Astrophysical observations of dark matter

Joseph Silk (IAP/JHU)

KMI, March 2, 2018

References

Dark matter in galaxies Zasov, A., Saburova, A., Khoperskov, A., Khoperskov, S.
2017PhyU...60....3Z
WIMP dark matter candidates and searches - current issues and future prospects
Roszkowski, L., Sessolo, E., Trojanowski, S.
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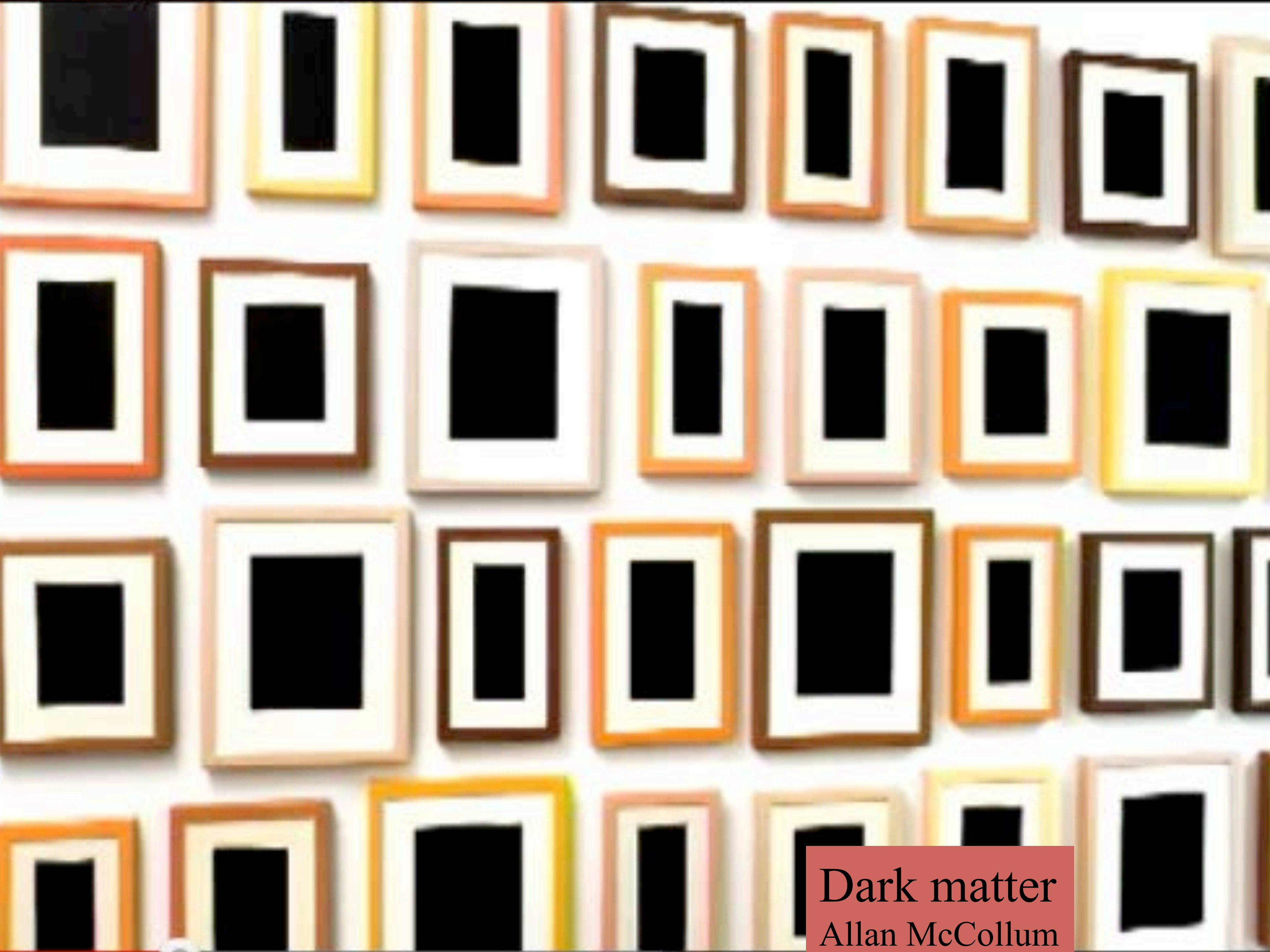
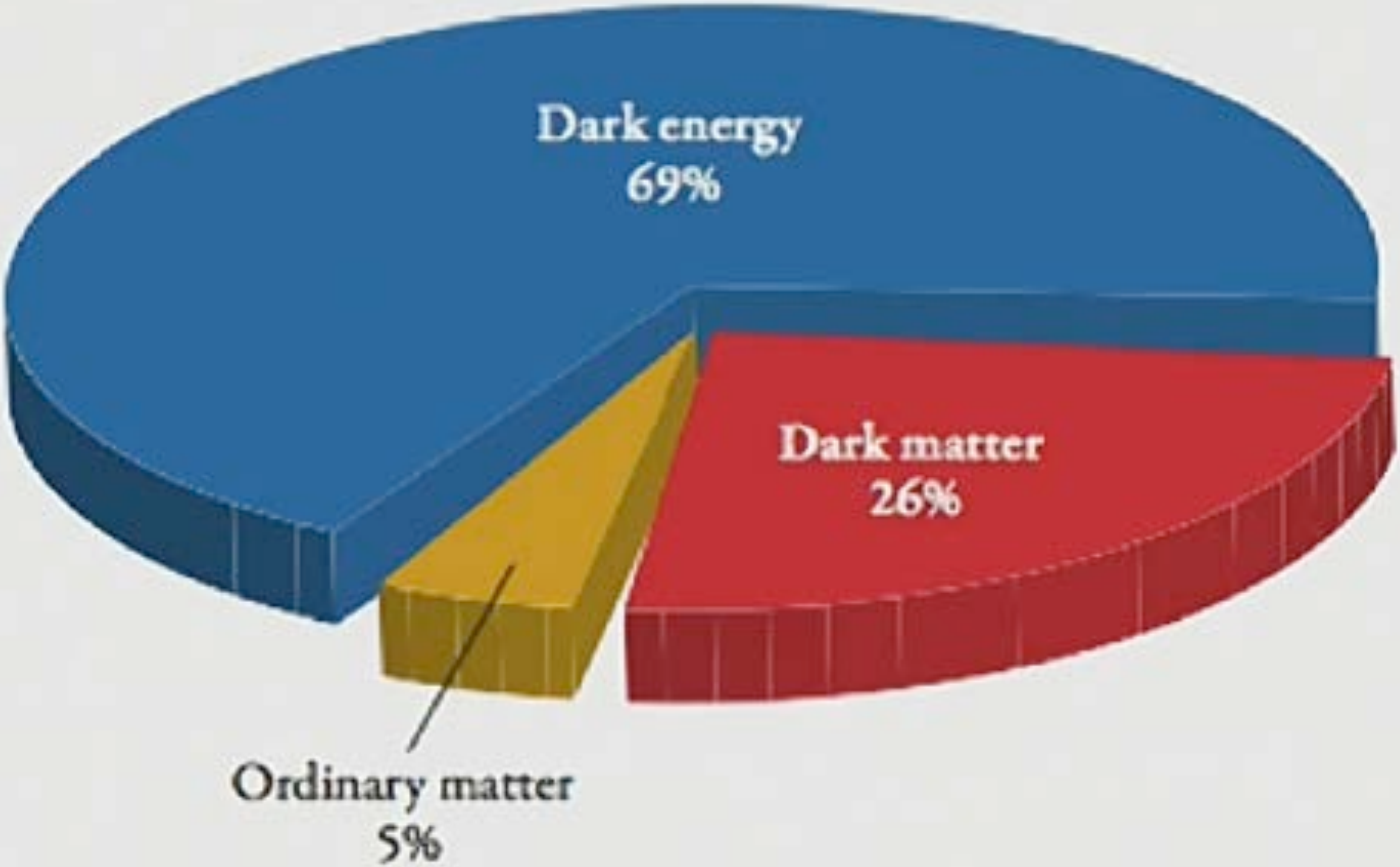


Dark matter
Allan McCollum

Modern observations of the expanding universe require dark matter (and dark energy)



What is the matter?

- Predictions

Direct, collider, indirect signals

- Compact objects

Sun, neutron stars, massive black holes, microlensing, primordial black holes

- Galaxies

galactic centre, dwarf galaxies, galaxy clusters

- Cosmology

CMB, modified gravity

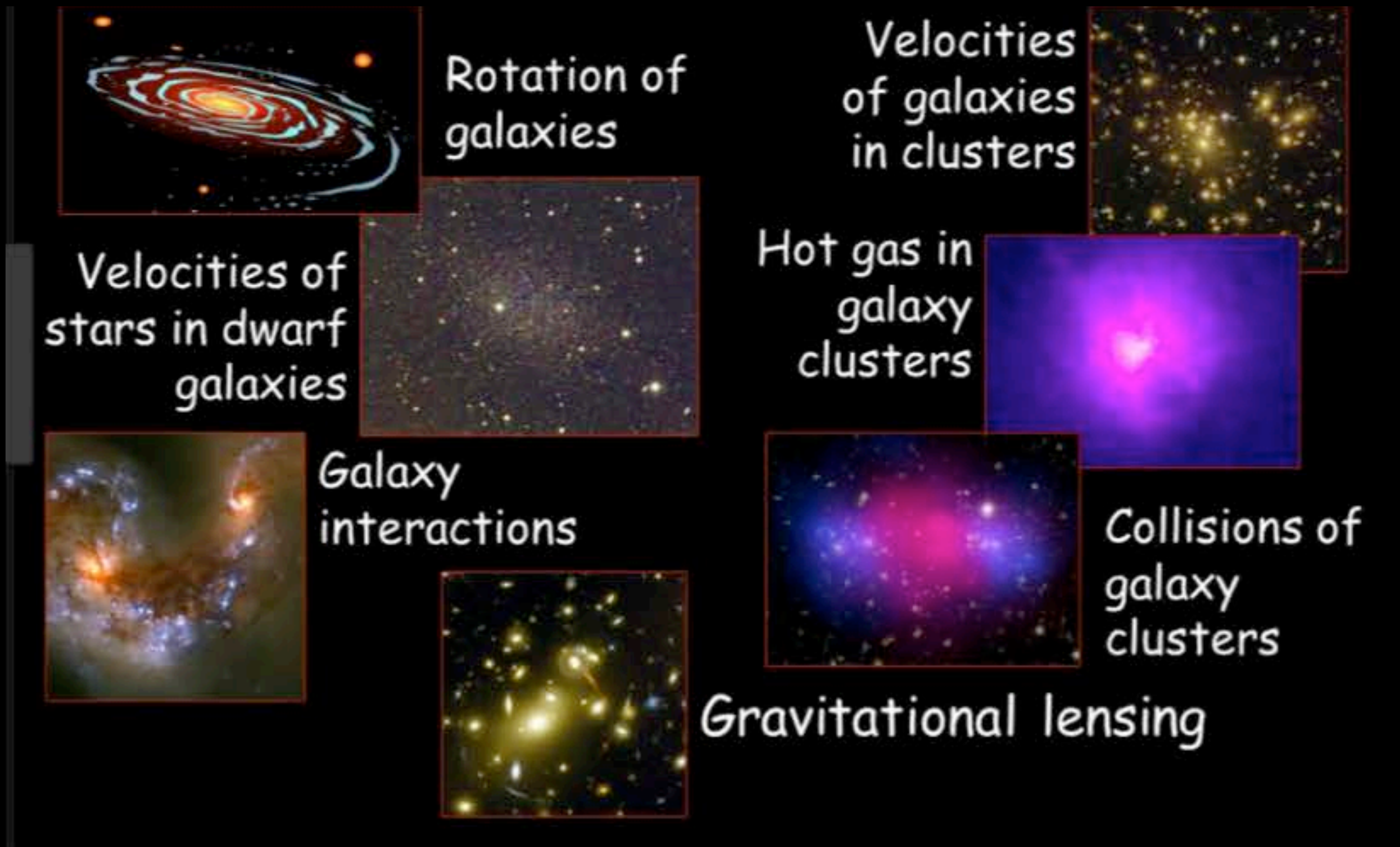
DM is nonbaryonic

Lecture

1a

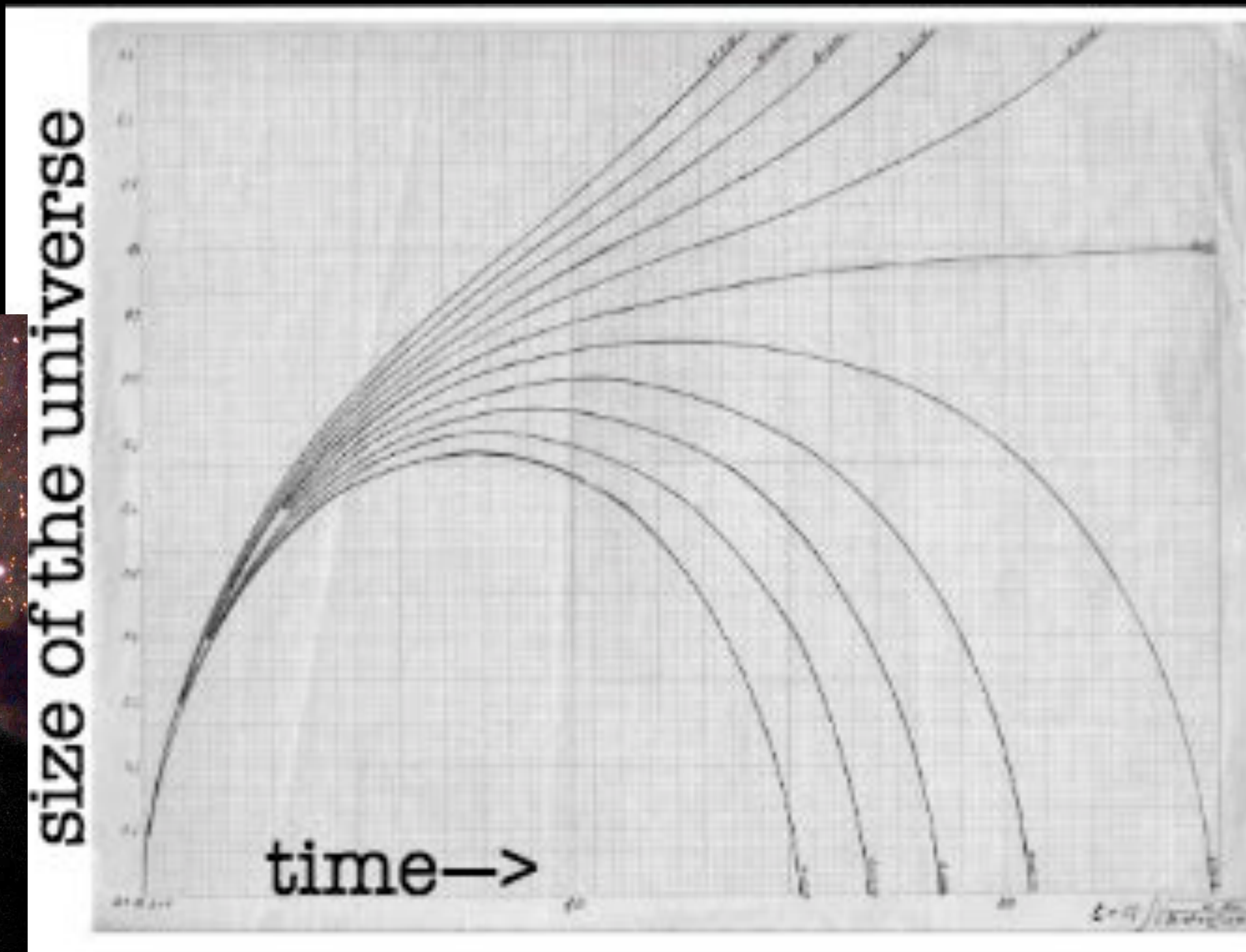
DARK MATTER : OBSERVATION

Much evidence for dark matter

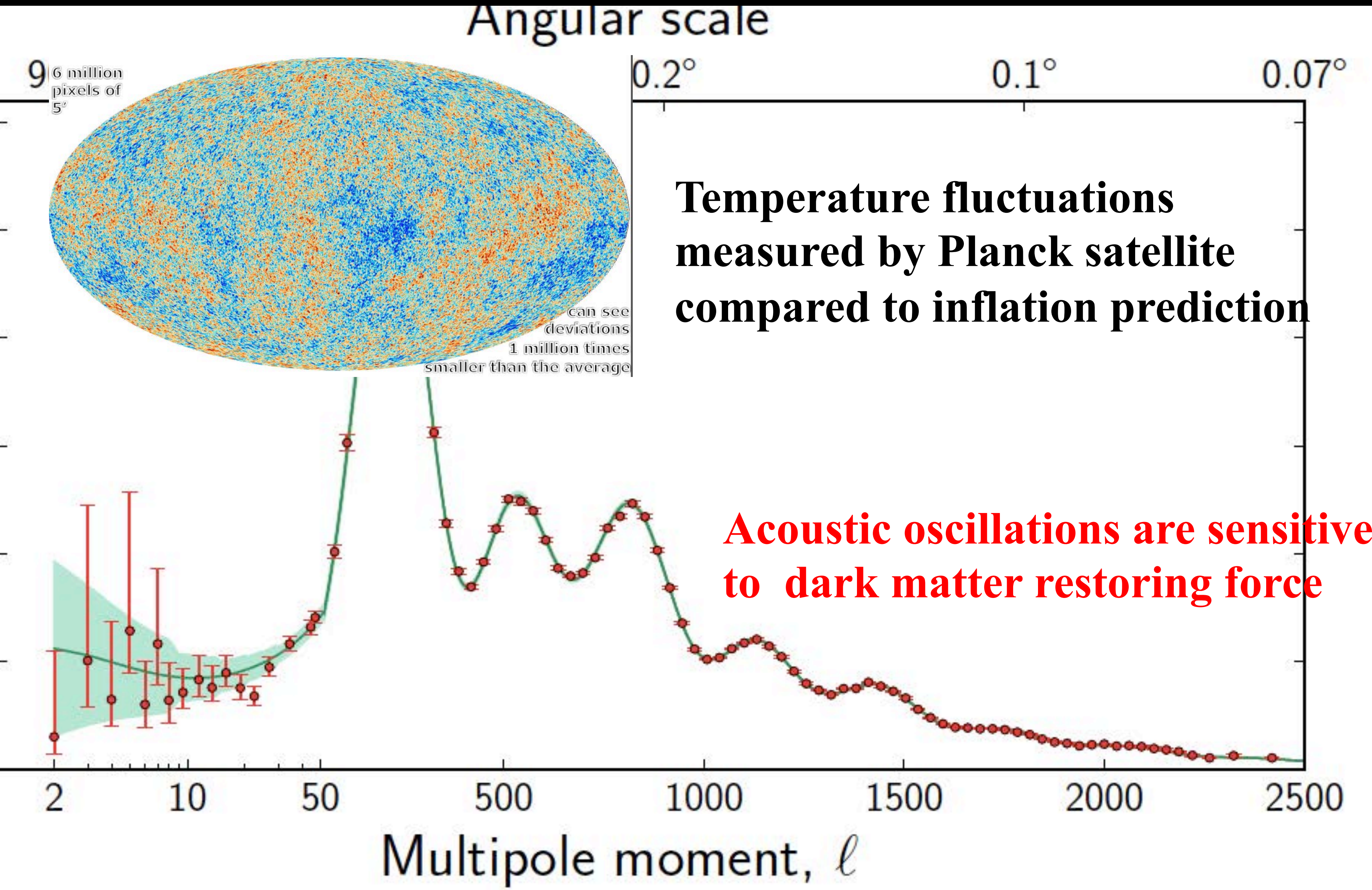


Georges Lemaitre's sketch of cosmological models from 1928

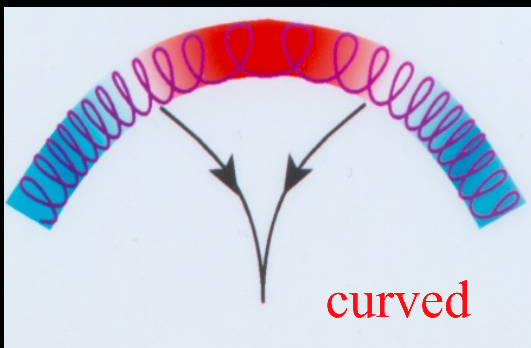
Modern cosmology requires dark matter

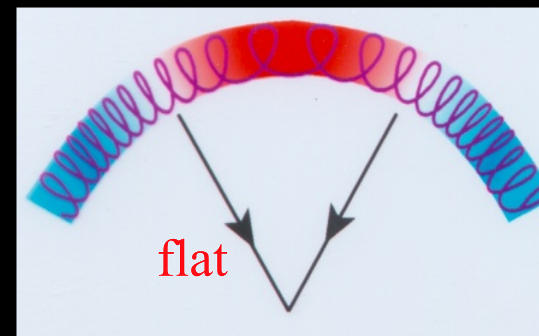


USING THE CMB TO PROBE DARK MATTER



$\Omega = 8\pi G\rho / 3H_0^2$ $\quad$ $H_0 = 68 \pm 1 \text{ km s}^{-1} \text{ Mpc}^{-1}$





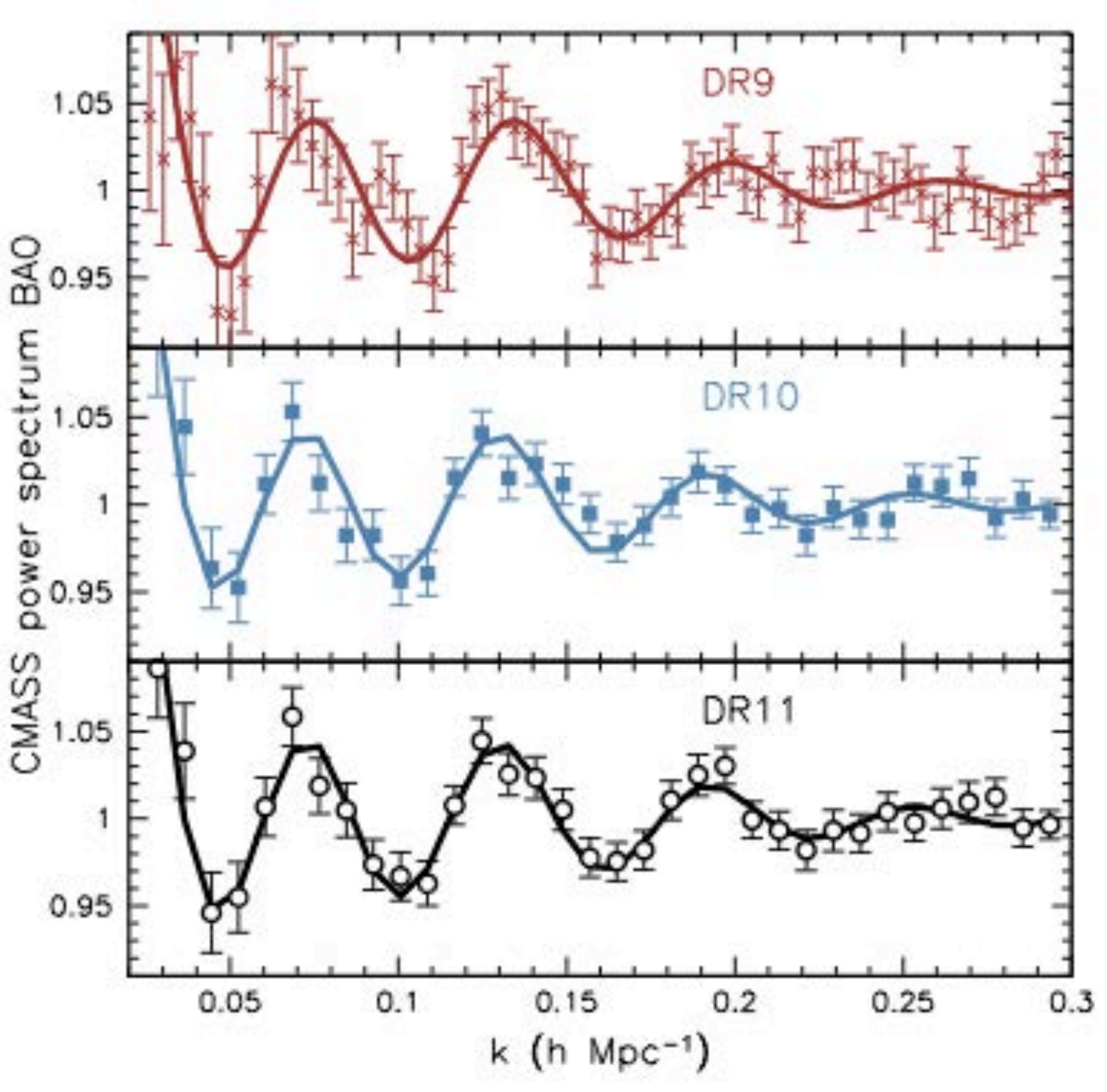
$\Omega_\Lambda = 0.697 \pm 0.011$

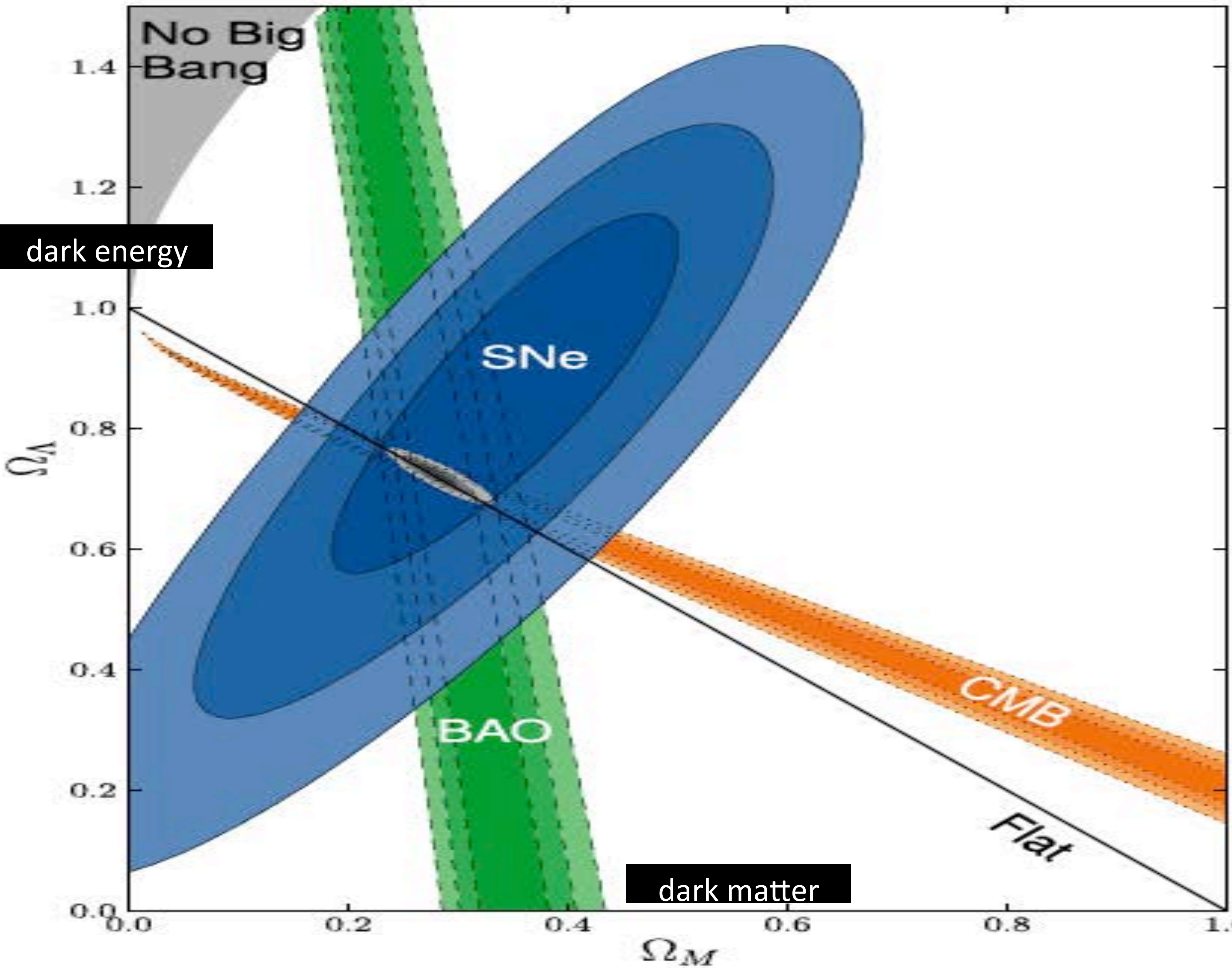
$\Omega_m = 0.303 \pm 0.011$

$\Omega_B = 0.0484 \pm 0.0007$

$t_0 = 13.804 \pm 0.058$ Gyr $\quad$ degeneracy with age

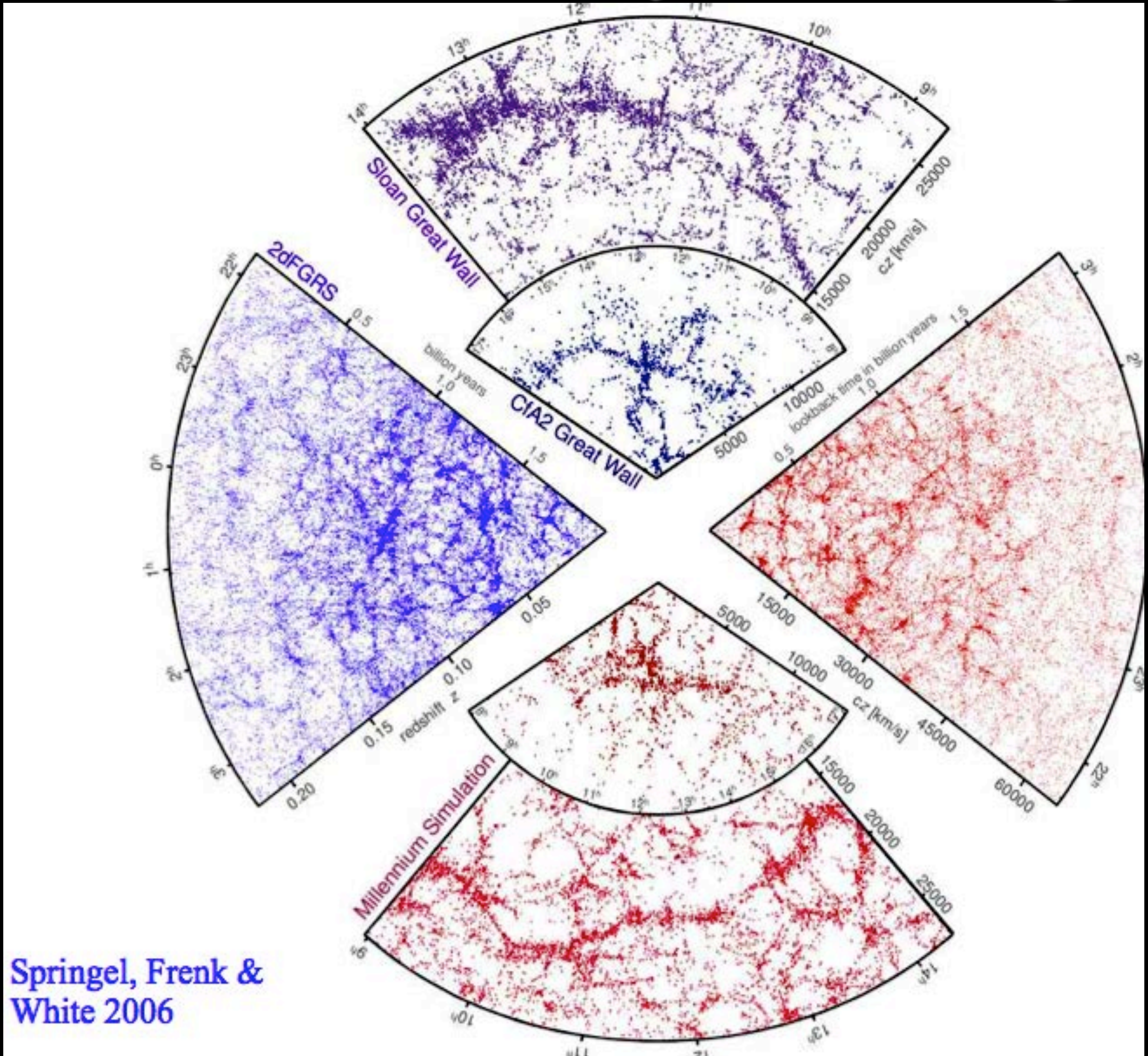
ACOUSTIC OSCILLATIONS IN BARYONS





Amanullah et al 2010

Dark Matter is weakly interacting & cold



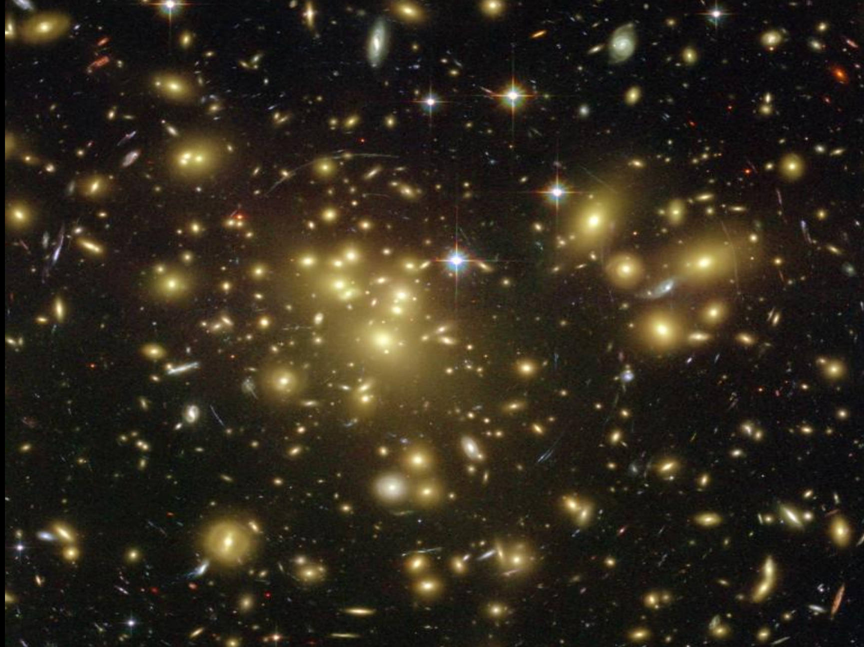
Springel, Frenk & White 2006

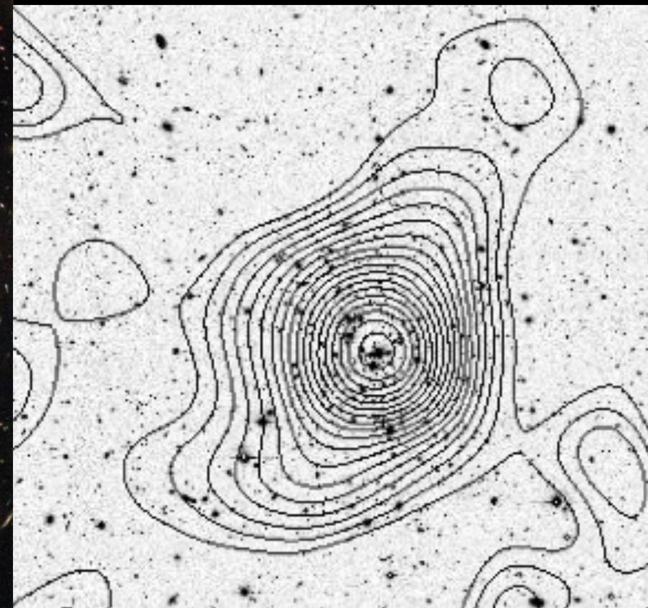
How to measure dark matter

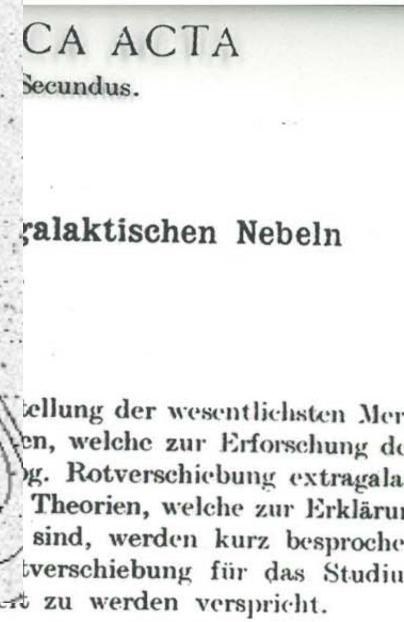
From velocity dispersion of galaxies in a cluster or rotation speed of a galaxy

$$v^2 = G\, M\,(< r)\,/\,r$$

Measure v at radius and infer M (<r)



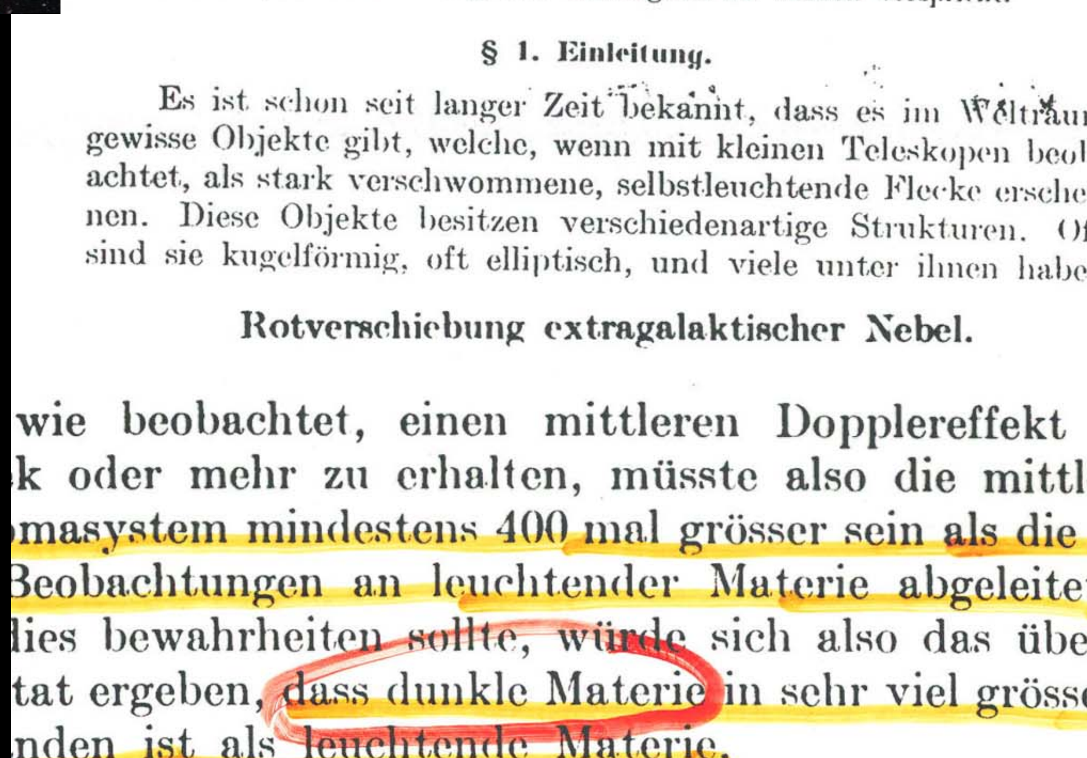




CA ACTA
Secundus.

ʒalaktischen Nebeln

tellung der wesentlichsten Mer
en, welche zur Erforschung d
ɡg. Rotverschiebung extragala
Theorien, welche zur Erkläru
sind, werden kurz besproche
tverschiebung für das Studiu
zu werden verspricht.



§ 1. Einleitung.

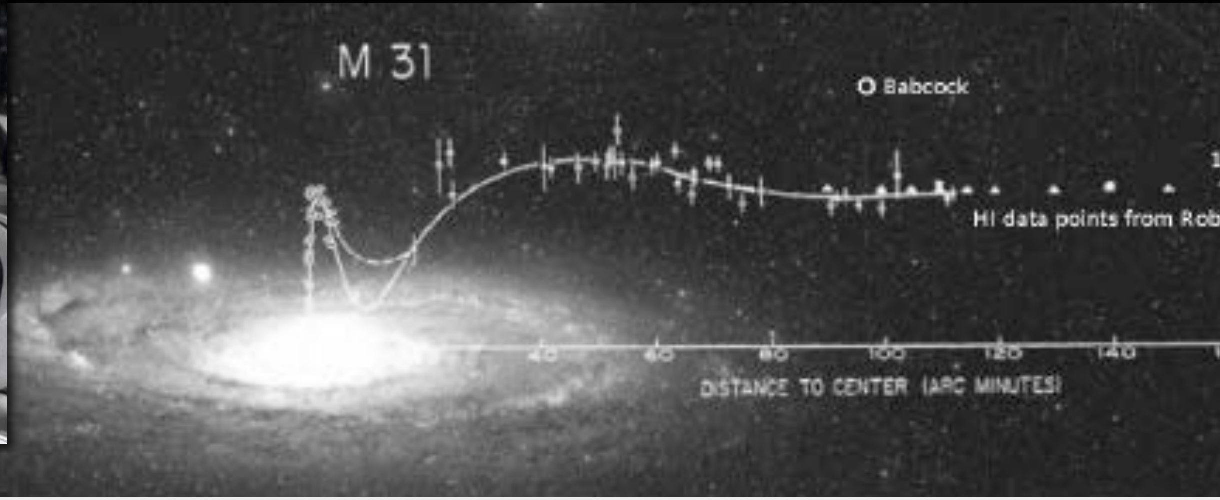
Es ist schon seit langer Zeit bekannt, dass es im Weltrau
gewisse Objekte gibt, welche, wenn mit kleinen Teleskopen beol
achtet, als stark verschwommene, selbstleuchtende Flecke ersche
nen. Diese Objekte besitzen verschiedenartige Strukturen. O
sind sie kugelförmig, oft elliptisch, und viele unter ihnen habe

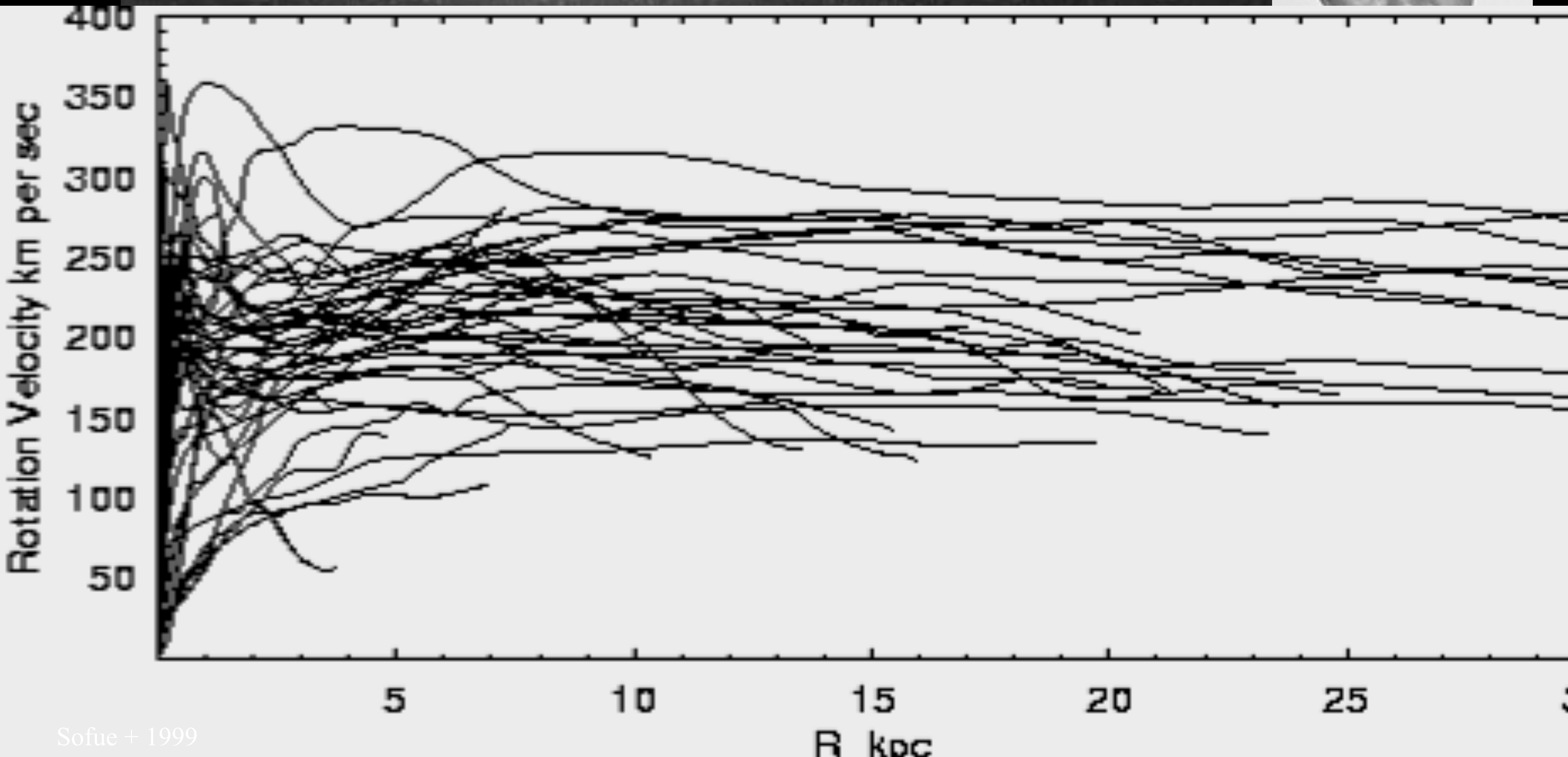
Rotverschiebung extragalaktischer Nebel.

wie beobachtet, einen mittleren Dopplereffekt
k oder mehr zu erhalten, müsste also die mittl
masystem mindestens 400 mal grösser sein als die
Beobachtungen an leuchtender Materie abgeleite
lies bewahrheiten sollte, würde sich also das übe
tat ergeben, dass dunkle Materie in sehr viel gröss
nden ist als leuchtende Materie.

Clusters of galaxies are mosly dark matter
otherwise they'd fly apart

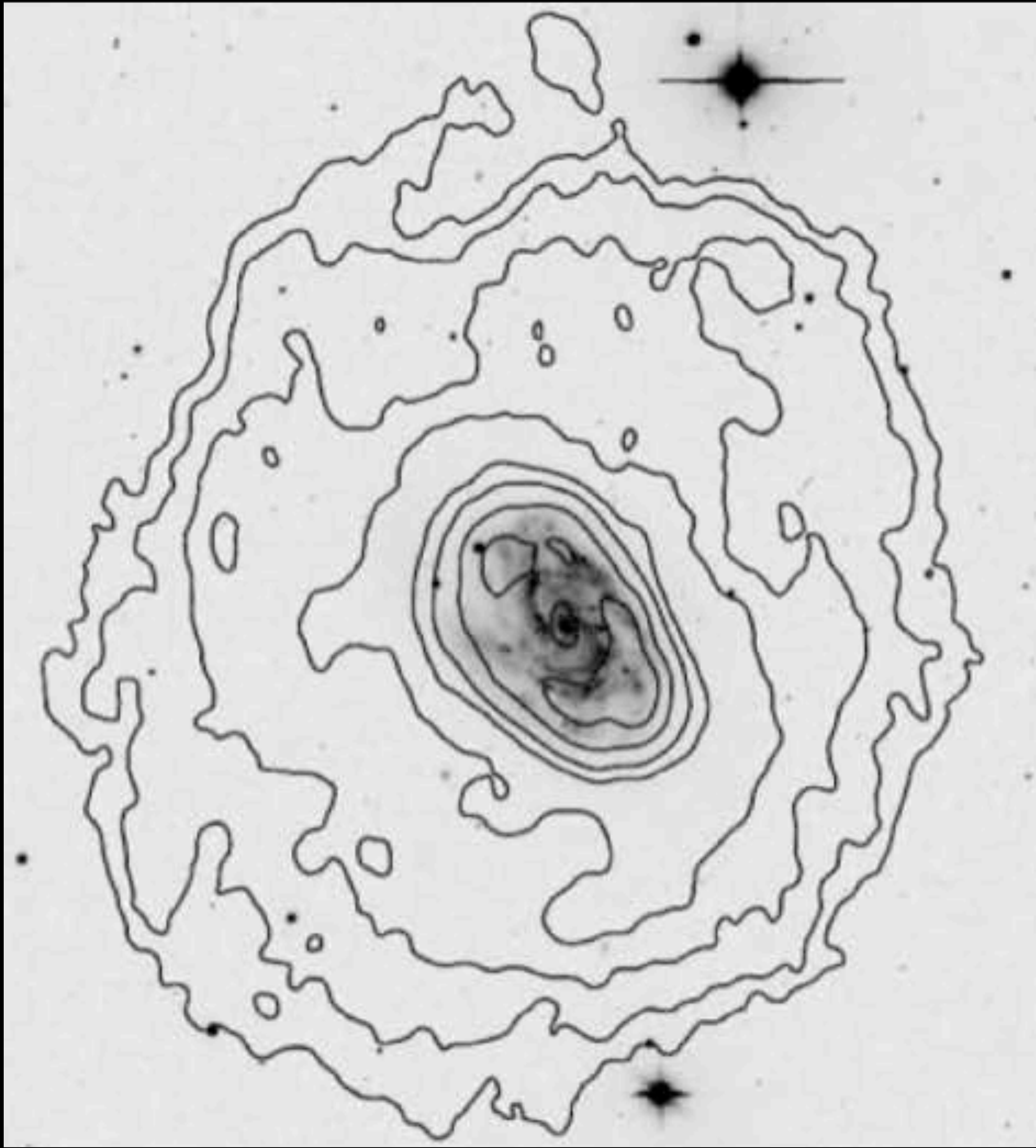
Vera Rubin

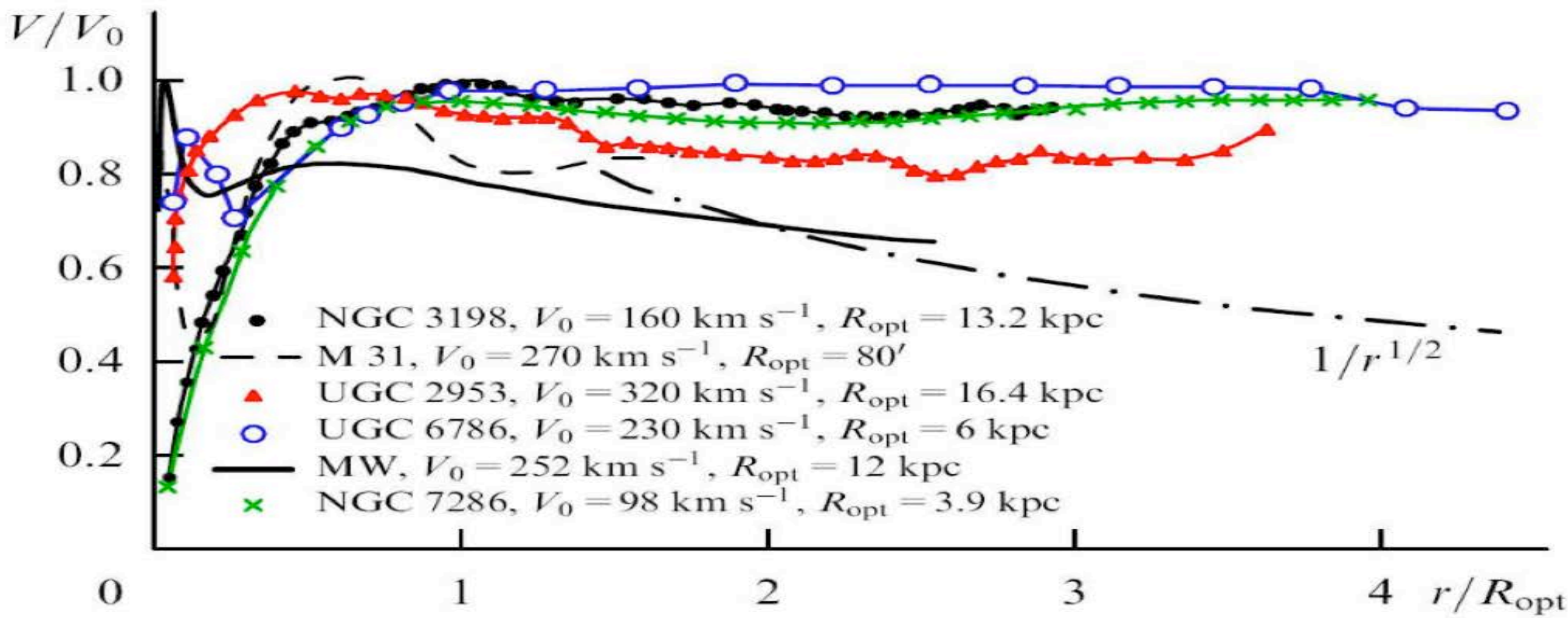




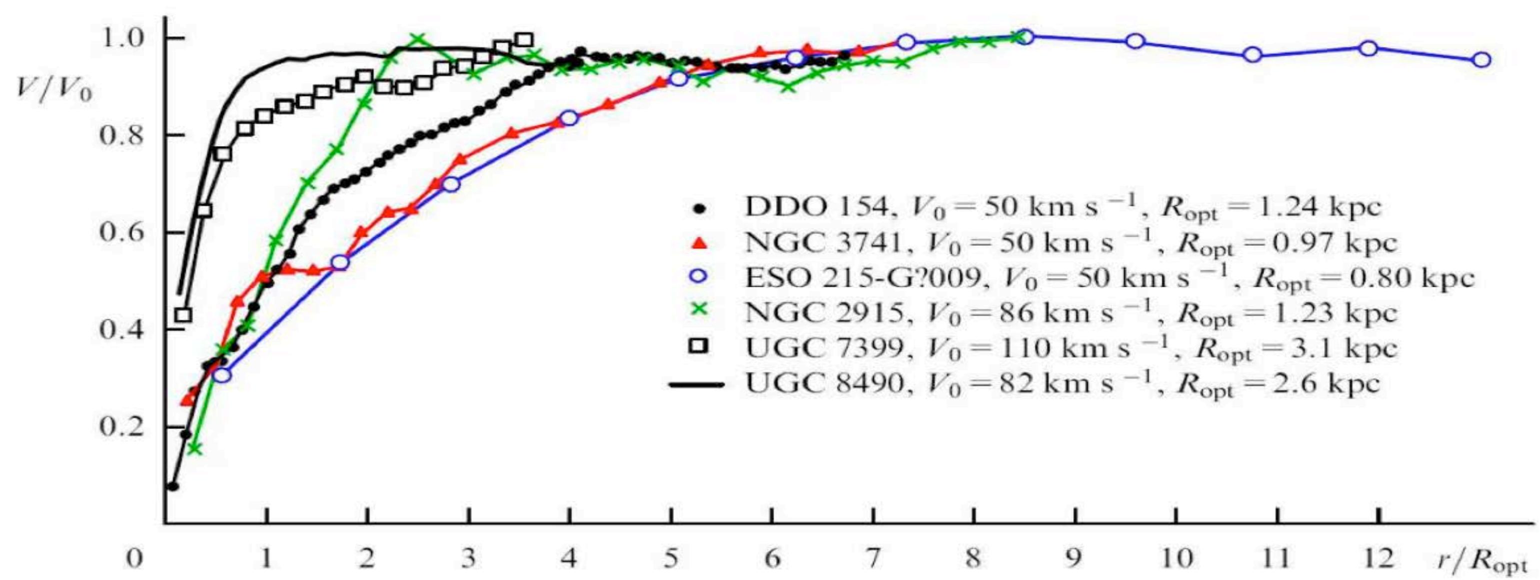
Sofue + 1999

Interstellar hydrogen kinematics is a probe of dark halo





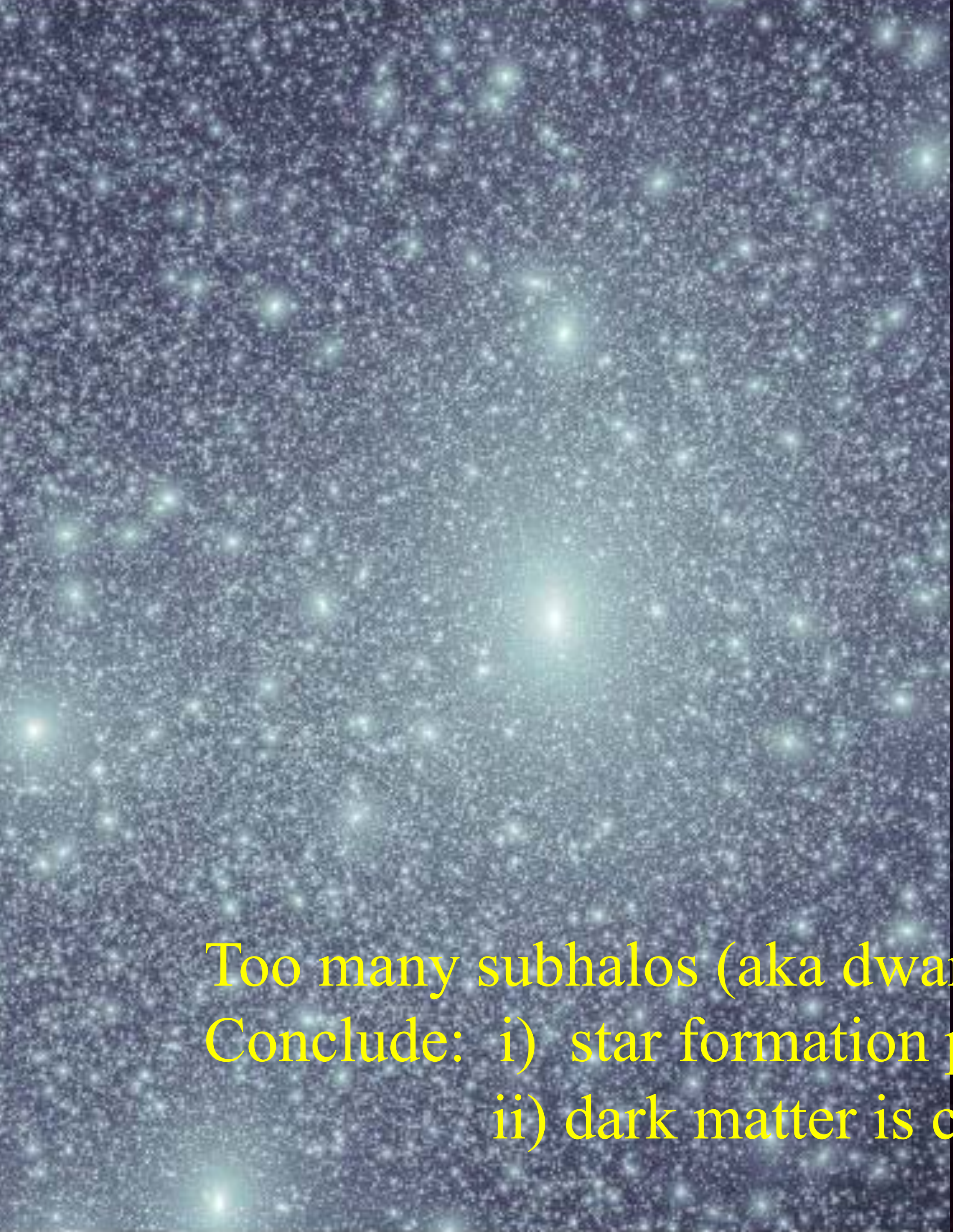
V/V0
1.0
0.8
0.6
0.4
0.2
0
1
2
3
4
r/Ropt
NGC 3198, V0 = 160 km s−1, Ropt = 13.2 kpc
M 31, V0 = 270 km s−1, Ropt = 80′
UGC 2953, V0 = 320 km s−1, Ropt = 16.4 kpc
UGC 6786, V0 = 230 km s−1, Ropt = 6 kpc
MW, V0 = 252 km s−1, Ropt = 12 kpc
NGC 7286, V0 = 98 km s−1, Ropt = 3.9 kpc
1/r1/2



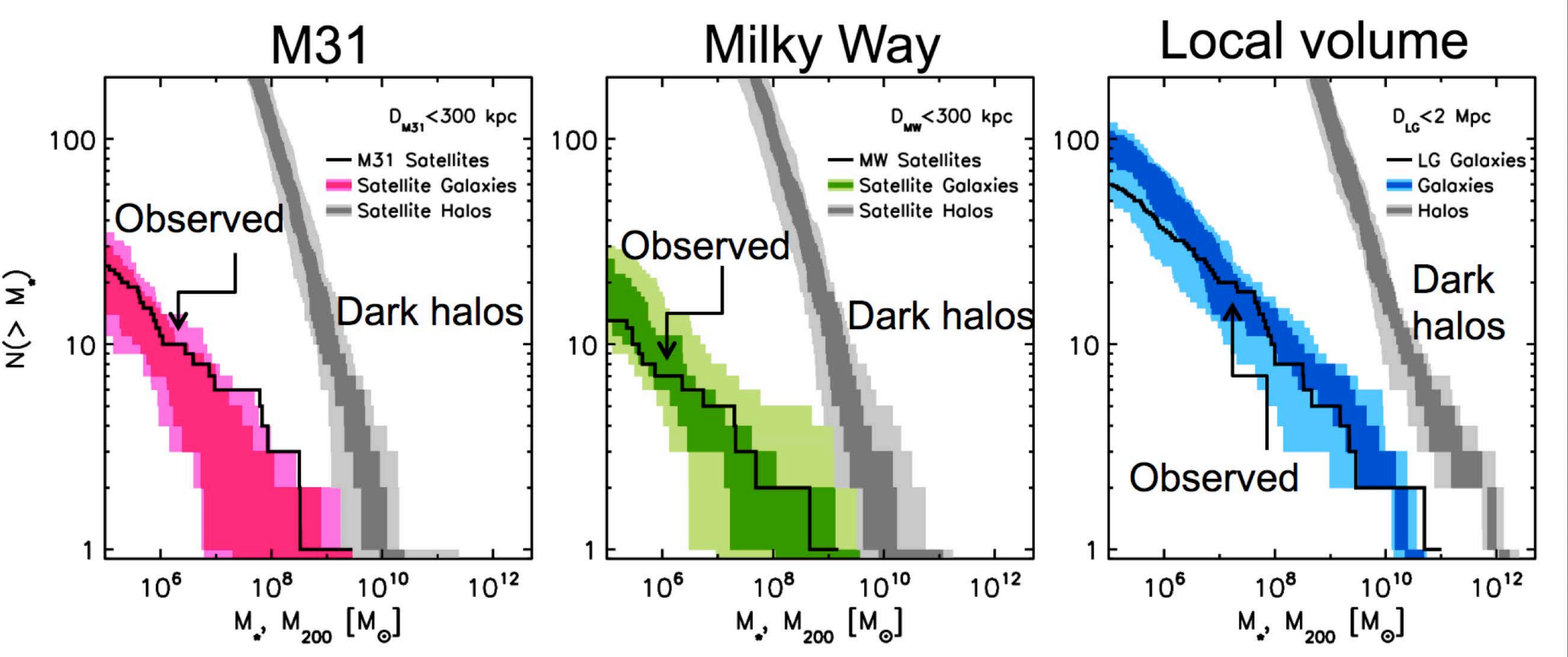
V/V0
1.0
0.8
0.6
0.4
0.2
0
1
2
3
4
5
6
7
8
9
10
11
12
r/Ropt
DDO 154, V0 = 50 km s−1, Ropt = 1.24 kpc
NGC 3741, V0 = 50 km s−1, Ropt = 0.97 kpc
ESO 215-G?009, V0 = 50 km s−1, Ropt = 0.80 kpc
NGC 2915, V0 = 86 km s−1, Ropt = 1.23 kpc
UGC 7399, V0 = 110 km s−1, Ropt = 3.1 kpc
UGC 8490, V0 = 82 km s−1, Ropt = 2.6 kpc

So where is the dark matter?

Via Lactea 2 simulation
(10^9 particles of 4000 M_O)



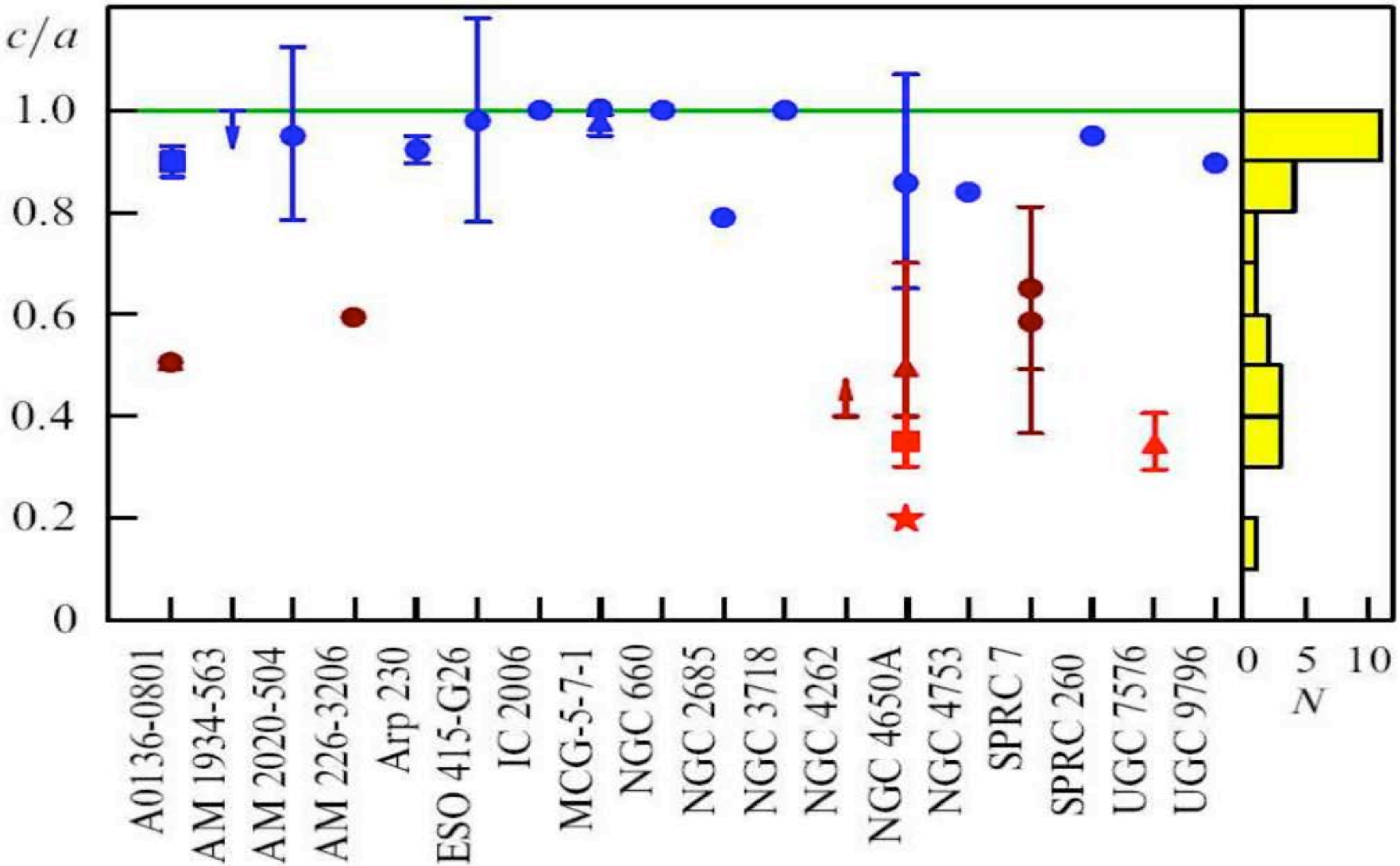
Too many subhalos (aka dwarf galaxies) are predicted
Conclude: i) star formation physics is complex
ii) dark matter is clumpy



M31
Milky Way
Local volume
D_{M31}<300 kpc
M31 Satellites
Satellite Galaxies
Satellite Halos
Observed
Dark halos
D_{MW}<300 kpc
MW Satellites
Satellite Galaxies
Satellite Halos
Observed
Dark halos
D_{LG}<2 Mpc
LG Galaxies
Galaxies
Halos
Dark halos
Observed
N(> M_*)
100
10
1
10^6
10^8
10^{10}
10^{12}
M_*, M_{200} [$M_\odot$]

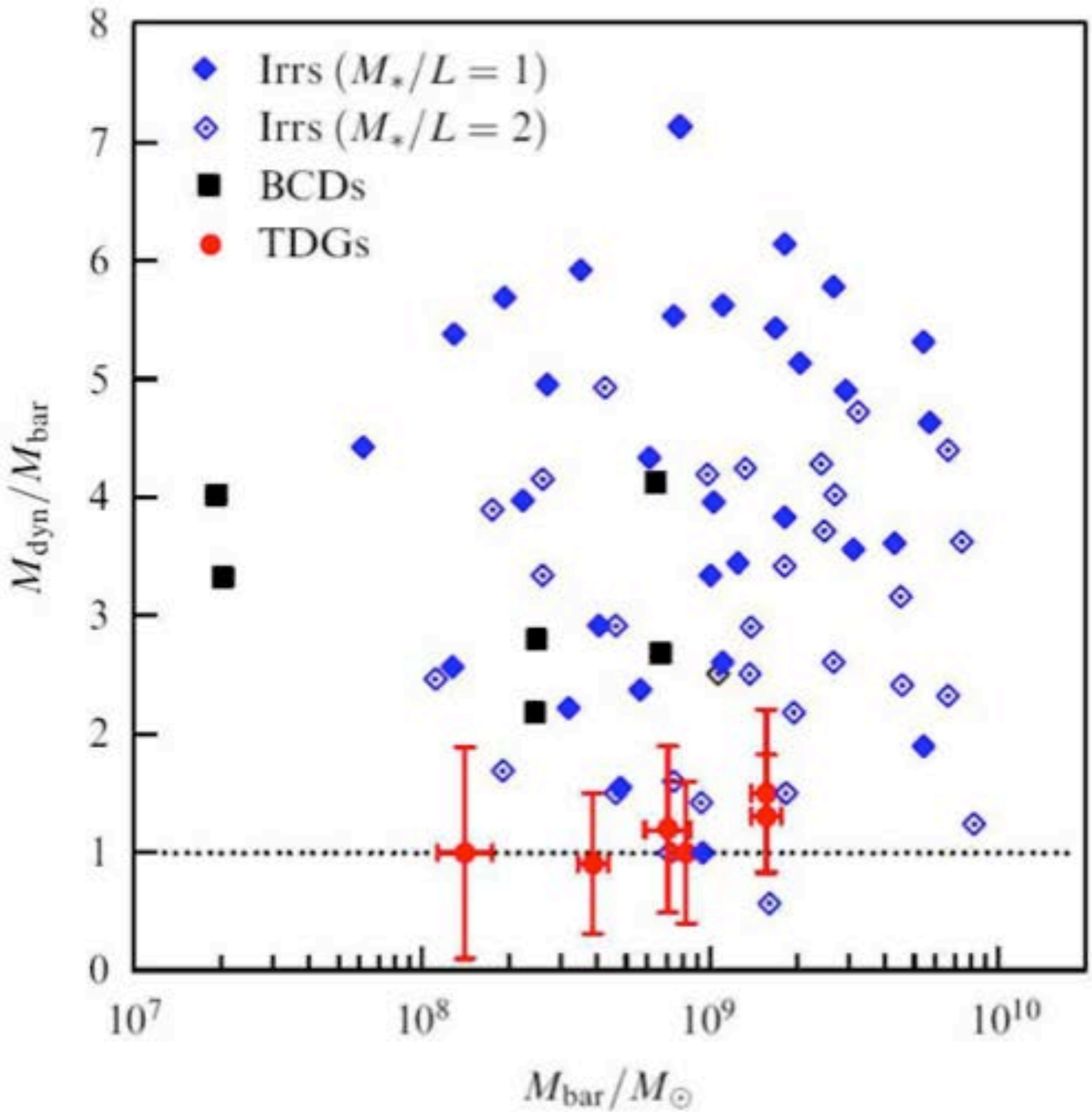
Sawala 16

Are dark halos spherical?



Zasov 2017

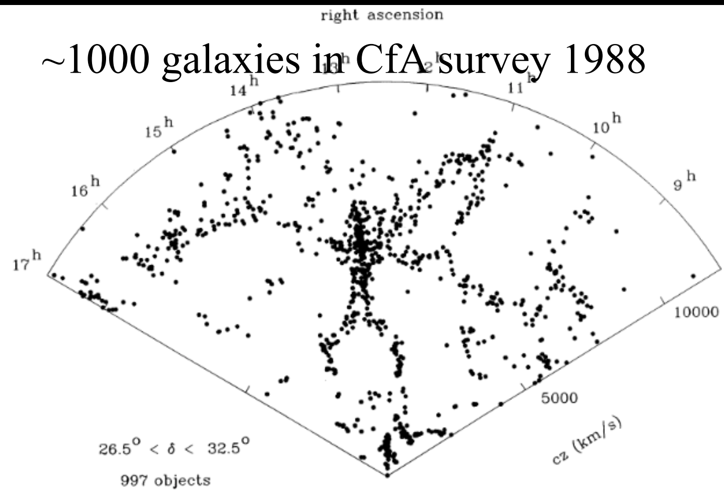
Not all galaxies have dark matter halos



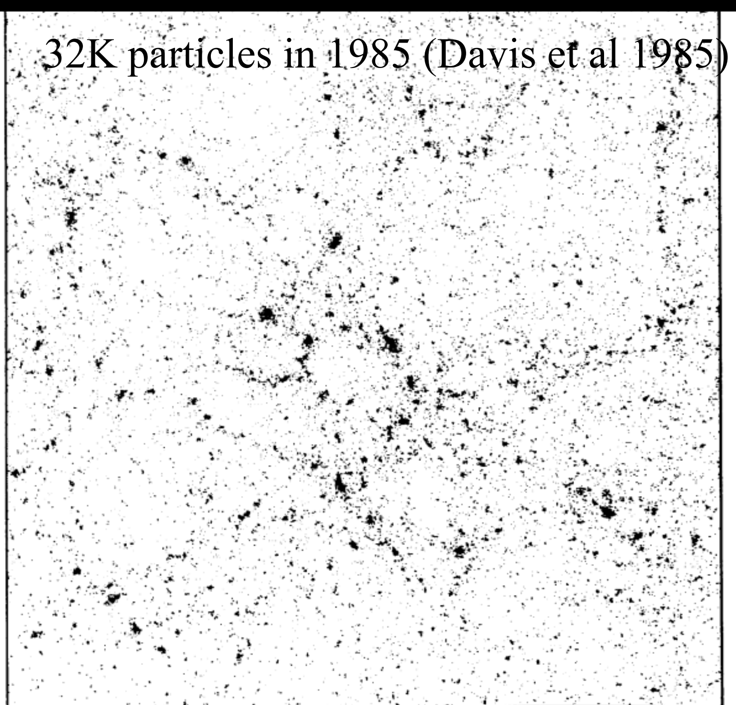
Zasov 2017

THE CASE FOR COLD DARK MATTER

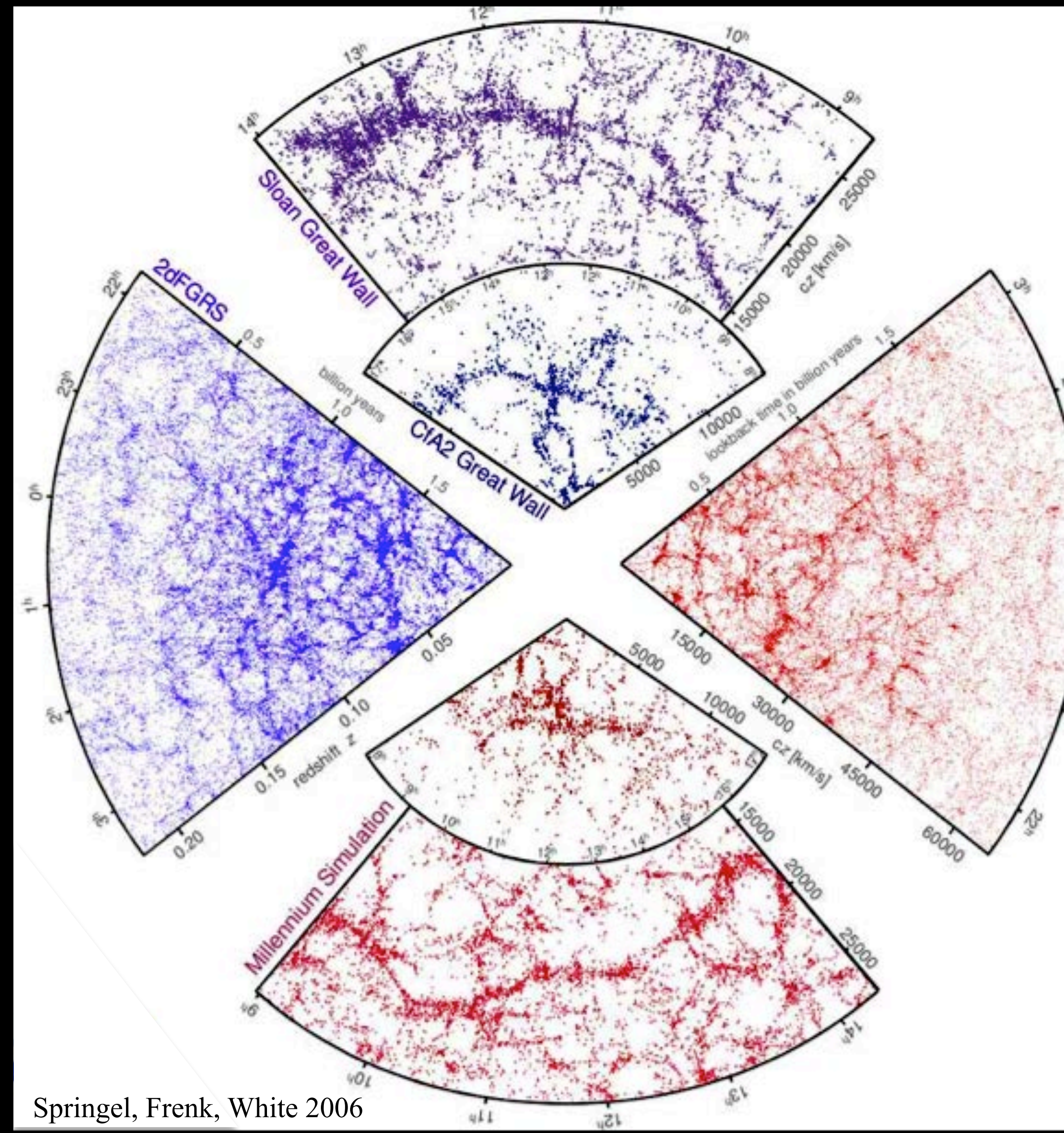
data and simulations
2006: ~10^6 galaxies, 10^8 particles
2018: a trillion particles but still limited by dynamical range



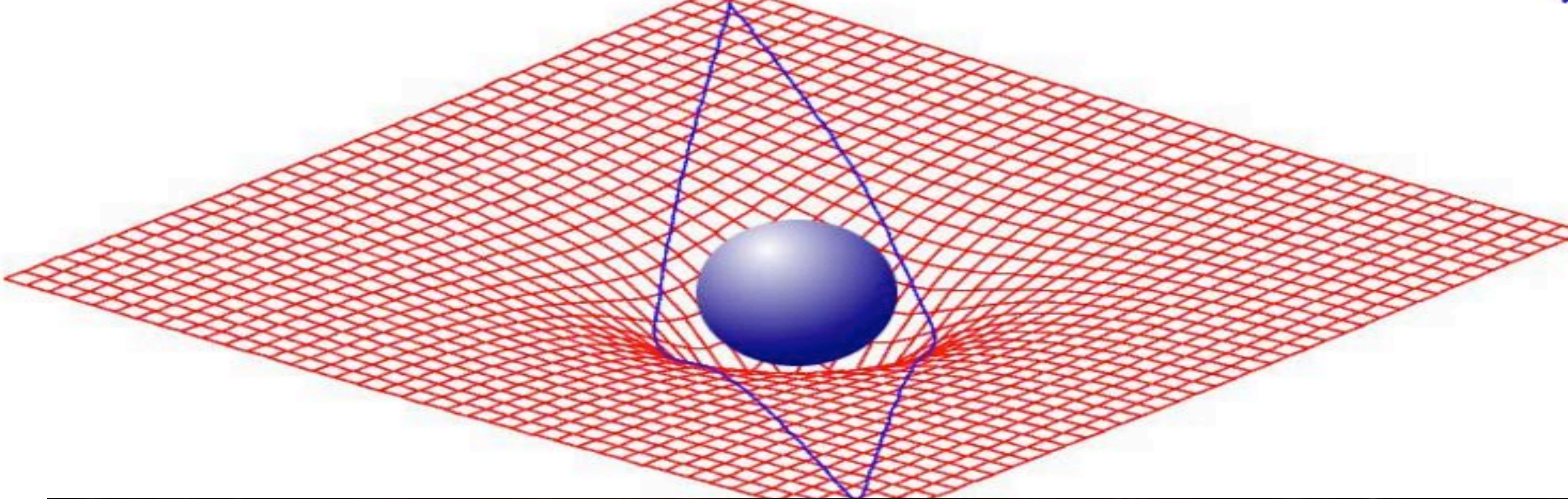
~1000 galaxies in CfA survey 1988



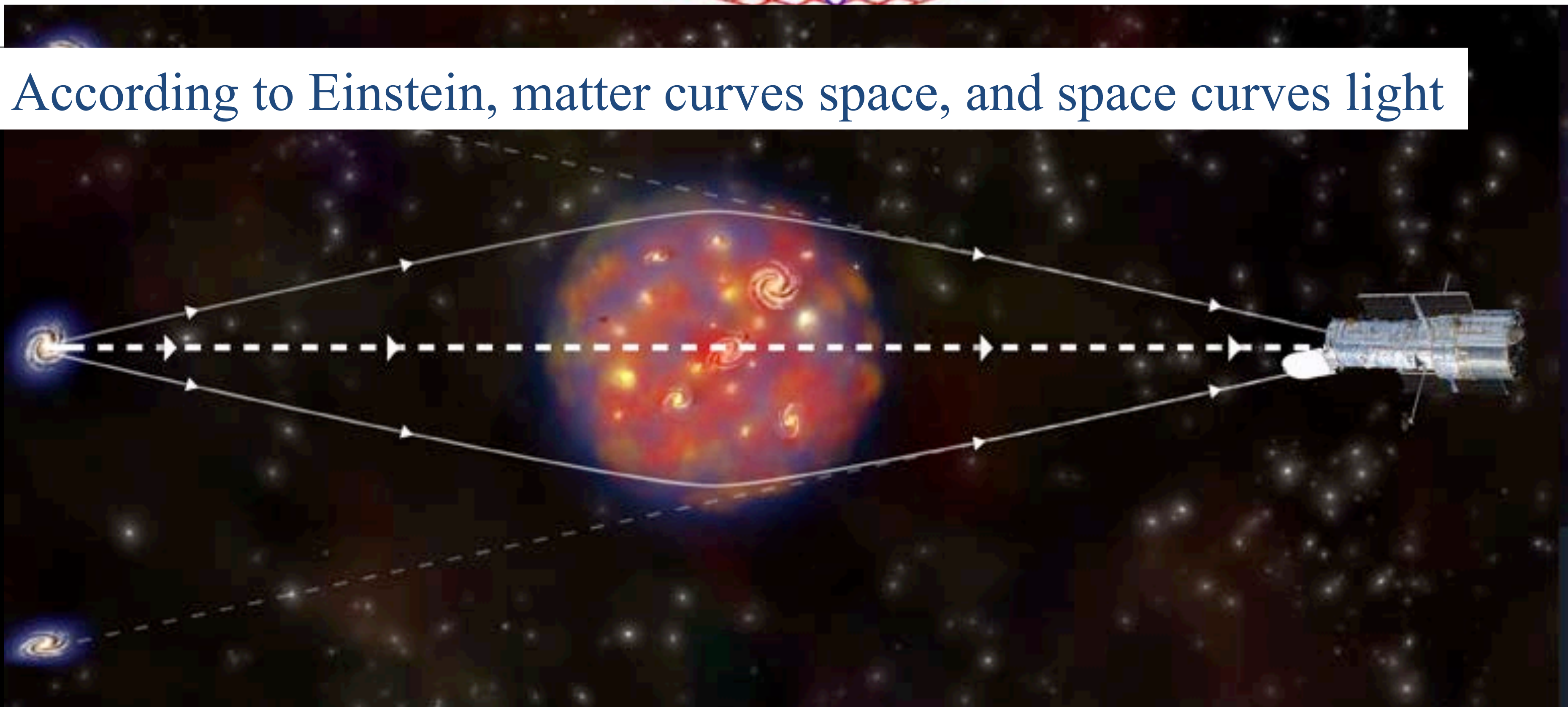
32K particles in 1985 (Davis et al 1985)



Springel, Frenk, White 2006

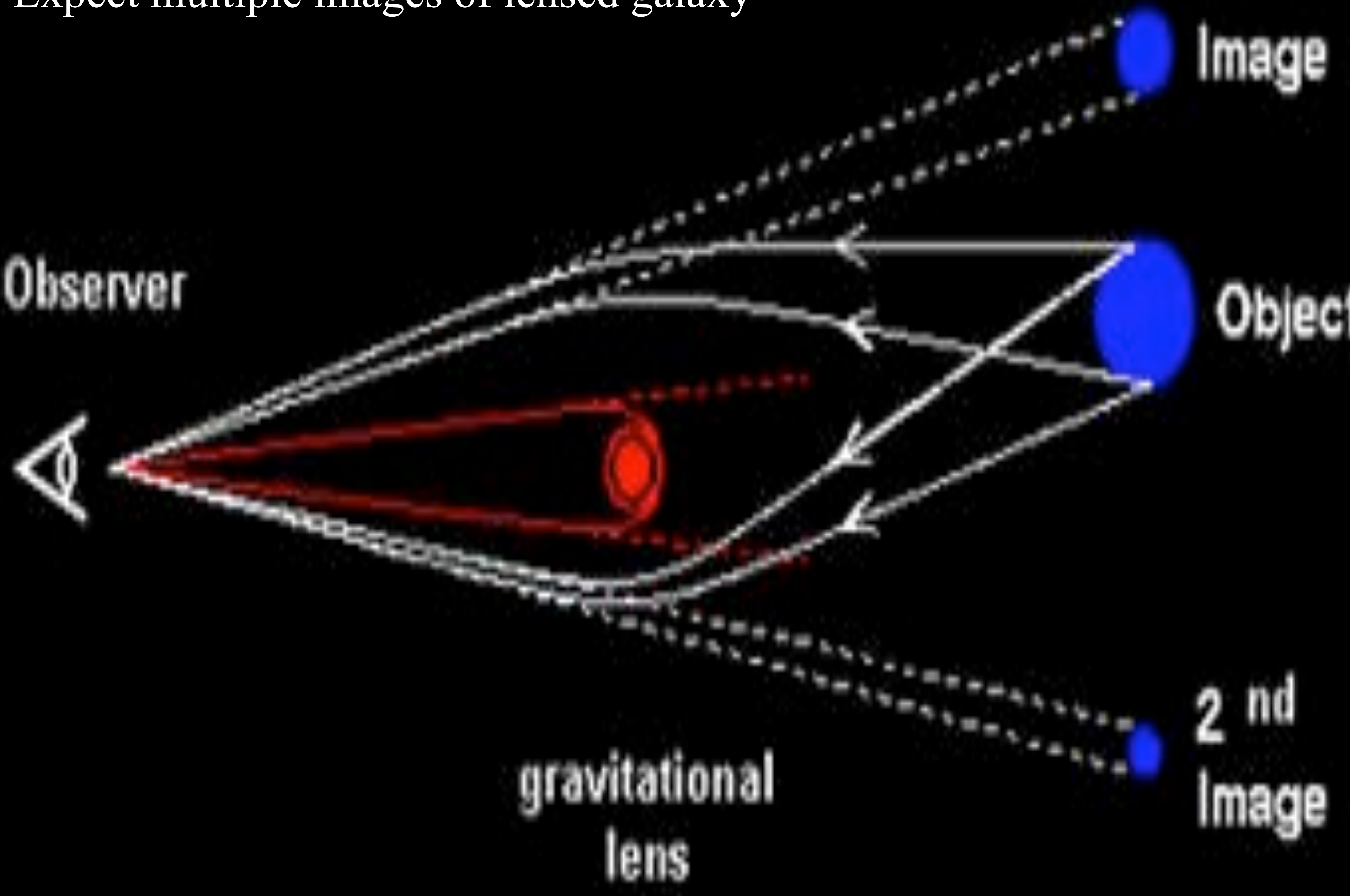


According to Einstein, matter curves space, and space curves light




horseshoe gravitational lens

Expect multiple images of lensed galaxy



galaxy lensing of a quasar

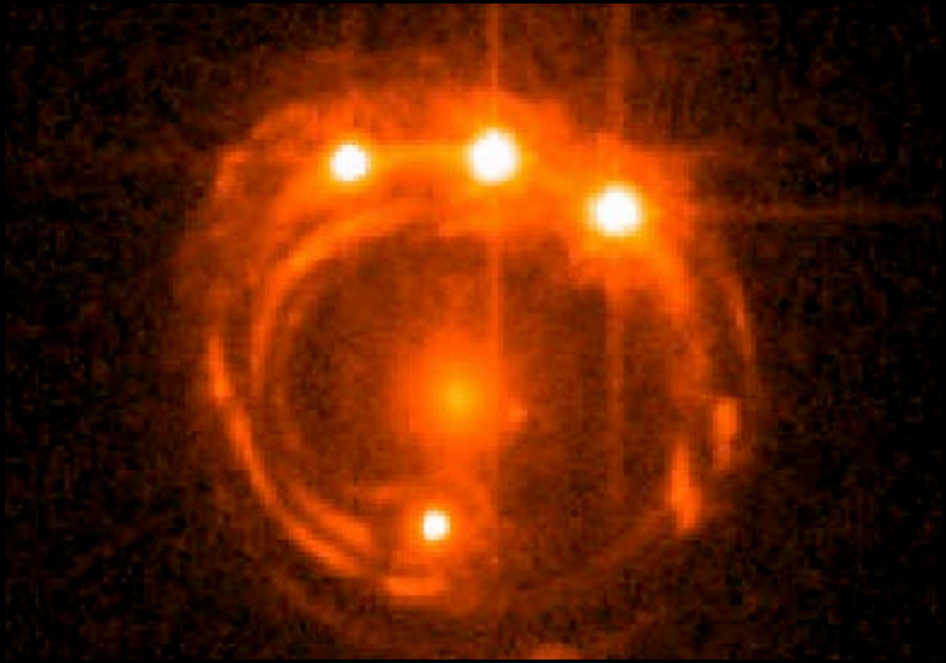
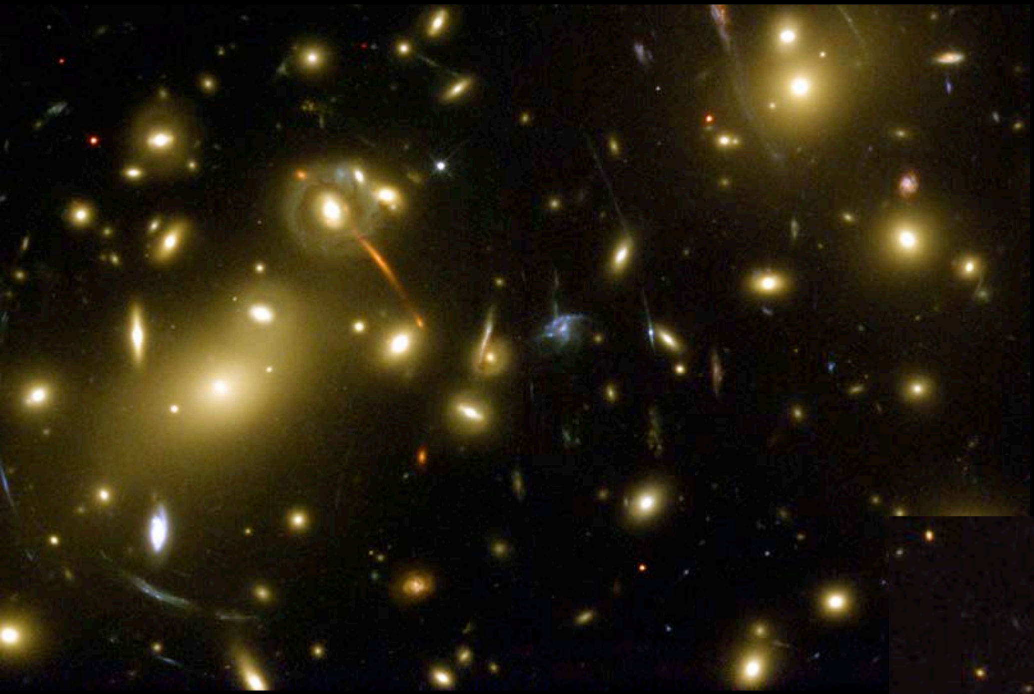


Image ratios show clumpiness of DM on 10^6 M_{sun} scales

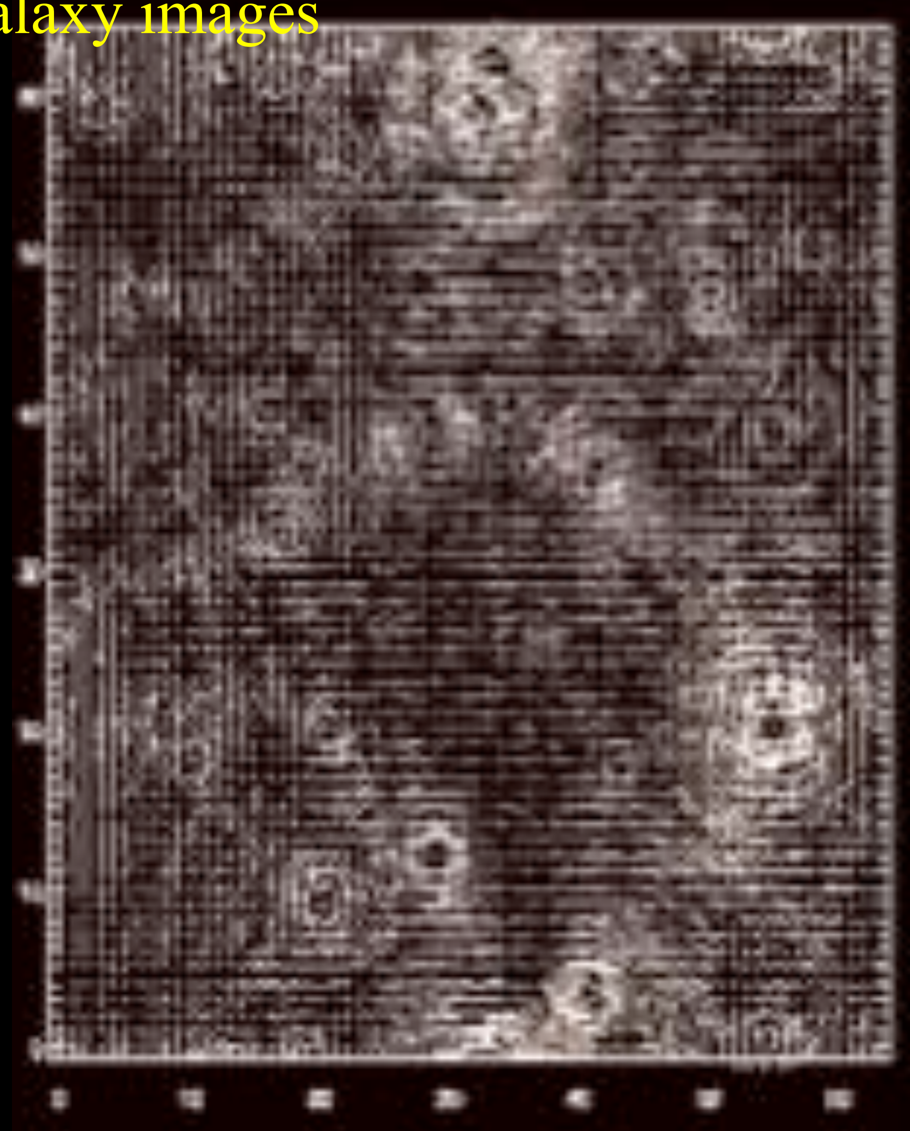
Galaxy cluster lens



Gravitational lensing measures all the dark matter in the universe

Map of distortions in galaxy images

Average density of dark matter
just balances expansion energy



1/3 critical density of dark matter
and 2/3 dark energy (which doesn’t lens)

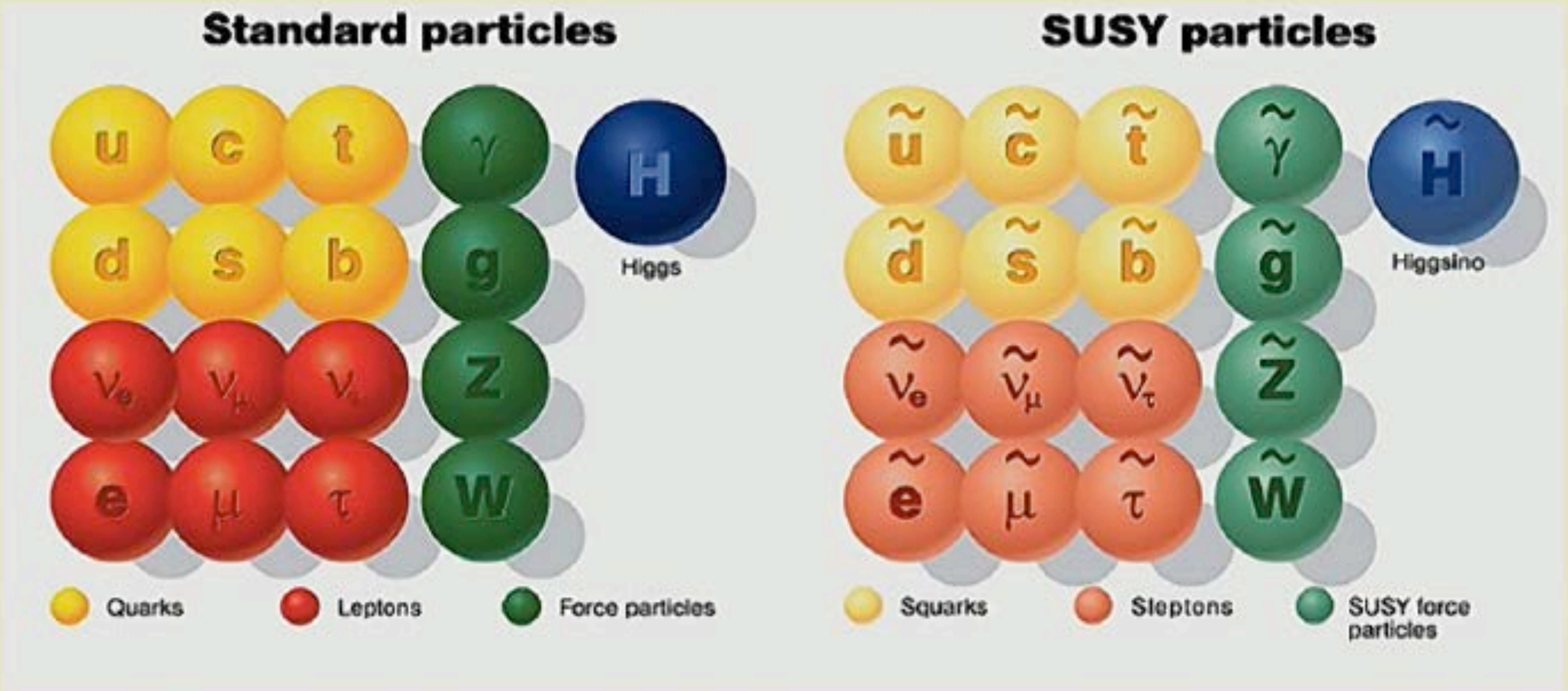
THIS IS OUR UNIVERSE!

DARK MATTER: THEORY

Lecture

1b

- Every particle we know has a partner



- The lightest supersymmetric particle may be the dark matter.

Courtesy K. Freese

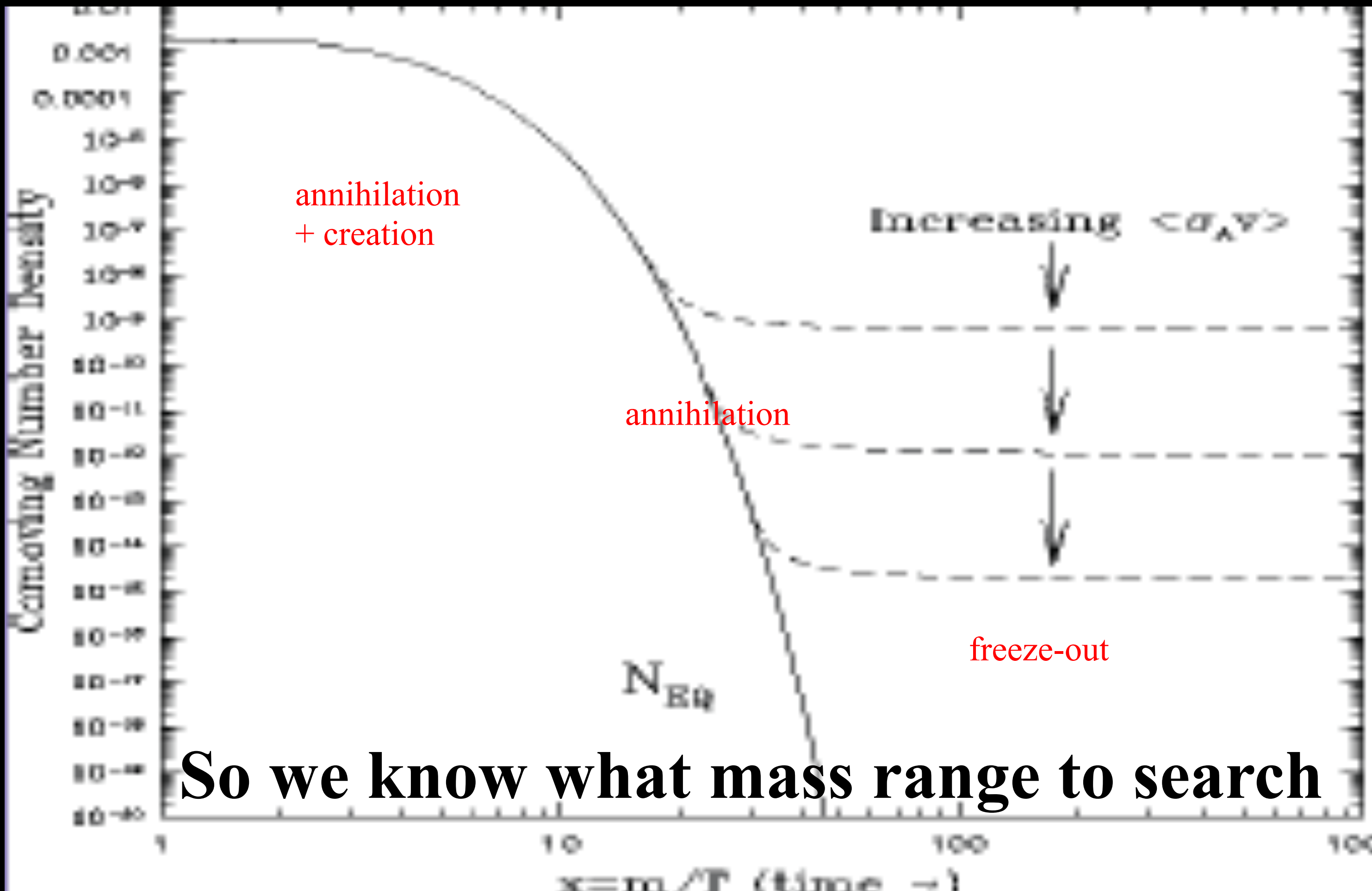
This is the WIMP!

SUSY WIMP in thermal equilibrium: $n\langle\sigma_{ann}v\rangle > t_{exp}^{-1}$
relic abundance if $\langle\sigma_{ann}v\rangle \sim 3\times10^{-26}\ cm^3/s \sim 0.23/\Omega_x$

generic WIMP
$\langle\sigma_{ann}v\rangle \sim \alpha_w^2/m_x^2 = \alpha_w^2/1\ TeV^2$

Dark matter is most likely a weakly interacting massive particle

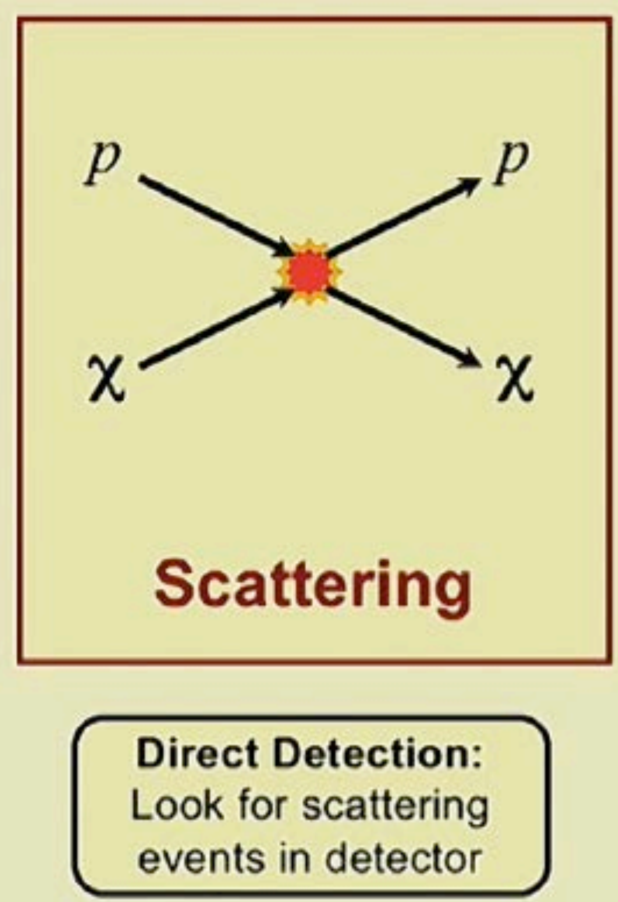
PREDICTING <σv> for a WIMP

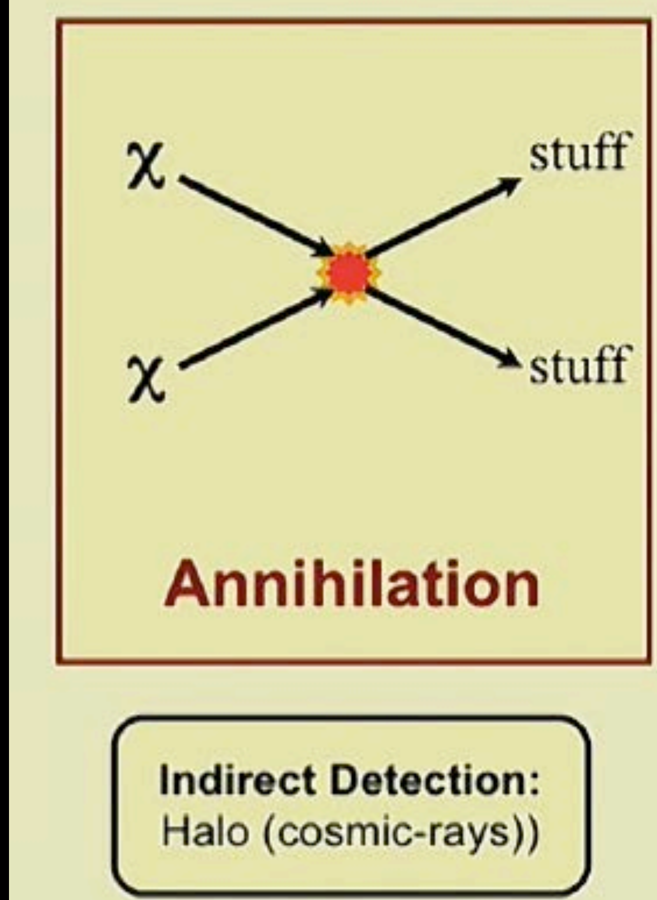


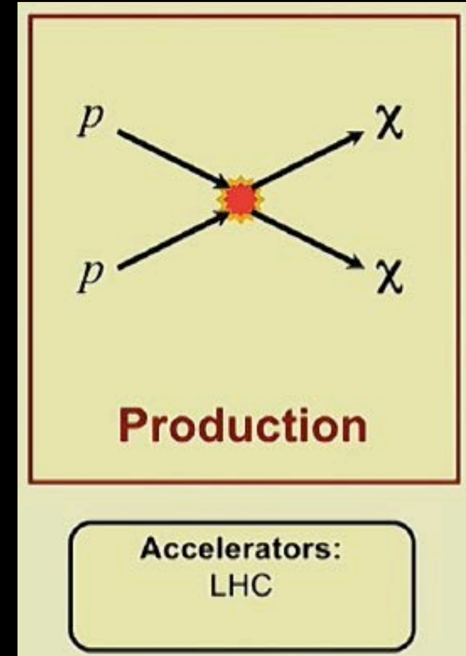
So we know what mass range to search

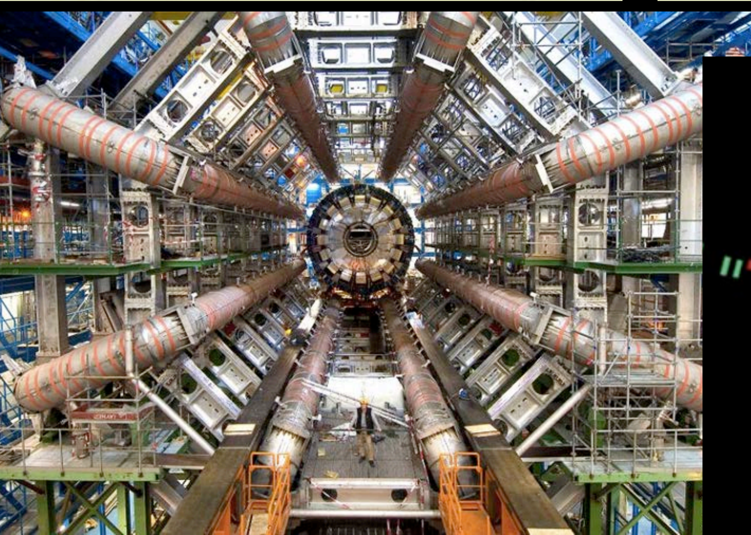
Maximum mass of thermal relic is ~ 100 TeV to avoid excessive density

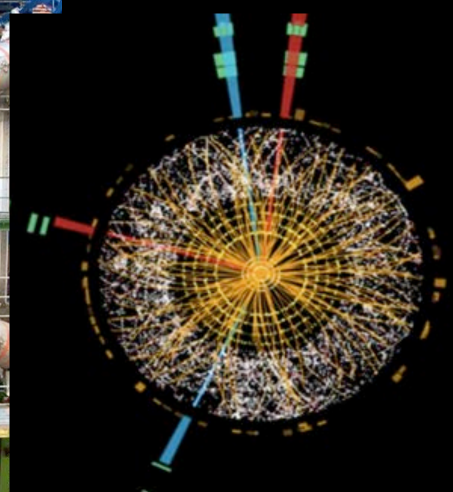
but SUSY has 100+ free parameters…


p
p
χ
χ
Scattering
Direct Detection:
Look for scattering
events in detector


χ
stuff
χ
stuff
Annihilation
Indirect Detection:
Halo (cosmic-rays))

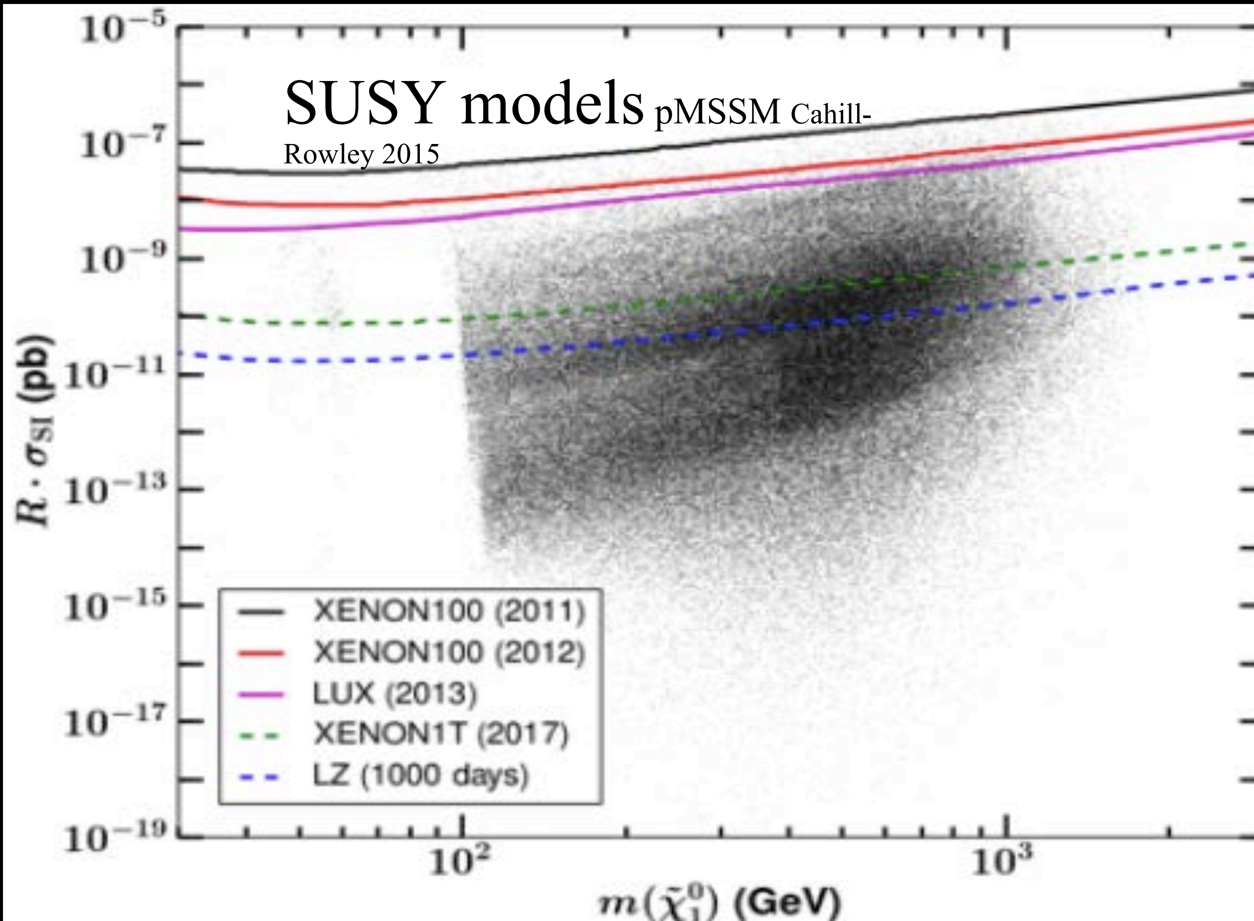

p
χ
p
χ
Production
Accelerators:
LHC





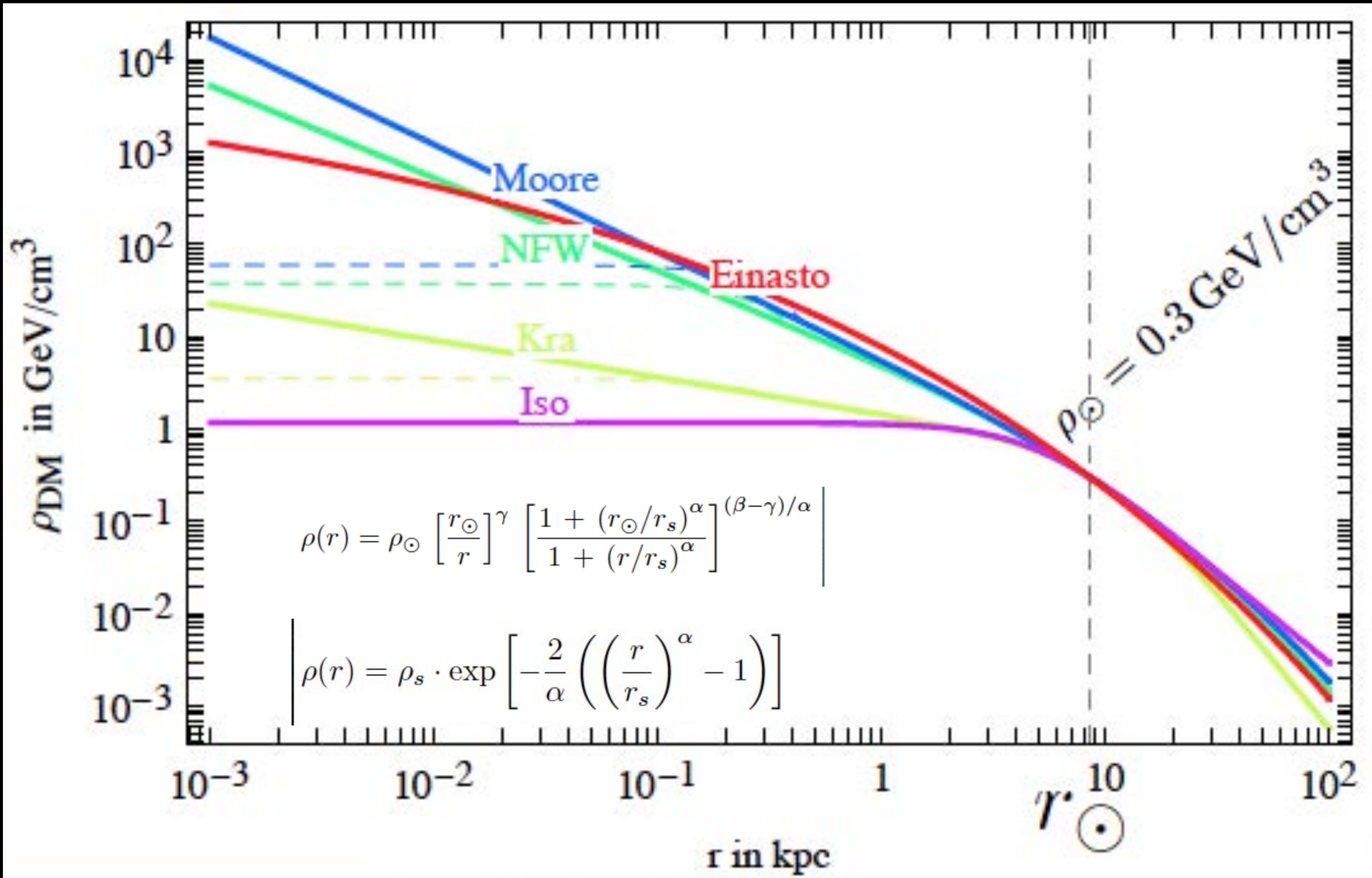
enormous uncertainties in astrophysics and in particle physics

Dark matter distribution
profiles, streams, clumps, velocity distribution
Cosmic ray propagation
diffusion, solar modulation, energy losses
Particle physics issues
fragmentation codes,
higher order corrections at TeVscales
Astrophysical backgrounds

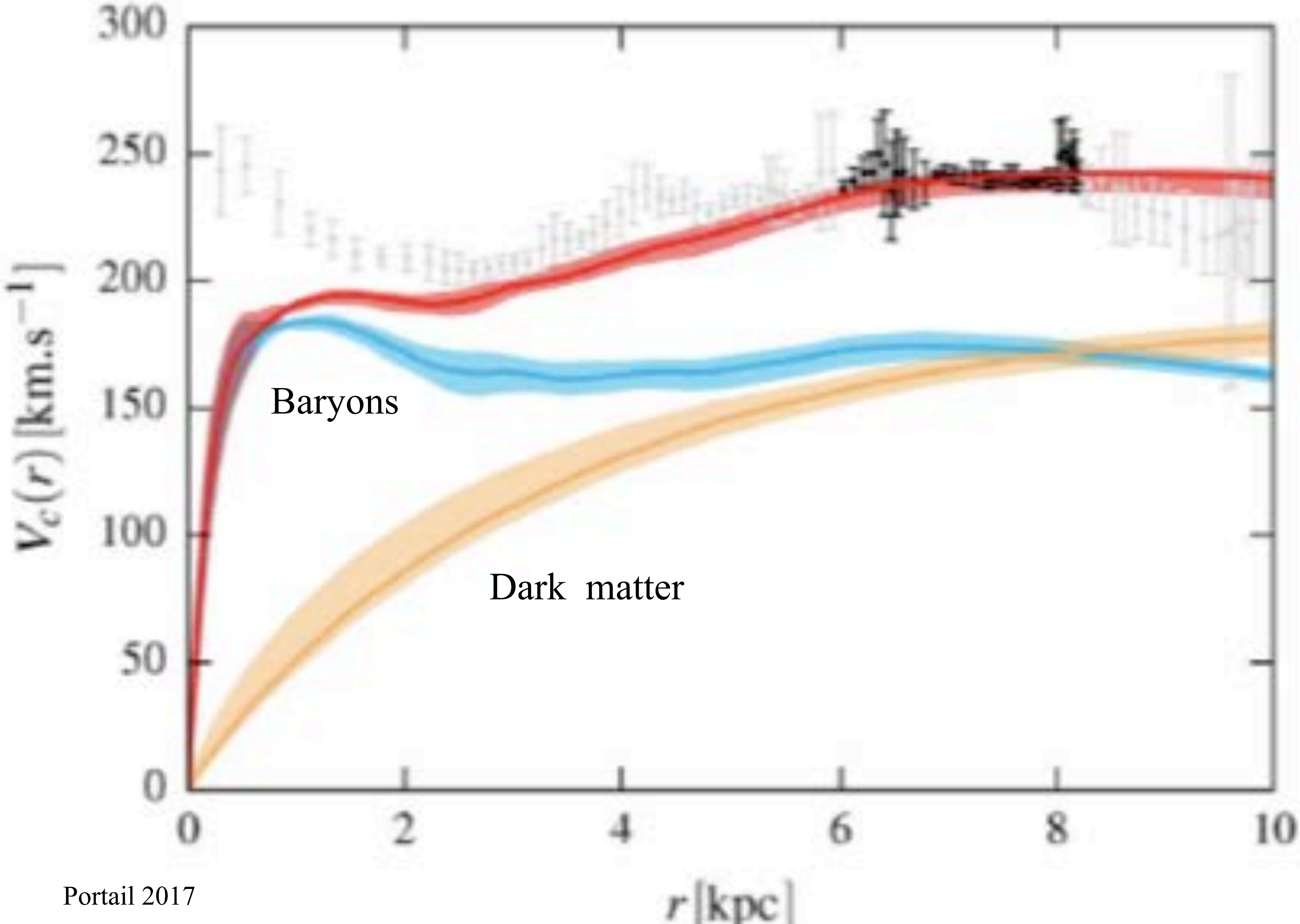


Nesti & Salucci 2013

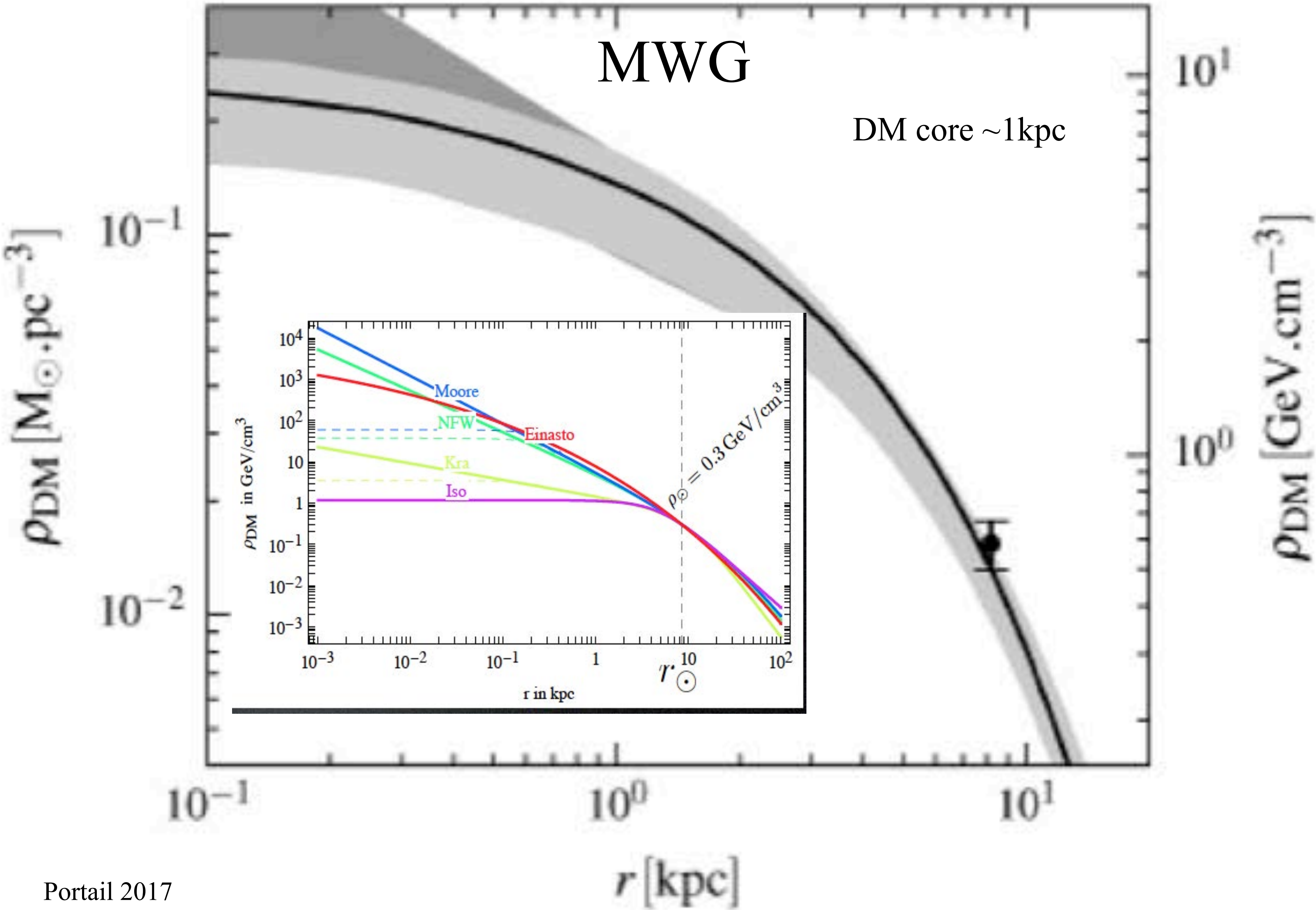
Possible dark matter profiles in our galaxy



Observationally constrained in MWG



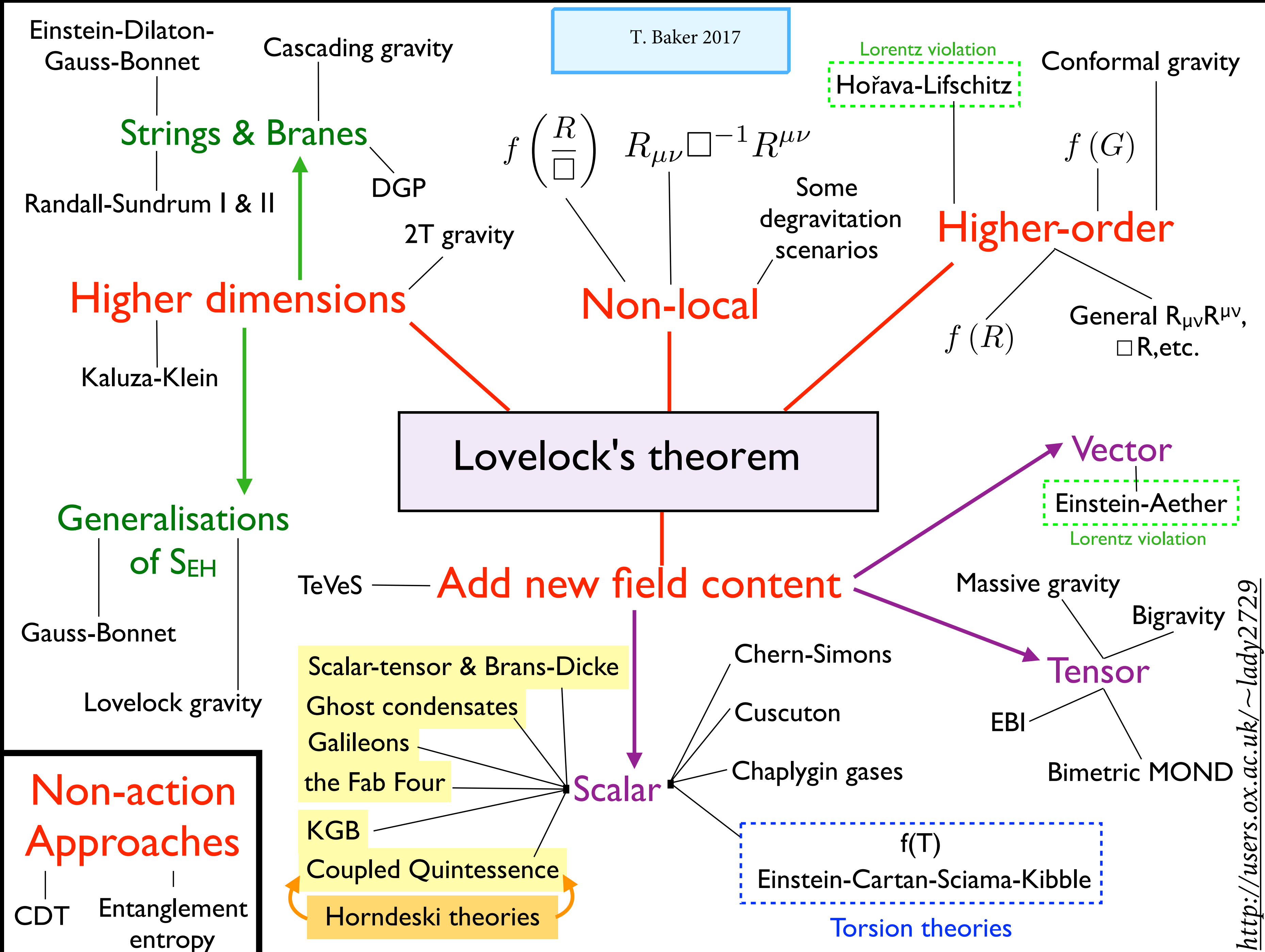
Portail 2017



Portail 2017

MODIFIED GRAVITY

What if we don't find dark matter in the next decade(s)?


T. Baker 2017
Einstein-Dilaton-Gauss-Bonnet
Cascading gravity
Strings & Branes
DGP
Randall-Sundrum I & II
2T gravity
Higher dimensions
Kaluza-Klein
Generalisations of S_{EH}
Gauss-Bonnet
Lovelock gravity
$f\left(\frac{R}{\Box}\right)$
$R_{\mu\nu}\Box^{-1}R^{\mu\nu}$
Some degravitation scenarios
Non-local
Lorentz violation
Hořava-Lifschitz
Conformal gravity
$f(G)$
Higher-order
$f(R)$
General $R_{\mu\nu}R^{\mu\nu}$, $\Box R$, etc.
Lovelock's theorem
Vector
Einstein-Aether
Lorentz violation
TeVeS
Add new field content
Massive gravity
Bigravity
Tensor
EBI
Bimetric MOND
Scalar-tensor & Brans-Dicke
Ghost condensates
Galileons
the Fab Four
KGB
Coupled Quintessence
Horndeski theories
Scalar
Chern-Simons
Cuscuton
Chaplygin gases
f(T)
Einstein-Cartan-Sciama-Kibble
Torsion theories
Non-action Approaches
CDT
Entanglement entropy
http://users.ox.ac.uk/~lady2729

THE NEW THEORY LANDSCAPE

Quintessence

Horndeski

Quintic Galileons

K-essence

Generalised Proca

Quartic Galileons

Bigravity

Einstein-Aether

TeVeS

Massive Gravity

DHOST

SVT

Brans-Dicke

Horava-Lifschitz

Fab Four

f(R)

KGB

Cubic Galileon

THE NEW THEORY LANDSCAPE

CTD

Quintessence

Horndeski

Quintic Galileons

K-essence

Generalised Proca

Quartic Galileons

Einstein-Aether

Bigravity

TeVeS

DHOST

Massive Gravity

SVT

Horava-Lifschitz

Fab Four

KGB

Brans-Dicke

f(R)

Cubic Galileon

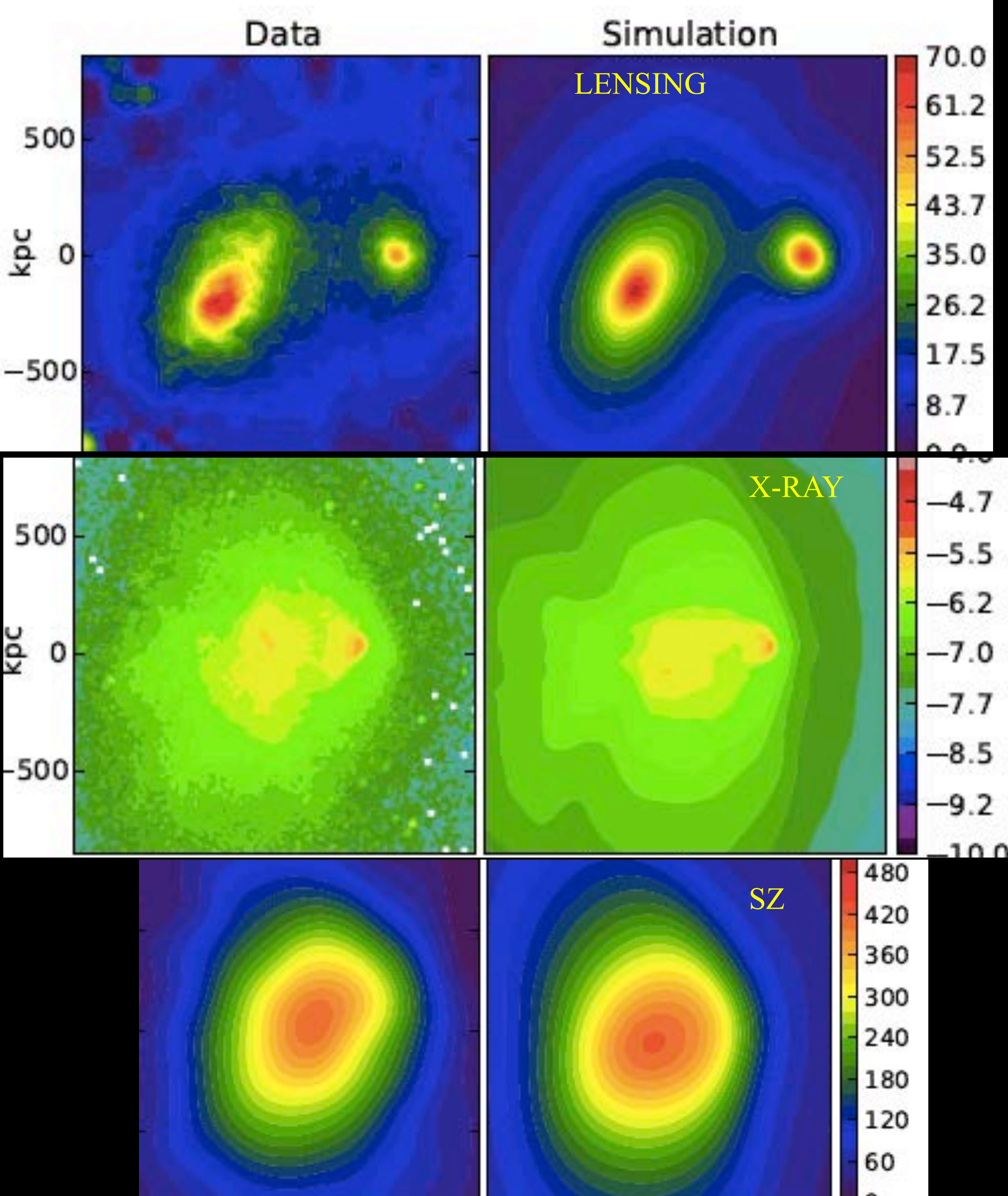
T. Baker 2018

Evidence for modified gravity?

Dark matter is weakly interacting

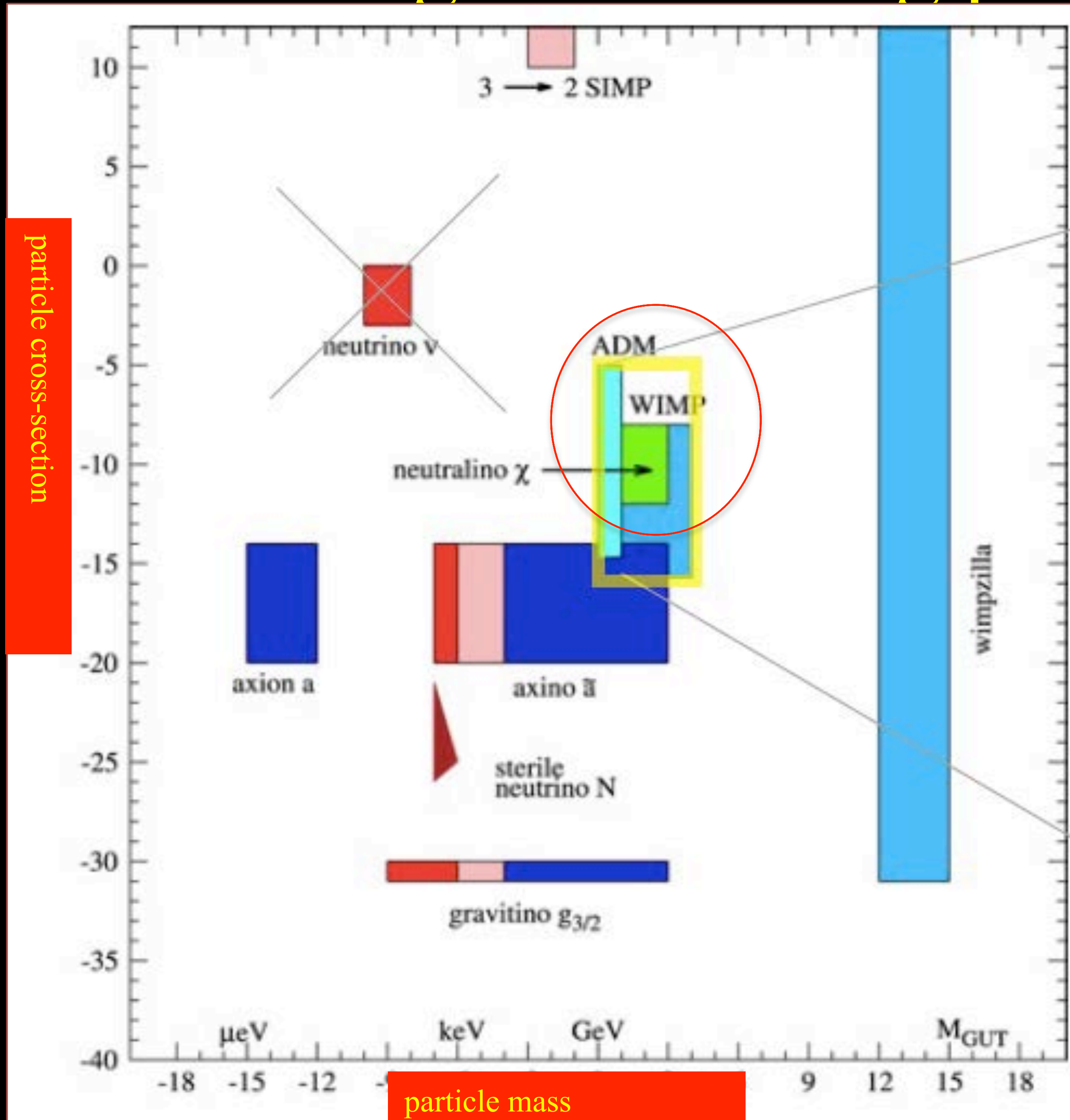
Lage & Farrar 2014

CDM accounts for Bullet Cluster



Modified gravity:
works maybe for dark energy
but so far not for dark matter

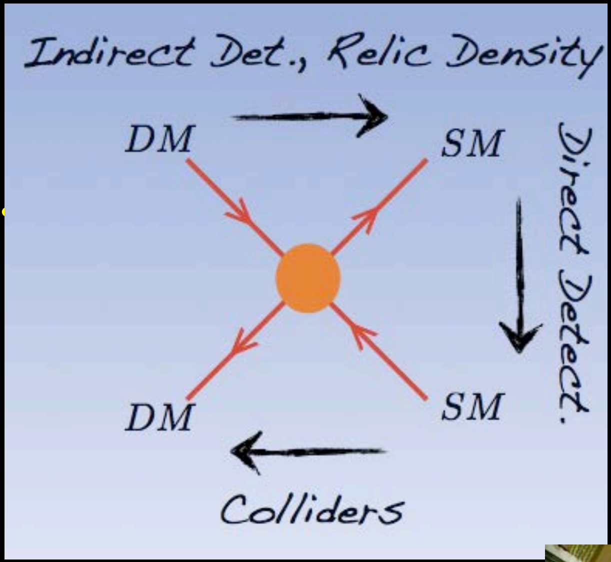
Are we looking in the wrong place?



DARK MATTER DETECTION

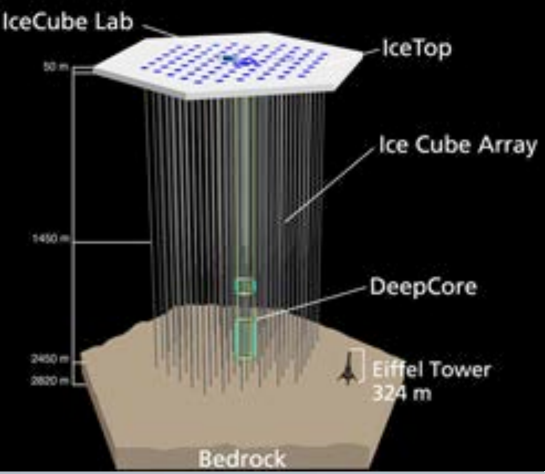
Indirect detection of energetic γ, ν, e^+…

$\sigma v >\sim 3\times10^{-26}$ cm^3/s , $\sigma_{ann} \sim 10^{-36}$ cm^2

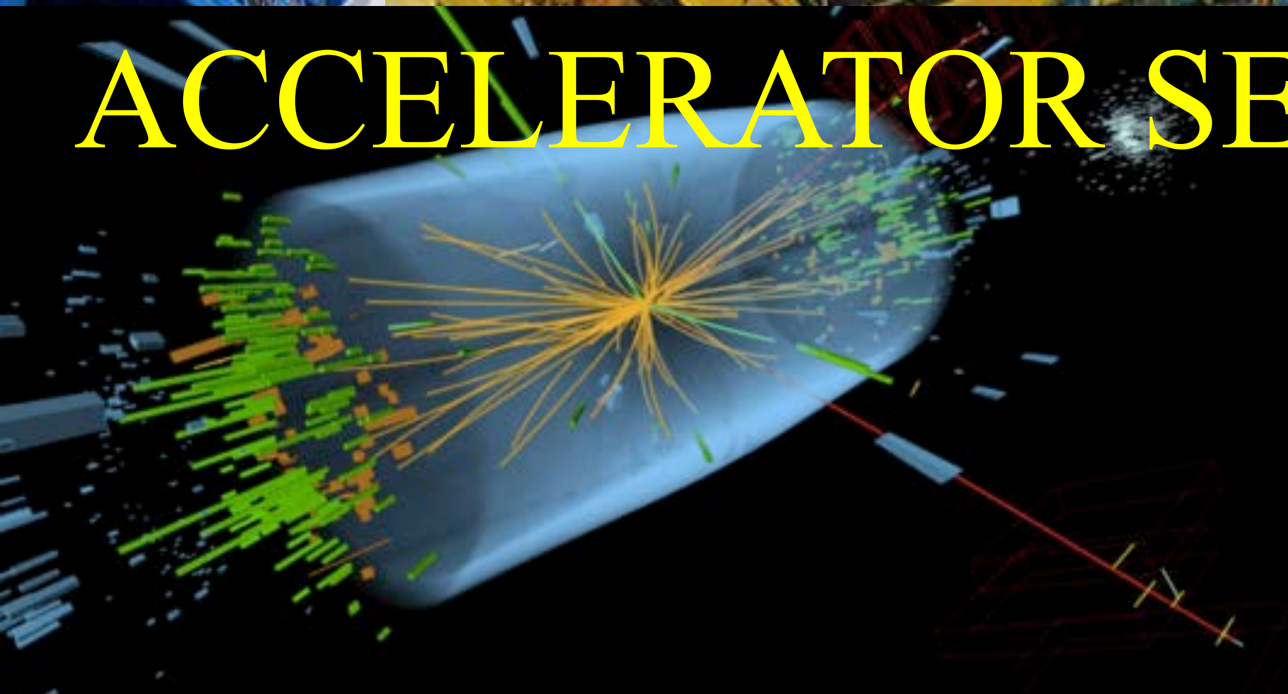


direct detection and colliders

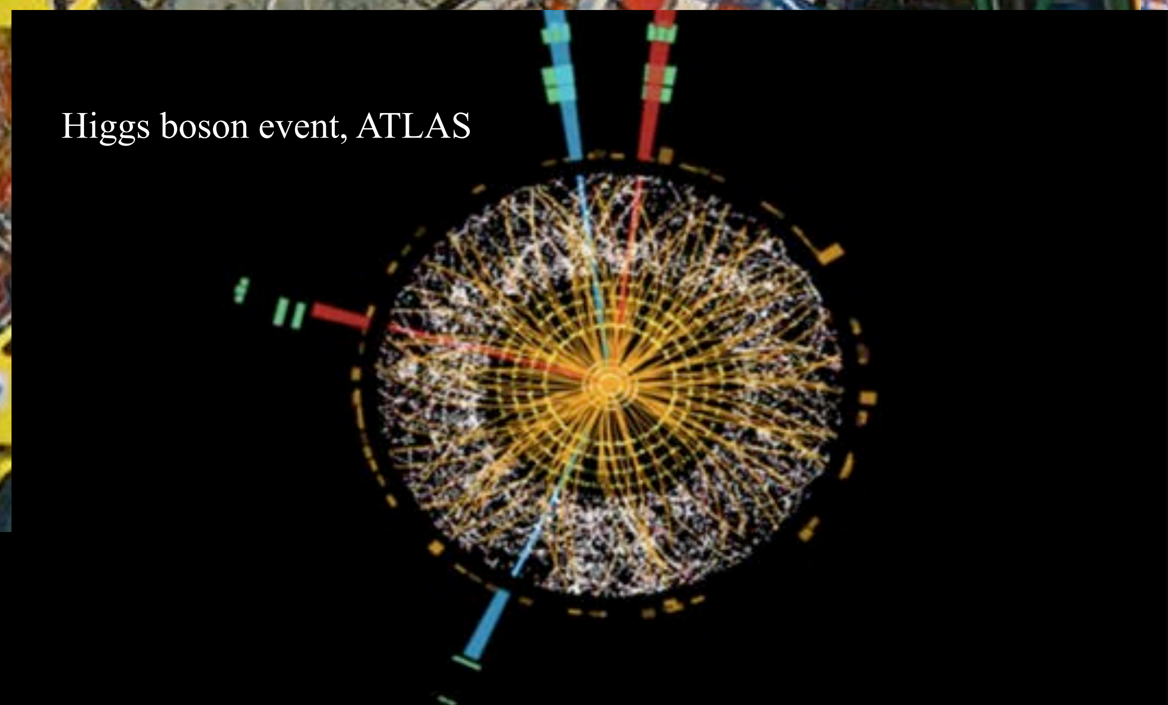
$\sigma_{sca} \sim 10^{-38}$ cm^2



ACCELERATOR SEARCHES



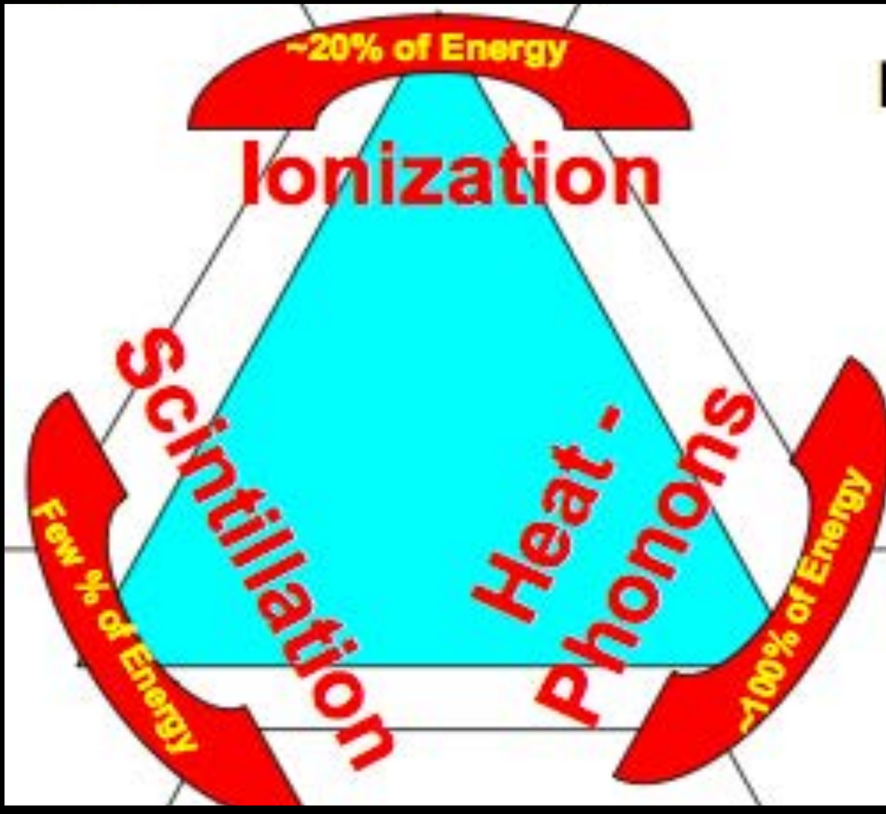
ATLAS

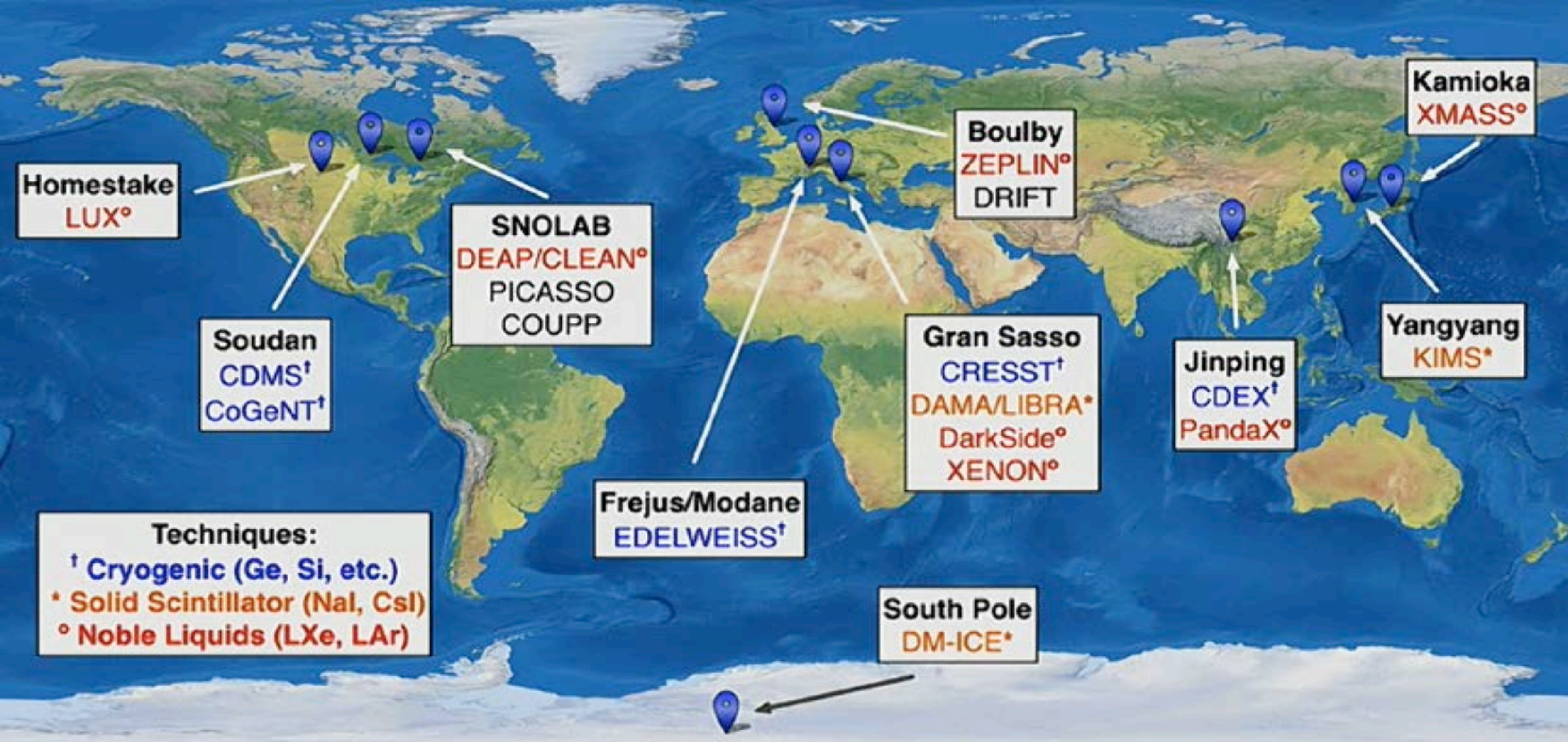


Higgs boson event, ATLAS

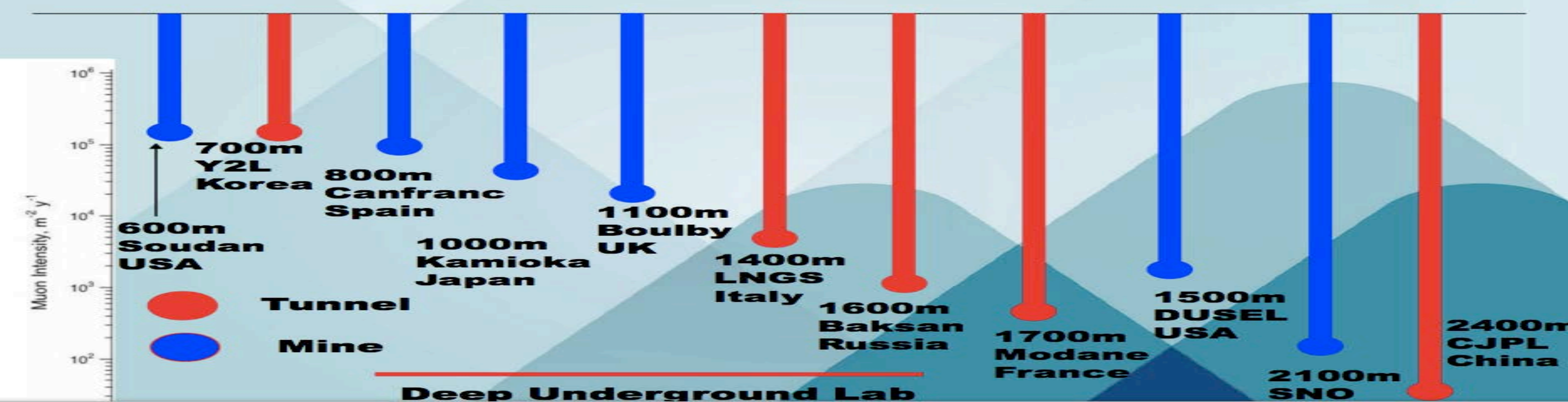
DIRECT DETECTION

many WIMPs pass through us every second

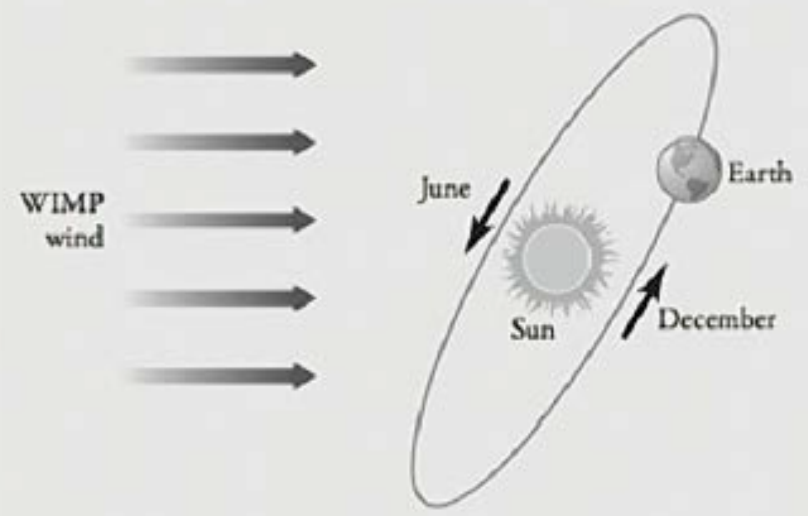




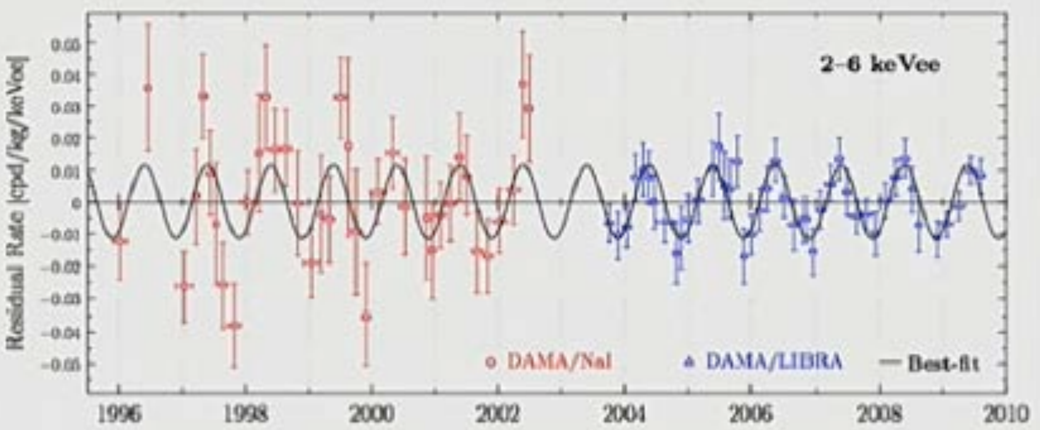
UL in the world(rock overburden)

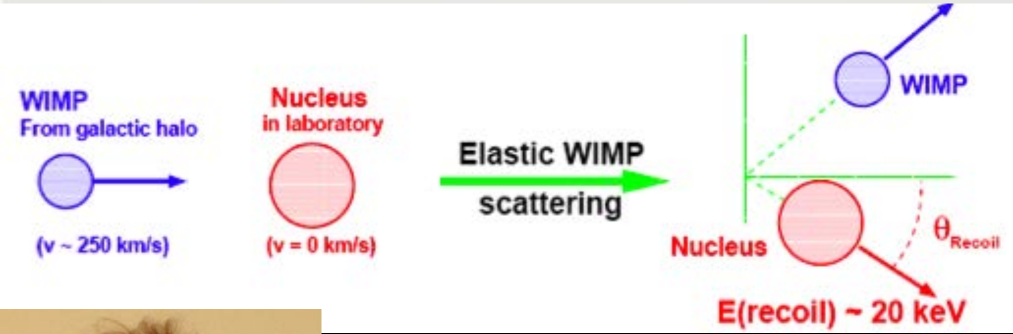


Sodium iodide crystals detect WIMPS by scintillations



13 yrs, 8.9 σ

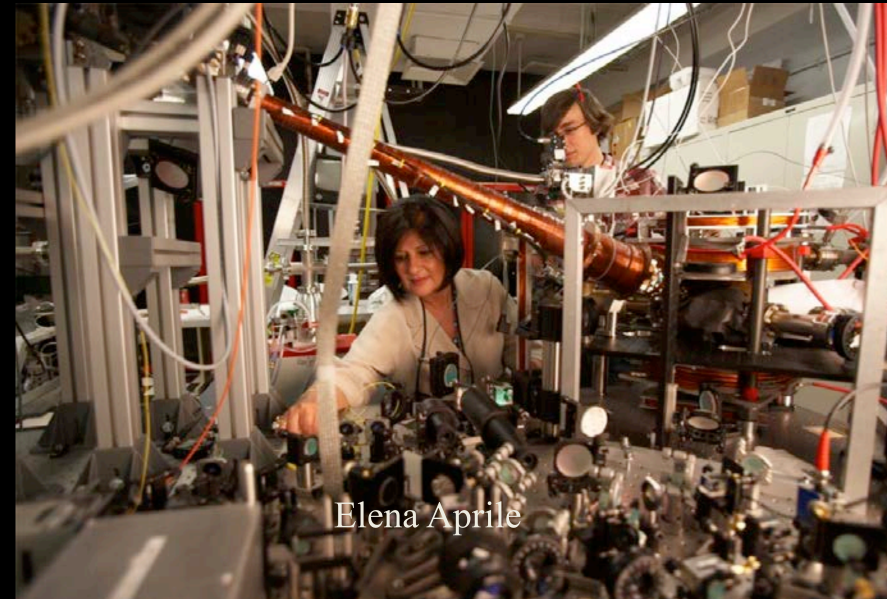




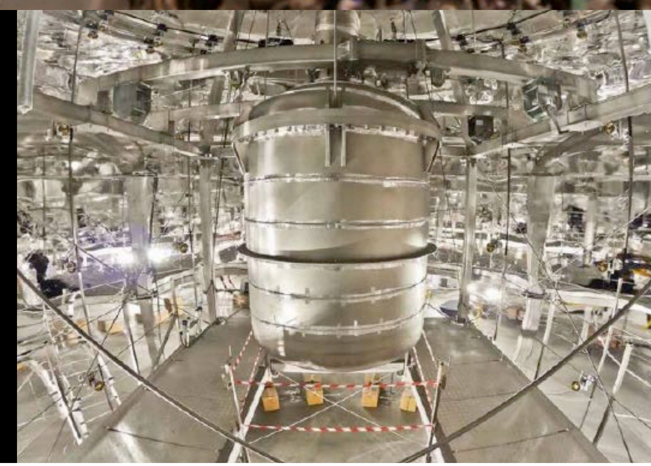
This result was a red flag for the competition!

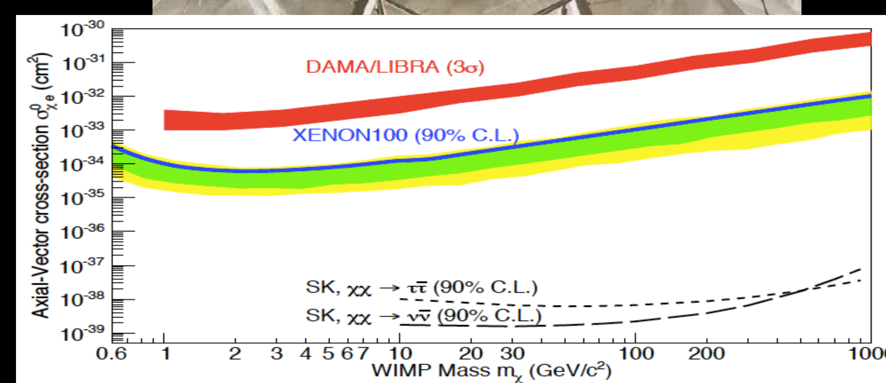
Liquid xenon 1 ton

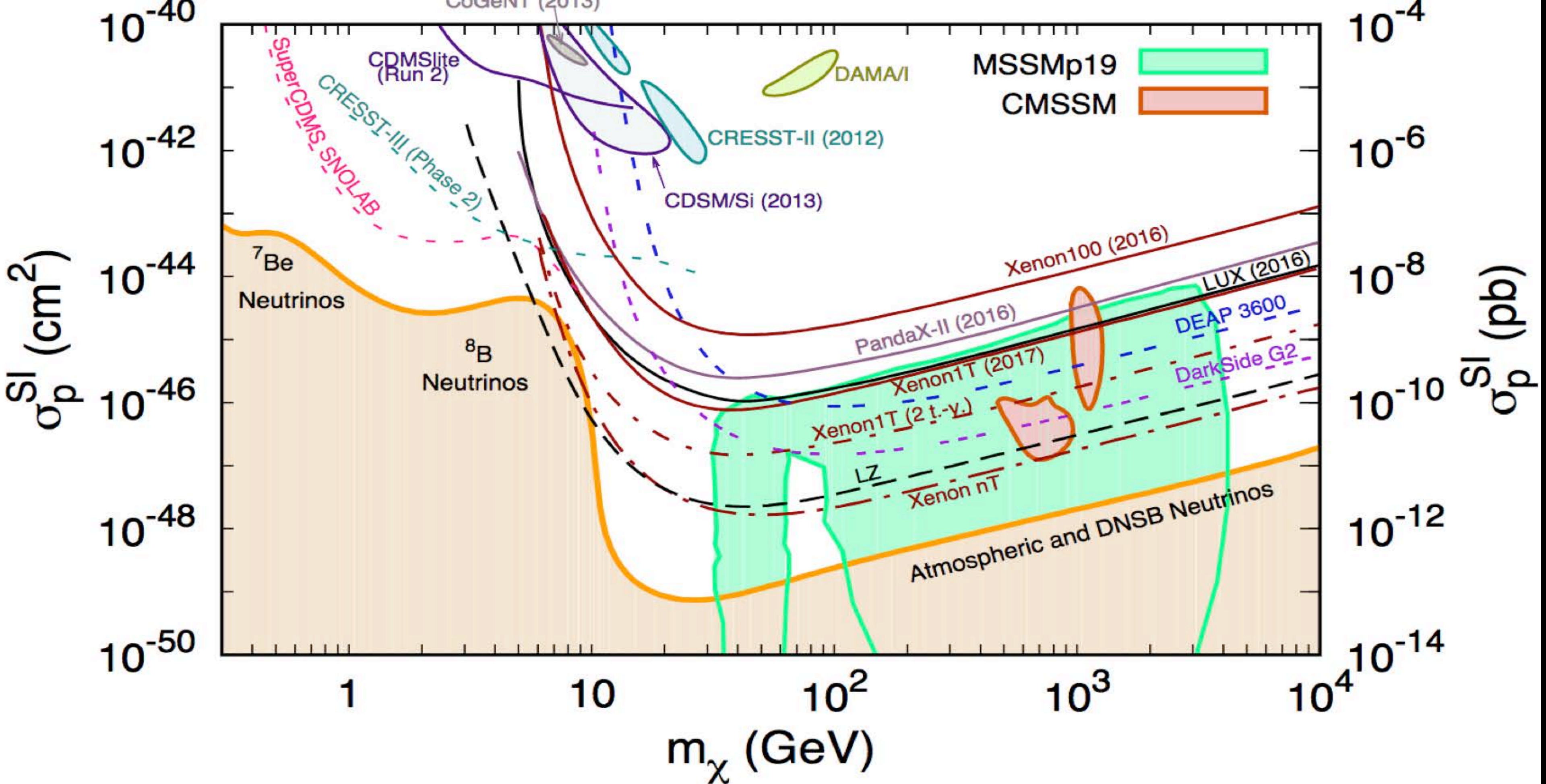
in the Gran Sasso National Lab in Abruzzo, Italy, under 1.4 km of rock, reached by a 10 km freeway tunnel under the Gran Sasso mountain



In the Black Hills of South Dakota, one mile undergound in a former gold mine. 0.3 ton of liquid xenon

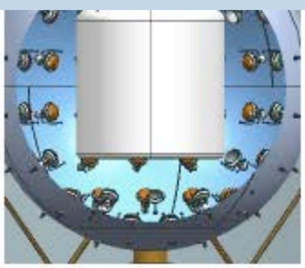




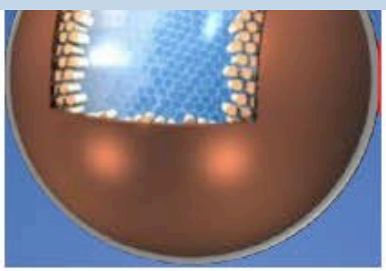


The future for direct detection

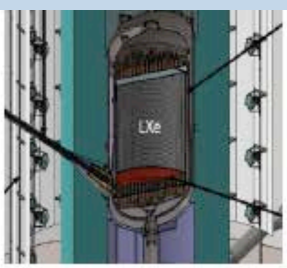
XENON1T: 3.3 t LXe



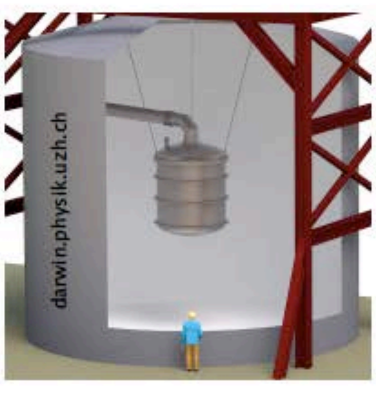
DarkSide: 20 t LAr



XMASS: 5t LXe



LZ: 7t LXe



DARWIN: 50 t LXe

Lecture

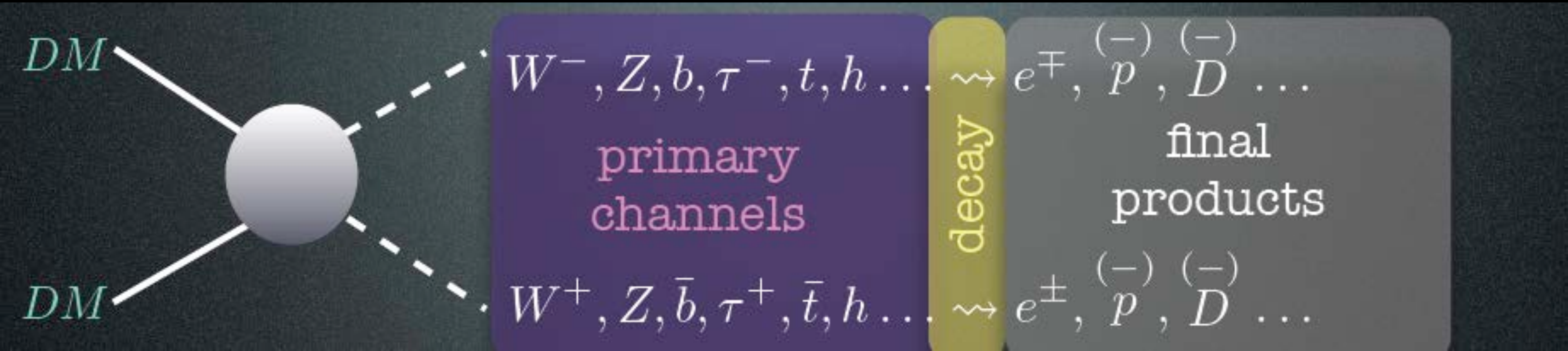
2

DARK MATTER ANNIHILATION PREDICTIONS

INDIRECT DETECTION

halo WIMPS are majorana particles and occasionally annihilate today into energetic particles:

Neutrinos, gamma rays, positrons…



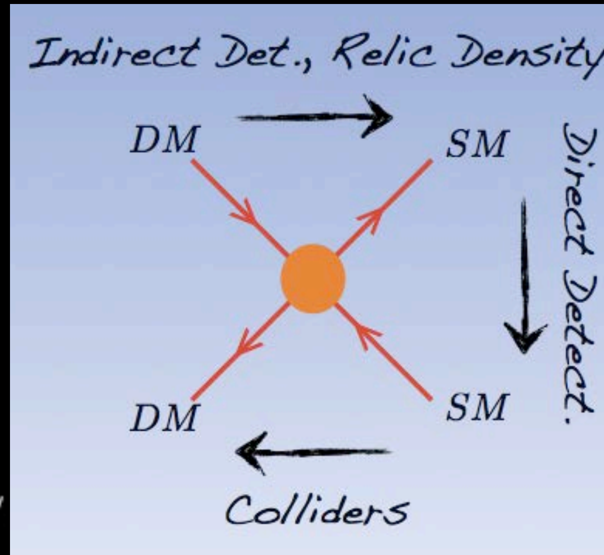
COMPACT OBJECTS

a. The Sun
b. Neutron stars
c. Black holes

DARK MATTER DETECTION

Indirect detection
of high energy γ, ν, e^+…

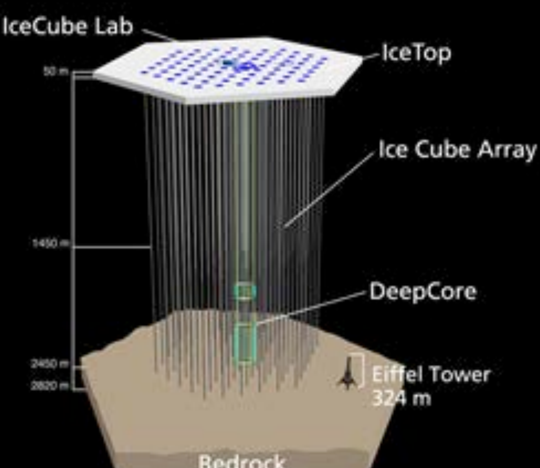
σv>~$3x10^{-26}$ cm^3/s
σ_{ann} ~10^{-36} cm^2



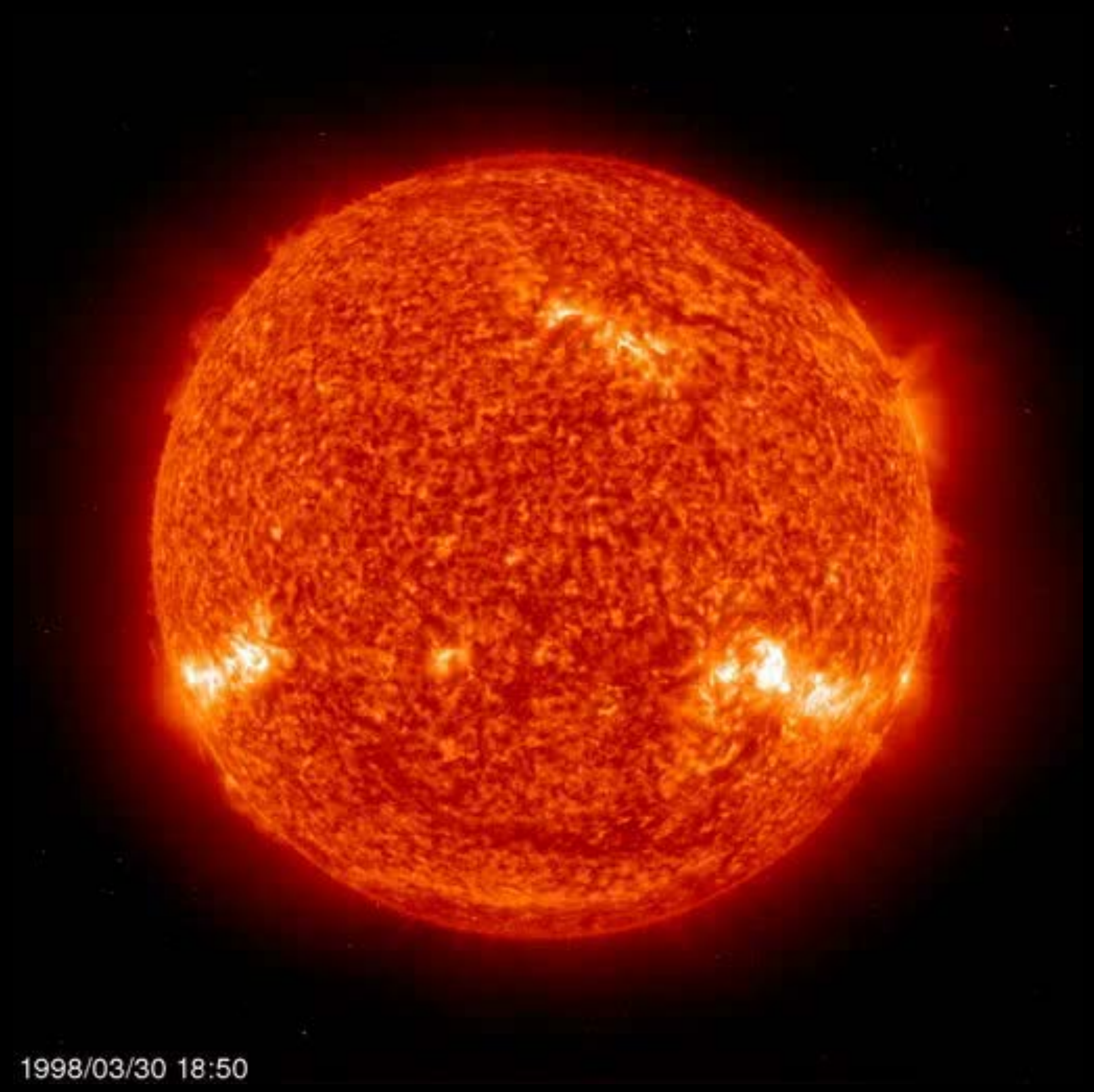
Hambye 2014

direct detection
and colliders

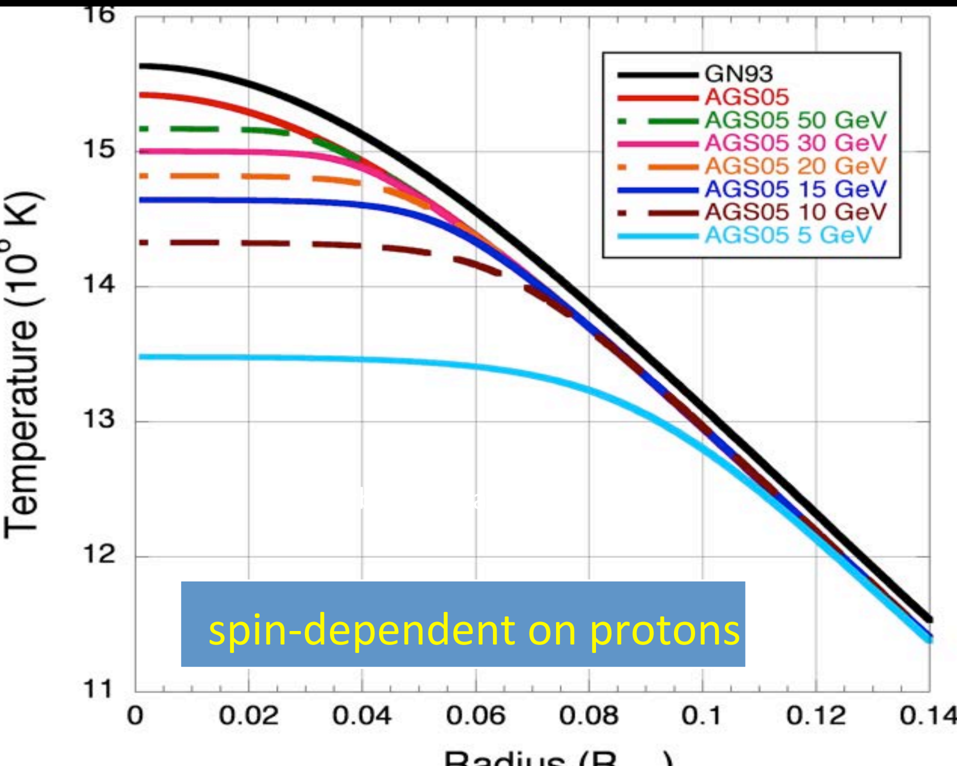
σ_{sca} ~10^{-38} cm^2

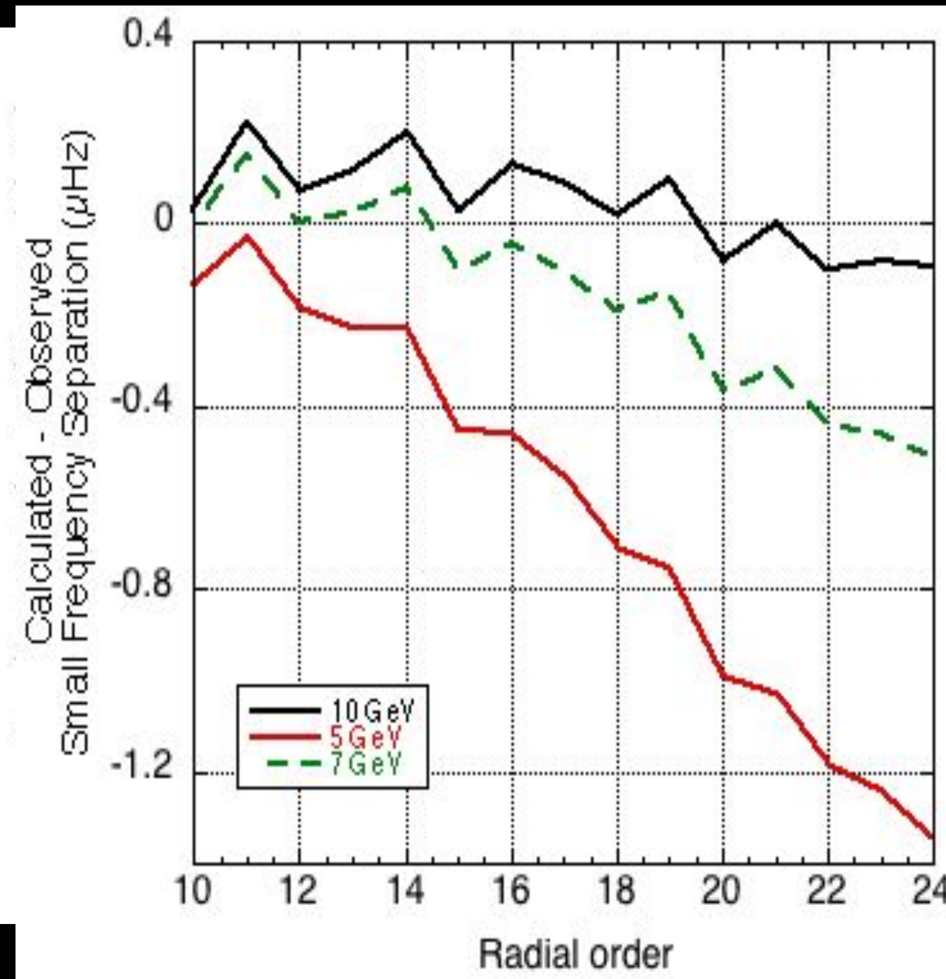


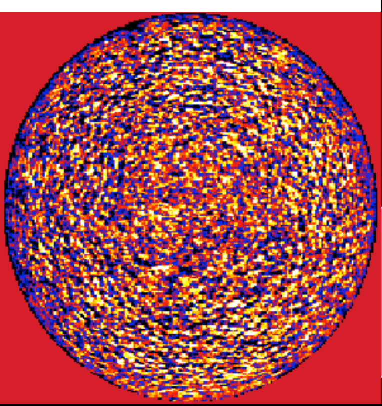
the SUN collects dark matter!

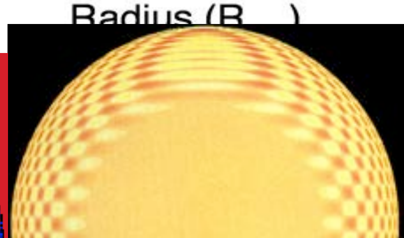


low mass (m_x ~5-10 GeV) WIMPS are trapped, fill the solar core…. and modify T(r) if non-annihilating





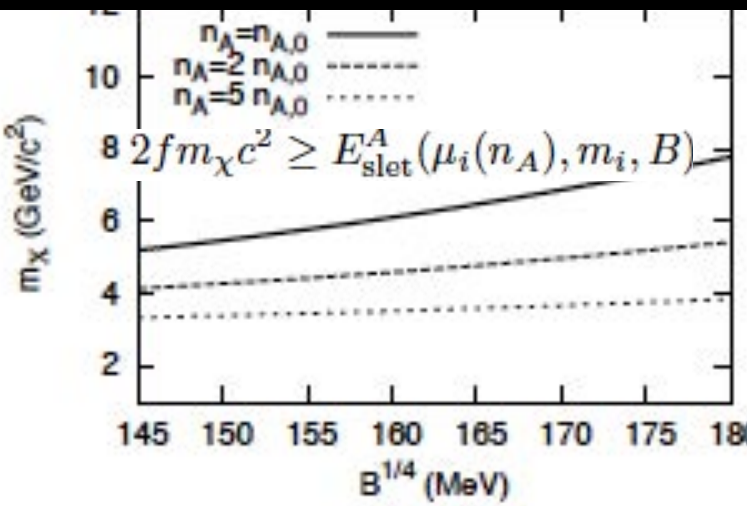




helioseismology rules out 5 GeV
in some cases…

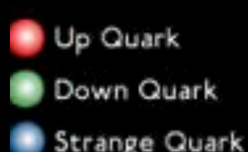
NEUTRON STARS

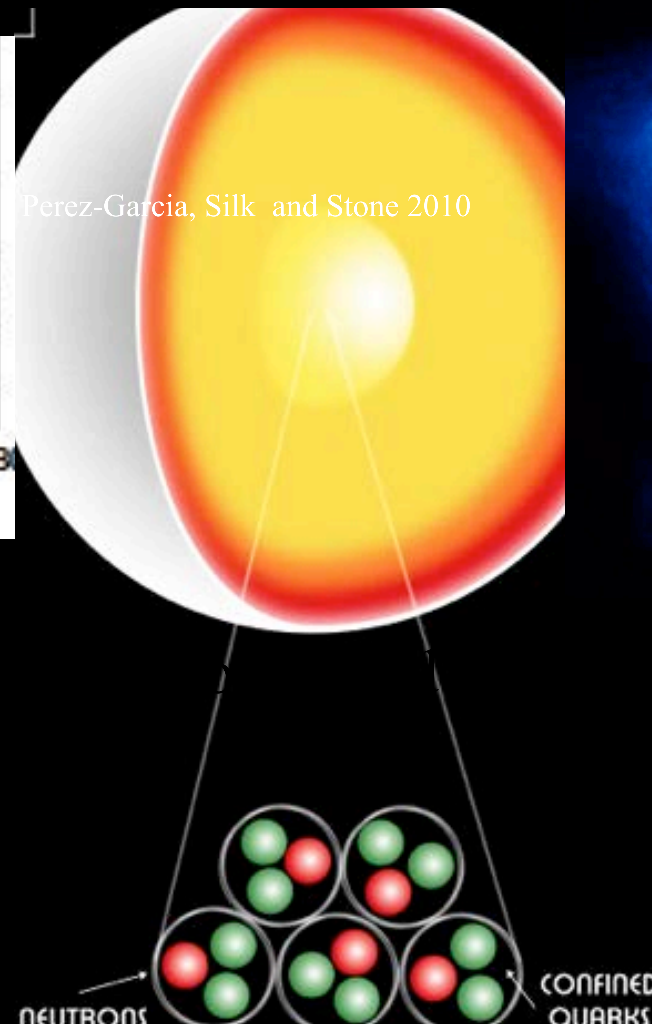
WIMP ANNIHILATIONS MAY CONVERT A NEUTRON STAR TO A QUARK STAR if neutron matter is metastable

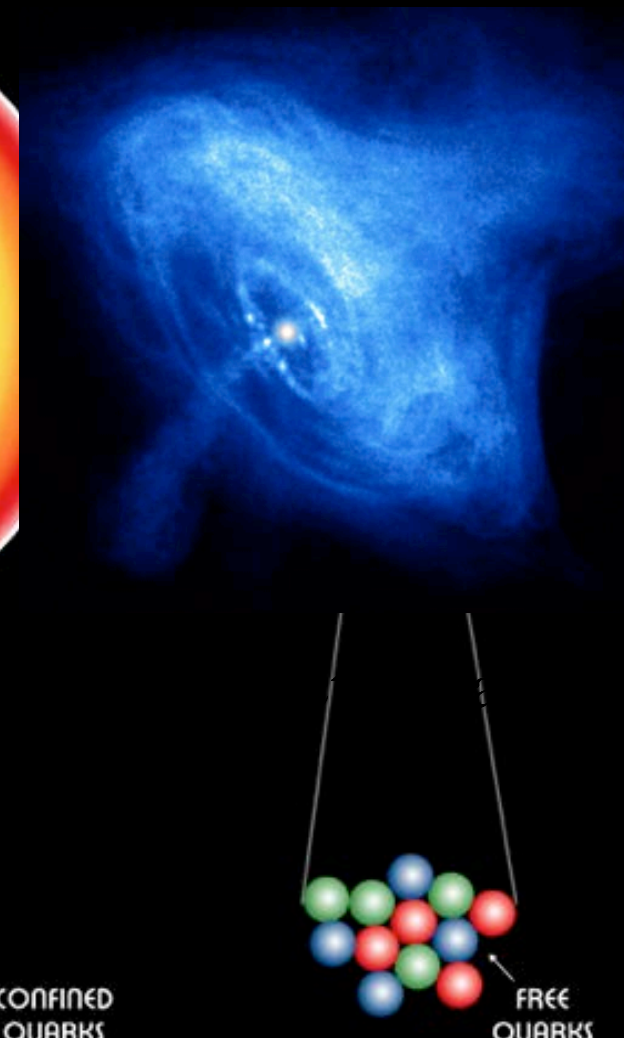


$$2fm_\chi c^2 \geq E^A_{\rm slet}(\mu_i(n_A), m_i, B)$$

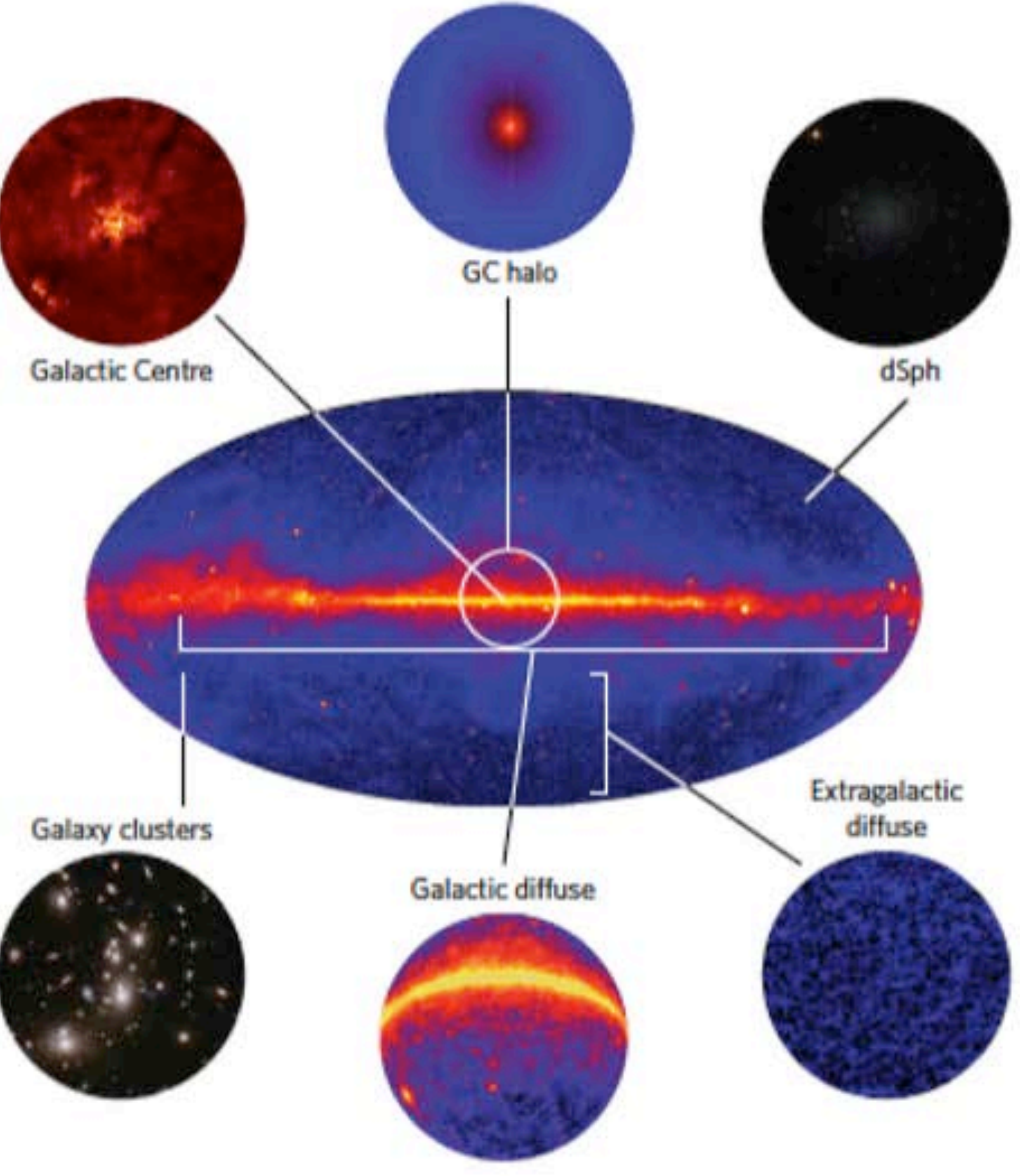
Perez-Garcia, Silk and Stone 2010







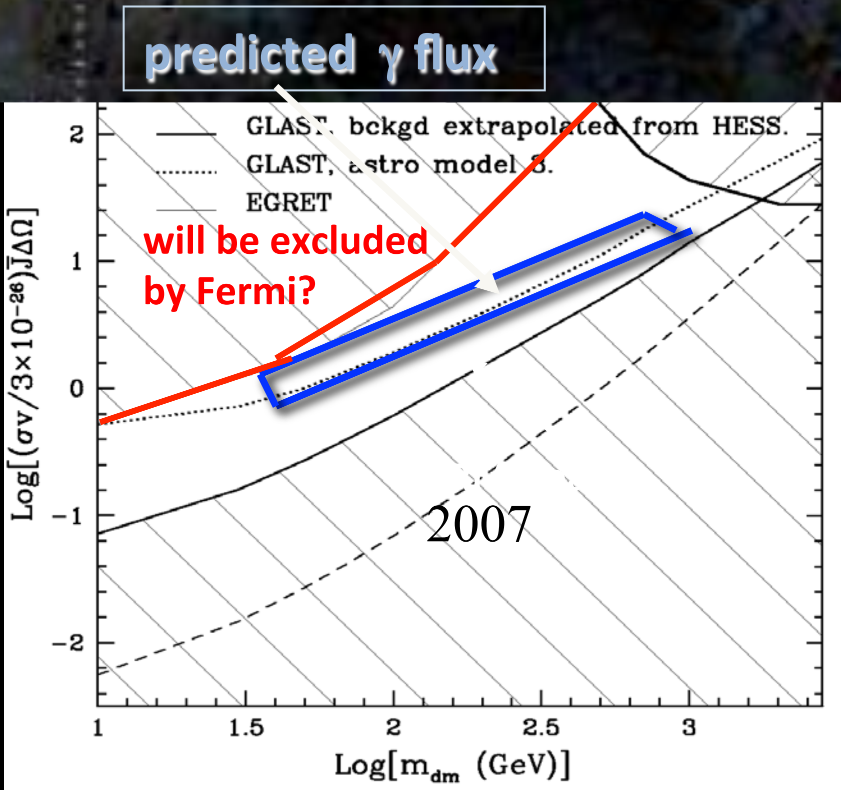
GALAXIES

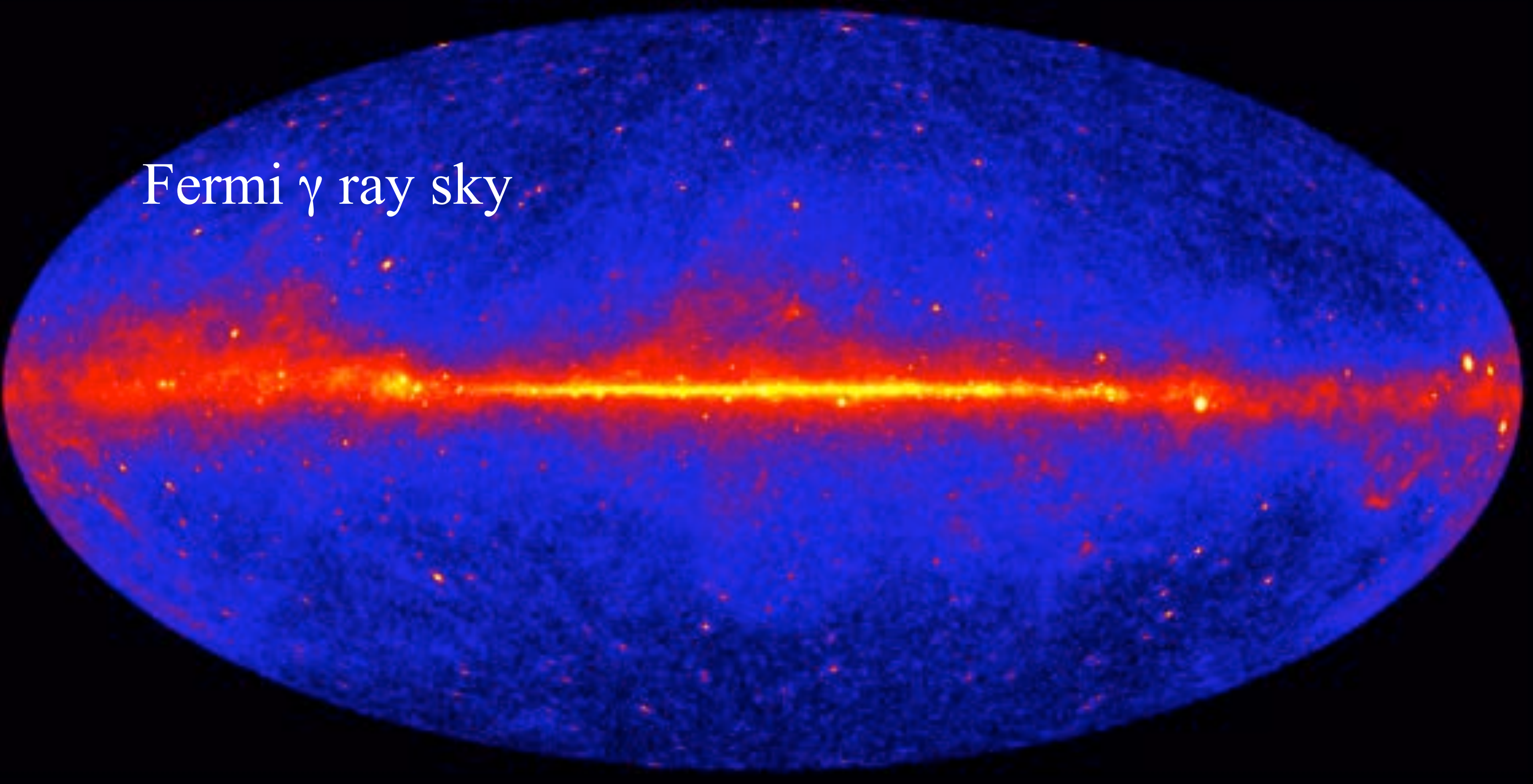


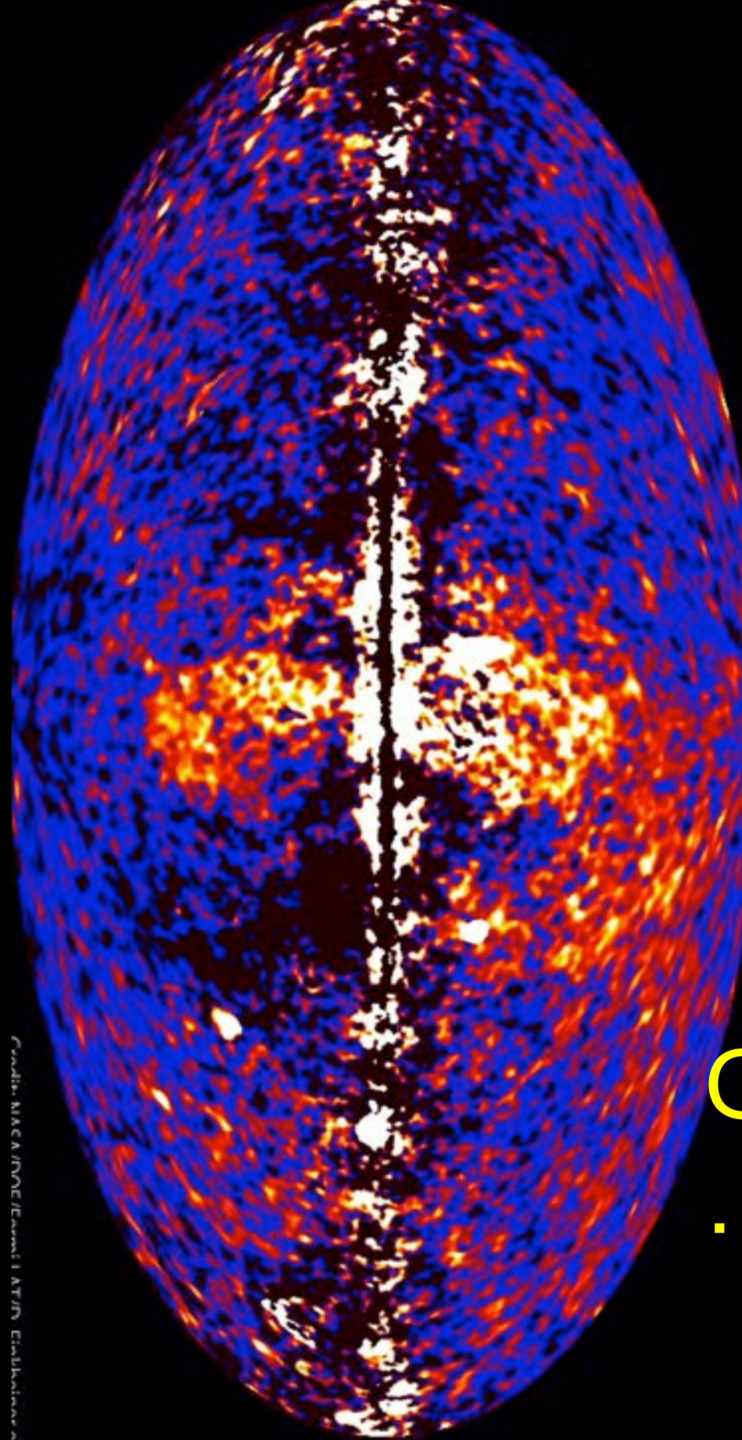
Conrad & Reimer 2017

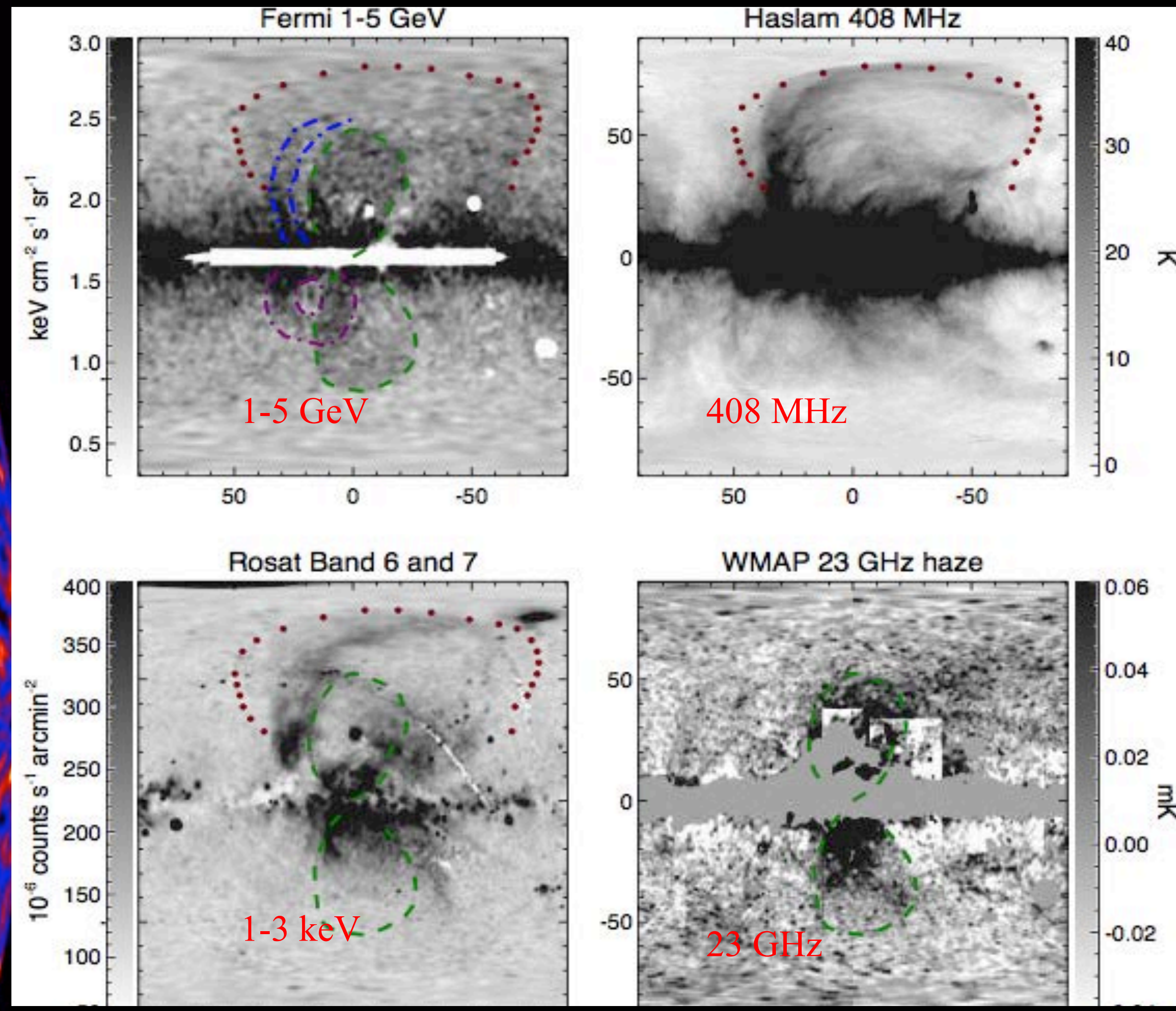
Radio synchrotron emission

The WMAP microwave haze: dark matter annihilations?




Fermi γ ray sky

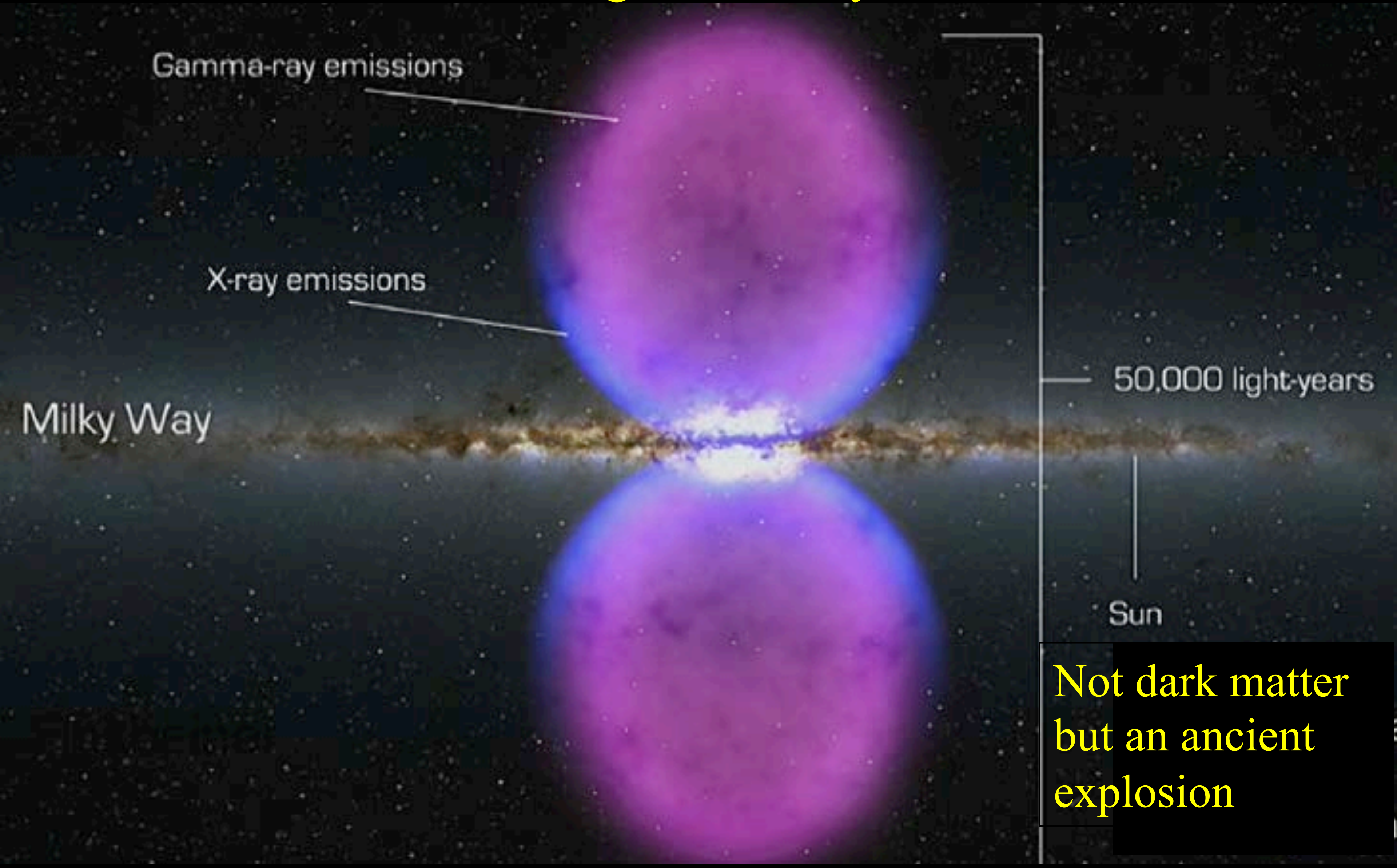




Giant gamma ray bubbles …not dark matter

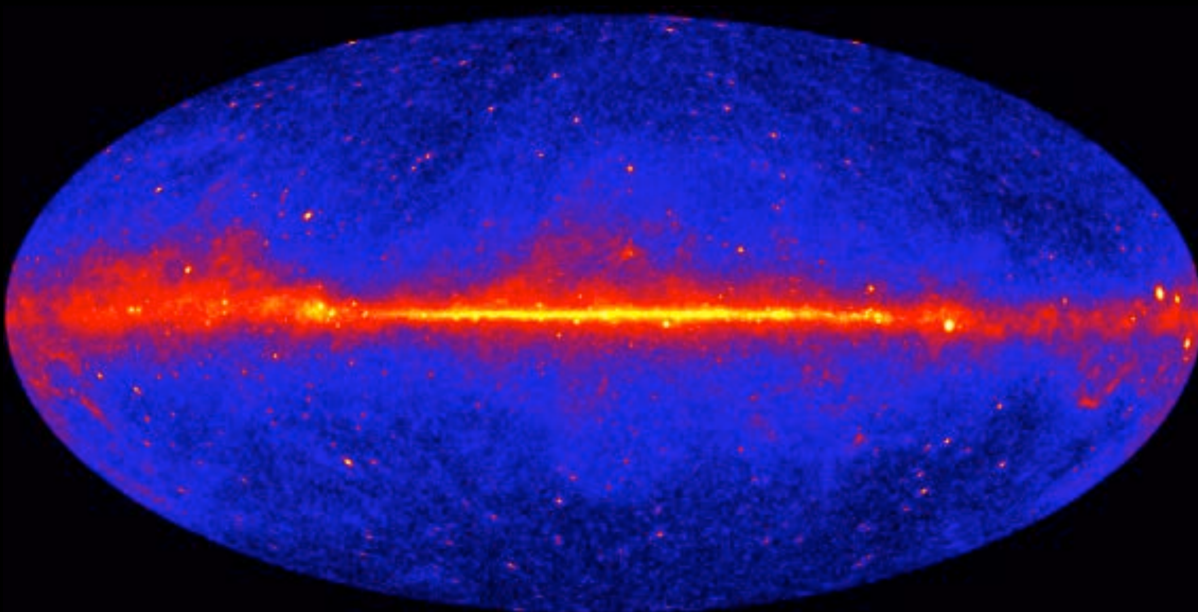
haze is inverse Compton of e^+e^- on interstellar radiation

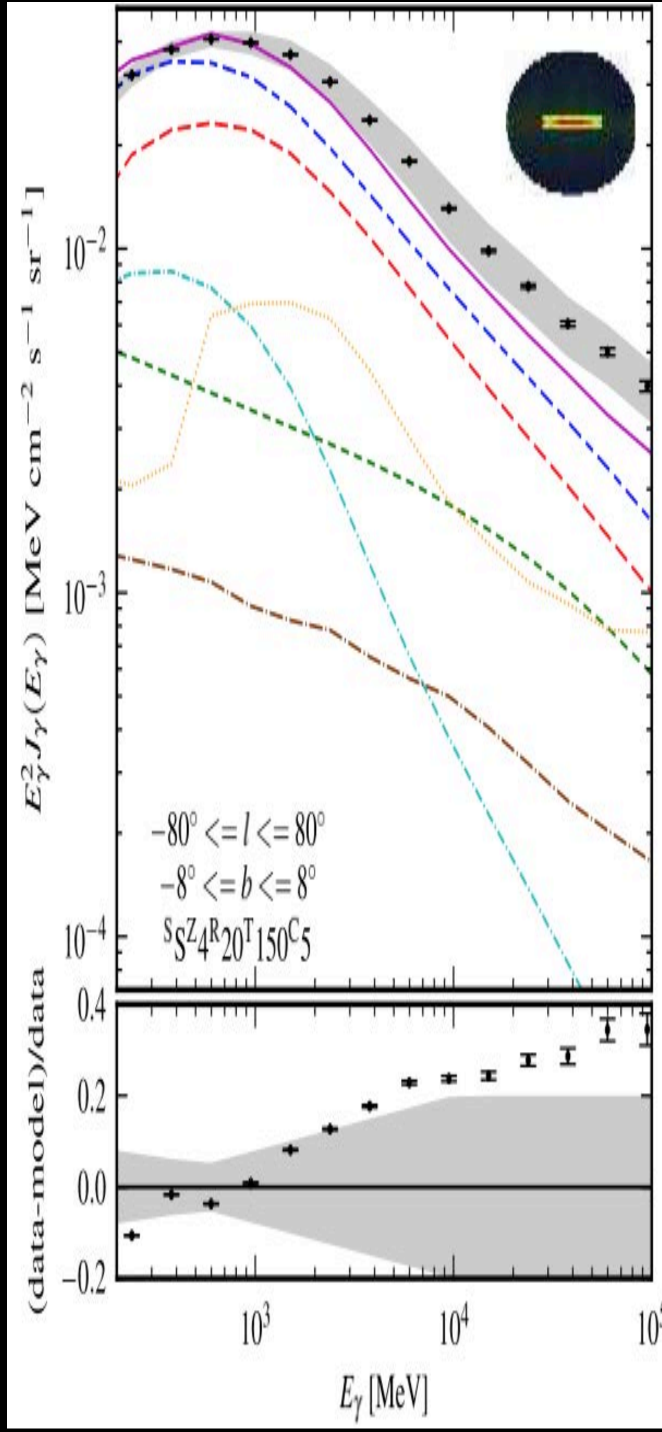
The Fermi gamma ray bubble

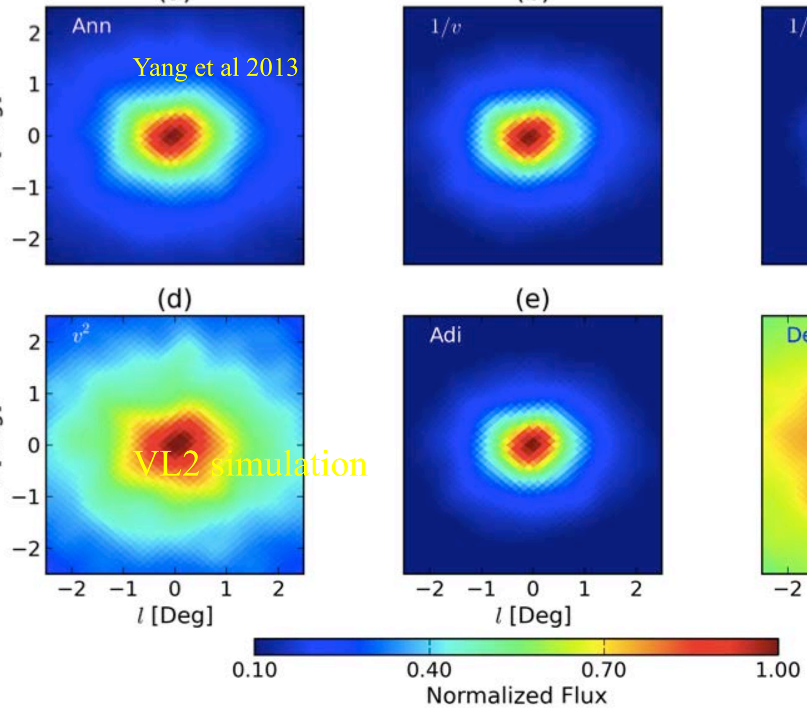


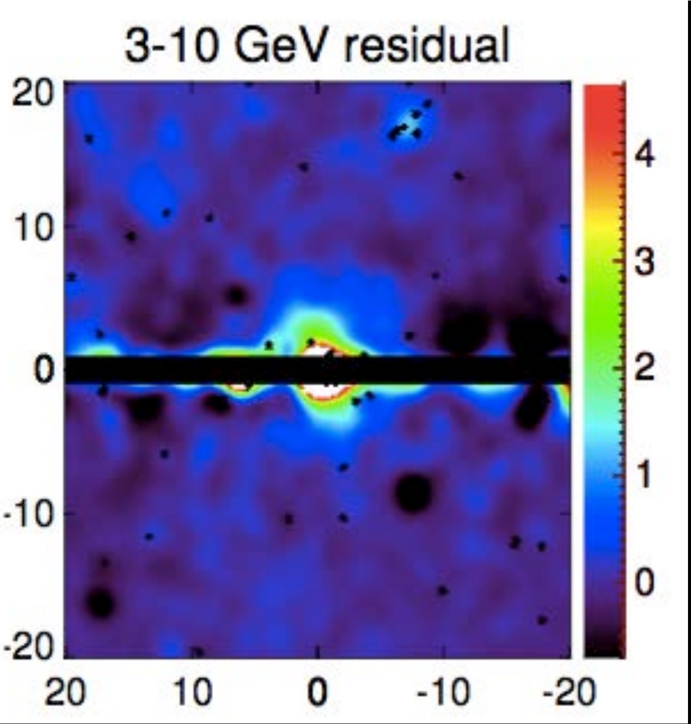
Not dark matter but an ancient explosion

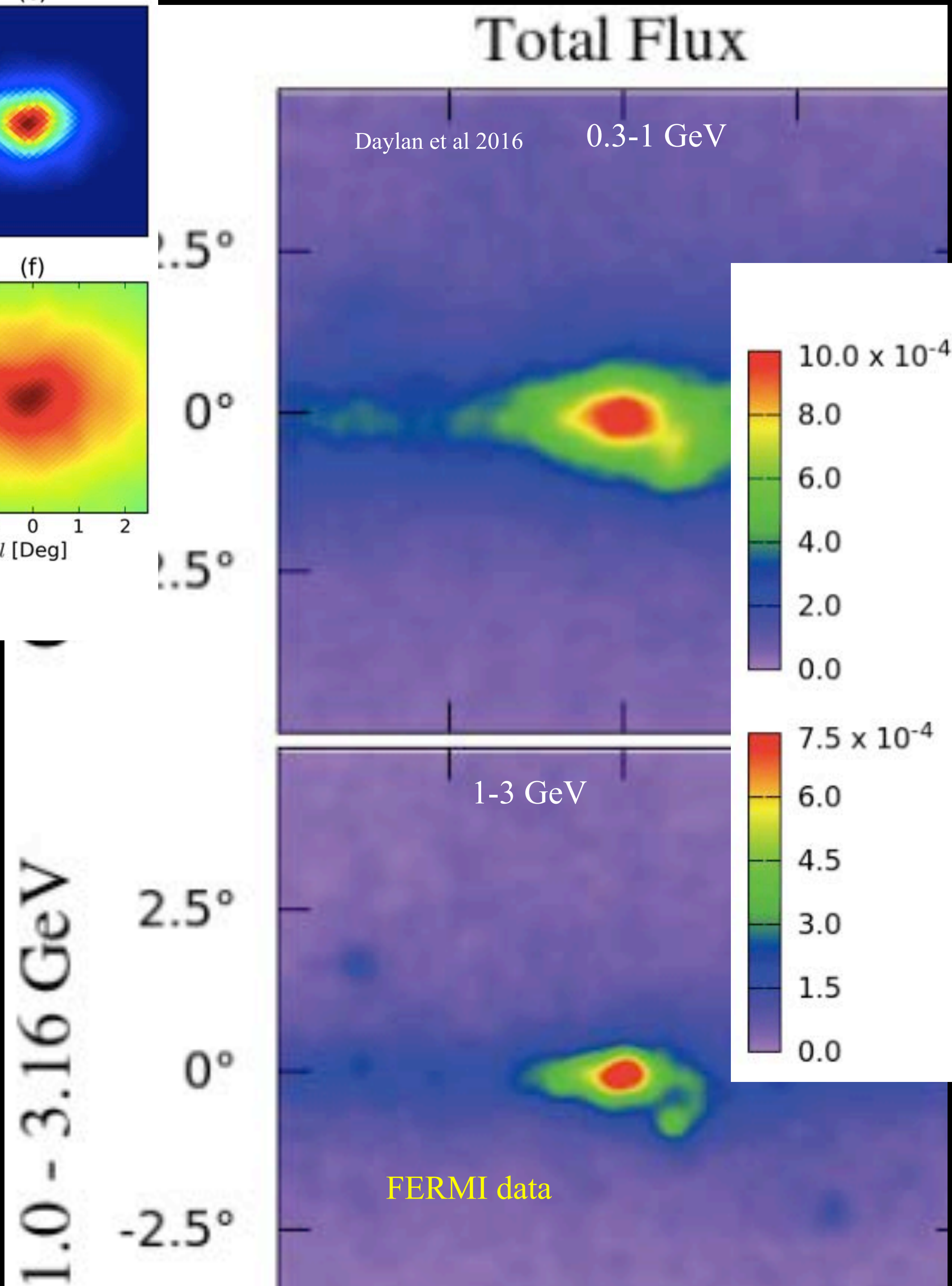
THE GALACTIC CENTER 7ºx7º



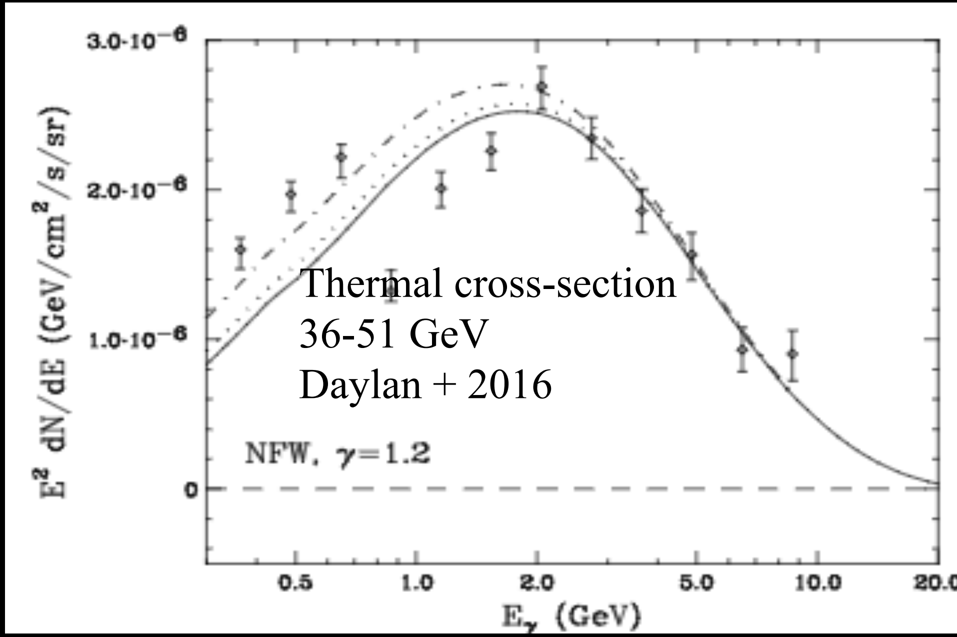


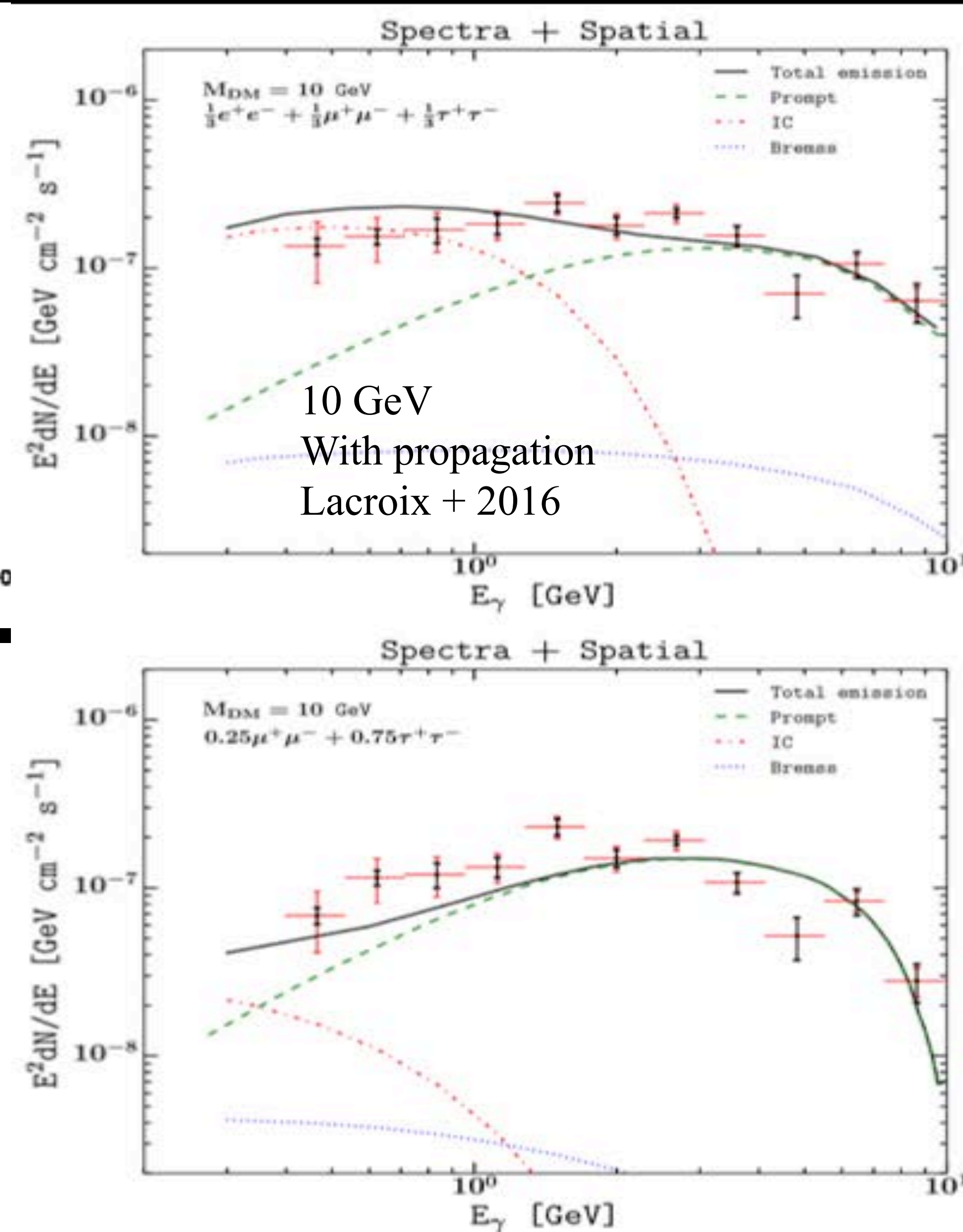

Ann
Yang et al 2013
1/v
1/v²
(d)
(e)
(f)
v²
VL2 simulation
Adi
Dec
l [Deg]
l [Deg]
l [Deg]
0.10
0.40
0.70
1.00
Normalized Flux

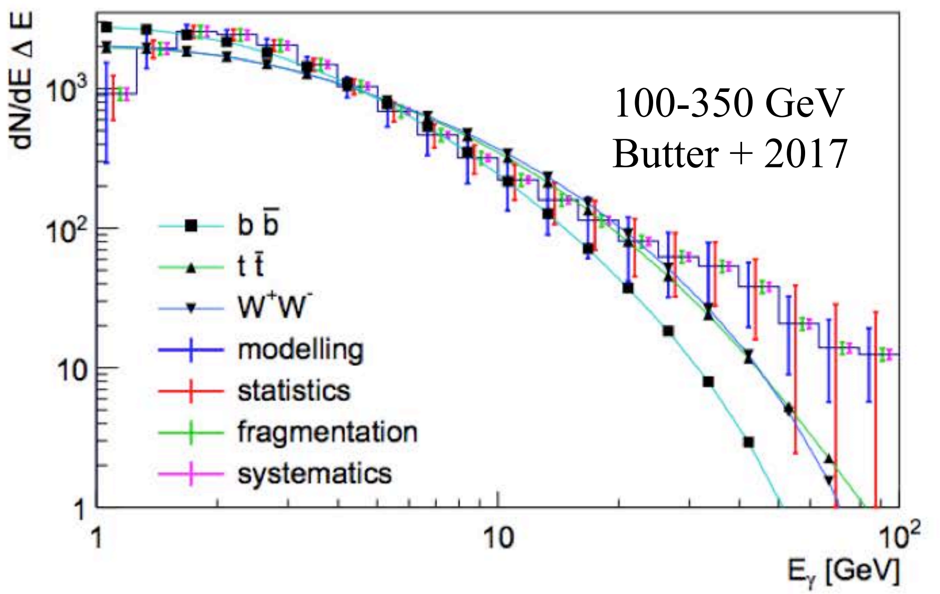

3-10 GeV residual
20
10
0
-10
-20
4
3
2
1
0


Total Flux
Daylan et al 2016
0.3-1 GeV
1-3 GeV
FERMI data
1.0 - 3.16 GeV
2.5°
0°
-2.5°
10.0 x 10-4
8.0
6.0
4.0
2.0
0.0
7.5 x 10-4
6.0
4.5
3.0
1.5
0.0

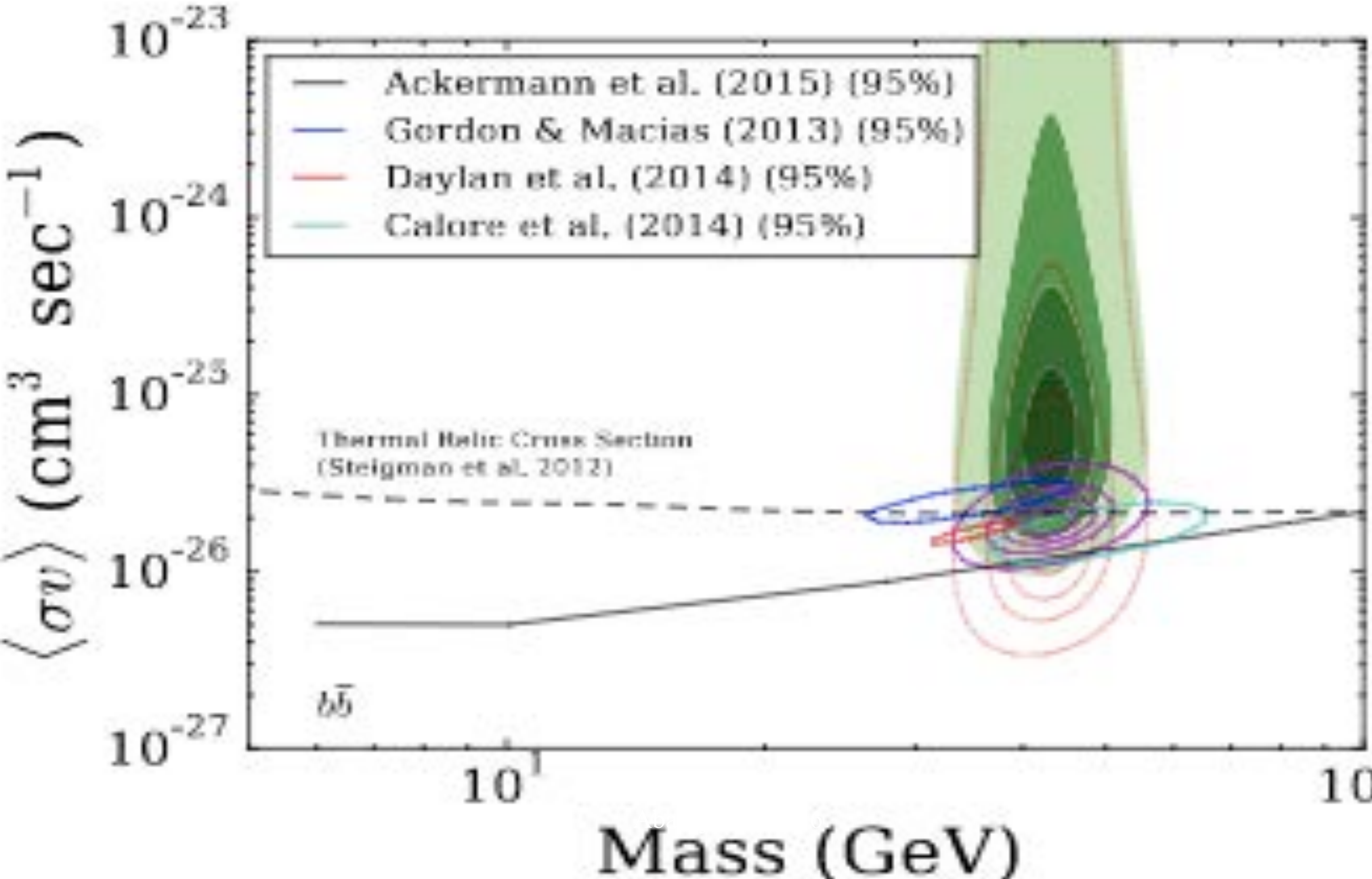
Fermi inner galaxy excess: spectrum





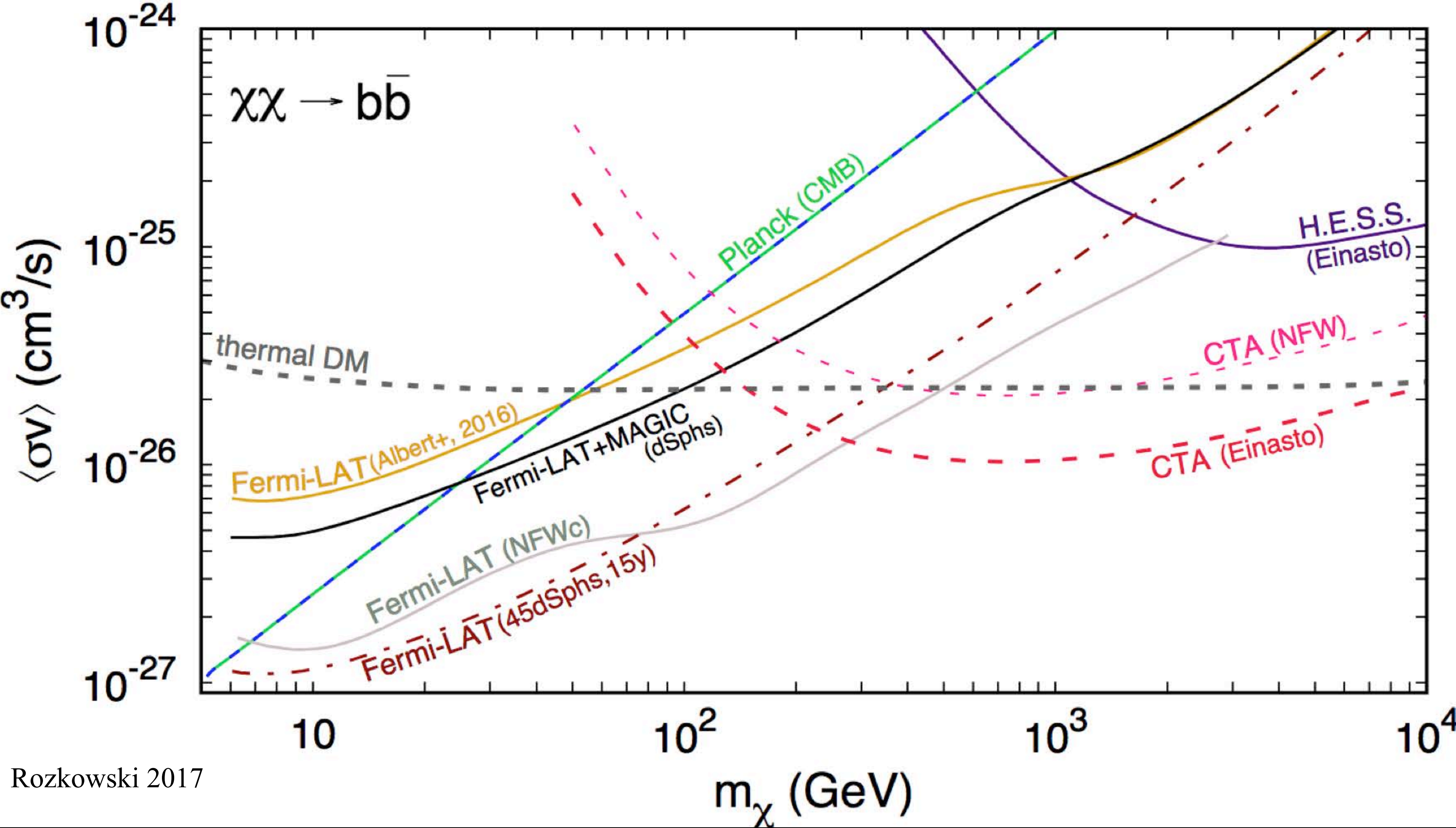


fits



Ackermann et al. (2015) (95%)
Gordon & Macias (2013) (95%)
Daylan et al. (2014) (95%)
Calore et al. (2014) (95%)
Thermal Relic Cross Section
(Steigman et al. 2012)
$b\bar{b}$
$\langle \sigma v \rangle$ (cm^3 sec^{-1})
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^1
Mass (GeV)

cross-section limits



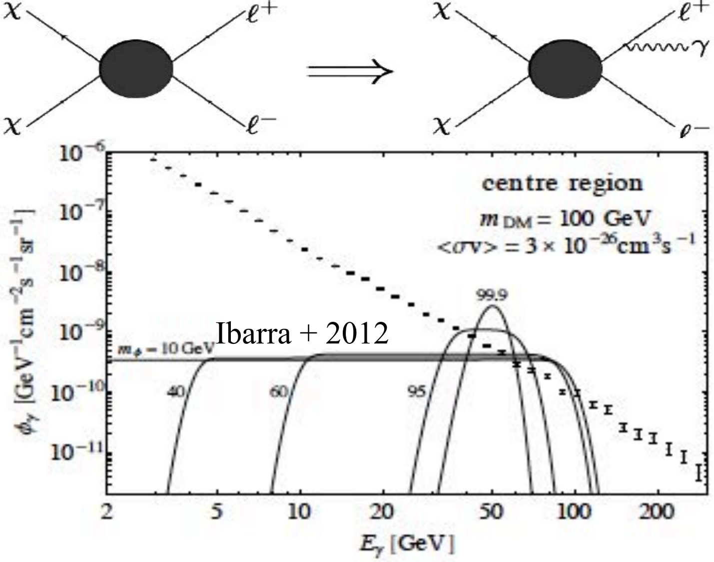
Rozkowski 2017

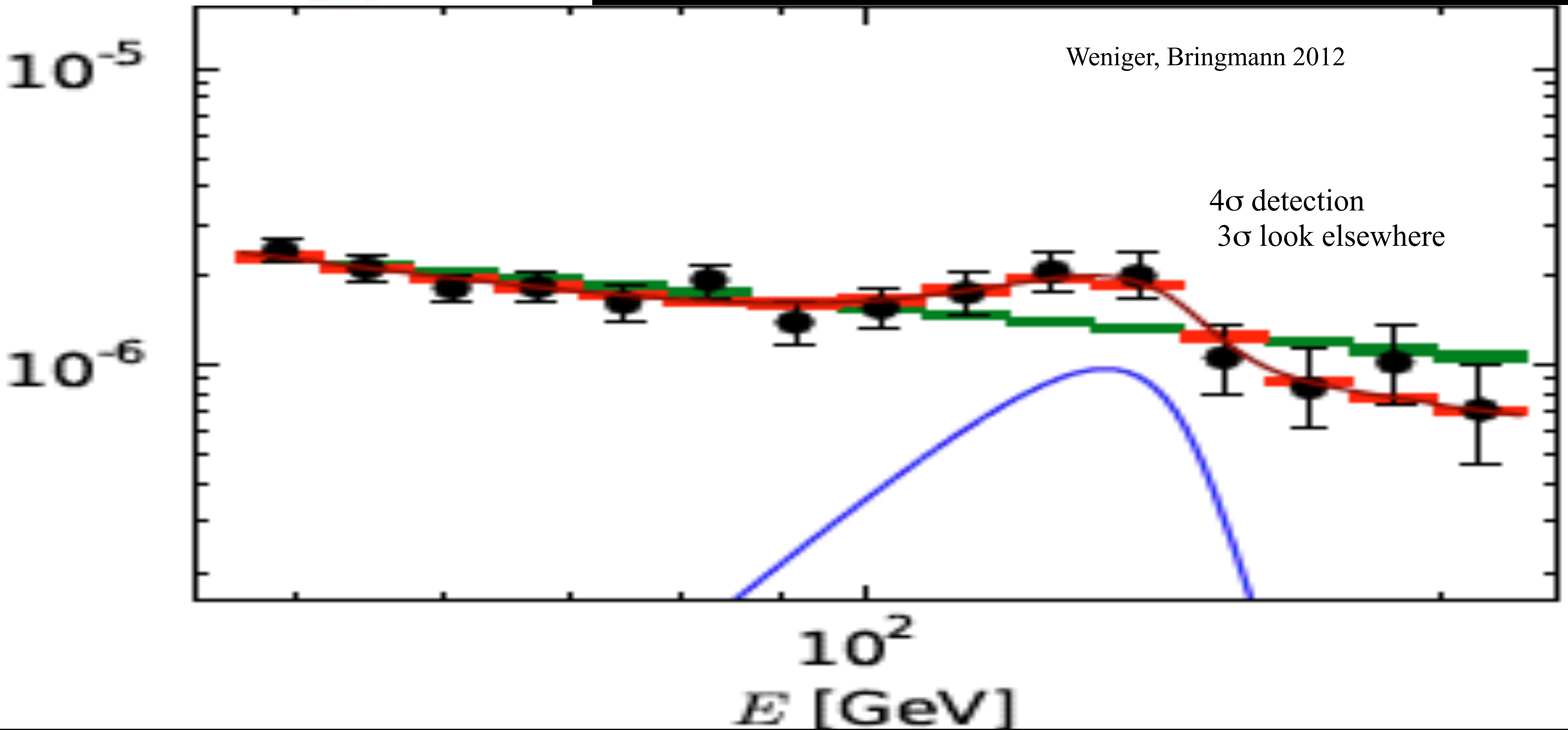
morpholgy

spectrum

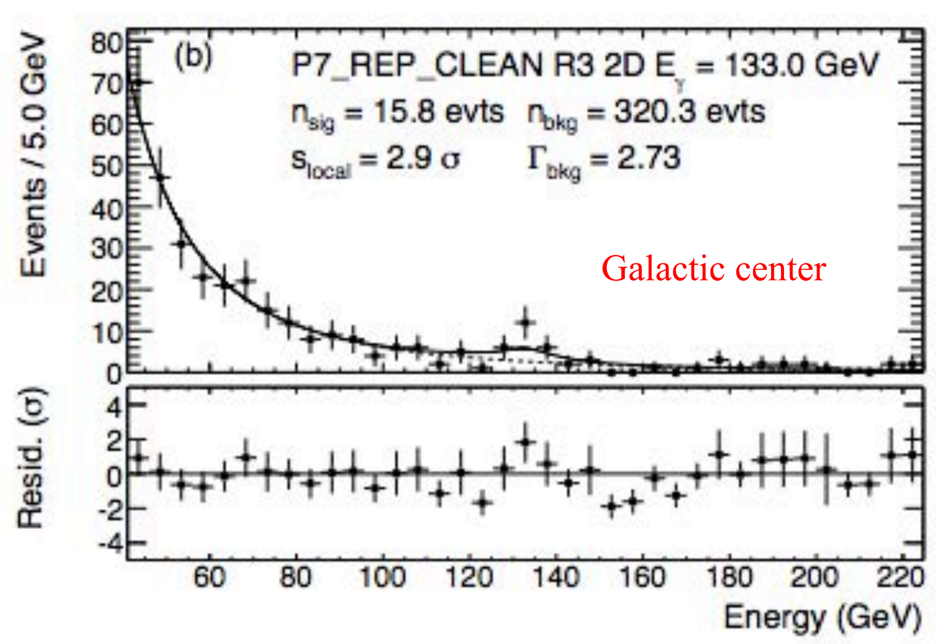
γ-ray lines?

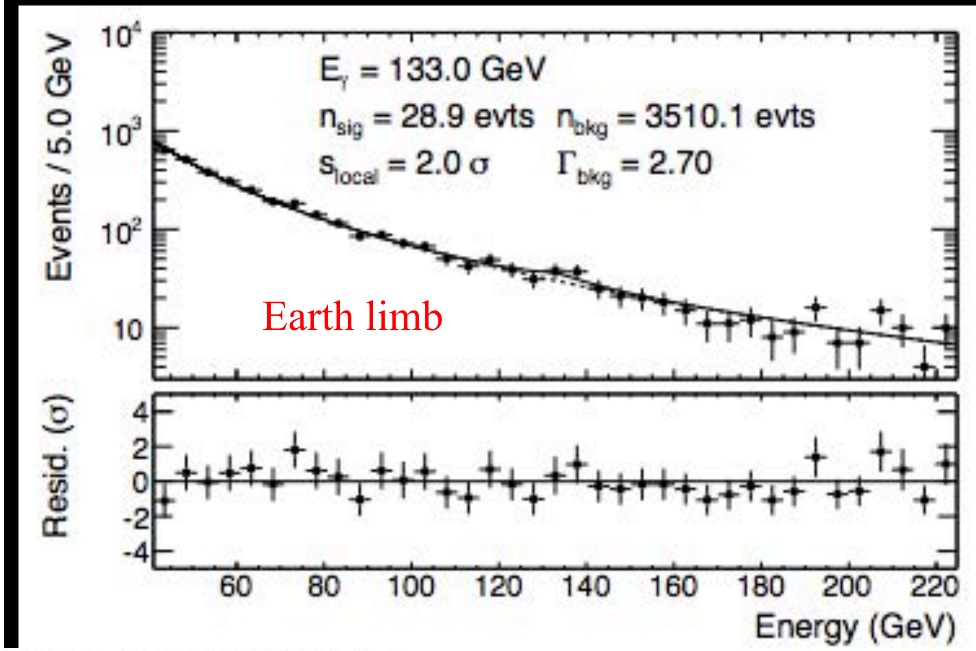
2012: 130 GeV line in Galactic Centre

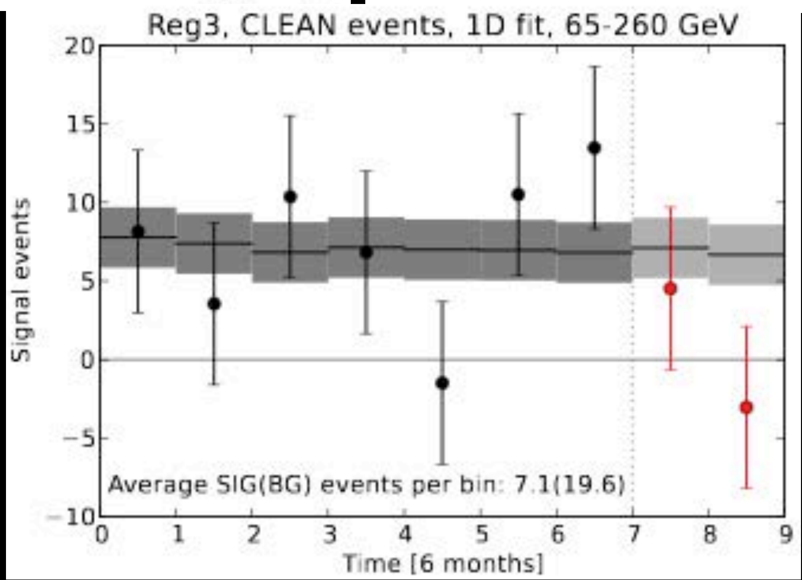




Fermi γ line @ 130 GeV: 2013

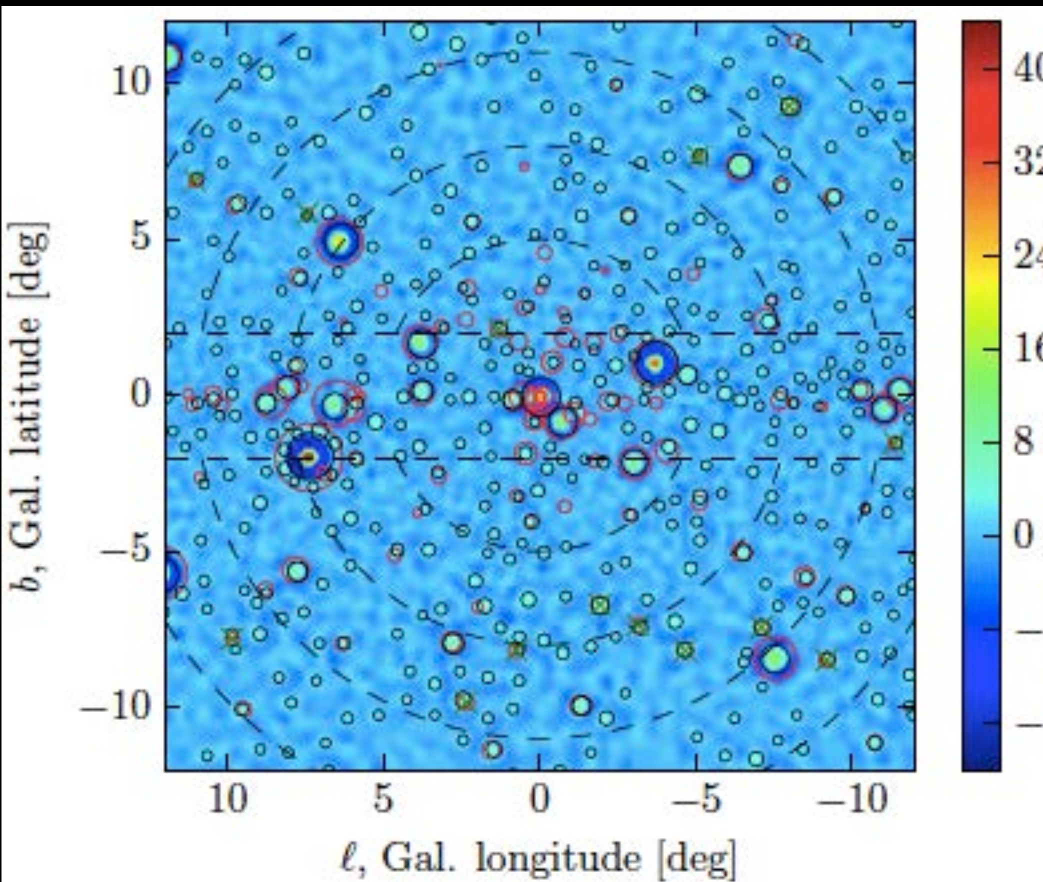




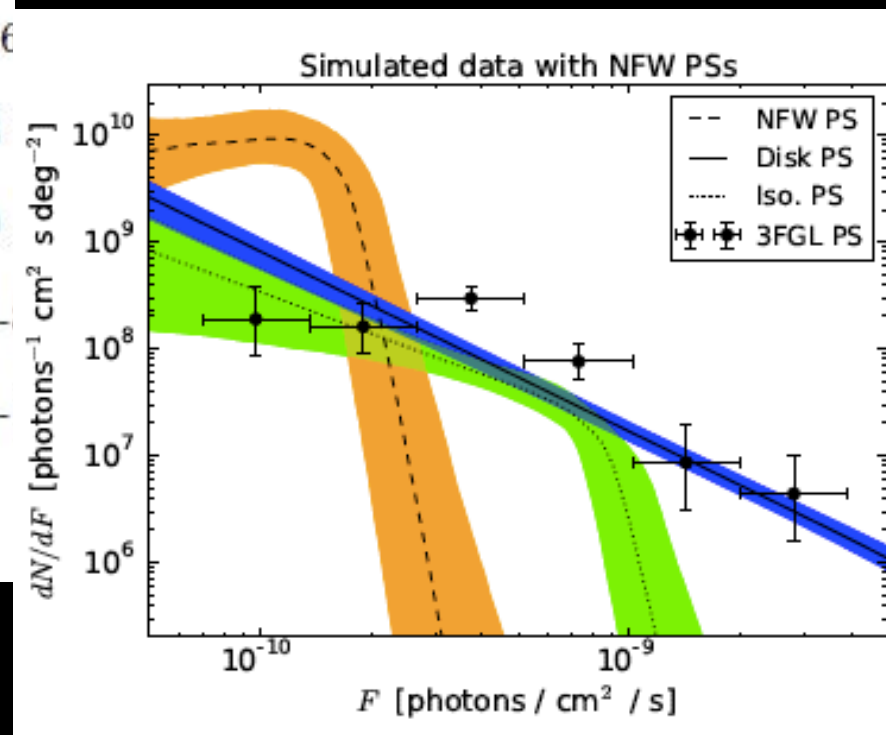


FERMI EXCESS IS STELLAR?

fluctuations require ~1000 sources



faint millisecond pulsars?



Lee, S. et al. 2016, PRL 116, 051103

Bartels, R. et al. 2016, PRL 116, 051102

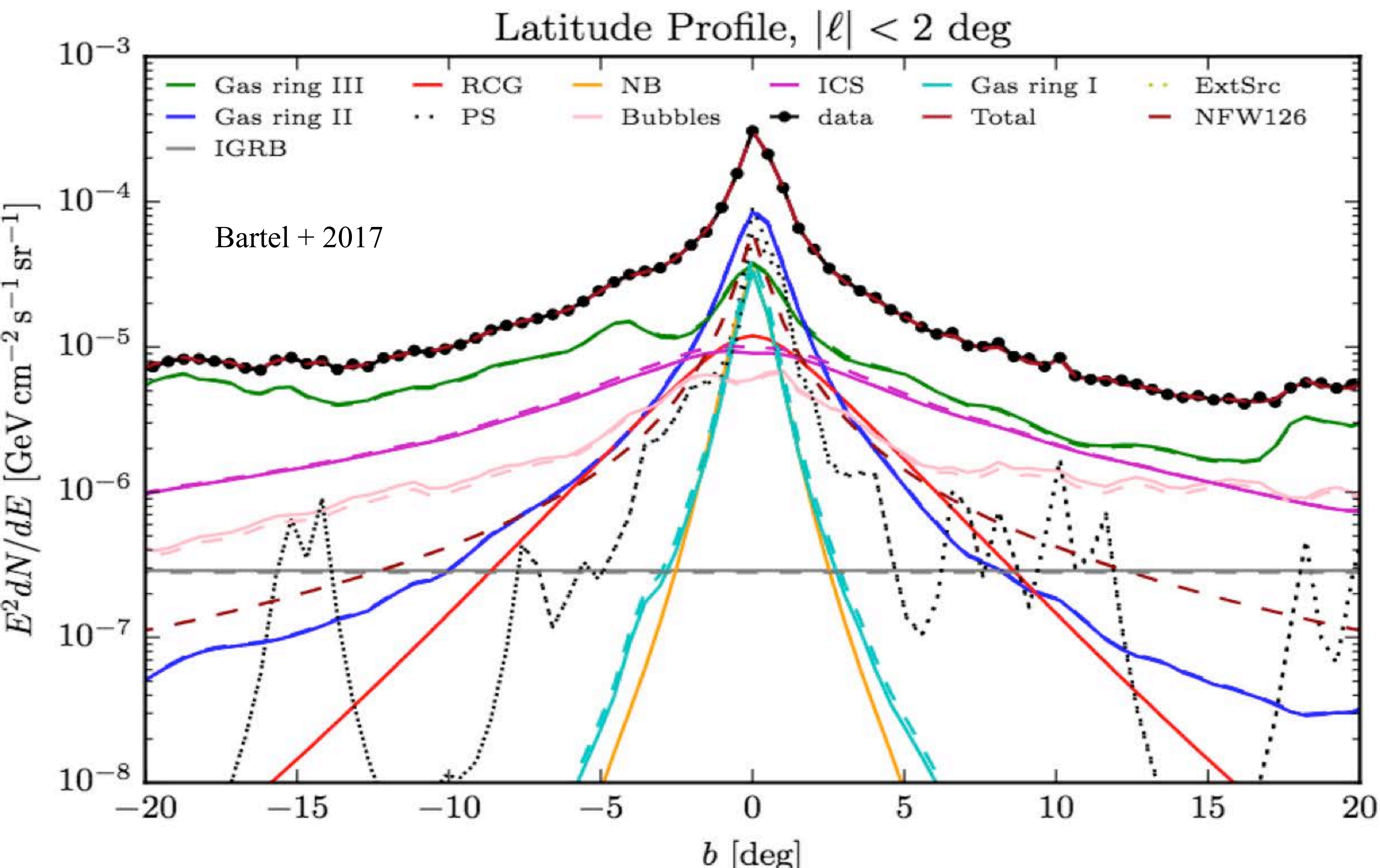
morphology

spectrum

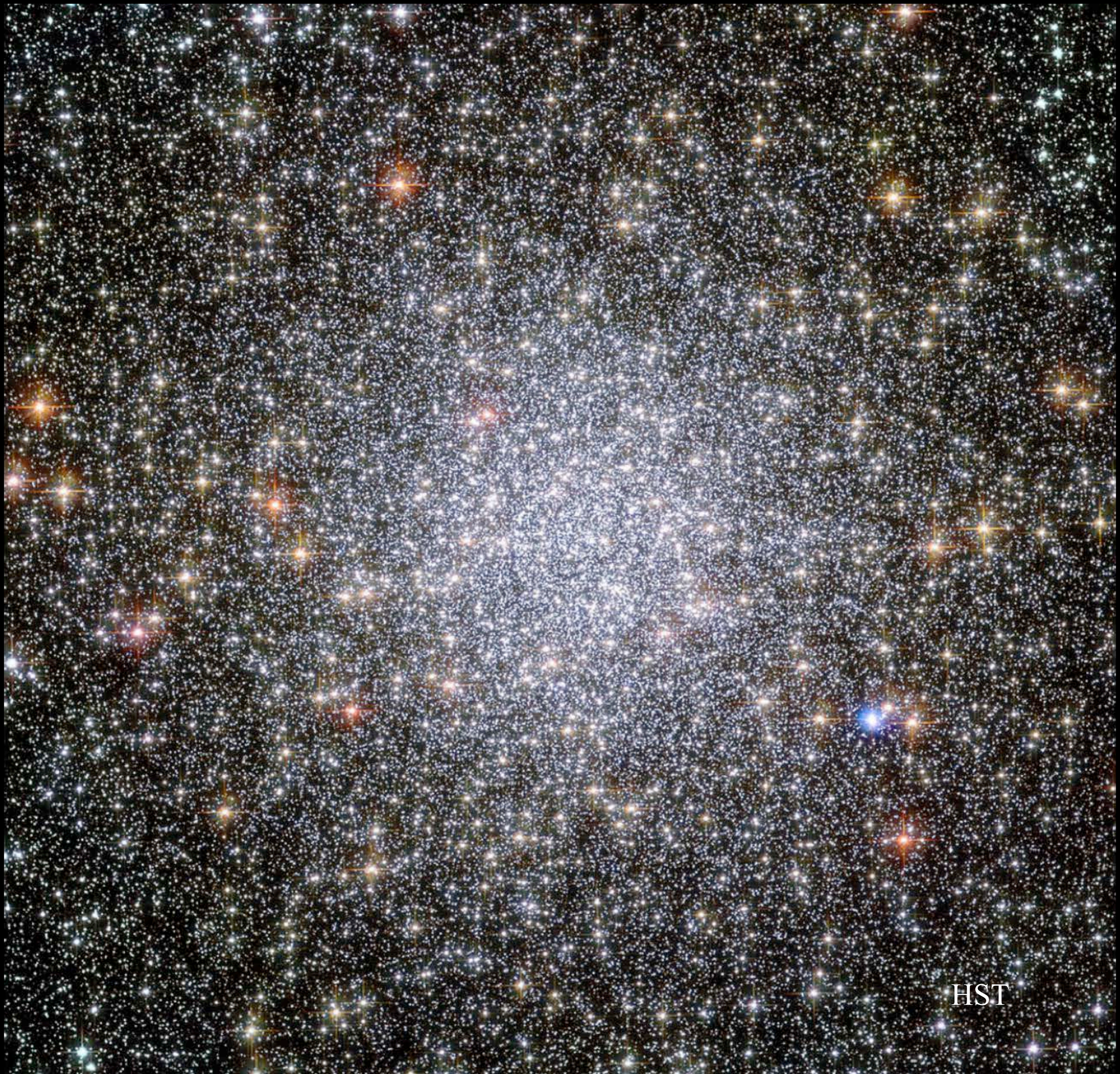
cross-section

γ-r fluctuations

Profile of FERMI excess matches bulge/nuclear stars & gas



GLOBULAR STAR CLUSTERS



massive GCs do not contain much DM since M/L~1

But\ may contain central IMBH ~1000 M_{sun}

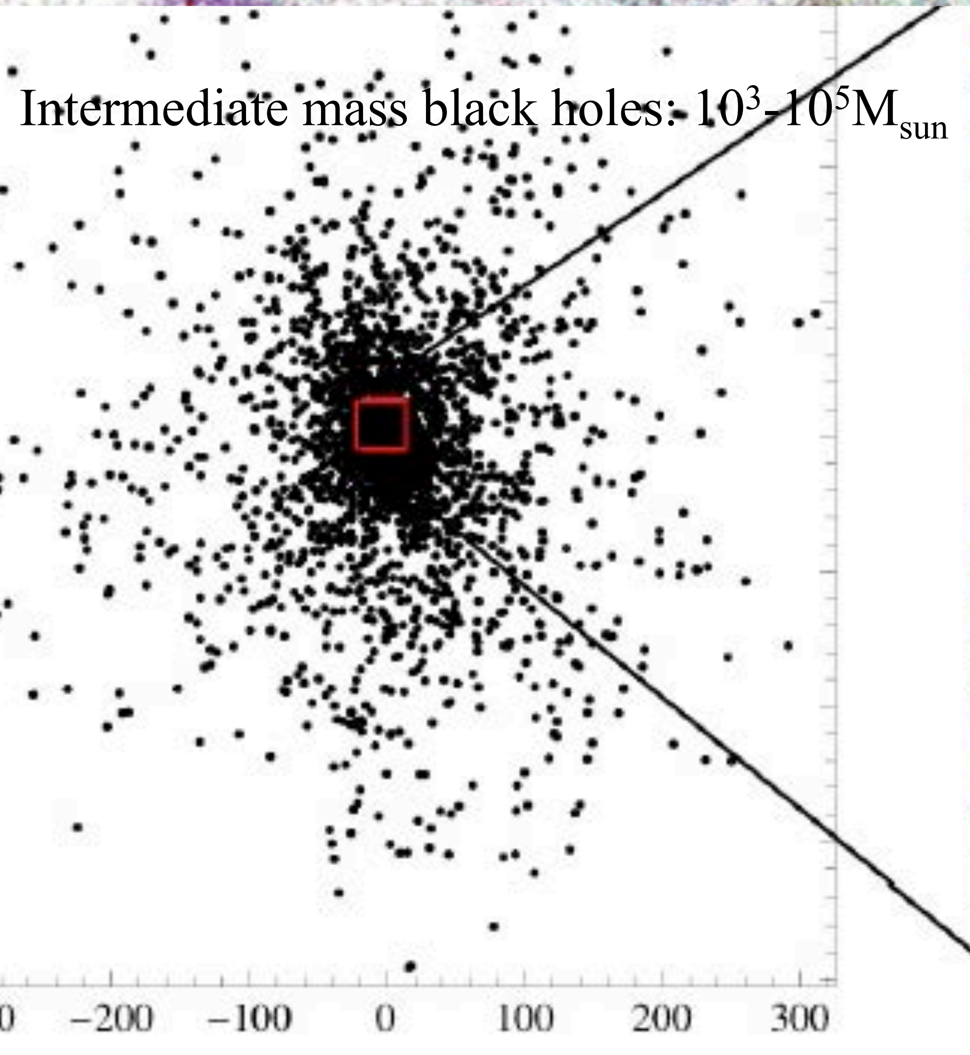
and contain many millisecond pulsars:

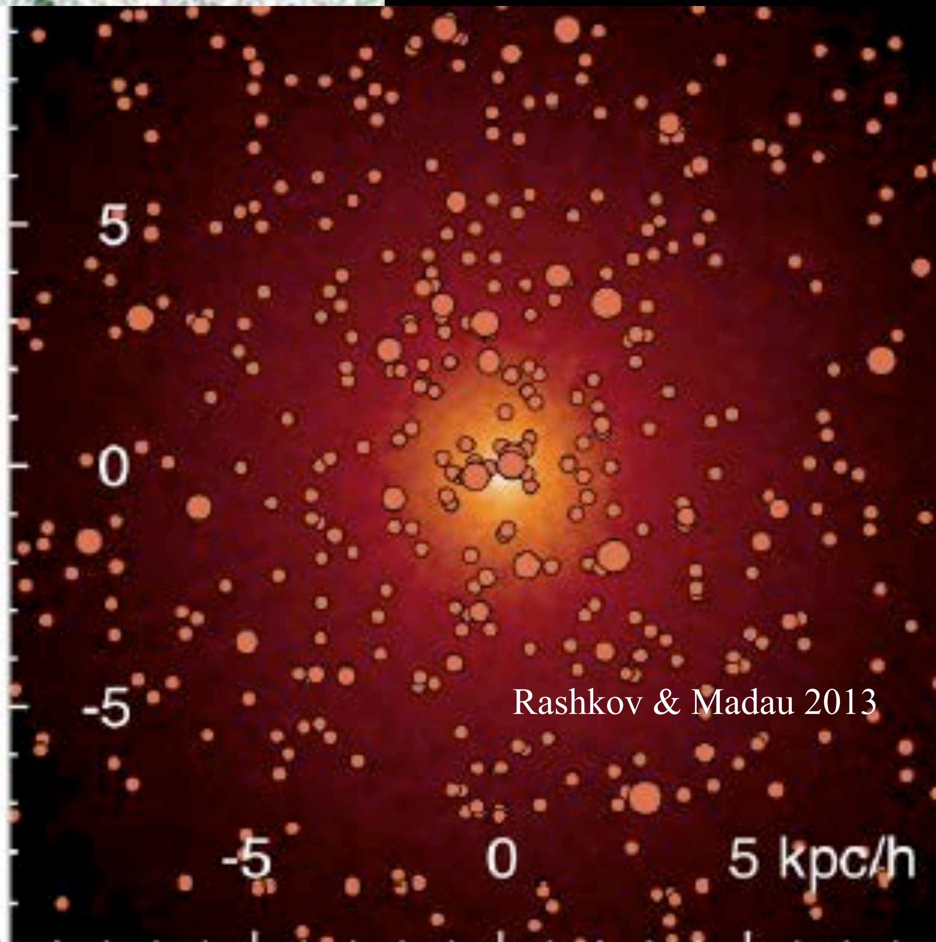
these are γ-ray sources

GCs merged to form central nuclear star cluster

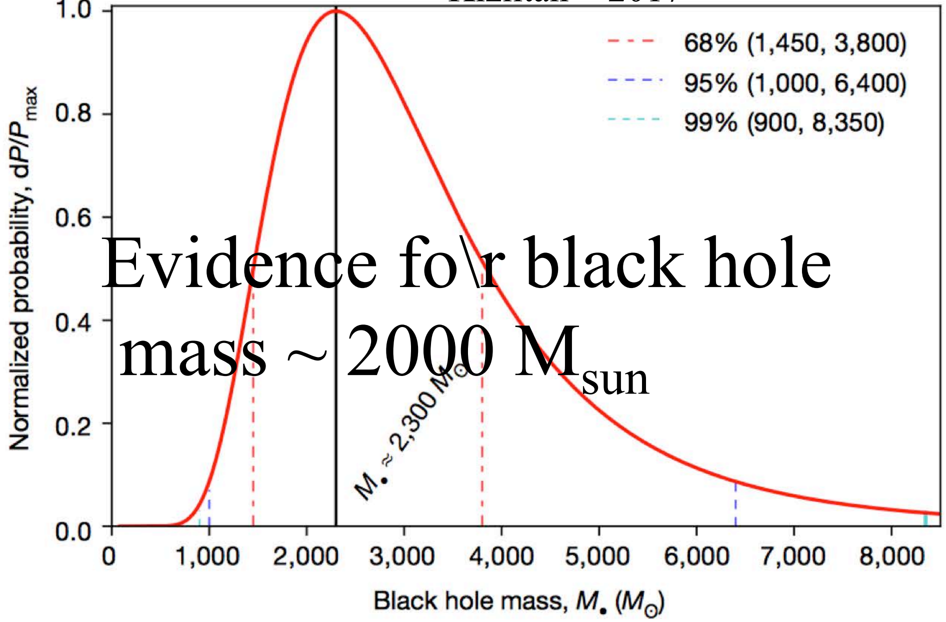
MWG forms from merging dwarfs,
each contains an IMBH
Silk 2017

Intermediate mass black holes: 10^3-$10^5 M_{sun}$

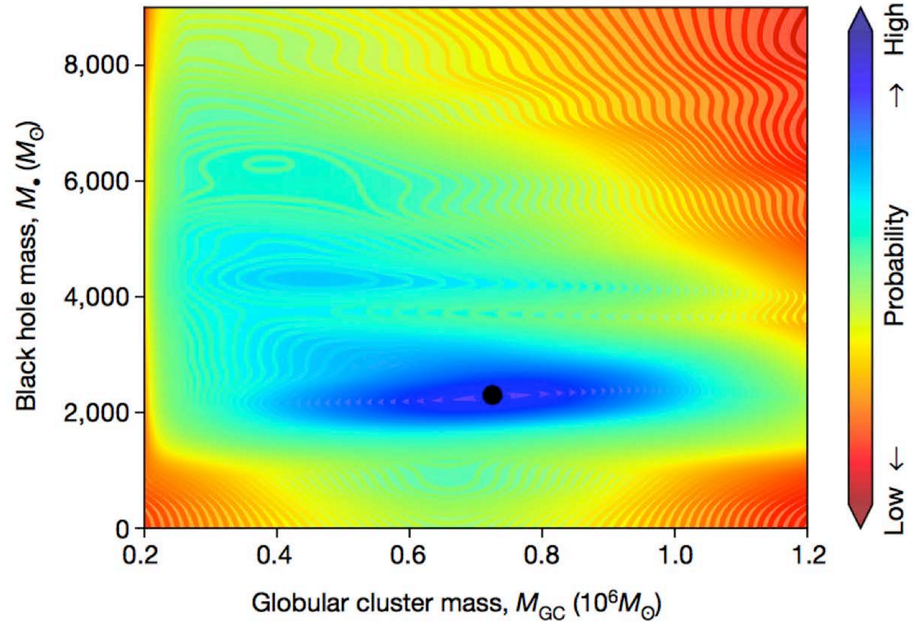


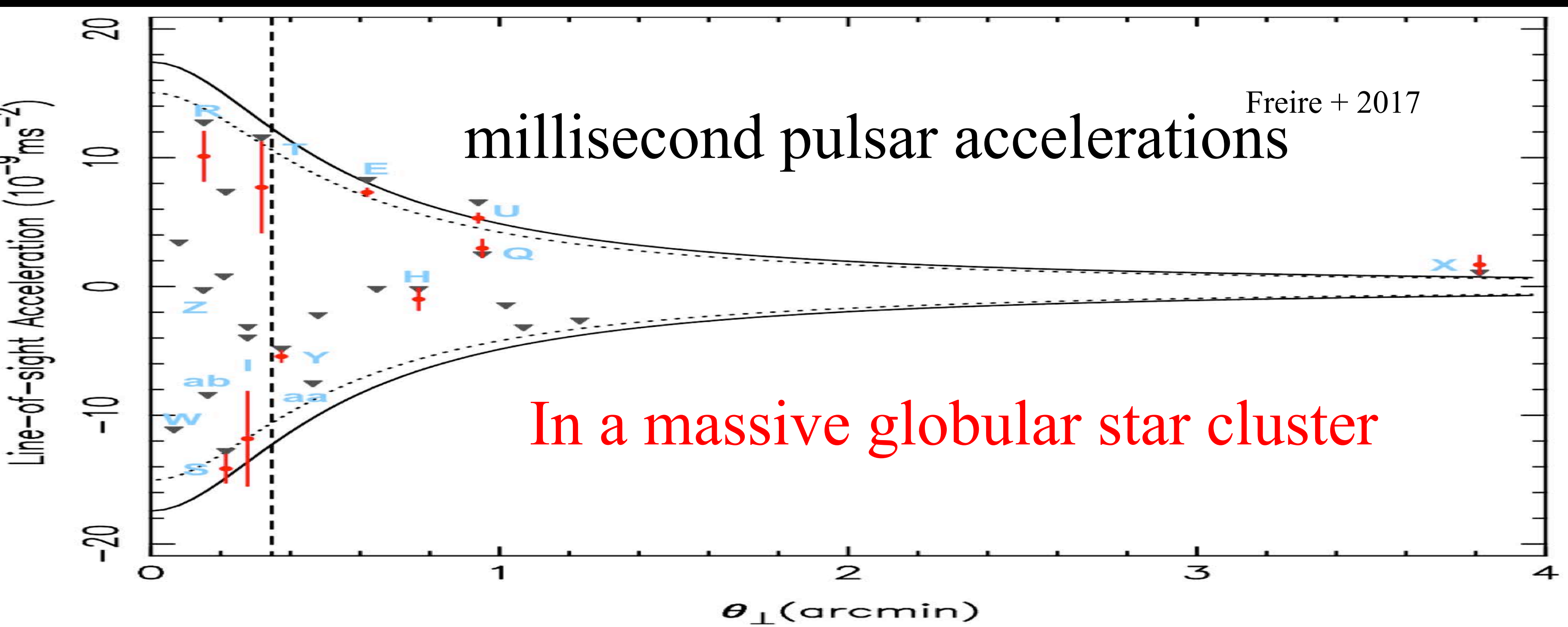


Kiziltan + 2017



Evidence fo\r black hole mass ~ 2000 M_{sun}



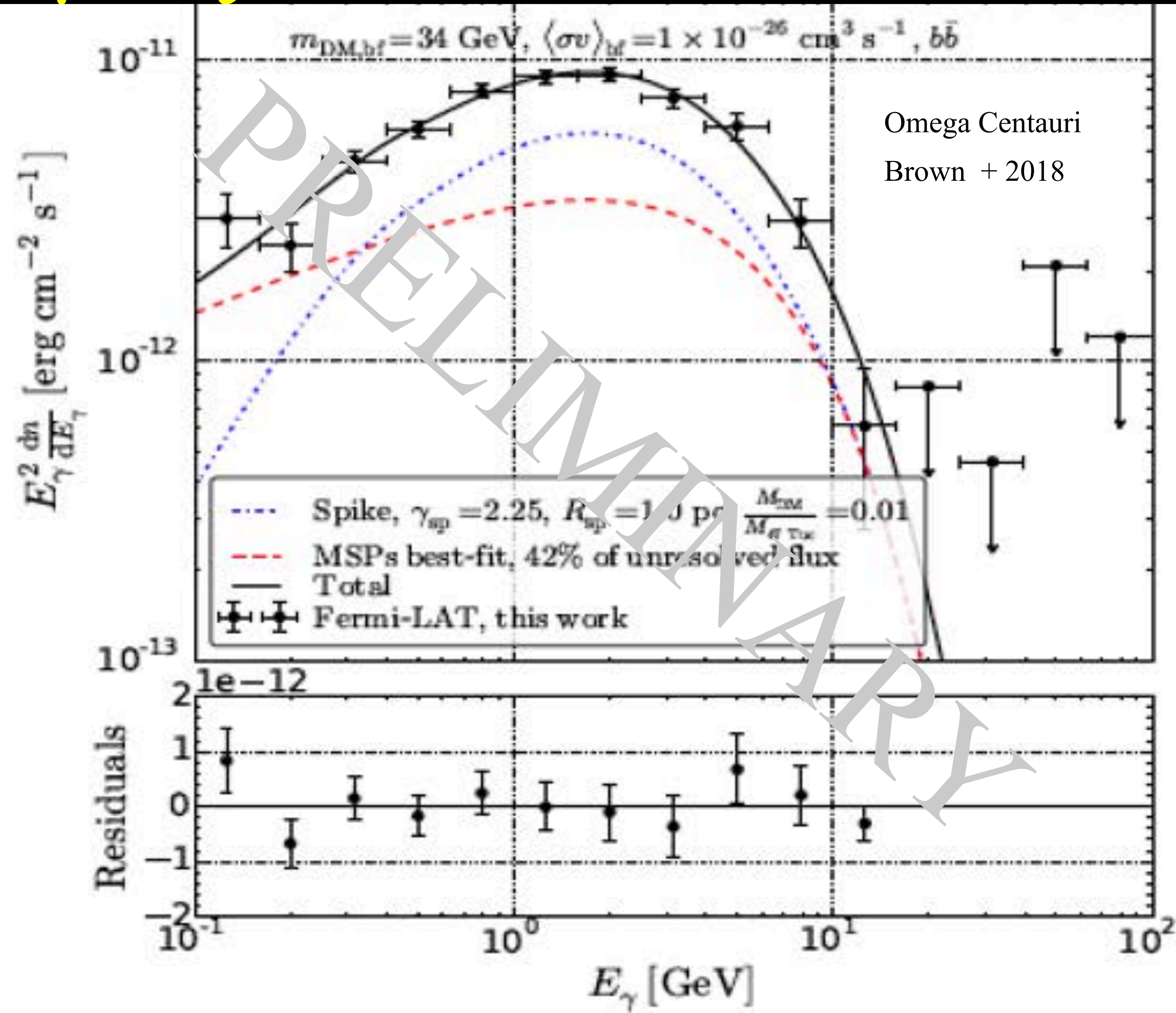


Freire + 2017

millisecond pulsar accelerations

In a massive globular star cluster

γ-ray evidence for DM + IMBH

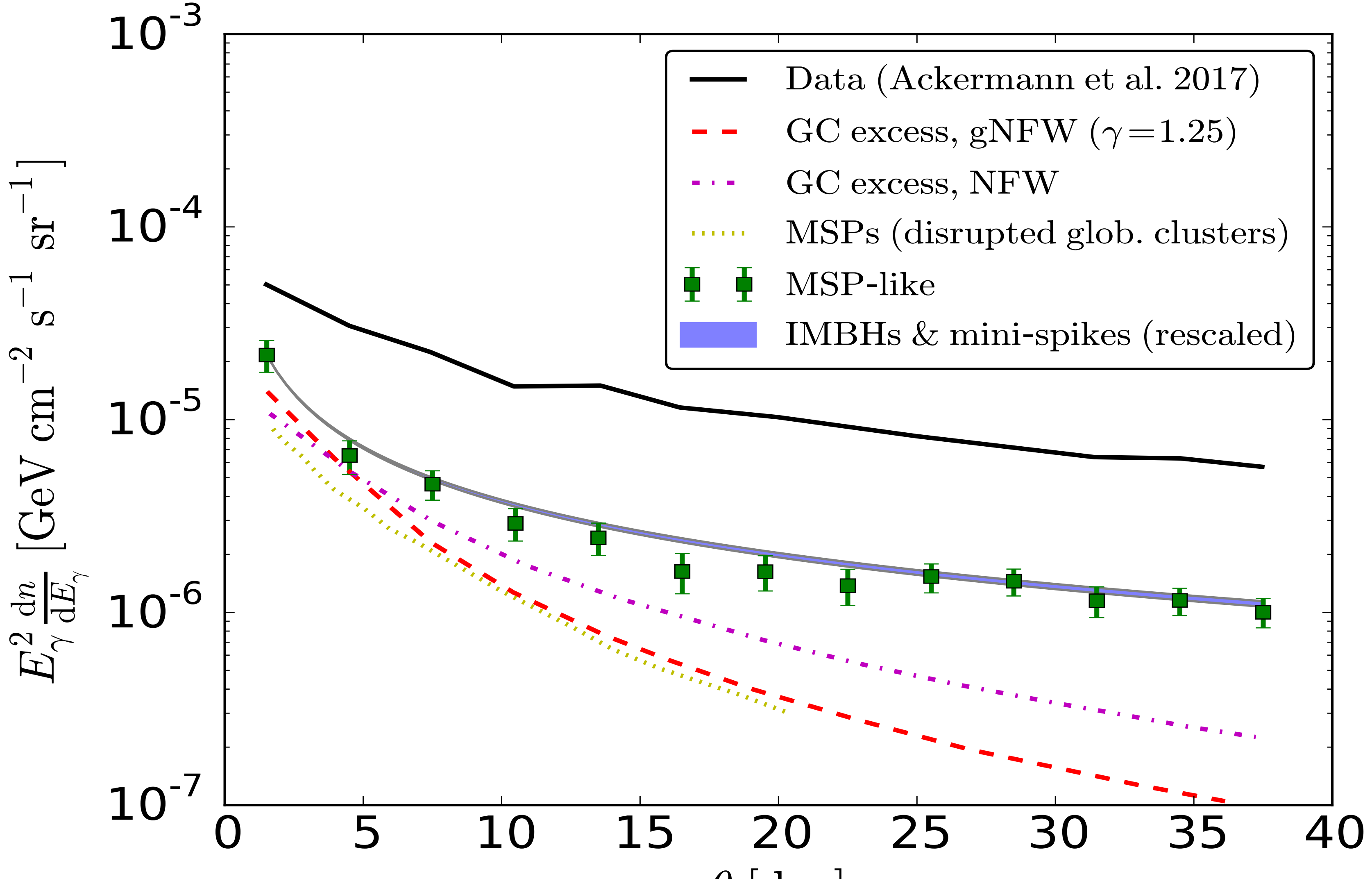


in a globular star cluster

not much DM is needed, eg

$M_{spike} \sim 0.1\ M_{BH}$

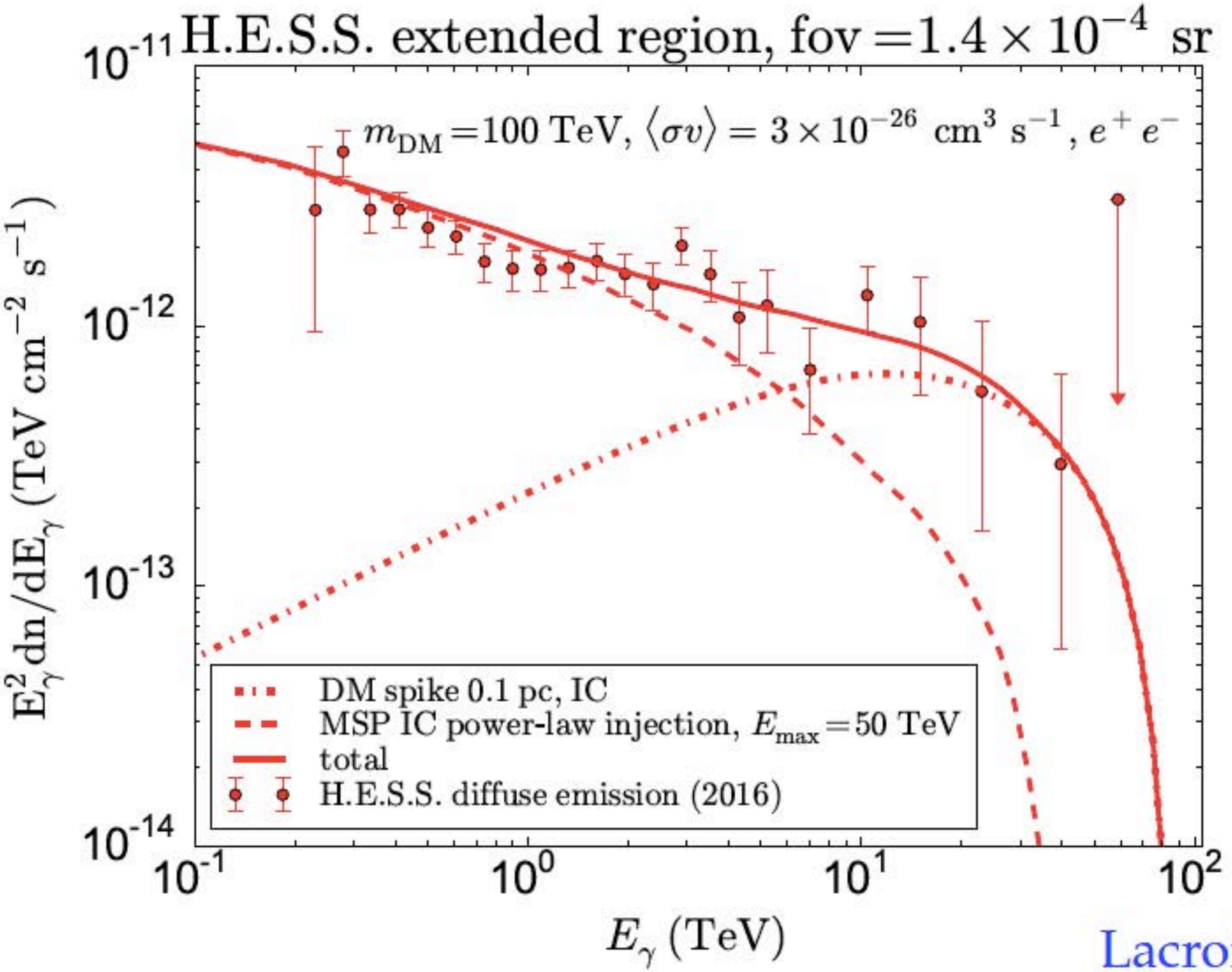
Black hole + DM spikes: account for fluctuations in Fermi Galactic Center γ-ray excess



Lacroix and JS 2018

Explaining the Galactic Center TeV excess

H.E.S.S. diffuse emission can be accounted for by ICS from MSPs + heavy DM annihilating into e^+e^- (or $\mu^+\mu^-$)

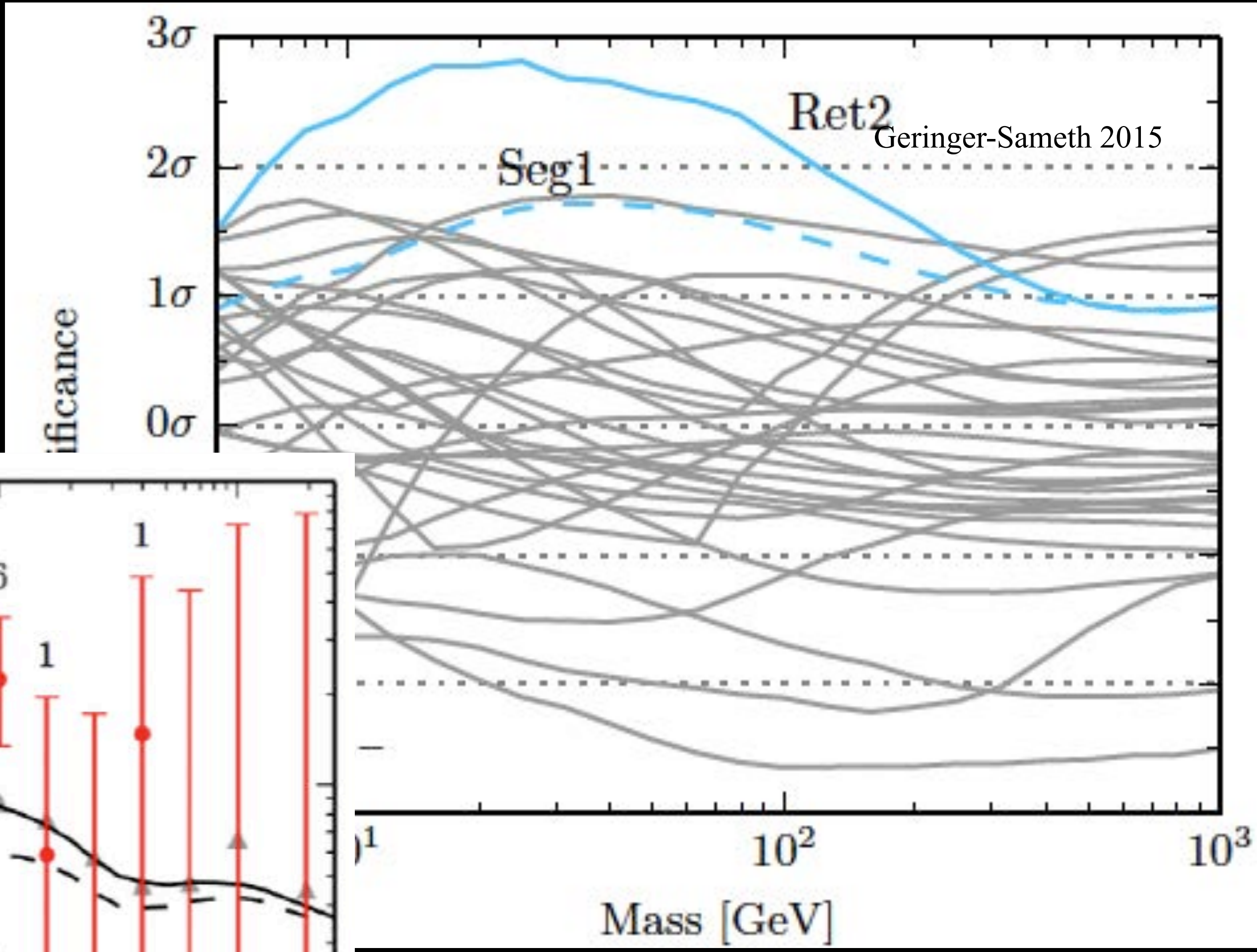


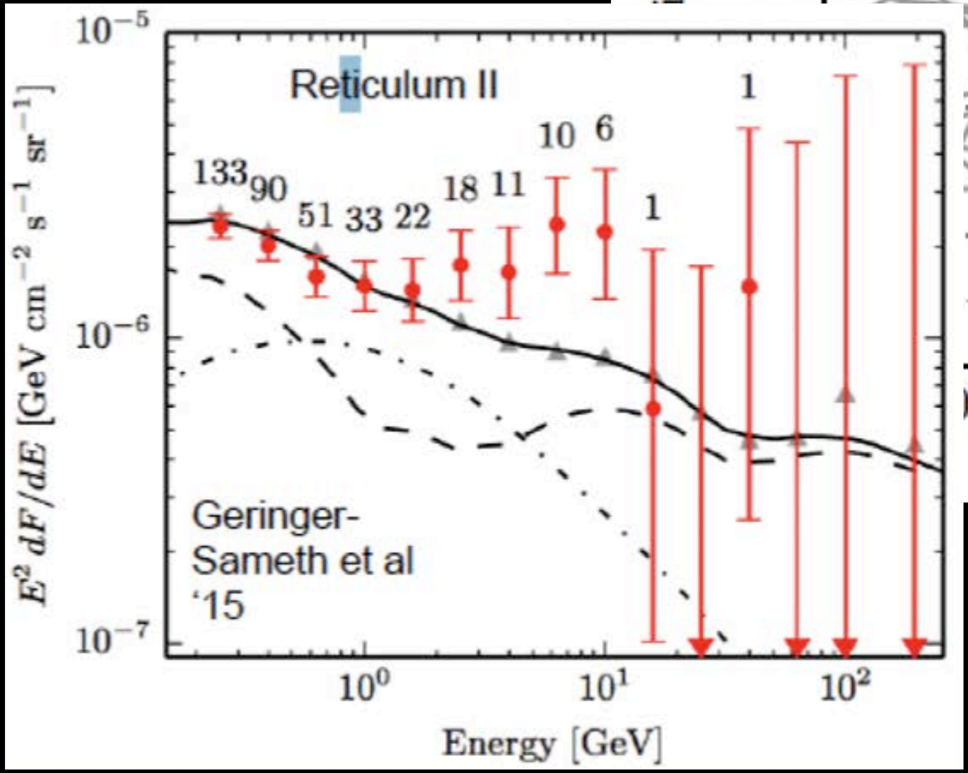
Lacroix+ 2016

DWARF GALAXIES

Ultra-faint dwarf galaxies

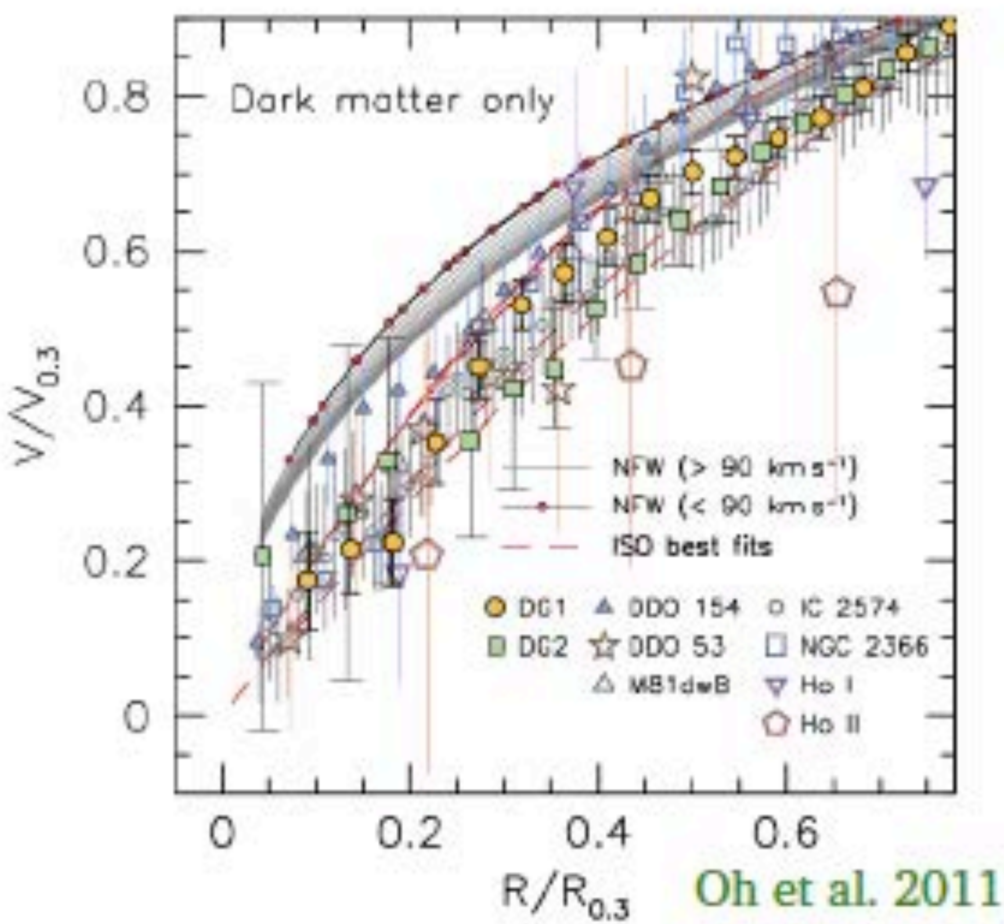
HINT OF DETECTION??



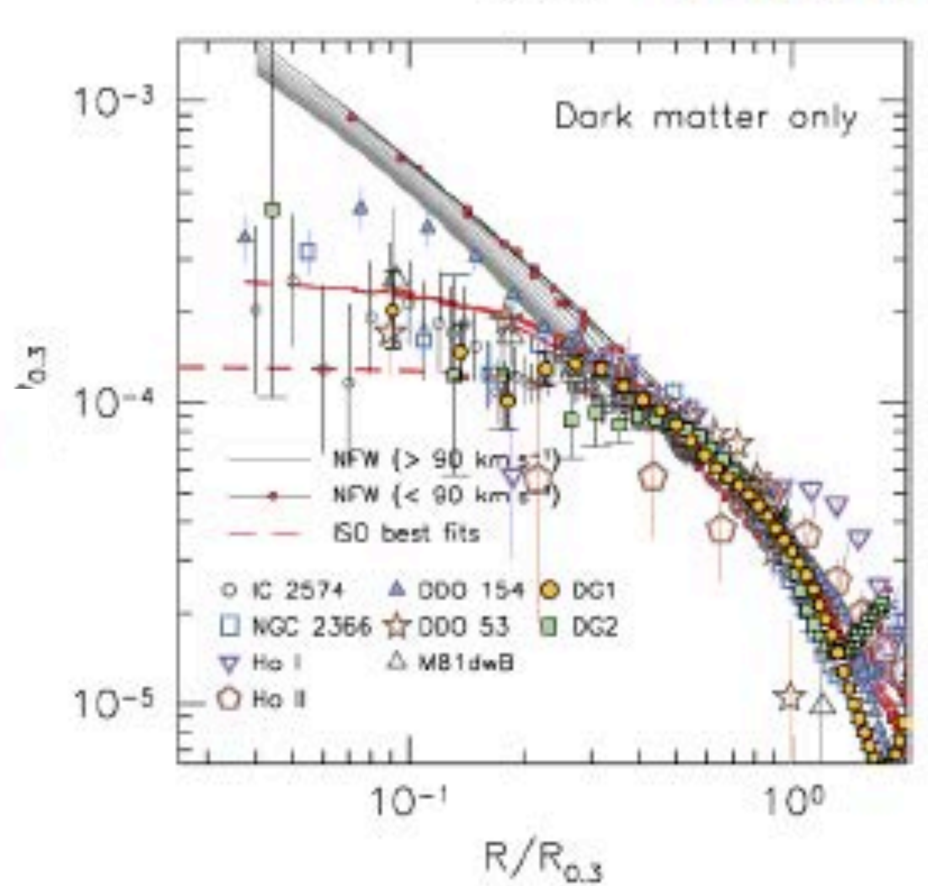


Dwarf cores

Dwarf galaxies have cores



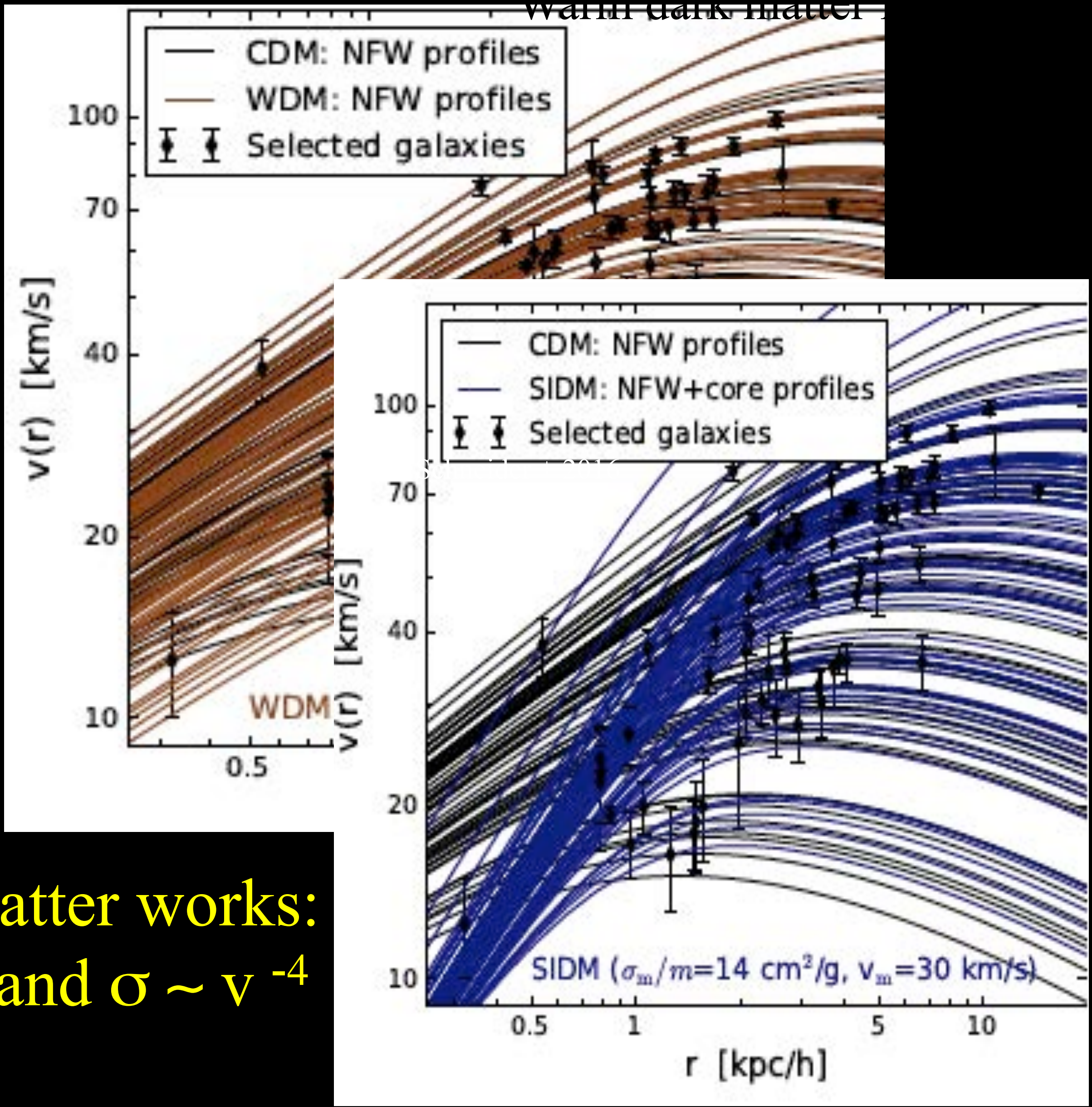
Oh et al. 2011



Explained by baryon feedback?

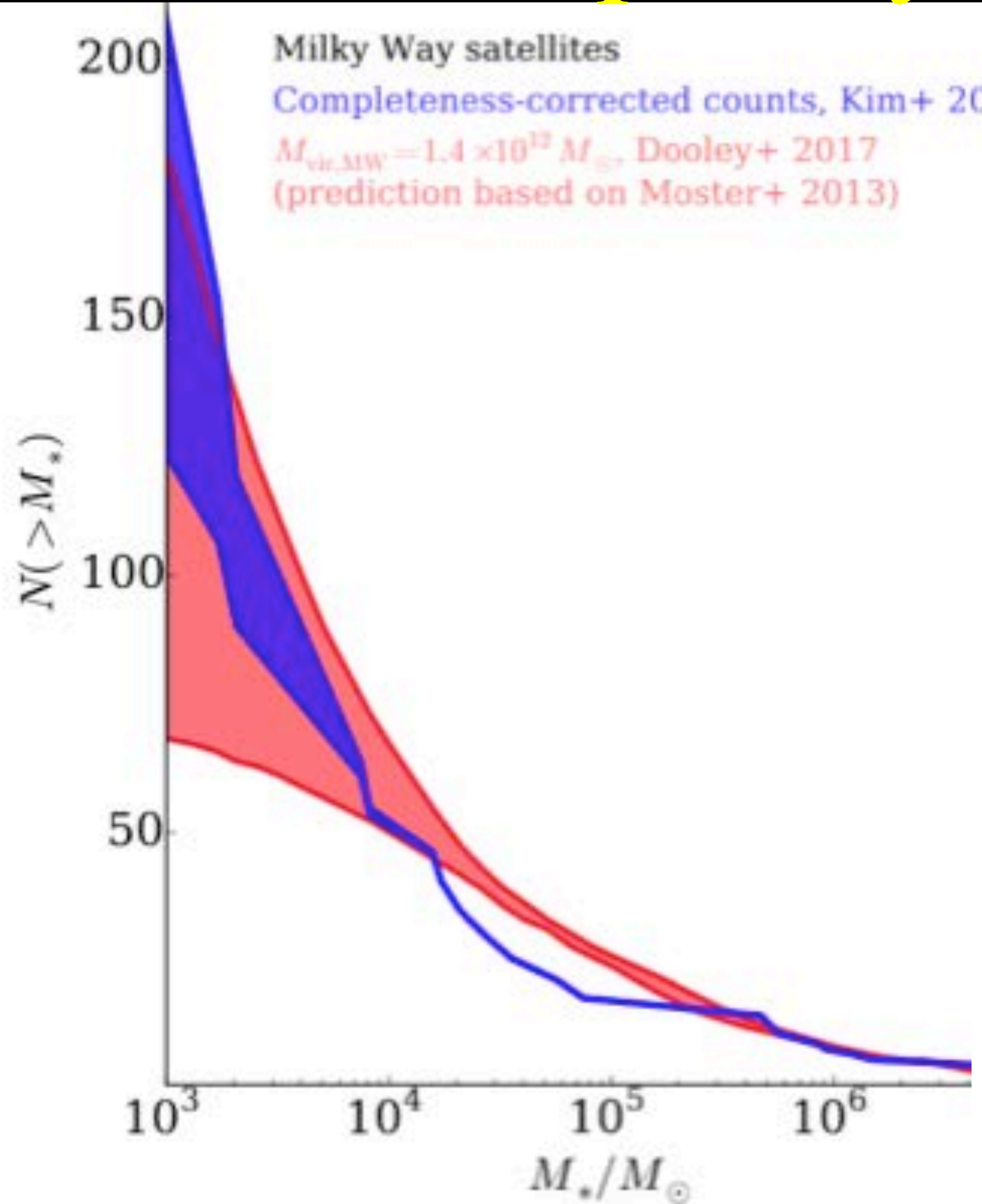
Dwarfs: cores explained?

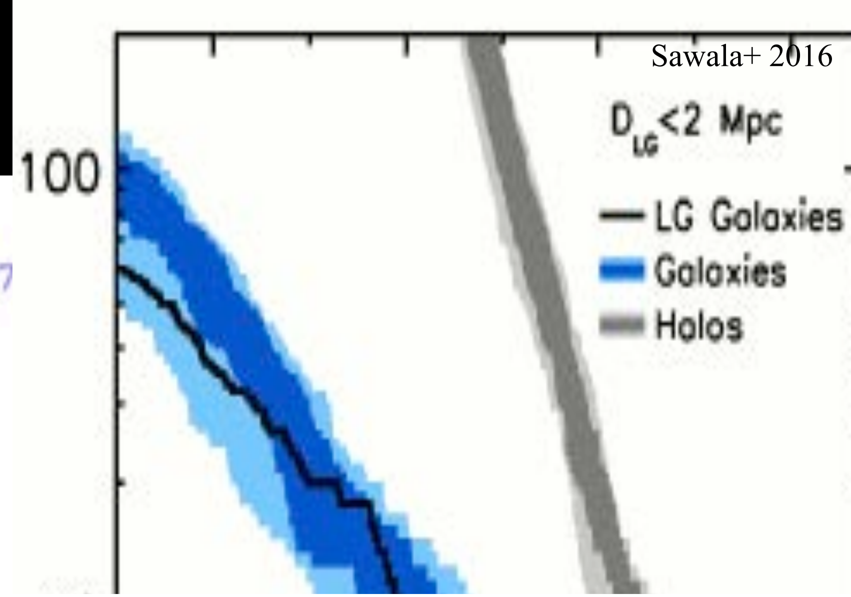
CDM/ WDM fails

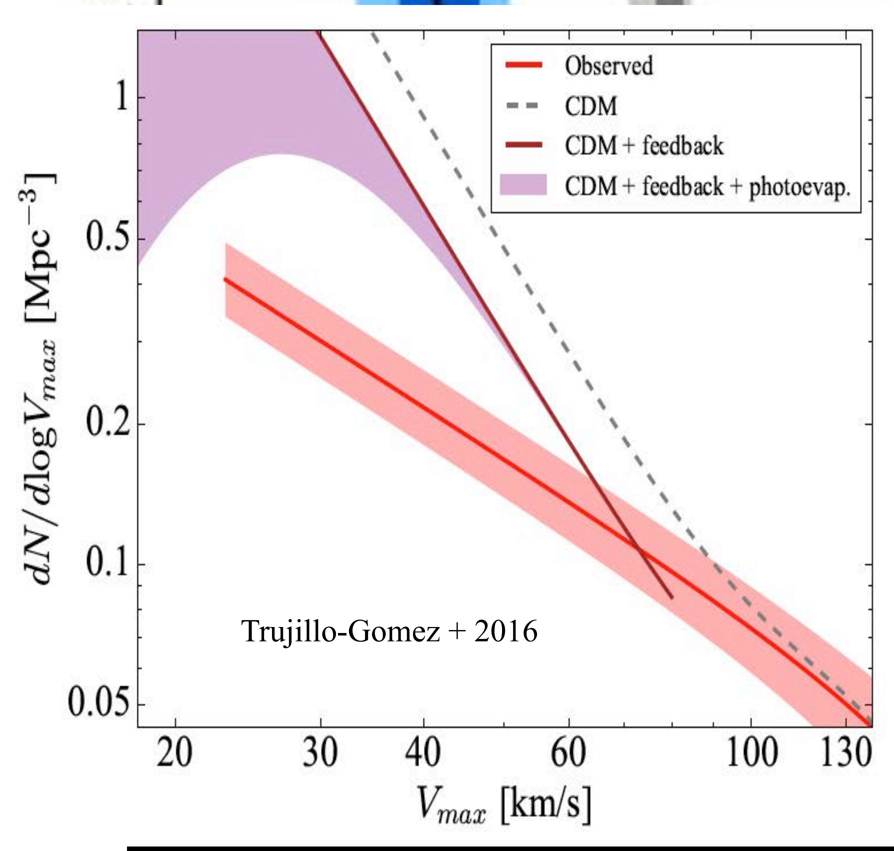


Self-interacting dark matter works: with $\sigma/m_p \sim 1\ cm^2/gm$ and $\sigma \sim v^{-4}$

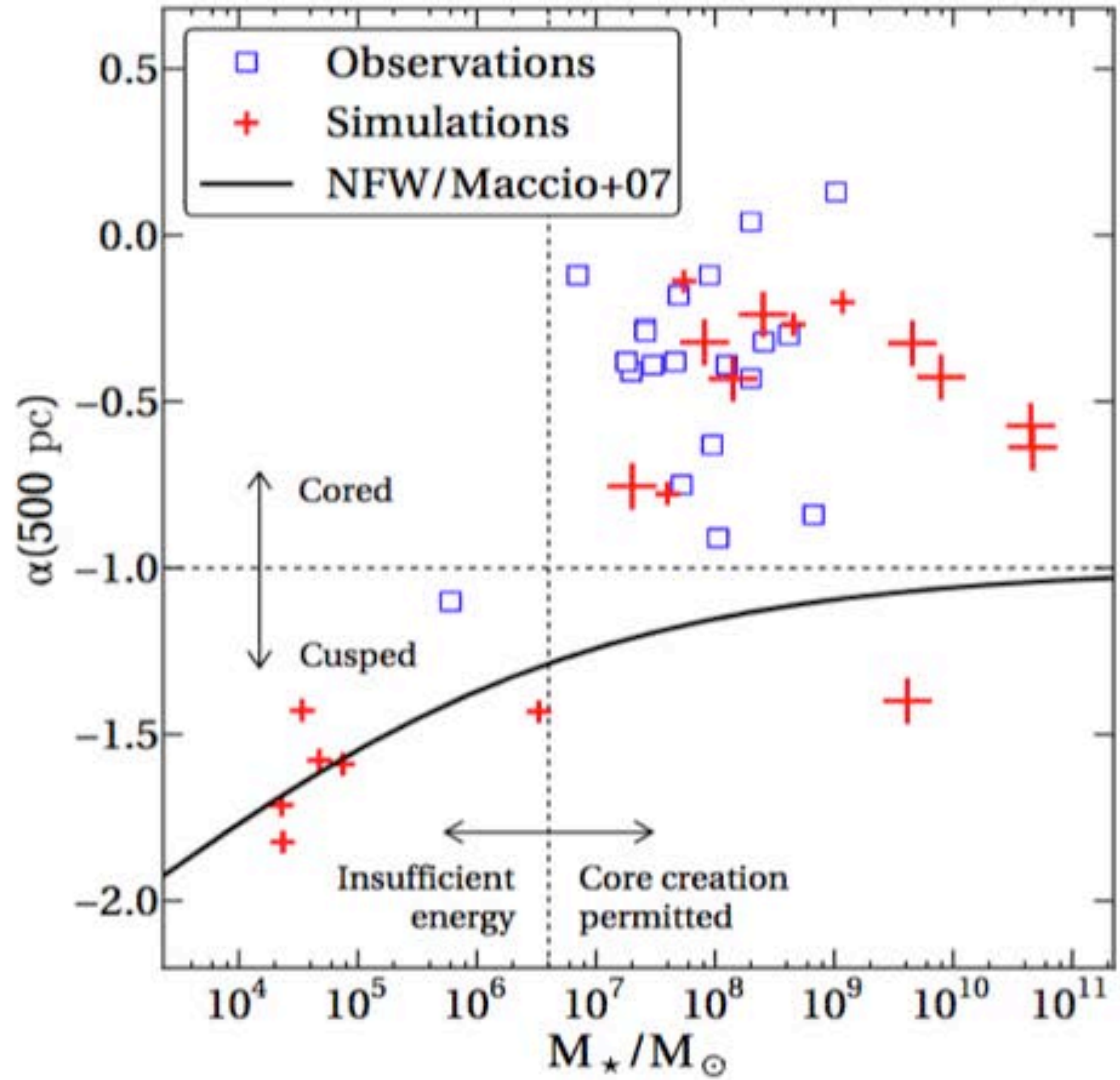
Dwarf frequency



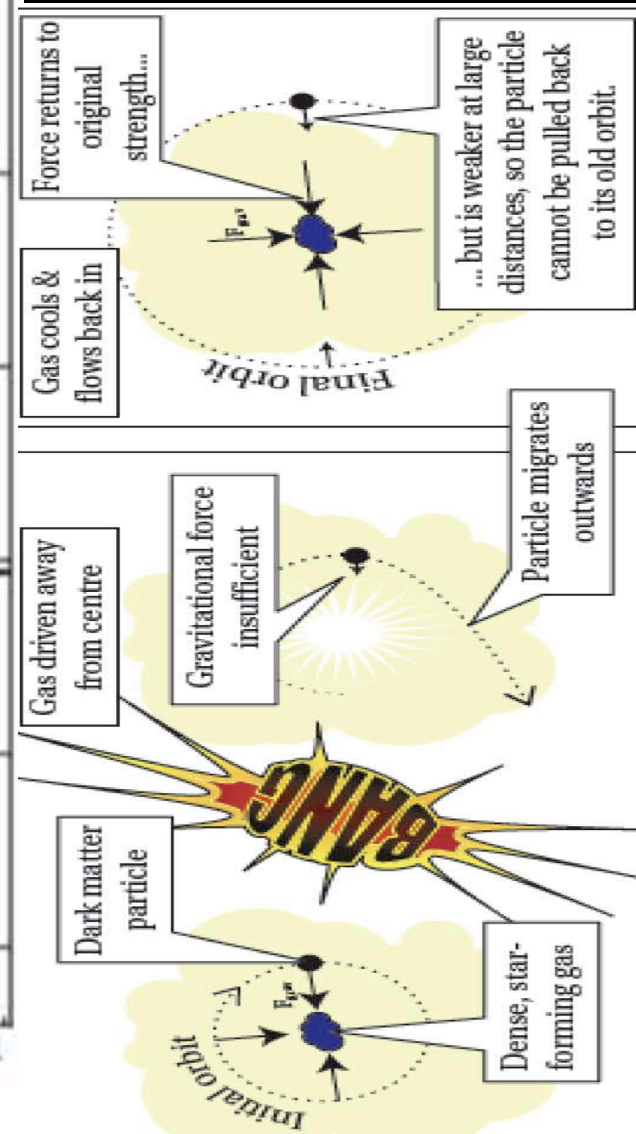




Supernova feedback generates cores



Pontzen & Governato 2014



Dwarf galaxy issues: summary

- Number density NO PROBLEM
- Cores SN FEEDBACK
- Too big to fail ???

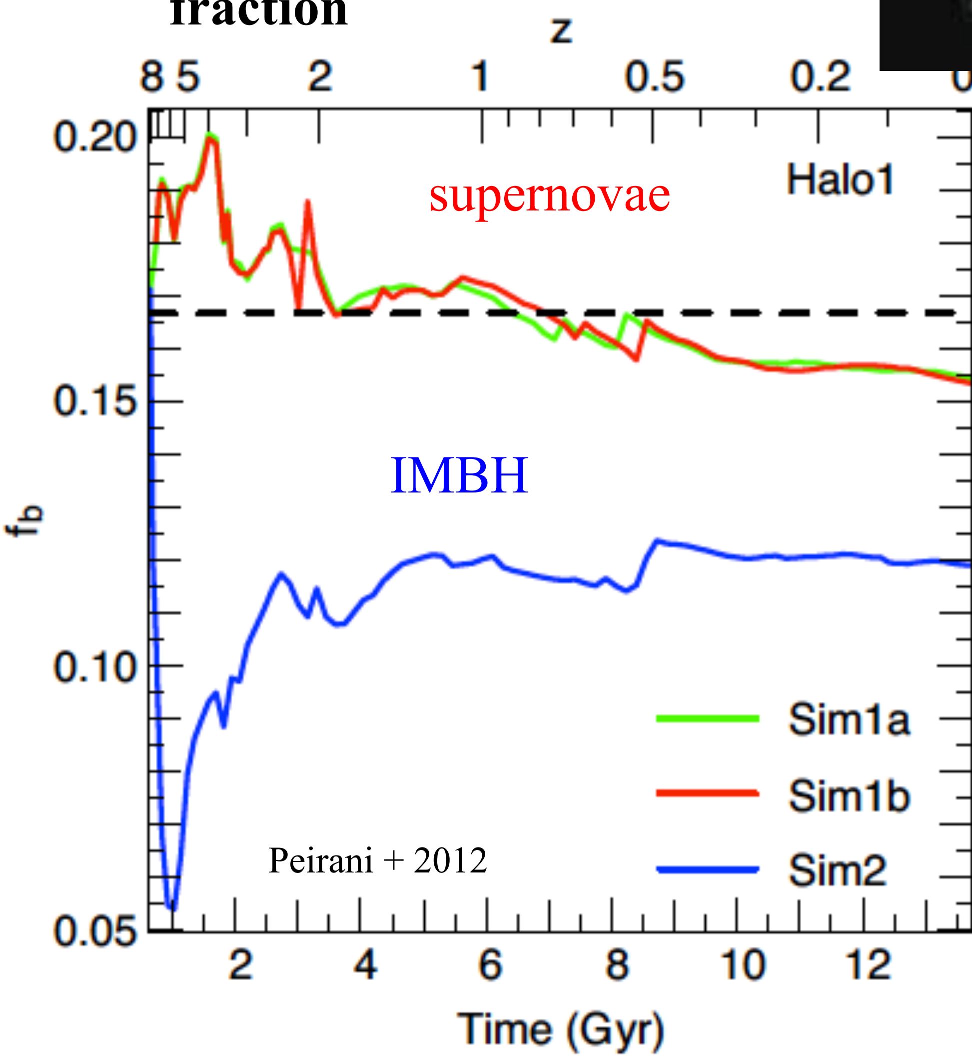
Dwarf galaxy issues: solutions

- Selection effects on numbers
- Baryonic physics on cores: SN?
- Feedback from IMBH also resolves too big to fail

IMBH EXPEL BARYONS

A problem for all galaxies

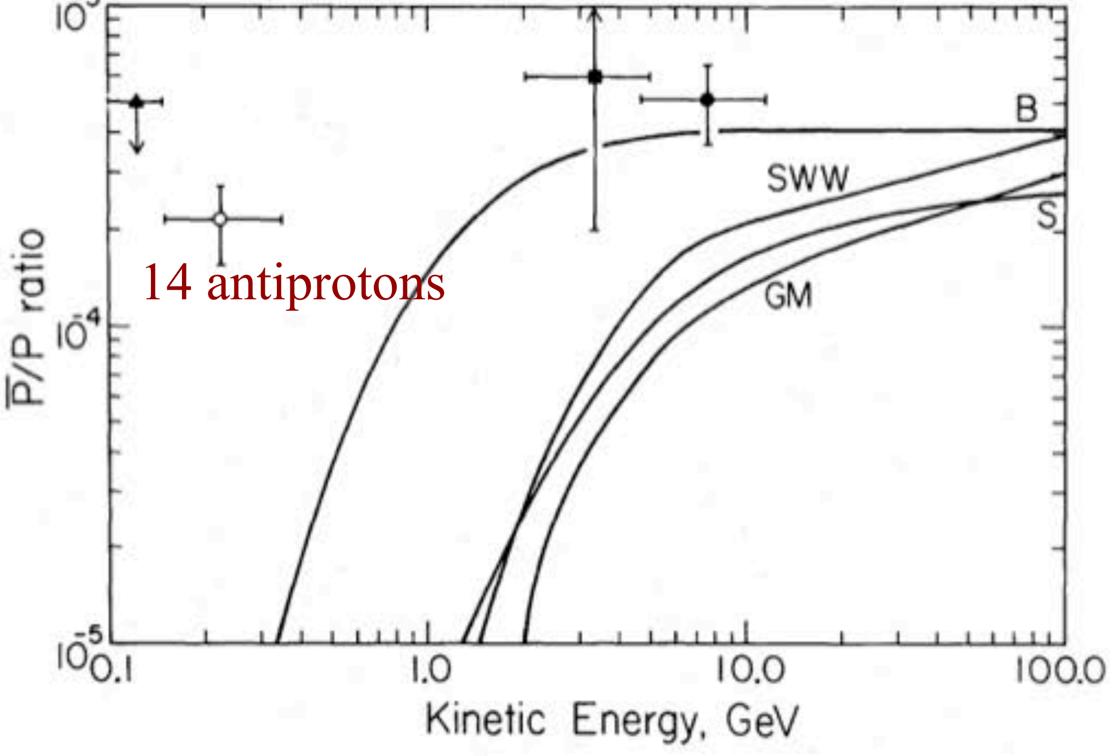
...and resolve TBTF



IMBH feedback resolves cores, too big to fail and the baryon budget problem

ANTI-COSMIC RAYS

Buffington + 1981
JS & Srednicki 1984



UME 53, NUMBER 6 PHYSICAL REVIEW LETTERS 6 AUGUST

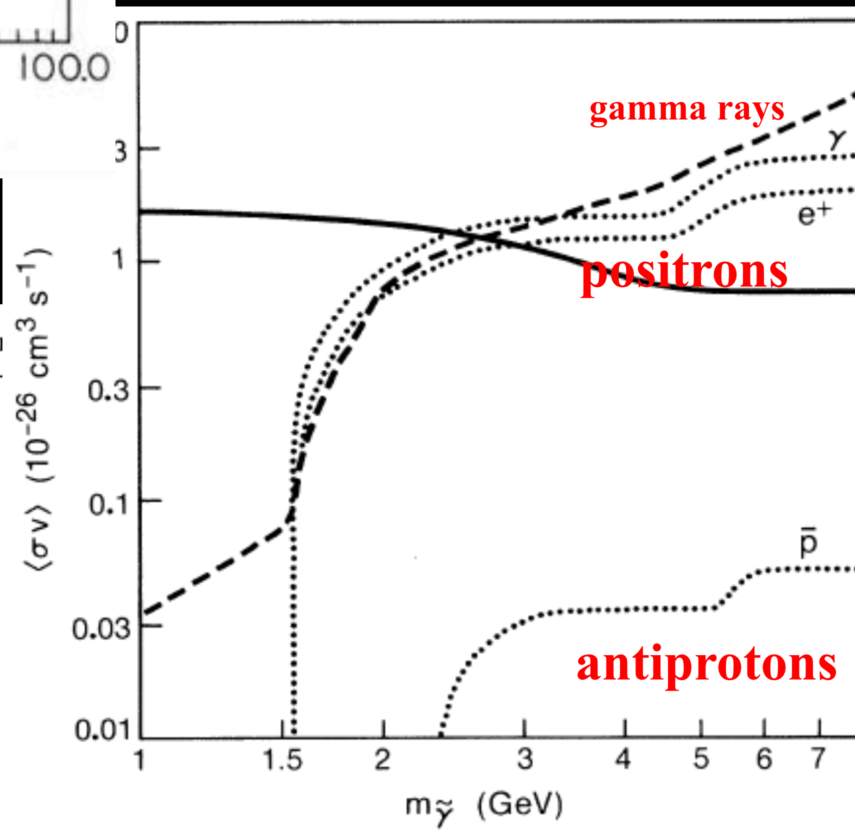
Cosmic-Ray Antiprotons as a Probe of a Photino-Dominated Universe

Joseph Silk
Astronomy Department, University of California, Berkeley, California 94720, and Institute for Theoretical Physics, University of California, Santa Barbara, California 93106

and

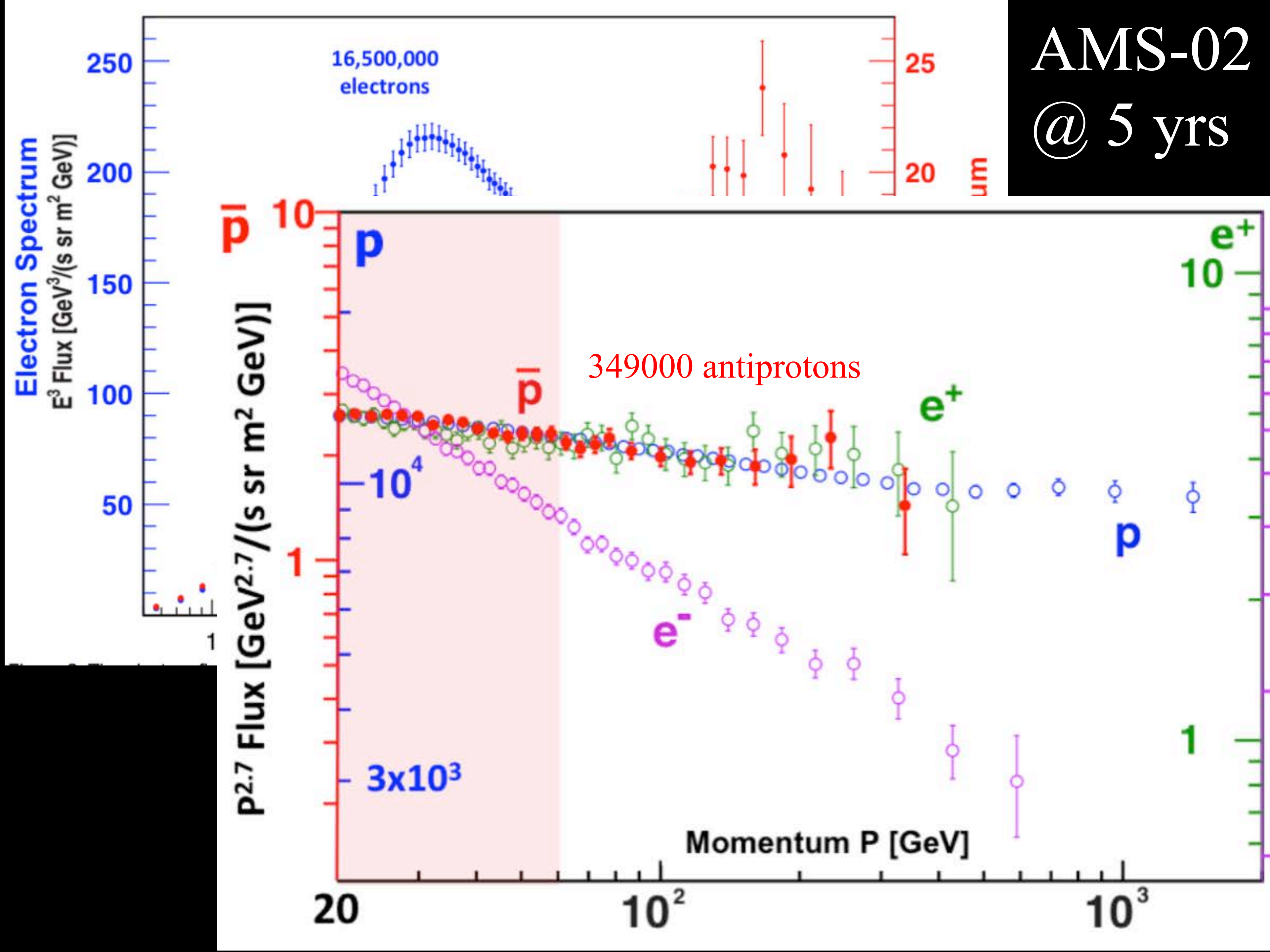
Mark Srednicki
Physics Department, University of California, Santa Barbara, California 93106
(Received 8 June 1984)

Observational tests of the hypothesis that the universe is flat and dominated by dark matter in the form of massive photinos include the production of significant fluxes of cosmic rays and gamma rays in our galactic halo. Specification of the cosmological photino density and the masses of scalar quarks and leptons determines the present annihilation rate. The predicted number of low-energy cosmic-ray antiprotons is comparable to the observed flux.

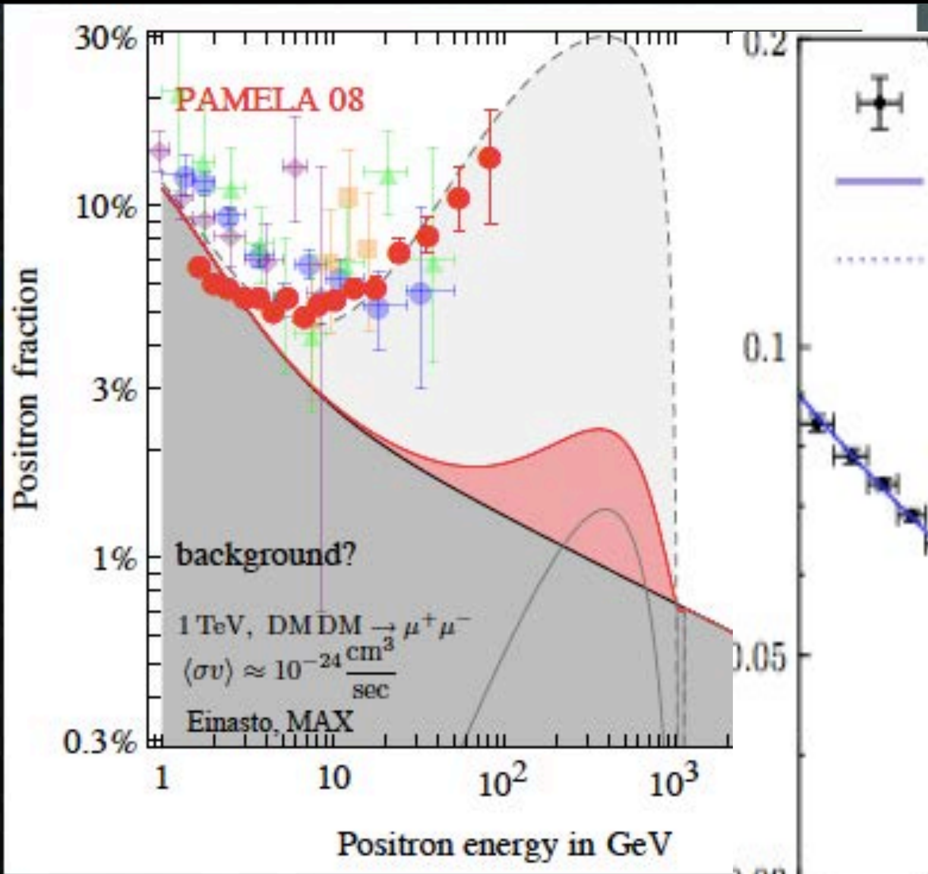


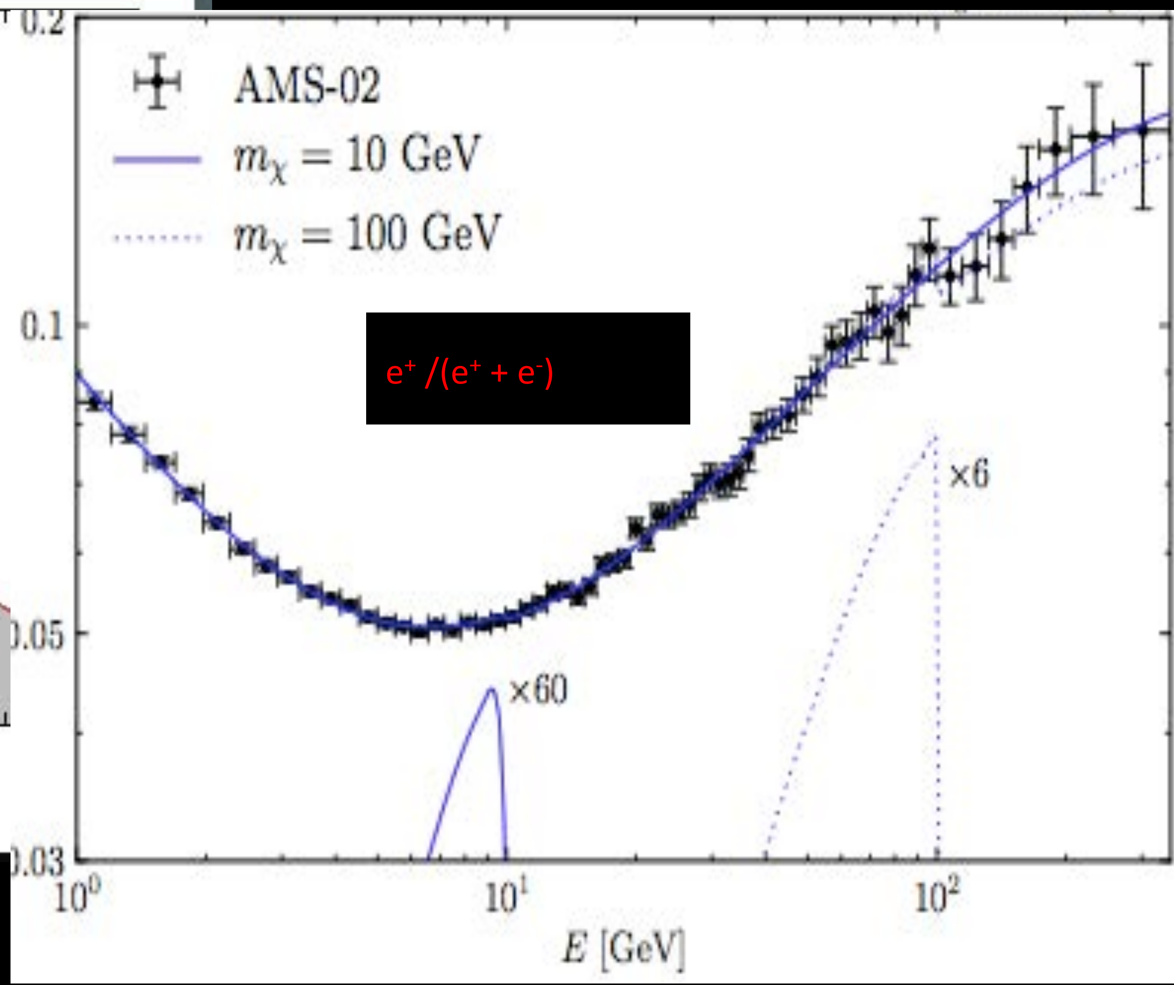
Dark matter annihilations produce high energy positrons.
Normally these are very rare in the cosmic rays that bombard the earth

Dark matter experiment on board the
International Space Station:
AMS-02, a charged cosmic ray detector, sensitive to antimatter


AMS-02
@ 5 yrs
16,500,000
electrons
Electron Spectrum
E3 Flux [GeV3/(s sr m2 GeV)]
250
200
150
100
50
25
20
1
p̄
p
10
1
e+
10
1
349000 antiprotons
p̄
e+
e-
p
10^4
3x10^3
P2.7 Flux [GeV2.7/(s sr m2 GeV)]
Momentum P [GeV]
20
10^2
10^3

The mysterious rising positron flux

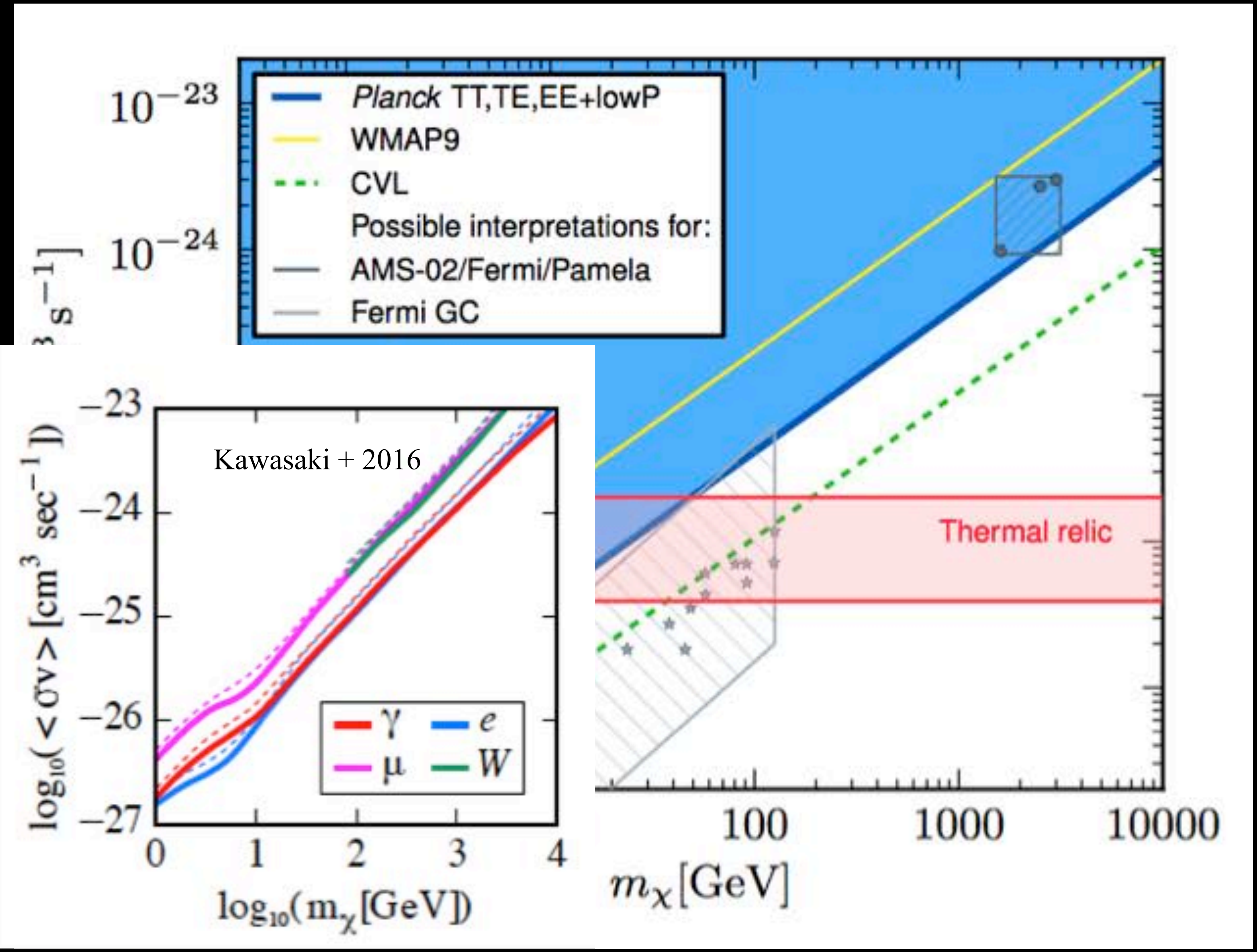




Cirelli 2009

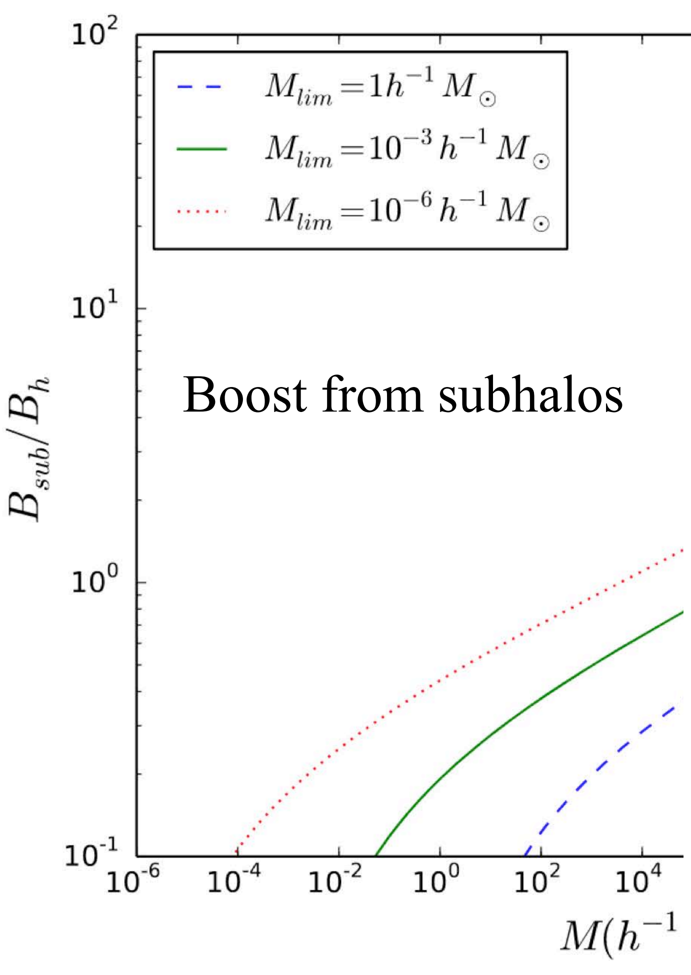
Bergstrom + 2013

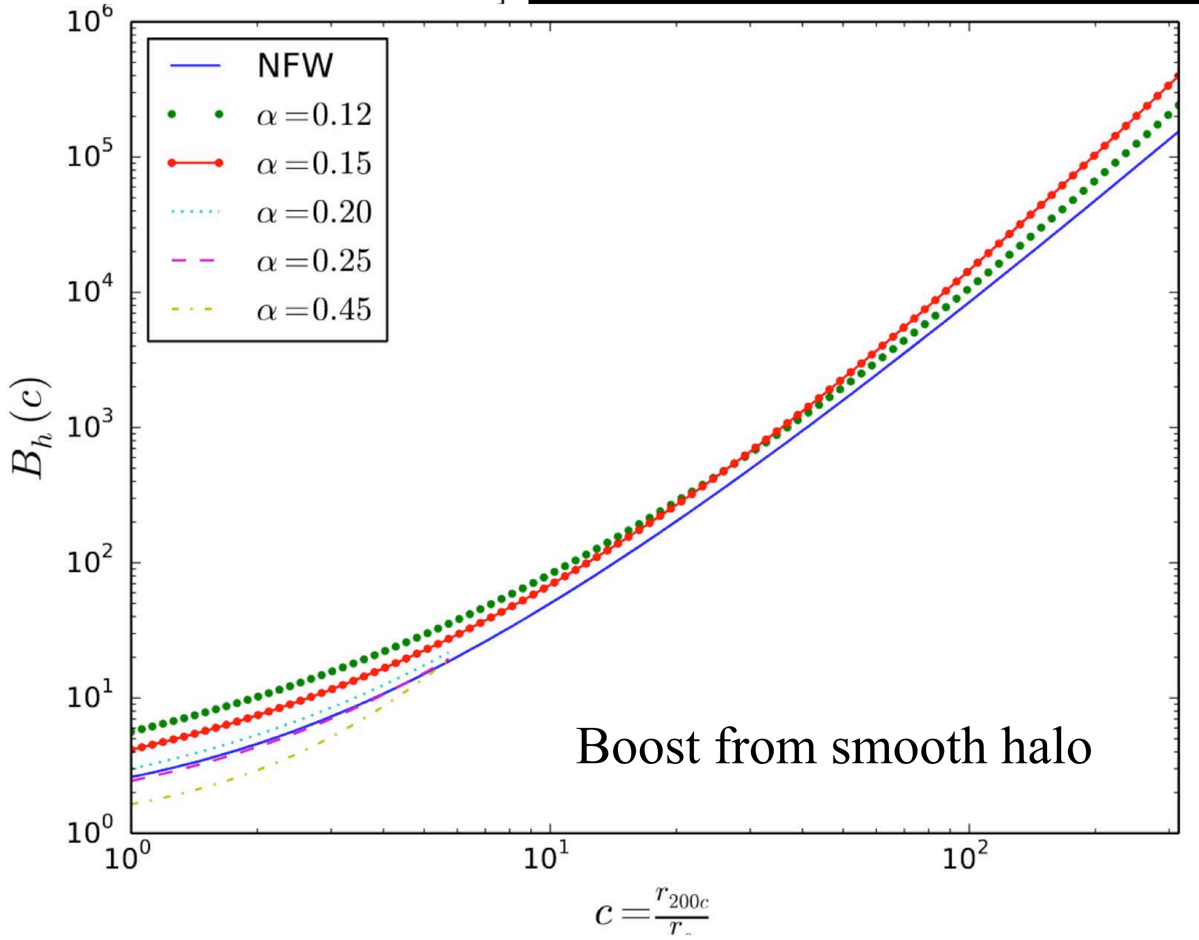
Planck constraint on DM contribution



DM BOOST FACTOR REVISITED

Annihilations are proportional to ρ^2



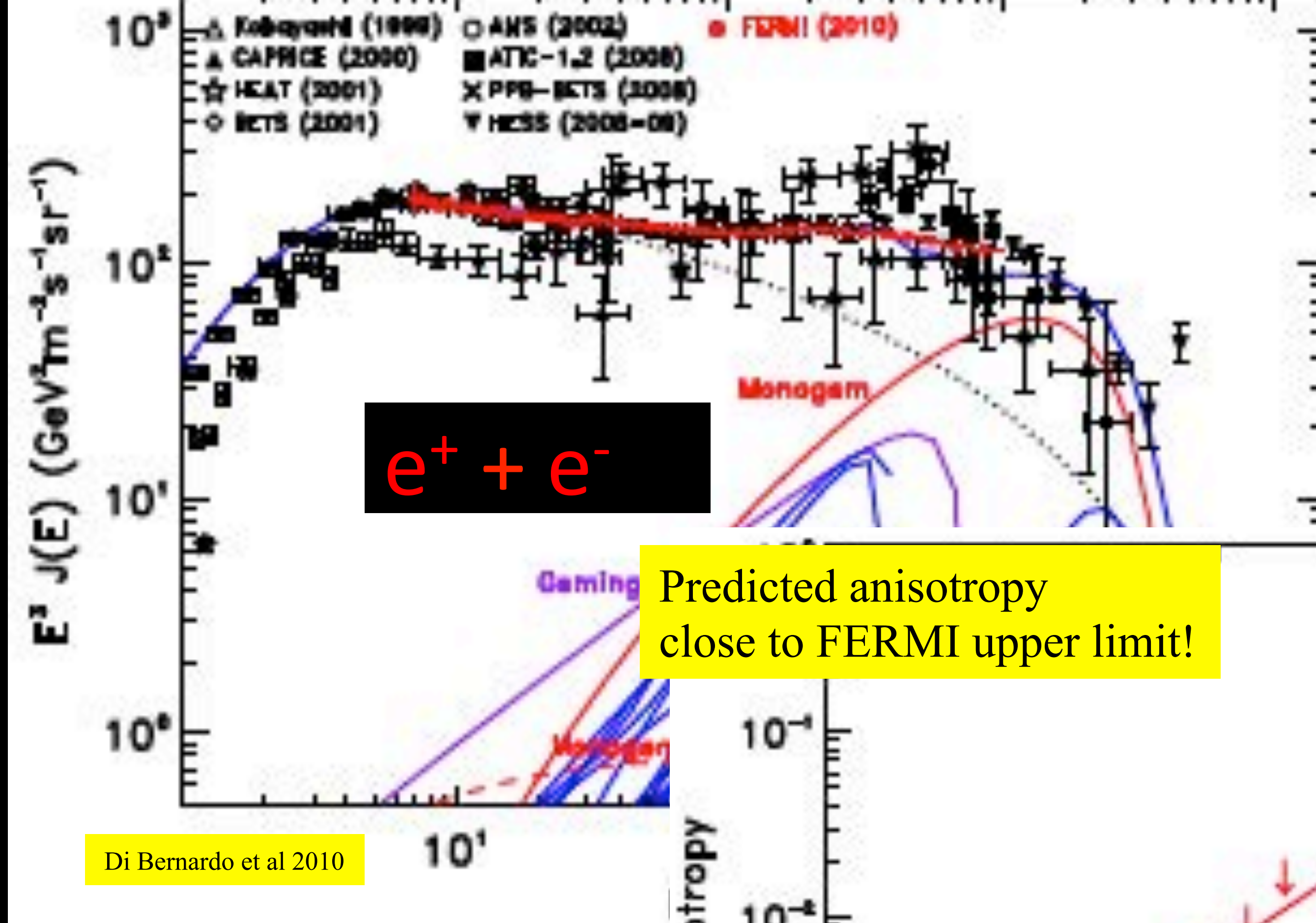


Searching for dark matter annihilation from individual halos

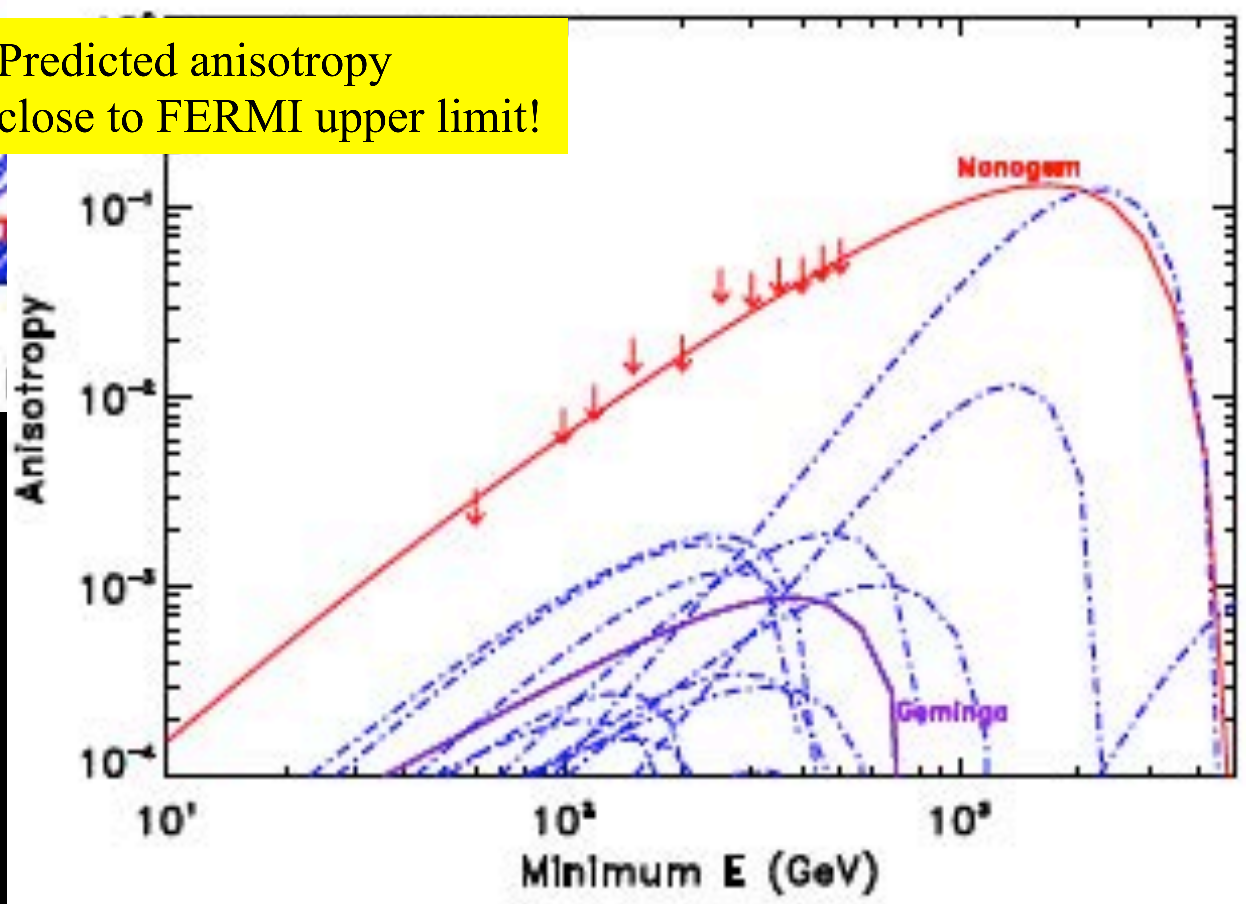
Chiamaka Okoli, James E. Taylor, Niayesh Afshordi arXiv 1711.05271 astrophysical origin

PULSAR WIND?

$e^+ + e^-$

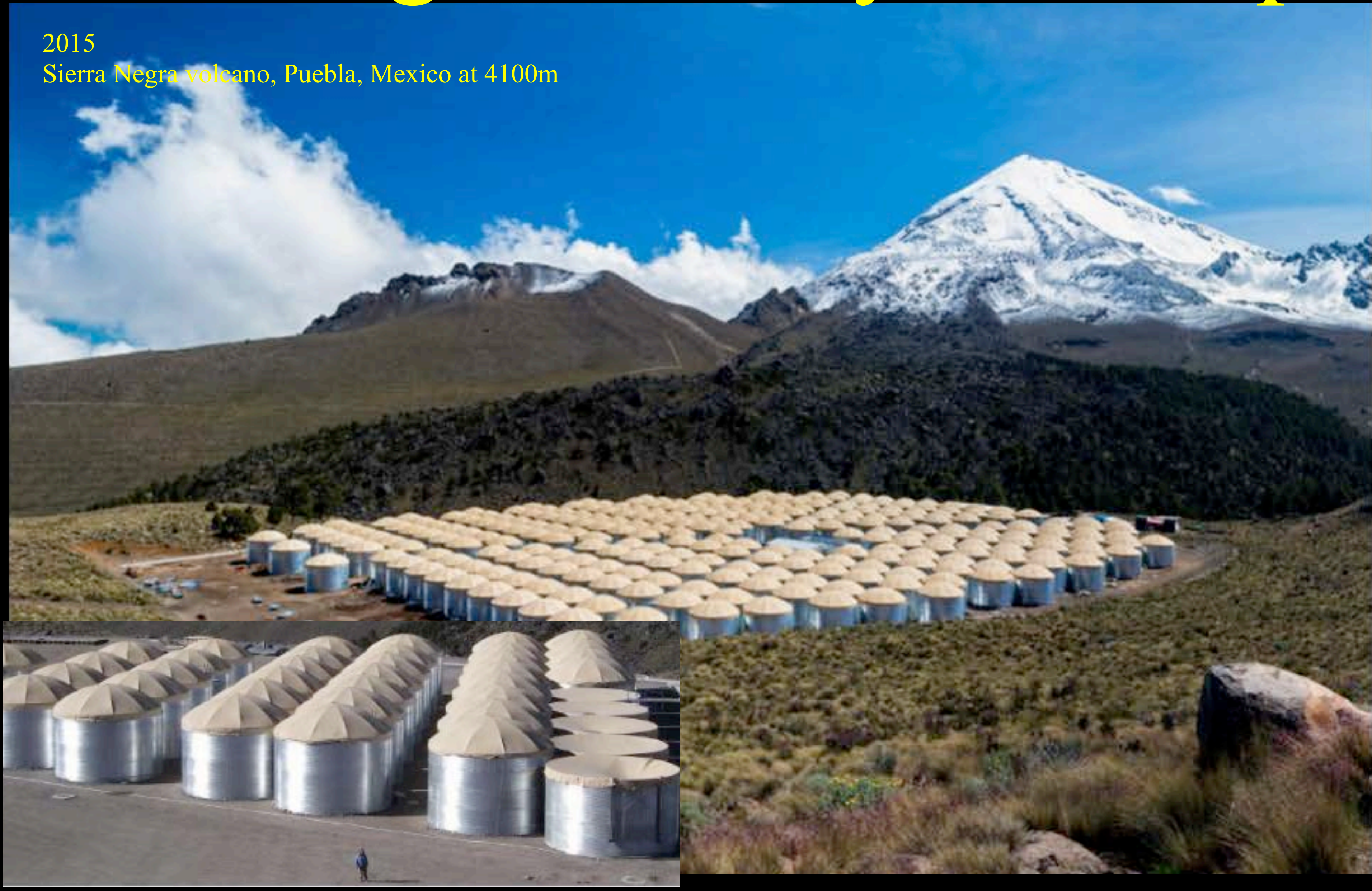


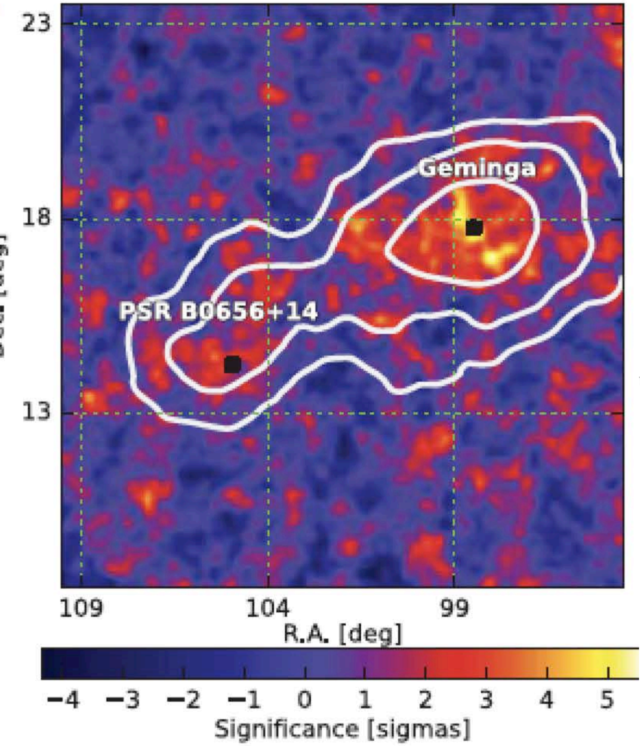
Predicted anisotropy close to FERMI upper limit!

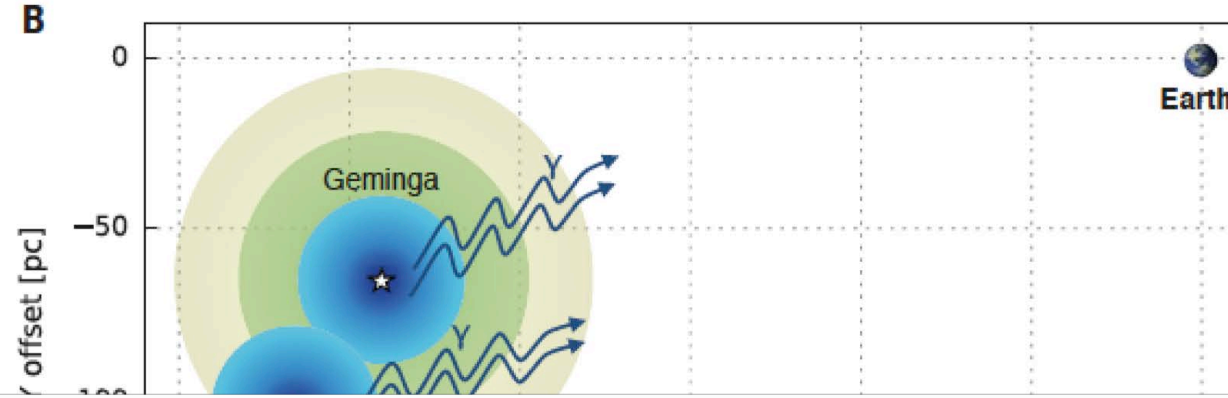


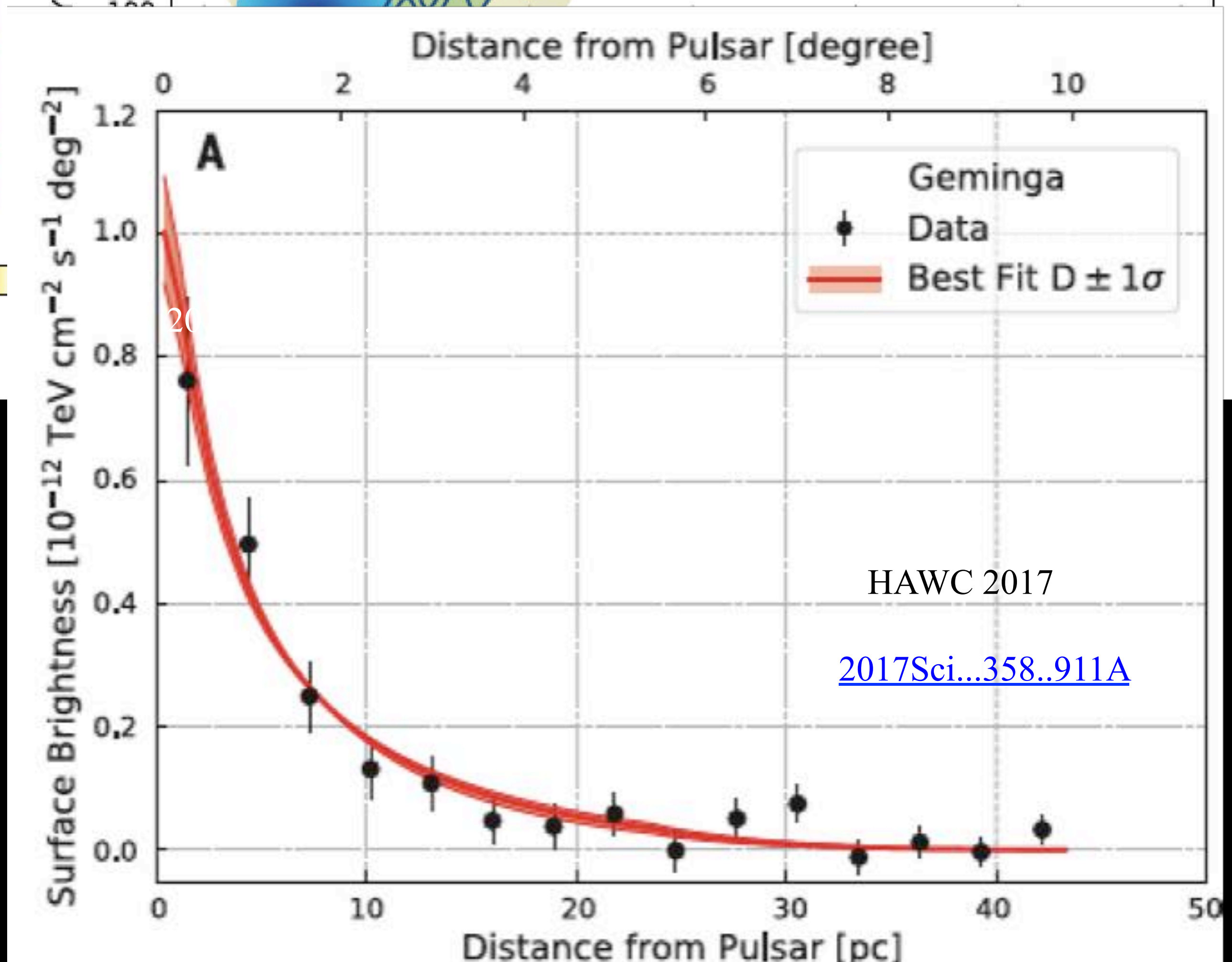
Di Bernardo et al 2010

HAWC gamma-ray telescope



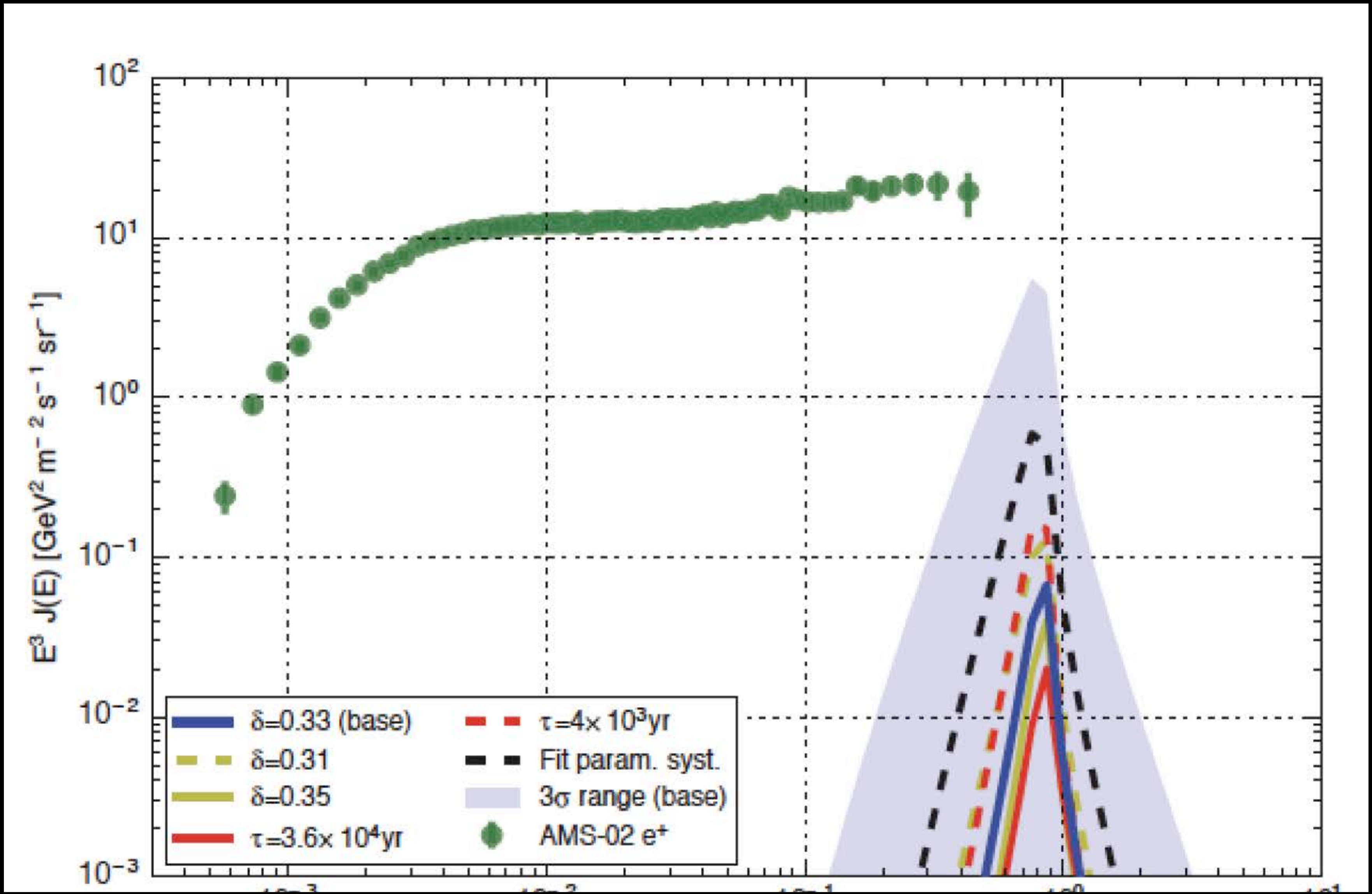




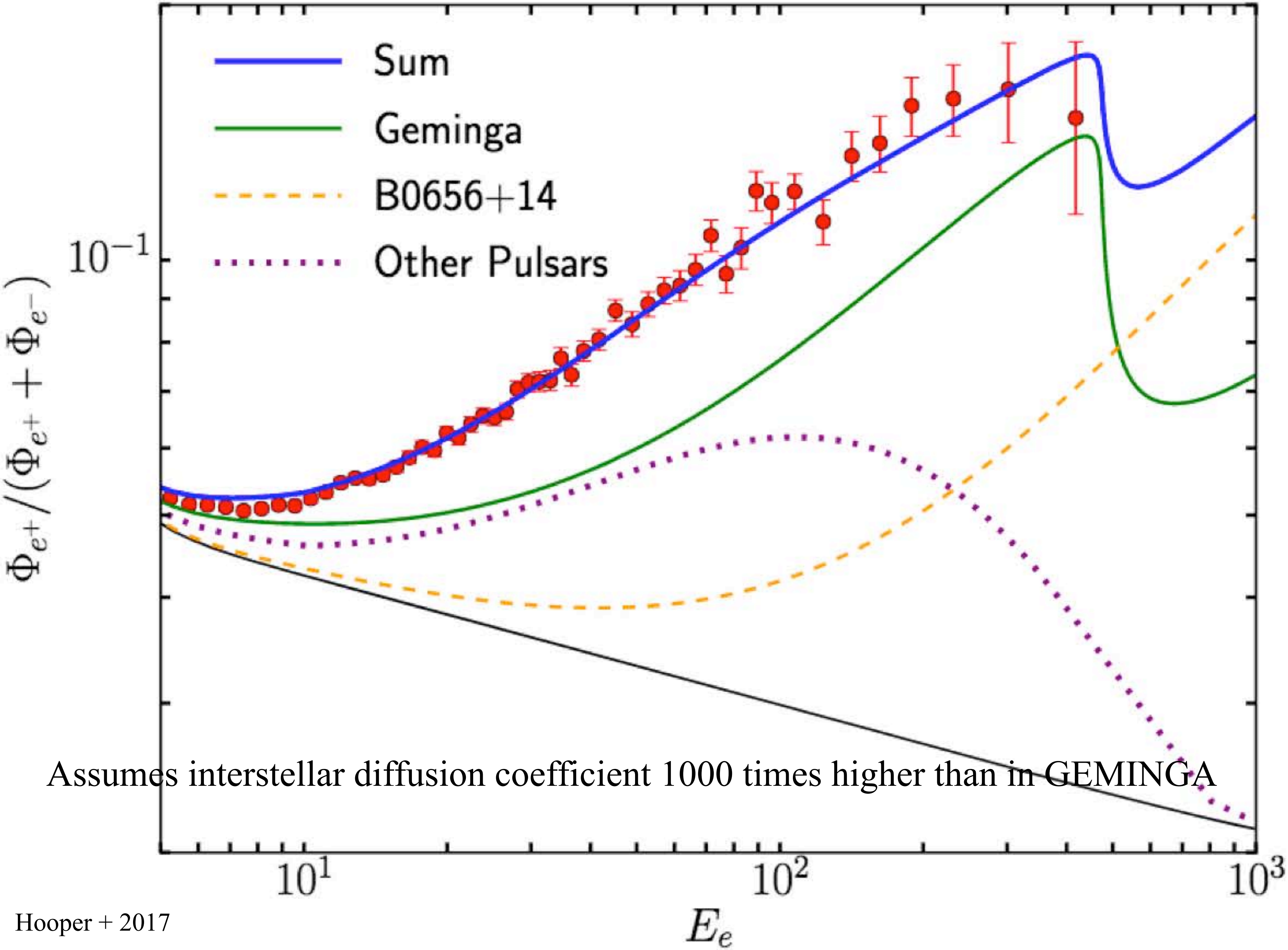


HAWC 2017

2017Sci...358..911A


E³ J(E) [GeV² m⁻² s⁻¹ sr⁻¹]
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
δ=0.33 (base)
δ=0.31
δ=0.35
τ=3.6× 10⁴yr
τ=4× 10³yr
Fit param. syst.
3σ range (base)
AMS-02 e⁺

HAWC 2017



Assumes interstellar diffusion coefficient 1000 times higher than in GEMINGA

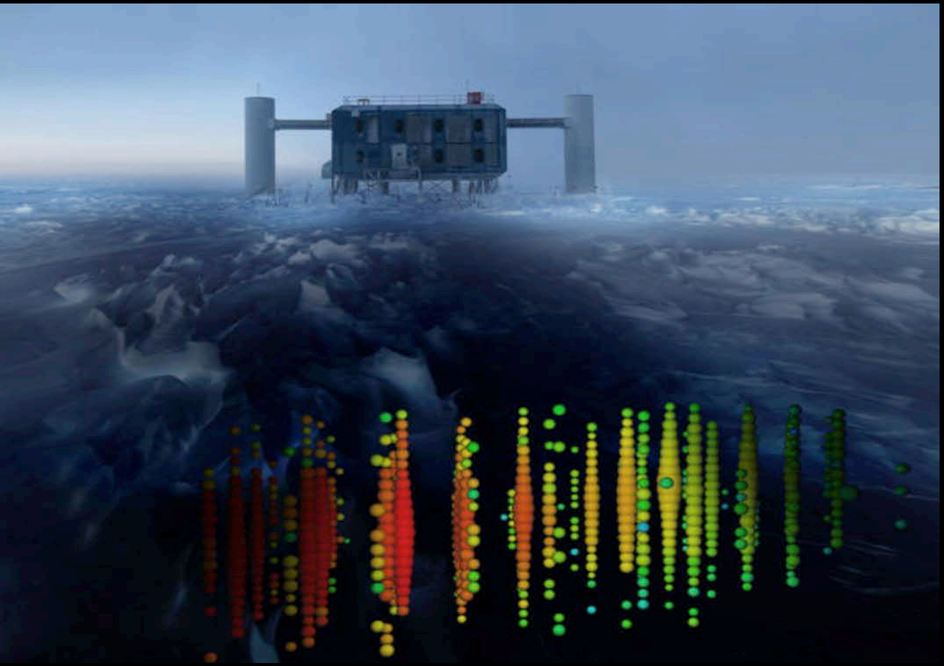
Hooper + 2017

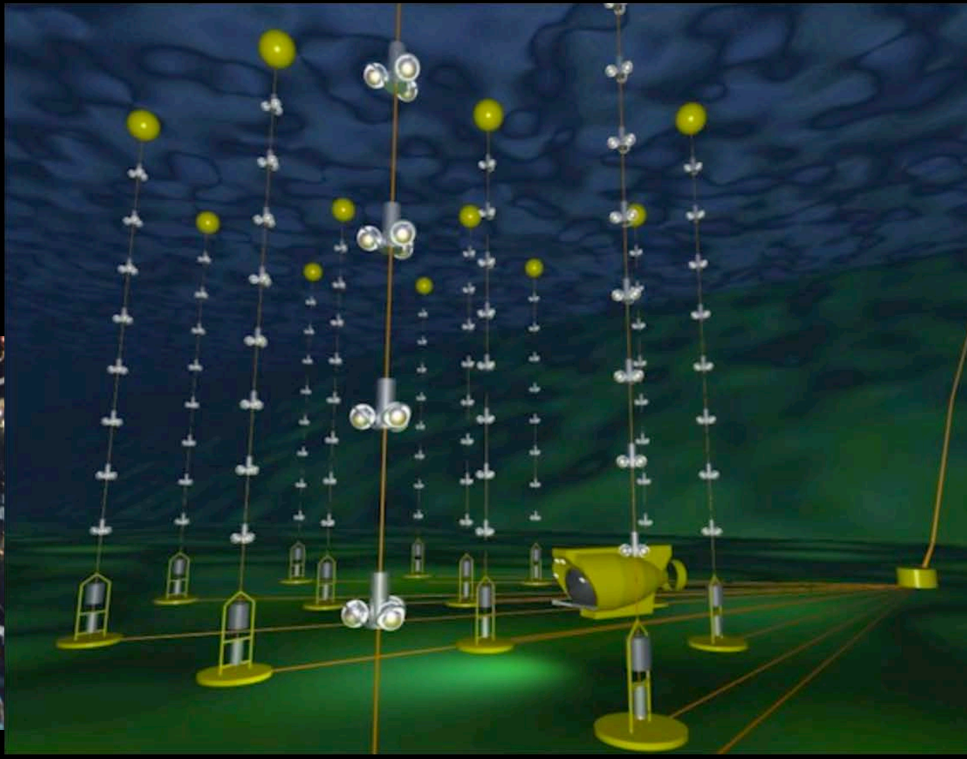
Lecture

3

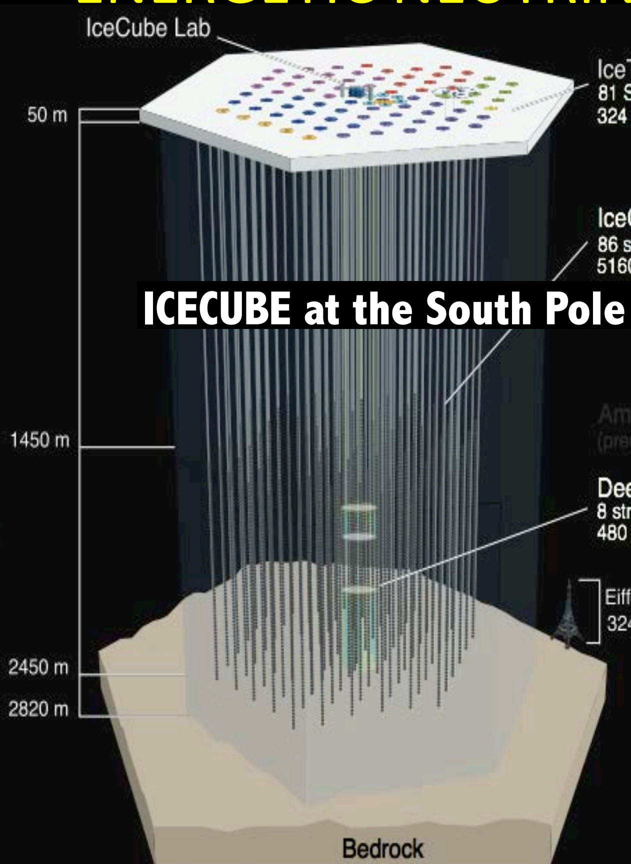
DARK MATTER
WHERE NEXT?

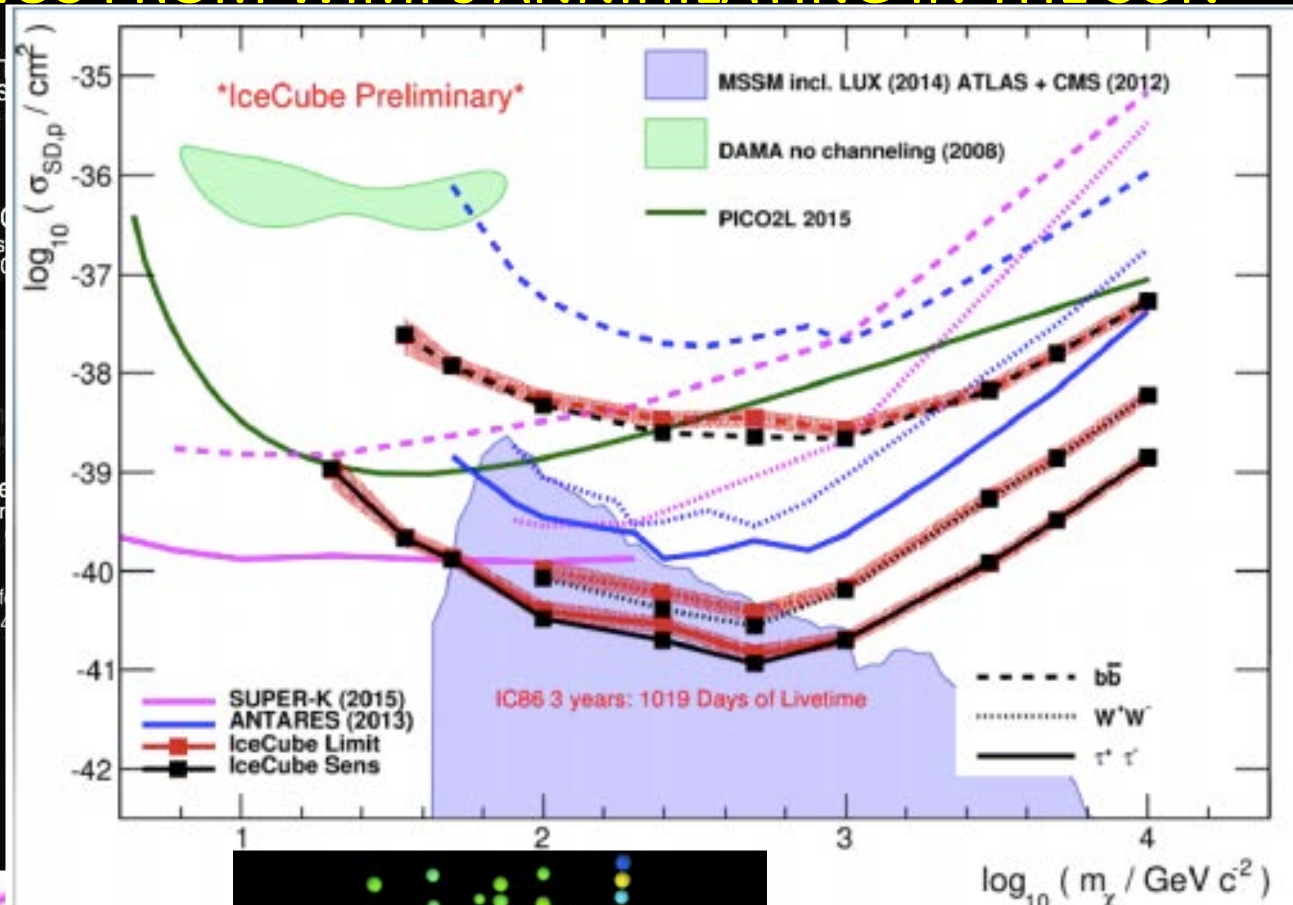
NEUTRINOS

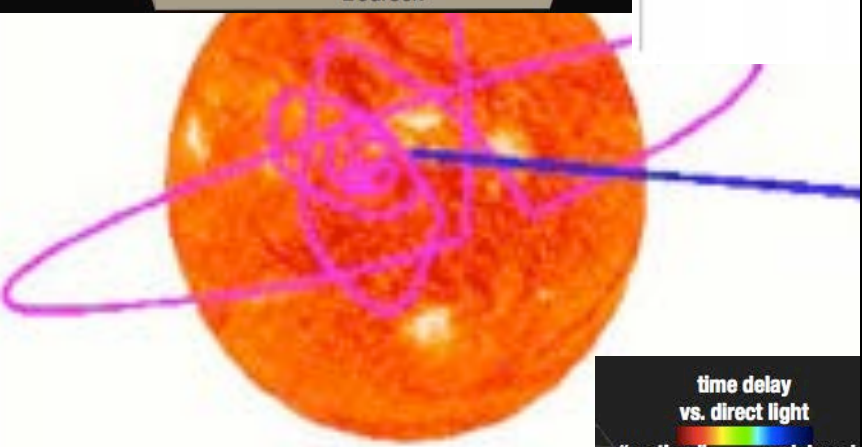


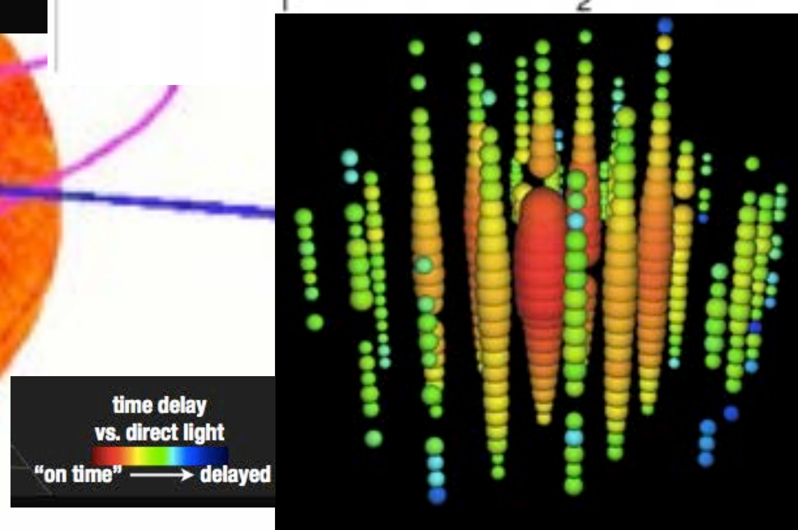


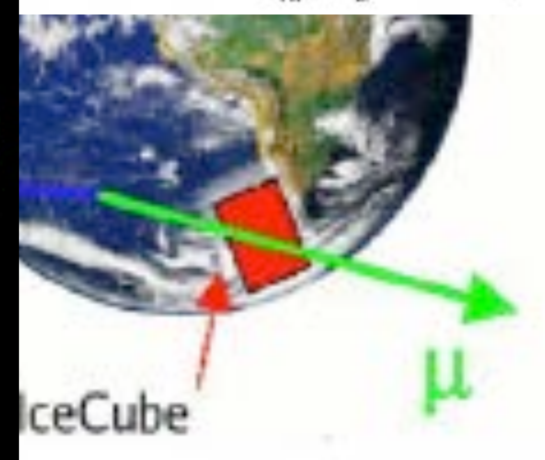
ENERGETIC NEUTRINOS FROM WIMPs ANNIHILATING IN THE SUN

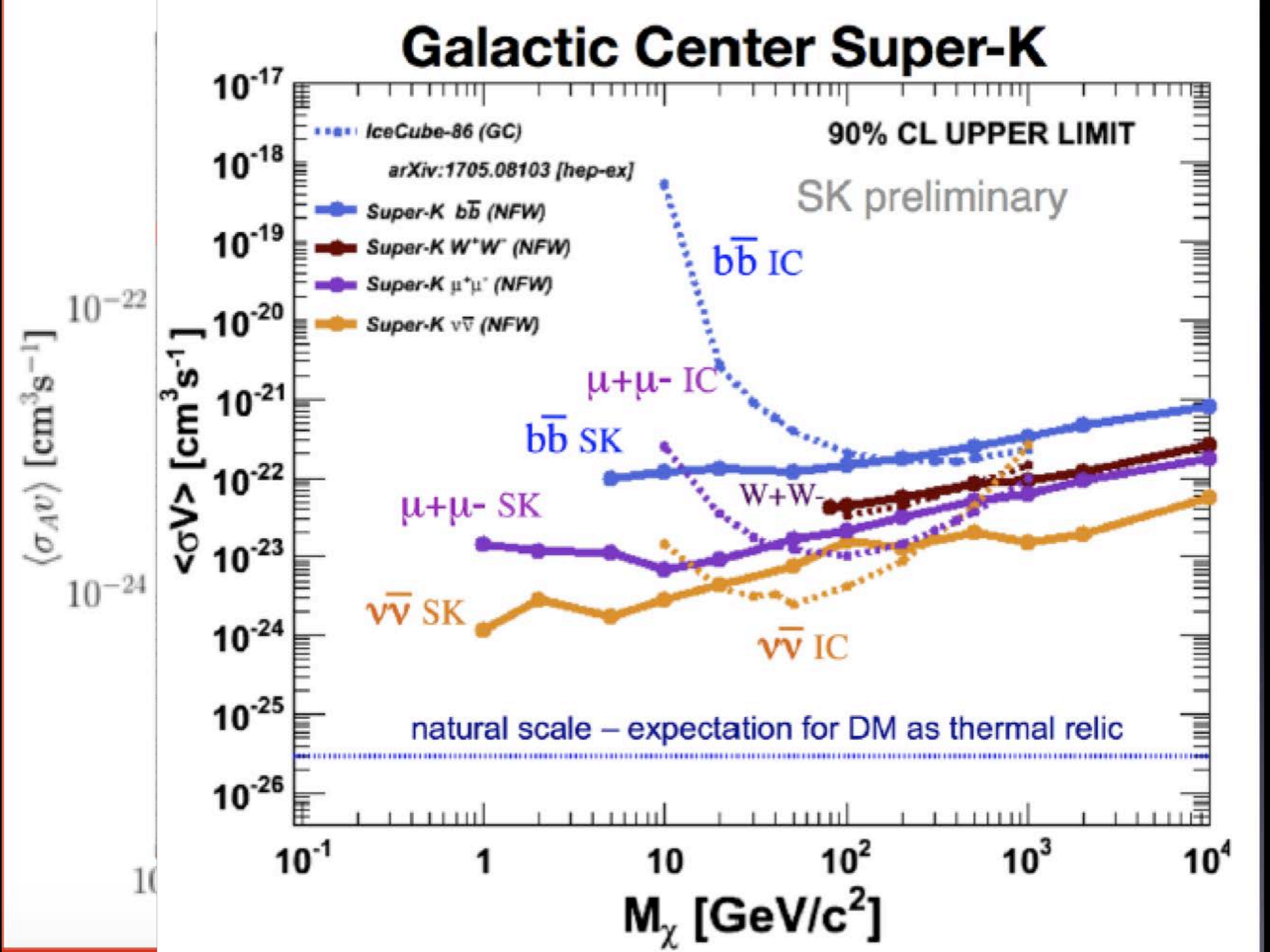






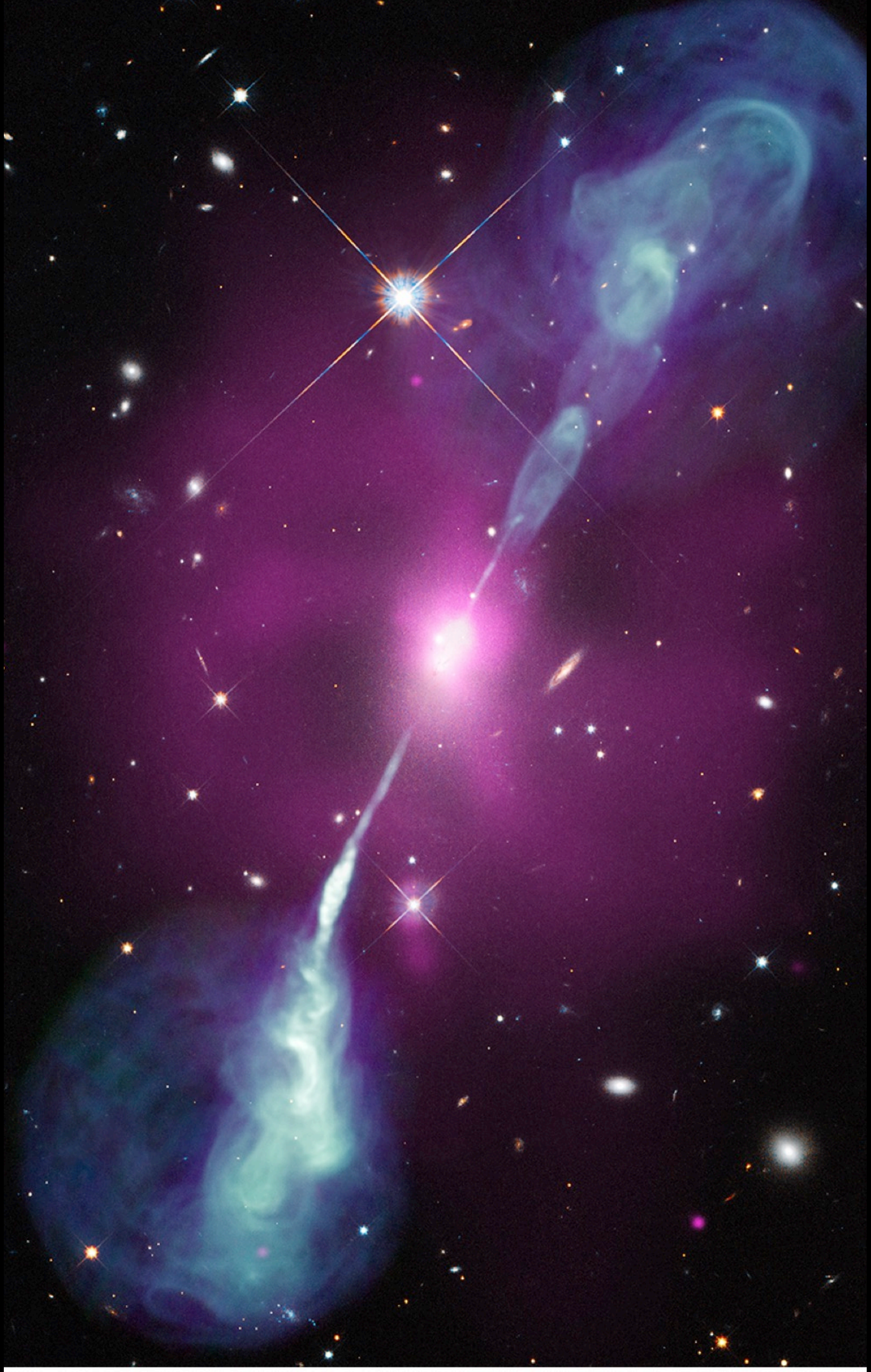





Galactic Center Super-K
90% CL UPPER LIMIT
SK preliminary
IceCube-86 (GC)
arXiv:1705.08103 [hep-ex]
Super-K $b\bar{b}$ (NFW)
Super-K W^+W^- (NFW)
Super-K $\mu^+\mu^-$ (NFW)
Super-K $\nu\bar{\nu}$ (NFW)
$b\bar{b}$ IC
μ+μ- IC
$b\bar{b}$ SK
W+W-
μ+μ- SK
$\nu\bar{\nu}$ SK
$\nu\bar{\nu}$ IC
natural scale – expectation for DM as thermal relic
<σV> [cm^{3}s^{-1}]
M_χ [GeV/c^2]
$\langle \sigma_A v \rangle$ [cm^{3}s^{-1}]

BLACK HOLES AS PROBES

Hercules A

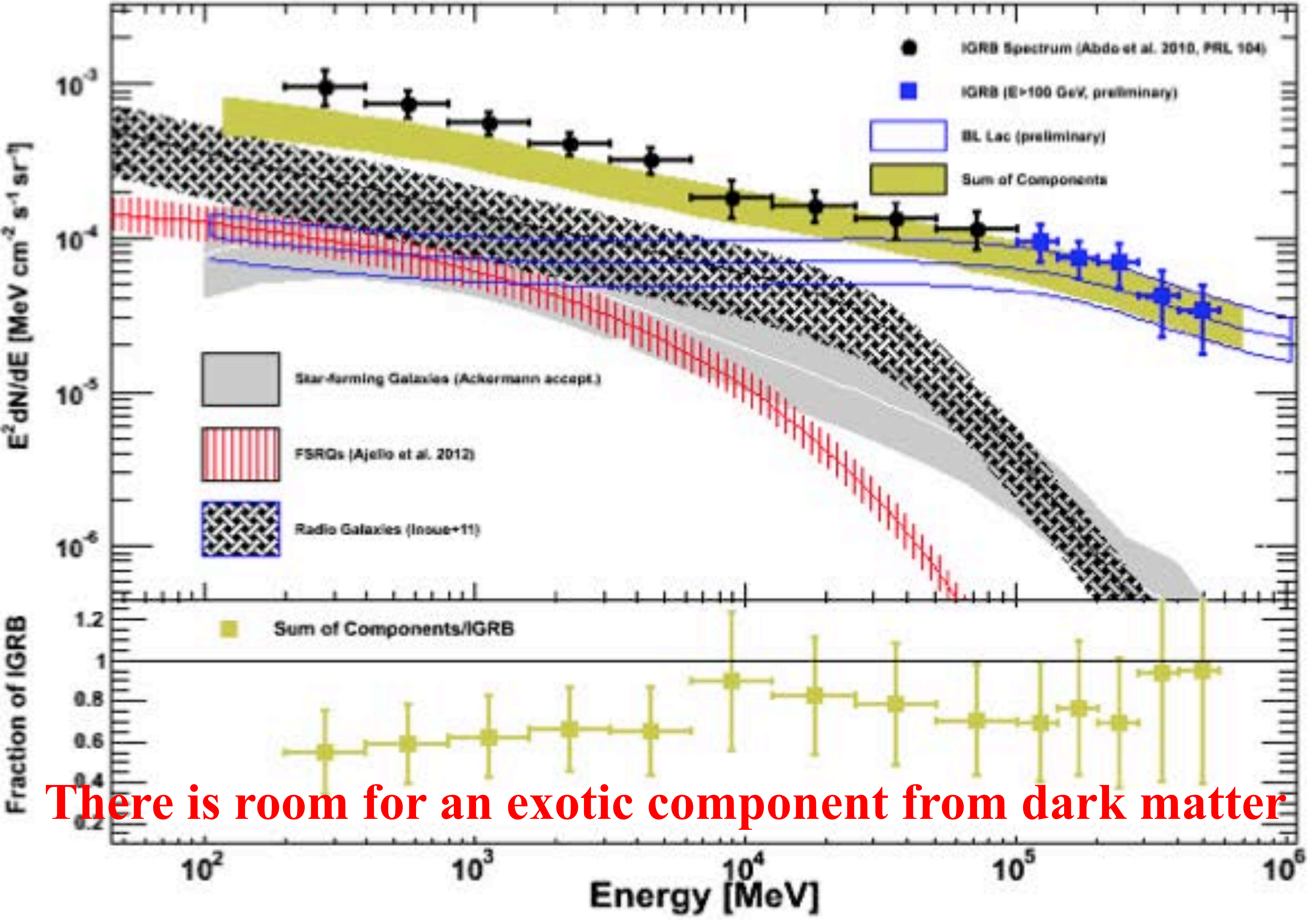


Core of Galaxy NGC 4261

Hubble Space Telescope

Wide Field / Planetary Camera

EXTRAGALACTIC GAMMA RAY BACKGROUND



There is room for an exotic component from dark matter

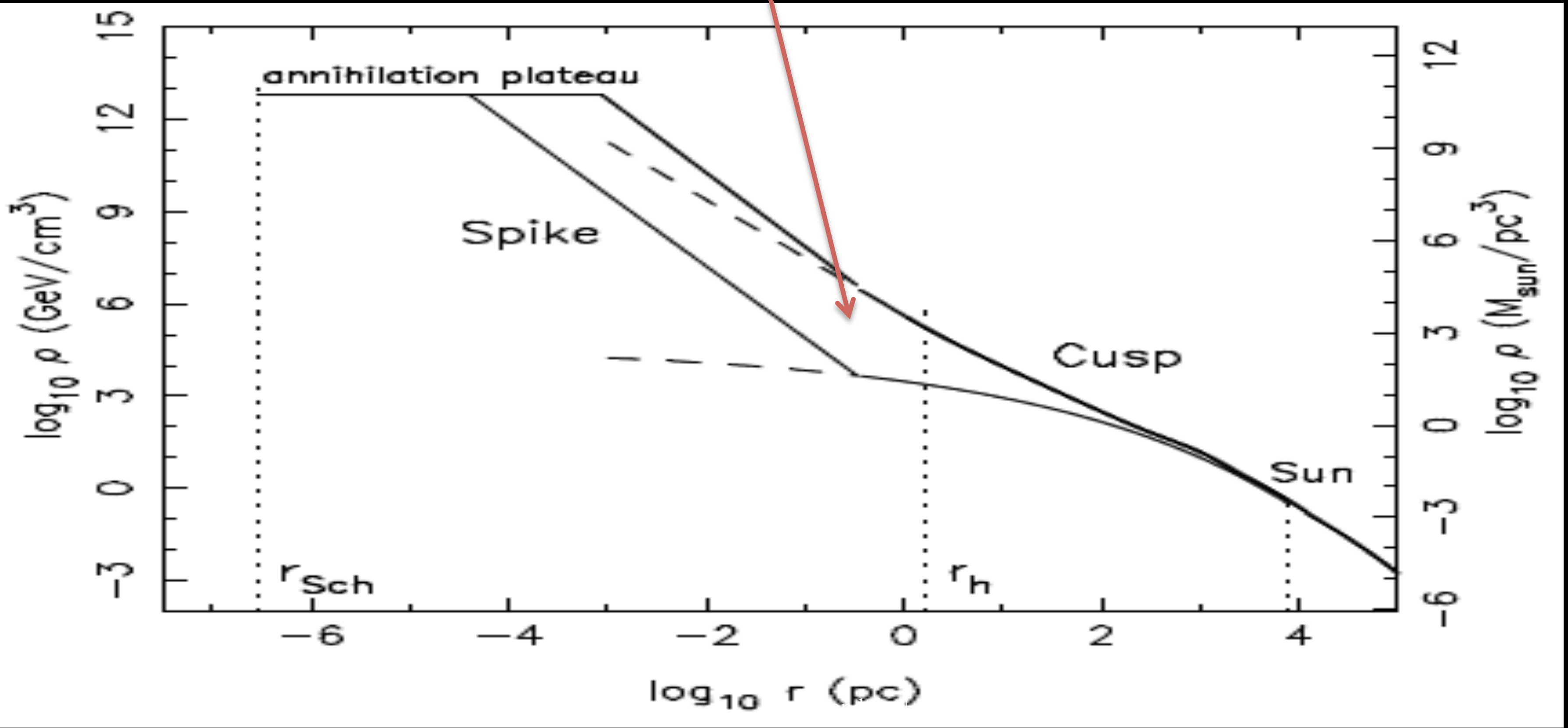
What happens to DM within the gravitational sphere of influence of a growing SMBH?

CDM cusp steepens by adiabatic growth of IMBH: $\rho \propto r^{-\gamma} \Rightarrow \rho \propto r^{-\gamma'}$, **with** $\gamma' = \frac{9-2\gamma}{4-\gamma}$

Annihilation rate is amplified within a radius $GM_{bh}/\sigma^2 \sim 0.003(M_{BH}/10^5 M_\odot)\mathrm{pc}$

DM density profile

Plateau: $n_x(\mathbf{r})\langle\sigma v\rangle\, t_{BH} \sim 1$



Especially important for SMBH

NEARBY AGN

begin with SagA*

M87 is another attractive target

Distance 2000 x GC but M_{BH} 1500 x SagA*

Flux ~ $n_x^2 \langle \sigma v \rangle (2r_p)^3 \sim M_{BH}^3 / \langle \sigma v \rangle$

Important for low $\langle \sigma v \rangle$

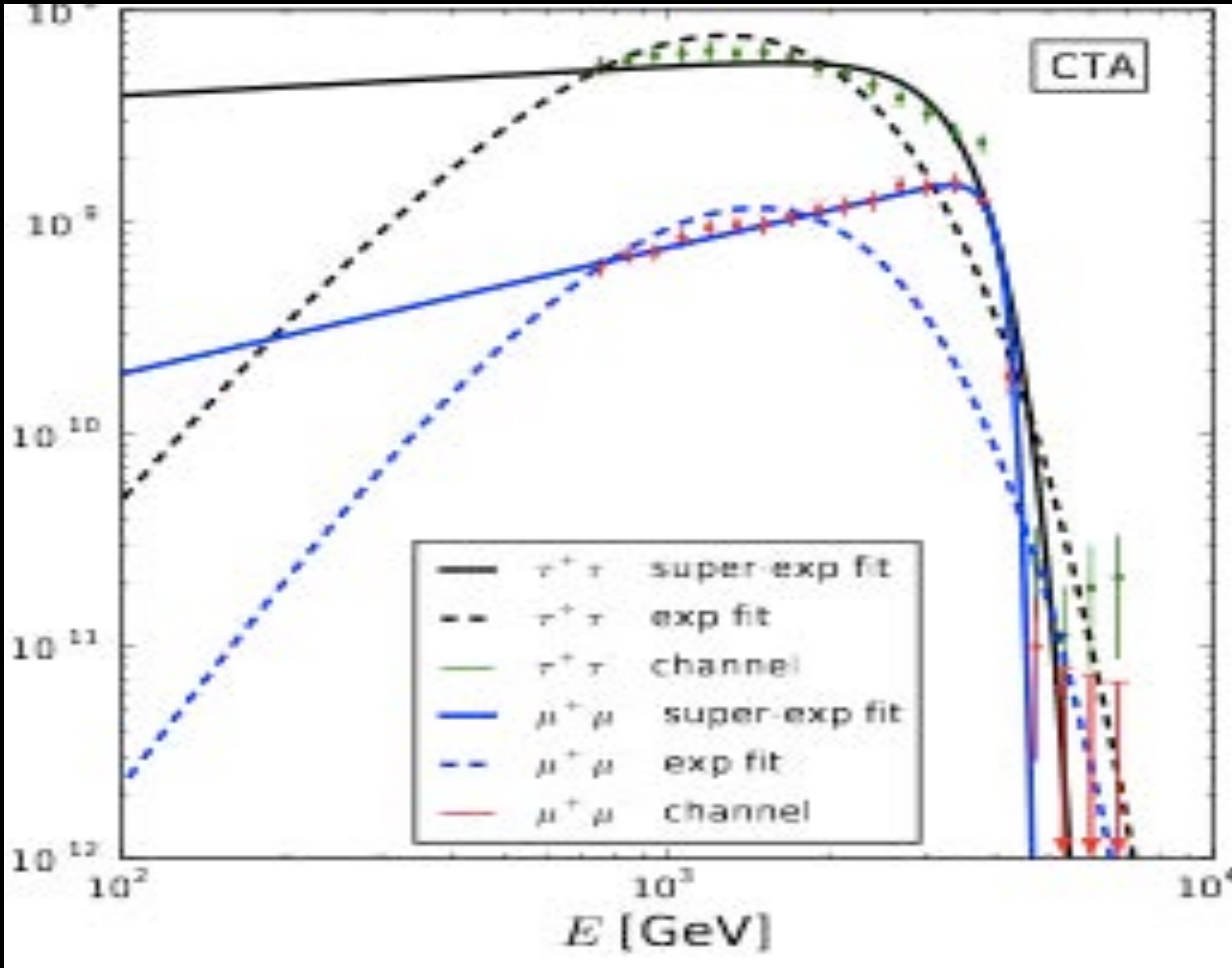
$n_x(\mathbf{r_p}) \langle \sigma v \rangle t_{BH} \sim 1$

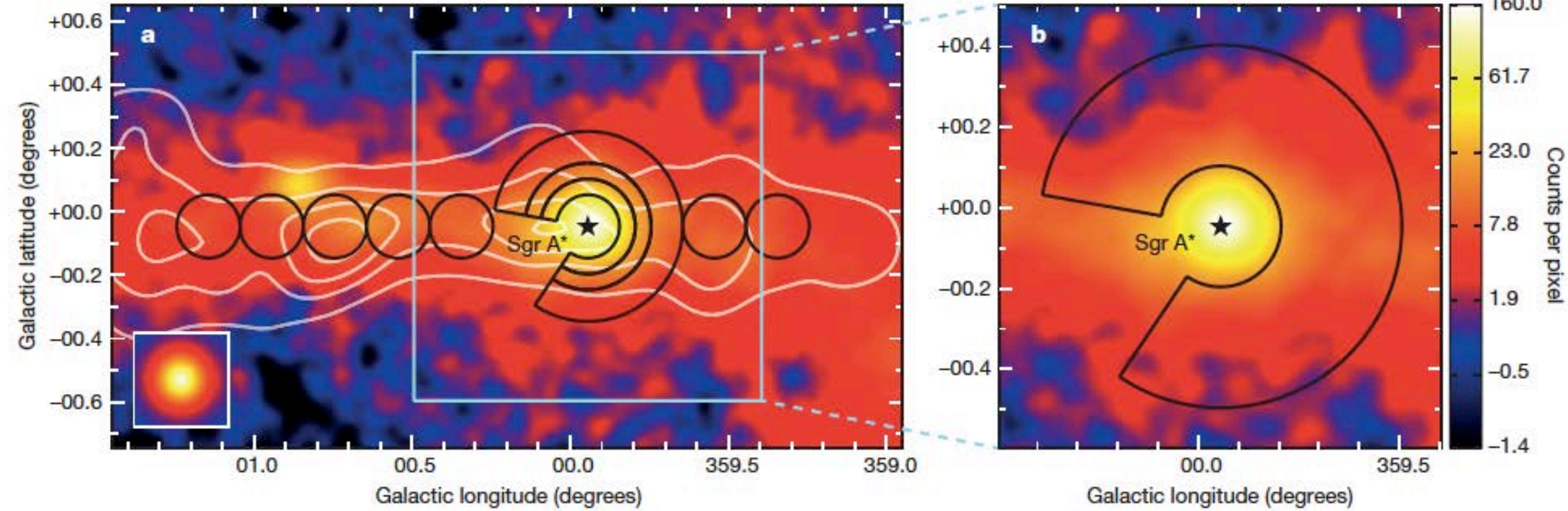
Dynamical heating of spike ~ 10^{14} yr vs 10^9 yr (GC)

HESS gamma-ray telescope

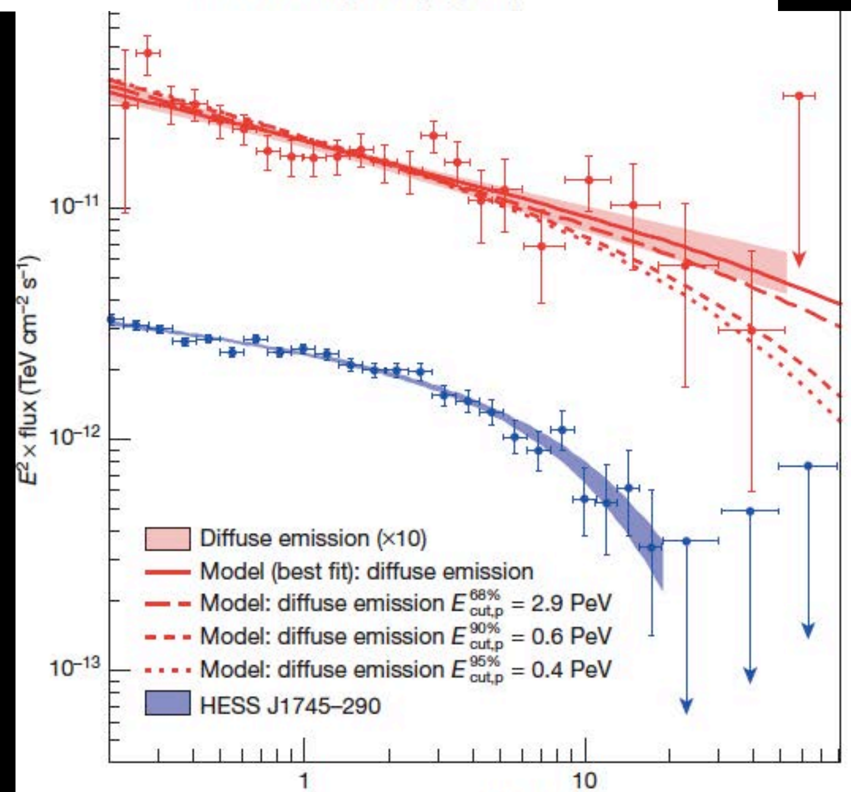
supermassive black hole at Galactic Center HESS J1745-290

prediction for CTA: superexponential signature of TeV DM annihilations



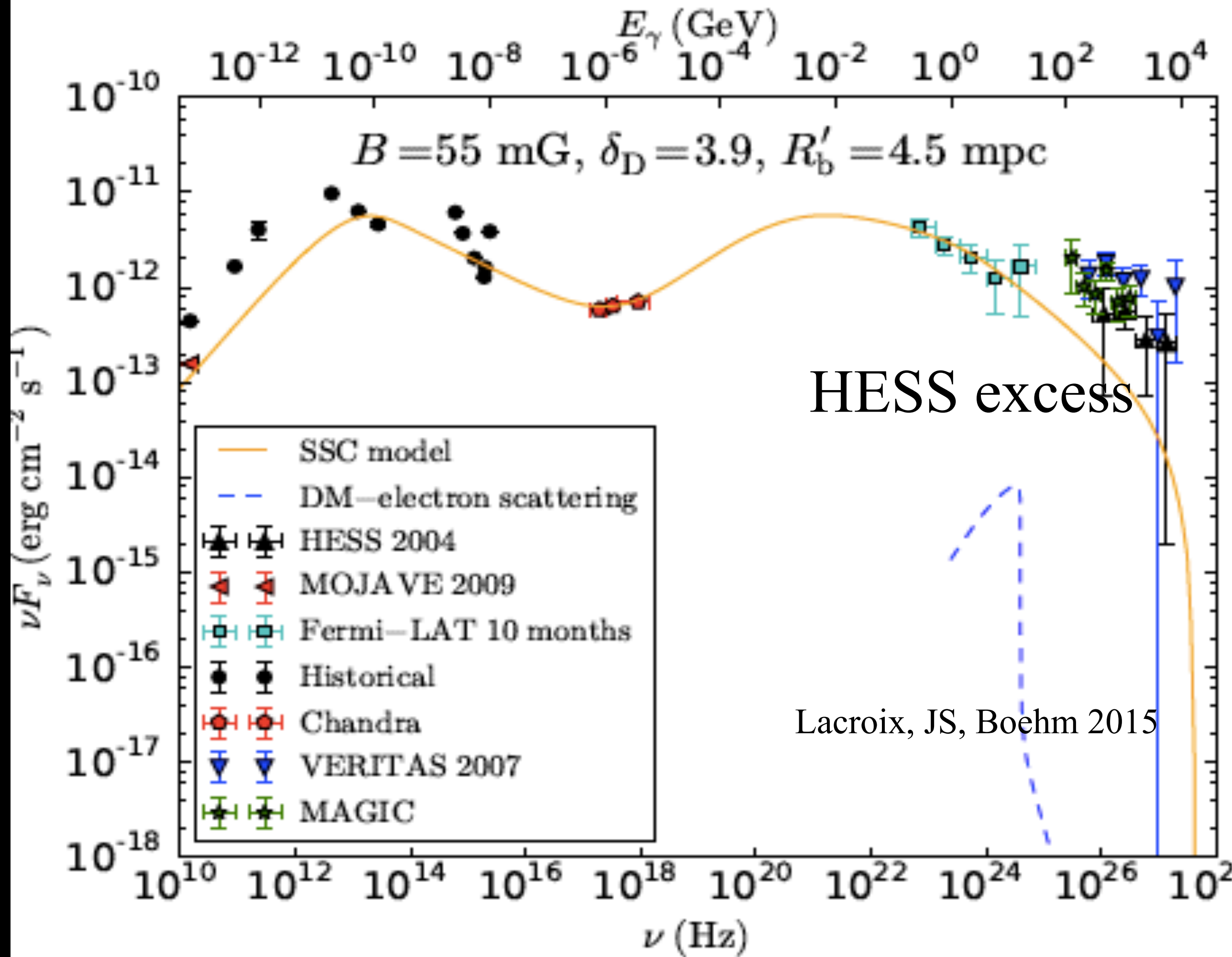


HESS detection of quasispherical TeV emission about GC

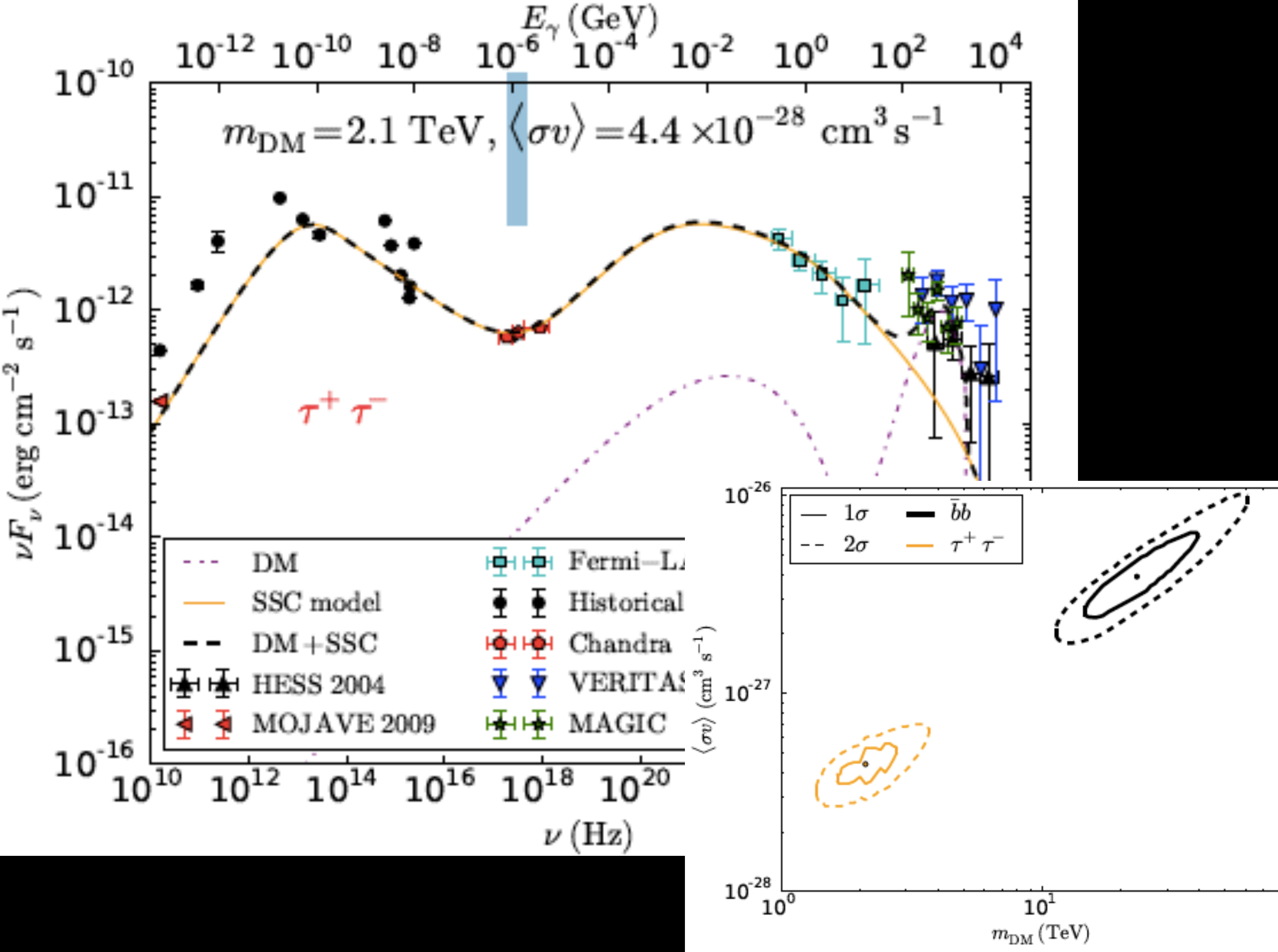


Moulin + JS 2018

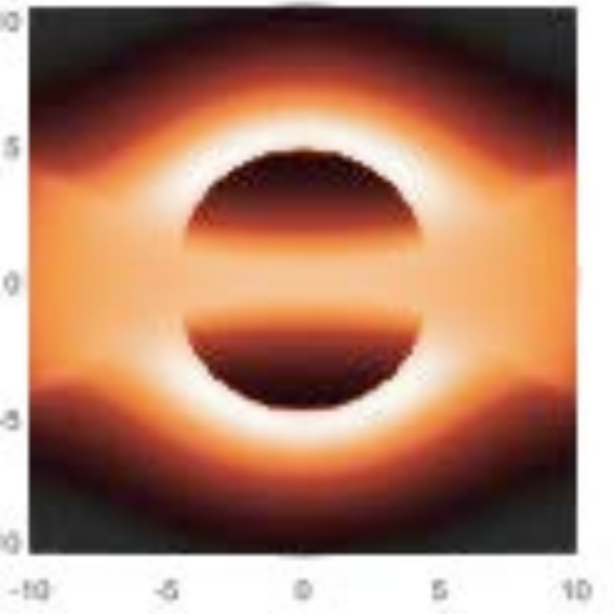
M87 jet



relativistic jets from BH ergosphere collide with DM …but it's a small effect



E_γ (GeV)
10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4}
$m_{DM} = 2.1$ TeV, $\langle \sigma v \rangle = 4.4 \times 10^{-28}$ cm^{3}s^{-1}
10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14} 10^{-15} 10^{-16}
νF_ν (erg cm^{-2} s^{-1})
$\tau^+ \tau^-$
DM
SSC model
DM+SSC
HESS 2004
MOJAVE 2009
Fermi–LA
Historical
Chandra
VERITAS
MAGIC
10^{10} 10^{12} 10^{14} 10^{16} 10^{18} 10^{20}
ν (Hz)
10^{-26} 10^{-27} 10^{-28}
1σ
2σ
$\bar{b}b$
$\tau^+ \tau^-$
$\langle \sigma v \rangle$ (cm^3 s^{-1})
10^{0} 10^{1}
m_{DM} (TeV)



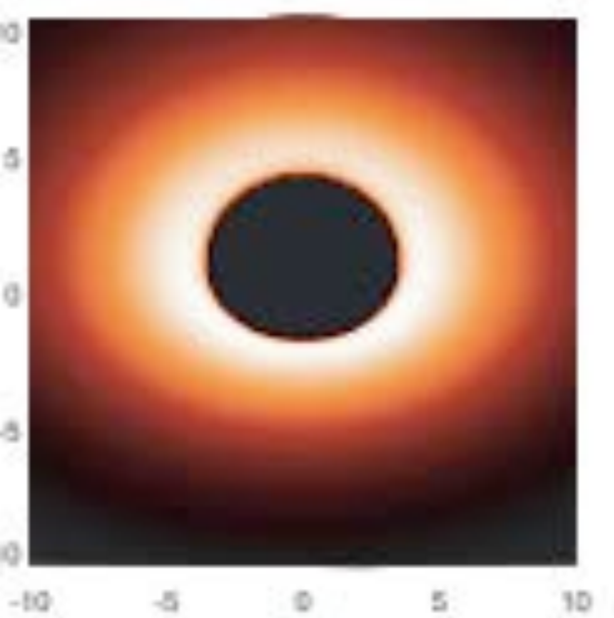
Black hole shadow

Event Horizon Telescope

Simulated image at 1mm
of M87 or SagA* black hole

Resolve horizon scale
GM/c^2 at $\sim 5\ \mu$ arcsec

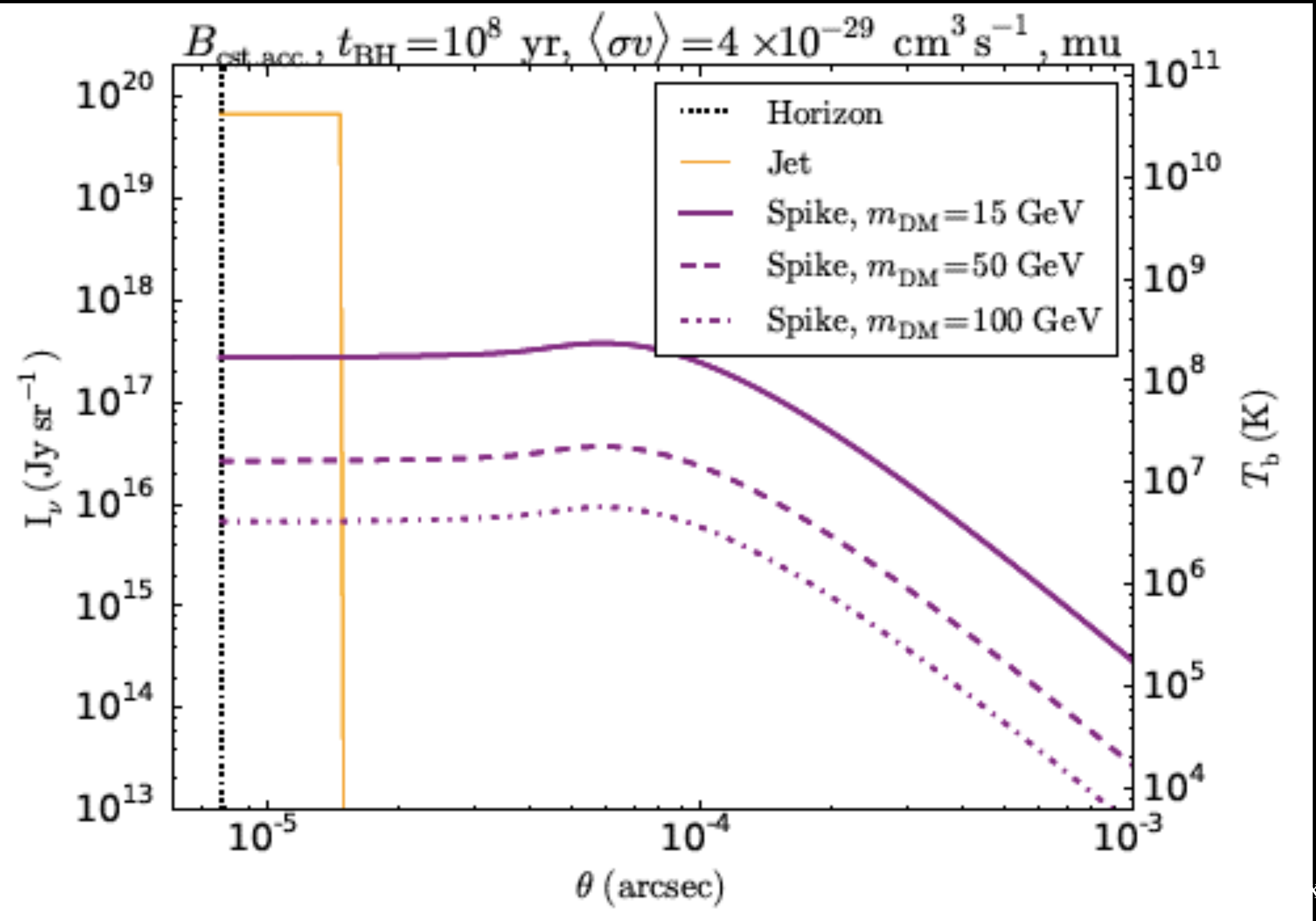
M87 distance 2000 x GC
but M_{BH} 1500 x SagA*



inverse

Event Horizon Telescope predictions

230GHZ

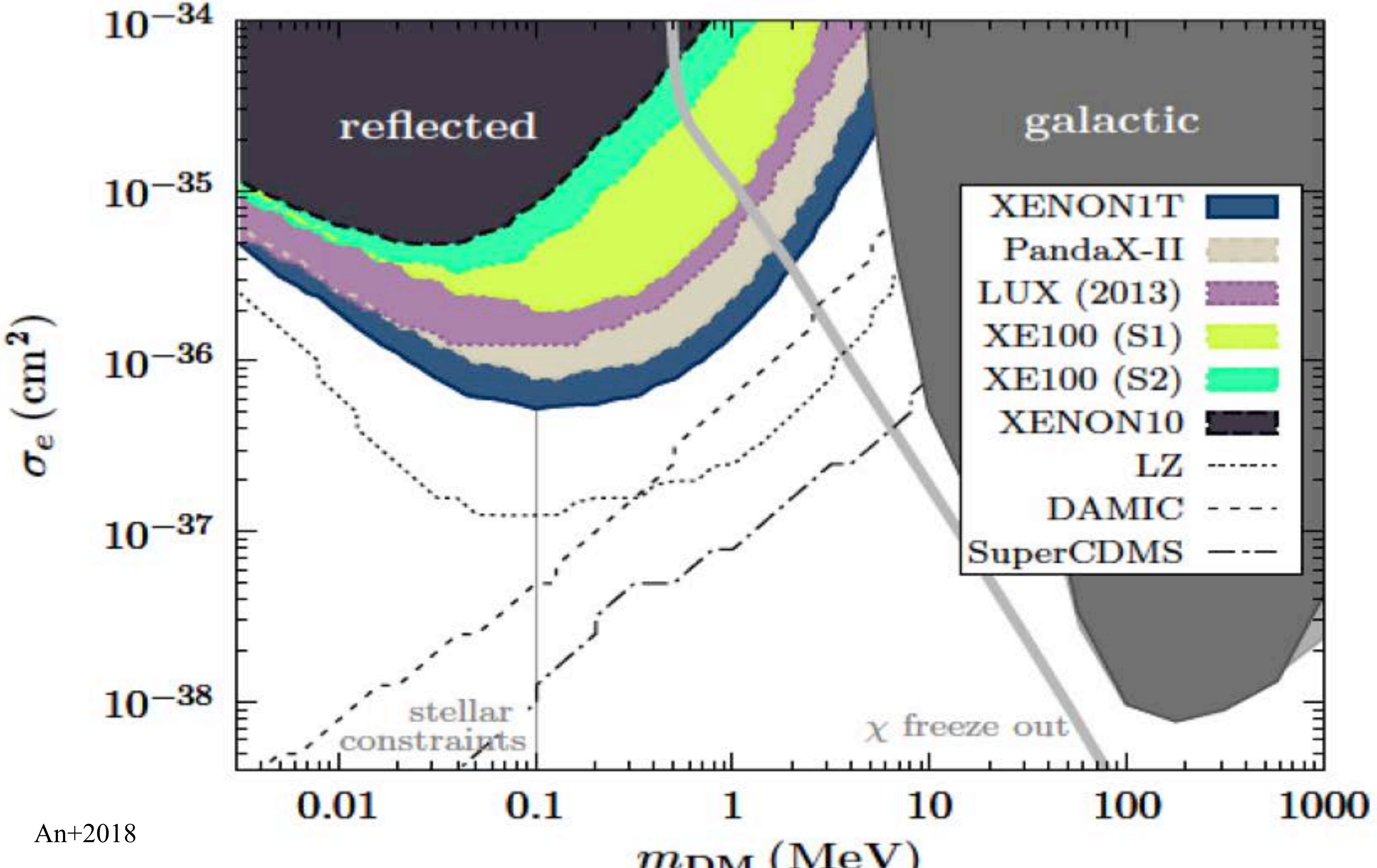


x, JS, Boehm 2015

M87 spike probes subthermal cross-section: flux ~ $M_{BH}^3/\langle\sigma v\rangle$

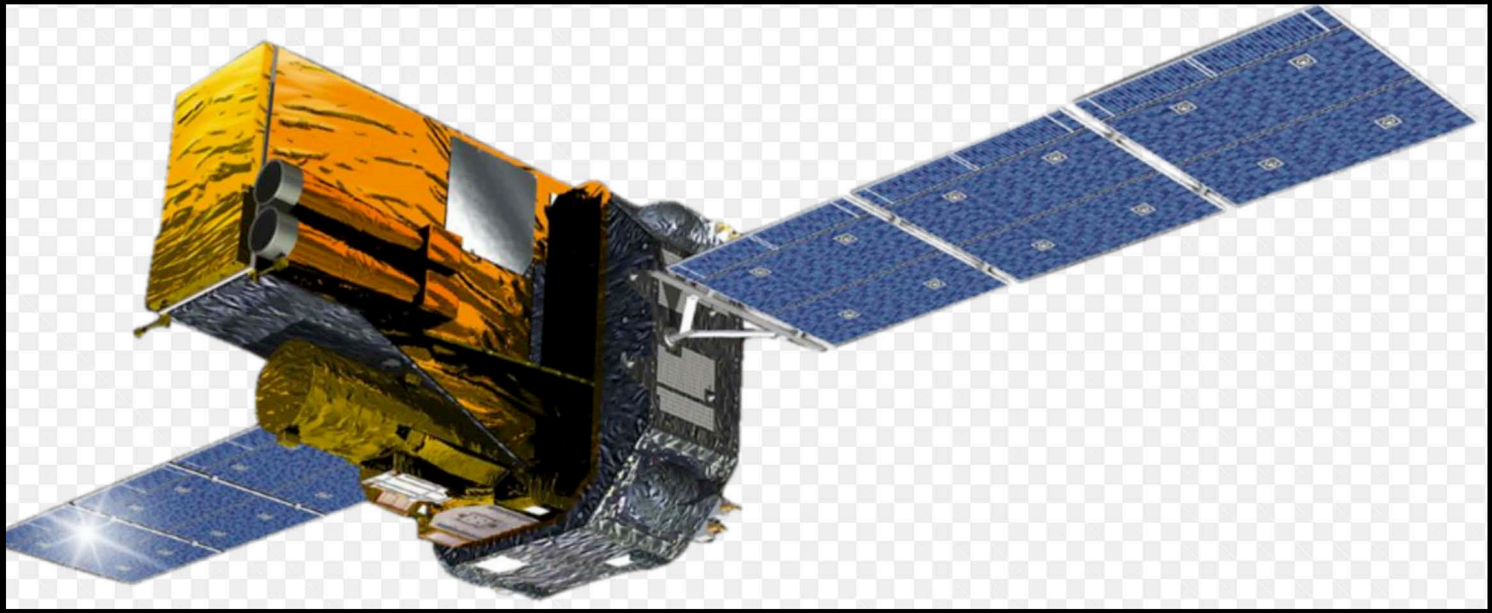
LIGHT DARK MATTER

The sun is a light dark matter reflector

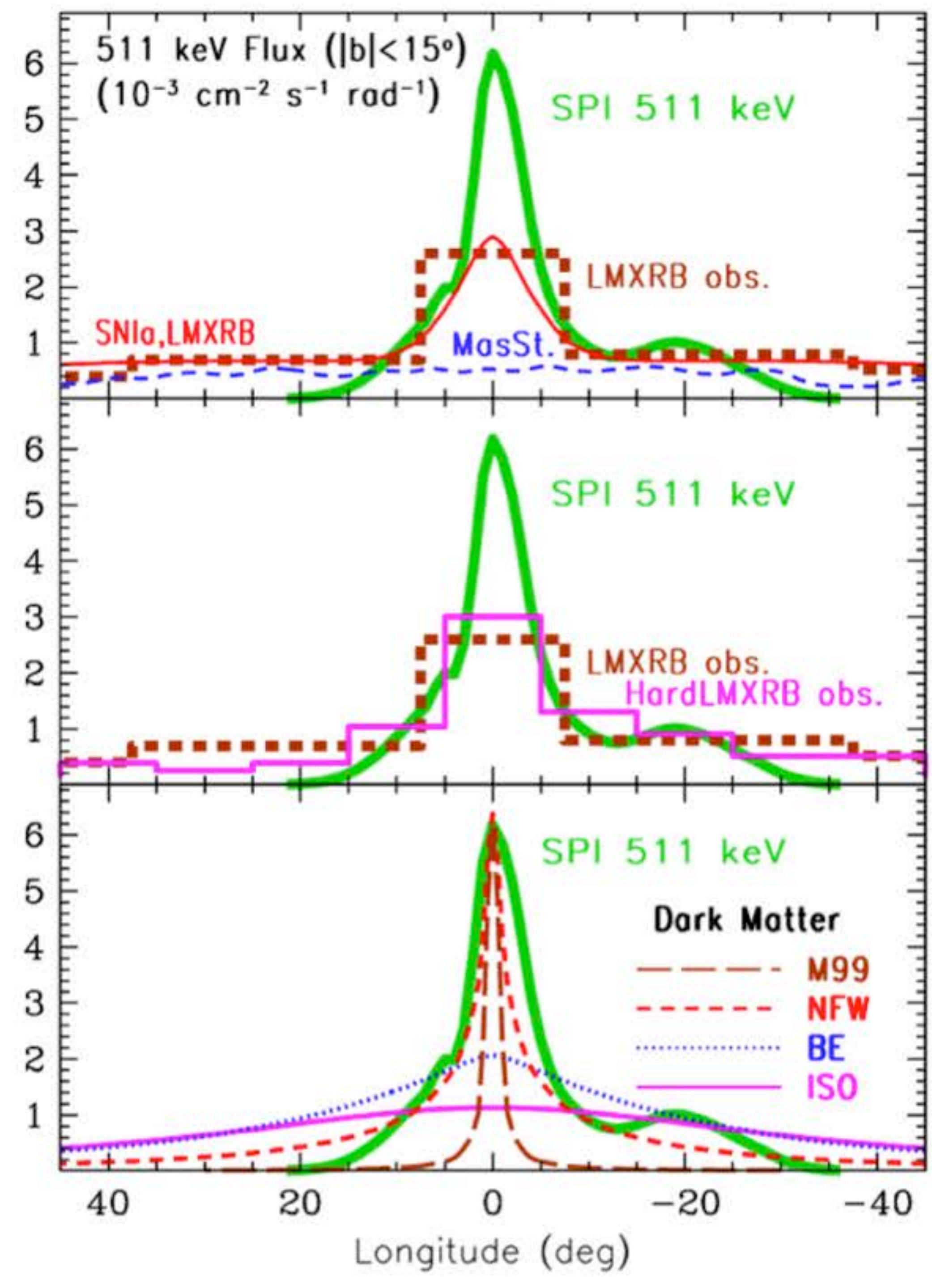


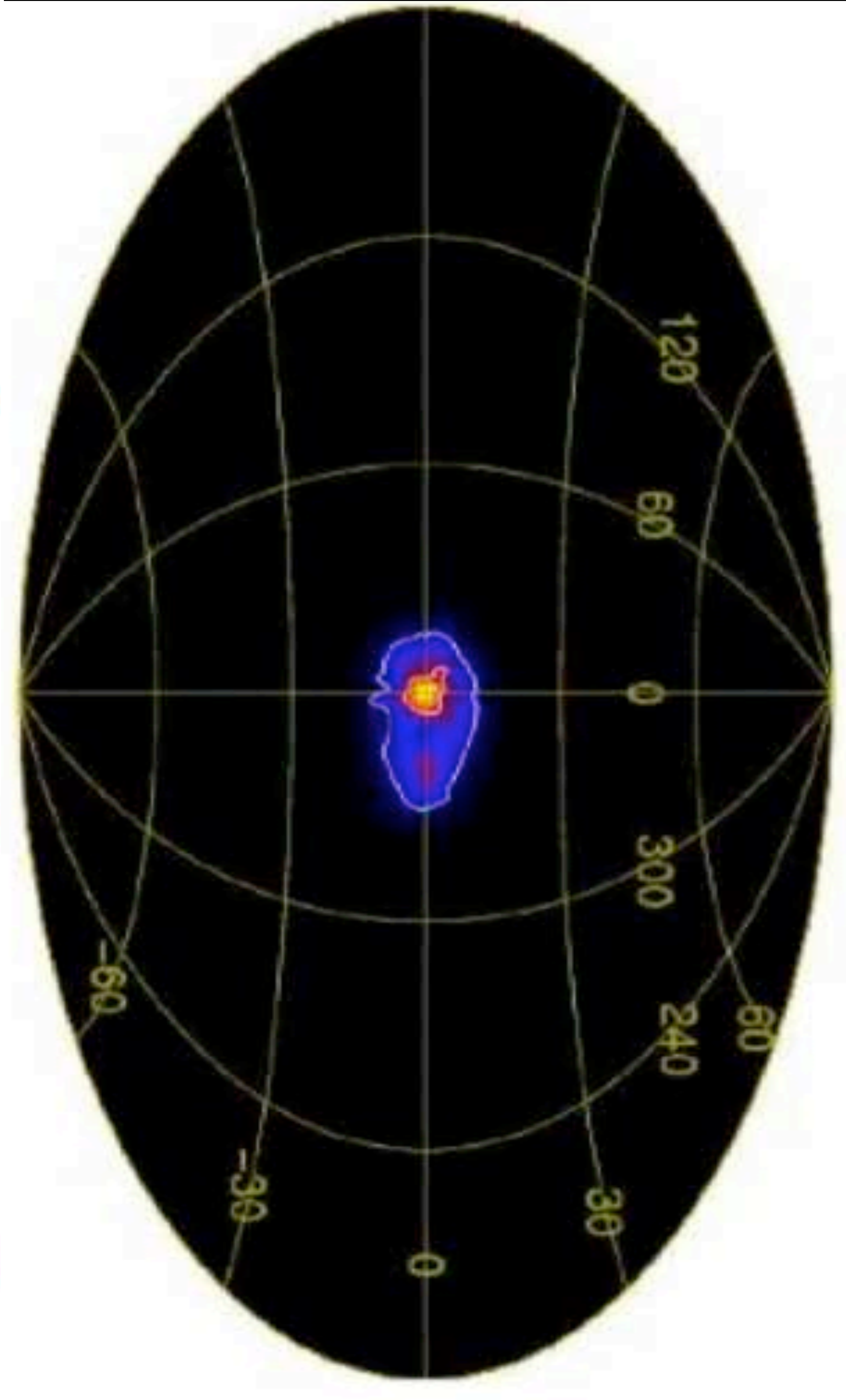
An+2018

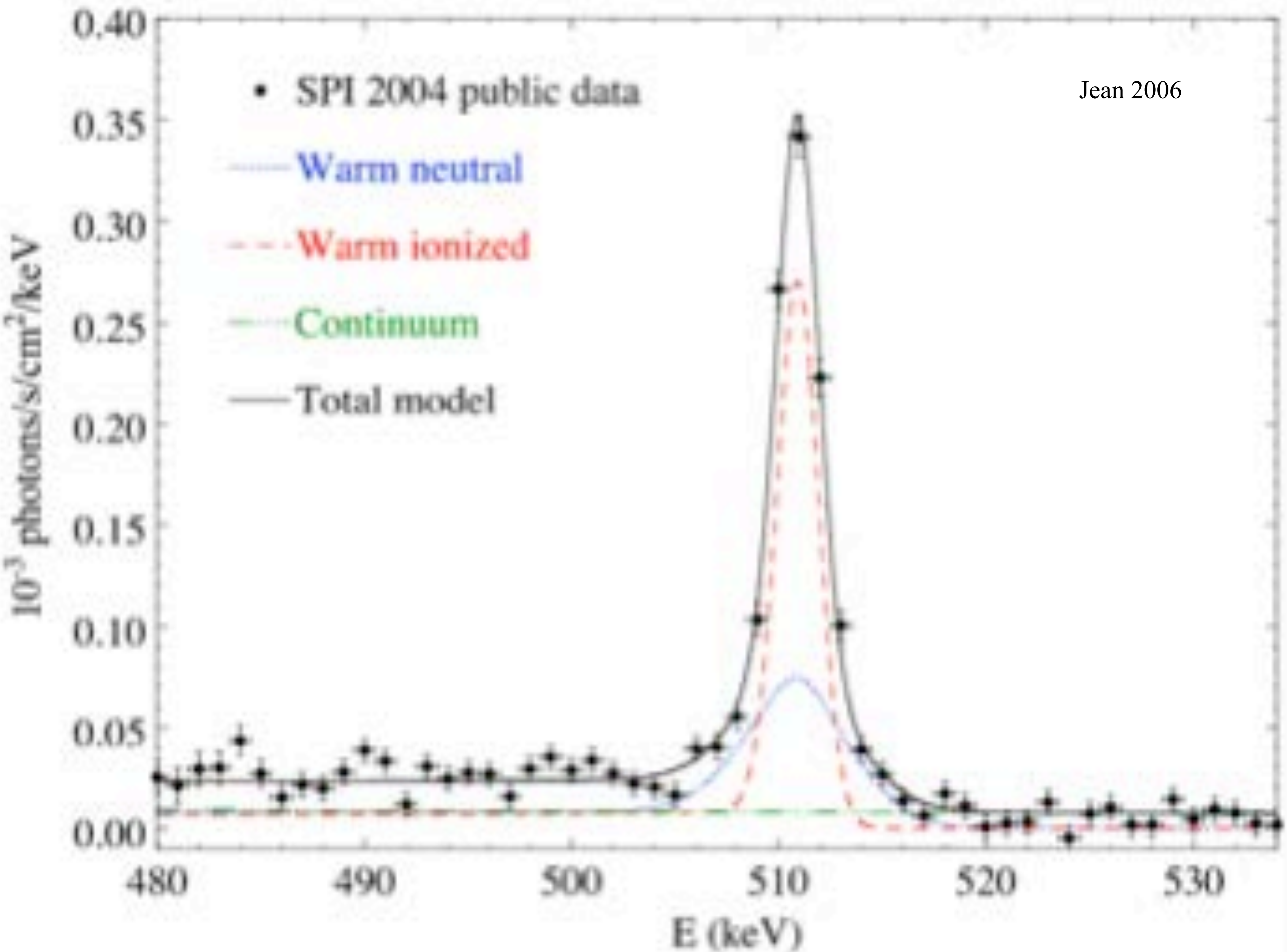
The INTEGRAL story



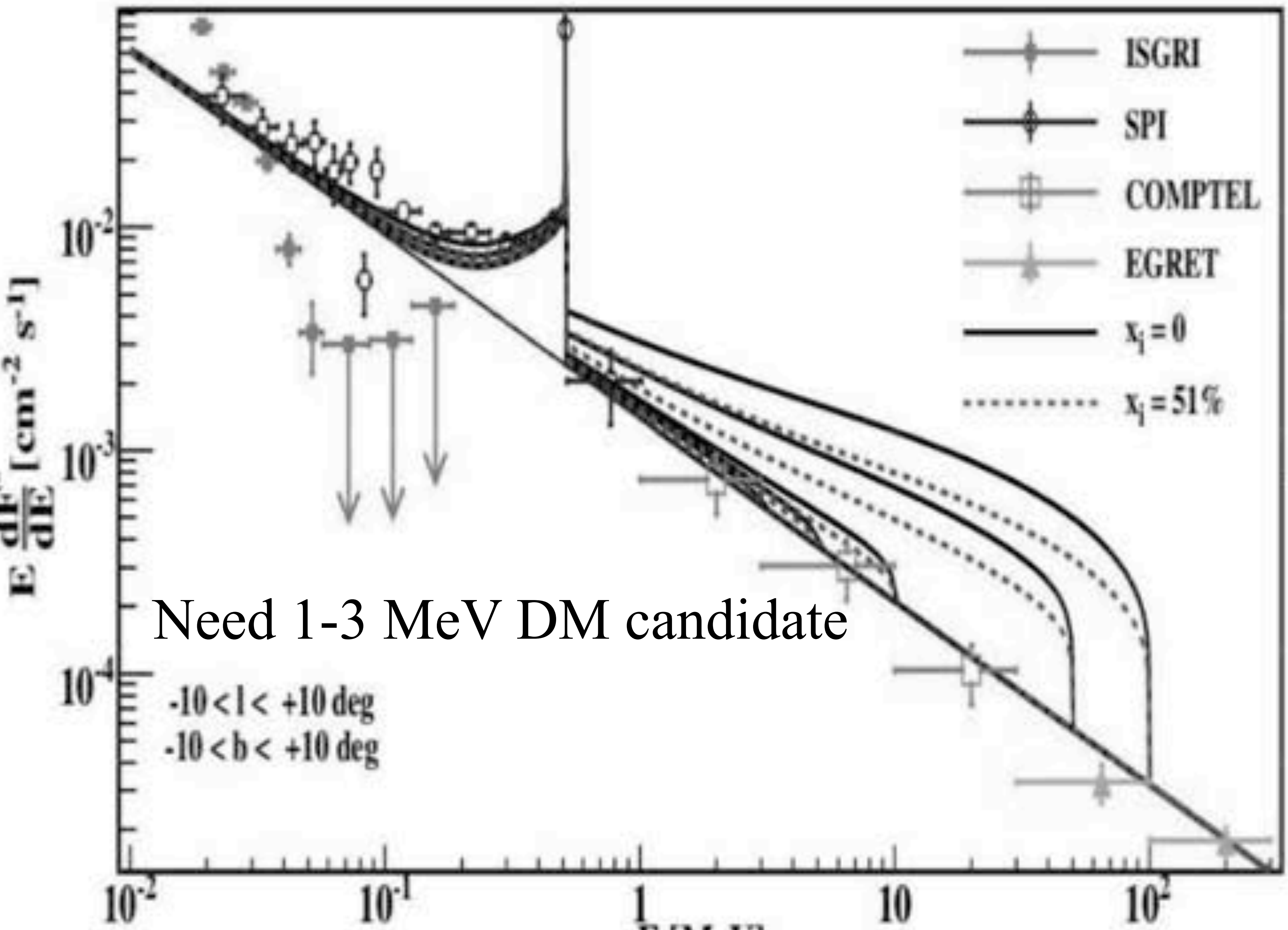
Gamma Ray Telescope:
launched by ESA in 2002


511 keV Flux (|b|<15°)
(10^{-3} cm^{-2} s^{-1} rad^{-1})
SPI 511 keV
LMXRB obs.
SNIa,LMXRB
MasSt.
SPI 511 keV
LMXRB obs.
HardLMXRB obs.
SPI 511 keV
Dark Matter
M99
NFW
BE
ISO
Longitude (deg)


120
60
0
300
240
-60
60
-30
30
0

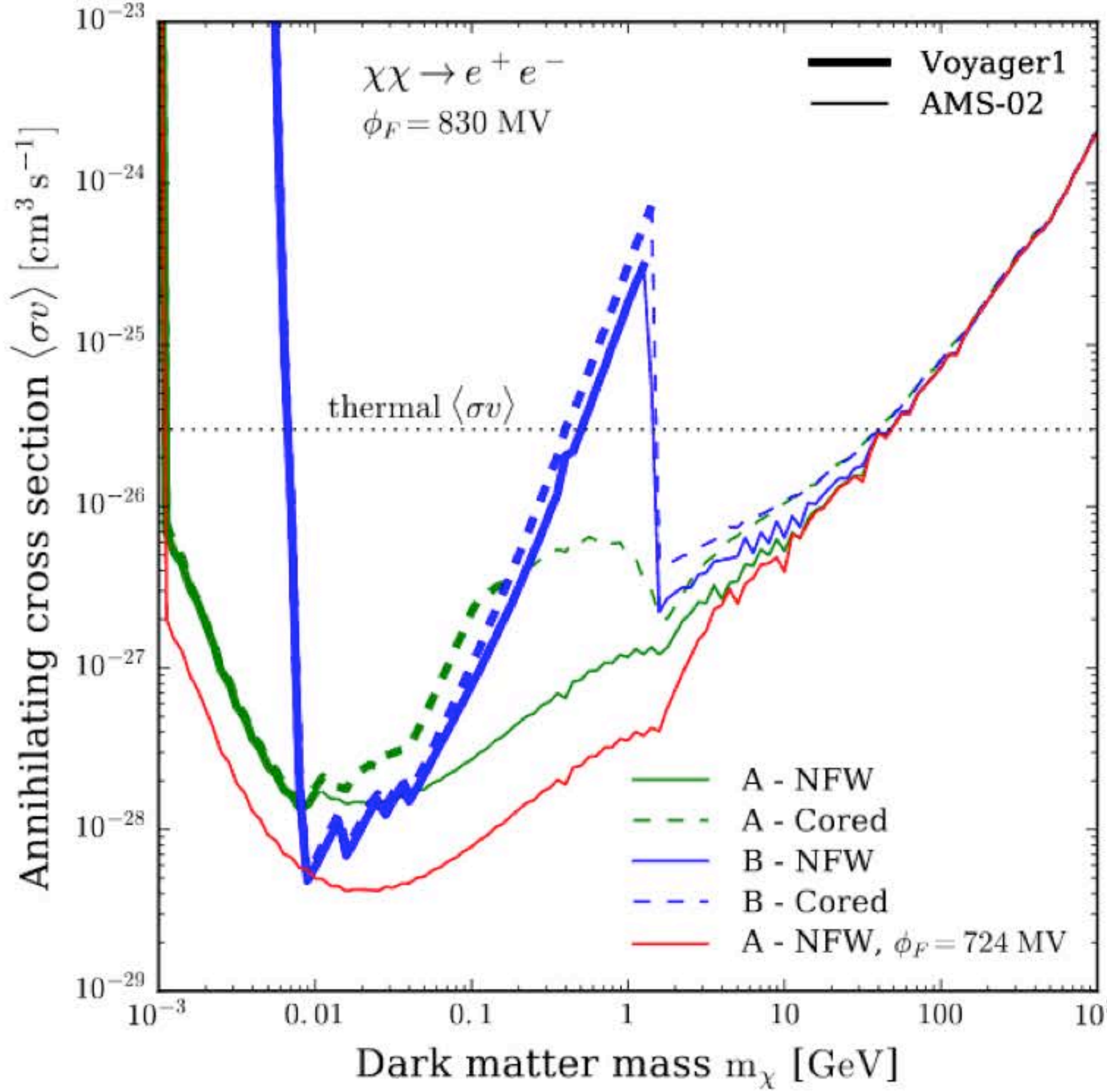


SPI 2004 public data
Warm neutral
Warm ionized
Continuum
Total model
Jean 2006
10^{-3} photons/s/cm^2/keV
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
480
490
500
510
520
530
E (keV)



Need 1-3 MeV DM candidate

Beacom + Yutzel 2006, Sizun + 2006



Boudaud + 2017

Galactic positron source

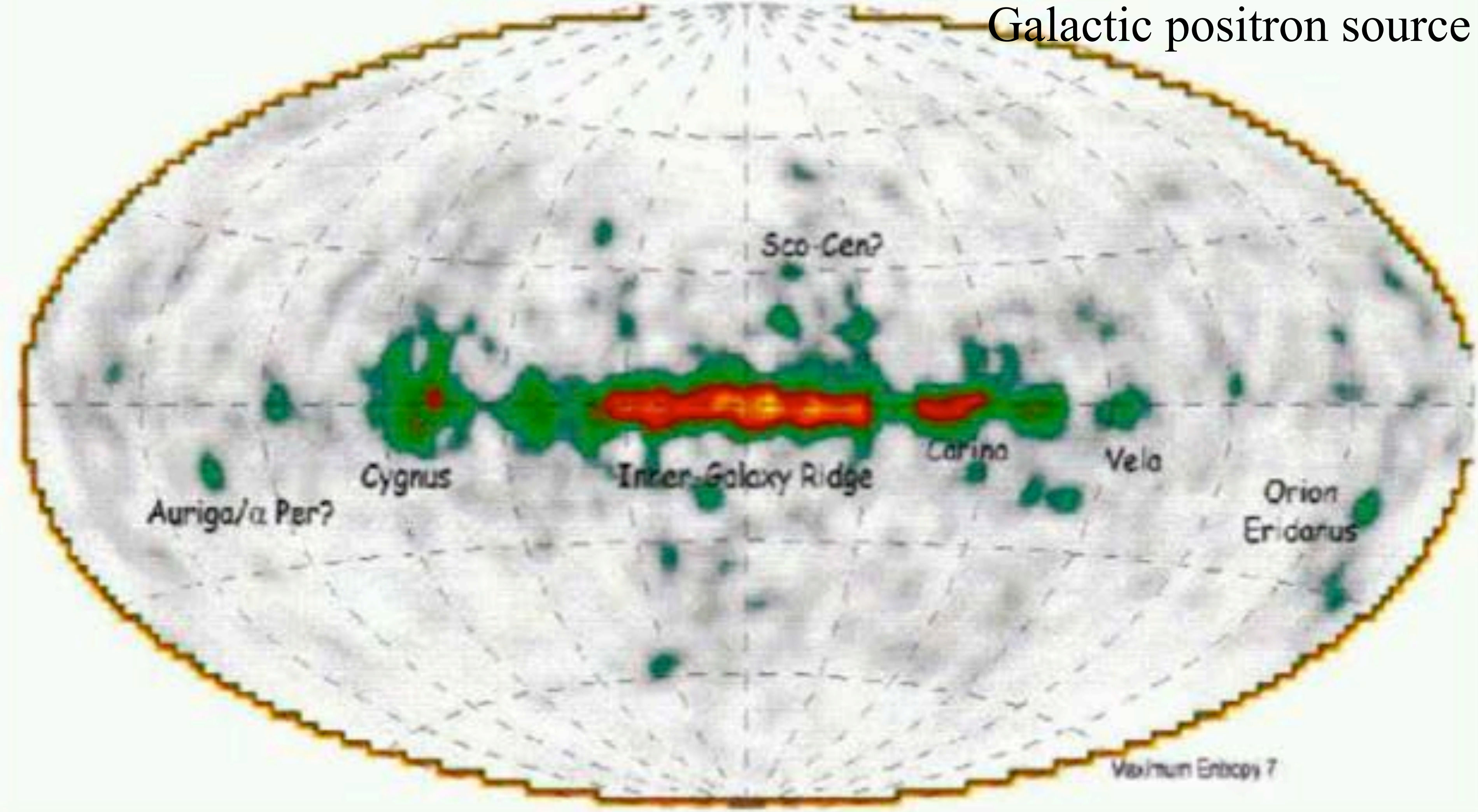
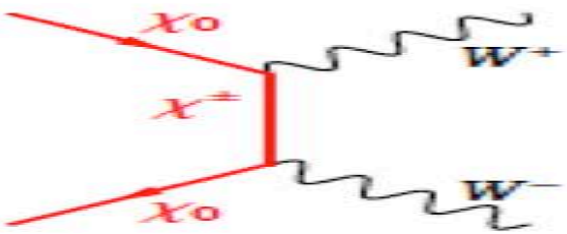
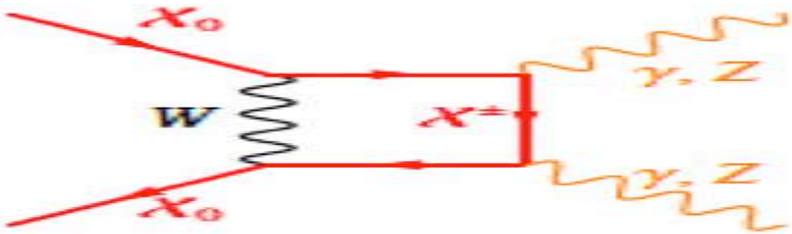


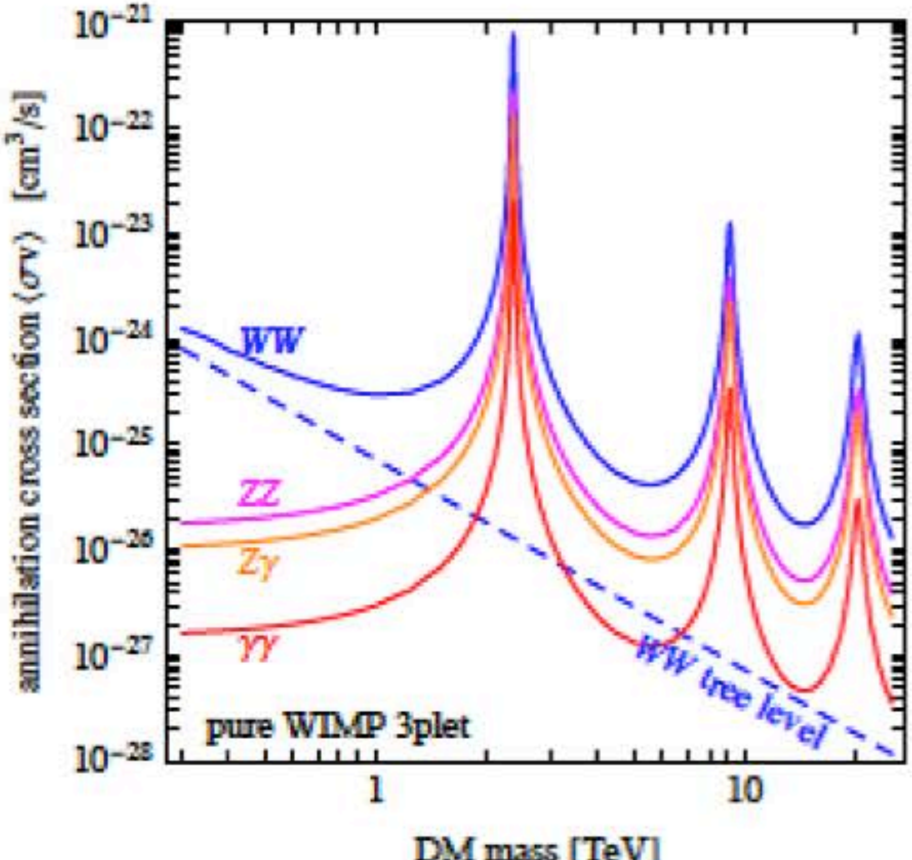
FIG. 7 Map of Galactic ^{26}Al γ-ray emission after 9-year observations with COMPTEL/CGRO (from Plüschke *et al.*, 2001).

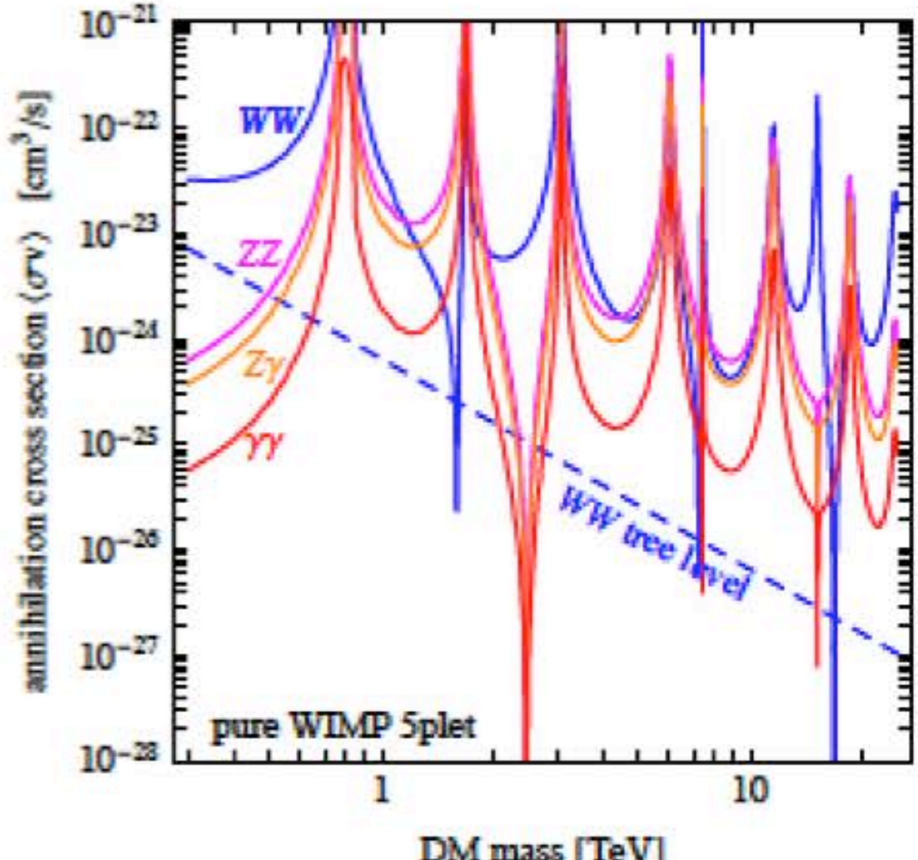
SPECTRAL FEATURES

γ-ray lines revisited

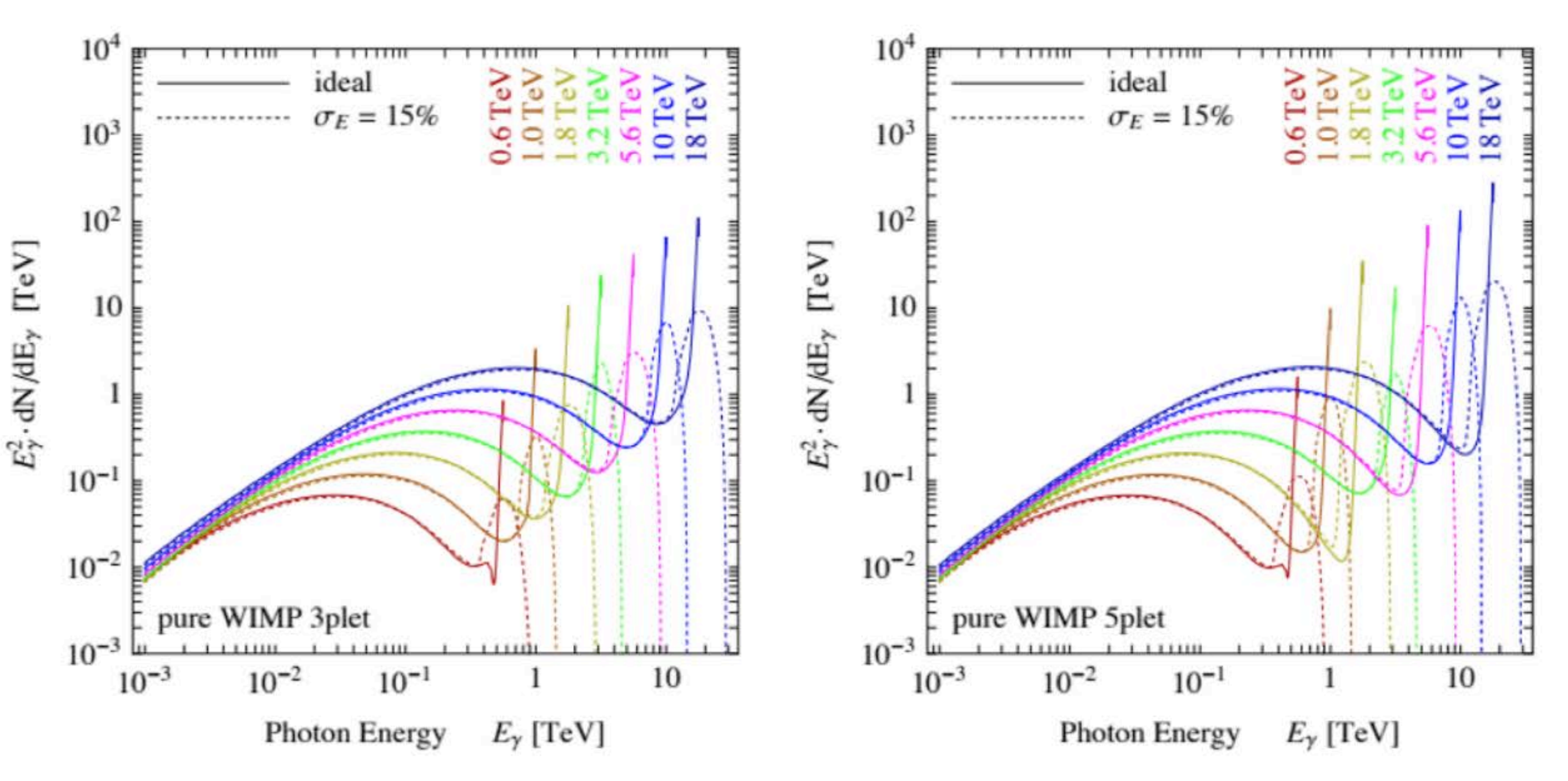






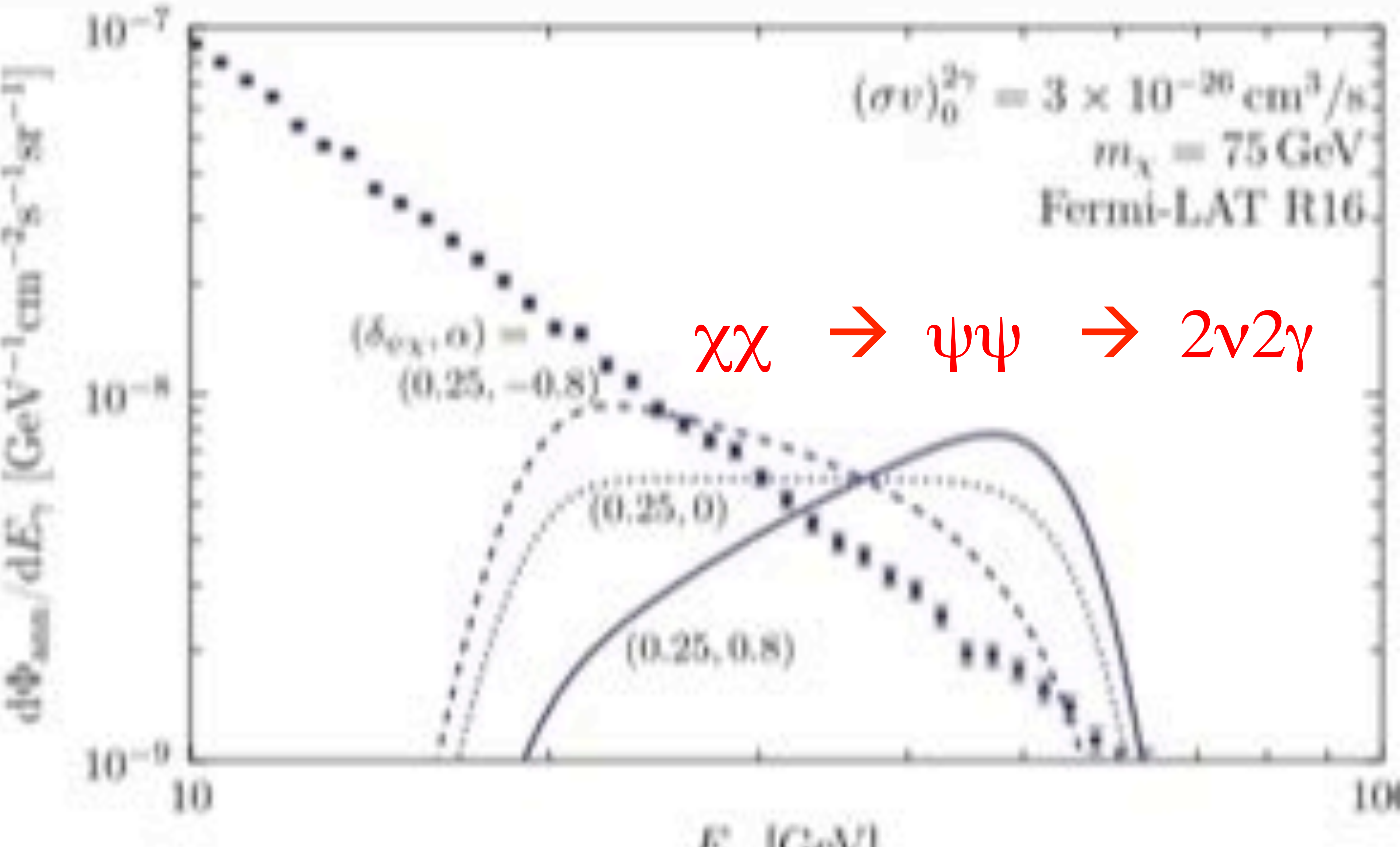


CTA line predictions



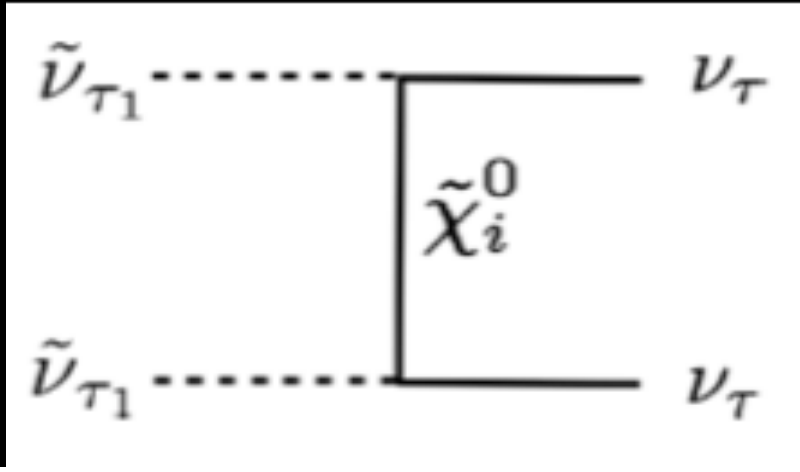
Oakes + 2018

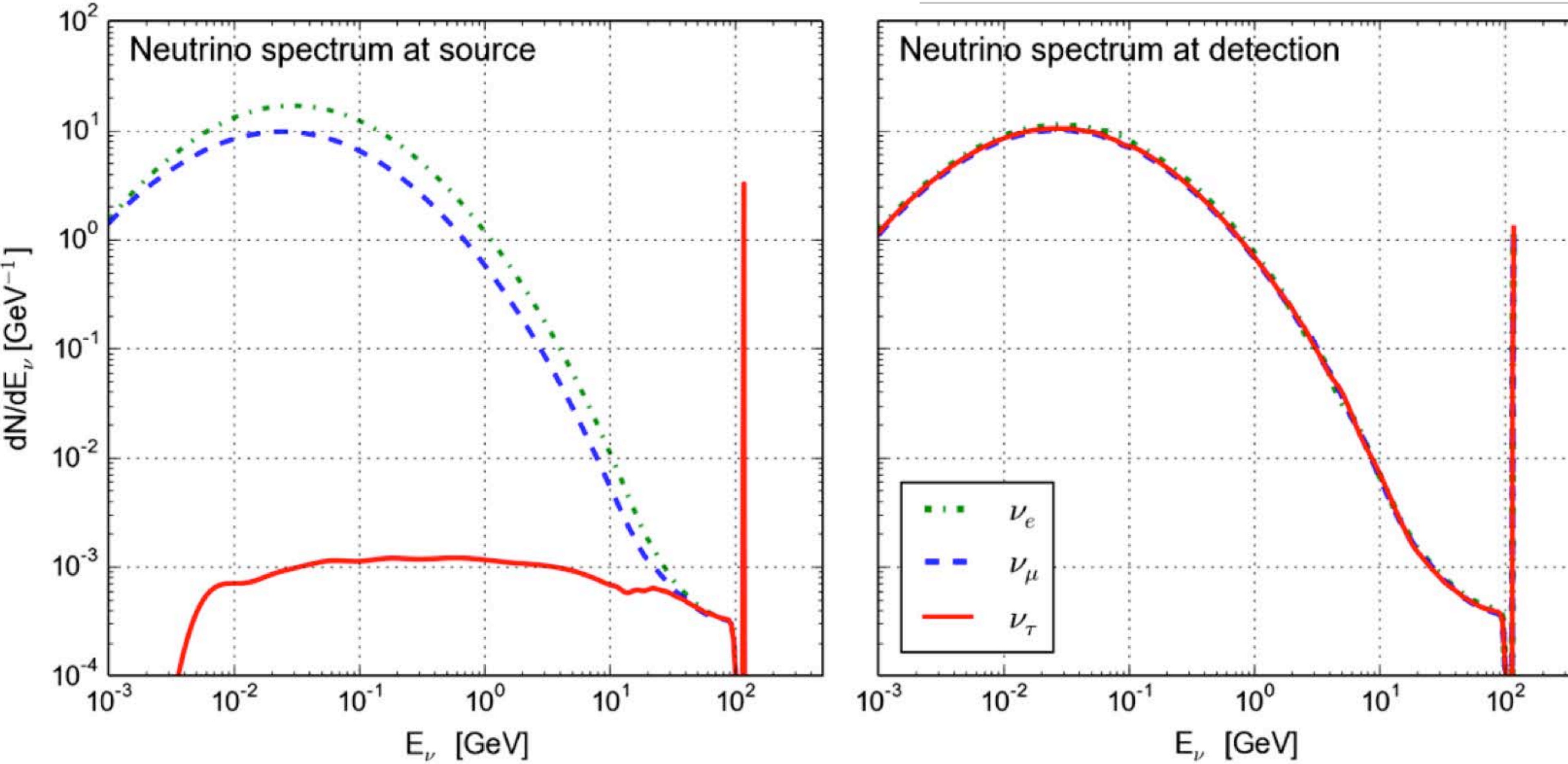
Asymmetric DM: γ-ray features



Ibarra + 2016

ν telescope –lines





STERILE NEUTRINOS

If dark matter is a sterile neutrino

- Lyman alpha forest and hi z galaxies fix minimum mass ~ 1 keV

Markovic & Viel 2013

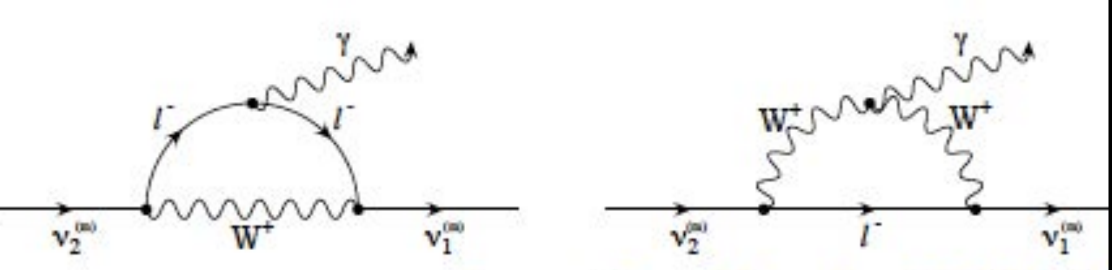
- maximum mass should be warm

(~5 keV ~ co-moving mass of dwarf galaxy) Pacucci + 2013

- decay time (+ mixing angle) specifies relic abundance
- 7 keV ν decays into 3.5 keV photons
- the favoured mass range is constrained:

$$\Gamma_{\nu_s \to \gamma \nu_a} = \frac{9}{256\pi^4} \alpha_{\rm EM}\, G_F^2\, \sin^2\theta\, m_s^5 = \frac{1}{1.8 \times 10^{21} {\rm s}} \sin^2\theta \left(\frac{m_s}{\rm keV}\right)^5$$

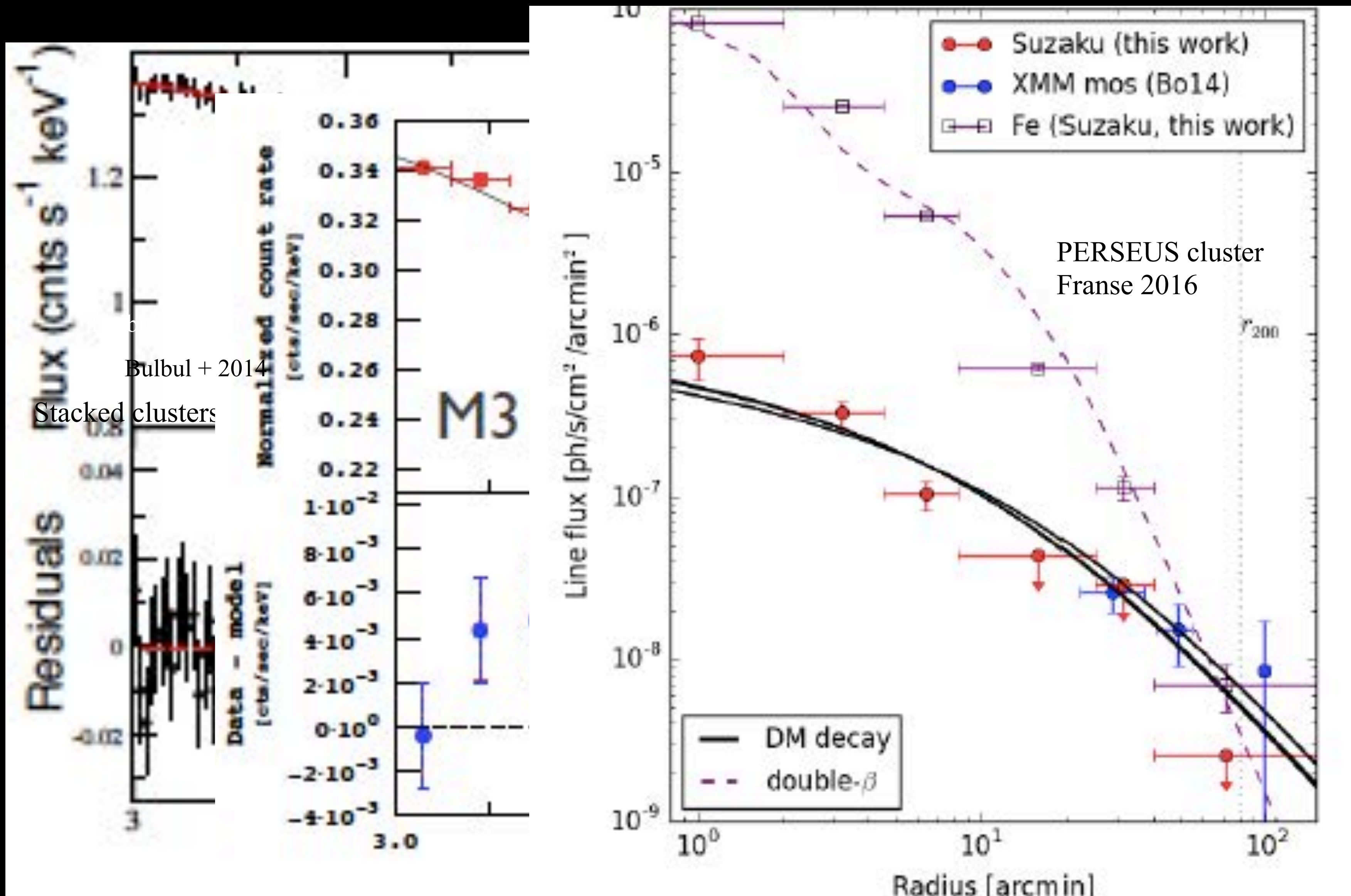
Kusenko 2009

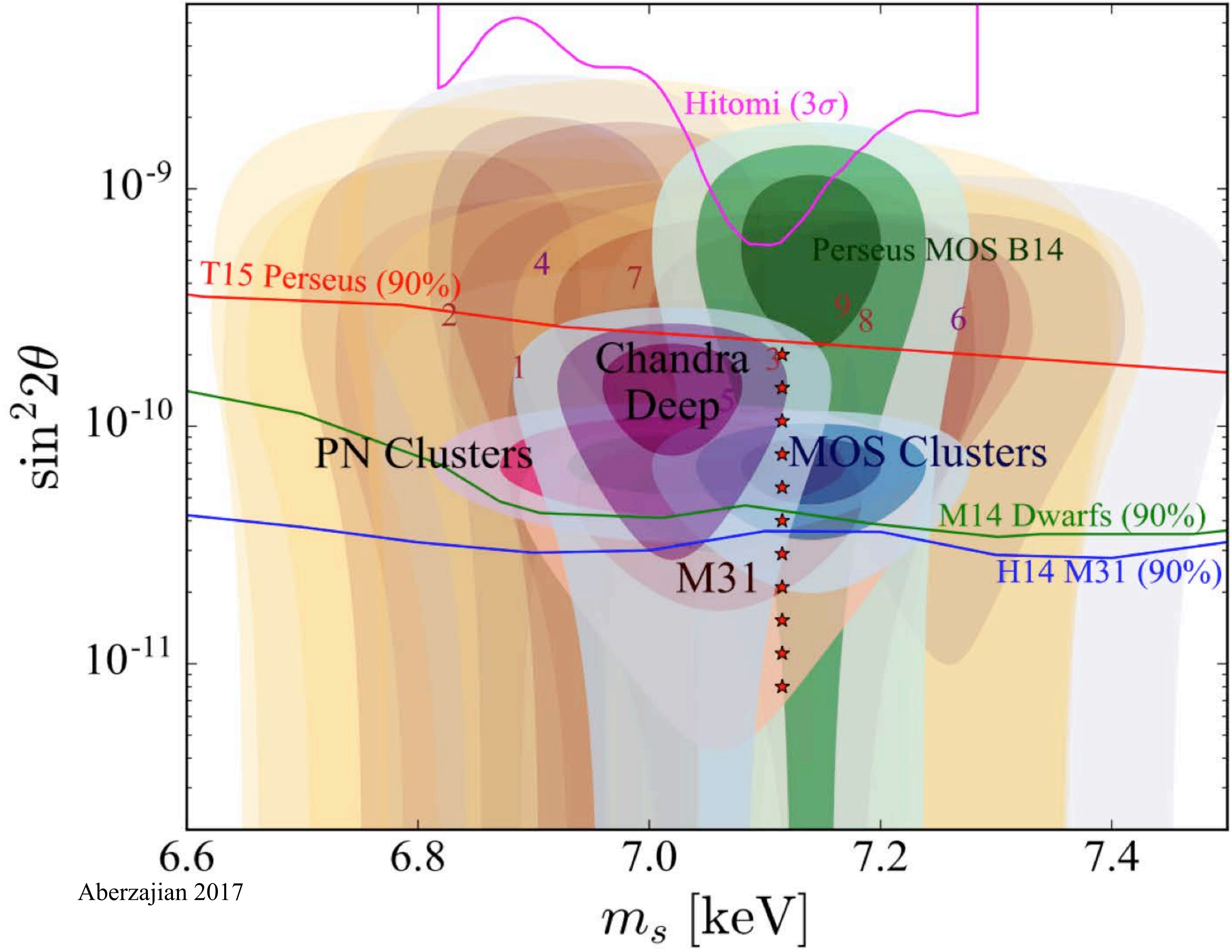


Bose + 2016

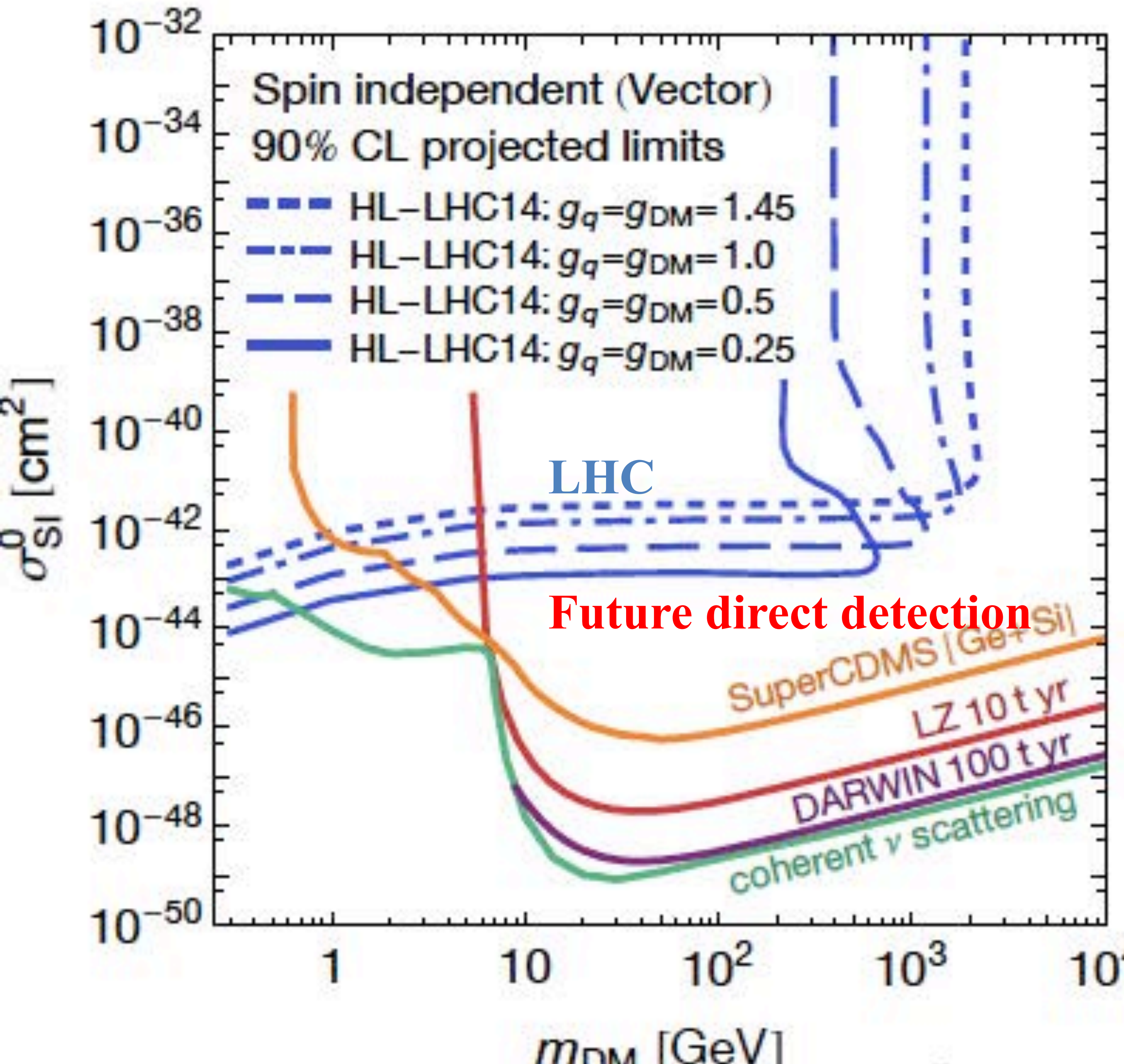
CDM WDM

a 3.5 keV line from DM decays ?





Aberzajian 2017



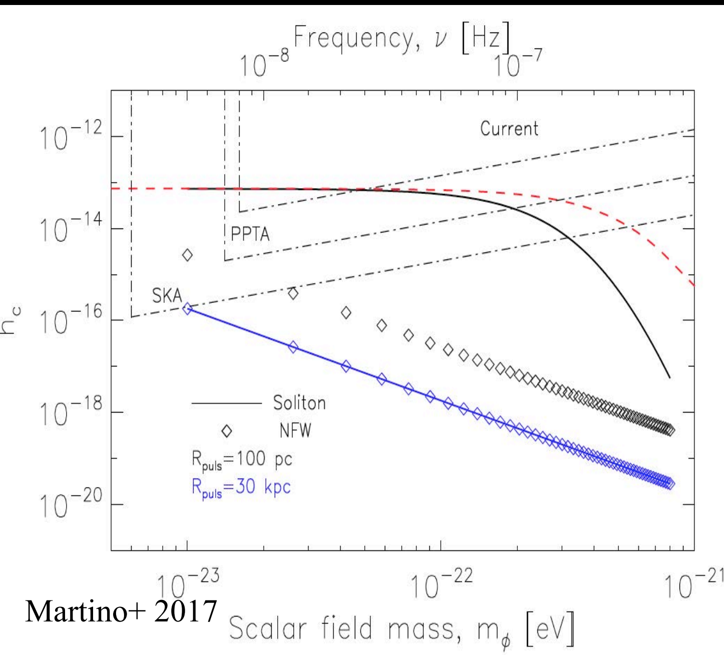
Future limits

Best bet is direct detection

ULTRALIGHT DARK MATTER

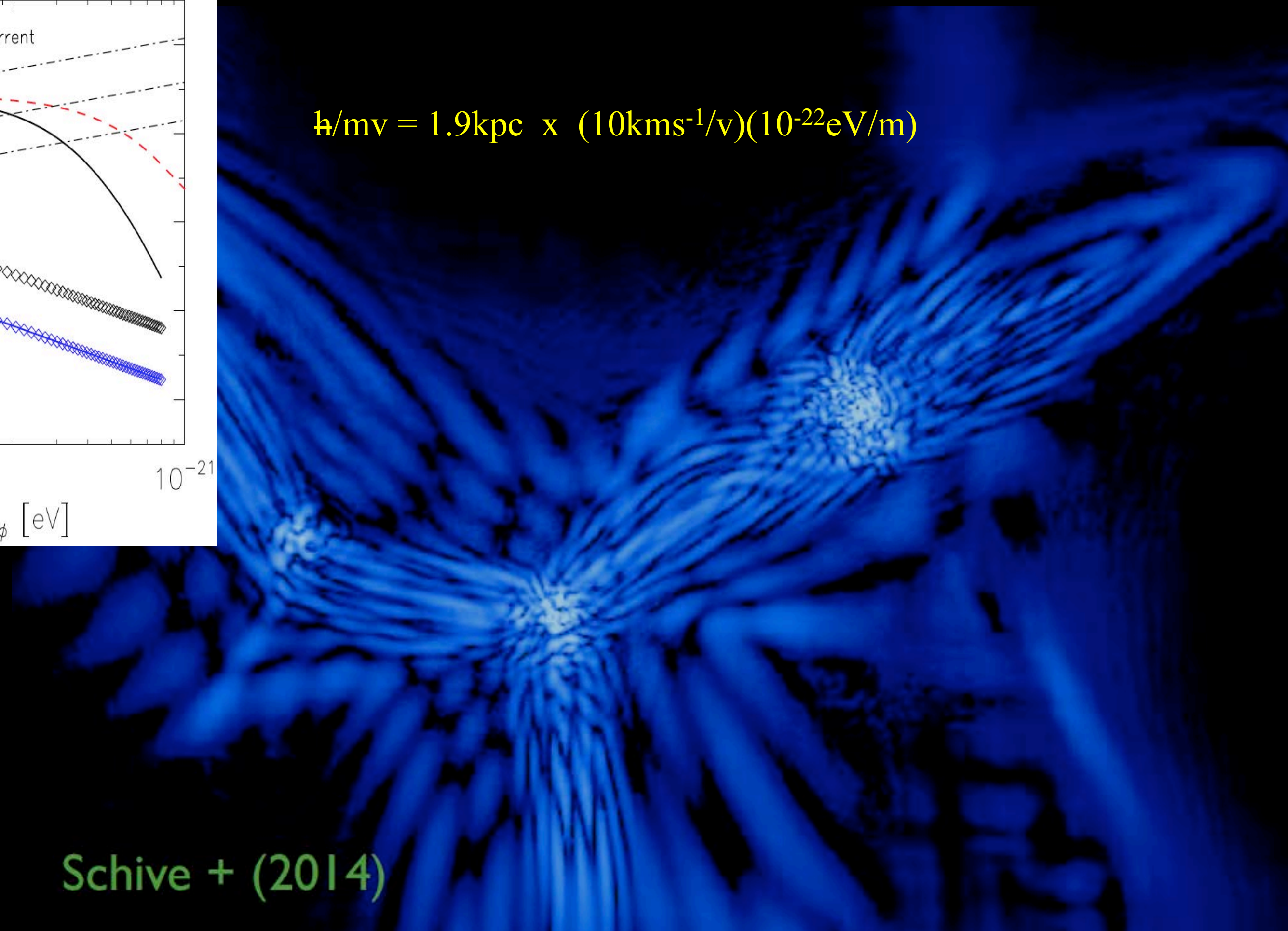
fuzzy dark matter & pulsar timing

very light bosons as DM with large de Broglie wavelength)



Martino+ 2017

$\hbar/mv = 1.9\text{kpc} \ \text{x} \ (10\text{kms}^{-1}/v)(10^{-22}\text{eV}/m)$

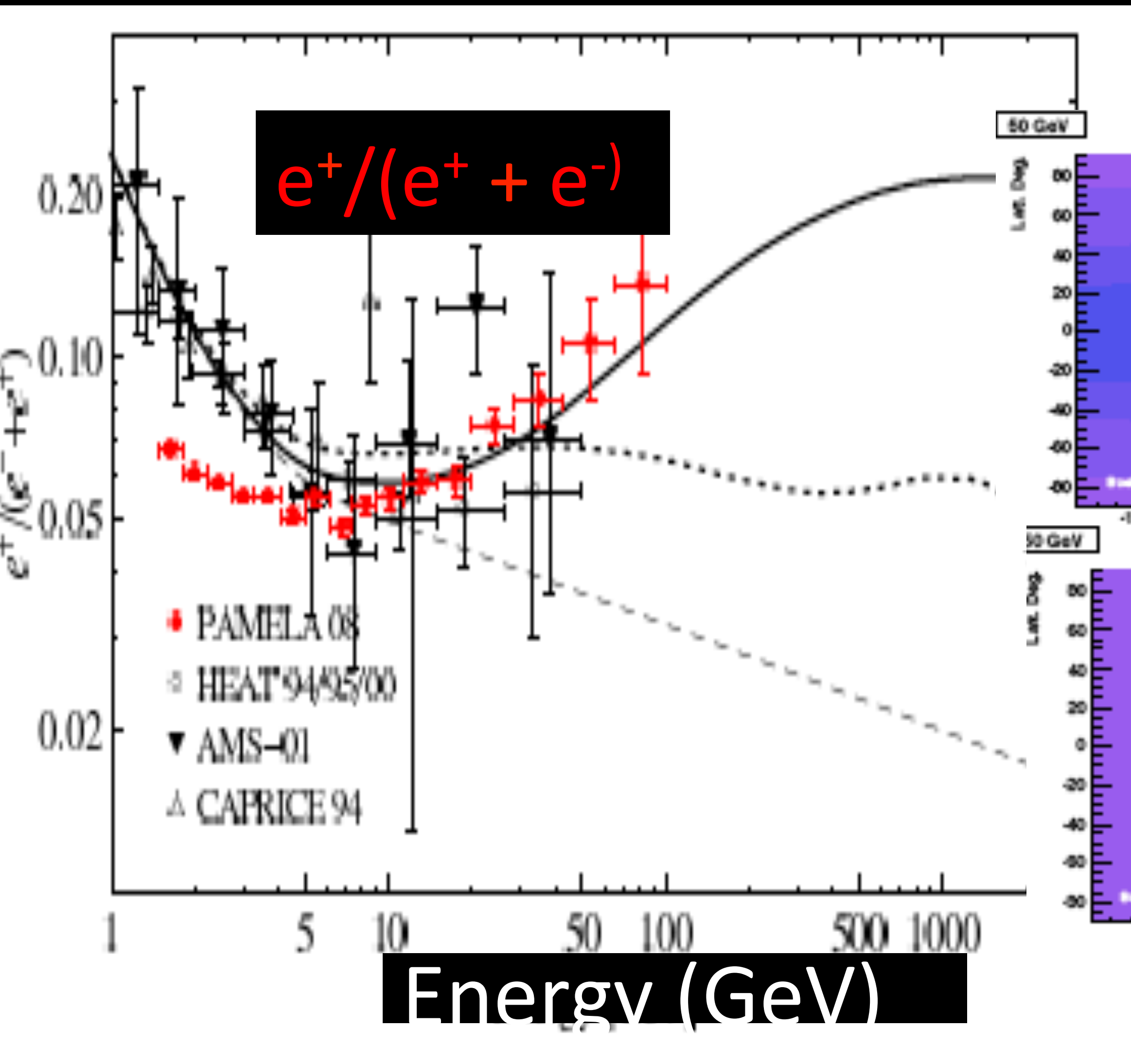


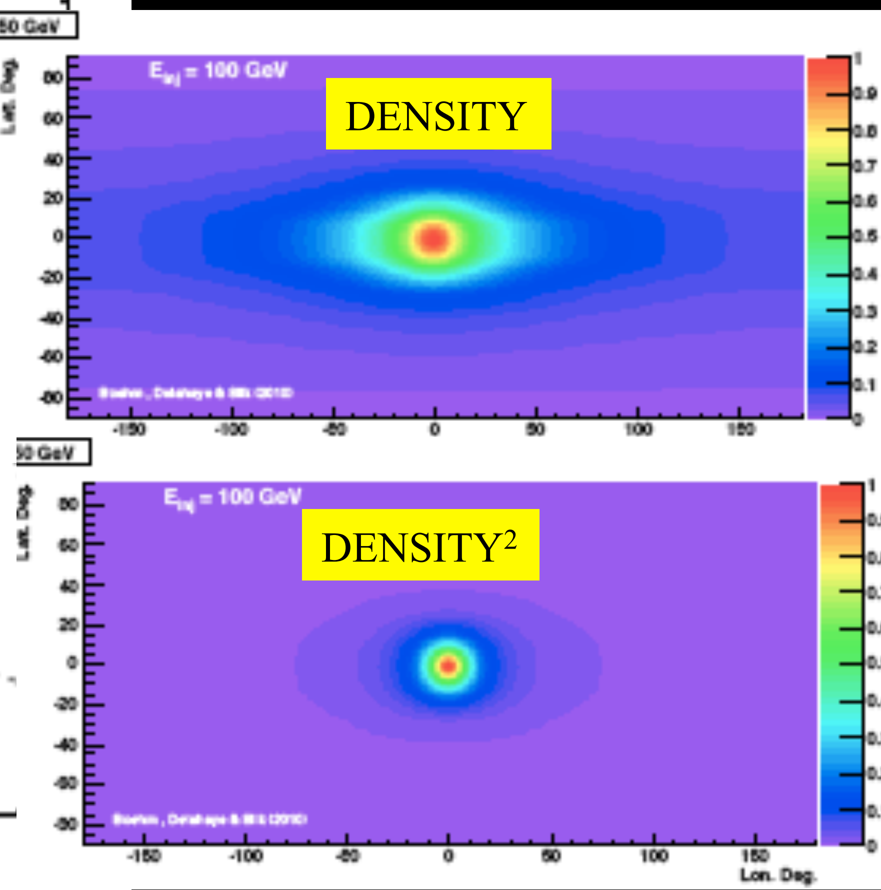
Schive + (2014)

DECAYING DARK MATTER

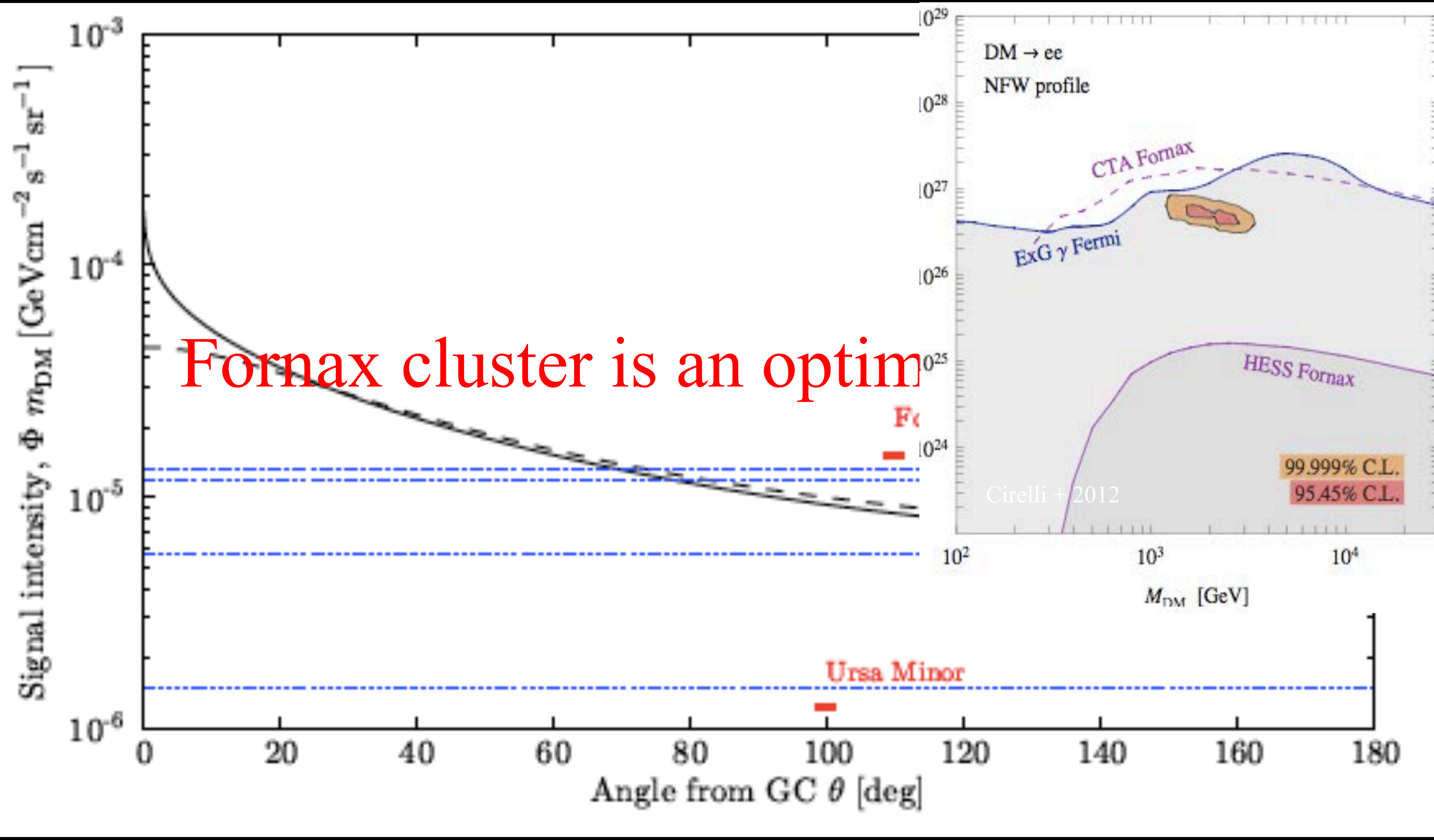
Decaying dark matter & e^+ excess

massive neutralino requires decay time ~ 10^{26} sec



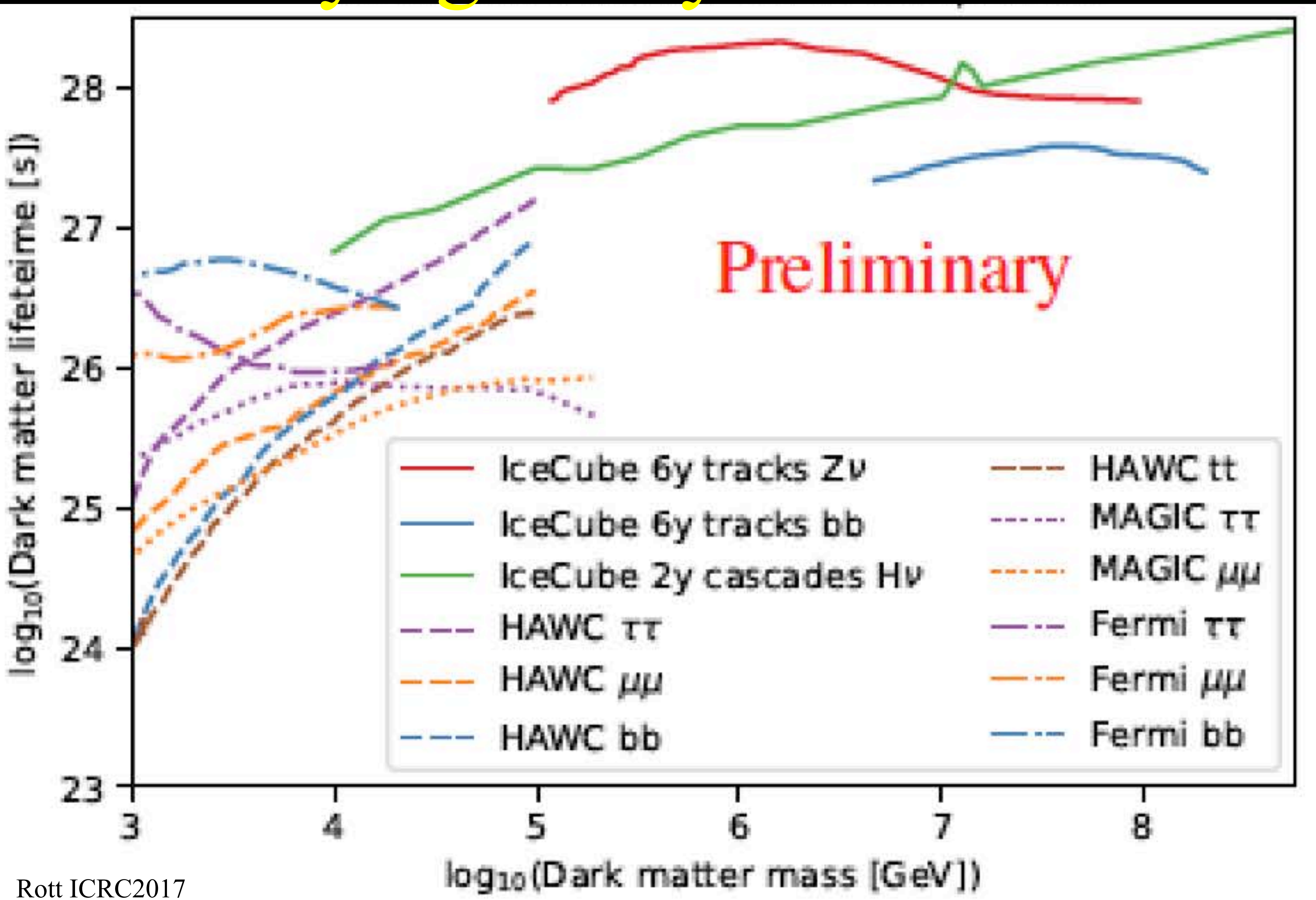


limits on decaying Dark Matter from clusters



Cannot exclude AMS-02 e^+e^- but C TA will

Decaying heavy DM limits



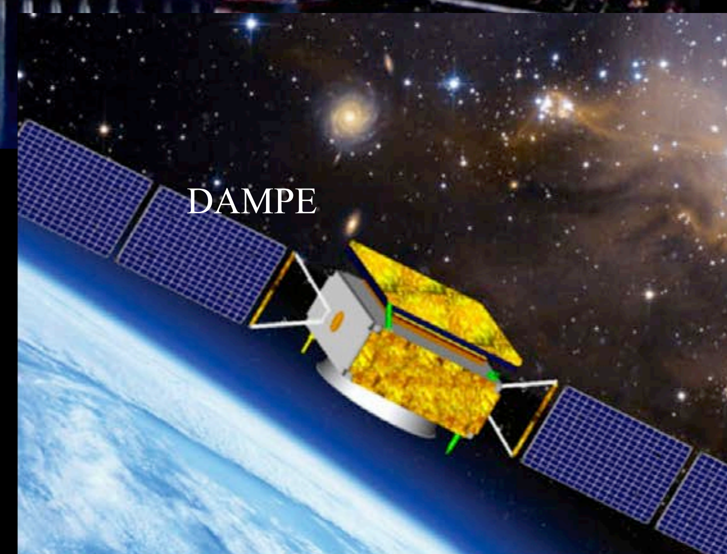
Rott ICRC2017

THE FUTURE

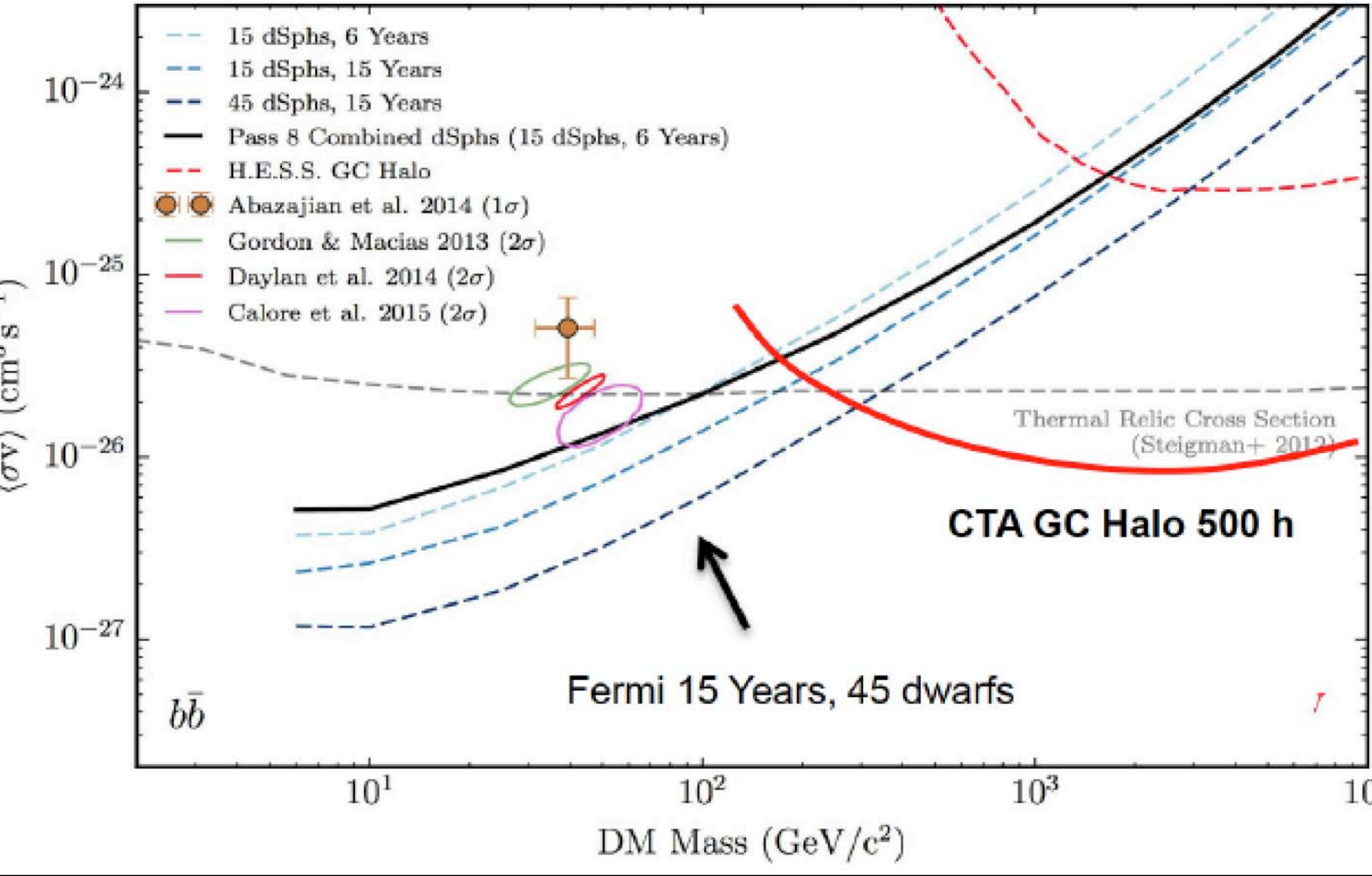
The future for dark

2019 CTA

South: Atacama
North: La Palma



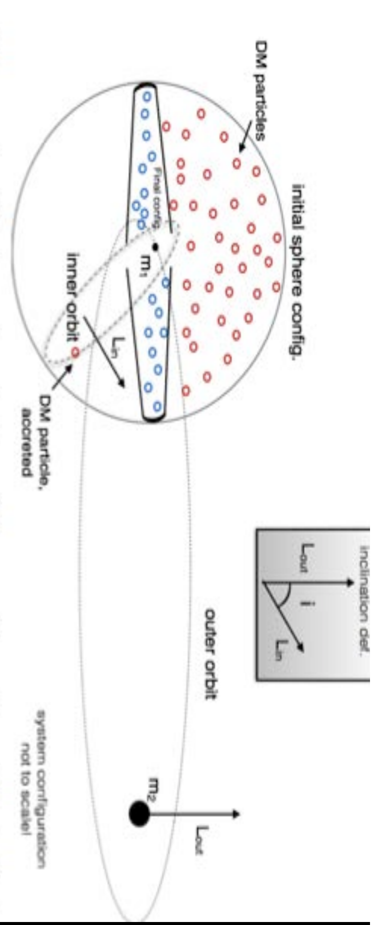
in 2023

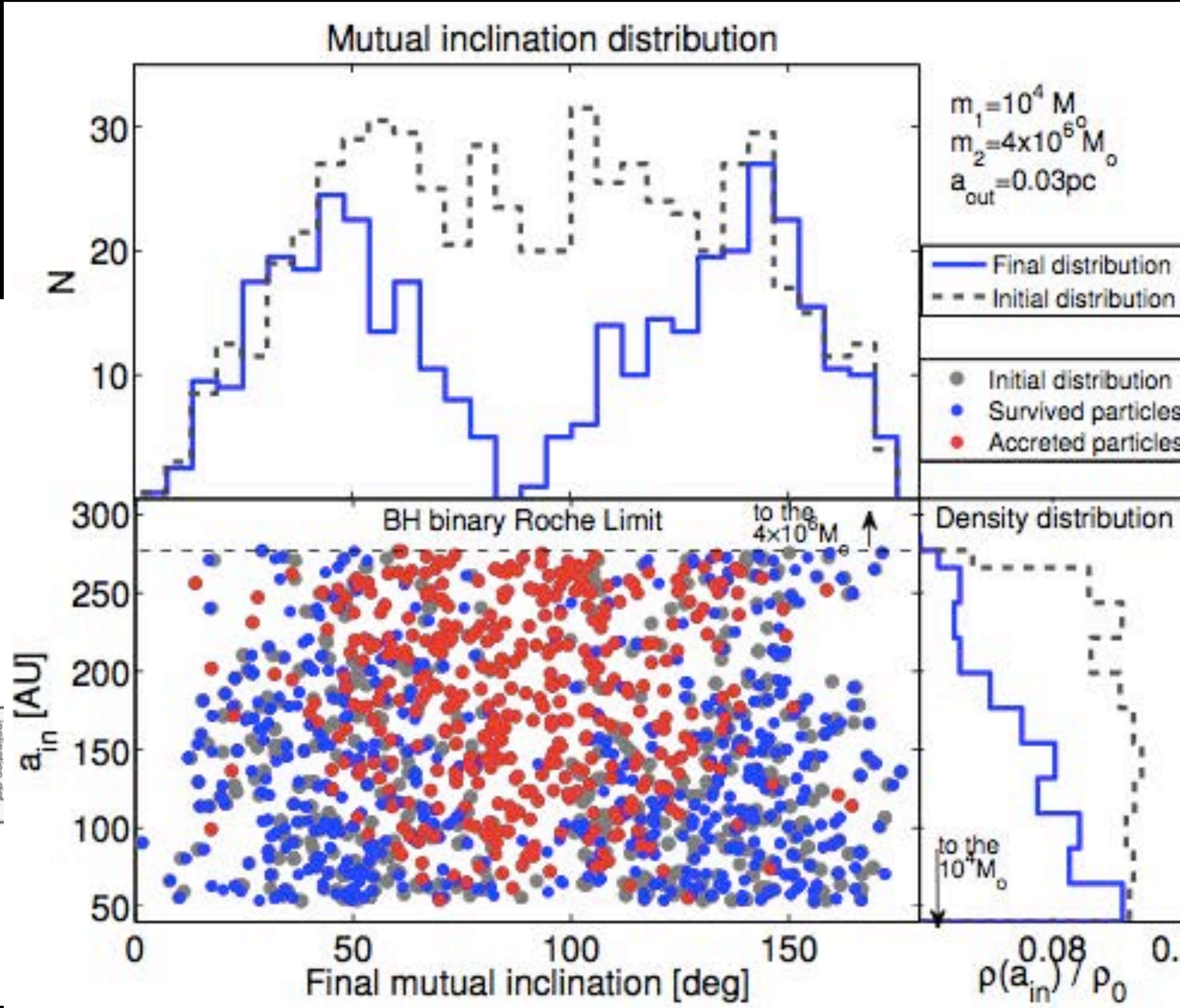

15 dSphs, 6 Years
15 dSphs, 15 Years
45 dSphs, 15 Years
Pass 8 Combined dSphs (15 dSphs, 6 Years)
H.E.S.S. GC Halo
Abazajian et al. 2014 (1σ)
Gordon & Macias 2013 (2σ)
Daylan et al. 2014 (2σ)
Calore et al. 2015 (2σ)
Thermal Relic Cross Section
(Steigman+ 2012)
CTA GC Halo 500 h
Fermi 15 Years, 45 dwarfs
$b\bar{b}$
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{1}
10^{2}
10^{3}
DM Mass (GeV/c²)

Ordinary matter, exotic matter….

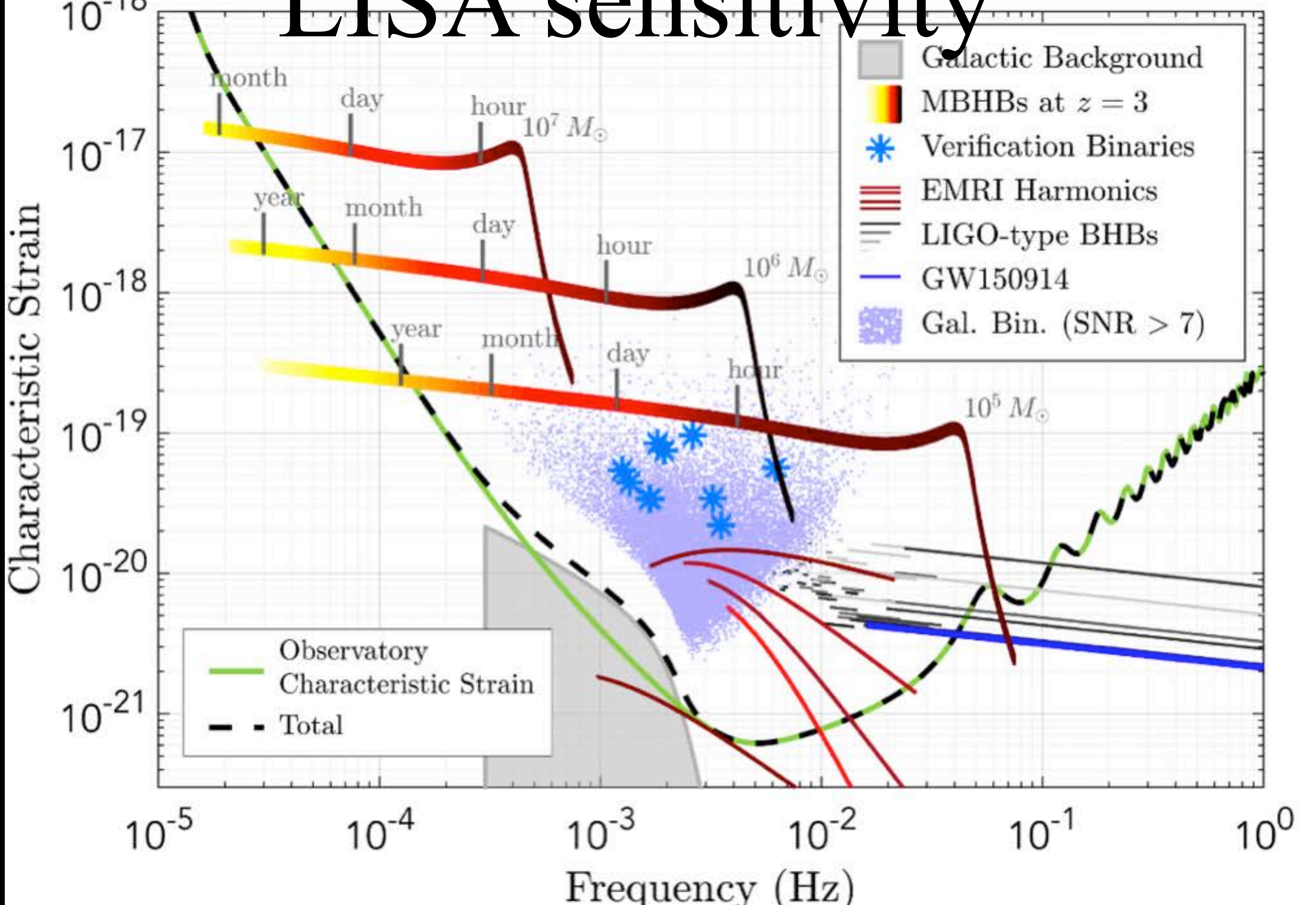
LISA as a DM detector

Naoz & Silk 2014





LISA sensitivity

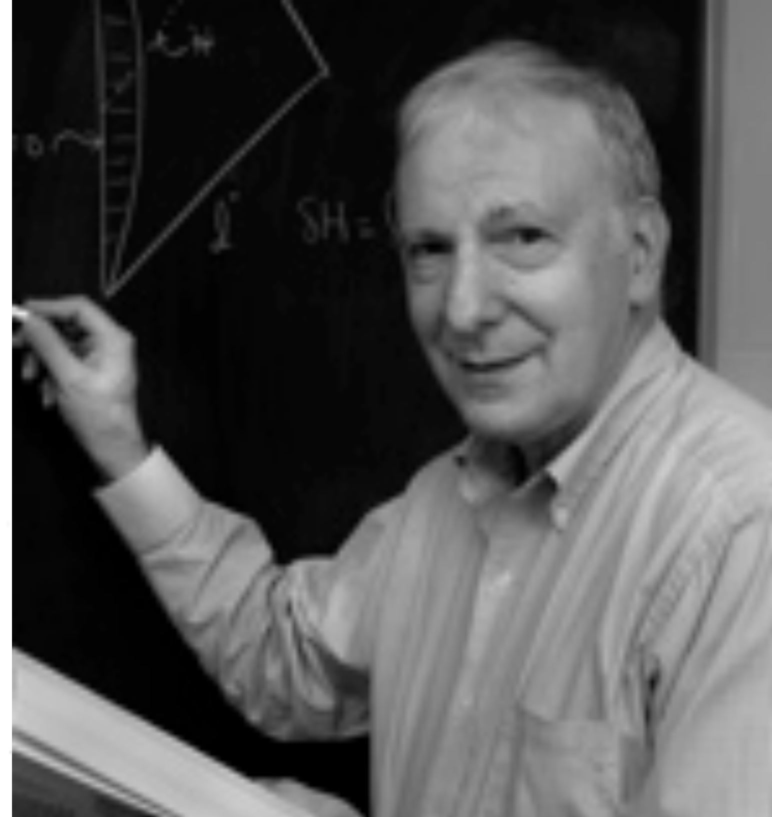


Black hole as a dark matter collider

Extraction of Rotational Energy from a Black Hole

THERE has been considerable interest recently in the question of the gravitational collapse of a massive body and of the possible astrophysical consequences of the existence of the "black hole" which general relativity predicts should sometimes be the result of such a collapse. In particular, the question has arisen whether the mass–energy content of a black hole could, under suitable circumstances, be a source of available energy. We now

ASTROPHYSICAL JOURNAL, 191:231–233, 1974 July 1



ENERGY LIMITS ON THE PENROSE PROCESS

ROBERT M. WALD
Department of Physics and Astronomy, University of Maryland, College Park

Received 1973 December 26

ABSTRACT

If a body in the vicinity of a rotating black hole breaks apart into two or more fragments, then under appropriate conditions the rotational energy of the black hole can be used to enhance the energy of one of the fragments (Penrose process). Wheeler and others have suggested that the Penrose process could serve as an energy mechanism for jets. In this paper we derive strict limits on the energies which can be achieved by the Penrose process. It is shown that in no case can one obtain energies which are greater by a significant factor than those which already could be obtained by a similar breakup process without the presence of a black hole.

Black holes as particle accelerators: a history

Piran & Shaham (1977)

Upper bounds on collisional Penrose processes near rotating black-hole horizons

Banados, Silk, & West (2009)

Kerr Black Holes as Particle Accelerators to Arbitrarily High Energy

Bejger , Piran, Abramowicz, Hakansonet (2012)

Collisional Penrose process near the horizon of extreme Kerr black holes

Harada et al.(2012)

Upper limits of particle emission from high-energy collision and reaction near a maximally rotating Kerr black holes

Zaslavskii (2012)

Acceleration of particles by black holes as a result of deceleration: ultimate manifestation of kinematic nature of BSW effect

Schnittman (2014)

A revised upper limit to energy extraction from a Kerr black hole

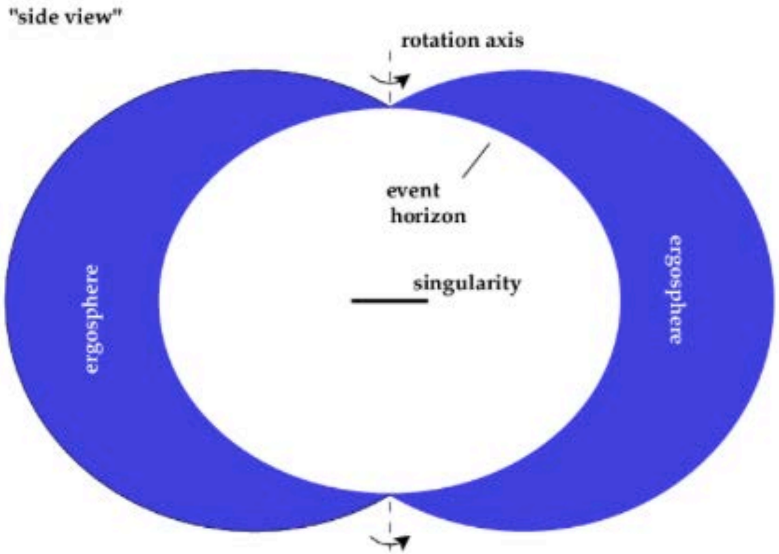
Berti, Brito, Cardoso (2014)

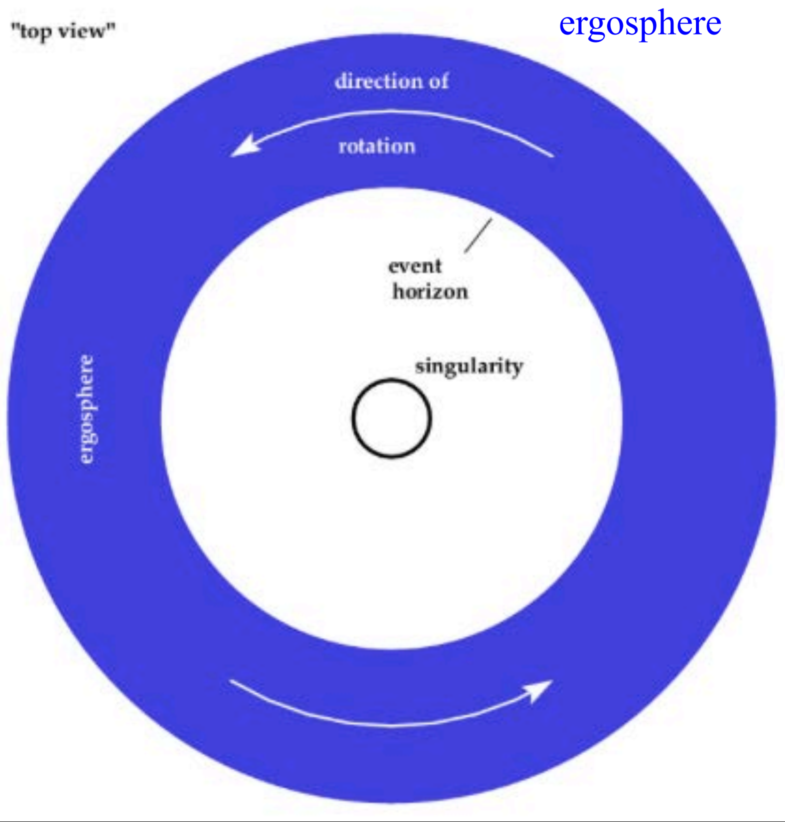
Energy debris from the collisional Penrose process

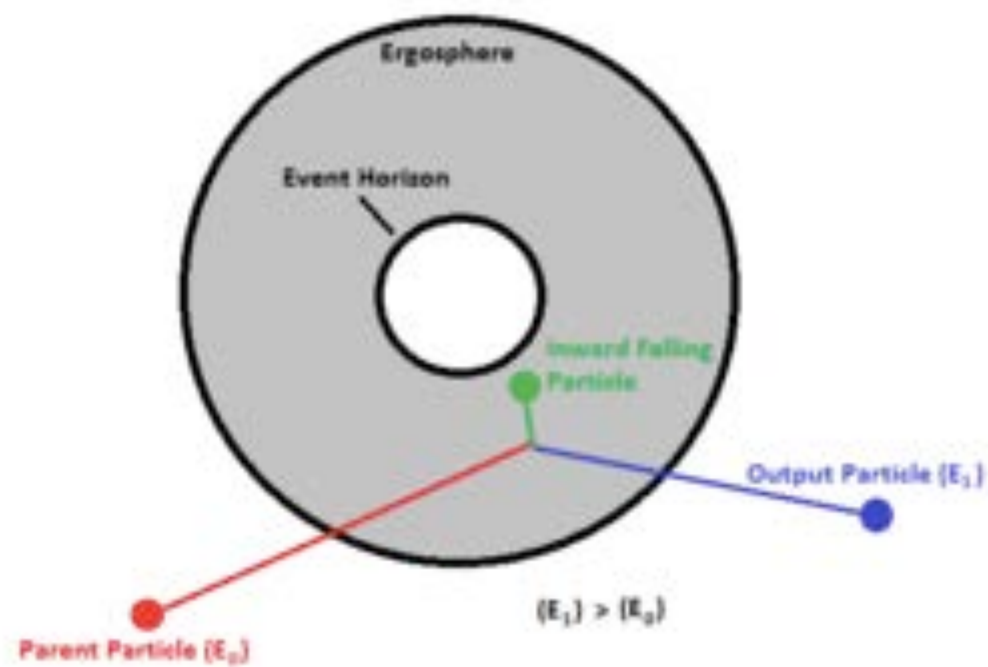
Zaslavskii (2014)

- Unbounded energies of debris from head-on particle collisions near black holes

NEAR KERR BLACK HOLES

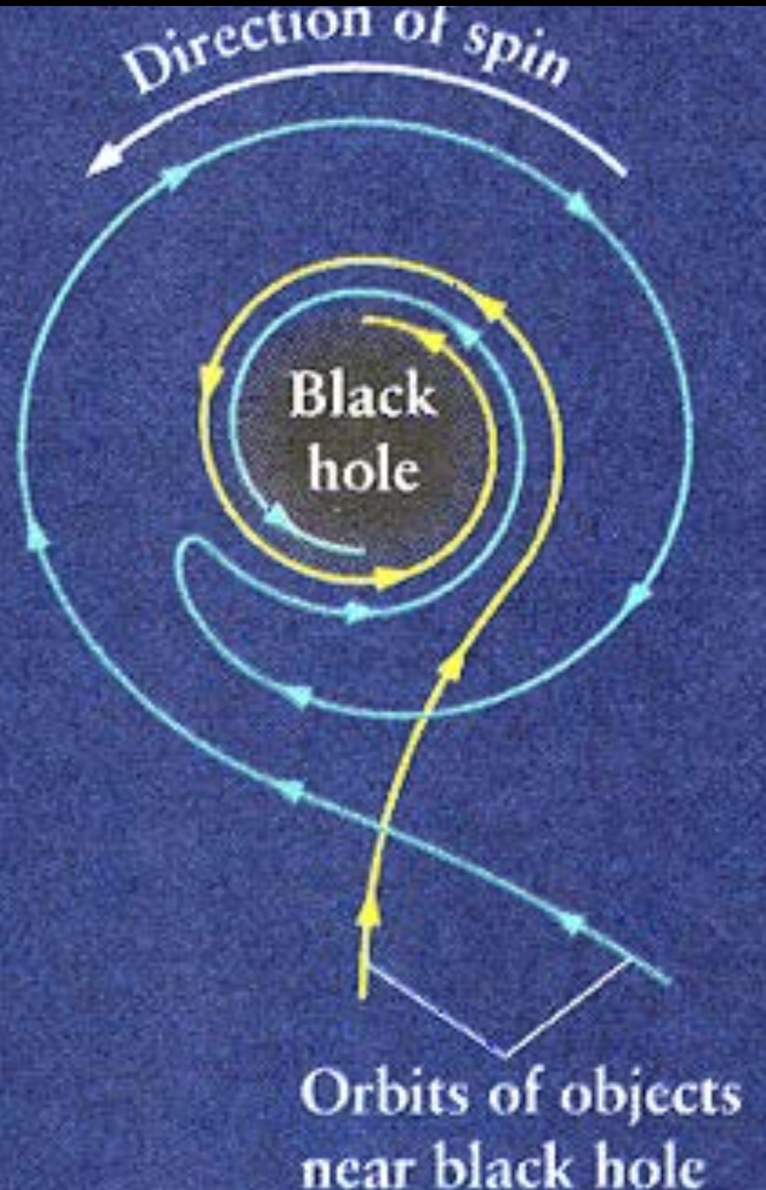


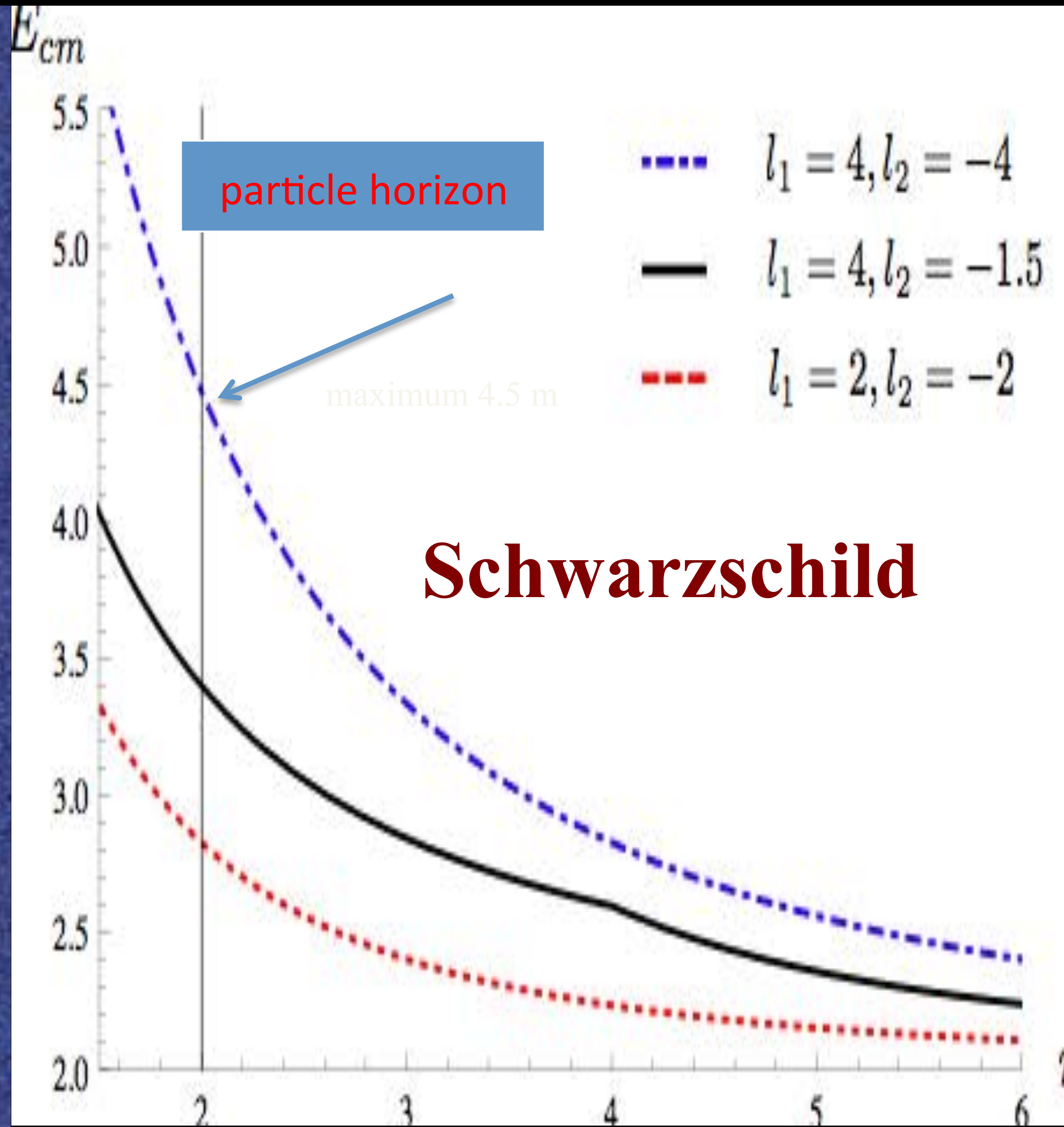




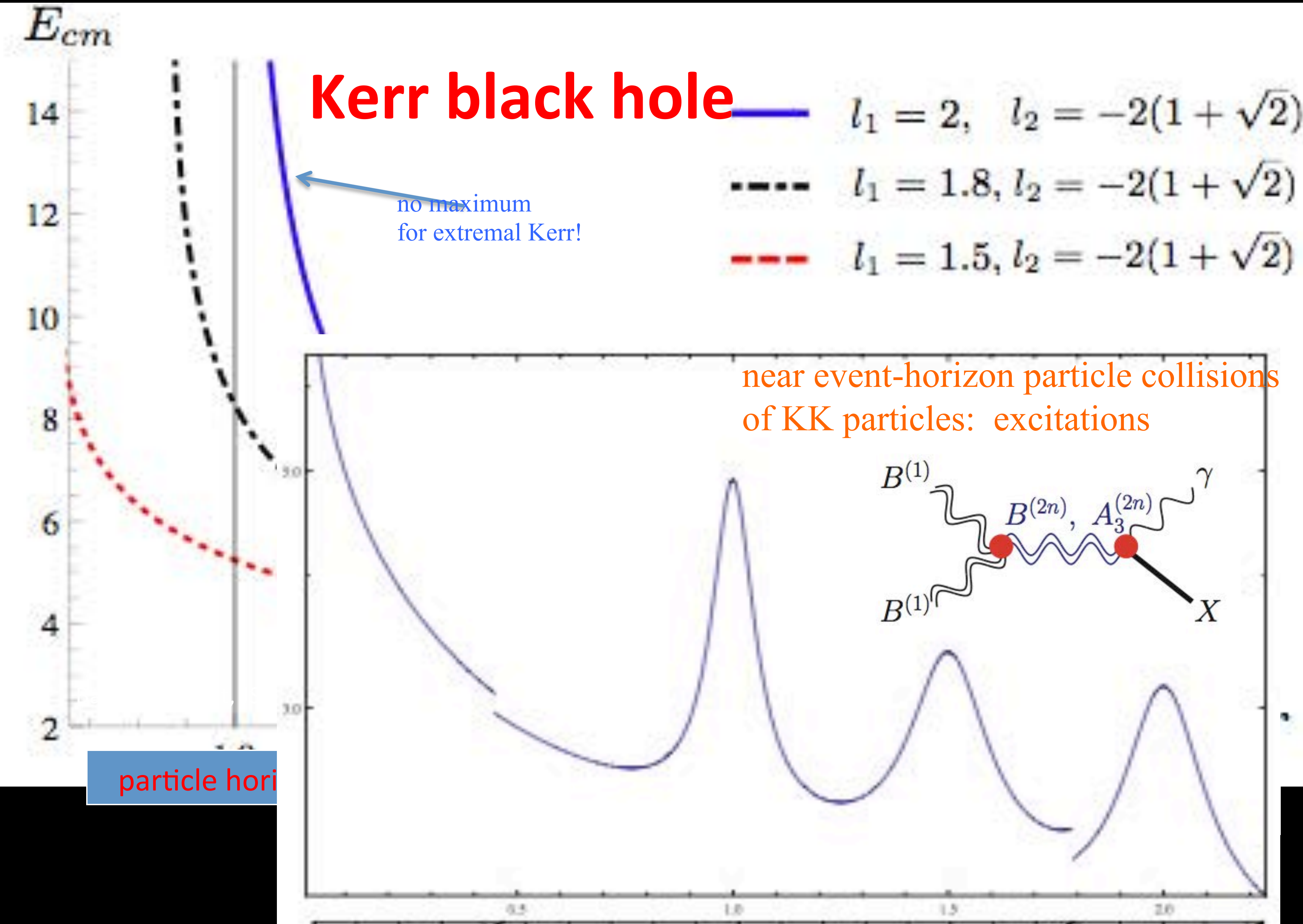
BLACK HOLES

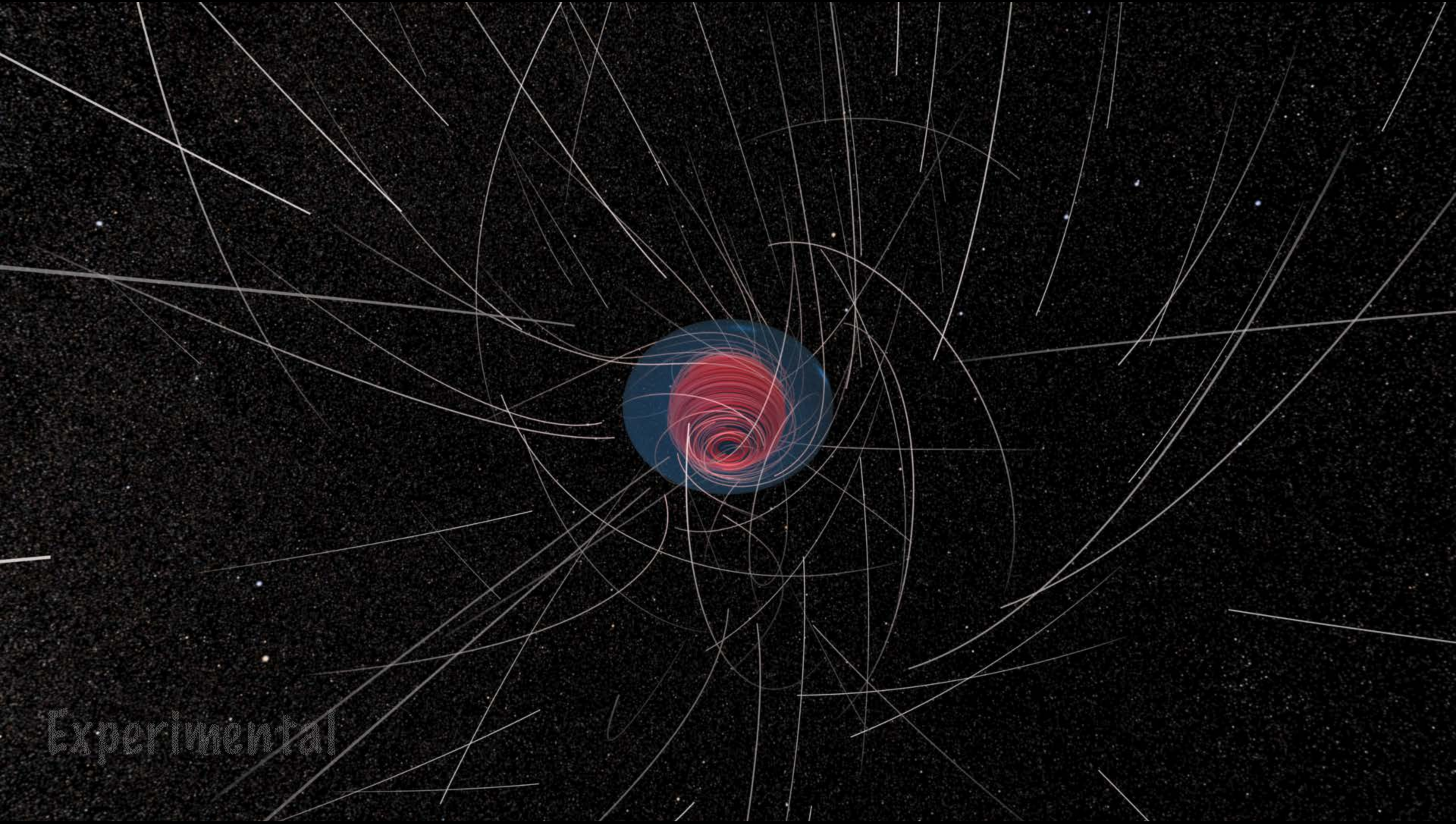
THE ULTIMATE PARTICLE ACCELERATOR: dark matter cusp around black hole

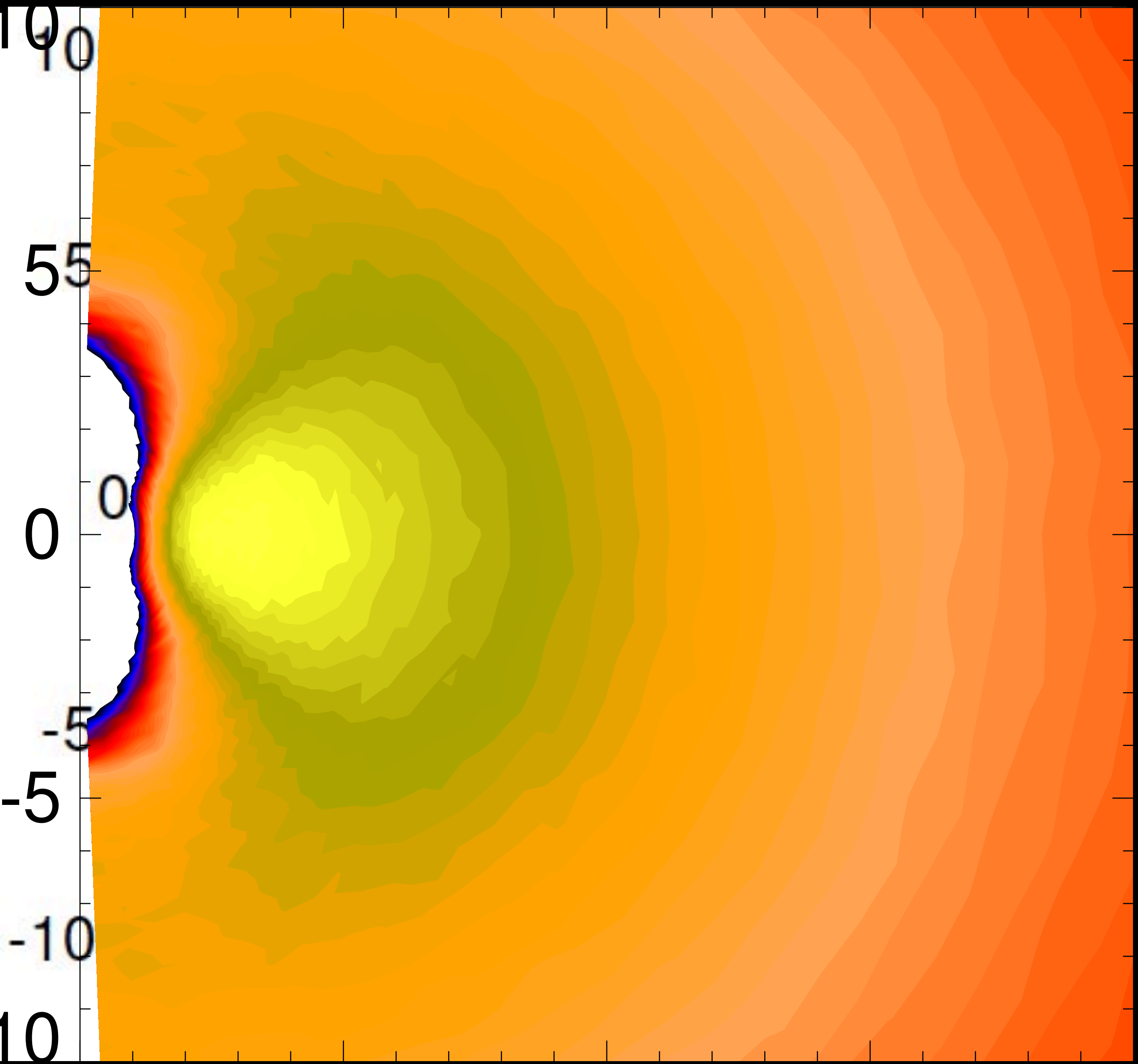




Rotating black hole can feed Penrose effect via DM particle collisions

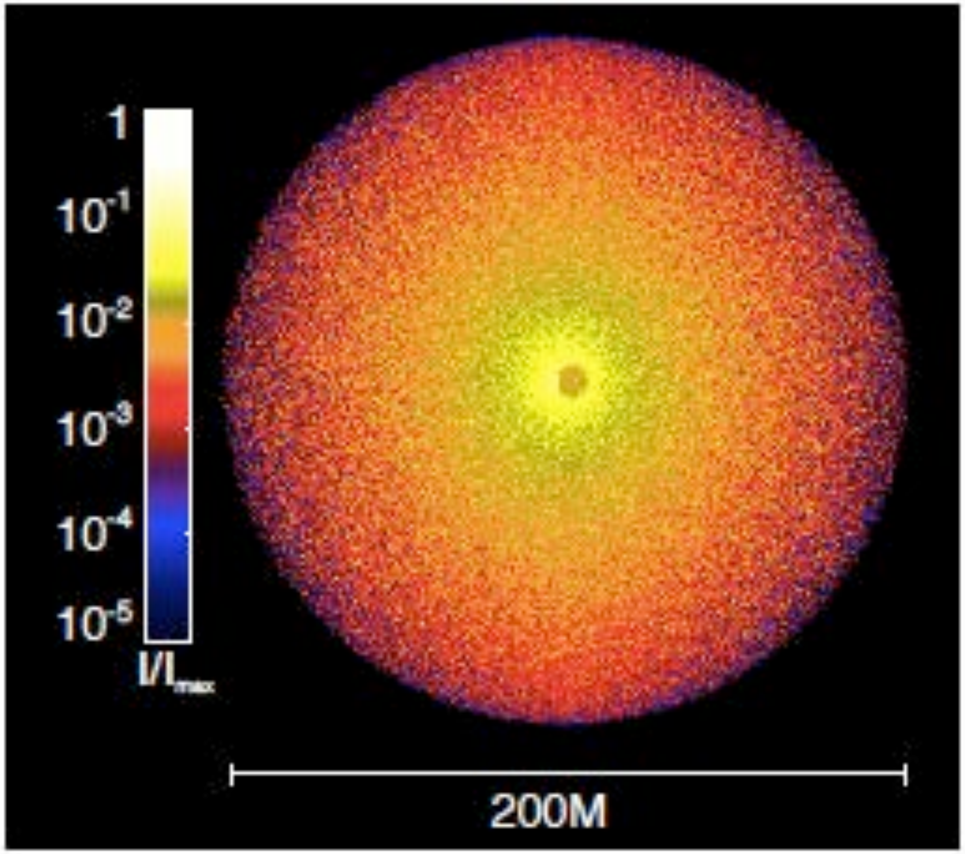


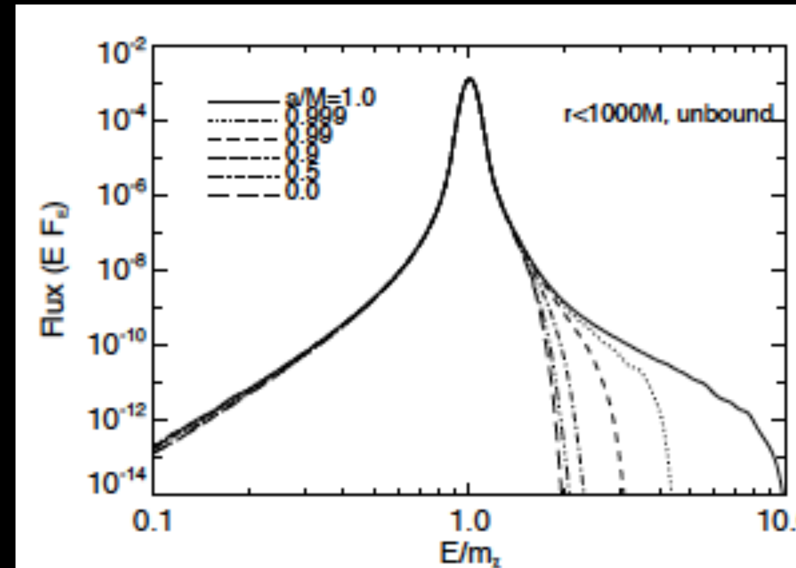

Experimental

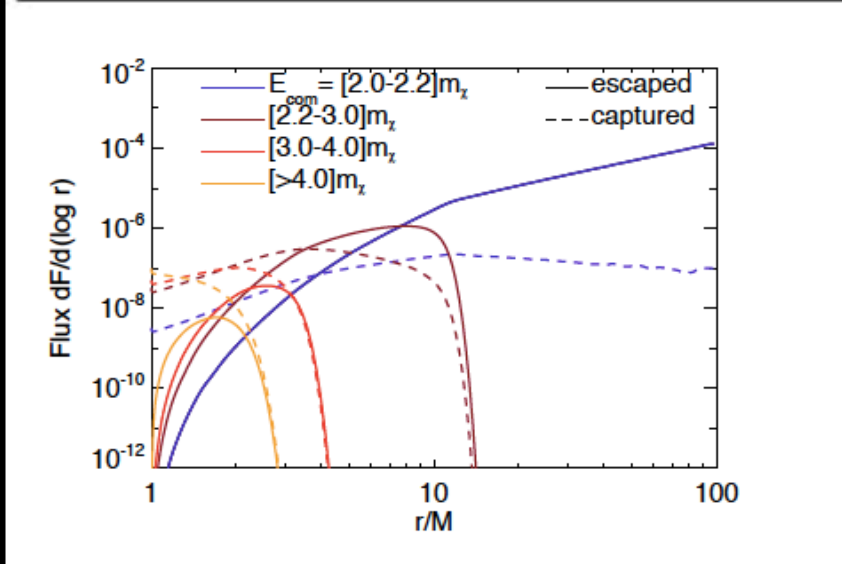


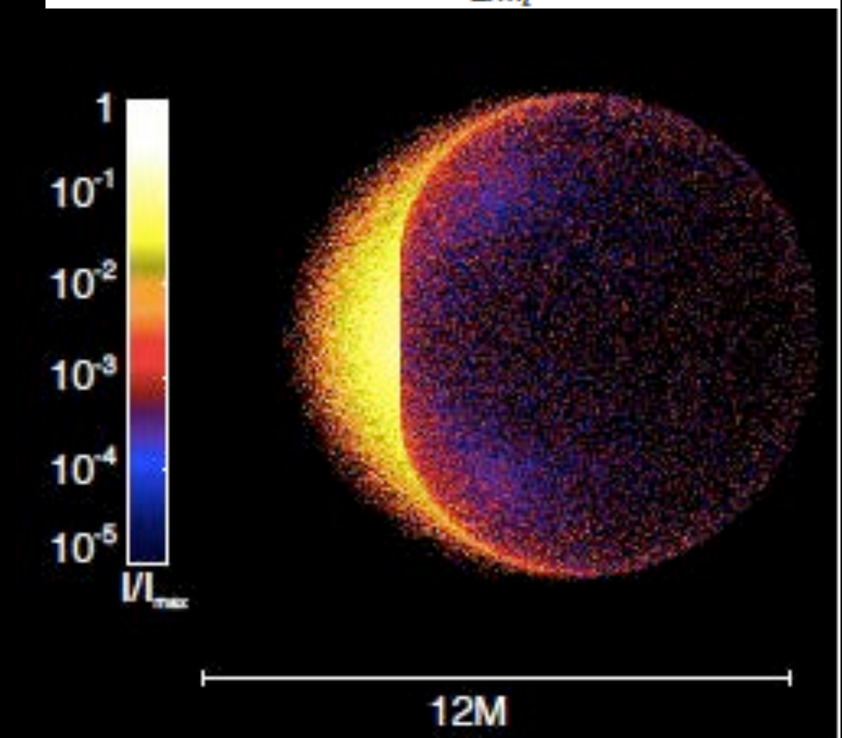
Frame dragging
generates a
near-horizon torus

Annihilation images

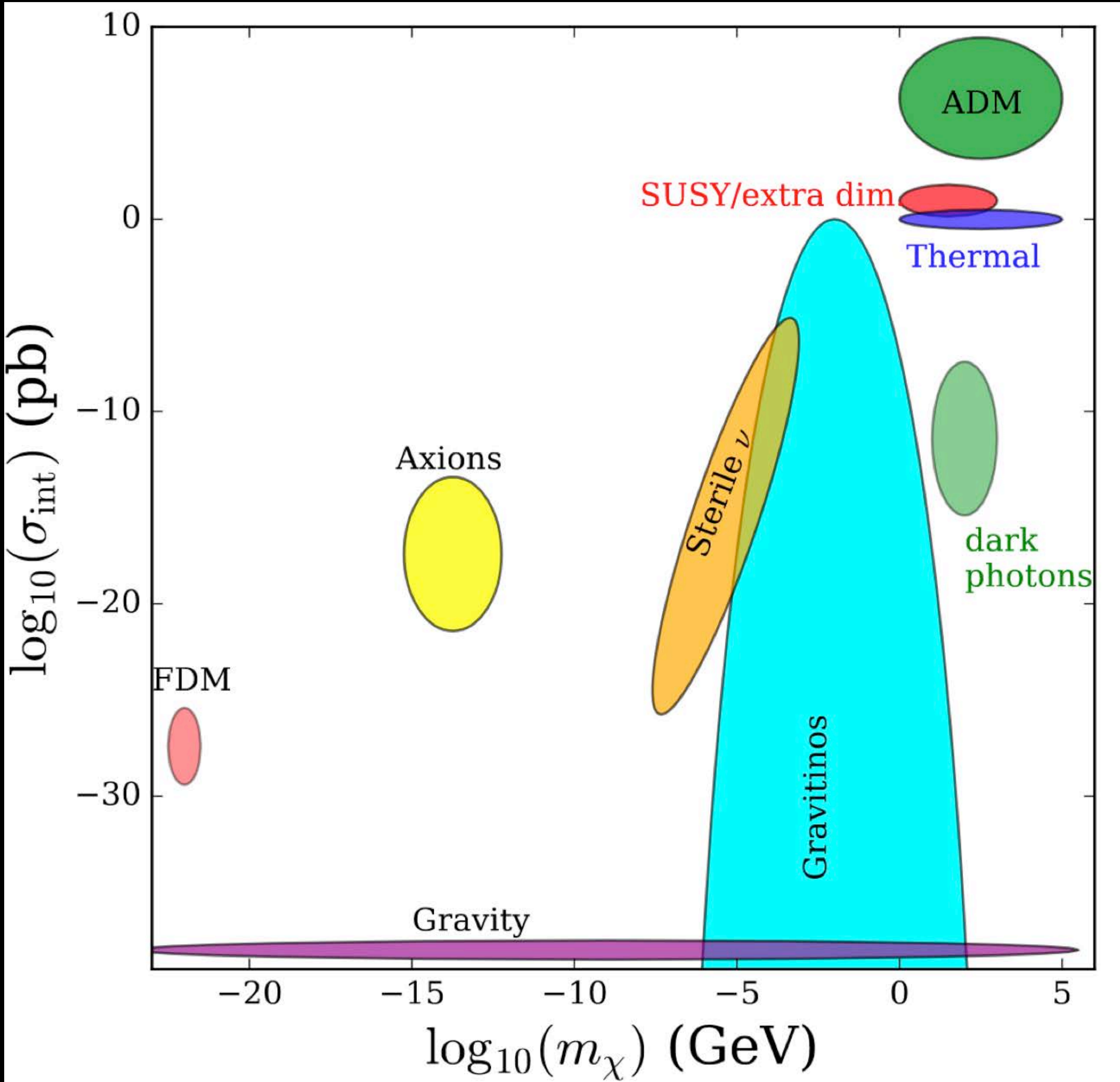




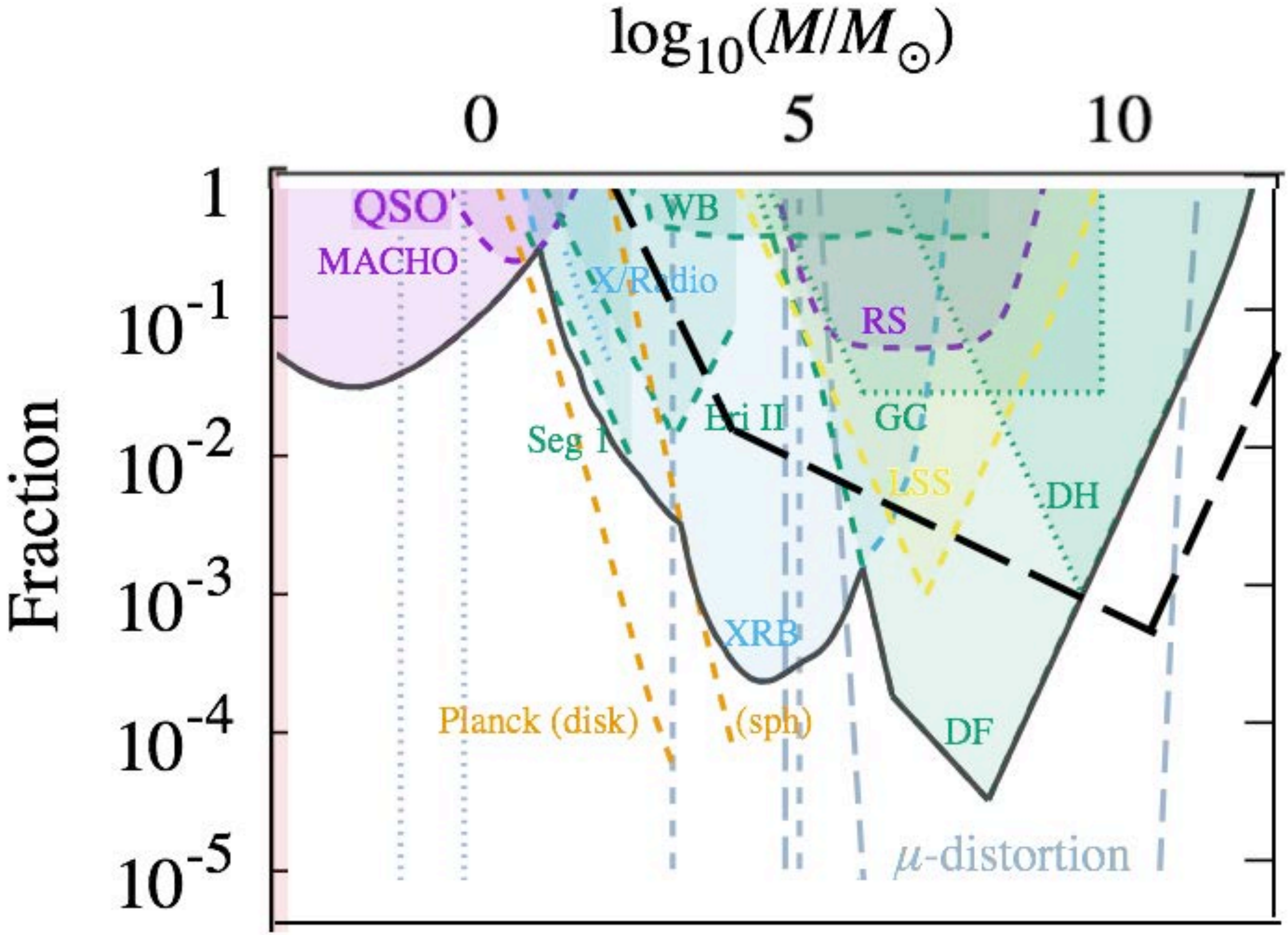




The future for dark matter theory

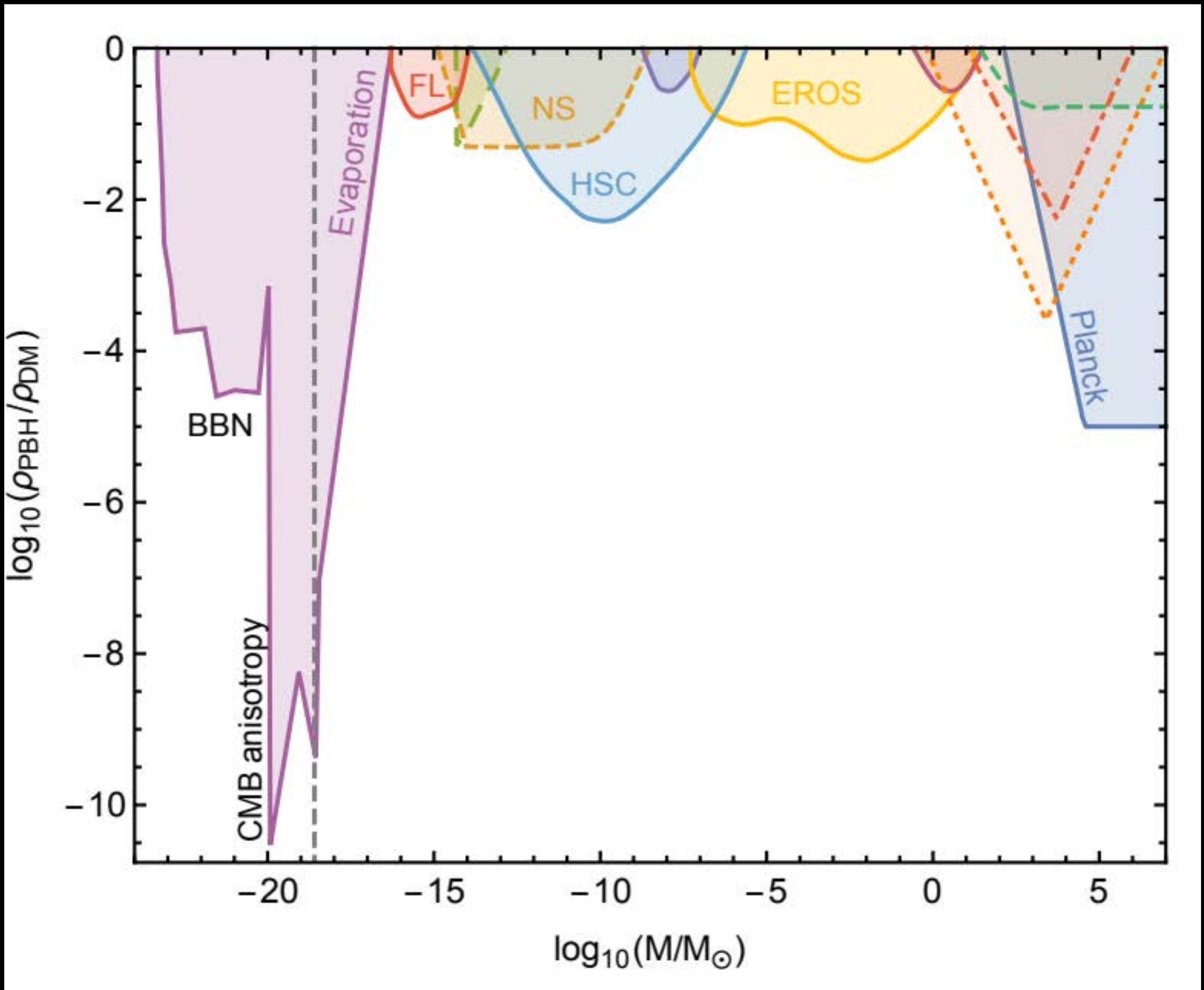


PRIMORDIAL BLACK HOLES AS DARK MATTER?



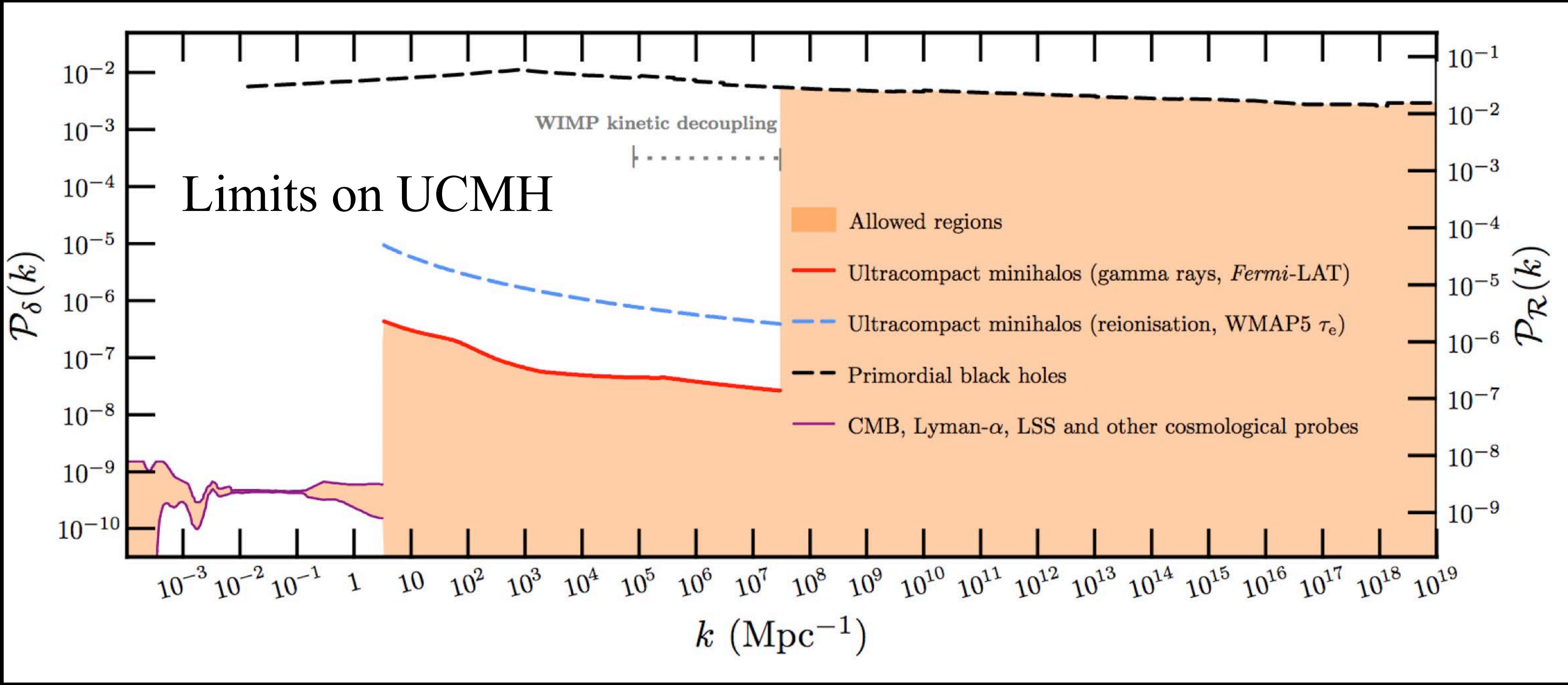
$\log_{10}(M/M_\odot)$
0
5
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Fraction
QSO
MACHO
WB
X/Radio
RS
Eri II
GG
Seg 1
LSS
DH
XRB
Planck (disk)
(sph)
DF
μ-distortion

PBH windows for DM are $(\sim 10^{-16}$ or $\sim 10)$ M_{sun}



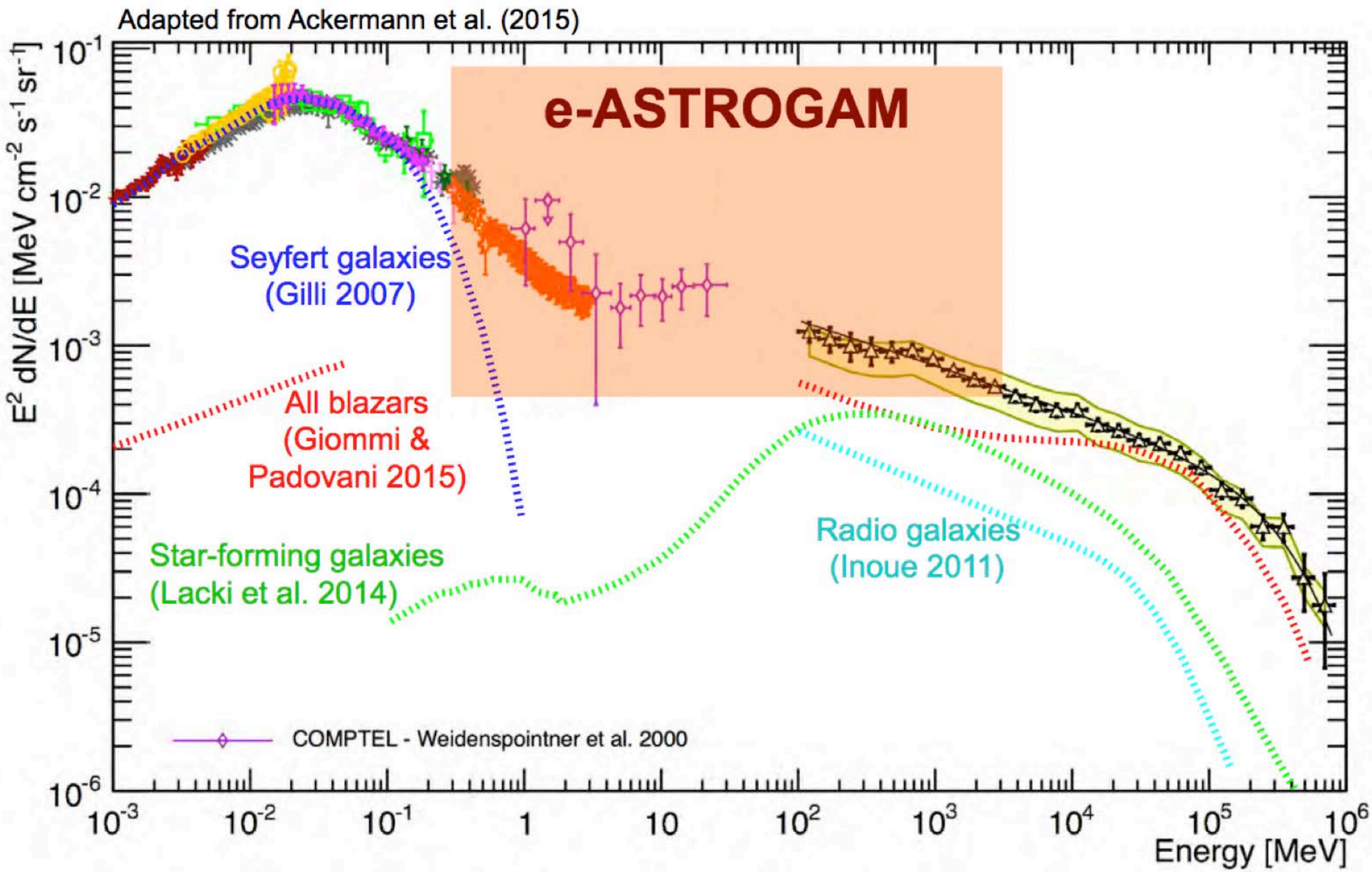
Casrr + 2017

prediction: ultracompact minihalos are inevitable if primordial black holes are formed

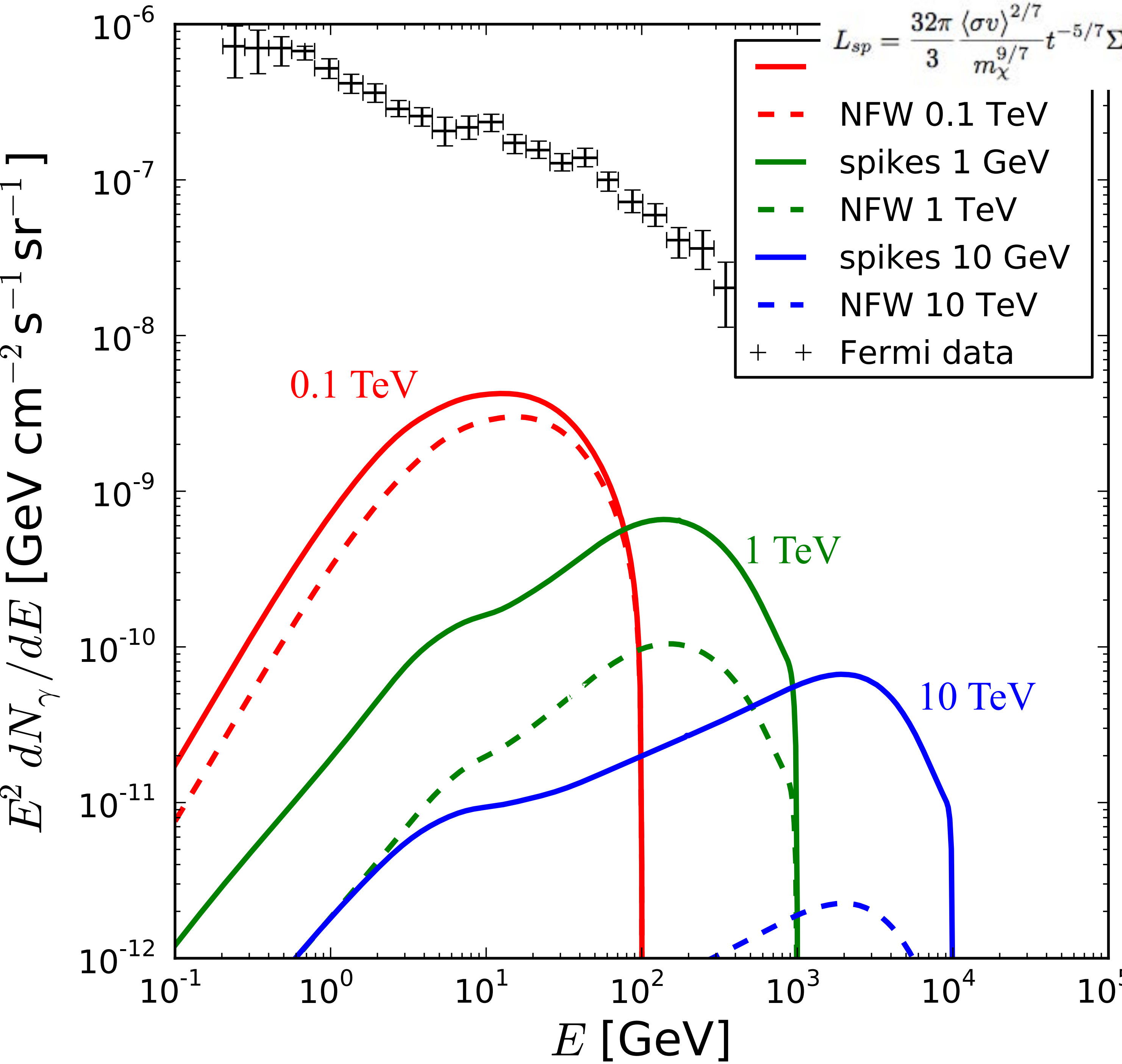


Bringmann + 2012

Diffuse γ-ray background signatures?



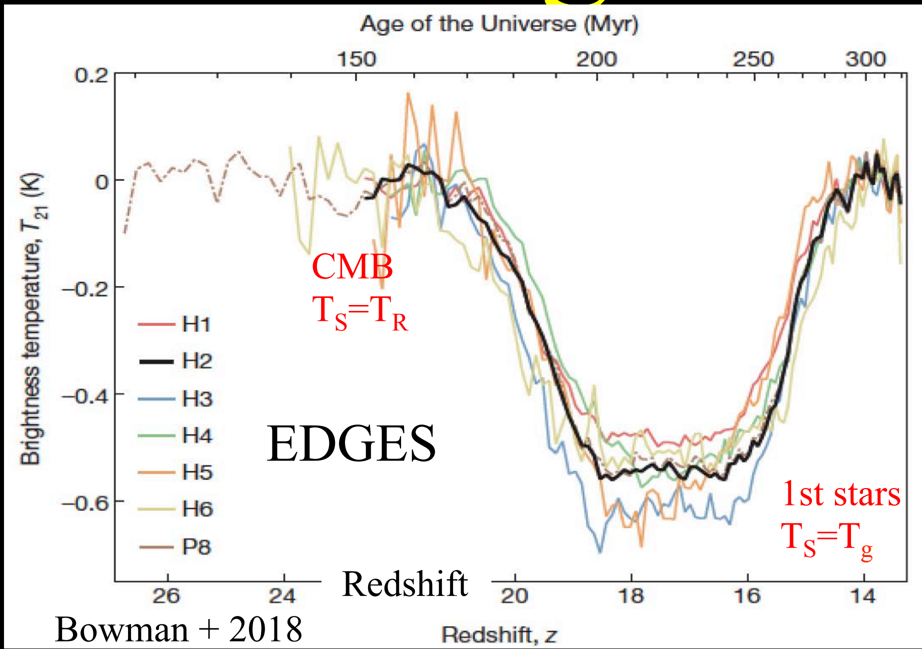
$$L_{sp} = \frac{32\pi}{3}\frac{\langle\sigma v\rangle^{2/7}}{m_\chi^{9/7}} t^{-5/7}\Sigma_{1/2}^{3/7}\left(\frac{M_{BH}}{M_{1/2}}\right)^{6/7} M_{BH}^{6/7}$$



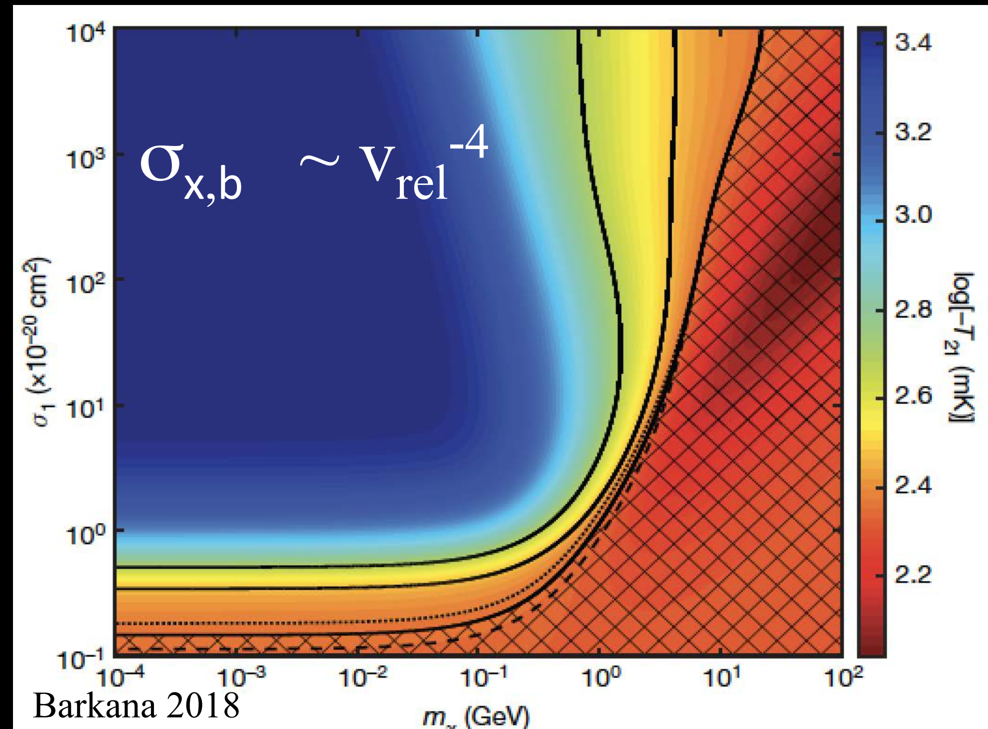
Annihilations
In dark matter
spikes around
supermassive
black holes

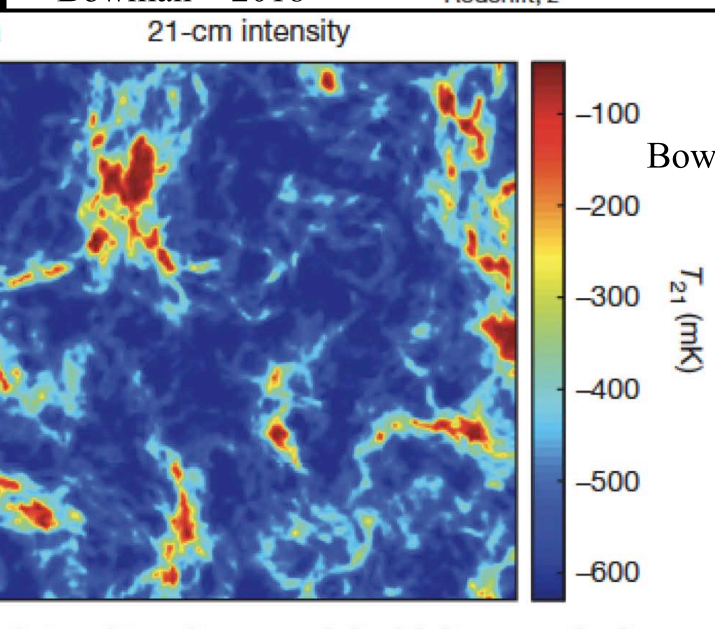
Belikov & Silk 2013

Breaking news: Nature, today



$$T_{21}(z) \approx 0.023\,\mathrm{K} \times x_{\mathrm{HI}}(z)\left[\left(\frac{0.15}{\Omega_{\mathrm{m}}}\right)\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}\left(\frac{\Omega_{\mathrm{b}}h}{0.02}\right)\left[1-\frac{T_{\mathrm{R}}(z)}{T_{\mathrm{S}}(z)}\right]$$



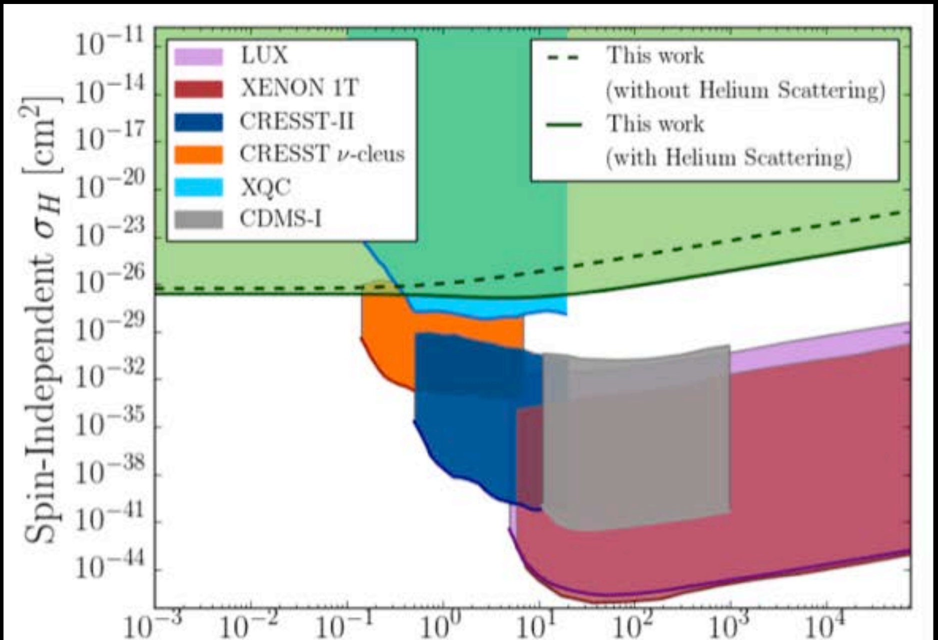


Need extra cooling of HI at z~ 17

Hypothesis: DM-baryon scattering

Predict global 21 cm absorption signal from cold HI blobs on ~ BAO scale ~ 100 Mpc

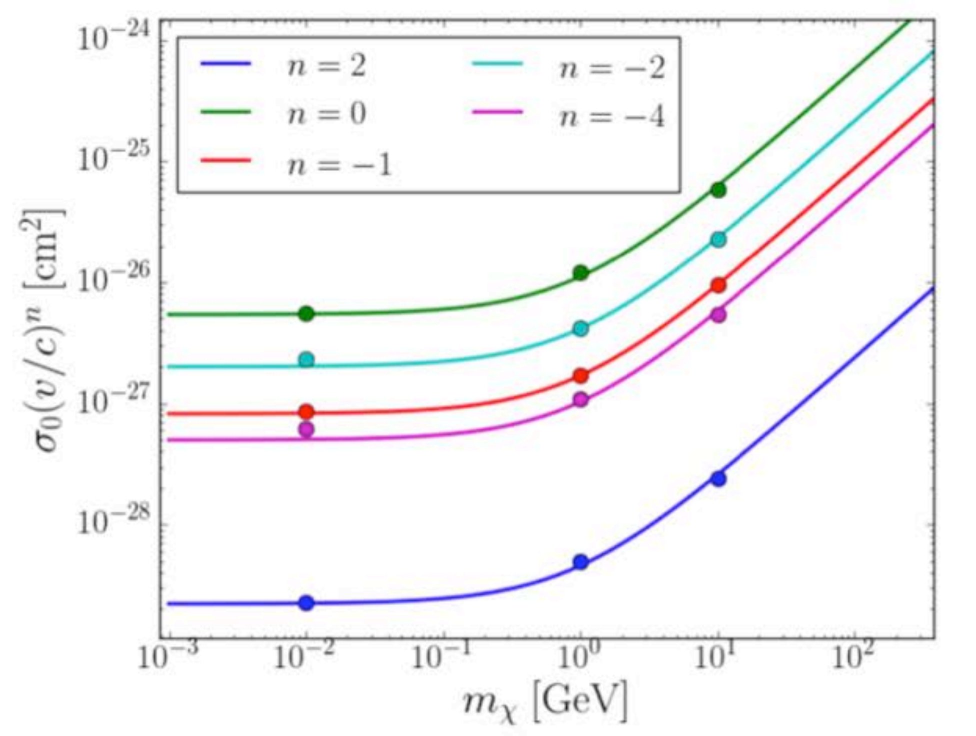
Limits on DM-baryon scattering



Xu + 2018

direct detection

indirect detection



Dark matter is here to stay
But what is it?

Many experiments worldwide.
Hints of indirect detection signatures.
But its dangerous to invent exotic DM
to explain one ~3σ signal!

In a decade we'd better detect it
by a multimessenger approach……
or else we'll need to radically change our theory