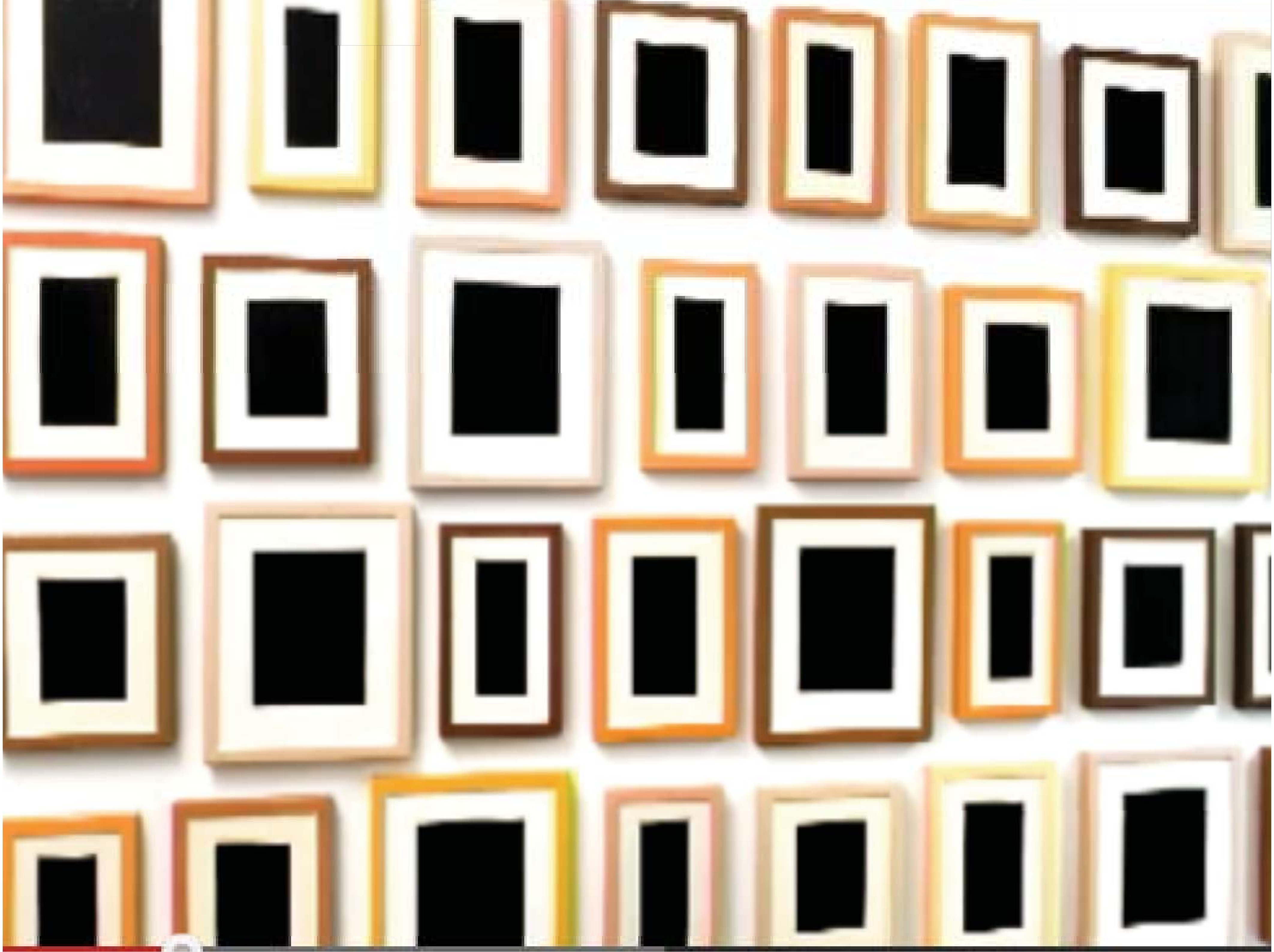
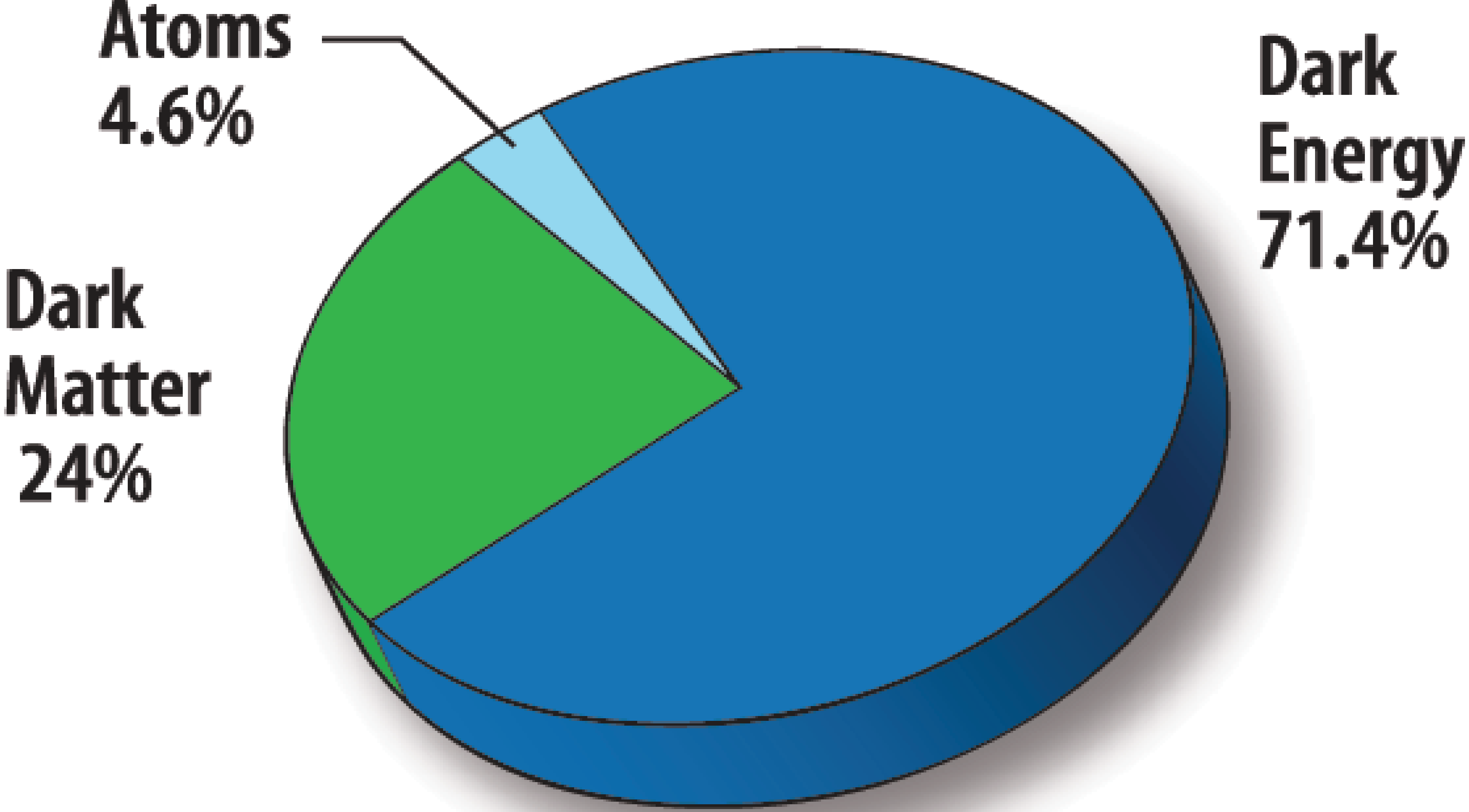
DARK MATTER and COSMOLOGY

Joe Silk (IAP, JHU)

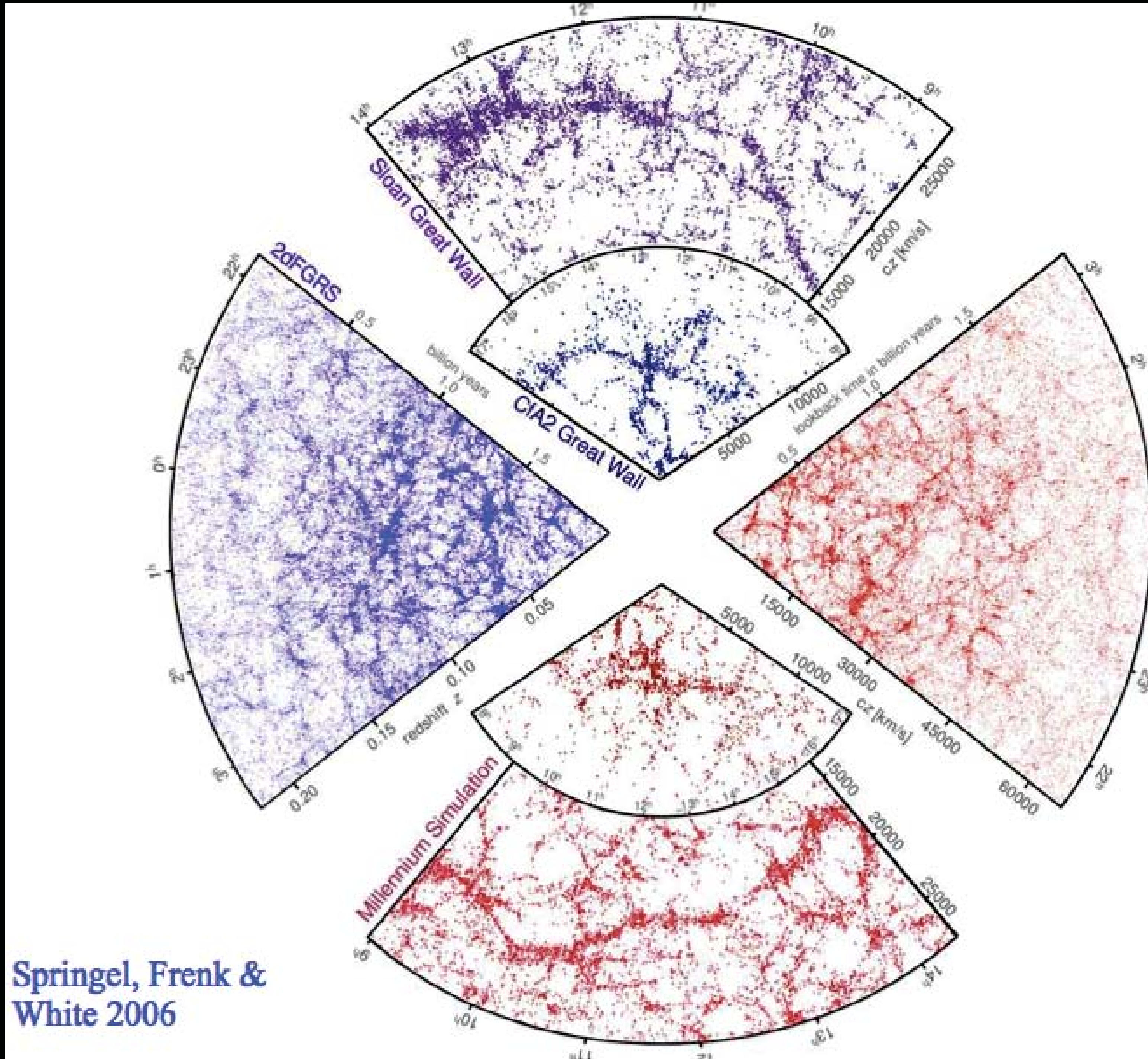
College de France 18 Fevrier 2015





[redacted]

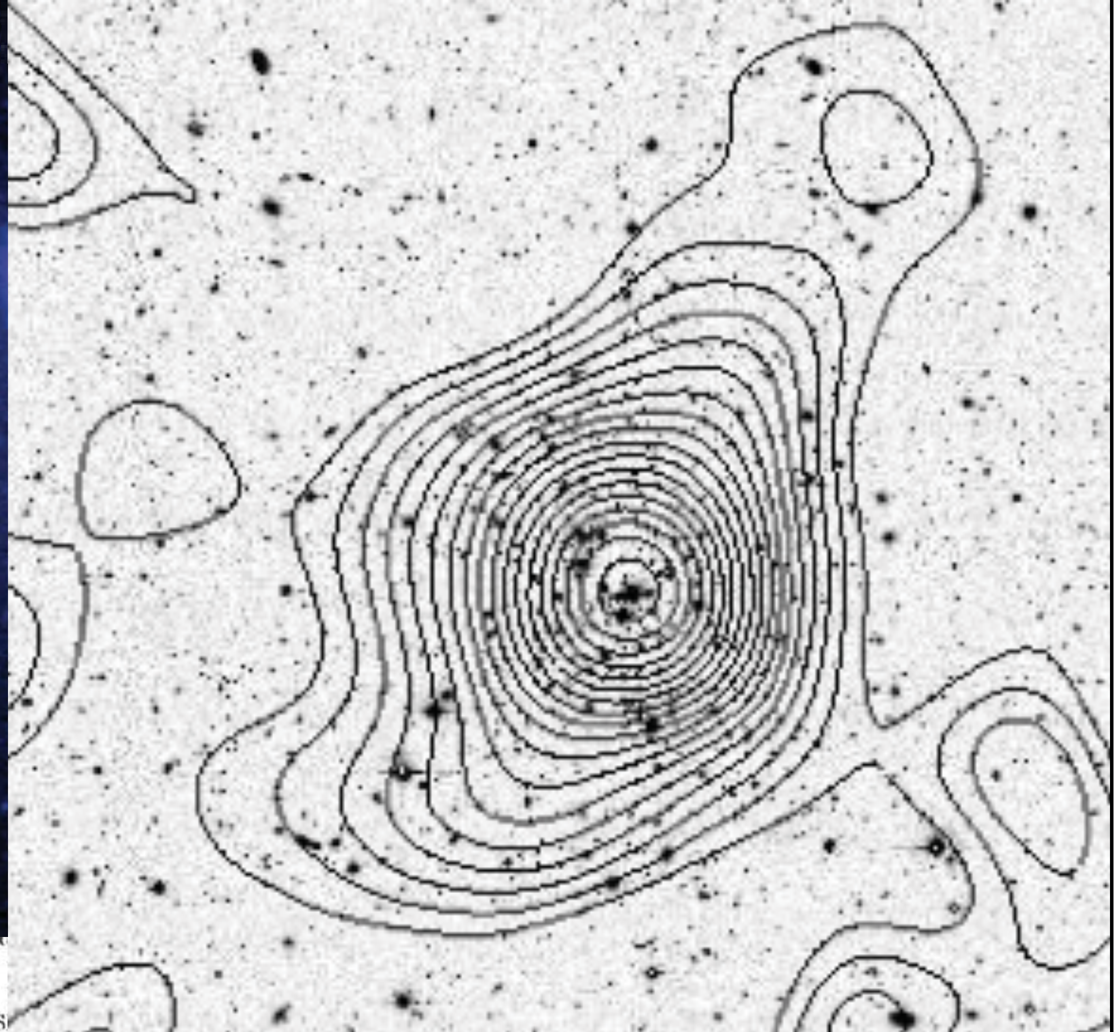
Dark Matter is weakly interacting & cold

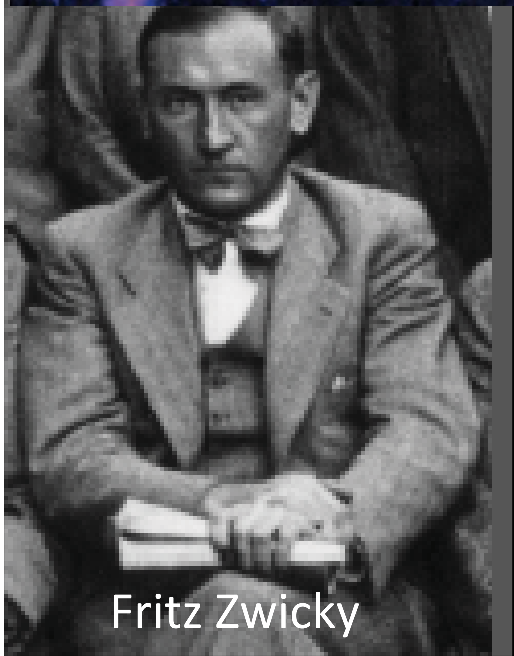


1. ASTROPHYSICAL CONSTRAINTS
2. DIRECT DETECTION
3. INDIRECT DETECTION

1

GRAVITATIONAL LENSING





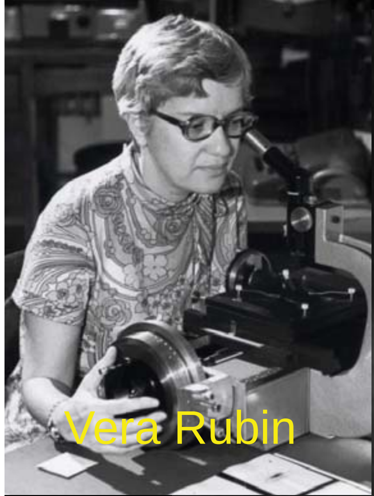
Fritz Zwicky

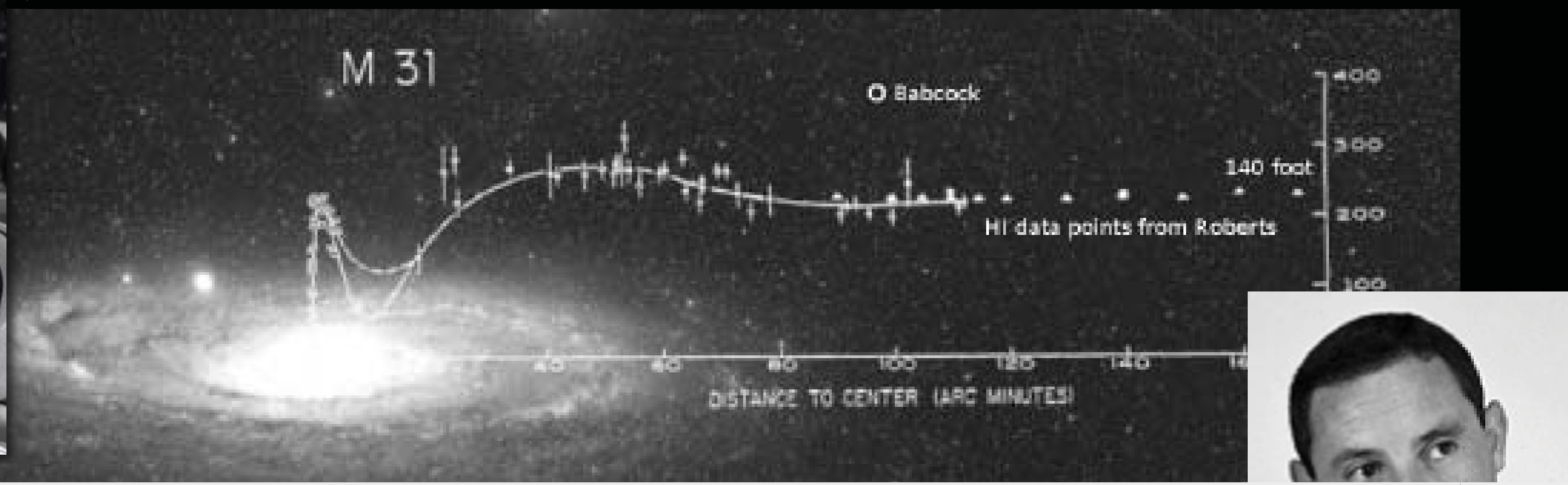
nen.
sind s

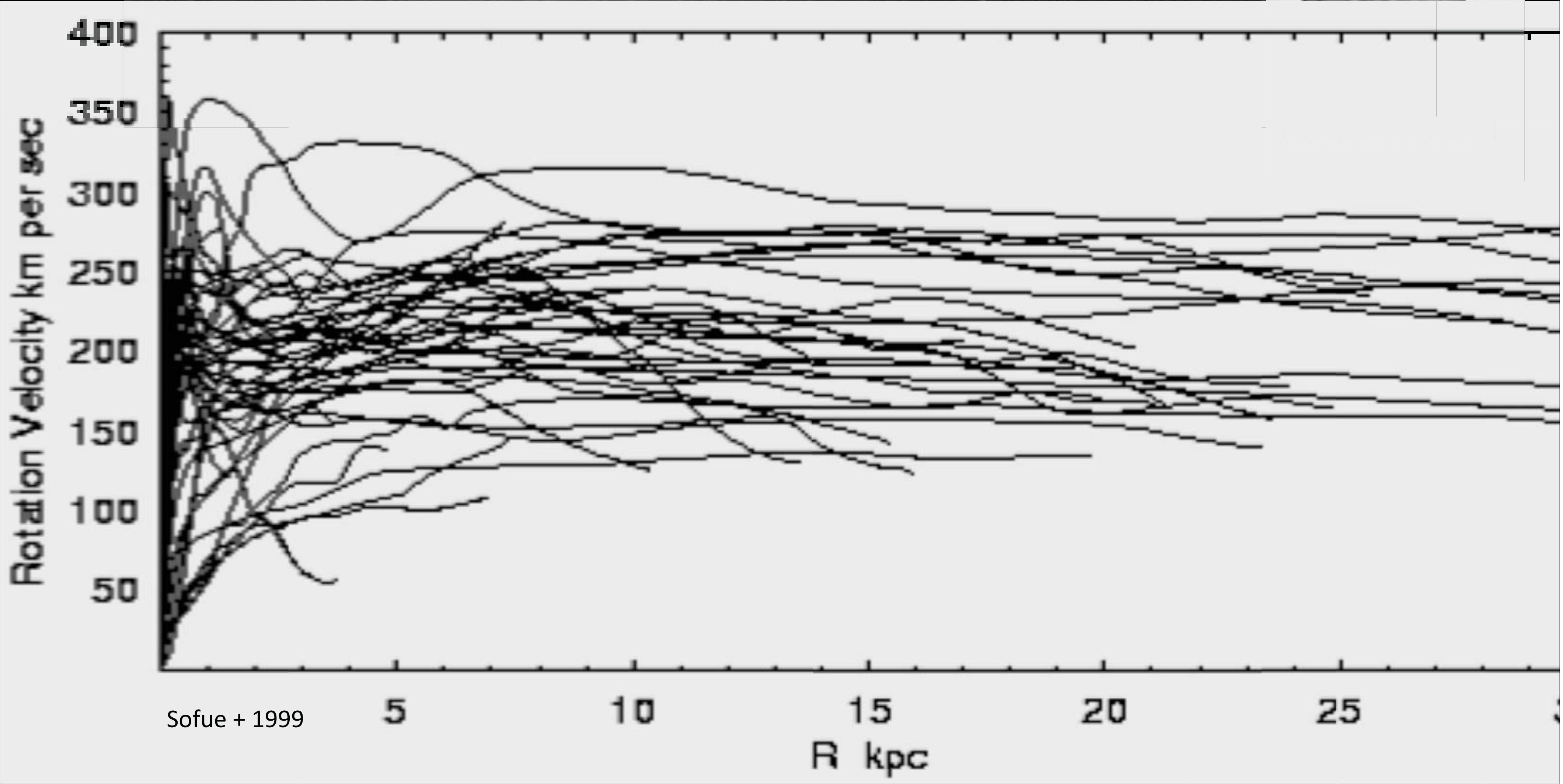
Rotverschiebung extragalaktischer Nebel.

wie beobachtet, einen mittleren Dopplereffekt von
k oder mehr zu erhalten, müsste also die mittlere
masystem mindestens 400 mal grösser sein als die auf
Beobachtungen an leuchtender Materie abgeleitete[1]).
lies bewahrheiten sollte, würde sich also das überrasc
tat ergeben, dass dunkle Materie in sehr viel grösserer
nden ist als leuchtende Materie.

GALAXY ROTATION CURVES


Vera Rubin

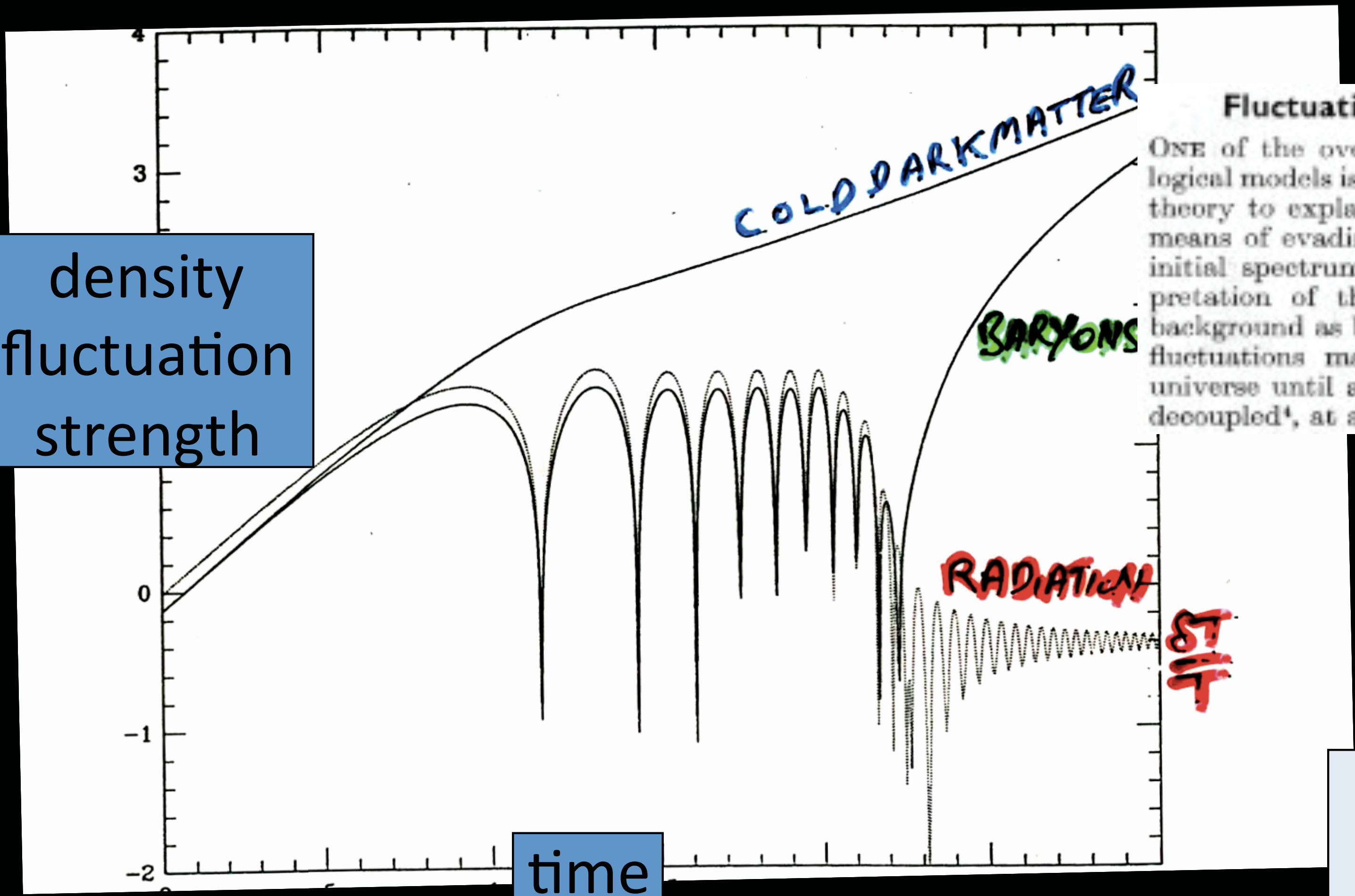

M 31
O Babcock
140 foot
HI data points from Roberts
400
300
200
100
40
60
80
100
120
140
DISTANCE TO CENTER (ARC MINUTES)


Rotation Velocity km per sec
400
350
300
250
200
150
100
50
5
10
15
20
25
R kpc

Sofue + 1999

ACOUSTIC OSCILLATIONS IN CMB

PRIMORDIAL SOUND WAVES IN THE PHOTON-BARYON PLASMA BECOME DENSITY FLUCTUATIONS IN DARK MATTER-DOMINATED ERA



Fluctuations in the Primordial Fireball

ONE of the overwhelming difficulties of realistic cosmological models is the inadequacy of Ein[...] theory to explain the process of gala[...] means of evading this problem has be[...] initial spectrum of primordial fluctuations[7]. The interpretation of the recently discovered 3° K microwave background as being of cosmological origin[8,9] implies that fluctuations may not condense out of the expanding universe until an epoch when matter and radiation have decoupled[4], at a temperature T_D of the order of 4,000° K.

Silk 1967

WEAKLY INTERACTING DARK MATTER BOOSTS FLUCTUATION GROWTH

FINE-SCALE ANISOTROPY OF THE COSMIC MICROWAVE BACKGROUND IN A UNIVERSE DOMINATED BY COLD DARK MATTER

NICOL[...]
Department of Astronomy, University of California, Berkeley; [...] Roma
AND
JOSEPH SILK
Department of Astronomy, University of California, Berkeley

Received 1984 May 30; accepted 1984 July 10

Vittorio and Silk 1984

CAN A RELIC COSMOLOGICAL CONSTANT RECONCILE INFLATIONARY PREDICTIONS WITH THE OBSERVATIONS?

NICOLA VITTORIO[1,2,3]
AND
JOSEPH SILK[1,2]

Received 1985 April 11; accepted 1985 July 9

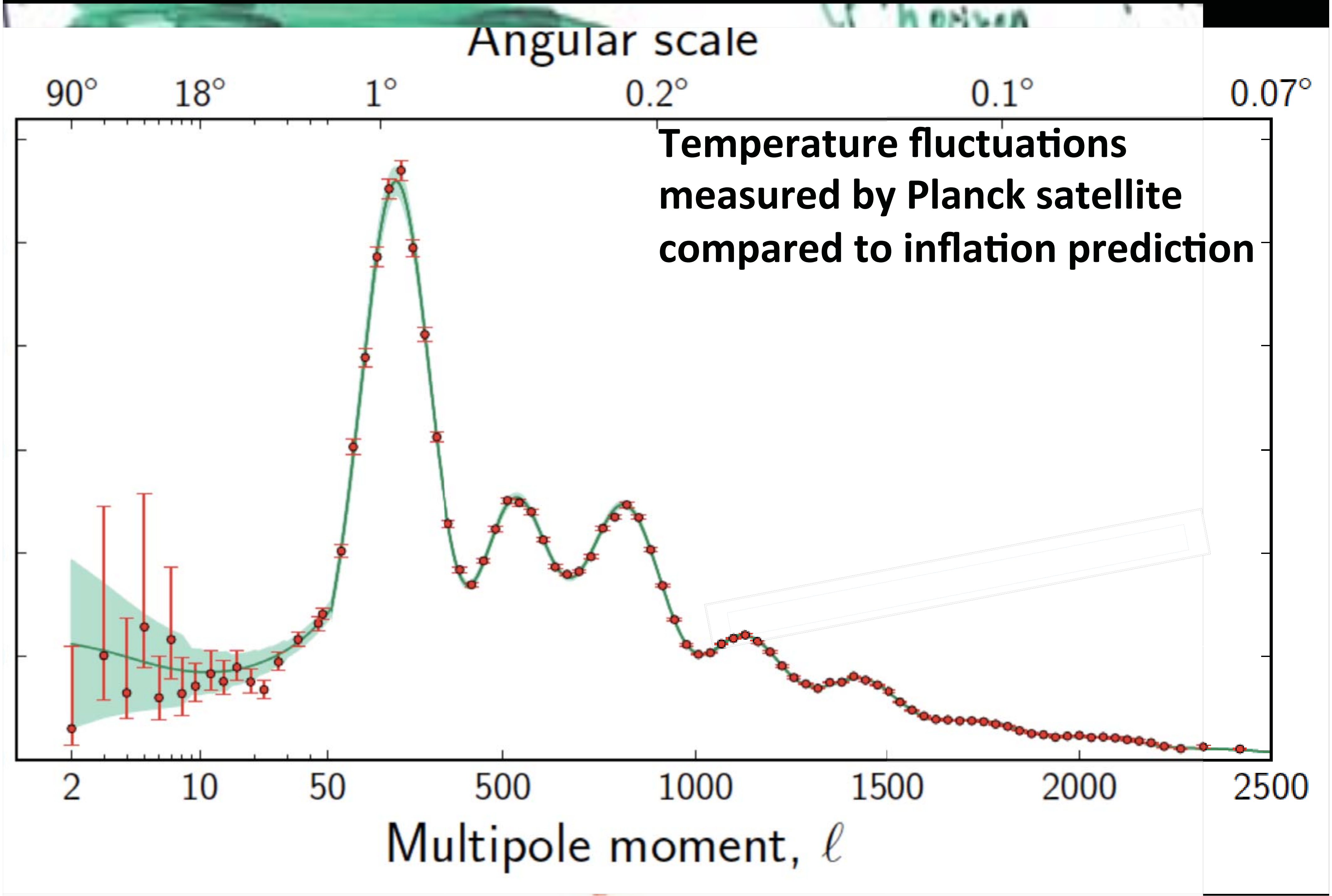
COSMIC BACKGROUND RADIATION ANISOTROPIES IN UNIVERSES DOMINATED BY NONBARYONIC DARK MATTER

J. R. BOND[1,2] AND G. EFSTATHIOU[2,3]

Received 1984 June 4; accepted 1984 July 17

Bond and Efstathiou 1984

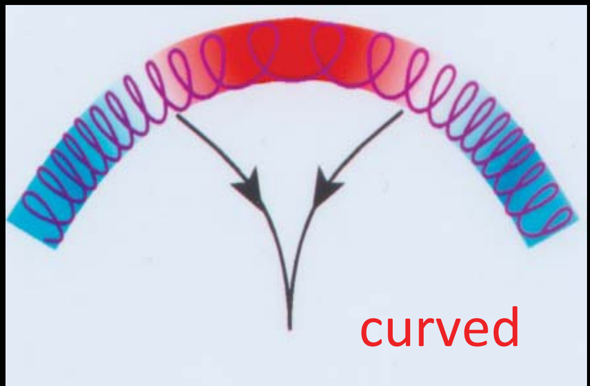
FROM DENSITY FLUCTUATIONS TO GALAXIES

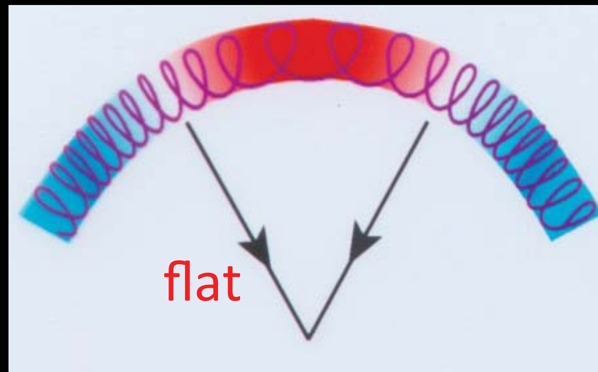


EUCLIDEAN or flat space FITS TO HIGH PRECISION!

$\Omega = 8\pi G\rho/3H_0^2$

H_0=68+-1 km s^{-1} Mpc $^{-1}$





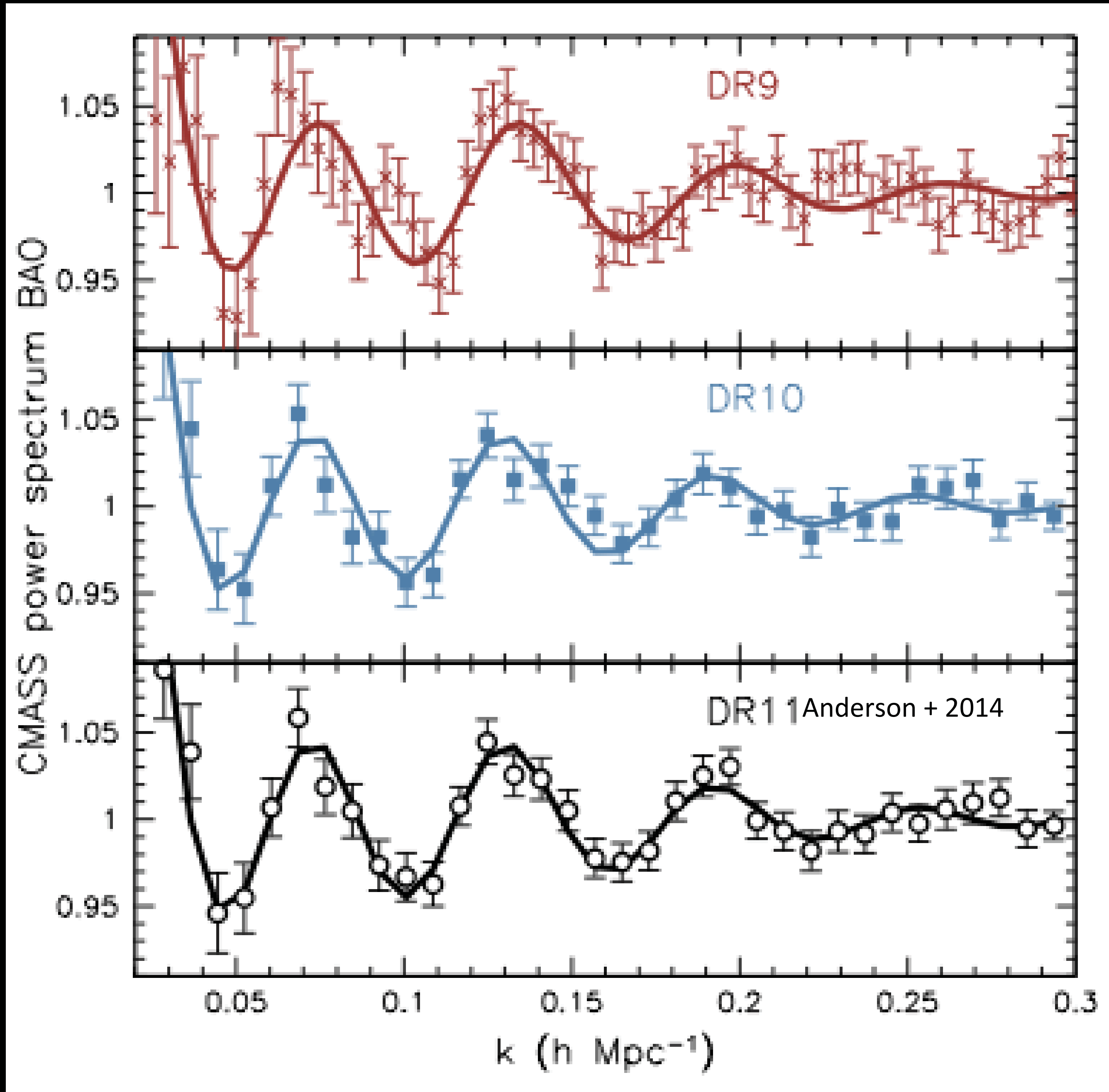
$\Omega_\Lambda = 0.697 +- 0.011$

$\Omega_m = 0.303 +- 0.011$

$\Omega_B = 0.0484 +- 0.0007$

t_0=13.804+-0.058 Gyr

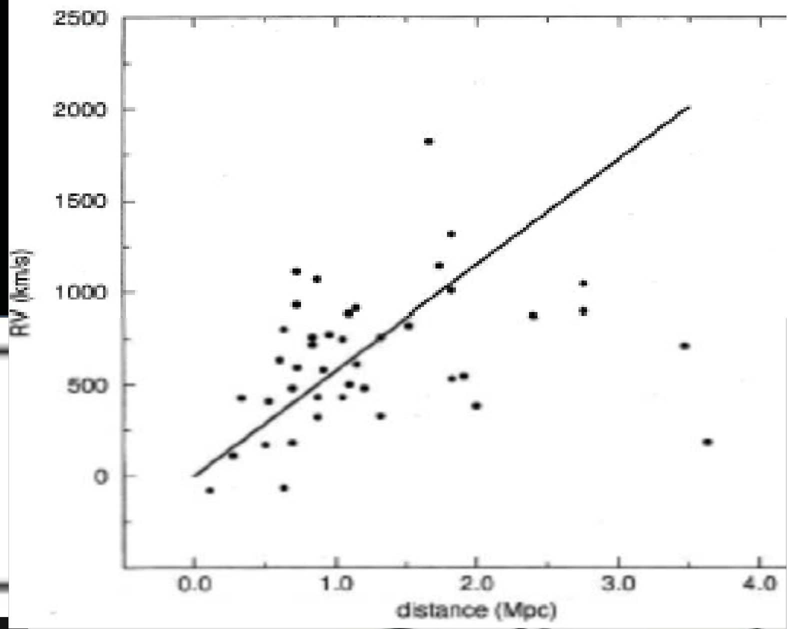
ACOUSTIC OSCILLATIONS IN BARYONS



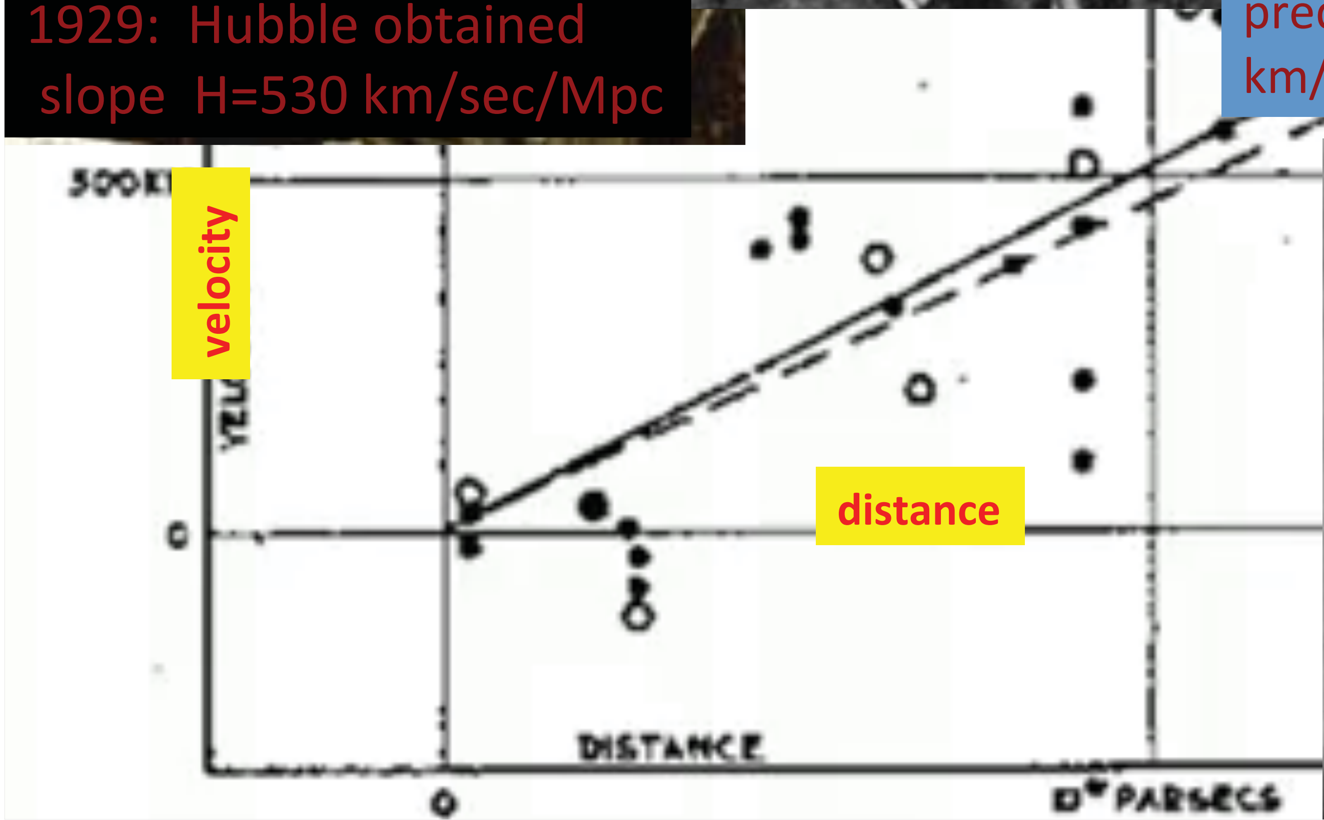
SUPERNOVAE AS STANDARD CANDLES FOR COSMOLOGY

1929: Hubble obtained slope H=530 km/sec/Mpc

Alexander Friedmann: 1924 prediction of expansion

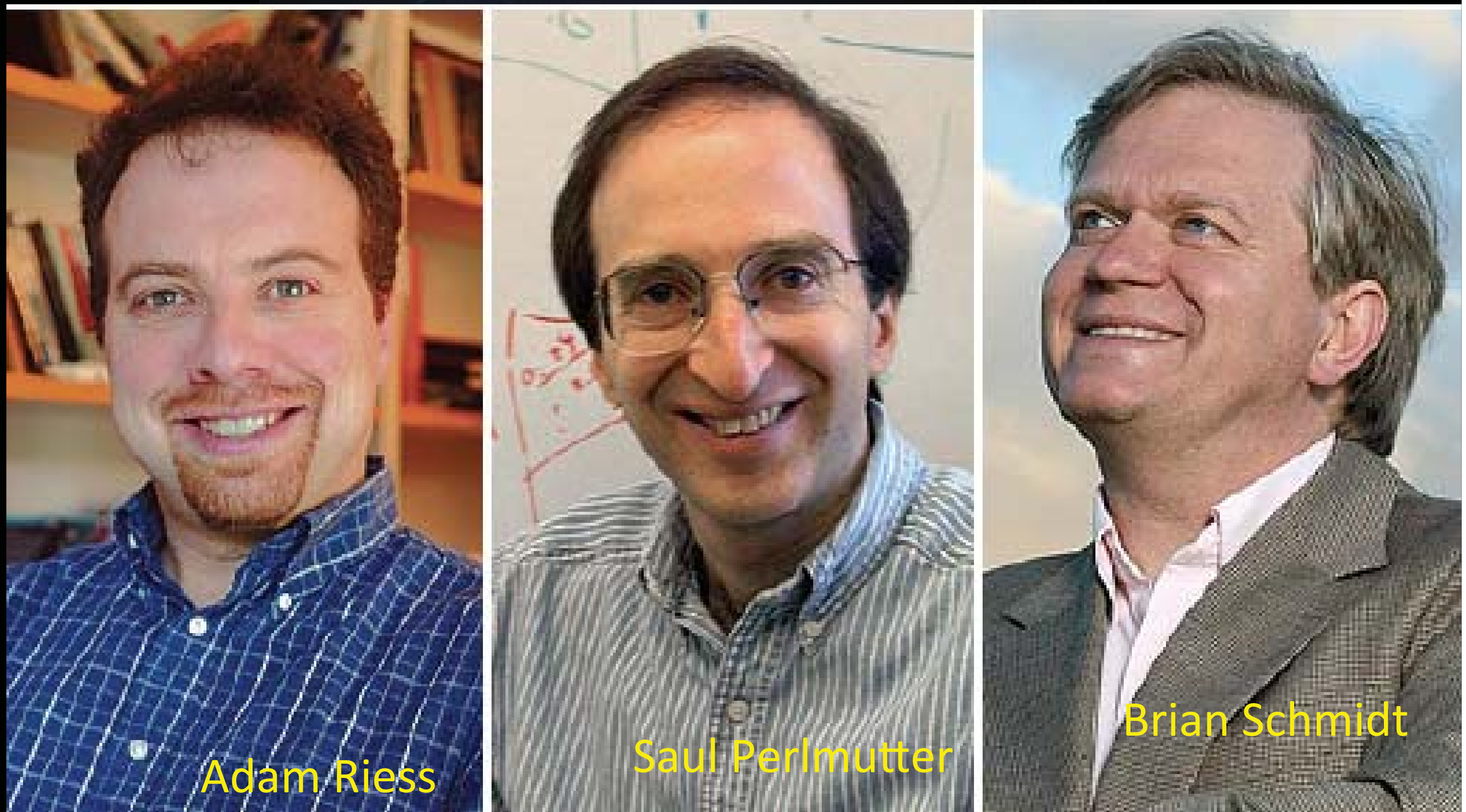


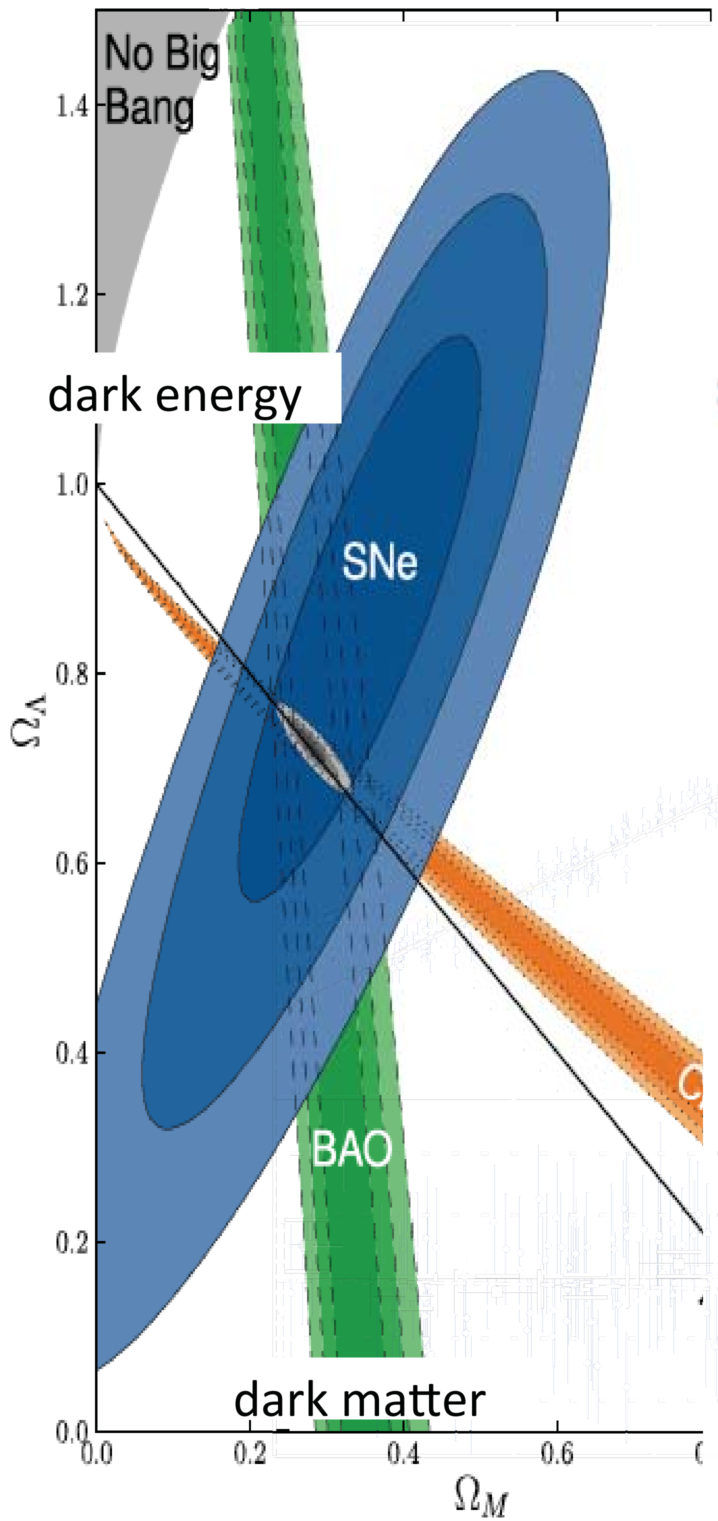
1927: Georges Lemaitre independently predicted expansion, obtained H=625 km/sec/Mpc but published in French



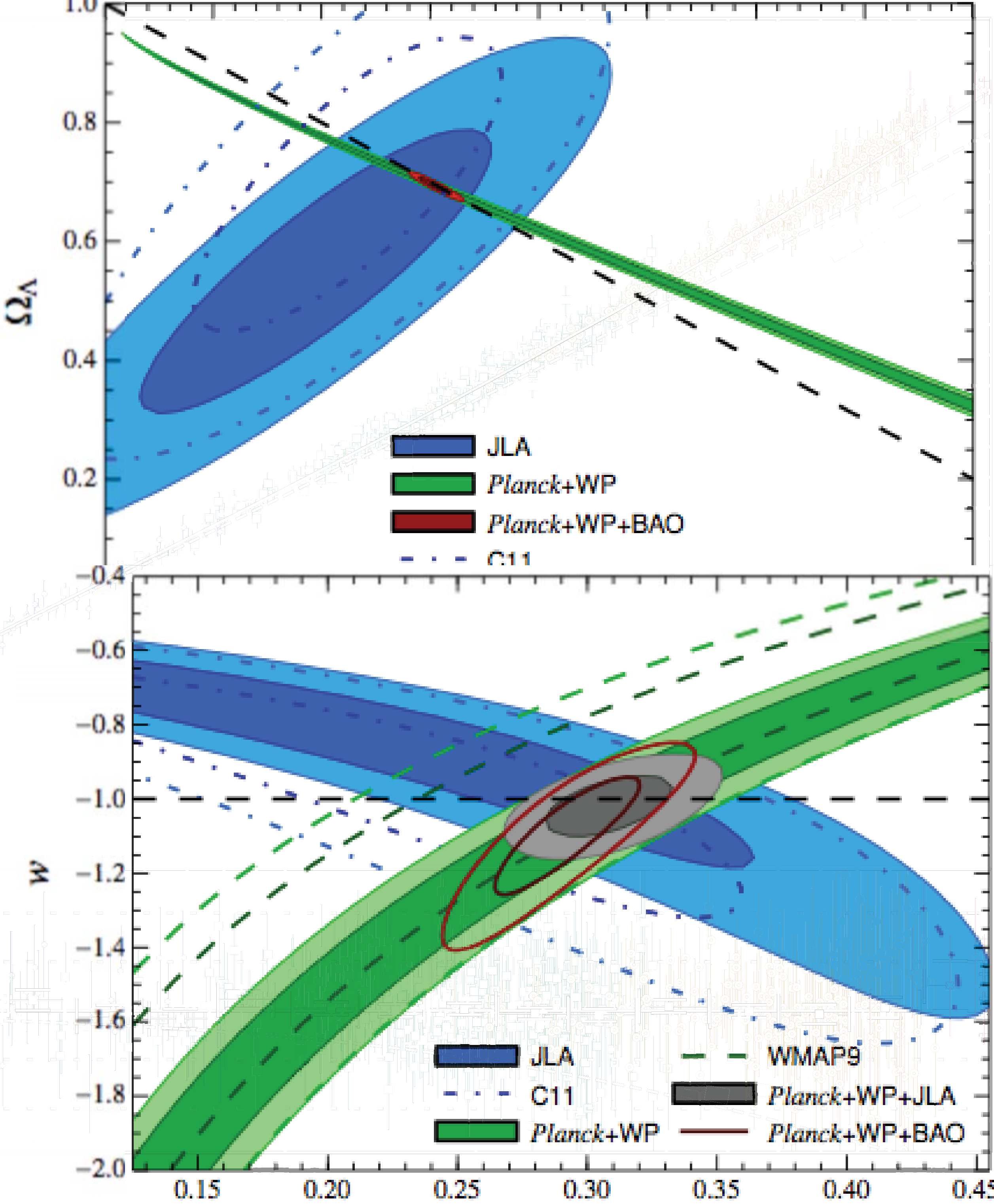
Distant type Ia supernovae are too faint by ~25%

most of the mass-energy in the universe is dark





Amanullah et al 2010



Betoule + 2014

1. ASTROPHYSICAL CONSTRAINTS
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2

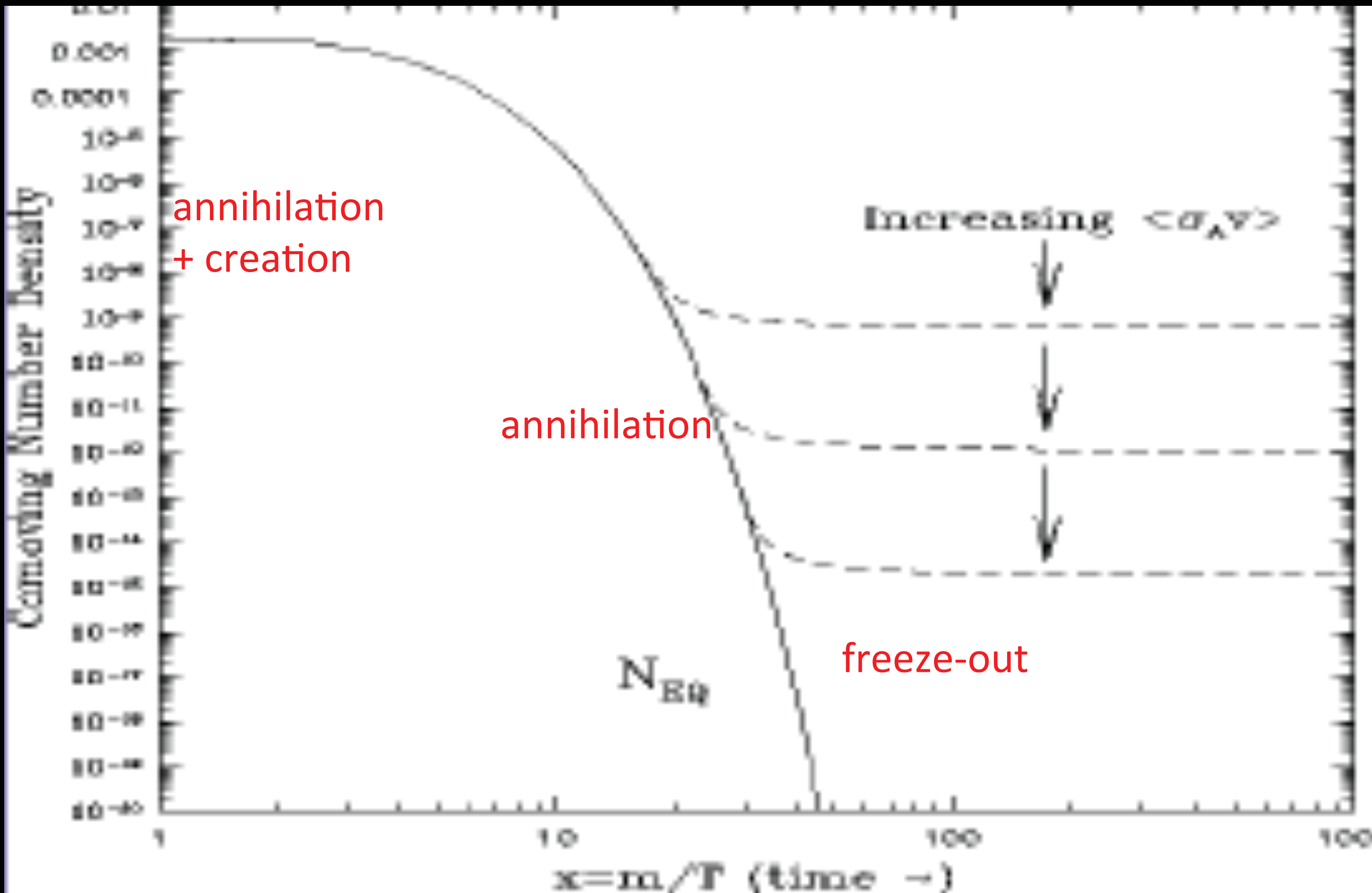
SUSY WIMP in thermal equilibrium

relic abundance if $\langle\sigma_{ann}v\rangle \sim 3\times10^{-26}$ cm^3/s $\sim 0.23/\Omega_x$

generic WIMP

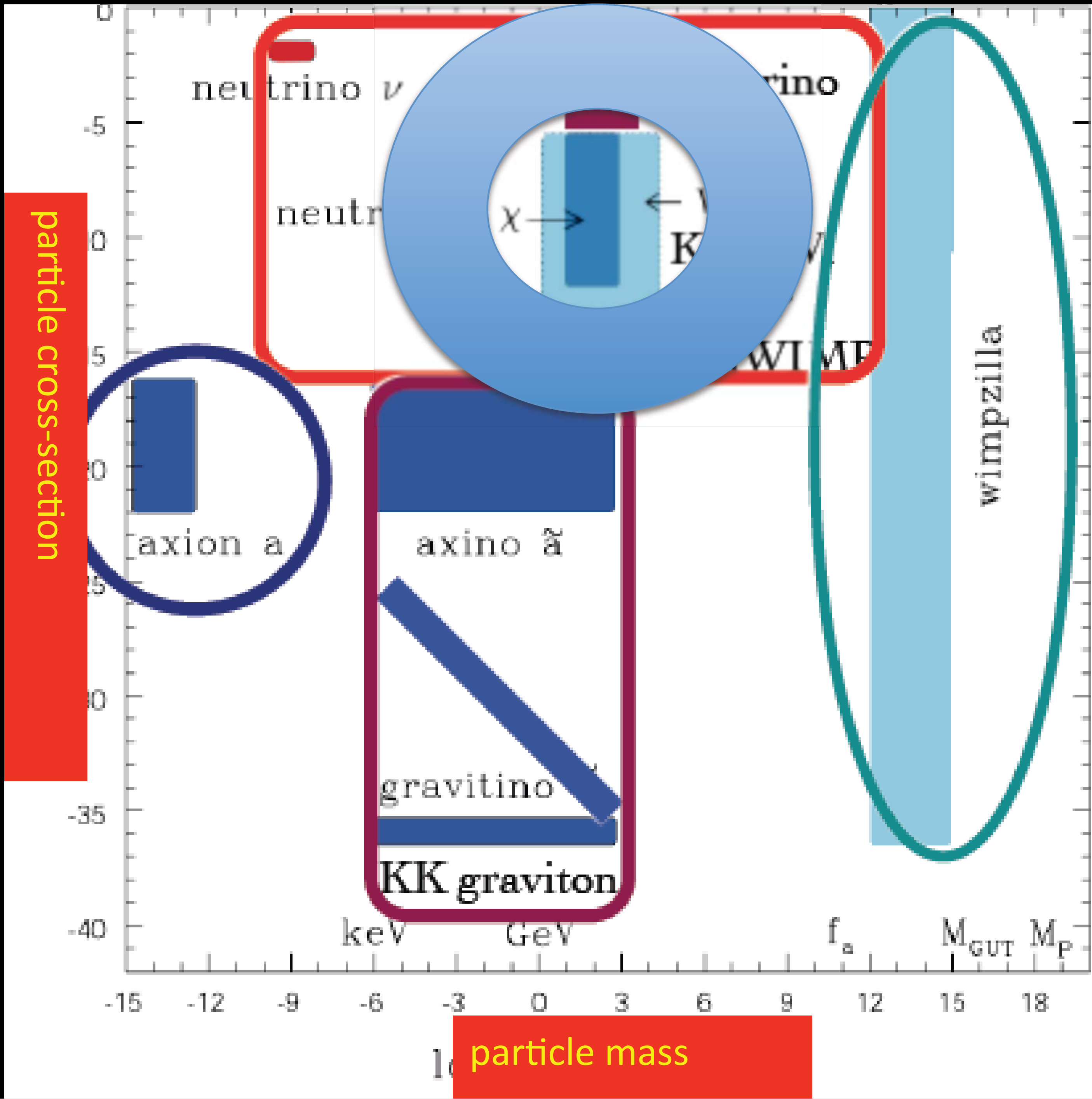
$\langle\sigma_{ann}v\rangle \sim \alpha_w^{\,2}/m_x^{\,2} = \alpha_w^{\,2}/1\ \text{TeV}^{\,2}$

PREDICTING $\langle\sigma v\rangle$



SUSY has 100+ free parameters

WIMPS or nonWIMPs



L. Roszkowski

NOW its one of many DM candidates…

One natural choice is asymmetric DM for which m_x=5 GeV

lepton-like asymmetry: $\rho_B=\eta_B n_\gamma m_B$ $\rho_x=\eta_B n_x m_x$

Nussinov, Kaplan….

of interest for direct detection...

Another is minimal DM for which m_x=10 TeV

SM + quintuplet………… neutral, stable, thermal freeze-out + relic abundance

of interest for indirect detection….

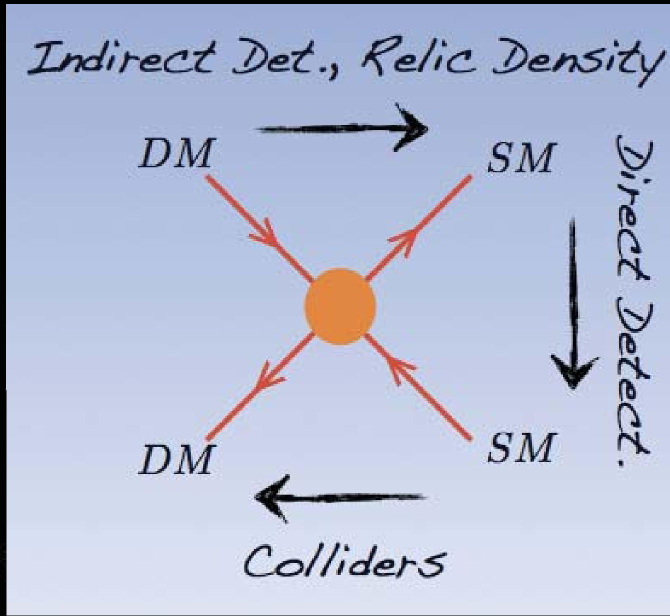
Cirelli +

DARK MATTER DETECTION

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

$\langle\sigma v\rangle \sim 3\text{x}10^{-26}\ cm^3/s$

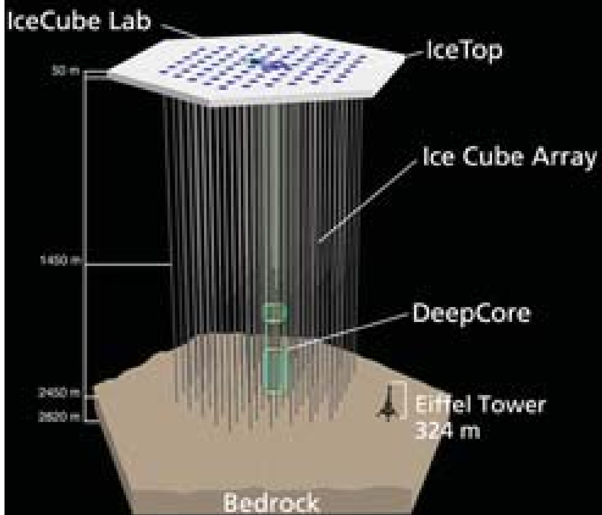
$\sigma_{ann} \sim 10^{-36}\ cm^2$



Hambye 2014

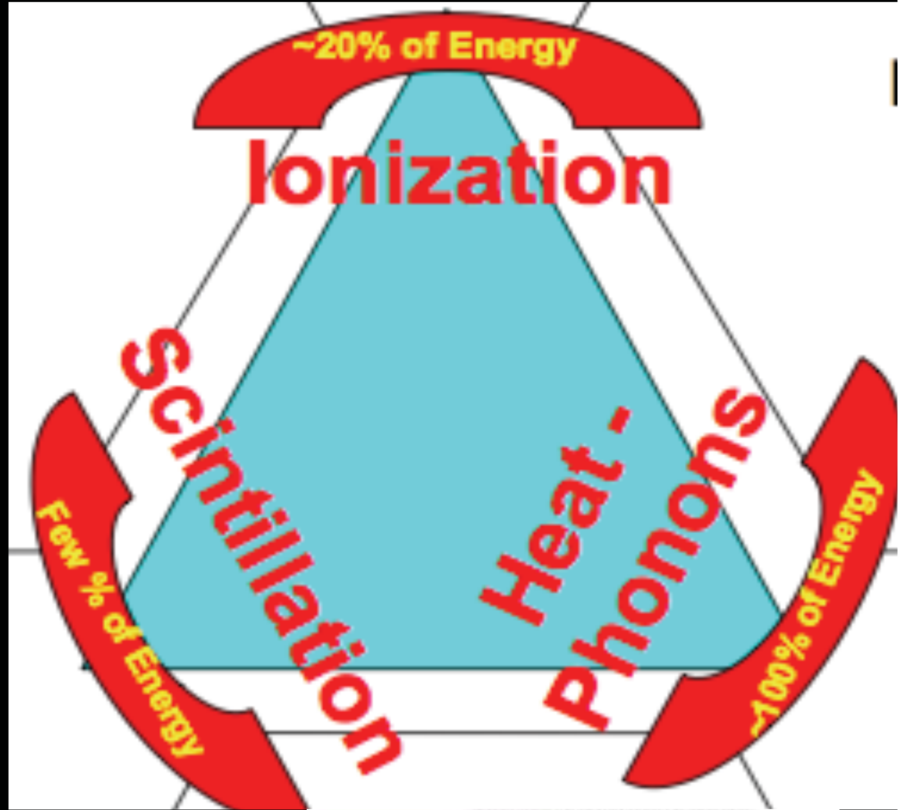
direct detection
and colliders

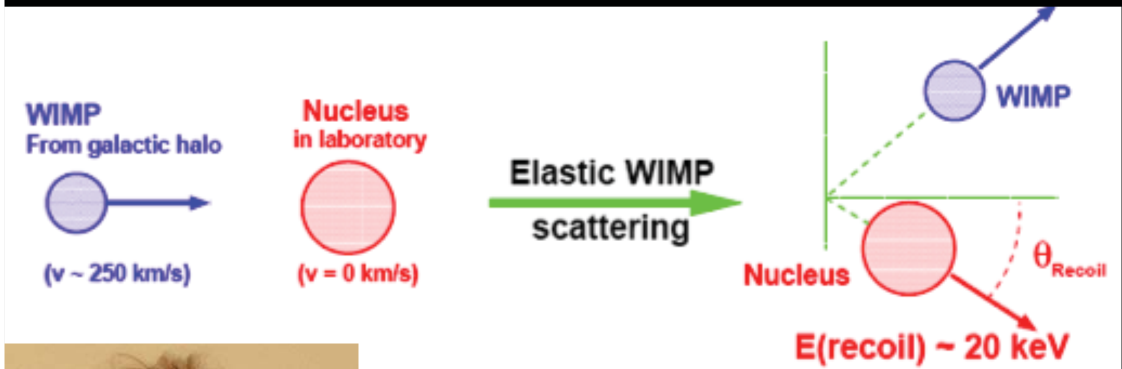
$\sigma_{sca} \sim 10^{-38}\ cm^2$

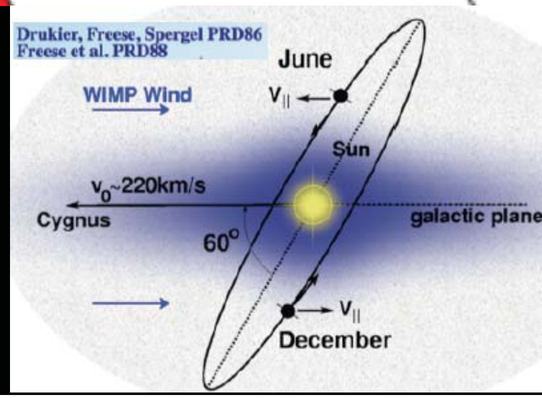


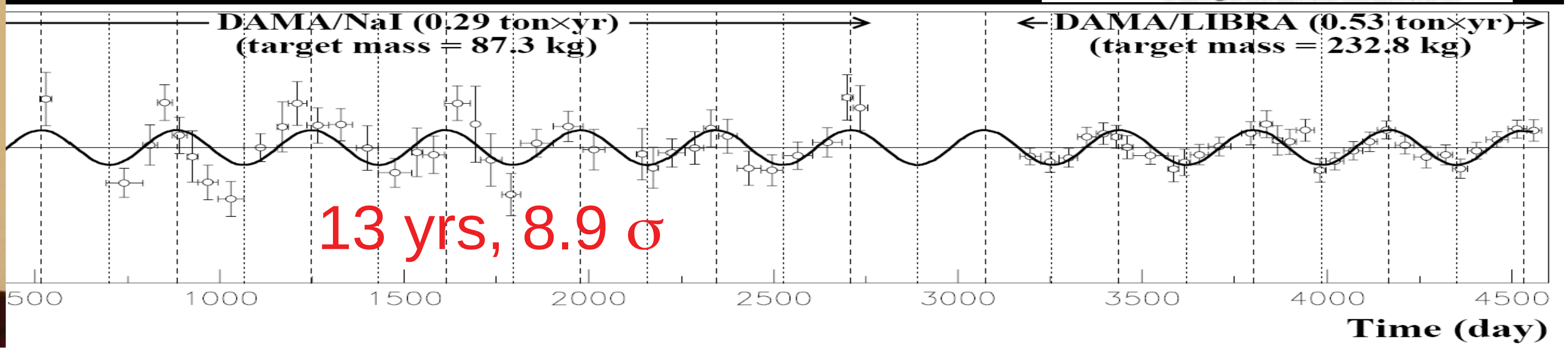
DIRECT DETECTION

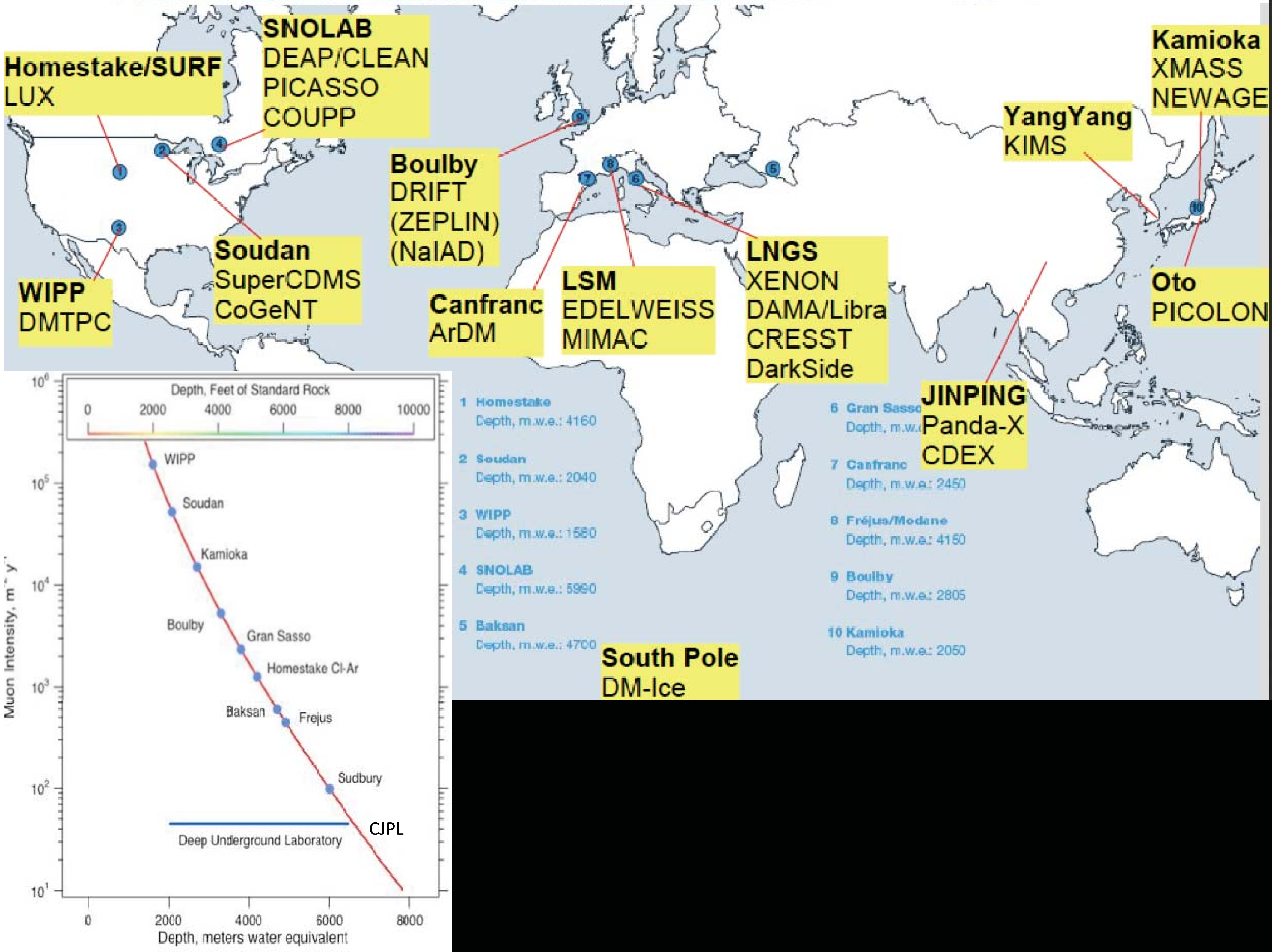
many WIMPs pass through lab per second







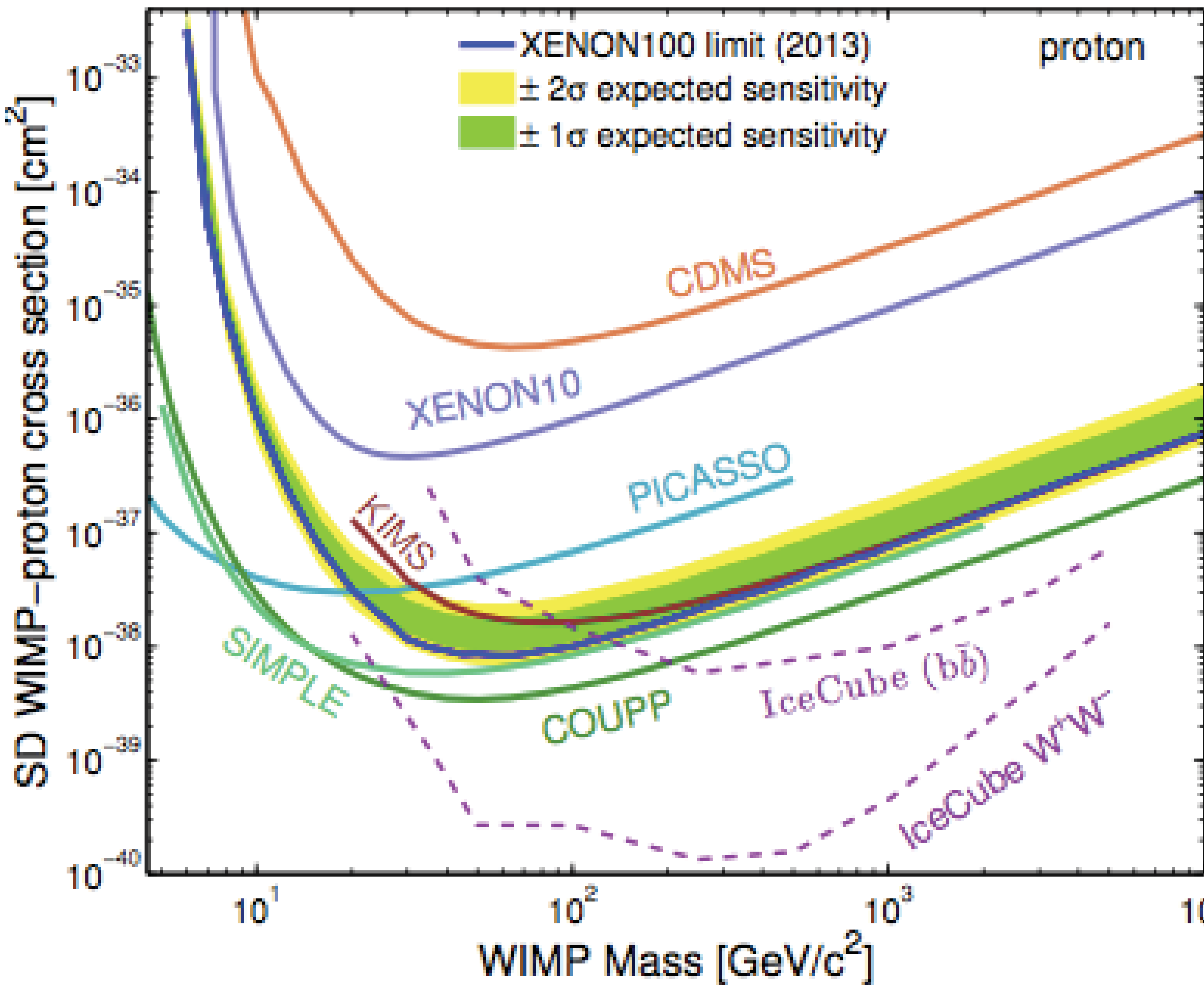




Homestake/SURF
LUX
SNOLAB
DEAP/CLEAN
PICASSO
COUPP
Boulby
DRIFT
(ZEPLIN)
(NaIAD)
Soudan
SuperCDMS
CoGeNT
WIPP
DMTPC
Canfranc
ArDM
LSM
EDELWEISS
MIMAC
LNGS
XENON
DAMA/Libra
CRESST
DarkSide
YangYang
KIMS
Kamioka
XMASS
NEWAGE
Oto
PICOLON
JINPING
Panda-X
CDEX
South Pole
DM-Ice
1 Homestake
Depth, m.w.e.: 4160
2 Soudan
Depth, m.w.e.: 2040
3 WIPP
Depth, m.w.e.: 1580
4 SNOLAB
Depth, m.w.e.: 5990
5 Baksan
Depth, m.w.e.: 4700
6 Gran Sasso
7 Canfranc
Depth, m.w.e.: 2450
8 Fréjus/Modane
Depth, m.w.e.: 4150
9 Boulby
Depth, m.w.e.: 2805
10 Kamioka
Depth, m.w.e.: 2050
Depth, Feet of Standard Rock
0
2000
4000
6000
8000
10000
WIPP
Soudan
Kamioka
Boulby
Gran Sasso
Homestake Cl-Ar
Baksan
Frejus
Sudbury
CJPL
Deep Underground Laboratory
Muon Intensity, m⁻² y⁻¹
Depth, meters water equivalent

Spin-dependent elastic scattering sums incoherently

(couples to nucleon spin, cancels in pairs)

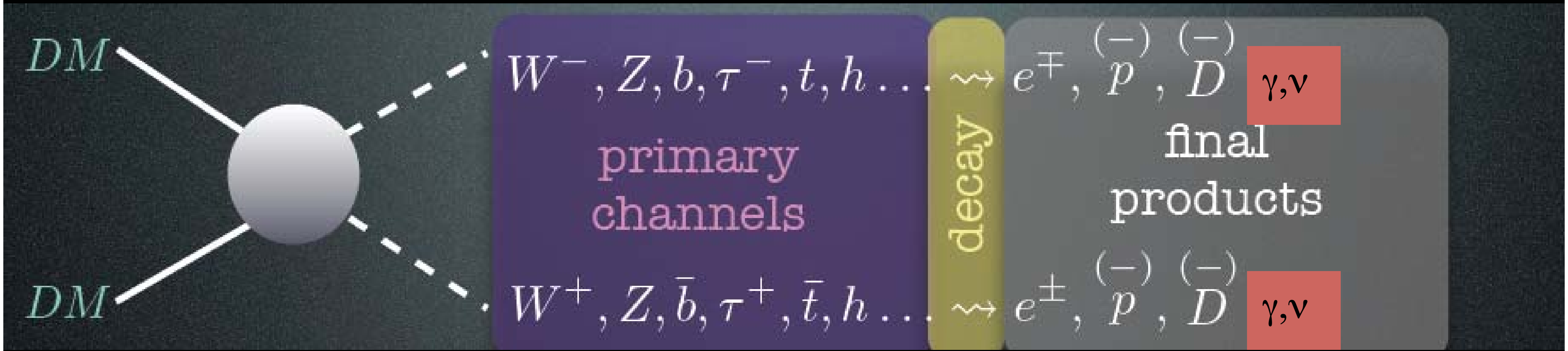


1. ASTROPHYSICAL CONSTRAINTS
2. DIRECT DETECTION
3. INDIRECT DETECTION

3

INDIRECT DETECTION

halo WIMPS occasionally annihilate into energetic particles



UNCERTAINTIES

Dark matter distribution

profiles, streams, clumps, velocity distribution

Cosmic ray propagation

diffusion, solar modulation, energy losses

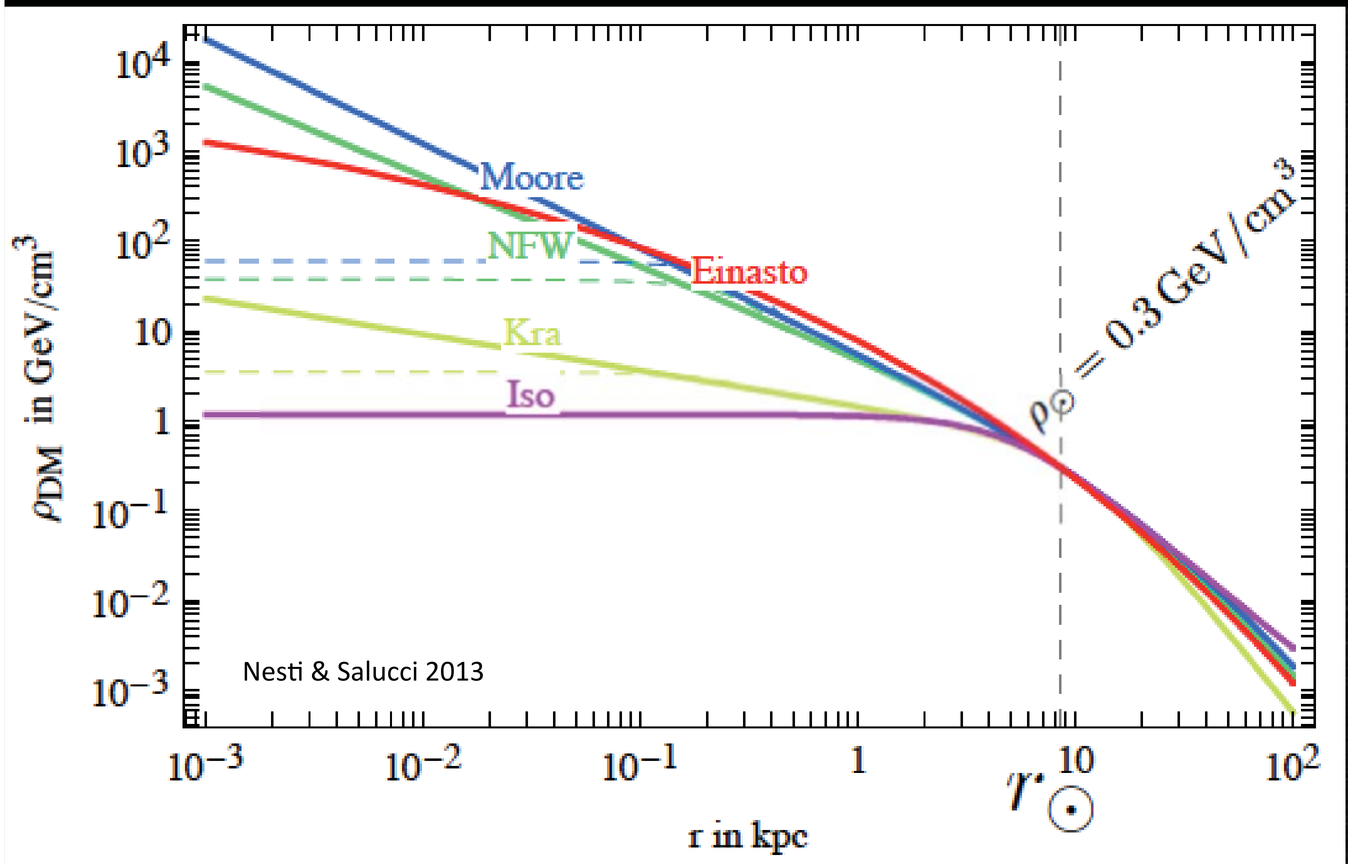
Particle physics issues

fragmentation codes,

higher order corrections at TeVscales

Astrophysical backgrounds

Possible dark matter profiles in our galaxy



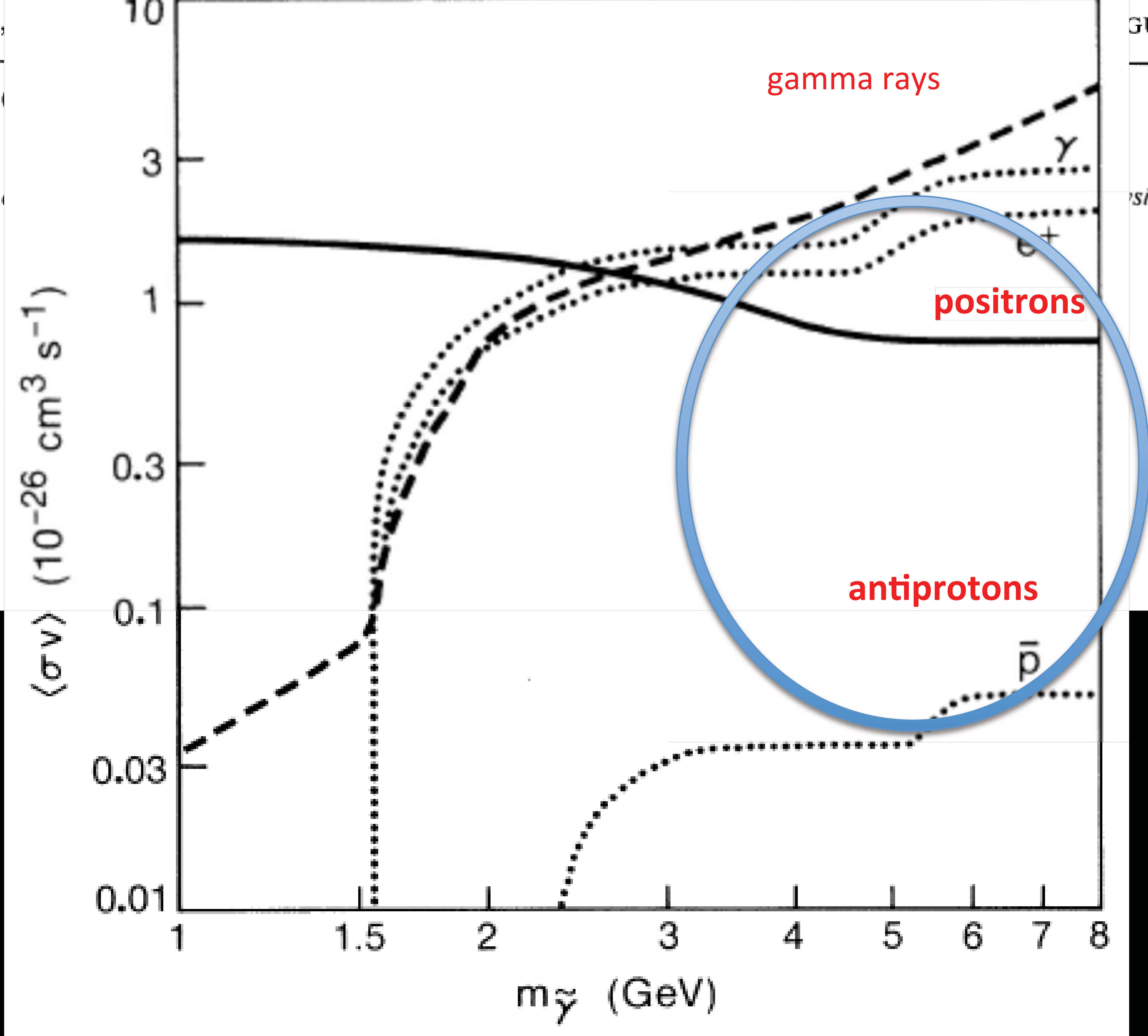
1. ASTROPHYSICAL CONSTRAINTS
2. DIRECT DETECTION
3. INDIRECT DETECTION

positrons

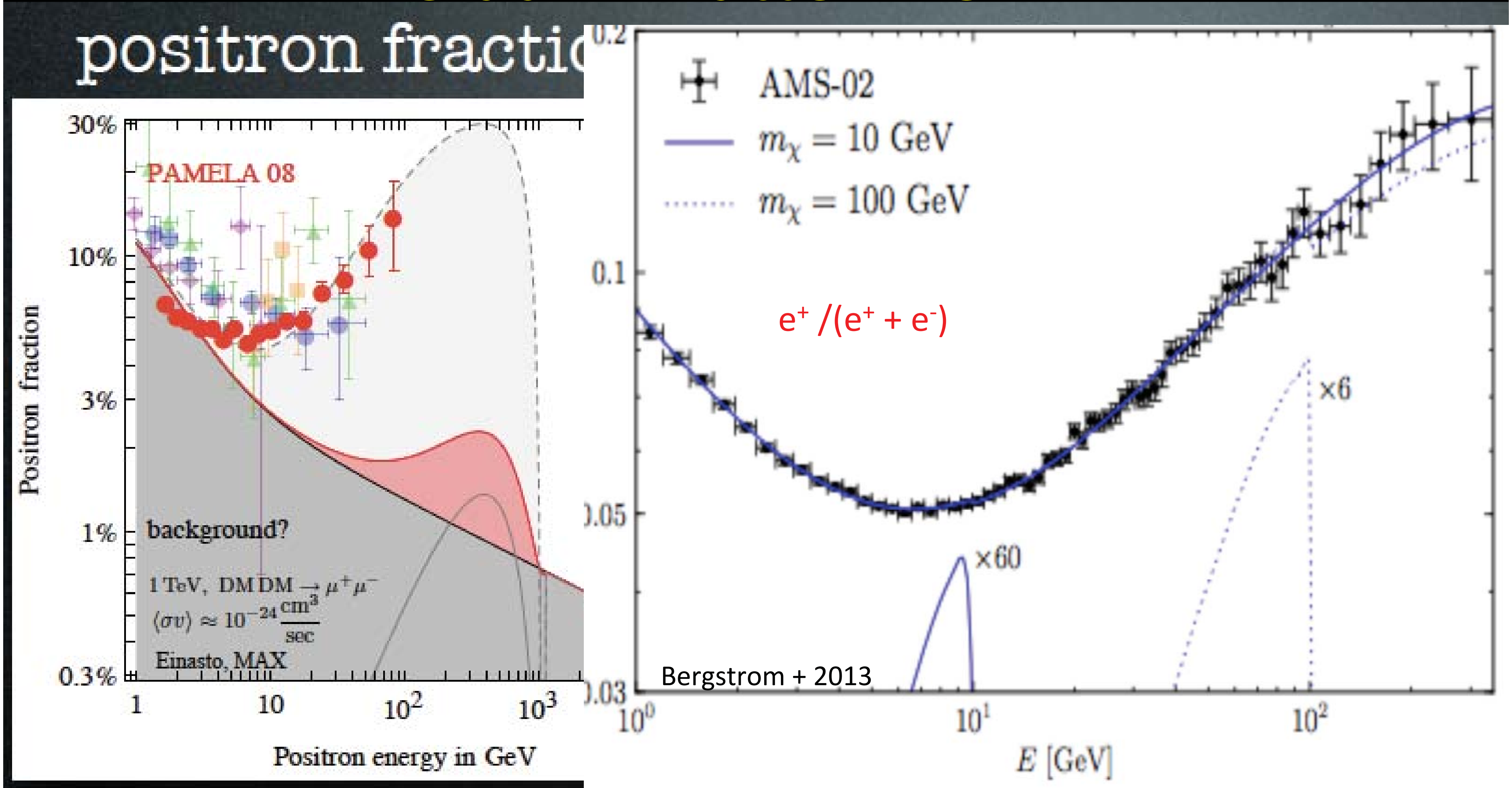
3a

Astron

sics,


gamma rays
γ
e+
positrons
antiprotons
p̄
10
3
1
0.3
0.1
0.03
0.01
⟨σv⟩ (10^-26 cm^3 s^-1)
1
1.5
2
3
4
5
6
7
8
m_γ̃ (GeV)

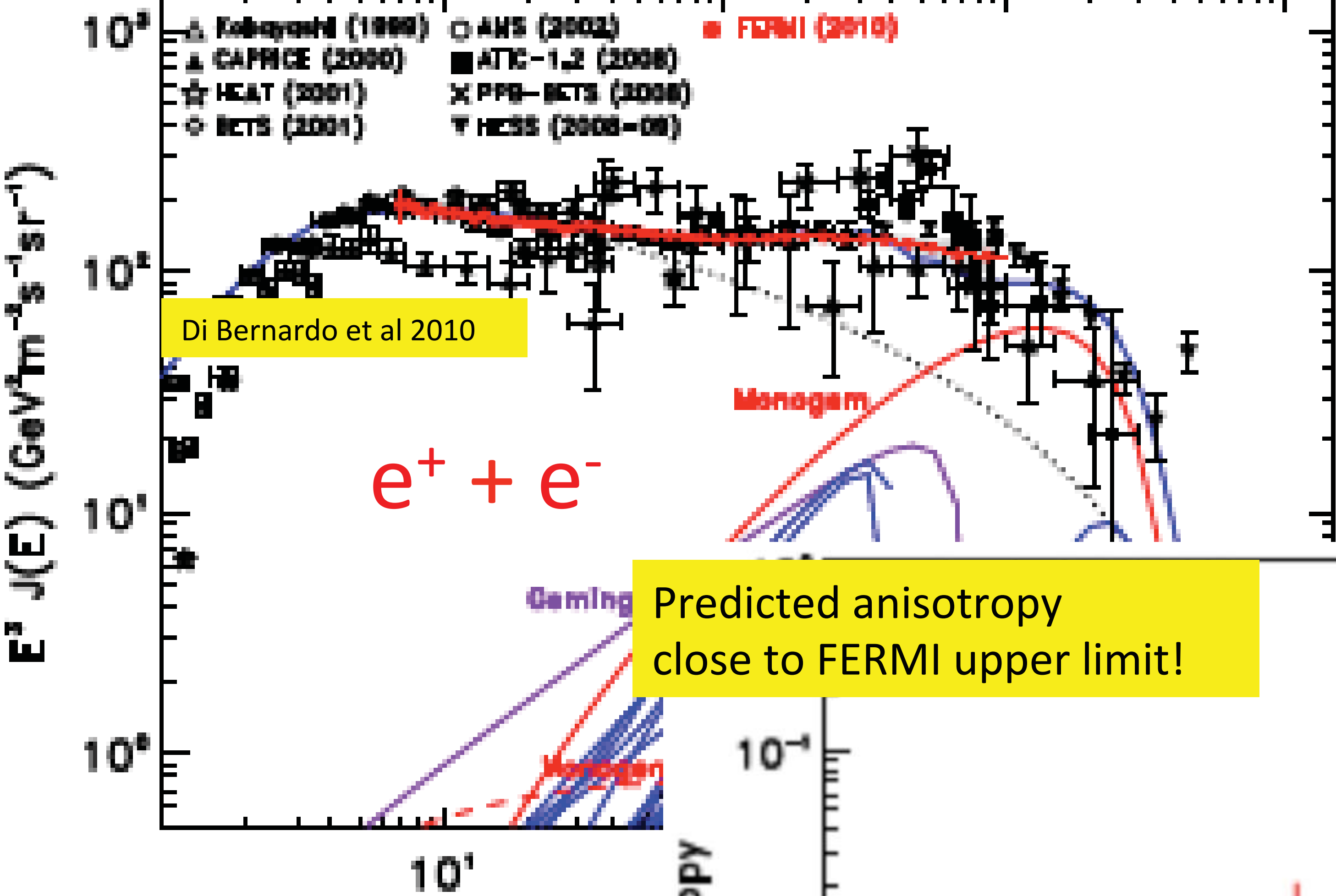
The dark matter view

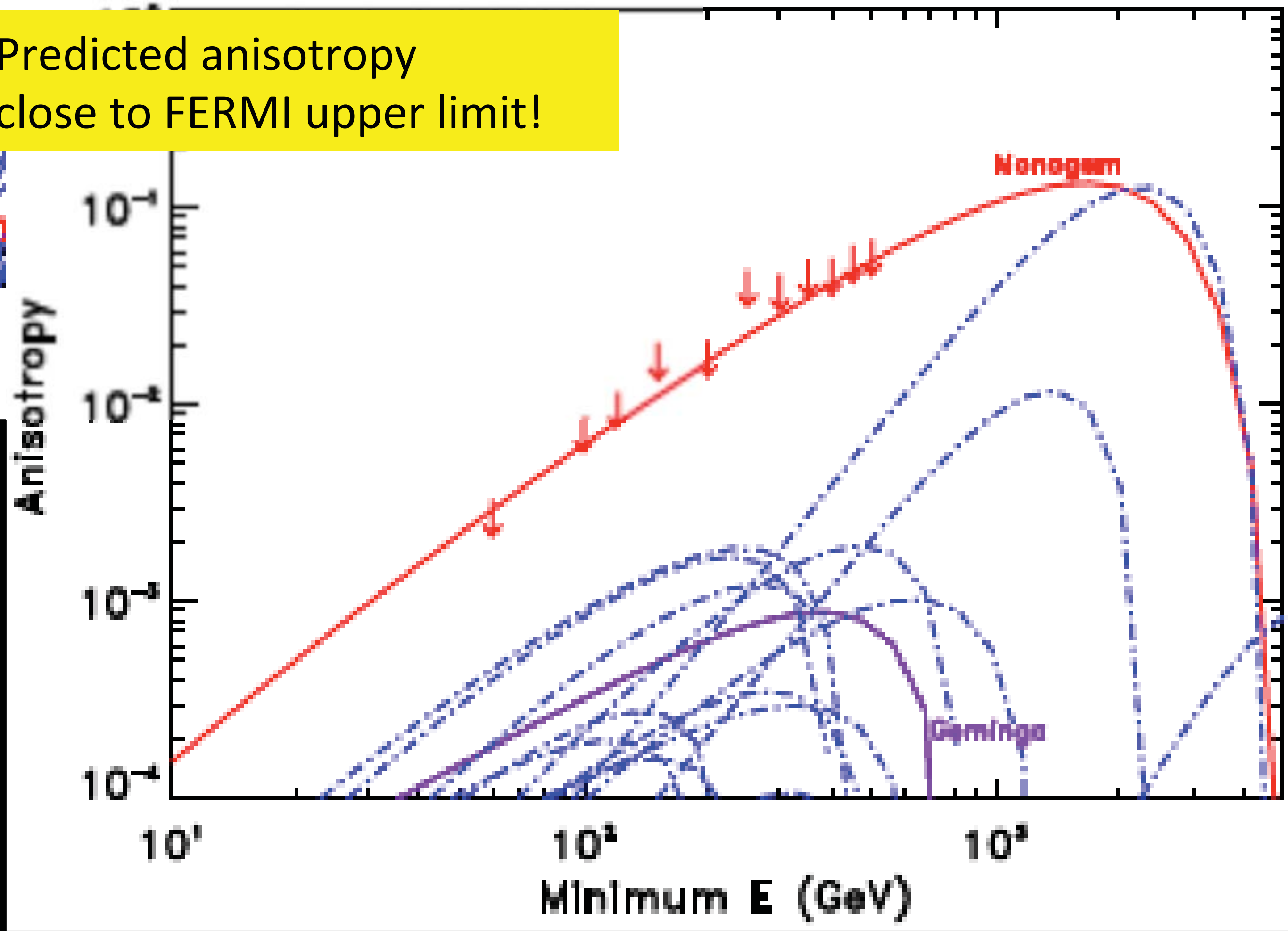


Cirelli 2009

astrophysical origin

via PULSAR WIND





1. ASTROPHYSICAL CONSTRAINTS
2. DIRECT DETECTION
3. INDIRECT DETECTION

positrons

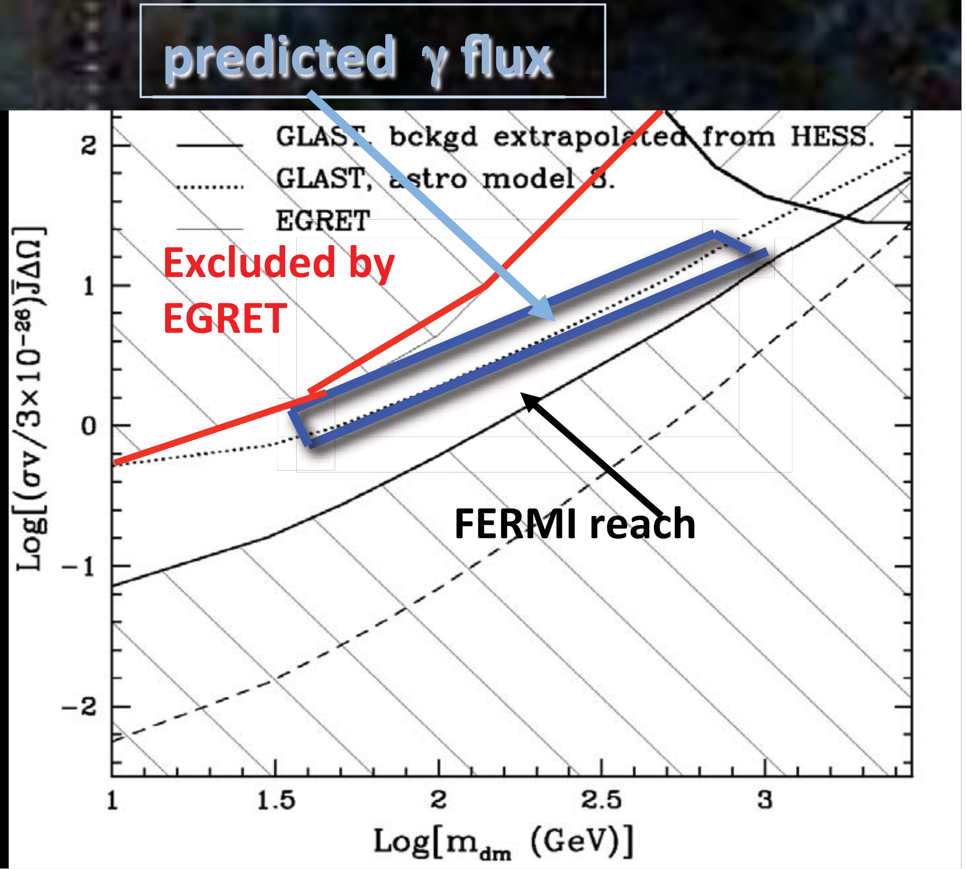
γ rays

3b

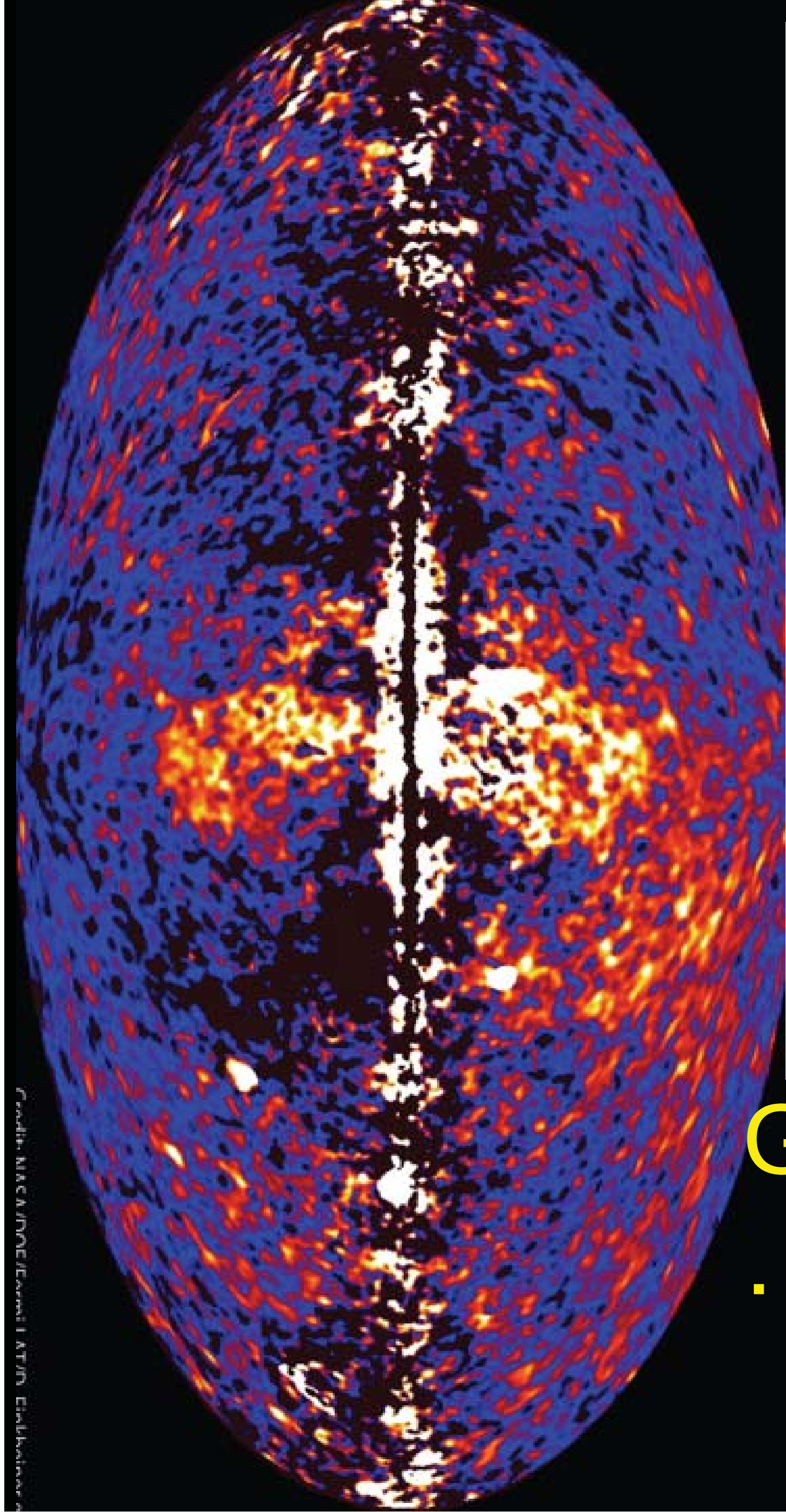
Radio synchrotron emission

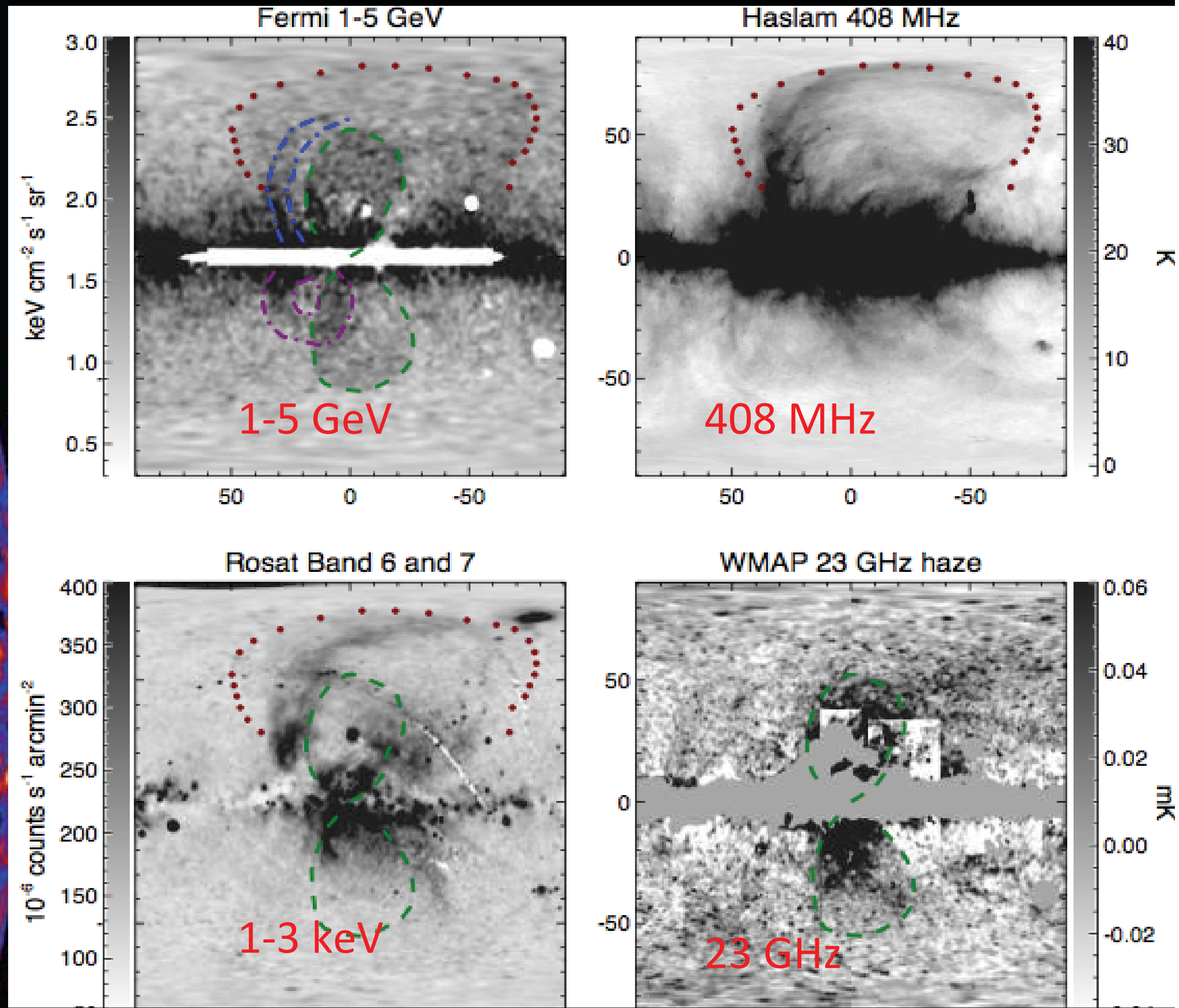
The WMAP microwave haze

Finkbeiner 2007



Hooper and Zaharias 2007





Giant gamma ray bubbles …not dark matter

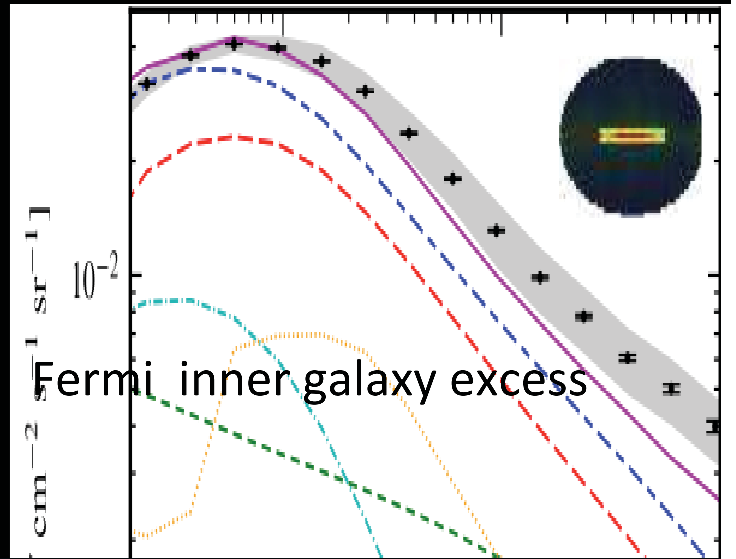
Fermi haze is inverse Compton of e^+e^- on interstellar radiation

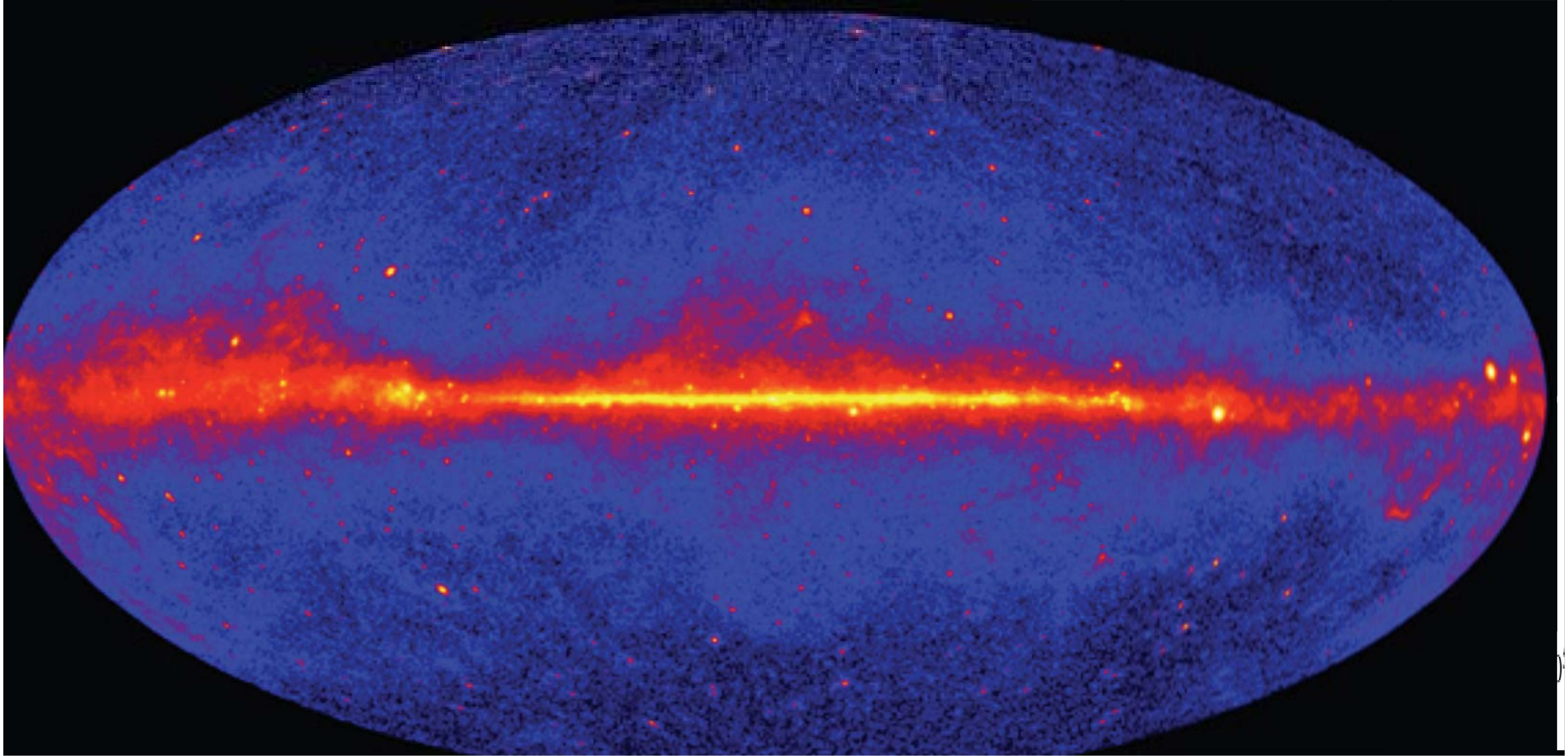
Su et al. 2010

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

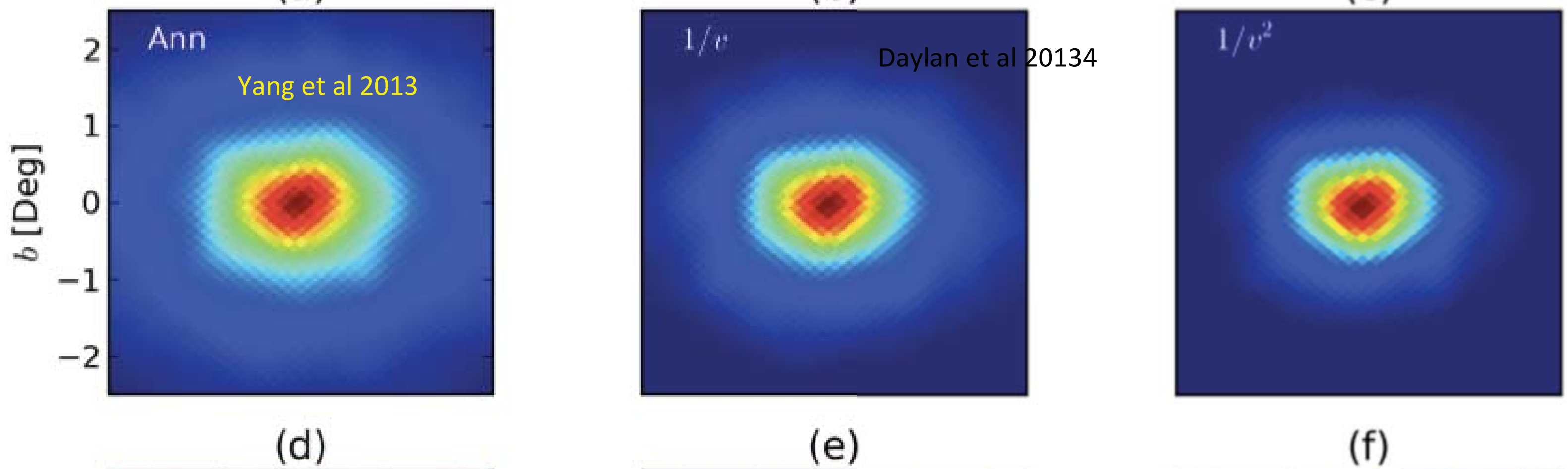
Fermi inner galaxy excess

DM renderings by Lin Yang (2013)

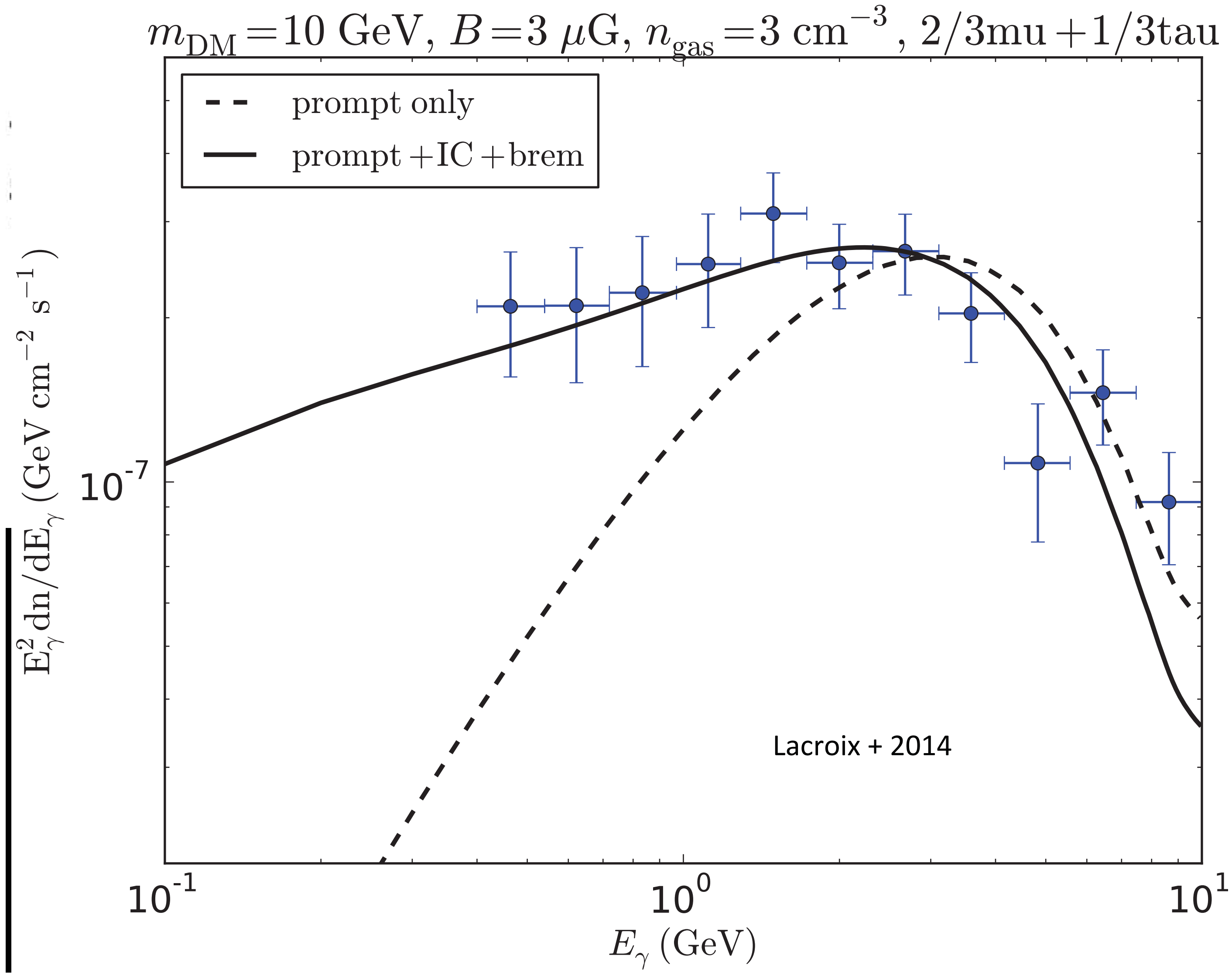




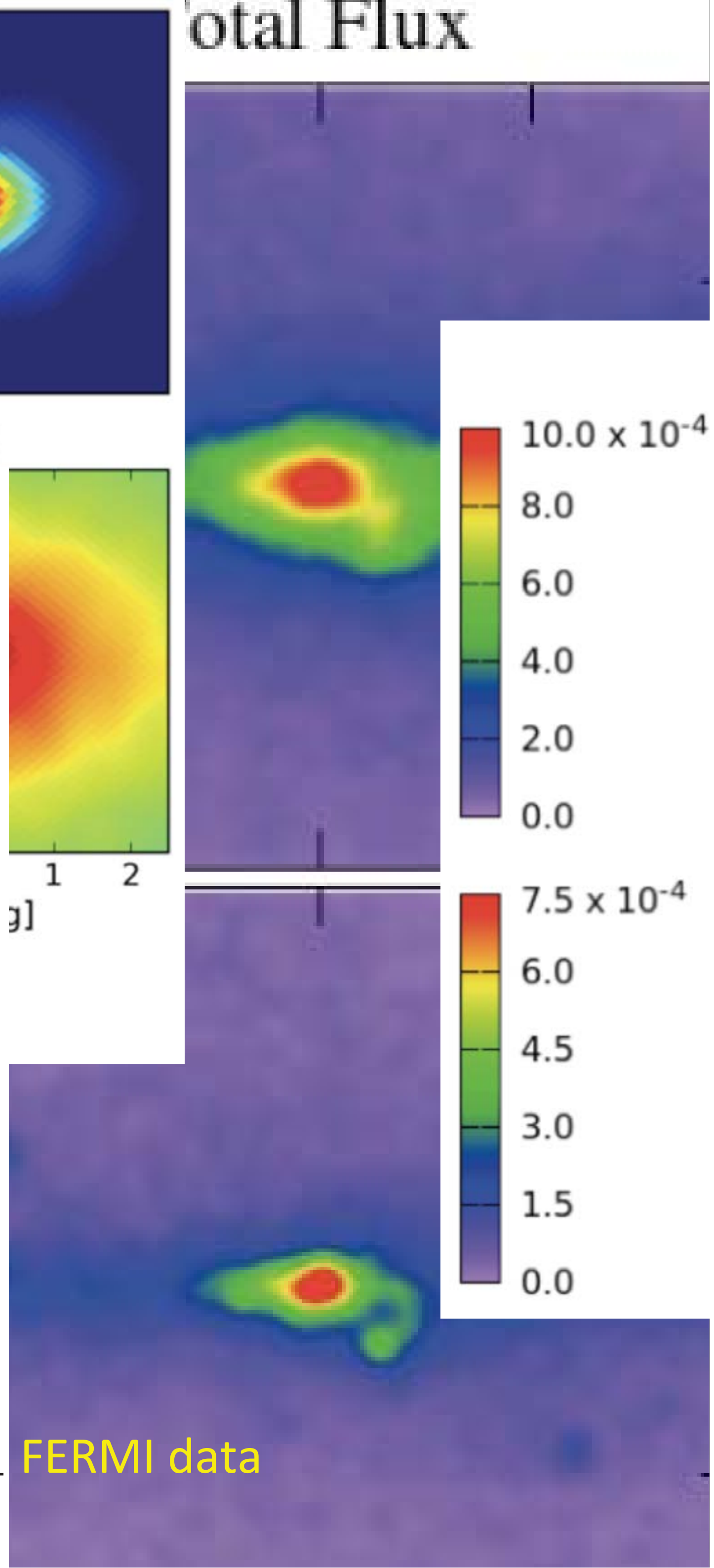
THE GALACTIC CENTER 7ºx7º



Ann
Yang et al 2013
1/v
Daylan et al 20134
1/v²
b [Deg]
2
1
0
−1
−2
(d)
(e)
(f)



m_DM = 10 GeV, B = 3 μG, n_gas = 3 cm^−3, 2/3mu + 1/3tau
prompt only
prompt + IC + brem
Lacroix + 2014
E²_γ dn/dE_γ (GeV cm^−2 s^−1)
10^−7
10^−1
10^0
10^1
E_γ (GeV)



otal Flux
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
1
2
FERMI data

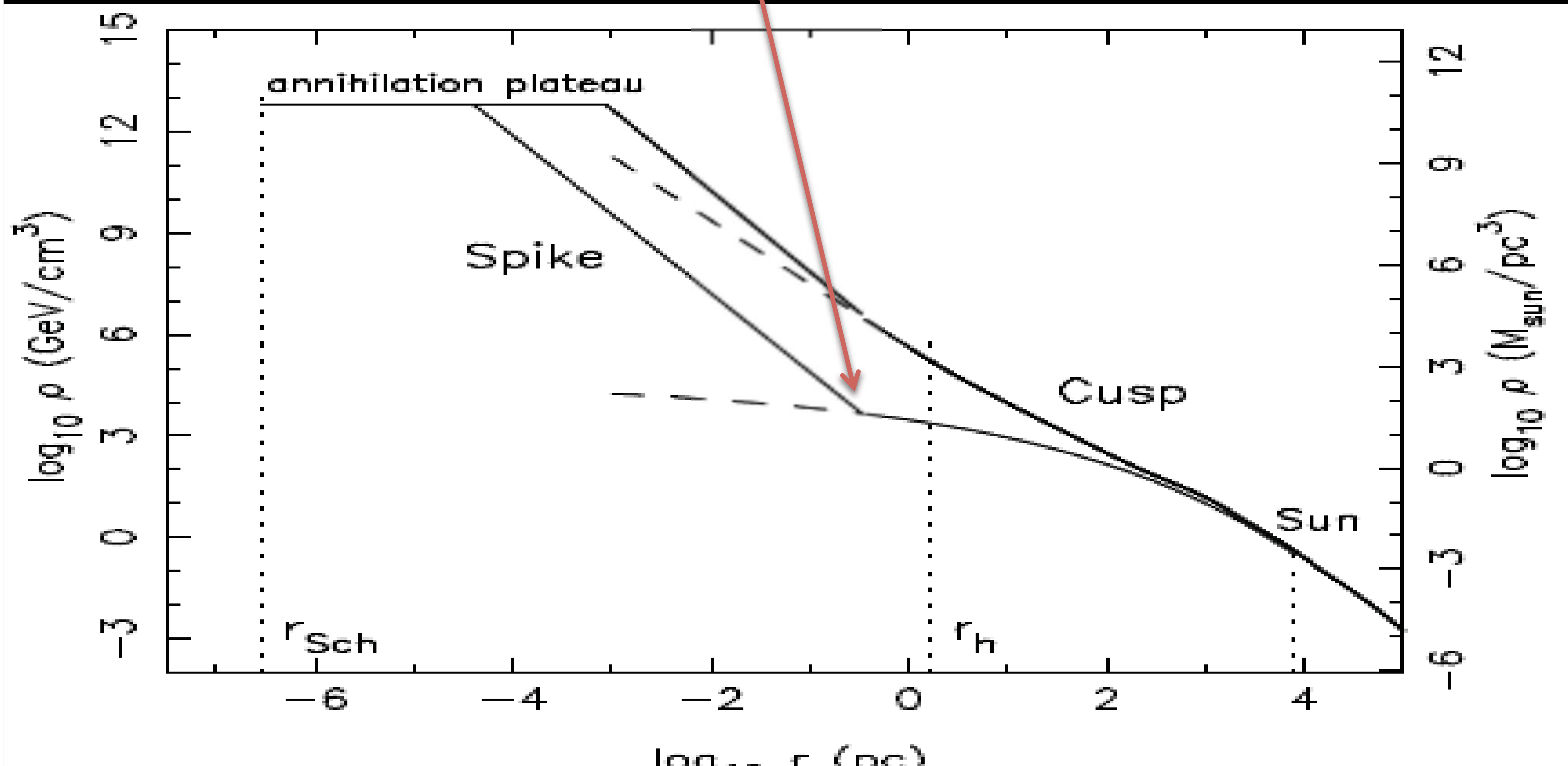
Dark Matter around our SMBH

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 $GM_{bh}/\sigma^2 \sim 0.003(M_{BH}/10^5 M_\odot)$pc

Density profile

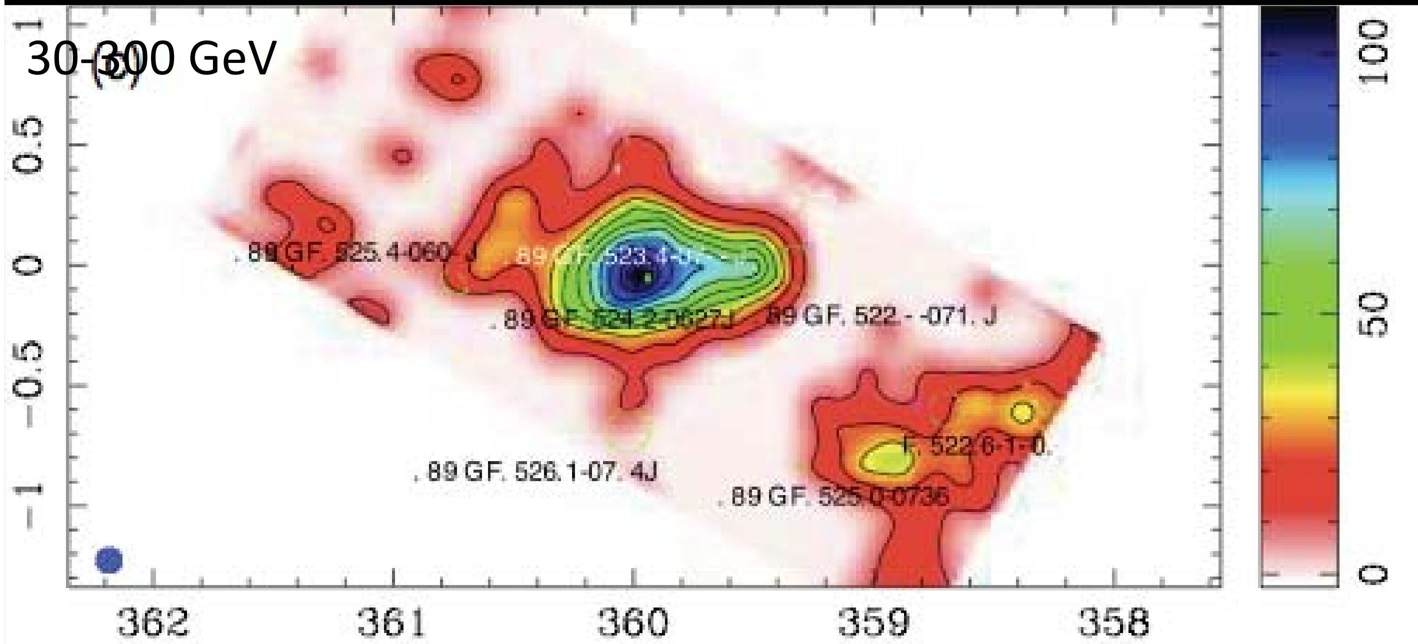
Plateau: $n_x(\mathbf{r})\langle\sigma v\rangle\, t_{BH} \sim 1$

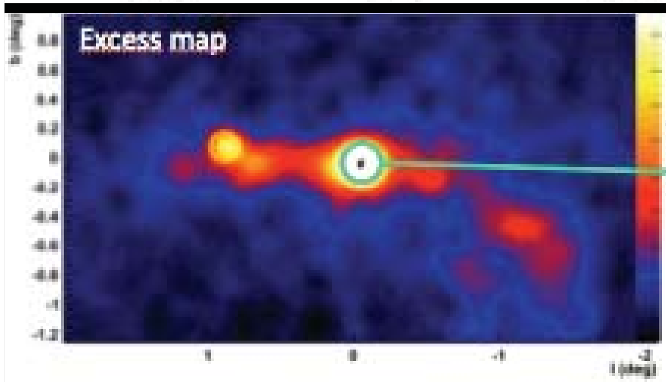


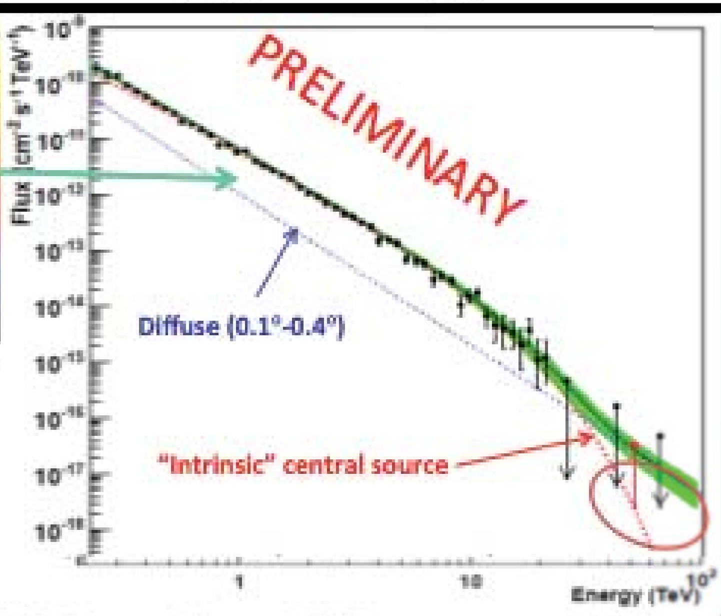
Gondolo + JS 1999, Gnedin & Primack 2004, Sadeghian, Ferrer + Will 2013

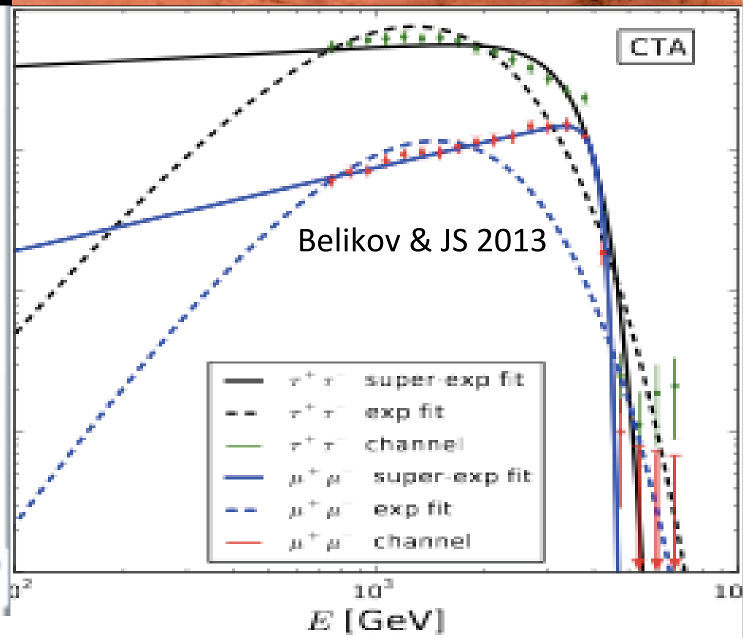
supermassive black hole at Galactic Center

prediction for CTA: superexponential signature of TeV DM annihilations









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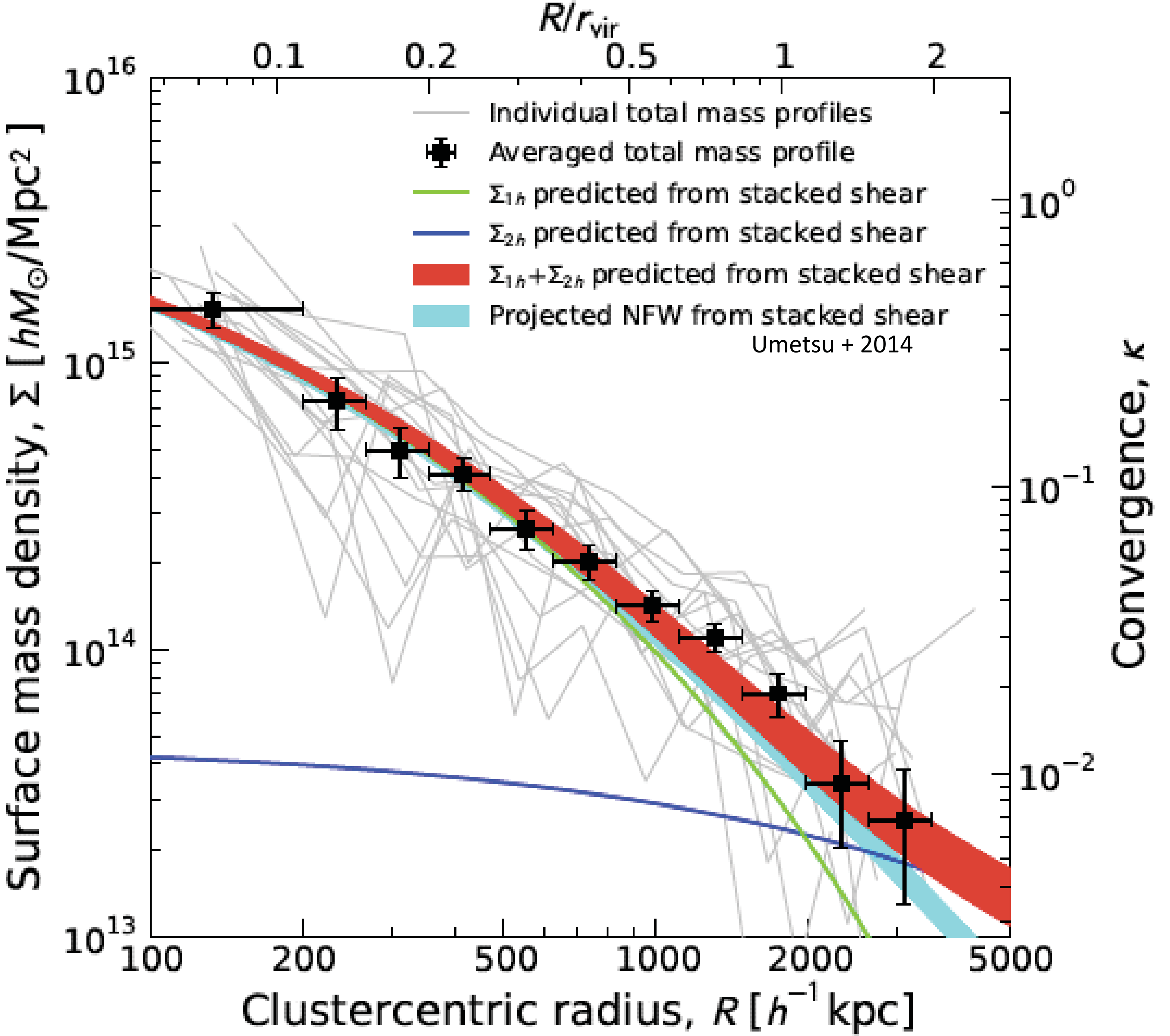
positrons

γ rays

galaxy clusters

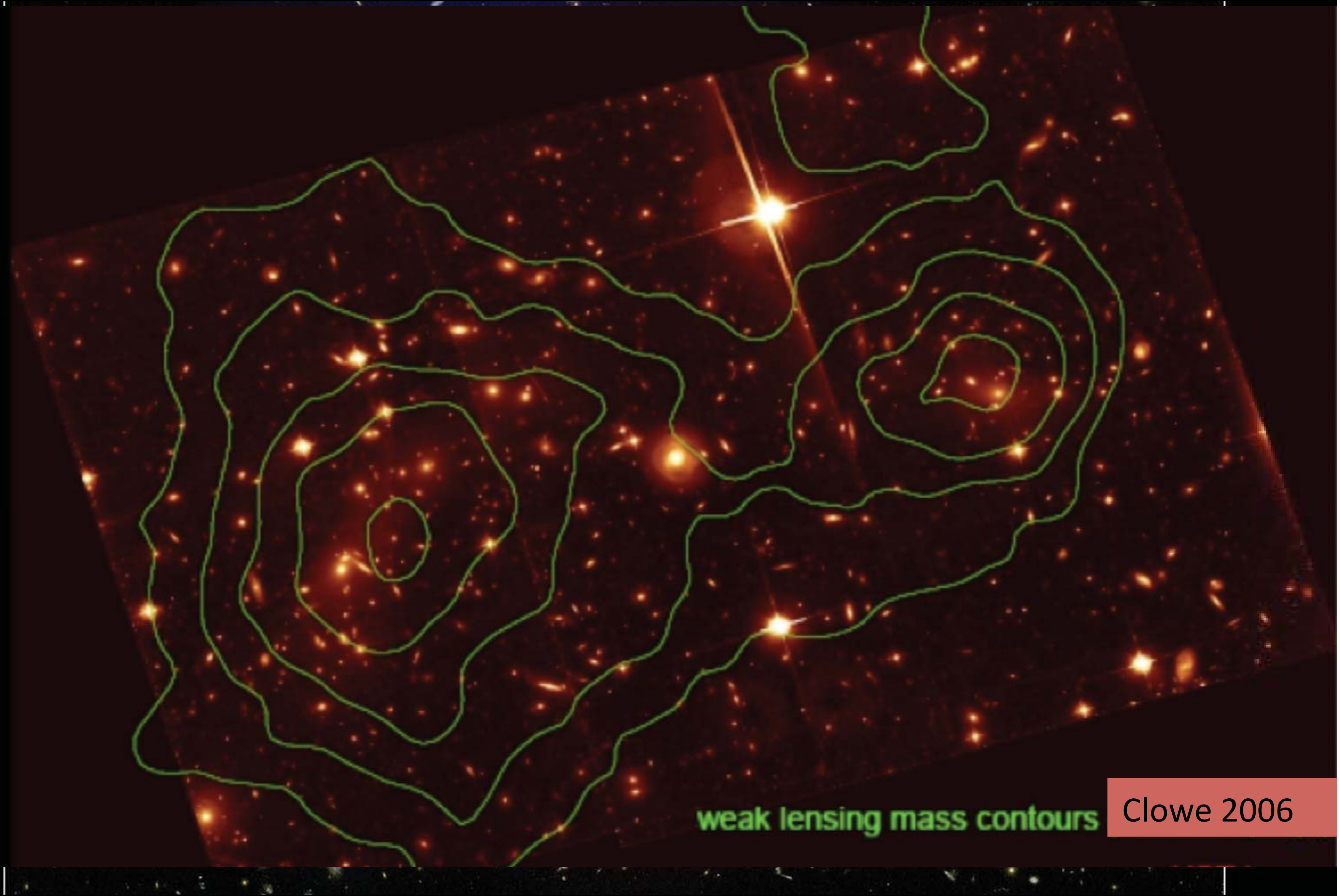
3c

CLUSTER PROFILE



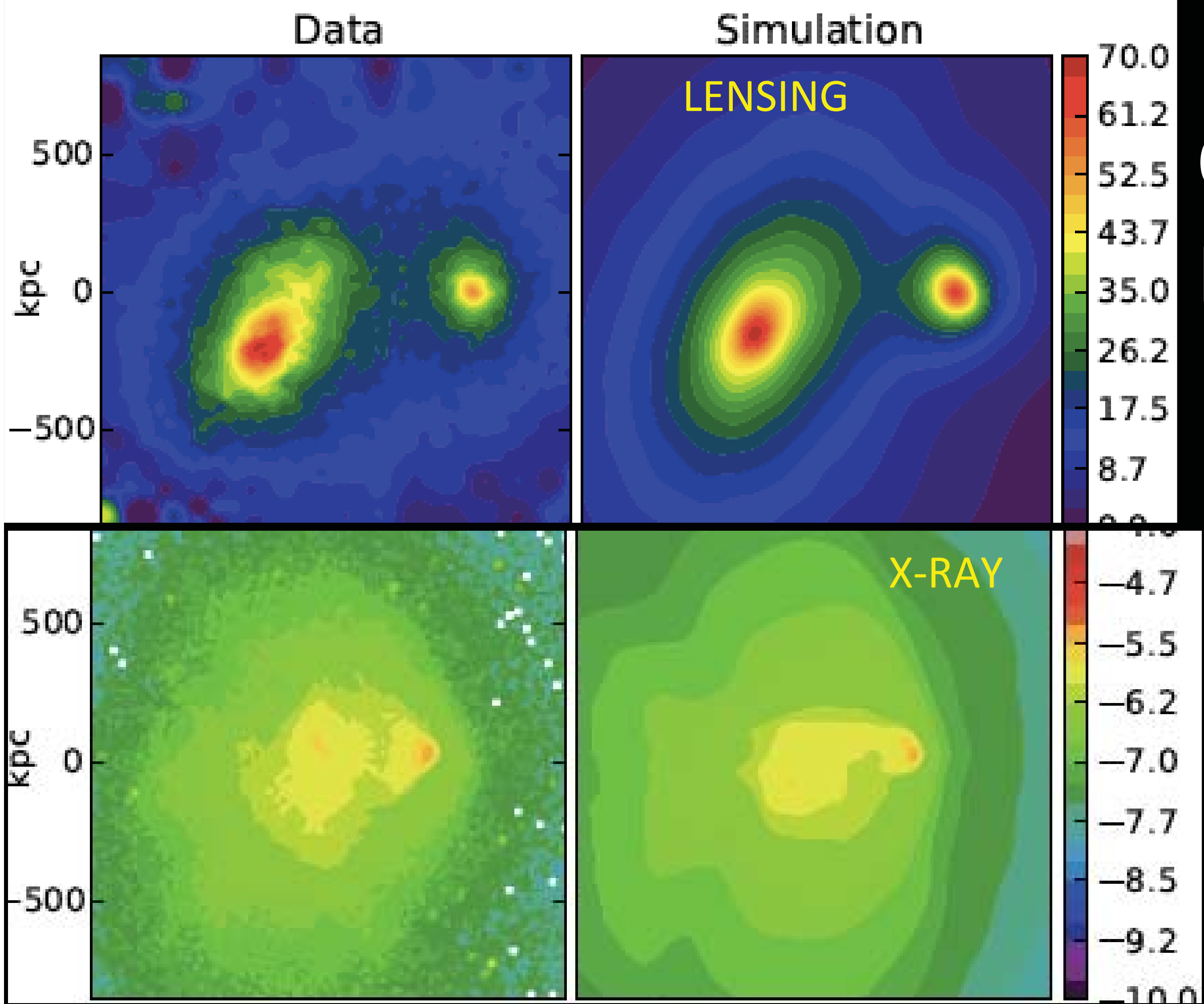
shear
+magnification

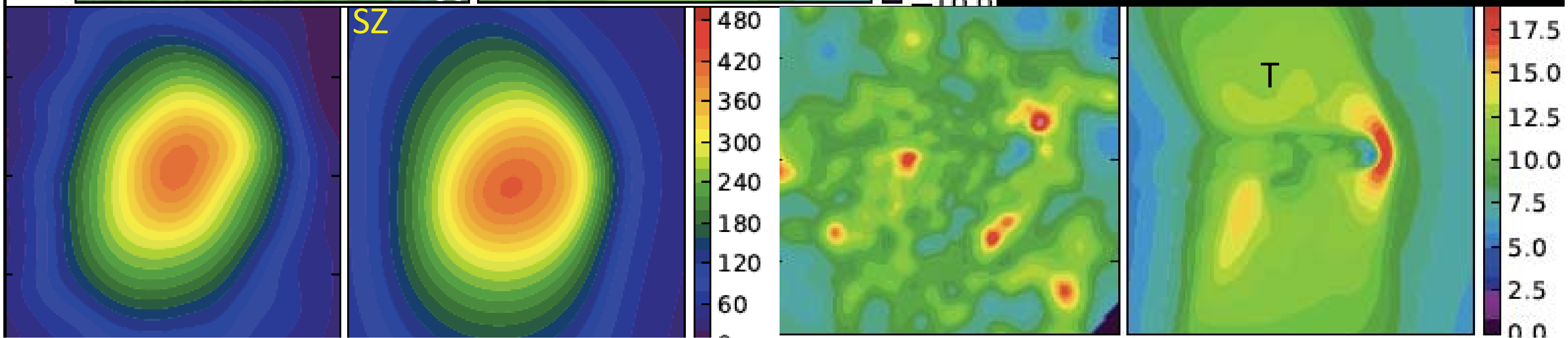
BULLET CLUSTER



Lage & Farrar 2014

CDM accounts for Bullet Cluster



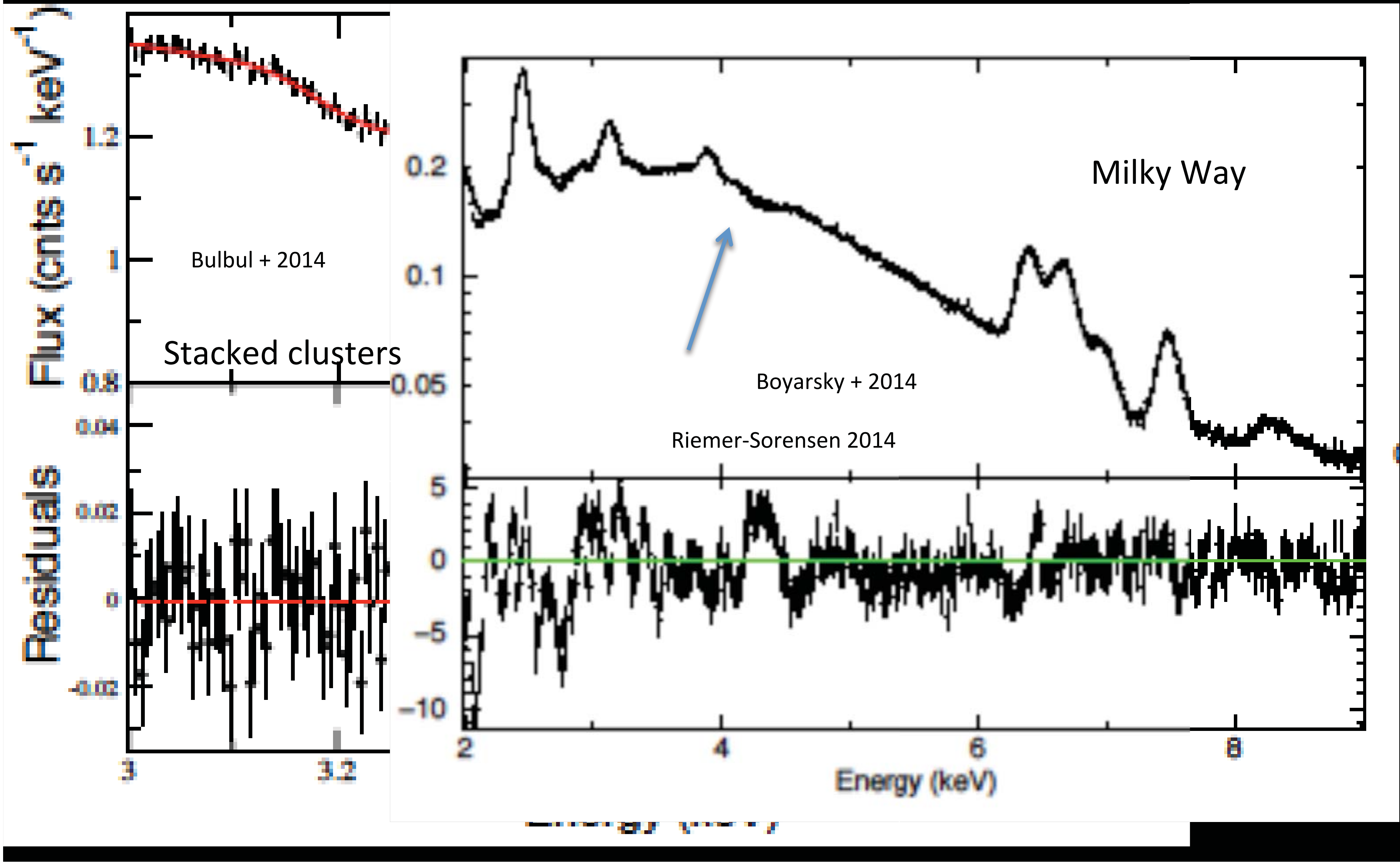


a 3.5 keV line ?

decay time (+ mixing angle) specifies relic abundance
7 keV ν decays into 3.5 keV photons

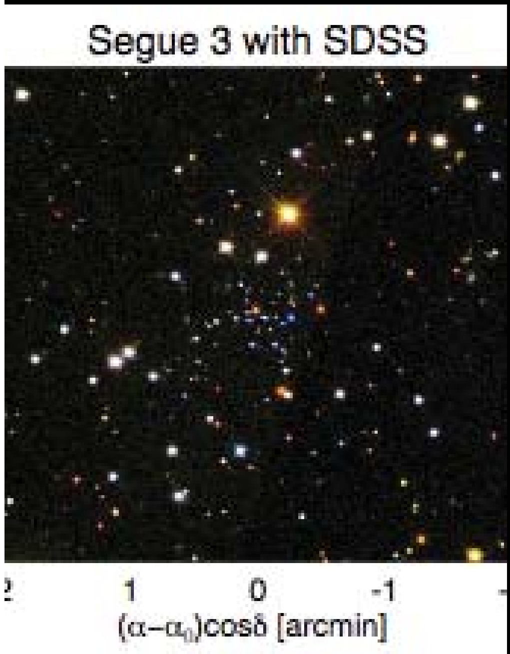
If dark matter is a sterile neutrino

Warm dark matter suppresses small galaxies:
few keV is co-moving mass of dwarf galaxy

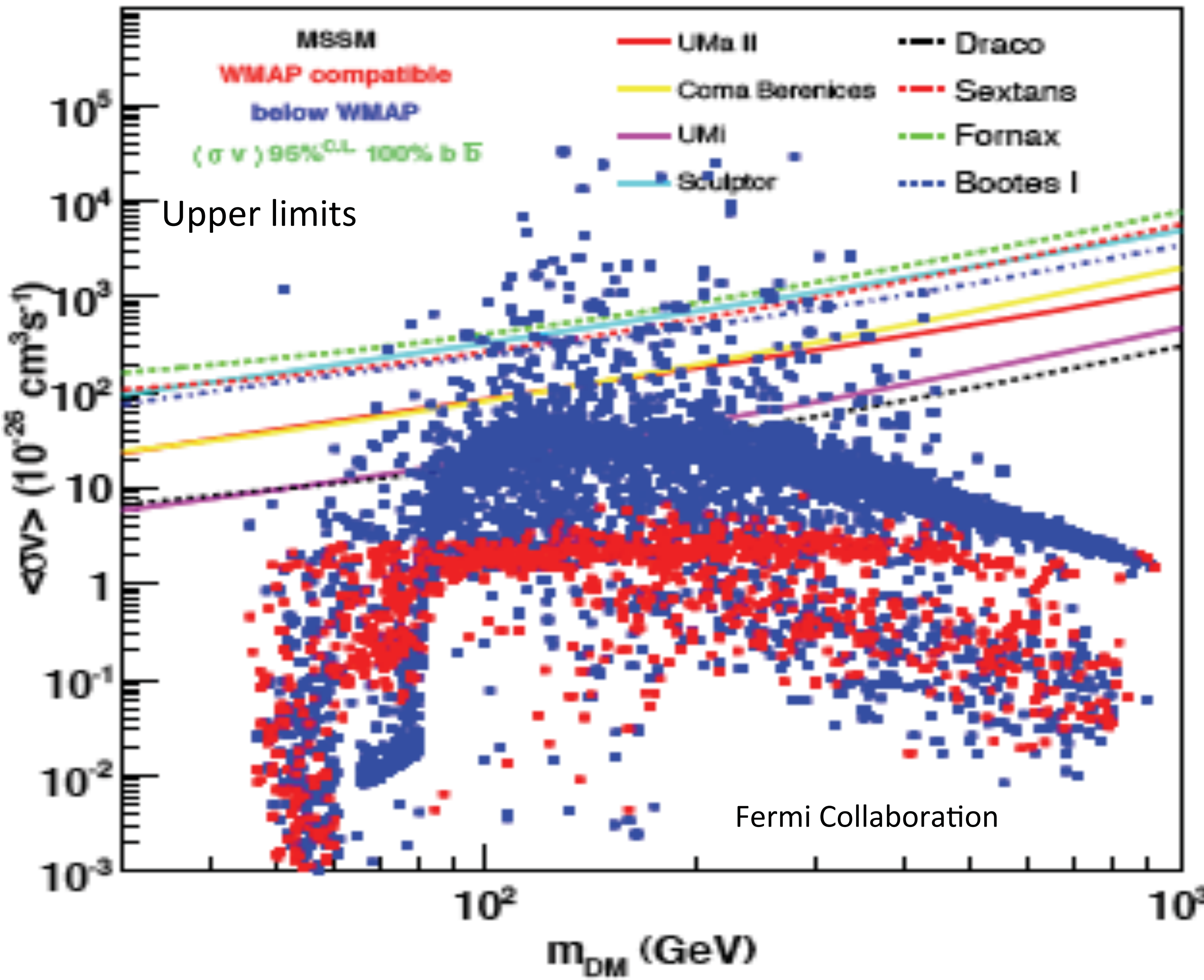


Ultra-faint dwarf galaxies predicted by CDM

So far no γ detection

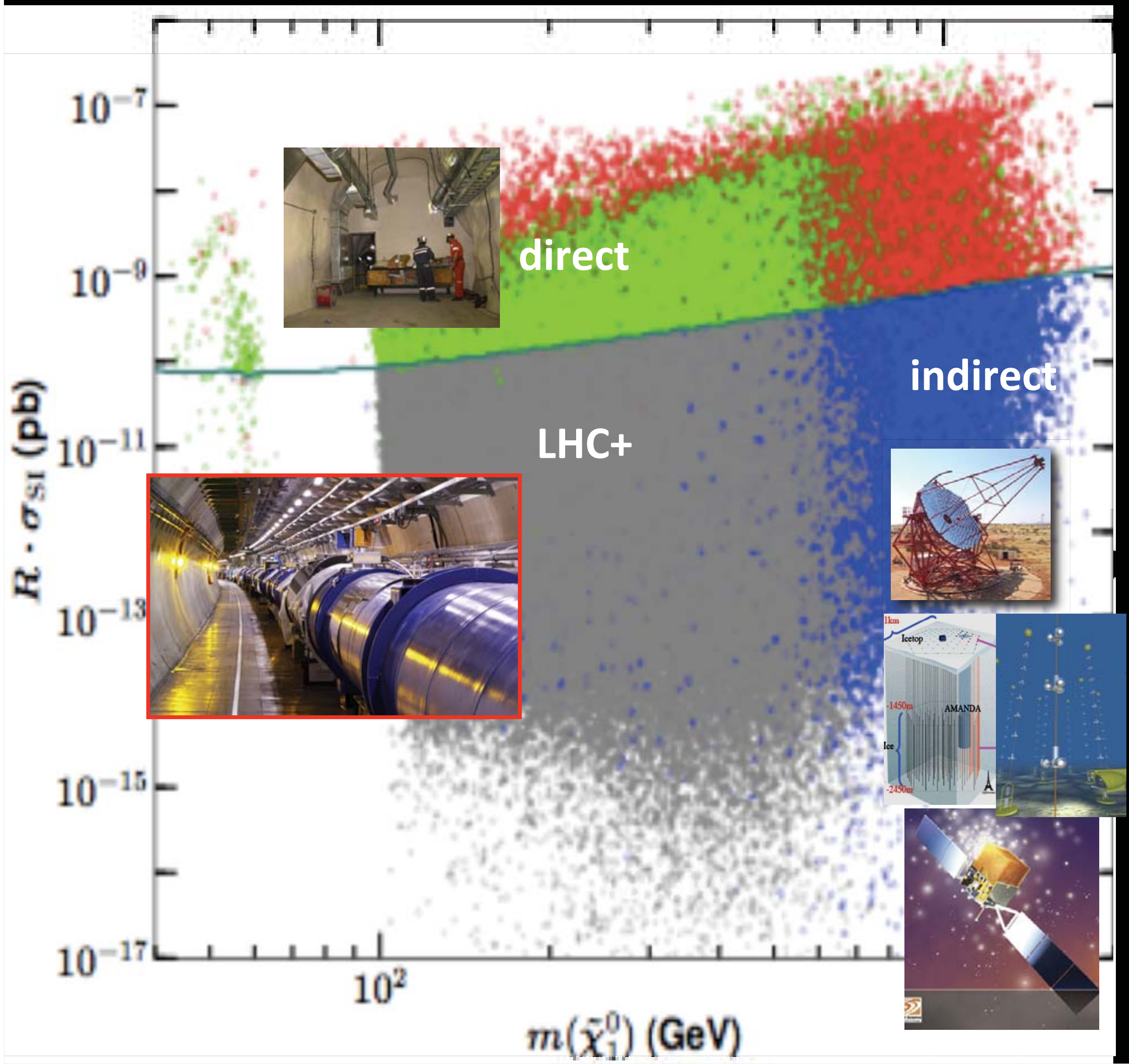


If GC is DM signal, then we should soon detect dwarf spheroidal galaxies: ideal DM laboratories



THE FUTURE

Following the light Higgs discovery and the failure to find evidence for SUSY, the new frontier for particle physics is likely to be a 100 TeV collider



The new frontier for DM detection will shift from light DM (10-100 GeV) where the constraints are increasingly tight to heavy DM (1-30 TeV)