Dark Matter, Low-Background Physics

RHUL *Jocelyn Monroe*

Nov. 6, 2012

1. Evidence (Astrophysical Detection)

2. Candidates, Properties

3. Direct Detection (Particle Physics)

1^{st} Observation: 1930s

Fritz Zwicky

(Kitt Peak)

Virial Theorem: kinetic energy ∝ potential energy

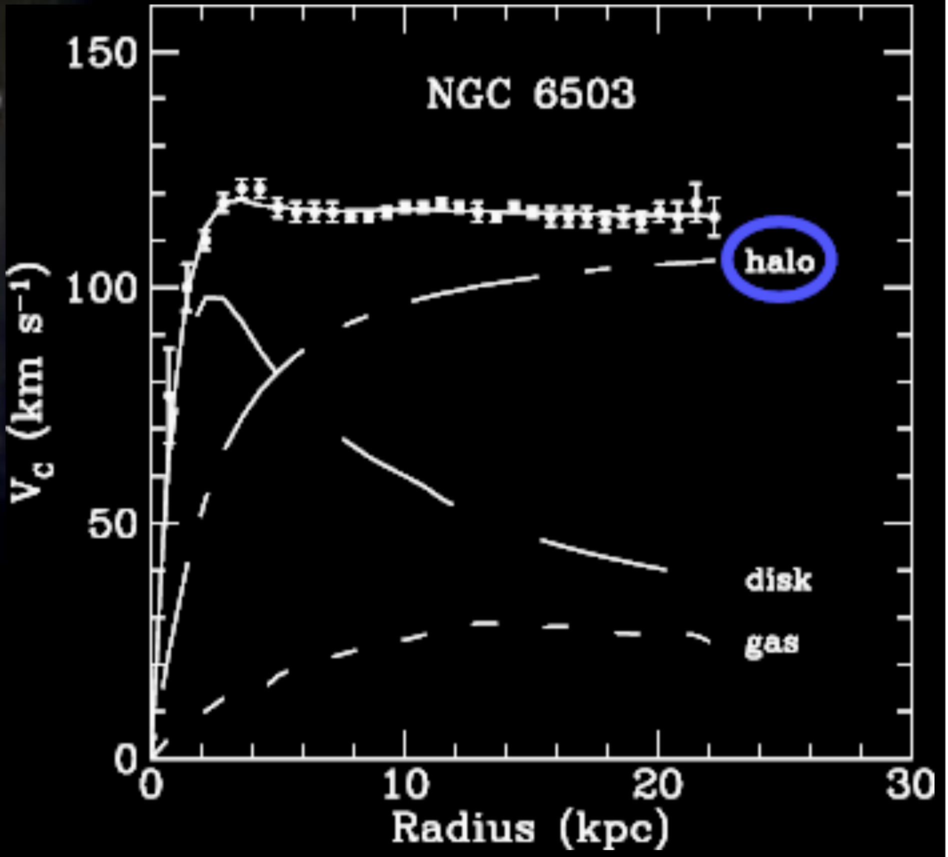
implies 400x more mass than visible!

Confirmation: 1980s

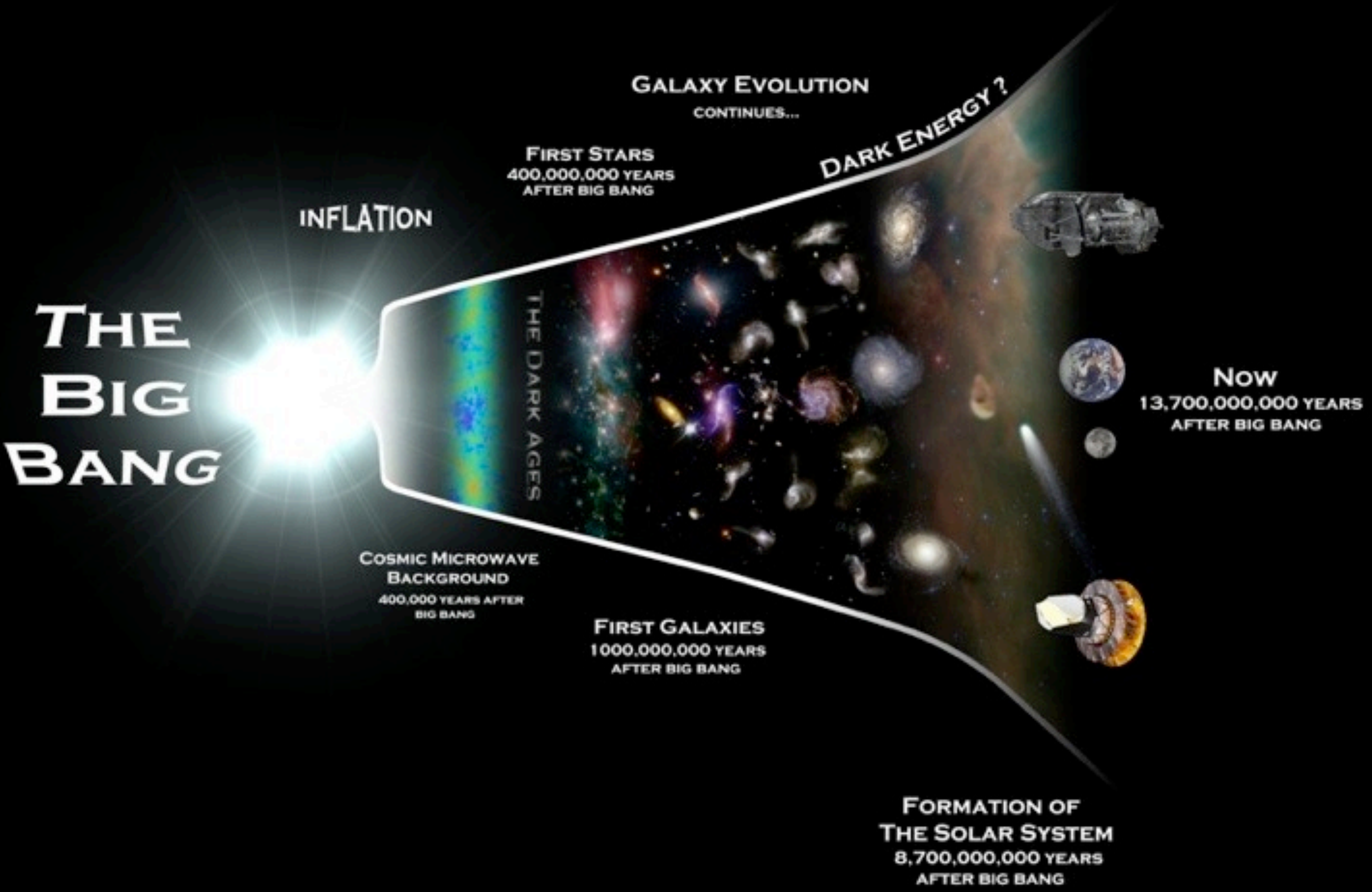
Vera Rubin

Rotation velocity v(r) of spiral galaxies

(M. Kamionkowski, astro-ph/9809214)



implies 100x more mass than visible!



THE
BIG
BANG

INFLATION

COSMIC MICROWAVE
BACKGROUND
400,000 YEARS AFTER
BIG BANG

THE DARK AGES

FIRST STARS
400,000,000 YEARS
AFTER BIG BANG

FIRST GALAXIES
1000,000,000 YEARS
AFTER BIG BANG

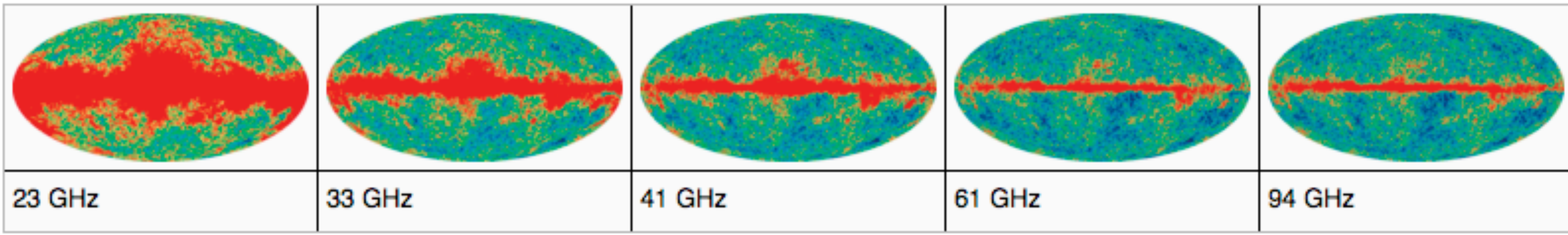
GALAXY EVOLUTION
CONTINUES...

DARK ENERGY ?

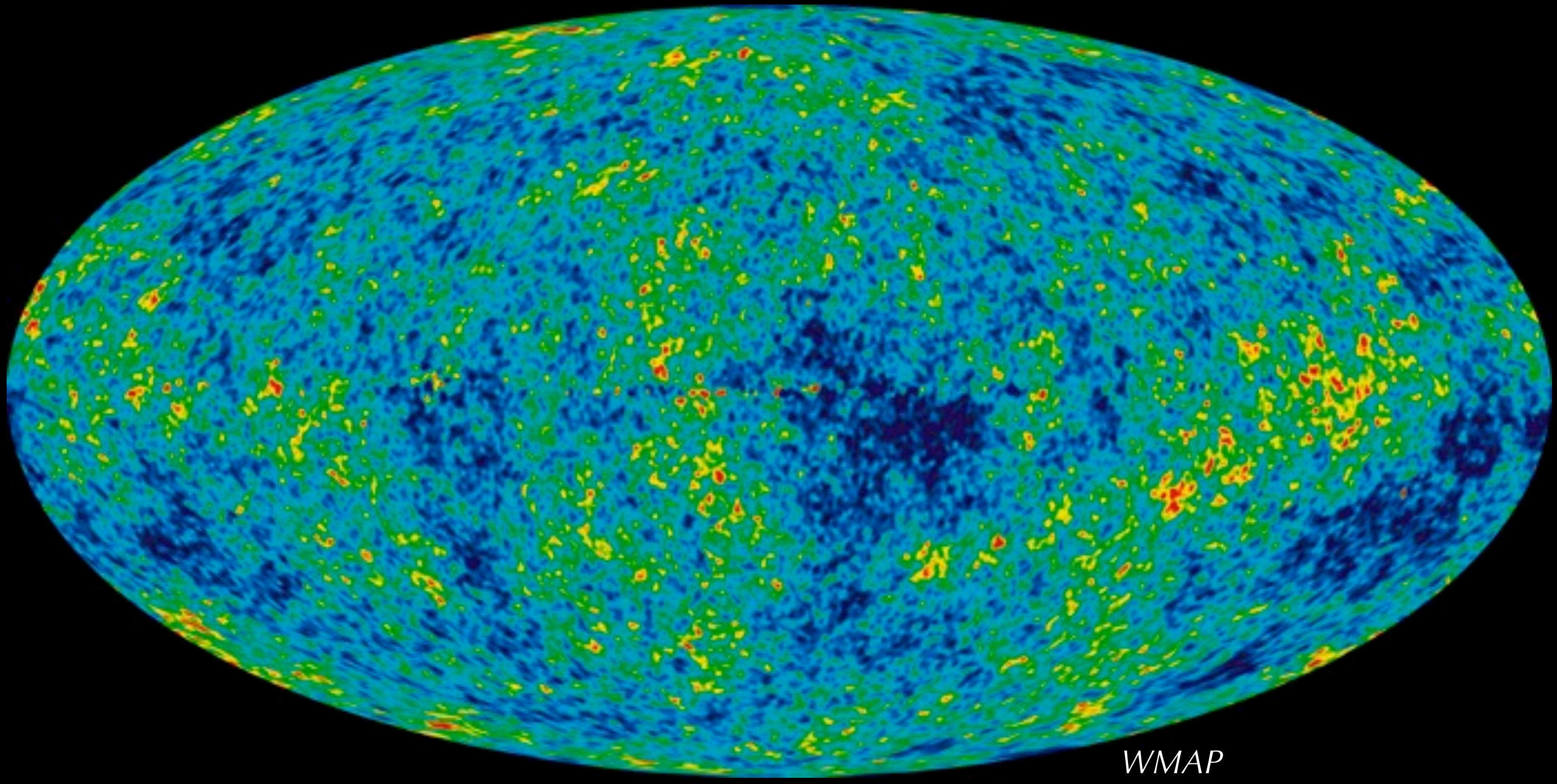
FORMATION OF
THE SOLAR SYSTEM
8,700,000,000 YEARS
AFTER BIG BANG

NOW
13,700,000,000 YEARS
AFTER BIG BANG

WMAP Cosmic Microwave Background



23 GHz 33 GHz 41 GHz 61 GHz 94 GHz

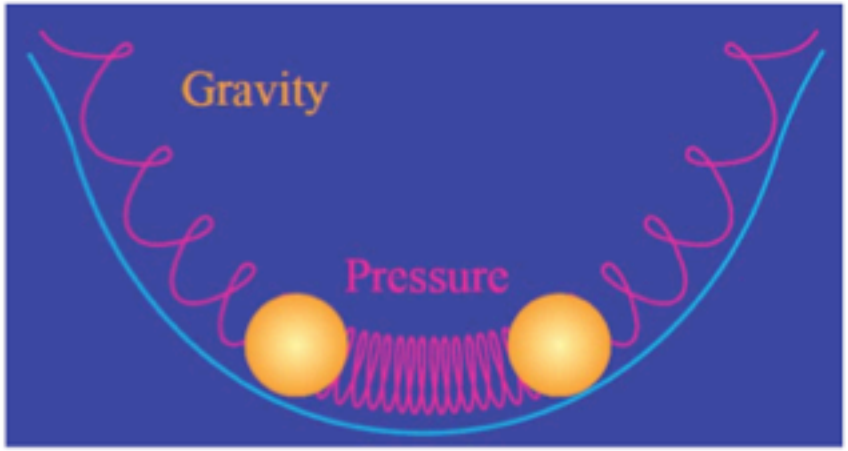


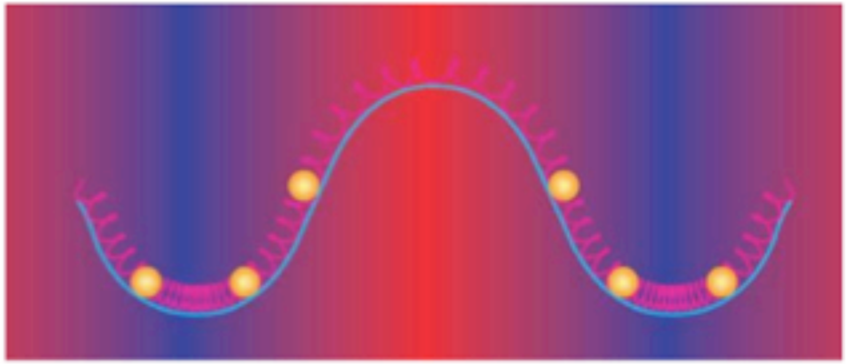
WMAP

CMB Acoustic Spectrum

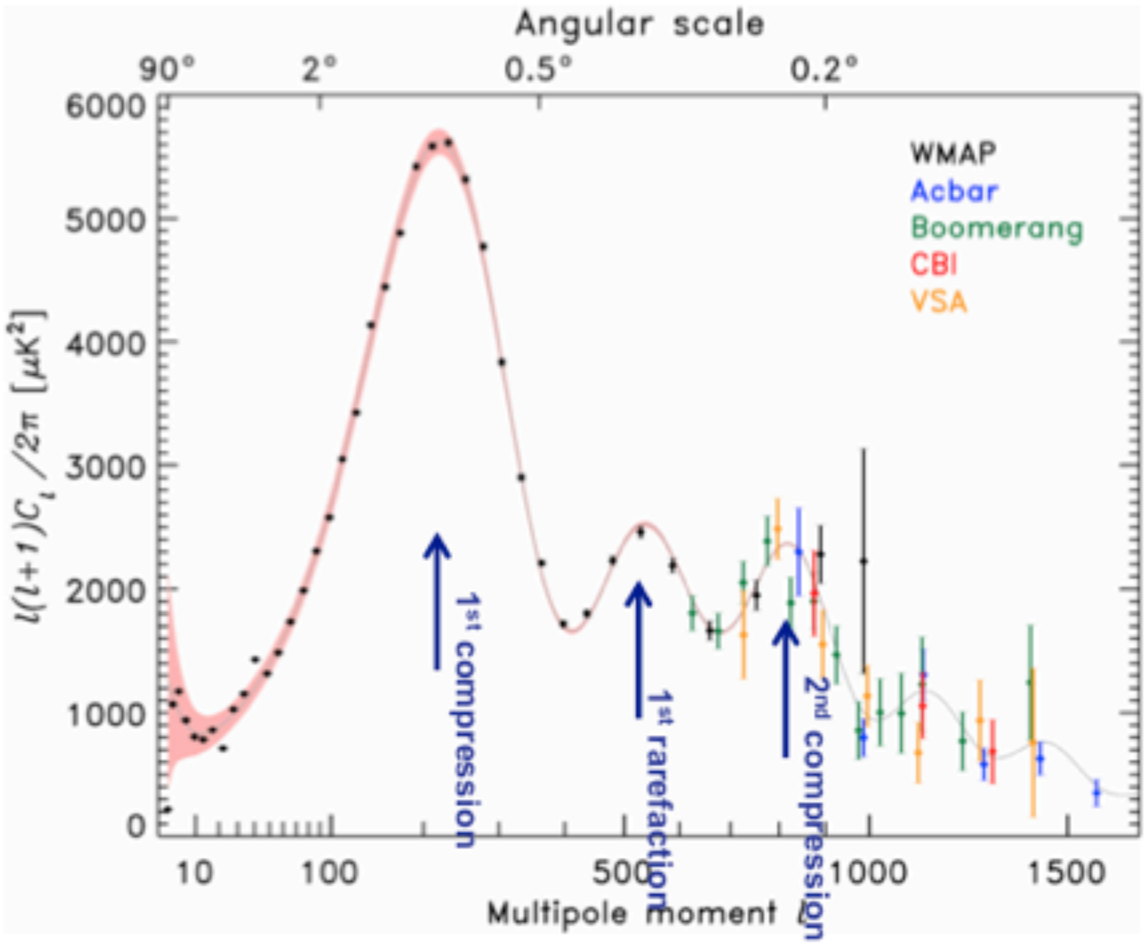
CMB “Baryometer”

From W. Wu (Chicago)



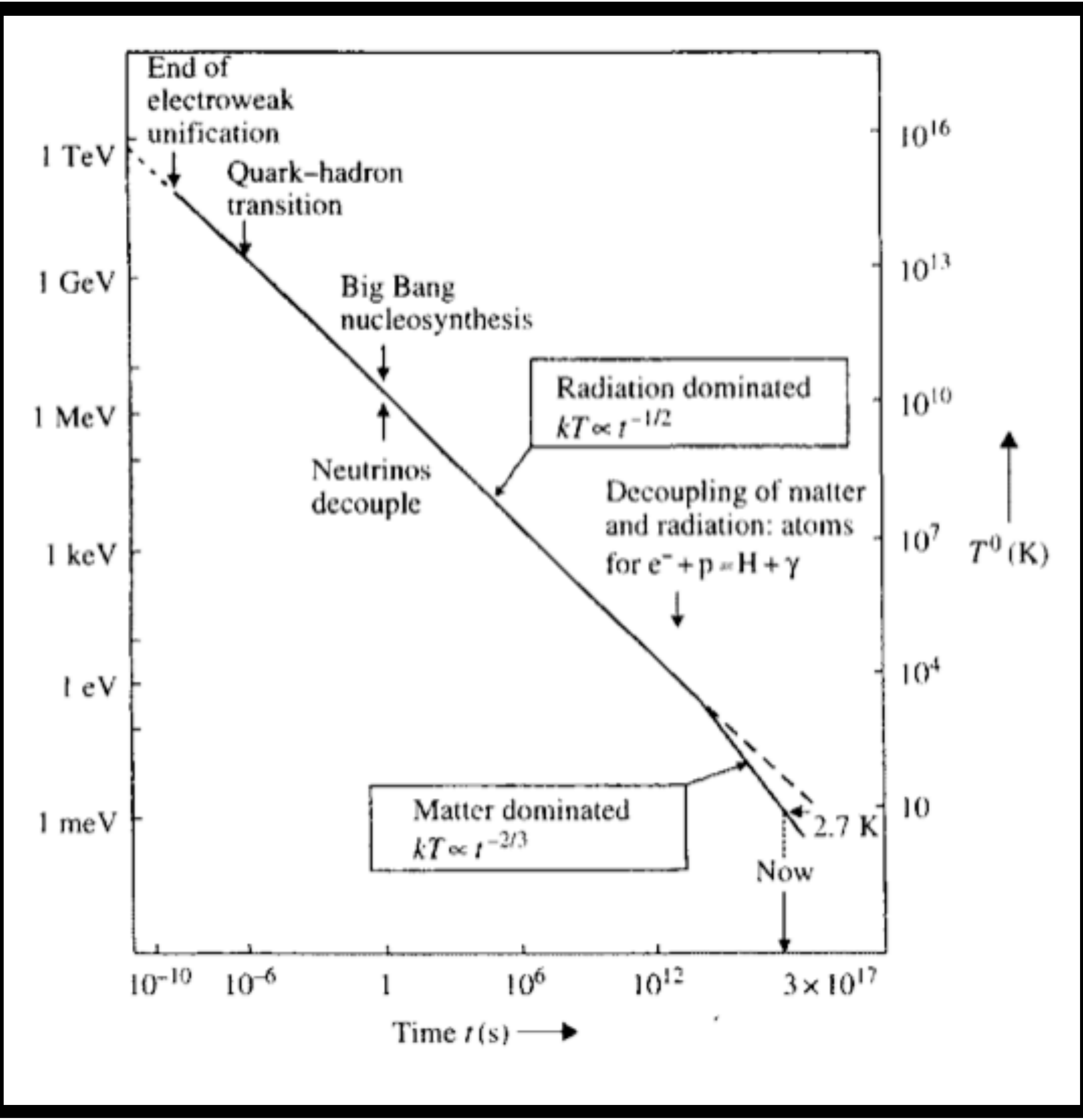


Baryon Acoustic Oscillations



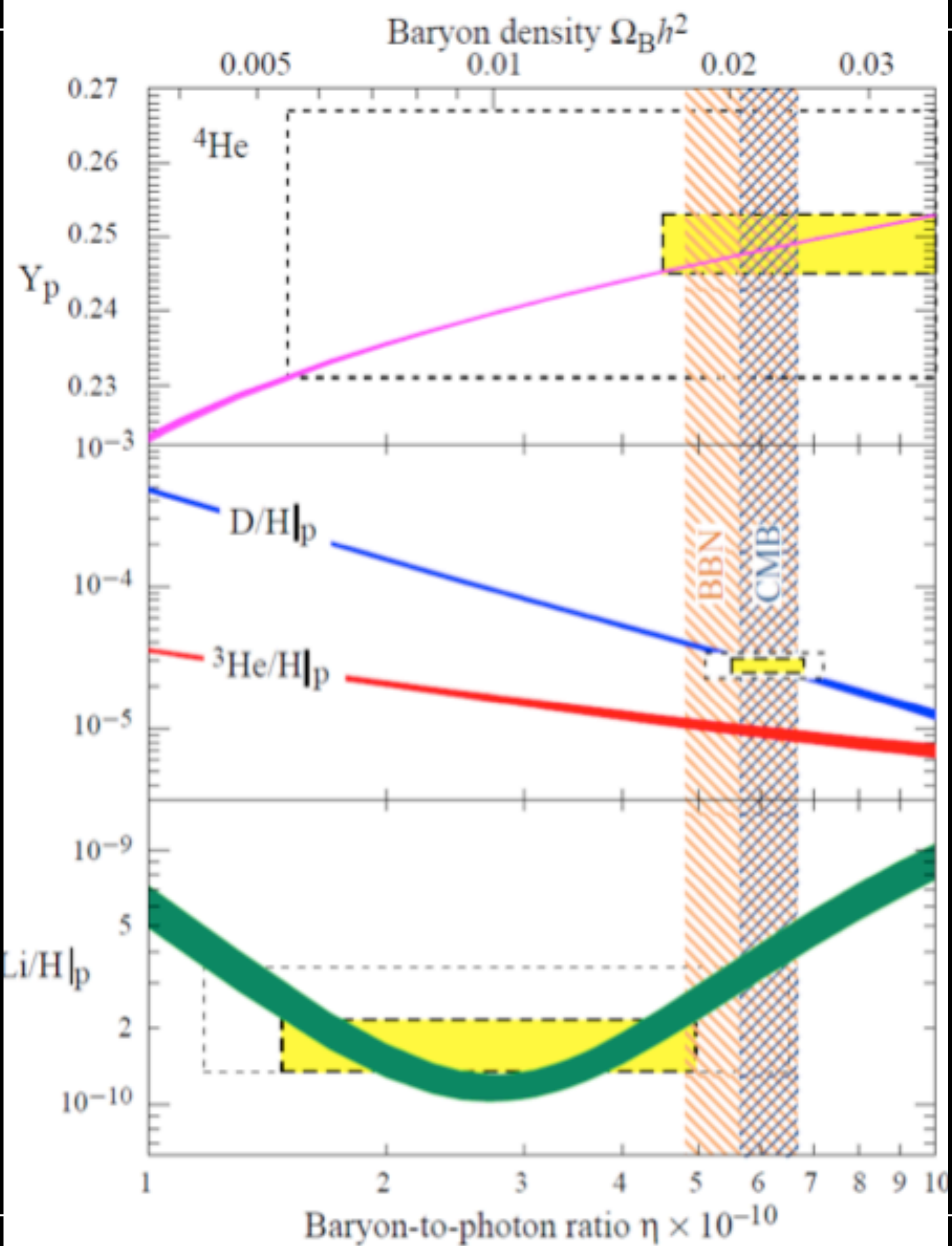
Baryons compress photon-baryon plasma at recombination, photons exert pressure, competition gives rise to pressure wave

BBN



D. H. Perkins, Particle Astrophysics (2004)

BBN

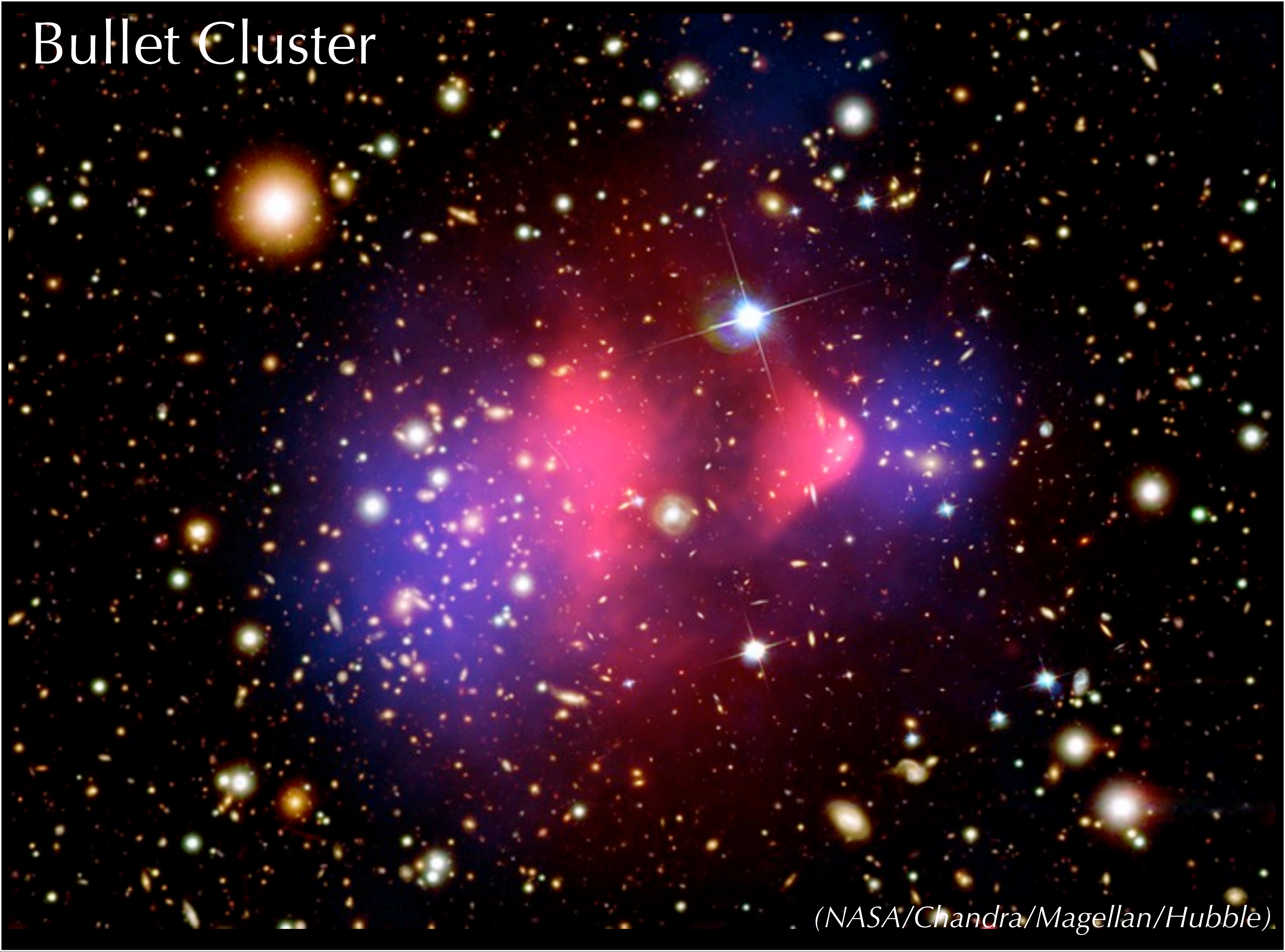


lines = predicted light element abundances vs. baryon density

boxes = observed abundances (1, 2 sigma)

vertical band = CMB measure of baryon density (PDG)

Bullet Cluster

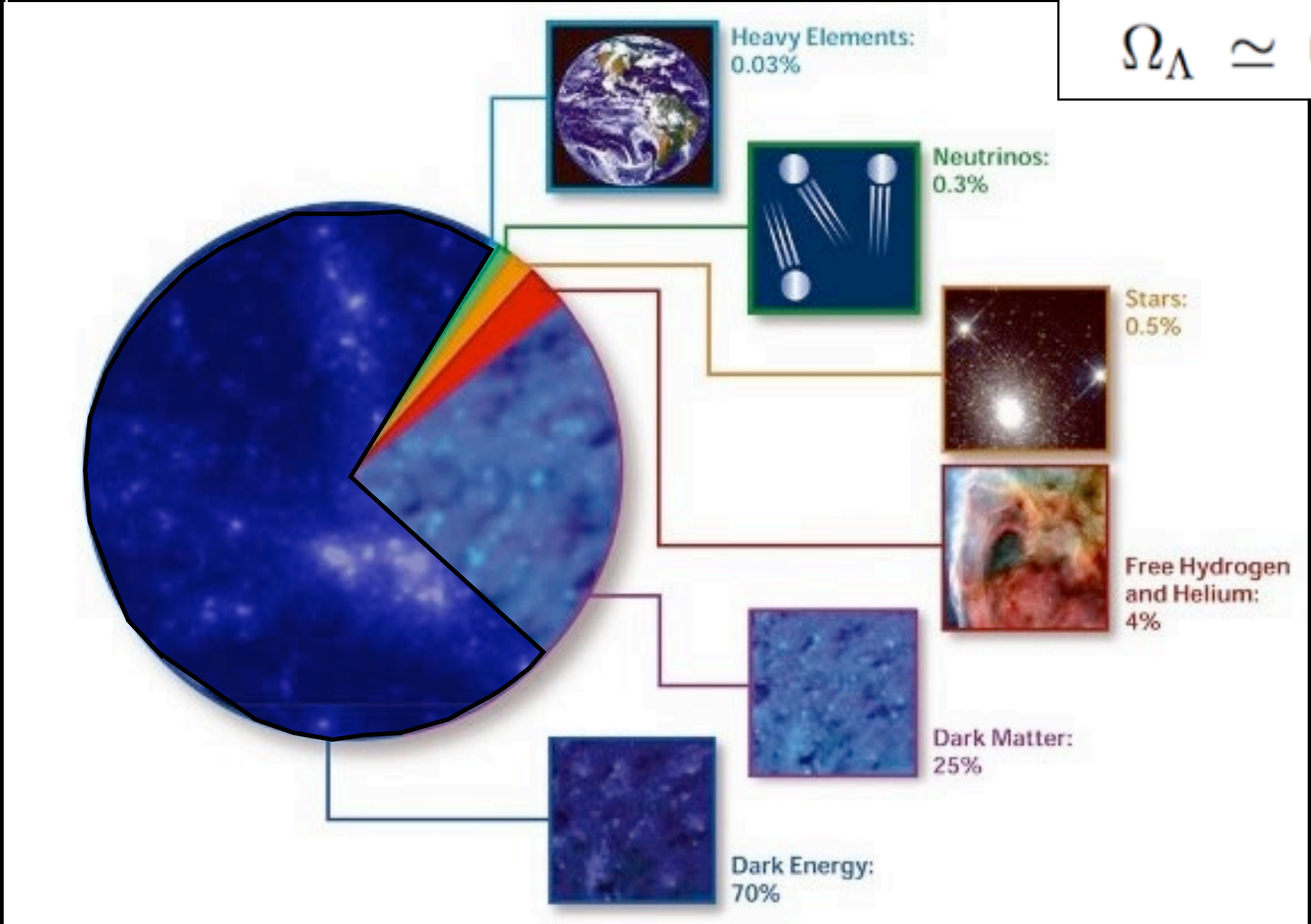


(NASA/Chandra/Magellan/Hubble)

The Standard Model of Cosmology

$$\Omega_B \simeq 0.0456 \pm 0.0016$$
$$\Omega_{DM} \simeq 0.227 \pm 0.014$$
$$\Omega_\Lambda \simeq 0.728 \pm 0.015\ .$$

E. Komatsu et al., Astrophys. J. Suppl 192 (2011) 18



Dark Matter is ~23% of the universe.

Dark Matter Candidates

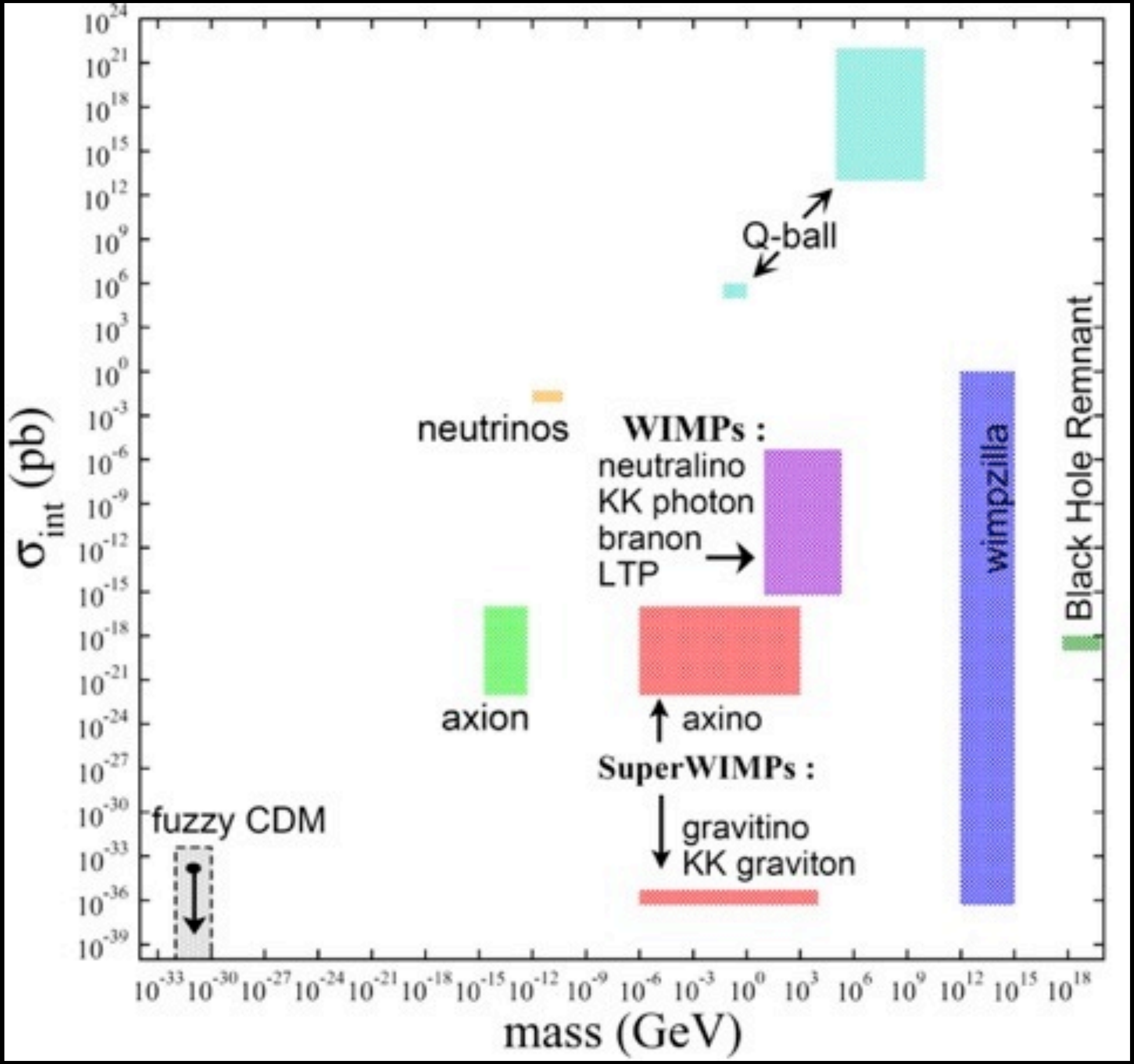
strong

e.m.

weak

gravity

interaction strengths



HEPAP/AAAC DMSAG Subpanel (2007)

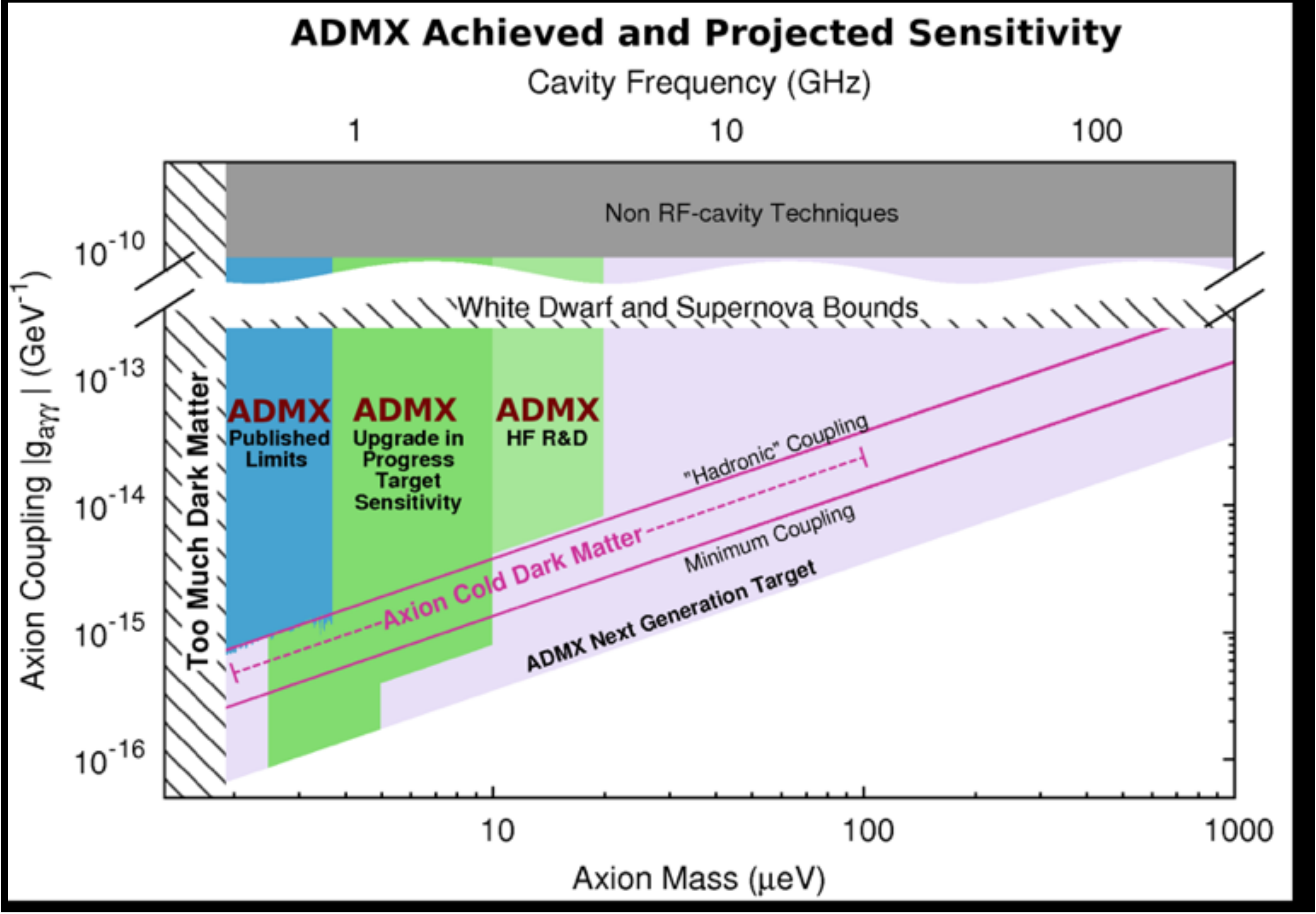
masses

neutrino?

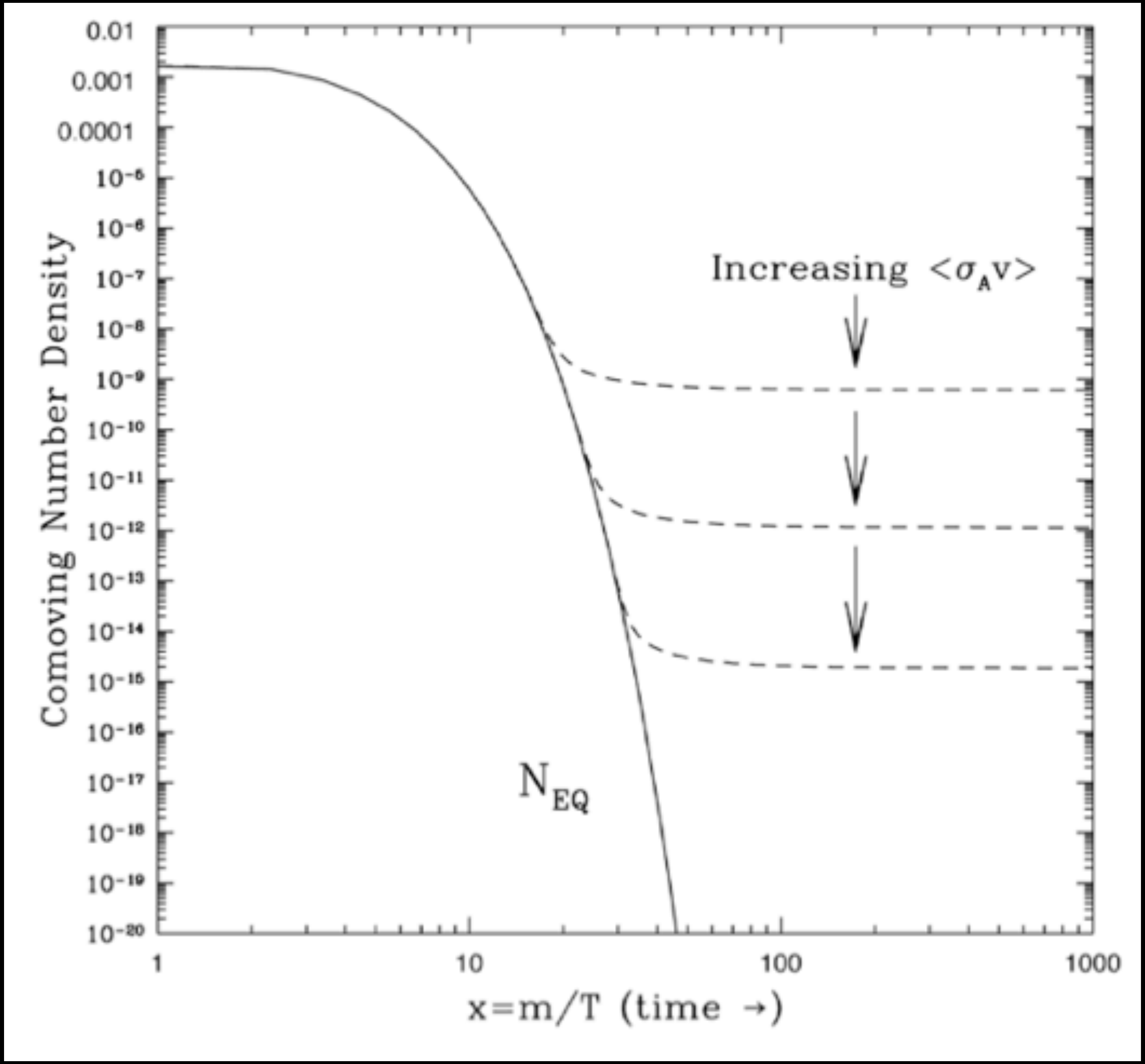
electron

t-quark

Axions


ADMX Achieved and Projected Sensitivity
Cavity Frequency (GHz)
1
10
100
Non RF-cavity Techniques
White Dwarf and Supernova Bounds
Too Much Dark Matter
ADMX Published Limits
ADMX Upgrade in Progress Target Sensitivity
ADMX HF R&D
"Hadronic" Coupling
Axion Cold Dark Matter
Minimum Coupling
ADMX Next Generation Target
Axion Coupling |$g_{a\gamma\gamma}$| (GeV^{-1})
10^{-10}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10
100
1000
Axion Mass (μeV)

WIMP Number Density



D. H. Perkins, Particle Astrophysics (2004)

WIMP Mass Range

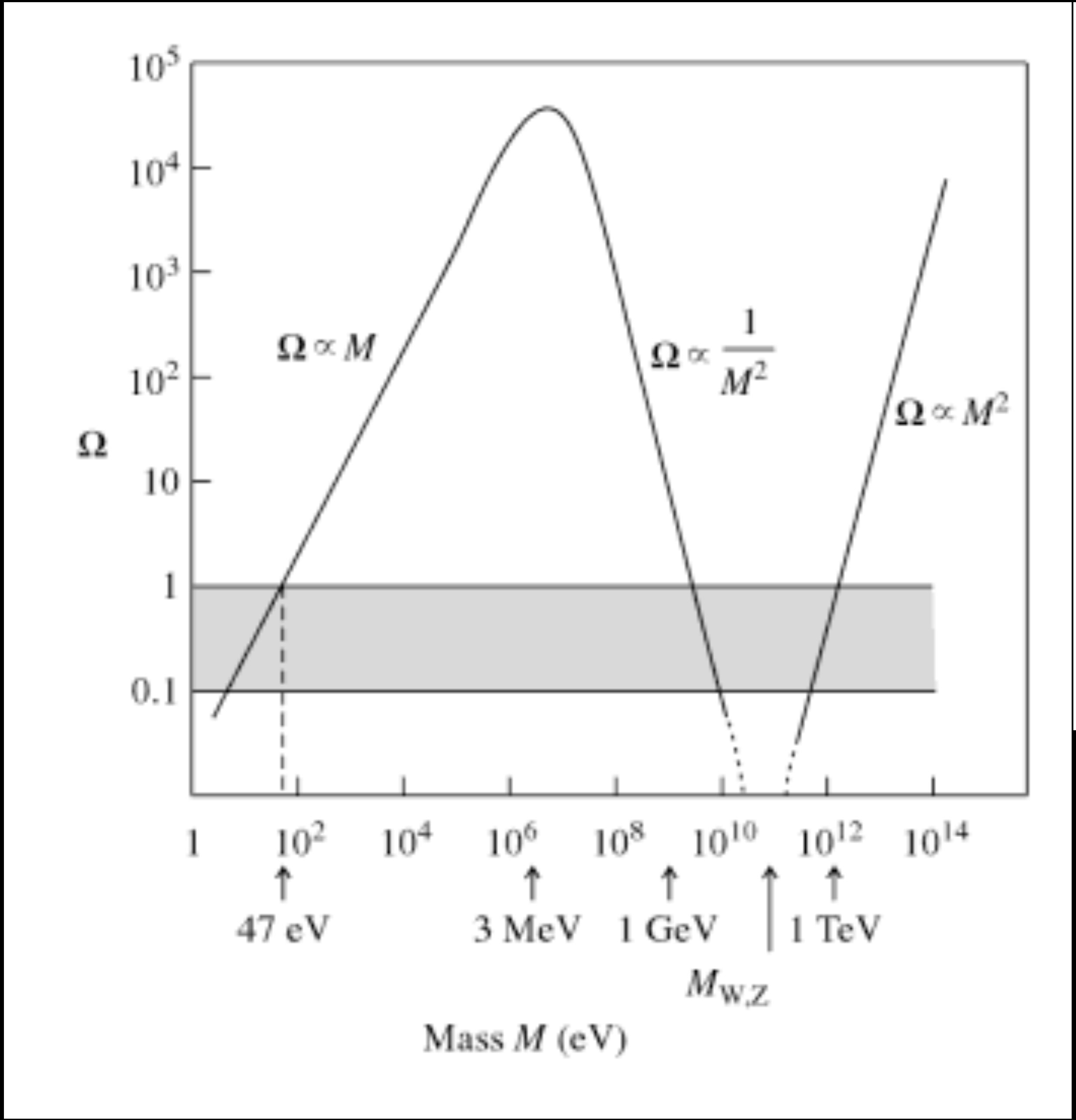
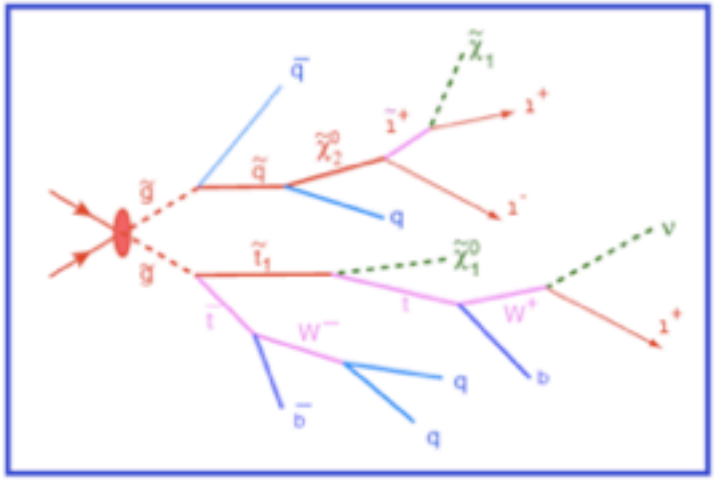


Fig. 7.11 Variation of the closure parameter with WIMP mass, assuming conventional weak coupling. The shaded region, corresponding to $\Omega = 0.1 - 1$, is that in which the contribution to the closure parameter from massive neutrinos or WIMPs must lie, thus excluding the range of masses 100 eV–3 GeV. Accelerator experiments suggest that WIMPs must have masses exceeding $M_Z/2 = 45\,\text{GeV}$, otherwise Z bosons could decay into WIMP–antiWIMP pairs. However, for masses which are large compared with the Z boson mass, the weak cross-section falls rapidly because of propagator effects, so that WIMPs in the TeV mass range are possible dark matter candidates, depending on the precise values of the WIMP coupling.

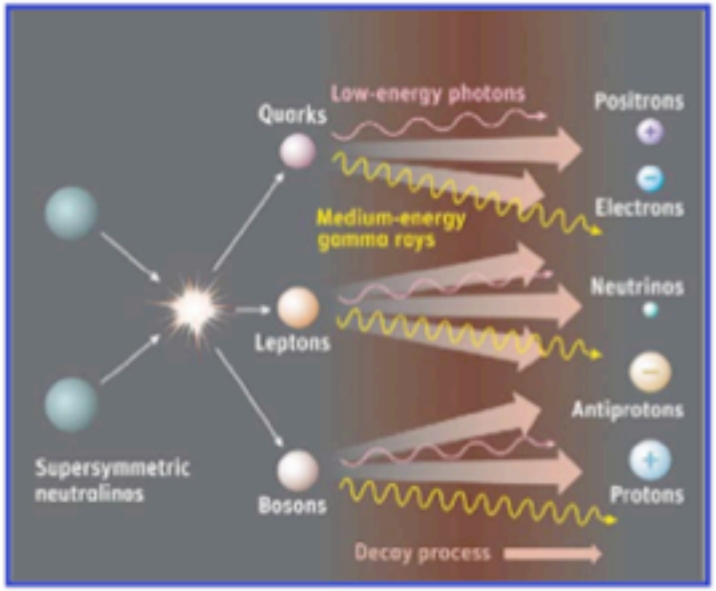
D. H. Perkins, Particle Astrophysics (2004)

Neutralino interactions

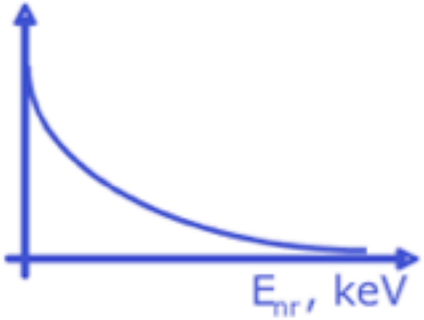
- Production
  - Accelerators such as LHC
  - Searches for missing E_T



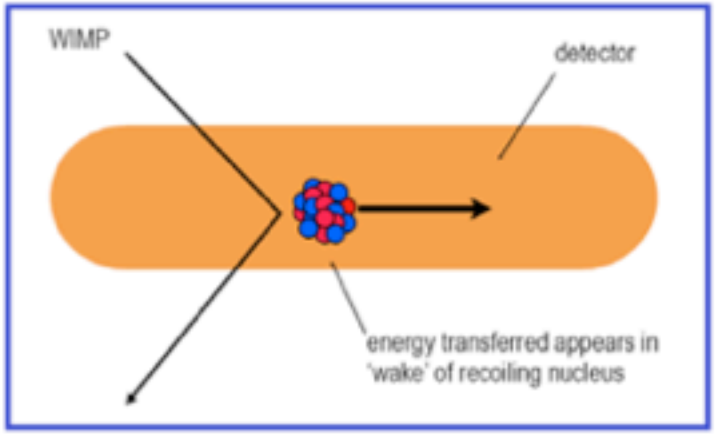
- Annihilation
  - into fermion pairs, photons, …
  - Indirect searches (FERMI, AMS,…)



- Elastic interaction
  - Spin-independent, $\sigma \sim A^2$
  - Spin-dependent, $\sigma \sim J/(J+1)$
  - Direct searches with terrestrial detectors



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



WIMP-Nucleon Scattering Event Rate

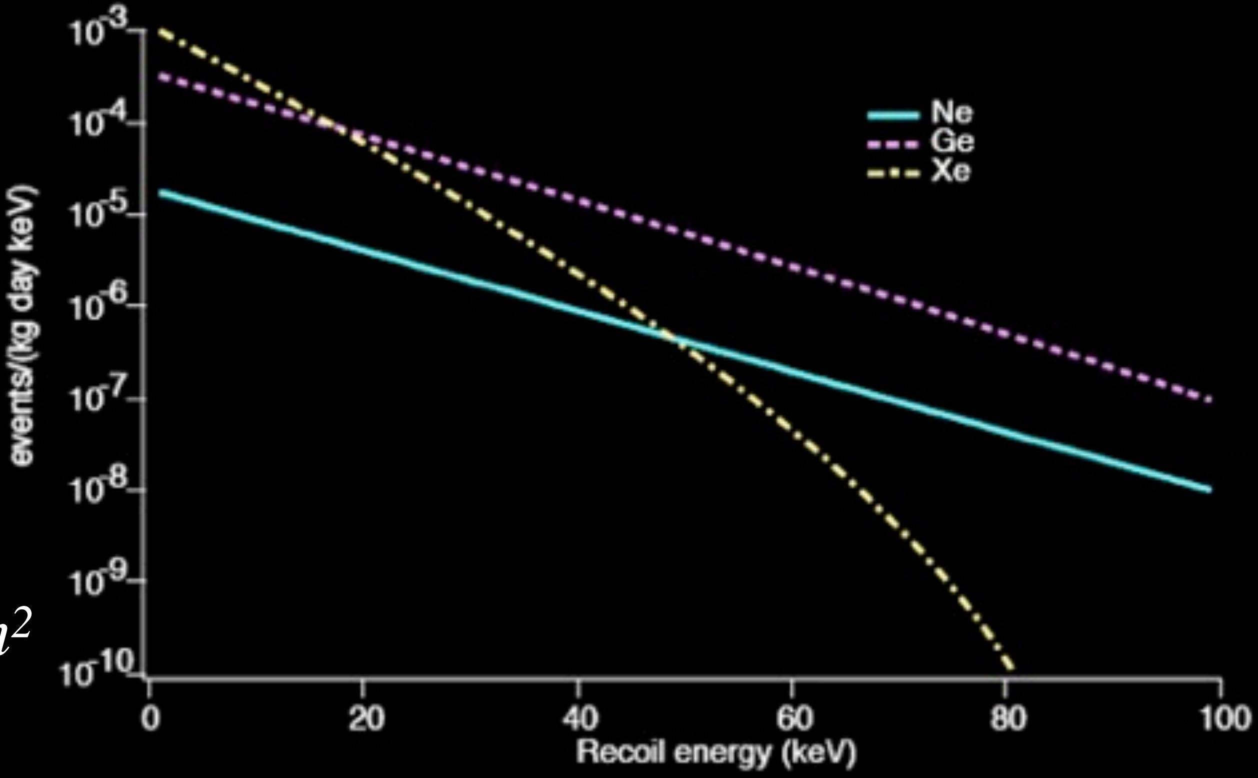
kinematics: *v/c ~ 1E-3!*

Spin Independent:
χ scatters coherently off of the entire nucleus A: $\sigma \sim A^2$
D. Z. Freedman, PRD 9, 1389 (1974)

Spin Dependent:
only unpaired nucleons contribute to scattering amplitude: $\sigma \sim J(J+1)$

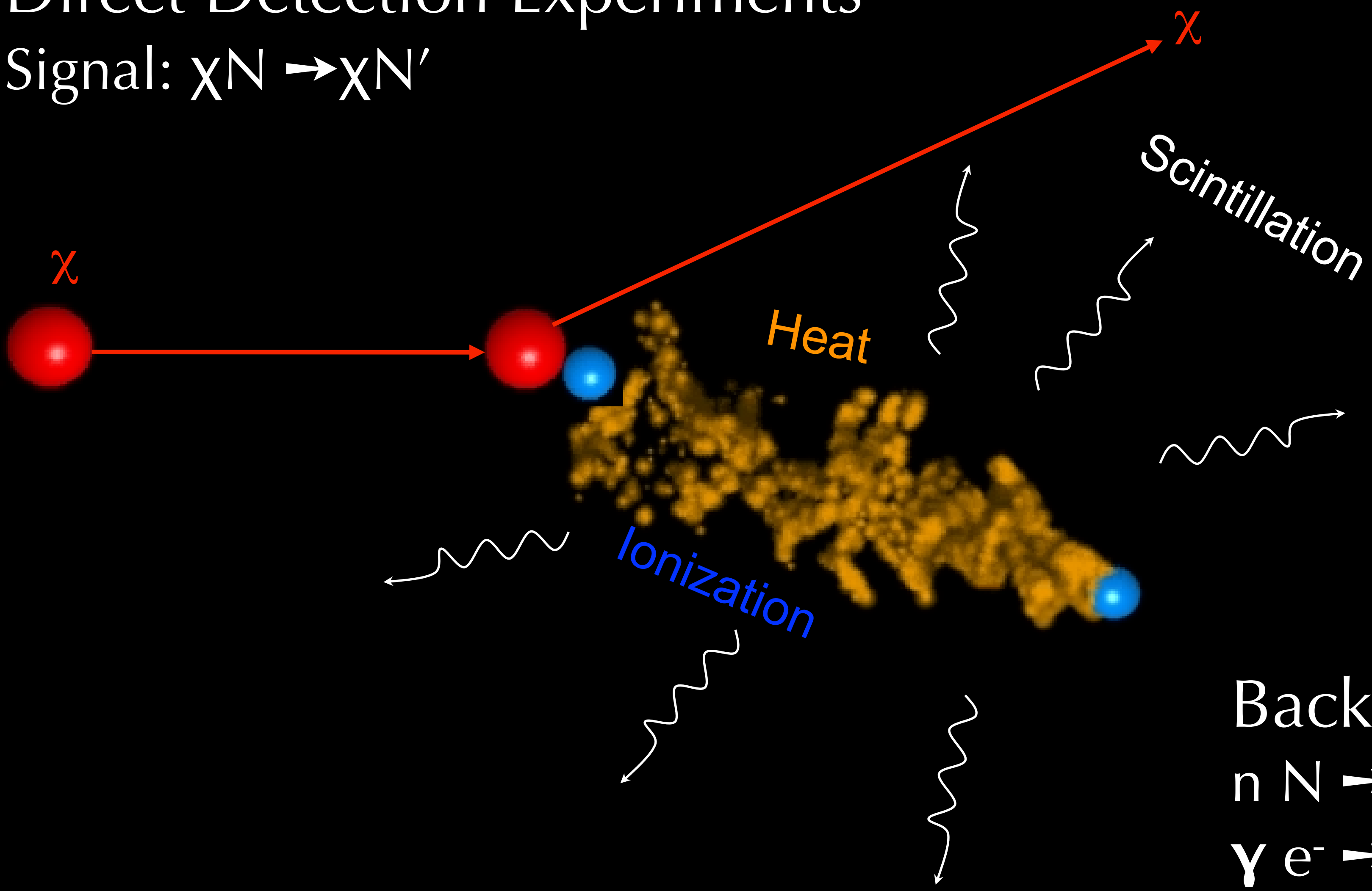
$M_\chi = 100$ GeV

$\sigma_{SI} = 1E\text{-}44\ \mathrm{cm}^2$



Direct Detection Experiments

Signal: $\chi N \rightarrow \chi N'$



Backgrounds:

$n\ N \rightarrow n\ N'$

$\gamma\ e^- \rightarrow \gamma\ e^{-\prime}$

$N \rightarrow N' + \alpha,\ e^-$

$\nu\ N \rightarrow \nu\ N'$

DRIFT

IGEX

Picasso

WARP

Newage

ArDM

COUPP

CDMS

ZeplinIII

Edelweiss

Xenon100

LUX

CoGeNT

DMTPC

ANaIS

DEAP/CLEAN

XMASS

KIMS

CRESST

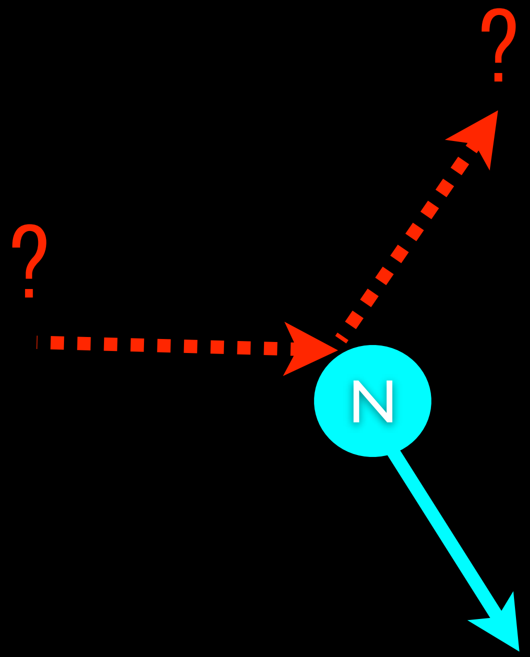
Dama/LIBRA

CRESSTII

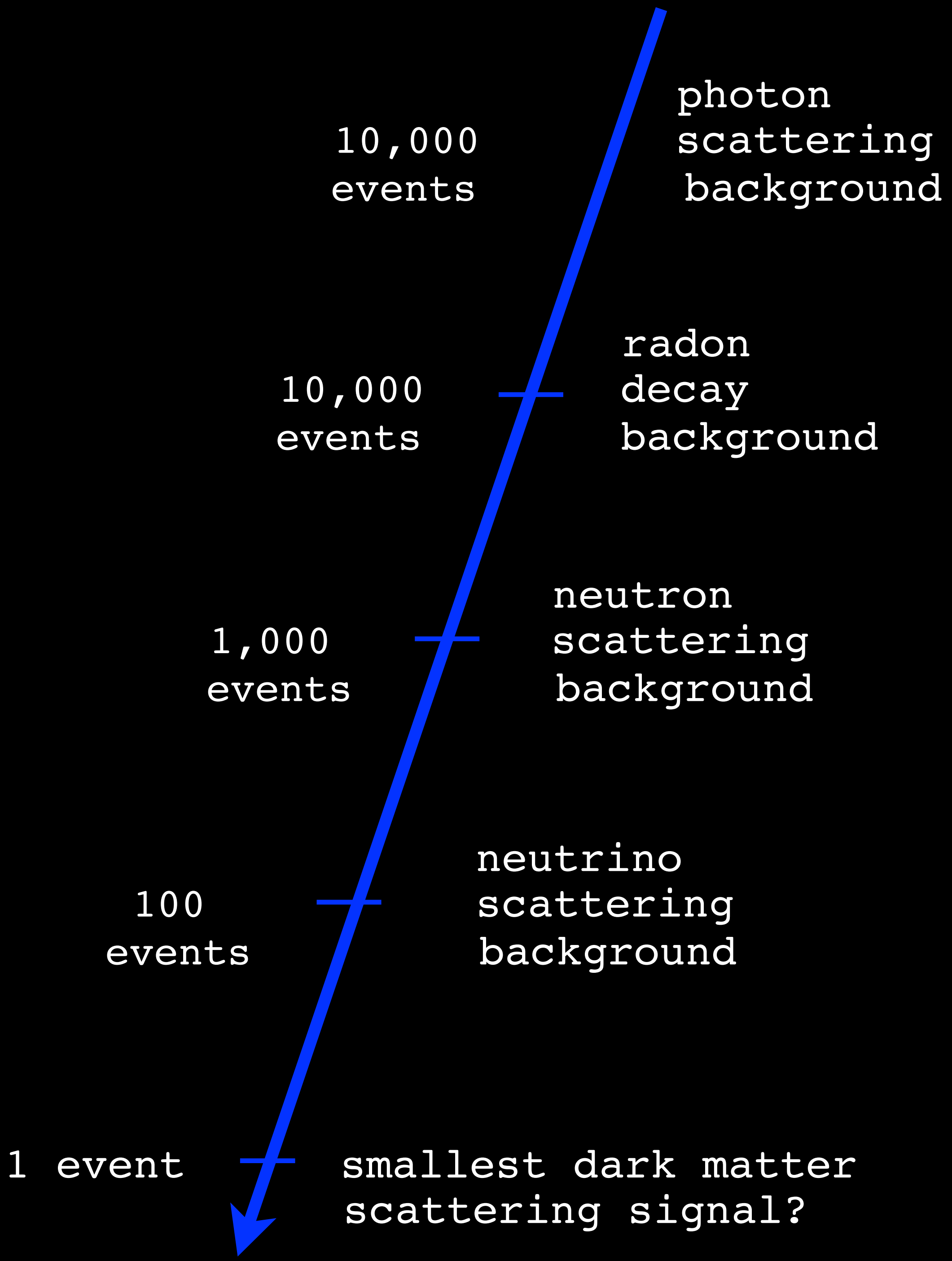
ROSEBUD

Backgrounds

In dark matter experiments…



Anything else that does this can fake a dark matter signal!



10,000 events — photon scattering background

10,000 events — radon decay background

1,000 events — neutron scattering background

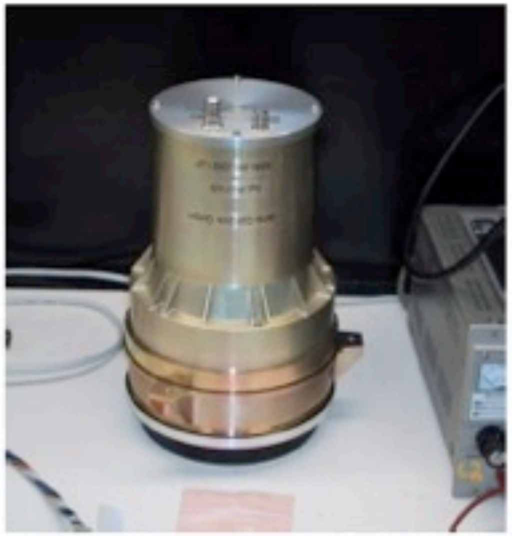
100 events — neutrino scattering background

1 event — smallest dark matter scattering signal?

EM Backgrounds

(D. McKinsey)

Geiger counter



Sodium iodide crystal

Germanium

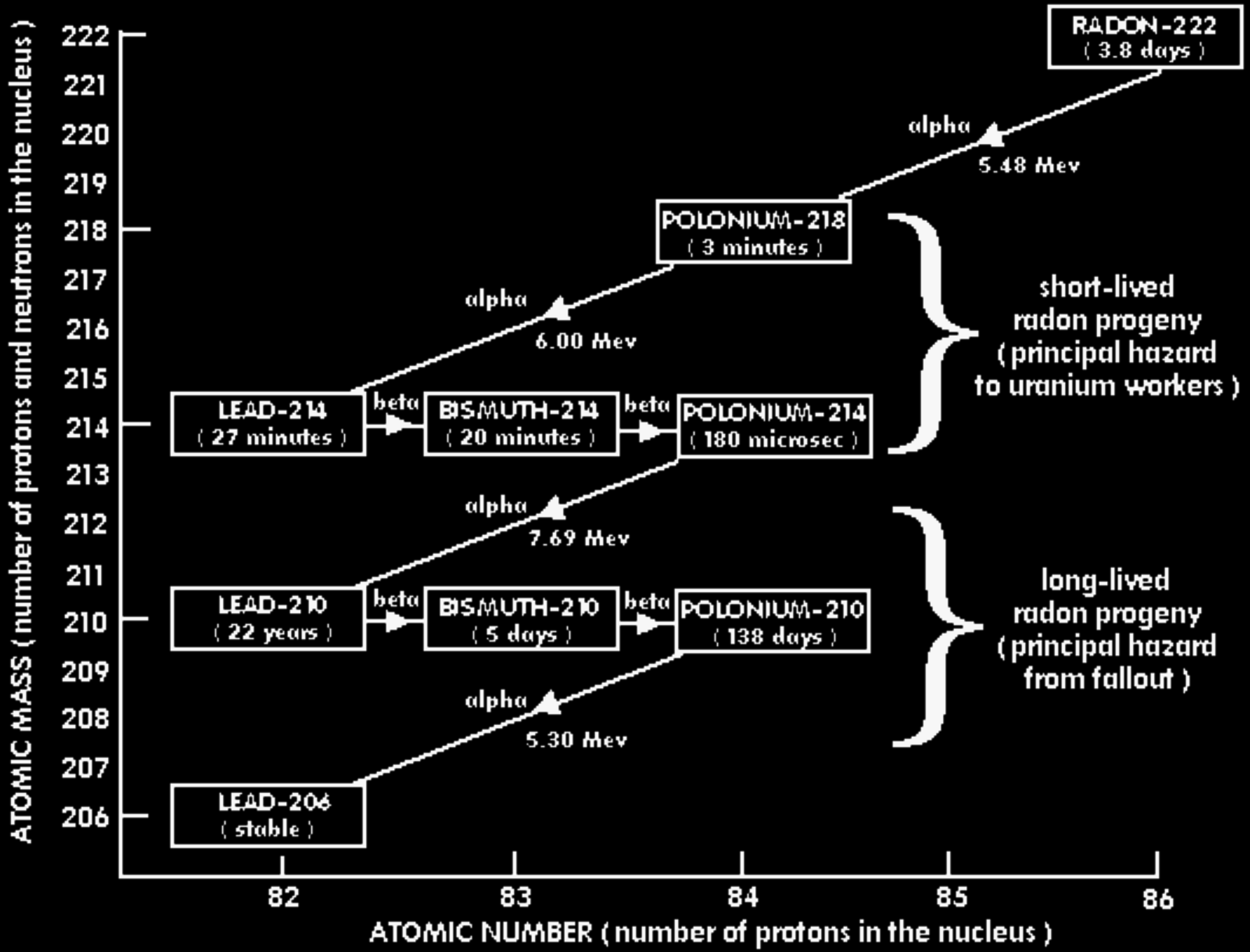
Gamma ray interaction rate is proportional to
(# of electrons in detector) x (gamma ray flux)

Typical count rate = 100 events/s/kg = 10,000,000 events/day/kg
in a good lead shield, rate drops to 100 events/day/kg

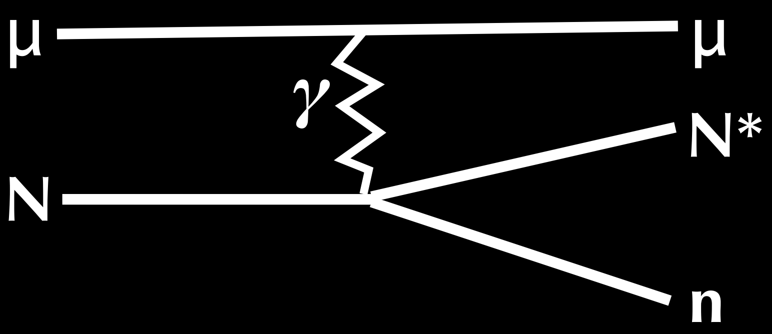
Best dark matter detectors: sensitive to **0.01 events/day/kg**
(σ~1E-44 cm^2)

U and Th Decay Backgrounds

can't shield a detector from U and Th inside, recoiling progeny and associated betas can fake nuclear recoils



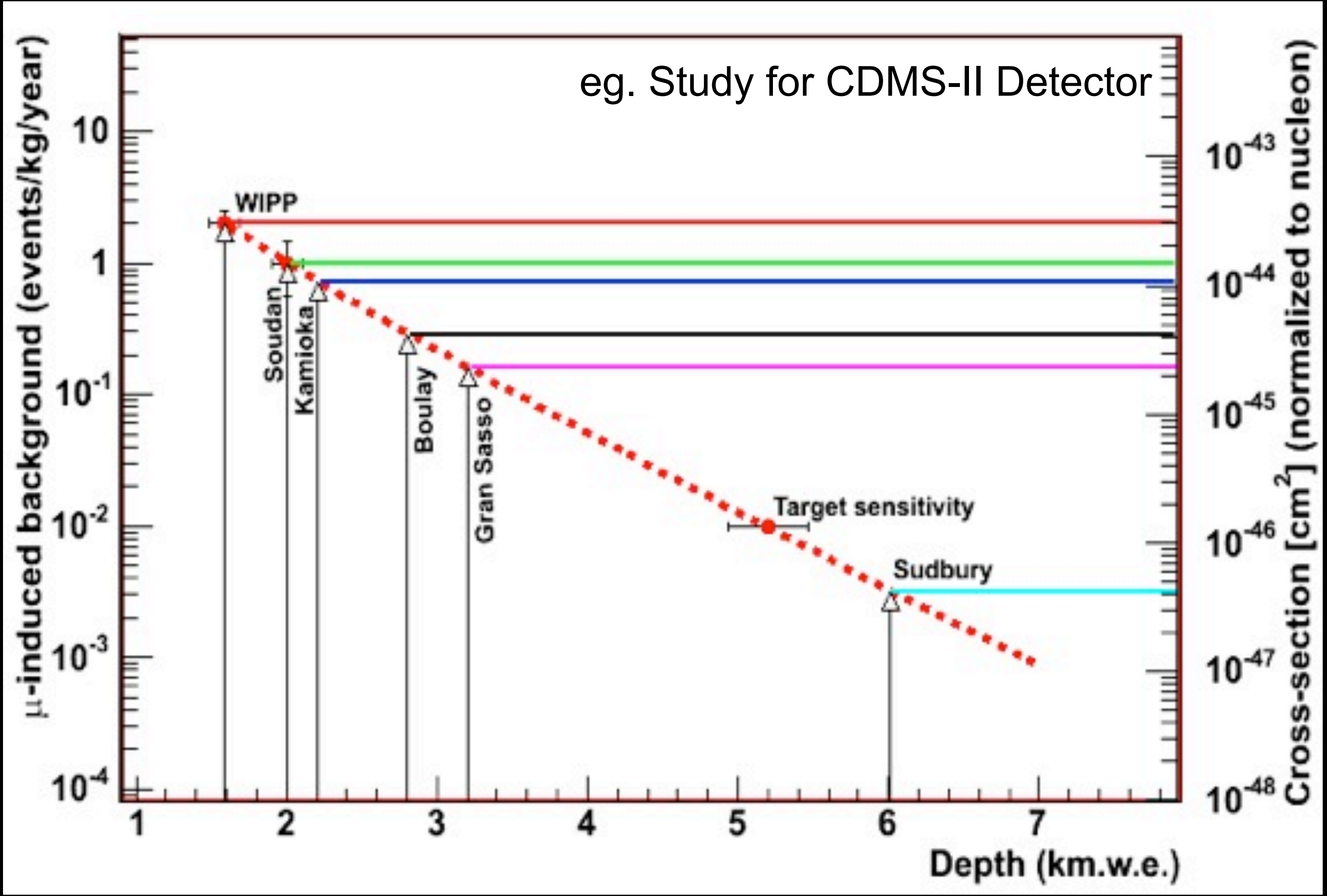
Neutron Backgrounds



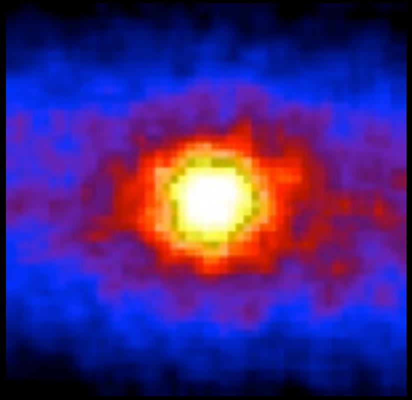
Cosmic muons spall neutrons: ~10^{-4} neutrons/(100 GeV μ)/gm/cm^2

neutron flux: 10^{-8} - 10^{-10}/cm^2/s (range for depth)

D.-M. Mei, A. Hime, PRD73:053004 (2006)

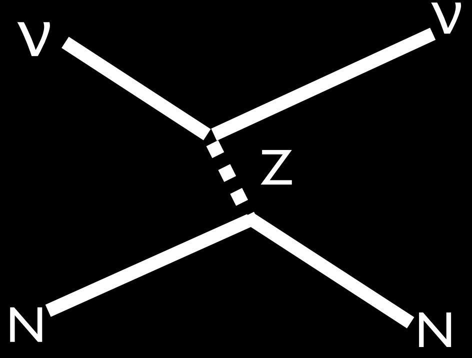


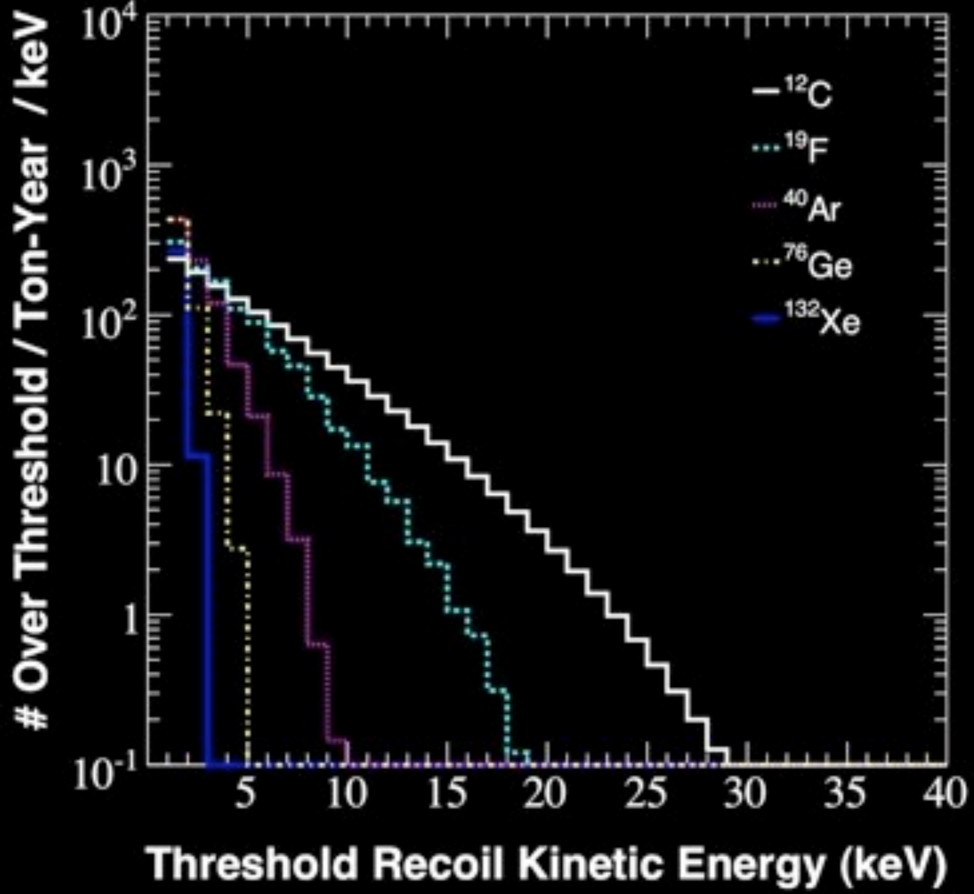
ν Backgrounds



can't shield a detector from coherent elastic scattering of solar neutrinos

$\Phi_{(B^8)} = 5.86 \times 10^6\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$



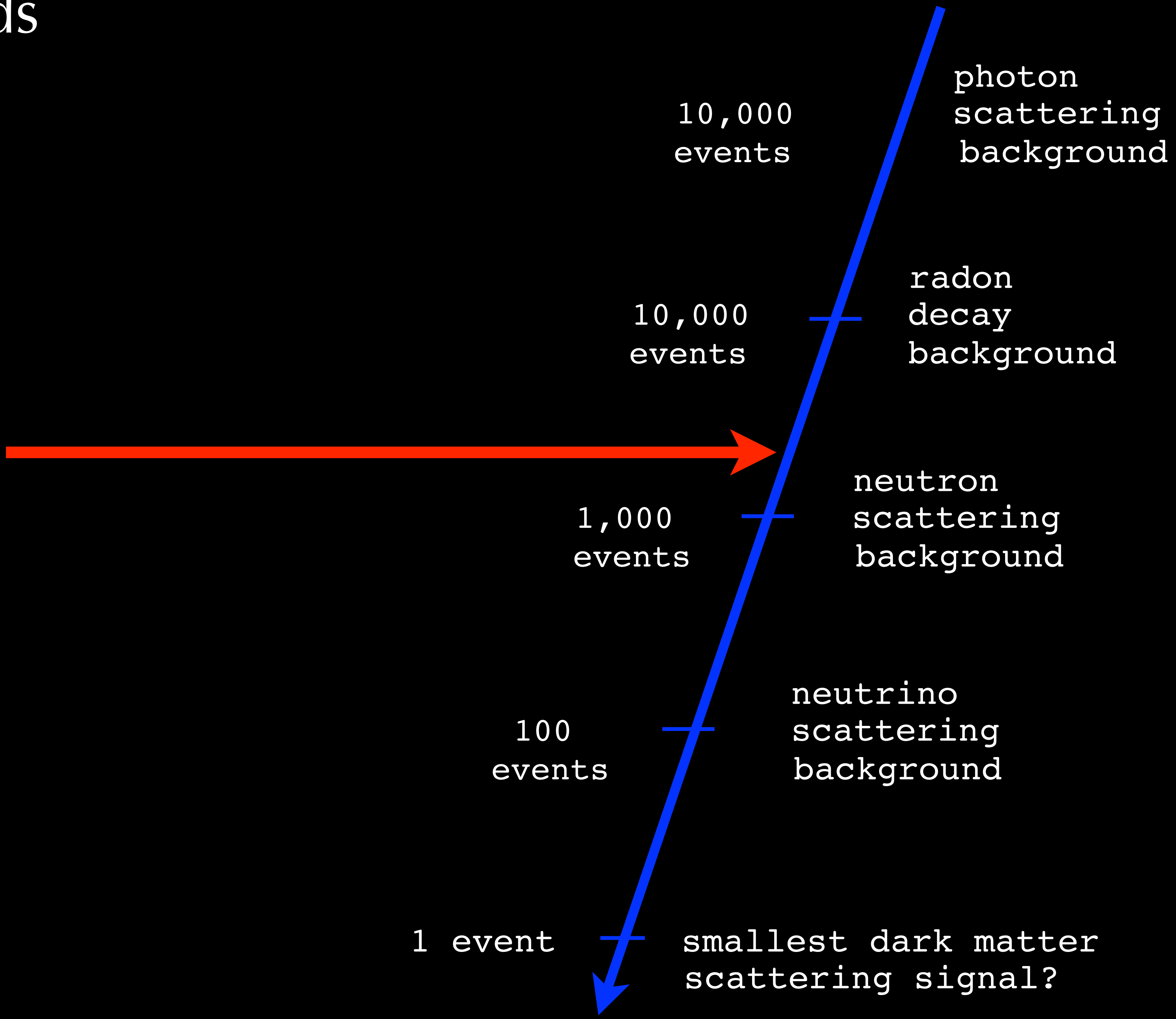


100 events/ton-year =
~ 10^{-46} cm^2 limit

unless you measure
the direction!

JM, P. Fisher, PRD76:033007 (2007)

Backgrounds



10,000
events

photon
scattering
background

10,000
events

radon
decay
background

the best experiments are here

1,000
events

neutron
scattering
background

100
events

neutrino
scattering
background

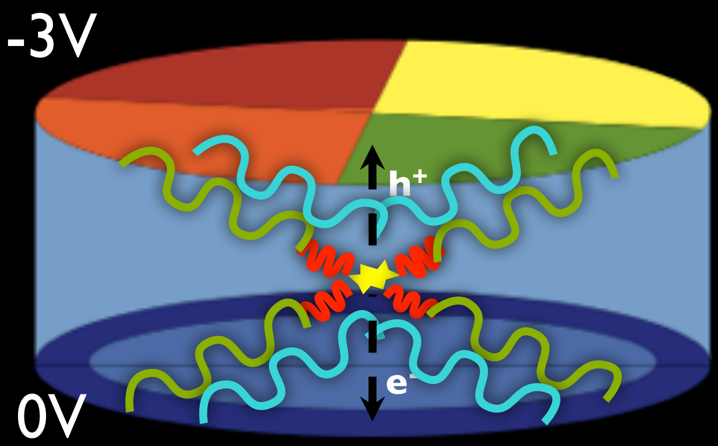
1 event

smallest dark matter
scattering signal?

CDMS

(material thanks to E. Figuroa)

Phonon side: 4 quadrants of phonon sensors for energy & position (timing)



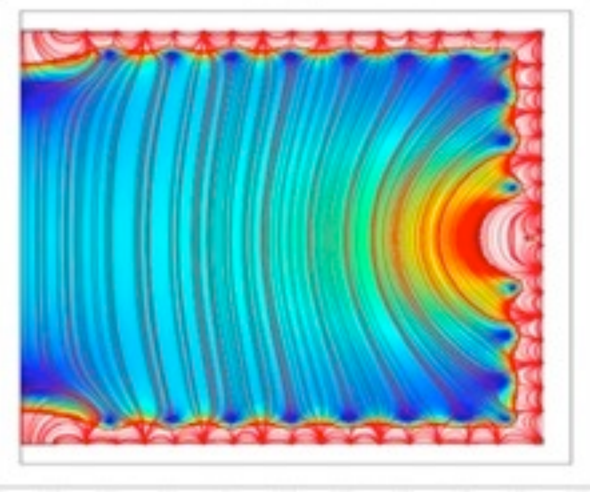
Charge side: 2 concentric electrodes (inner & outer) energy (& veto)

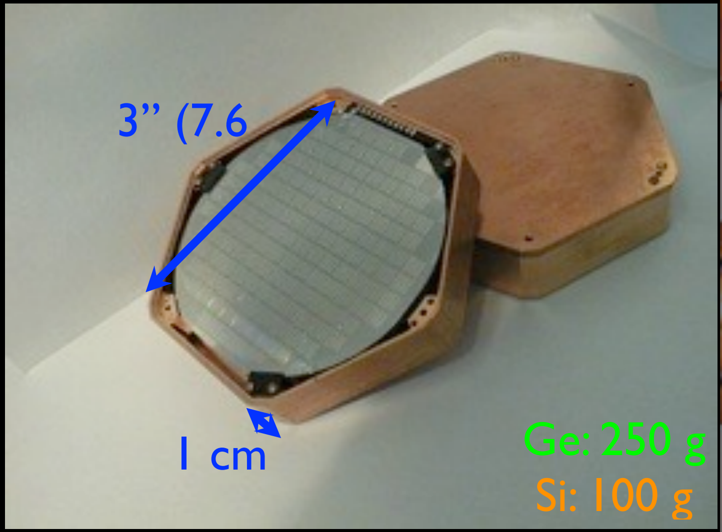
Transition Edge Sensors, operated at ~40 mK on Ge and Si crystals, in Soudan

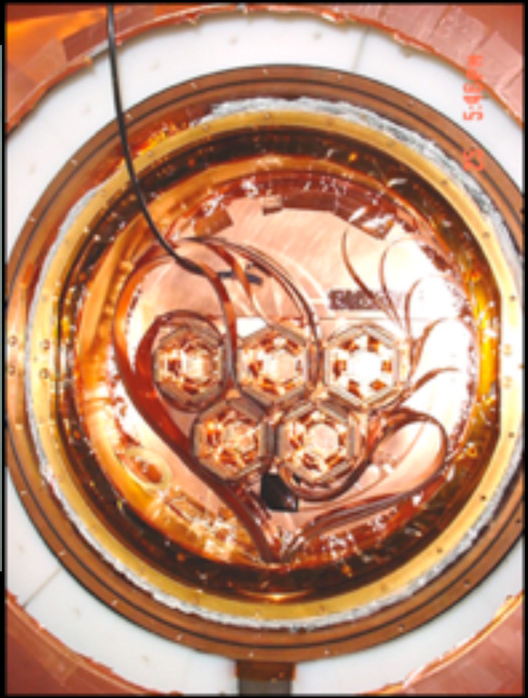
arXiv:0907.1438v1

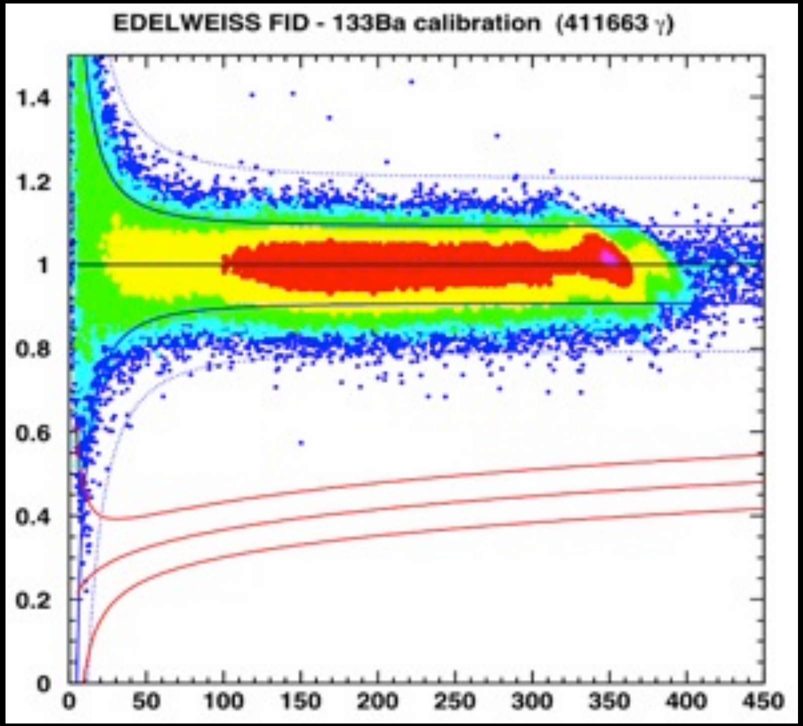
arXiv:0912.3592v1

Detector re-design a la EDELWEISS to reduce surface backgrounds x10^4





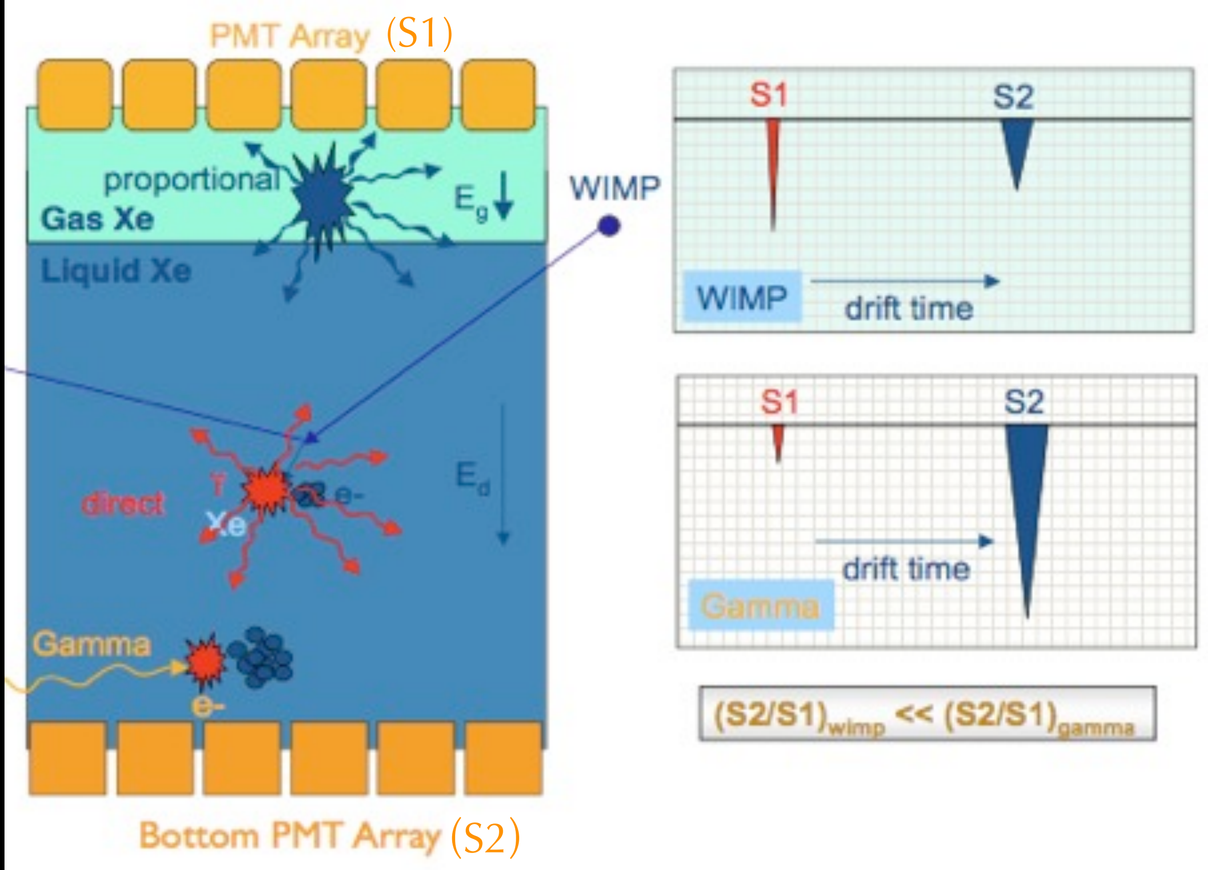


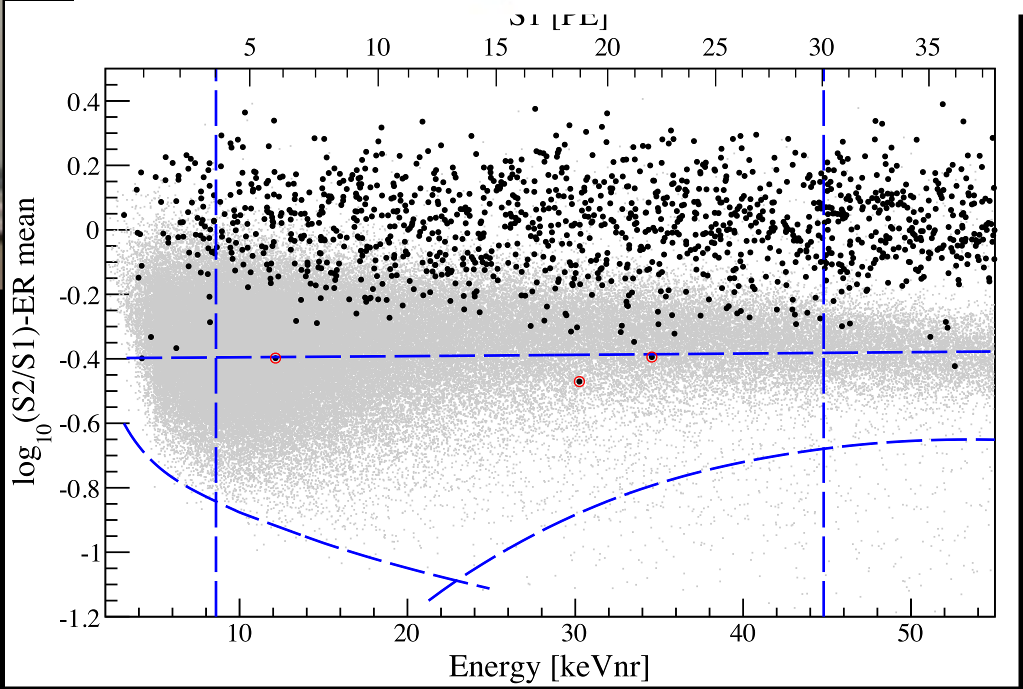


Ionization/Phonon yield vs. E_{recoil} (keV)

Xenon100

Two-Phase liquid Xenon TPC,
operated in LNGS





(E. Aprile)

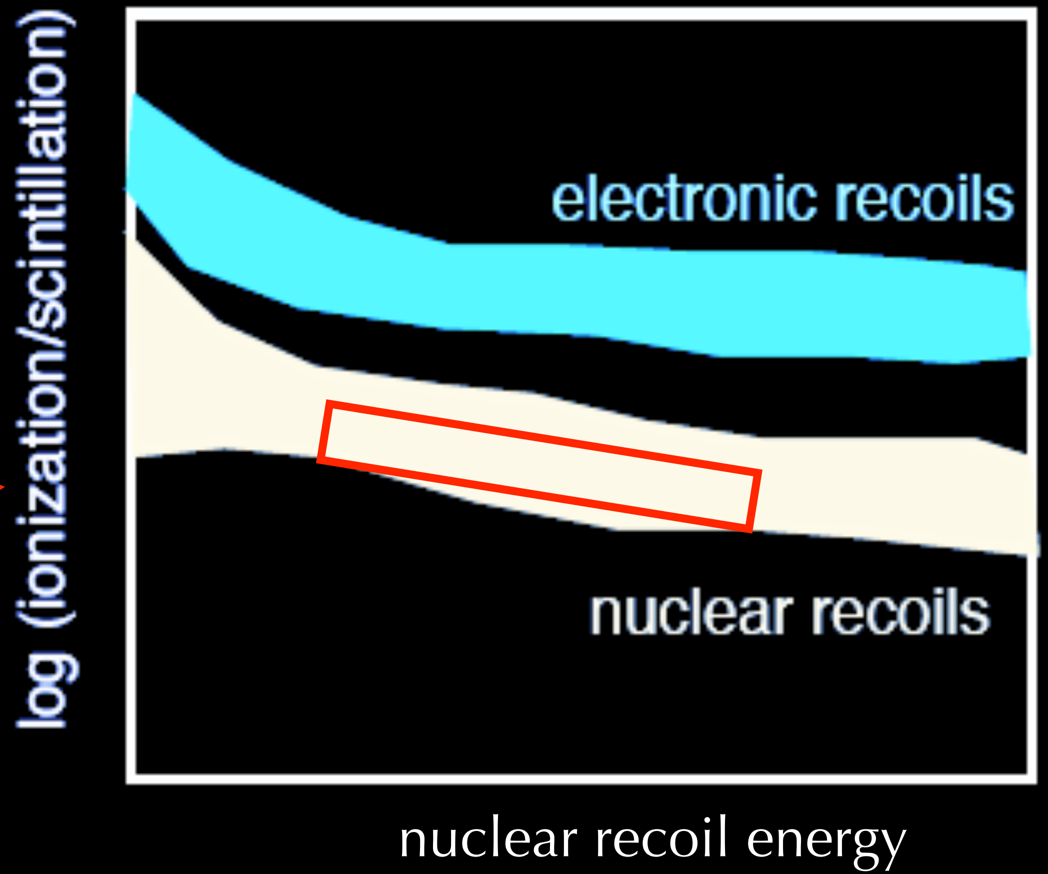
arXiv: 1104.2549v2

"S2": primary scintillation
"S1": amplified, drifted
ionization signal
both read out with PMTs

Experimental Procedure

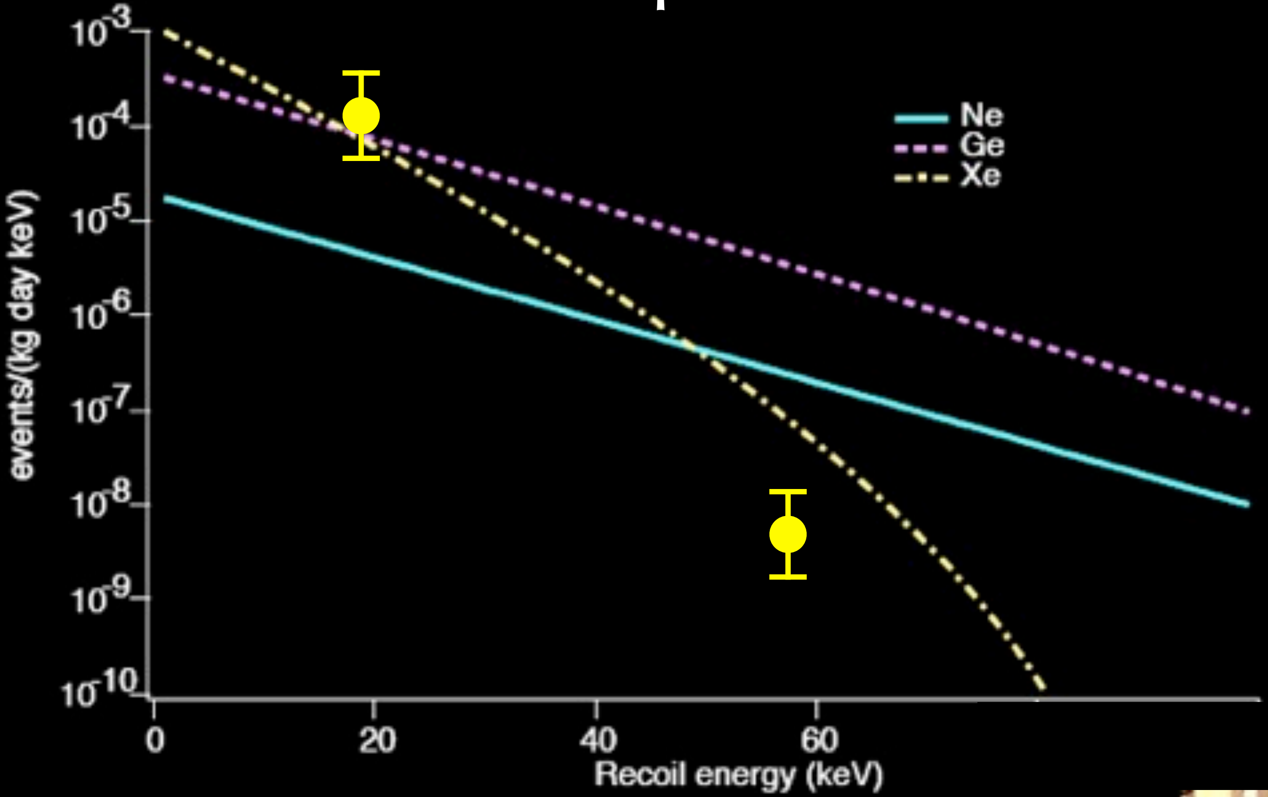
1. using calibration data,
define background
and signal regions

2. using calibration data,
define a region
with zero expected
background events



(*any events* in the blind region are signal candidates)

Experimental Procedure



theorist:

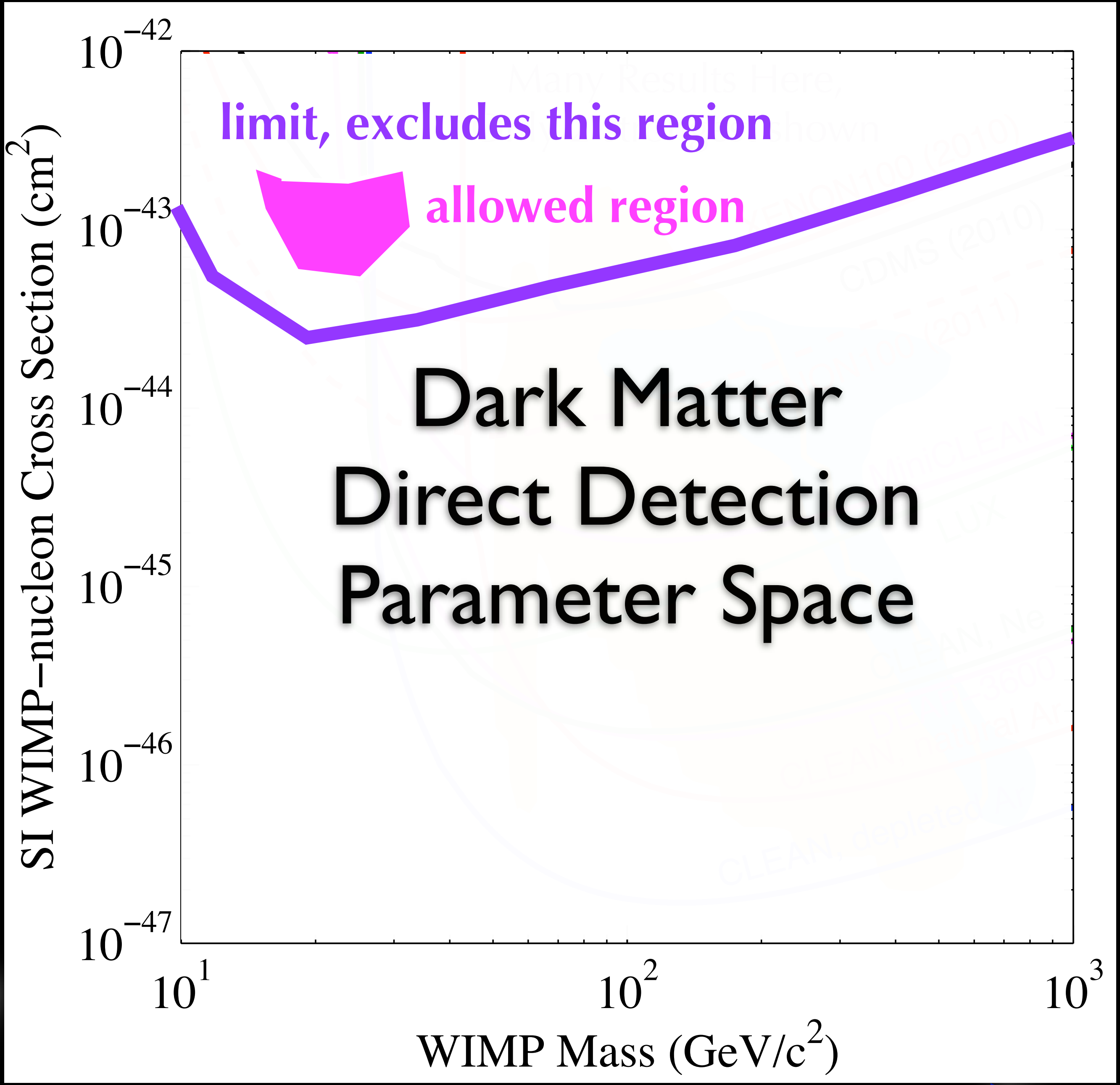
what model explains this rate?

experimentalist:

see a signal or set a limit?

The Low Background Frontier

Scalability of Detector Technology



Dark Matter Direct Detection Parameter Space

← 1 event/ kg/day

← 1 event/ 100 kg/day

← 1 event/ 100 kg/ 100 days

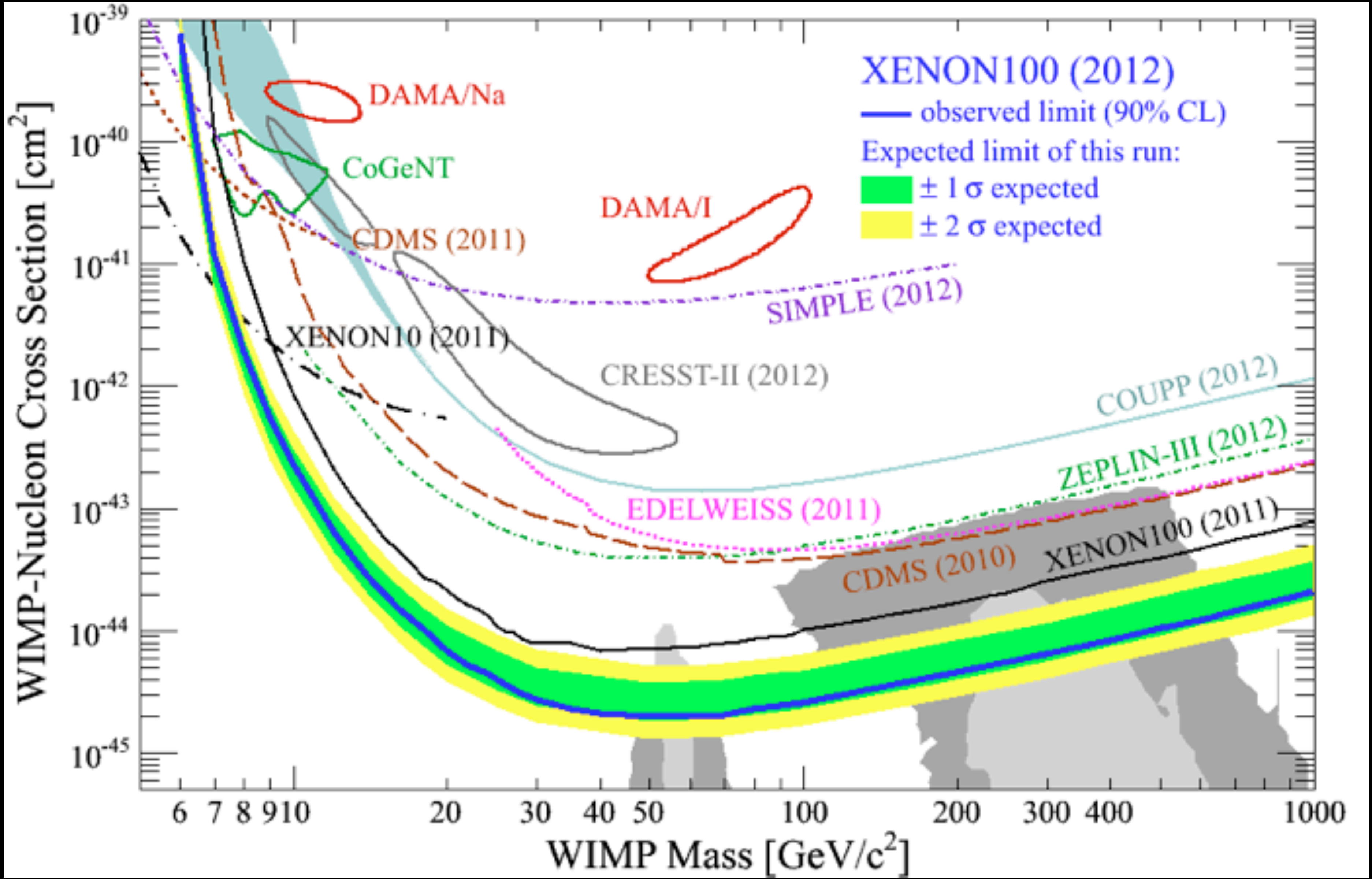
New Techniques for Backgrounds

Complementary with High-Energy Frontier

need 100-1000 dark matter events to measure mass, cross section

Spin-Independent Cross Section: Latest Experiment Results

E. Aprile et al., arXiv:1207.5988



1 event/ kg/day ←

1 event/ 100 kg/day ←

tonne-scale detectors likely required for discovery

Spin-Independent Cross Section: Latest Theory Results

O. Buchmuller et al., arXiv:1207.7315

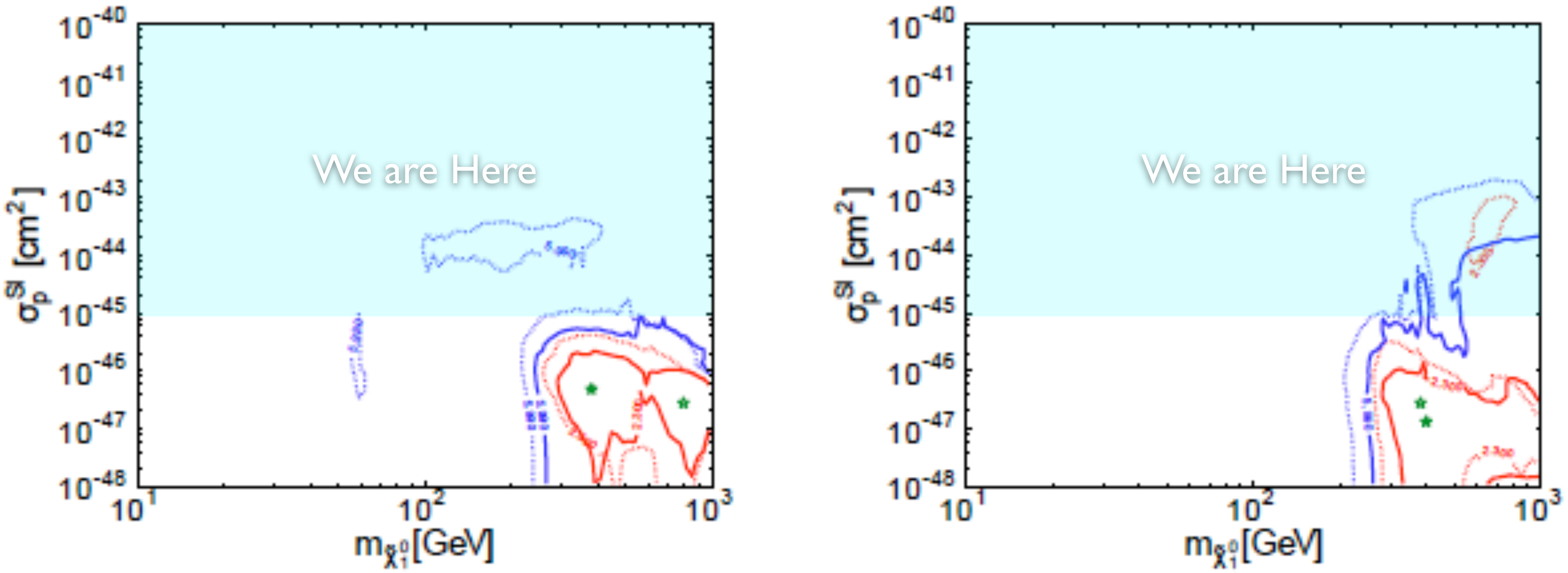


Figure 17. *The* $(m_{\tilde\chi^0_1}, \sigma_p^{\rm SI})$ *planes in the CMSSM (left panel) and the NUHM1 (right panel). The* $\Delta\chi^2 = 2.30(5.99)$ *contours, corresponding to the 68(95)% CL are coloured red (blue). The solid (dashed) lines are for global fits to the* $LHC_{5/\rm fb}$, $\mathrm{BR}(B_s \to \mu^+\mu^-)$ *and new XENON100* ($LHC_{1/\rm fb}$) *data, and the corresponding best-fit points are indicated by solid (open) green stars.*

CAVEAT: many more exotic models (Asymmetric DM, Dark Forces Models, Magnetic Inelastic DM, Sterile Nus + Freeze-In, Isospin-Violating DM, Emergent DM and L# models .....

10^3 is a lot of σ

10^{-24} cm^2: σ(neutron-A elastic scattering)

10^{-28} cm^2: σ(total inelastic pp at TeVatron)

10^{-35} cm^2: σ(gg → H) at LHC (Standard Model)

10^{-39} cm^2: σ(single top) at TeVatron

10^{-40} cm^2: σ(ν QE) at MINOS

10^{-45} cm^2: σ(ν-e Elastic) for solar ν

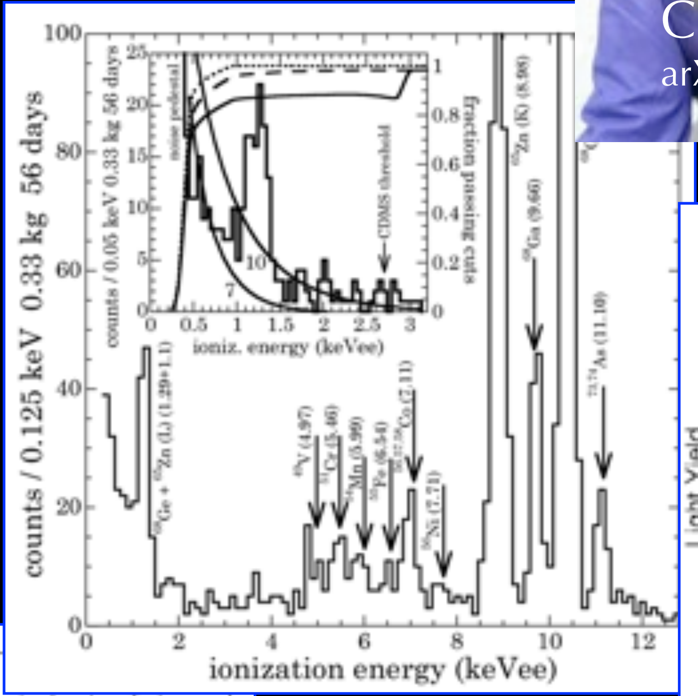
σ(DM coherent scattering)? 10^{-48} cm^2

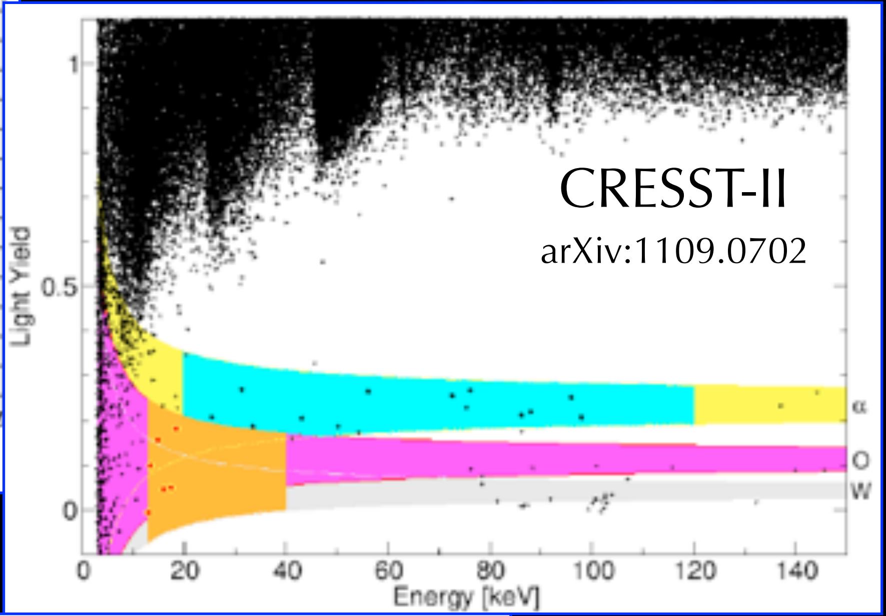
Not to Scale

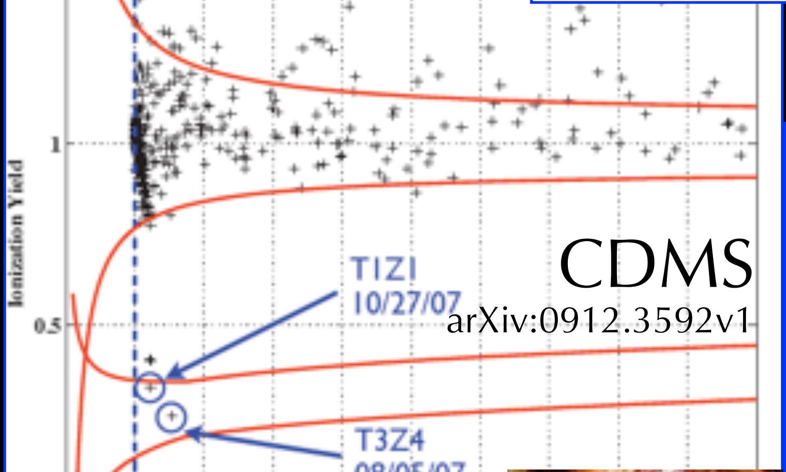
Direct Dark Matter Signals?

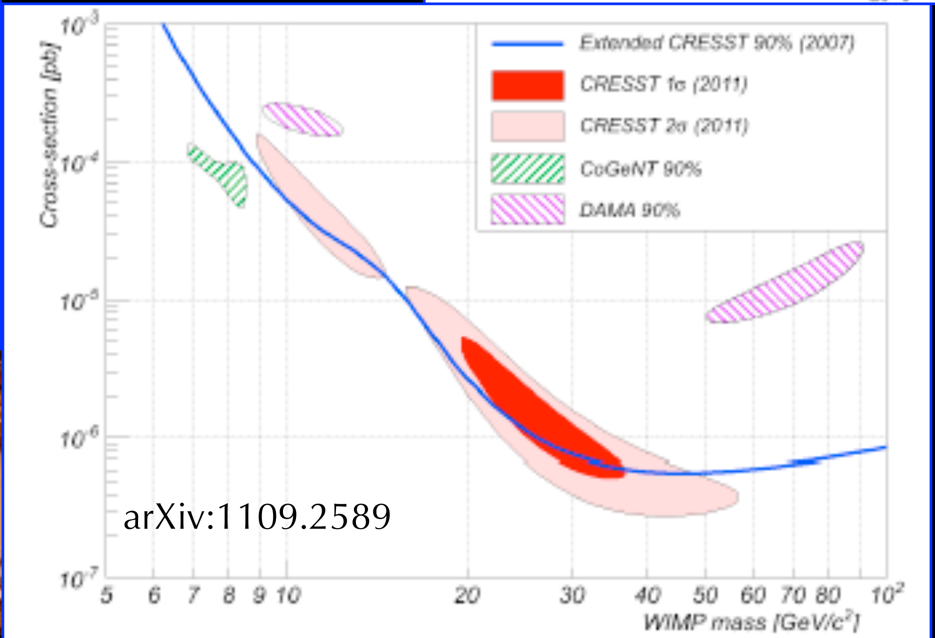

COGENT
arXiv:1002.4703

DAMA/Libra



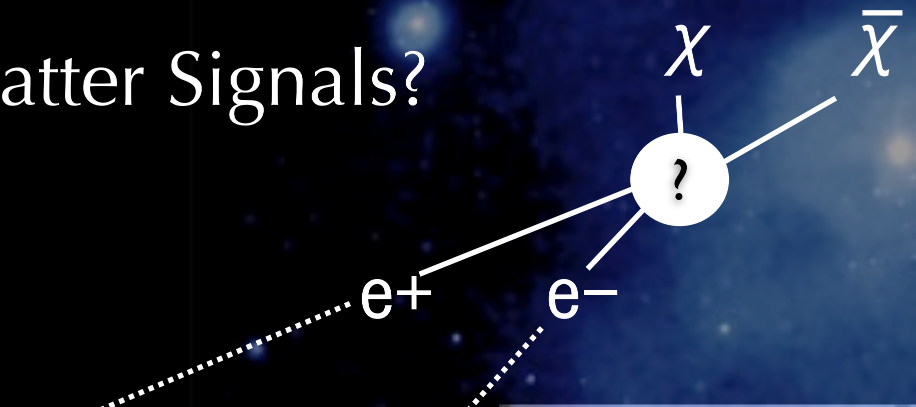

CRESST-II
arXiv:1109.0702


CDMS
arXiv:0912.3592v1

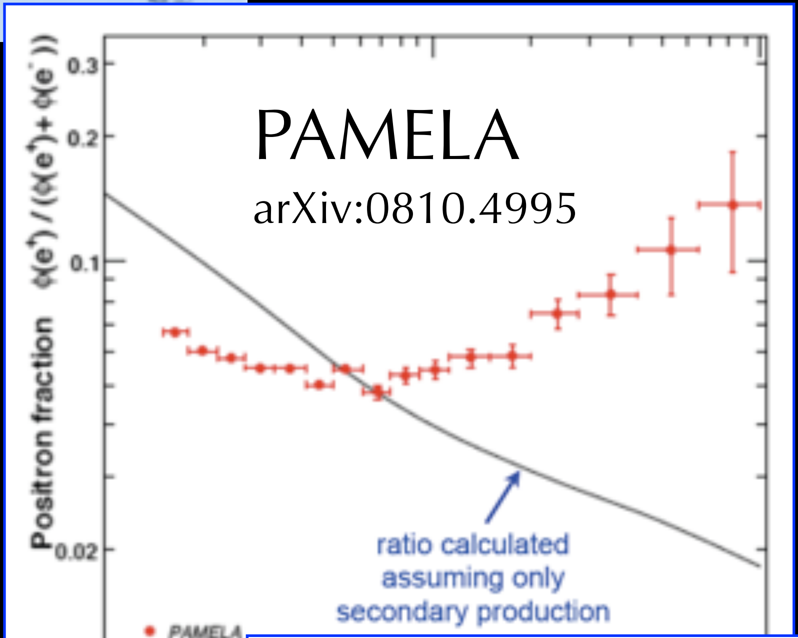

arXiv:1109.2589

dark matter?
backgrounds?

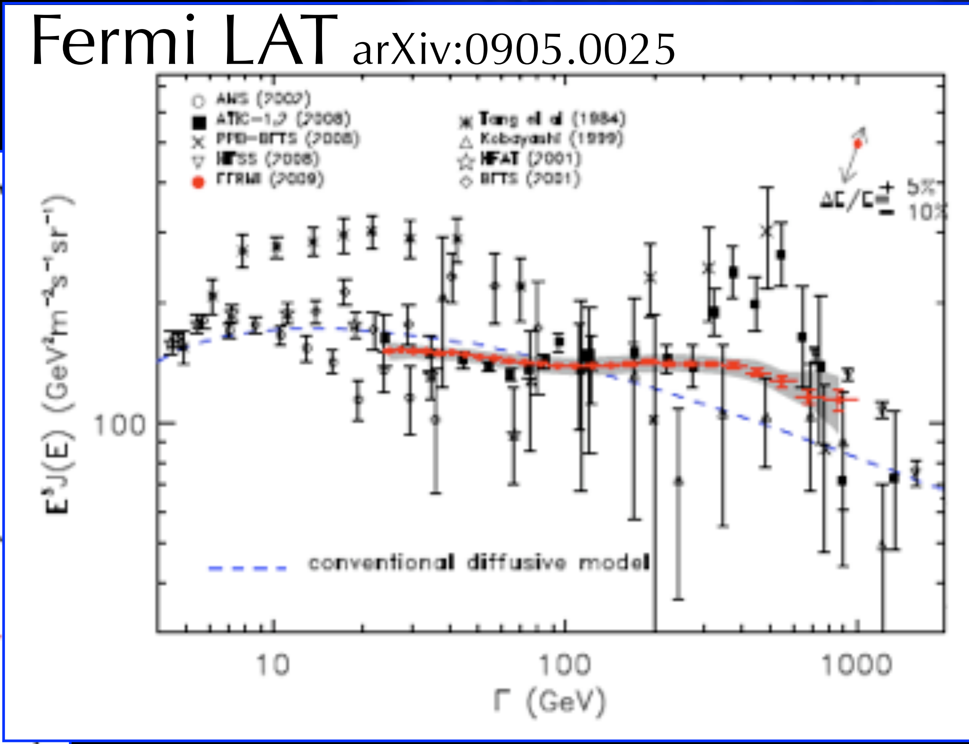
Indirect Dark Matter Signals?



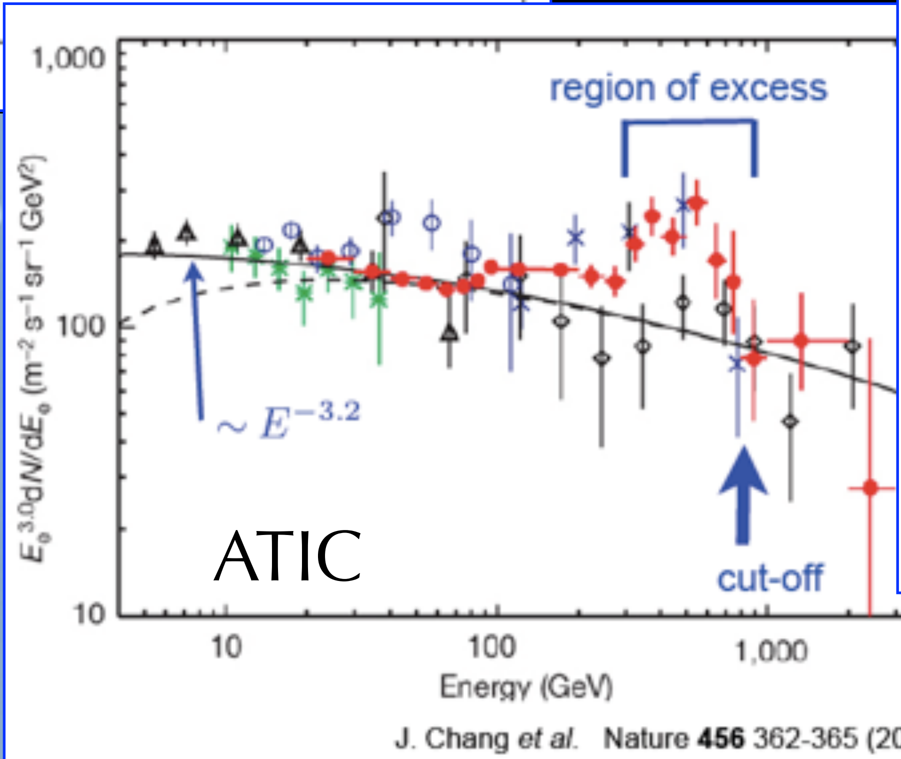
PAMELA
arXiv:0810.4995



Fermi LAT arXiv:0905.0025



ATIC



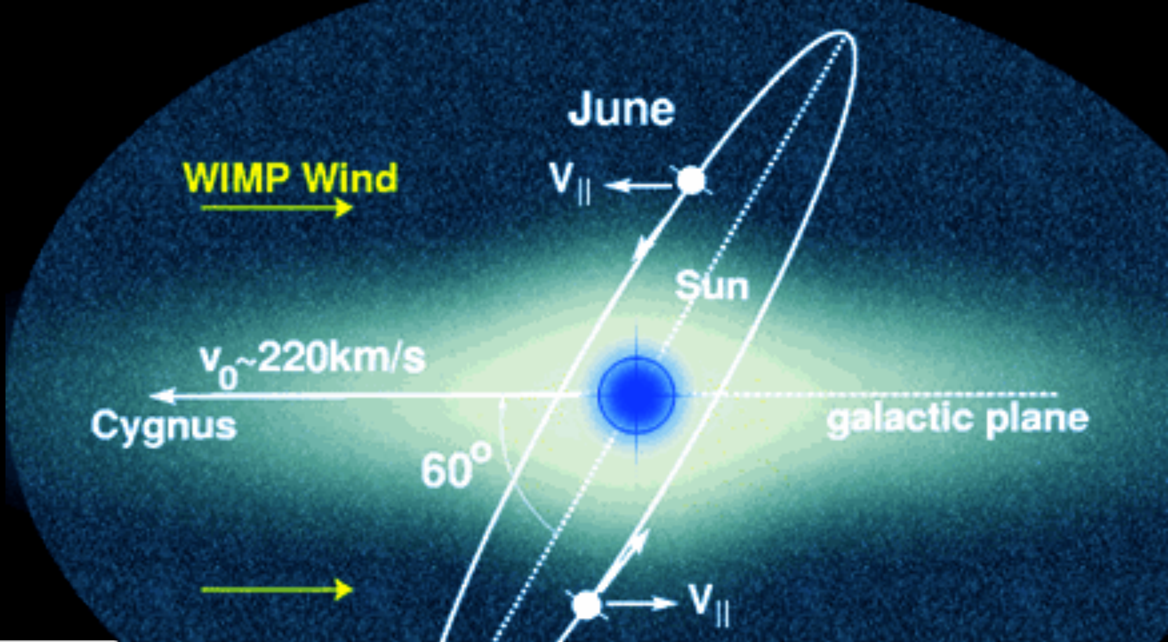
J. Chang *et al.* Nature **456** 362-365 (2008)

dark matter? local astrophysics?

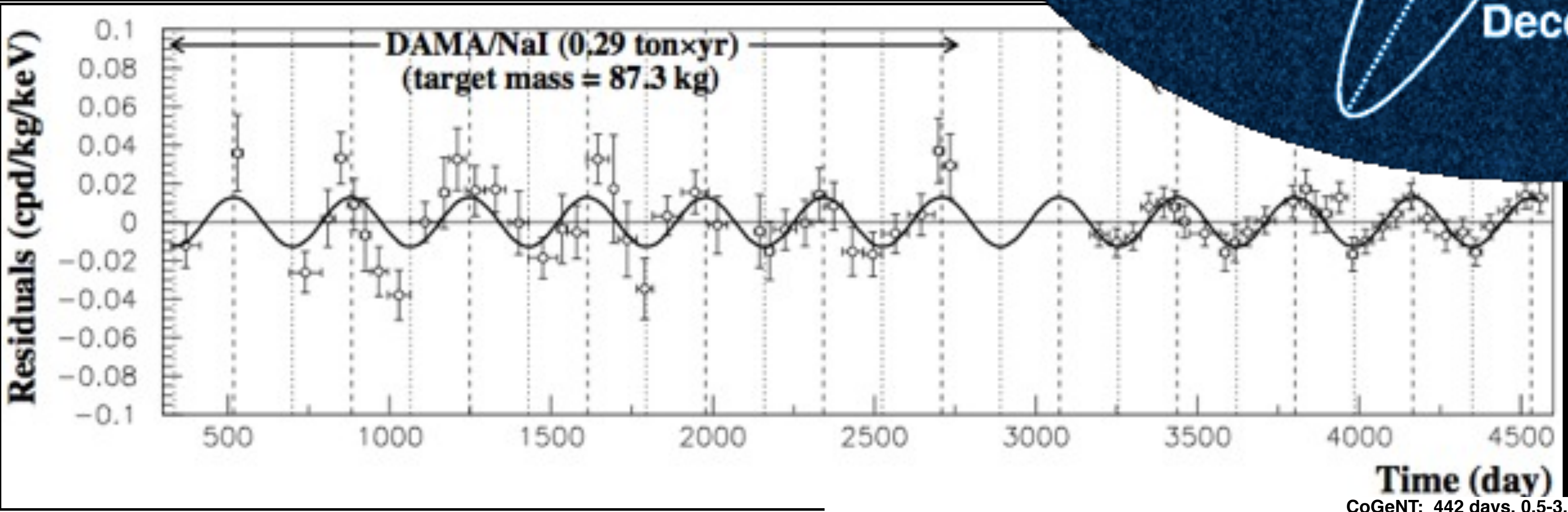
Annual Modulation

June-December event rate asymmetry ~2-10%

Drukier, Freese, Spergel,
Phys. Rev. D33:3495 (1986)



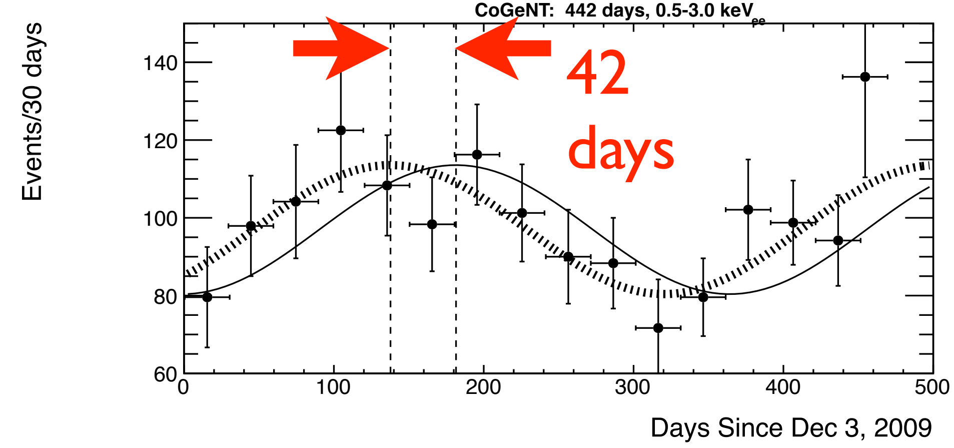
Eur. Phys. J. C56:333-355 (2008)



DAMA/Libra positive result, $>8\sigma$, *inconsistent with many expts*

CoGeNT modulation result, 2.8σ, *~consistent with DAMA/Libra*

J. Collar, STSI (2011), arXiv:1106.0650v1



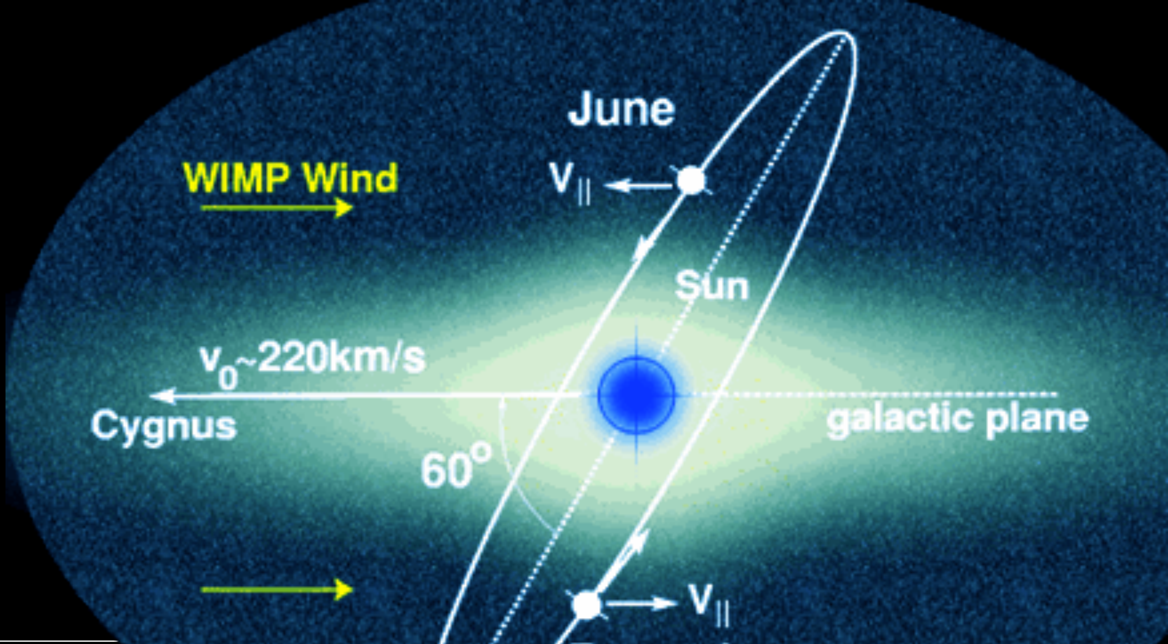
CoGeNT (dashed line)

DAMA (solid line)

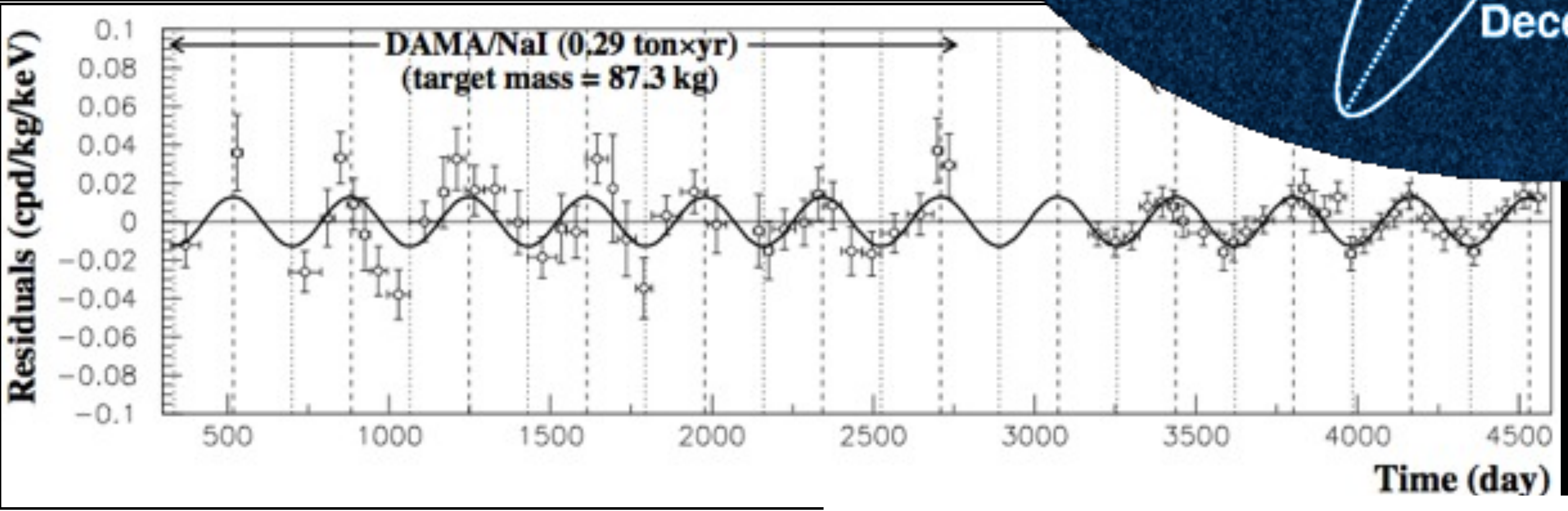
Annual Modulation

June-December event rate asymmetry ~2-10%

Drukier, Freese, Spergel,
Phys. Rev. D33:3495 (1986)

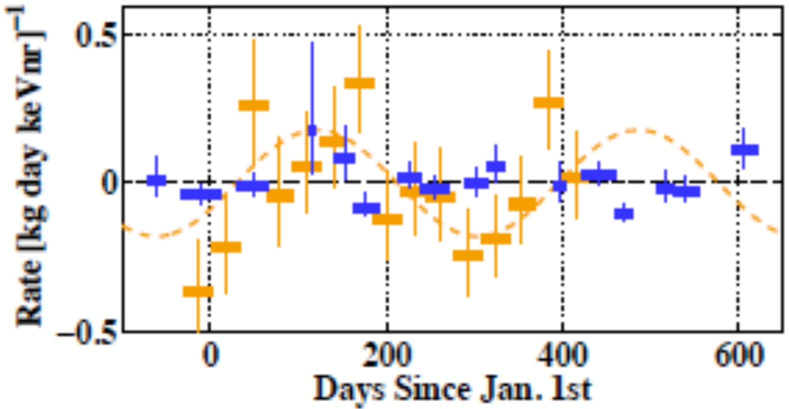


Eur. Phys. J. C56:333-355 (2008)



DAMA/Libra positive result, >8σ, *inconsistent with many expts*

BUT...
CDMS modulation search
not consistent with CoGeNT or DAMA/Libra (98.3% CL)
arXiv:1203.1309

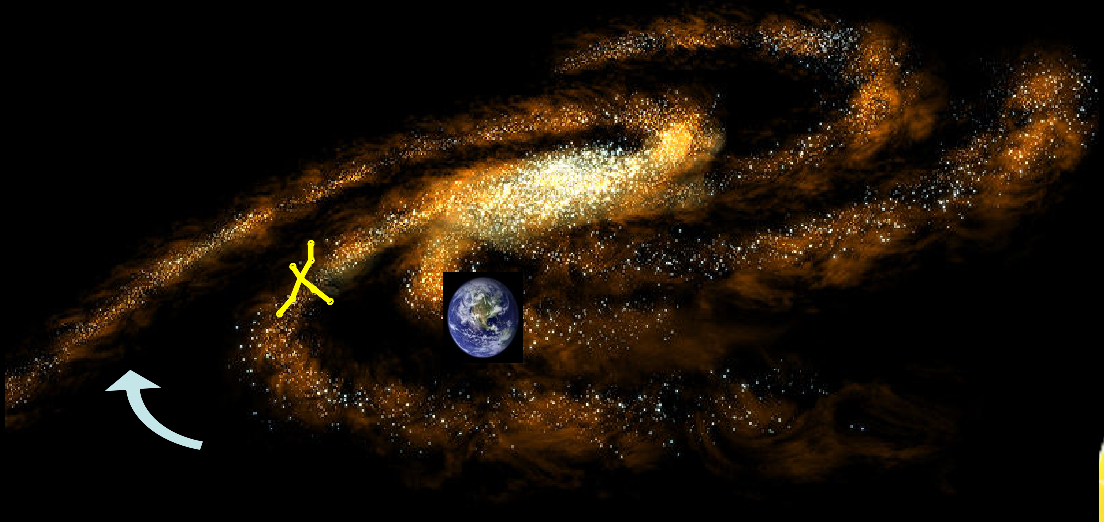


CoGeNT
(dashed line)

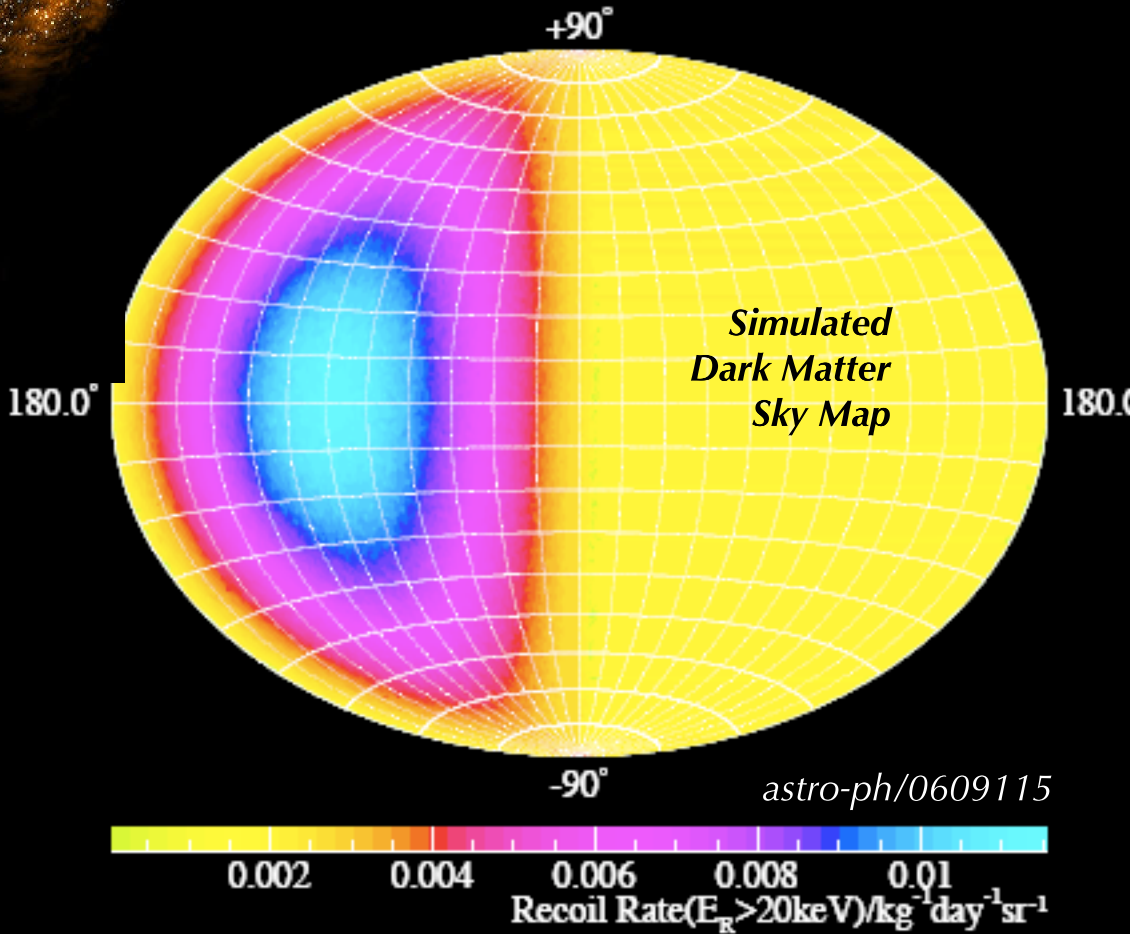
CDMS
(solid points)

Directional Detection

The Dark Matter Wind “blows” from Cygnus



search for a dark matter source

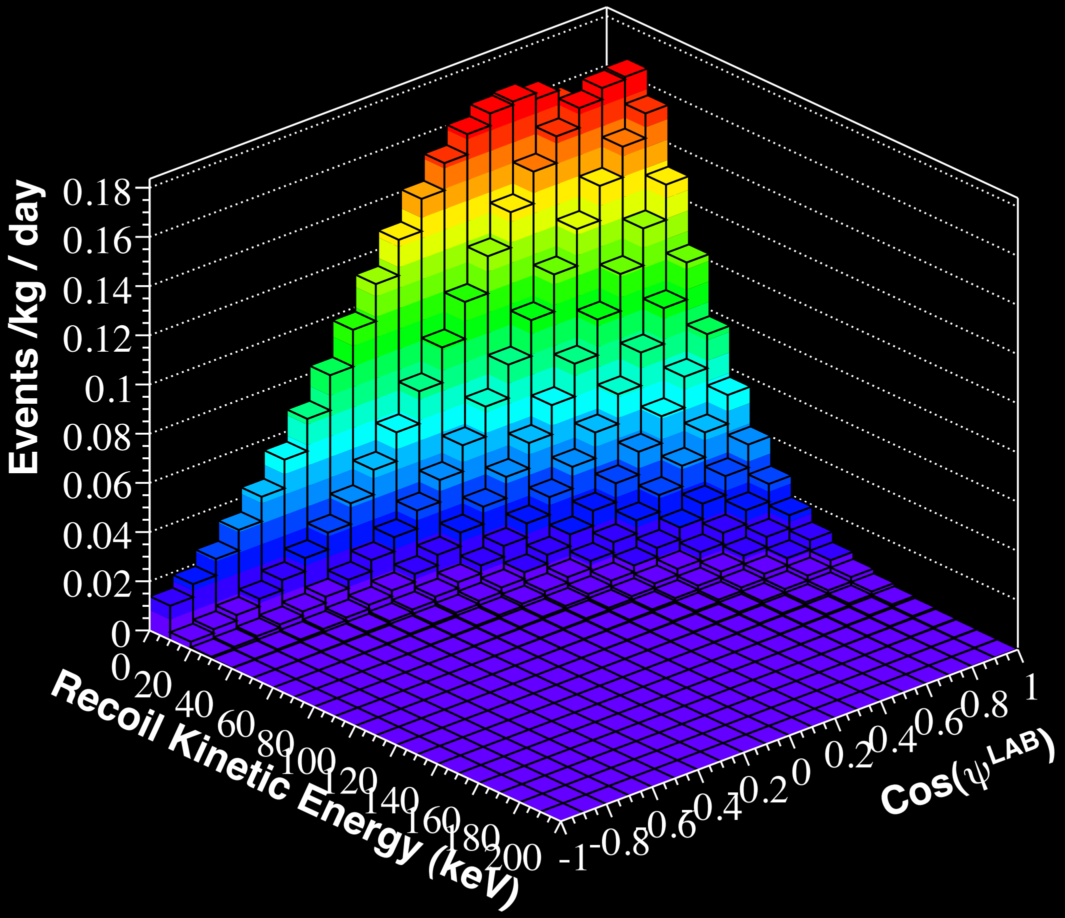


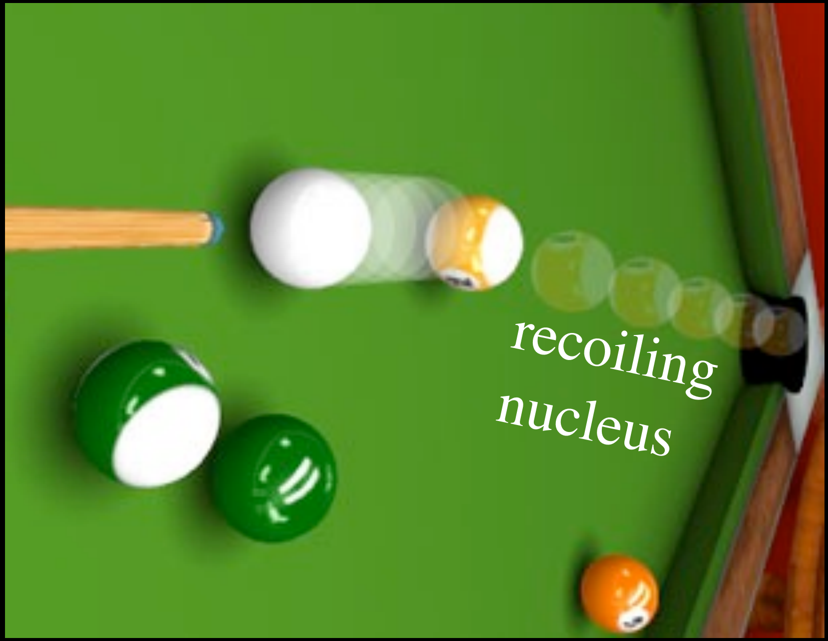
astro-ph/0609115

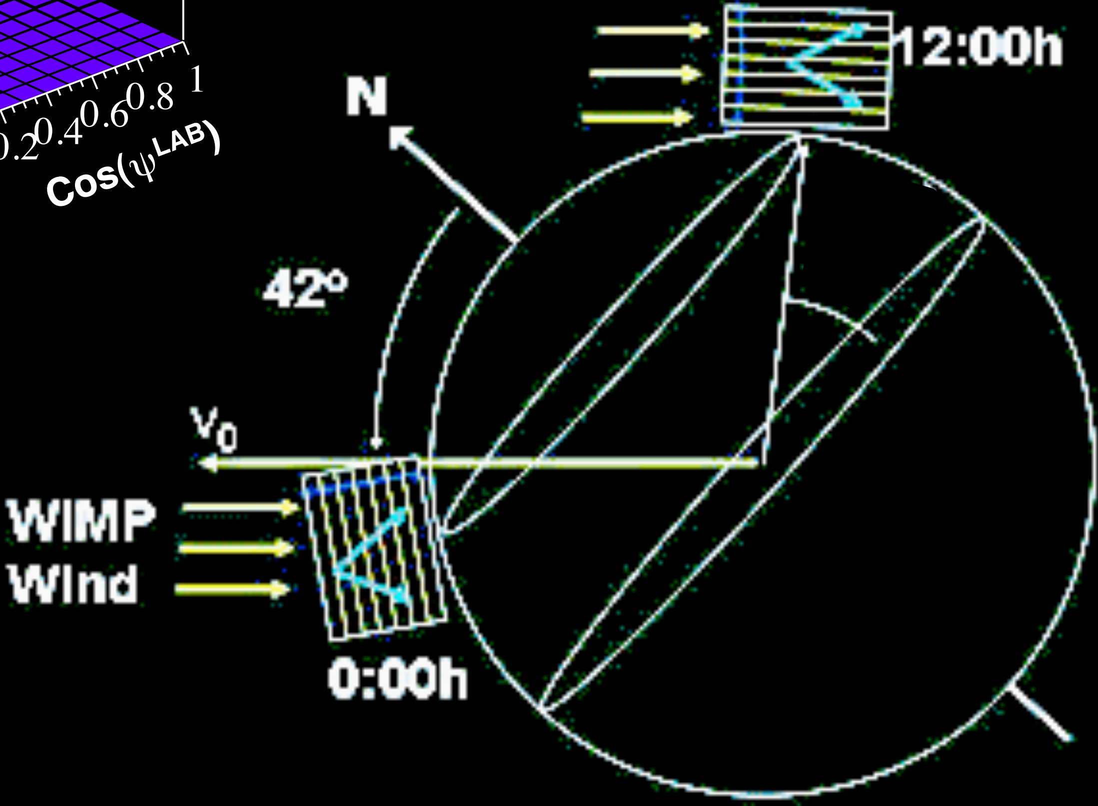
simulated reconstructed dark matter sky map: search for anisotropy

Unambiguous proof:
Correlation of WIMP-induced nuclear recoil signal with galactic motion

Directional Detection







Daily direction modulation:
asymmetry ~ 20-100%
in forward-backward
event rate.

Spergel, Phys. Rev. D36:1353 (1988)

Directionality Around the World

DRIFT: in Boulby (UK)

S. Burgos et al., Astropart. Phys. 28, 409 (2007)

NEWAGE: in Kamioka (JP),
first directional dark matter limit!

K. Miuchi, et al., Phys.Lett.B654:58-64 (2007)

MiMAC-He3: ILL/Modane (FR)

D. Santos, et al., J. Phys. Conf. Ser. 65, 021012 (2007)

DMTPC: in WIPP (US)
CCD readout

D. Dujmic, et al., NIM A 584:337 (2008)

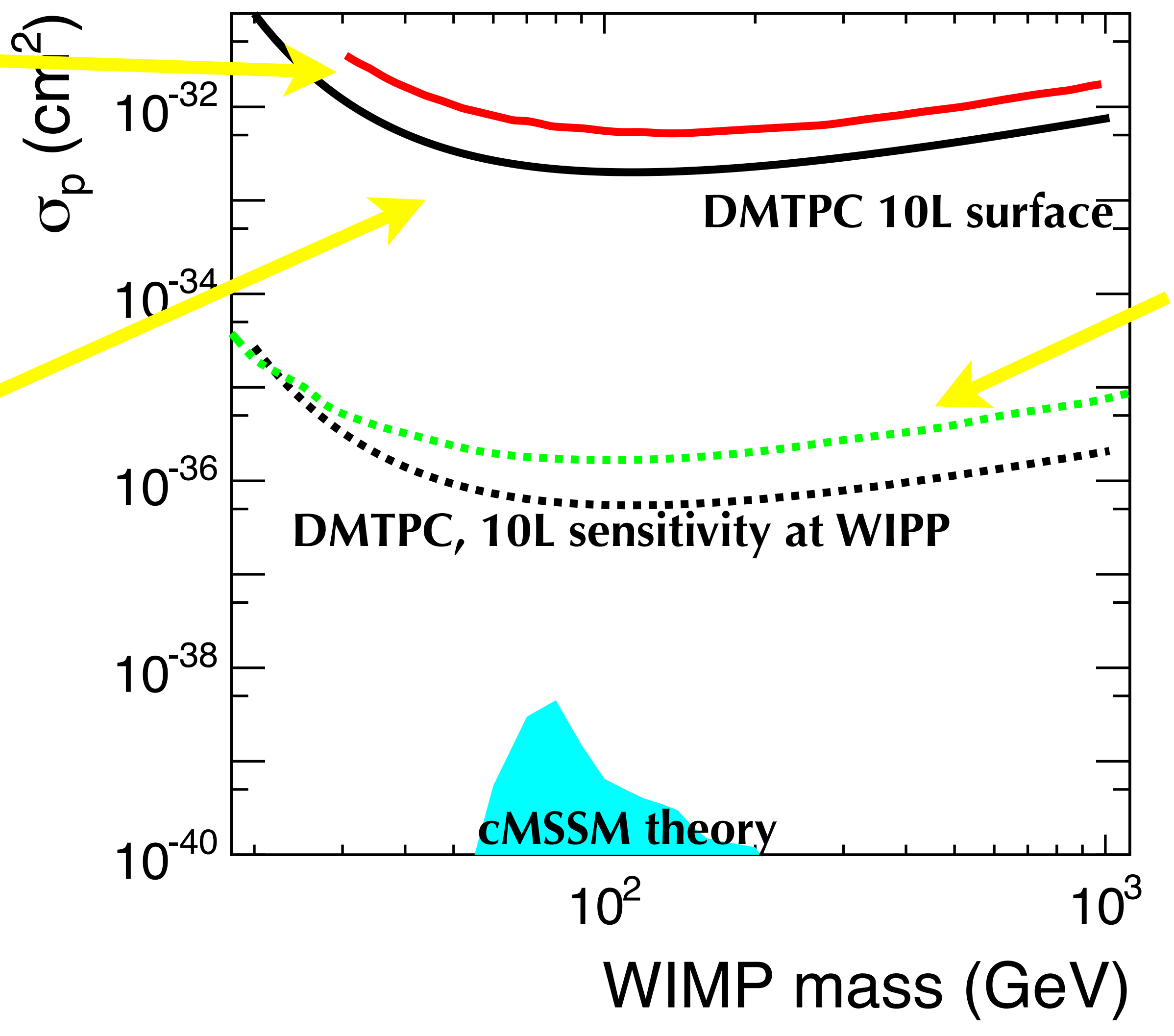
Spin-Dependent Cross Section: Latest Experiment Results

NEWAGE limit
(Kamioka)

K. Miuchi et al.,
Phys.Lett.B686:11-17
(2010)

DMTPC limit
(surface, 38 gm-day)

S. Ahlen et al.,
Phys. Lett. B 695 (2011)



directional searches

DRIFT sensitivity,
Astropart.Phys.
25 (2012) 397

Theory region:
Rozkowski et al JHEP 07 (2007) 075
Ellis et al PRD63 (2001) 065016

Spin-Dependent Cross Section: Latest Experiment Results

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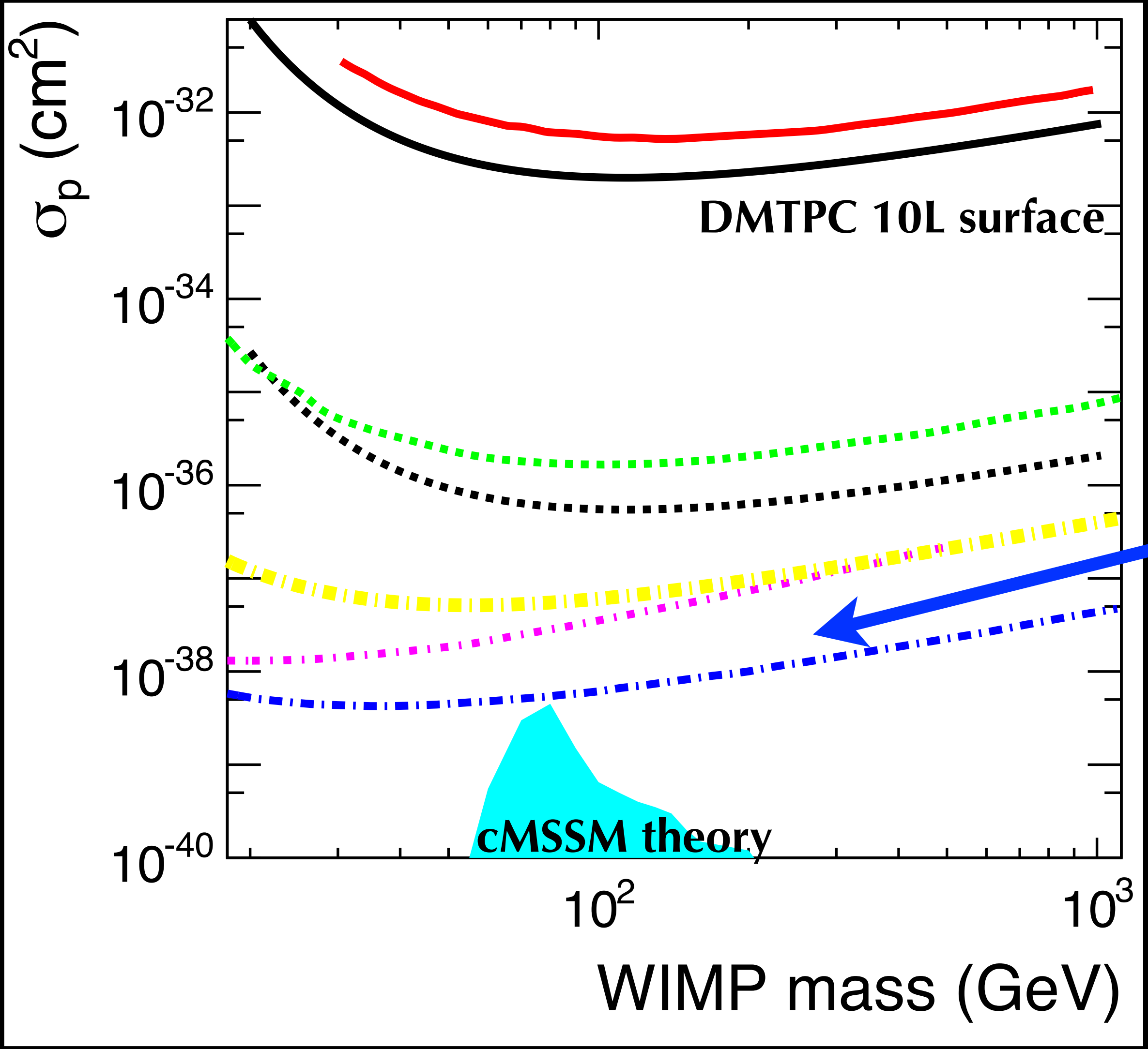

directional searches

DRIFT sensitivity, *Astropart.Phys. 25 (2012) 397*

1D results

COUPP
PRL.106, 021303 (2011)

SIMPLE
arXiv:1106.3014

PICASSO
arXiv:1202.1240

Theory region:
Rozkowski et al JHEP 07 (2007) 075
Ellis et al PRD63 (2001) 065016

Spin-Dependent Cross Section: Latest Experiment Results

NEWAGE limit
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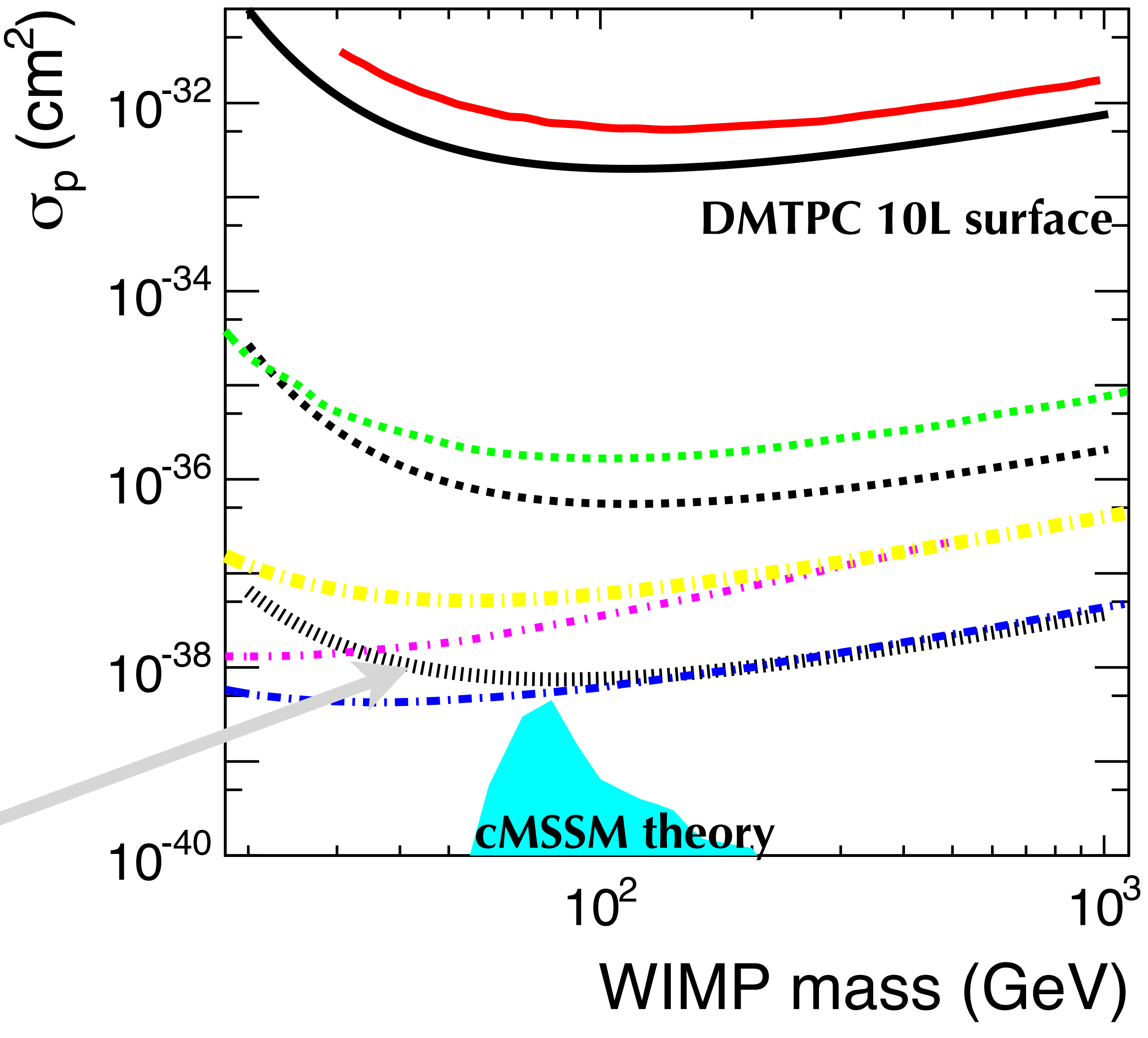
K. Miuchi et al.,
Phys.Lett.B686:11-17
(2010)

DMTPC limit
(surface, 38 gm-day)

S. Ahlen et al.,
Phys. Lett. B 695 (2011)

1m^3 at WIPP
(DMTPCino)
projected
sensitivity



directional searches

DRIFT sensitivity,
Astropart.Phys. 25 (2012) 397

1D results

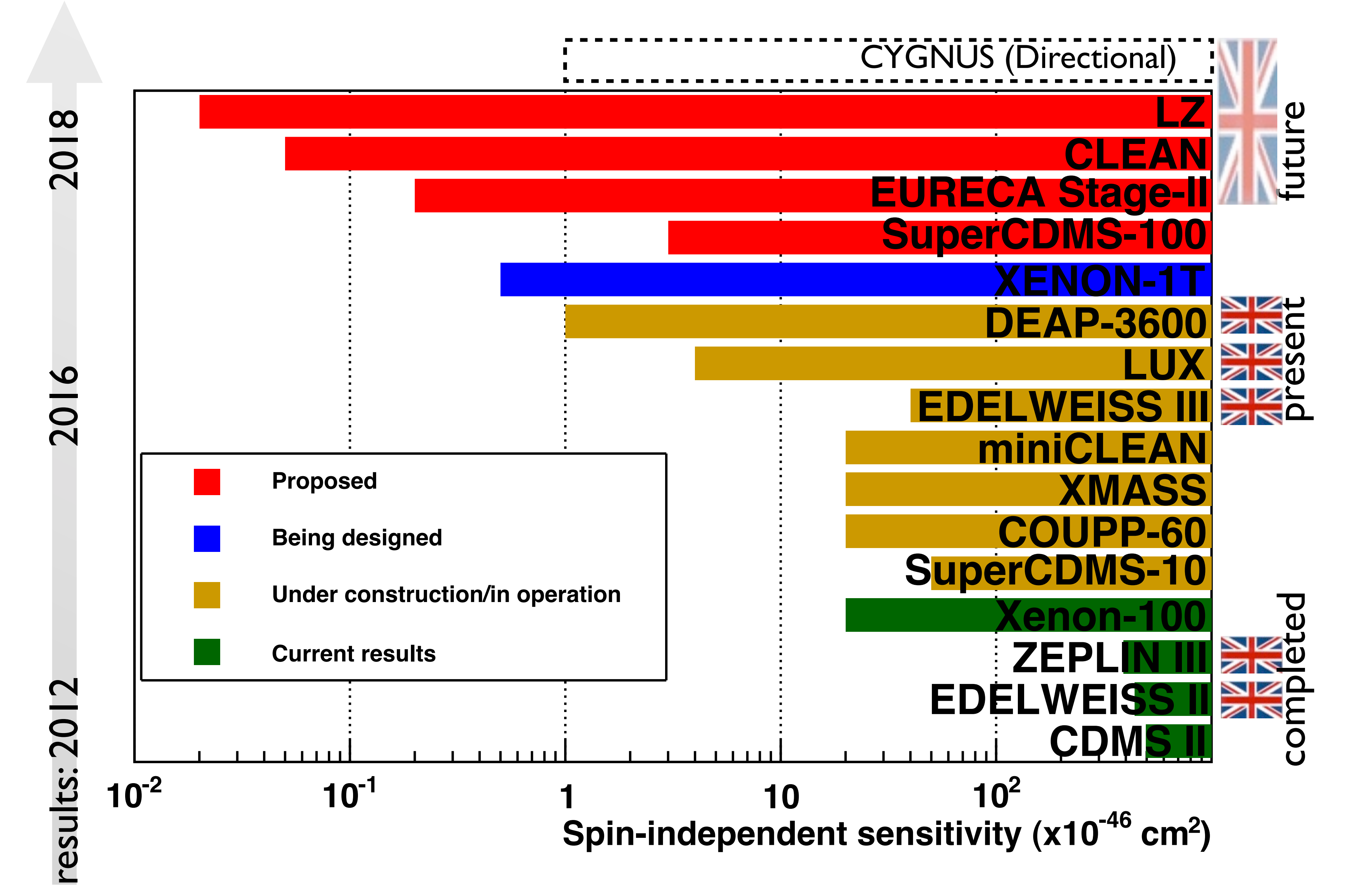
COUPP
PRL.106, 021303 (2011)

SIMPLE
arXiv:1106.3014

PICASSO
arXiv:1202.1240

Theory region:
Rozkowski et al JHEP 07 (2007) 075
Ellis et al PRD63 (2001) 065016

Global SI Dark Matter Programme, Sensitivity Reach



NB: projected sensitivities (all except green) assume zero background.

Backup Slides

Setting a Limit

1. The theoretical dark matter interaction rate is:

$$\frac{dR}{dE_R} = \left(\frac{c_1 R_0}{E_0 r}\right) exp\left(\frac{-c_2 E_R}{E_0 r}\right)$$

E_R = *nuclear recoil energy,*
E_0 = *dark matter particle energy*

2. Experiments measure:

$$R_0 = \left[\left(\frac{2v_0}{\sqrt{\pi}}\right)\left(\frac{N_0(\rho_D/m_D)}{A}\right)\right]\sigma_0 \times exposure$$

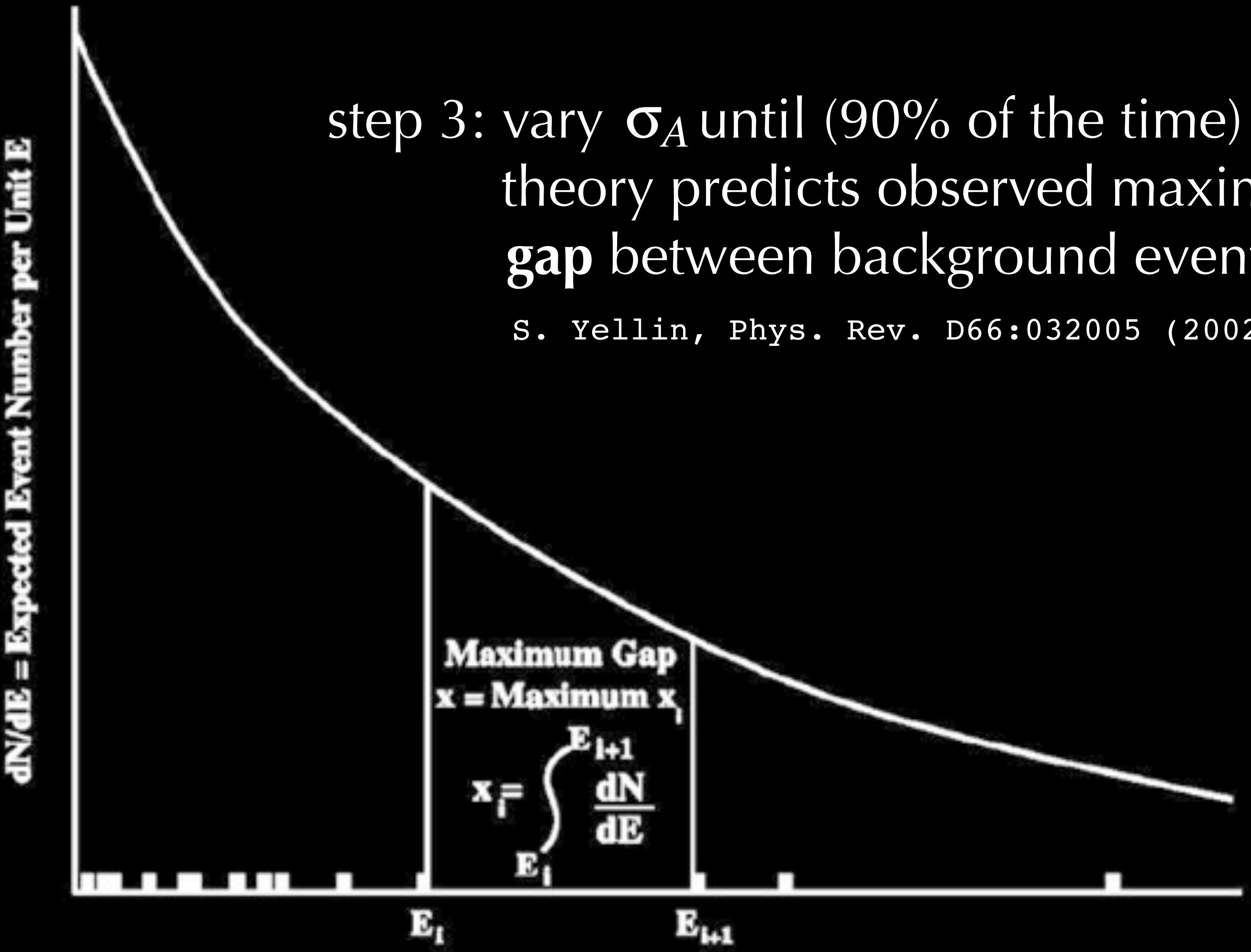
$$\sigma_A = \sigma_0 F^2(E_R,A) I_c\,, \quad F^2(E_R,A) = nuclear\ form\ factor, \quad I_c = A^2$$

3. vary σ_A until (90% of the time) theory predicts observed rate

4. Normalize to σ_{W-N} to compare limits:

$$\sigma_{W-N} = \left(\frac{\mu_1}{\mu_A}\right)^2 \left(\frac{1}{A}\right)^2 \sigma_A \qquad \mu = \frac{m_D\, m_{target}}{(m_D + m_{target})}$$

… in the Presence of Background



step 3: vary σ_A until (90% of the time)
theory predicts observed maximum
gap between background events

`S. Yellin, Phys. Rev. D66:032005 (2002)`

Yellin gap method: a way to make a “zero-background” measurement over a restricted range of an experiment’s acceptance (zero signal too)

SI vs. SD

Savage et al.,
arXiv:0808.3607

$$\sigma = \sigma_{\rm SI} + \sigma_{\rm SD};$$

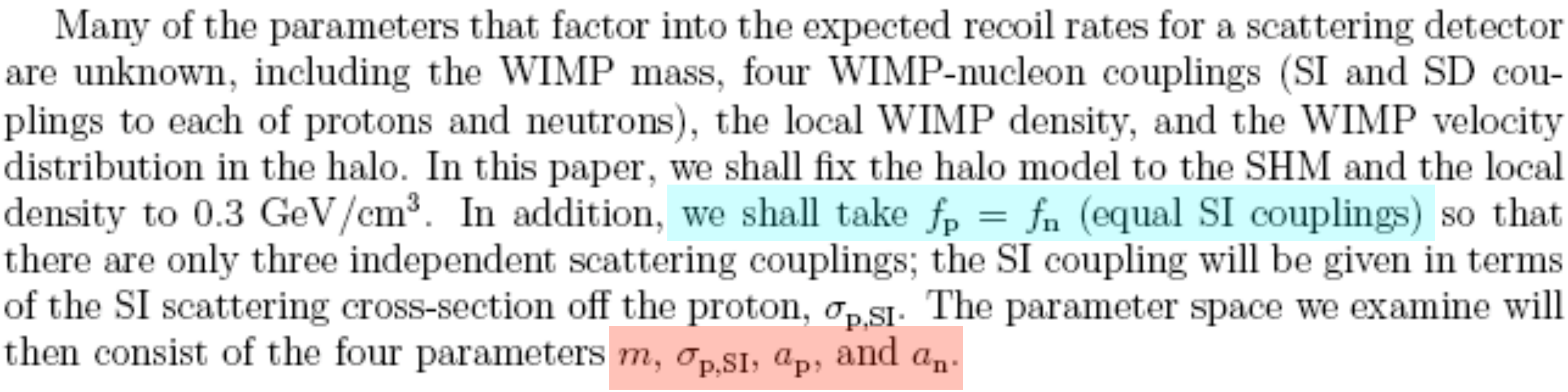
$$\sigma_{0,\rm SI} = \frac{4\mu^2}{\pi}[Z f_{\rm p} + (A-Z) f_{\rm n}]^2 \, .$$

$$\sigma_{0,\rm SI} = \sigma_{\rm p,SI} \left(\frac{\mu}{\mu_{\rm p}}\right)^2 A^2$$

$$\sigma = \sigma_0 \, |F(E)|^2$$

(nuclear form factor)

$$\sigma_{SD}(q) = \frac{32\mu^2 G_F^2}{2J+1}\left[a_p^2 S_{pp}(q) + a_p a_n S_{pn}(q) + a_n^2 S_{nn}(q)\right] \, .$$



Many of the parameters that factor into the expected recoil rates for a scattering detector are unknown, including the WIMP mass, four WIMP-nucleon couplings (SI and SD couplings to each of protons and neutrons), the local WIMP density, and the WIMP velocity distribution in the halo. In this paper, we shall fix the halo model to the SHM and the local density to 0.3 GeV/cm^3. In addition, we shall take $f_{\rm p} = f_{\rm n}$ (equal SI couplings) so that there are only three independent scattering couplings; the SI coupling will be given in terms of the SI scattering cross-section off the proton, $\sigma_{\rm p,SI}$. The parameter space we examine will then consist of the four parameters m, $\sigma_{\rm p,SI}$, $a_{\rm p}$, and $a_{\rm n}$.

Ellis et al.,
arXiv:0808.3607

Nuclear physics uncertainties are important!

Scale Parameters

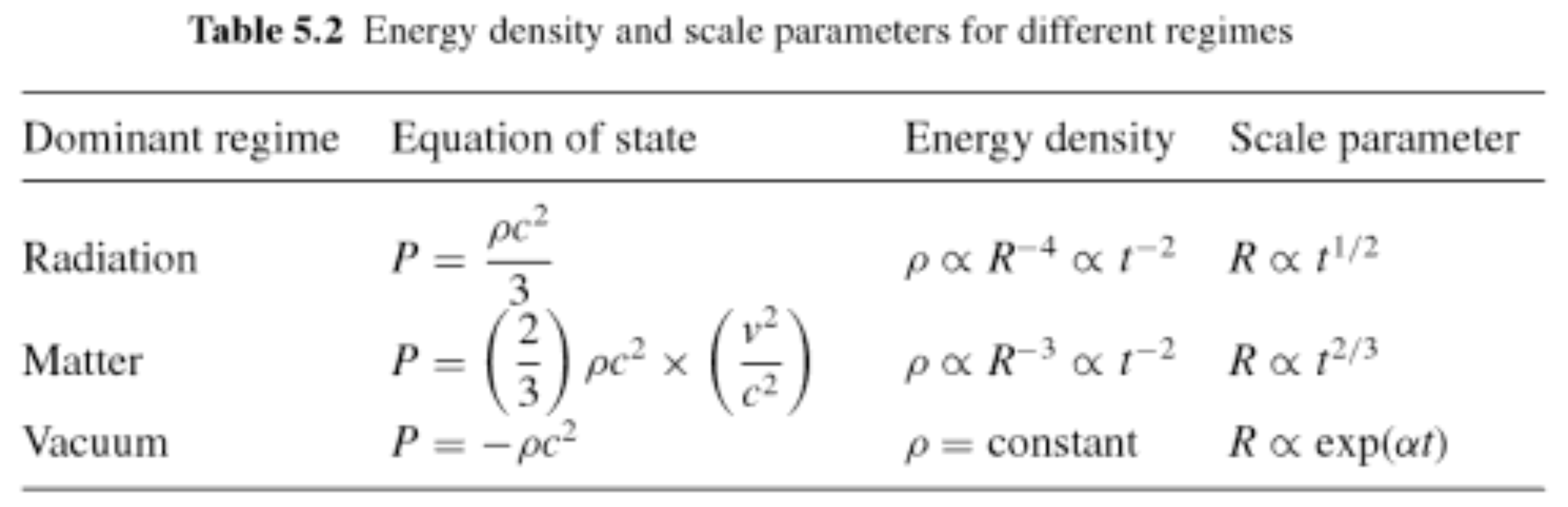


Table 5.2 Energy density and scale parameters for different regimes

Dominant regime	Equation of state	Energy density	Scale parameter
Radiation	$P = \frac{\rho c^2}{3}$	$\rho \propto R^{-4} \propto t^{-2}$	$R \propto t^{1/2}$
Matter	$P = \left(\frac{2}{3}\right) \rho c^2 \times \left(\frac{v^2}{c^2}\right)$	$\rho \propto R^{-3} \propto t^{-2}$	$R \propto t^{2/3}$
Vacuum	$P = -\rho c^2$	$\rho = \text{constant}$	$R \propto \exp(\alpha t)$

SN1A Data

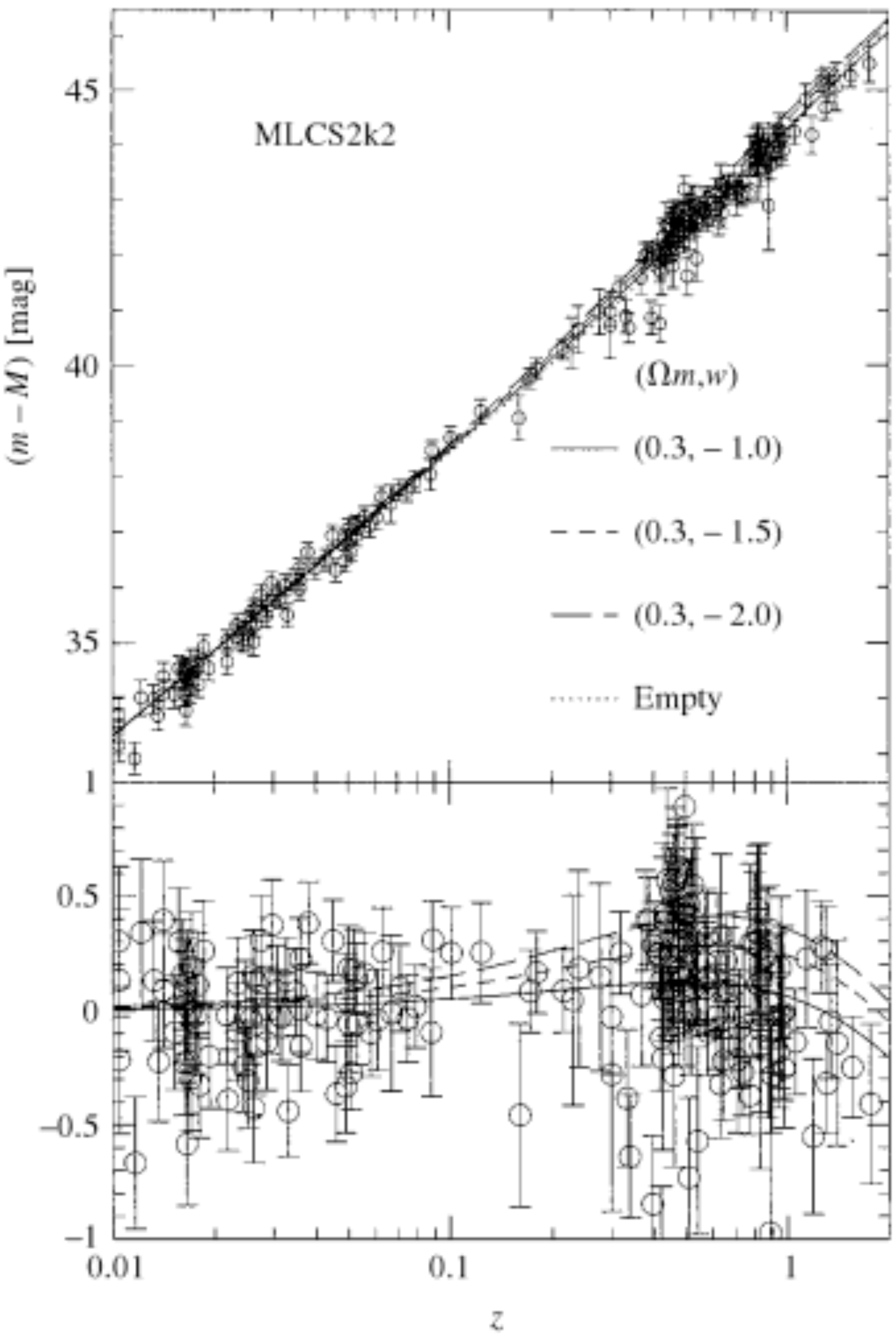


Fig. 7.13 Hubble plot from Type Ia supernovae at low and high redshifts, after Clocchiatti *et al.* (2006). The upper panel shows the measured values of the distance modulus (or logarithm of the luminosity distance) plotted against redshift. The lower panel shows the *difference* in magnitude as compared with the value expected for an empty universe. For averaged values, see Fig. 7.14.

Fig. 7.14 Differential Hubble plot from Type Ia supernovae, after Riess *et al.* (2004). The experimental points represent averages over several supernovae. An empty universe ($\Omega_k = 1,\ \Omega_m = \Omega_\Lambda = 0$) is represented by the horizontal dotted line. A flat, matter-dominated (so-called Einstein–de Sitter) universe ($\Omega_m = 1,\ \Omega_\Lambda = \Omega_k = 0$) is shown by the solid curve; while the dashed curve represents their best fit, with $\Omega_m = 0.27$,