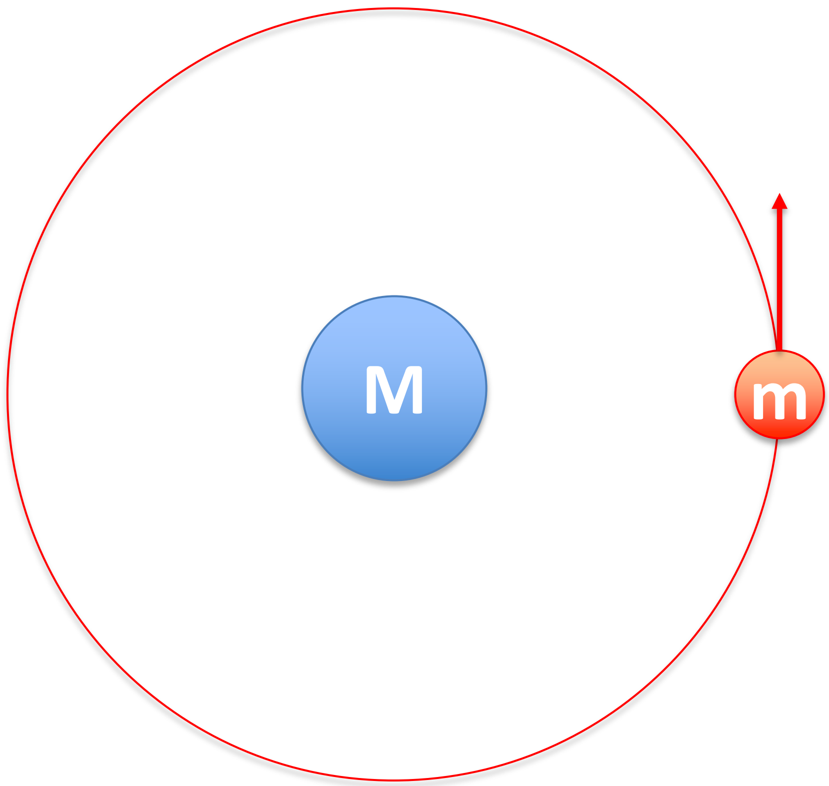
a new

elementary particle

a (likely) portal to new physics

(biased) survey of possible signals from (particle) dark matter

“stuff” moves faster than it should if only visible matter were around

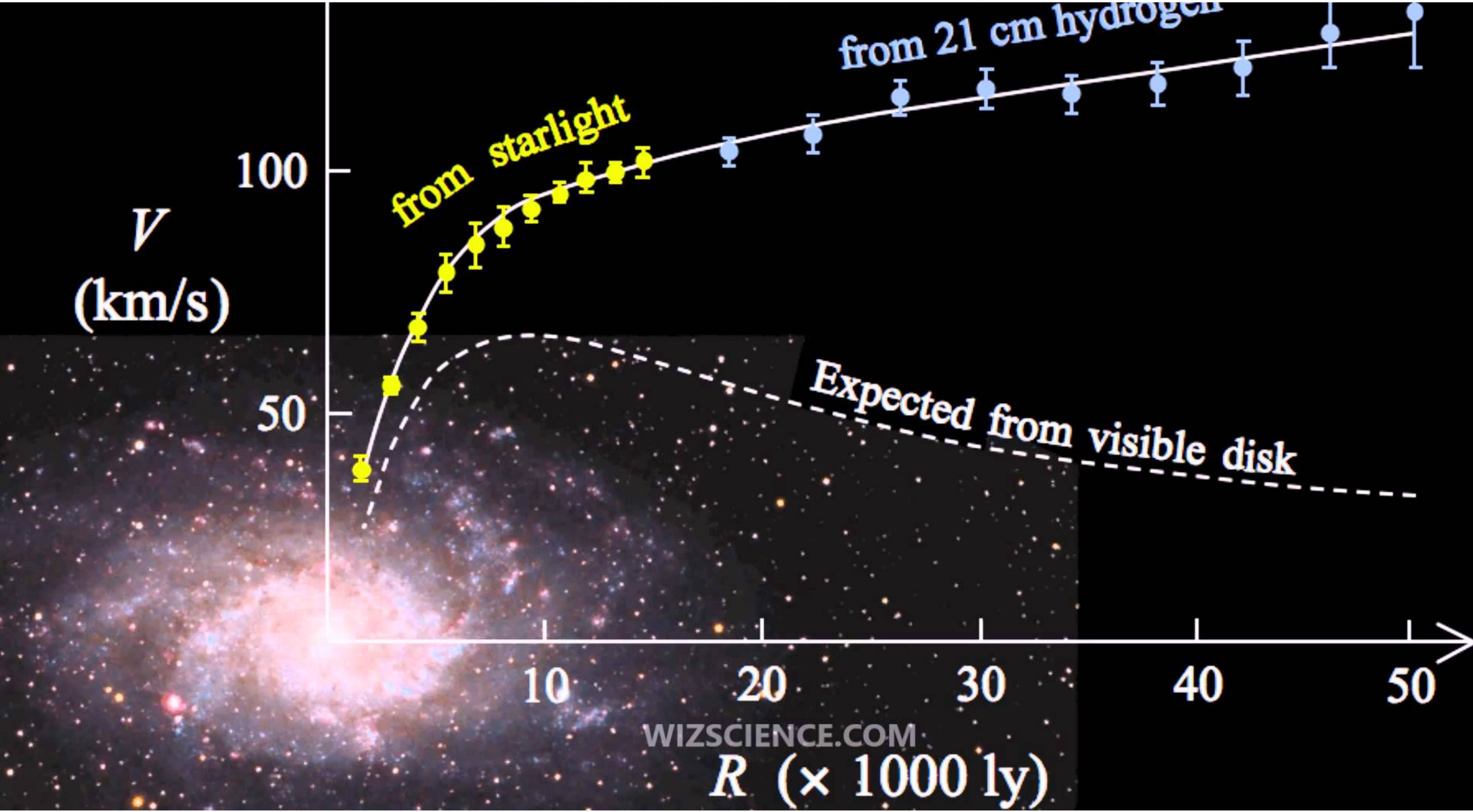


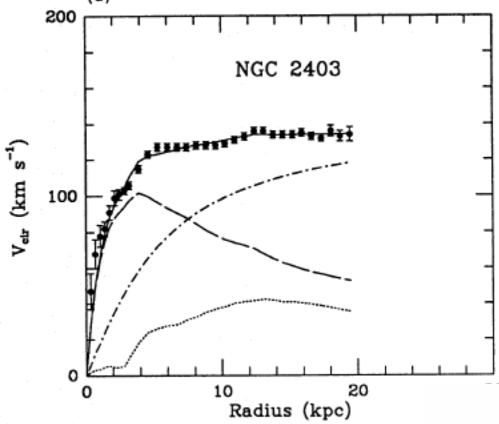
$$F = ma$$

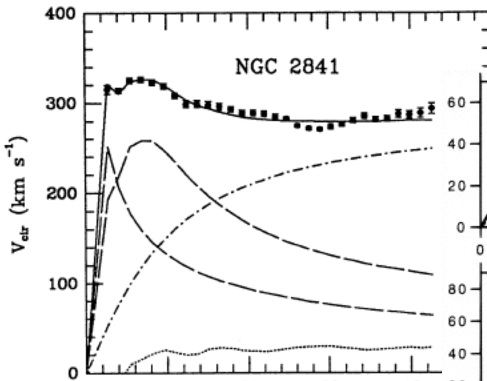
$$G\frac{Mm}{r^2} = m\frac{v^2}{r}$$

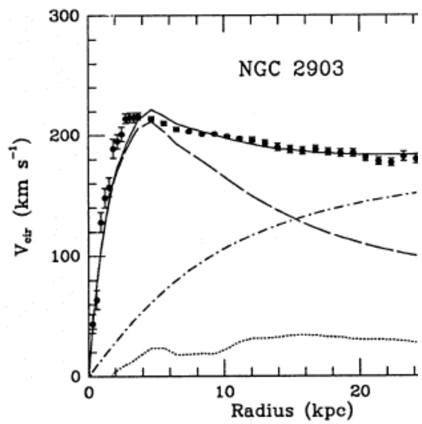
$$v = \sqrt{\frac{GM}{r}}$$

$$v = \sqrt{\frac{GM}{r}}$$

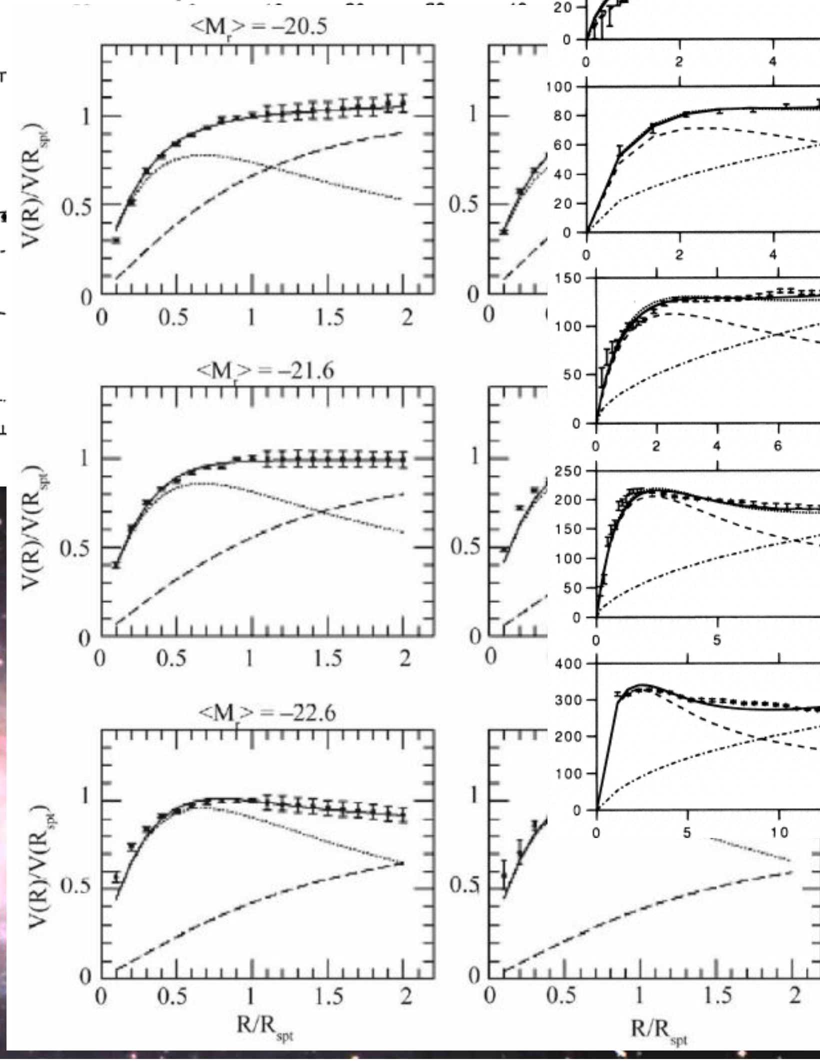


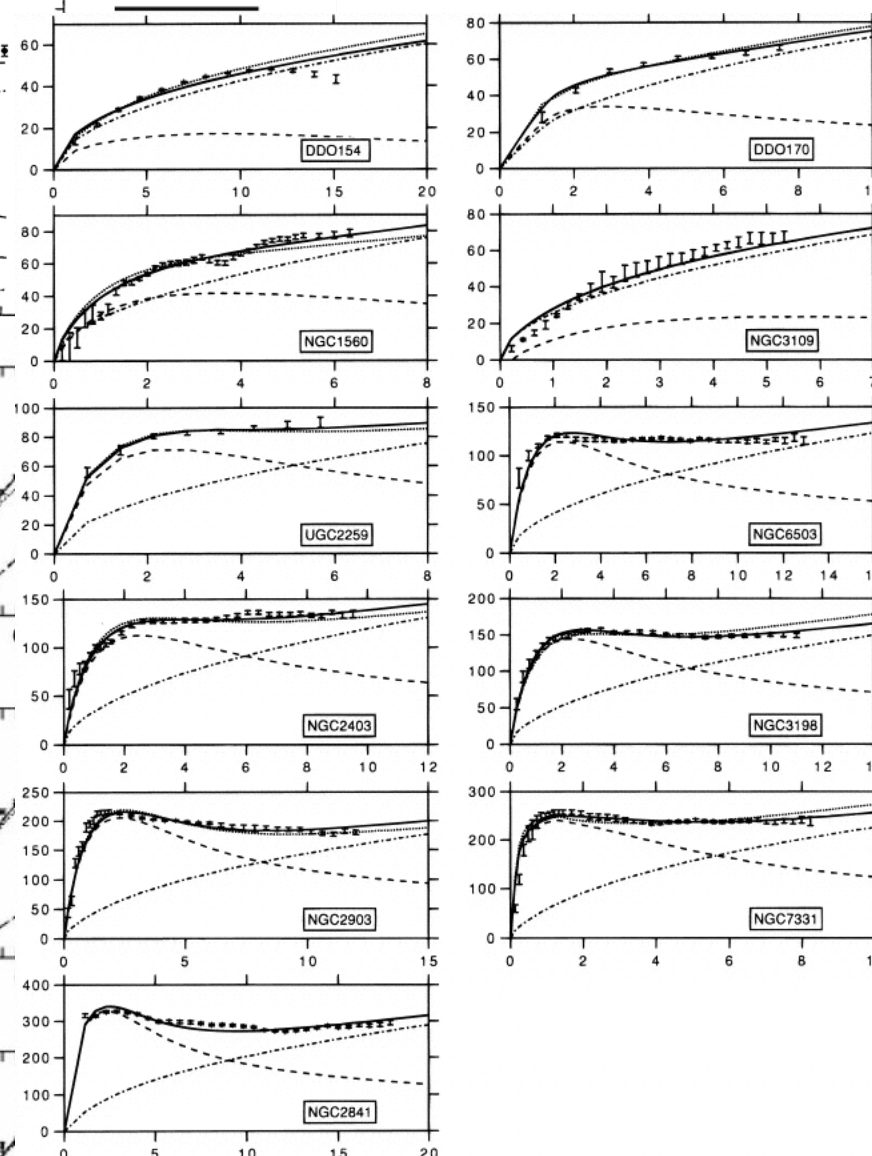

NGC 2403
V_{cir} (km s^{-1})
Radius (kpc)

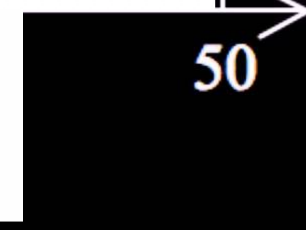

NGC 2841
V_{cir} (km s^{-1})

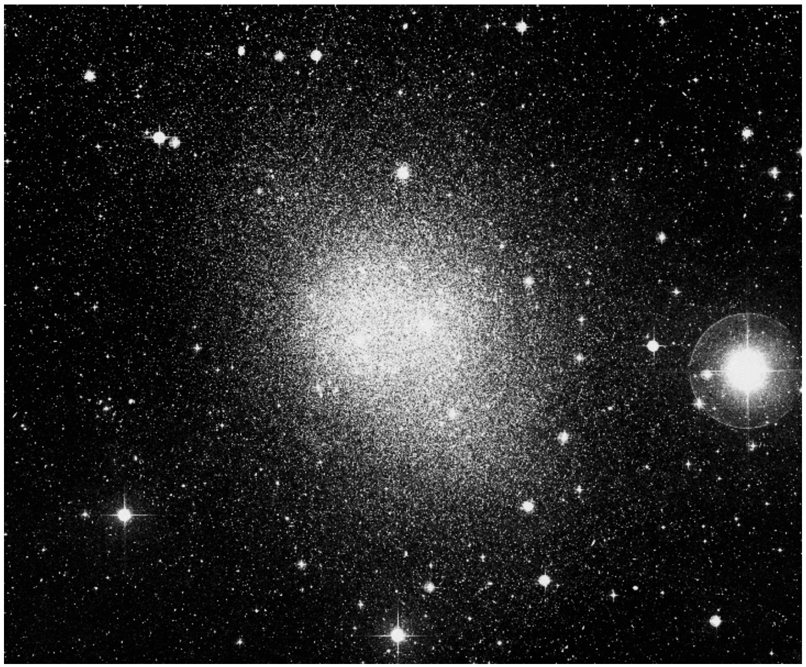

NGC 2903
V_{cir} (km s^{-1})
Radius (kpc)


50

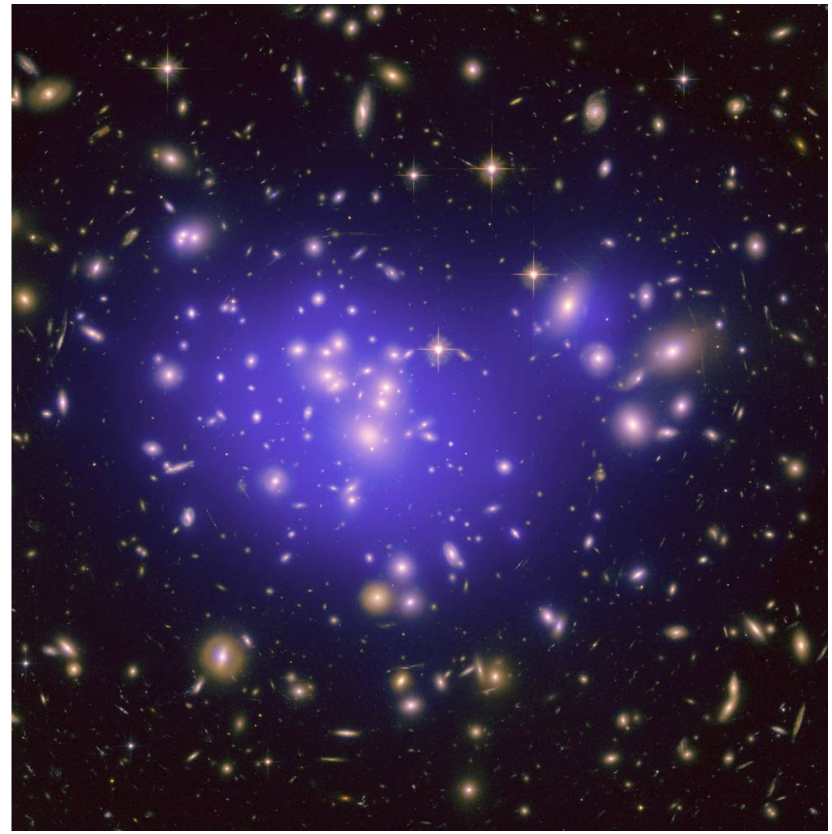

$\langle M_r \rangle = -20.5$
$\langle M_r \rangle = -21.6$
$\langle M_r \rangle = -22.6$
$V(R)/V(R_{spt})$
R/R_{spt}


DDO154
DDO170
NGC1560
NGC3109
UGC2259
NGC6503
NGC2403
NGC3198
NGC2903
NGC7331
NGC2841


50

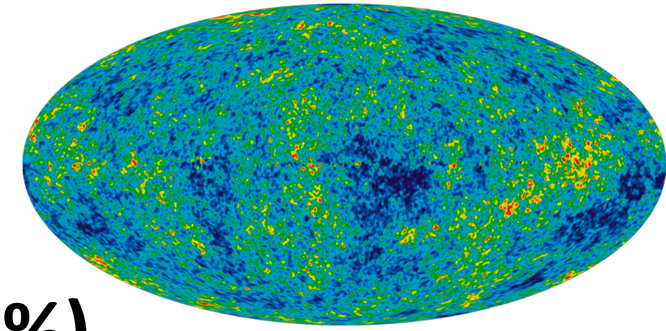


~ 1 kpc, ~ 3000 light-years

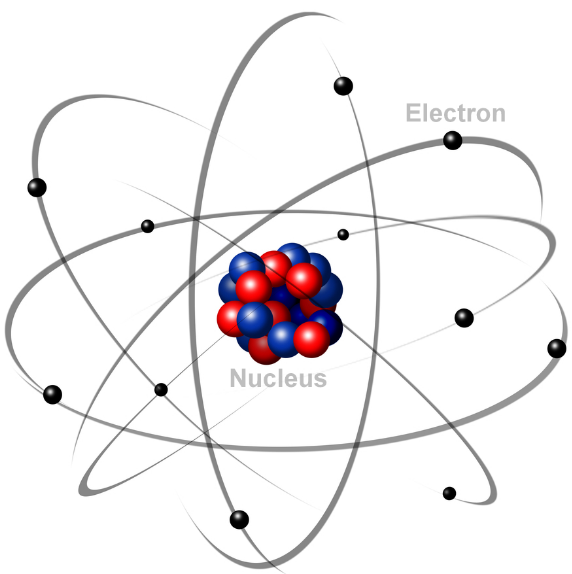


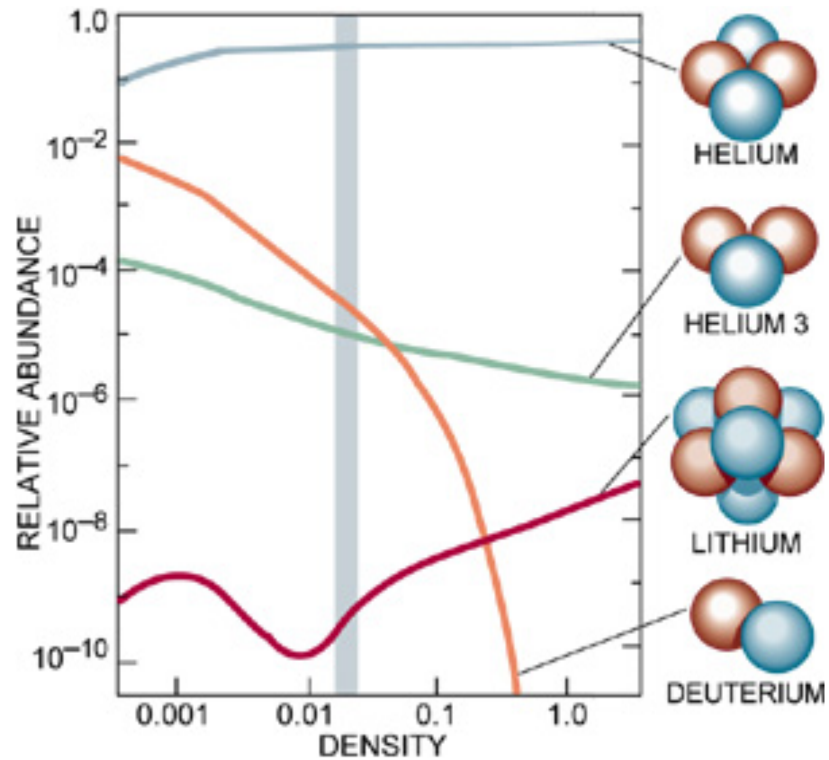
~ 1 Mpc, ~ 3,000,000 light-years

5/6



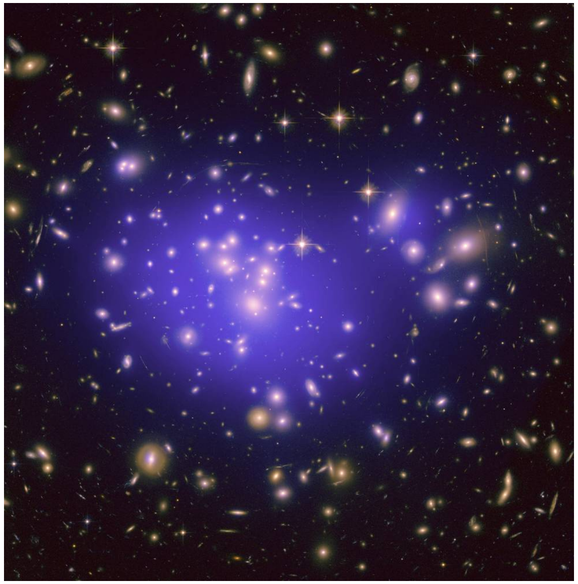
1. Weigh "ordinary" matter (5%)

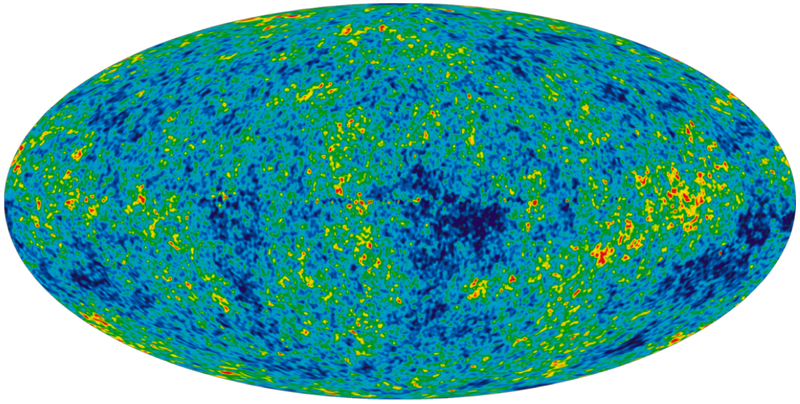




5/6

1. Weigh "**ordinary**" matter (5%)
2. Weigh **all matter** (30%)



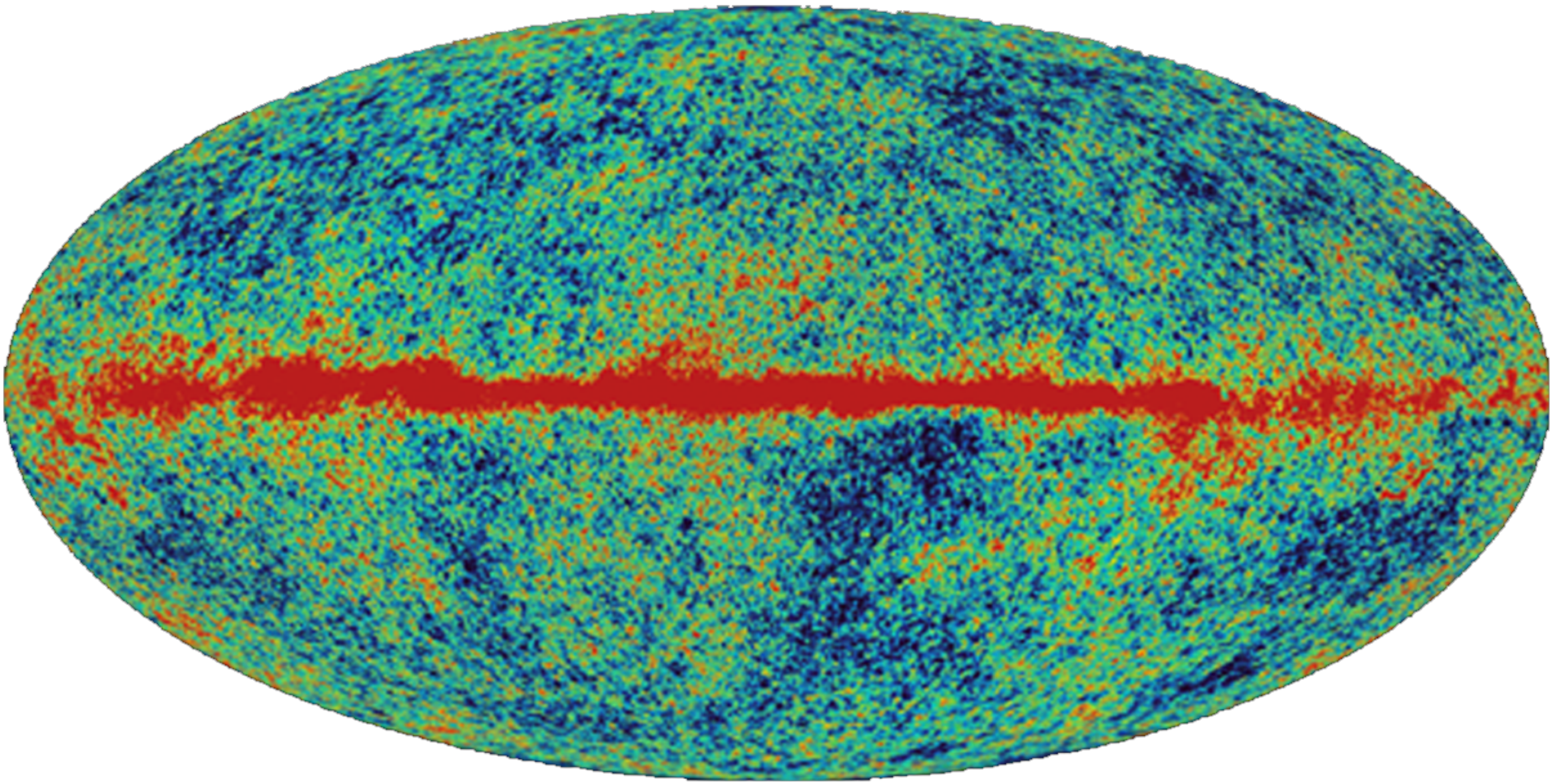


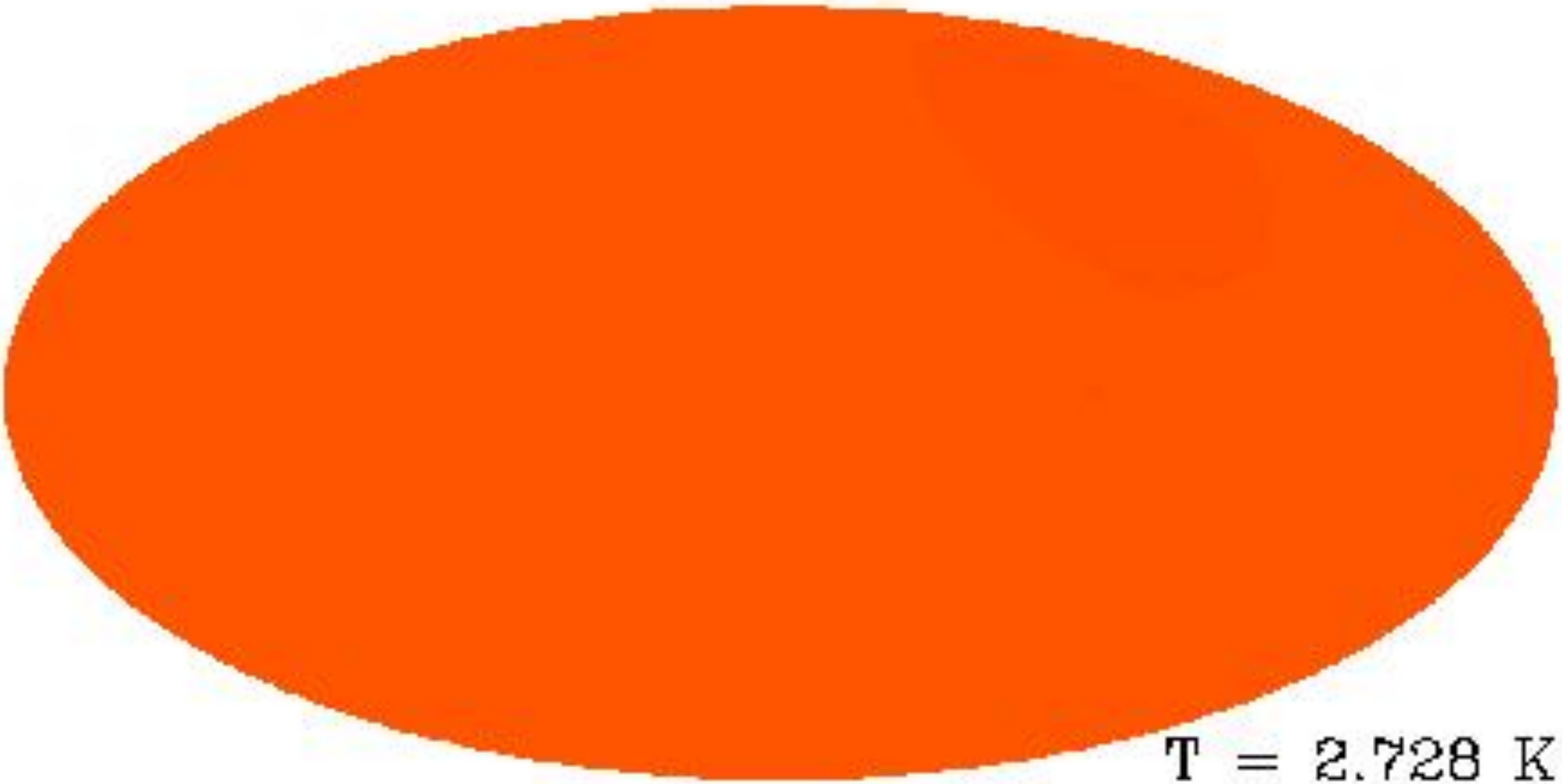
5/6

1. Weigh "ordinary" matter (5%)
2. Weigh all matter (30%)
3. Take the difference!

…OK, but what if gravity "works differently" at very large scales?

A simple argument that shows modified gravity without dark matter does not work: the timing of structure formation




T = 2.728 K

CMB sky is very boring – *T* fluctuations very small!!

***T* fluctuations prop. to (baryonic) density fluctuations,**

$$\delta\rho/\rho < 10^{-4}$$

Small matter over-densities

grow linearly with scale factor:

$\delta\rho/\rho$ **(today)**$=\delta\rho/\rho$ **(z) * z**

But the scale factor since CMB decoupling grew by z_{rec}~1,100

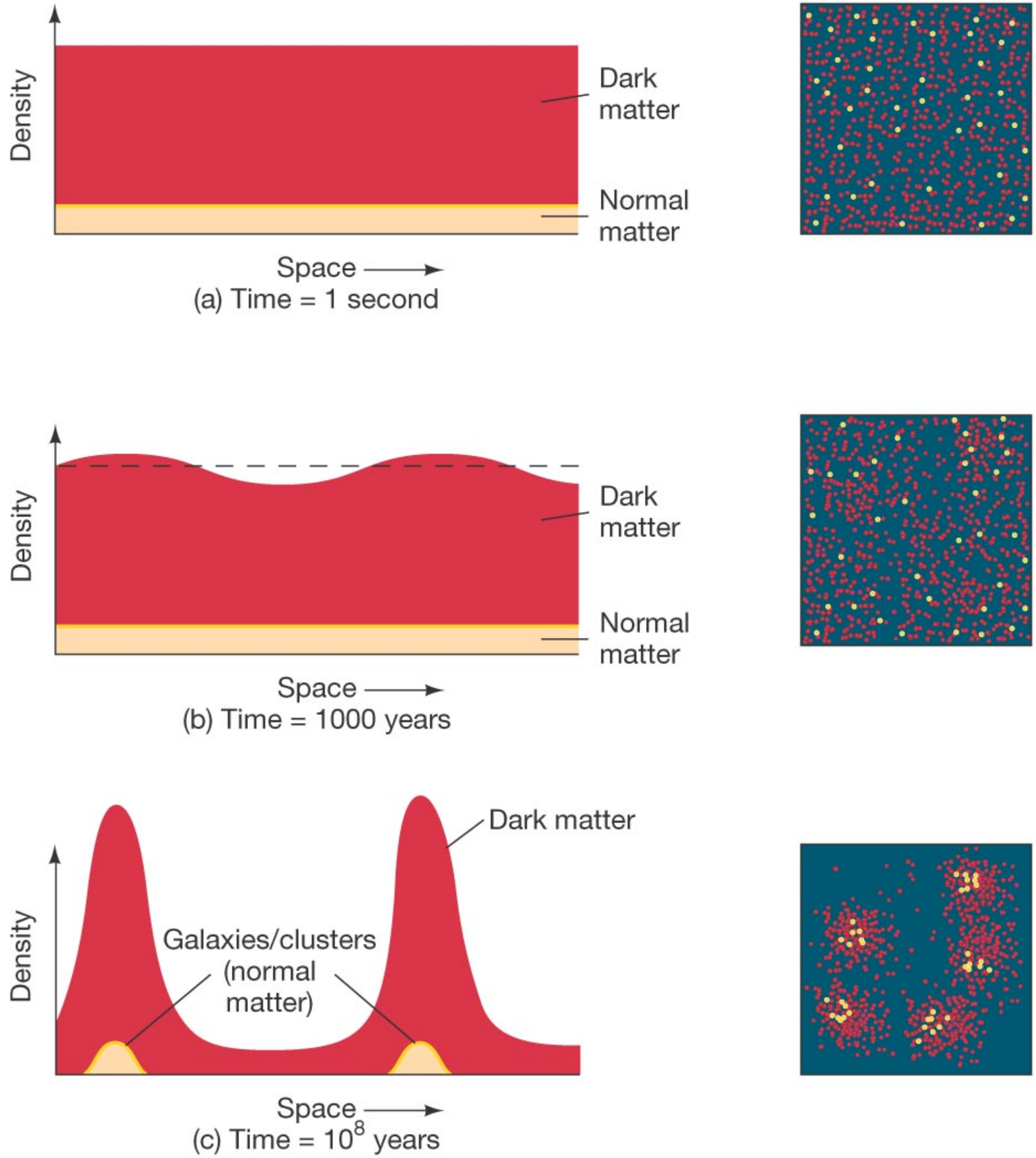
Not enough time (since recombination)

for structures to go non-linear: 10^{-4} x 1,100 < 1 !!

We need a species that has decoupled from photons much earlier (Dark Matter) so that its density perturbations are much larger at recombination!

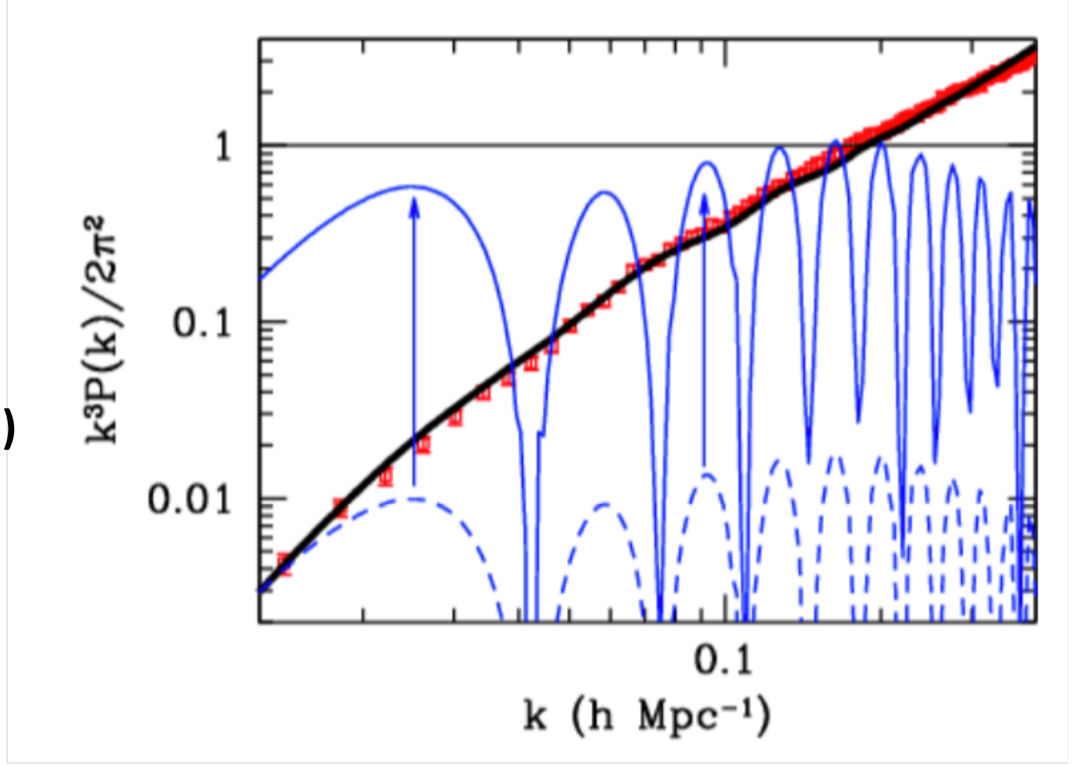
$$(\delta\rho/\rho)_{\rm DM} \gg 10^{-4}$$

Dark matter seeds timely structure formation!


Density
Dark matter
Normal matter
Space
(a) Time = 1 second
Density
Dark matter
Normal matter
Space
(b) Time = 1000 years
Dark matter
Density
Galaxies/clusters (normal matter)
Space
(c) Time = 10^8 years

Structure formation fails badly without Dark Matter!

Power spectrum of density perturbations (credit: Scott Dodelson)



$\delta\rho/\rho \sim 1$

Even with best (covariant) incarnation of modified gravity (TeVeS), structure goes non-linear, but the power spectrum of matter density fluctuation is entirely wrong...

- **more stuff than ordinary matter***
- **more precisely, 5/6**
- **really need this dark stuff**

what is it?

do we know of a particle that could be the dark matter?

***protons, neutrons (electrons, photons)**


MATTER
FORCE
u
c
t
d
s
b
Quarks
W
Z
Gauge Bosons
H
Higgs Boson?
e
Leptons
THE STANDARD MODEL OF
PARTICLES AND FORCES
IS THIS ALL THAT EXISTS?

a new
elementary particle

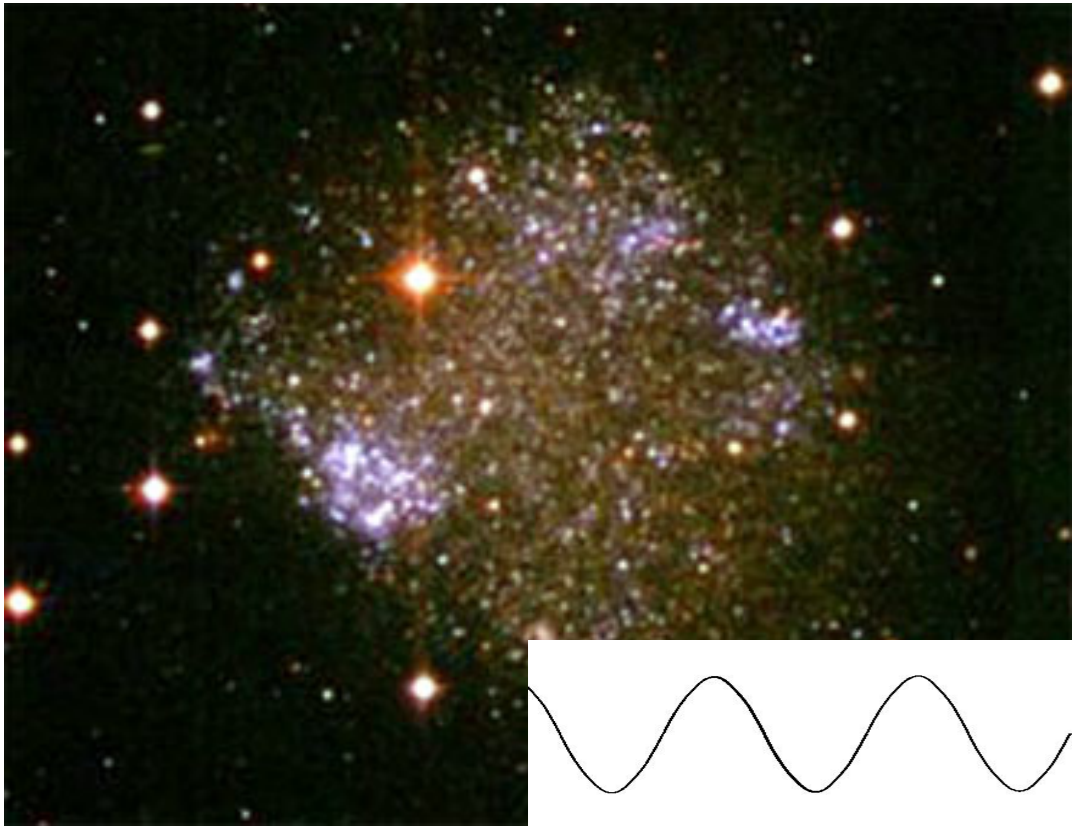
what is an elementary particle?

what is an
elementary particle?

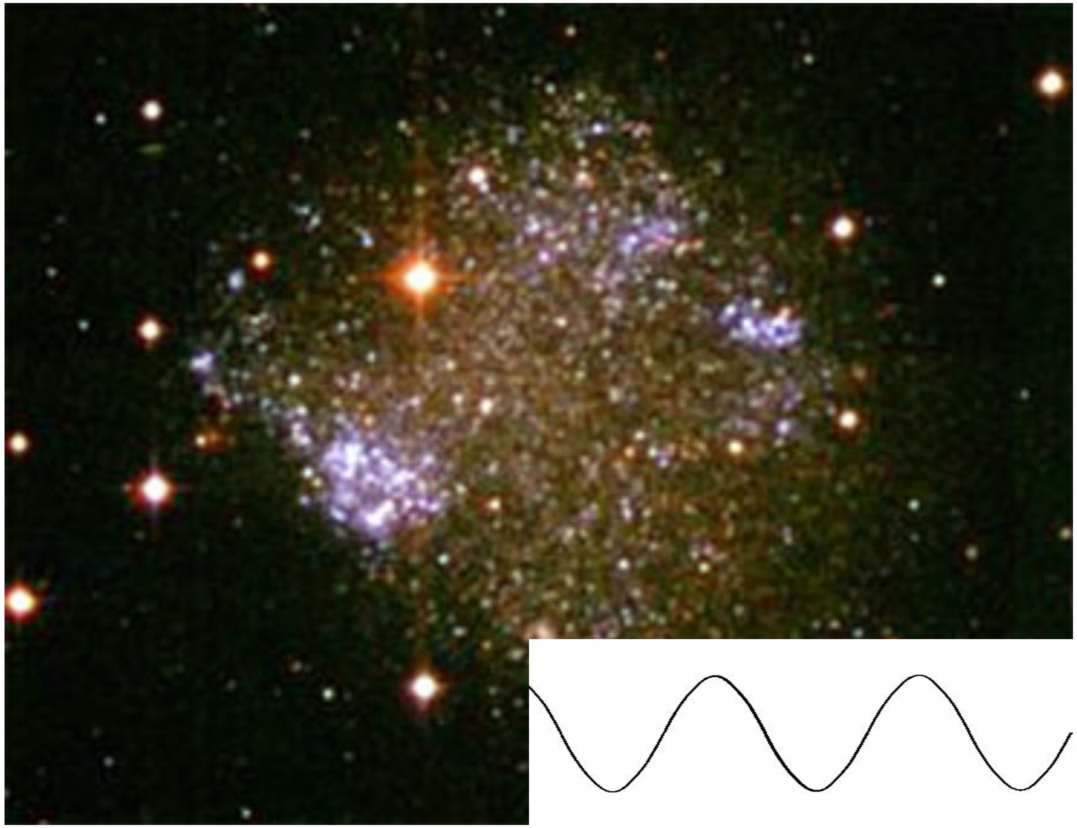
an irreducible, unitary
representation of the
Poincaré Group

(m, J)

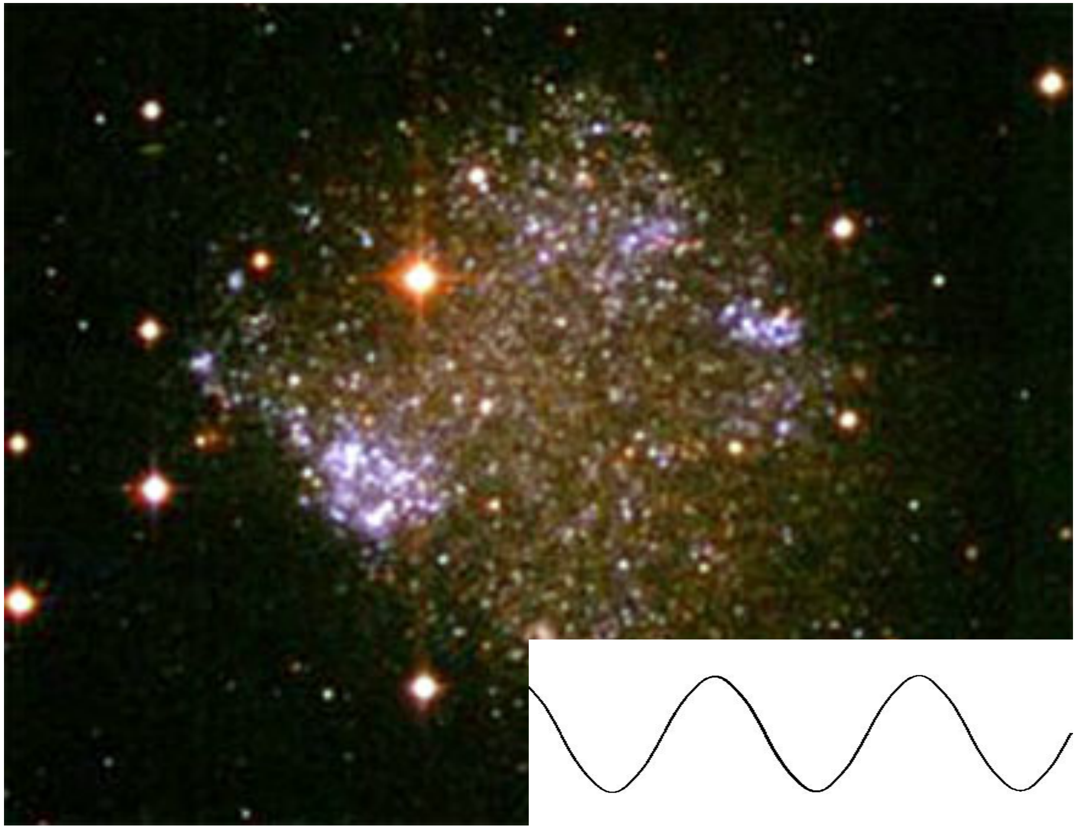
what do we know about m and J?



what do we know about m and J?

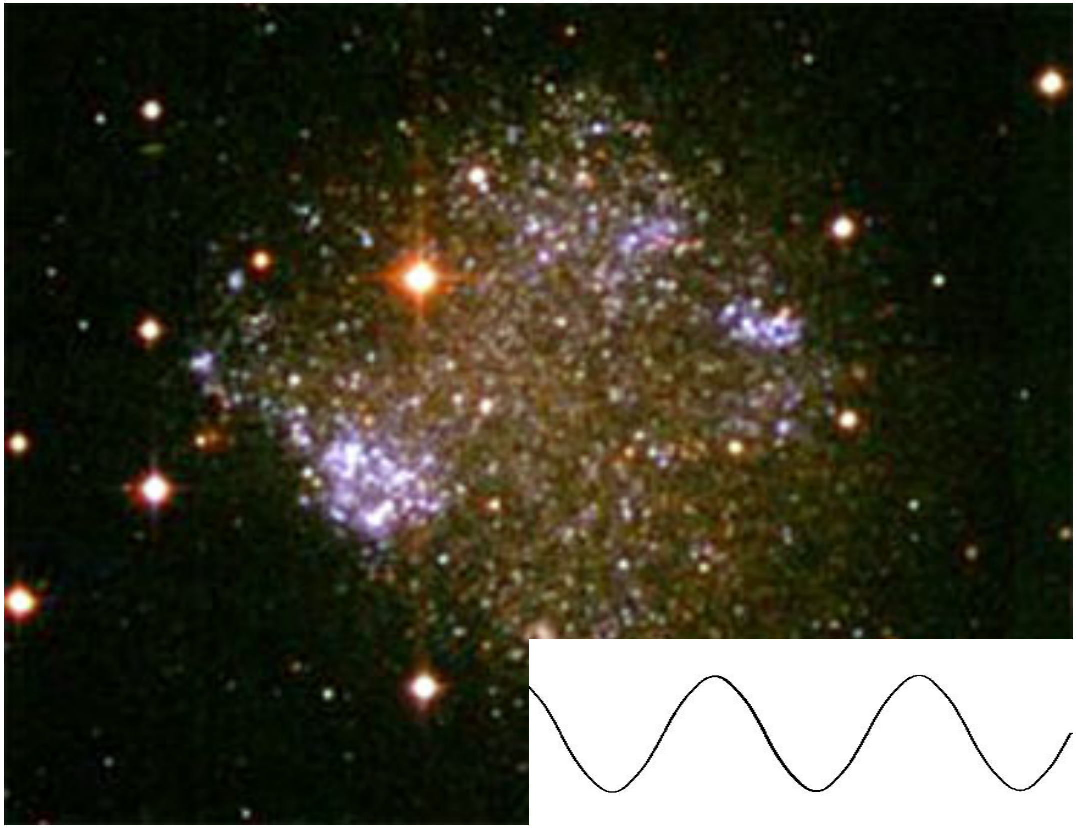


quantum effects must be smaller than halos!



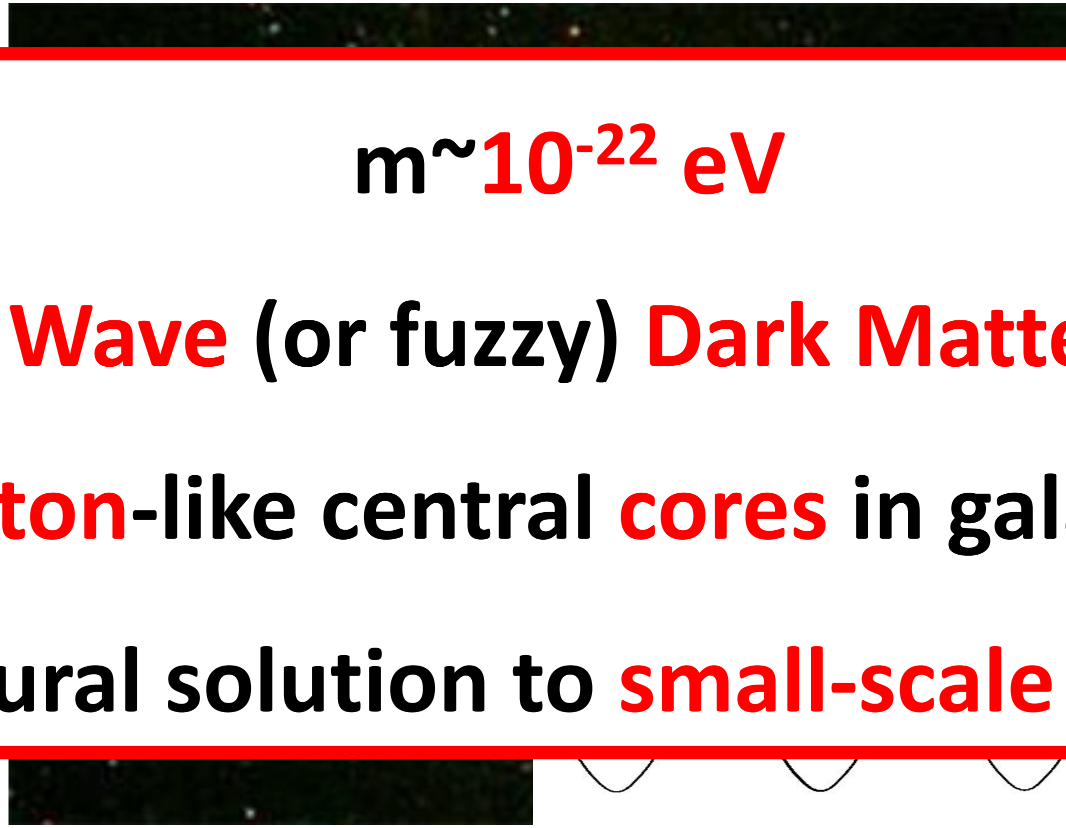
$$\lambda_{DB} = h/(mv) < 1\ \text{kpc}$$

$$\lambda_{DB} = 0.3\ \text{cm}\ (1\ \text{eV}/m) < 3\text{x}10^{21}\ \text{cm}$$



$m > 10^{-22}$ eV

$$\lambda_{DB} = 0.3 \text{ cm } (1 \text{ eV}/m) < 3\text{x}10^{21} \text{ cm}$$



m~10^{-22} eV

Wave (or fuzzy) Dark Matter

- soliton-like central cores in galaxies
- natural solution to small-scale issues

m>10^{-22} eV

λ_{DB} = 0.3 cm (1 eV/m) < 3×10^{21} cm

what if $J=(2n+1)/2$, i.e. fermion?

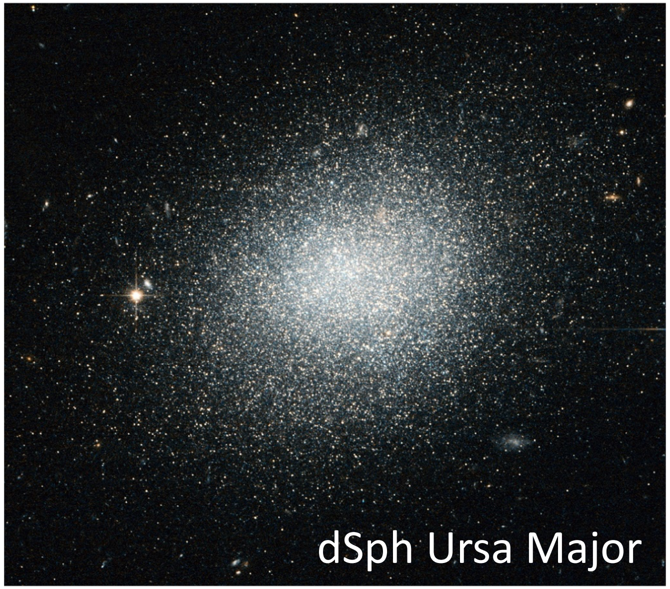
the **phase space** density is bounded (**Pauli** blocking): ***f= gh⁻³***

upper limit: highest observed phase space density: **dSph**!

$$\frac{g}{h^3} \geq n \cdot f_p \geq \frac{\rho_{\rm DM}}{m} \frac{1}{\left(m \cdot \sqrt{2\pi\sigma^2}\right)^3}$$ *(MB with exp=1)*

$$m^4 \geq \frac{\rho_{\rm DM} h^3}{[g(2\pi\sigma^2)^{3/2}]} \sim (25\ {\rm eV})^4$$

Tremaine-Gunn limit (1979)



m>25 eV

what if J=(2n+1)/2, i.e. fermion?

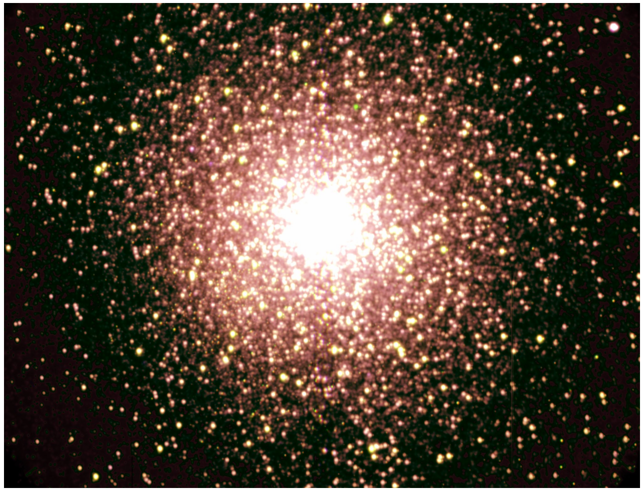
m>10^{-22} eV   m>25 eV

bosons   fermions

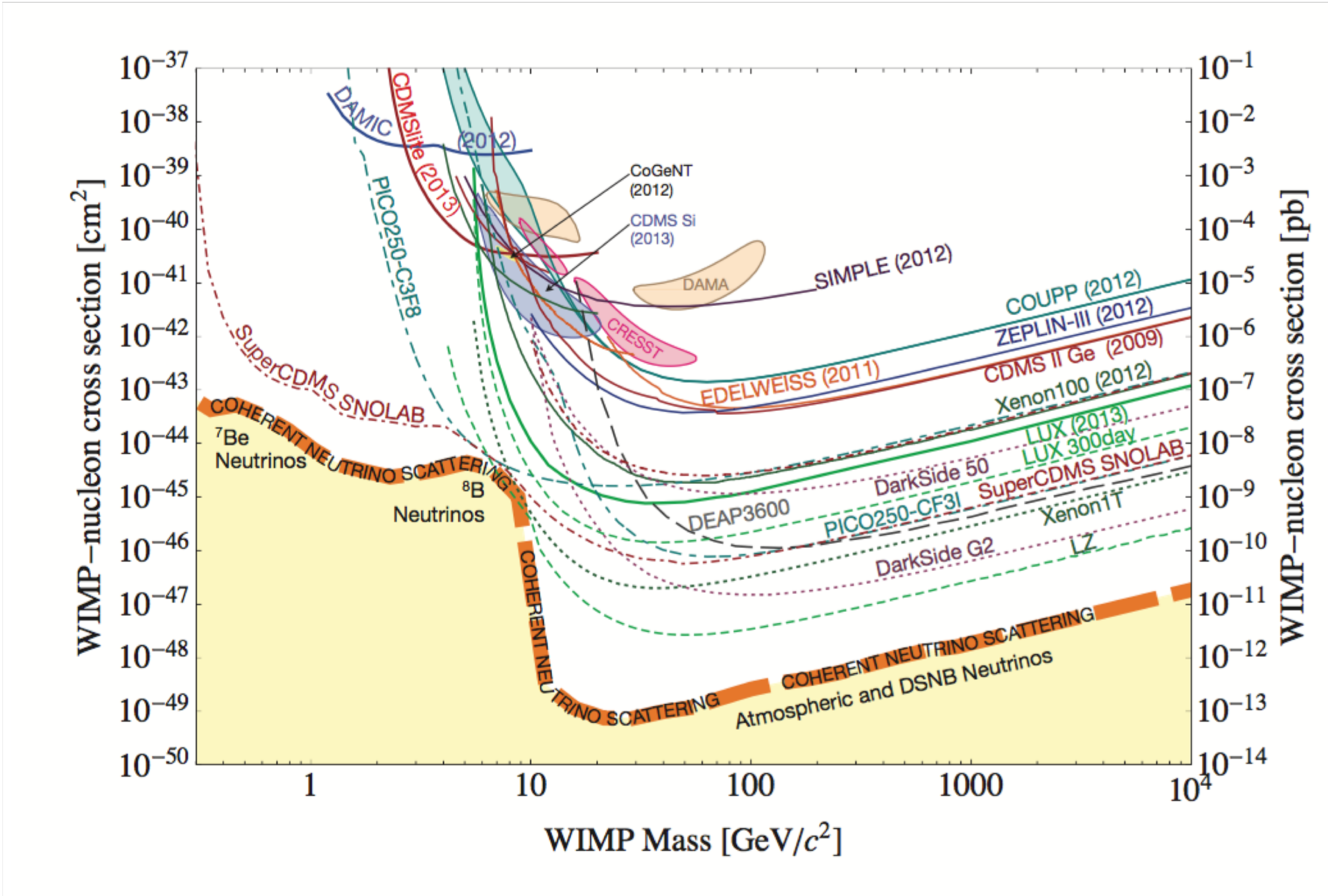
what is the upper limit
to the dark matter mass?

ultramassive DM: beyond M_P…
composite, primordial black holes!

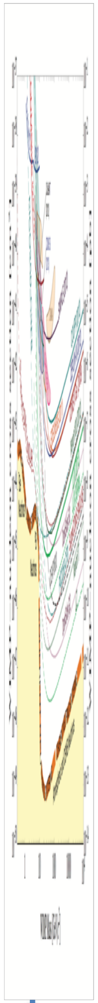
Macroscopic Dark Matter would **tidally disrupt** structure



***m* < 10^{3} solar masses ~ 10^{70} eV**


WIMP–nucleon cross section [cm²]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c²]
10⁻³⁷ 10⁻³⁸ 10⁻³⁹ 10⁻⁴⁰ 10⁻⁴¹ 10⁻⁴² 10⁻⁴³ 10⁻⁴⁴ 10⁻⁴⁵ 10⁻⁴⁶ 10⁻⁴⁷ 10⁻⁴⁸ 10⁻⁴⁹ 10⁻⁵⁰
10⁻¹ 10⁻² 10⁻³ 10⁻⁴ 10⁻⁵ 10⁻⁶ 10⁻⁷ 10⁻⁸ 10⁻⁹ 10⁻¹⁰ 10⁻¹¹ 10⁻¹² 10⁻¹³ 10⁻¹⁴
1 10 100 1000 10⁴
DAMIC
CDMSlite (2013)
(2012)
PICO250-C3F8
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
LUX 300day
SuperCDMS SNOLAB
DarkSide 50
DEAP3600
PICO250-CF3I
Xenon1T
DarkSide G2
LZ
SuperCDMS SNOLAB
COHERENT NEUTRINO SCATTERING
⁷Be Neutrinos
⁸B Neutrinos
COHERENT NEUTRINO SCATTERING
COHERENT NEUTRINO SCATTERING
Atmospheric and DSNB Neutrinos

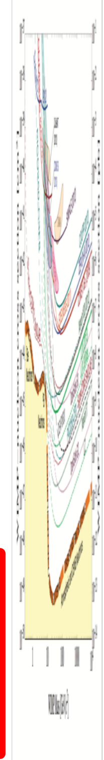

10⁻²⁰ eV
10⁻¹⁰ eV
10⁰ eV
10¹⁰ eV
10²⁰ eV
10³⁰ eV
10⁴⁰ eV
10⁵⁰ eV
10⁶⁰ eV
10⁷⁰ eV

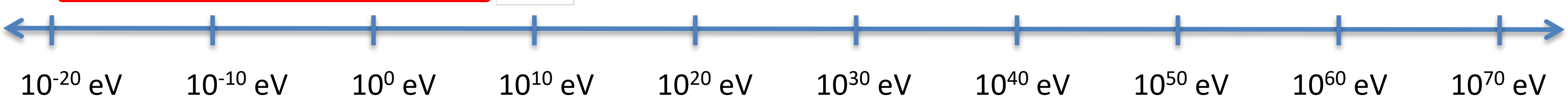


10^{-20} eV 10^{-10} eV 10^{0} eV 10^{10} eV 10^{20} eV 10^{30} eV 10^{40} eV 10^{50} eV 10^{60} eV 10^{70} eV

Fuzzy (wave) Dark Matter

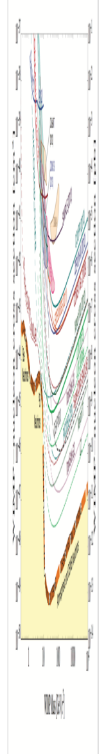
Many exciting new ideas!**





Strong constraints from 21 cm line*

* Nebrin et al 2018 ** This workshop

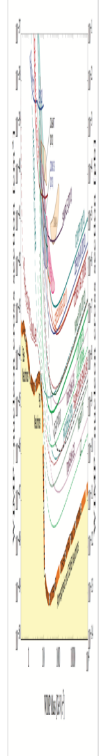


Stellar-Mass Black Holes

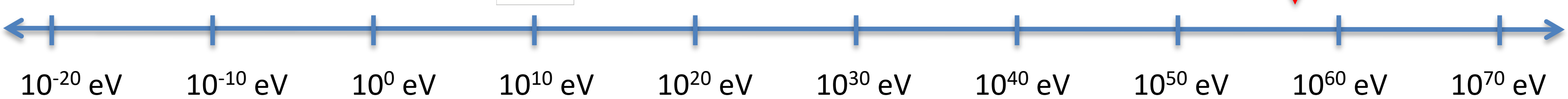
10^{-20} eV　10^{-10} eV　10^{0} eV　10^{10} eV　10^{20} eV　10^{30} eV　10^{40} eV　10^{50} eV　10^{60} eV　10^{70} eV

LIGO dark matter*?
CMB constraints; SN-Ia*****

*Bird+ '16; **Ali-Hiamoud+ '16, Poulin+ '17; ***Seljak+ '17



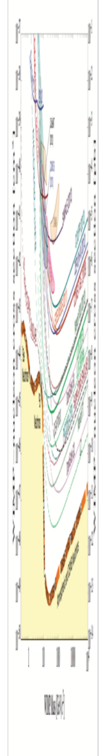
“Asteroid-Mass” (10^{22} g) Black Holes

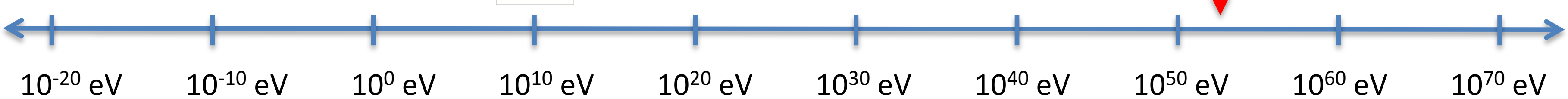


Microlensing constraints don’t apply*!
($R_S << \lambda$)

*Niikura et al 2017

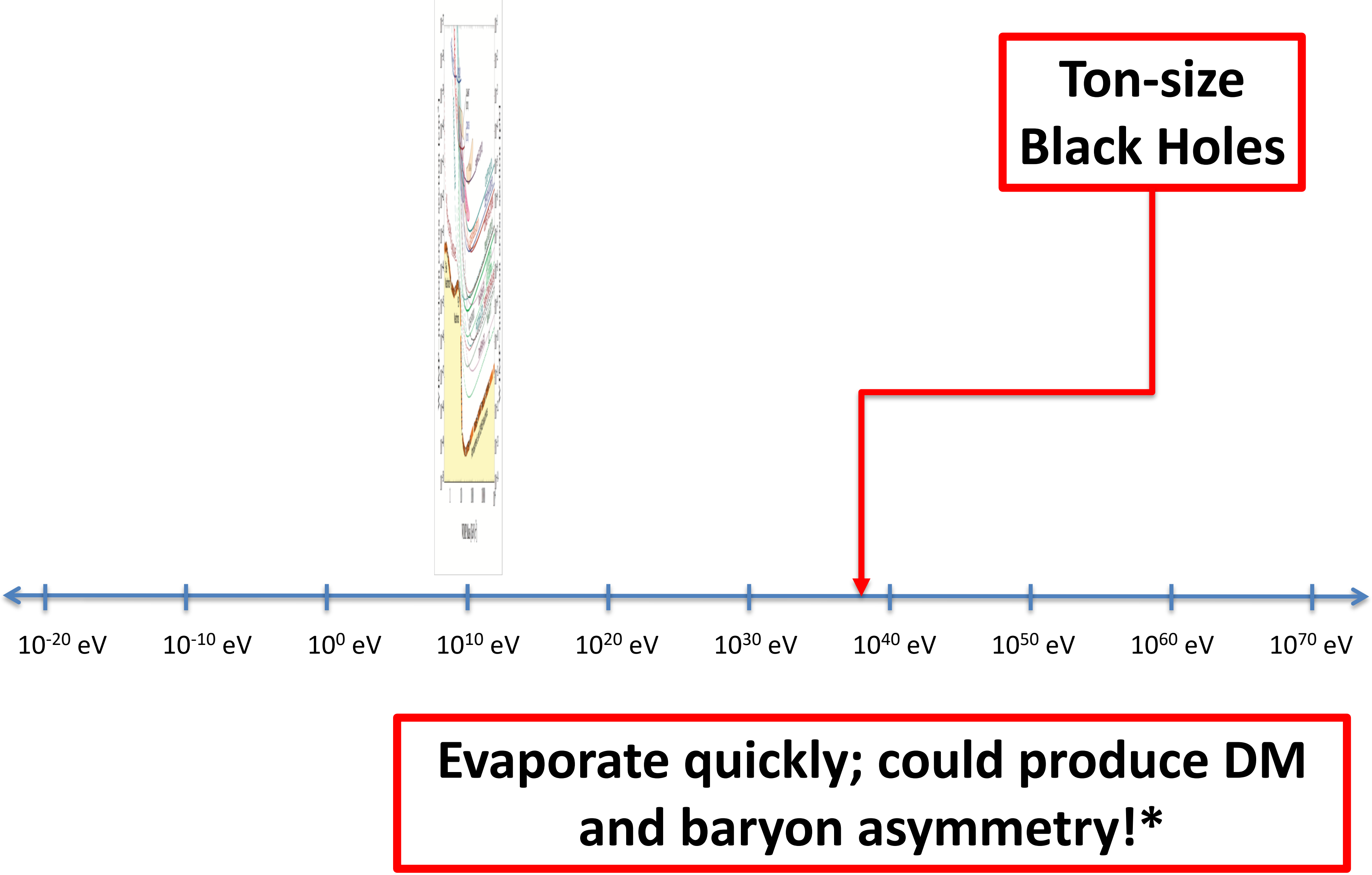
Everest-Mass (10^{18} g) Black Holes



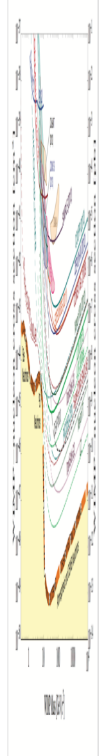


Femtloensing constraints don’t apply*!
(GRB emission region too large)

*Katz et al 2018



*Harigaya et al 2014; Profumo et al 2018

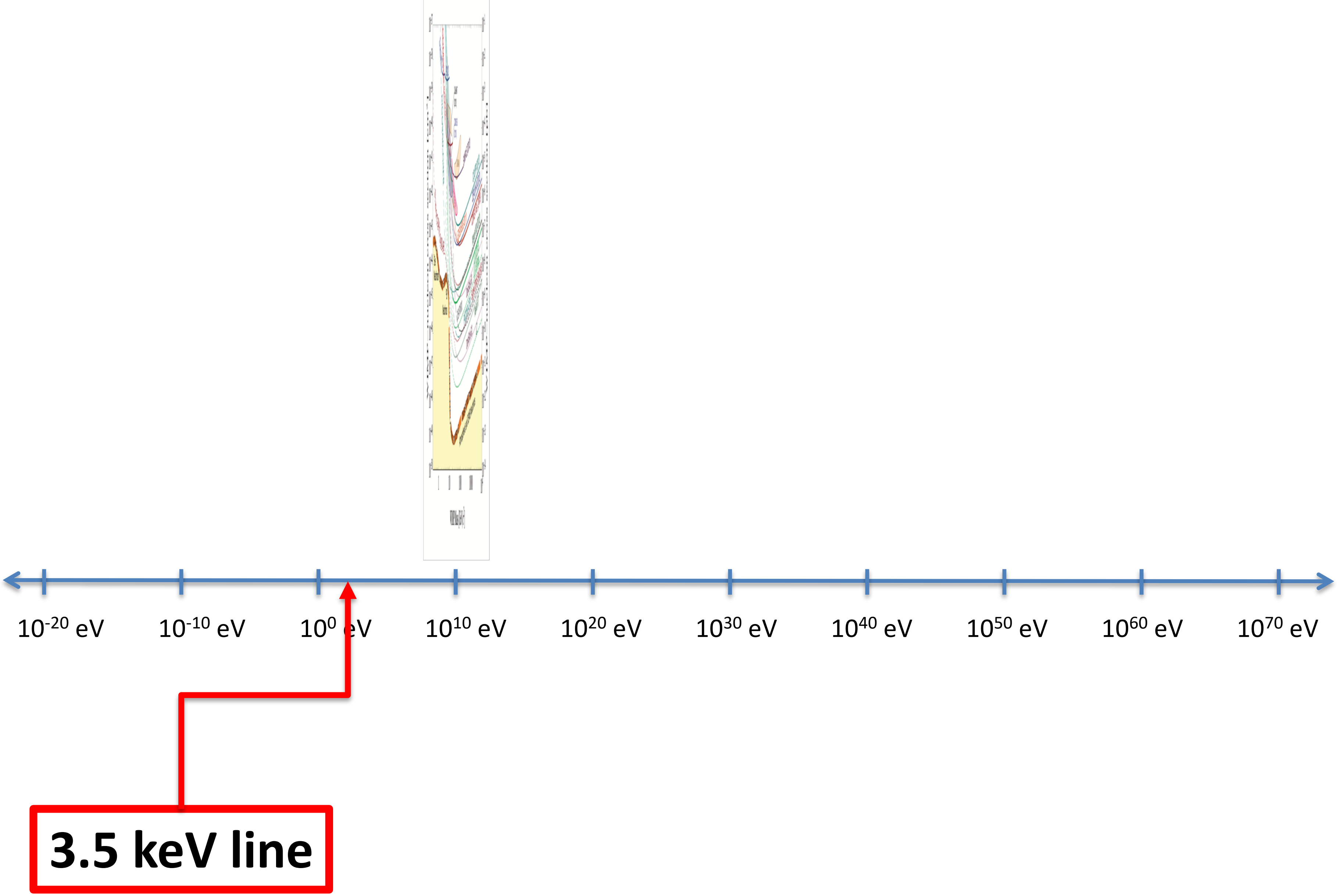


Grain-of-Salt Black Holes

10^{-20} eV | 10^{-10} eV | 10^{0} eV | 10^{10} eV | 10^{20} eV | 10^{30} eV | 10^{40} eV | 10^{50} eV | 10^{60} eV | 10^{70} eV

Could be stable
Could be charged!
Could be detectable!!*

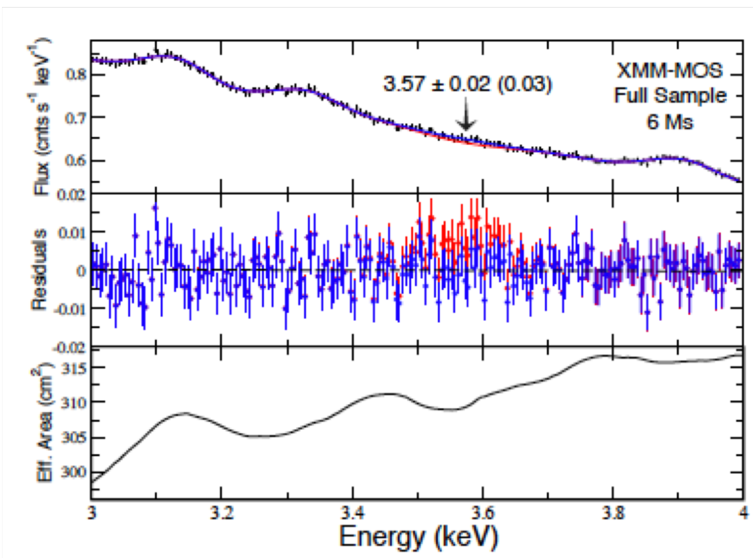
*Lehmann, Profumo+, in preparation

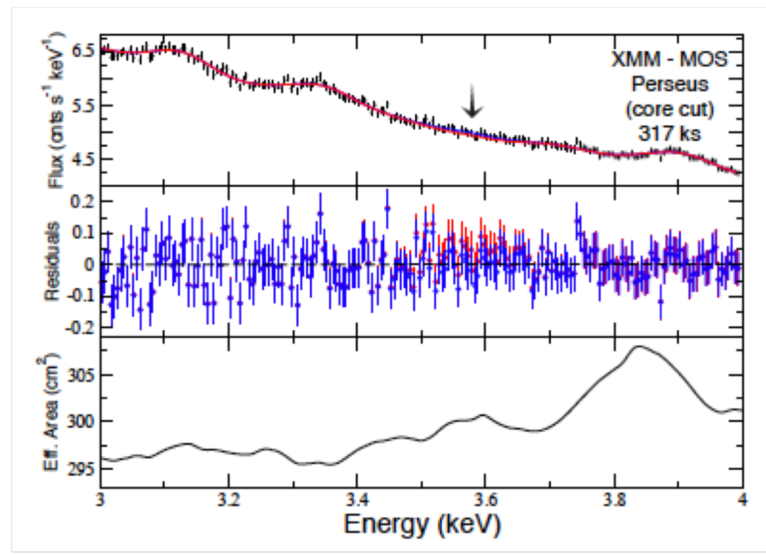


10^{-20} eV
10^{-10} eV
10^{0} eV
10^{10} eV
10^{20} eV
10^{30} eV
10^{40} eV
10^{50} eV
10^{60} eV
10^{70} eV
3.5 keV line

Bulbul+ (2014)

- Stacked clusters
- Perseus



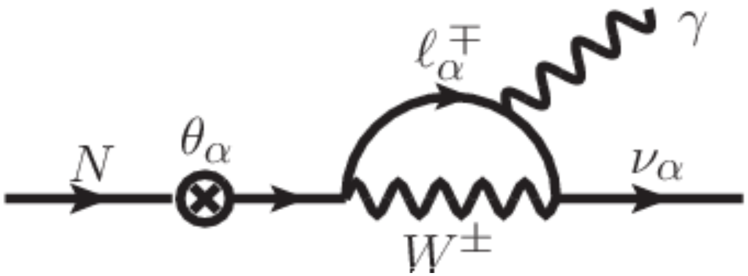


Bulbul+ (2014)
- Stacked clusters
- Perseus

Boyarsky+ (2014)
- M31 (Andromeda)
- Perseus

Jeltema+Profumo (2014)
- Galactic Center

X-ray lines predicted from sterile neutrinos



- $SU(2)_L$ gauge singlet, but (small) mixing angle θ_α with active neutrinos
- Viable DM candidates (Dodelson-Woodrow production; "warm" DM)
- Possibly connected with baryogenesis (νMSM)
- Would decay via mixing with active neutrinos

3.5 keV lines (roughly) compatible with this!

Jeltema+Profumo (2014) showed that for clusters, and for our Galaxy atomic lines (Potassium) could explain the 3.5 keV line

Dark matter searches going bananas: the contribution of Potassium (and Chlorine) to the 3.5 keV line

Tesla Jeltema[1*] and Stefano Profumo[1†]
[1] *Department of Physics and Santa Cruz Institute for Particle Physics University of California, Sa*

7 August 2014

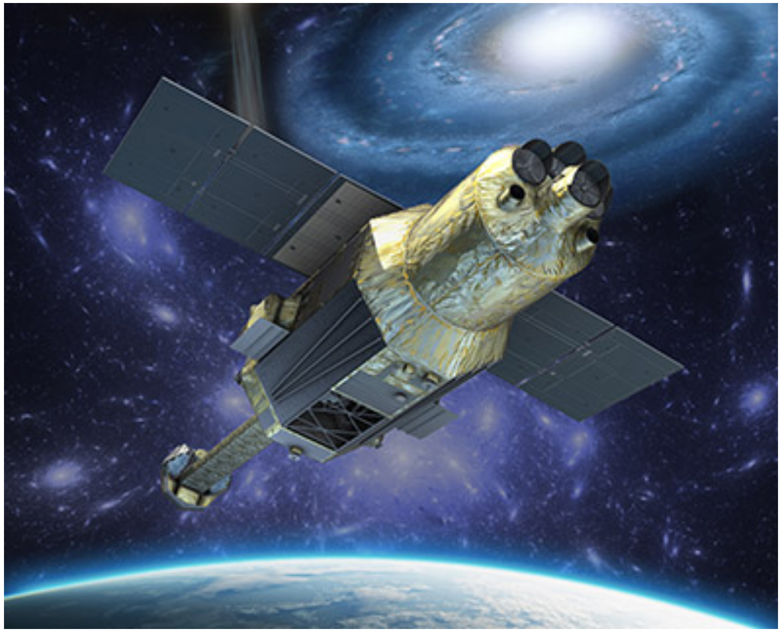
UC SANTA CRUZ

BANANA SLUGS

Since then, new (somewhat, sometimes controversial) observational results

Long (>1.5Ms) observation of Draco inconclusive (but no significant 3.5 keV line)

Hitomi! (Astro-H)



Hitomi didn't see the 3.5 keV line

(it shouldn't have; also, shouldn't have seen the Potassium line complex!)

...sadly, Hitomi died (there will be a replacement)

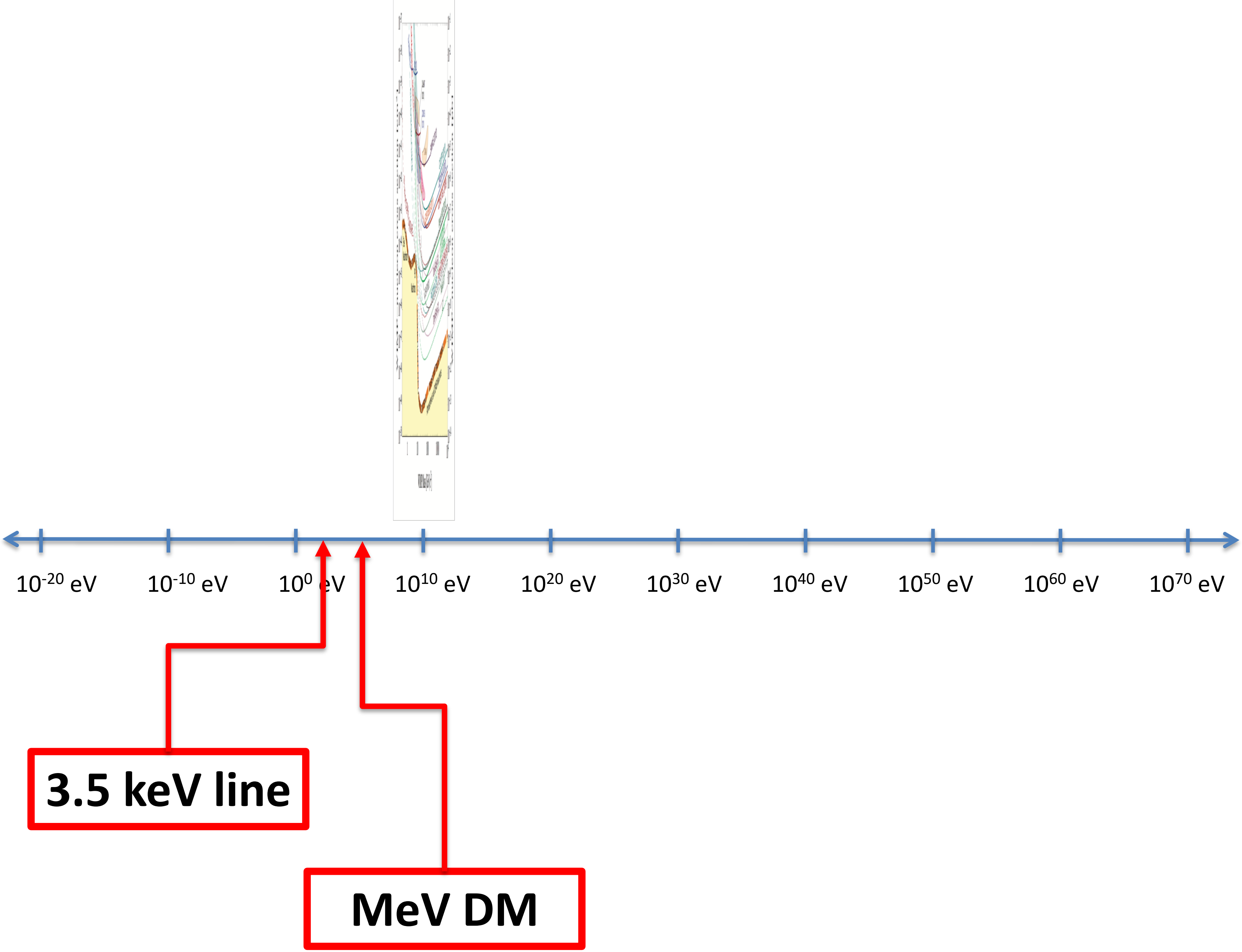
New astro background, with much progress (including in the lab): CX processes with Sulfur

Null Draco result*, null MW halo results put pressure on sterile neutrinos**

New ideas include axion-like particle conversion, and "fluorescent" dark matter

Such ideas are testable observationally, can have important effects on structure formation

* Jeltema and Profumo, MNRAS (2016); ** Dessert et al (2018)



10^-20 eV
10^-10 eV
10^0 eV
10^10 eV
10^20 eV
10^30 eV
10^40 eV
10^50 eV
10^60 eV
10^70 eV
3.5 keV line
MeV DM

MeV dark matter: exciting new observational & theoretical landscape!

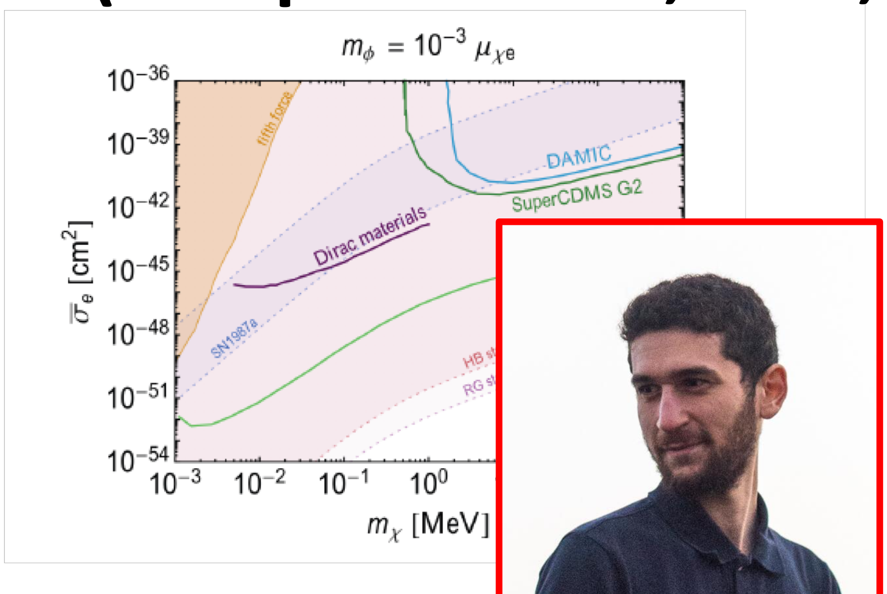
- New MeV gamma-ray capabilities (perhaps?)
- How do DM signals look like? (if hadro-philic, annihilation to light mesons, χPT?*)
- Can we expect any indirect detection signal? (how do you evade CMB constraints?**)

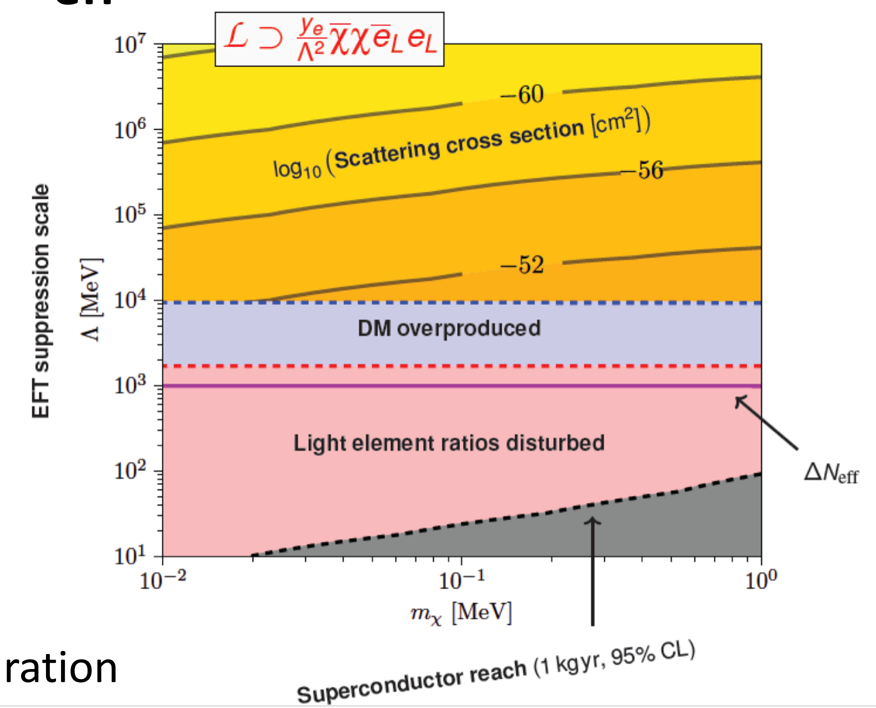
* Coogan, D'Eramo, Morrison, Profumo, 2019 in preparation

** D'Eramo and Profumo, PRL 2018

MeV dark matter: exciting new observational & theoretical landscape!

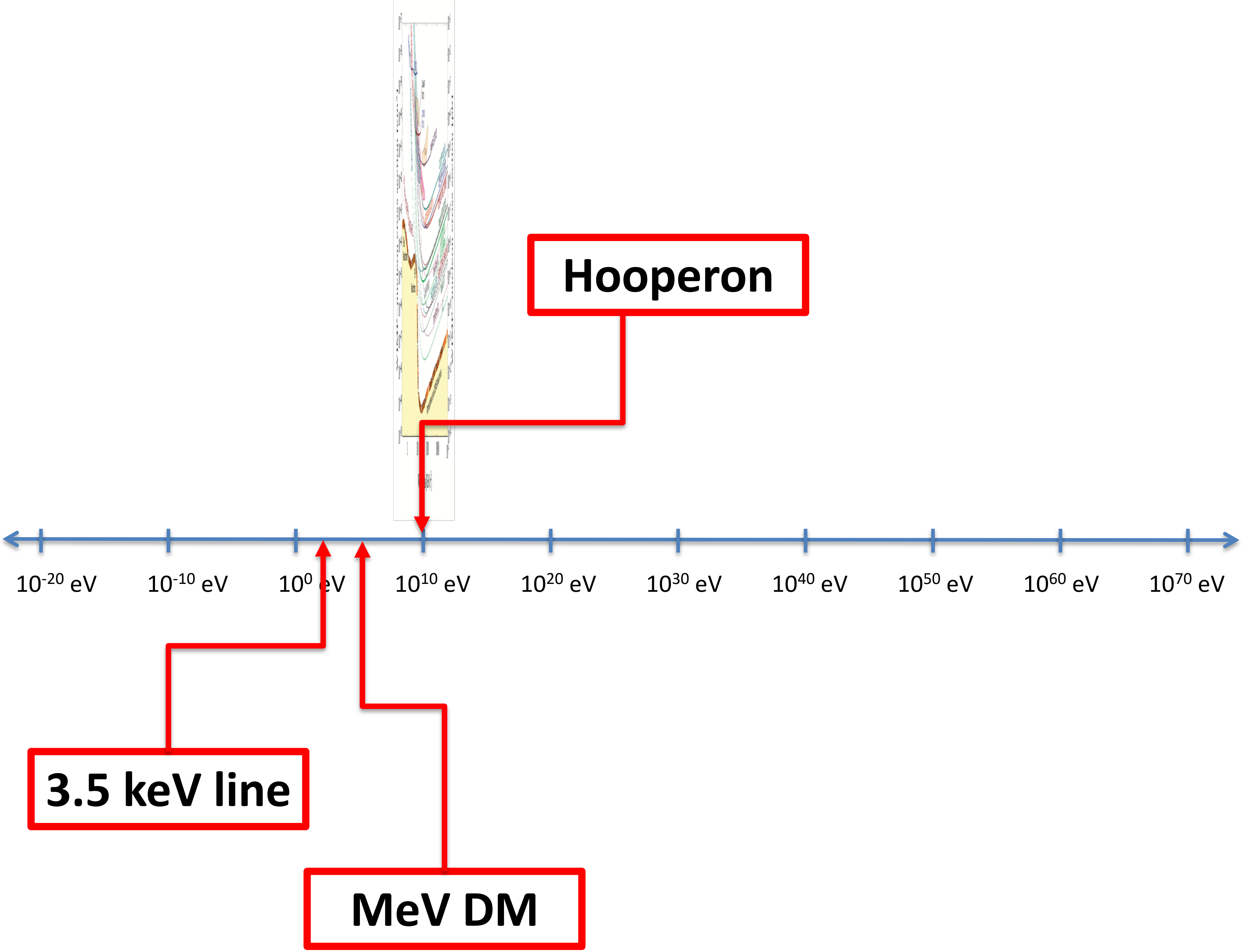
- New direct detection capabilities (perhaps?)
- Can we expect any direct detection signal? (overproduction, BBN, N_{eff}...)*





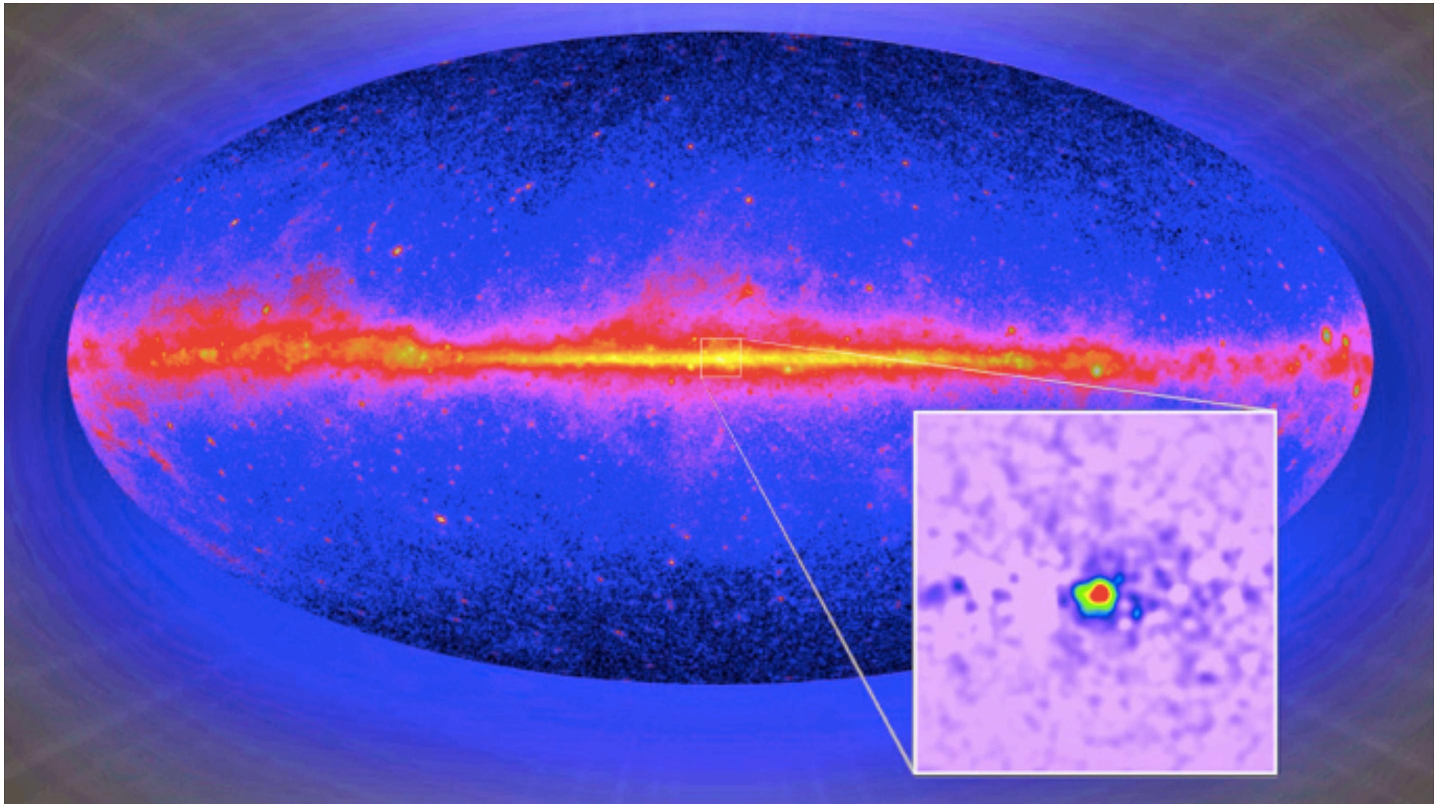
* Knapen et al 2017

**D'Eramo, Lehmann and Profumo, 2019 in preparation


Hooperon
10^{-20} eV
10^{-10} eV
10^{0} eV
10^{10} eV
10^{20} eV
10^{30} eV
10^{40} eV
10^{50} eV
10^{60} eV
10^{70} eV
3.5 keV line
MeV DM

Puzzling situation!

- **Incontrovertible "excess" over standard diffuse gamma-ray background models**



Puzzling situation!

- Incontrovertible "excess" over standard diffuse gamma-ray background models

- Dark Matter explanation very "natural"

$\simeq$

Puzzling situation!

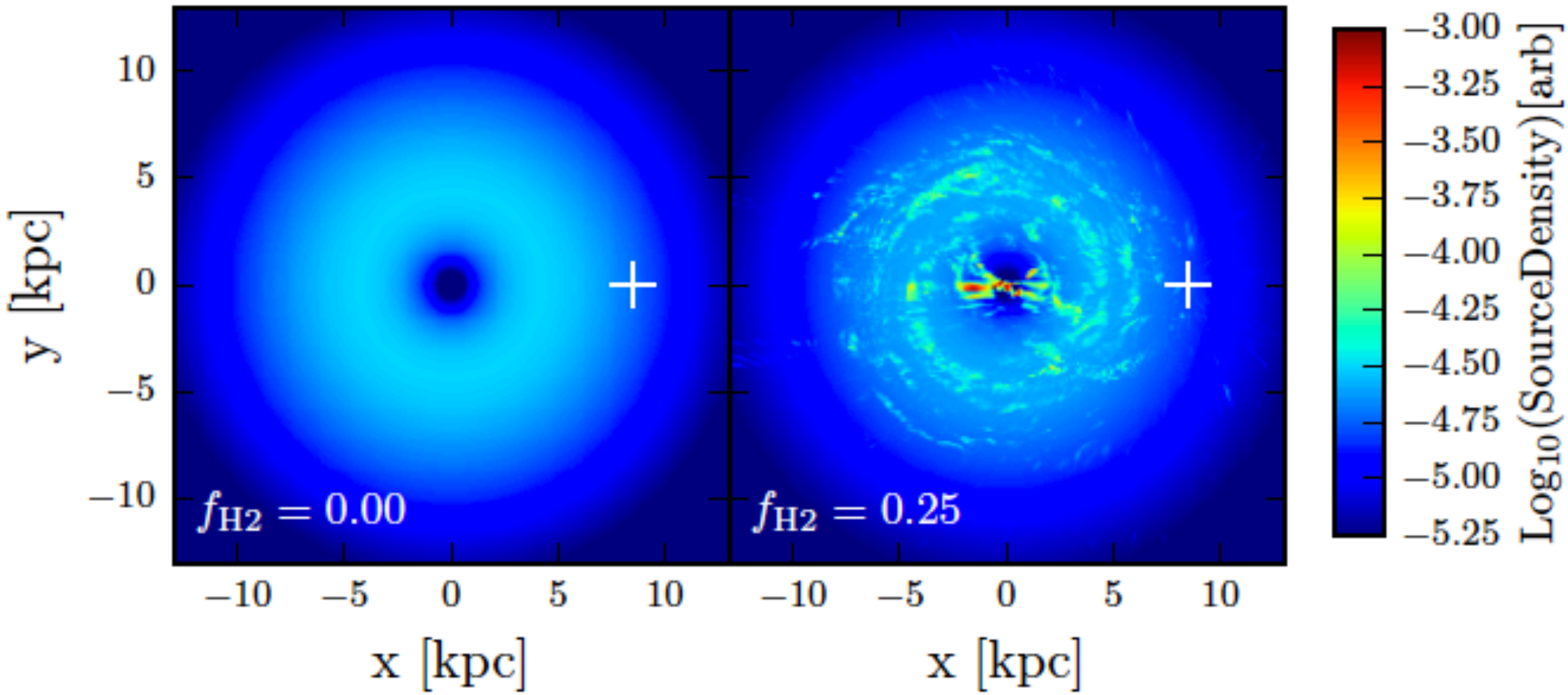
- Incontrovertible "excess" over standard diffuse gamma-ray background models

- Dark Matter explanation very "natural"

- Astrophysical counterparts (esp. MSP) possible but unlikely

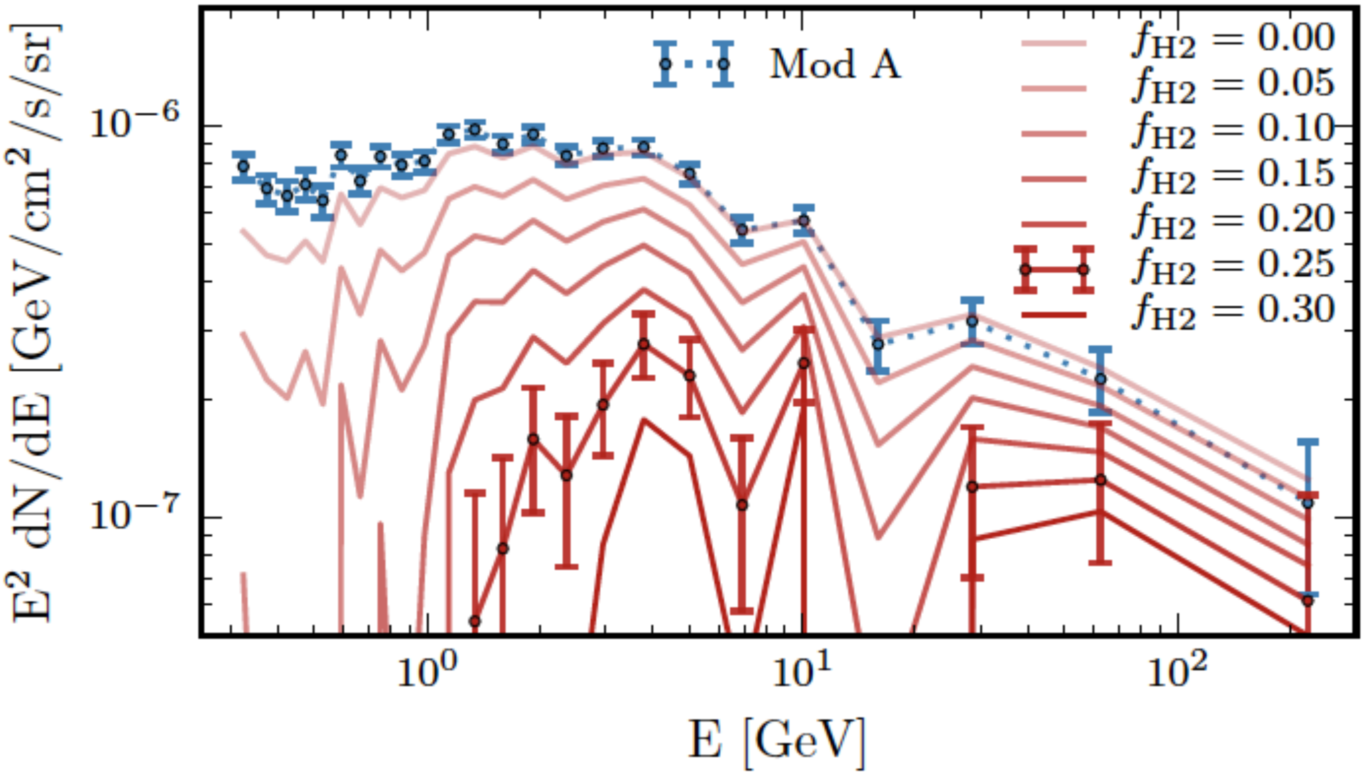
Are we using the right cosmic ray source models?

No. Put CR sources where they should be!



*** Carlson, Linden, Profumo 1510.04698 (Phys.Rev.Lett.), 1603.06584**

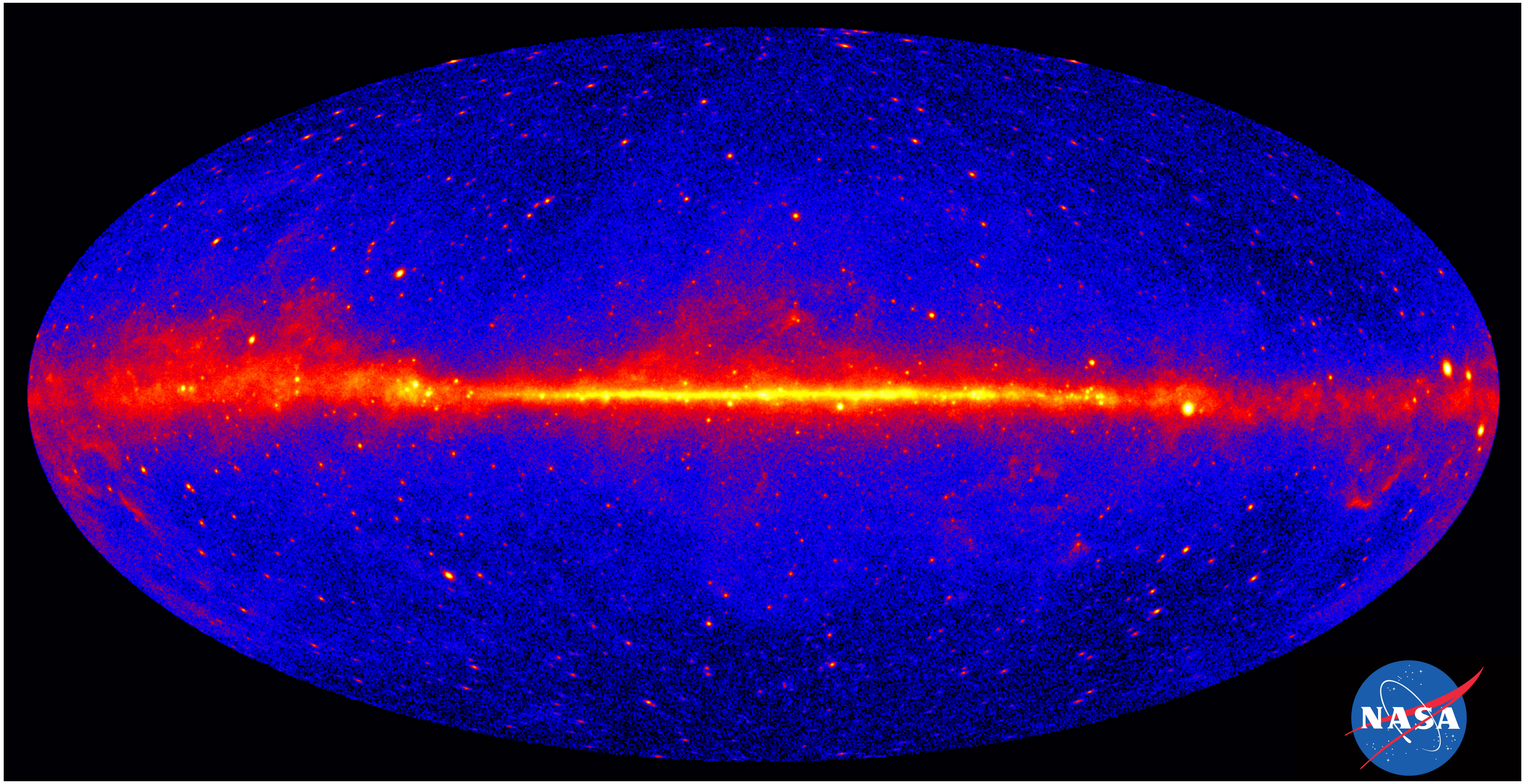
What do these improved CR source models imply for the Galactic Center "Excess"?



*** Carlson, Linden, Profumo 1510.04698 (Phys.Rev.Lett.), 1603.06584**

Good to push the (theory) envelope.

But do you get a better or worse fit to data?



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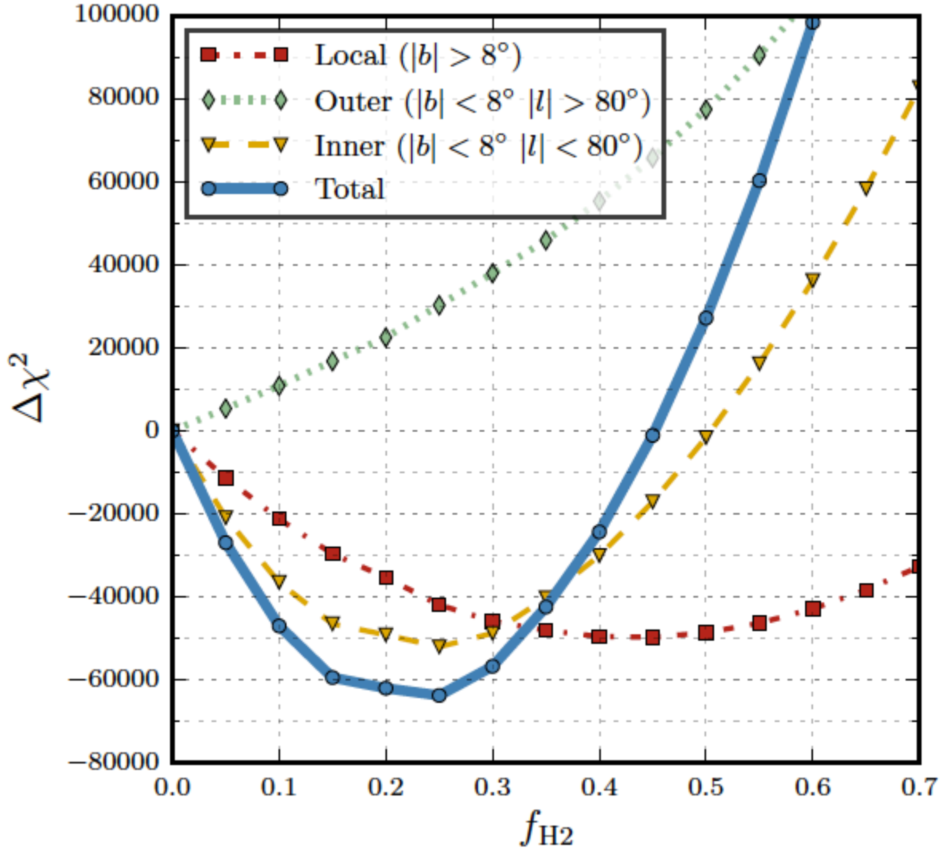


*** Carlson, Linden, Profumo Phys.Rev.Lett. (2016)**

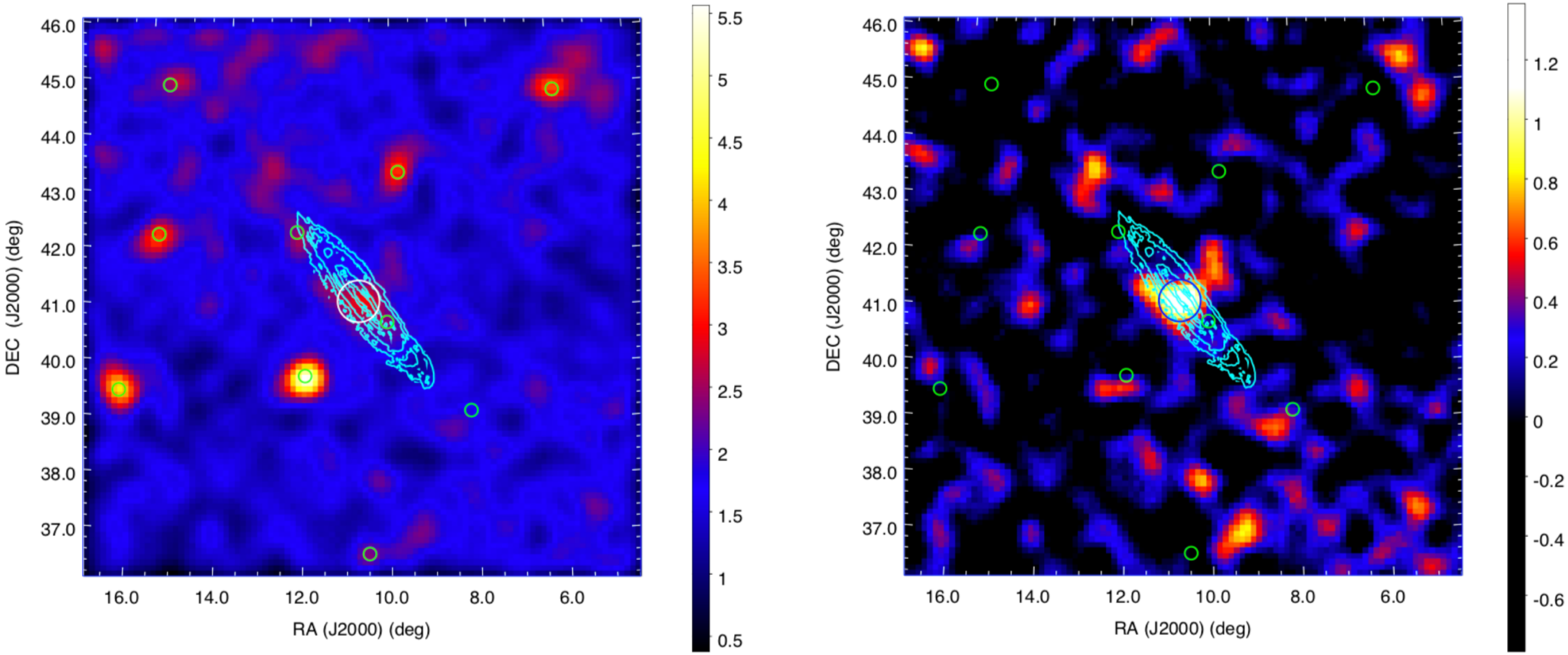
If there is an excess in the Milky Way, there should be other “excesses”

Most similar excess from the most similar, nearby object to the Milky Way: M31

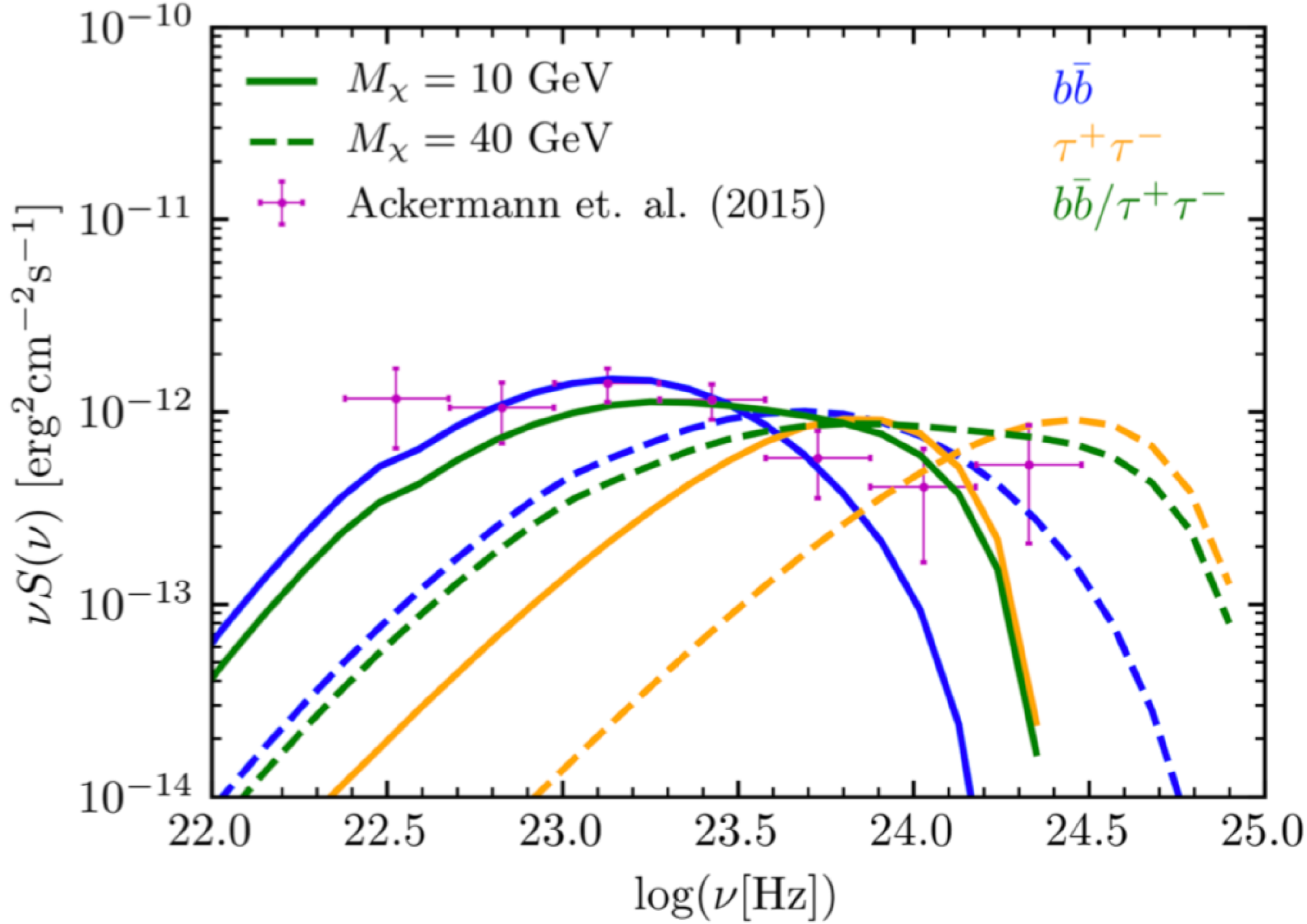
Are there Hooperons in Andromeda?

NASA press release, 2017

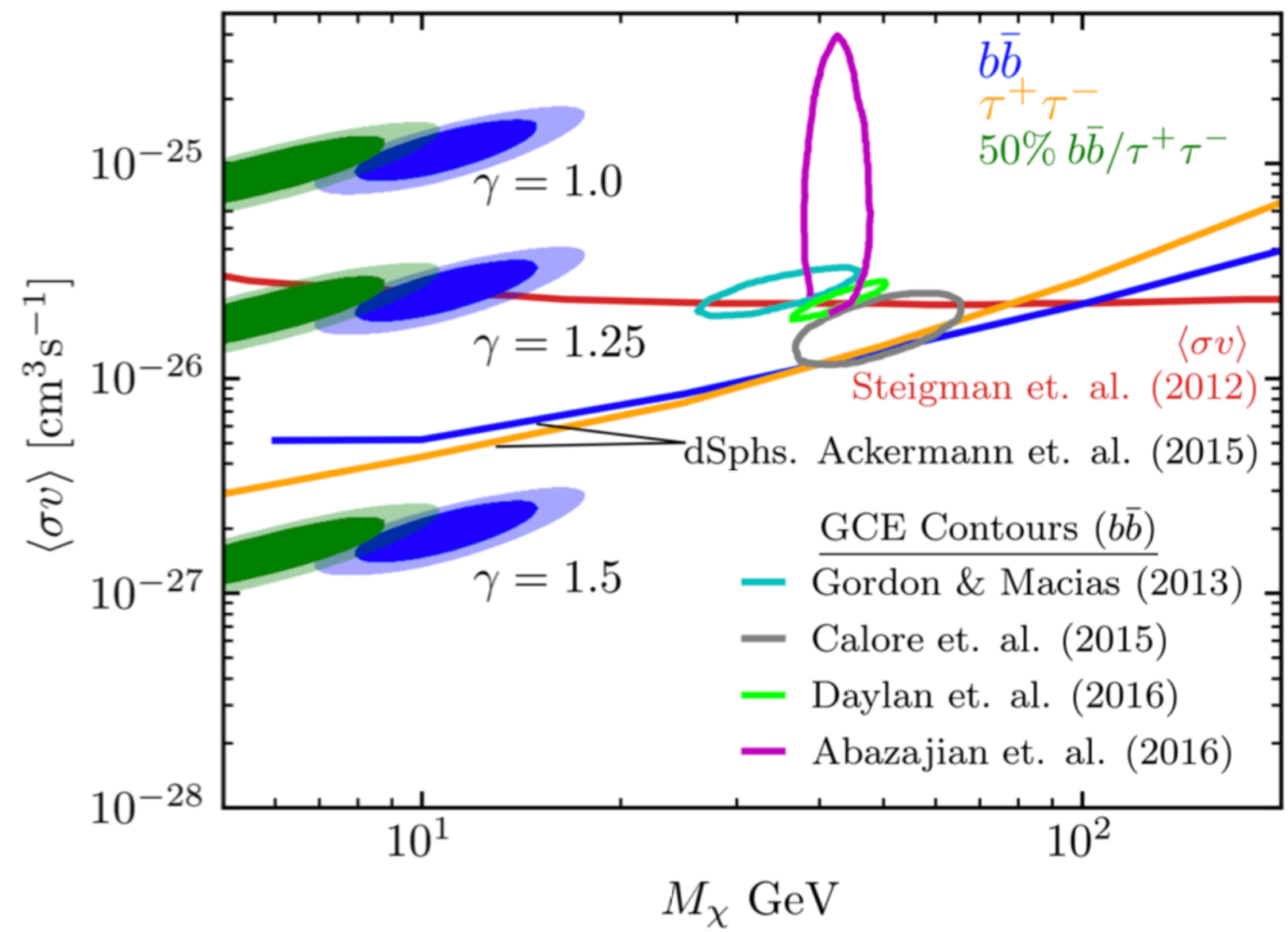
Are there Hooperons in Andromeda?



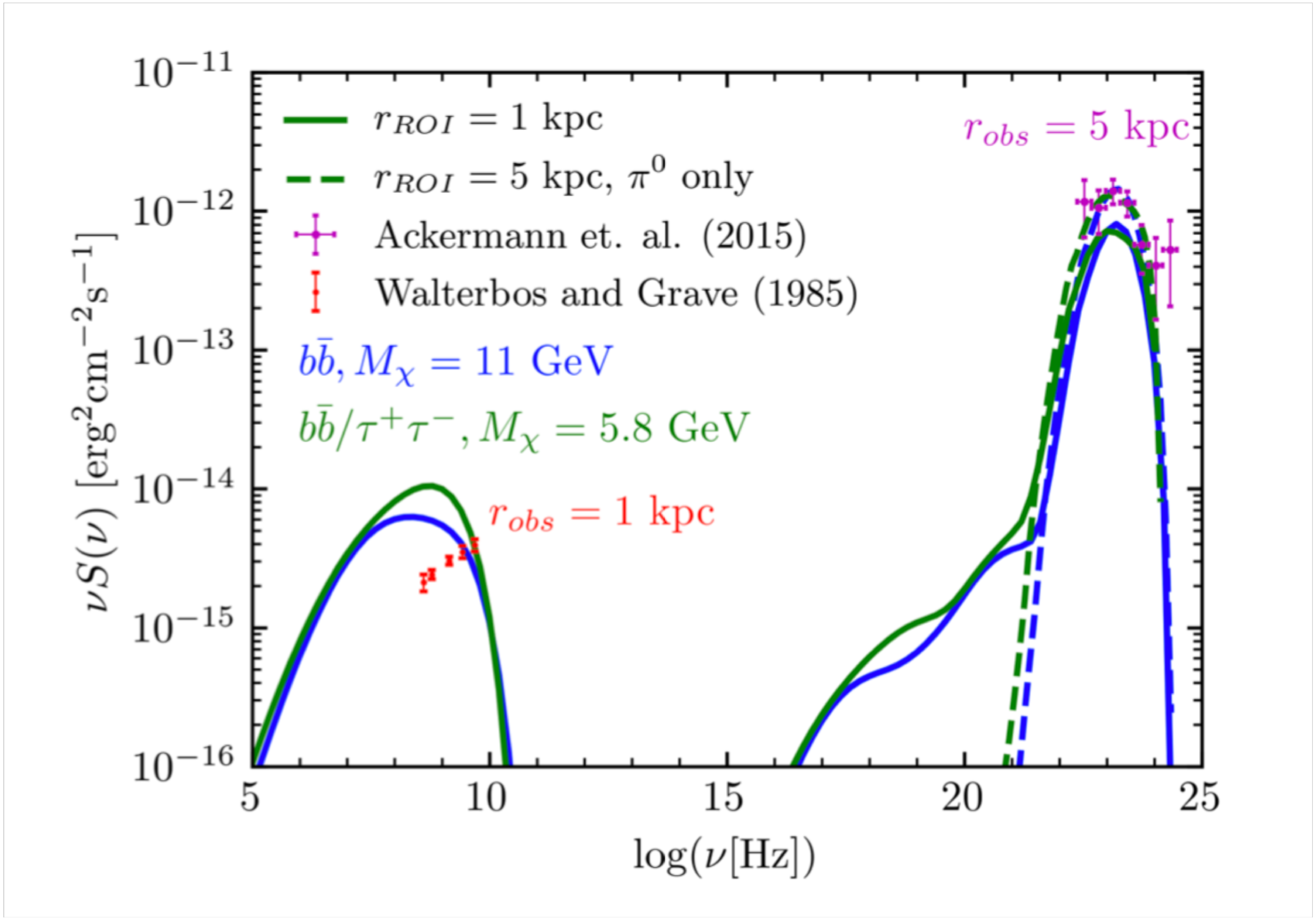
Ackermann et al 2017



McDaniel, Jeltema and Profumo, 2018

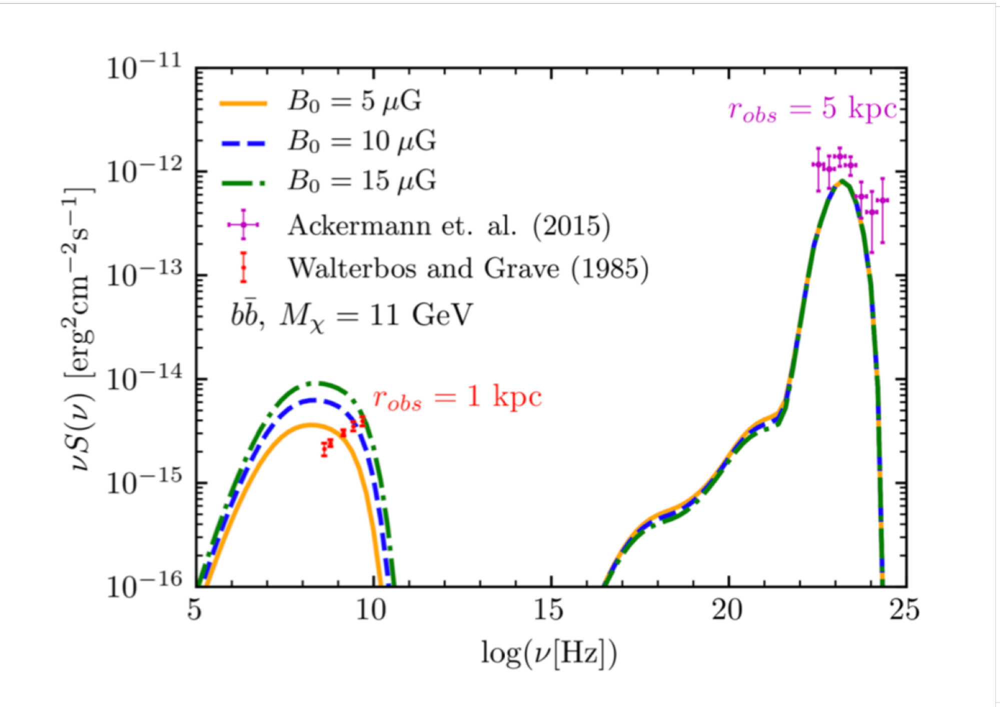


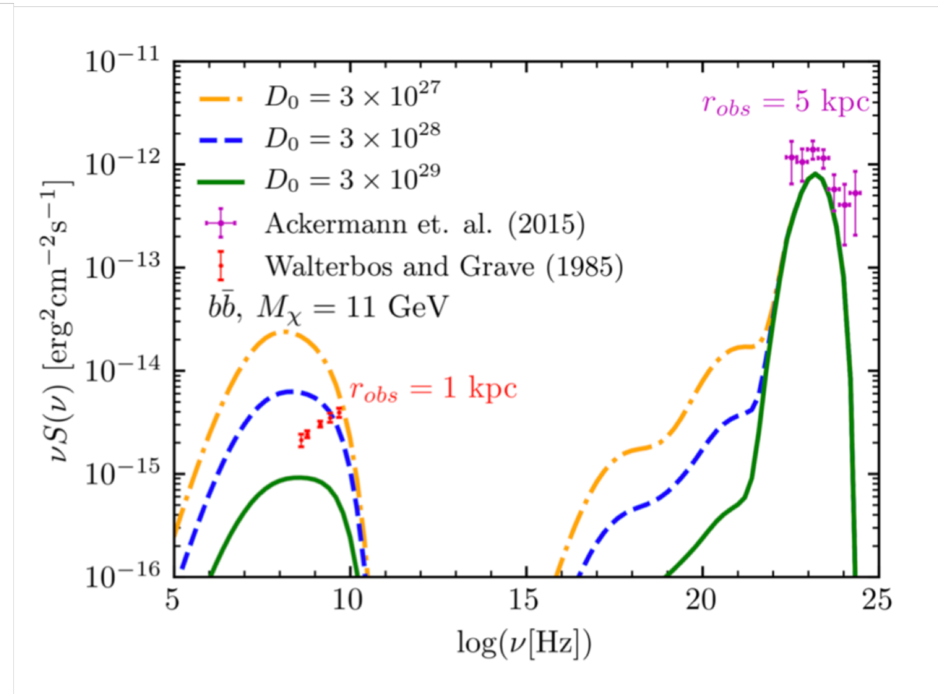
McDaniel, Jeltema and Profumo, 2018



best fit magnetic field model: radio data are trouble!

McDaniel, Jeltema and Profumo, 2018

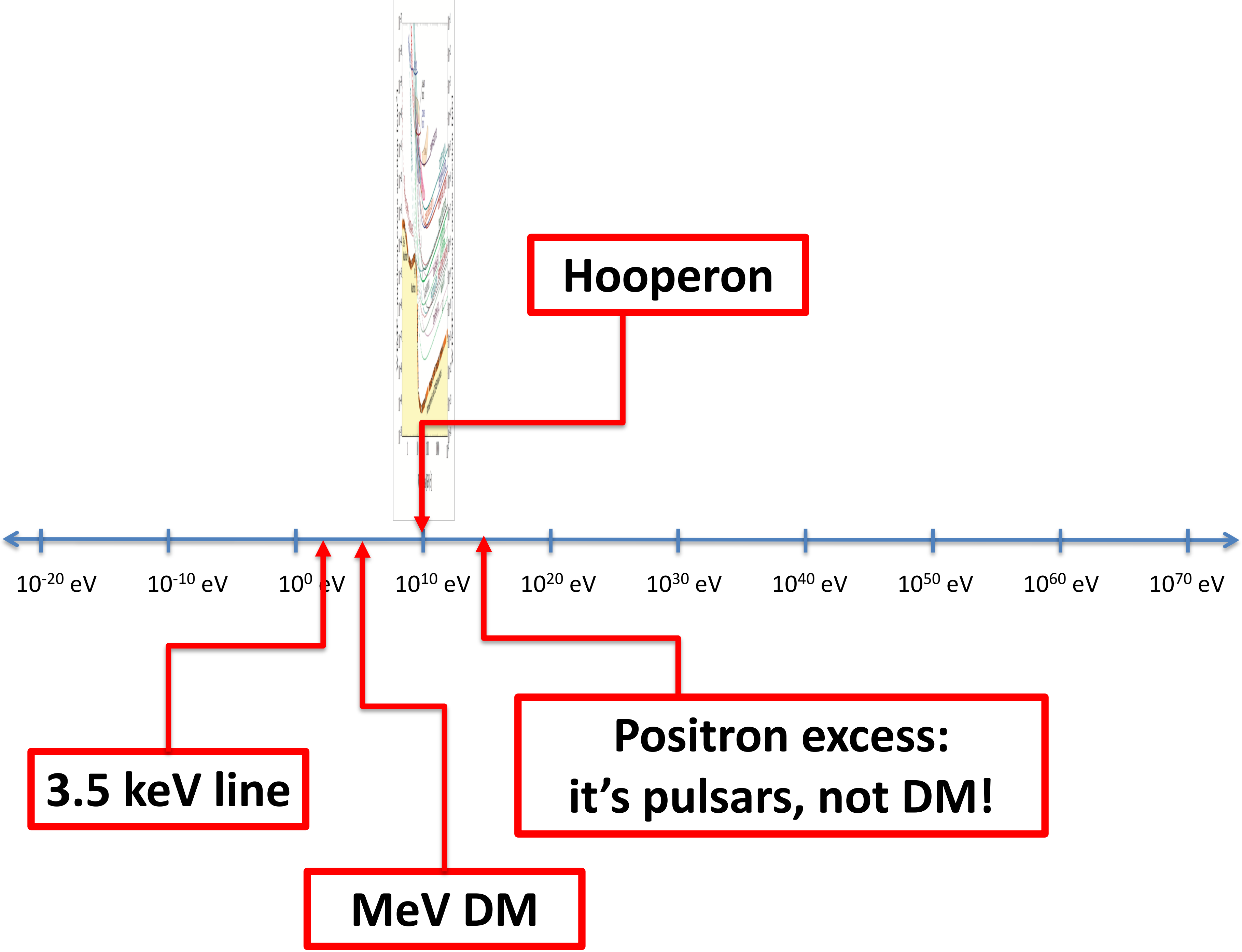




…diffusion and B modeling cut some slack

Forthcoming: can you explain everything with cosmic rays?

McDaniel, Jeltema and Profumo, 2018, 2019 in preparation


Hooperon
10^-20 eV
10^-10 eV
10^0 eV
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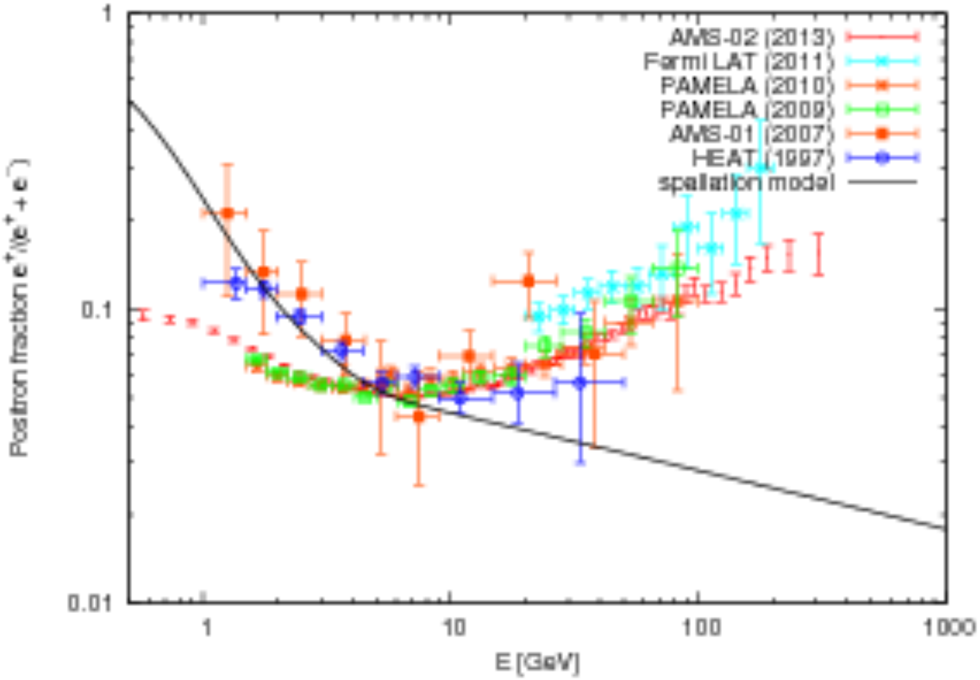
10^20 eV
10^30 eV
10^40 eV
10^50 eV
10^60 eV
10^70 eV
3.5 keV line
Positron excess:
it's pulsars, not DM!
MeV DM

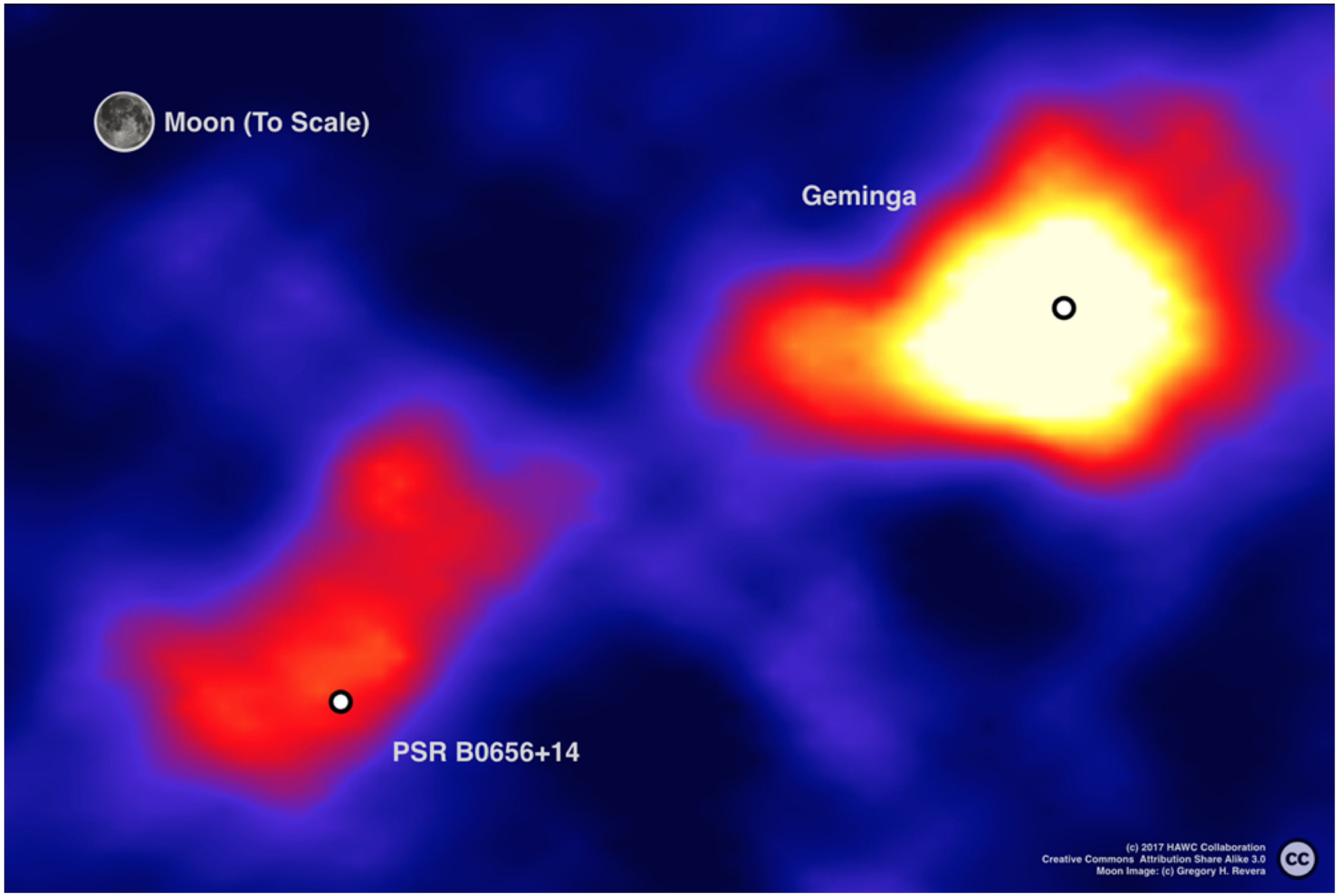
Rising Positron Fraction with energy cut-off at Dark Matter particle mass, envisioned ~30 years ago, as smoking gun for Dark Matter searches

[Tylka 1989, Turner and Wilczek, 1990]

First hint of a rising positron fraction >20 year old!

- ✓ HEAT 1997
- ✓ Pamela 2009
- ✓ Fermi 2010
- ✓ AMS 2013, 2015




Moon (To Scale)
Geminga
PSR B0656+14
(c) 2017 HAWC Collaboration
Creative Commons Attribution Share Alike 3.0
Moon Image: (c) Gregory H. Revera
CC

PARTICLE ASTROPHYSICS

Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth

A. U. Abeysekara,[1] A. Albert,[2] R. Alfaro,[3] C. Alvarez,[4] J. D. Álvarez,[5] R. Arceo,[4]
J. C. Arteaga-Velázquez,[5] D. Avila Rojas,[3] H. A. Ayala Solares,[6] A. S. Barber,[1]
N. Bautista-Elivar,[7] A. Becerril,[3] E. Belmont-Moreno,[3] S. Y. BenZvi,[8] D. Berley,[9] A. Bernal,[10]

demonstrate that these pulsars are indeed local sources of accelerated leptons, but the measured tera–electron volt emission profile constrains the diffusion of particles away from these sources to be much slower than previously assumed. We demonstrate that the leptons emitted by these objects are therefore unlikely to be the origin of the excess positrons, which may have a more exotic origin.

* Abeysekara et al 2017

New pulsar result supports particle dark matter

The nature of dark matter remains elusive, but astronomers are now one step closer to the answer.

By Robert Naeye | Published: Thursday, November 16, 2017

My key problem: (while writing numerous papers on the dark matter interpretation) I have a decade-old emotional attachment to the pulsar interpretation, that named names…

Dissecting Pamela (and ATIC) with Occam's Razor: existing, well-known Pulsars naturally account for the "anomalous" Cosmic-Ray Electron and Positron Data

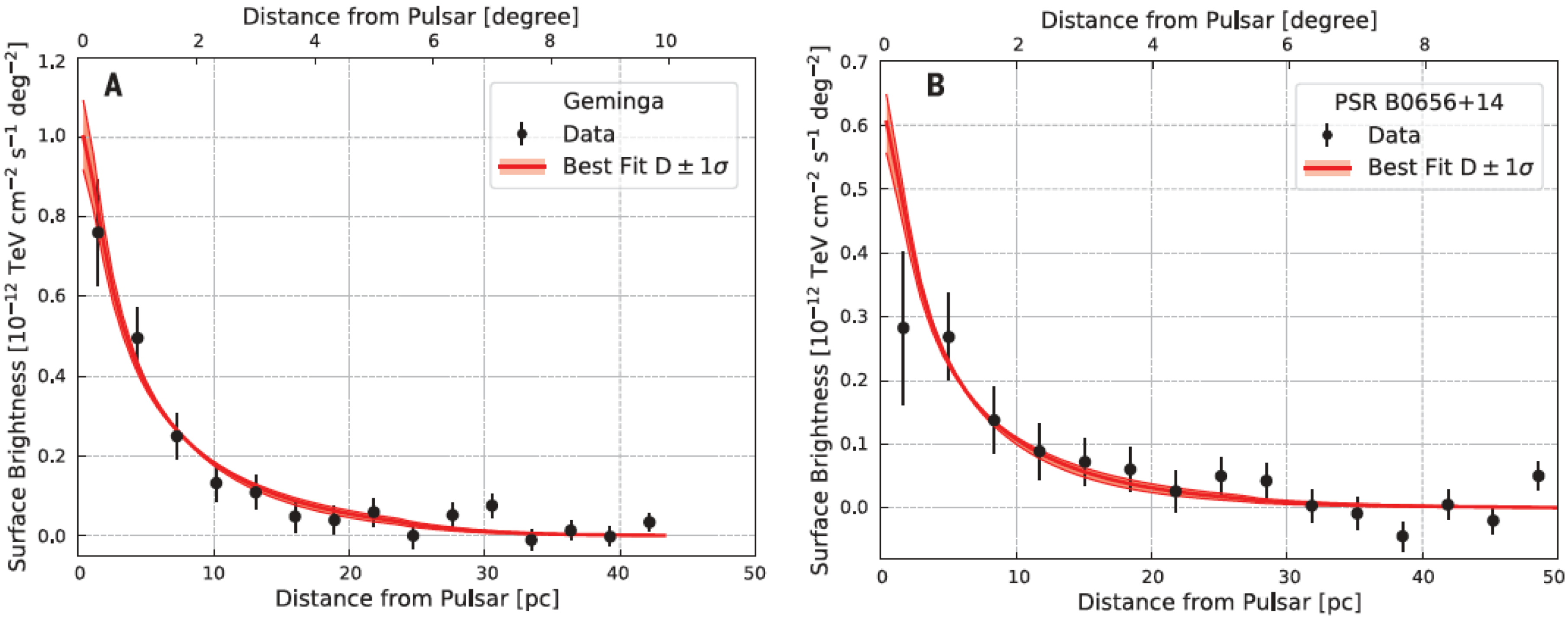
Stefano Profumo[1,2]
[1] *Department of Physics, University of California, Santa Cruz, CA 95064, USA*
[2] *Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, CA 95064, USA*
(Dated: April 14, 2018)

We argue that both the positron fraction measured by PAMELA and the peculiar spectral features reported in the total differential electron-positron flux measured by ATIC have a very natural explanation in electron-positron pairs produced by nearby pulsars. While this possibility was pointed

Name	Distance [kpc]	Age [yr]	$\dot{E}$ [ergs/s]	$E_{\rm out}$ [ST]	$E_{\rm out}$ [CCY]	$E_{\rm out}$ [HR]	$E_{\rm out}$ [ZC]	$f_{e\pm}$	g
Geminga [J0633+1746]	0.16	3.42×10^5	3.2×10^{34}	0.360	0.344	0.013	0.053	0.005	0.70
Monogem [B0656+14]	0.29	1.11×10^5	3.8×10^{34}	0.084	0.456	0.004	0.372	0.015	0.14

simple theoretical models for estimating the energy output, the diffusion setup and the injection spectral index of electron-positron pairs, and by (2) considering all known pulsars (as given in the ATNF catalogue). It appears unlikely that a single pulsar be responsible for both the PAMELA result and for the ATIC excess, although two sources are enough to naturally explain both of the experimental results. The PAMELA data favor mature pulsars (age $\sim 2 \times 10^6$ yr), with a distance of 0.8-1 kpc, or a younger and closer source like Geminga or the SNR Loop I. The ATIC data require a larger (and marginally unlikely) energy output, and favor an origin associated to powerful, more distant (1-2 kpc) and younger (age $\sim 5 \times 10^5$ yr) pulsars. We list several candidate pulsars that can

Key observational result: angular surface brightness



Gamma-ray energies as large as 20 TeV → e+e- as energetic as 100 TeV

100 TeV is deep in KN regime for starlight
→ only relevant photons: CMB

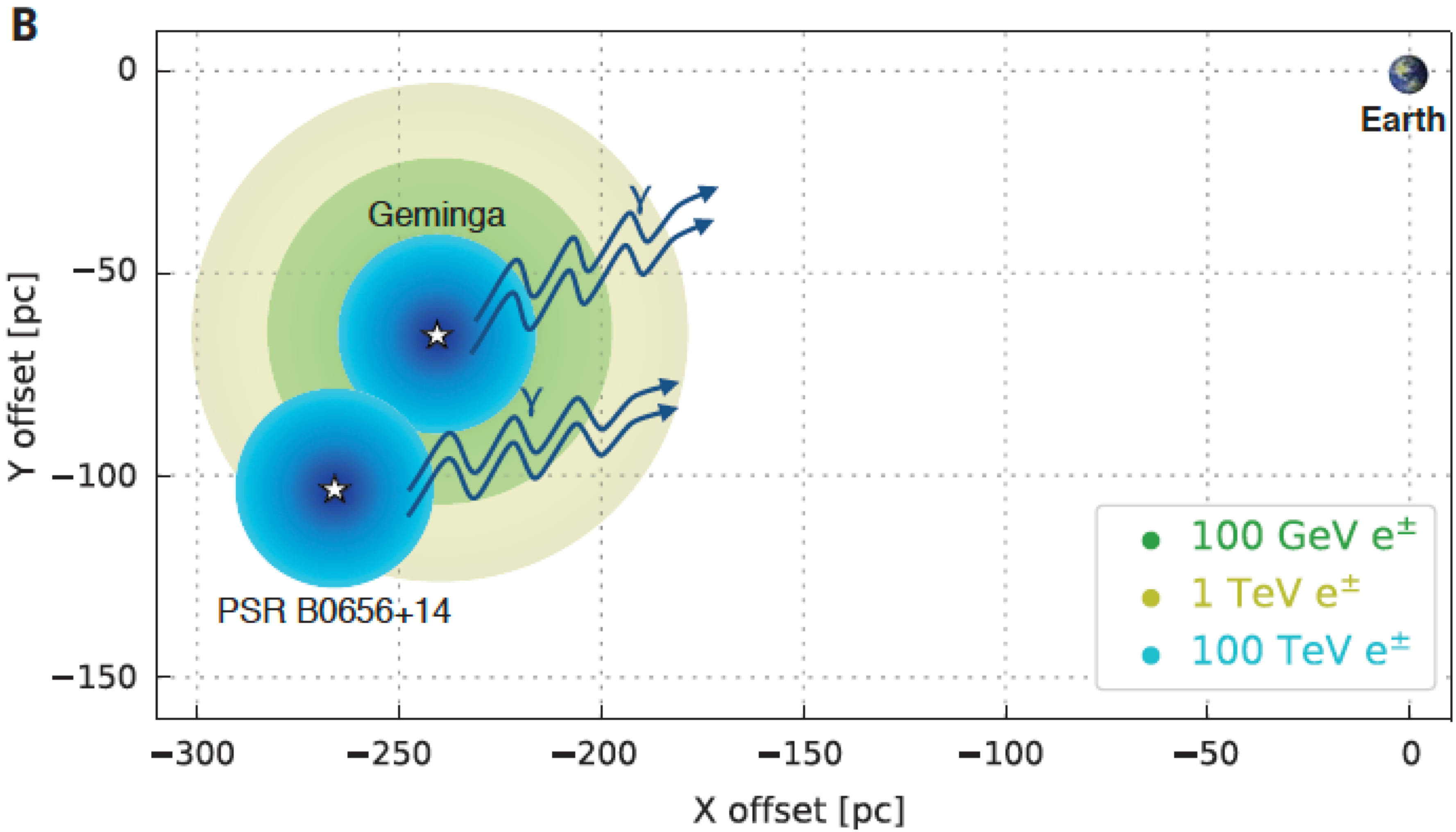
Inferred diffusion coefficients:

	Geminga	PSR B0656+14
D_{100} (diffusion coefficient of 100-TeV electrons from joint fit of two PWNe) ($\times 10^{27}$ square centimeters per second)	4.5 ± 1.2	4.5 ± 1.2
D_{100} (diffusion coefficient of 100-TeV electrons from individual fit of PWN) ($\times 10^{27}$ square centimeters per second)	$3.2^{+1.4}_{-1.0}$	15^{+49}_{-9}

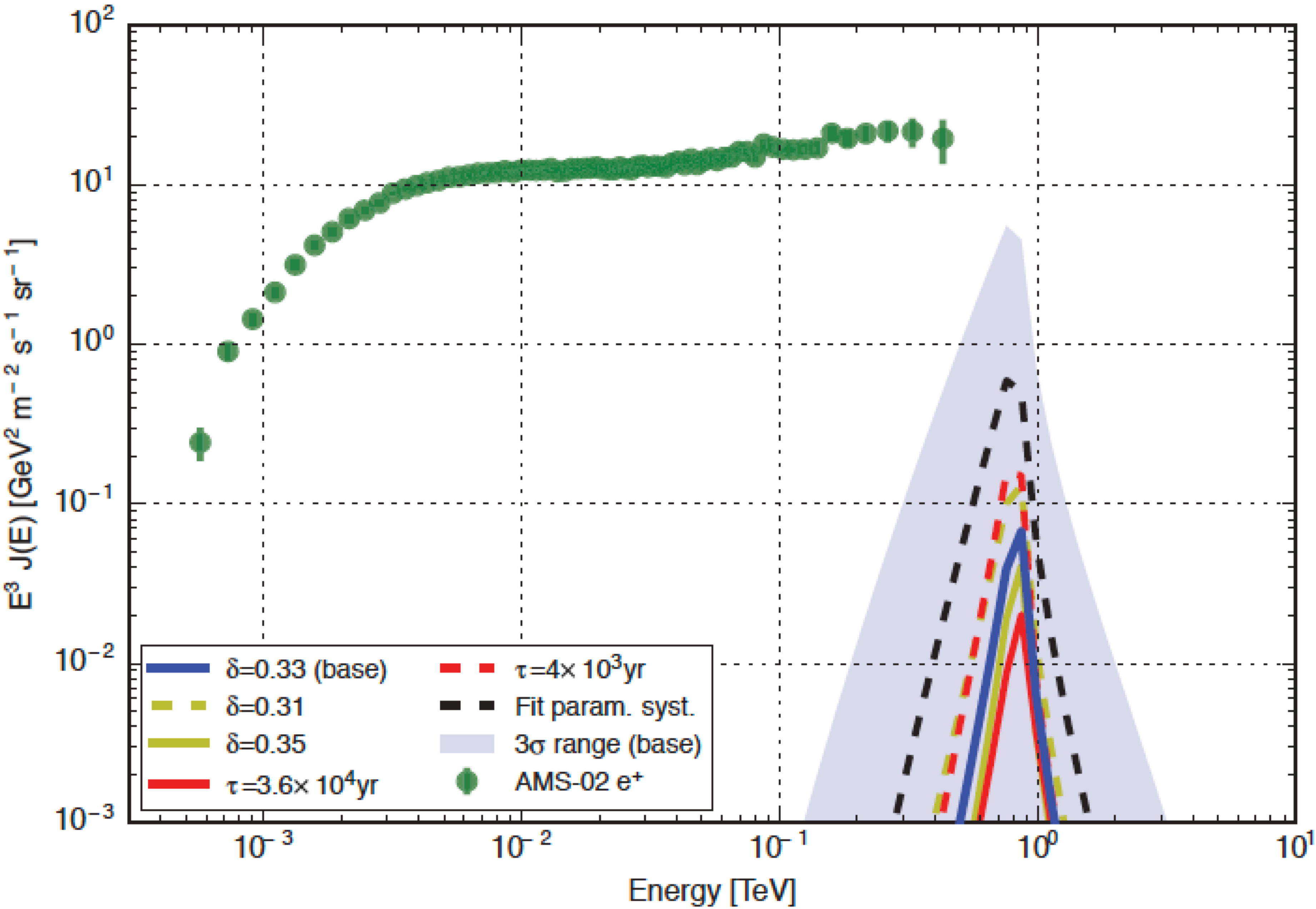
…versus ISM diffusion coefficient (GALPROP, AMS-02…)

$$D_{100}^{\rm ISM} \simeq 3.86 \times 10^{28} \left(\frac{E_e}{\rm GeV}\right)^{0.33} {\rm cm}^2/{\rm s} \rightarrow 1,720 \times 10^{27}\ {\rm cm}^2/{\rm s}$$

…thus the inferred diffusion coefficient is 100-500 times smaller than the ISM effective value!



* Abaysekara et al (HAWC Coll.) 2017



* Abaysekara et al (HAWC Coll.) 2017

Is this conclusion plausible?

Very probably NO.
Two key arguments:

1. Lifetime of TeV electrons is short: $\tau_e \sim 3 \times 10^5 \text{ yr} \times (1 \text{ TeV}/E_e).$

We observe directly CR electrons with energies >20 TeV

$$d \lesssim \sqrt{D\tau_e}$$

for HAWC Diff.Coeff., this means a source within 10-20 pc.
Such a source however doesn't exist!

* Profumo et al, 2018; Hooper and Linden 2017

Is this conclusion plausible?

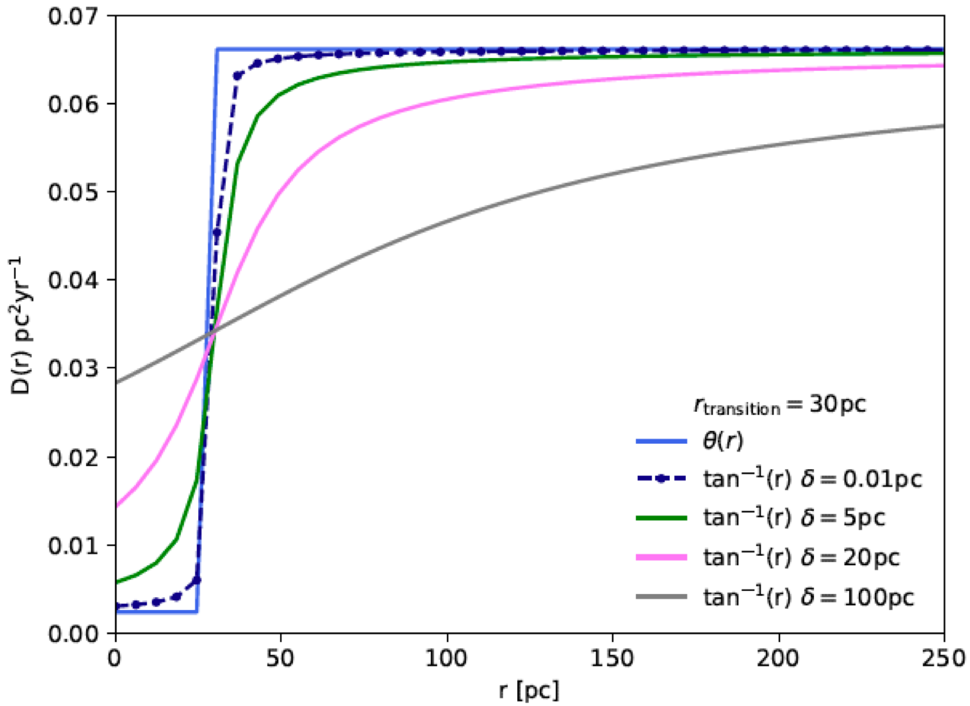
Very probably NO.
Two key arguments:

2. Models of CR emission predict inefficient diffusion near sources

Alfven waves generated by cosmic rays induce a net force that suppresses diffusion near the sites of cosmic-ray acceleration and, more generally, where cosmic-ray fluxes are larger

* Malkov et al 2012, Nava et al 2016, D'Angelo et al 2018

What happens to the local electron flux if indeed diffusion is not homogeneous?

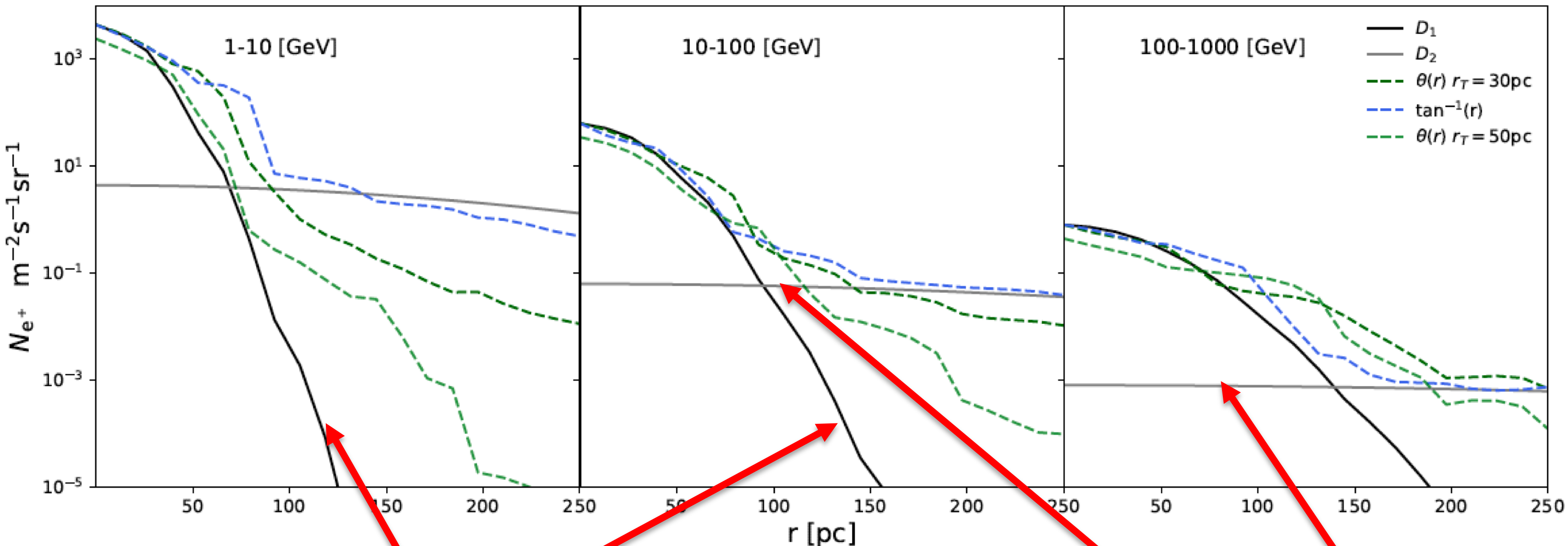


$$D_\theta(r) = D_1\theta(r_T - r) + D_2\theta(r - r_T)$$

$$D_{\rm T}(r) = D_1 + \frac{(D_2 - D_1)}{\pi}\left(\tan^{-1}\left(\frac{\rm r - r_T}{\delta}\right) + \frac{\pi}{2}\right)$$

*Profumo, Reynoso, Kaaz, Silverman PRD 2018

What happens to the local electron flux if indeed diffusion is not homogeneous?

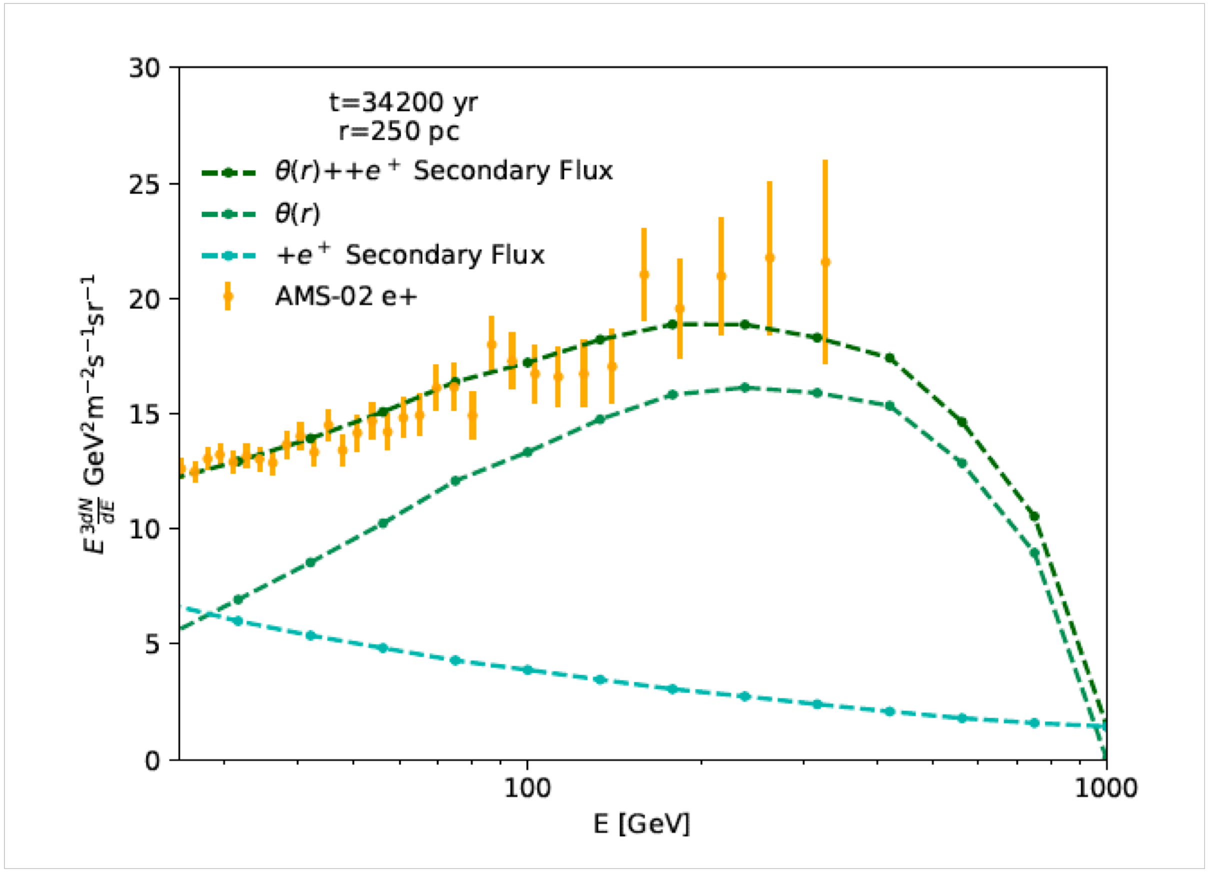


"HAWC" (inefficient) diffusion

"GALPROP" (efficient) diffusion

*Profumo, Reynoso, Kaaz, Silverman PRD 2018

What happens to the local electron flux if indeed diffusion is not homogeneous?



*Profumo, Reynoso, Kaaz, Silverman PRD 2018

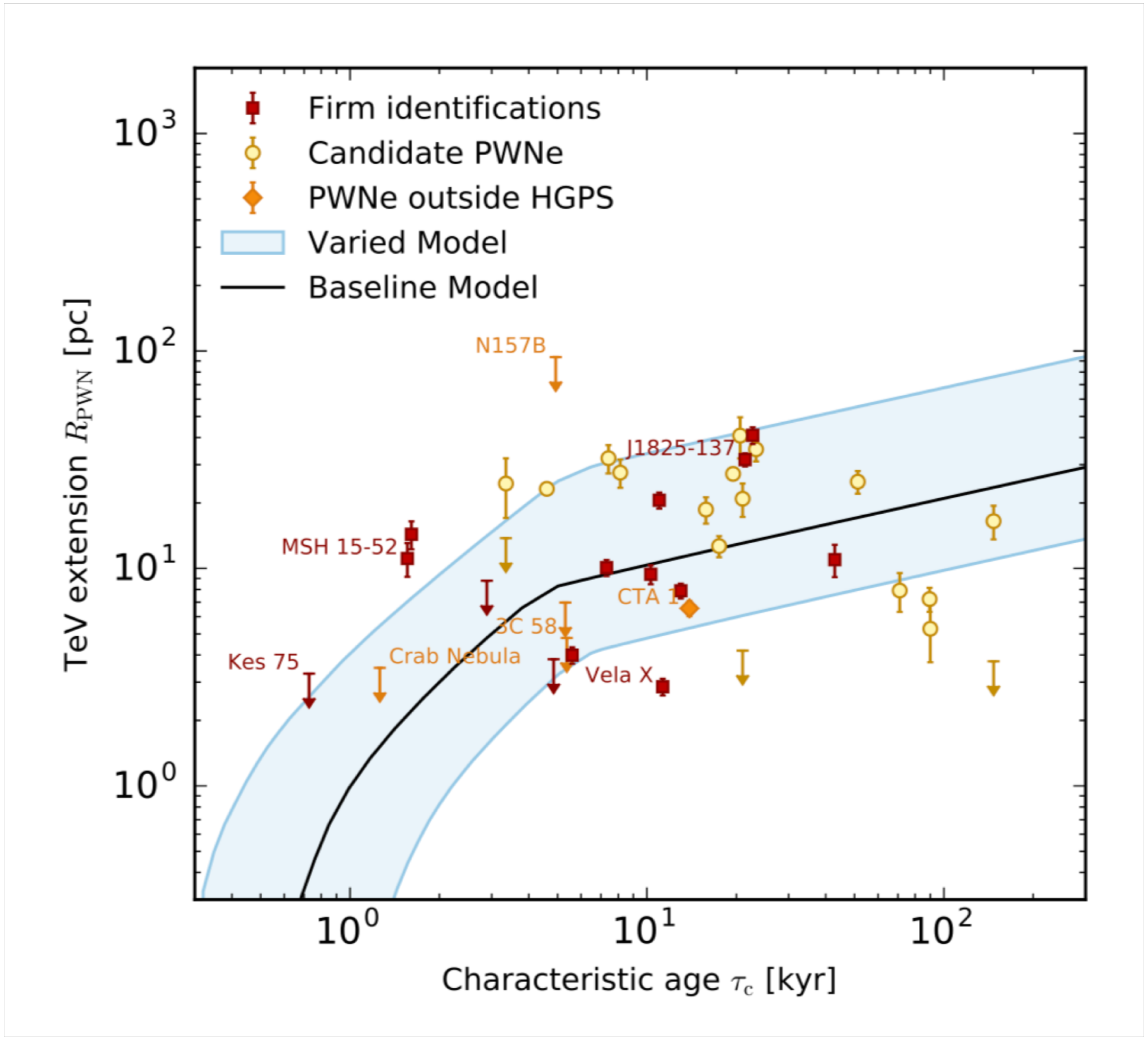
How can we test inhomogeneous diffusion?
Does it matter, globally on Galactic scales?

Estimate the volume of regions of inefficient diffusion

How big is a PWN as a function of time?

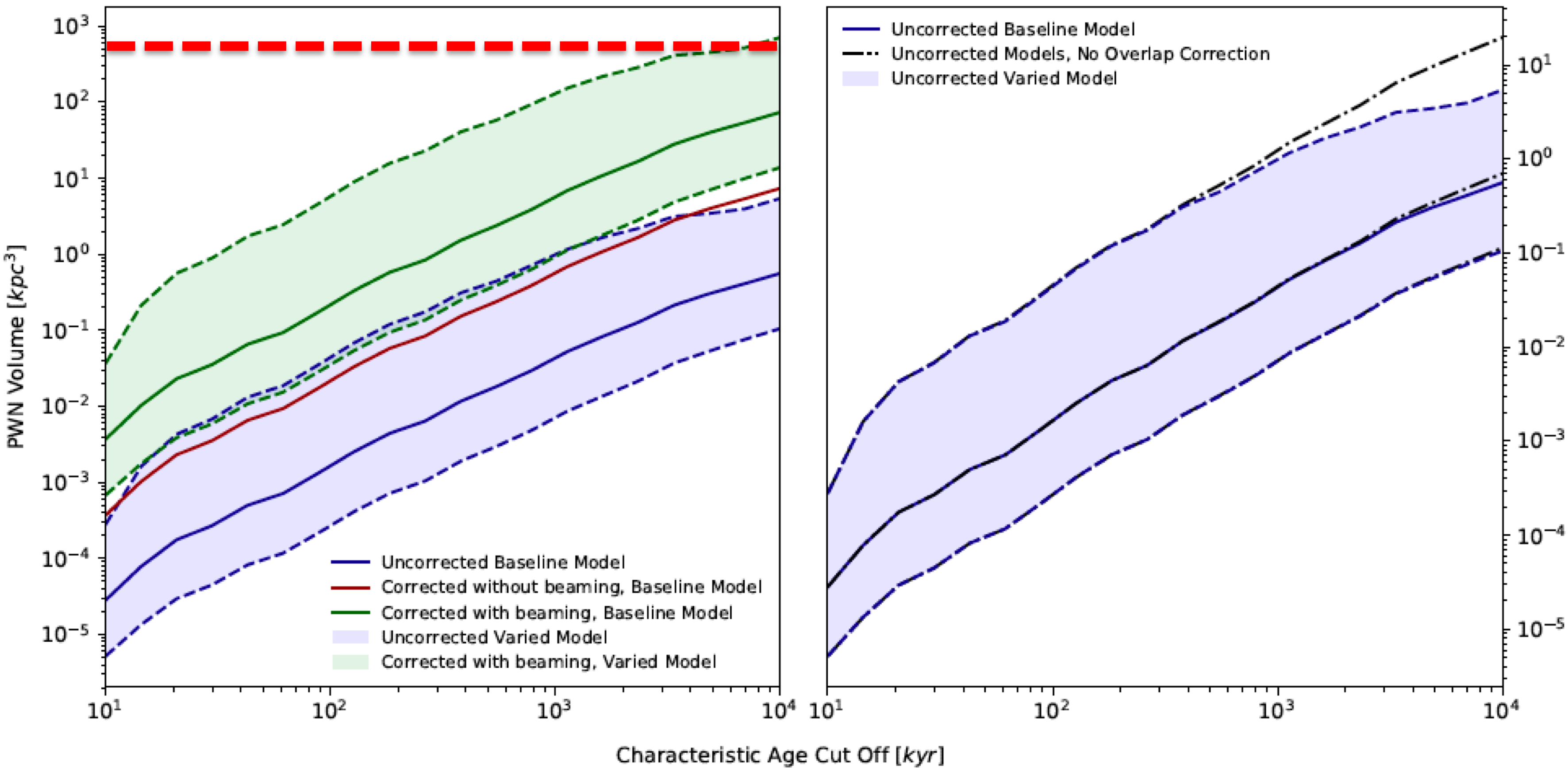
The population of TeV pulsar wind nebulae in the H.E.S.S. Galactic Plane Survey

H.E.S.S. Collaboration, H. Abdalla[1], A. Abramowski[2], F. Aharonian[3,4,5], F. Ait Benkhali[3], A.G. Akhperjanian[†6,5], T. Andersson[10], E.O. Angüner[7], M. Arrieta[15], P. Aubert[24], M. Backes[8], A. Balzer[9], M. Barnard[1], Y. Becherini[10], J. Becker Tjus[11], D. Berge[12], S. Bernhard[13], K. Bernlöhr[3], R. Blackwell[14], M. Böttcher[1], C. Boisson[15], J. Bolmont[16], P. Bordas[3], J. Bregeon[17], F. Brun[26], P. Brun[18], M. Bryan[9], T. Bulik[19], M. Capasso[29], J. Carr[20], S. Carrigan[‡,3], S. Casanova[21,3], M. Cerruti[16], N. Chakraborty[3], R. Chalme-Calvet[16], R.C.G. Chaves[17,22], A. Chen[23], J. Chevalier[24], M. Chrétien[16], S. Colafrancesco[23], G. Cologna[25], B. Condon[26], J. Conrad[27,28]



* Abdalla et al 2017

...but of course the sample is incomplete... (beaming+detectability)
...and we don't know when PWN run out of steam...



$$\langle V \rangle_{\rm ISM} \simeq 500\ {\rm kpc}^3 \left(\frac{R_h}{20\ {\rm kpc}}\right)^2 \left(\frac{z_h}{0.2\ {\rm kpc}}\right)$$

*Profumo, Reynoso, Kaaz, Silverman 2018

so, does this matter?
well, the time spent in inefficient diffusion pockets is potentially much larger than volume ratios!

$$\langle L \rangle \sim \sqrt{D \cdot t},$$

$$\frac{t_{\rm PWN}}{t_{\rm ISM}} \sim \left(\frac{\langle V \rangle_{\rm PWN}}{\langle V \rangle_{\rm ISM}}\right)^{2/3} \frac{D_{\rm ISM}}{D_{\rm PWN}} \sim 10^2 \left(\frac{\langle V \rangle_{\rm PWN}}{\langle V \rangle_{\rm ISM}}\right)^{2/3}$$

$$\langle V \rangle_{\rm PWN} \gtrsim 0.5 \text{ kpc}^3$$

Thus, t_{PWN} ~ t_{ISM} and cosmic rays should illuminate bubbles of inefficient diffusion!

*Profumo, Reynoso, Kaaz, Silverman 2018

…OK, but how can we **test** this?

if a large fraction of CR electrons are trapped in inefficient diffusion pockets, those pockets will be illuminated by energy-loss radiative processes (radio, IC, brems)

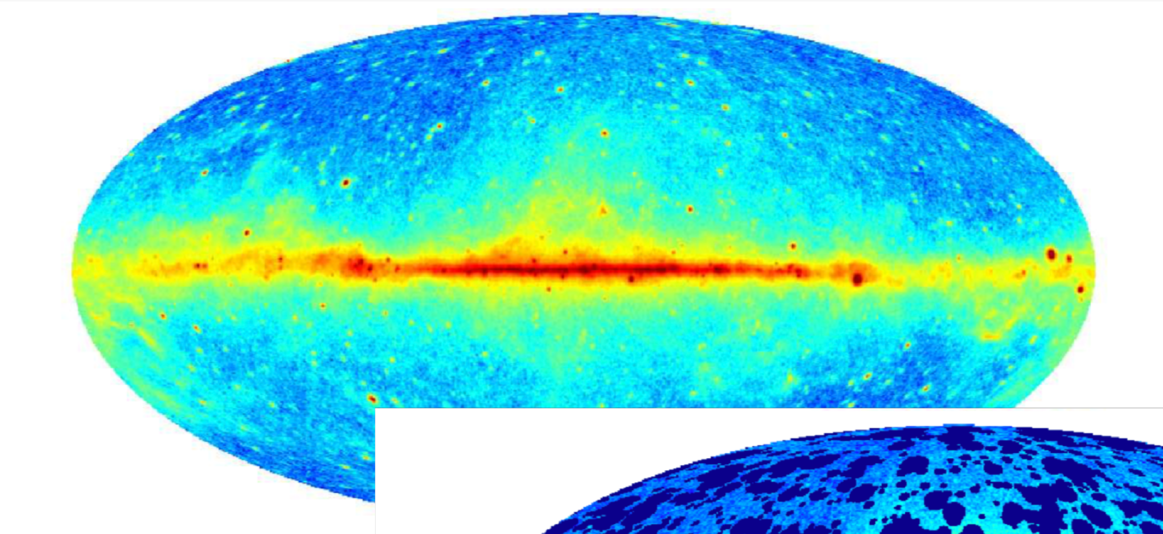
$$\theta \sim \frac{R_{\rm PWN}}{d_{\rm PWN}}$$

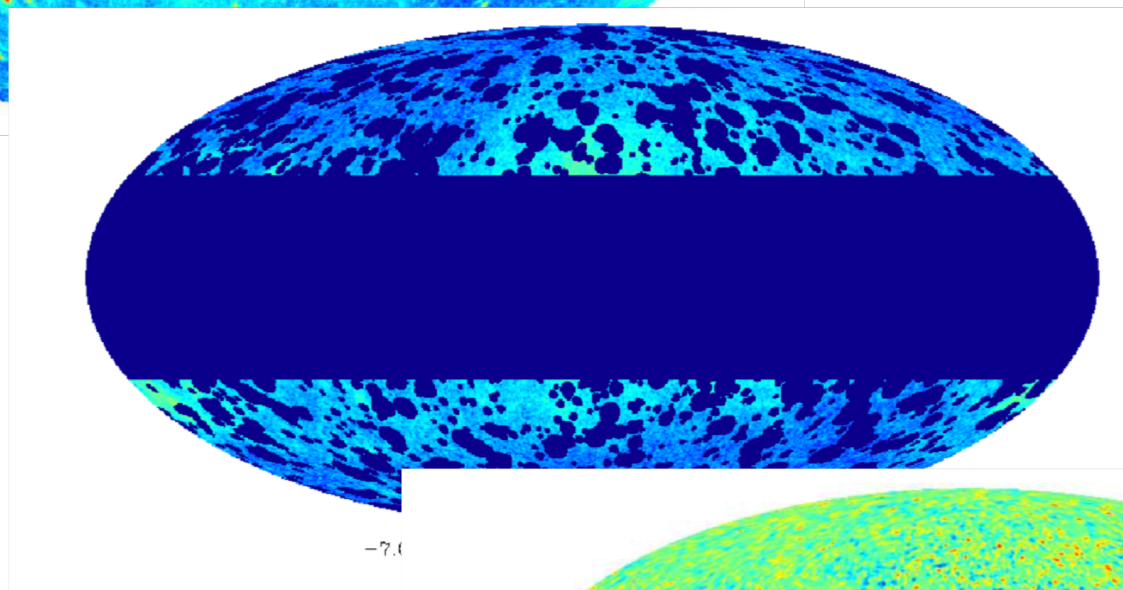
theta ranges from few degrees to 0.1 degrees

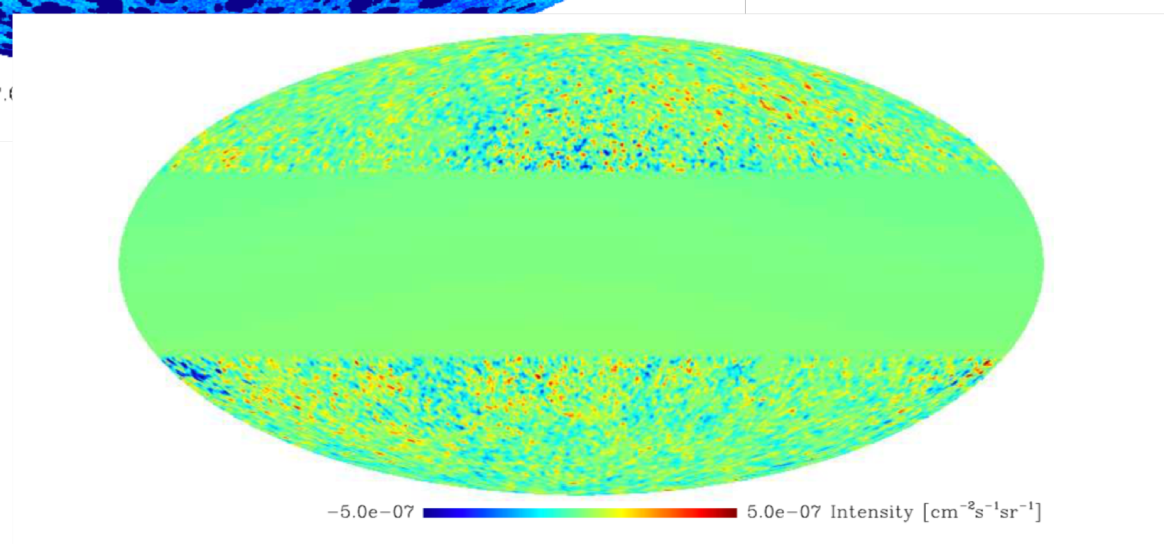
can use any frequency from radio (with additional B uncert.) to X-ray to gamma rays

Can use simple angular power spectrum, or wavelet transforms, Poissonian noise analysis

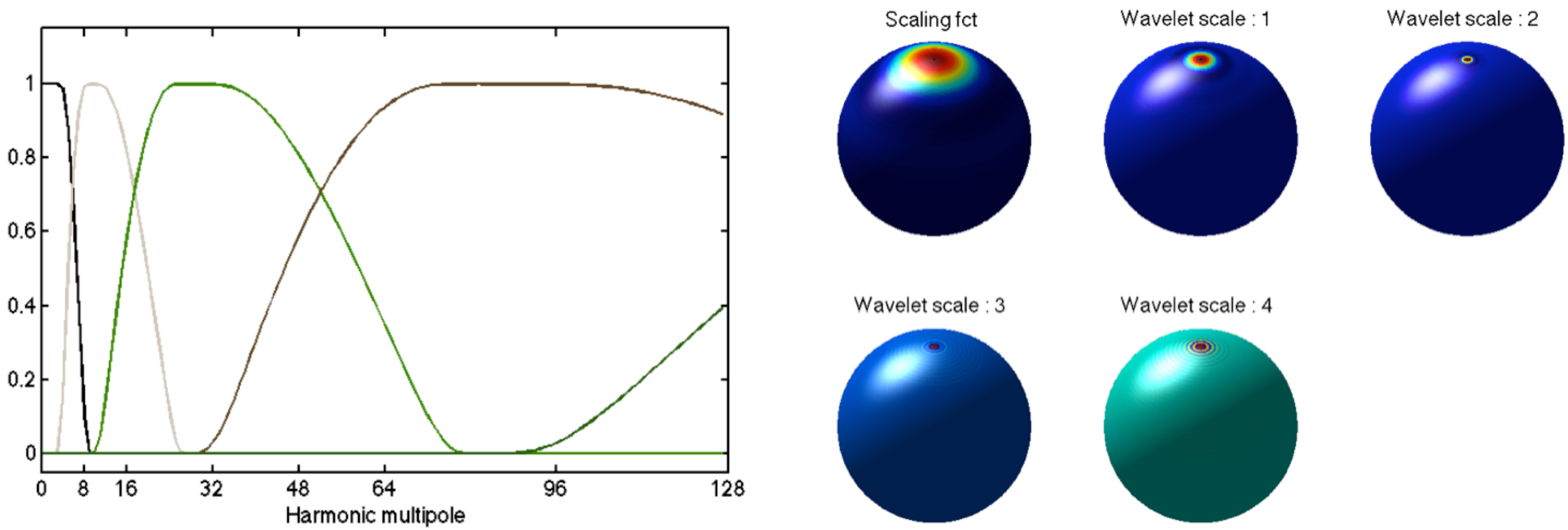
*Profumo, Reynoso, Kaaz, Silverman 2018







* Fornasa et al



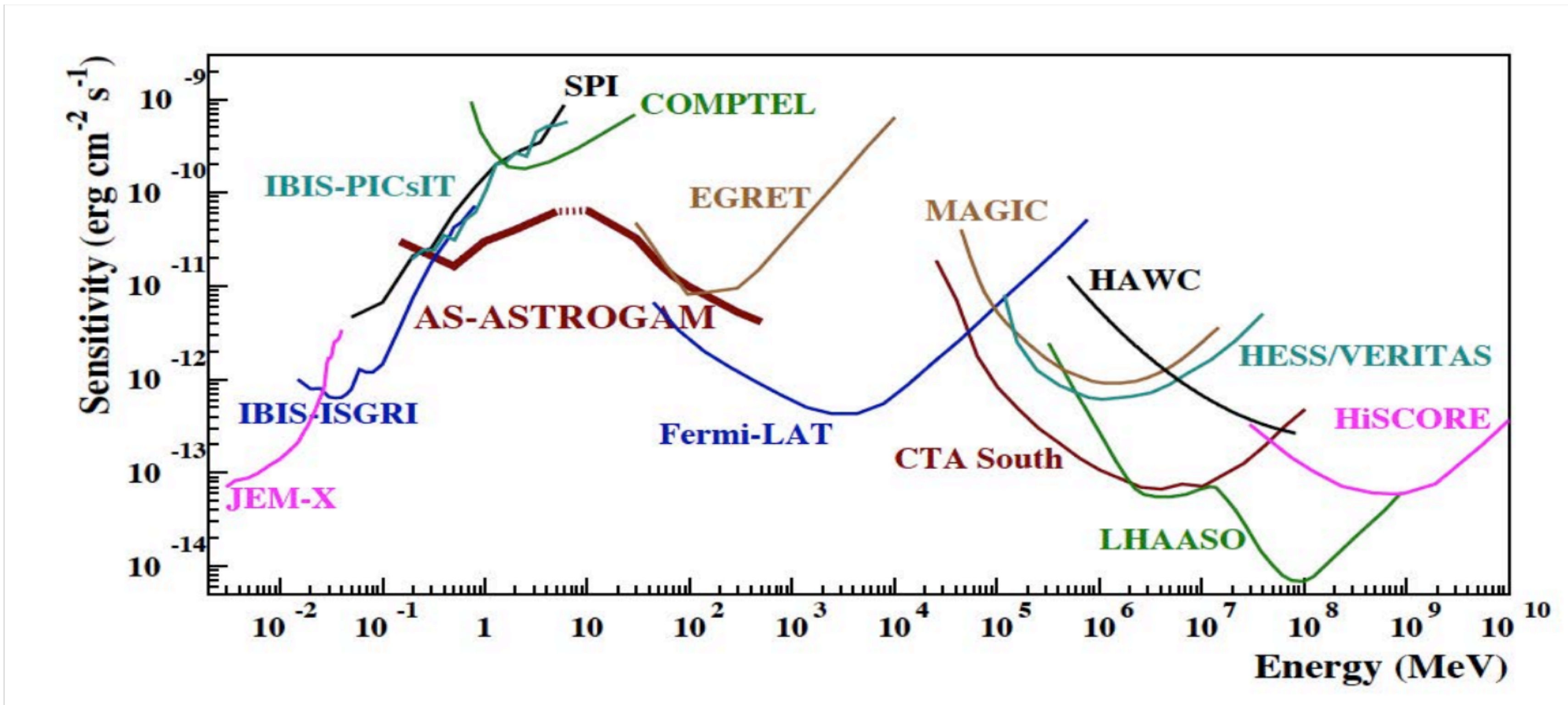
1
0.8
0.6
0.4
0.2
0
0
8
16
32
48
64
96
128
Harmonic multipole
Scaling fct
Wavelet scale : 1
Wavelet scale : 2
Wavelet scale : 3
Wavelet scale : 4

- **New observational facilities**

- **New ideas on dir**

pe

AZ



e-ASTROGAM just selected for ESA Call F Phase 2 (results: July)