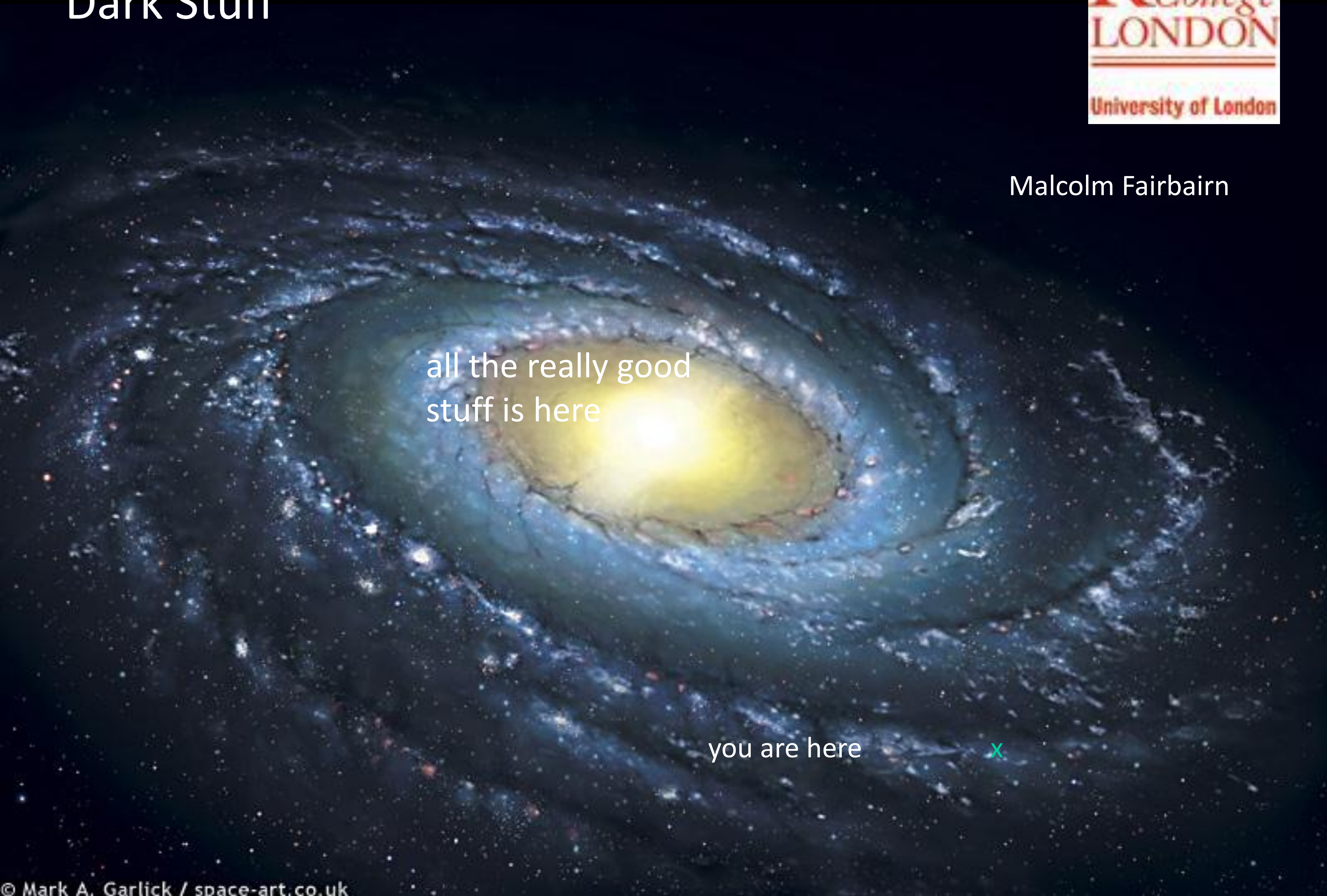
Dark Stuff

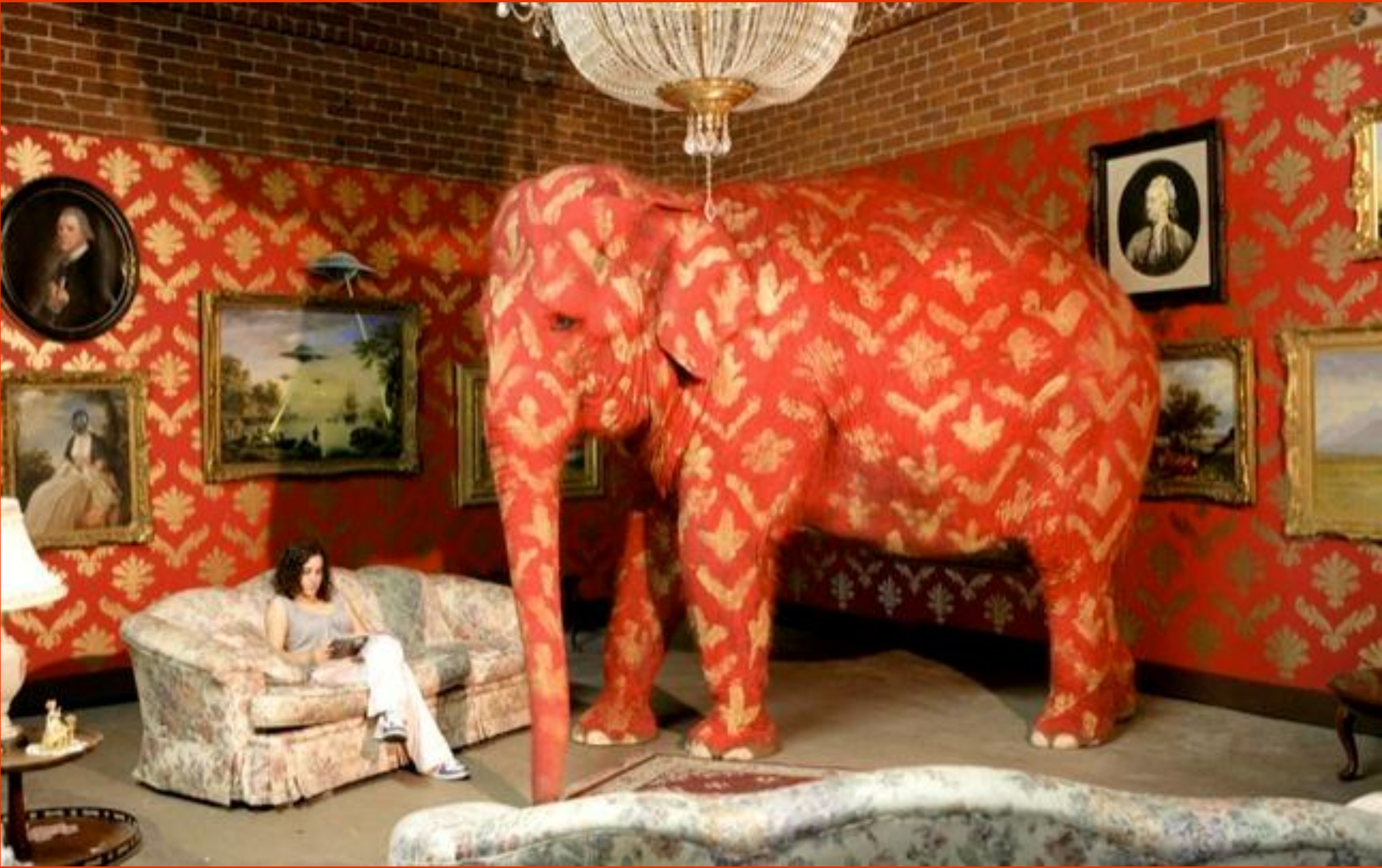
Malcolm Fairbairn

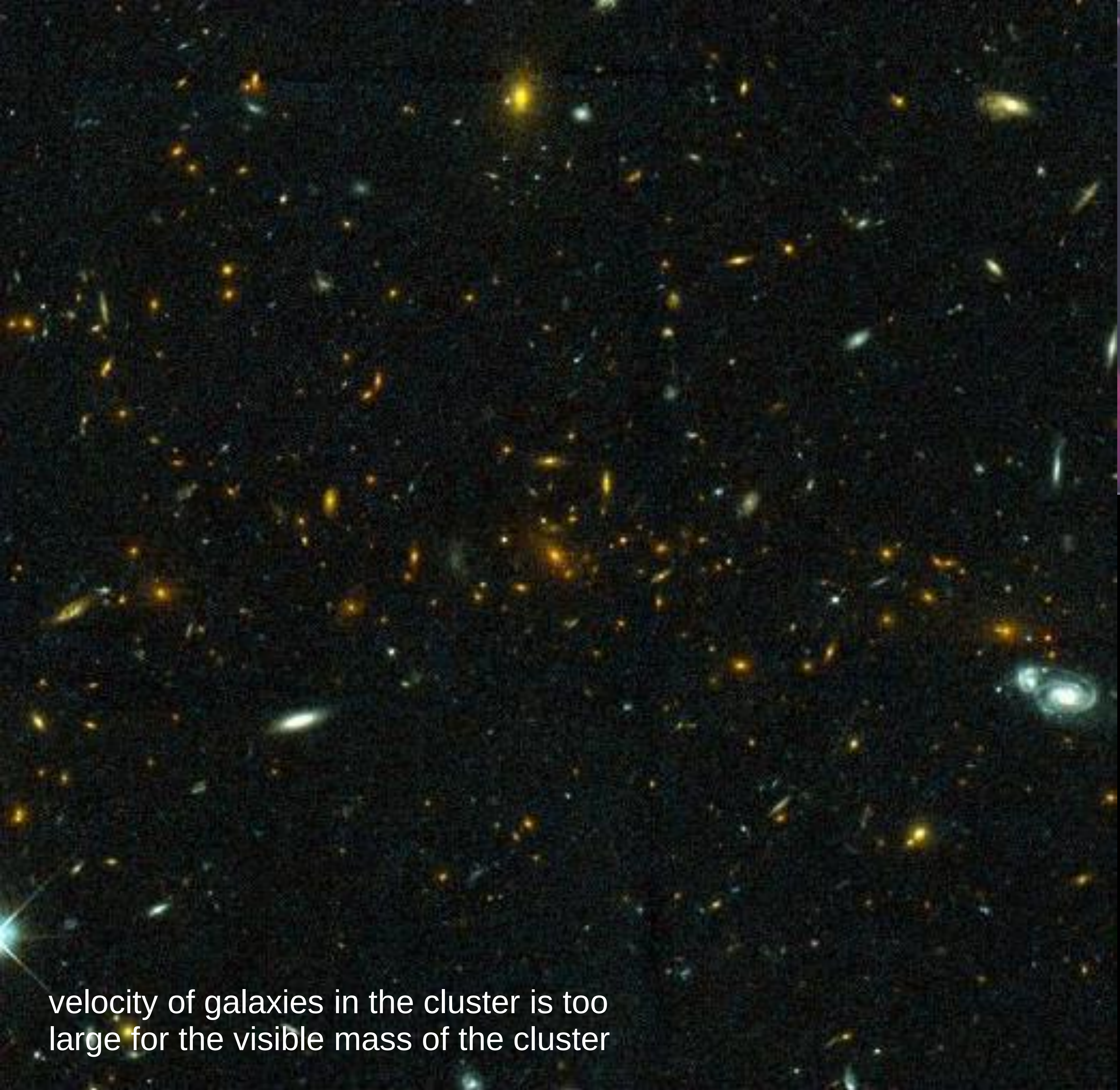


Agenda

- Evidence for Dark matter
- A few different candidates
- Indirect detection
- Direct detection
- Dark Energy (if I have time)

Evidence for Dark Matter

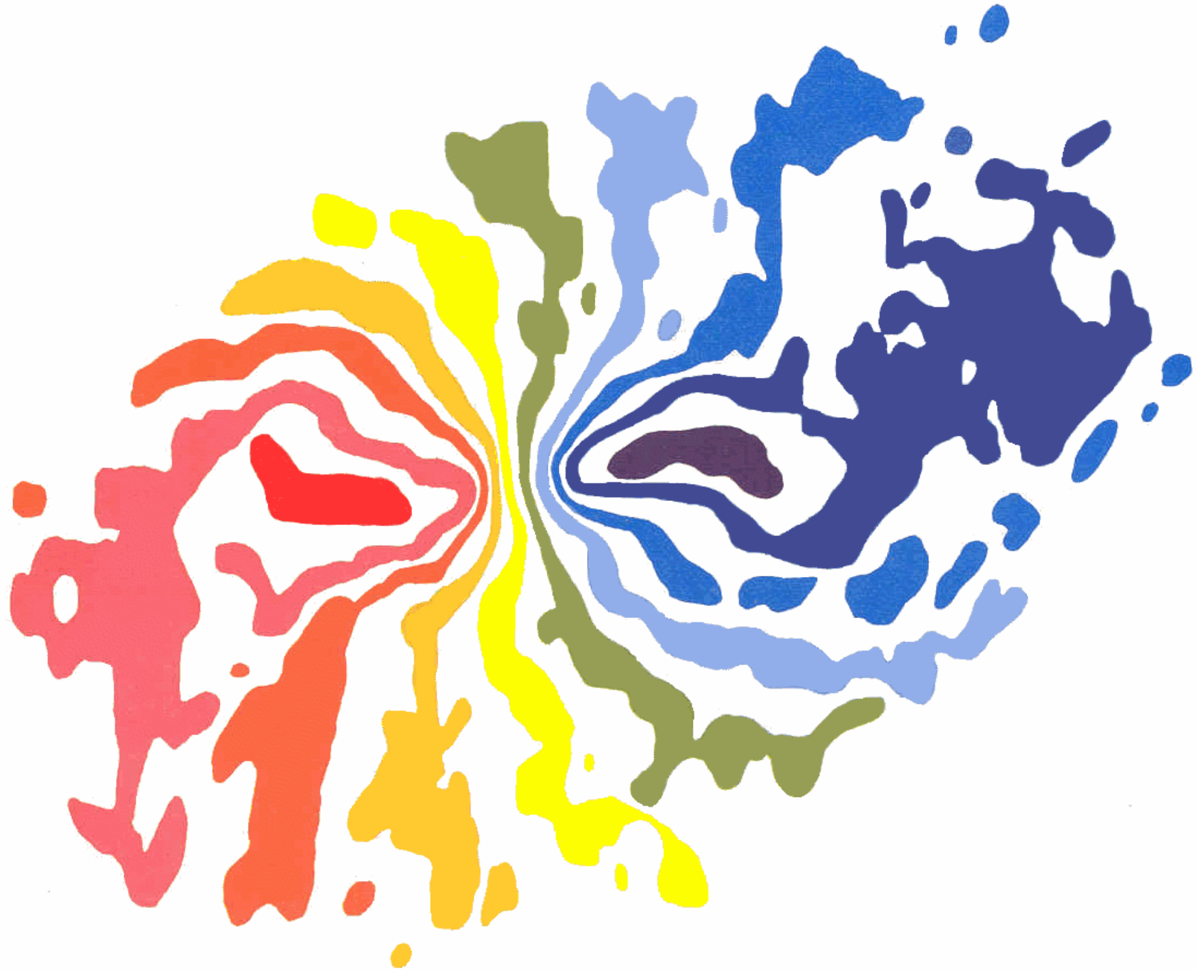




"I have a good idea every two years. Give me a topic, I will give you the idea!"

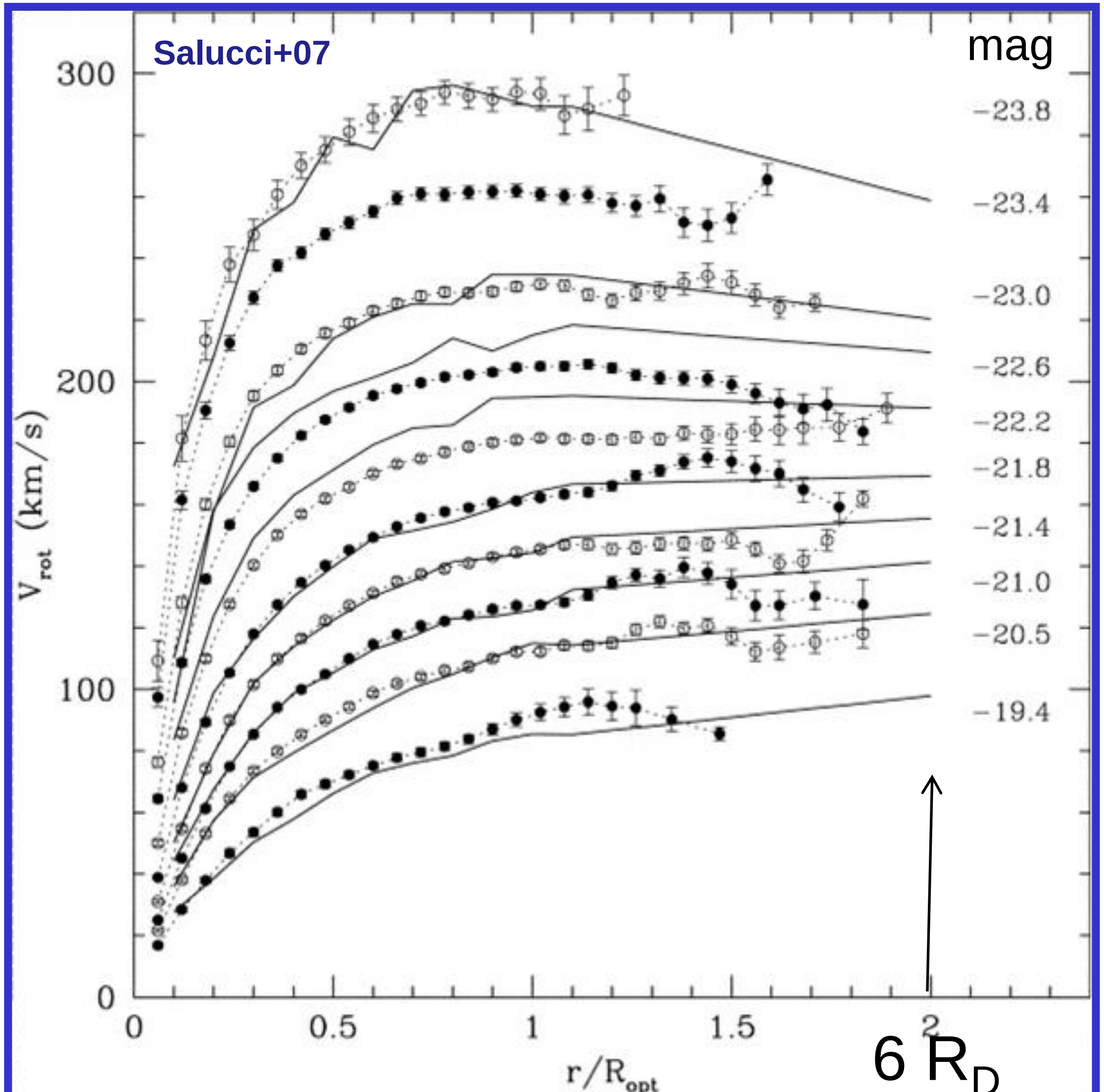
Fritz Zwicky
Coma Cluster 1933

HI velocity field of NGC 5055

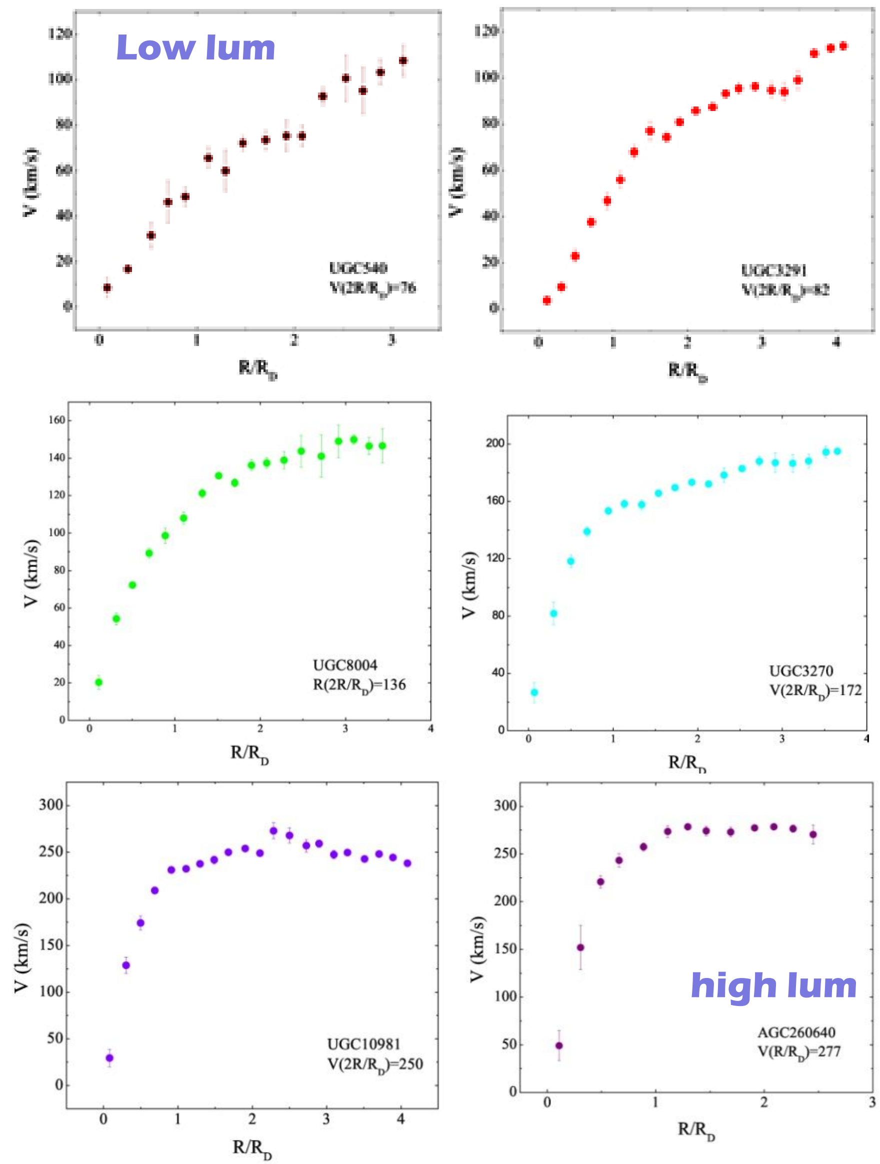


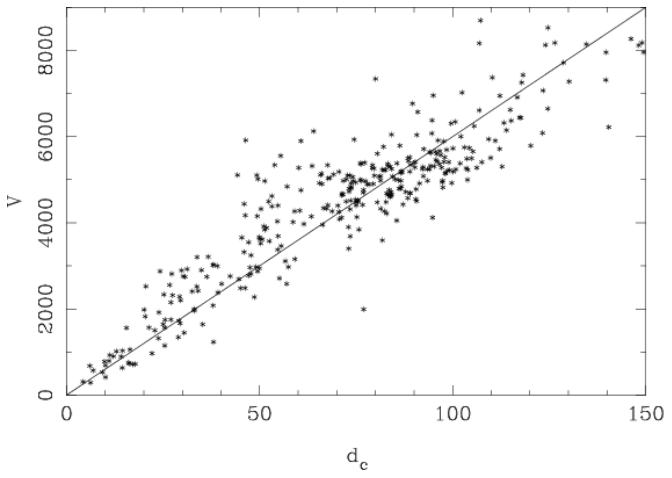
Rotation Curves

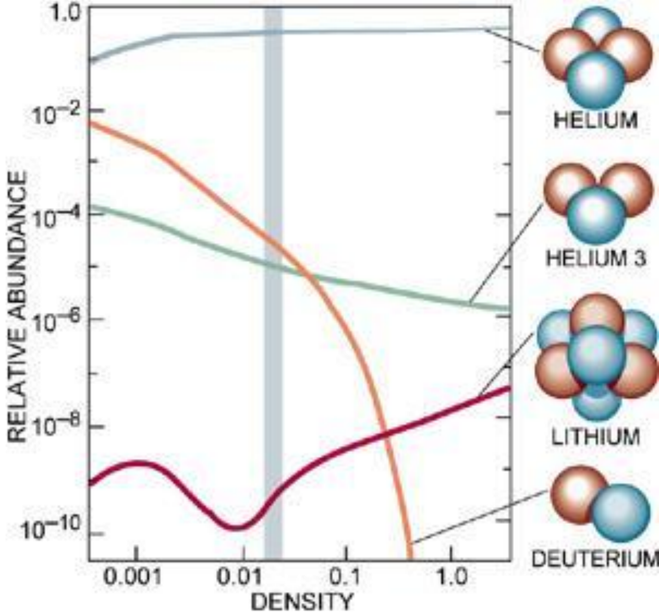
Coadded from 3200 individual RCs



TYPICAL INDIVIDUAL RCs OF INCREASING LUMINOSITY





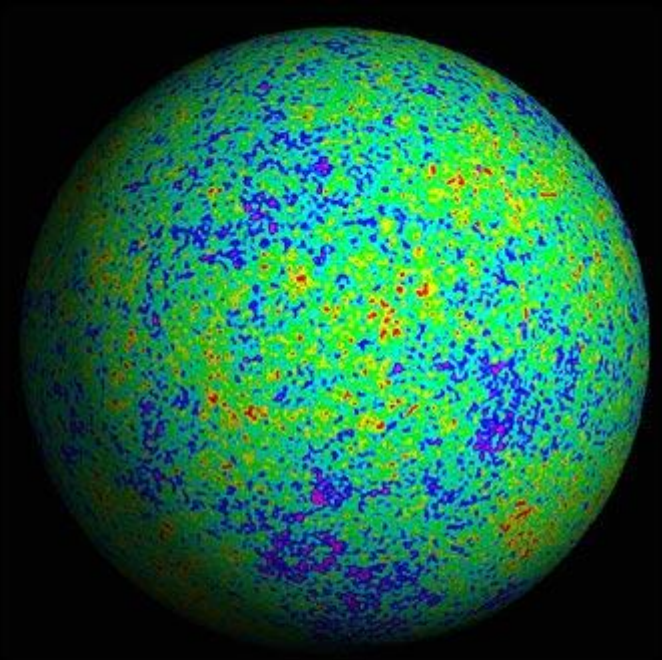


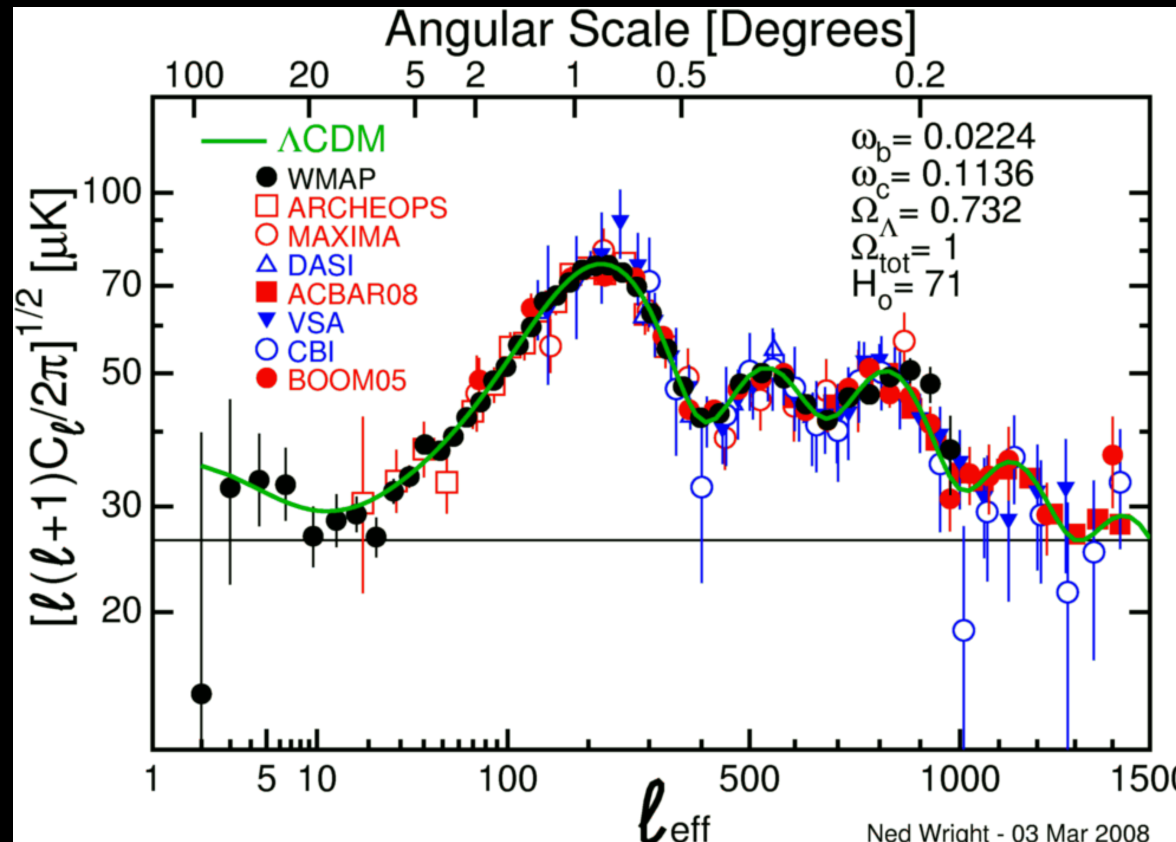
$$H^2 = \frac{8\pi G\rho}{3}$$

10^{-29} g cm^{-3}

4×10^{-31} g cm^{-3}

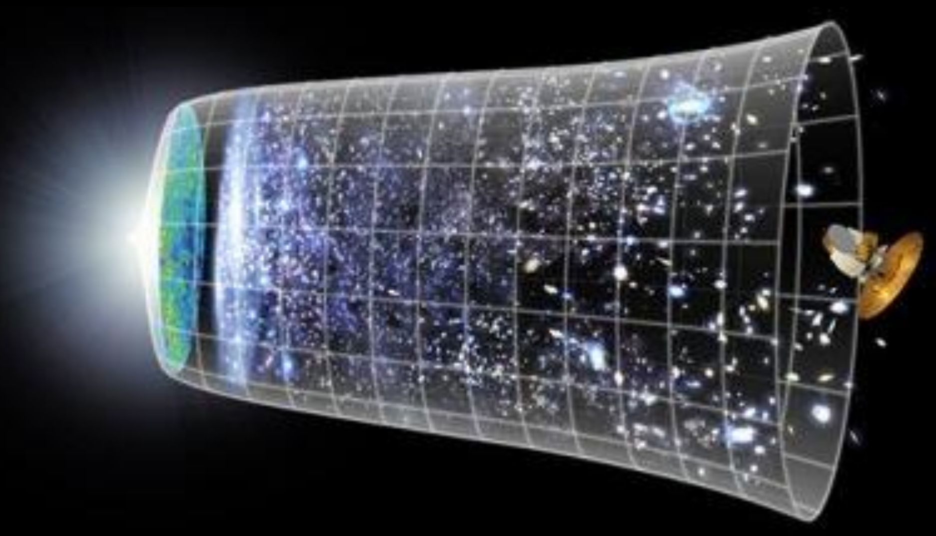
What's all the rest???





Angular Scale [Degrees]
100 20 5 2 1 0.5 0.2
ΛCDM
WMAP
ARCHEOPS
MAXIMA
DASI
ACBAR08
VSA
CBI
BOOM05
ω_b= 0.0224
ω_c= 0.1136
Ω_Λ= 0.732
Ω_{tot}= 1
H_o= 71
$[\ell(\ell+1)C_\ell/2\pi]^{1/2}$ [μK]
100 70 50 30 20
1 5 10 100 500 1000 1500
ℓ_{eff}
Ned Wright - 03 Mar 2008

The expansion of the universe is accelerating!



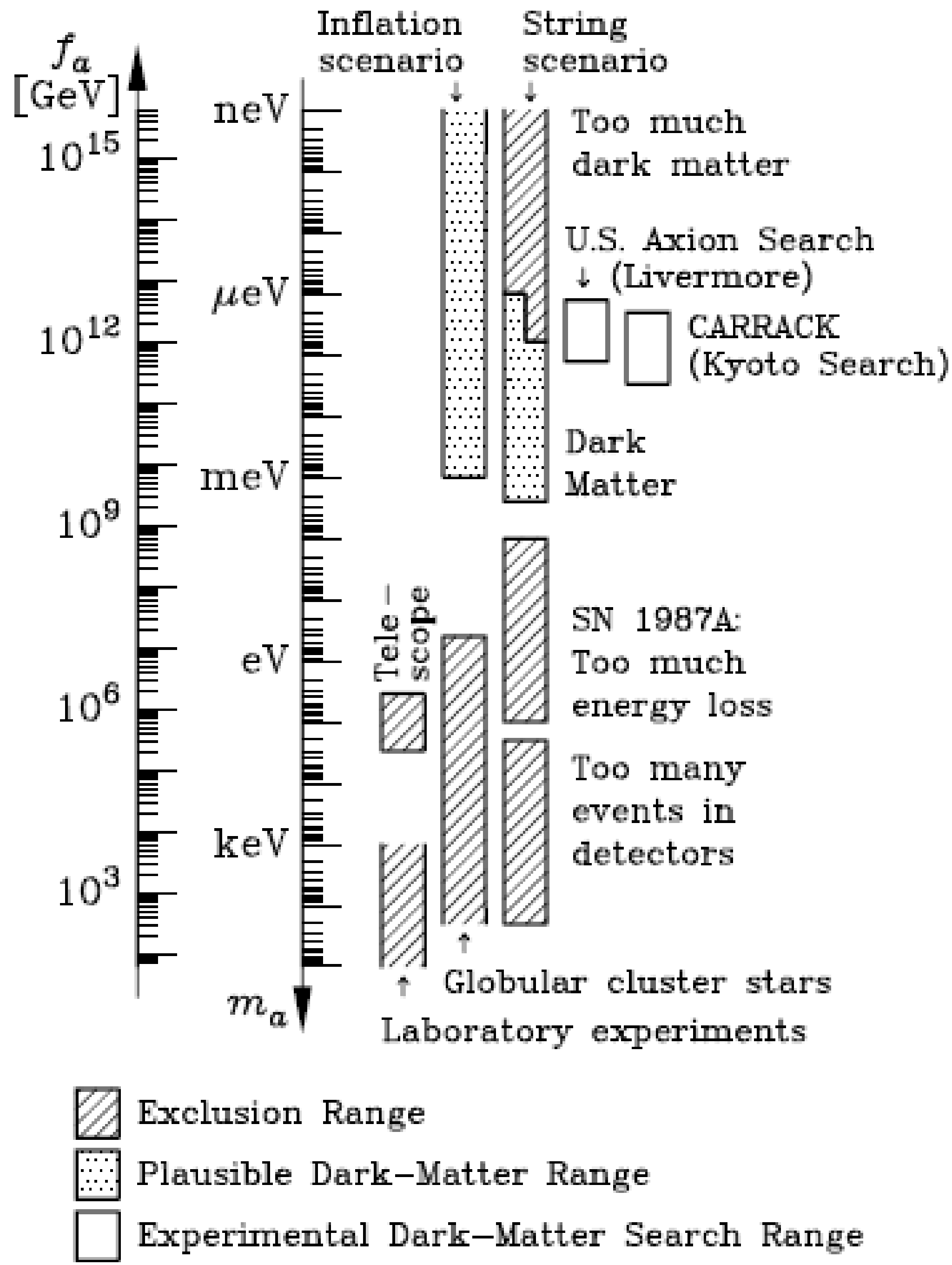
Axions as Dark Matter

$$S = \int d^4x \left[-\frac{1}{4g^2} G^{a,\mu\nu} G^a_{\mu\nu} - \frac{\theta}{32\pi^2} G^{a,\mu\nu} \tilde{G}^a_{\mu\nu} + \imath \bar{\psi} D_\mu \gamma^\mu \psi + \bar{\psi} \mathrm{M} \psi \right]$$

Promote θ to field a

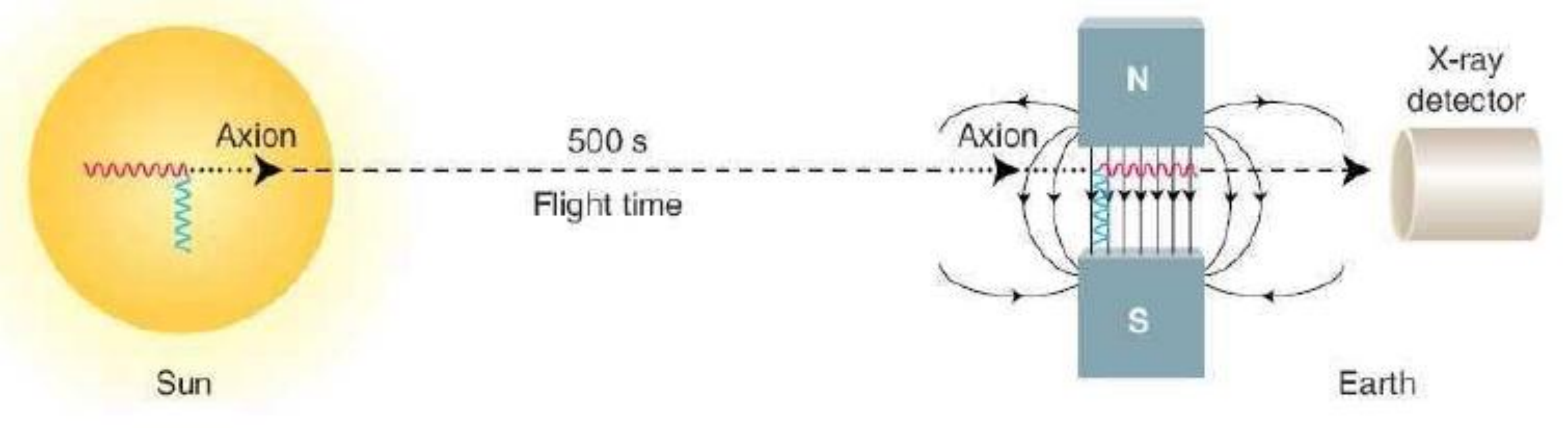
$$m_a^2 \sim \frac{f_\pi^2 m_\pi^2}{f_a^2}$$

Also induced coupling to photons



See e.g. Sikivie hep-ph/9709477 Raffelt hep-ph/9903472

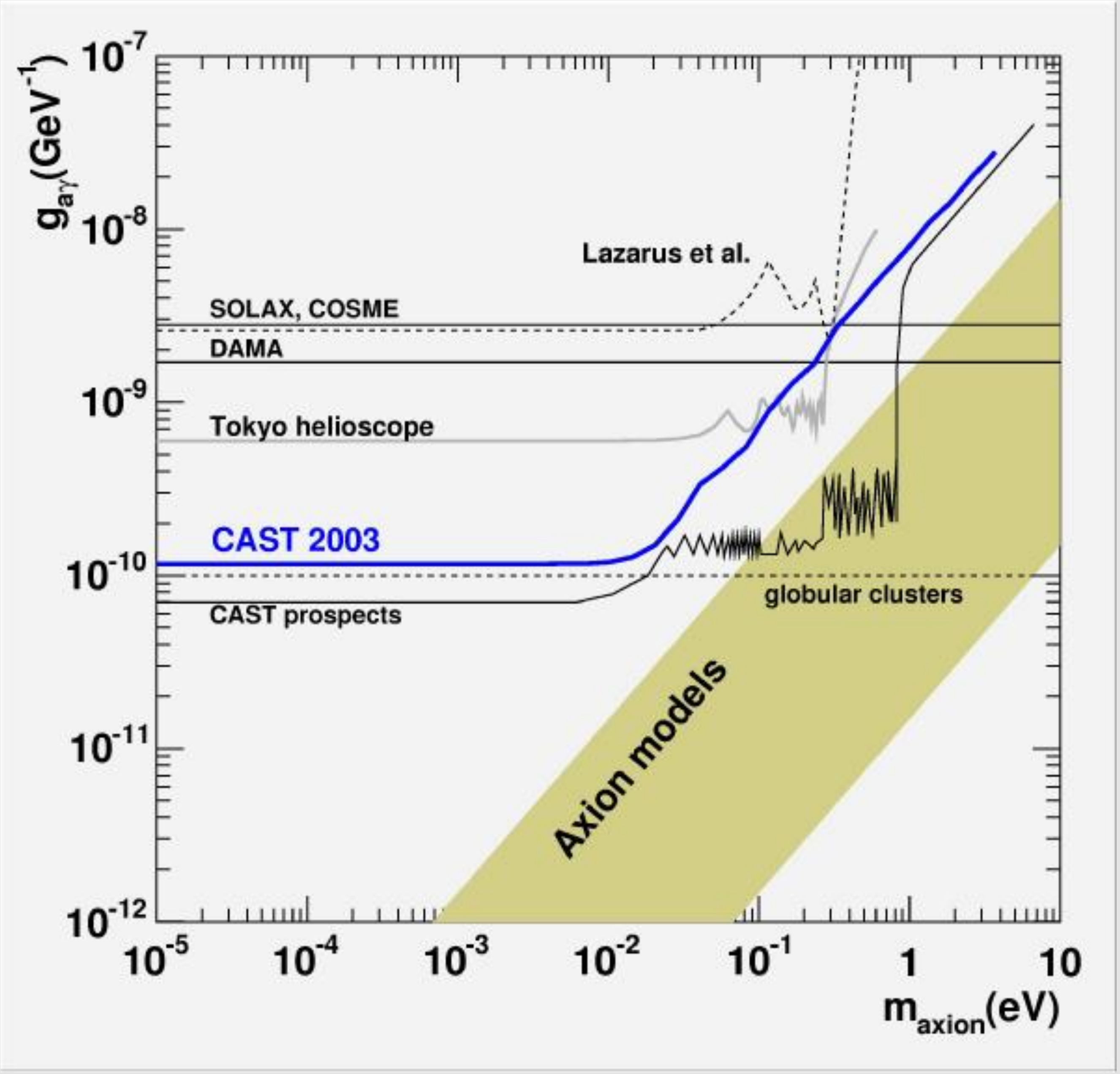
Search for Solar axions



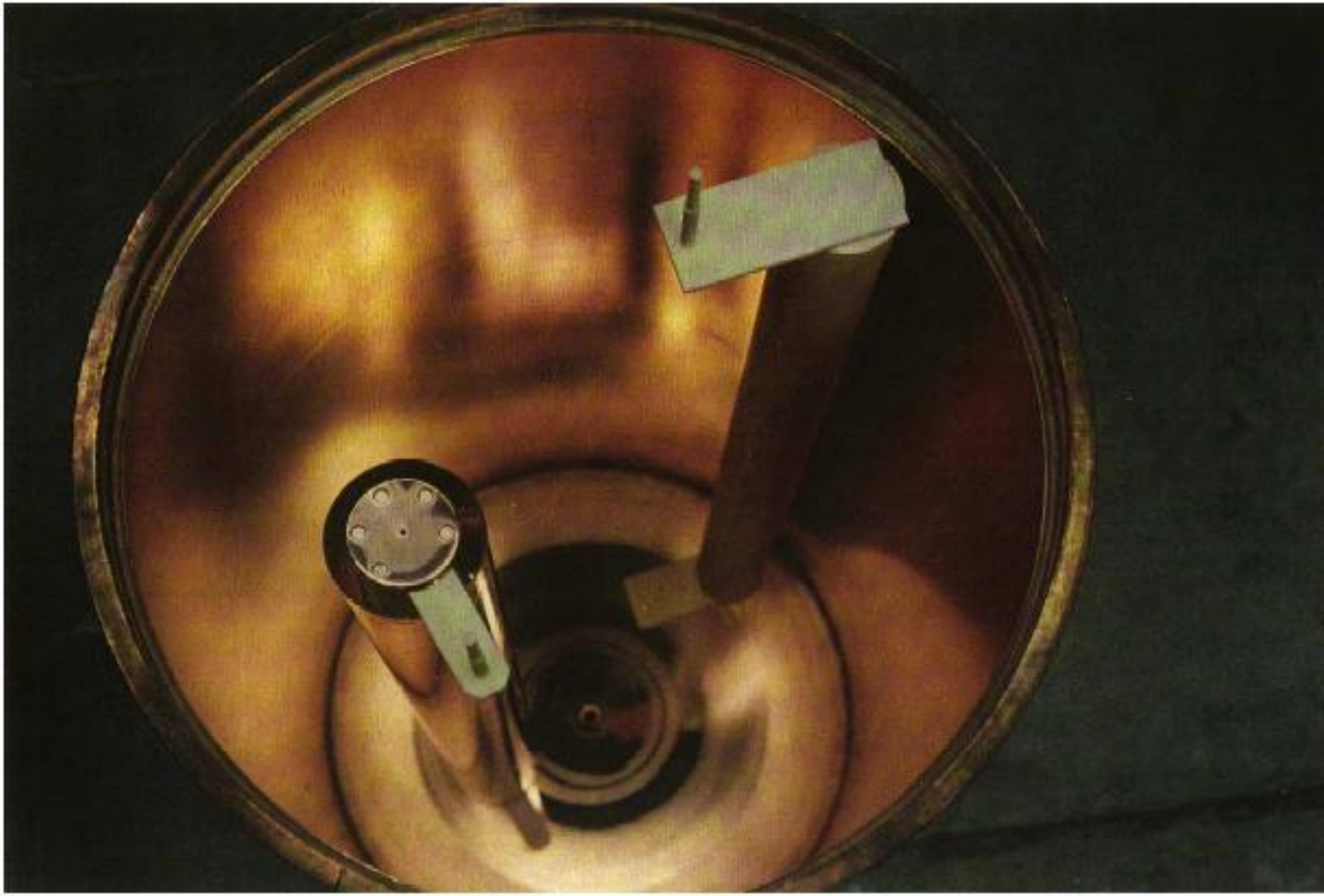
look for axions produced in the sun and turn them back into photons down here

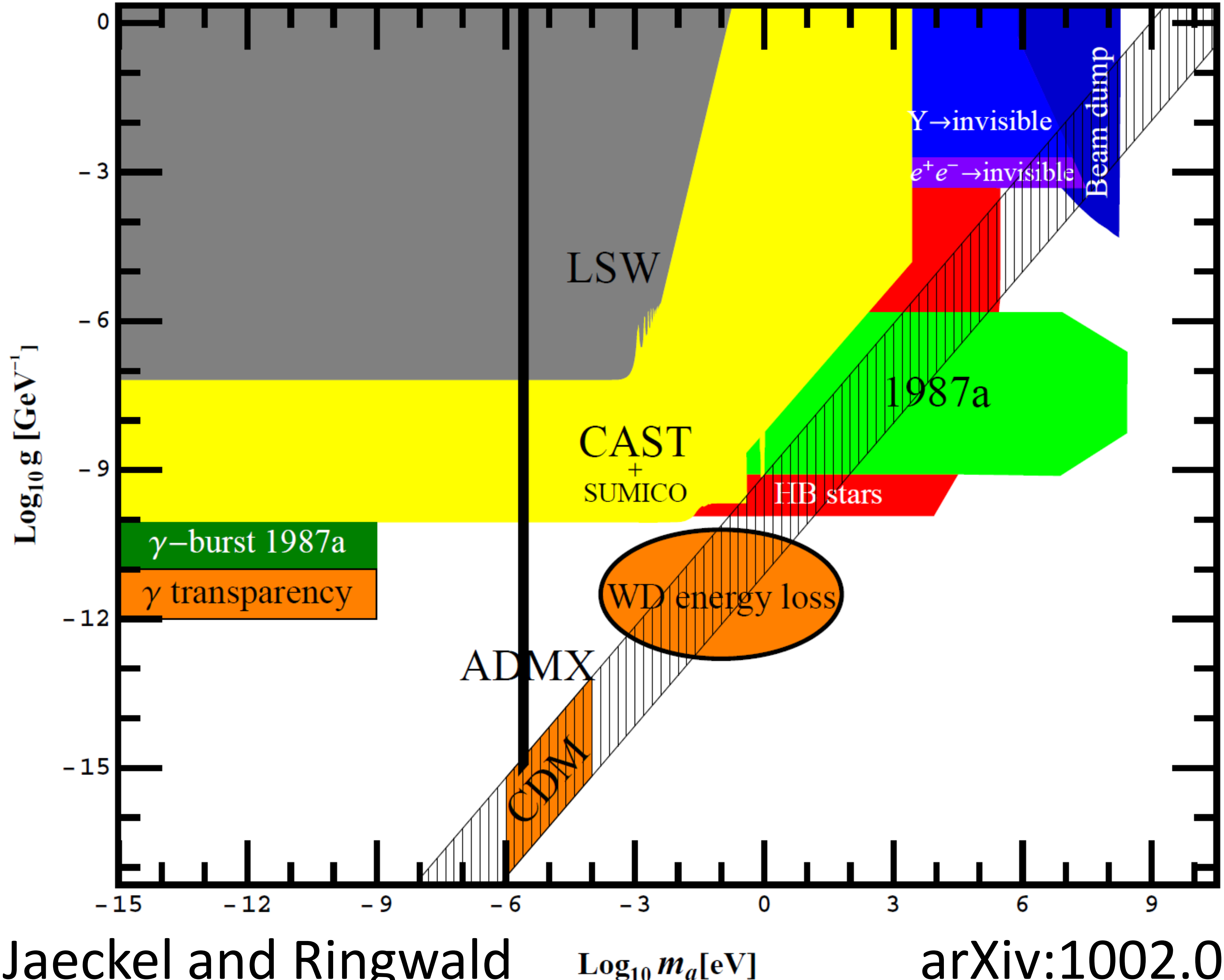
CAST: cern-axion-solar-telescope

CAST exclusion plot



ADMX – Axion Dark Matter Experiment PRD 69-11101(2004)





Jaeckel and Ringwald arXiv:1002.0329

Gravitinos

- Supersymmetric partner of graviton
- curved space - global SUSY is broken down to local SUGRA
- goldstino is particle associated with this breaking
- gravitino eats goldstino via Super Higgs mechanism
- gravitino mass therefore depends on SUSY breaking scale

Gravity mediated SUSY breaking

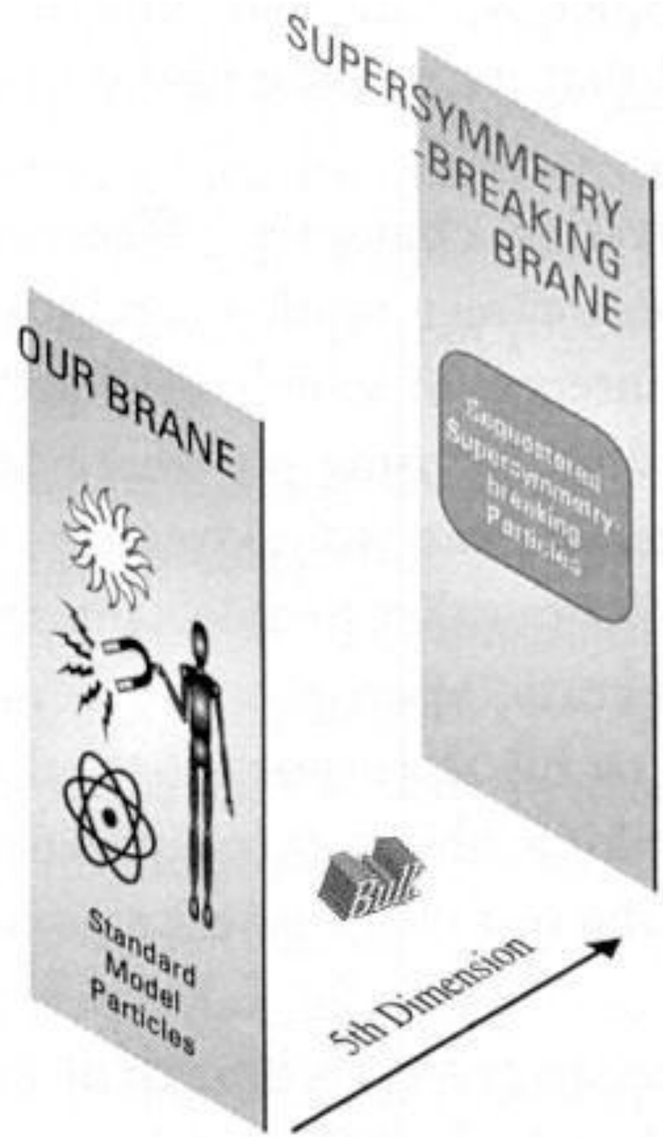
SUSY broken in hidden sector
transmitted to visible sector via gravity

$$M_S \sim \sqrt{F} \sim 10^{11-13}\ \mathrm{GeV}$$

Masses of superpartners
in visible sector

$$m \sim \frac{F}{M_{Pl}} \sim O(\mathrm{TeV})$$

Gravitino mass $m_{\tilde{G}} \sim \frac{M_S^2}{M_{Pl}}$

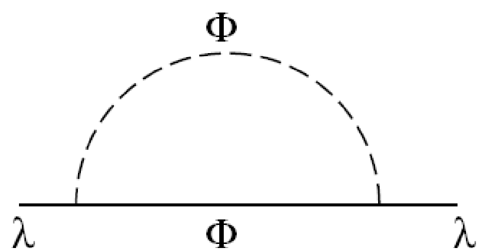


Gauge mediated SUSY breaking

Hidden sector superfield $\langle X \rangle = M_S + \theta^2 F$ ed at tree level to messenger

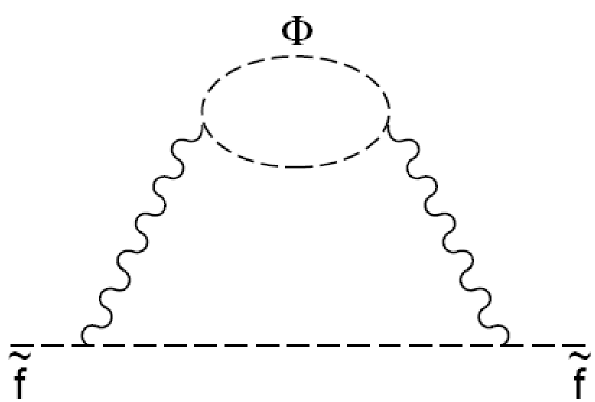
fields $W = \lambda_{ij} \bar{\Phi}_i X \Phi_j$ hich in turn give rise to :-

gaugino mass at 1-loop



$$m_{\tilde{\lambda}} \sim \frac{g^2}{(4\pi)^2} \frac{F}{M_S}$$

sfermion mass at 2-loop



$$m^2_{\tilde{f}} \sim \frac{g^4}{(4\pi)^4} \frac{F^2}{M_S^2}$$

$F \sim 10^{10-14}\text{GeV}^2$ $\quad M_S \sim 10^{5-9}\text{GeV}$ $\longrightarrow$ $m_{\tilde{G}} \ll \text{TeV}$

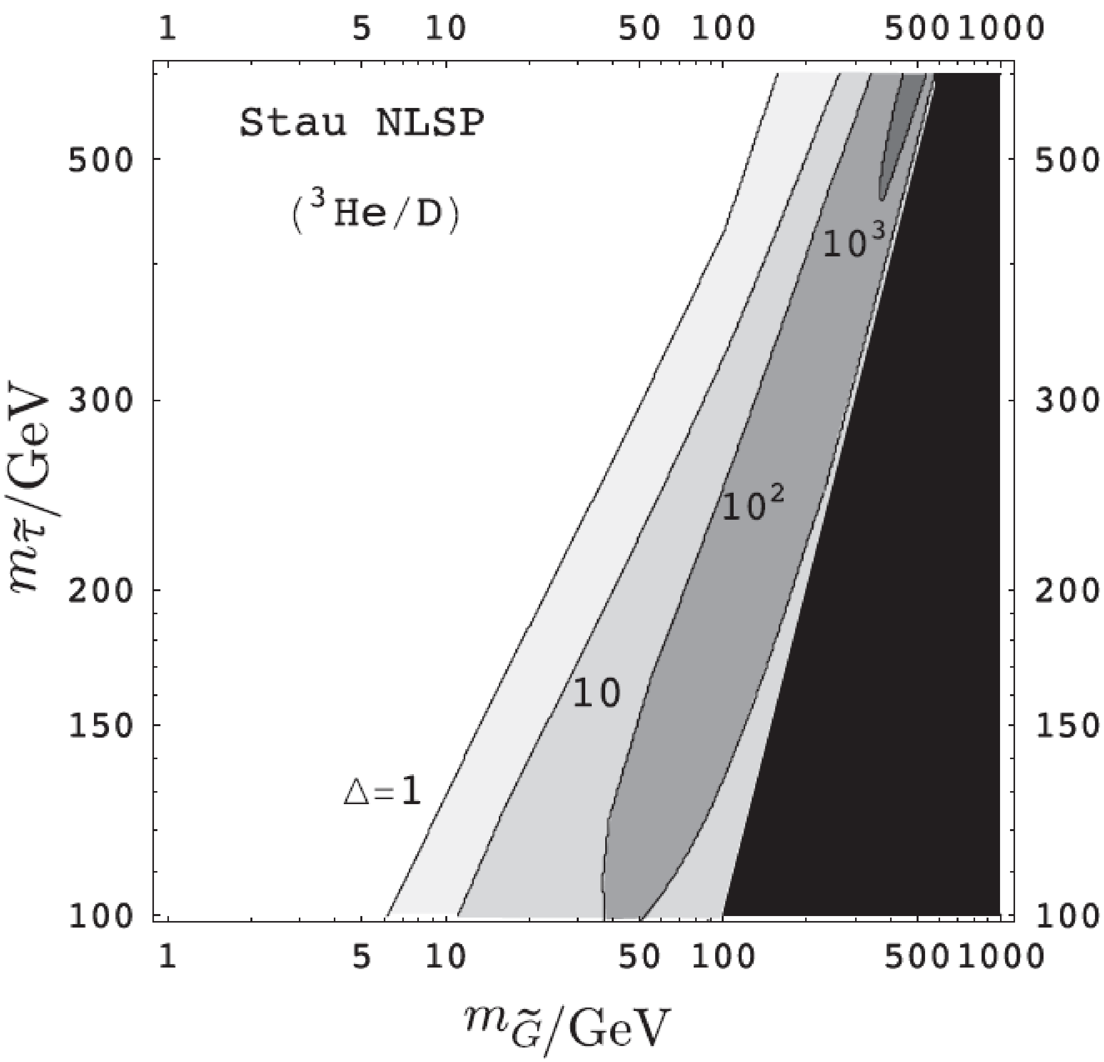
Gravitino LSP and stau NLSP is one typical scenario

Stau decay

$$\Gamma_{\tilde{\tau}}(\tilde{\tau} \to \tilde{G}\tau) = \frac{m_{\tilde{\tau}}^5}{48\pi m_{\tilde{G}}^2 M_P^2}\left(1 - \frac{m_{\tilde{G}}^2 + m_\tau^2}{m_{\tilde{\tau}}^2}\right)^4 \left[1 - \frac{4m_{\tilde{G}}^2 m_\tau^2}{(m_{\tilde{\tau}}^2 - m_{\tilde{G}}^2 - m_\tau^2)^2}\right]^{3/2}$$

Buchmuller et al 2006

$$\simeq (6 \times 10^6 \text{ sec})^{-1} \left(\frac{m_{\tilde{\tau}}}{100 \text{ GeV}}\right)^5 \left(\frac{10 \text{ GeV}}{m_{\tilde{G}}}\right)^2 \left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}}^2}\right)^4$$



Stau decays into gravitino and tau

Photodissociates light elements created during nucleosynthesis

Need to dilute thermal abundance of staus

$$Y_{\tilde{\tau}} = \frac{1}{\Delta} Y_{\tilde{\tau}}^{\text{thermal}}$$

Decays outside detector

Distance travelled before decay of NLSP into gravitino

$$c\tau(\widetilde{X} \to X\widetilde{G}) \simeq 100\ \mu\text{m} \left(\frac{100\text{GeV}}{m_{\tilde{X}}}\right)^5 \left(\frac{\sqrt{F}}{100\text{TeV}}\right)^4 \left(1 - \frac{m_X^2}{m_{\tilde{X}^2}}\right)^{-4}$$

decays here !

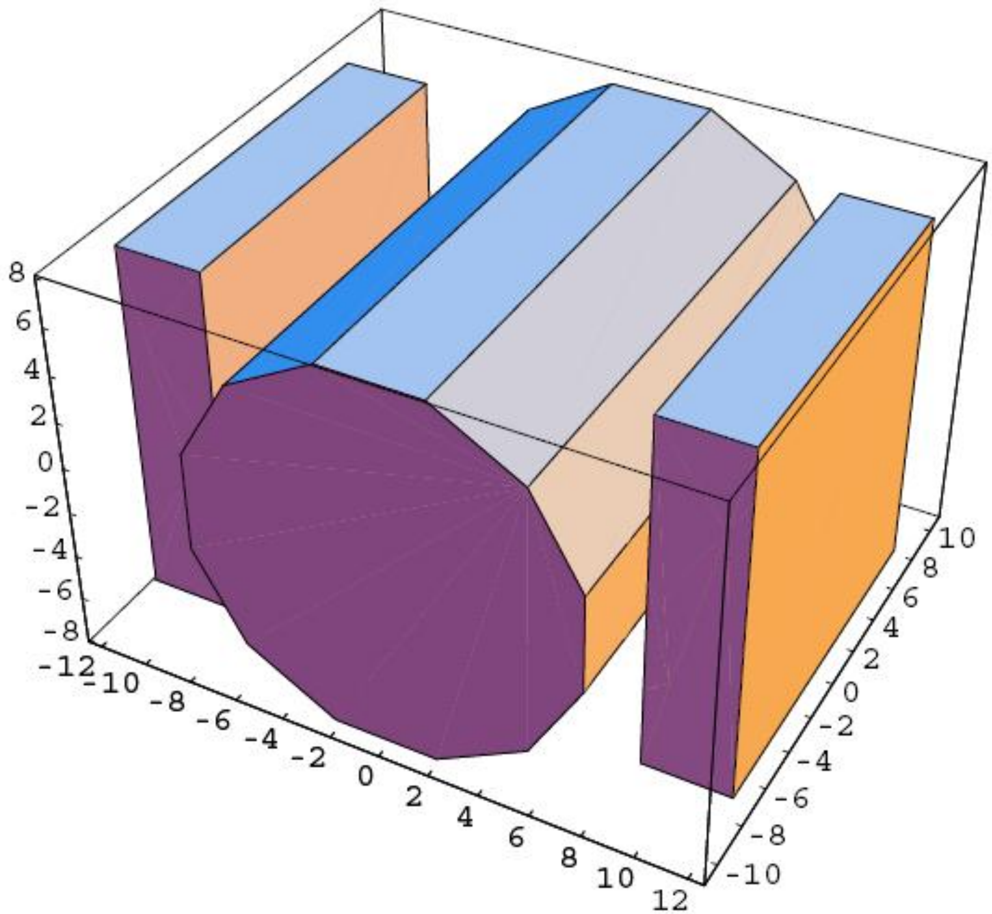
Gauge mediation:-
less than mm to more than km

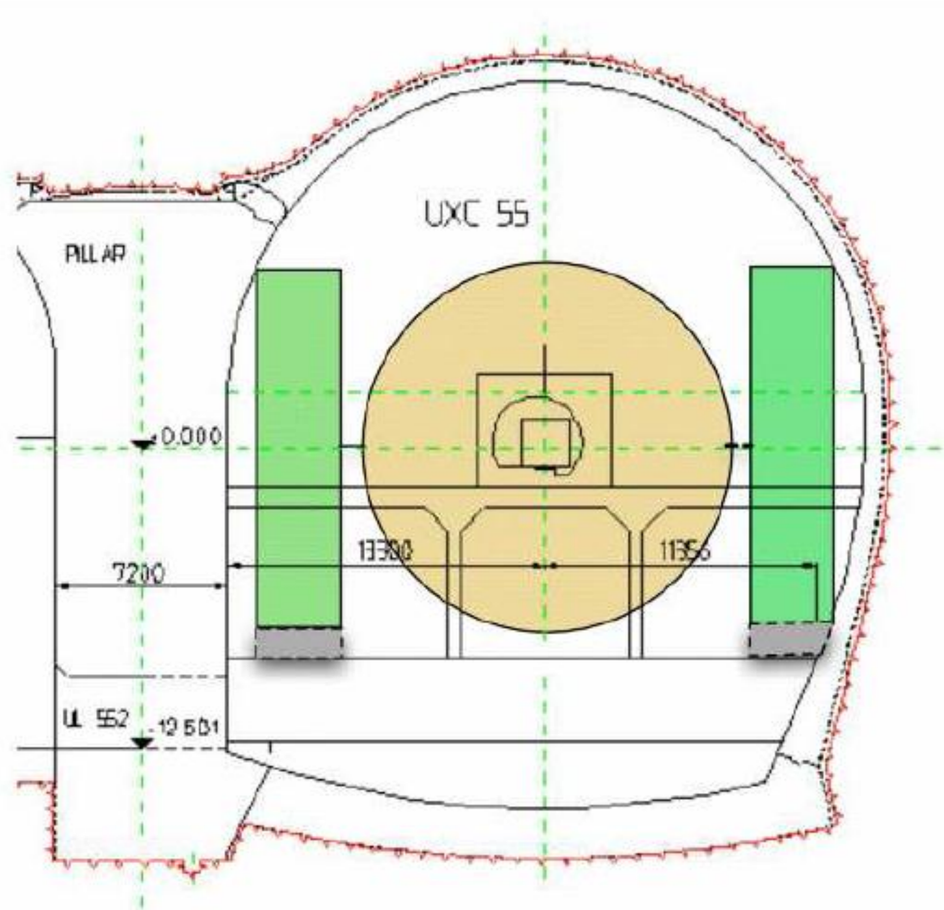
	diameter	weight of the detector	length
ATLAS	22m	7Kt	44m
CMS	15m	12.5Kt	21m

Need to slow down NLSP or may miss decay

Decays outside detector

ATLAS and CMS not really designed for this!!
Could install dense stoppers in CMS to stop charged NLSP
(no room in ATLAS cavern)



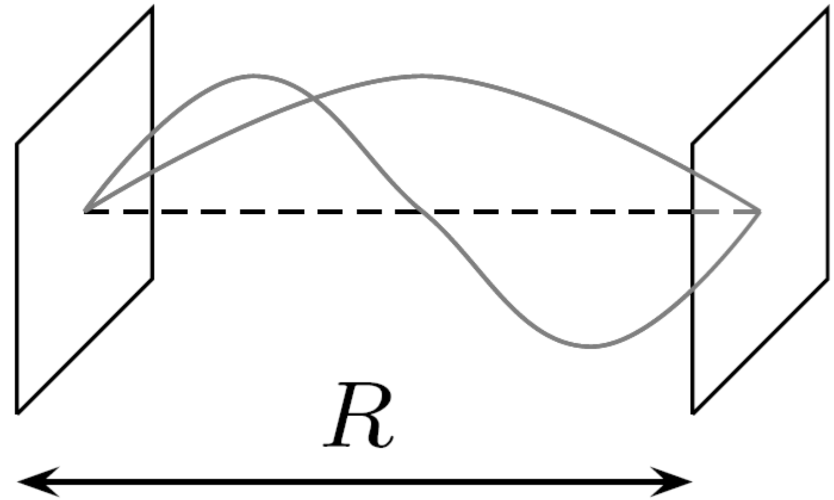


Useful for any charged particle with lifetime
10 nsec < τ < 10 years

Hamaguchi, Nojiri and de Roeck, 2006

Universal extra dimensions

Appelquist et al. 2001



Extra dimensions of size
R ~ 1 / TeV into which
SM gauge fields propagate

Simplest scenario is 1 extra dimension orbifolded S^1/Z_2

Orbifolding leads to spectrum of Kaluza Klein (KK) modes such that the lightest KK mode is stable.

Potential dark matter candidate (Servant and Tait 2002)

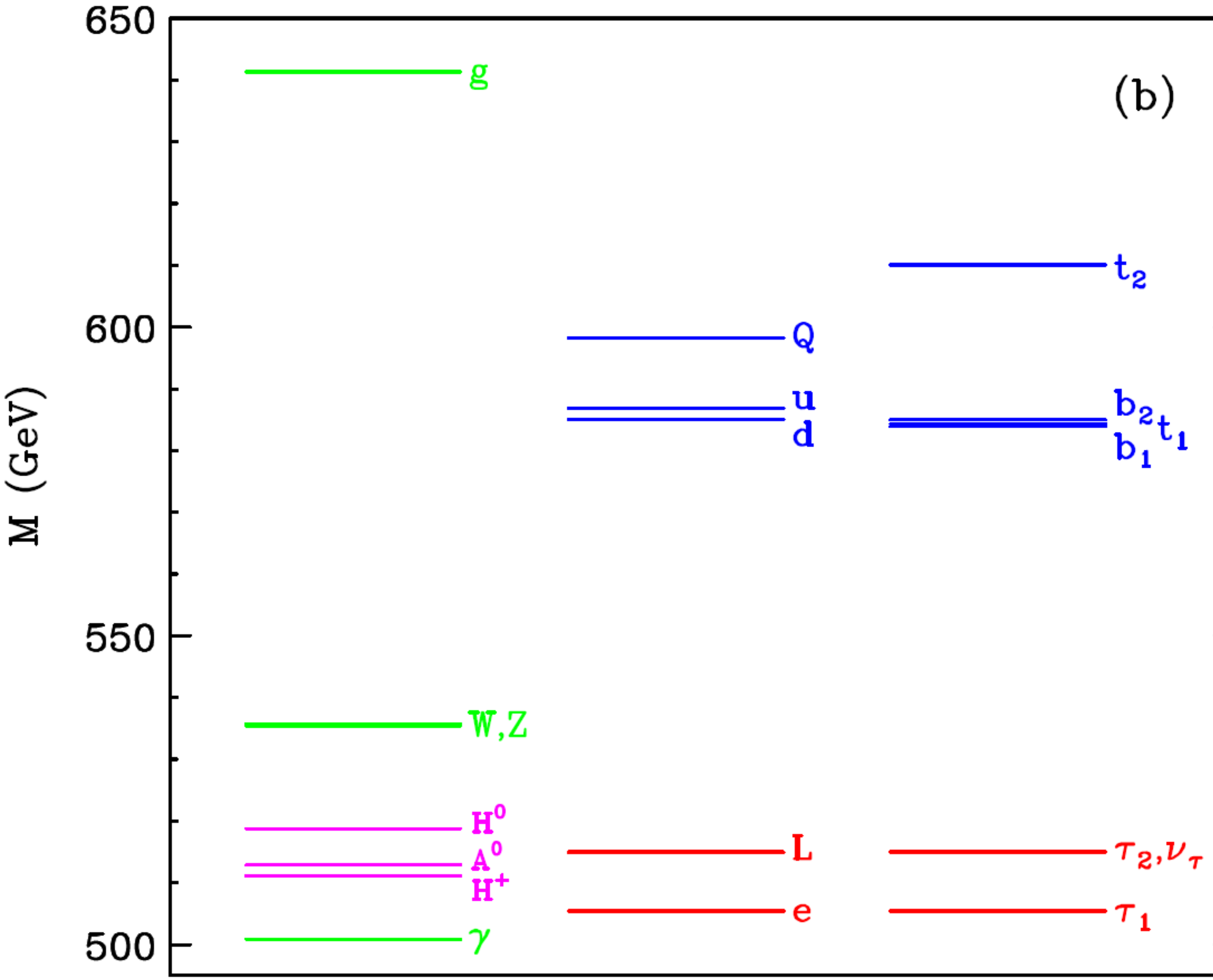
Simplest models fully determined by $R^{-1},\ m_h,\ \Lambda$

Mass spectrum of KK particles

KK mass ~ 1/R + normal mass from higgs sector + radiative corrections, e.g. for higgs:-

$$\delta m_H^2 = \left(\frac{3}{2}g^2 + \frac{3}{4}g'^2 - \frac{m_h^2}{v^2}\right)\frac{\ln(\Lambda^2 R^2)}{16\pi^2} R^{-2}$$

$$R^{-1} = 500 \text{ GeV},$$
$$\Lambda R = 20,$$
$$m_h = 120 \text{ GeV}$$



Cheng et al. 2006

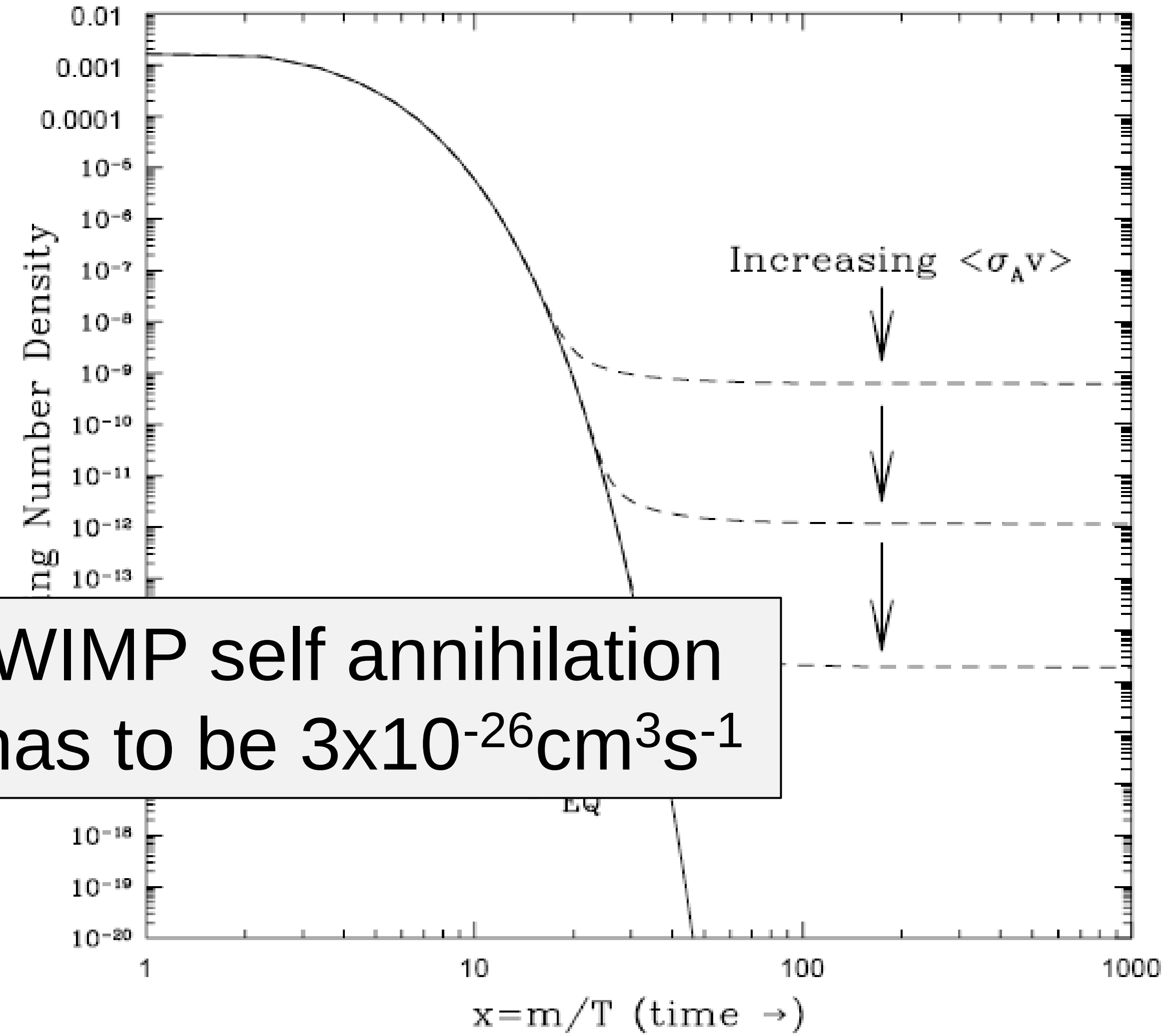
Wimps Work !

(at least for the dark matter bit)

$$\sigma_{\rm weak} \simeq \frac{\alpha^2}{m_{\rm weak}^2}$$

$$\alpha \simeq \mathcal{O}$$

We know that WIMP self annihilation cross section has to be $3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$



$$m_{\rm weak} \simeq \mathcal{O}(100\,{\rm GeV})$$

$$\Omega_\chi \sim 1$$

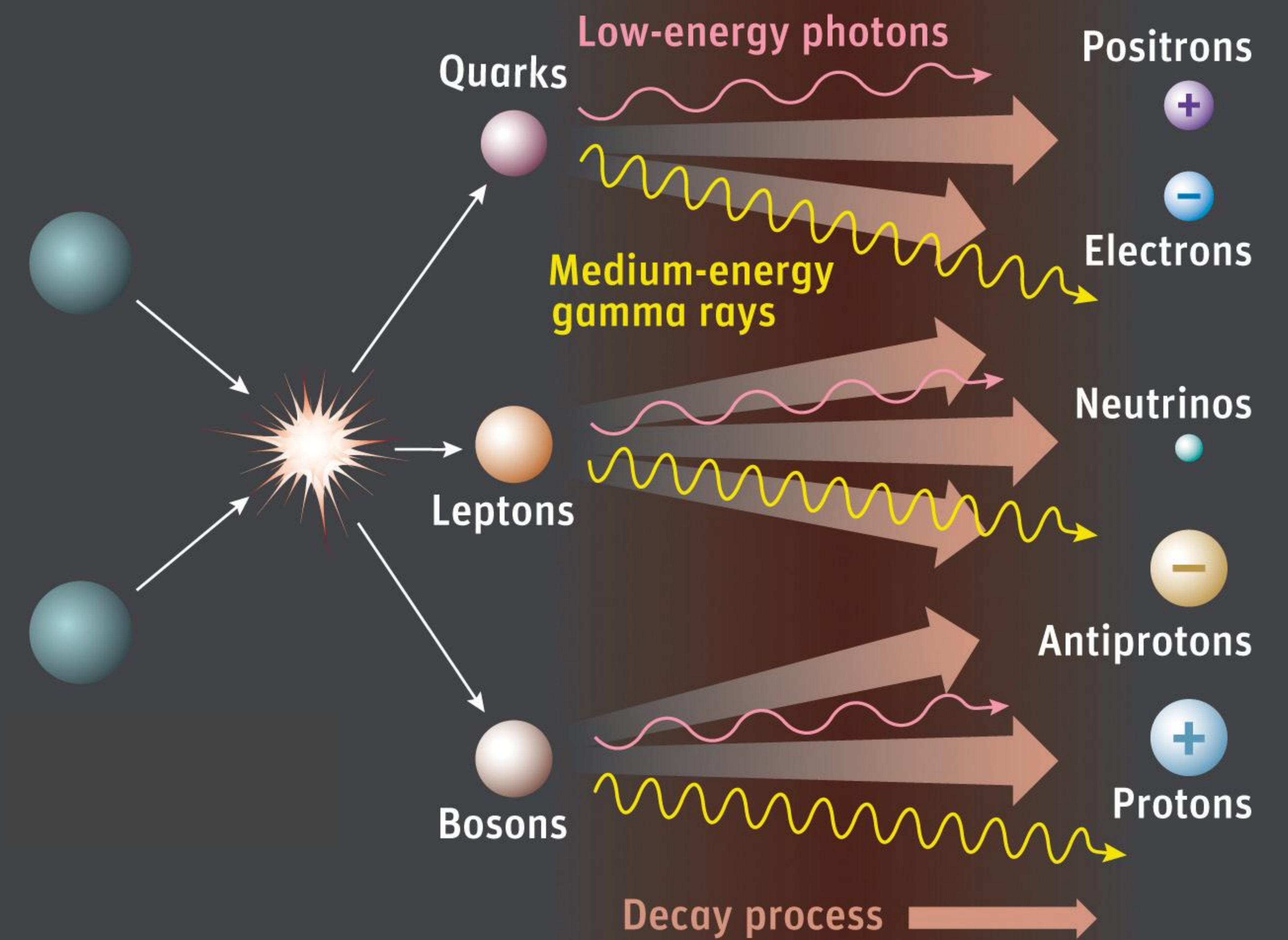
$$\frac{dn}{dt} = \langle \sigma v \rangle \left(\frac{\rho}{m_\chi} \right)^2$$

Right amount of dark matter if dark matter mass 100 MeV < M < 100 TeV

WIMPs may be produced at the Large Hadron Collider

Dark Matter indirect detection

Dark Matter Self-Annihilation



Rate of self-annihilation of Dark Matter

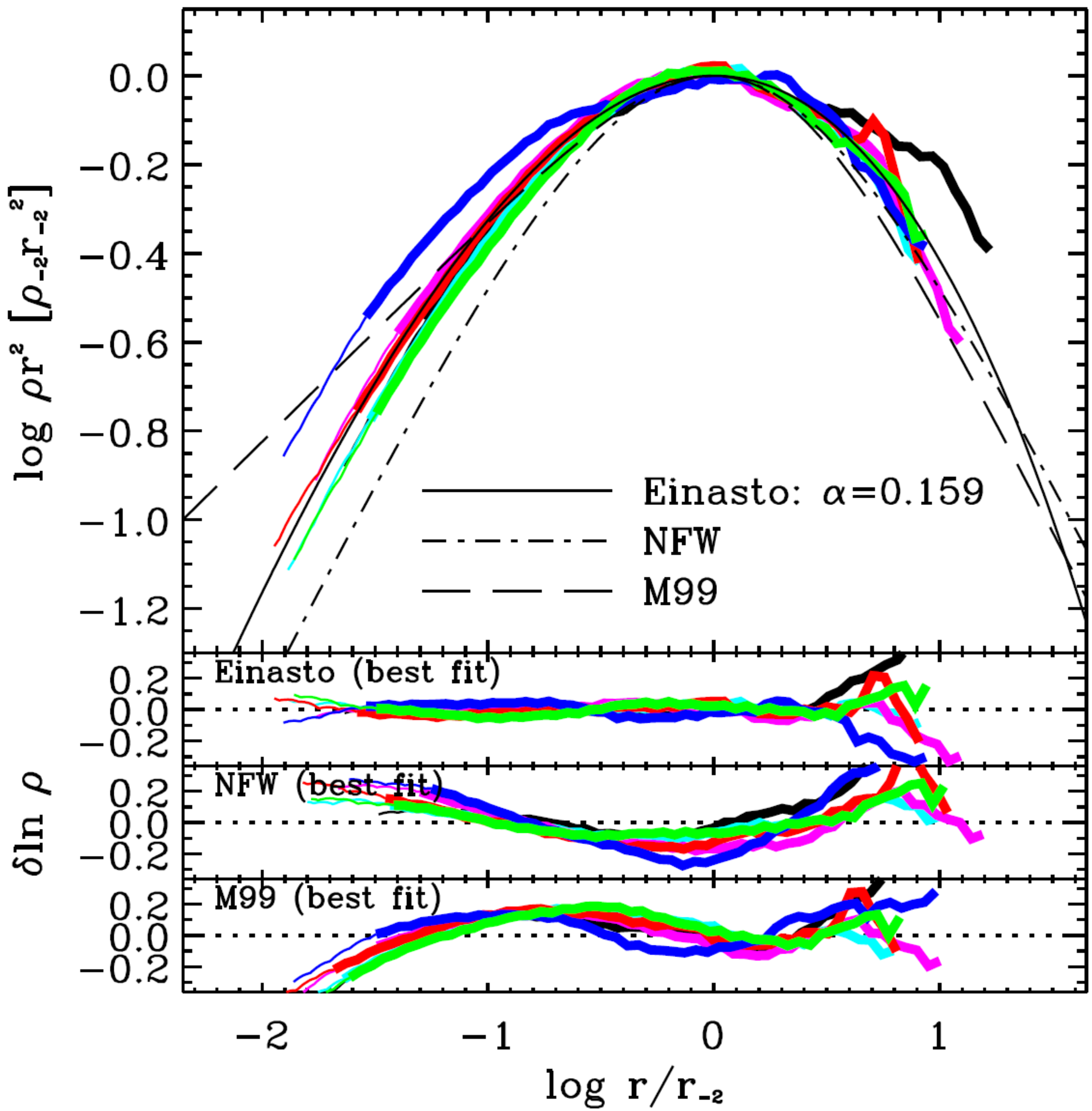
But how well do we know this at the Galactic Centre?

$$\frac{dn}{dt} = \langle \sigma v \rangle \left(\frac{\rho}{m_\chi} \right)^2$$

We think we might know this

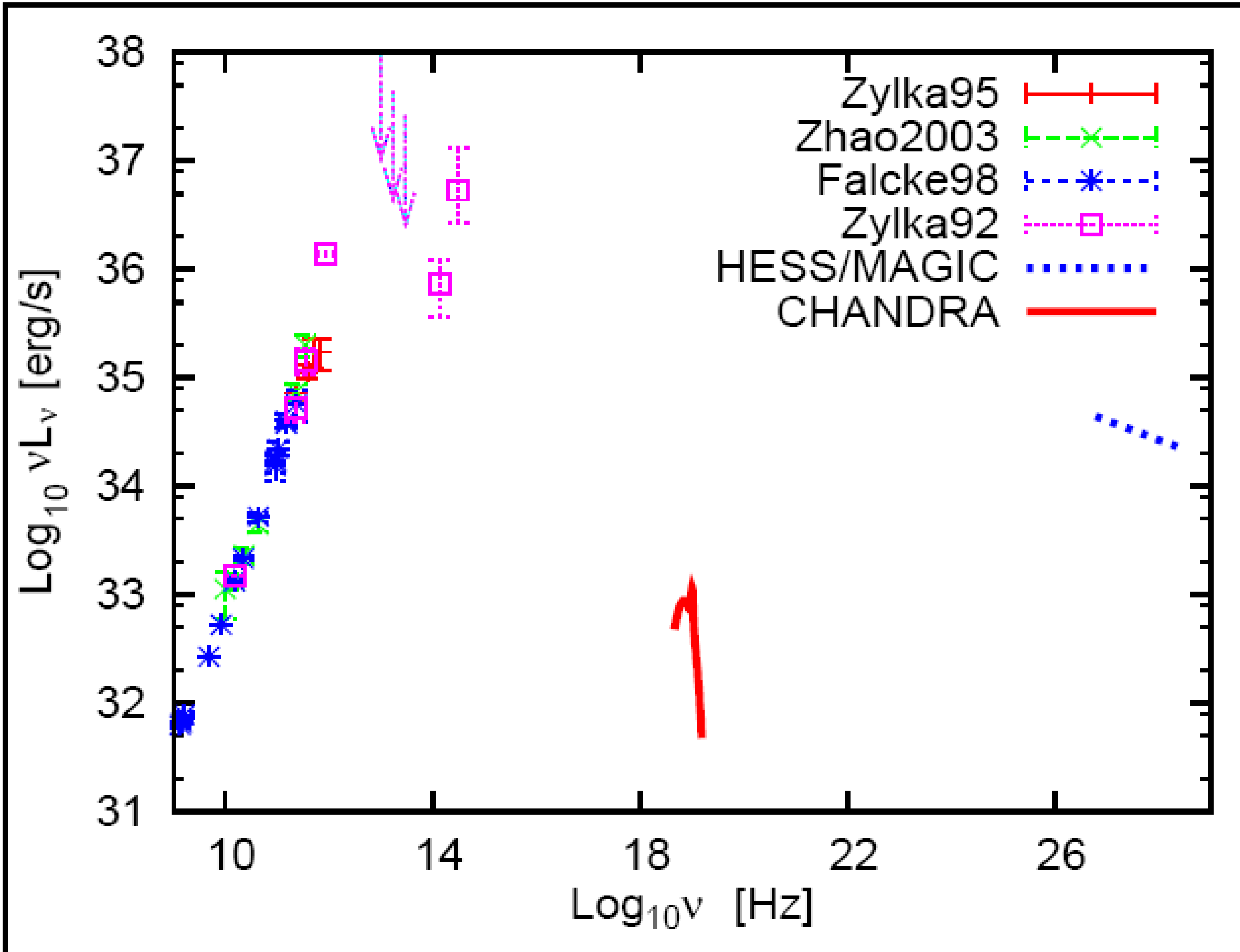
And we have some ideas about this

Simulations show halos denser in middle.

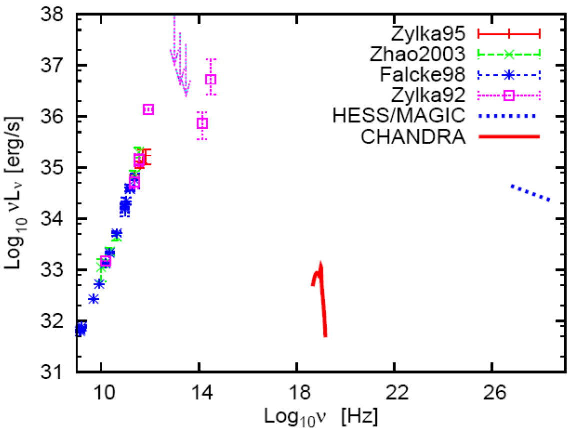


$$\rho(r) = \rho_{-2} e^{-\frac{2}{\alpha}\left[\left(\frac{r}{r_{-2}}\right)^{\alpha} - 1\right]}$$

Flux centred on Sagittarius A*



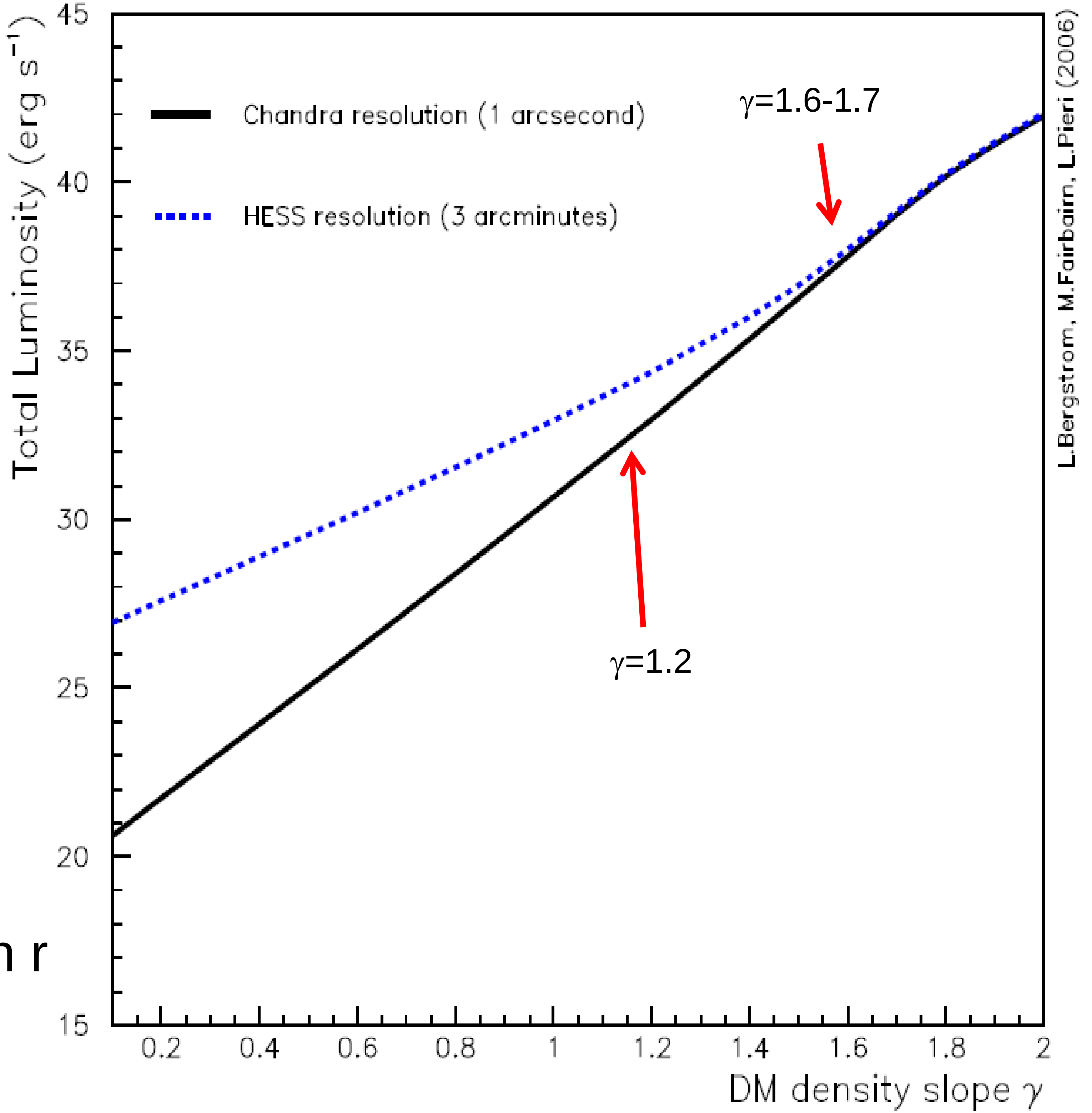
The Galactic Centre Coincidence



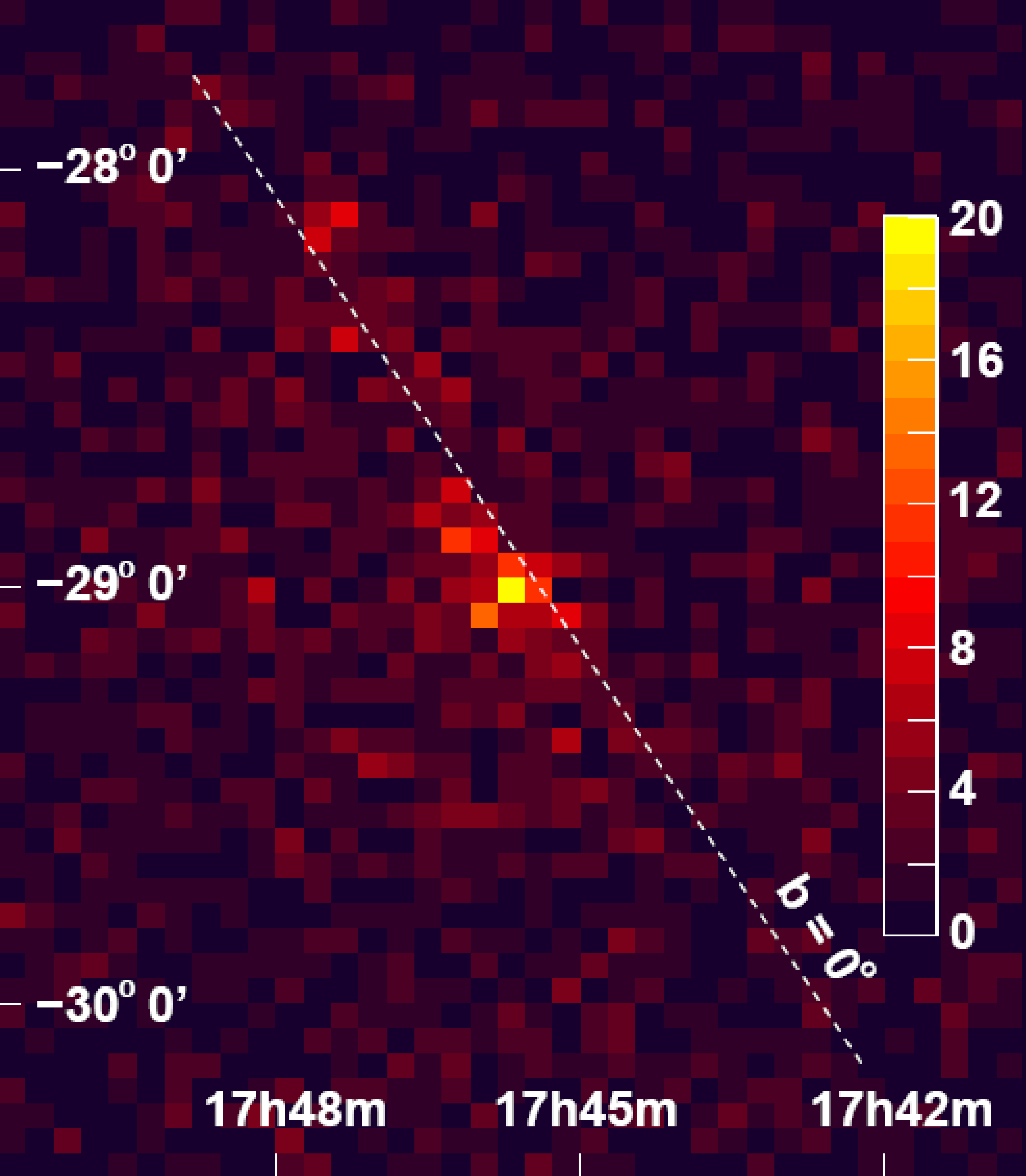
Comparison of actual flux with DM ann. flux

Same Vertical scale

$$\gamma = -\, d \ln \rho \,/\, d \ln r$$



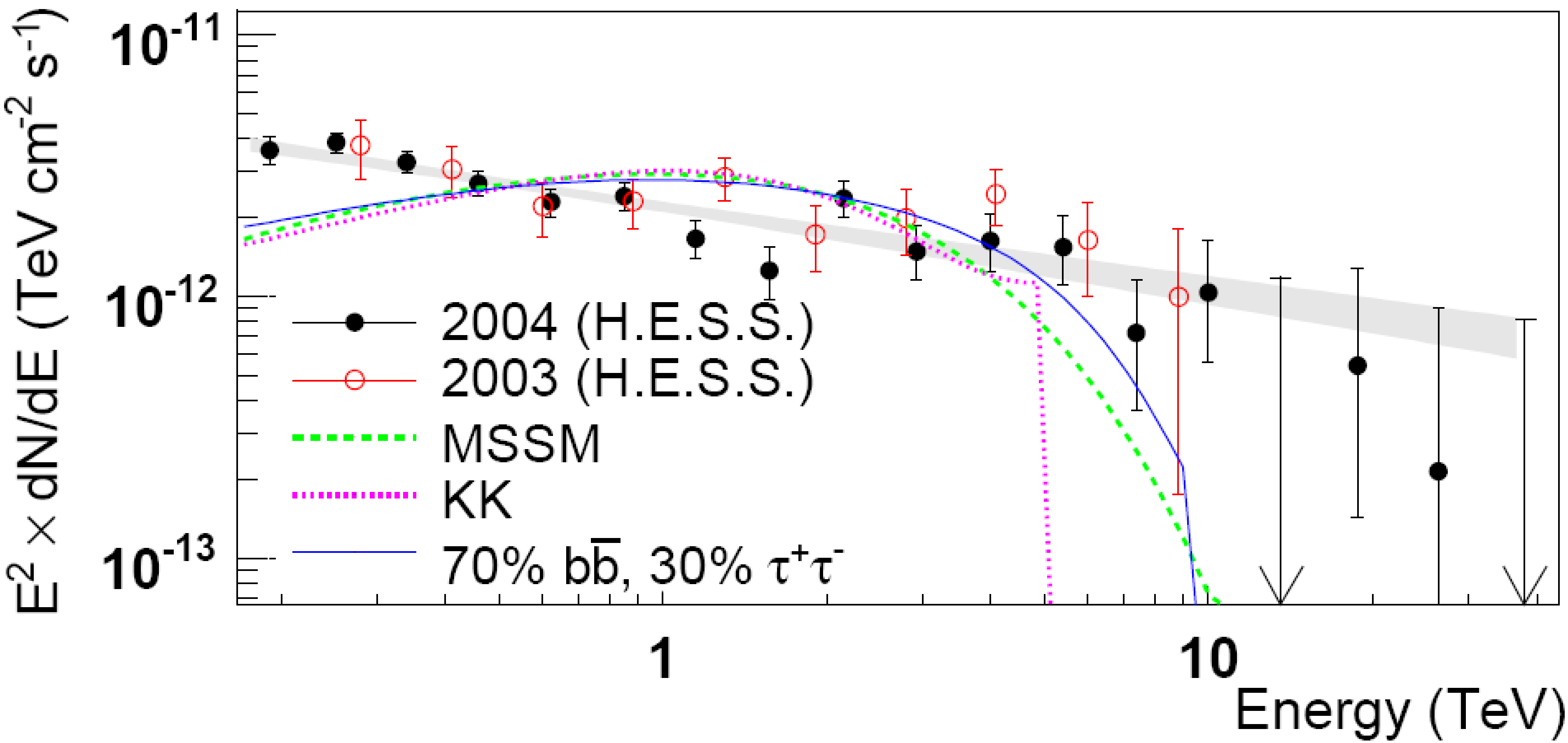

HESS - Namibia



HESS view of galactic centre

E > 165 GeV

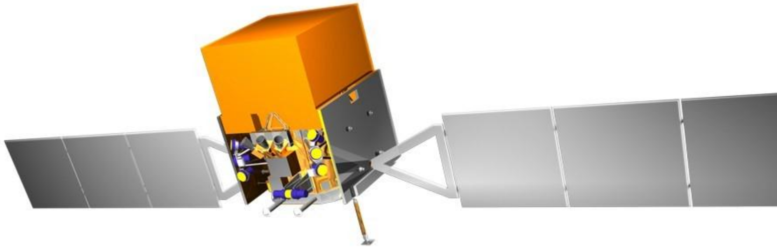
HESS spectrum of Galactic Centre



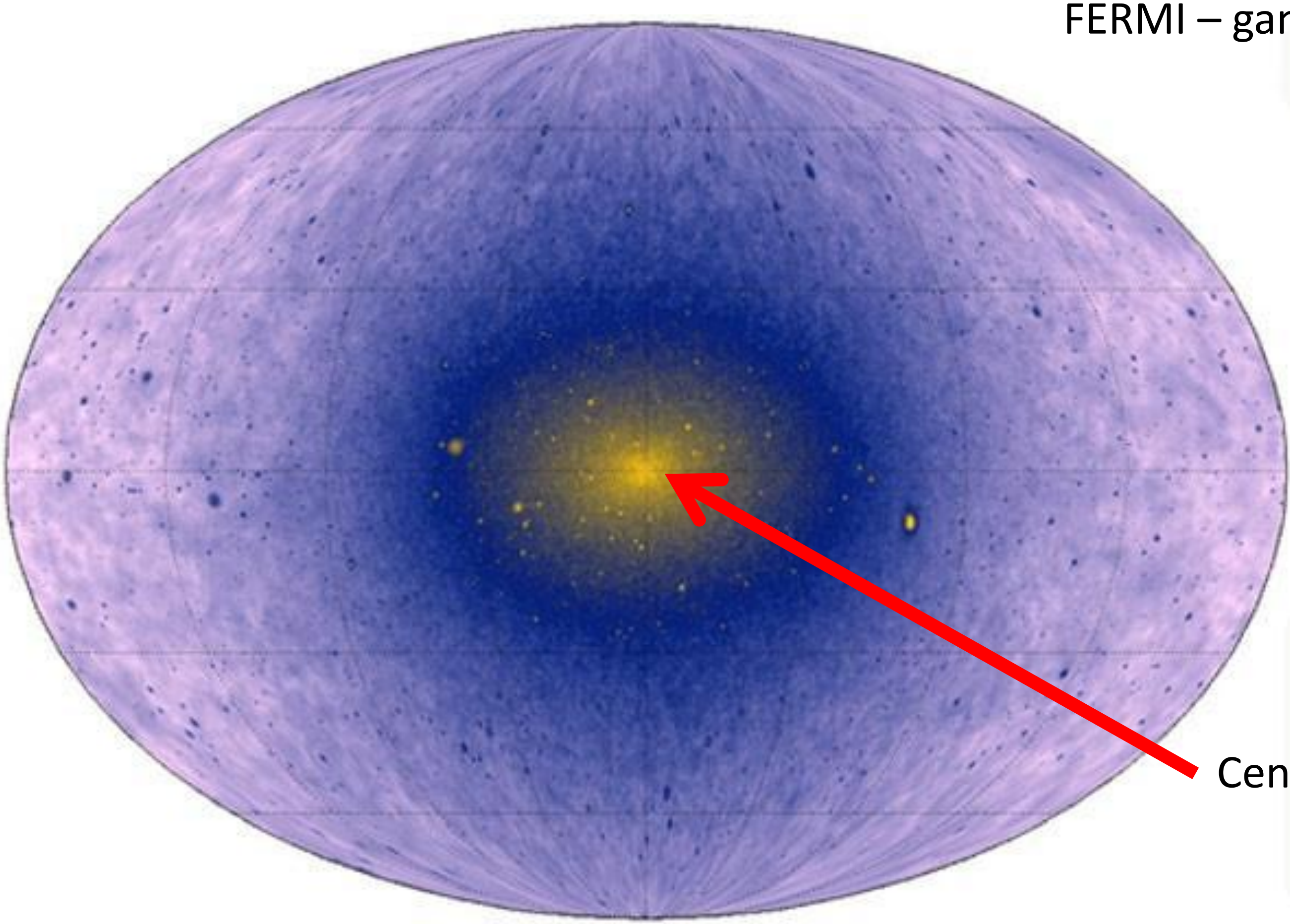
Aharnonian et al. astro-ph/0610509

Fermi Gamma Ray Telescope

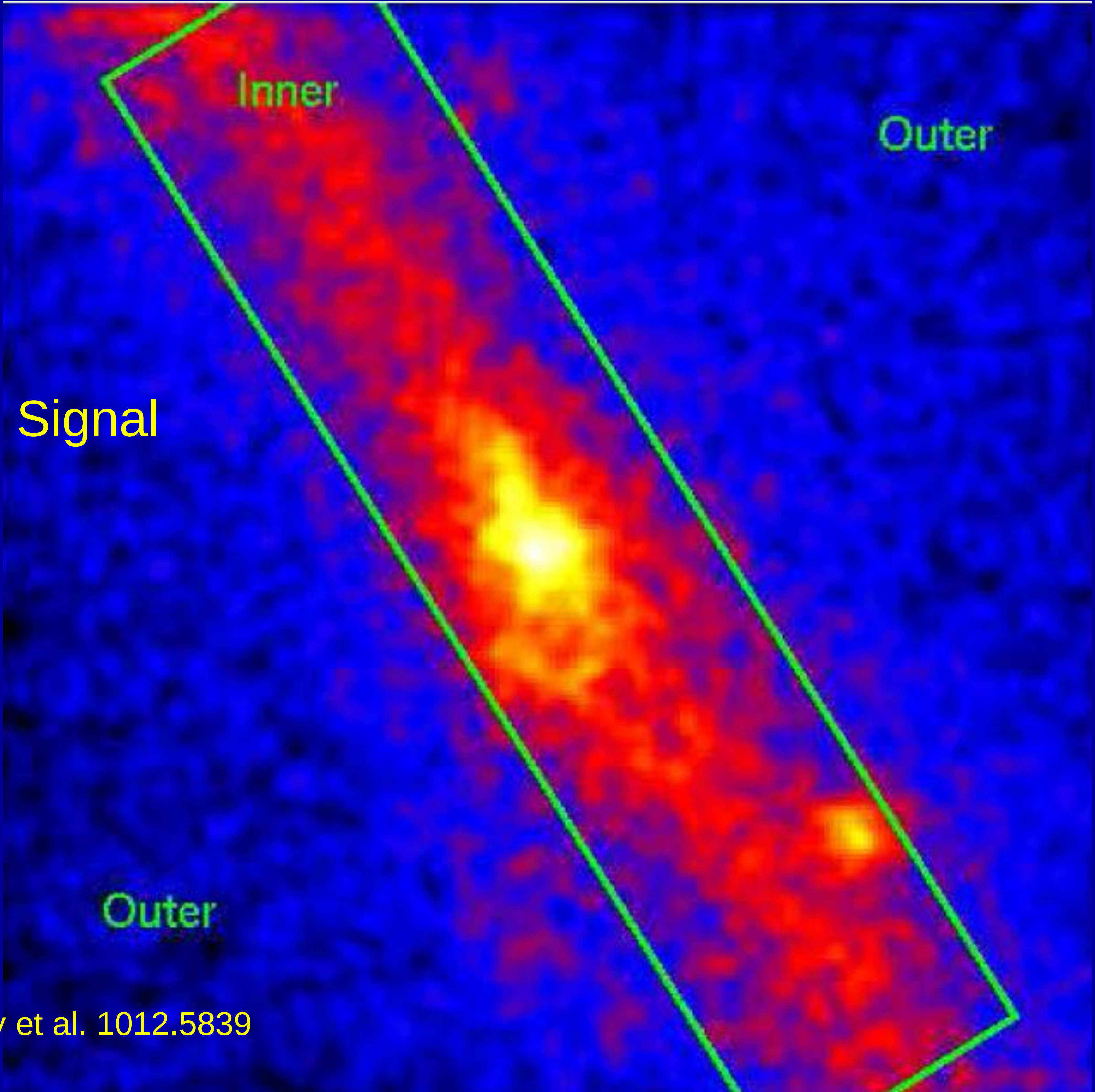
Can try to detect annihilation of dark matter with itself at Galactic Centre



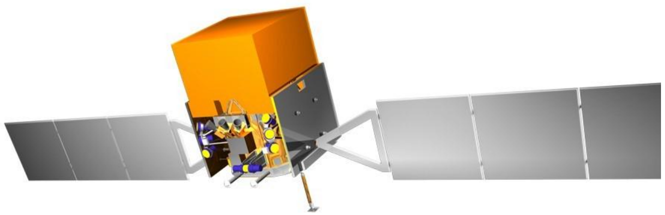
FERMI – gamma ray telescope



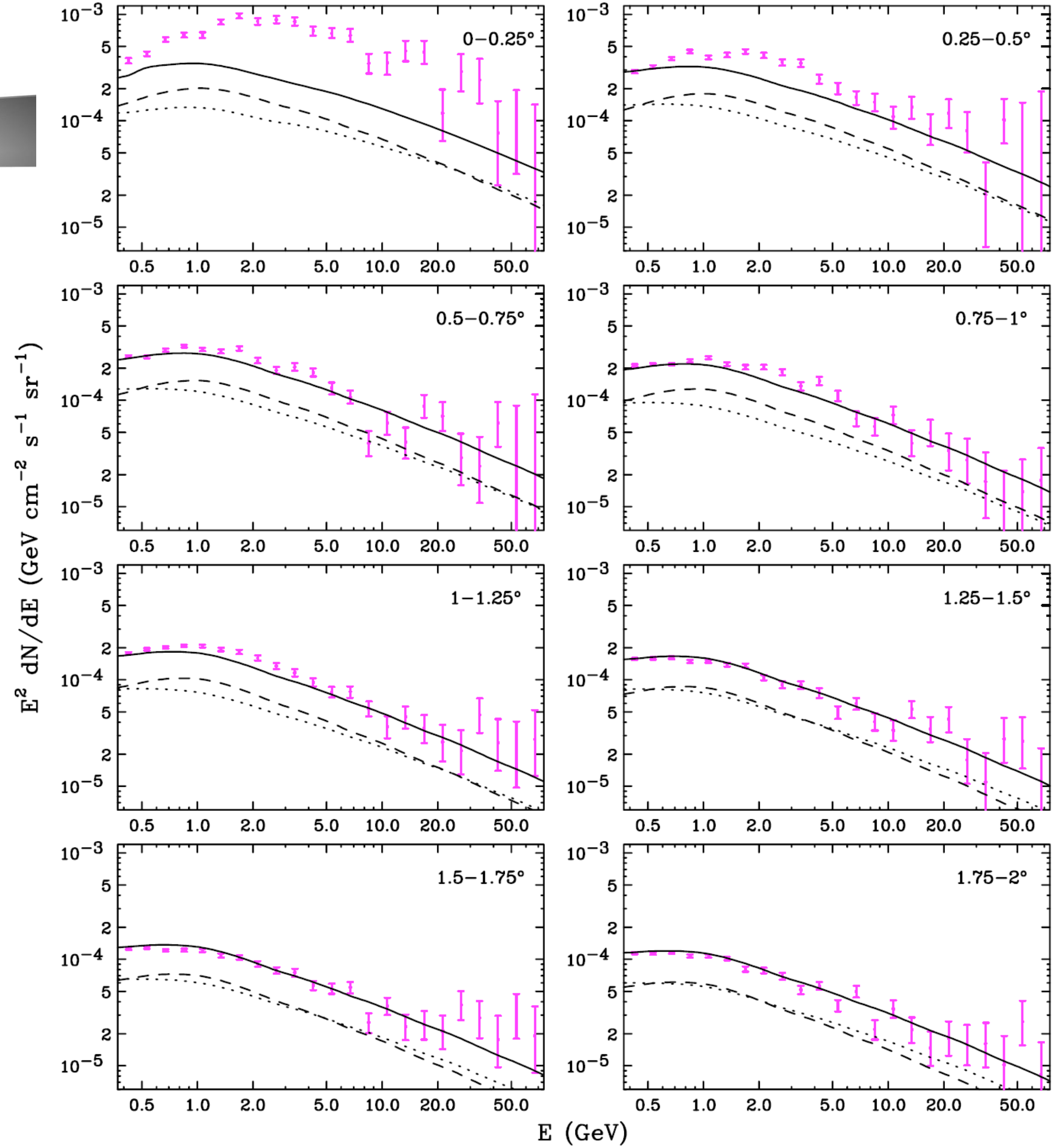
Fermi Signal



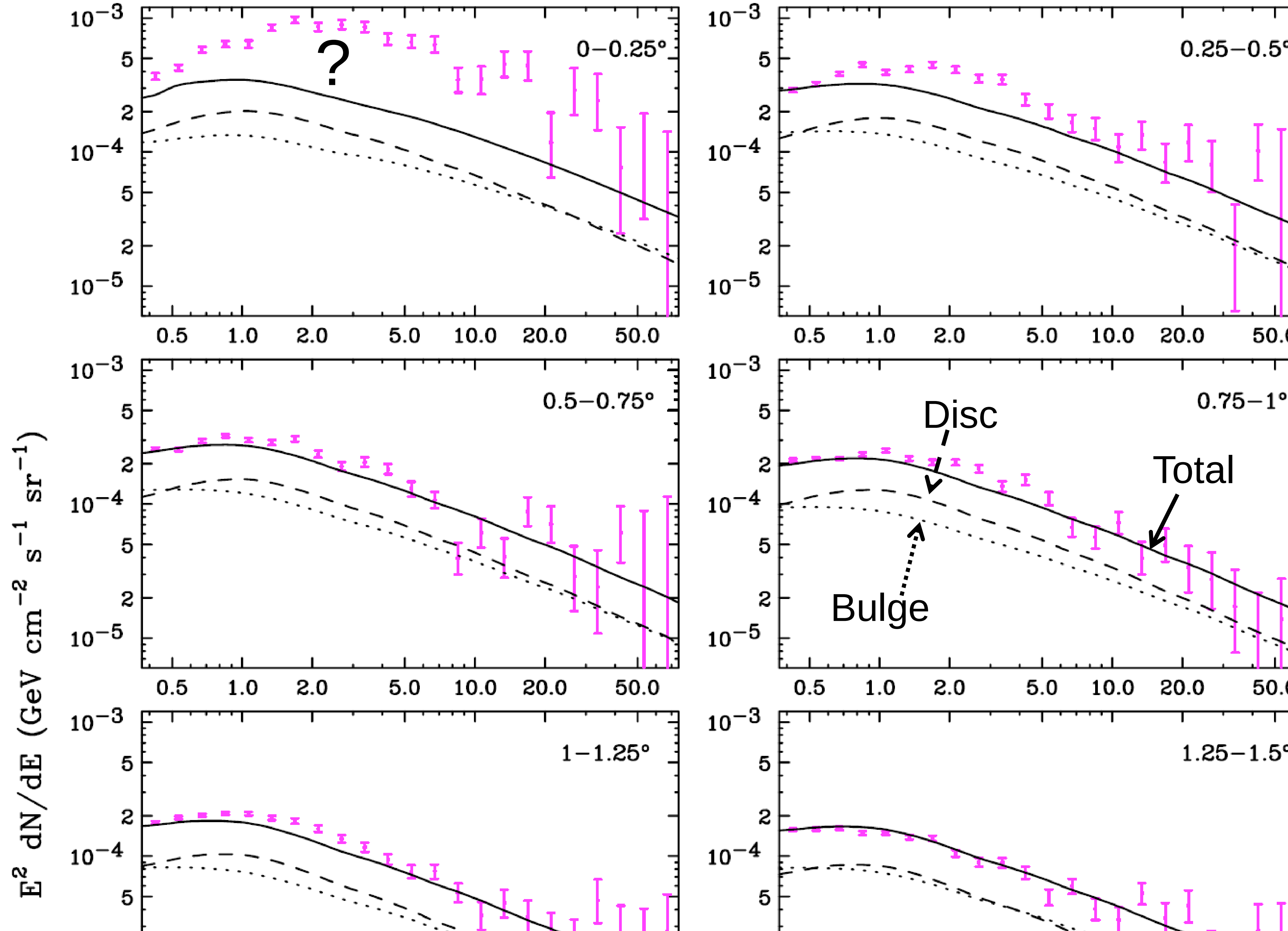
Boyarsky et al. 1012.5839



Has Fermi detected dark matter annihilation at the galactic centre?

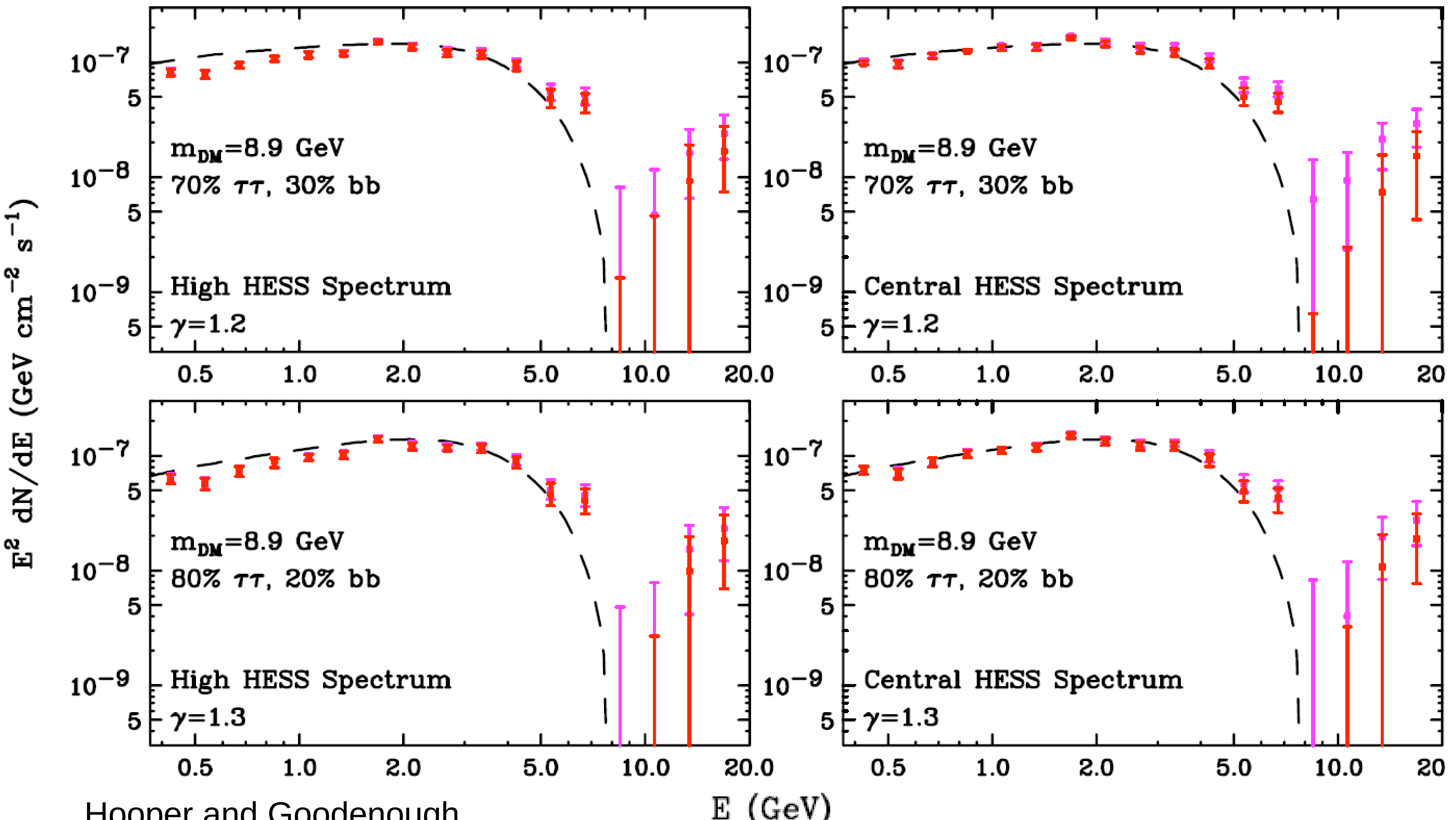


Hooper and Goodenough. arXiv:1010.2752



E² dN/dE (GeV cm⁻² s⁻¹ sr⁻¹)
0–0.25°
?
0.25–0.5°
0.5–0.75°
0.75–1°
Disc
Total
Bulge
1–1.25°
1.25–1.5°
0.5
1.0
2.0
5.0
10.0
20.0
50.0

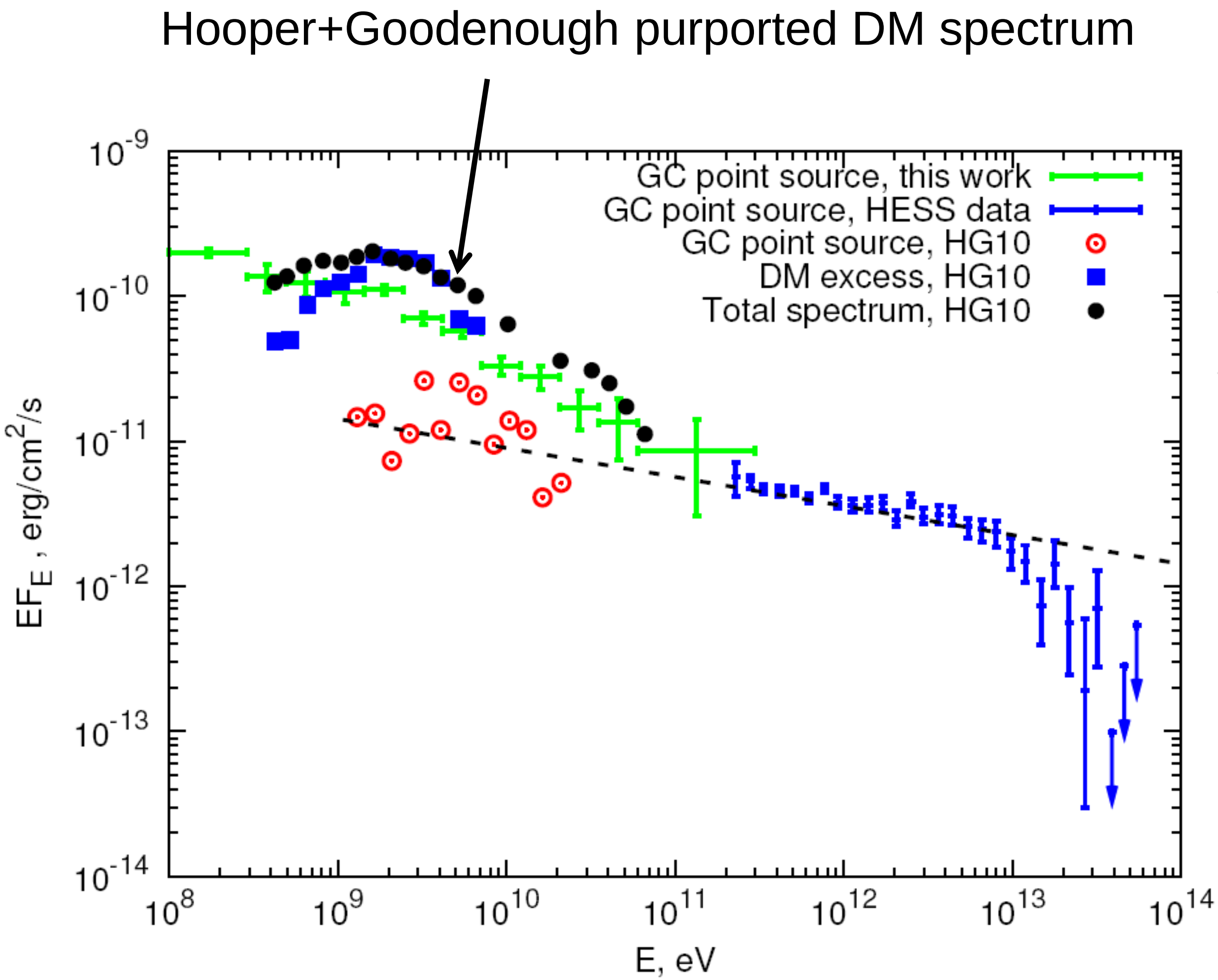
Spectrum to Explain Central Feature

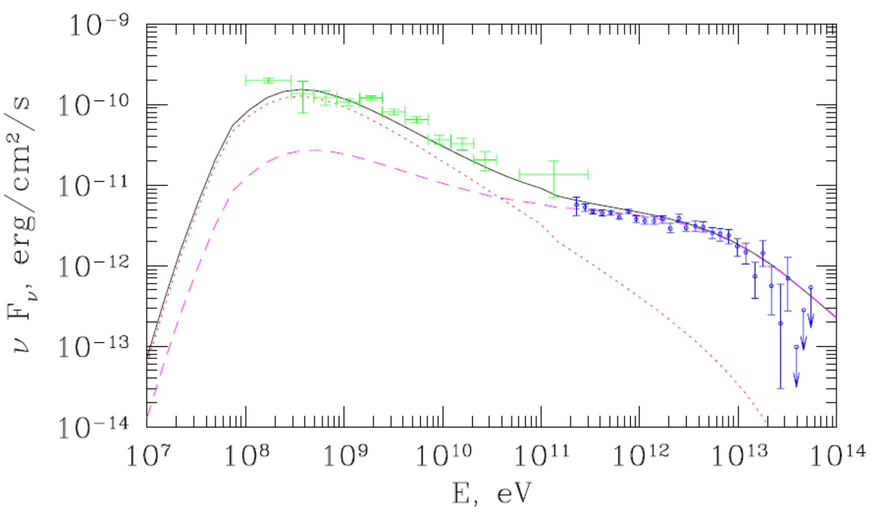


Hooper and Goodenough.
arXiv:1010.2752

PARTY!!!

Alternative explanation for spectrum



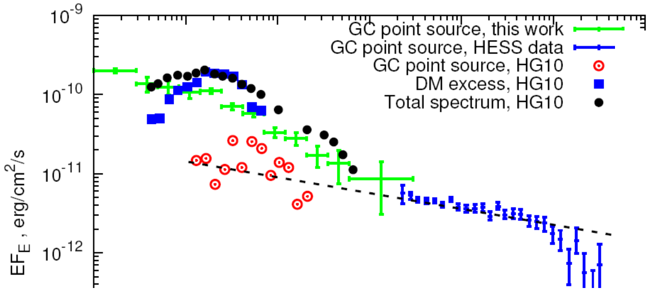


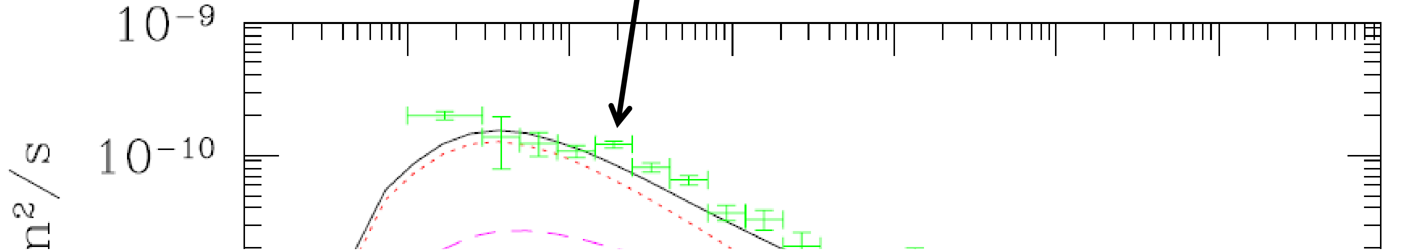
Boyarsky et al 1012.5839

Chernyakova et al. 1009.2630

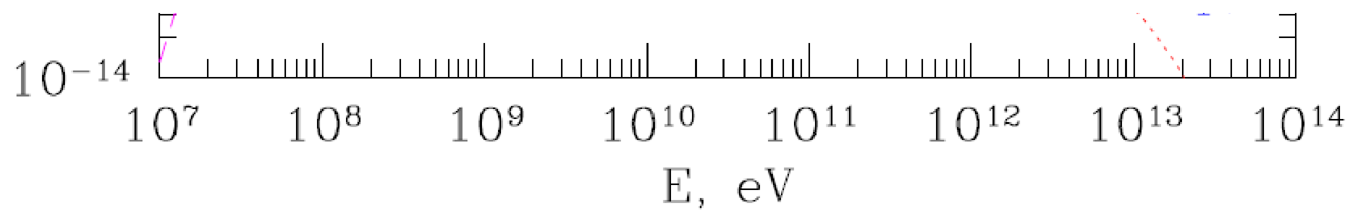
Alternative explanation for spectrum

Chernyakova et al. purported proton induced spectrum



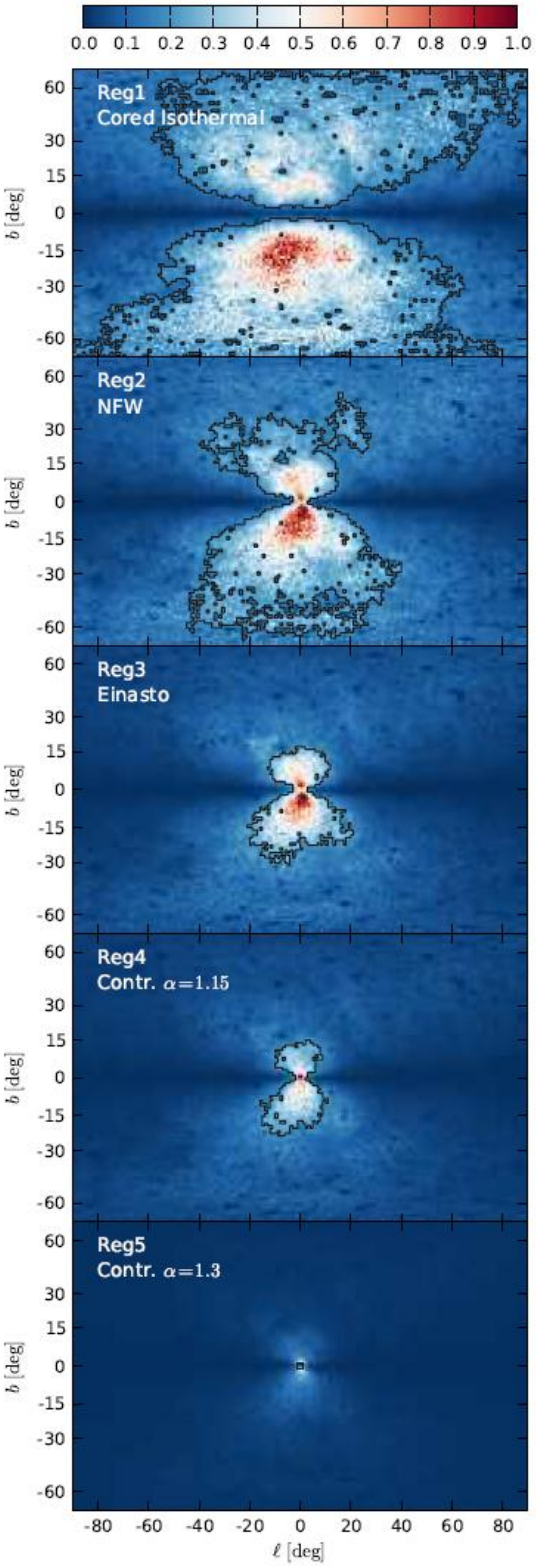


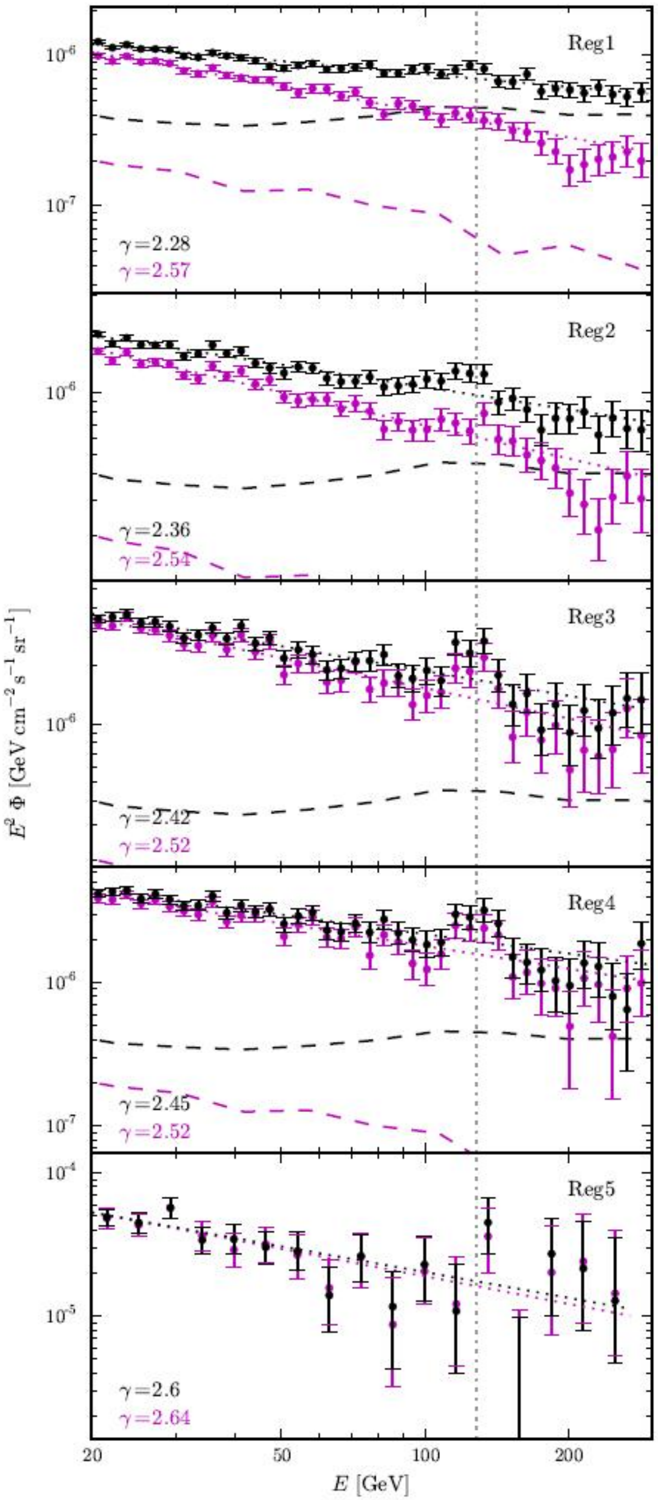
Difference between scenarios may be apparent using radio synchrotron, situation unclear as yet



Boyarsky et al 1012.5839

Chernyakova et al. 1009.2630



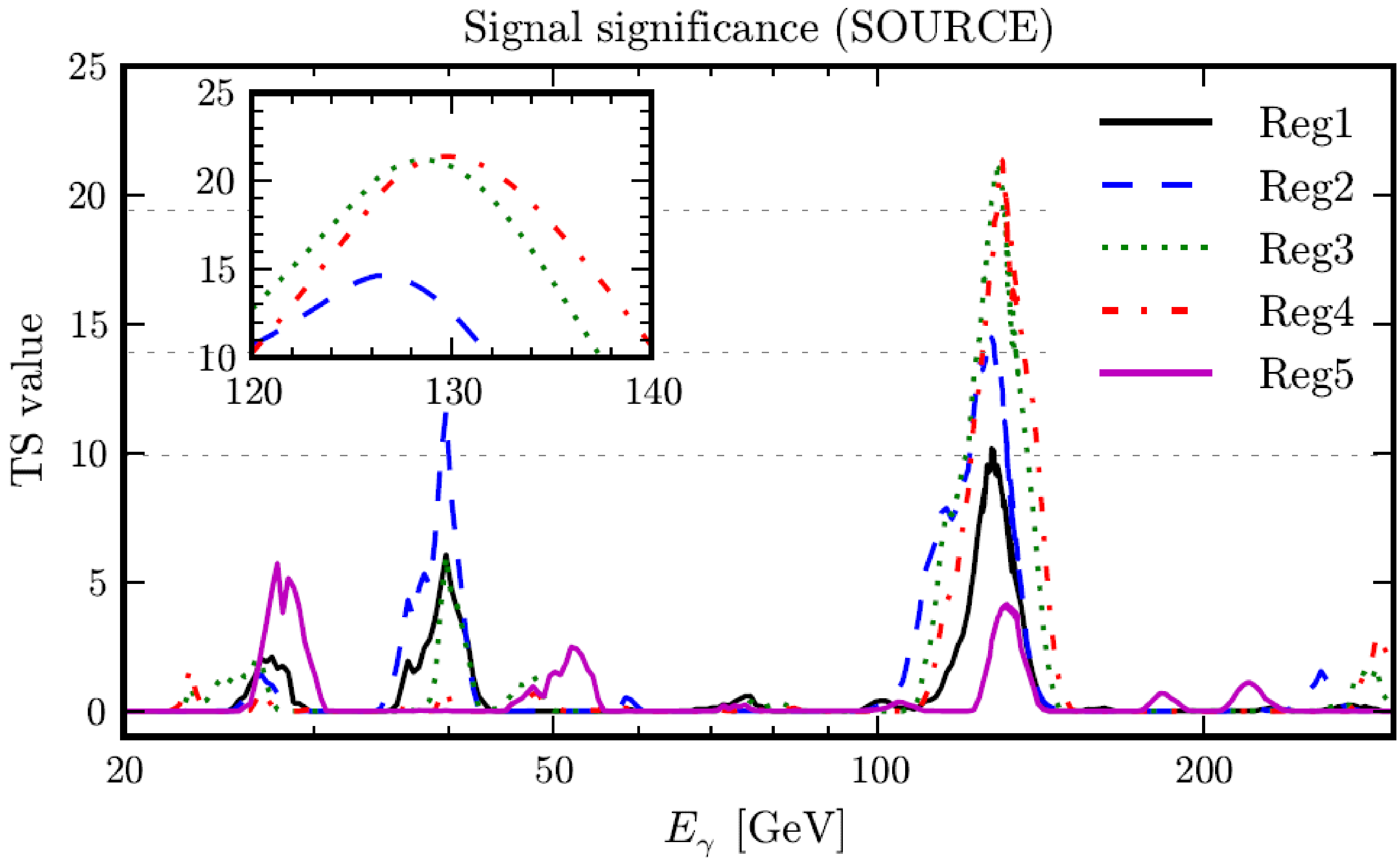


Fermi Analysis Looking specifically for Lines

(Weniger 1204.2797)

Choose only those pixels that will together maximise the overall signal to noise ratio.

This choice is based upon known sources and differs for each assumed halo model.

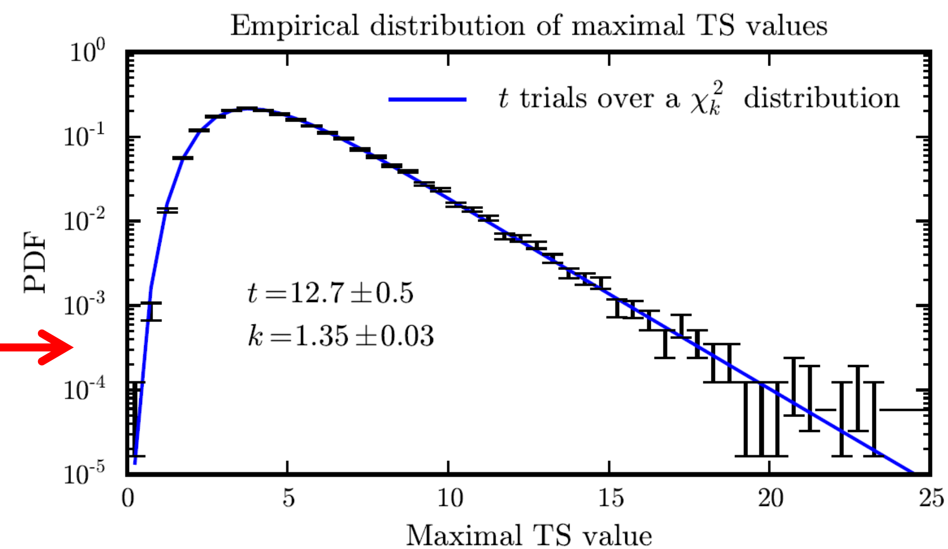


Possible Evidence for 130 GeV Dark Matter Annihilation Line?

4.6σ or 3.3σ when taking into account "look elsewhere" effect

$$TS \equiv -2 \ln \frac{\mathcal{L}_{\text{null}}}{\mathcal{L}_{\text{best}}}$$

Test statistic TS follows nice Poisson distribution when applied to random data where you don't expect signal.



Cuspy No More: How Outflows Affect the Central Dark Matter and Baryon Distribution in ΛCDM Galaxies.

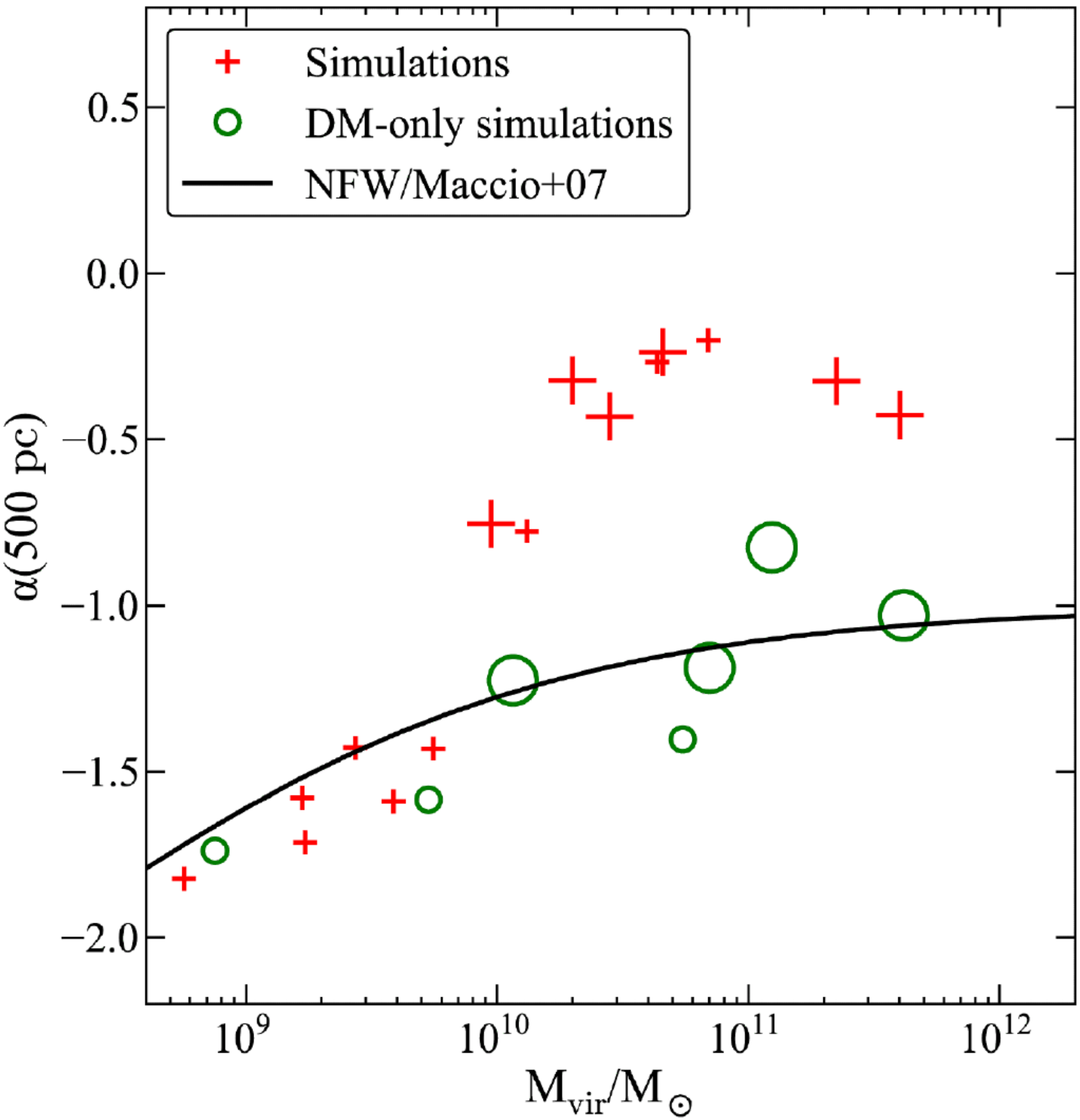
GENERAL NEW PROBLEM FOR INDIRECT SEARCHES?

F.Governato[1*] A.Zolotov[2], A.Pontzen[3], C.Christensen[4], S.H.Oh[5,6], A. M.Brooks[7], T.Quinn[1], S.Shen[8], J.Wadsley[9]

$$\rho \propto r^{\alpha}$$

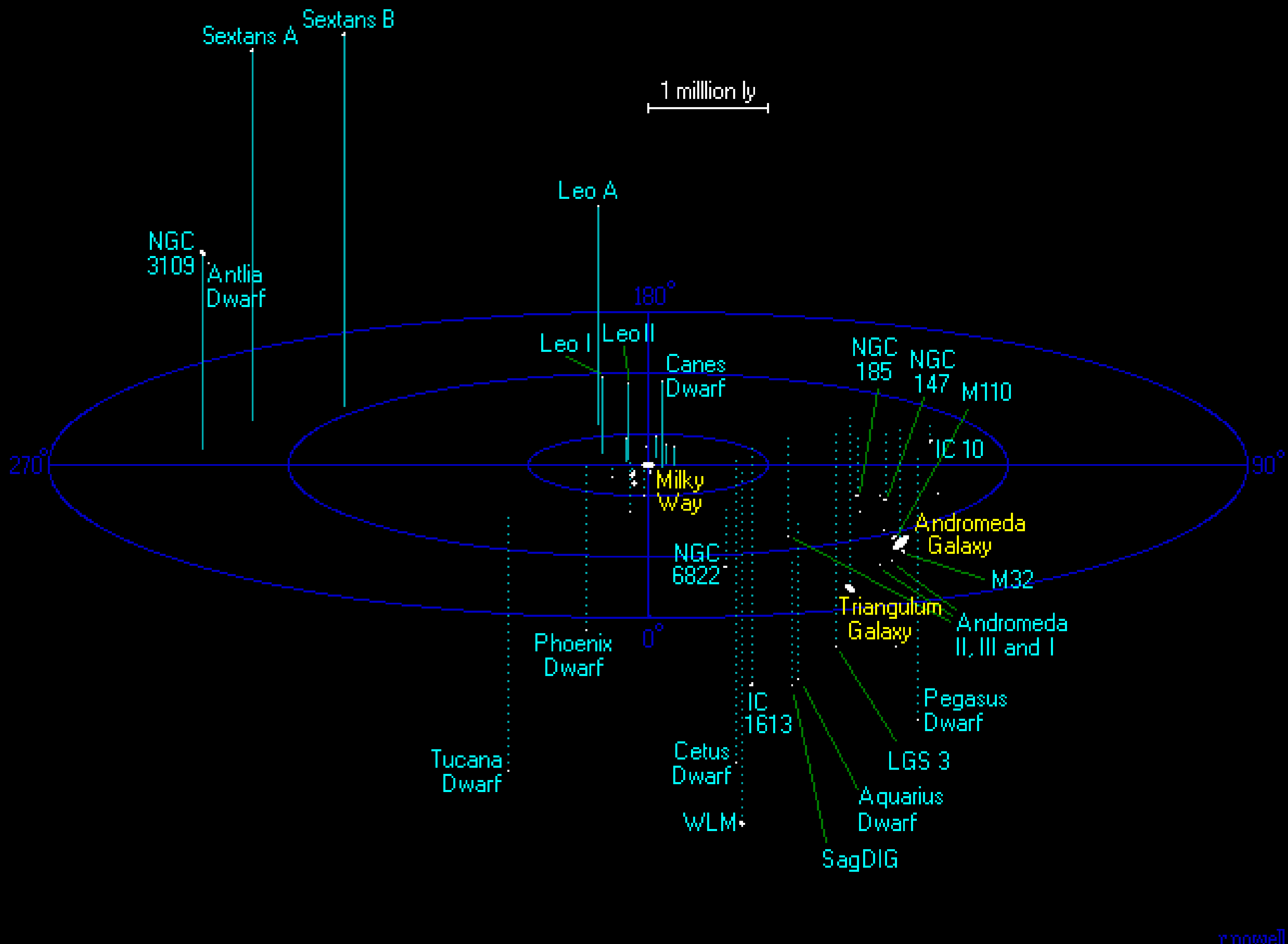
Repeated baryonic contraction and shocking reduces central density of dark matter.

Bad for indirect detection signals.
arXiv:0102.0554

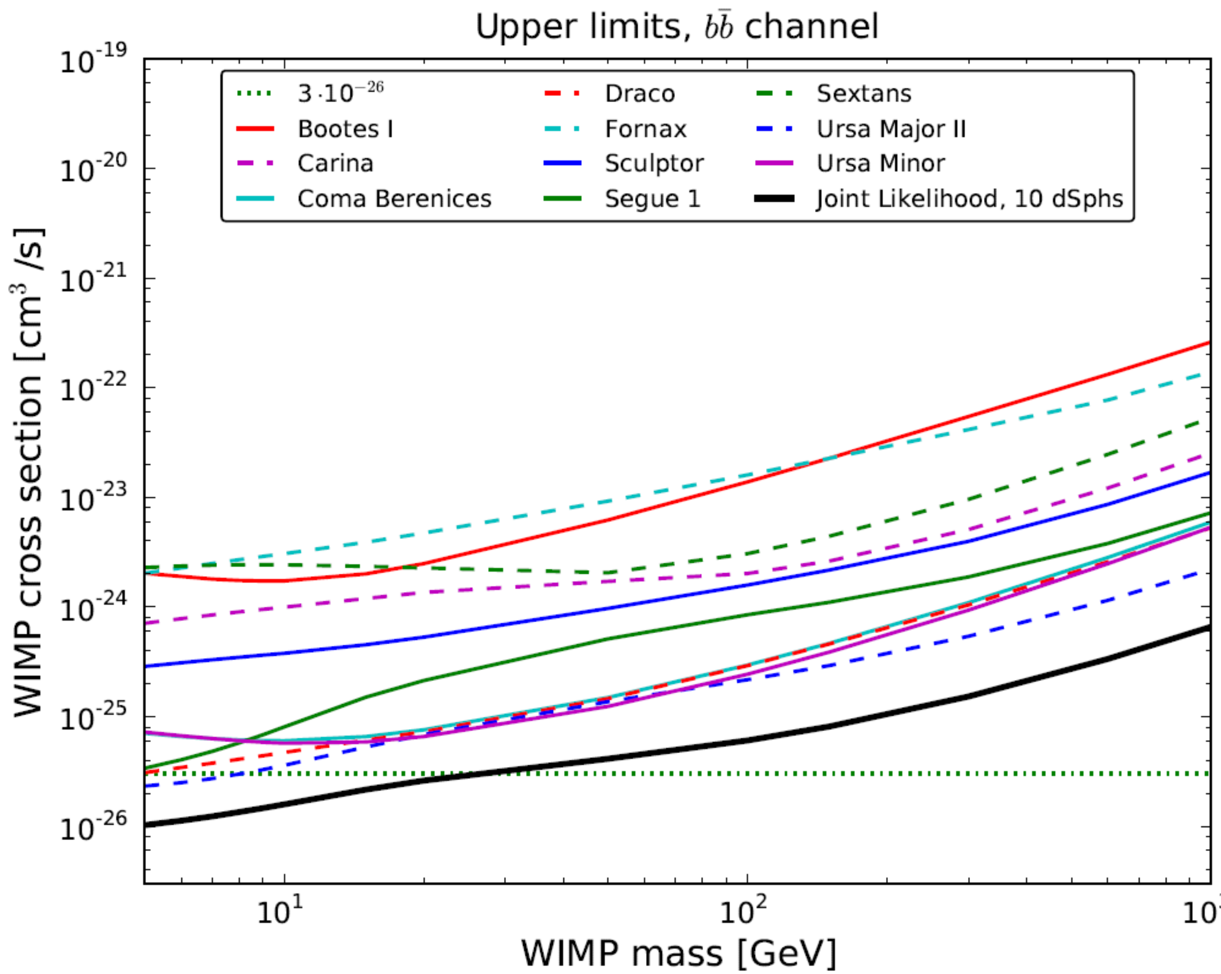


dSphs - Dwarf Spheroidal Galaxies

dSphs - Dwarf Spheroidal Galaxies



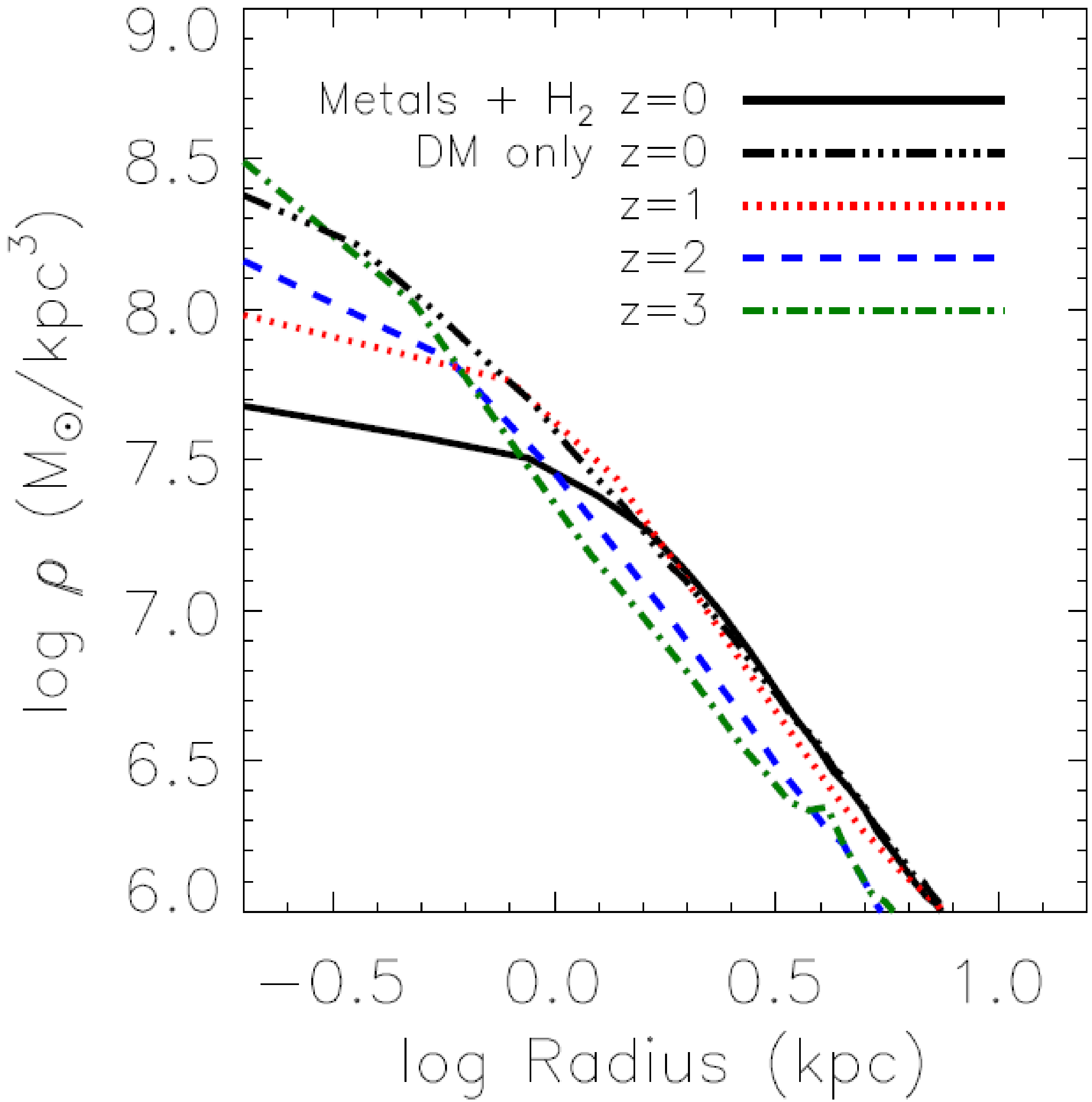
Fermi constraints on gamma ray emission from Dwarf Spheroidals



arXiv:1108.3546

However, this makes assumptions about the density distribution that many people think are unreasonable.

Again, Baryonic Effects on the Cusps May Be Important



Governato et al.

arXiv:1202.0554

INDIRECT DETECTION:- CONCLUSIONS

- Hints from galactic centre of low mass WIMPs.

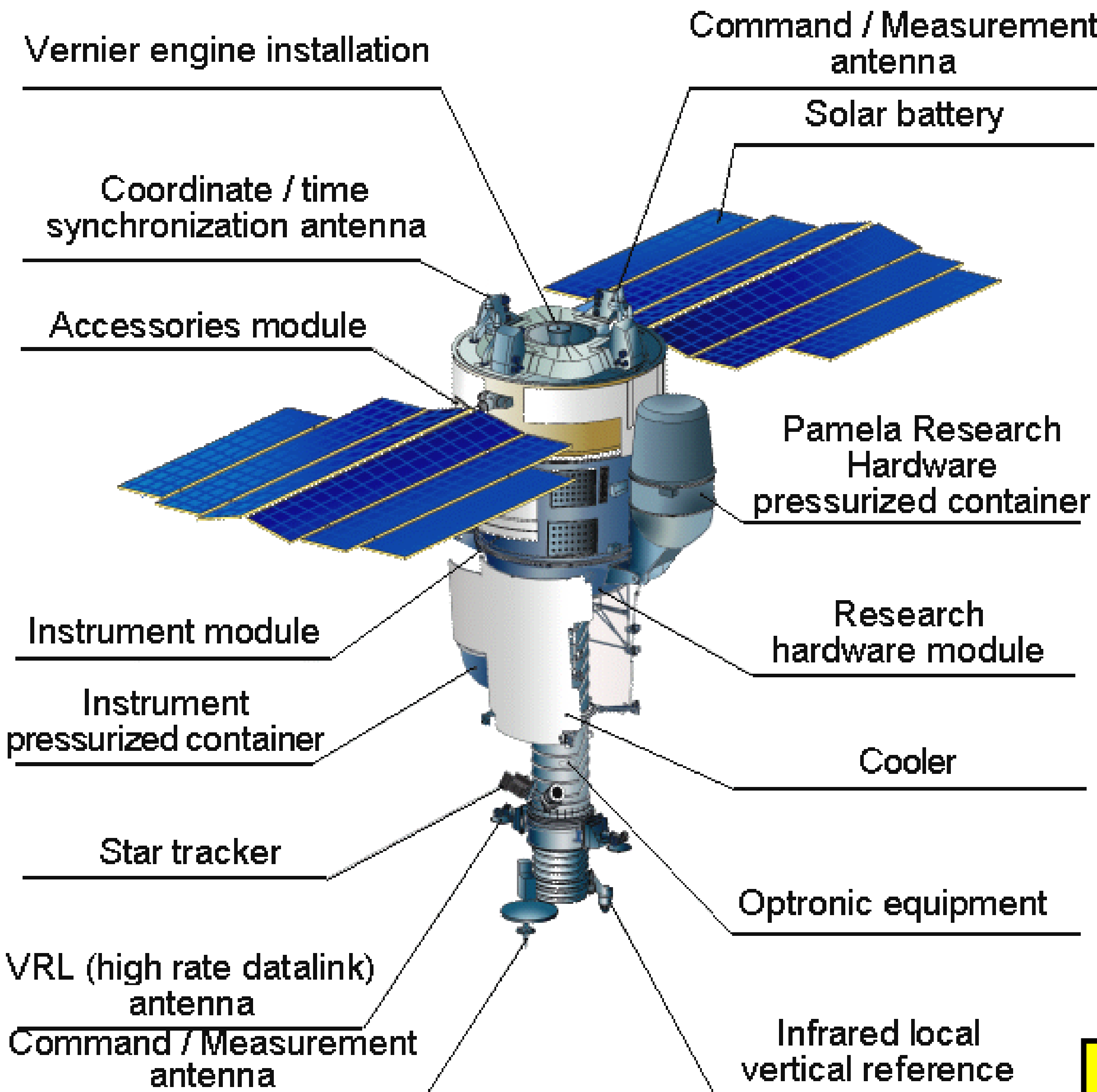
- Other astrophysical explanations exist.

- Hints from galactic centre of gamma ray delta function.

- Understanding the density profile of Dwarf Spheroidals is important.

STUFF YOU ALWAYS WANTED TO KNOW ABOUT ELECTRONS, POSITRONS, PAMELA, FERMI AND ALL THAT BUT WERE AFRAID TO ASK

Resurs-DK1 satellite



- **Main task:** multi-spectral remote sensing of earth's surface
- Built by TsSKB Progress in Samara, Russia

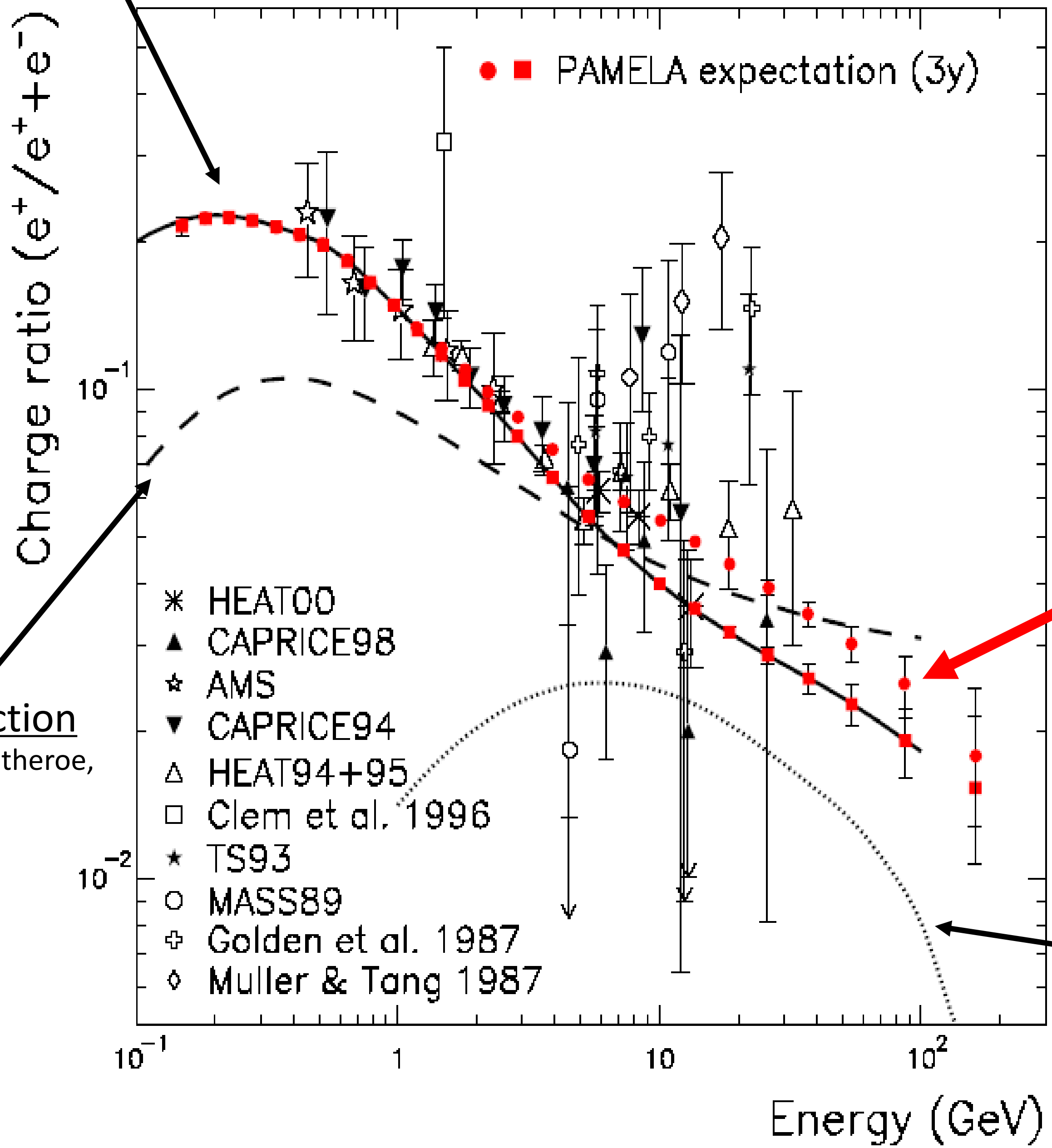
- **Lifetime >3 years (assisted)**
- Data transmitted to ground via high-speed radio downlink

- **PAMELA mounted inside a pressurized container**

Mass: 6.7 tonnes
Height: 7.4 m
Solar array area: 36 m^2

STOLEN FROM 2007 PRESENTATION BY MARK PEARCE, KTH STOCKHOLM

Secondary production
'Moskalenko + Strong model' without reacceleration. ApJ 493 (1998) 694.

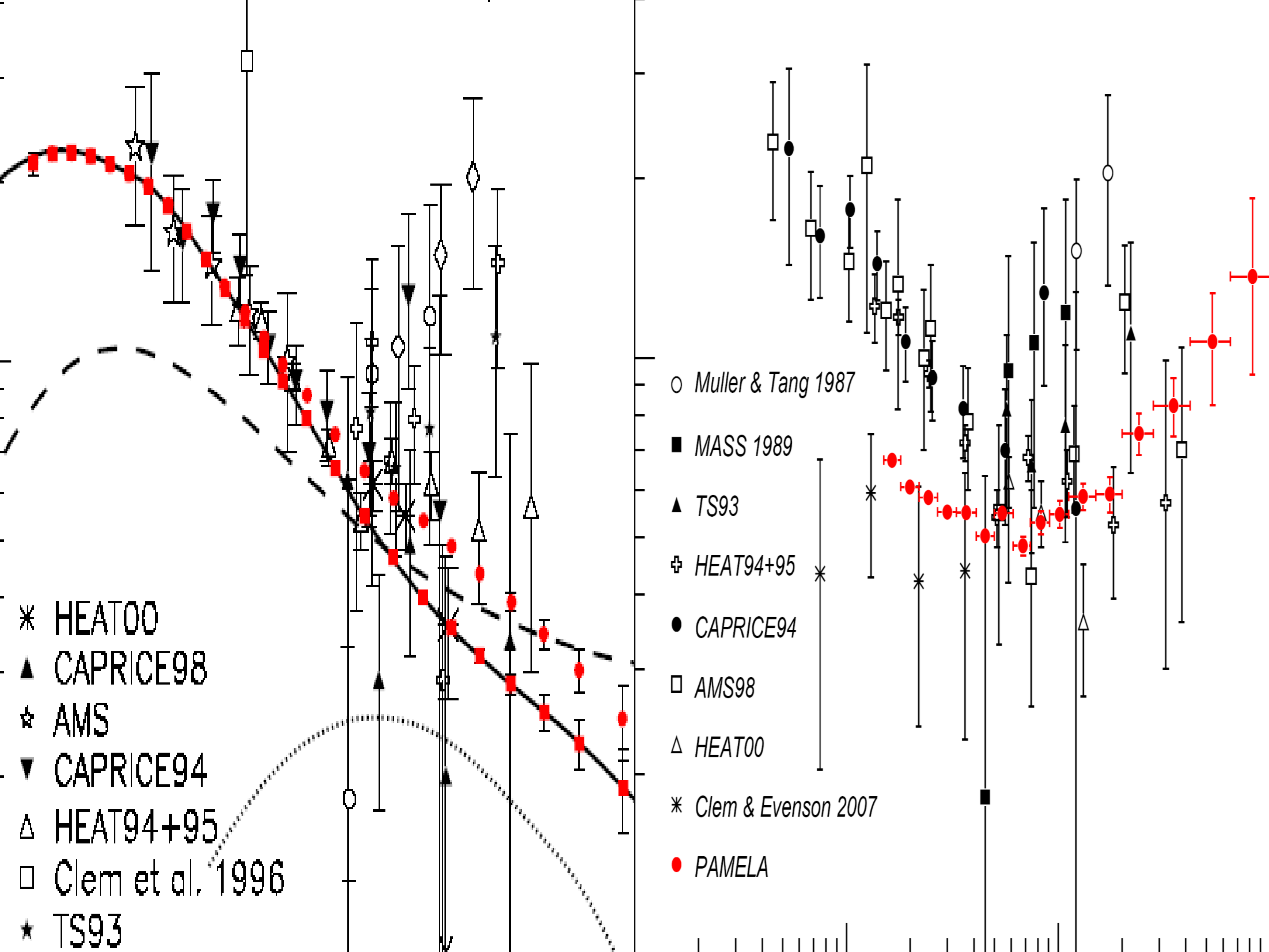


Secondary production
'Leaky box model' R. Protheroe, ApJ 254 (1982) 391.

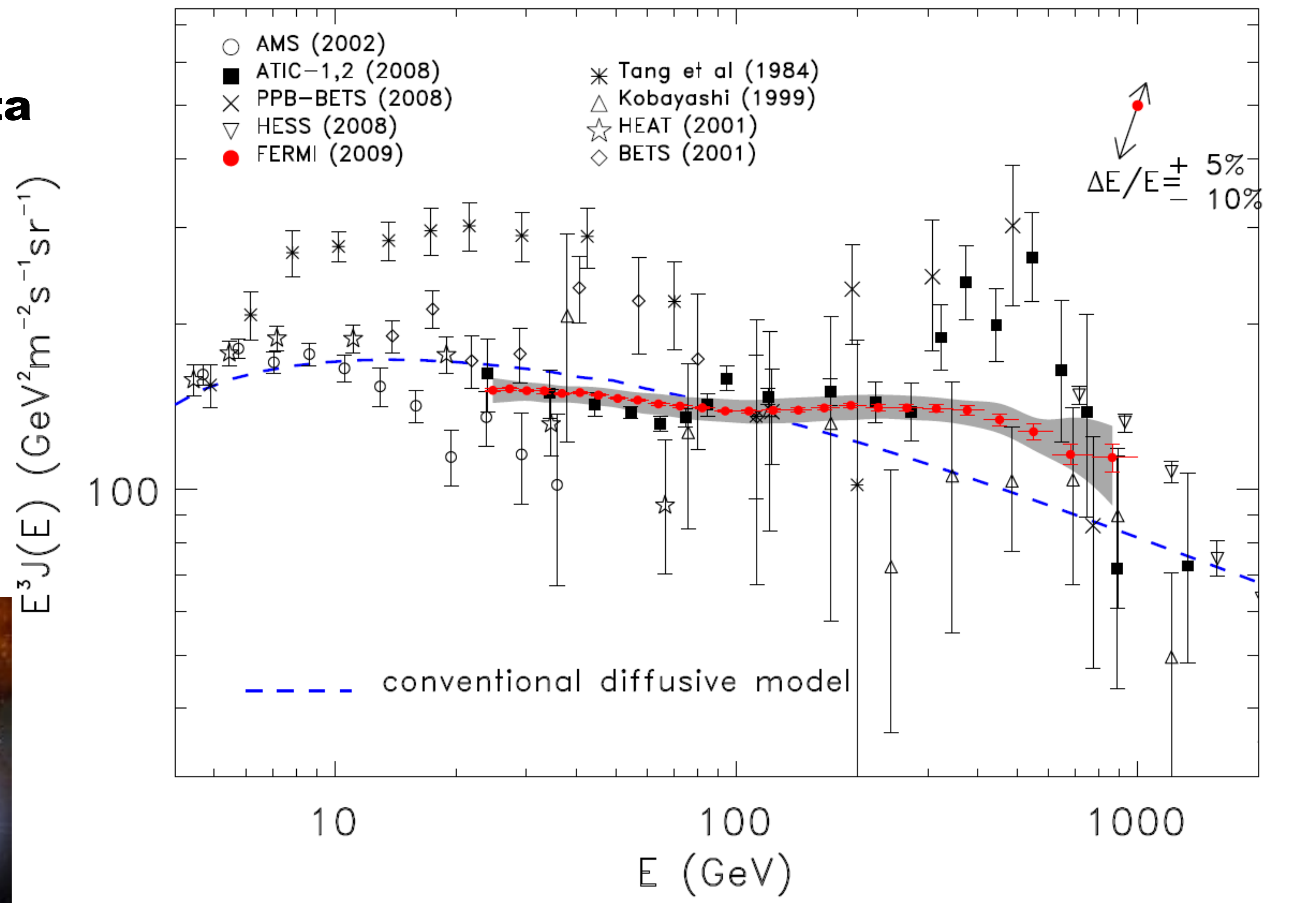
PAMELA

Secondary production
'M+S model' +
primary χχ
distortion

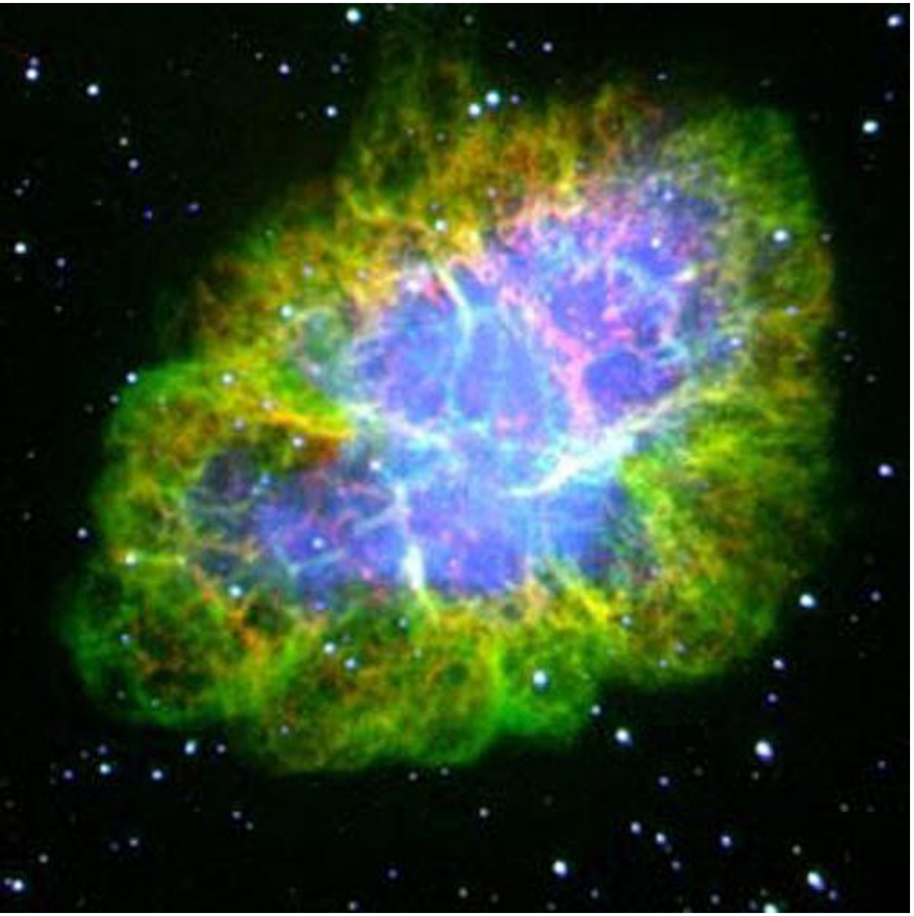
Primary production
from χχ annihilation
(m(χ) = 336 GeV)

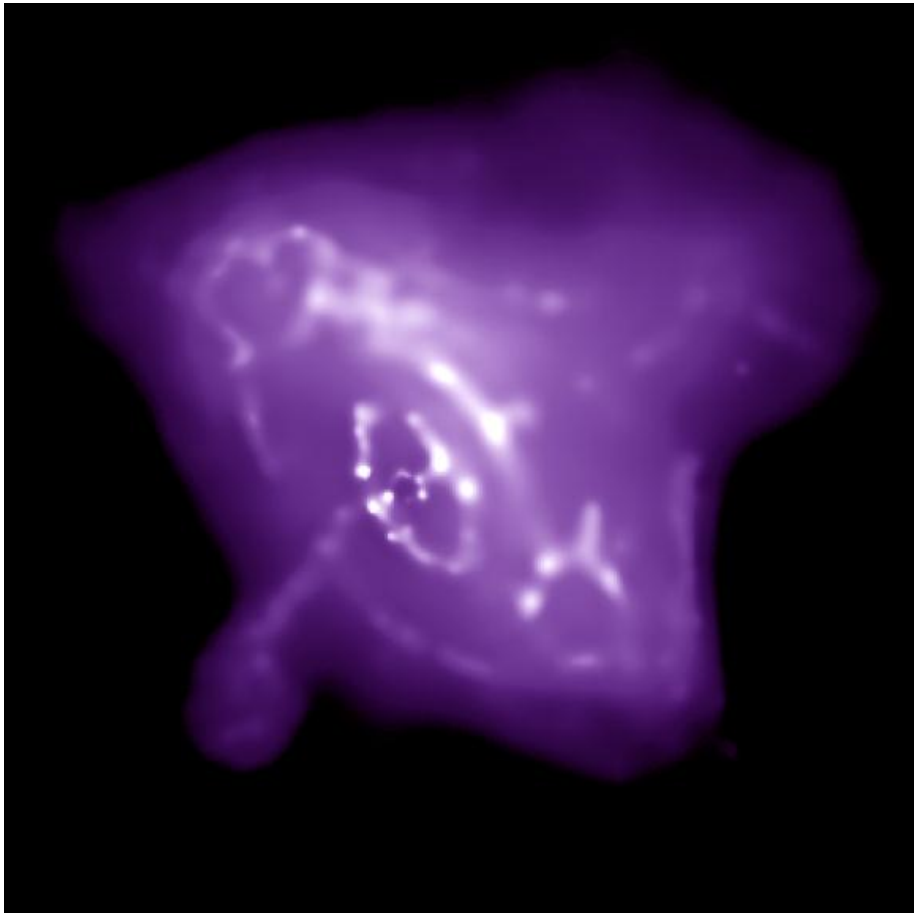

HEAT00
CAPRICE98
AMS
CAPRICE94
HEAT94+95
Clem et al. 1996
TS93
Muller & Tang 1987
MASS 1989
TS93
HEAT94+95
CAPRICE94
AMS98
HEAT00
Clem & Evenson 2007
PAMELA

Fermi Data Electron Data
0905.0025

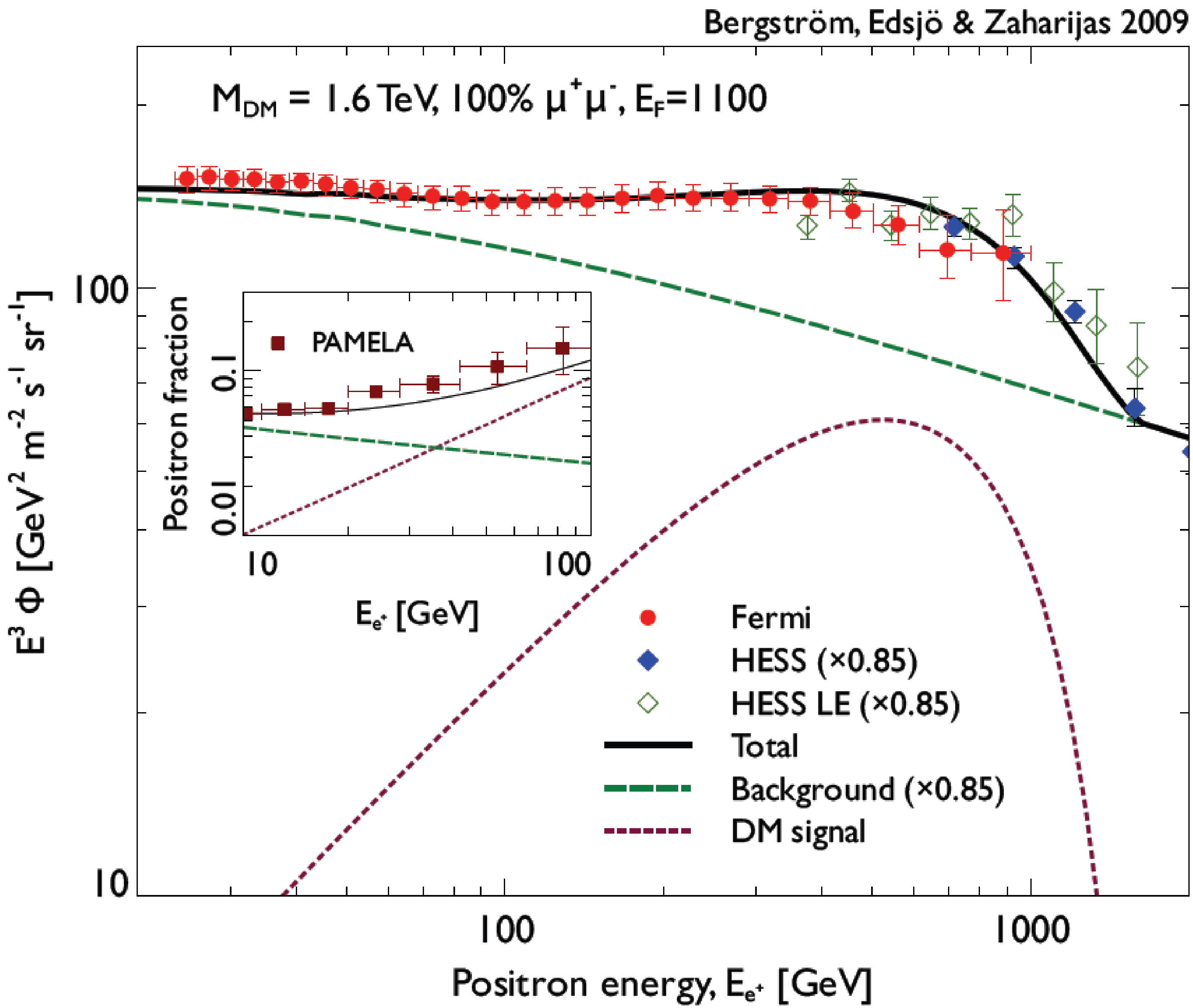


Possible astrophysical origin of electrons/positrons
10 GeV – 10 TeV





If you accept certain prerequisites, Fermi and PAMELA data can be fit by dark matter also…



Thermally averaged self annihilation cross section today

This enhancement not thought to be large enough, see e.g. Pieiri, Lavalle, Bertone and Branchini 0908.0195

Actual local density

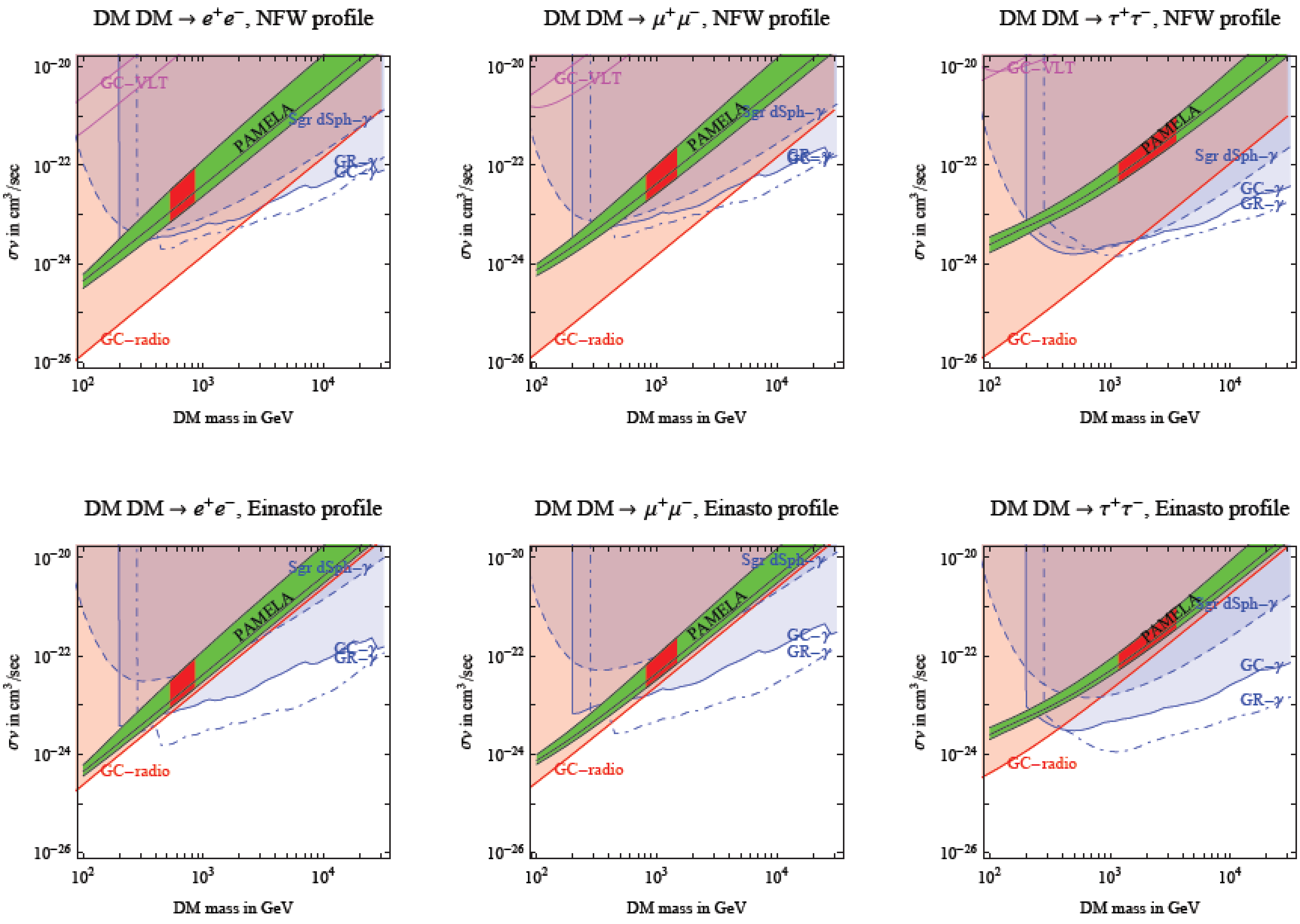
$$B \equiv Br_{e^+} \frac{\langle \sigma_A v \rangle \rho_{\mathrm{DM}}^2}{\langle \sigma_A v \rangle_F (\bar{\rho}_{\mathrm{DM}})^2}$$

Branching ratio into e^+e^-

Thermally averaged self annihilation cross section at freeze-out

Expected local density (0.3 GeV cm^{-3})

Is Dark Matter explanation of PAMELA ruled out by Synchrotron?



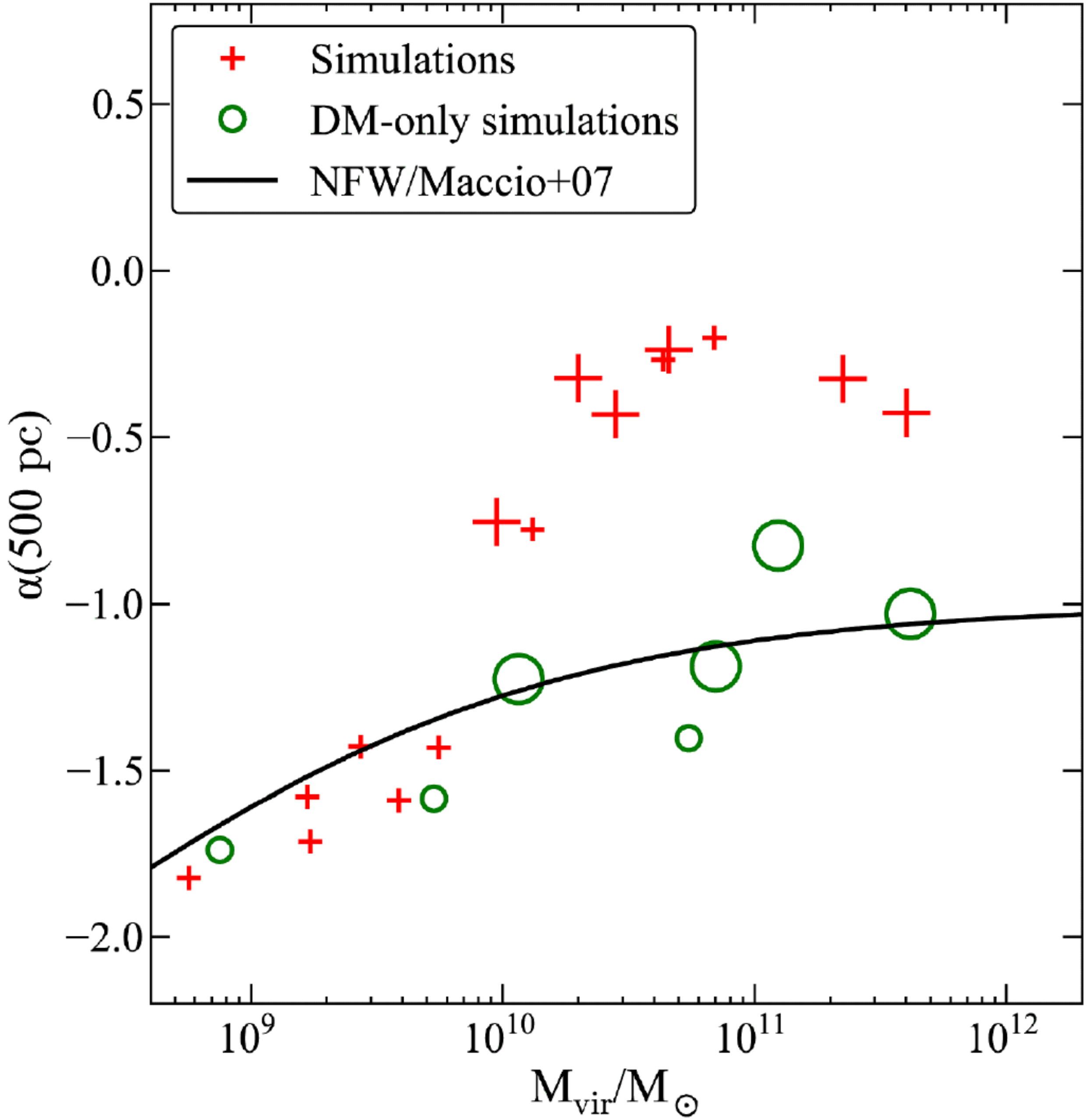
Bertone et al arXiv:0811.3744.

Cuspy No More: How Outflows Affect the Central Dark Matter and Baryon Distribution in ΛCDM Galaxies.

F.Governato[1*] A.Zolotov[2], A.Pontzen[3], C.Christensen[4], S.H.Oh[5,6], A. M.Brooks[7], T.Quinn[1], S.Shen[8], J.Wadsley[9]

GENERAL NEW PROBLEM FOR INDIRECT SEARCHES?

$$\rho \propto r^{\alpha}$$



AGAIN, all bets are off if baryons really do erase spikes

arXiv:0102.0554

PAMELA POSITRONS:- CONCLUSIONS

•There are more positrons than we expect in local space.

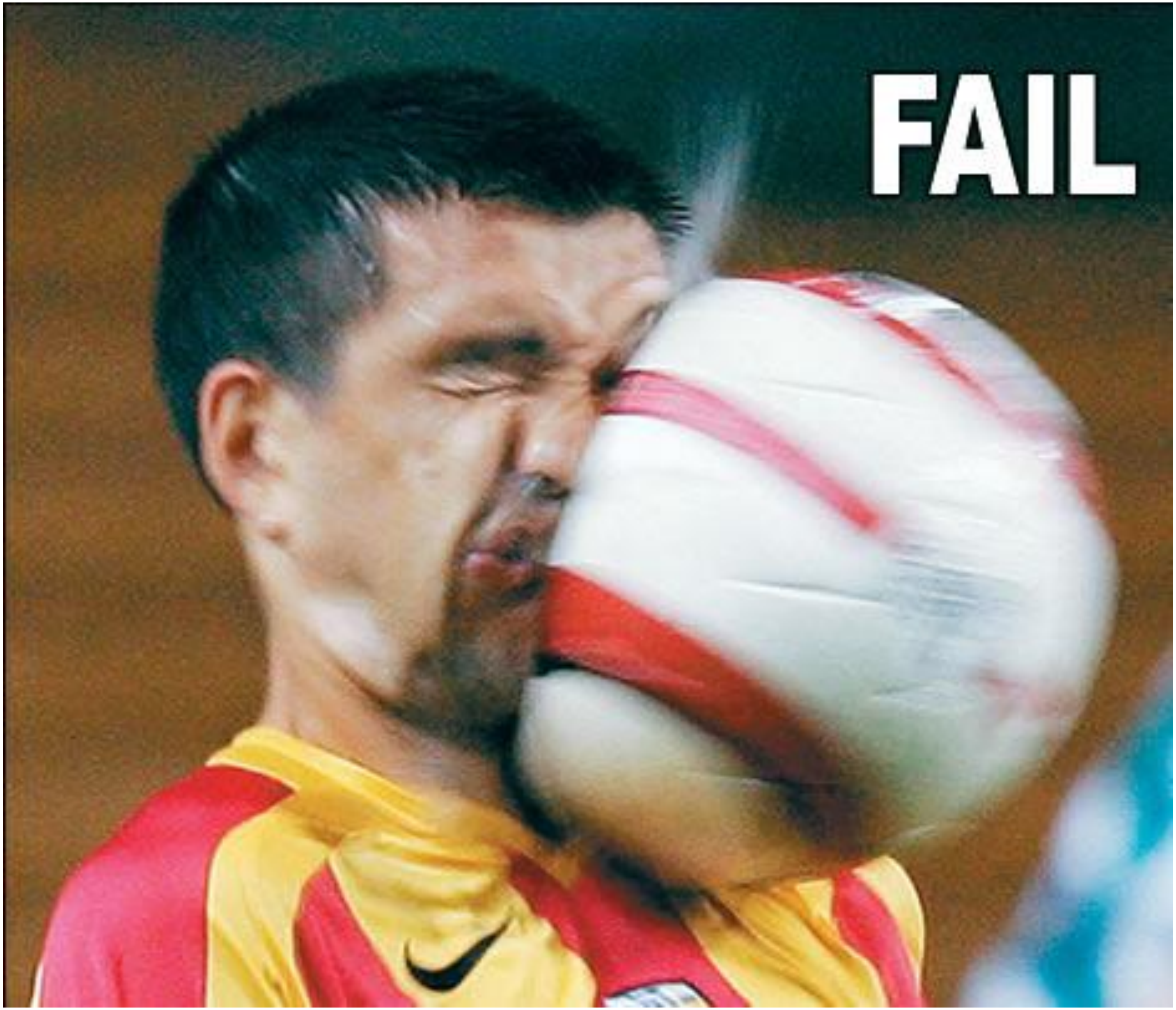
• There are more high energy electrons than we expect too.

•The two populations are roughly consistent with each other.

•Seems to be too many to be dark matter!

•Possible alternative solutions are astrophysical or complicated versions of dark matter models.

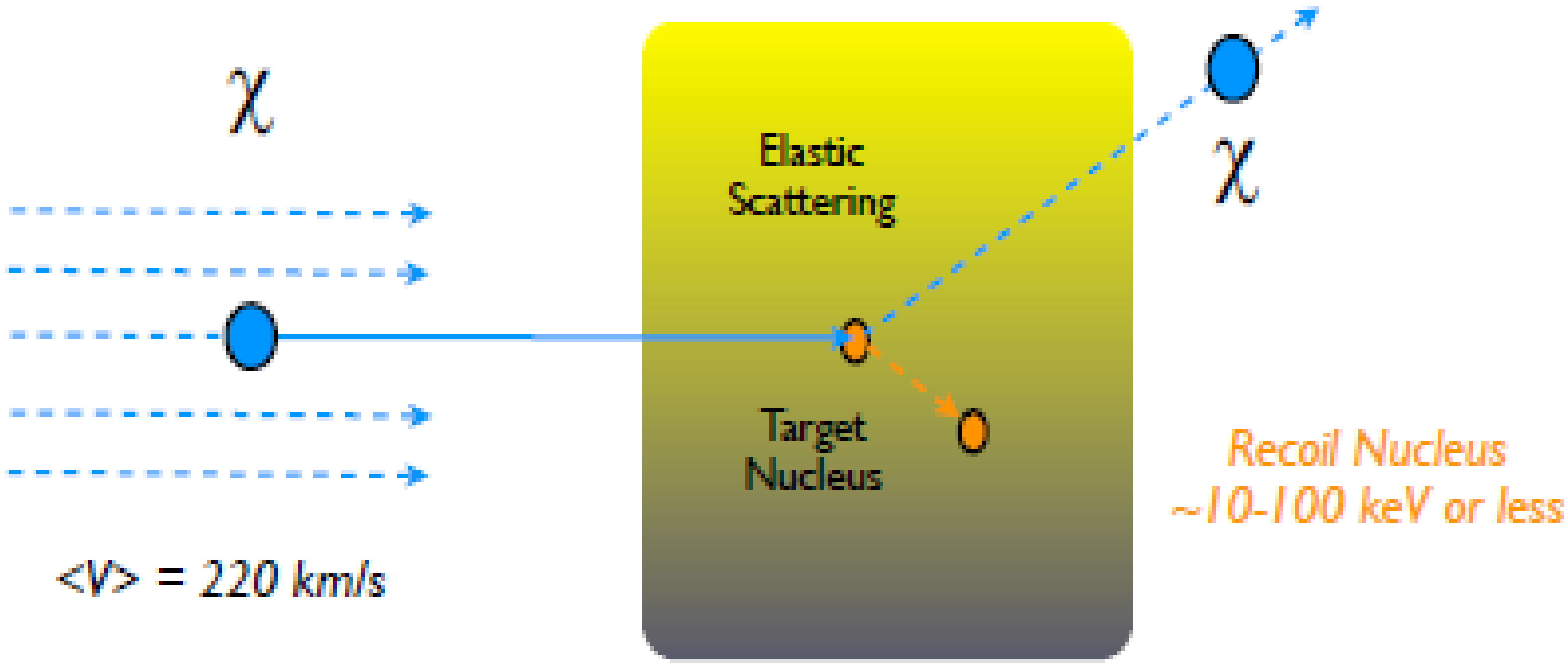
Direct Detection of Dark Matter



Direct detection of dark matter

Look for recoil of DM-nucleus scattering:

$$\chi + N \rightarrow \chi + N$$



Direct detection of dark matter

Look for recoil of DM-nucleus scattering:

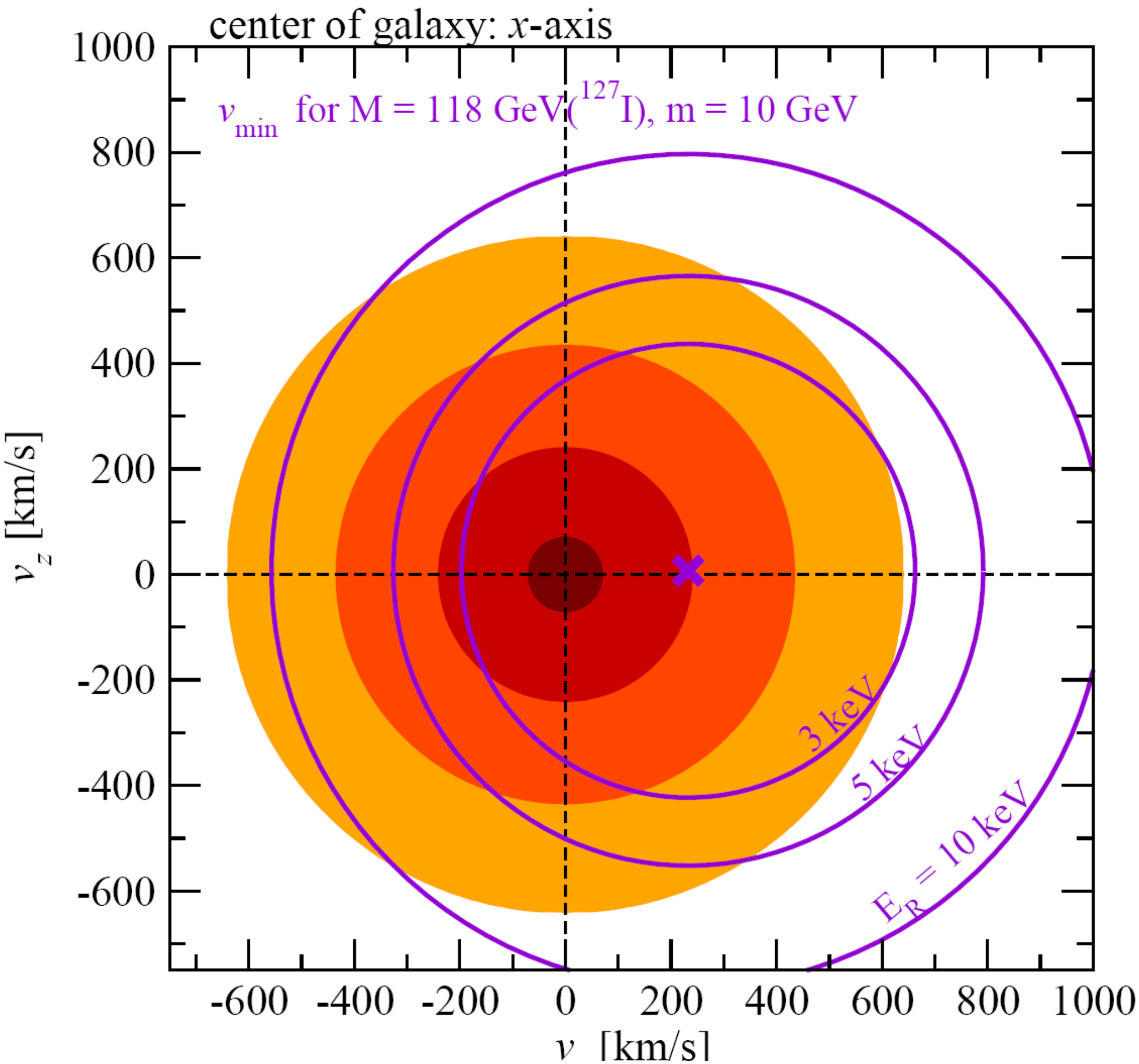
$$\chi + N \to \chi + N$$

cnts / kg-detector mass / keV recoil energy E_R:

$$\frac{dN}{dE_R}(t) = \frac{\rho_\chi}{m_\chi} \frac{\sigma(q)}{2\mu_\chi^2} \int_{v>v_{\min}} d^3v \, \frac{f_\oplus(\vec{v},t)}{v}$$

ρ_χ	DM energy density, default: 0.3 GeV cm^{-3}
$q = \sqrt{2ME_R}$	momentum transfer
$\mu_\chi = m_\chi M/(m_\chi + M)$	reduced DM/nucleus mass

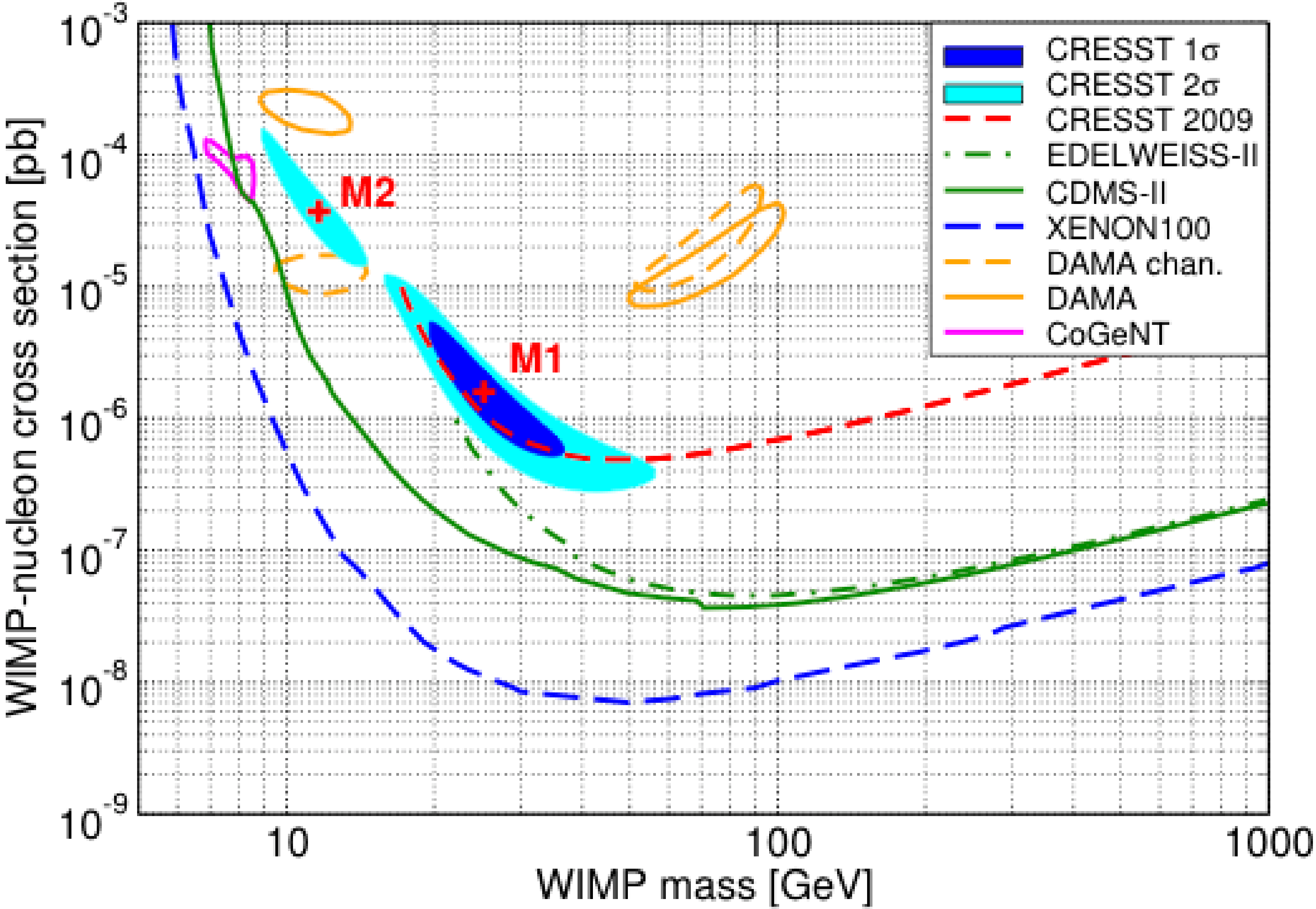
Solar Orbit signal



$$\int_{v>v_{\min}} d^3v \, \frac{f_{\oplus}(\vec{v},t)}{v}$$

$$v_{\min} = \sqrt{\frac{M E_R}{2\mu_\chi^2}}$$

Recent Constraints on Spin Independent Cross Section

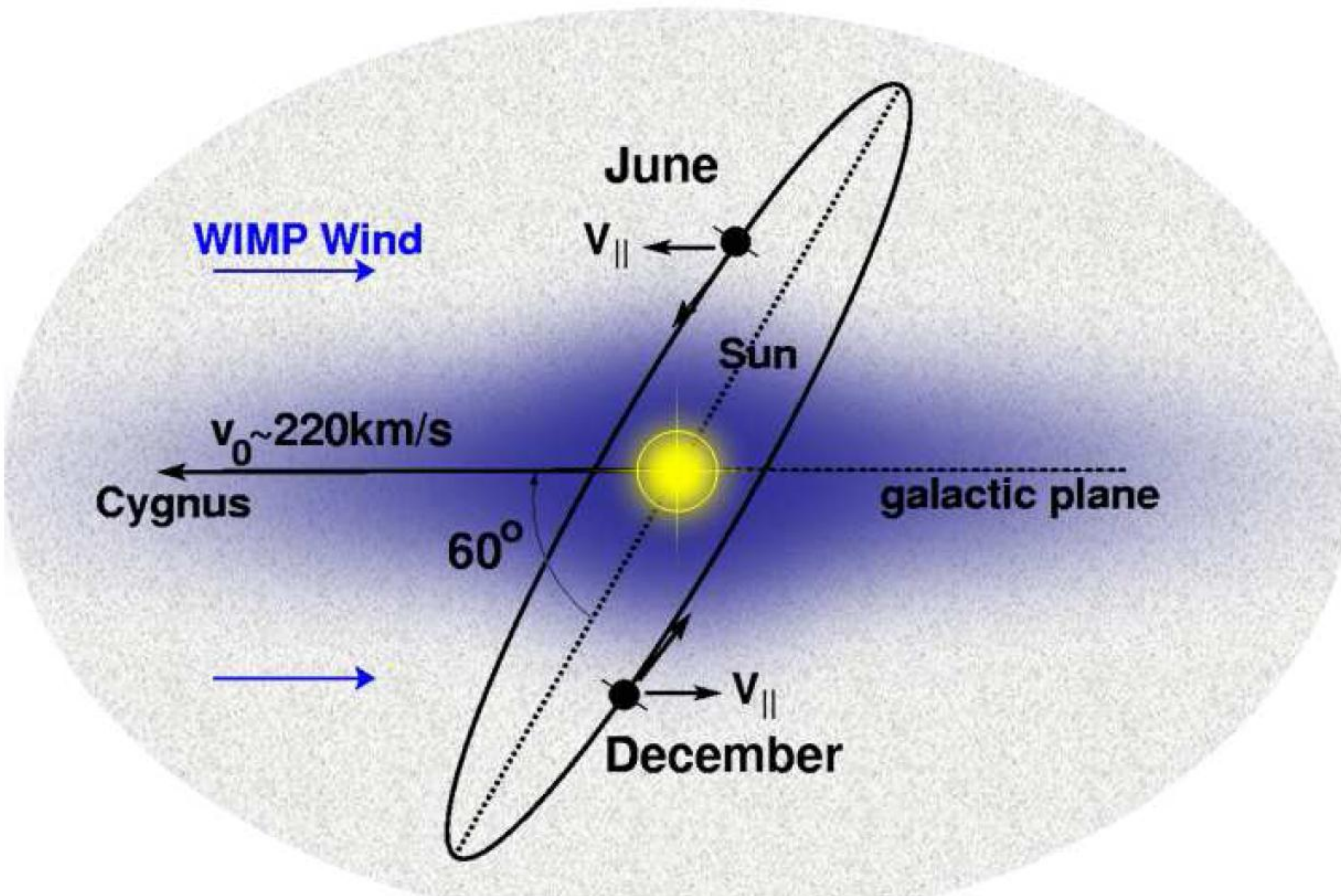


Annual Modulation Signal

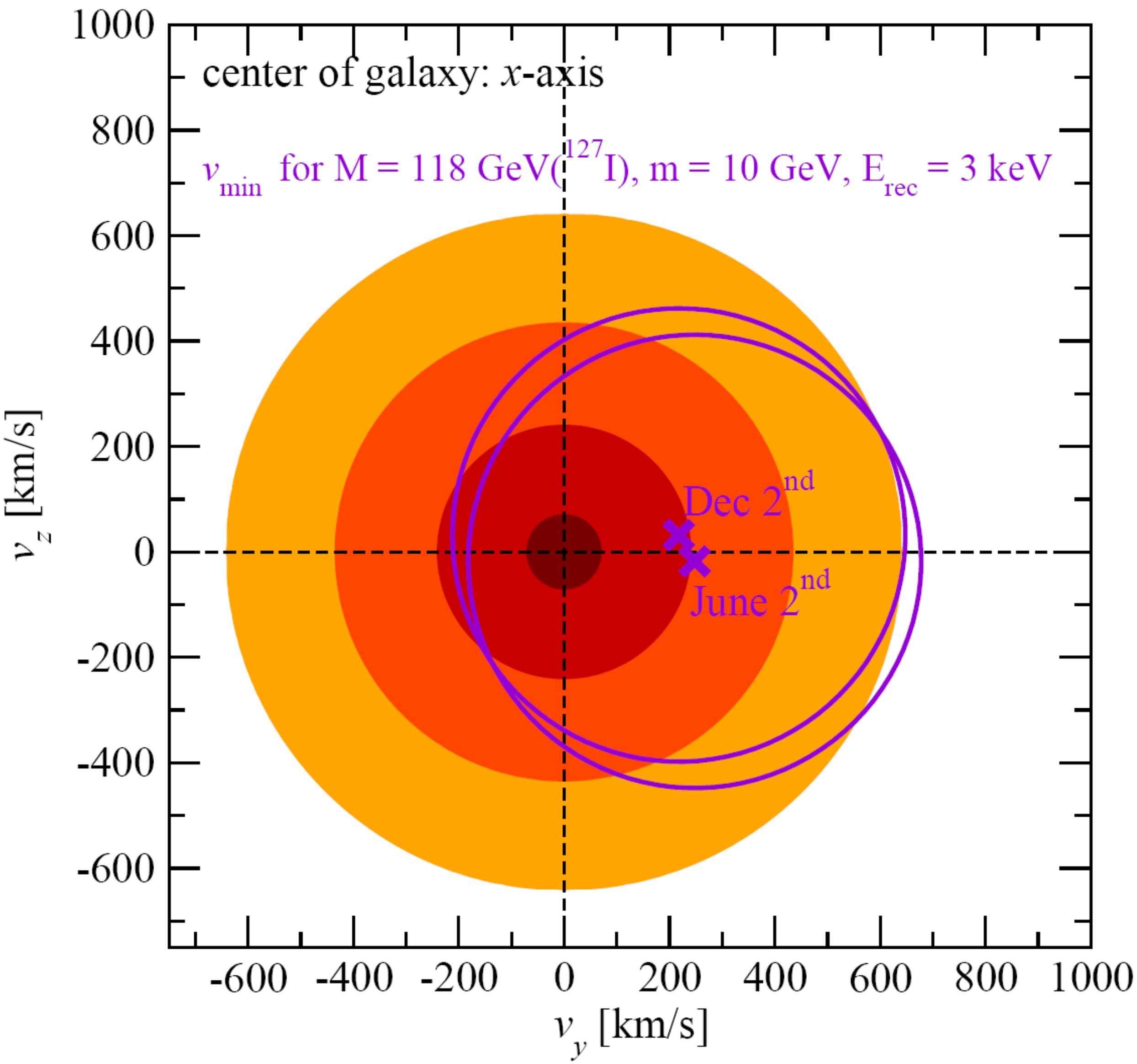
$$f_\oplus(\vec{v},t) = f_{\rm gal}(\vec{v} + \vec{v}_\odot + \vec{v}_\oplus(t))$$

sun velocity: $\vec{v}_\odot = (0, 220, 0) + (10, 13, 7)$ km/s

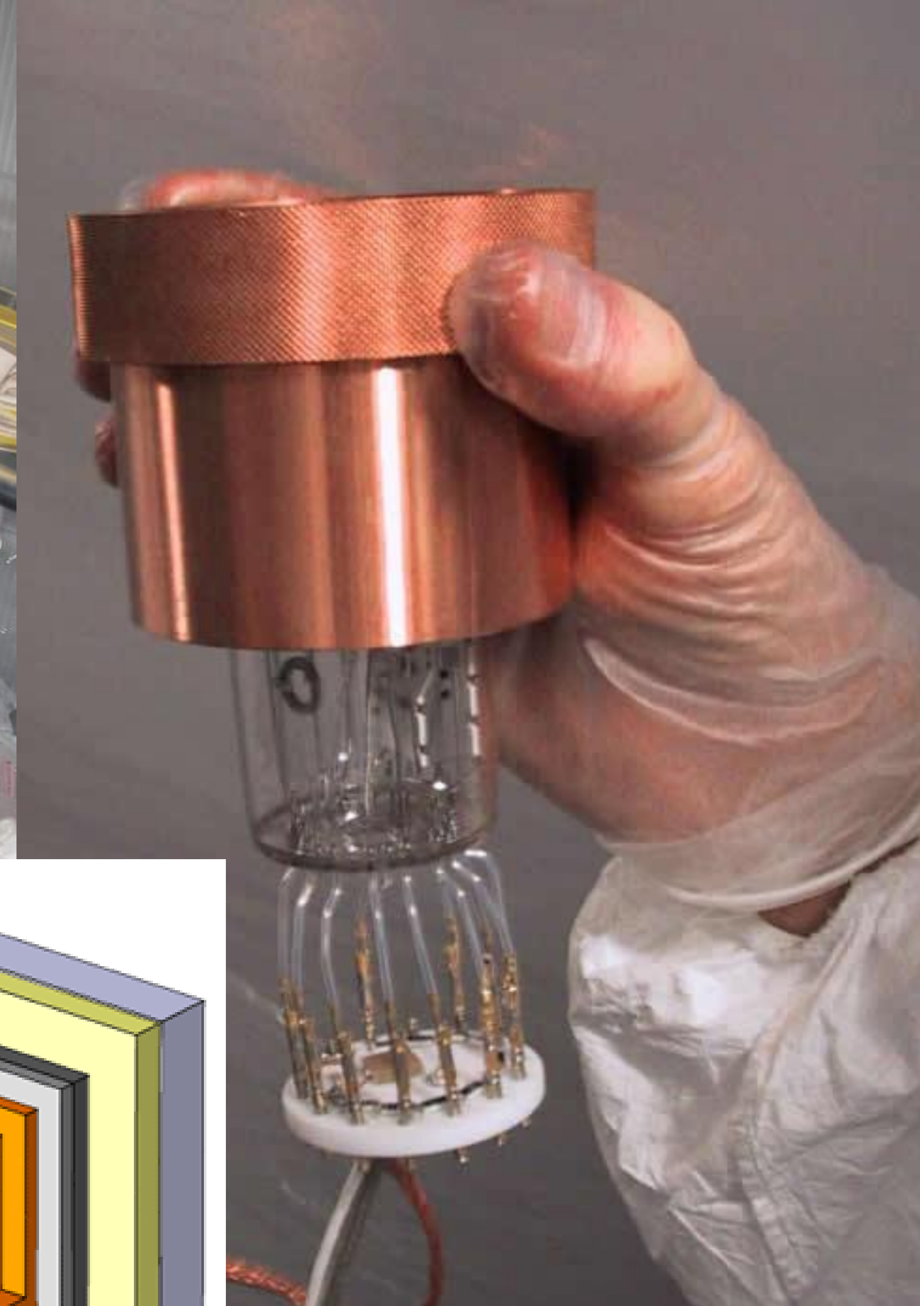
earth velocity: $\vec{v}_\oplus(t)$ with $v_\oplus \approx 30$ km/s



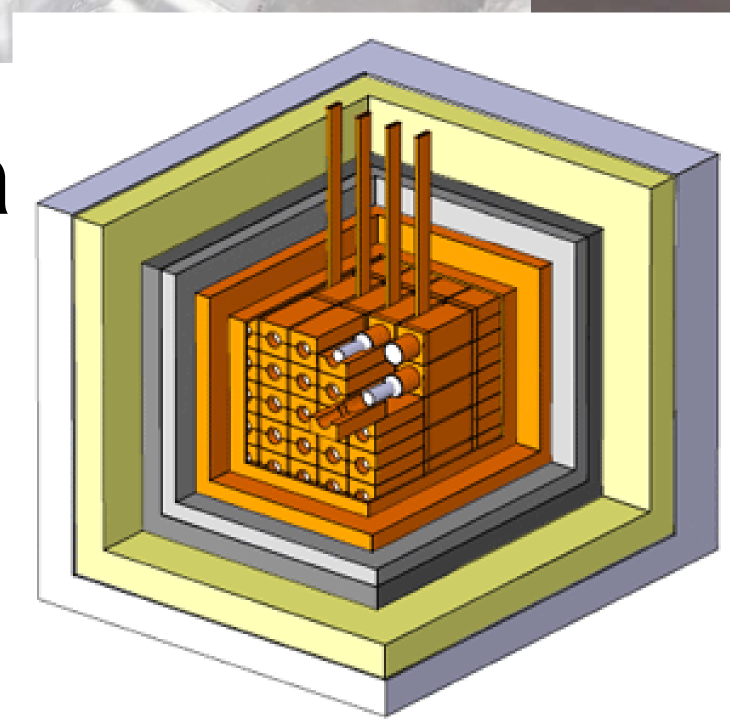
Annual modulation signal



$$\int_{v>v_{\min}} d^3v \, \frac{f_{\oplus}(\vec{v},t)}{v}$$



DAMA/Libra experiment

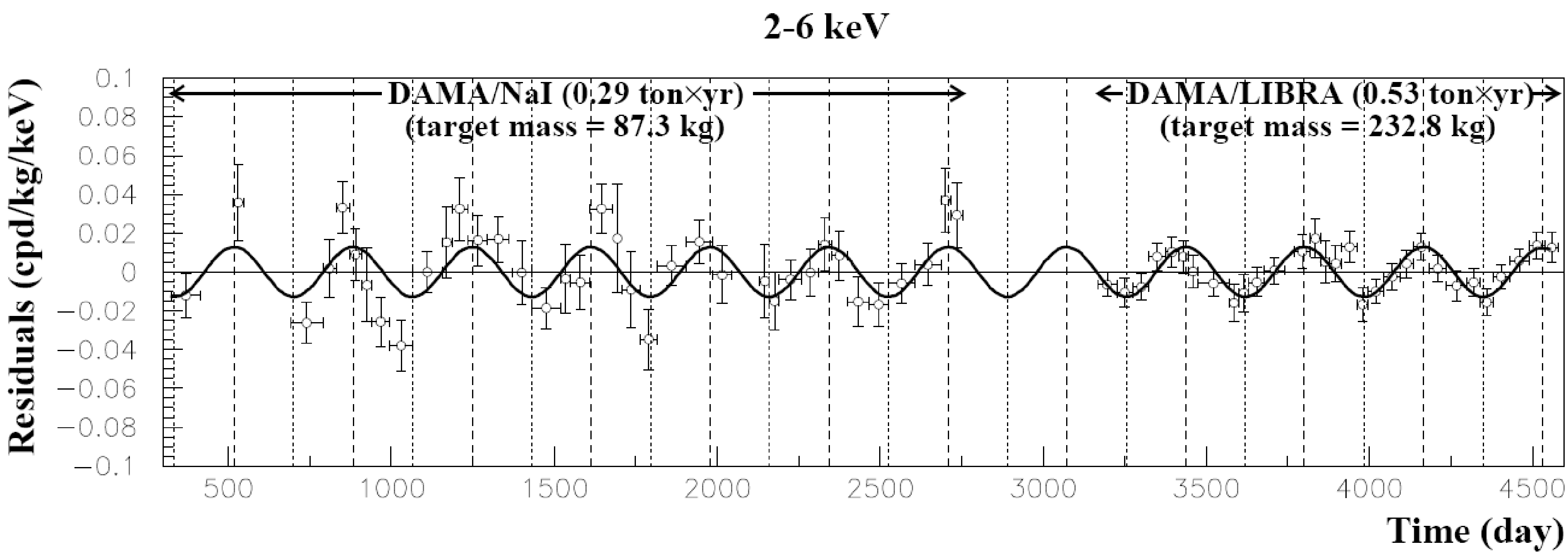


250 kg of NaI(Tl)

DAMA/LIBRA results

evidence for an annual modulation of the count rate:

Bernabei et al., 0804.2741

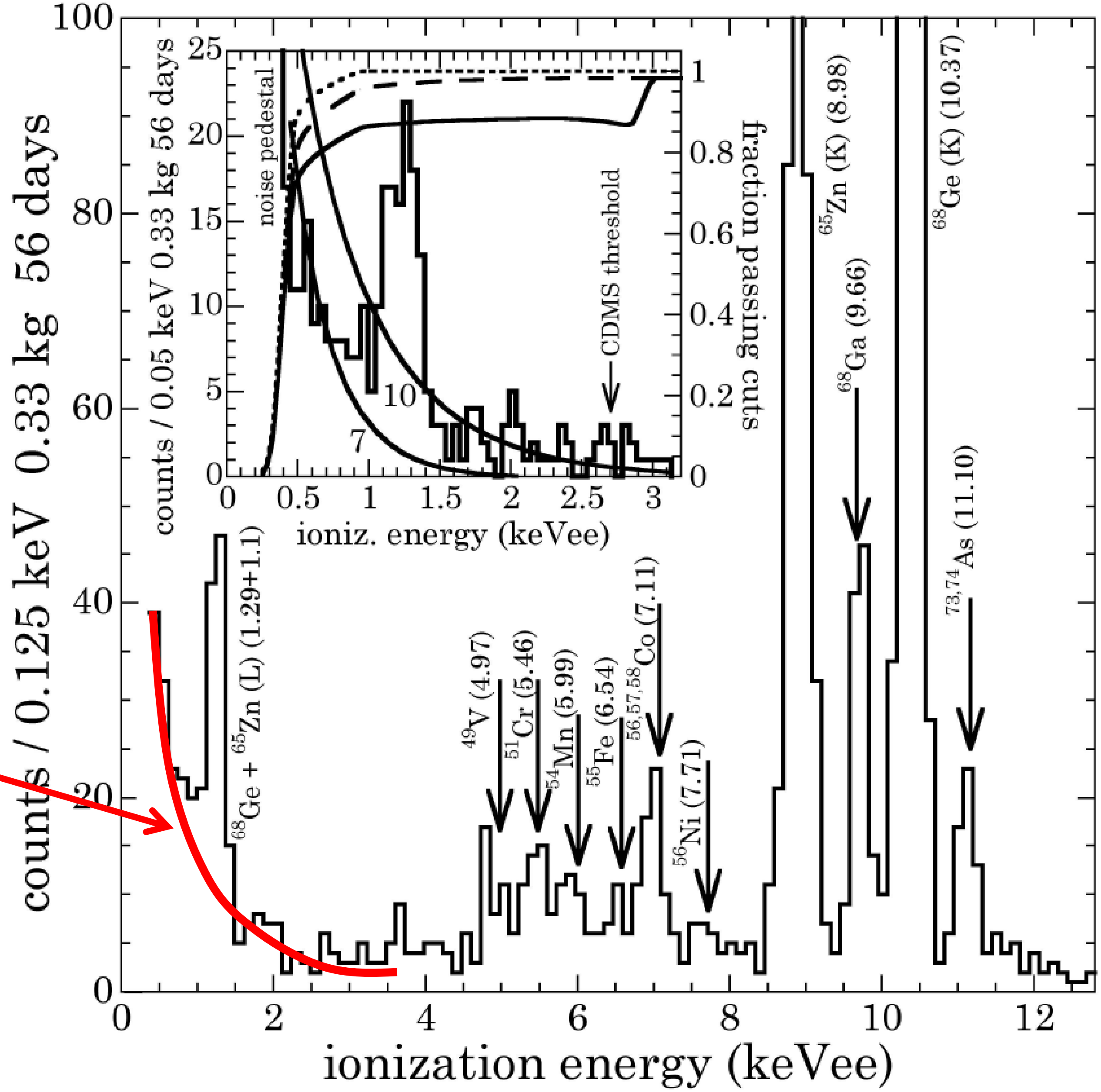


Contact GErmaNium deTector - COGENT

330g germanium Crystal

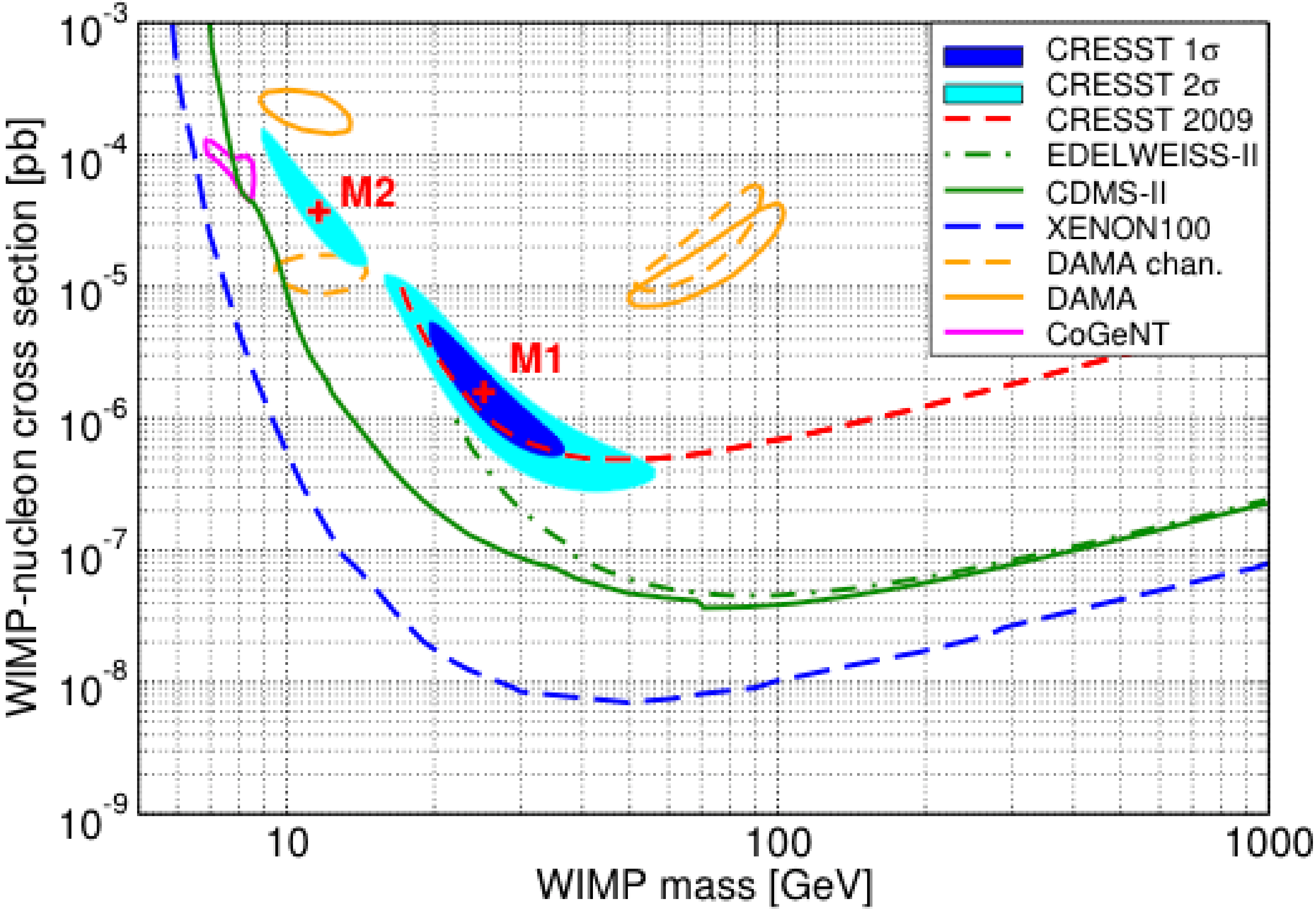
Soudan Mine Minnesota

excess background not understood in terms of radioactive contamination

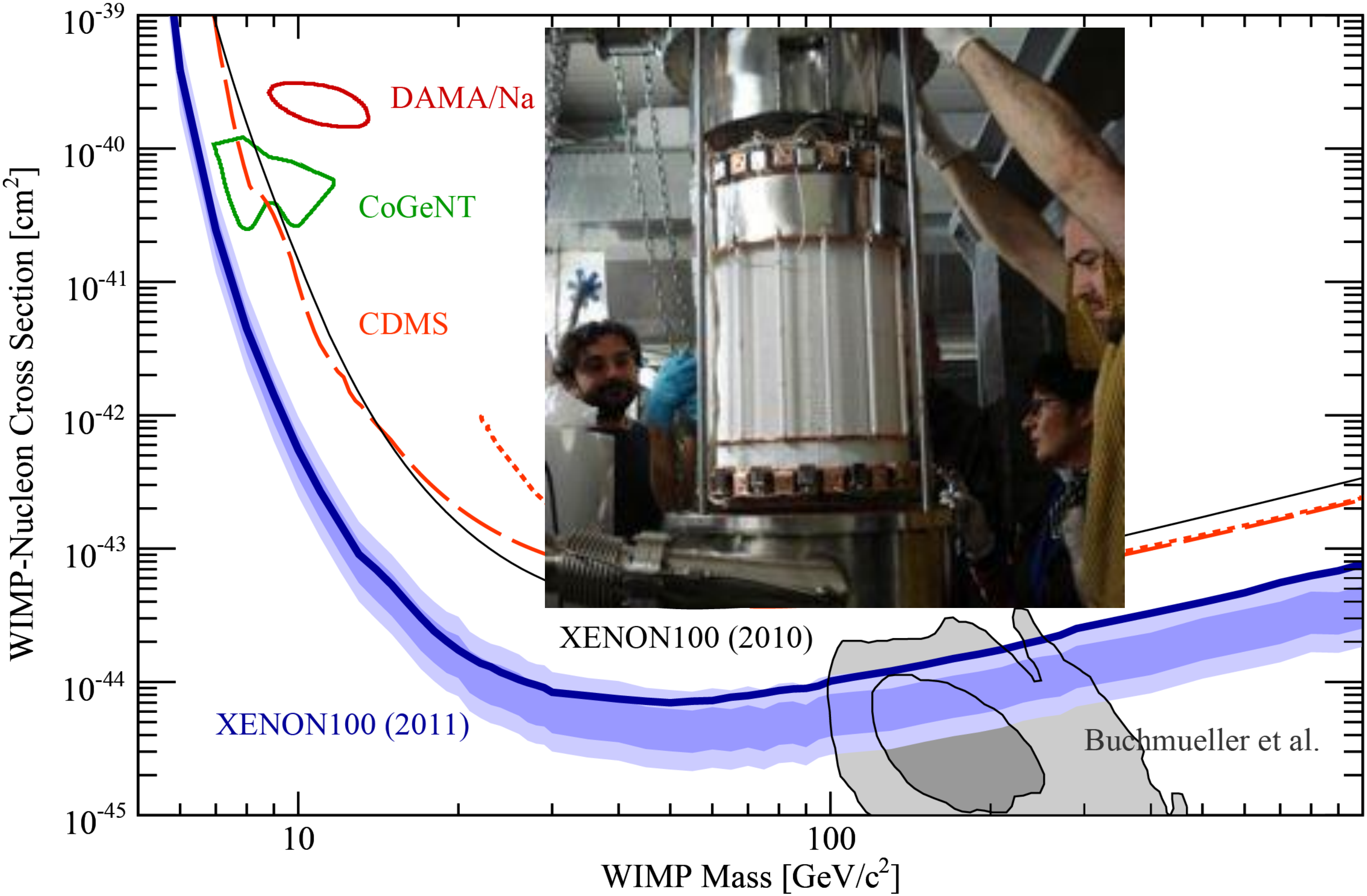


Aalseth et al arXiv: 1002.4703

CoGeNT, DAMA and CRESST Suggest Low Mass (10 GeV) Dark Matter but ruled out by XENON and CDMS



The State of the ART: XENON100

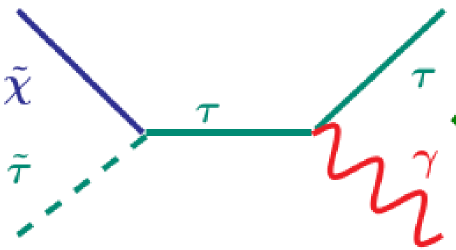


XENON 100 result using new scintillation data 1104.2549

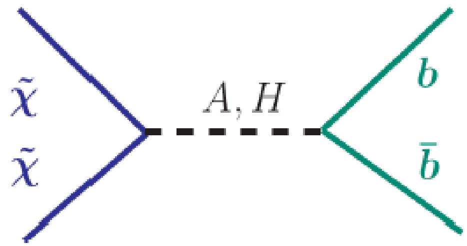
Neutralino relic density in mSUGRA

most of the parameter space is ruled out! $\Omega h^2 \gg 1$

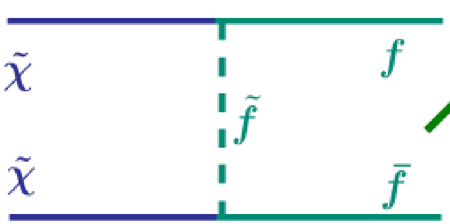
special regions with high σA *are required to get* $0.094 < \Omega h^2 < 0.129$

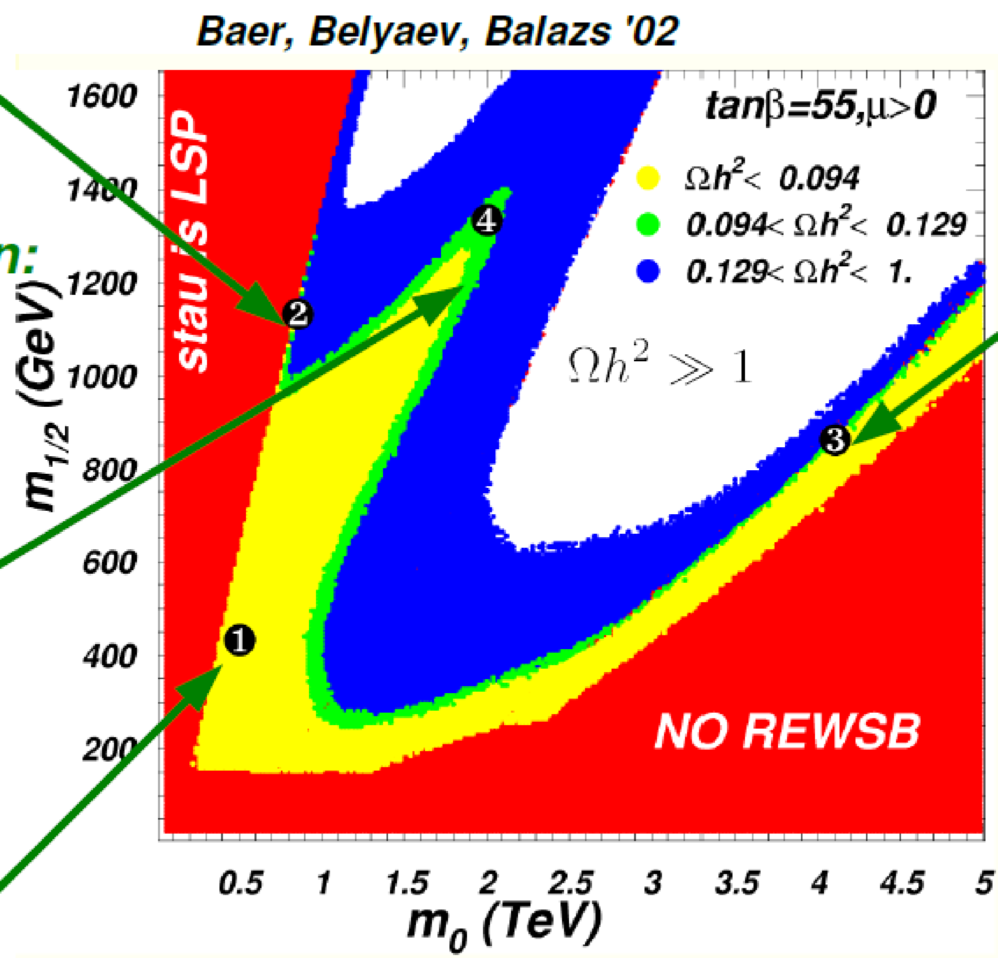


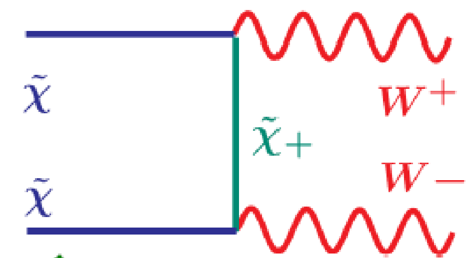
2. stau coannihilation:
degenerate χ and stau



4. funnel: *(large tanβ)*
annihilation via A, H







3. focus point:
mixed neutralino,
low μ, importance of
higgsino-wino
component

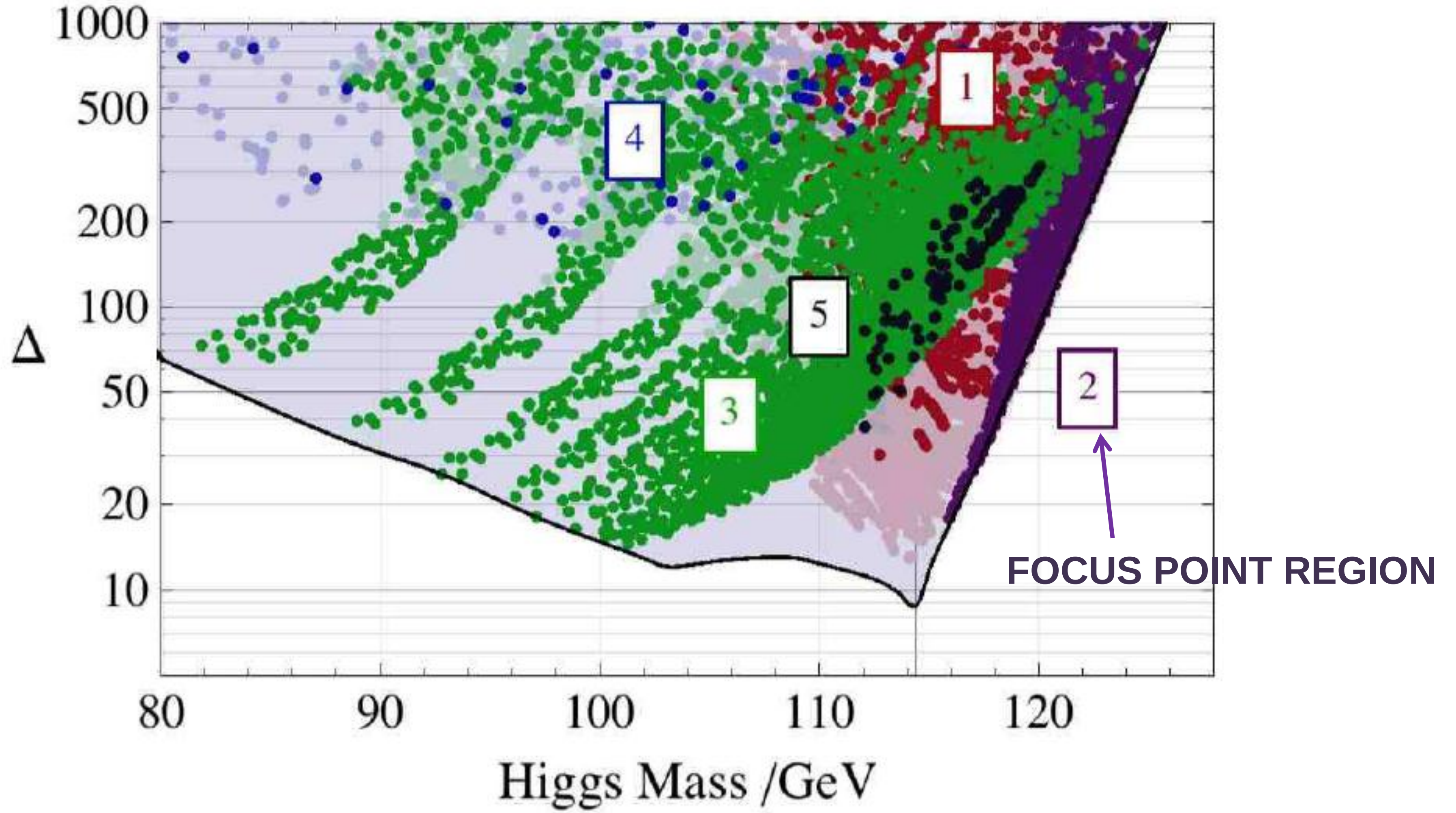
additional regions:
Z/h annihilation
stop coannihilation

1. bulk region: light sfermions

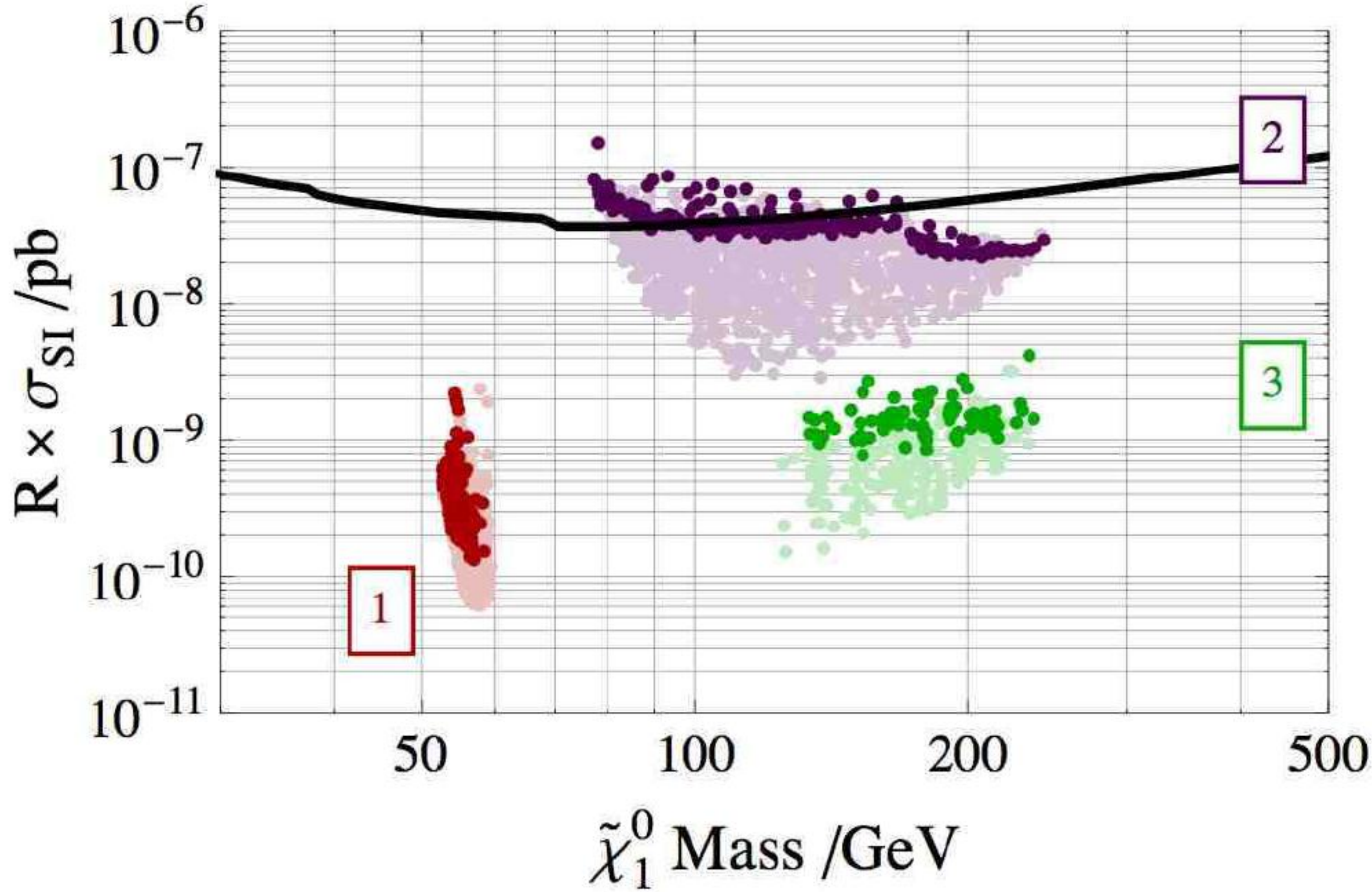
Fine Tuning in MSSM

Fine-tuning implications for complementary dark matter and LHC SUSY searches

S. Cassel [a], D. M. Ghilencea [b,c,§], S. Kraml [d], A. Lessa [e], G. G. Ross [a †]

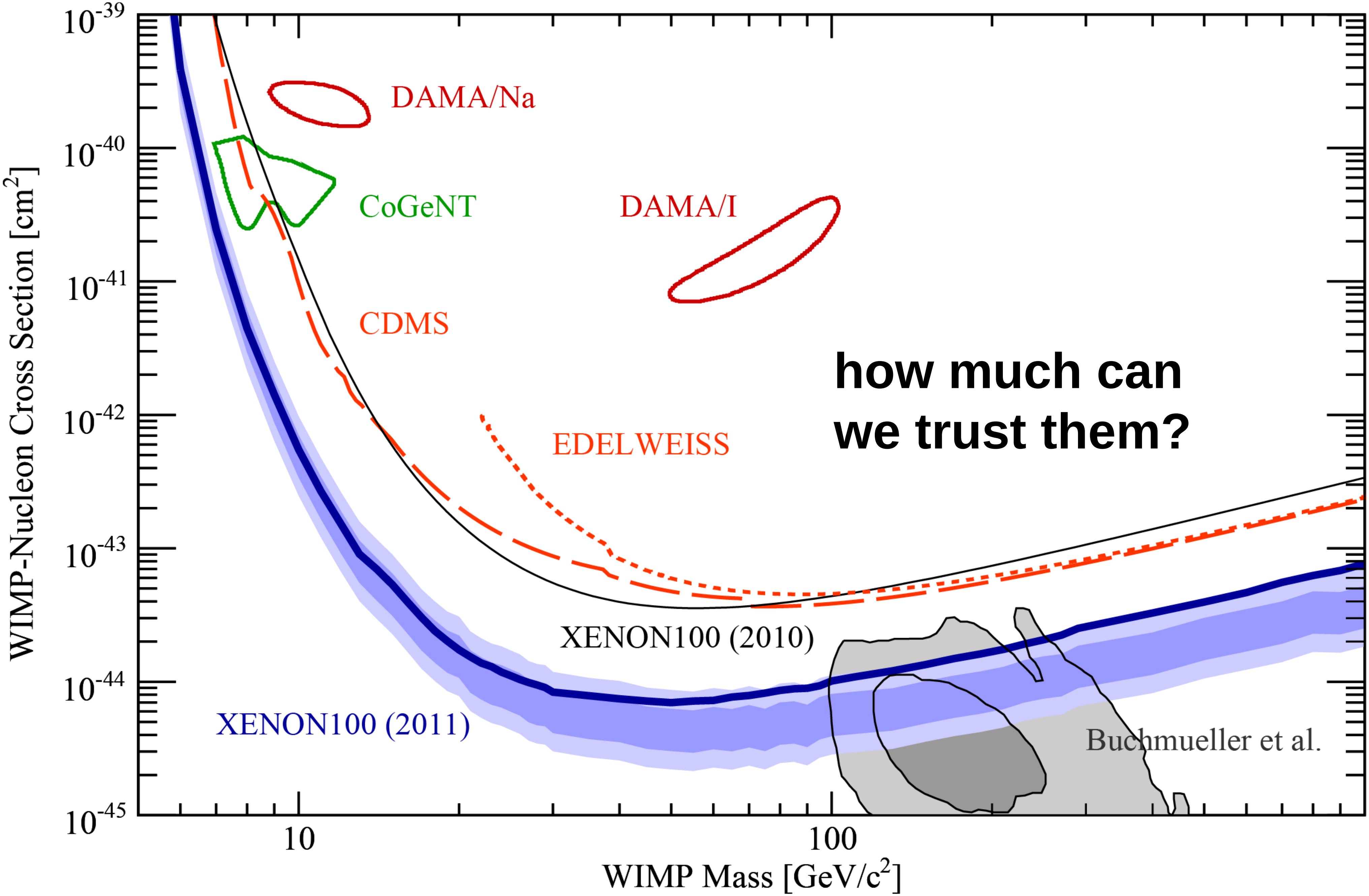


Focus point region in MSSM leads to large cross section



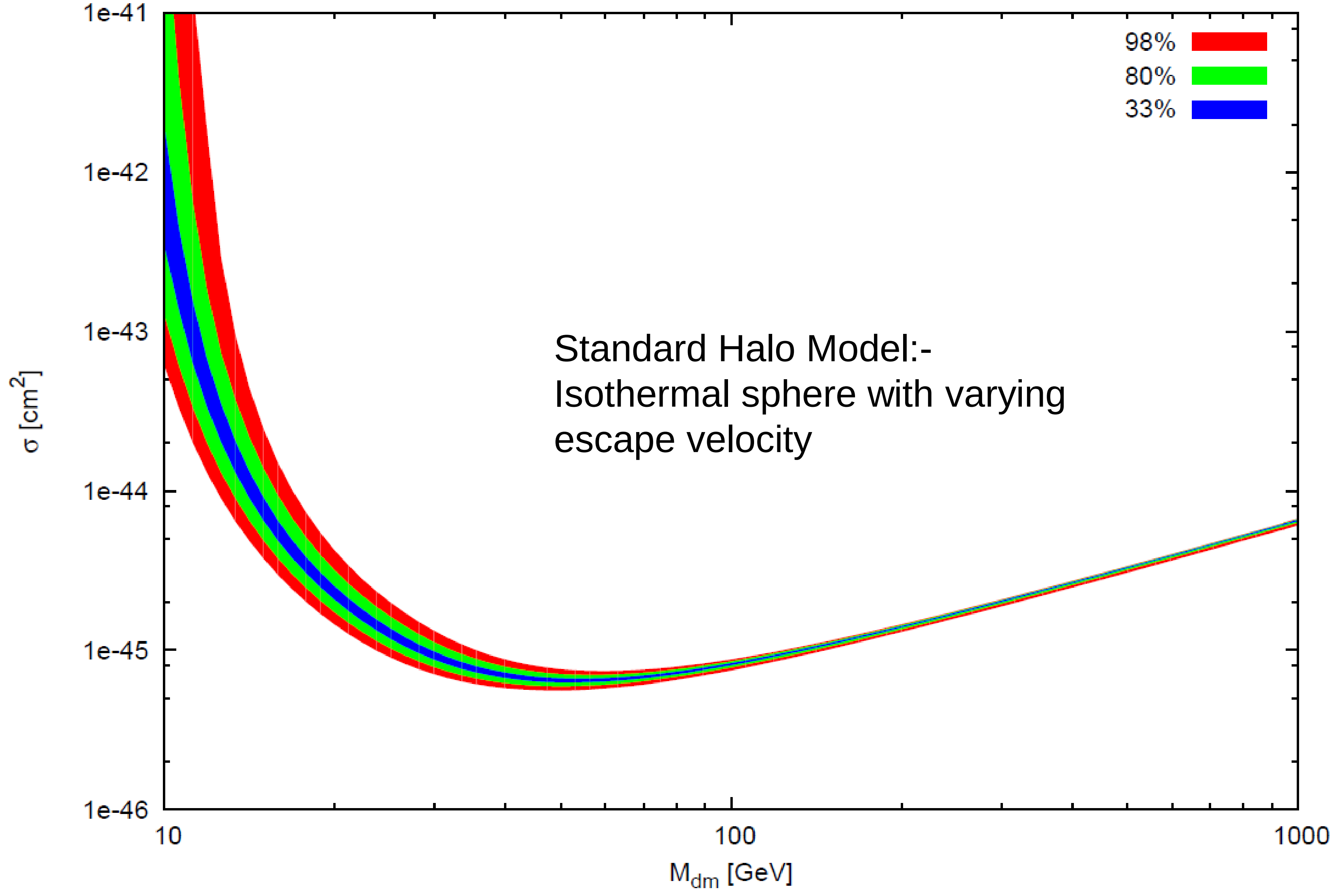
(a) $\tan\beta \leq 45$

Current Limits Becoming Severe.



XENON 100 result using new scintillation data 1104.2549

Idealised Xenon Detector
(to illustrate uncertainties assumed in their paper)



Spherical Sources of Astrophysical Uncertainty

- Uncertain Density profile
- Uncertain mass of galaxy
- Spherical Baryonic contraction
- Non Maxwellian Velocities
- Lack of knowledge of velocity Anisotropy β(r)
- Uncertain solutions to Jeans Equation

Solutions of Jeans Equations

Cannot observe this so cannot be fitted

Can obtain this by fitting data

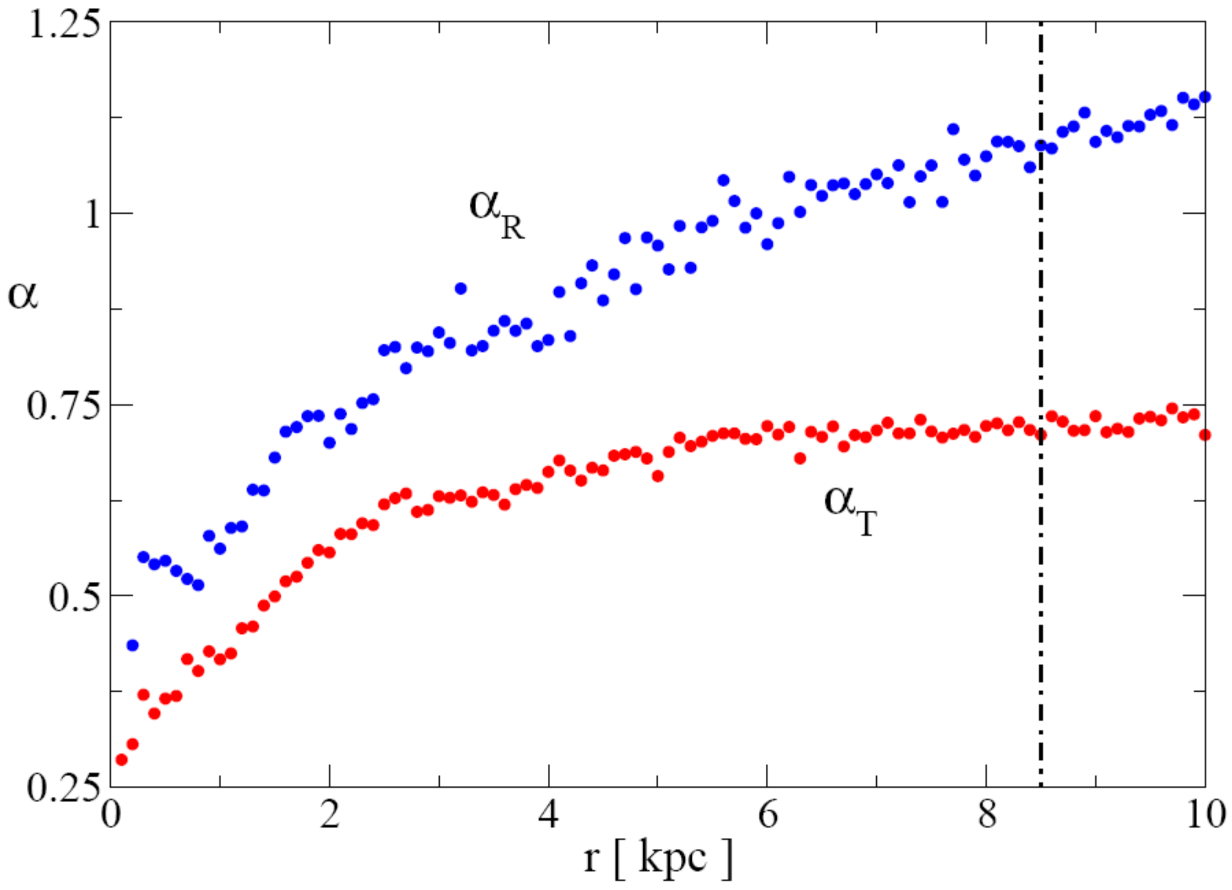
$$\frac{1}{\rho}\frac{\partial}{\partial r}\left(\rho\sigma_R^2\right) + 2\frac{\beta\sigma_R^2}{r} = -\frac{GM}{r^2}$$

Tangential Velocity Dispersion

$$\beta \equiv 1 - \frac{\sigma_t^2}{\sigma_r^2}$$

Radial Velocity Dispersion

Via Lactea non-Gaussianity and anisotropy

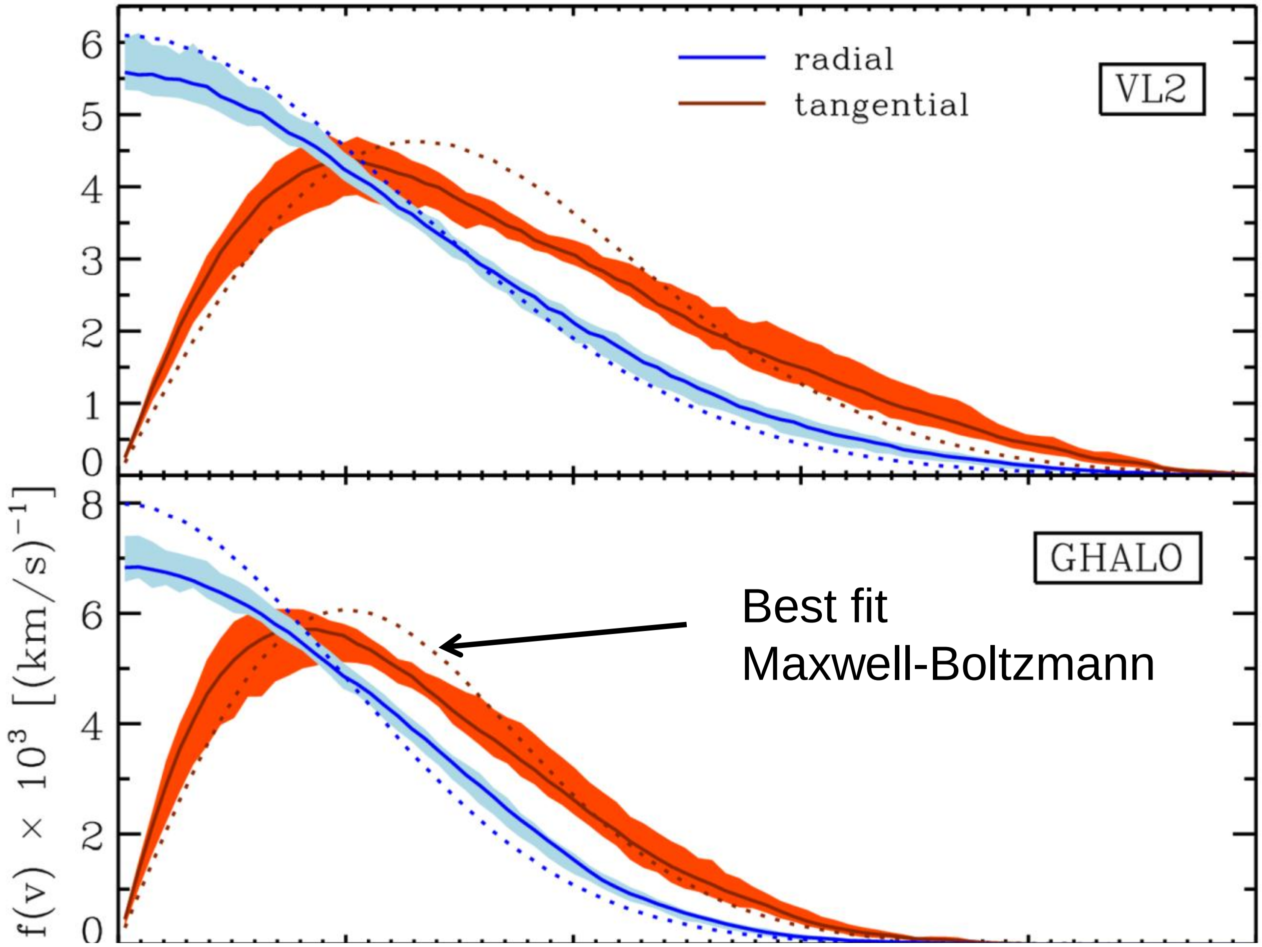


$$\frac{1}{N_R}\exp\left[-\left(\frac{\tilde{v}_R^2}{f_R^2}\right)^{\alpha_R}\right] \qquad \frac{2\pi v_T}{N_T}\exp\left[-\left(\frac{\tilde{v}_T^2}{f_T^2}\right)^{\alpha_T}\right]$$

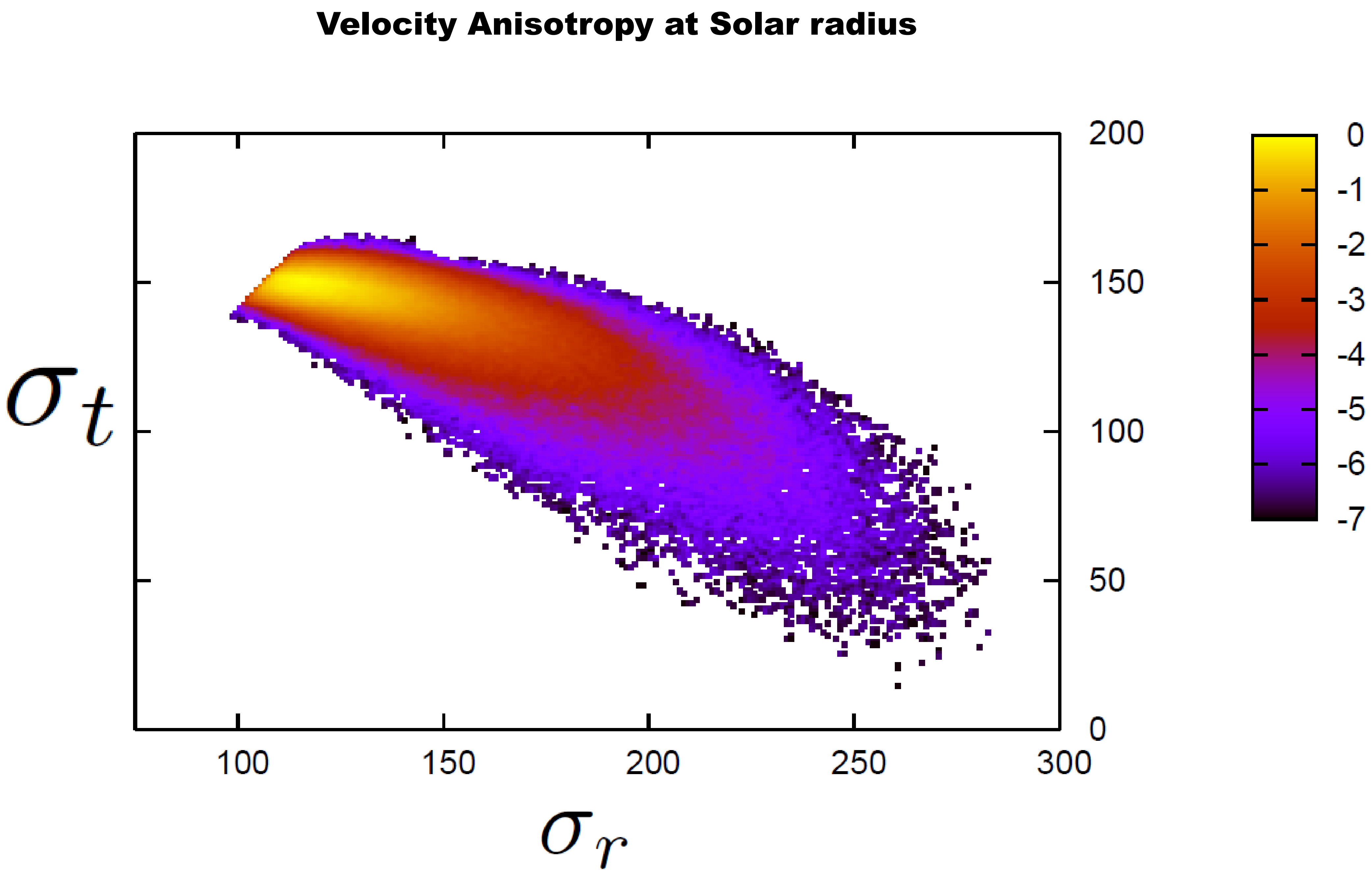
MF and Schwetz : arXiv 0808.0704 :

Velocity distributions around 8.5 kpc.

Kuhlen et al. arXiv: 0912.2358

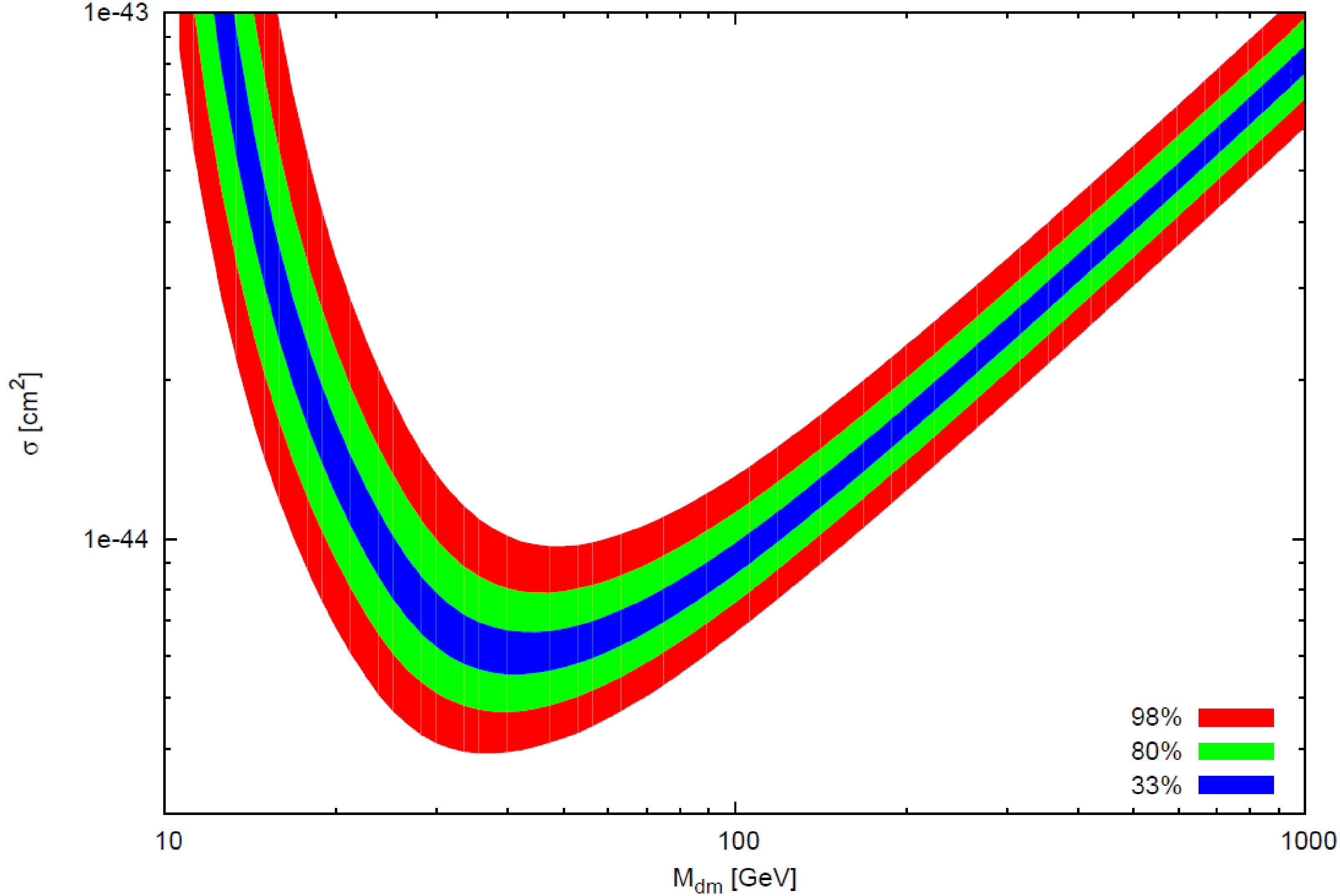


		radial				tangential			
		shell	median	16^{th}	84^{th}	shell	median	16^{th}	84^{th}
VL2	$\bar{v}_{r,t}$ [km/s]	202.4	199.9	185.5	212.7	128.9	135.1	124.2	148.9
	$\alpha_{r,t}$	0.934	0.941	0.877	0.985	0.642	0.657	0.638	0.674
GHALO	$\bar{v}_{r,t}$ [km/s]	167.9	163.6	156.4	173.0	103.1	114.3	93.21	137.0
	$\alpha_{r,t}$	1.12	1.11	1.02	1.20	0.685	0.719	0.666	0.819
$GHALO_s$	$\bar{v}_{r,t}$ [km/s]	217.9	213.8	202.3	226.6	138.2	162.2	125.1	183.1
	$\alpha_{r,t}$	1.11	1.11	1.01	1.18	0.687	0.759	0.664	0.842



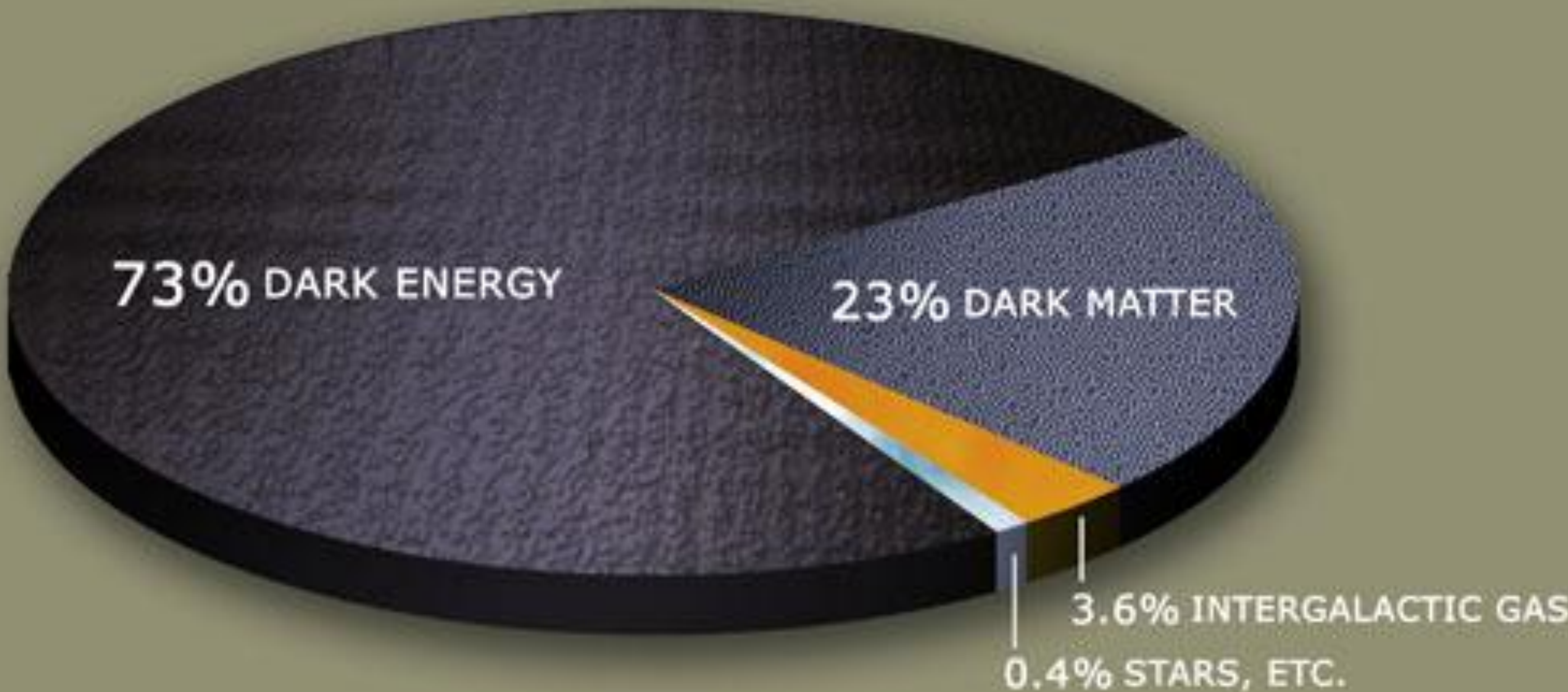
Velocity Anisotropy at Solar radius
σ_t
σ_r
100
150
200
250
300
0
50
100
150
200
0
-1
-2
-3
-4
-5
-6
-7

Final Broadening including all effects



If we also include Form Factors (yesterday's talk by Laurent Lellouch) uncertainty is easily more than an order of magnitude, even for Spherical halos. If we then start including dark disks…

Would be nice if it was about 7 GeV!



“Asymmetric Dark Matter”

Capture of dark matter onto stars

Capture rate can be approximated by simple expression

$$\Gamma_c = \left(\frac{8}{3\pi}\right)^{1/2} \frac{\rho_{dm}\bar{v}}{m_{dm}} \left(\frac{3v_{esc}^2}{2\bar{v}^2}\right) \frac{M_*}{m_p} \sigma$$

1. Dark matter density
2. Dark matter velocity
3. Escape velocity of star
4. Number of targets in star (nucleons)
5. Cross section per target

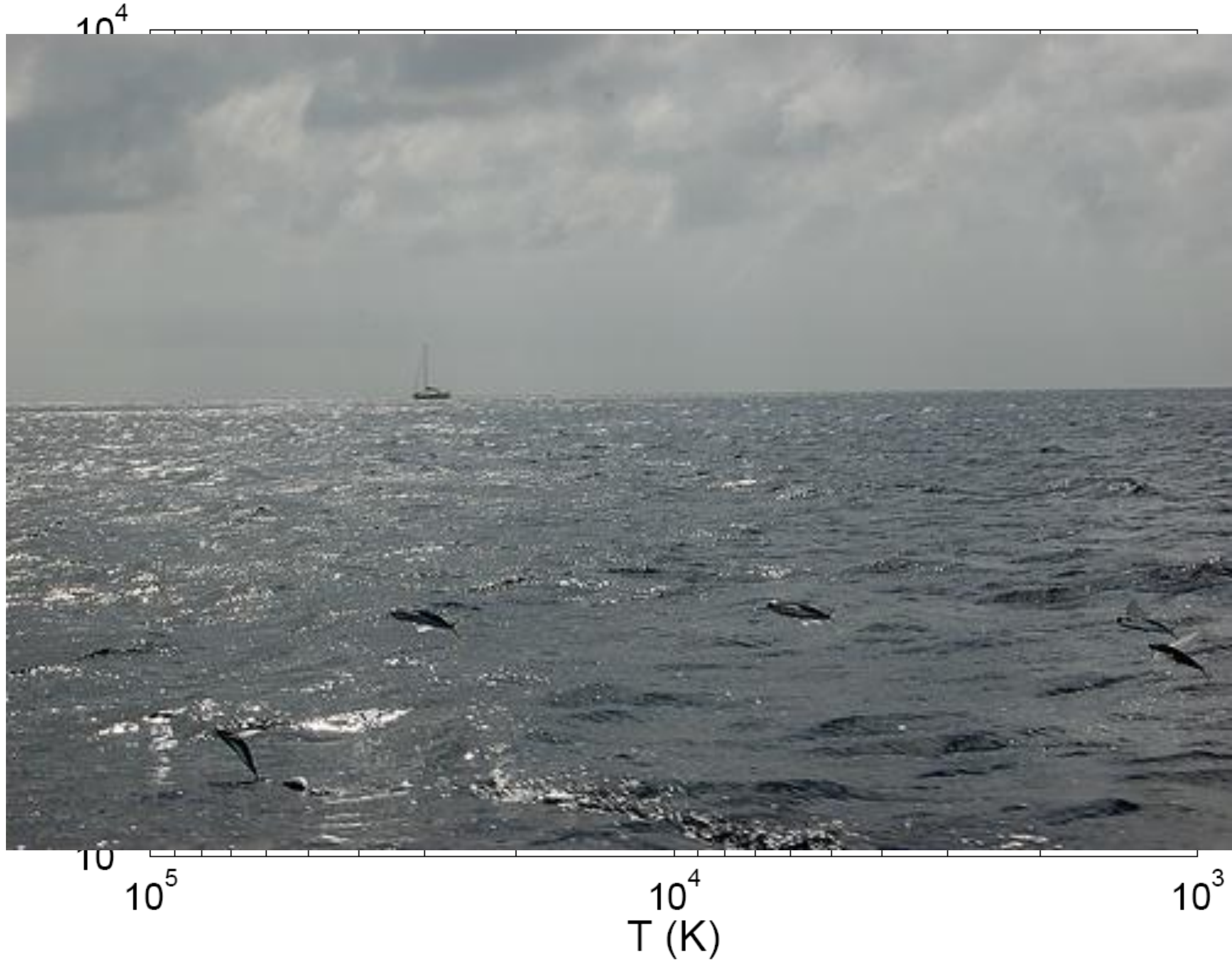
Equations of stellar structure have solutions which are stars

$$\frac{dM_r}{dr} = 4\pi r^2 \rho$$

$$\frac{dP}{dr} = -\frac{GM_r}{r^2}\rho$$

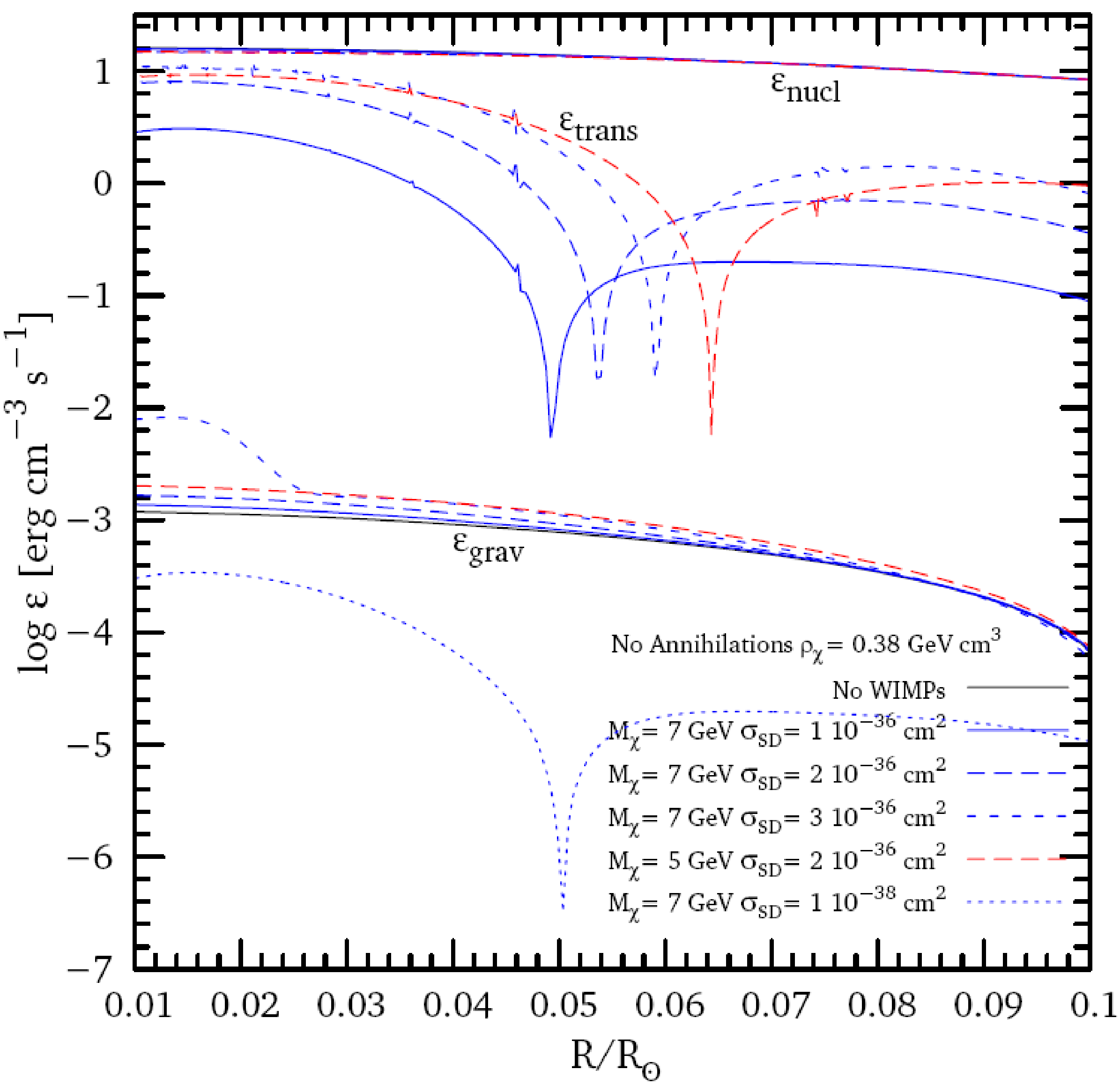
$$\frac{dL_r}{dr} = 4\pi r^2 \epsilon \rho$$

$$\frac{dT}{dr} = -\frac{1}{4\pi r^2 \lambda} L_r$$



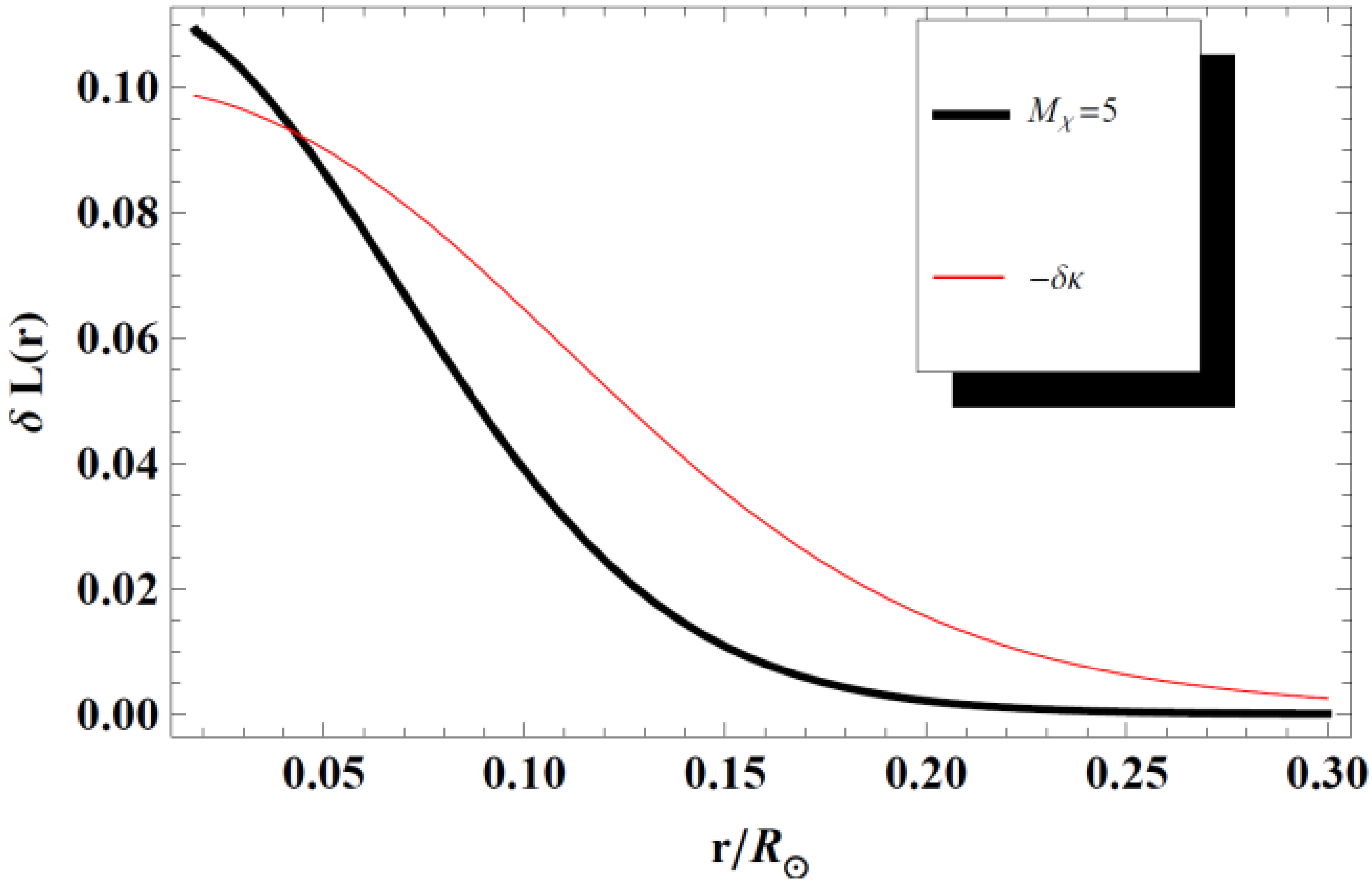
Scattering of WIMPs can reduce opacity

Energy transport for non-annihilating dark matter



Taoso et al arXiv:1005.5711

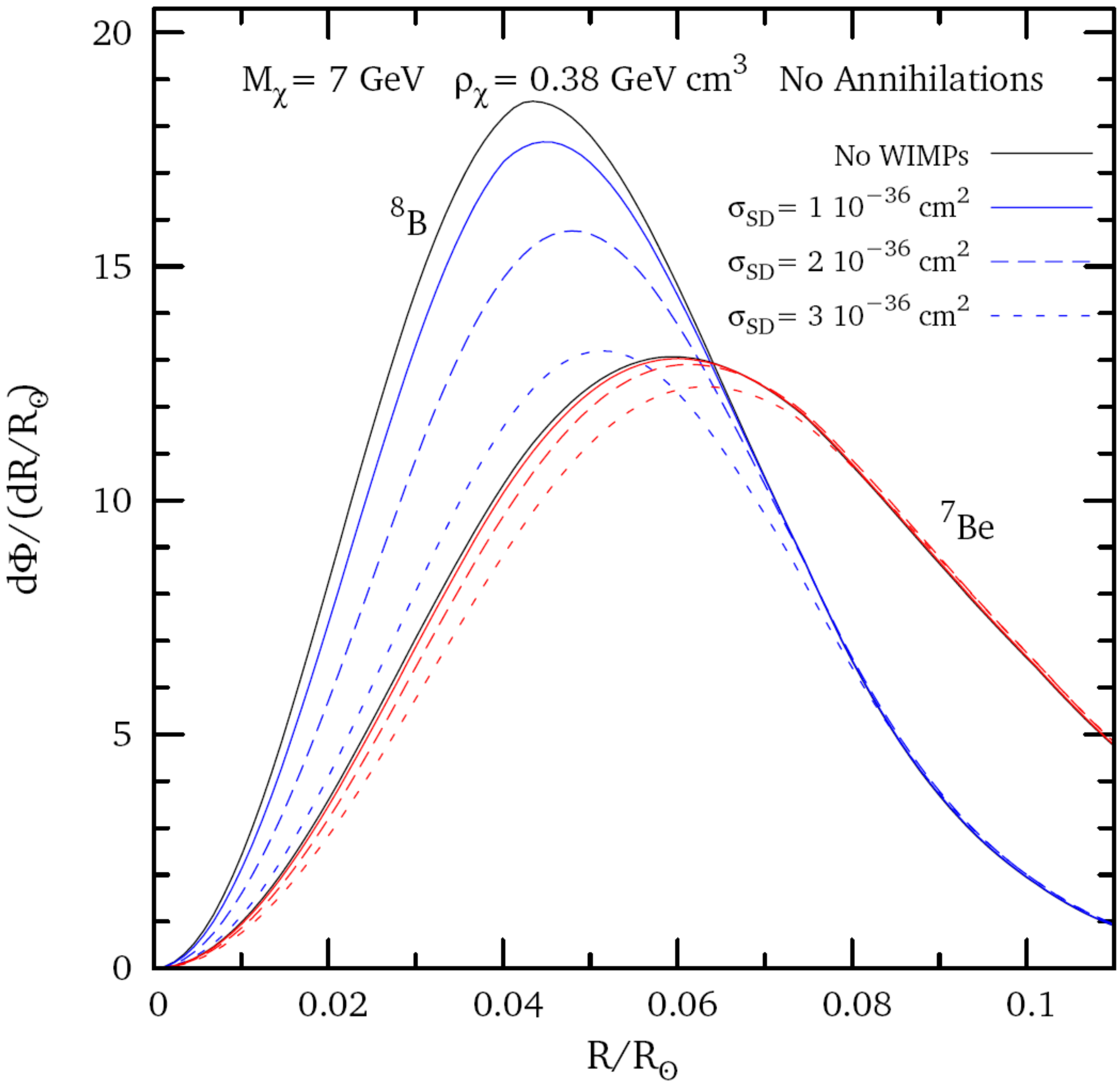
Fractional change in Luminosity as function of r



$$\delta L(r) \equiv L_\chi(r)/L_\odot(r) - 1$$

Frandsen and Sarkar arXiv:1003.4505

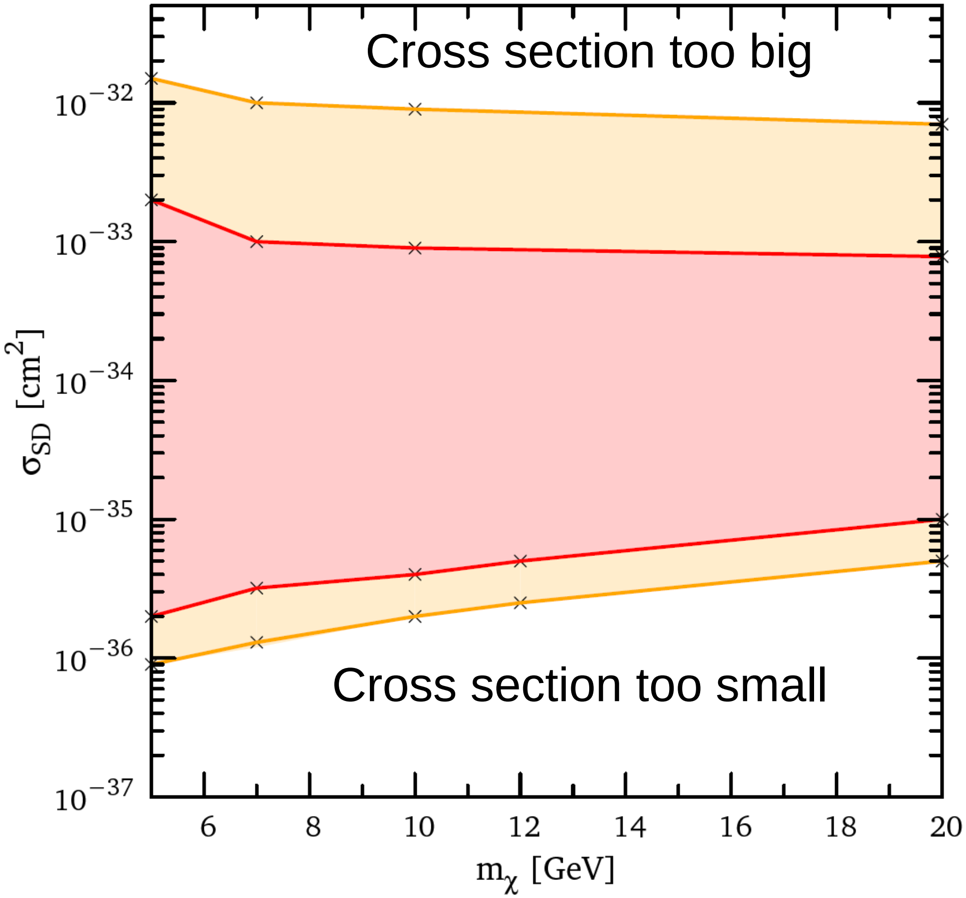
Change in Neutrino Flux due to Presence of Dark Matter

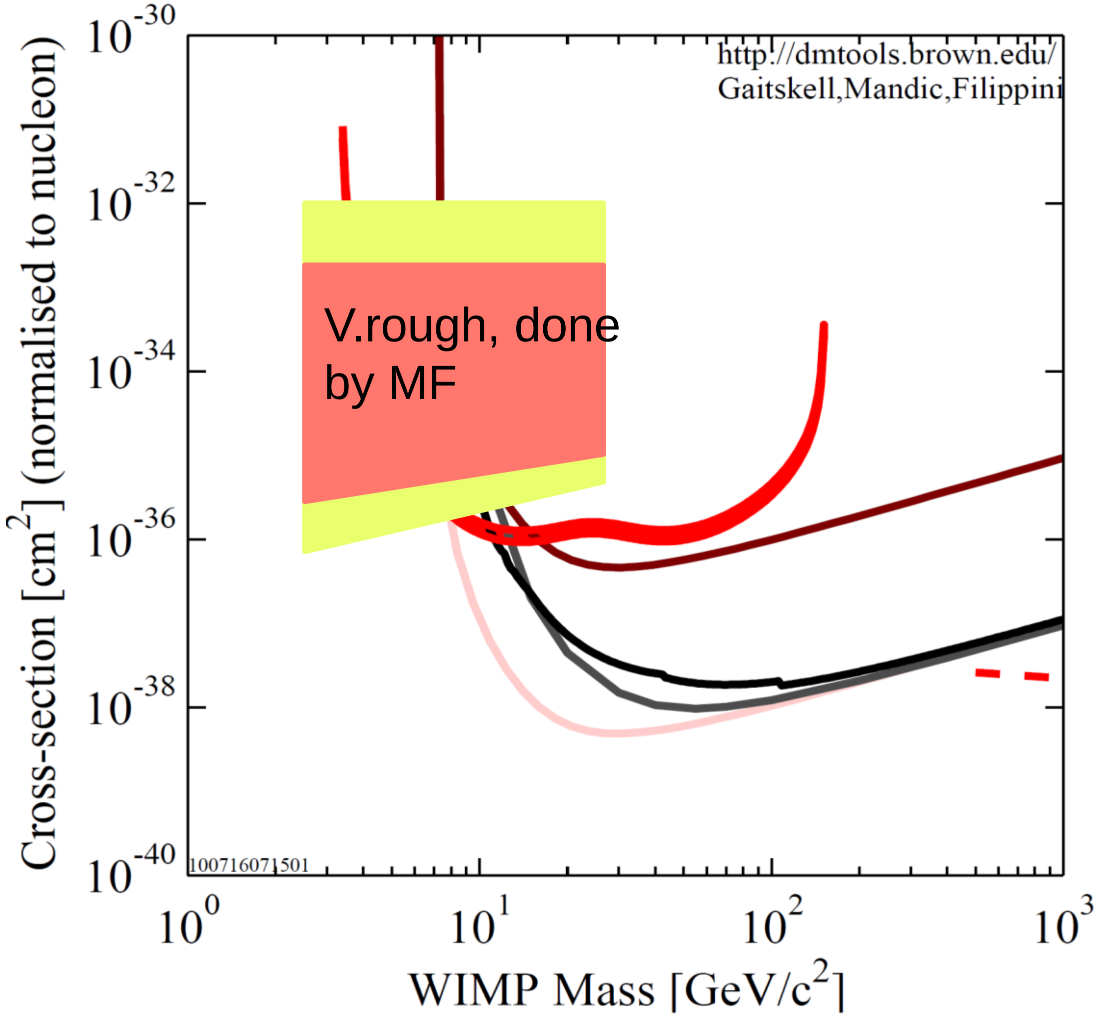


Taoso et al arXiv:1005.5711

^{8}B flux of neutrinos measured with 5% error
^{7}Be within 10%, means that one can put constraints...

… NEW INTERESTING CONSTRAINTS !!





Pink region 25% change
Yellow region 5% change

Taoso et al arXiv:1005.5711

CONCLUSIONS

- Lots of Dark Matter candidates.

- Plenty of independent evidence for WIMP Dark Matter.

- Plenty of people trying to identify its nature.

- Lots of false (?) alarms, there will be more, and more and more....

- If it is weakly interacting, it should be possible to detect it in the next decade.

Dark Energy

Relationship between time and redshift

$$a_0/a(t) = 1 + z$$

$$dt = \frac{-1}{(1+z)}\frac{dz}{H}$$

$$t_0 - t_1 = \int_0^{z_1} \frac{dz}{(1+z)H(z)}$$

To get age of universe take $t_1 \to 0$

$$H^2(z) = H_0^2\left[\Omega_\gamma (1+z)^4 + \Omega_M (1+z)^3 + \Omega_k (1+z)^2 + \Omega_\Lambda\right]$$

So for example for matter $$t_0 = \frac{2}{3H_0}$$

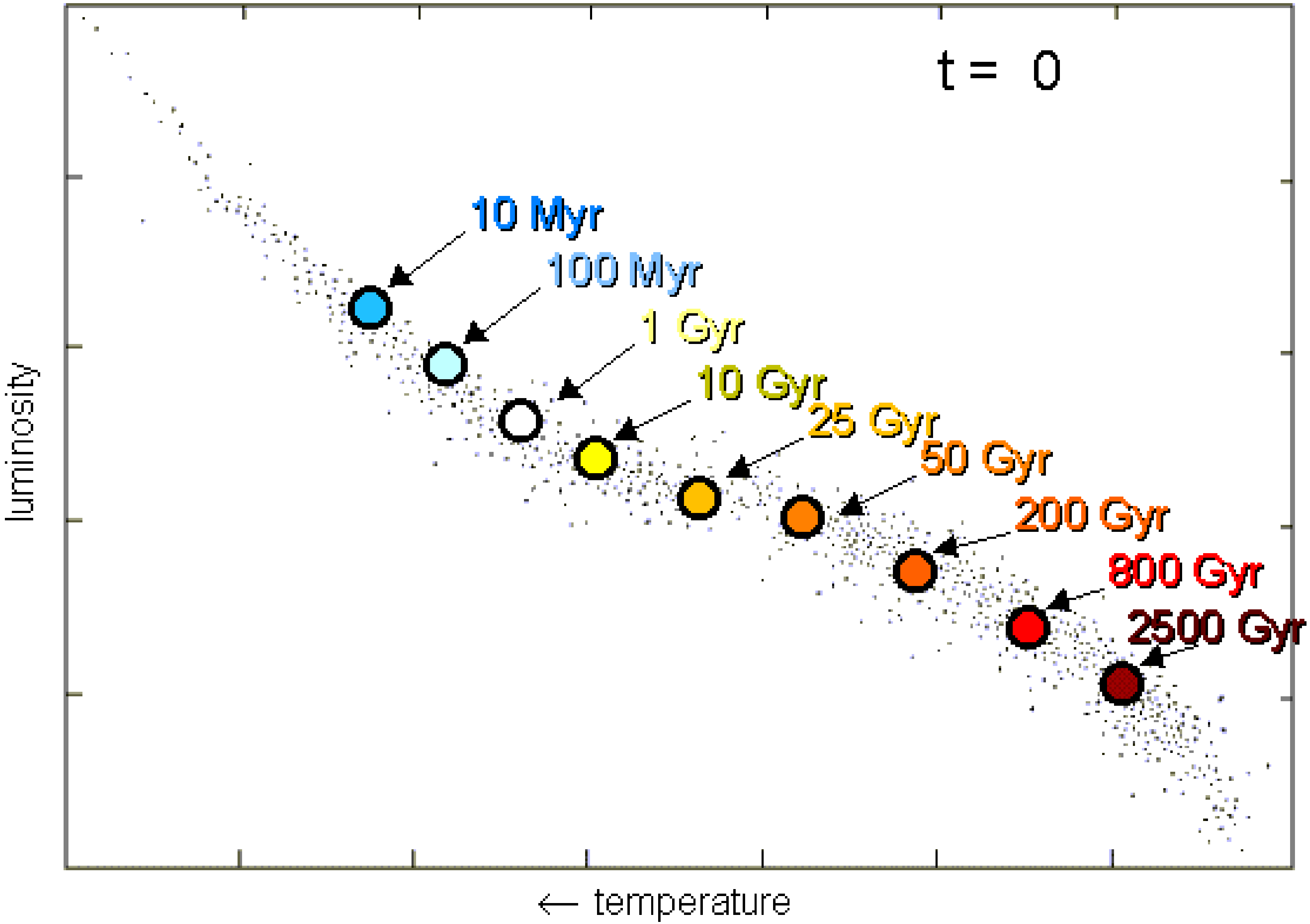
"The star which burns twice as bright burns half as long"
– from the film Bladerunner

A comparison of star sizes

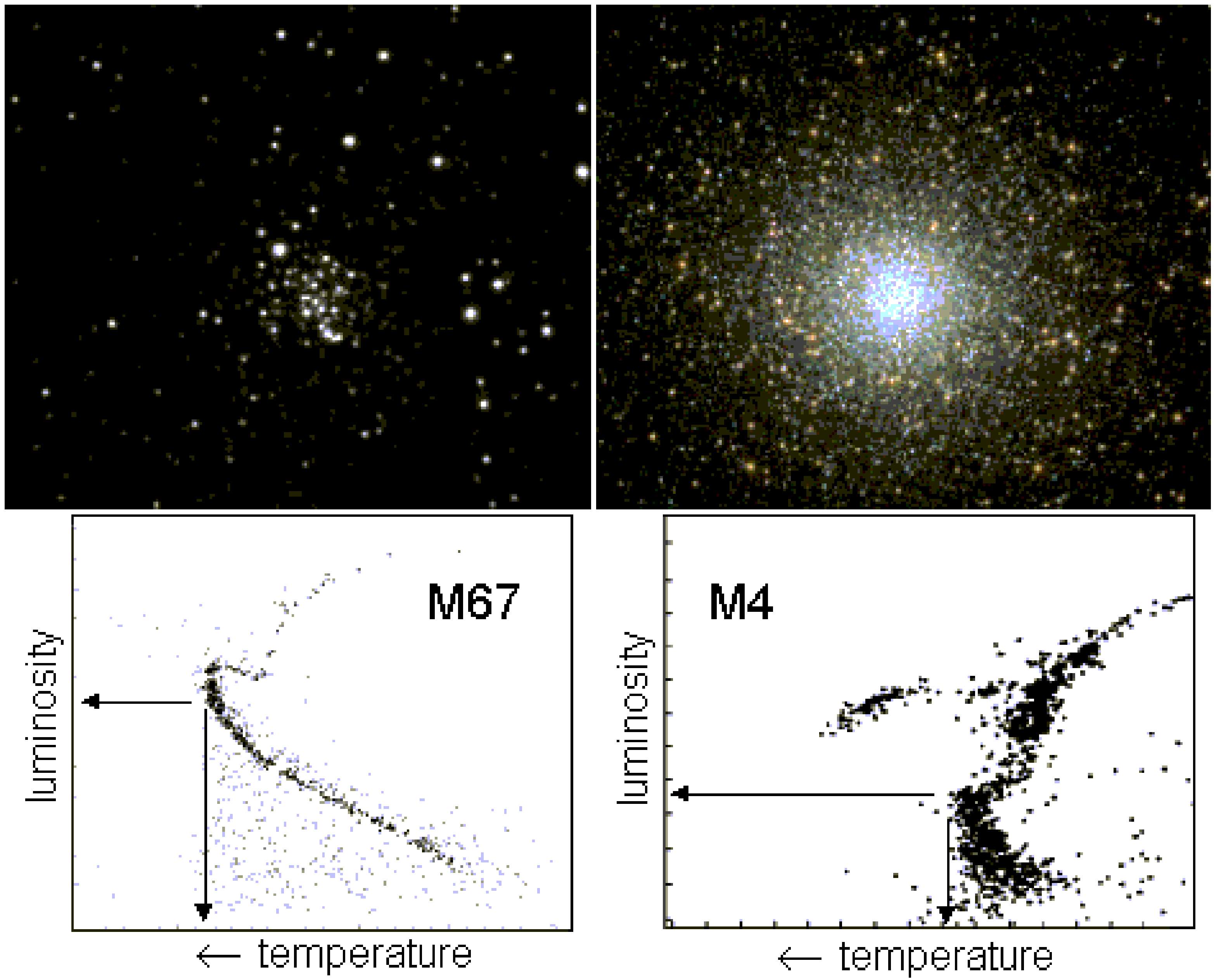
Star	Spectral Type	Mass, *M* (Solar Masses)	Central Temperature (10^6 K)	Luminosity, *L* (Solar Luminosities)	Estimated Lifetime (*M*/*L*) (10^6 years)
Spica B*	B2V	6.8	25	800	90
Vega	A0V	2.6	21	50	500
Sirius	A1V	2.1	20	22	1000
Alpha Centauri	G2V	1.1	17	1.6	7000
Sun	G2V	1.0	15	1.0	10,000
Proxima Centauri	M5V	0.1	0.6	0.00006	16,000,000

**The "star" Spica is, in fact, a binary system comprising a B1III giant primary (Spica A) and a B2V main-sequence secondary (Spica B).*

Time and the HR diagram

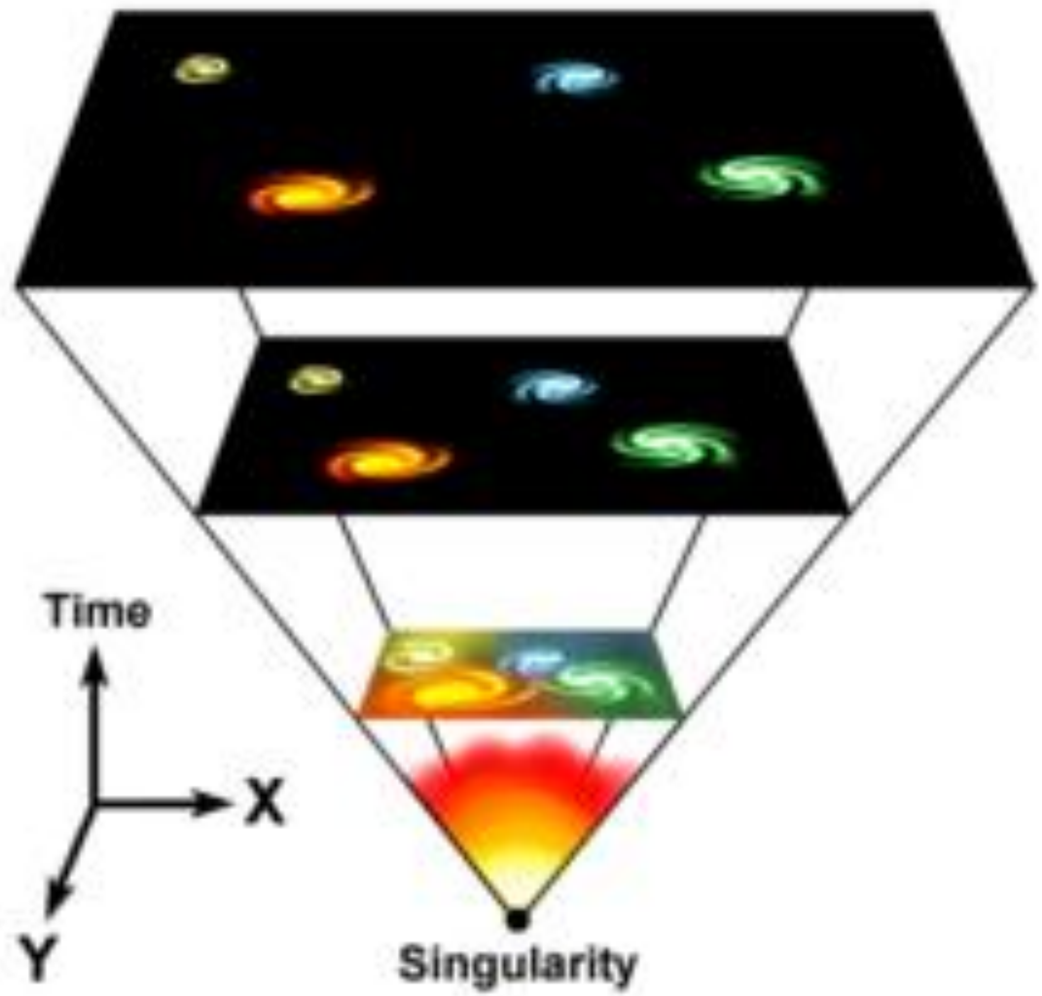


Age of the Universe from Globular Clusters

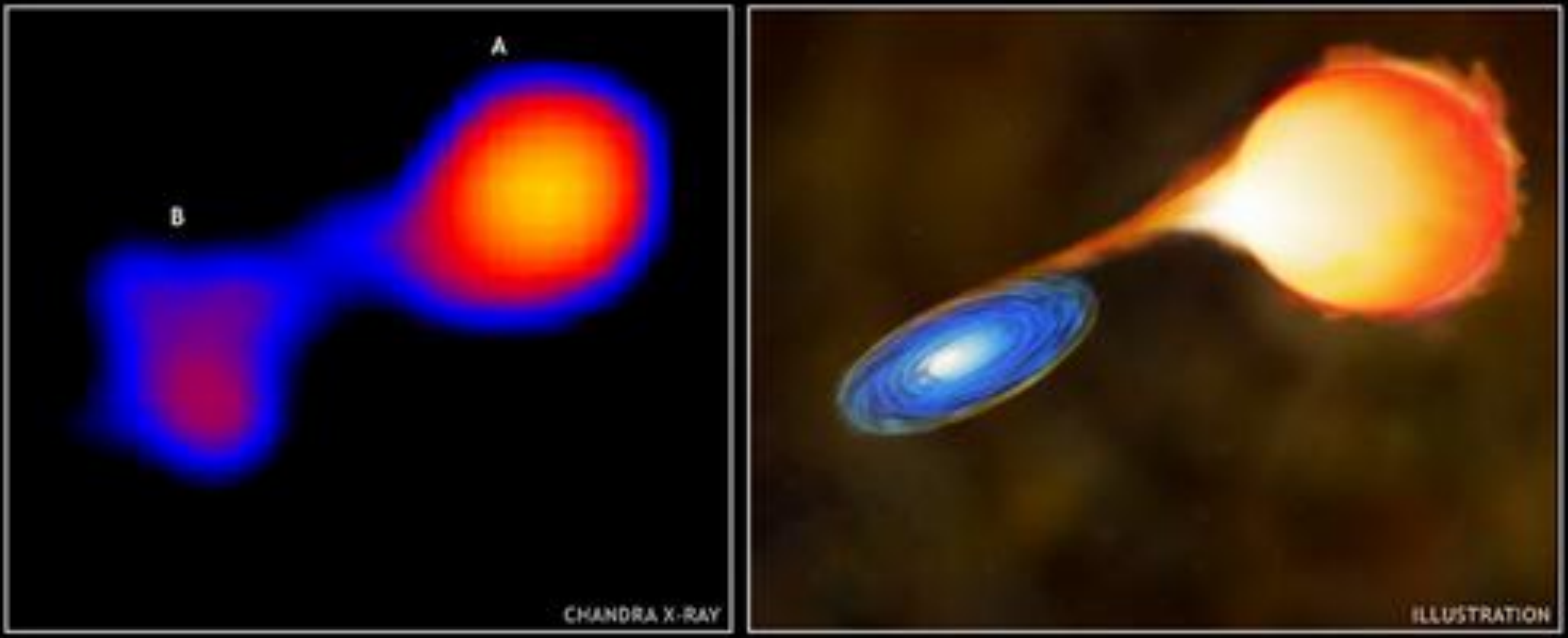


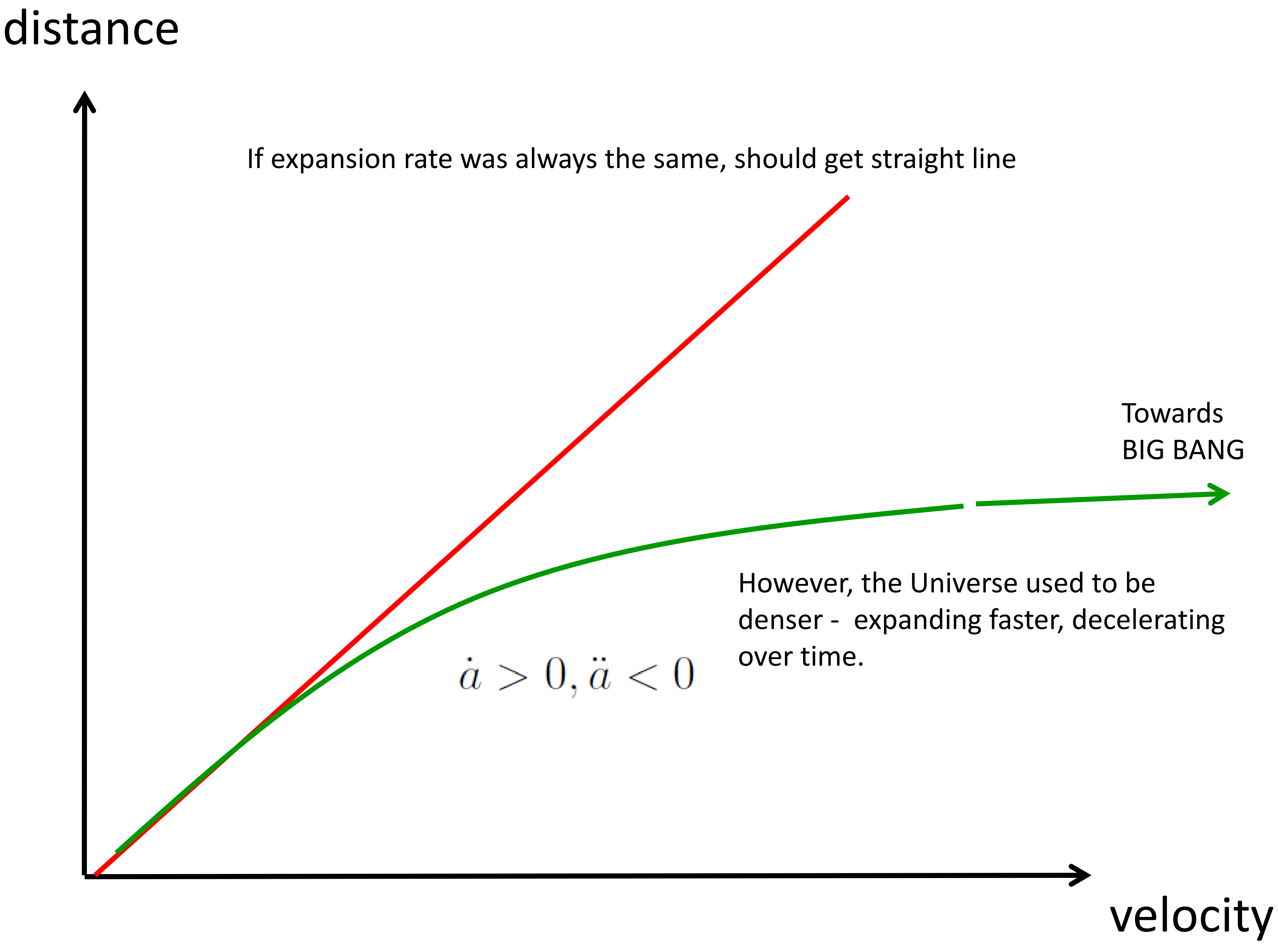
If the Universe just contained matter, its age would be about 9.2 billion years!!

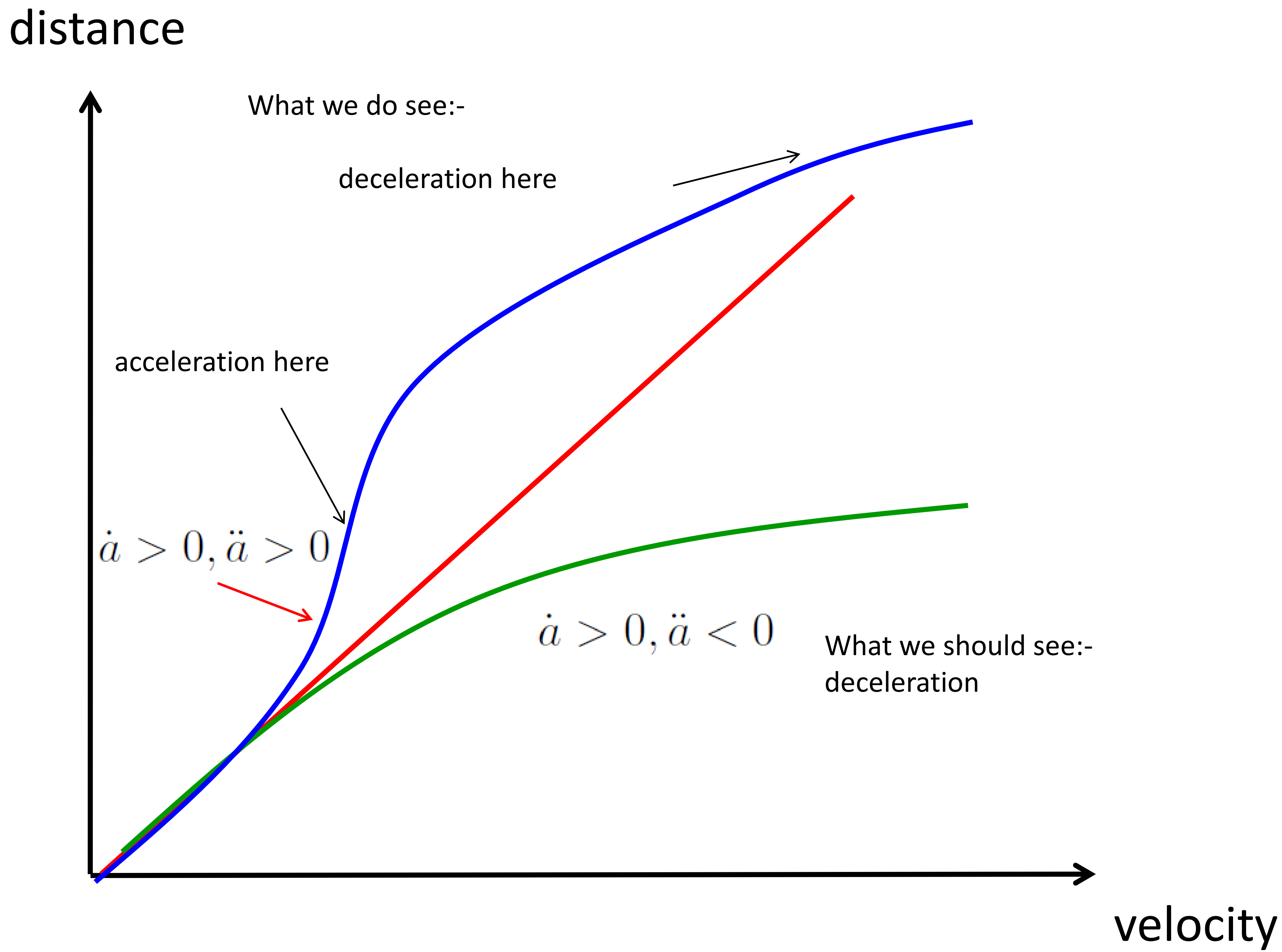
i.e. Not old enough to contain the stars inside it!

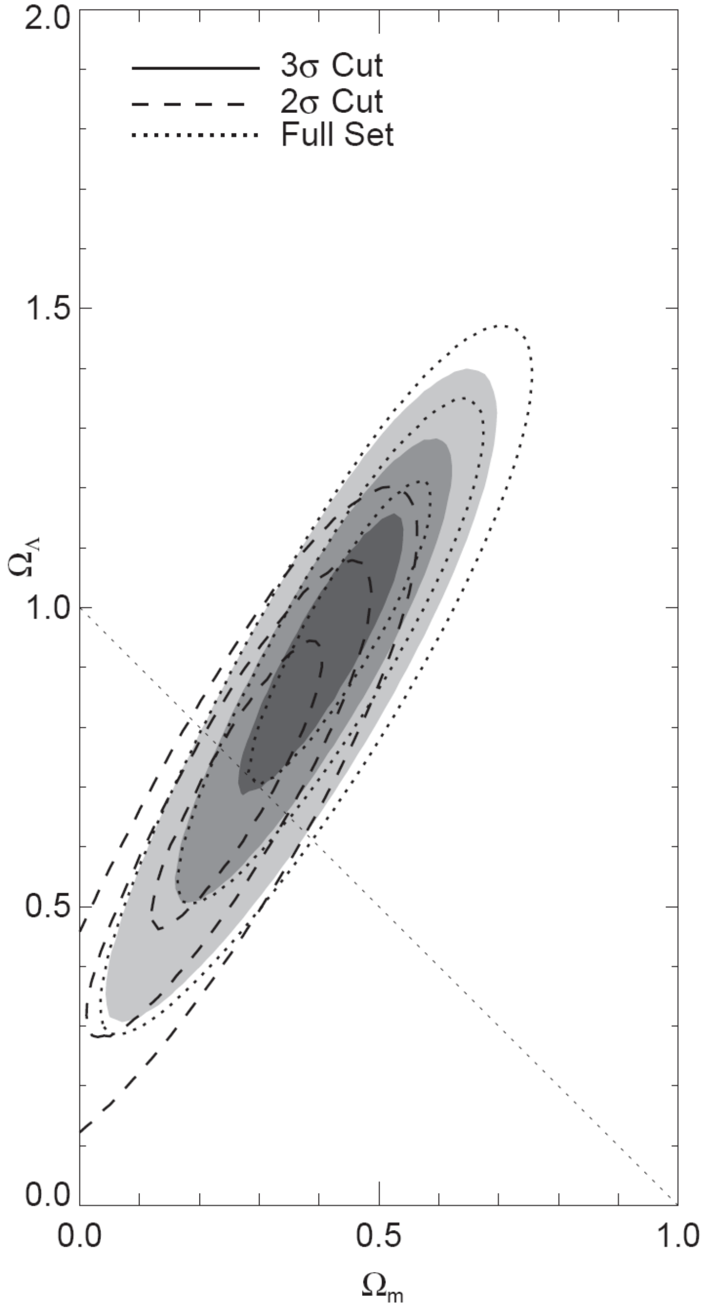


Type 1a supernovae as Standard candles

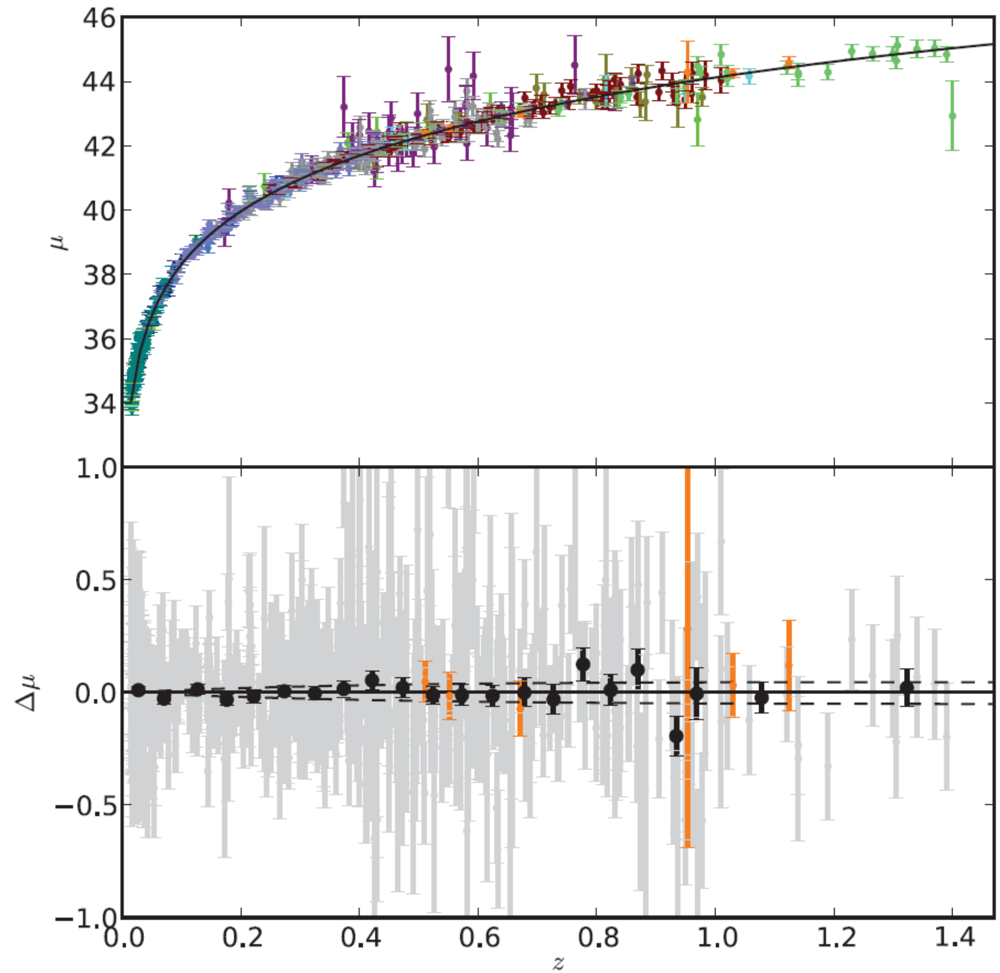



distance
If expansion rate was always the same, should get straight line
Towards
BIG BANG
However, the Universe used to be
denser - expanding faster, decelerating
over time.
$\dot{a} > 0, \ddot{a} < 0$
velocity


distance
What we do see:-
deceleration here
acceleration here
$\dot{a} > 0, \ddot{a} > 0$
$\dot{a} > 0, \ddot{a} < 0$
What we should see:-
deceleration
velocity



Union supernova data set 0804.4142

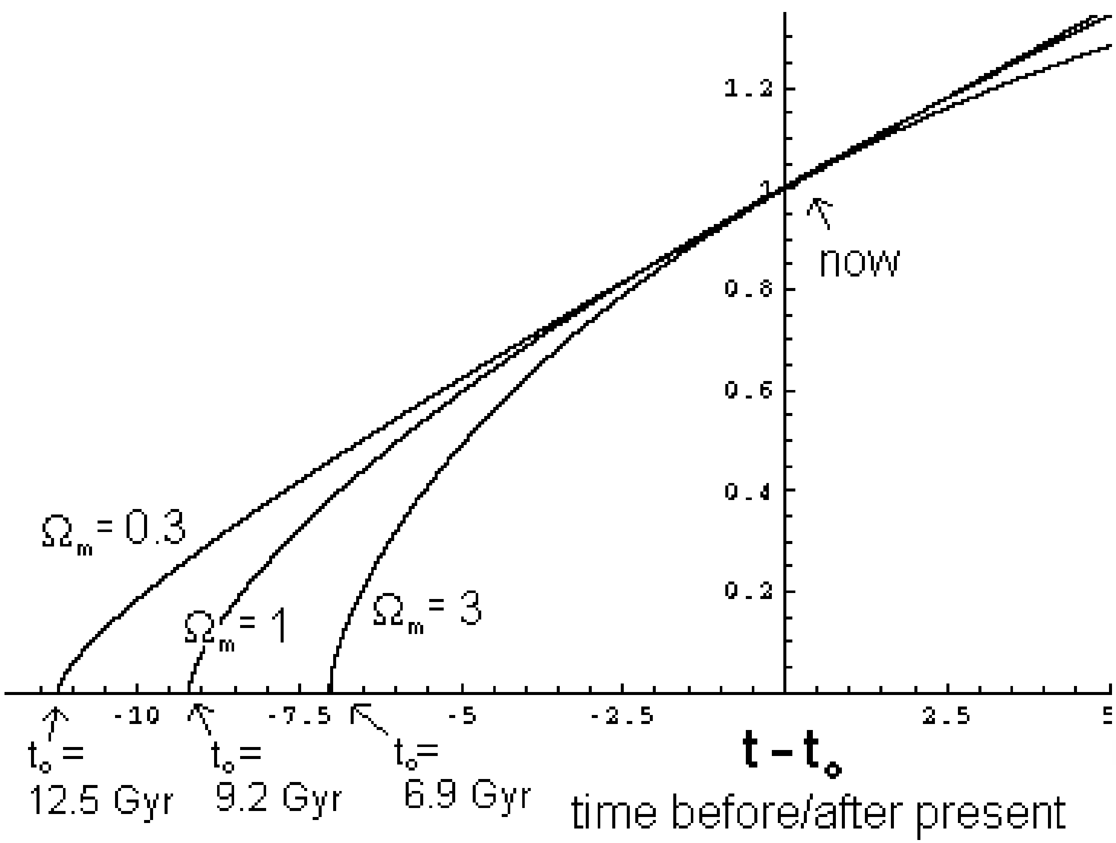


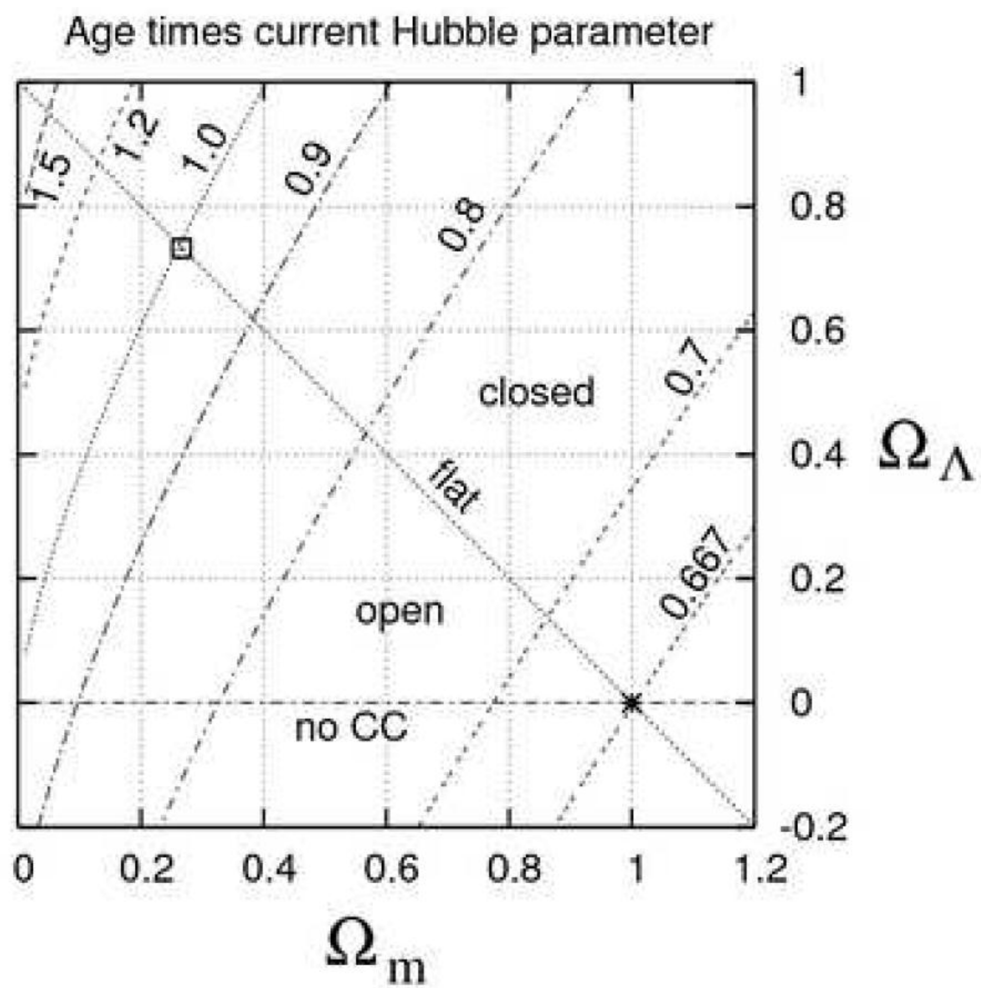
Union2 Compilation1004.1711

Constraint on Age of Universe

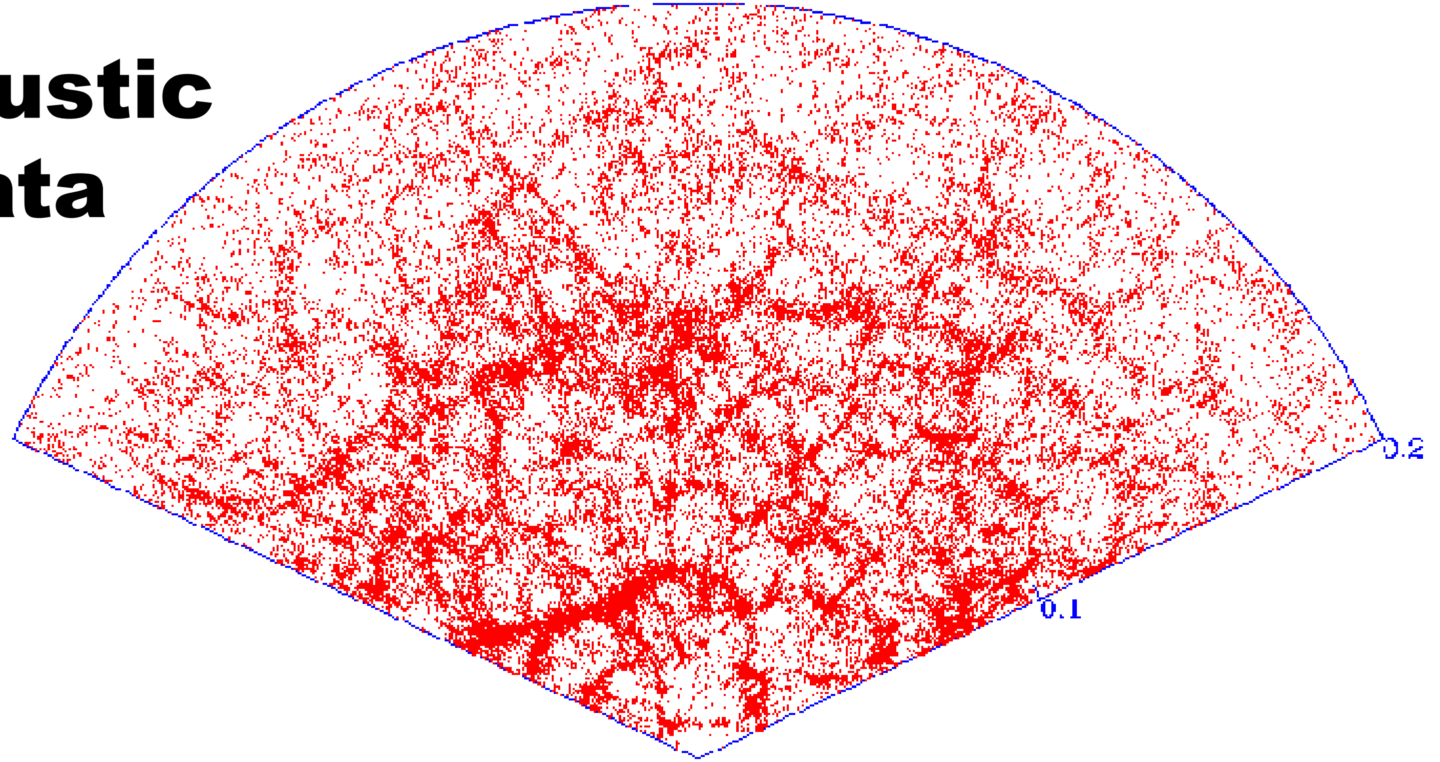
$$t_0 - t_1 \;=\; \int_0^{z_1} \frac{dz}{(1+z)H(z)}$$

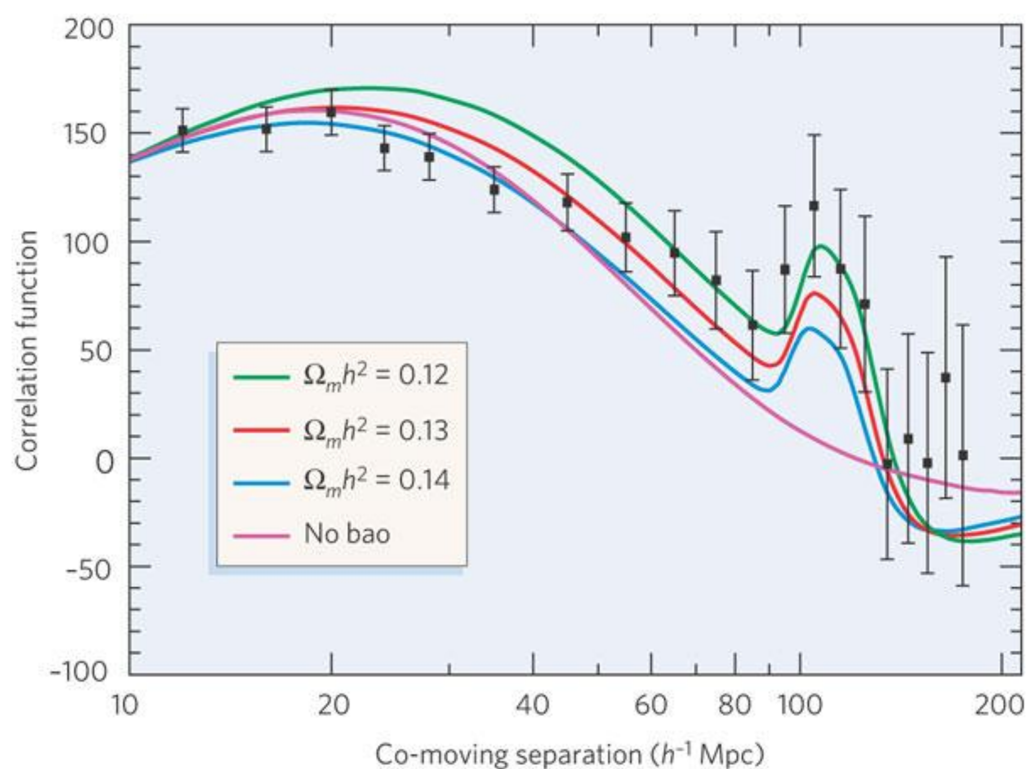
$$H^2(z) = H_0^2\left[\Omega_\gamma\,(1+z)^4 + \Omega_M\,(1+z)^3 + \Omega_k\,(1+z)^2 + \Omega_\Lambda\right]$$

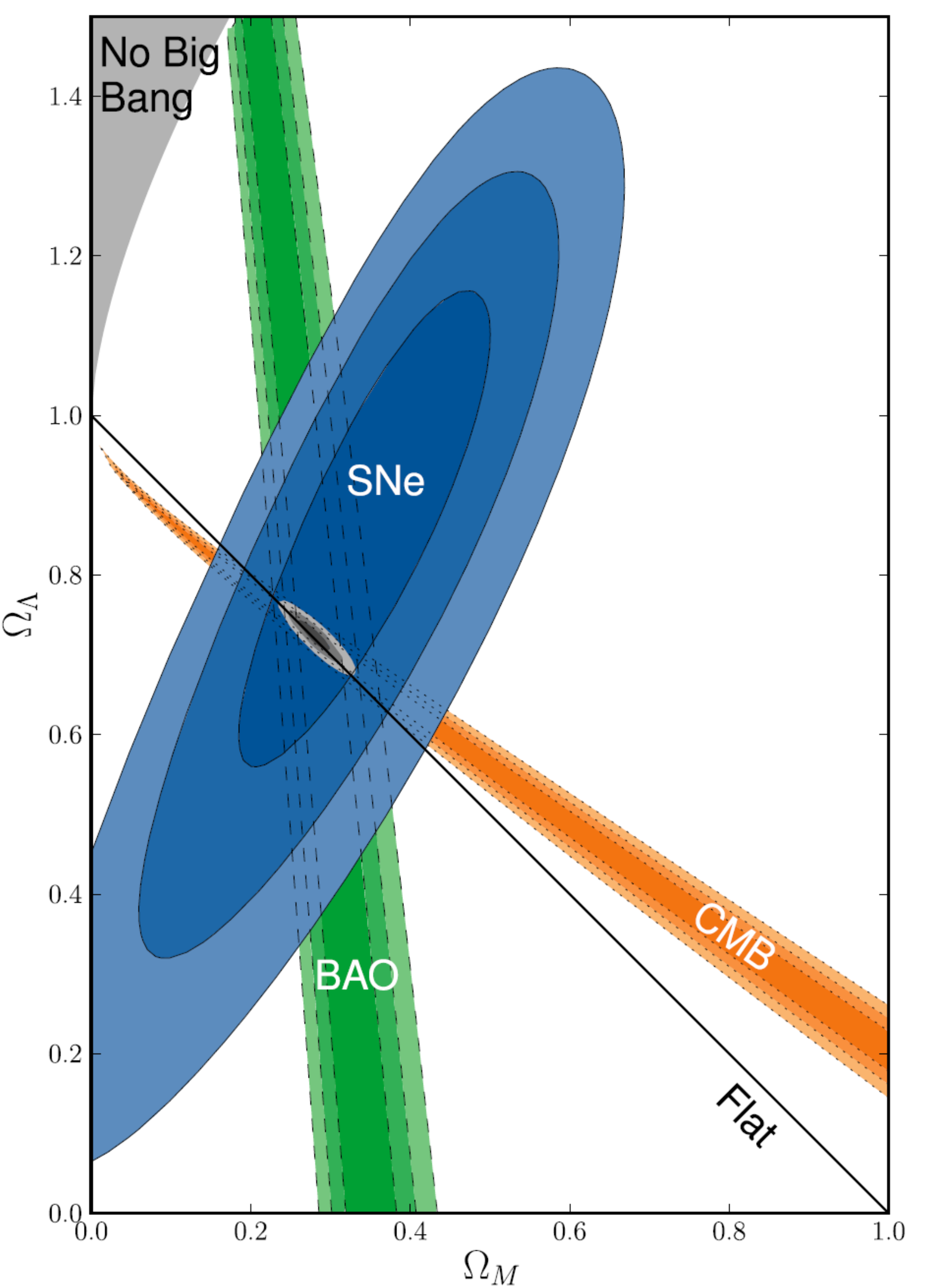




Baryonic Acoustic Oscillation Data






No Big Bang
SNe
BAO
CMB
Flat
Ω_Λ
Ω_M
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4


Dark Energy 73%
Cold Dark Matter 23%
Atoms 4%

Acceleration implies negative pressure

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + 3P\right)$$

To get positive acceleration we need P < -ρ/3

In cosmology, pressure tells you how fast the density of something decreases as the Universe expands

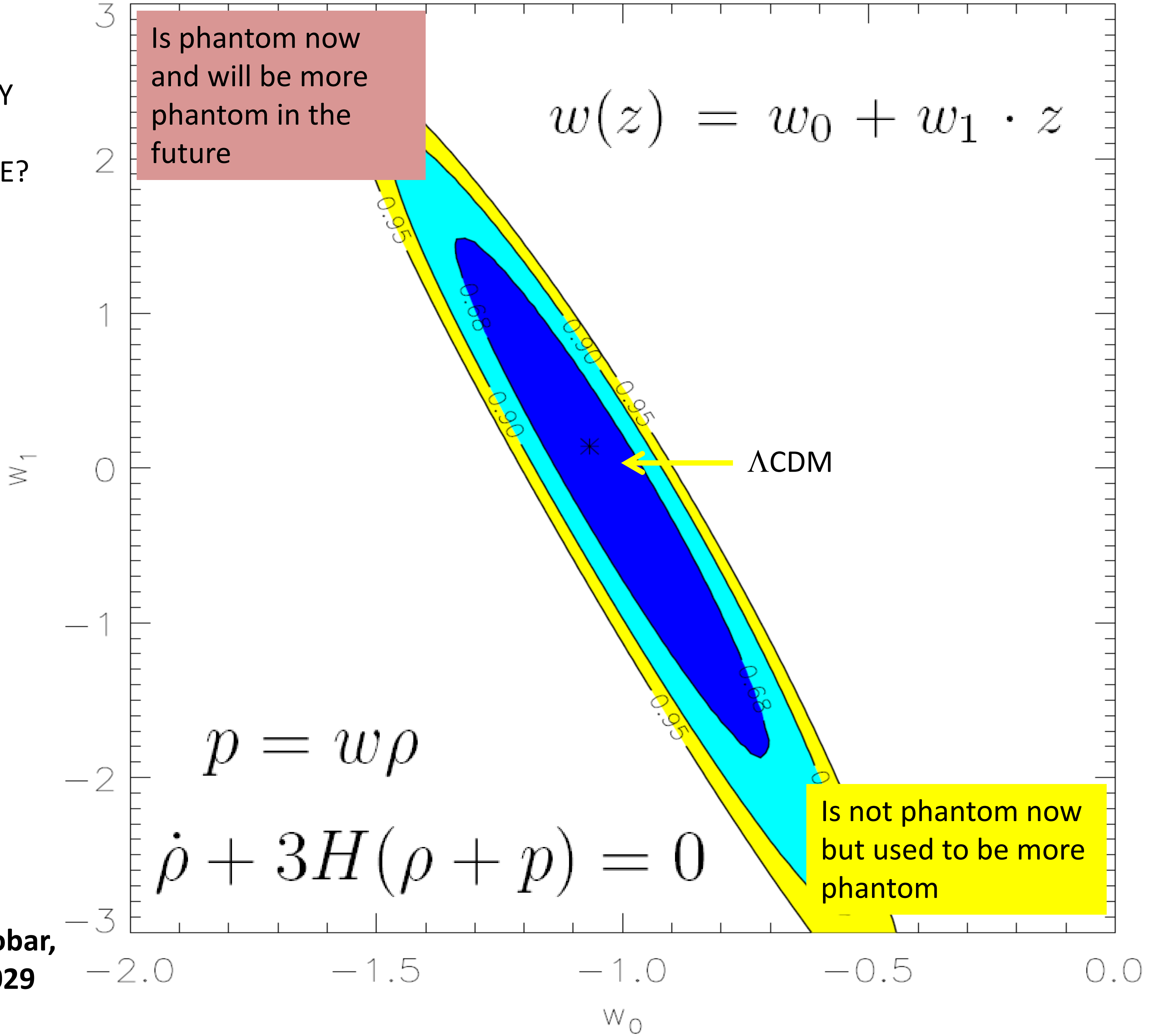
$$\dot{\rho} = -3H\left(\rho + P\right)$$

DOES DARK ENERGY HAVE CONSTANT EQUATION OF STATE?

Not neccessarily!

Phantom means

$\dot{\rho} > 0$



Fairbairn and Goobar, astro-ph/0511029

A low level of extragalactic background light as revealed by γ-rays from blazars

Nature 440:1018 (2006)

Quasar 3C279

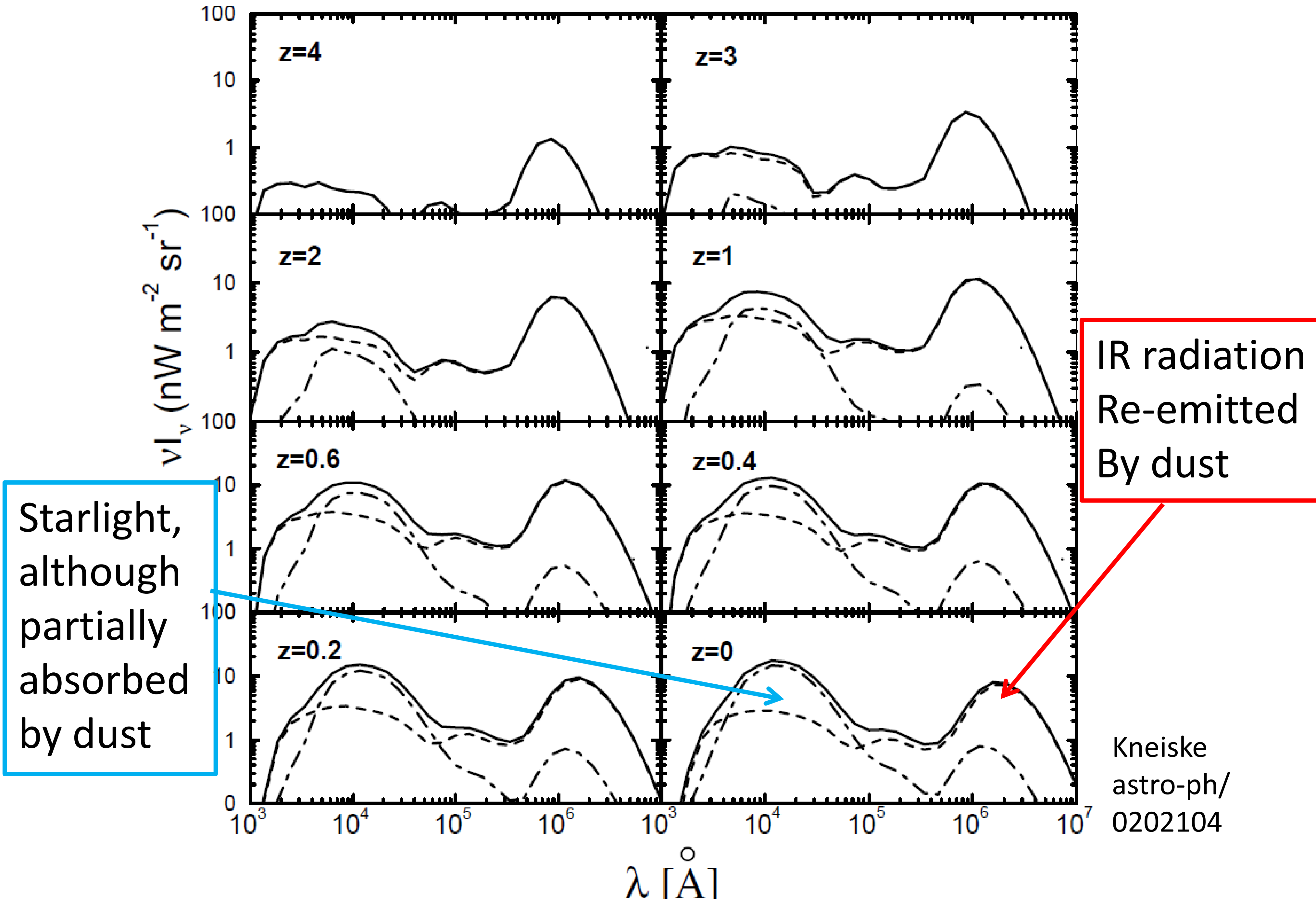
Z=0.536

Very-High-Energy Gamma Rays from a Distant Quasar: How Transparent Is the Universe?

The MAGIC Collaboration*

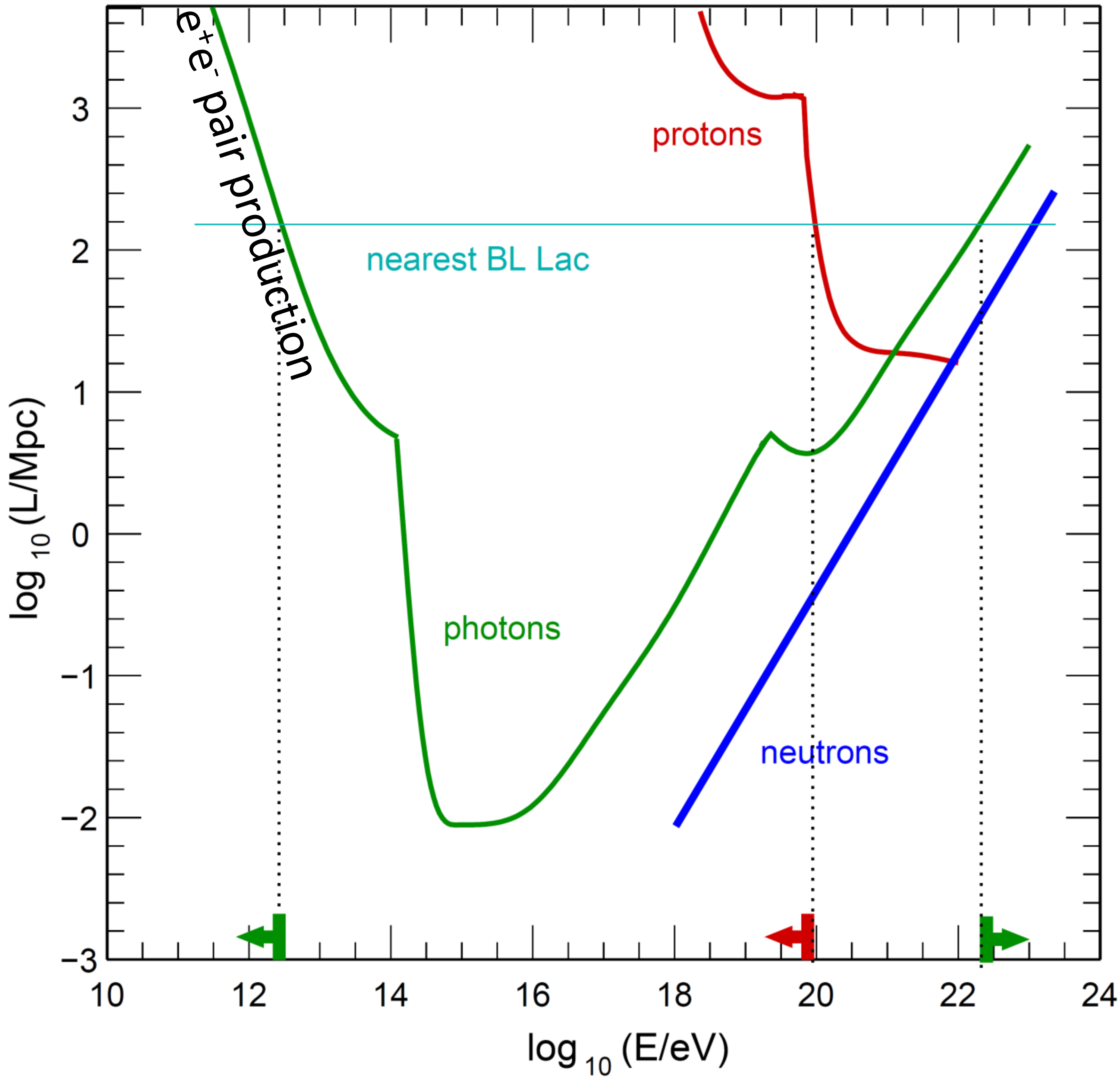
Science **320**, 1752 (2008); DOI: 10.1126/science.1157087

Extragalactic Background Light

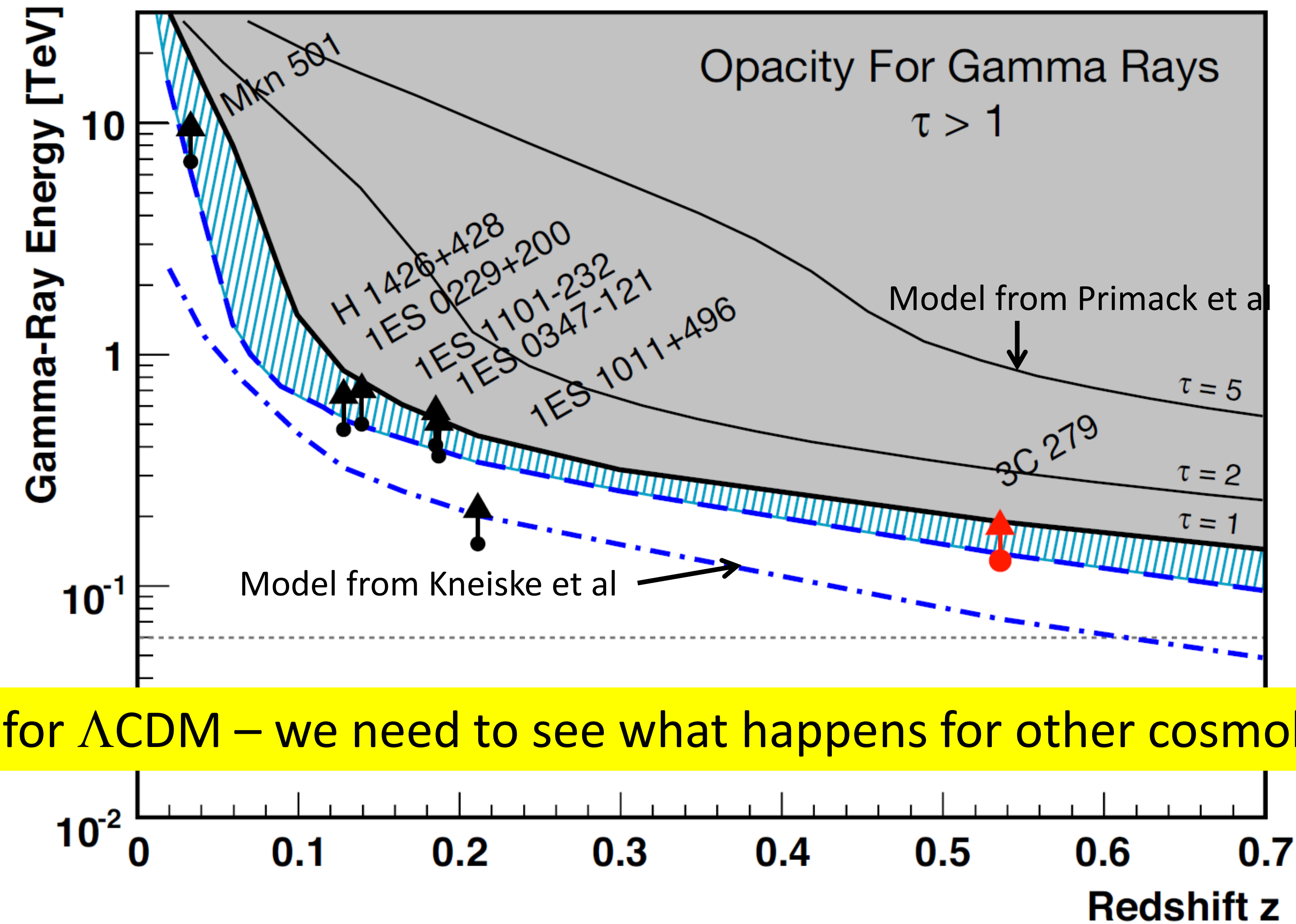


Kneiske astro-ph/ 0202104

Transparency of Universe at different wavelengths



Gamma Ray Horizon



This is for ΛCDM – we need to see what happens for other cosmologies

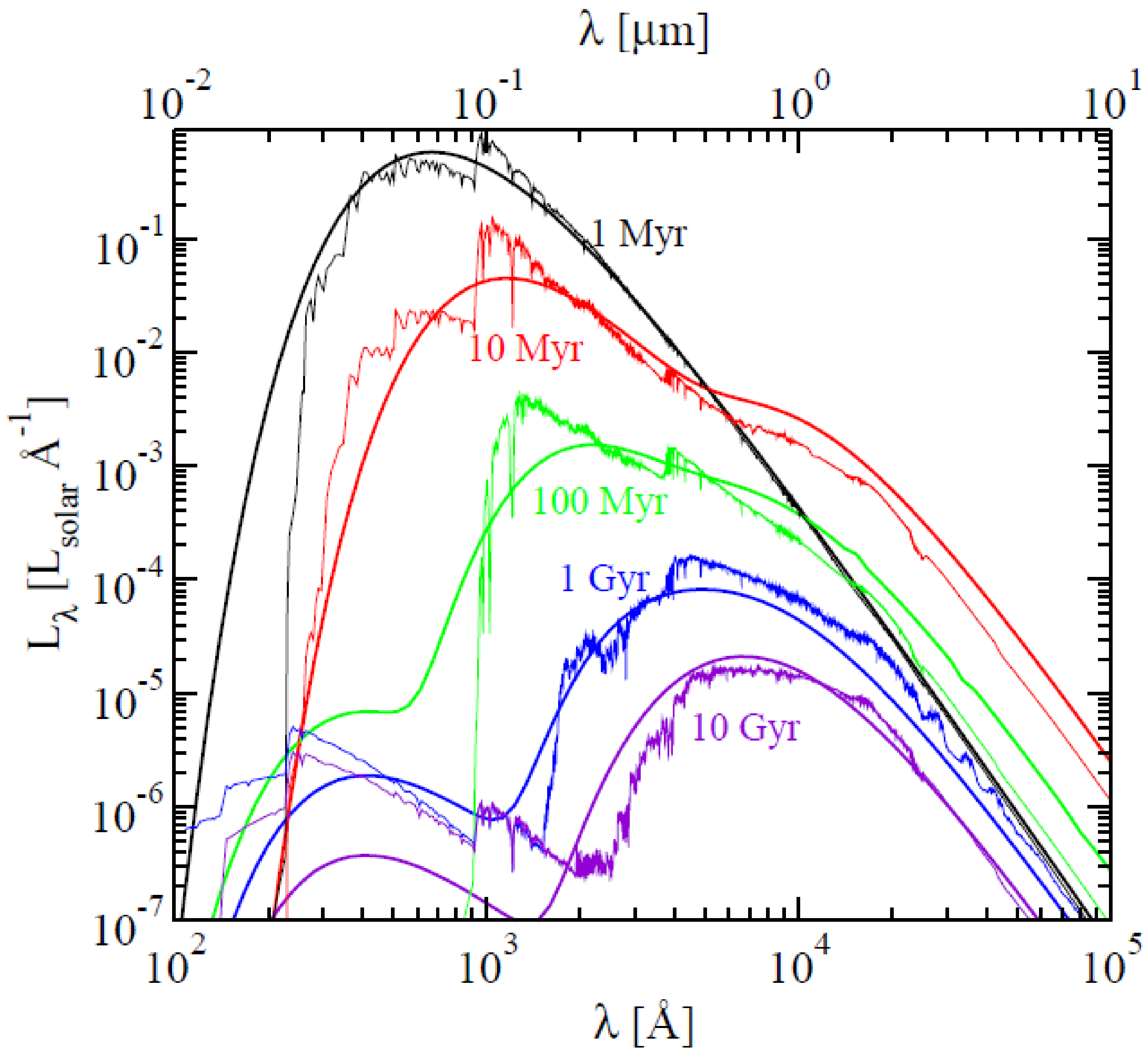
MAGIC COLLABORATION arXiv:0807.2822

Modelling the background light for different cosmologies

We followed quite closely the approach of Finke *et al.* arXiv:0905.1115

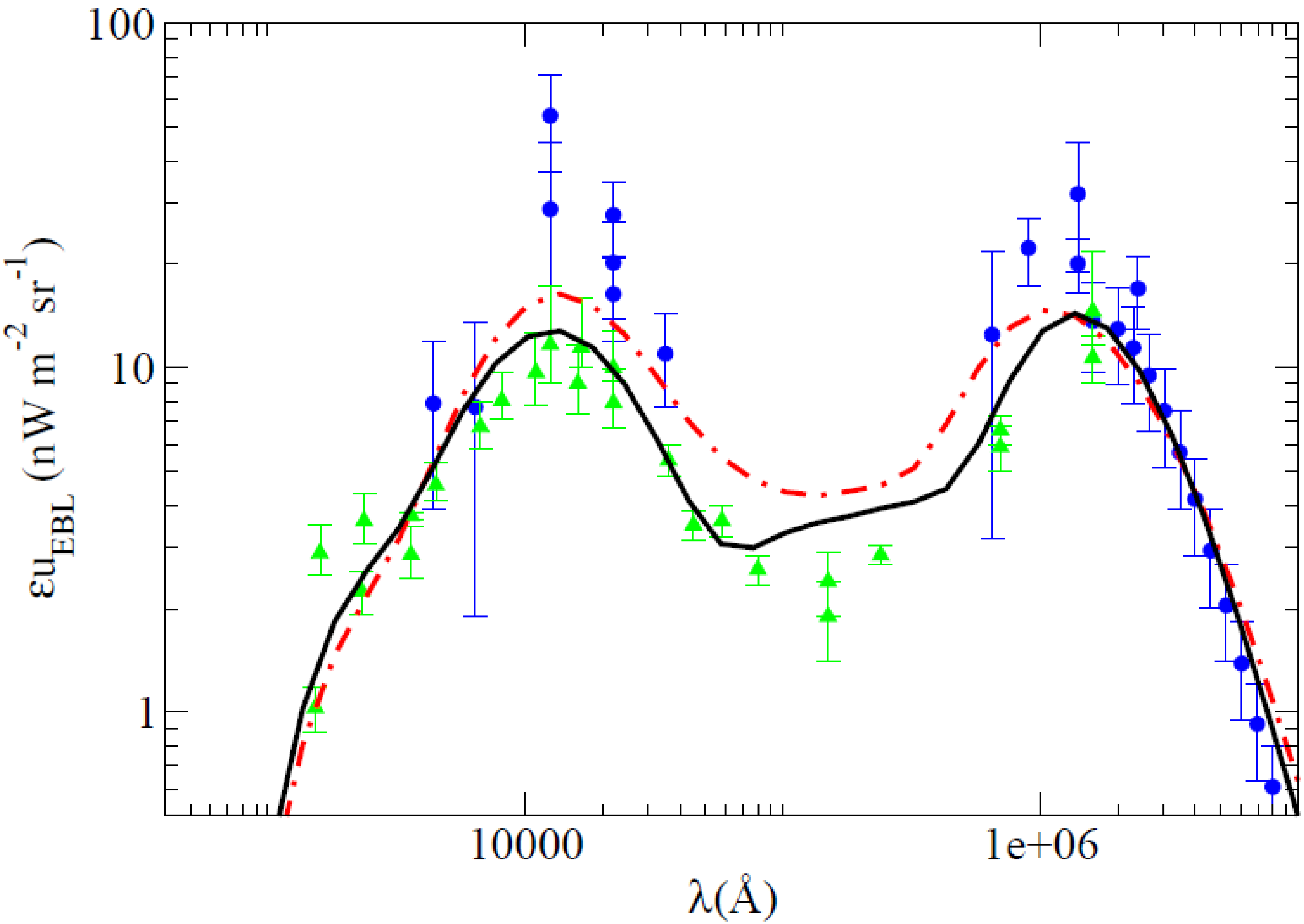
1. Treat stars as black bodies
2. Obtain approximate formulae for radius and temperature of star of mass M as a function of time (Eggleton, Fitchett and Tout provide us with this in the appendix of a paper on binaries from the end of the 1980s)
3. Assume an initial mass function, Salpeter will do for now, single power law.
4. Have stars being created at different rates throughout the history of the Universe.
5. Star light is partially absorbed, especially at high frequencies and re-emitted in the infra red and microwave
6. At any given redshift, light is due to combination of light being produced then, and light being produced at earlier times which is then redshifted.

Spectrum of stellar population created all at once
Data vs. observations



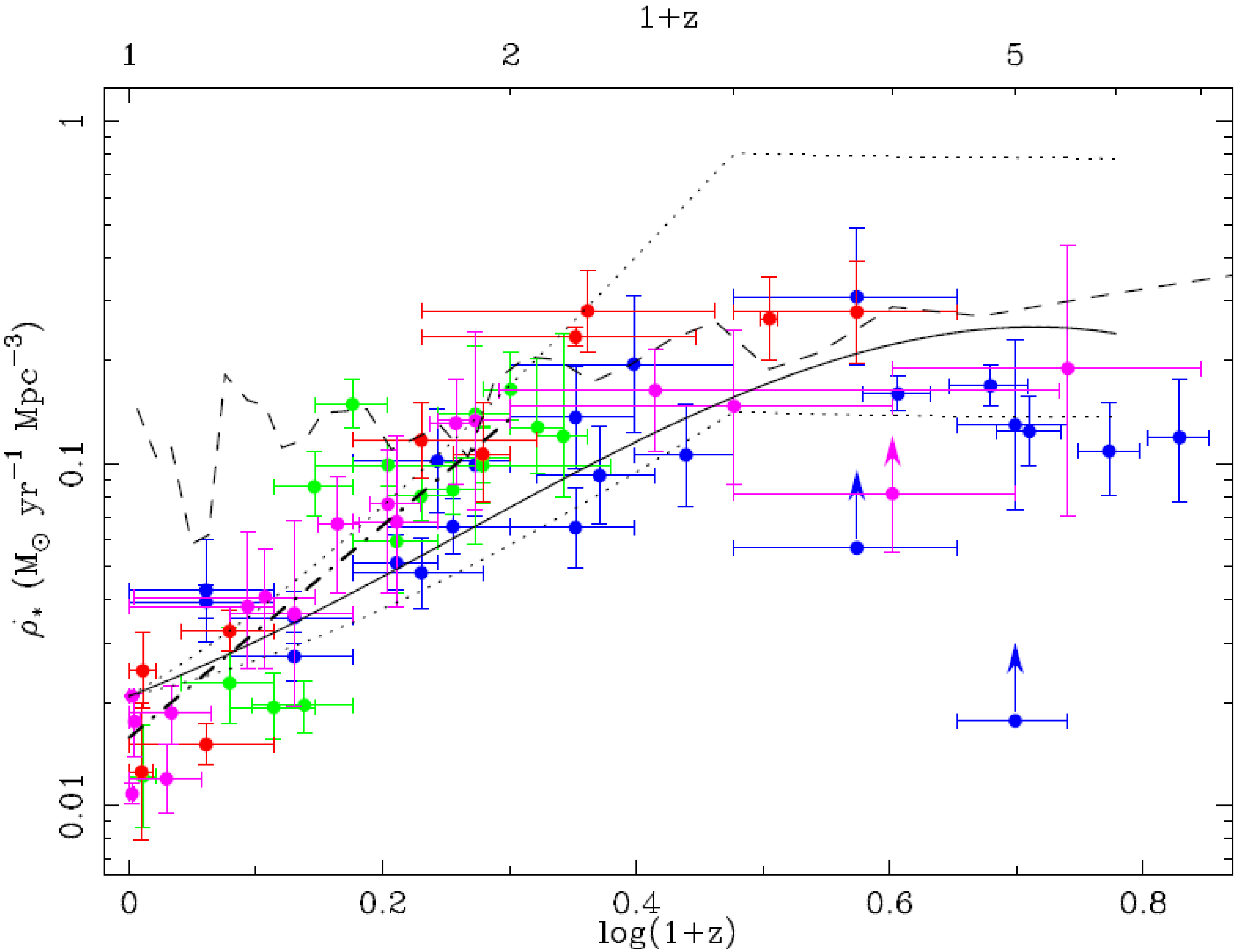
Plot from Finke *et al.* arXiv:0905.1115 . Ours is more or less the same.

Spectrum produced by our code



Data is from various sources, blue data is observed spectrum, green data is lower limits. Here we haven't fit this spectrum on the left, we just used the star formation rate data.

Star Formation Rate



Hopkins astro-ph/0407170

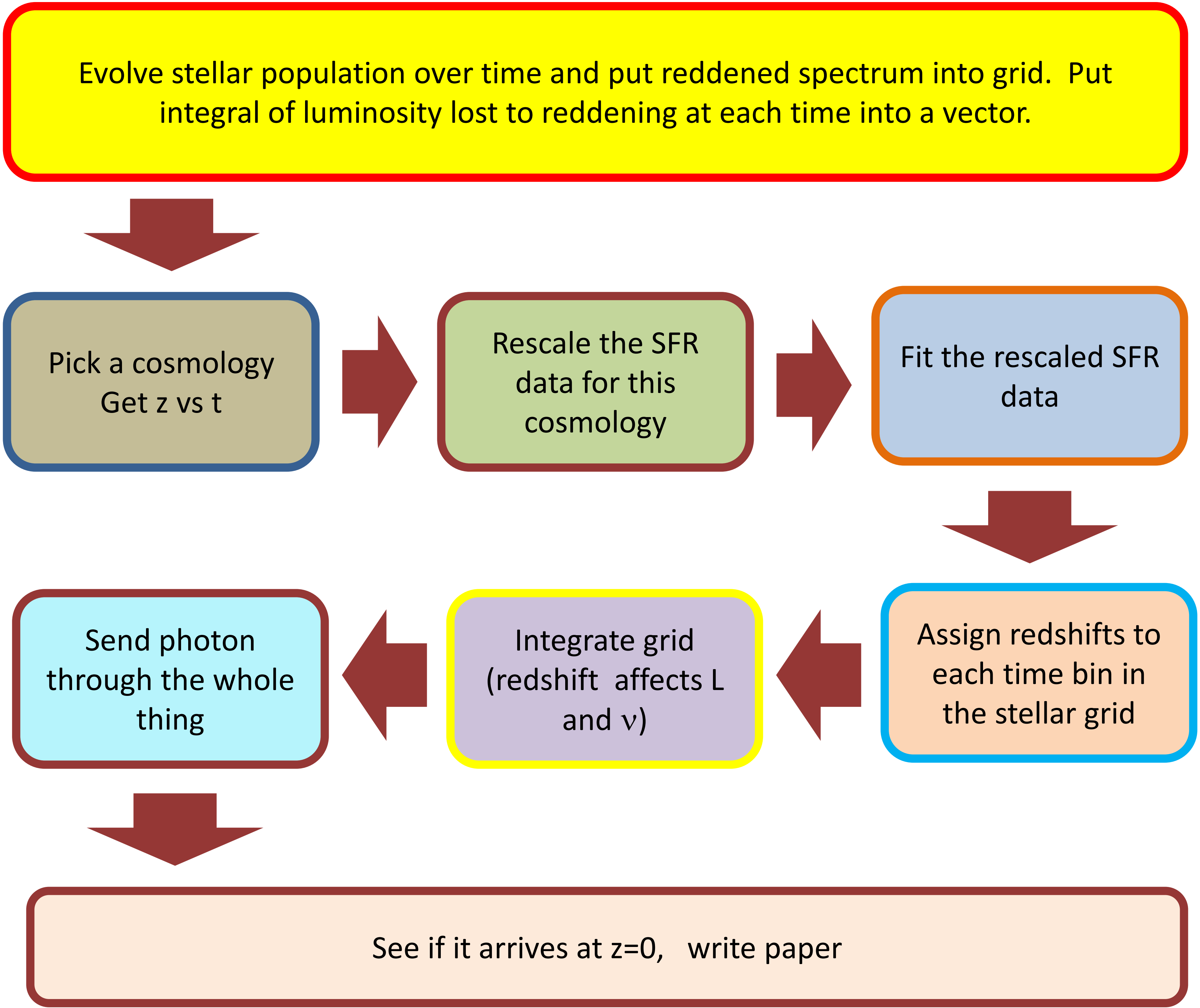
Can be fit with the expression

$$\dot{\rho}_* = \frac{a + bz}{1 + (z/c)^d}$$

$$\dot{\rho}_* \propto \frac{L(z)}{V_c(z, \Delta z)} \propto \frac{D_c^2(z)}{D_c^3(z+\Delta z) - D_c^3(z-\Delta z)}$$

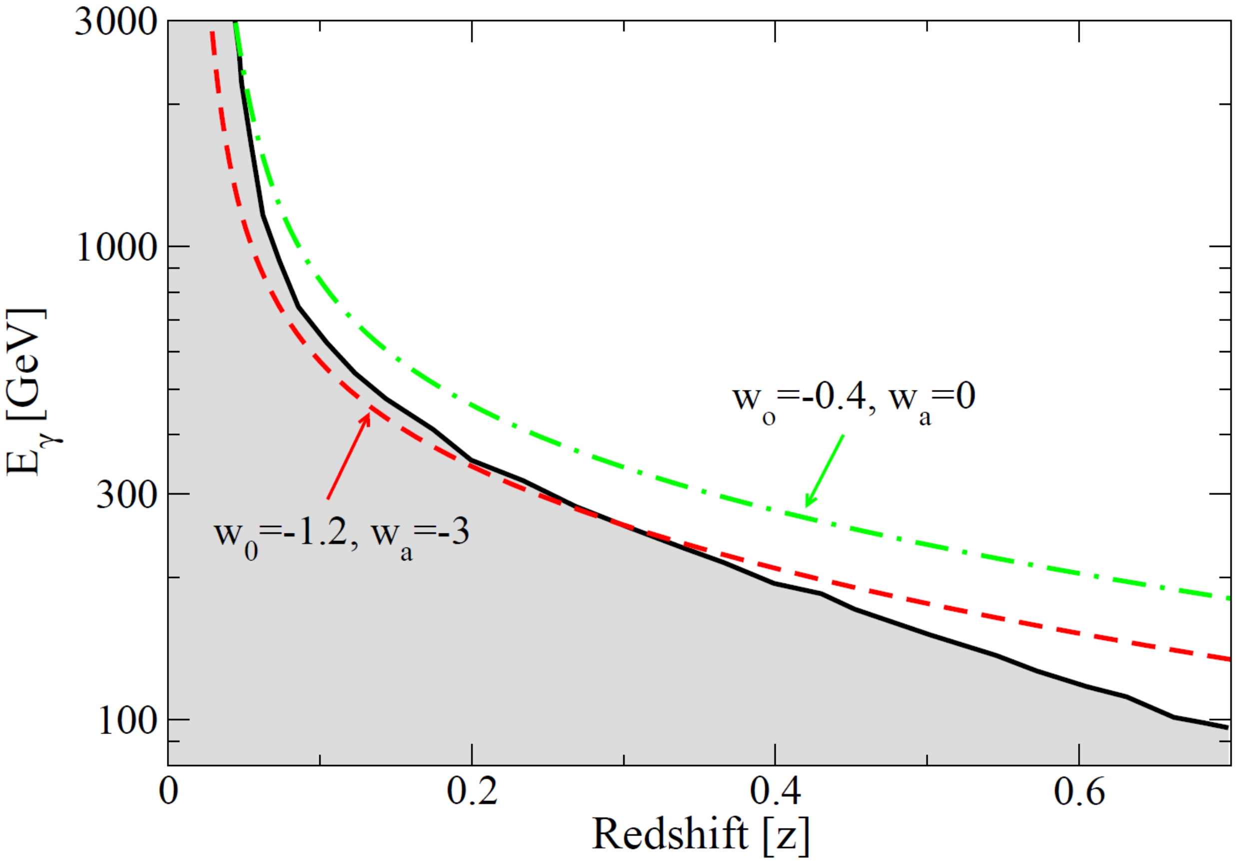
Need to renormalise if you change underlying cosmology.

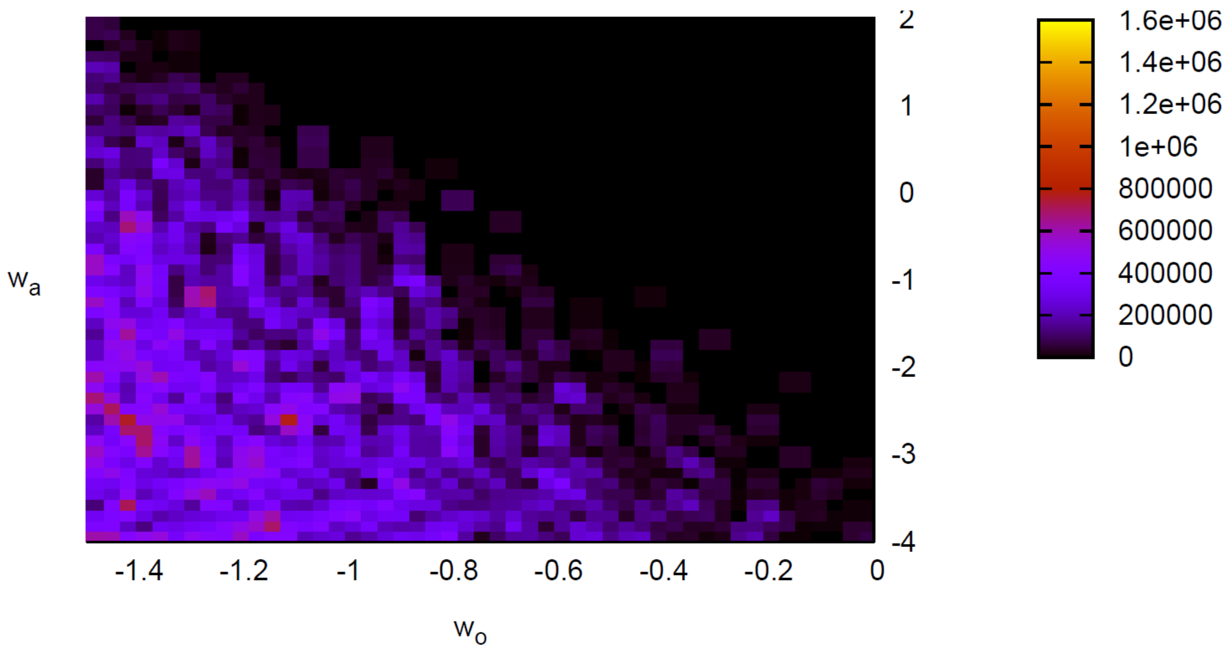
Our exact procedure



Results

Technique rules out regions which cannot be excluded by SN/BAO/CMB constraints.





Conclusions for Dark Energy

We still have no idea what it is and more and more people are ignoring it

THE REAL STANDARD COSMOLOGICAL MODEL

baryons = 100%

BUT THE UNIVERSE WE LIVE IN…

baryons = 4%, dark matter = 24%, dark energy = 72%

NONE STANDARD ??

Baryons = 100%