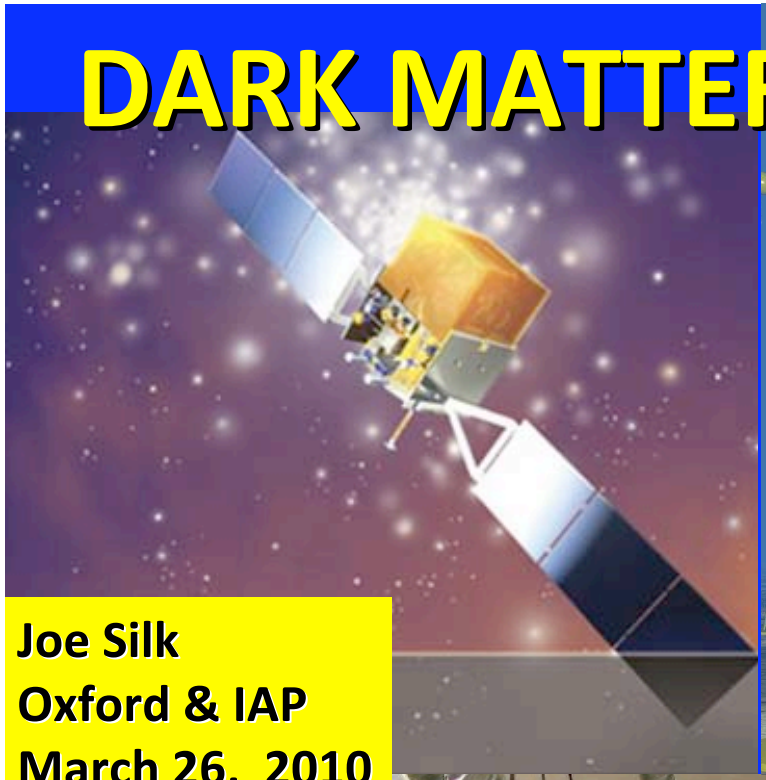
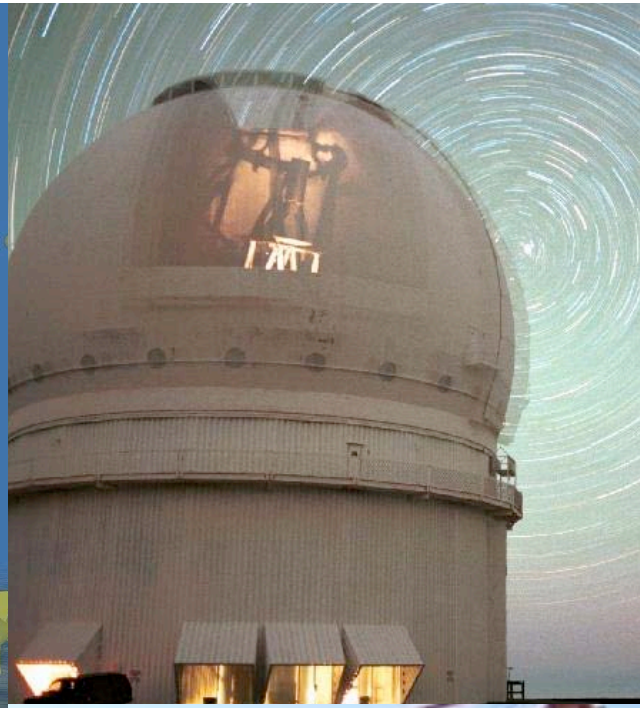
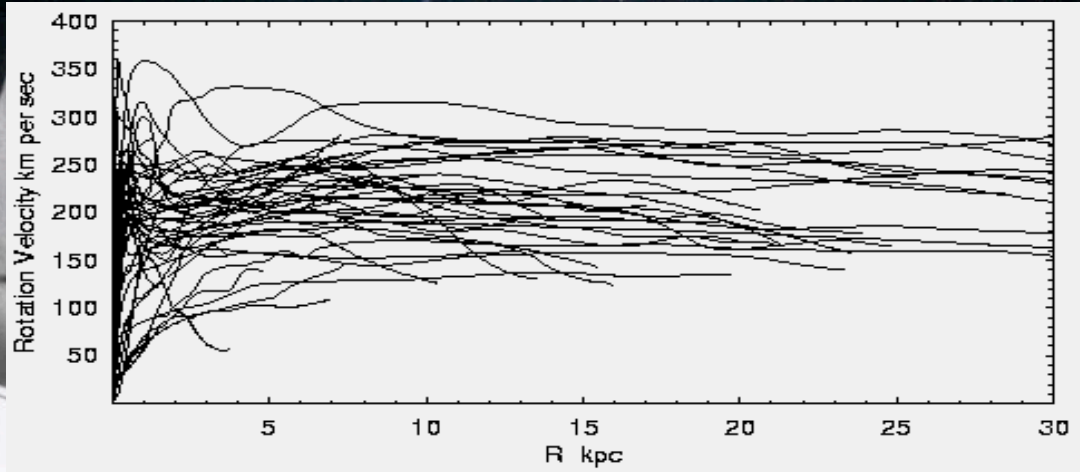
DARK MATTERS





Joe Silk
Oxford & IAP
March 26, 2010

Dark Matter in Galaxies



HELVETICA PHYSICA ACTA
Volumen VI Fasciculus Secundus.

Die Rotverschiebung von extragalaktischen Nebeln

von F. Zwicky.

(16. II. 33.)

Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten M
male extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung
selben gedient haben. Insbesondere wird die sog. Rotverschiebung extrag
tischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklä
dieses wichtigen Phänomens aufgestellt worden sind, werden kurz besproc
Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Stu
der durchdringenden Strahlung von Wichtigkeit zu werden verspricht.

§ 1. Einleitung.

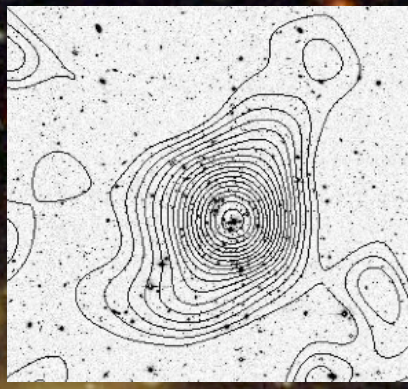
Es ist schon seit langer Zeit bekannt, dass es im Weltra
gewisse Objekte gibt, welche, wenn mit kleinen Teleskopen be
achtet, als stark verschwommene, selbstleuchtende Flecke ersc
nen. Diese Objekte besitzen verschiedenartige Strukturen.
sind sie kugelförmig, oft elliptisch, und viele unter ihnen ha

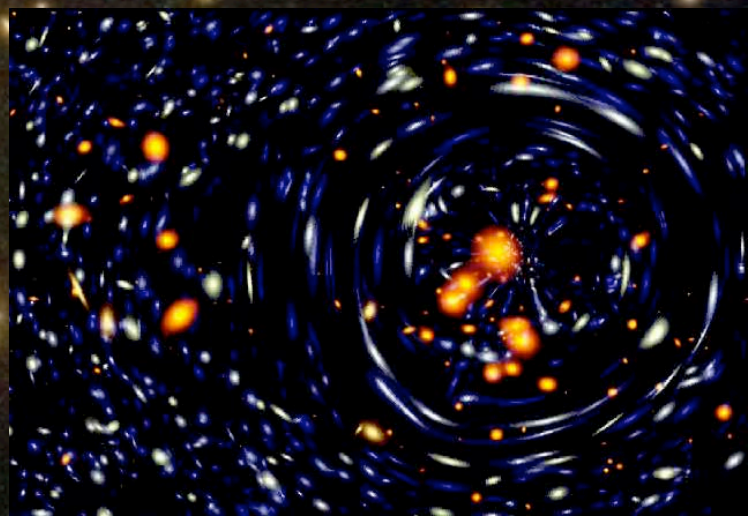
Rotverschiebung extragalaktischer Nebel.

m, wie beobachtet, einen mittleren Dopplereffekt
km/sek oder mehr zu erhalten, müsste also die mit
im Comasystem mindestens 400 mal grösser sein als di
von Beobachtungen an leuchtender Materie abgeleit
ch dies bewahrheiten sollte, würde sich also das ül
Resultat ergeben, dass dunkle Materie in sehr viel grös
vorhanden ist als leuchtende Materie.

2. Man kann auch annehmen, dass das Comasystem sich nicht im stationären Gleichgewicht befindet, sondern dass die ganze verfügbare potentielle Energie als kinetische Energie er-

Dark Matter in Galaxy Clusters





Dark matter:
its not baryons

Canberra Time
April 1990

AS the cerebral discussions on the composition of the universe continue among the world's academics, Professor J. Silk, from the Departments of Astronomy and Physics at the University of California arrives at the ANU to deliver a recitation on Baryonic Dark Matter, summarised in an advance notice thus: "At least 90 per cent of the mass of the university is in the form of non-luminous matter." Rumours that a class defamation action is pending are as yet unsubstan-

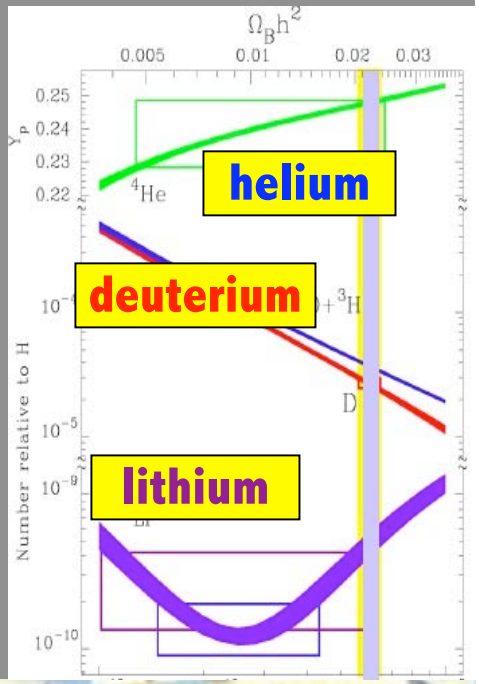
GEORGE GAMOW, ROBERT HERMAN, RALPH ALPHER
predicted fossil radiation in 1949

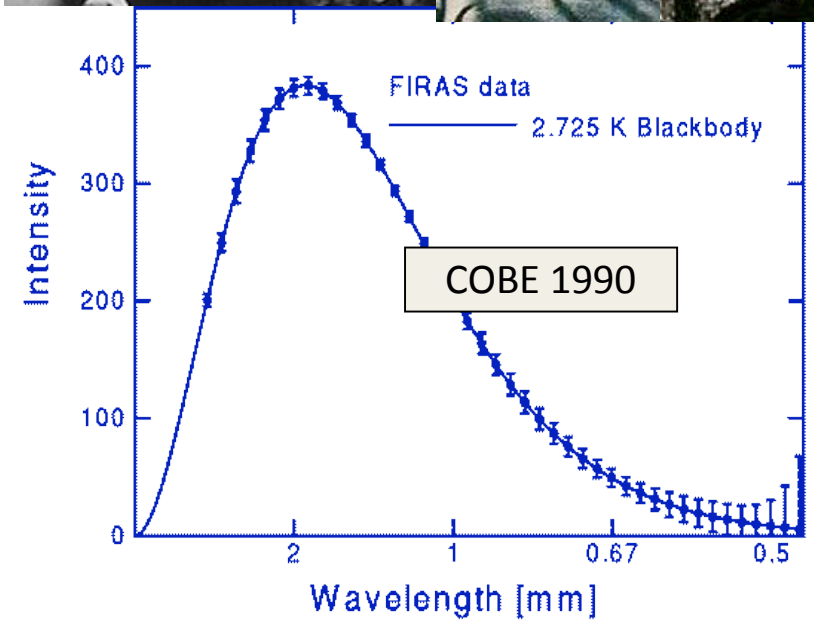
THE MATTER BUDGET

Ω_b=0.03

Ω_*=0.005

Ω_{dm}=0.2





RELIC RADIATION DISCOVERED BY ARNO PENZIAS AND ROBERT WILSON IN 1964

90% OF THE DARK MATTER IS NONBARYONIC

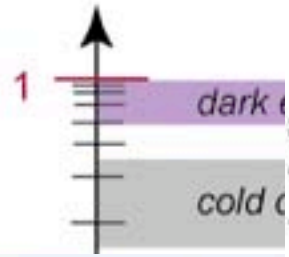
Dark matter:
its not neutrinos

NEUTRINO DARK MATTER

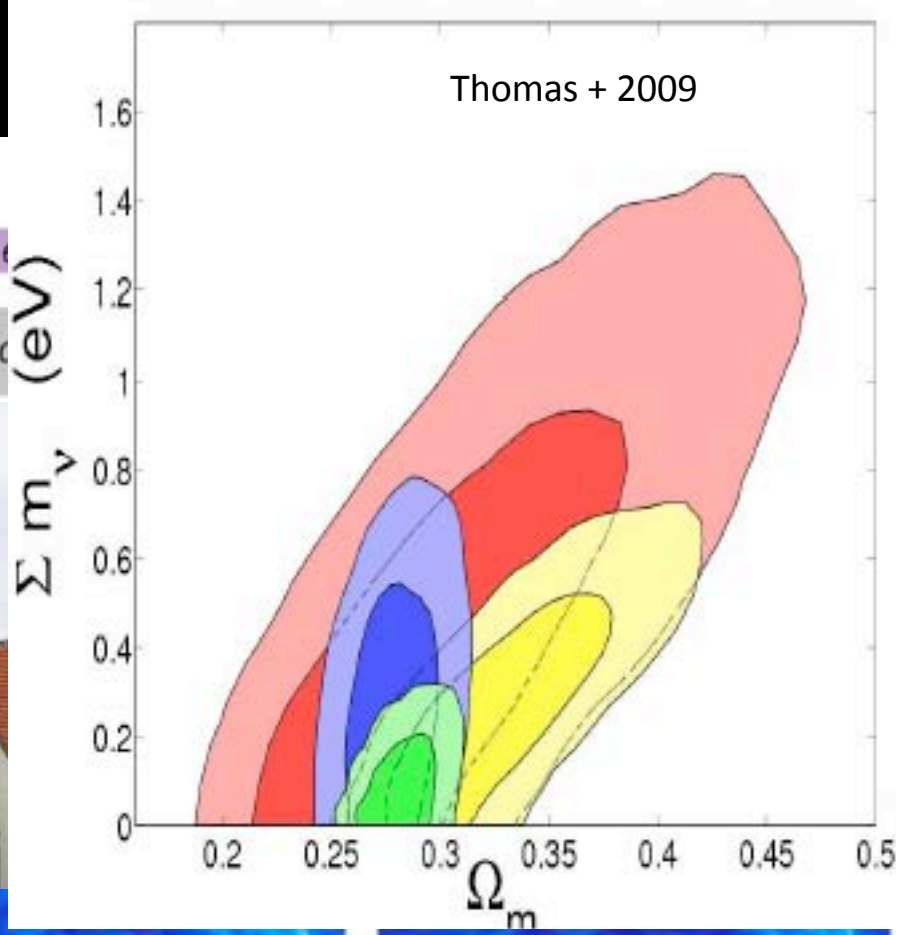
primordial neutrinos as hot dark matter

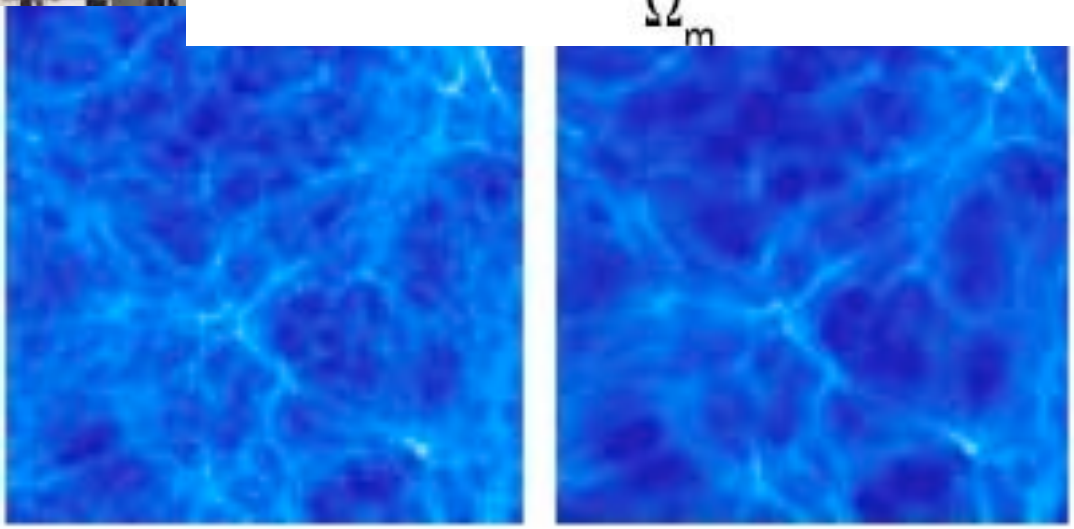
$\Omega_\nu h^2 = \Sigma m_\nu / 92$ eV

Hubble parameter h= 0.65 (65 km/s/Mpc)

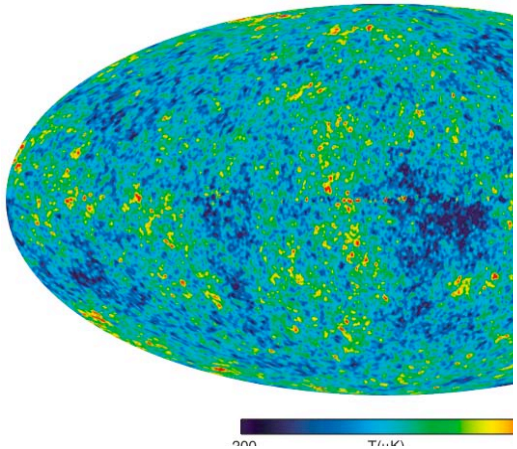


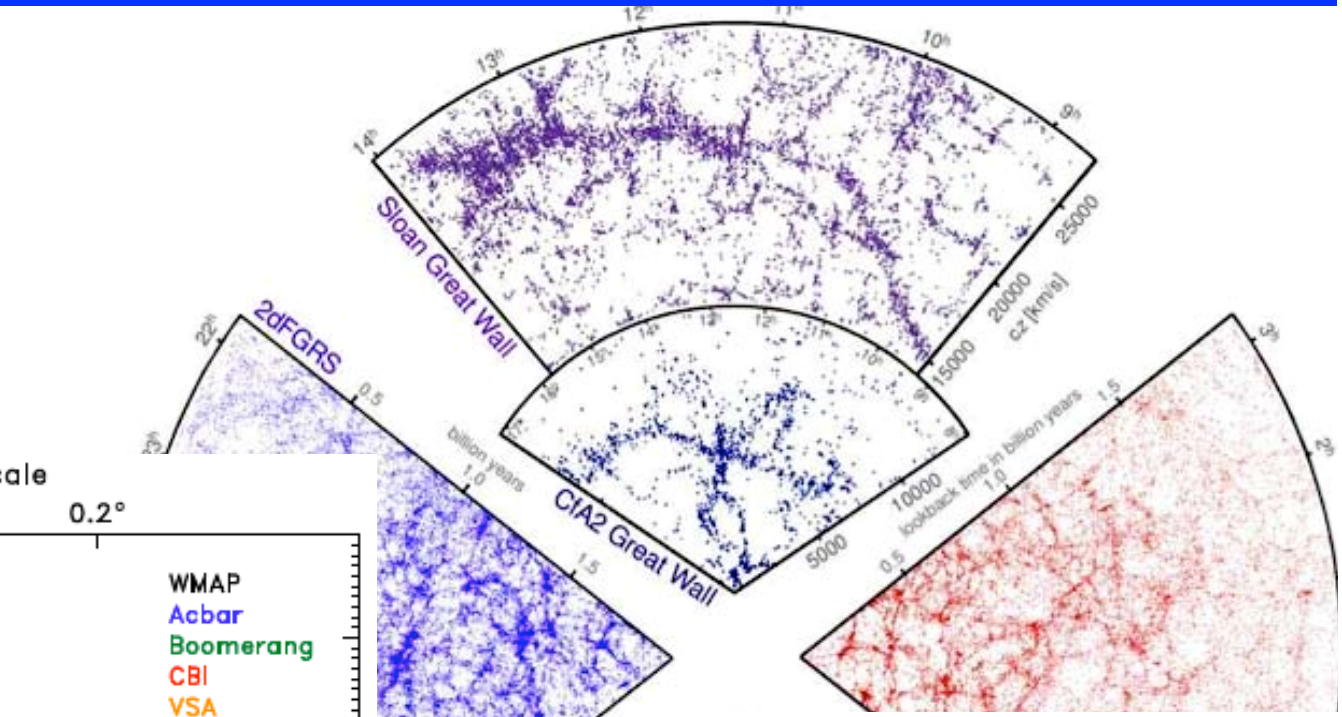
Thomas + 2009

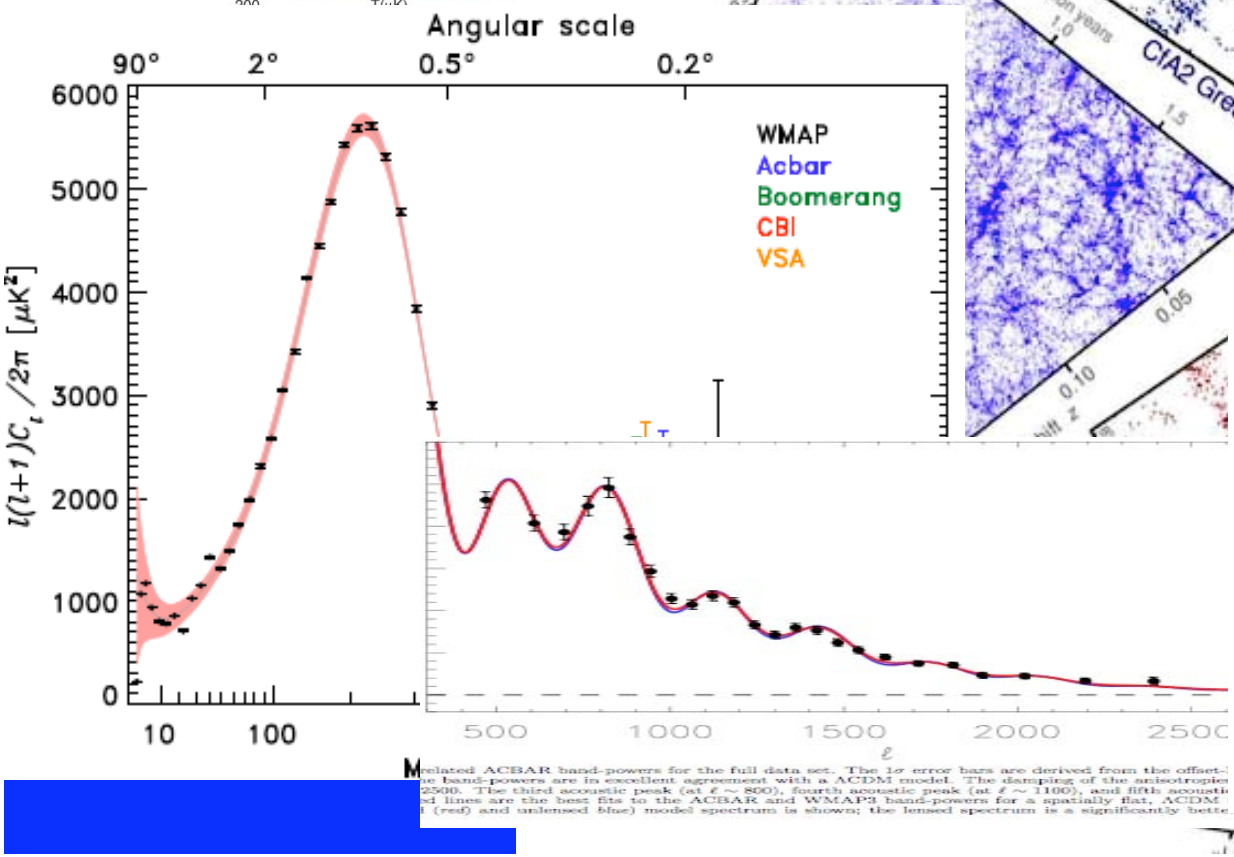




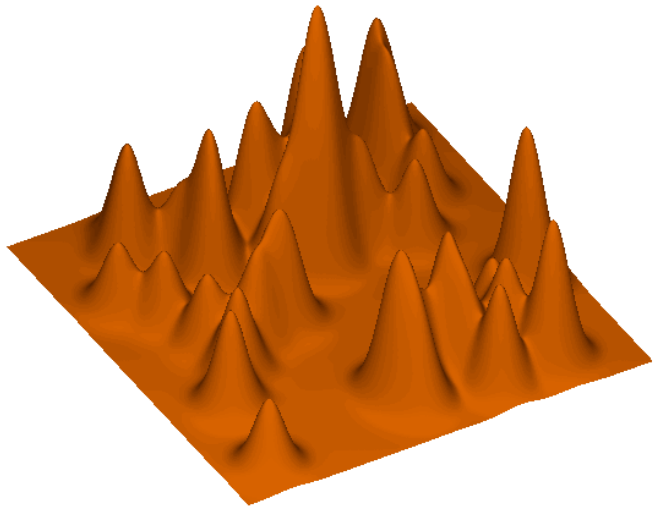
Dark Matter is weakly interacting & cold

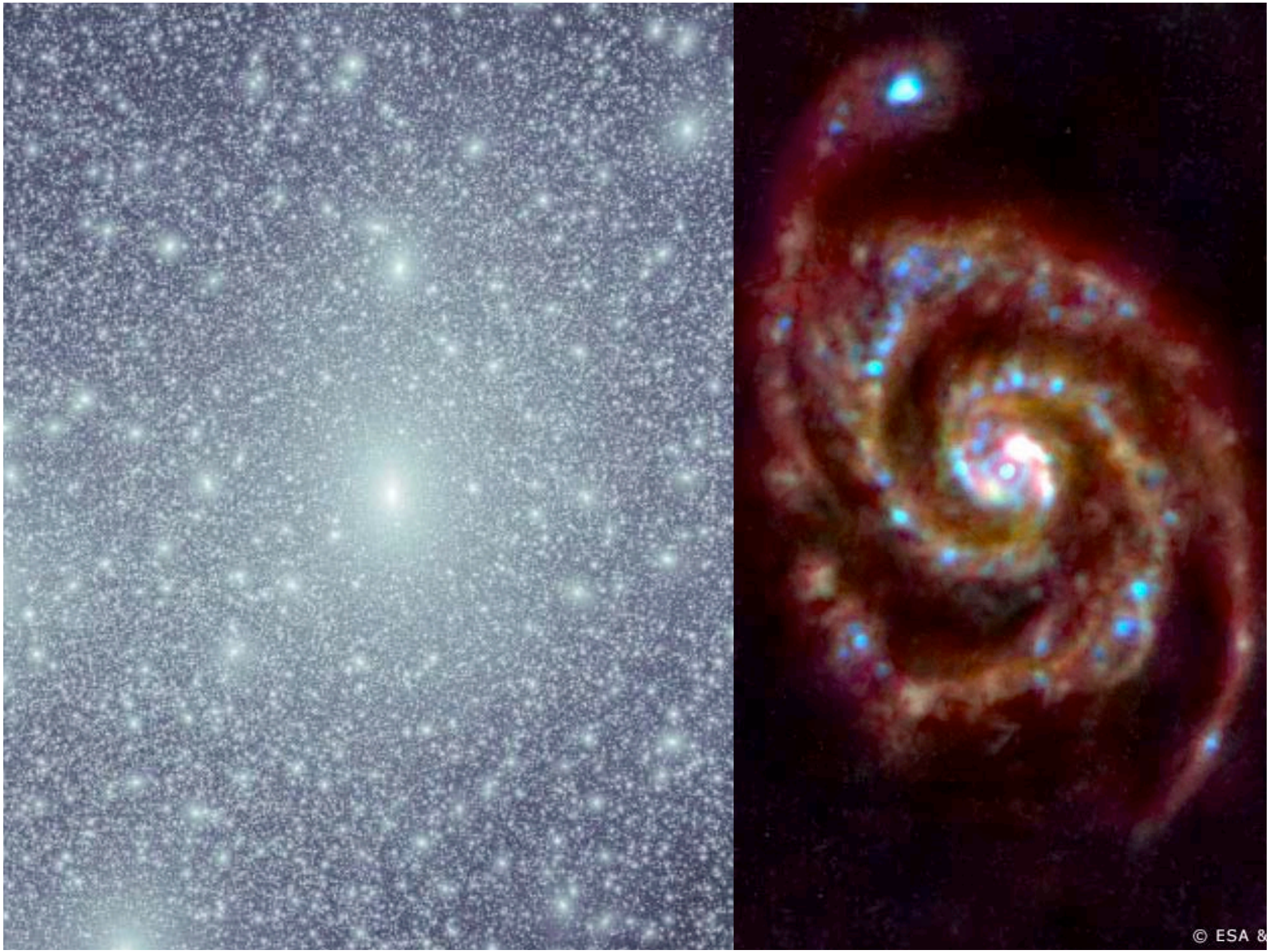


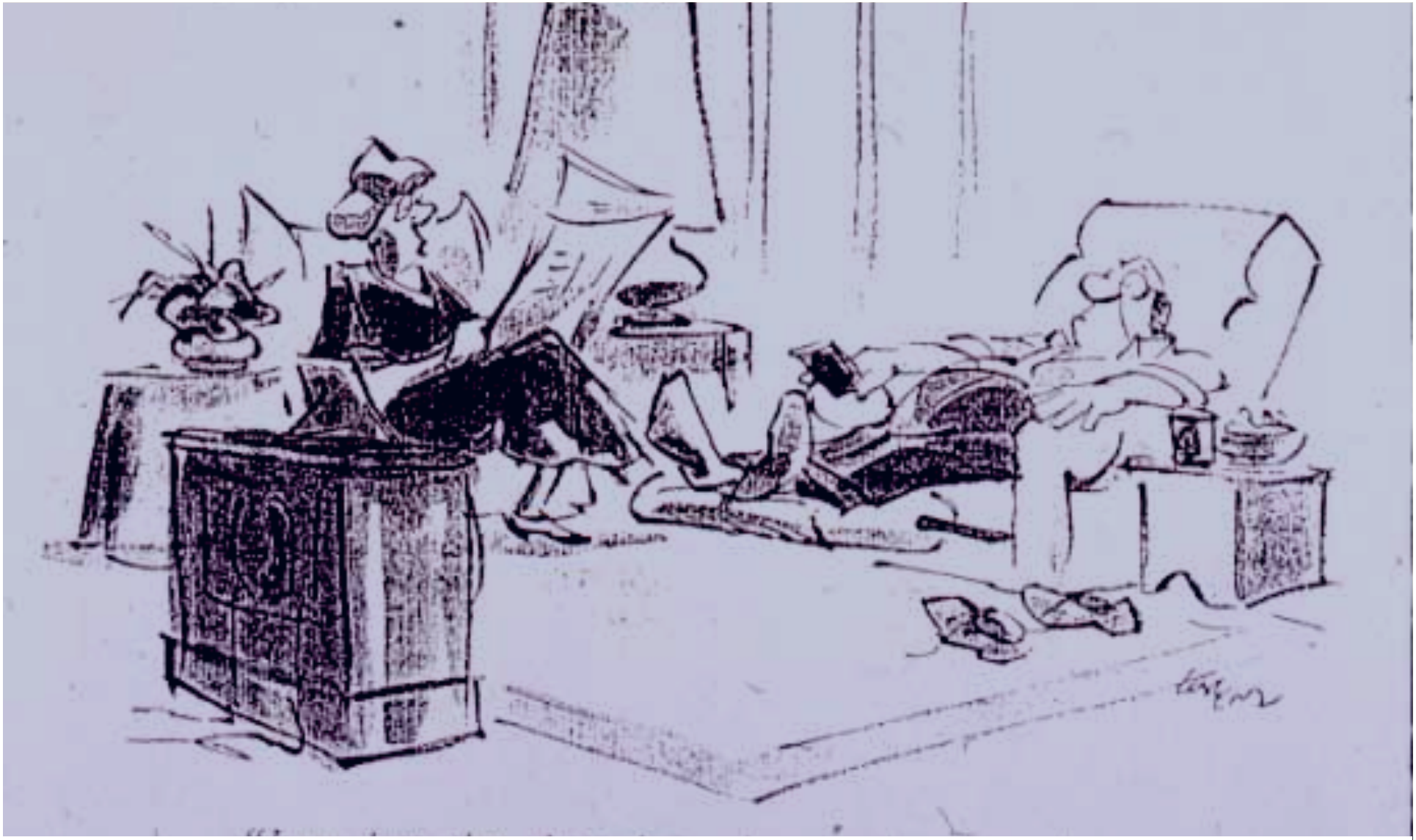




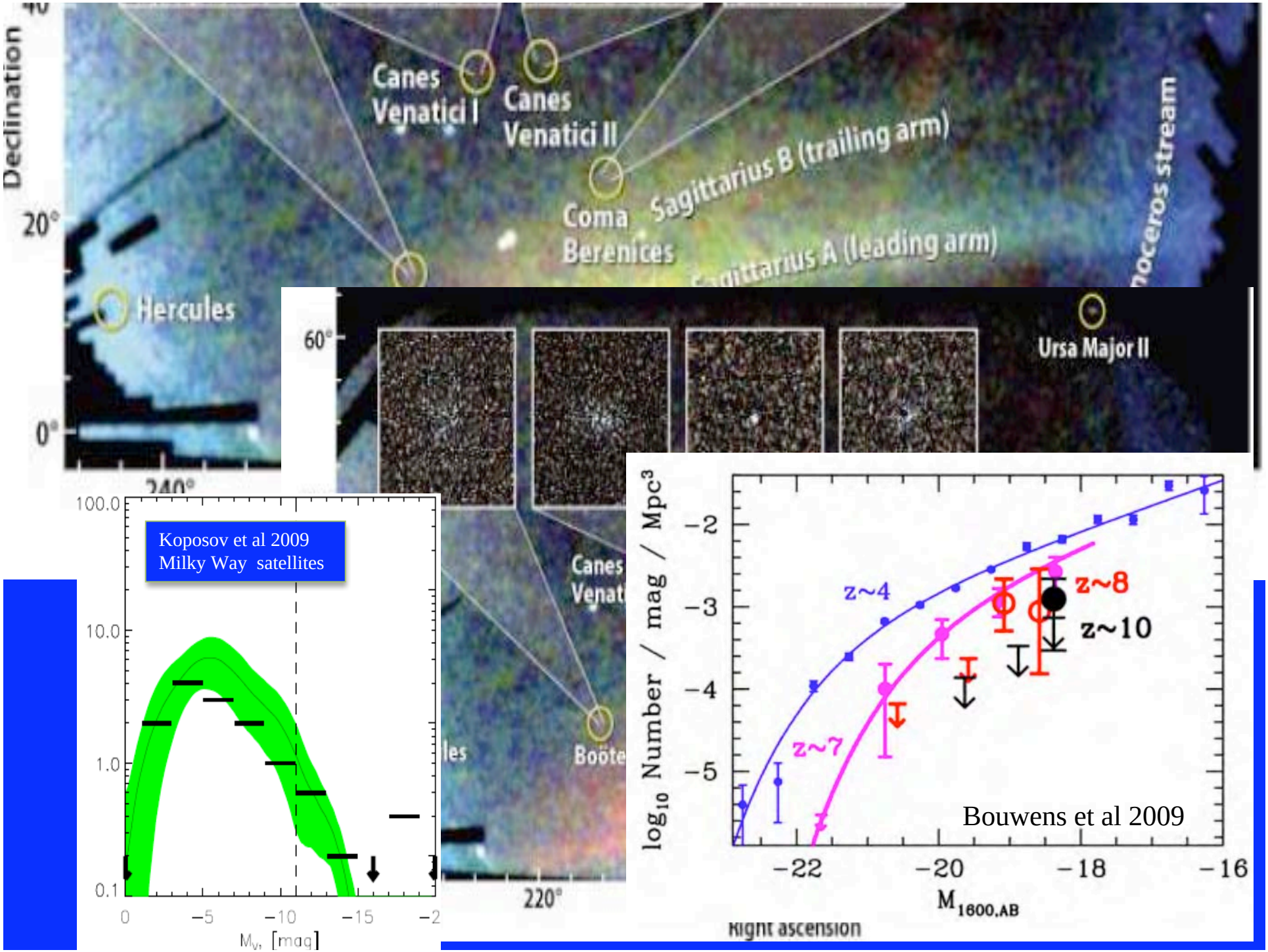
related ACBAR band-powers for the full data set. The 1σ error bars are derived from the offset-
e band-powers are in excellent agreement with a ΛCDM model. The damping of the anisotropies
2500. The third acoustic peak (at $\ell \sim 800$), fourth acoustic peak (at $\ell \sim 1100$), and fifth acoustic
d lines are the best fits to the ACBAR and WMAP3 band-powers for a spatially flat, ΛCDM
(red) and unlensed blue) model spectrum is shown; the lensed spectrum is a significantly bette




© ESA &



I see here that the universe is thought to be full of dense cold clumps


Declination
20°
0°
240°
Canes Venatici I
Canes Venatici II
Coma Berenices
Sagittarius B (trailing arm)
Sagittarius A (leading arm)
Hercules
60°
Ursa Major II
Canes Venat
Boöte
220°
Right ascension
Koposov et al 2009
Milky Way satellites
100.0
10.0
1.0
0.1
0
−5
−10
−15
−2
M_V, [mag]
$\log_{10}$ Number / mag / Mpc^3
−2
−3
−4
−5
z~4
z~7
z~8
z~10
−22
−20
−18
−16
$M_{1600,AB}$
Bouwens et al 2009

Dark matter:
it may be WIMPs

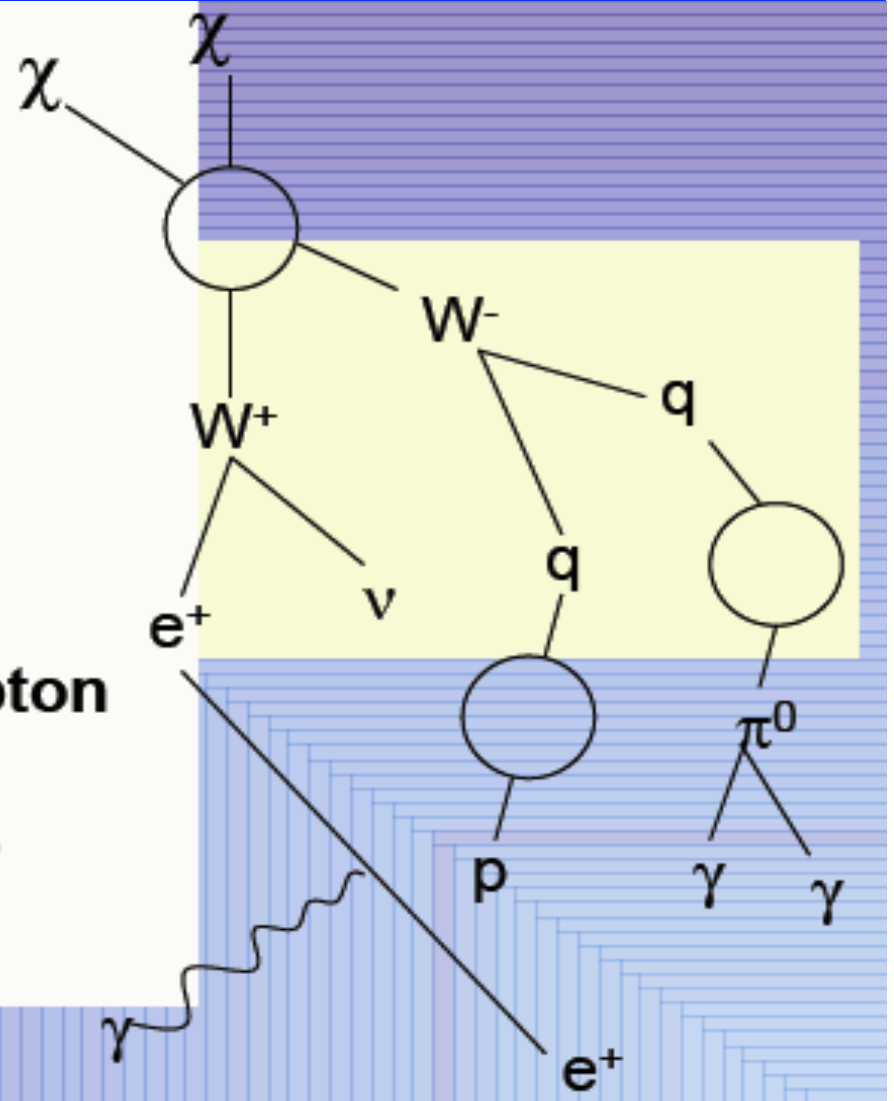
Favoured SUSY candidate: Weakly Interacting Massive Particle or WIMP

Relic abundance obtained if $\langle\sigma v\rangle \sim 3\times10^{-26}$ cm^3/s $\sim 1/\Omega_x$ for 0.1-10 TeV

1. **WIMP Annihilation**
   Typical final states include heavy fermions, gauge or Higgs bosons

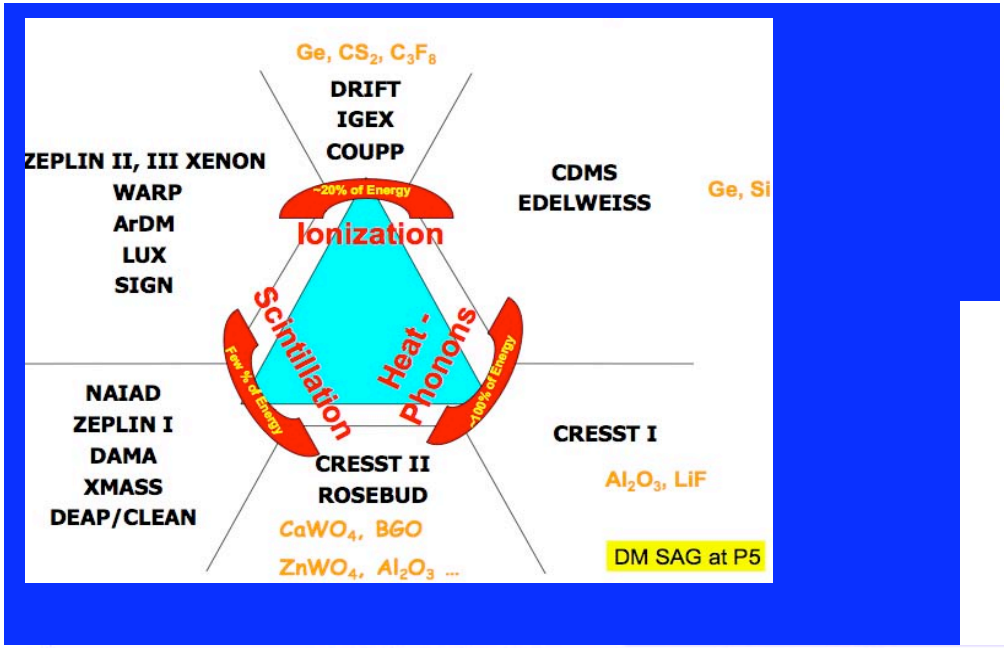
2. **Fragmentation/Decay**
   Annihilation products decay and/or fragment into combinations of electrons, protons, deuterium, neutrinos and gamma-rays

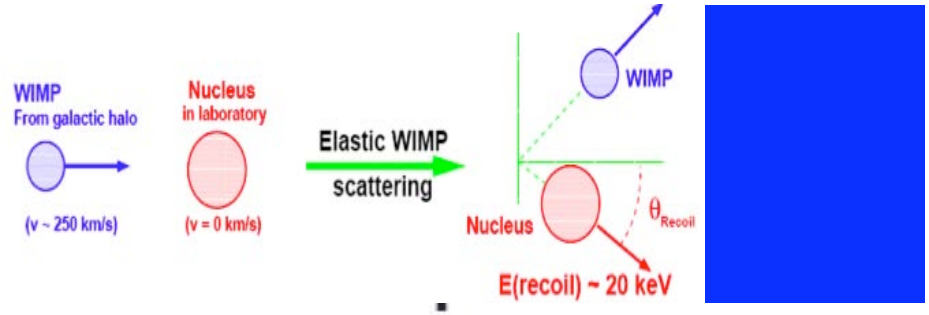
3. **Synchrotron and Inverse Compton**
   Relativistic electrons up-scatter starlight/CMB to MeV-GeV energies, and emit synchrotron photons via interactions with magnetic fields

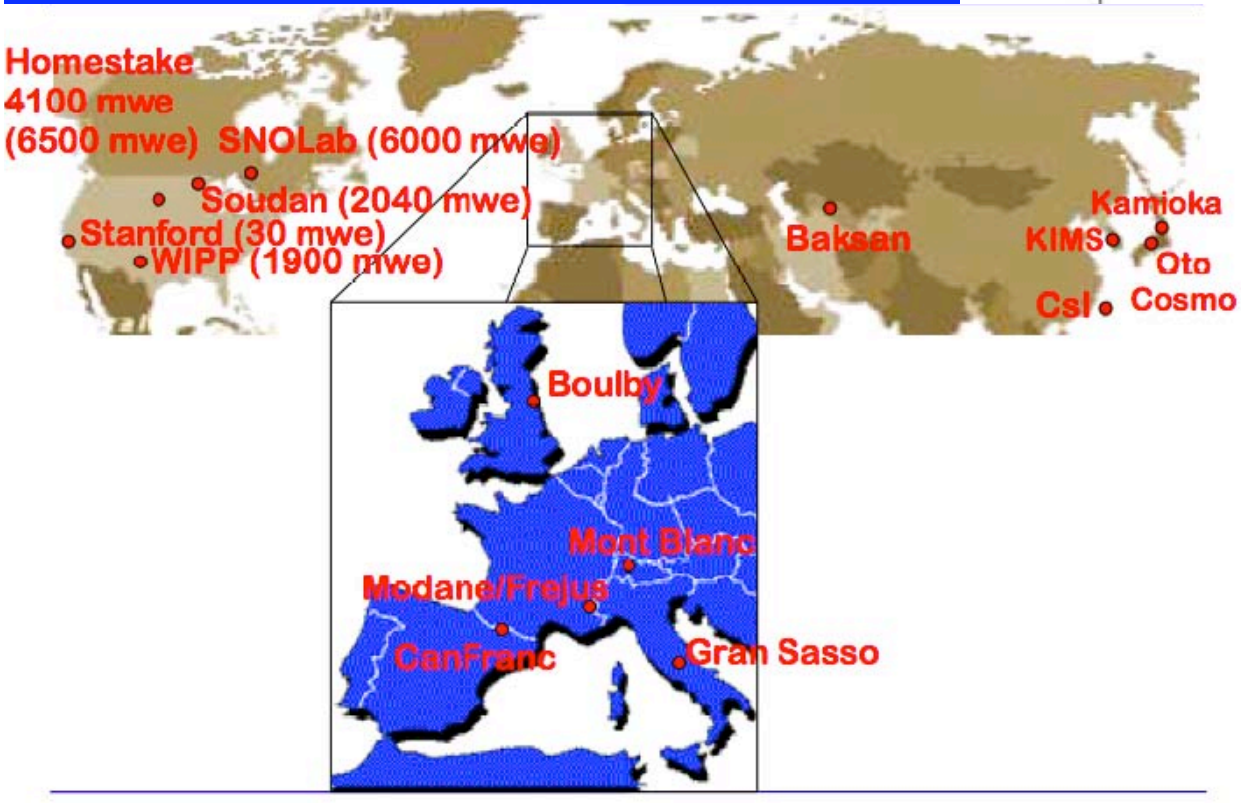


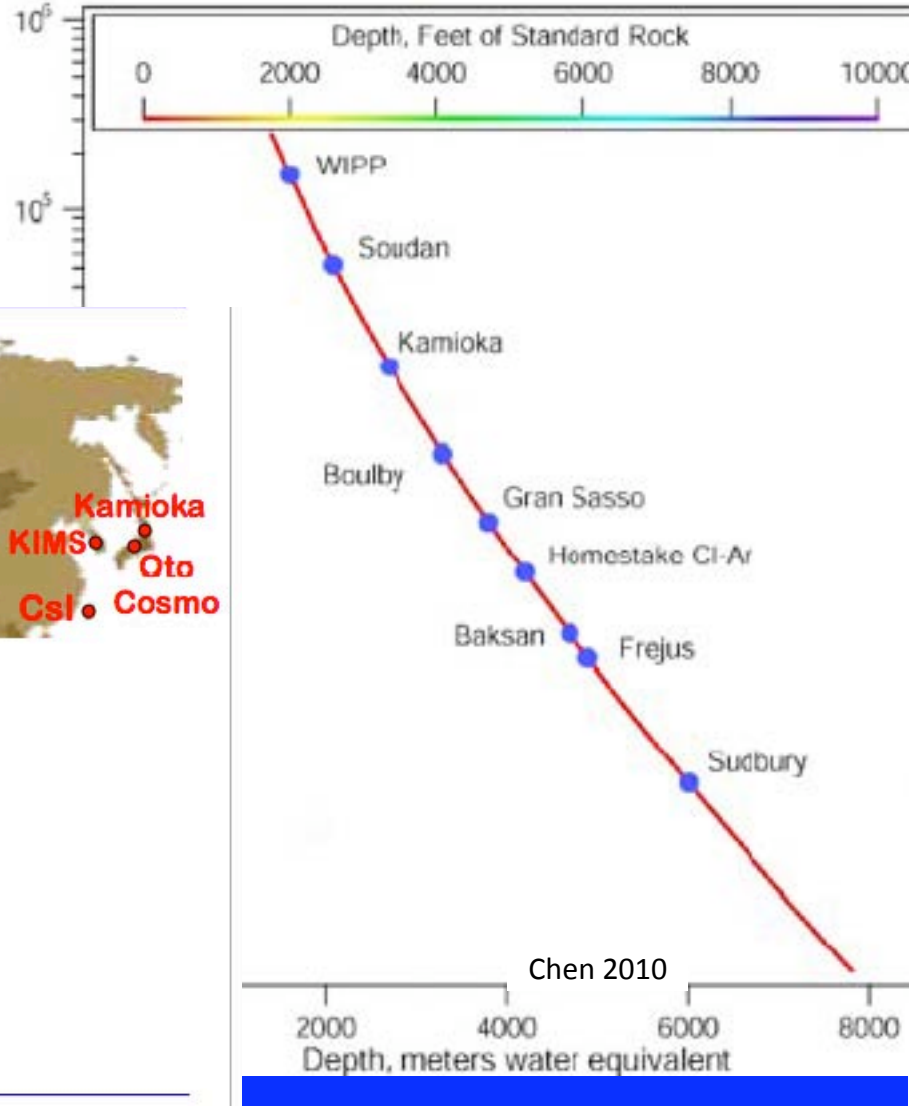
ASTROPHYSICAL PROBES OF DARK MATTER COMPLEMENT FUTURE COLLIDER EXPERIMENTS

Direct detection

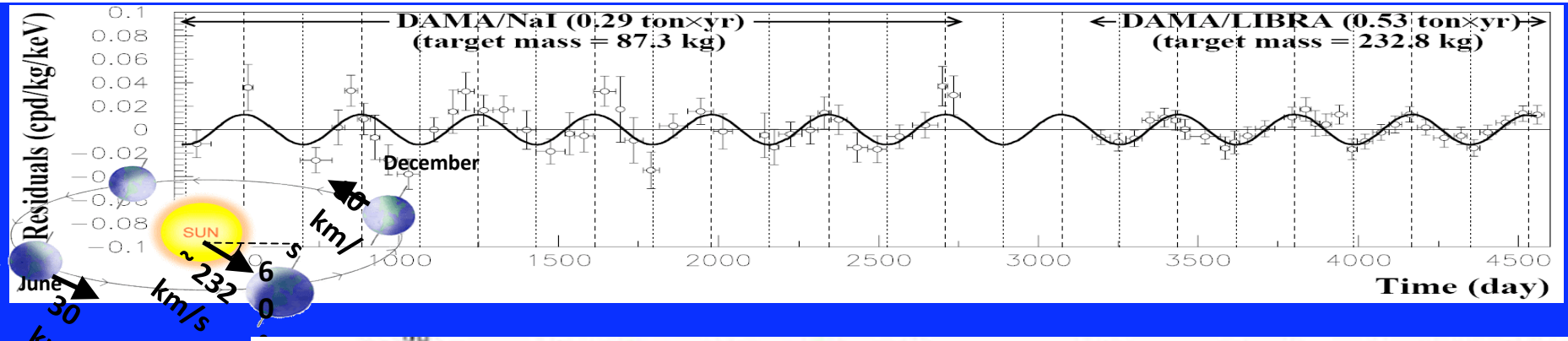

Ge, CS_2, C_3F_8
DRIFT
IGEX
COUPP
ZEPLIN II, III XENON
WARP
ArDM
LUX
SIGN
CDMS
EDELWEISS
Ge, Si
~20% of Energy
Ionization
Scintillation
Heat - Phonons
~70% of Energy
Few % of Energy
NAIAD
ZEPLIN I
DAMA
XMASS
DEAP/CLEAN
CRESST II
ROSEBUD
$CaWO_4$, BGO
$ZnWO_4$, Al_2O_3 ...
CRESST I
Al_2O_3, LiF
DM SAG at P5

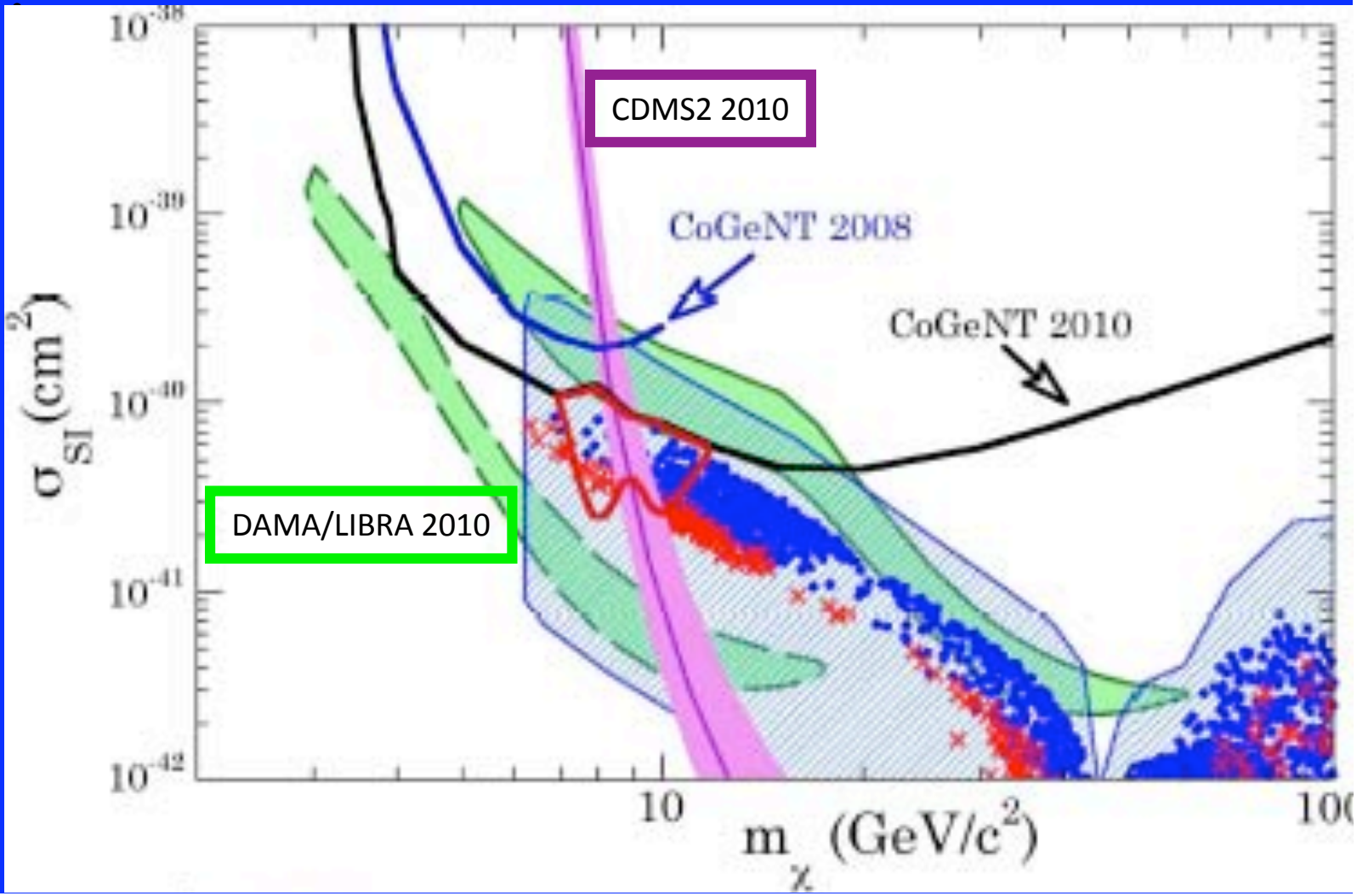

WIMP
From galactic halo
(v ~ 250 km/s)
Nucleus
in laboratory
(v = 0 km/s)
Elastic WIMP
scattering
WIMP
Nucleus
θ_{Recoil}
E(recoil) ~ 20 keV

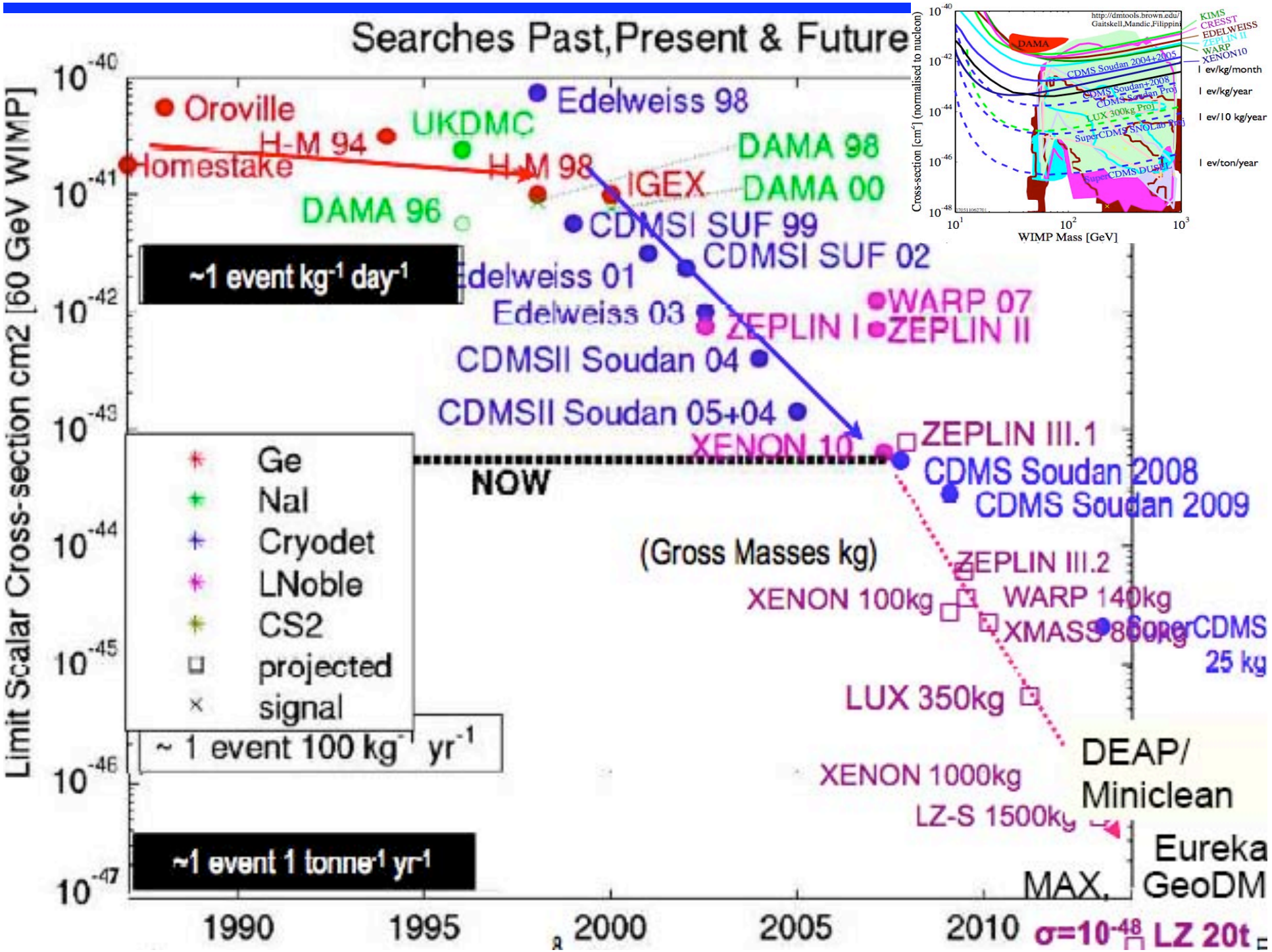

Homestake
4100 mwe
(6500 mwe)
SNOLab (6000 mwe)
Soudan (2040 mwe)
Stanford (30 mwe)
WIPP (1900 mwe)
Baksan
Kamioka
KIMS
Oto
Csl
Cosmo
Boulby
Mont Blanc
Modane/Frejus
CanFranc
Gran Sasso


10^6
10^5
Depth, Feet of Standard Rock
0
2000
4000
6000
8000
10000
WIPP
Soudan
Kamioka
Boulby
Gran Sasso
Homestake Cl-Ar
Baksan
Frejus
Sudbury
2000
4000
6000
8000
Depth, meters water equivalent

Chen 2010

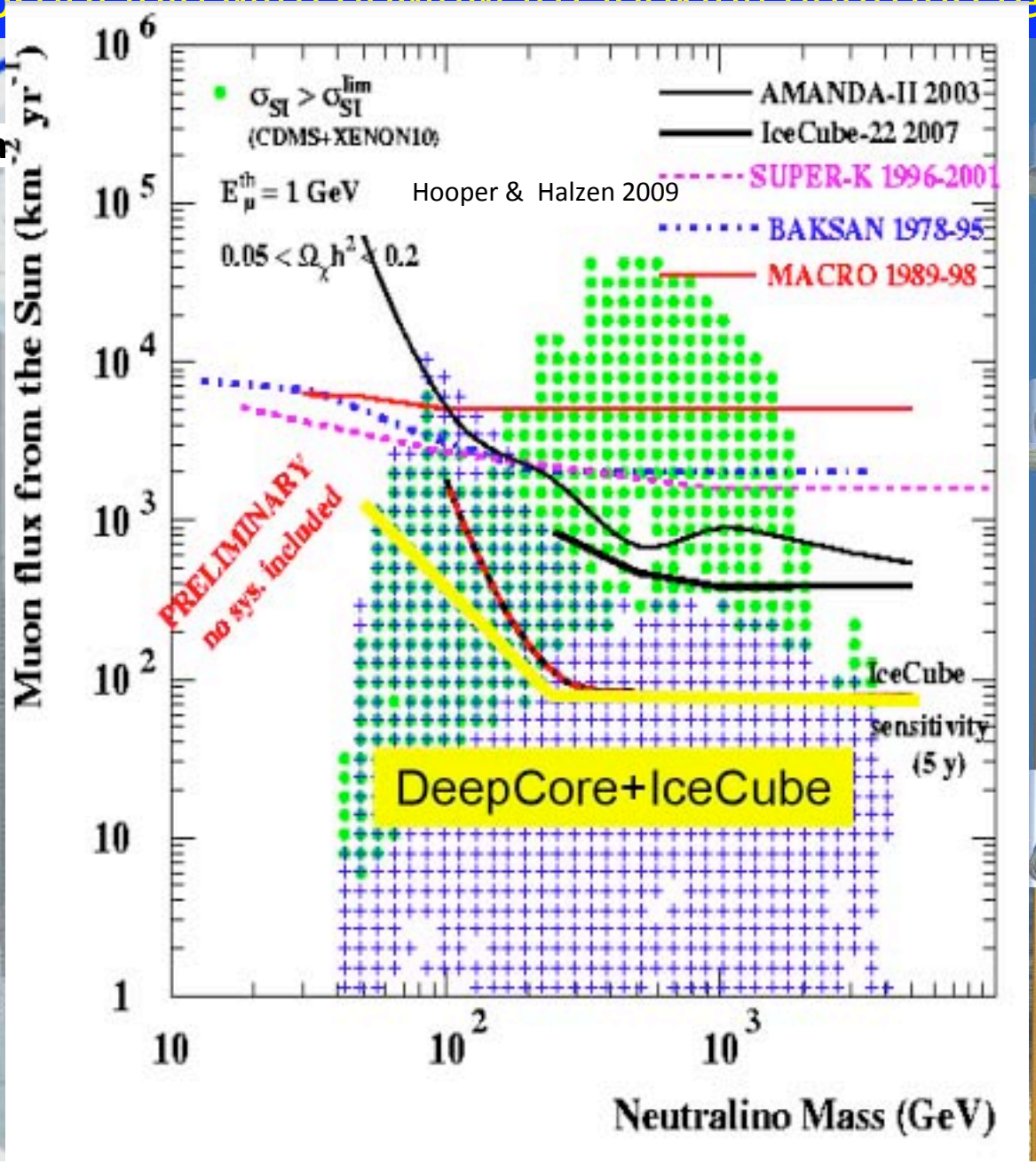

DAMA/NaI (0.29 ton×yr)
(target mass = 87.3 kg)
DAMA/LIBRA (0.53 ton×yr)
(target mass = 232.8 kg)
Residuals (cpd/kg/keV)
Time (day)
December
June
SUN
~ 232 km/s
~ 30 km/s
~ 60 km/s

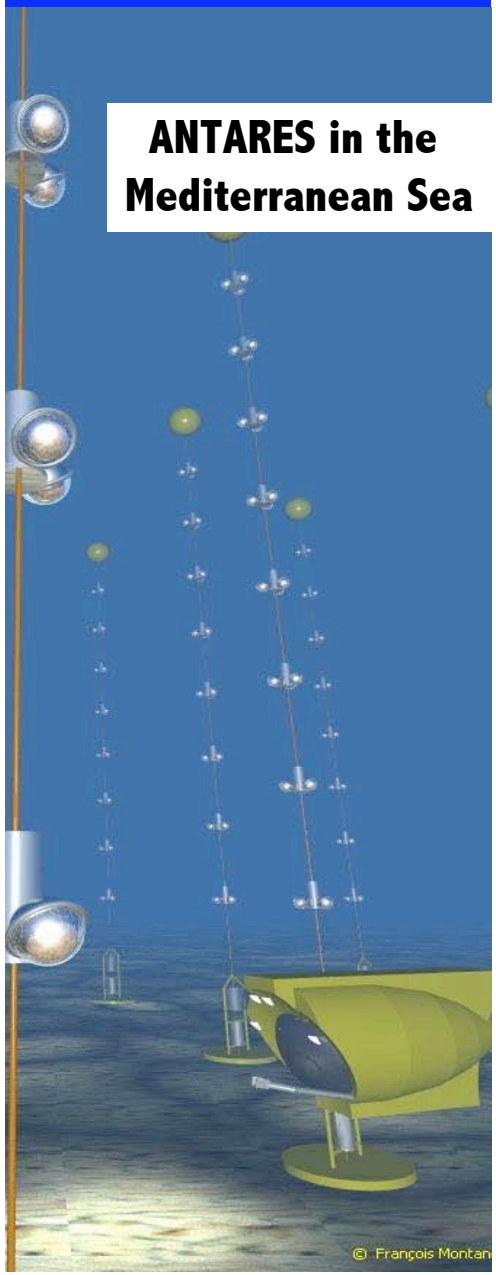

CDMS2 2010
CoGeNT 2008
CoGeNT 2010
DAMA/LIBRA 2010
σ_{SI} (cm^2)
m$_\chi$ (GeV/c^2)


Searches Past,Present & Future
Limit Scalar Cross-section cm2 [60 GeV WIMP]
Oroville
Homestake
H-M 94
UKDMC
H-M 98
Edelweiss 98
DAMA 96
DAMA 98
DAMA 00
IGEX
CDMSI SUF 99
CDMSI SUF 02
Edelweiss 01
Edelweiss 03
ZEPLIN I
WARP 07
ZEPLIN II
CDMSII Soudan 04
CDMSII Soudan 05+04
XENON 10
~1 event kg-1 day-1
NOW
Ge
NaI
Cryodet
LNoble
CS2
projected
signal
~ 1 event 100 kg-1 yr-1
~1 event 1 tonne-1 yr-1
ZEPLIN III.1
CDMS Soudan 2008
CDMS Soudan 2009
(Gross Masses kg)
ZEPLIN III.2
XENON 100kg
WARP 140kg
XMASS 800kg
SuperCDMS 25 kg
LUX 350kg
DEAP/ Miniclean
XENON 1000kg
LZ-S 1500kg
Eureka
MAX.
GeoDM
σ=10-48
LZ 20t
1990
1995
2000
2005
2010
Cross-section [cm2] (normalised to nucleon)
WIMP Mass [GeV]
http://dmtools.brown.edu/
Gaitskell,Mandic,Filippini
DAMA
CDMS Soudan 2004+2005
CDMS Soudan+2008
CDMS Soudan Proj
LUX 300kg Proj
SuperCDMS SNOLab Proj
SuperCDMS DUSEL
KIMS
CRESST
EDELWEISS
ZEPLIN II
WARP
XENON10
1 ev/kg/month
1 ev/kg/year
1 ev/10 kg/year
1 ev/ton/year

Indirect detection: neutrinos

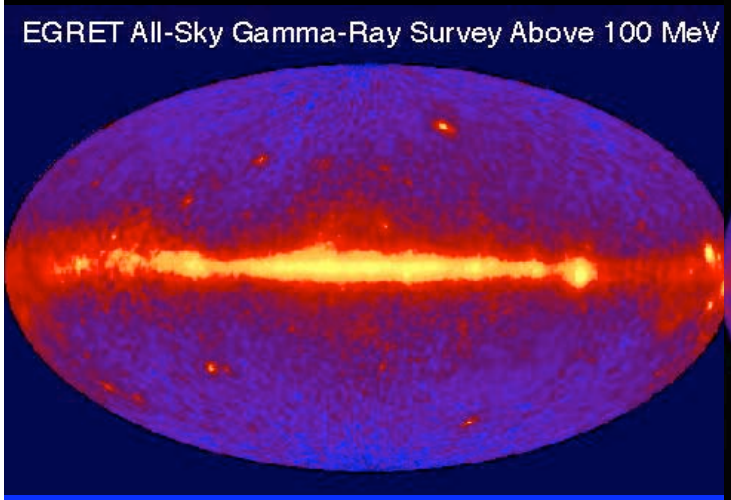
high energy neutrinos from WIMPs annihilating in the sun observable with downward looking neutrino telescopes

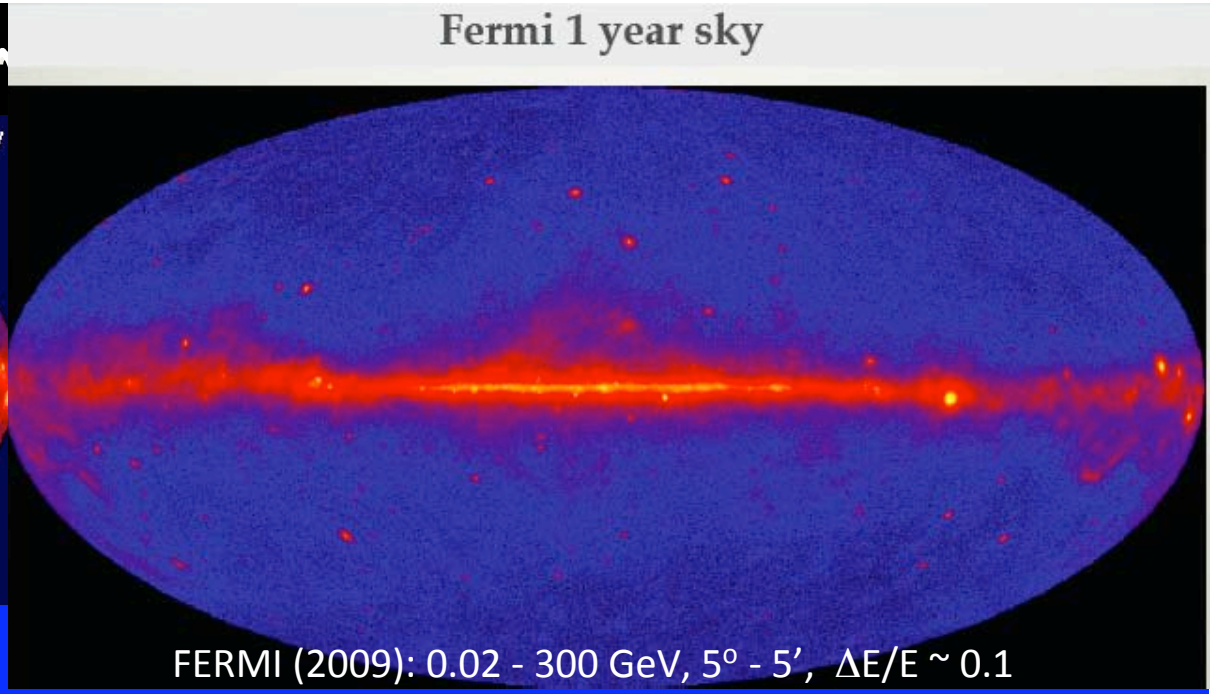




Indirect detection: γ rays

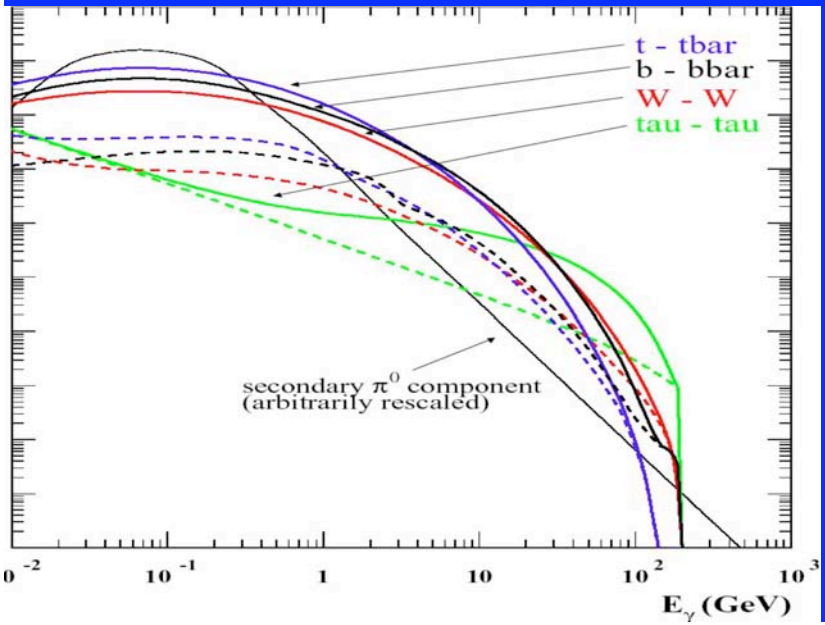
annihilation

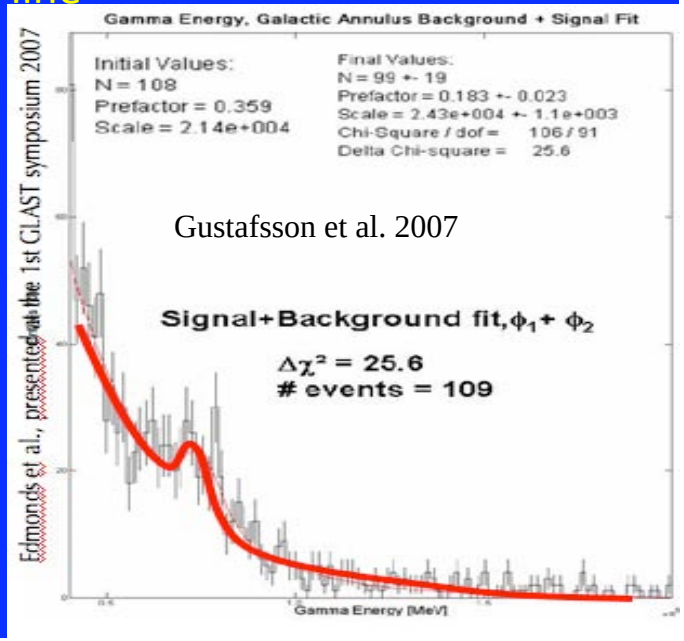


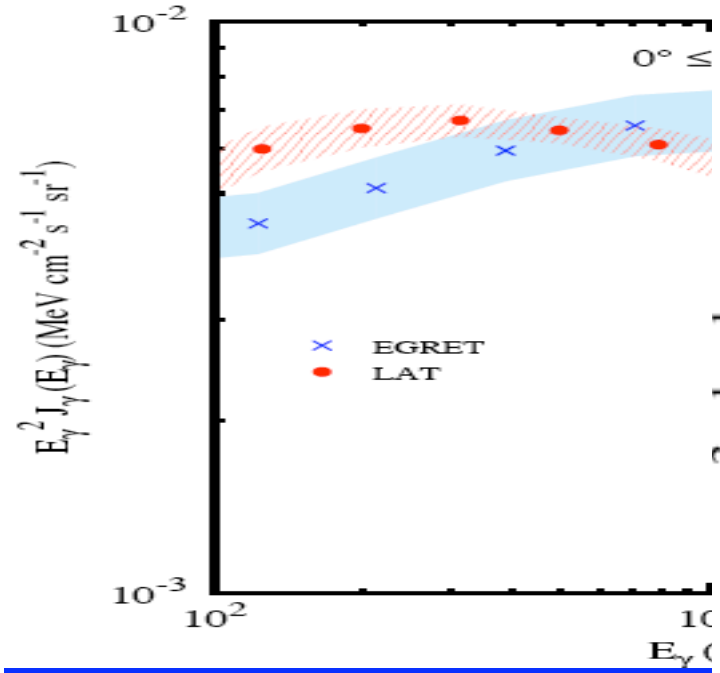


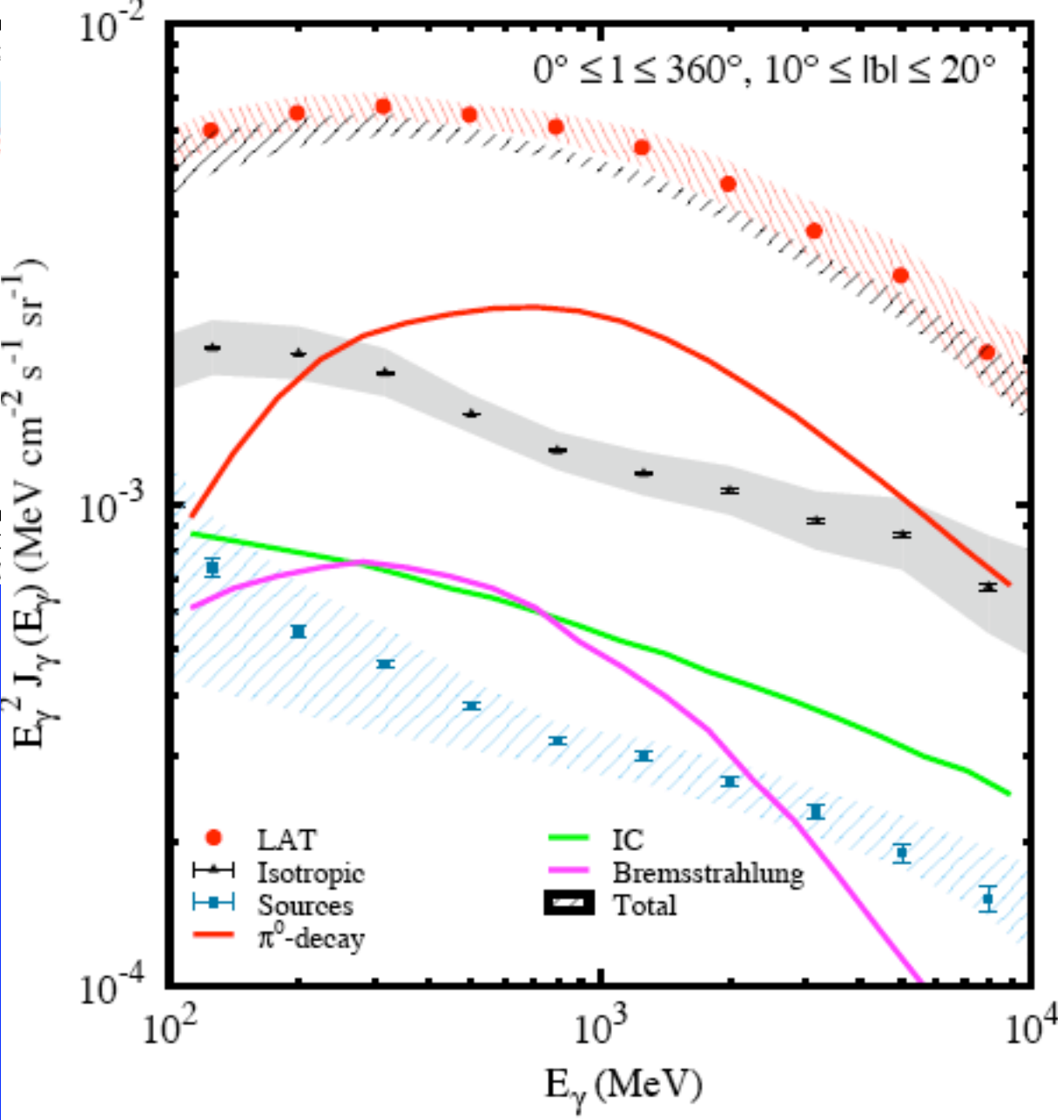
FERMI (2009): 0.02 - 300 GeV, 5° - 5', $\Delta E/E \sim 0.1$

predict γ ray "smoking guns": hard spectrum annihilation line





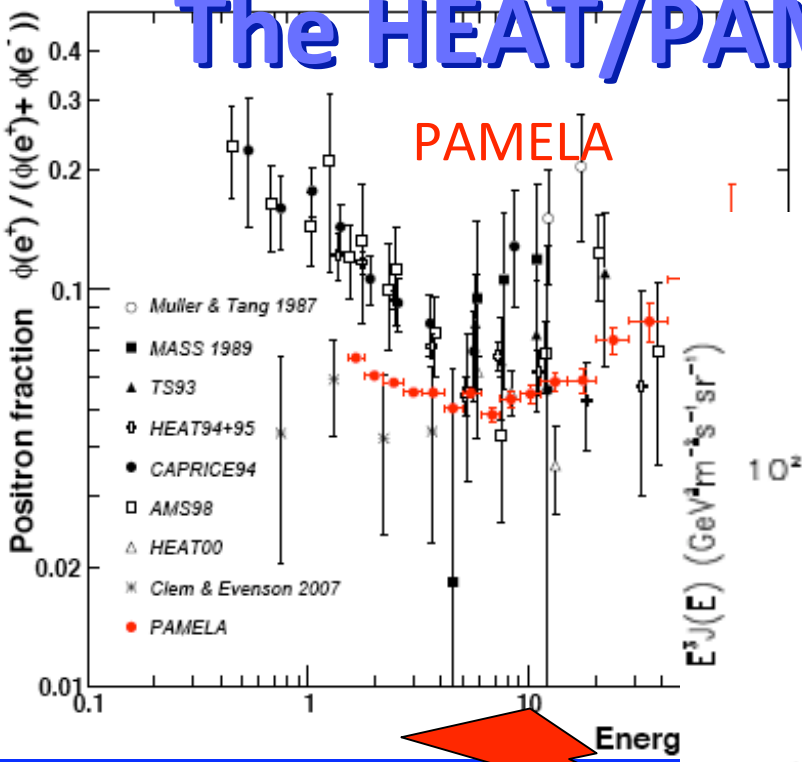

10^{-2}
10^{-3}
10^{2}
$E_\gamma^2 J_\gamma(E_\gamma)$ (MeV cm^{-2} s^{-1} sr^{-1})
EGRET
LAT


10^{-2}
10^{-3}
10^{-4}
10^{2}
10^{3}
10^{4}
E_γ (MeV)
$E_\gamma^2 J_\gamma(E_\gamma)$ (MeV cm^{-2} s^{-1} sr^{-1})
0° ≤ l ≤ 360°, 10° ≤ |b| ≤ 20°
LAT
Isotropic
Sources
π^0-decay
IC
Bremsstrahlung
Total

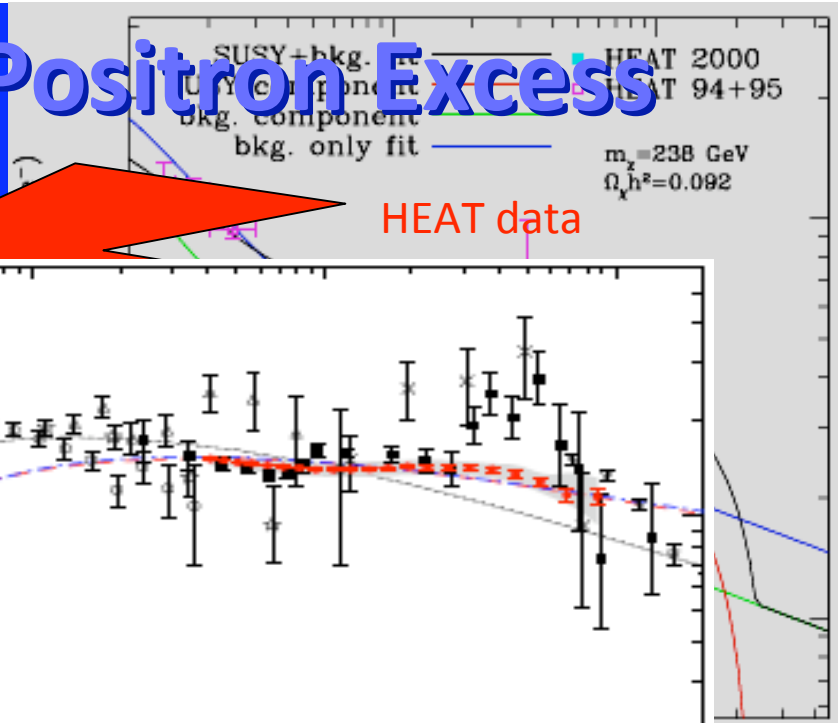
Indirect detection:

high energy e^+

The HEAT/PAMELA Positron Excess

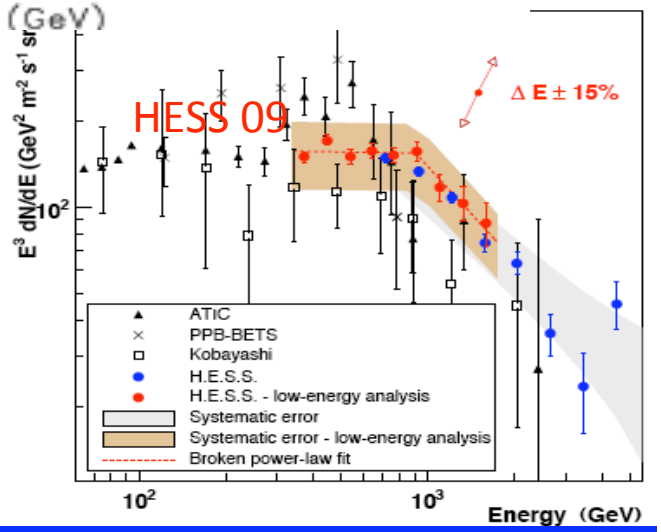


PAMELA

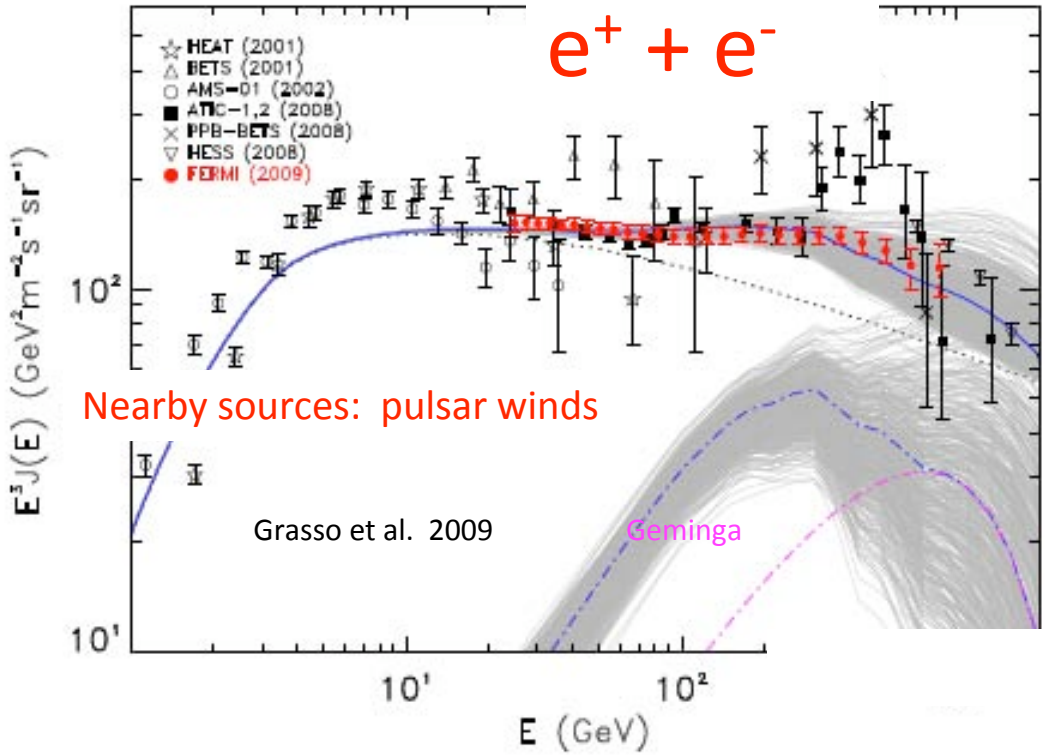


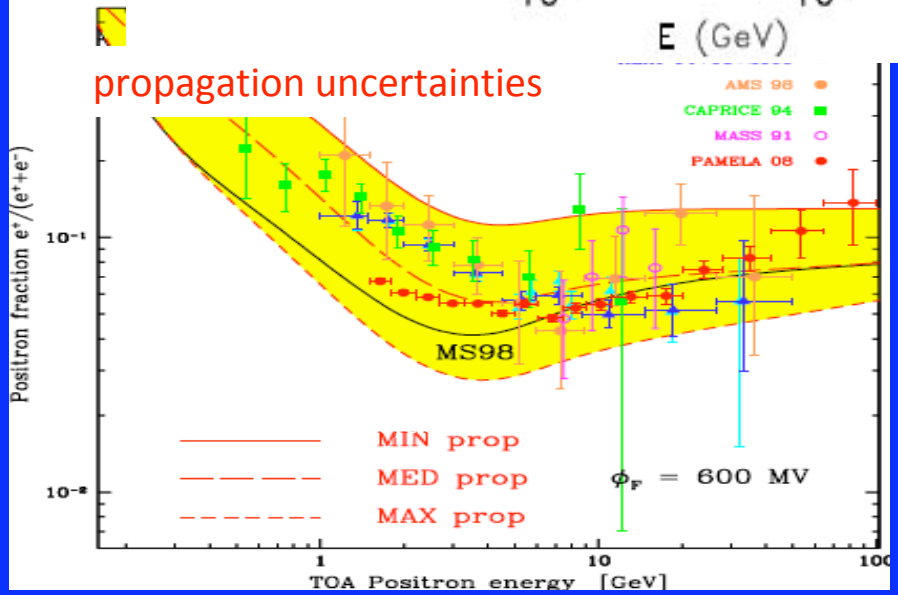
HEAT data

FERMI 09



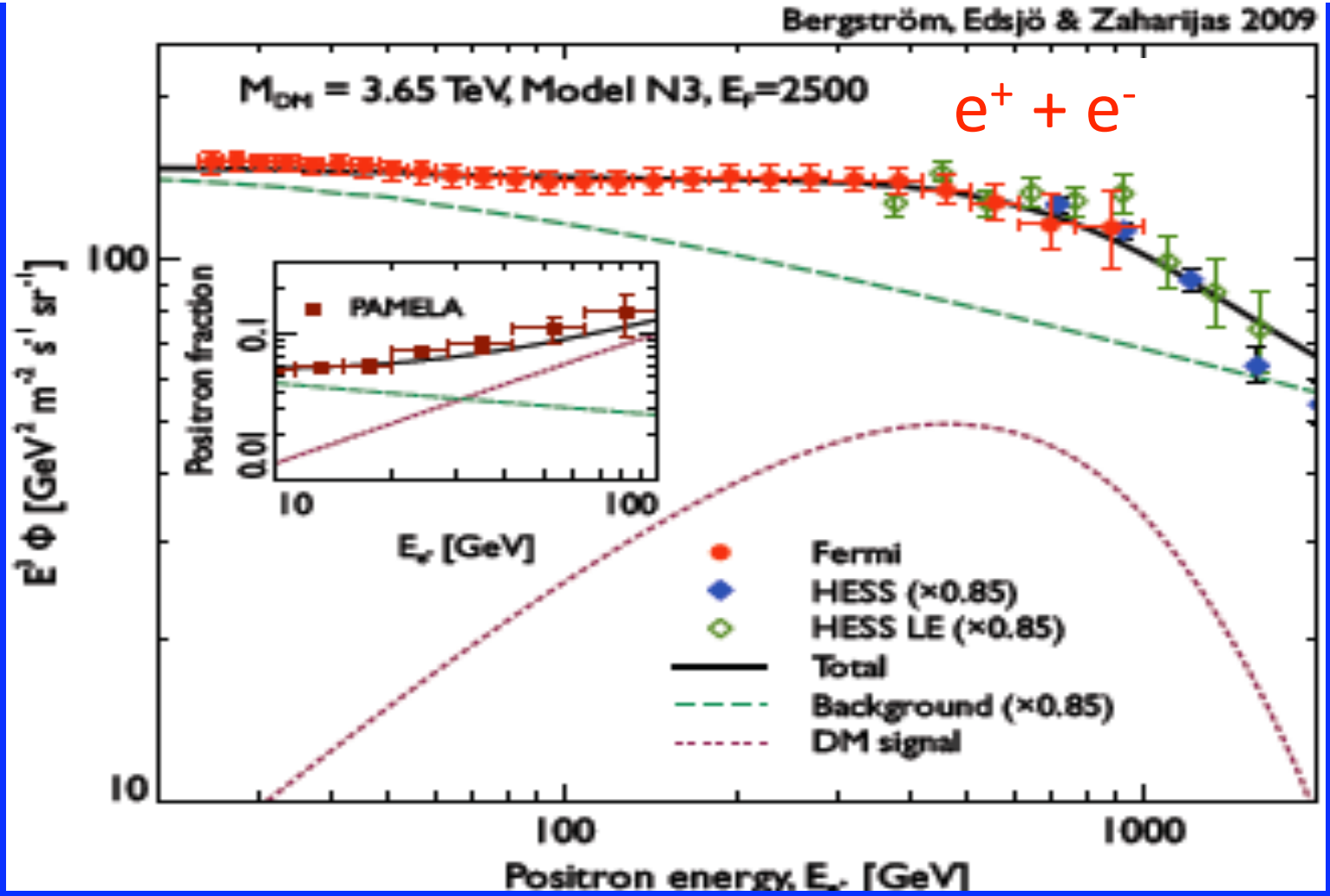
HESS 09





Blasi 2009

ASTROPHYSICS SOLUTIONS



massive neutralino requires large boost

since flux ~ ρ/m_x^2

PARTICLE PHYSICS SOLUTION with annihilating dark matter

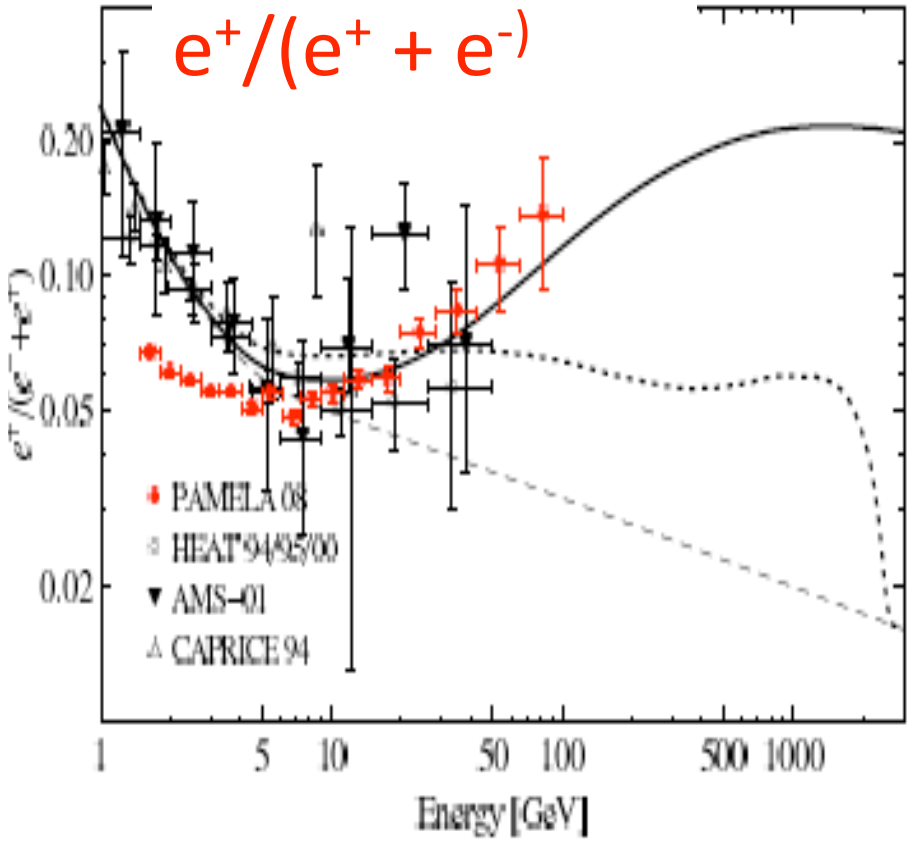
Sommerfeld effect provides boost

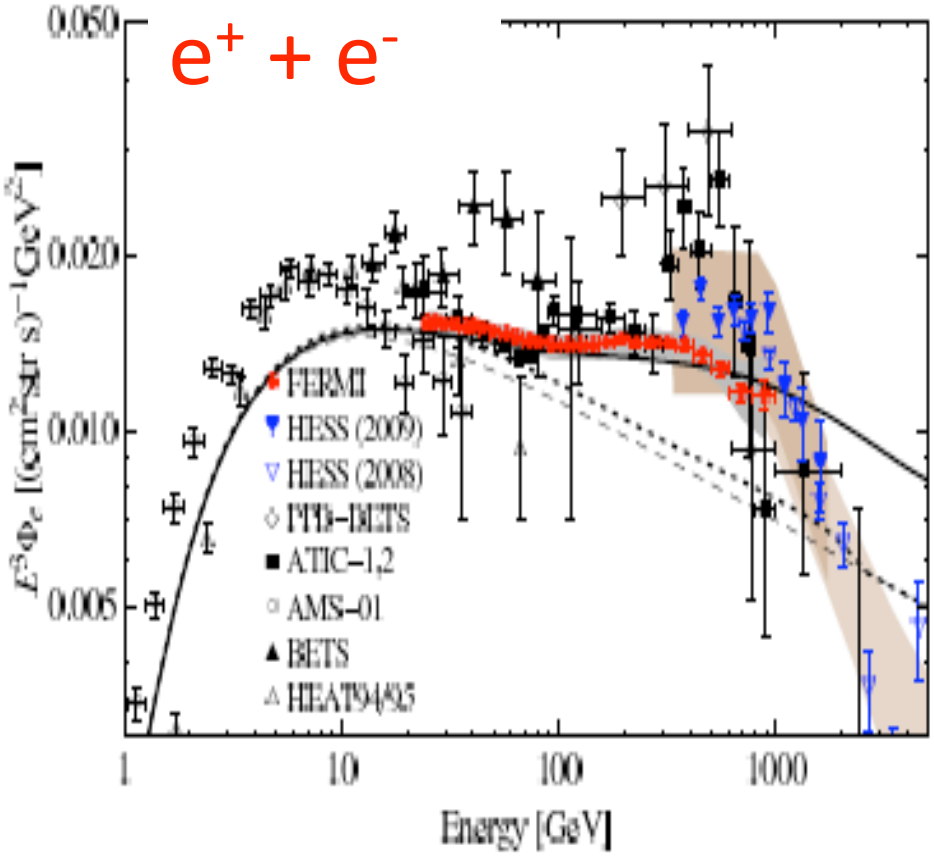
QM counterpart to gravity

$S=S_0[\ 1+(v_{esc}/v)^2]$

due to DM bound states

Arkani-Hamed et al 2008
Lattanzi and JS 2008
March-Russell and West 2809



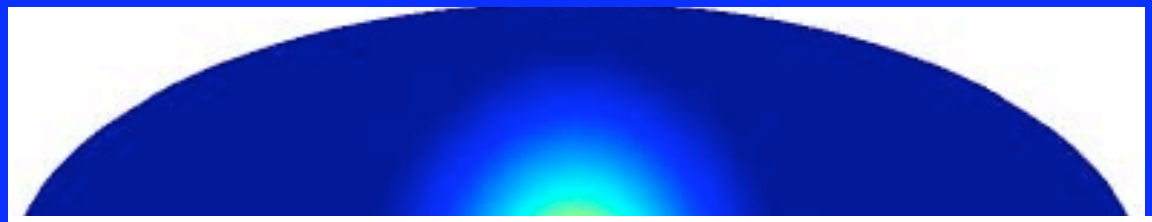


massive neutralino requires decay time ~ 10^{26} sec

PARTICLE PHYSICS SOLUTION with decaying dark matter

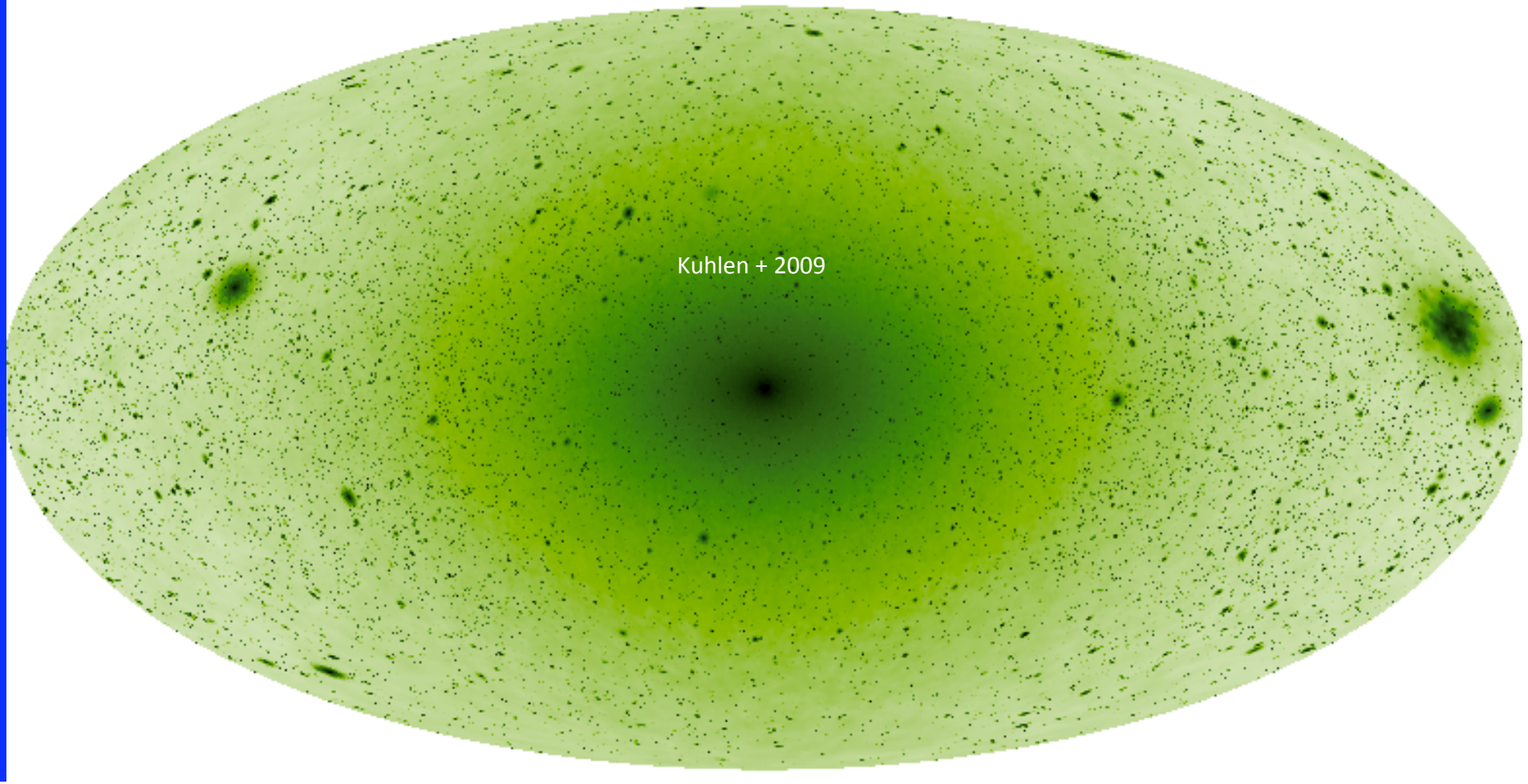
Ibarra + 2009

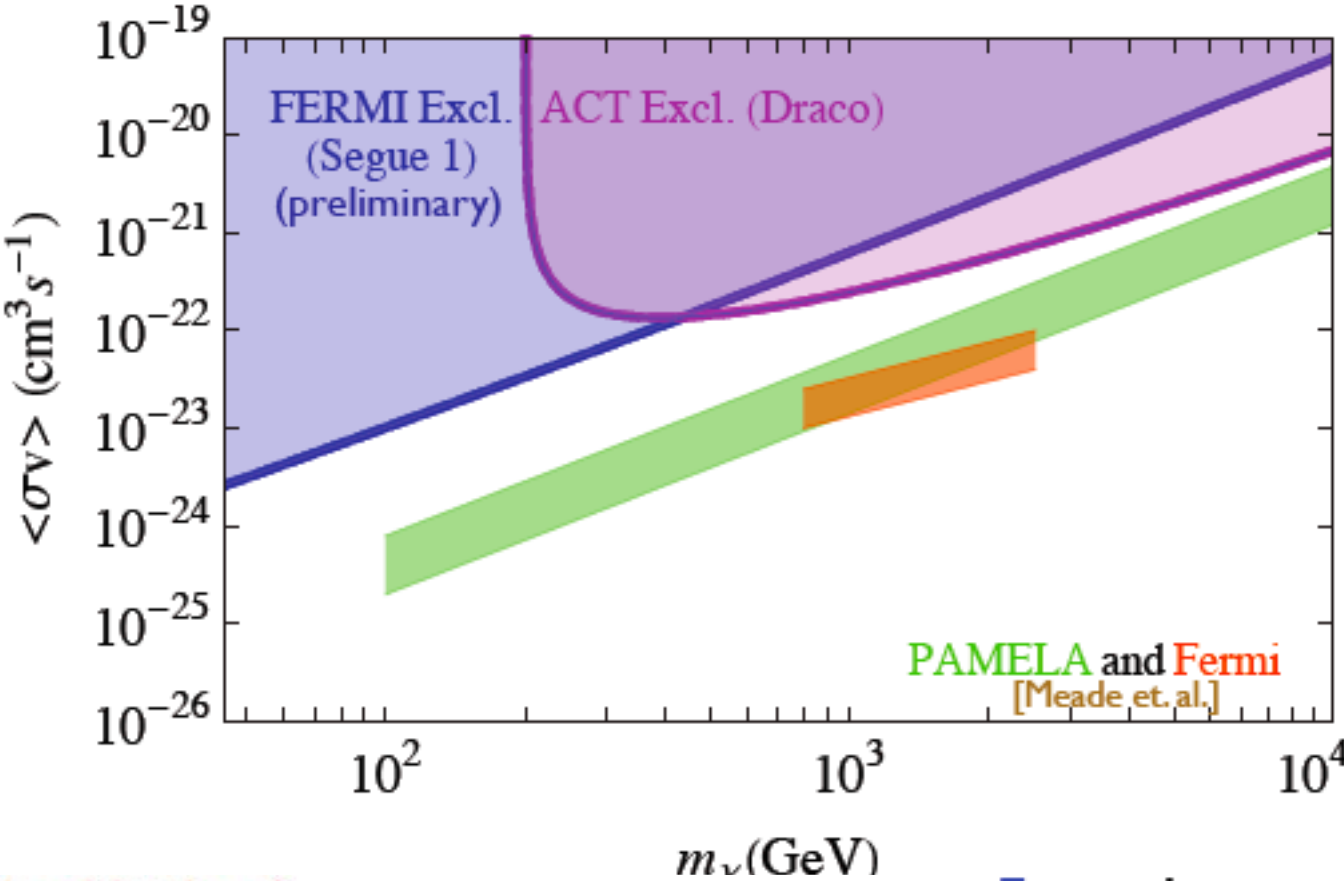
Prediction: dwarfs should be detectable for annihilating dark matter



CDM simulations with 1000 M_{sun} resolution weighted by density^2 /v^2

Kuhlen+ 2009

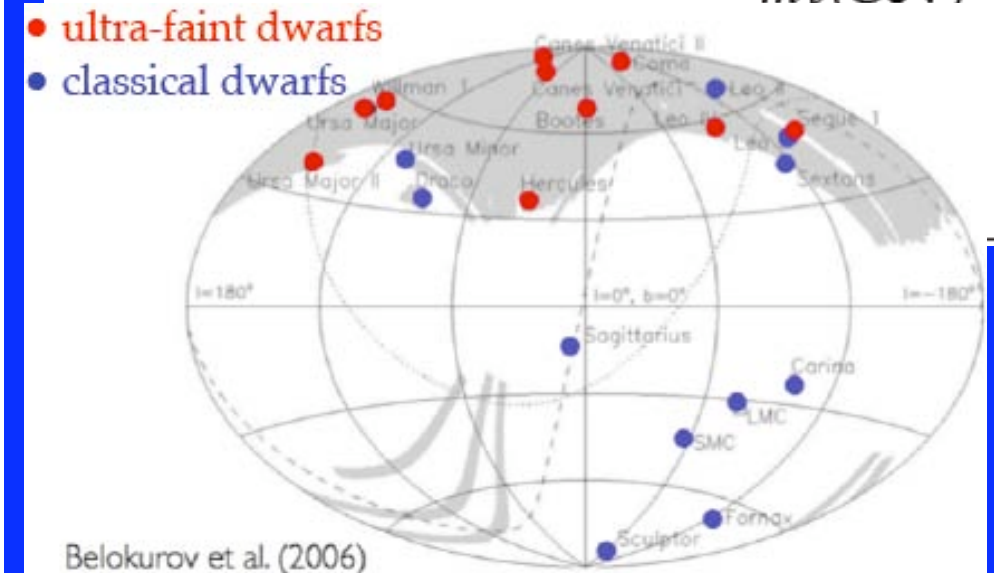




Fermi data:
9 months of data

[Farnier, RICAP'09]
[Wang, CINC'09]

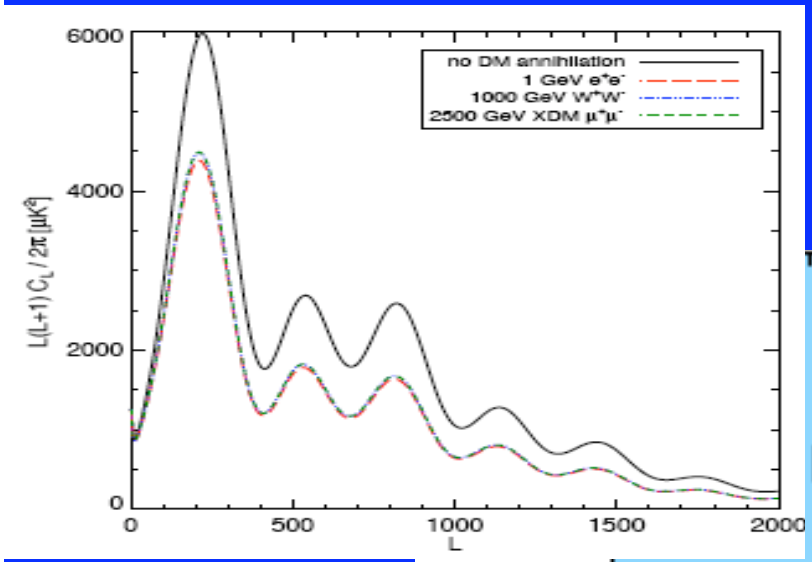
ACT data:
VERITAS obs. of Draco [0810.1913]



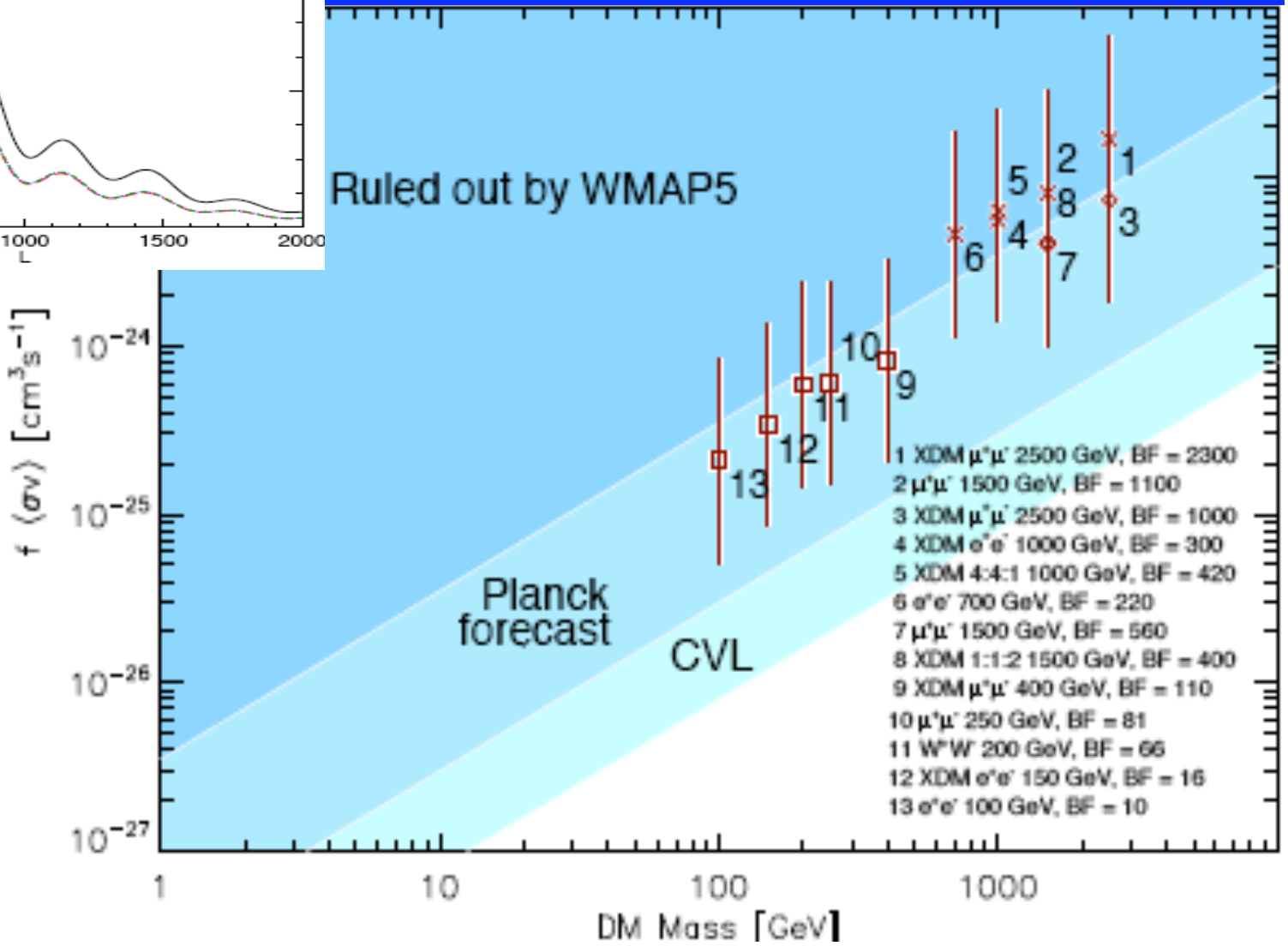
Fermi better at lower masses,
ACTs at higher masses

Neelima Sehgal, KIPAC

Prediction: annihilation and CMB distortions

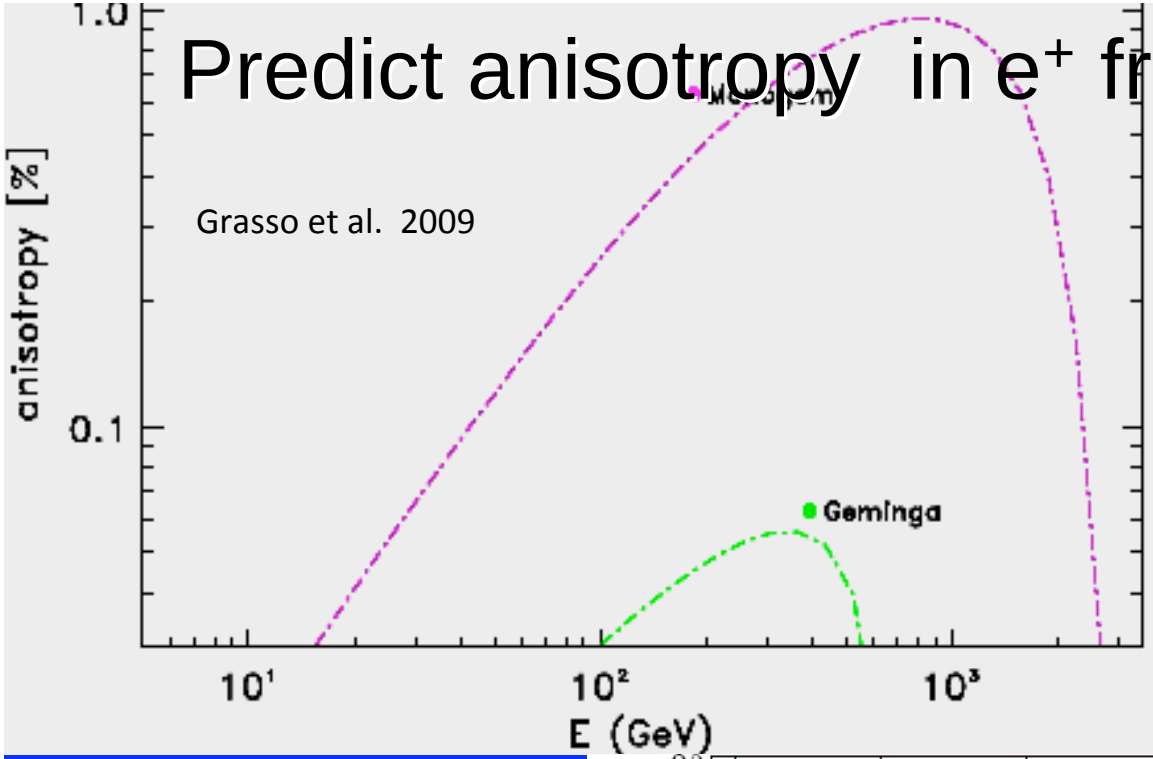


Slatyer et al. 2009



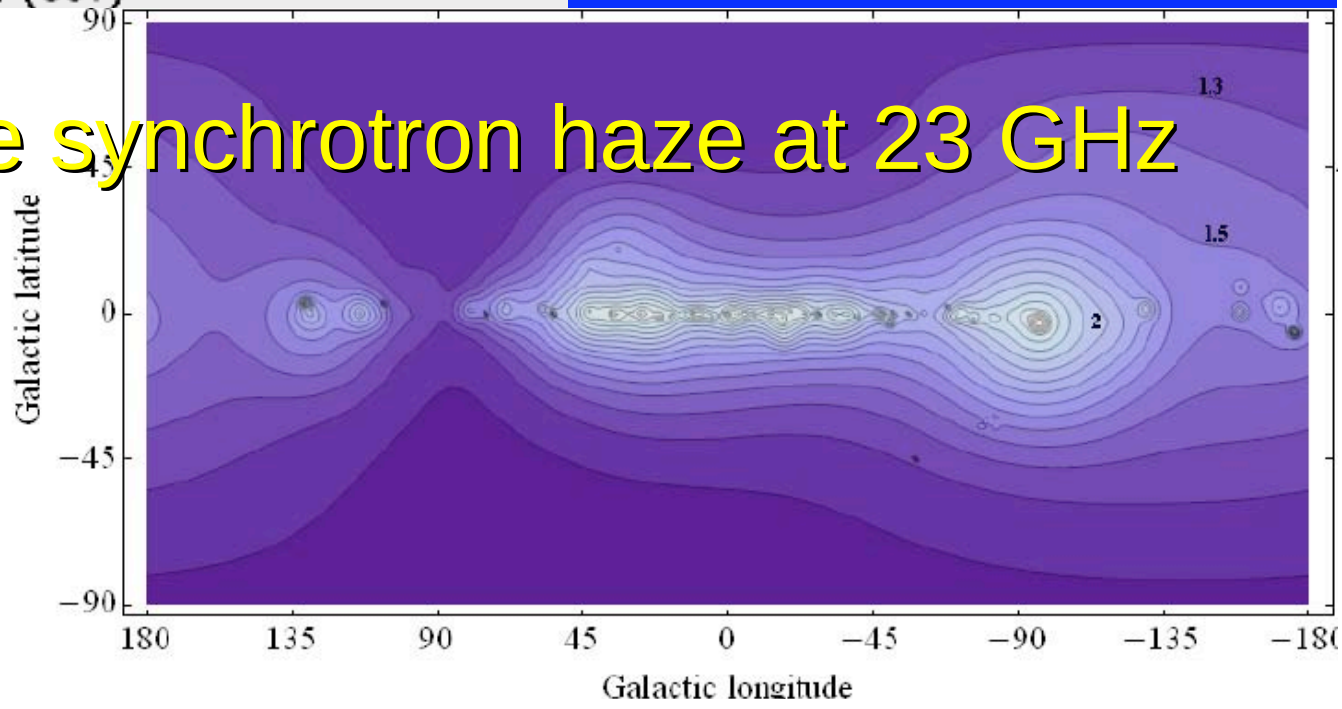
Predict anisotropy in e^+ from nearby pulsars

Grasso et al. 2009

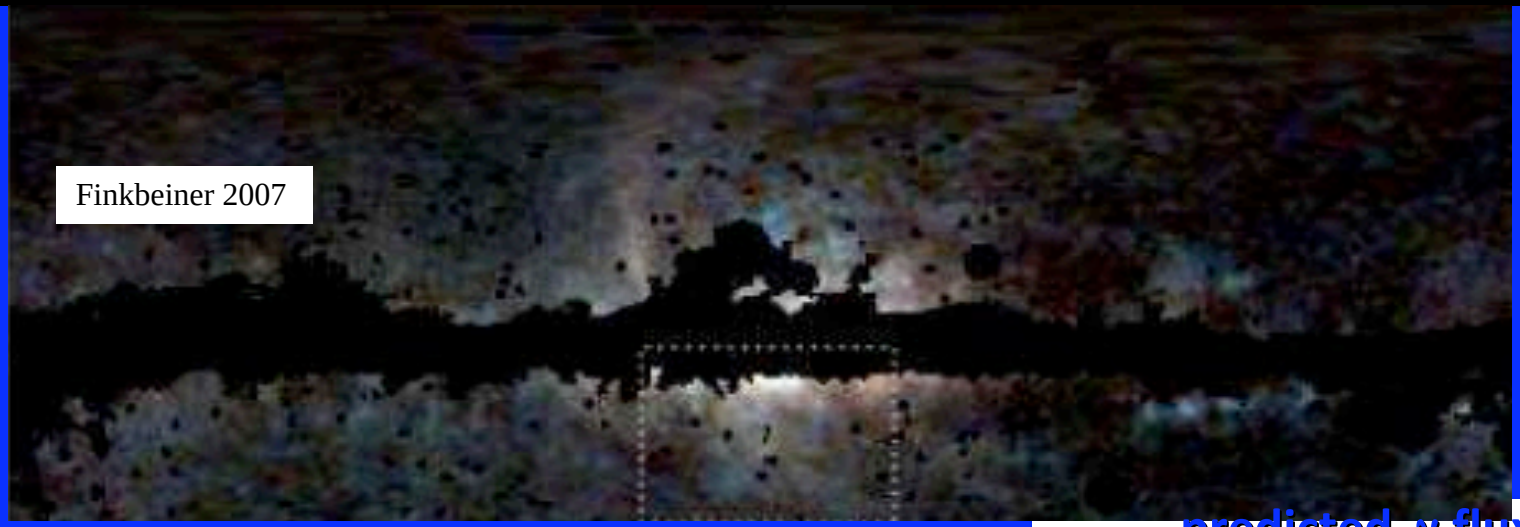


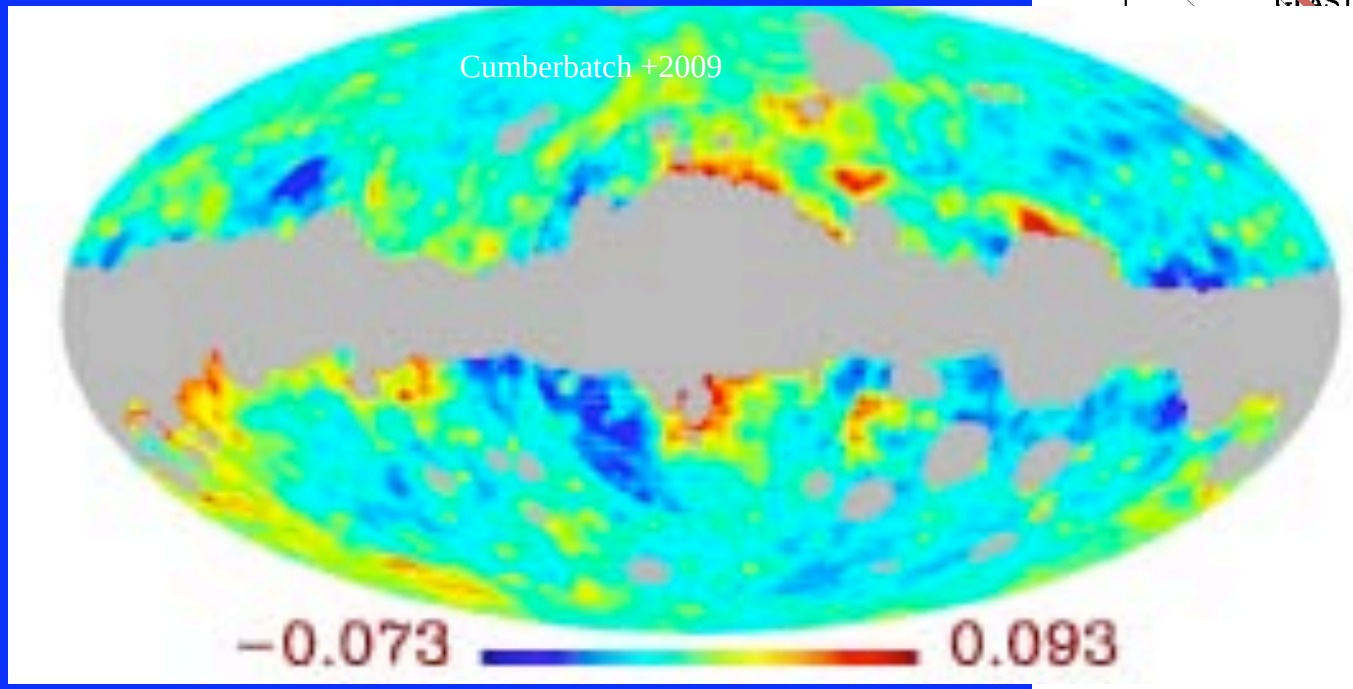
Predict diffuse synchrotron haze at 23 GHz

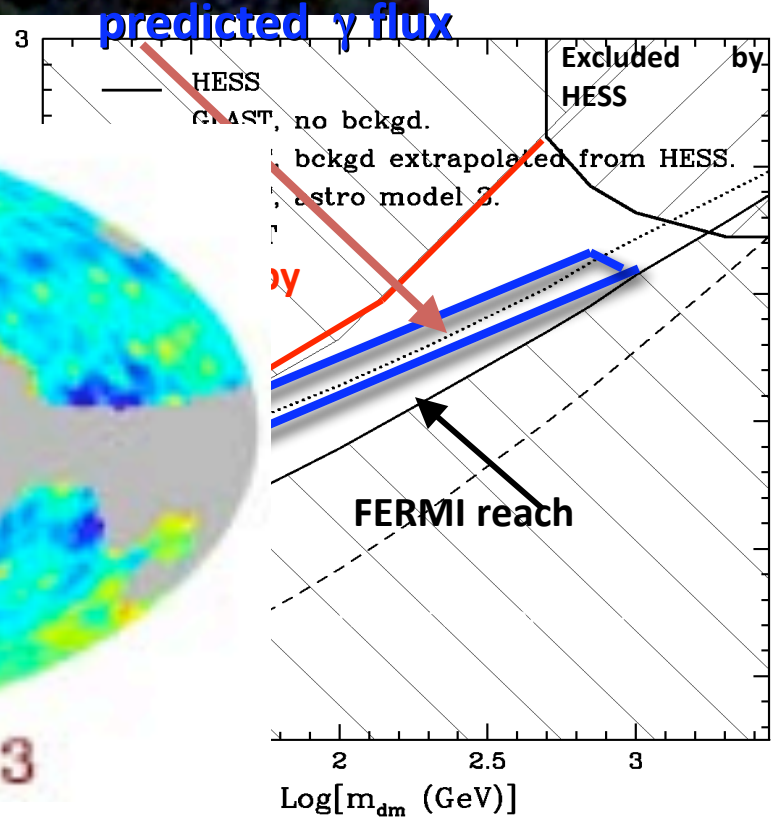
Kelso & Hooper 2010



The WMAP microwave haze



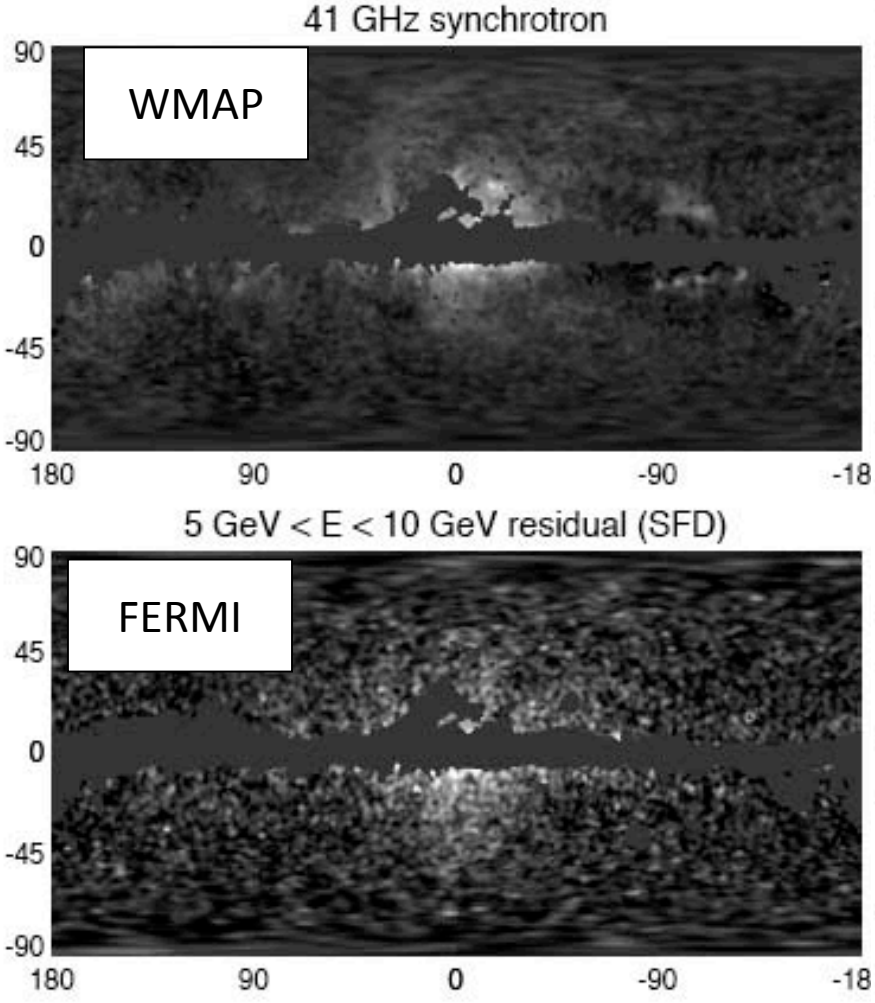


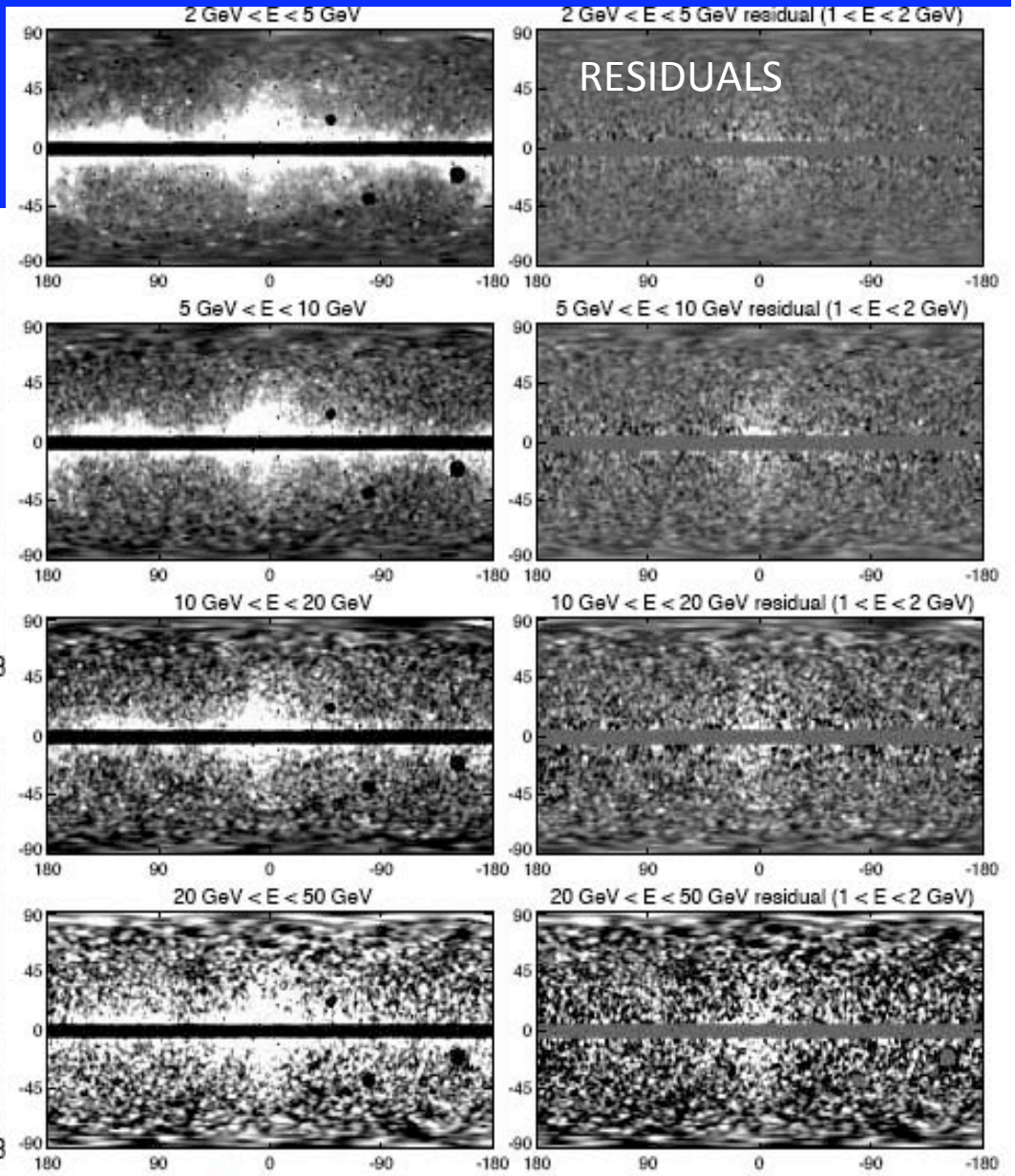


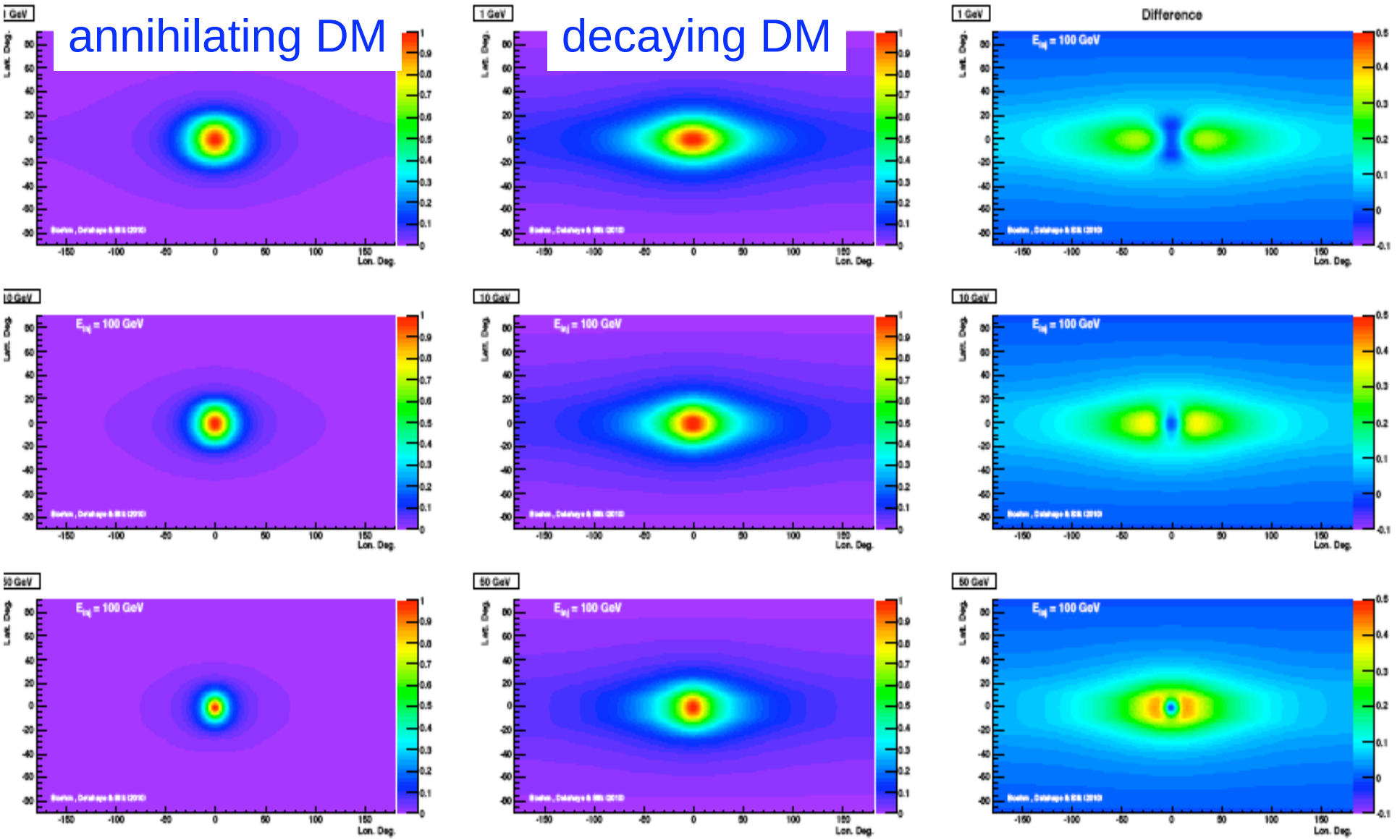
Fermi haze

Dobler et al. 2009

Inverse Compton of e^+e^- on interstellar radiation

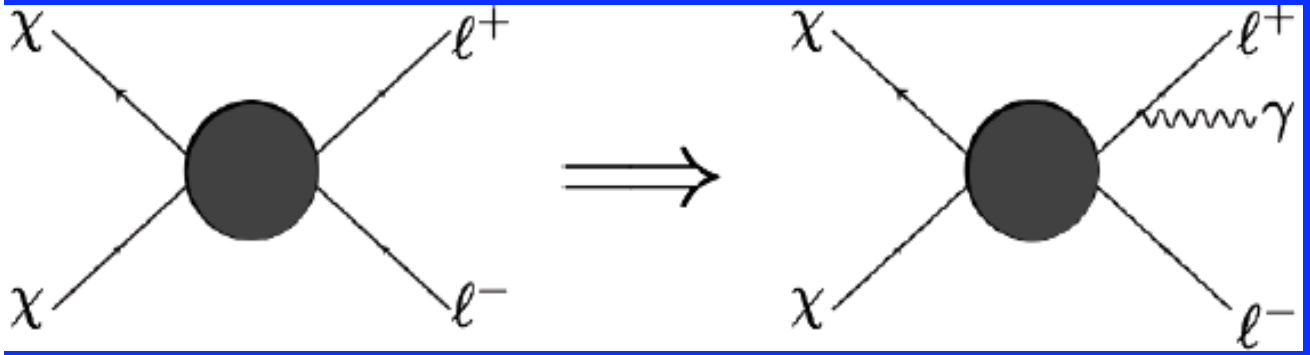


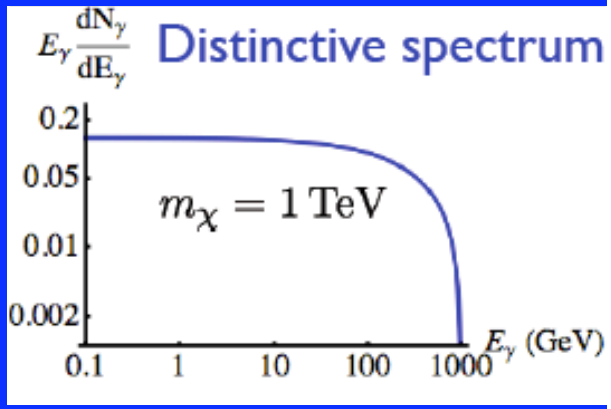




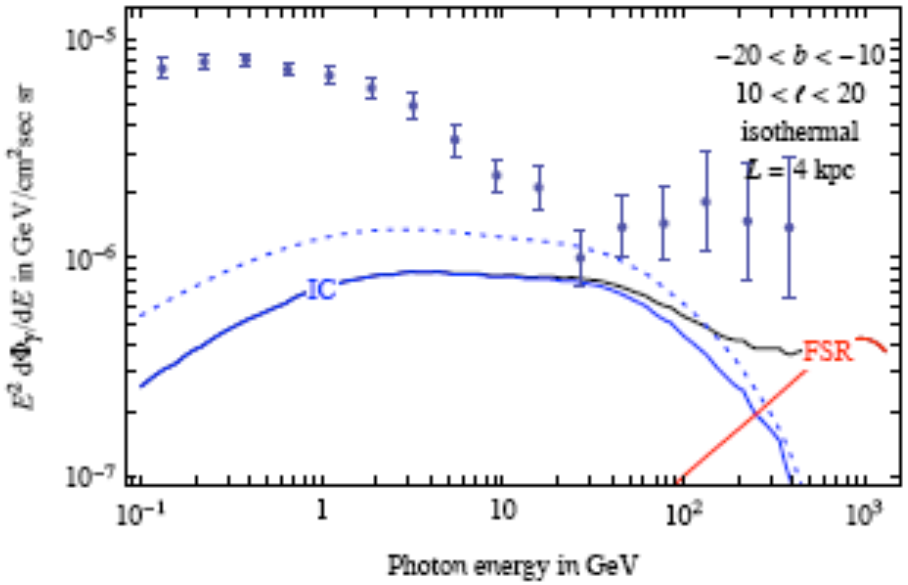
Boehm, Delahaye, JS 2010

FERMI/HESS prediction: final state gamma rays

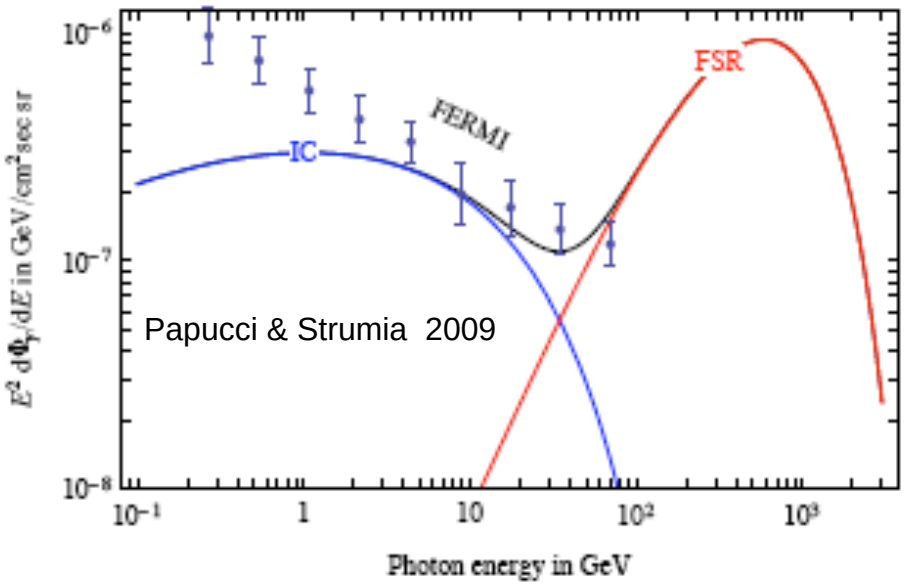




DM DM $\to \mu^+\mu^-$, $M = 1.3$ TeV, $\sigma v = 2.8 \times 10^{-23}$ cm^3/s

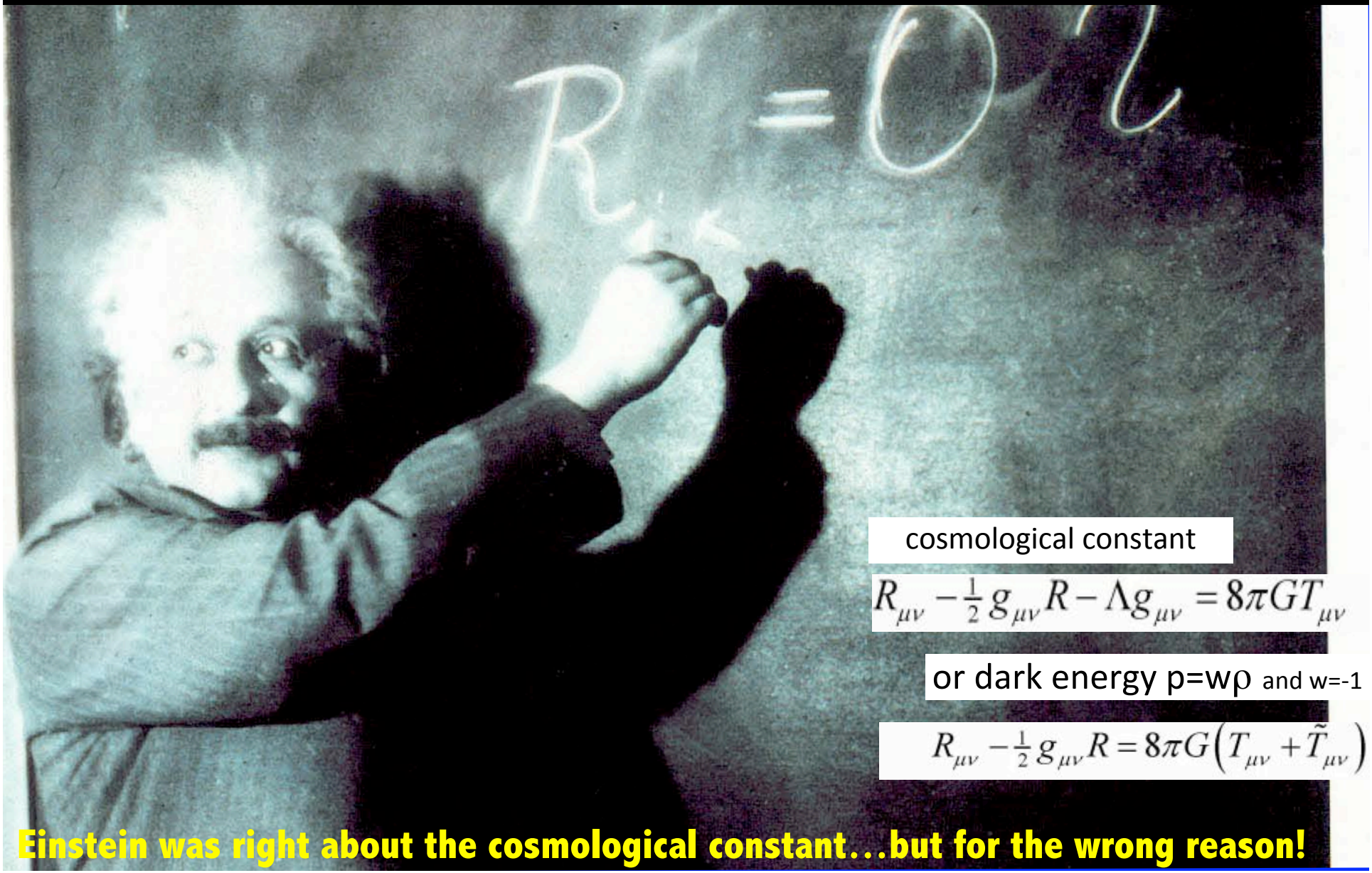


DM $\to \tau^+\tau^-$ with $M = 6.$ TeV and $\tau = 5.4 \times 10^{25}$ sec



Dark energy

WHERE DARK ENERGY ORIGINATED



cosmological constant

$$R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

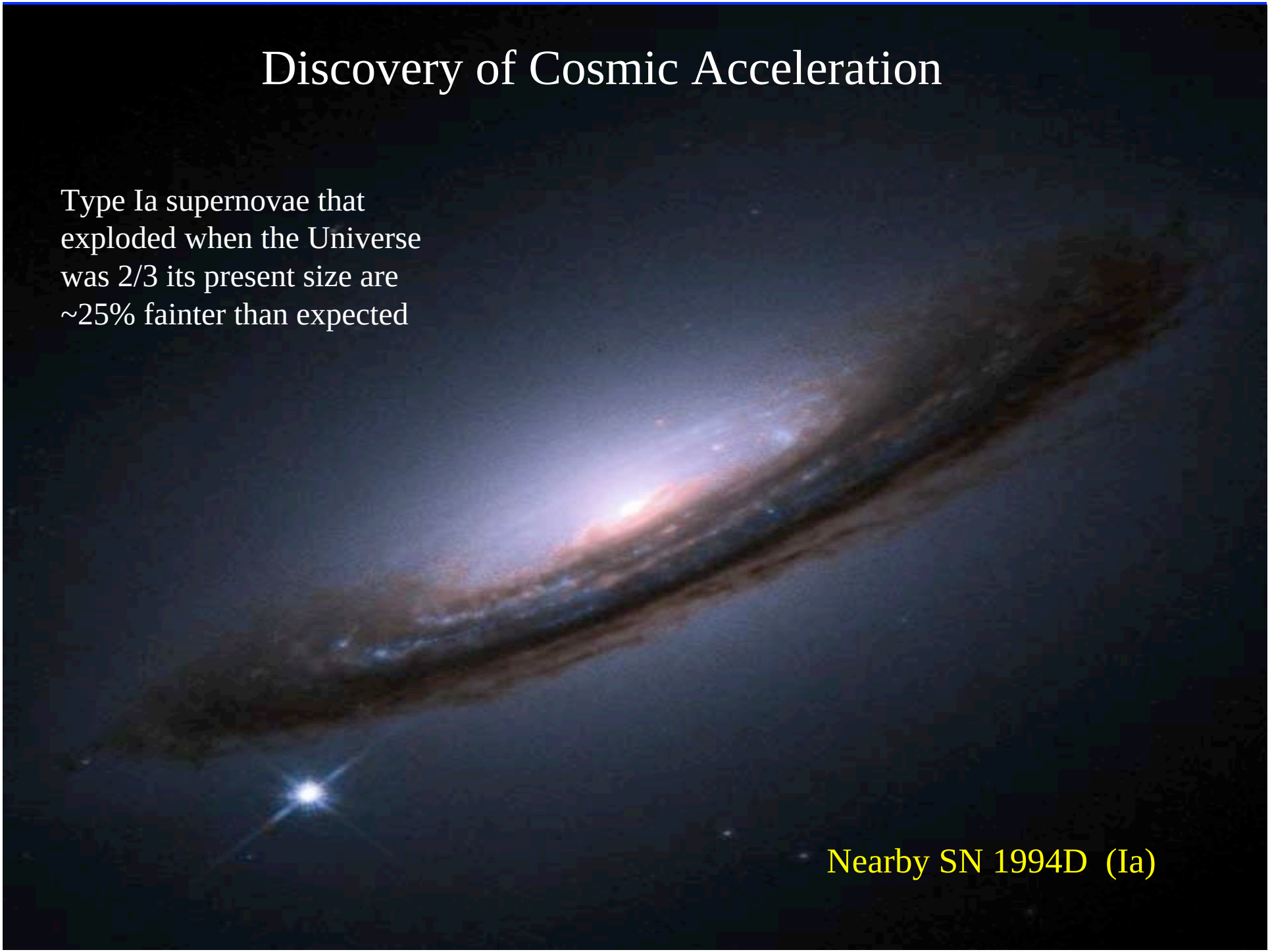
or dark energy $p = w\rho$ and $w = -1$

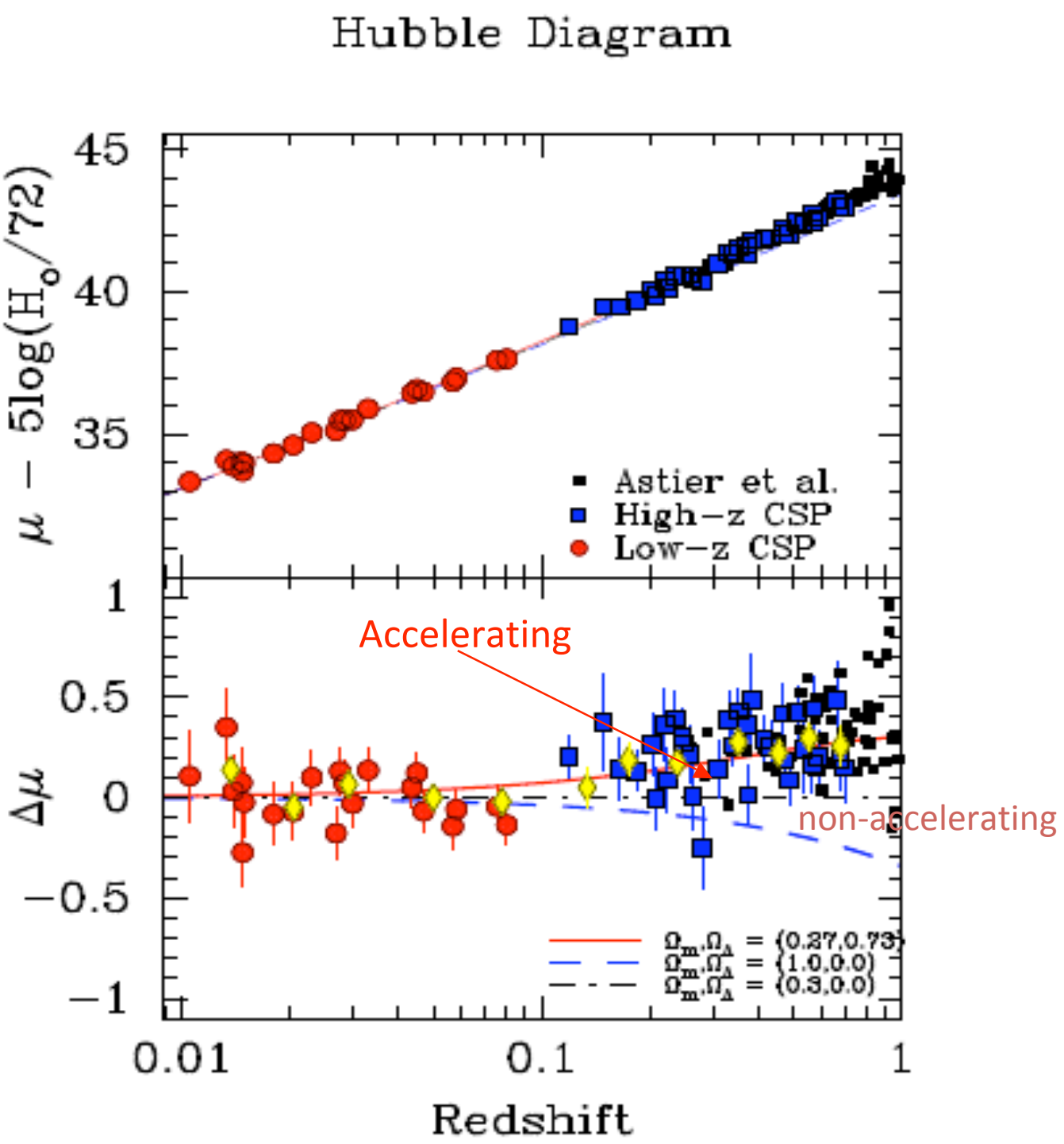
$$R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R = 8\pi G \left(T_{\mu\nu} + \tilde{T}_{\mu\nu} \right)$$

Einstein was right about the cosmological constant…but for the wrong reason!

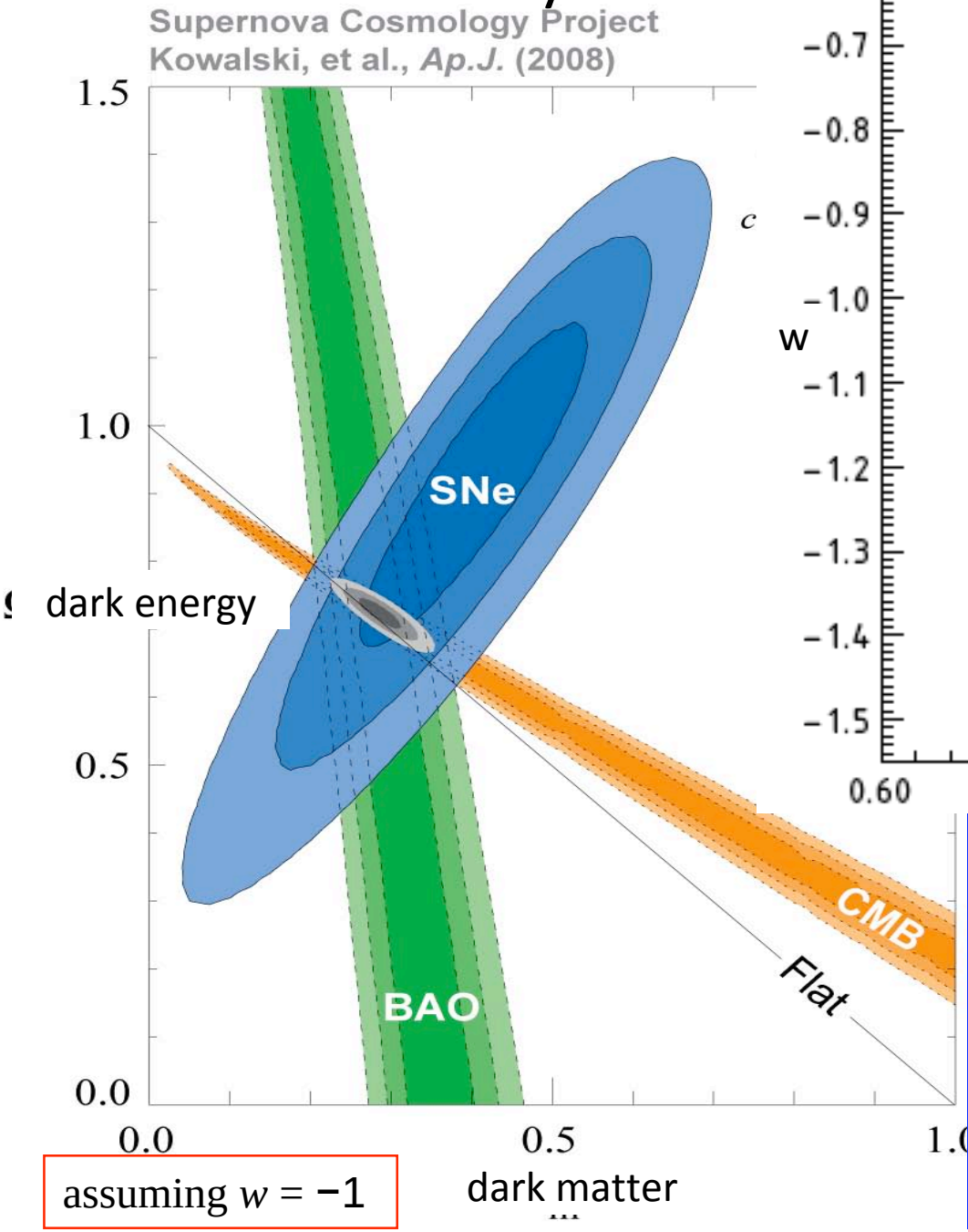
Discovery of Cosmic Acceleration

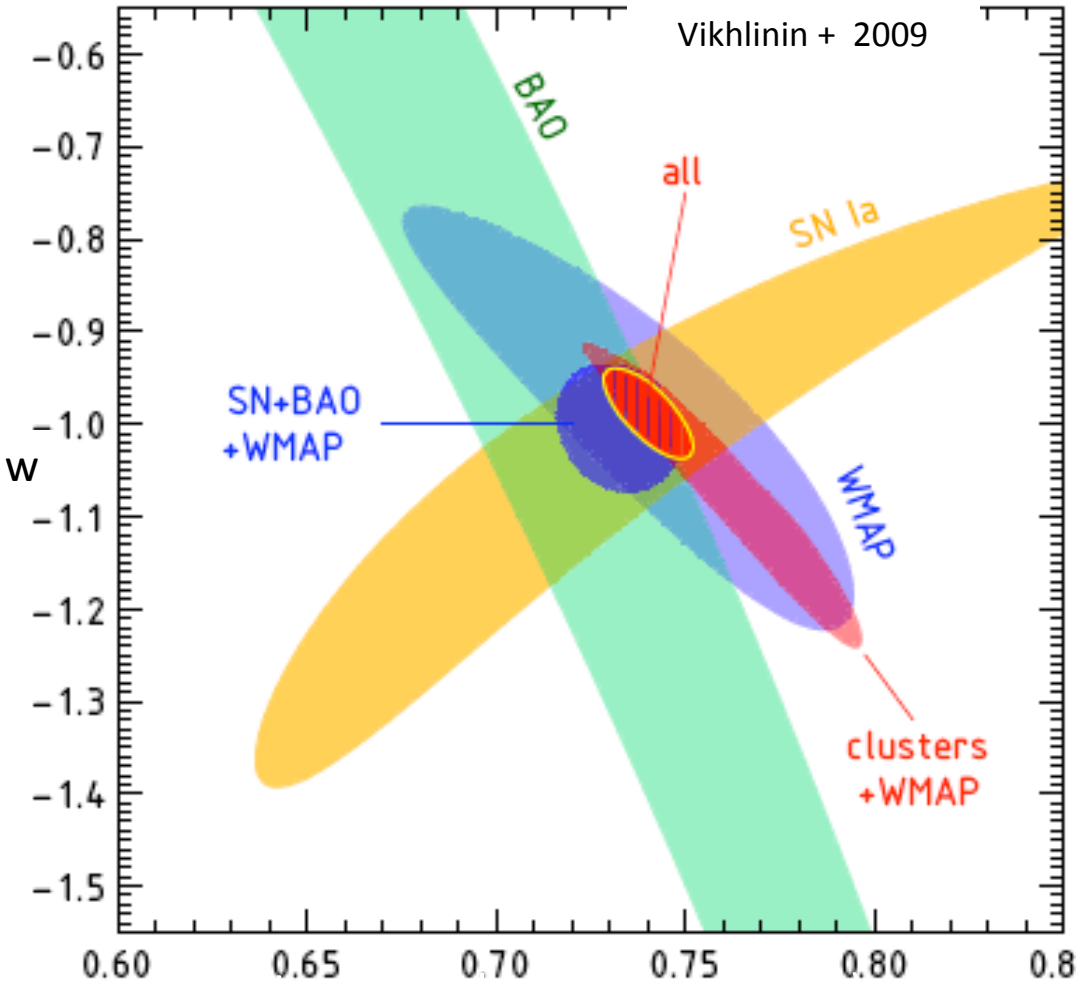
Type Ia supernovae that exploded when the Universe was 2/3 its present size are ~25% fainter than expected




Hubble Diagram
μ − 5log(H_o/72)
45
40
35
Astier et al.
High−z CSP
Low−z CSP
Accelerating
non-accelerating
1
0.5
0
−0.5
−1
Δμ
Ω_m,Ω_Λ = (0.27,0.73)
Ω_m,Ω_Λ = (1.0,0.0)
Ω_m,Ω_Λ = (0.3,0.0)
0.01
0.1
1
Redshift

Vacuum density

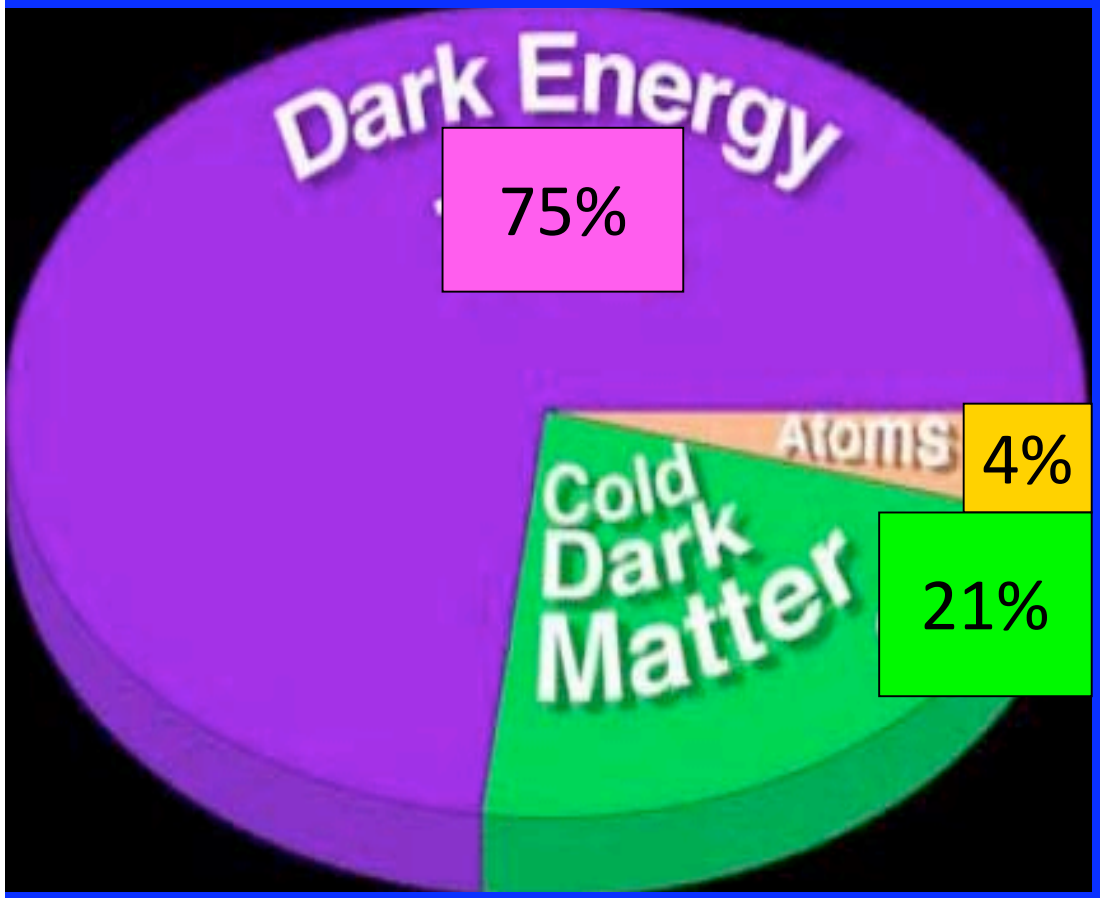




dark matter

CMB fluctuations (WMAP): DM +DE

Supernovae: DM - DE



observe

$$\rho_{\text{vac}} \approx 10^{-10}\,\text{eV}^4$$

predict

$$M \sim M_{Planck} = G^{-1/2} = 10^{28}\ \text{eV} \Rightarrow \rho_{vac} \sim 10^{112}\,\text{eV}^4$$

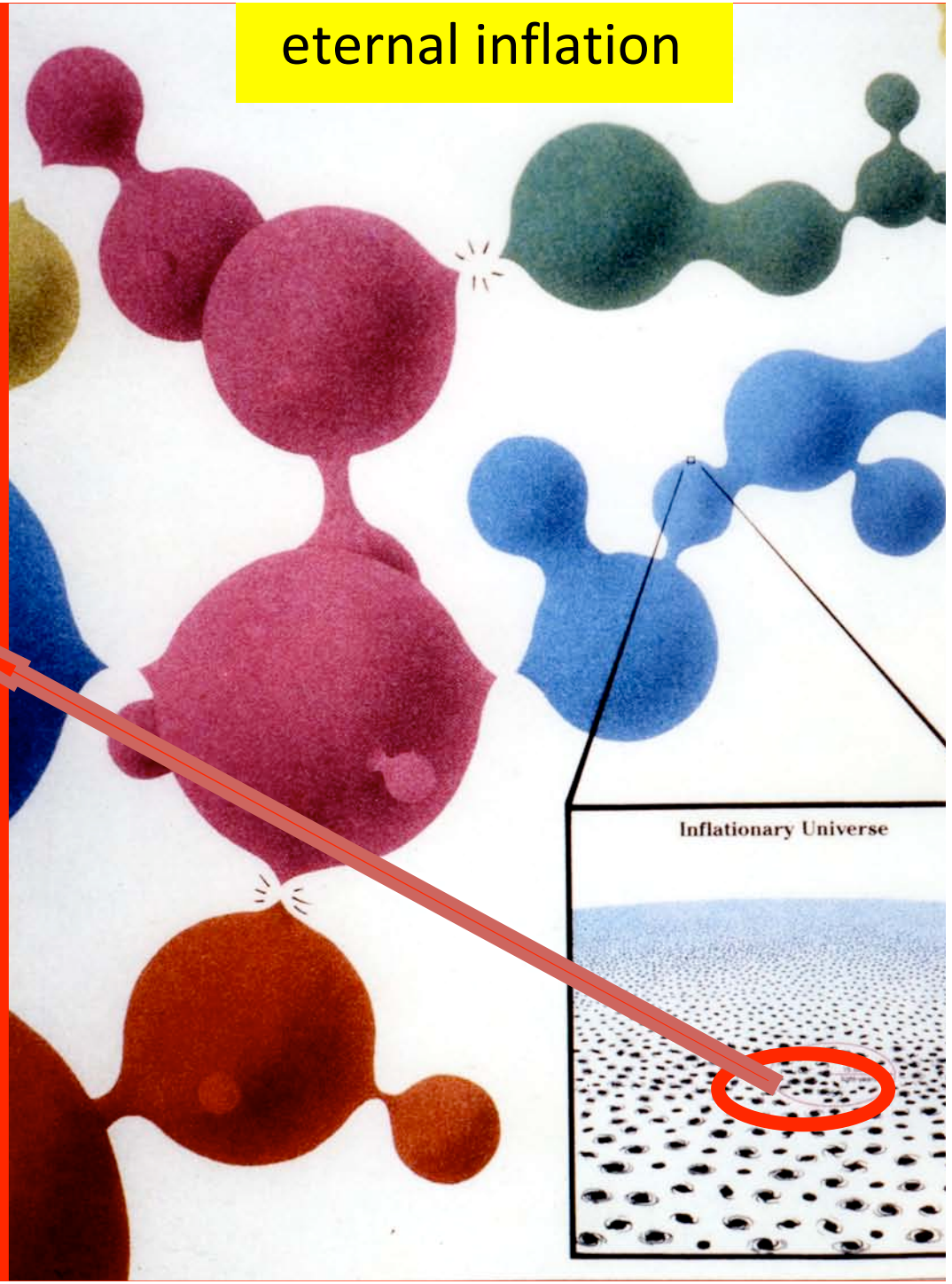
One of the greatest problems in physics!

Multiverse explanation

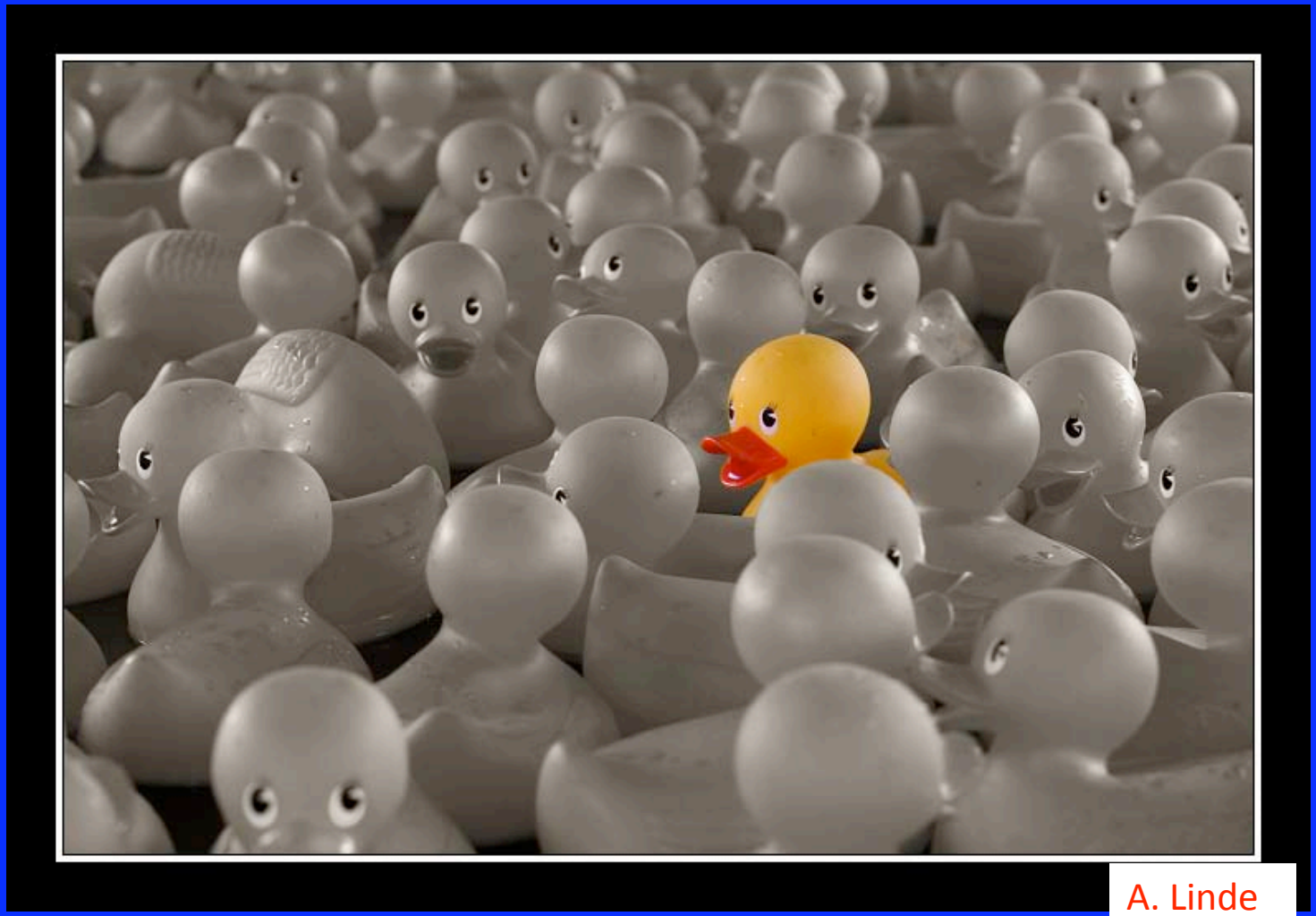
of why dark energy is so small

Eternal inflation produces an infinite number of inaccessible universes

eternal inflation



What is so special about our universe?



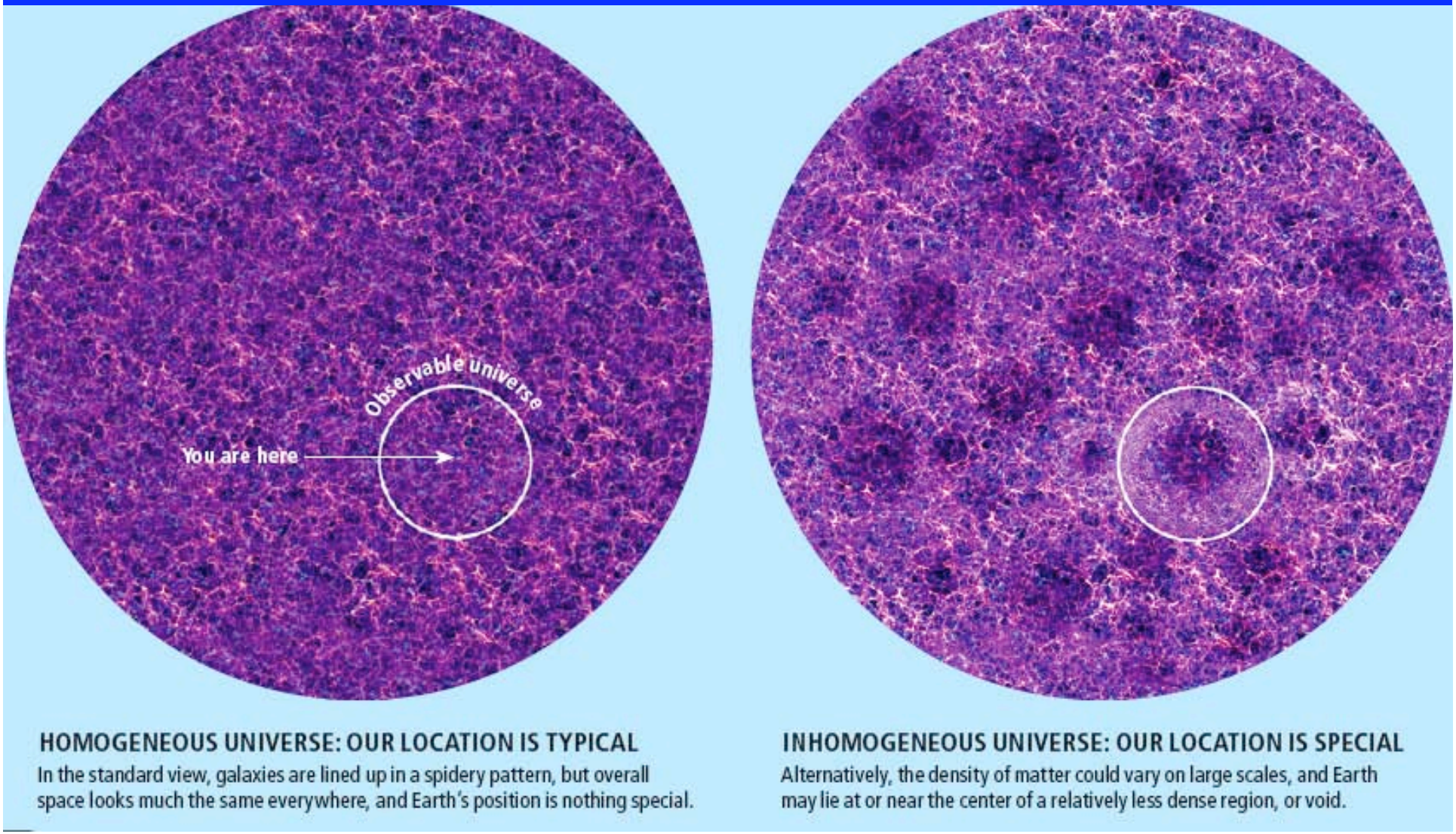
A. Linde

INVOKING THE ANTHROPIC PRINCIPLE

Alternatives:
we may hope for a fundamental physics theory
of why dark energy is so small

or seek an astrophysical theory

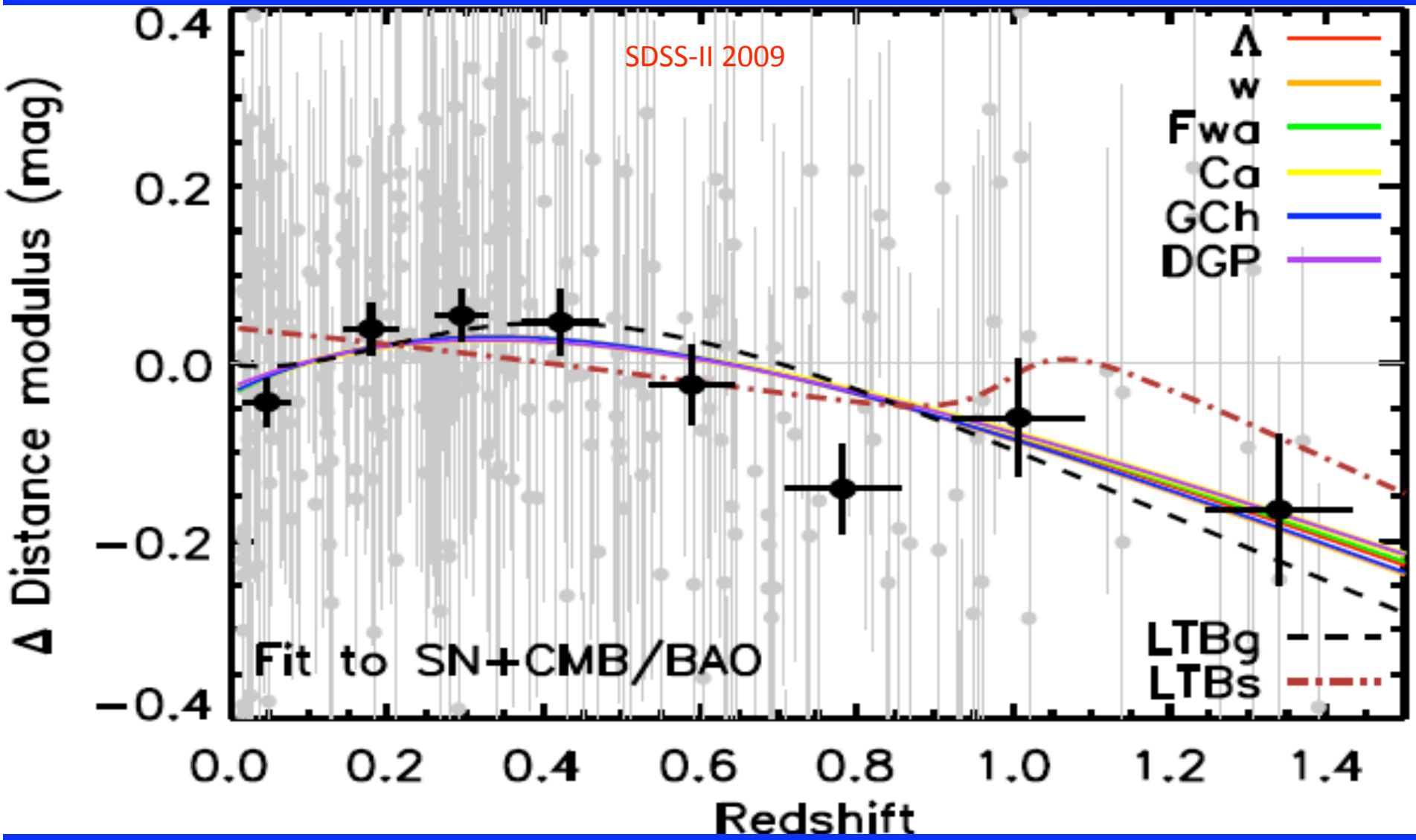
Clifton & Ferreira 2008



HOMOGENEOUS UNIVERSE: OUR LOCATION IS TYPICAL
In the standard view, galaxies are lined up in a spidery pattern, but overall space looks much the same everywhere, and Earth's position is nothing special.

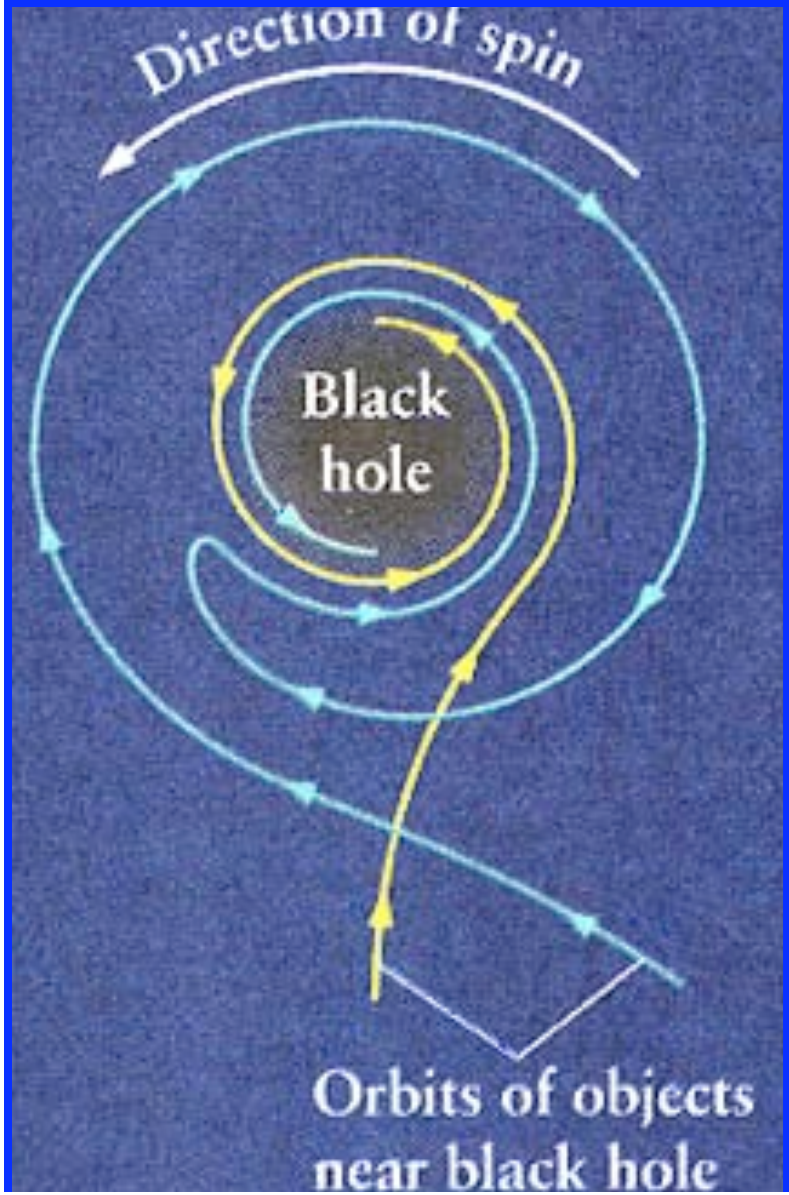
INHOMOGENEOUS UNIVERSE: OUR LOCATION IS SPECIAL
Alternatively, the density of matter could vary on large scales, and Earth may lie at or near the center of a relatively less dense region, or void.

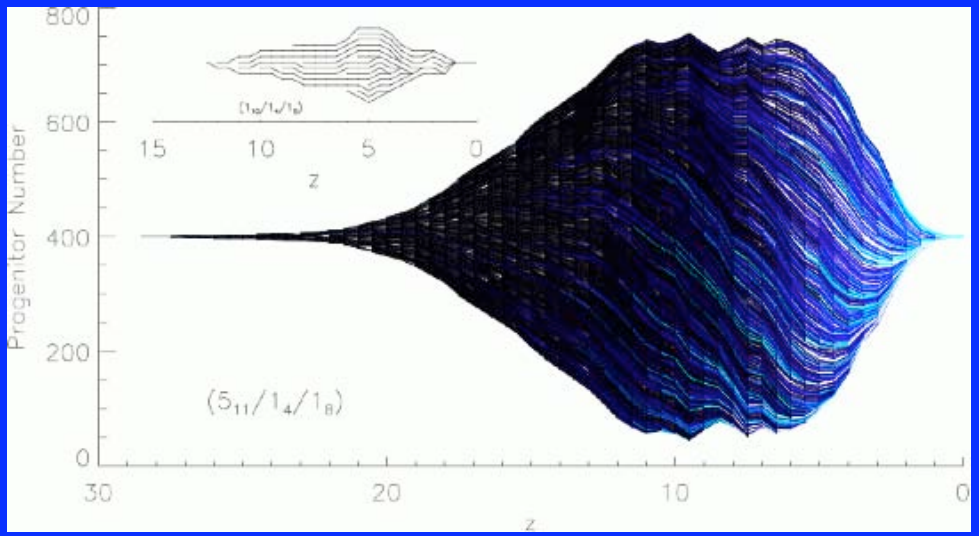
CAN REPLACE ACCELERATION BY A GIANT LOCAL VOID
in Lemaitre-Tolman-Bondi model



Which hypothesis is more “fine-tuned”?

THE ULTIMATE PARTICLE ACCELERATOR: dark matter cusp around a Kerr black hole





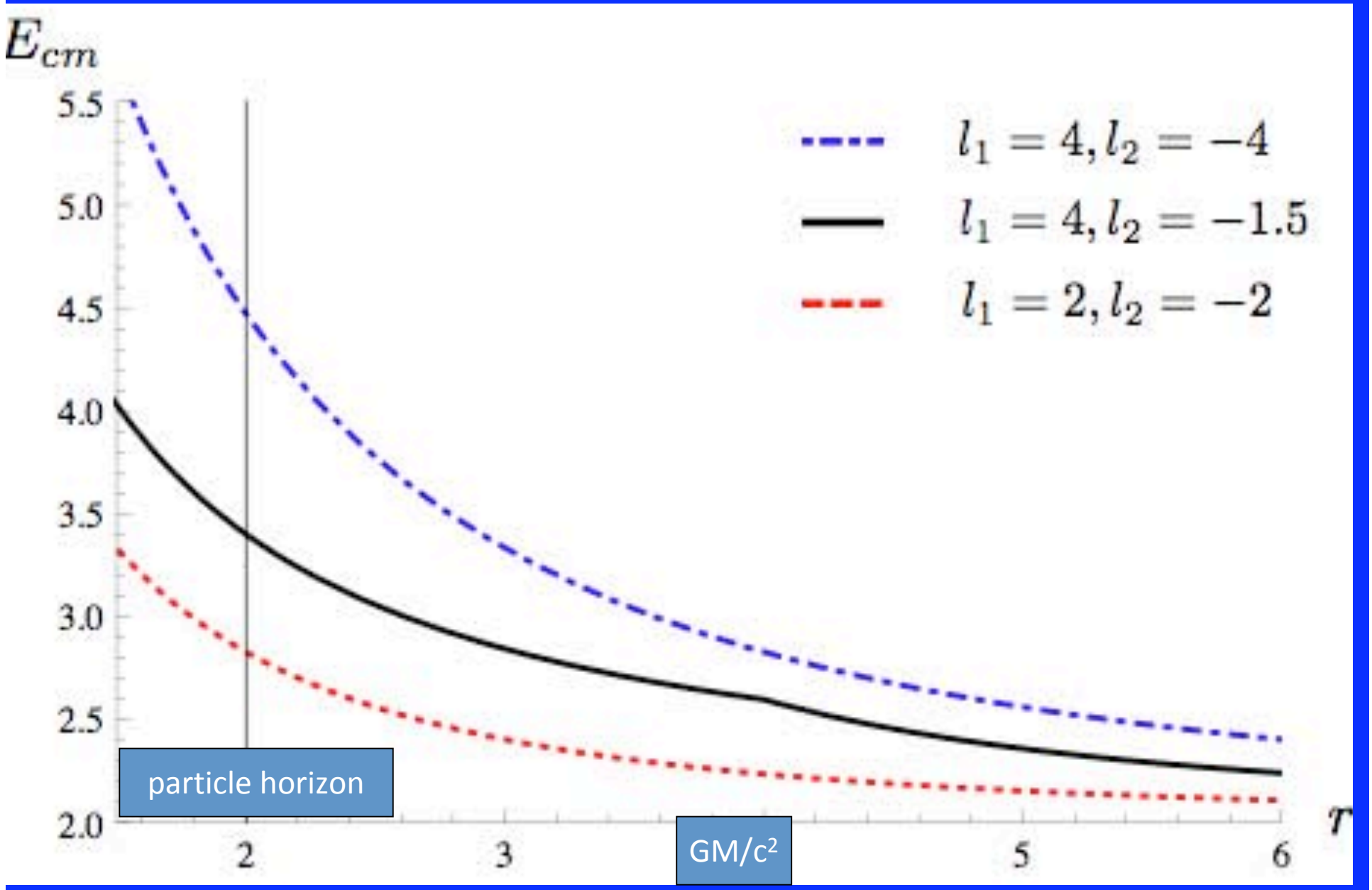
CDM cusp steepens by adiabatic growth of IMBH: $\rho \propto r^{-\gamma} \Rightarrow \rho \propto r^{-\gamma'}$, **with** $\gamma' = \frac{9-2\gamma}{4-\gamma}$

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

Identify left-over IMBH by γ or ν flux

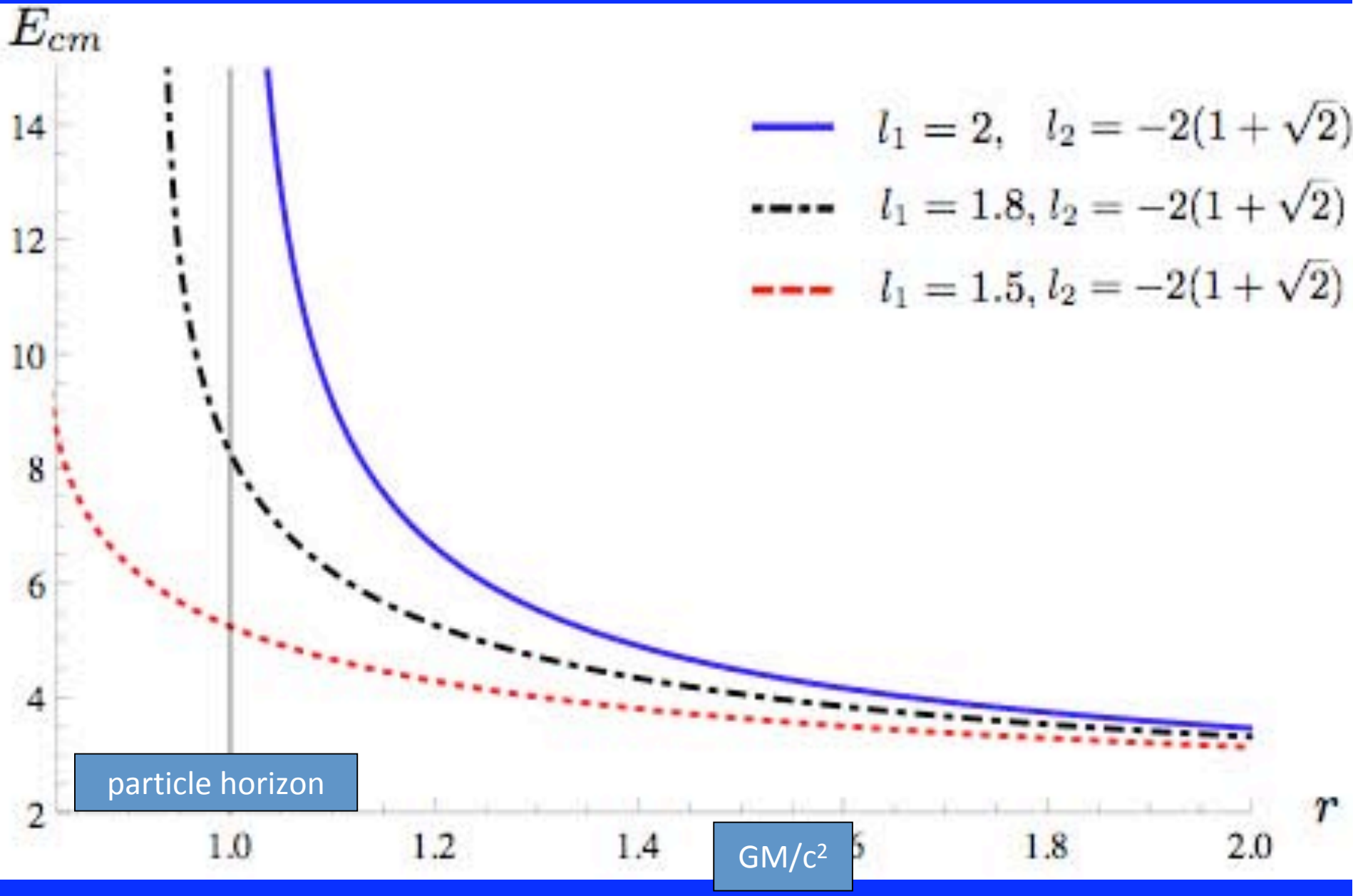
Schwarzschild black hole

Banados, West, JS 2009



Kerr black hole

Banados, West,JS 2009



DARK MATTERS ARE CHALLENGED BY COSMOLOGY

RESURRECTION VIA FUNDAMENTAL PHYSICS

- MODIFYING THE NATURE OF DARK MATTER?
- MODIFYING GRAVITY?
- INTRODUCING THE MULTIVERSE?

RESURRECTION VIA ASTROPHYSICS

- FEEDBACK
- GIANT VOID

DARK MATTER DETECTION IS ESSENTIAL FOR CREDIBILITY

ONLY INDIRECT DETECTION IN MULTIPLE WINDOWS WILL DEMONSTRATE ITS COSMOLOGICAL SIGNIFICANCE

AS FOR DARK ENERGY, WE AWAIT A NEW THEORY

LE FIN