Whither WIMP Dark Matter Search?

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Dictionary meaning of **Wimp**: (Mariam-Webster's Online Dictionary):

1. *A weak, cowardly, ineffectual, timid person* (Americanism)

Origin: around 1915 - 20; source: unknown

Example:

Schwarzenegger calls members of Congress 'wimps'

— Los Angeles Times, 27 October 2010

. . .

2. **W**(eakly) **I**(nteracting) **M**(assive) **P**(article)

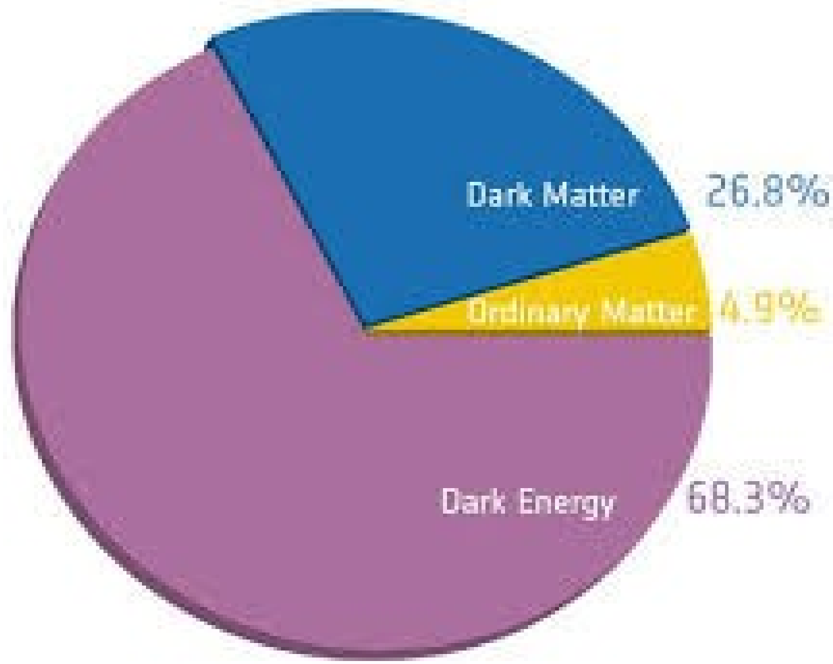
Origin: 1985 – 90; Source : Physics.

Planck 2015
Parameters of the Universe

Best fit model for flat ΛCDM model

Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046
τ	0.078 ± 0.019	0.066 ± 0.016
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060
H_0	67.31 ± 0.96	67.81 ± 0.92
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012
Ω_m	0.315 ± 0.013	0.308 ± 0.012

- Flat ΛCDM provides an excellent fit to Planck data
- No compelling evidence for extensions
- Percentage level precision on most parameters
- n_s significantly different from 1
- Reionization: τ significantly lower than before
  - WMAP: τ=0.089+/-0.014
- General good consistency between temperature, polarization and lensing results

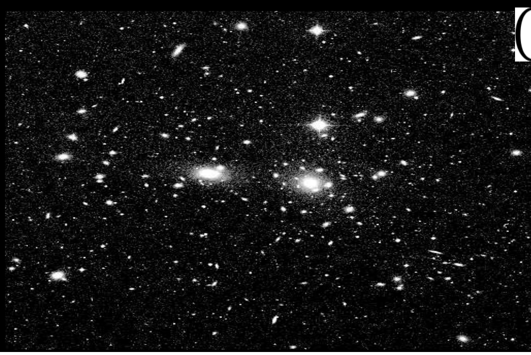


"Discovery" of Dark Matter
Fritz Zwicky (1933)

Fritz Zwicky (1898 - 1974)

F. Zwicky, "Die Rotverschiebung von extragalaktischen Nebeln", Helvetica Physica Acta 6: 110–127 (1933)

F. Zwicky, "On the Masses of Nebulae and of Clusters of Nebulae", Astrophysical Journal 86: 217 (1937)



Coma Cluster : ~ 1000 Galaxies

$D \sim 100\,\mathrm{Mpc}$

$M \sim 10^{14} M_\odot$

Virial Theorem $\Rightarrow \langle v^2 \rangle \sim \frac{1}{2} \frac{GM}{\langle r \rangle}$

Measured $\langle v^2 \rangle^{\frac{1}{2}} \sim 1000\,\mathrm{km\,s^{-1}} \Rightarrow M \sim 400 M_{\mathrm{visible}}$!!

— Radial velocities of galaxies in the Coma cluster are too large for the galaxies to be bound in the cluster with the known "visible" mass of the cluster.

Note: Zwicky used (wrong!) $H_0 = 558\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (as measured by Hubble!). Correct result $M_{\mathrm{Coma\ cluster}} \sim 50 M_{\mathrm{visible}}$

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 86 — OCTOBER 1937 — NUMBER 3

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

ABSTRACT

Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal rotations alone no determination of the masses of nebulae is possible (sec. ii). The observed internal motions of nebulae can be understood on the basis of a simple mechanical model, some properties of which are discussed. The essential feature is a central core whose internal *viscosity* due to the gravitational interactions of its component masses is so high as to cause it to rotate like a solid body.

In sections iii, iv, and v three new methods for the determination of nebular masses are discussed, each of which makes use of a different fundamental principle of physics.

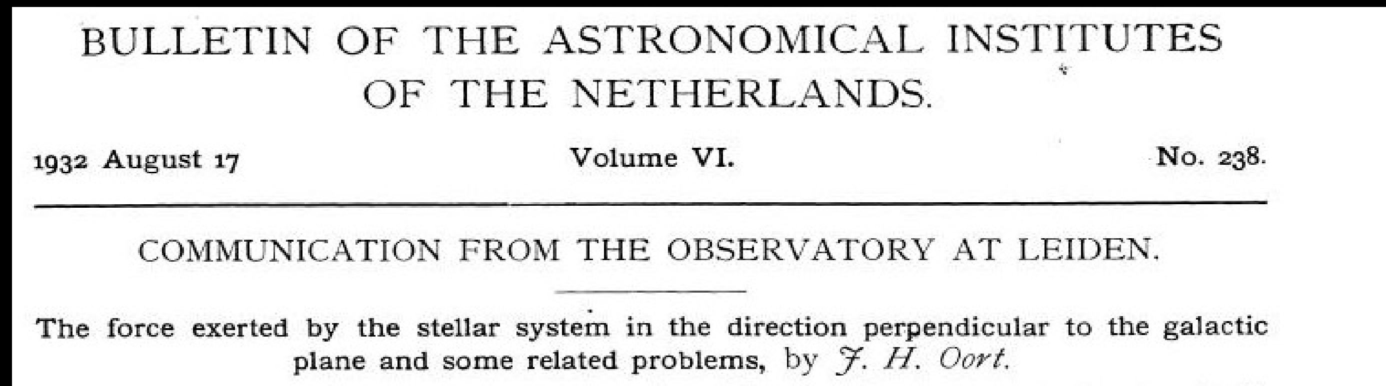
Method iii is based on the *virial theorem* of classical mechanics. The application of this theorem to the Coma cluster leads to a minimum value $\overline{M} = 4.5 \times 10^{10} M_\odot$ for the average mass of its member nebulae.

Method iv calls for the observation among nebulae of certain *gravitational lens* effects.

Section v gives a generalization of the principles of ordinary *statistical mechanics* to the whole system of nebulae, which suggests a new and powerful method which ultimately should enable us to determine the masses of all types of nebulae. This method is very flexible and is capable of many modes of application. It is proposed, in particular, to investigate the distribution of nebulae in individual great clusters.

As a first step toward the realization of the proposed program, the Coma cluster of nebulae was photographed with the new 18-inch Schmidt telescope on Mount Palomar.

Also, earlier Oort (1932) …



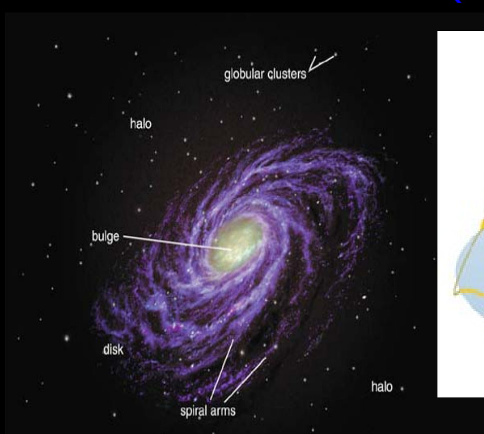
BULLETIN OF THE ASTRONOMICAL INSTITUTES OF THE NETHERLANDS.

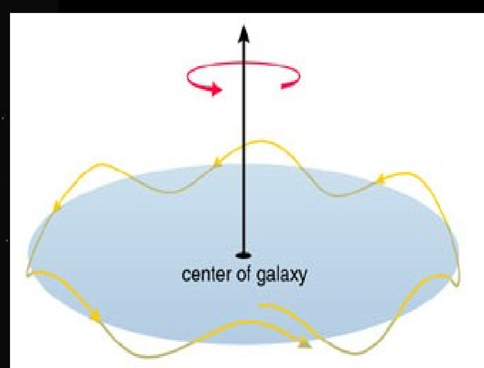
1932 August 17 Volume VI. No. 238.

COMMUNICATION FROM THE OBSERVATORY AT LEIDEN.

The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems, by *J. H. Oort.*

Jan Hendrik Oort (1900-1992)





To explain kinematics of vertical motion of the disk stars, Oort needed “invisible mass” of density ~ 2 GeV / cm^3 at the solar neighborhood.

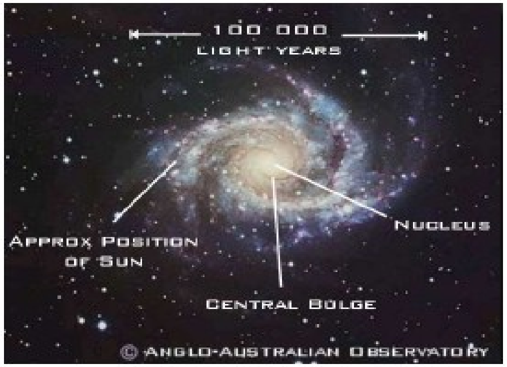
Modern value ~ 0.3 Gev / cm^3

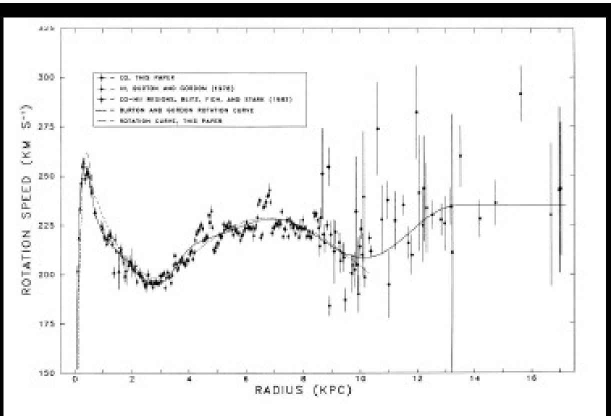
Rotation Curve of Spiral Galaxies and Dark Matter

Galactic scale Dark Matter seriously studied only begining early 1970s: Vera Rubin: Rotation Curve of Spiral galaxies.

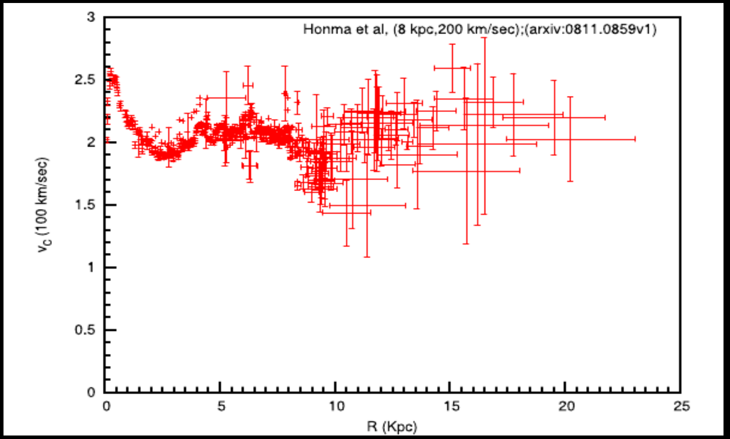
Circular Rotation Speed: $v_c^2(R) = R\frac{\partial \phi}{\partial R} = G\frac{M(R)}{R}$

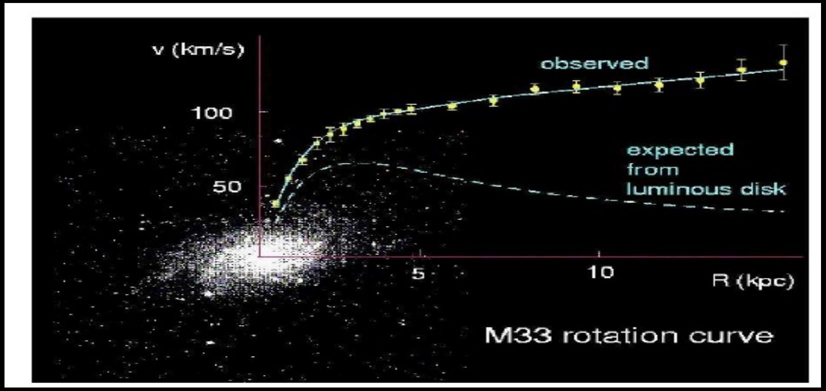
Rotation Curve of Milky Way

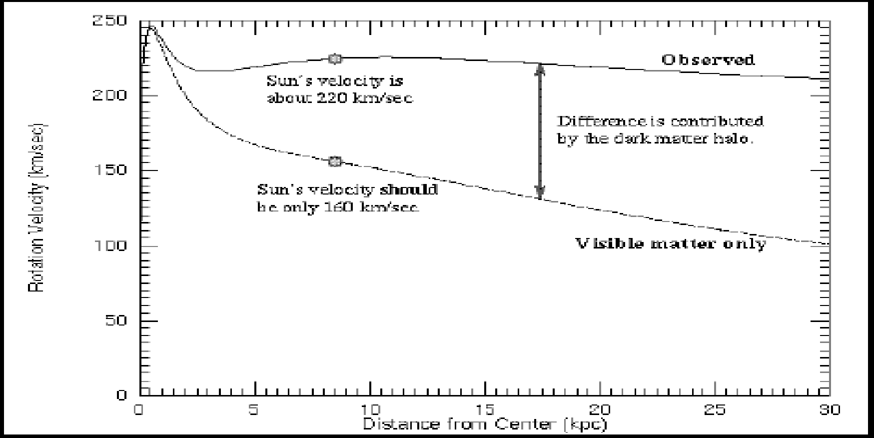




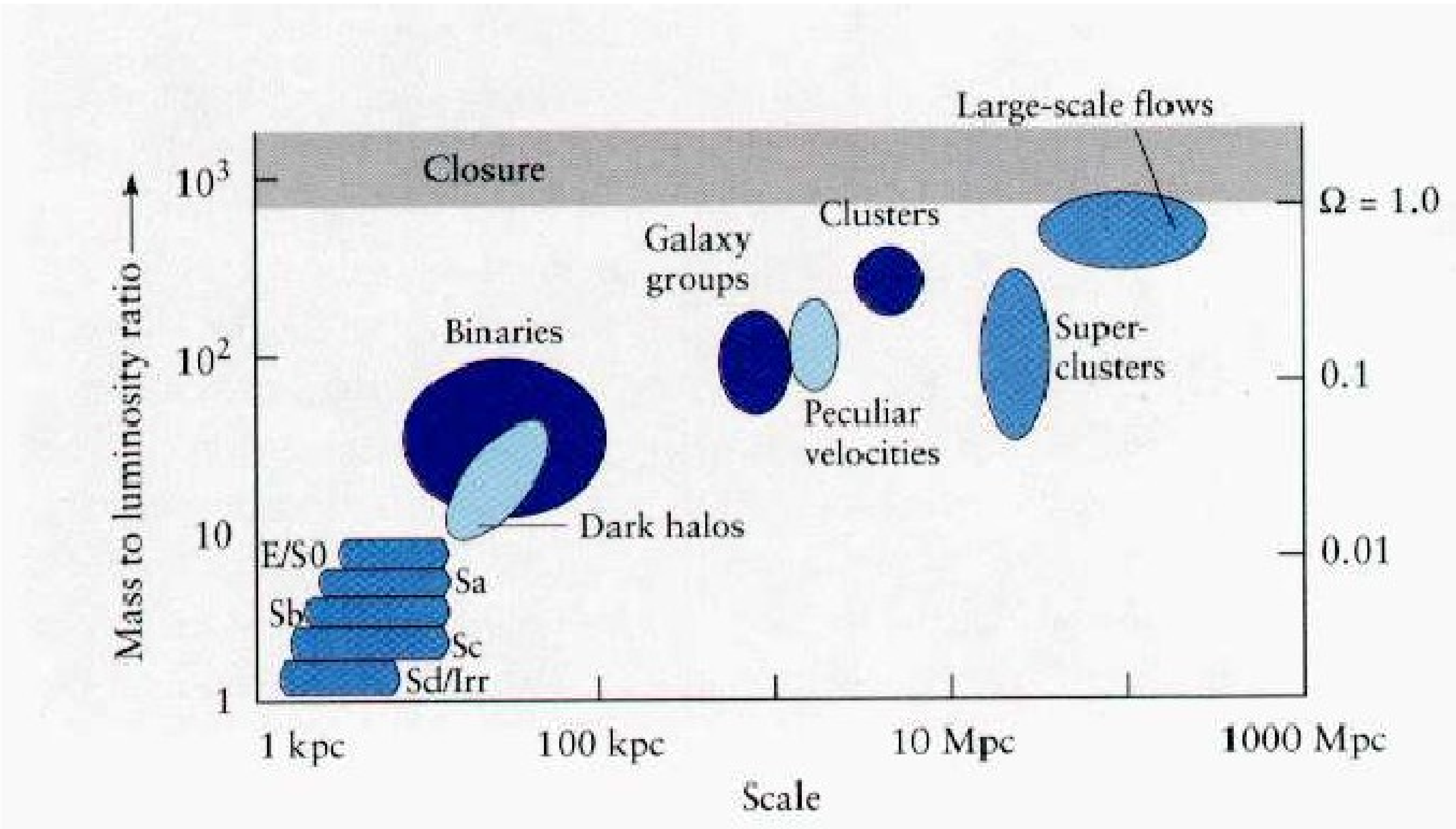
Clemens (1985)







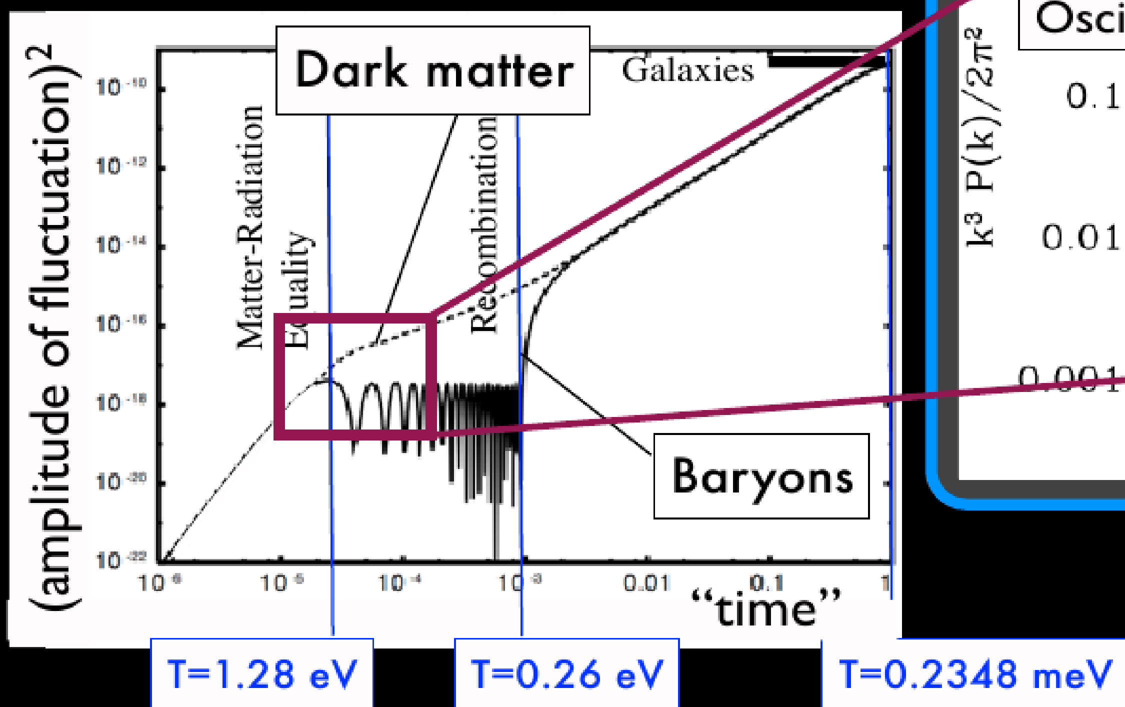
Dark Matter in the large scale Universe



Evidence for *nonbaryonic* cold dark matter

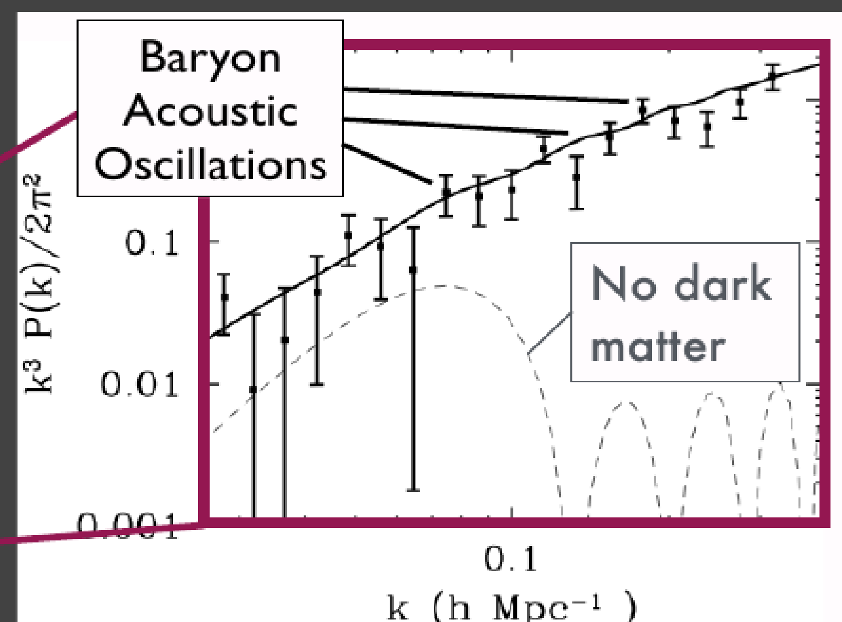
GALAXY FORMATION

Matter fluctuations uncoupled to the plasma can gravitationally grow into galaxies in the given 13 Gyr



Dark matter is non-baryonic

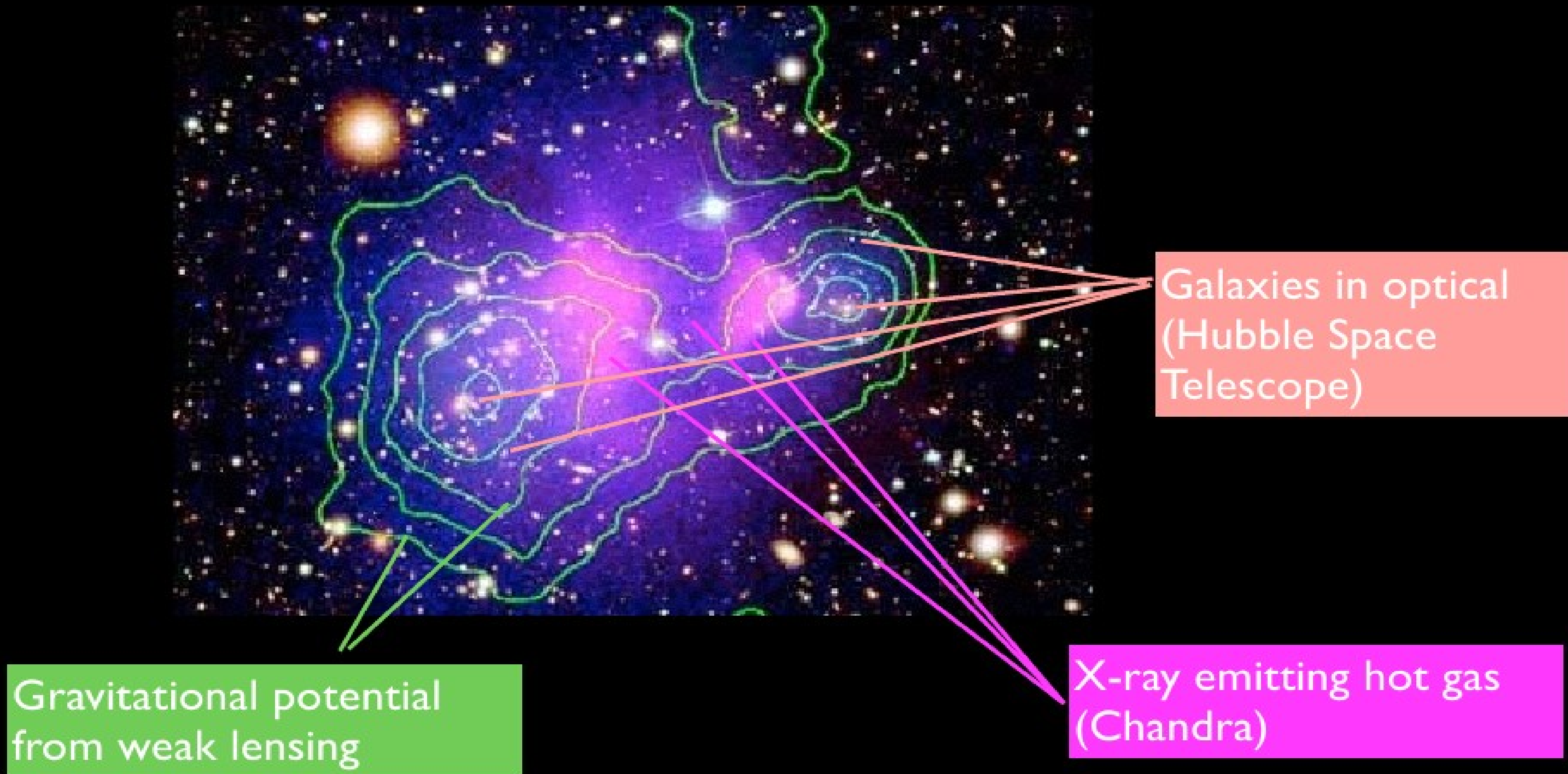
More than 80% of all matter does not couple to the primordial plasma!



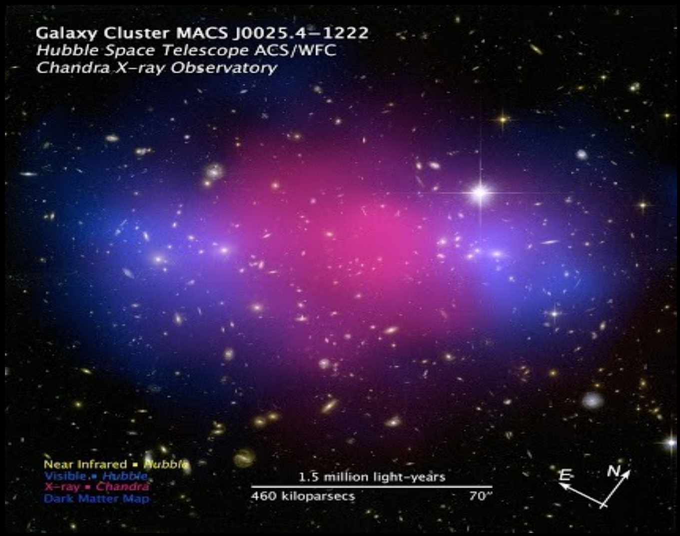
Paolo Gondolo, AAPCOS 2015 SINP

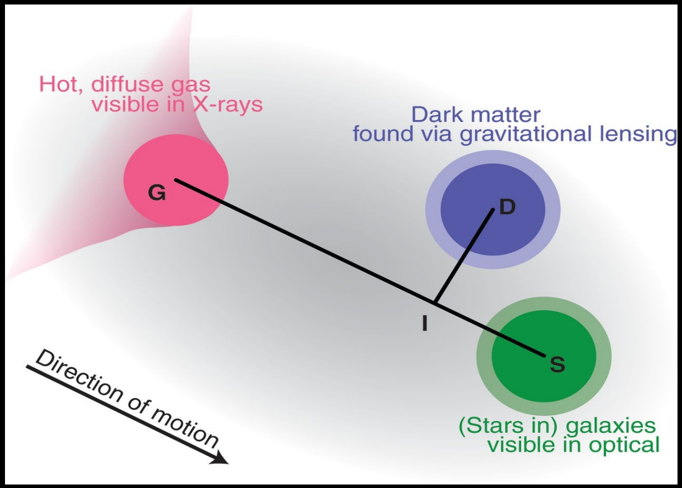
Colliding Galaxy Clusters

“Bullet Cluster”



Colliding Galaxy Clusters





A. Presence of DM at 7.6σ

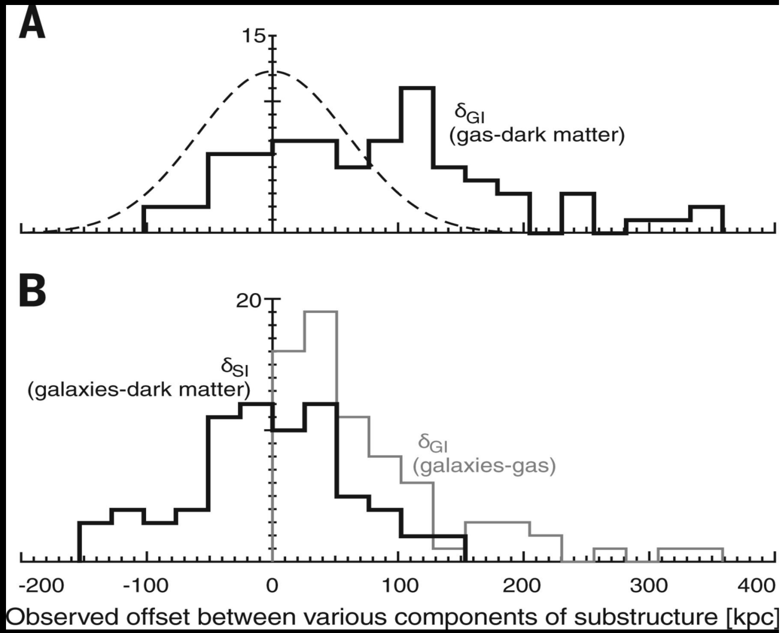
B. (Absence of) lag between stars and DM

$\Rightarrow$ upper limit on DM self − interaction

$$F_{\rm drag}/m_{\rm DM} \sim (\sigma_{\rm DM}/m_{\rm DM})\, v^2 \rho_{\rm DM}$$

$$(\sigma_{\rm DM}/m_{\rm DM}) < 0.47 {\rm cm}^2/{\rm g} = 0.83\, ({\rm barn/GeV})$$

(95% C.L.)

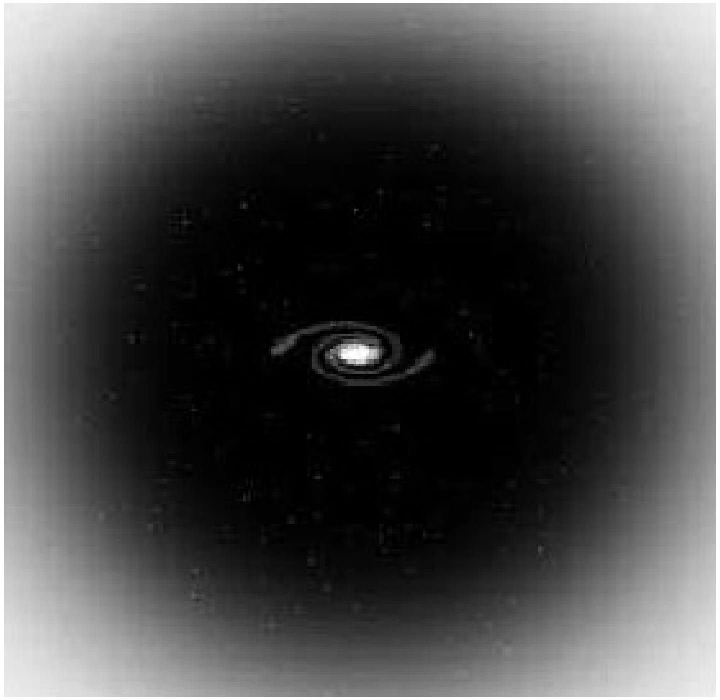


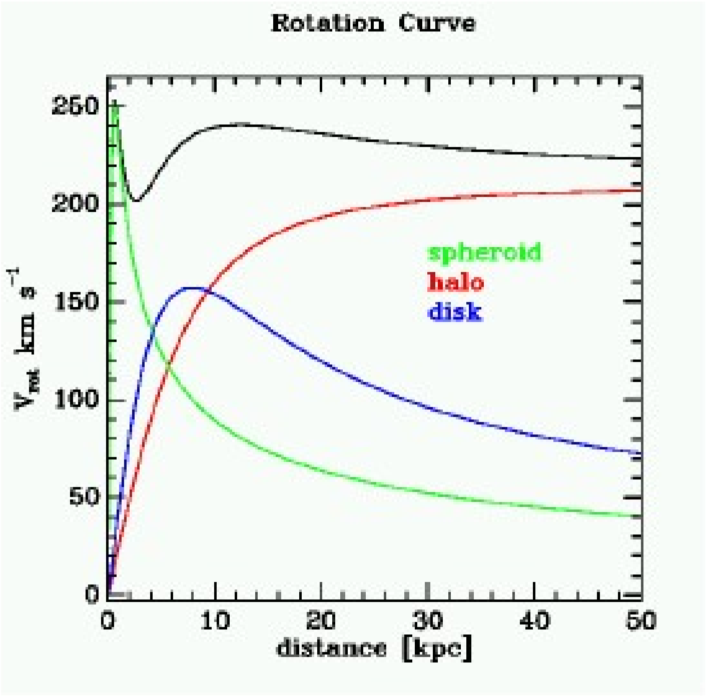
Harvey et al, Science (27 March 2015

DM self-interaction can solve some problems of CDM

Dark Matter in the Galaxy

Mass Models : Dark Matter Halo

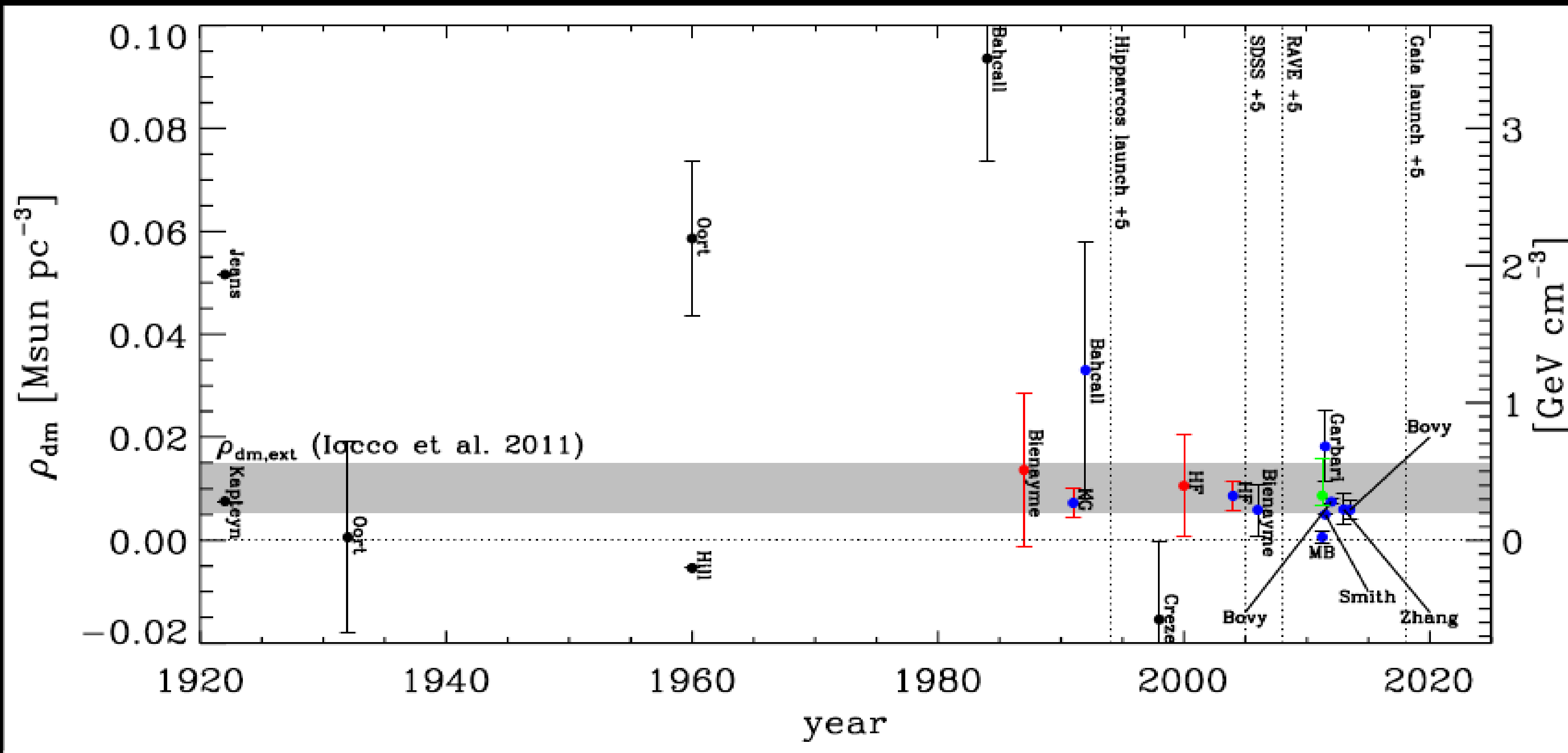




$$\Phi_{\rm total} = \Phi_{\rm visible} + \Phi_{\rm DarkMatter}$$

$$v_c^2 = (v_c^2)_{\rm vis} + (v_c^2)_{\rm DM}$$

Dark Matter Density near the Solar System



$$\rho_{\rm dm} = 0.33^{+0.26}_{-0.075}\,{\rm GeV\,cm^{-3}}$$

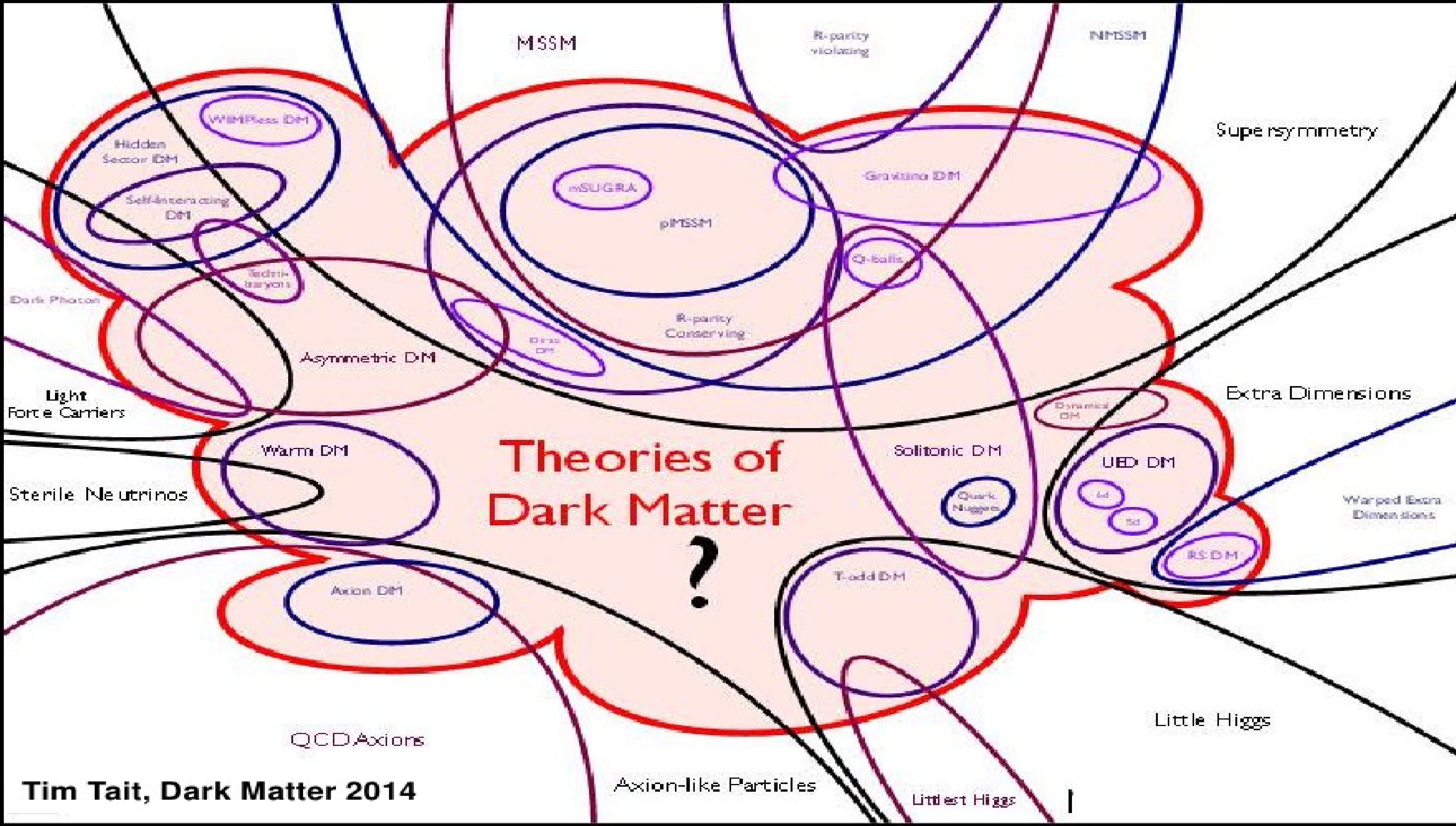
[volume complete; G12*;R14]

$$\rho_{\rm dm} = 0.25 \pm 0.09\,{\rm GeV\,cm^{-3}}$$

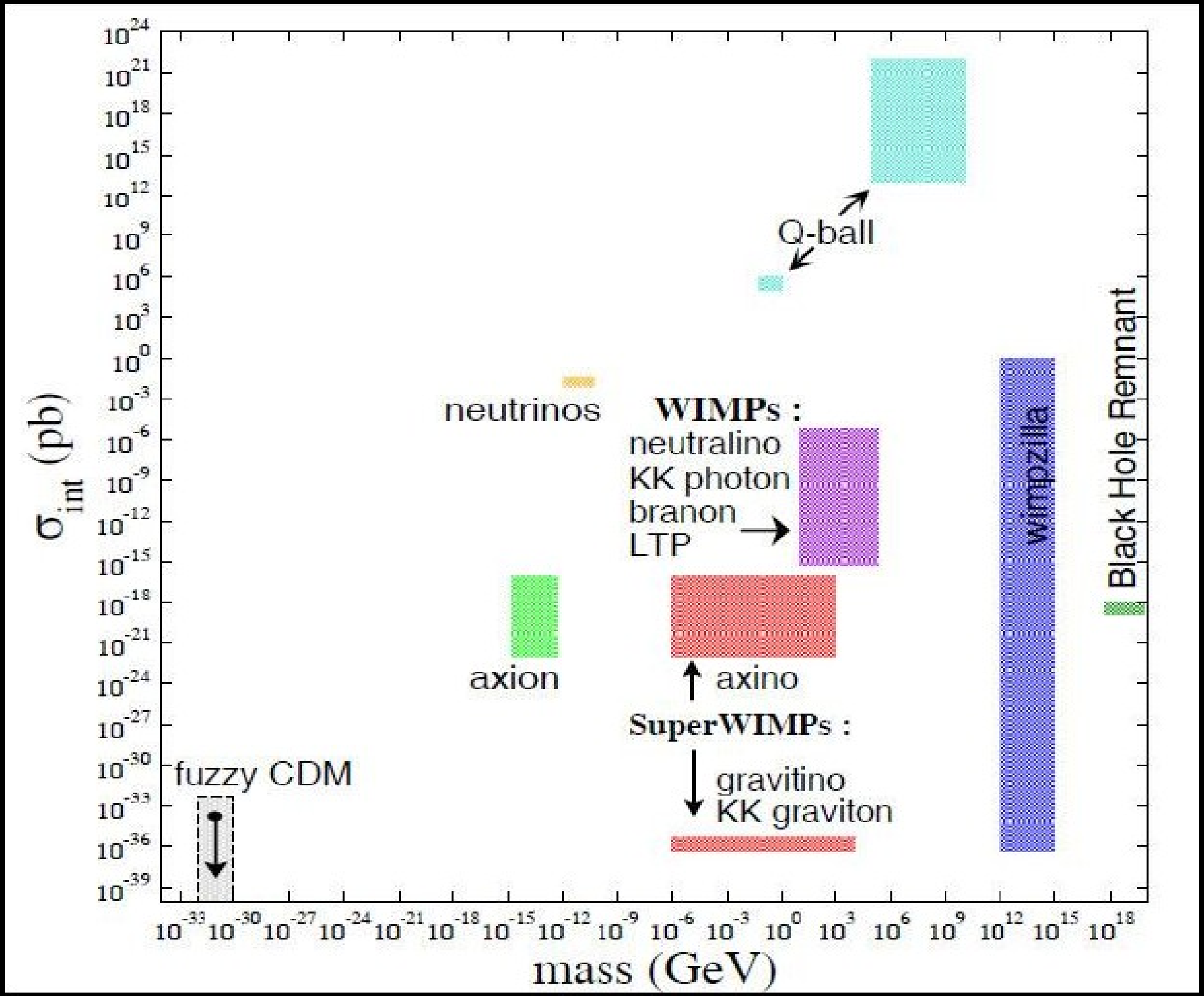
[SDSS; Z13]

Read at IDM 2014

Candidates of DM:
No lack of options!



Scattering Cross Sections



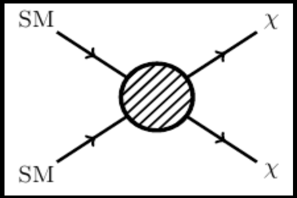
- +
- Hidden sector particles
- Dark photons
- Sterile neutrinos
- Asymmetric dark matter
-
-
-

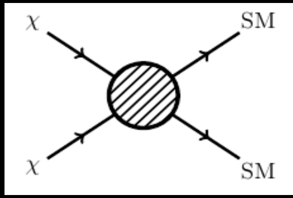
WIMP: Weakly Interacting Massive Particle

The WIMP `Miracle'

DM must be non-baryonic, and can have only very weak interaction with SM particles

Clustering on (sub)Galactic scales => 'cold', i.e., massive, and hence non-relativistic





$\Rightarrow$ Weakly Interacting Massive Particles (WIMPs)

In the sufficiently early universe, WIMPs would be in thermal equilibrium due to thermal production by collision of, and annihilation into, SM particles: $\chi\chi \leftrightarrow f\bar{f}$

In thermal equilibrium, $\left(\frac{n}{s}\right)_{\rm eq} \propto \left(\frac{m}{T}\right)^{3/2} e^{-m/T}$

$\Rightarrow$ If thermal equilibrium prevailed till today, present-day abundance would be negligible! But, ...

The WIMP Miracle …

Annihilation rate $\Gamma_{\rm ann} = n < \sigma v >_{\rm ann} \propto T^{3+p}$

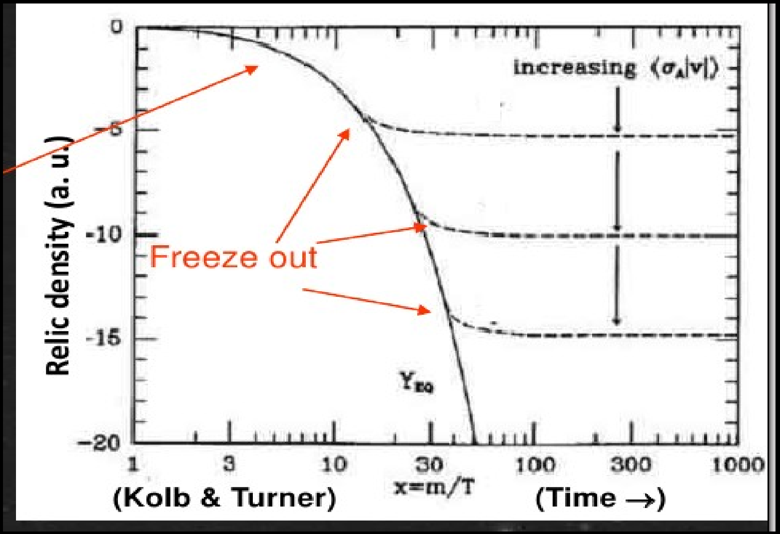
since $n \propto T^3,\ < \sigma v >_{\rm ann} \propto T^p\ [p = 0(1)\ {\rm for}\ s(p)\ {\rm wave\ ann}]$

But expansion rate $H \propto T^2$ So, at some T=T_f, at which $\Gamma_{\rm ann}(T_f) \leq H(T_f)$

The species "freezes out" or "decouples" and leaves the exponentially falling abundance curve

Present -day abundance:

$$\Omega_{\rm WIMP} \propto < \sigma v >^{-1}$$



The WIMP Miracle …

WIMP abundance today:

$\Omega_\chi h^2 \sim 0.1 \left(\frac{3 \times 10^{-26}\,\mathrm{cm}^3/\,\mathrm{sec}}{\langle \sigma v \rangle} \right) + \log$ corrections

Typically, $\sigma \sim \alpha^2 / \mathrm{m}_\chi \sim 10^{-8}\,\mathrm{GeV}^{-2} \sim 4 \times 10^{-36}\,\mathrm{cm}^2$ (with $\alpha \sim 10^{-2}$ $m_\chi \sim 100\,\mathrm{GeV}$), and $\langle v \rangle_f \sim 0.25c$. Also, $h \sim 0.7$.

Thus, if there is a WIMP, it is the natural DM candidate! ("WIMP miracle")

The meek (weakly interacting!) shall inherit the Universe!

WIMP annihilation into SM particles ⇒ WIMPs must also have some (weak) interaction (albeit small) with nuclei, via crossing symmetry ⇒ Direct detection of WIMPs may be possible.

Also, WIMPs captured within astrophysical bodies (e.g., Sun) would annihilate ⇒ annihilation products (e.g., neutrinos) may be detectable.

Some numbers

$$\rho_{\rm DM} \approx 0.3\,{\rm GeV\,cm^{-3}}$$

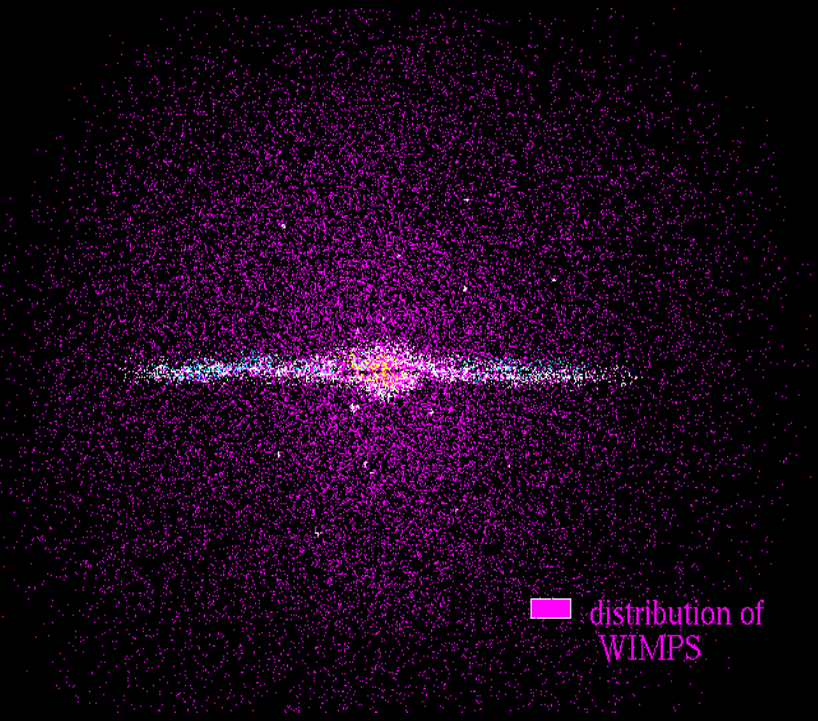
$$n_{\rm DM} \approx 3000\,\left(\frac{100\,{\rm GeV}}{m_{\rm DM}}\right)\,{\rm m^{-3}}$$

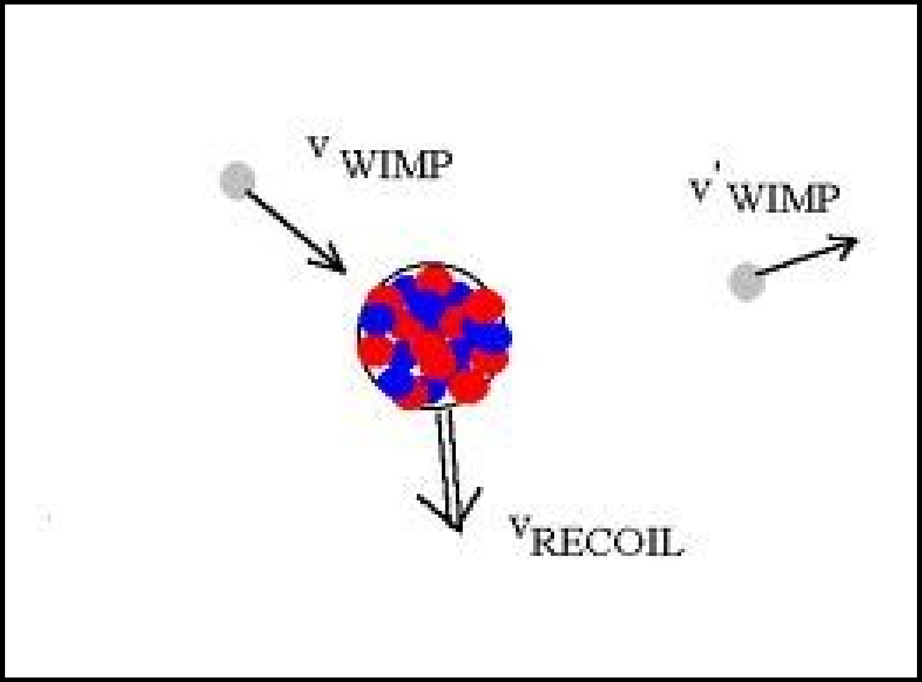
More than 10 million DM particles in this room

Typical speed ~ 300 km/s. Thus, about 10 trillion DM particles will have passed through your body during this presentation!

Can't we detect them?

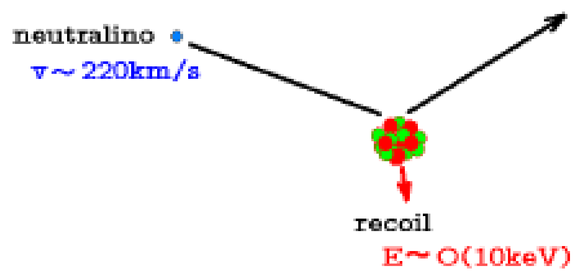
Direct Detection of WIMPs :





Drukier & Stodilsky (1984); Goodman & Witten (1985); Primack, Seckel, Sadulet (1988)

Direct Detection: Order-of-magnitude Estimates



Event rate :

For a single detector nucleus, the rate of WIMP scatterings, $R \sim n_\chi v \sigma_{\chi N}$, gives

$$R \sim 2.7 \times 10^{-24}\,\mathrm{yr}^{-1} \left(\frac{\rho_\chi}{0.3\,\mathrm{GeV\,cm^{-3}}}\right)\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)\left(\frac{v}{300\,\mathrm{km\,s^{-1}}}\right)\left(\frac{\sigma_{\chi N}}{10^{-36}\,\mathrm{cm}^2}\right)$$

No. of nuclei of atomic number A in 1 gm is $6 \times 10^{23}/A$. So, total rate

$$R_{\mathrm{total}} \sim 16\ \ \mathrm{events\,kg^{-1}\,yr^{-1}} \left(\frac{100}{A}\right)\left(\frac{\rho_\chi}{0.3\,\mathrm{GeV\,cm^{-3}}}\right)\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)\left(\frac{v}{300\,\mathrm{km\,s^{-1}}}\right)\left(\frac{\sigma_{\chi N}}{10^{-36}\,\mathrm{cm}^2}\right)$$

Recoil Energy :

For a WIMP of mass m_χ and velocity v striking a nucleus of mass M at rest, $\Delta p \sim m_\chi v$. $\Rightarrow$ Recoil energy of nucleus,

$$E_r \sim (\Delta p)^2/2M \sim 50\,\mathrm{keV} \left(\frac{m_\chi}{100\,\mathrm{GeV}}\right)^2 \left(\frac{v}{300\,\mathrm{km\,s^{-1}}}\right)^2 \left(\frac{100\,\mathrm{GeV}}{M}\right) .$$

Proper calculations :

Recoil energy: $E_R = (\mu^2 v^2/M)(1 - \cos\theta^*)$, where $\mu \equiv m_\chi M/(m_\chi + M) =$ reduced mass, $v =$ WIMP speed relative to the nucleus, and $\theta^* =$ scattering angle in the center of mass frame.

Differential recoil rate per unit detector mass, in units of counts/day/kg/keV :

$\frac{dR}{dE_R} = \frac{\sigma(q)}{2\, m_\chi \mu^2}\, \rho\, \eta(E_R, t) \equiv$ Particle Physics $\otimes$ Astrophysics,

with $q = \sqrt{2ME_R} =$ nucleus recoil momentum, $\sigma(q) =$ WIMP-nucleus cross-section,

$\eta(E_R, t) = \int_{v > v_{\min}} \frac{f(\mathbf{v}, t)}{v}\, \mathrm{d}^3 v$,

$v_{\min} = \sqrt{\frac{M E_R}{2\mu^2}} =$ minimum WIMP velocity that can result in a recoil energy E_R.

$f(\mathbf{v}, t)$ is the (time-dependent) velocity distribution of the WIMPs relative to detector at rest on Earth.

WIMP-Nucleus (Effective) Interaction

The effective WIMP-Nucleus X-section can be obtained from fundamental WIMP-quark/gluon x-section: $\sigma_{\chi-A} \leftarrow \sigma_{\chi-N} \leftarrow \sigma_{\chi-q}$

Spin-independent (SI) interaction:

$$\frac{d\sigma(q)}{dq^2} = \frac{1}{4m_n^2 v^2}\sigma_n A^2 F^2(q)$$

V= WIMP-nucleus relative velocity

Coherence

Form factor: loss of coherence

WIMP-nucleon x-section

WIMP-nucleon reduced mass = nucleon mass for m_WIMP>>m_n

Spin-dependent (SD) Interaction

$$\frac{d\sigma(q)}{dq^2} = \frac{8}{\pi v^2}\Lambda^2 G_F^2 J(J+1) F^2(q)$$

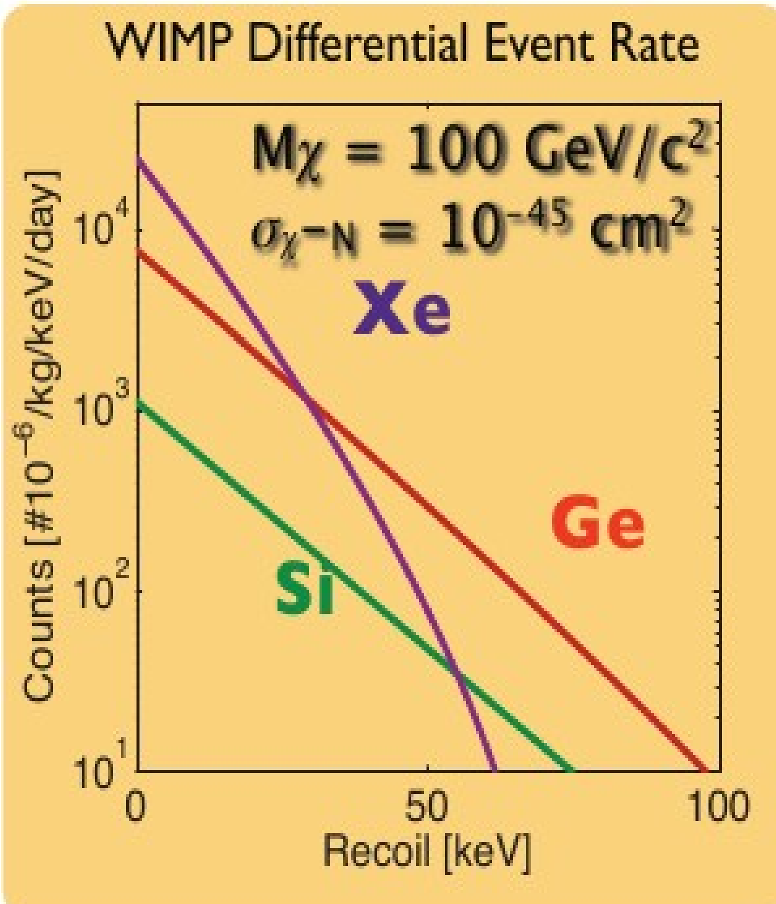
$$\Lambda = \frac{1}{J}\left[a_p \langle S_p \rangle + a_n \langle S_n \rangle\right]$$

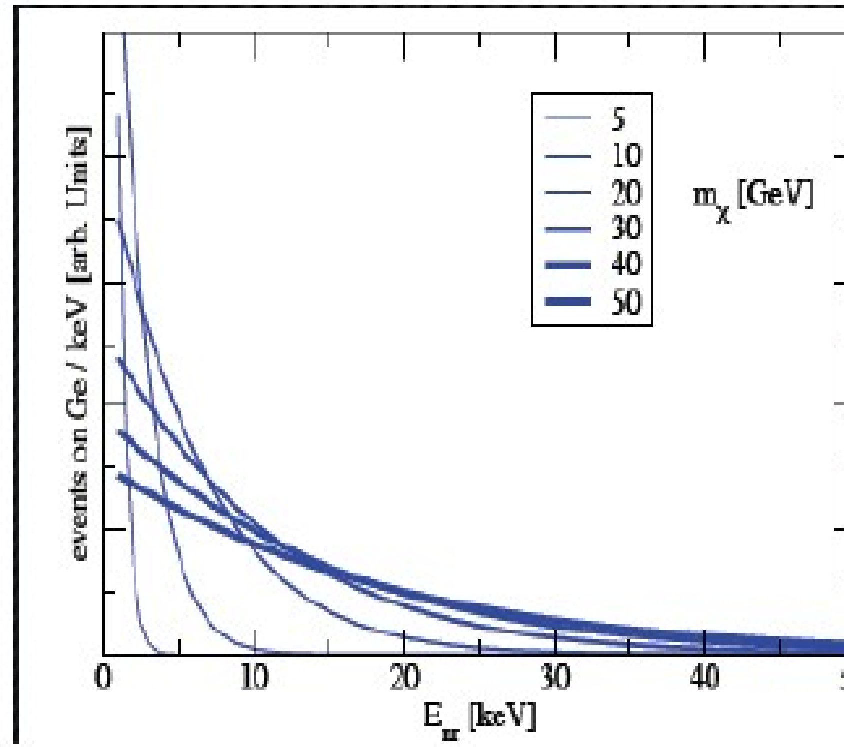
$$\langle S_{p,n} \rangle = \langle N | S_{p,n} | N \rangle$$

measure the amount of spin carried by the p- and n-groups inside the nucleus

a_p, a_n: effective coupling of the WIMPs to protons and neutrons, typically α/m_W^2

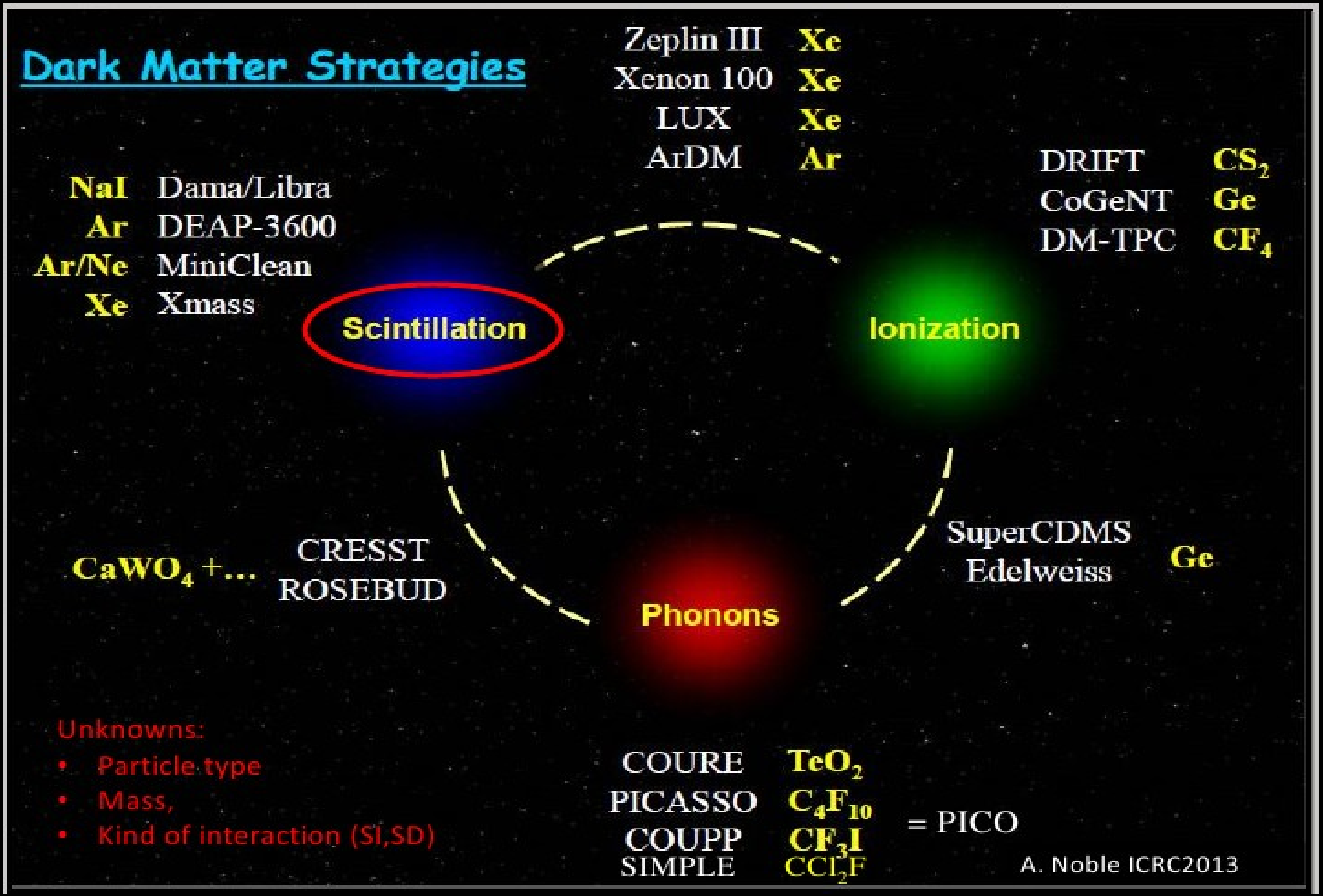
Nuclear Recoil Spectrum



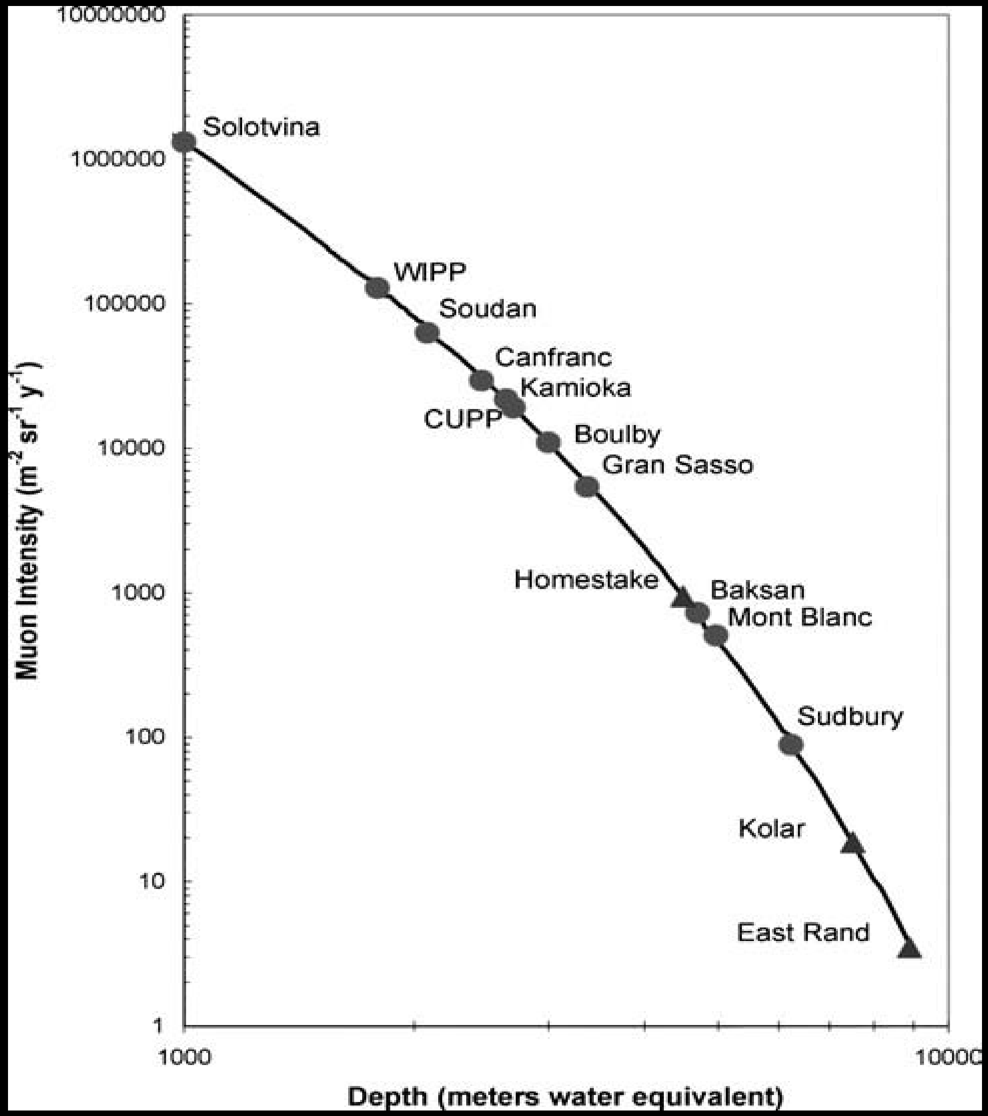


Detection Strategies

The energy deposited by WIMP-induced nuclear recoil in the detector medium manifests as light (scintillation), sound (acoustic waves/phonons) and charge (ionization)



Go Underground to reduce Cosmic Ray Background



J. Formaggio and C. Martoff, Ann. Rev. Nucl. Part. Sci. 54 (2004) 361

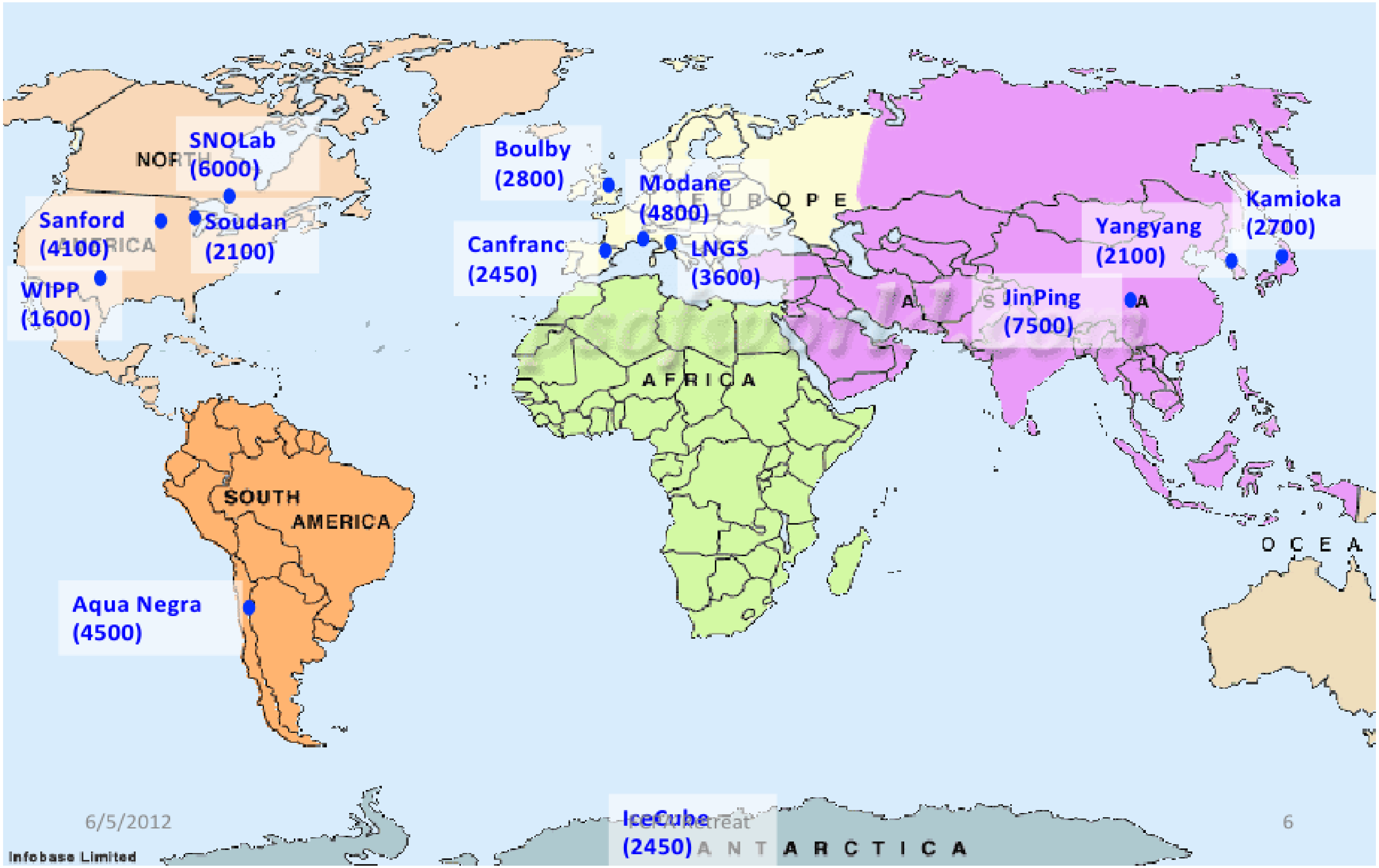
Direct Detection Technology Summary

Project	Strengths	Weaknesses
Cryogenic Ge detectors (CDMS, Edelweiss, CRESST)	Proven background rejection, experience	Expensive to build/test detectors
Threshold Detectors (COUPP, SIMPLE, PICASSO)	Ultimate EM rejection, inexpensive, easy to change target material	Alpha backgrounds, no energy spectrum, scaling to large mass?
Single-phase LAr, LXe (DEAP, Clean, XMASS)	Simple and reasonably inexpensive	Not clear if rejection good enough, E thresholds high
Dual-phase LAr (Darkside, WARP)	Excellent EM rejection and relatively inexpensive compared with Xe, Ge	39Ar reduction needed, ~x10 more target mass needed than Ge or Xe, E threshold high
Dual-phase LXe (Xenon, LUX)	Suitable target for both SI and SD, low E threshold possible	Poor intrinsic EM rejection, low E performance not understood
Low pressure TPCs (DMTPC, Drift)	Directional detection of WIMPs possible	Very hard to get sufficient target mass, backgrounds unknown
Scintillating Crystals (DAMA/LIBRA, KIMS)	Annual modulation with large target mass	No background rejection. Long-term stability crucial
Ionization Detectors (CoGeNT, DAMIC,...)	Very low E threshold and good E resolution	Background rejection difficult and small target masses

There may not be one clear winner; all experiments run into backgrounds!
More than one technology will be needed to establish a WIMP signal

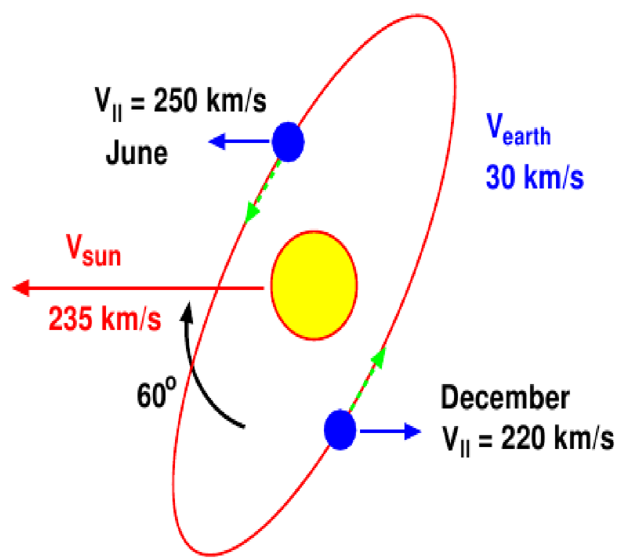
From: Dan Bauer, 2012

Underground Laboratories



Annual Modulation:DAMA Expt.

Modulation Signal



$$f(\mathbf{v},t) = f_{\rm Galaxy}(\mathbf{v} + \mathbf{v}^{\rm Earth}(t))\,.$$

DAMA + DAMA/LIBRA claimed detection based on a claimed positive modulation signal

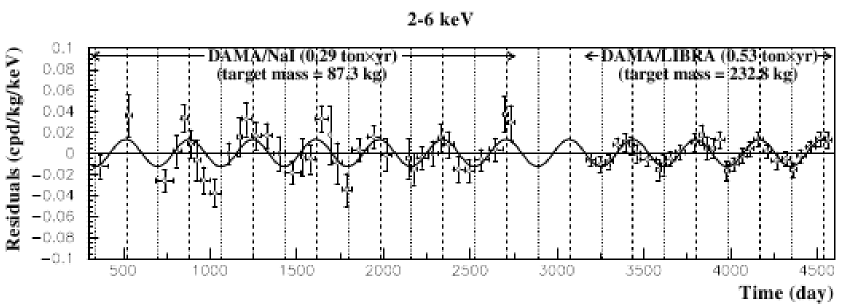
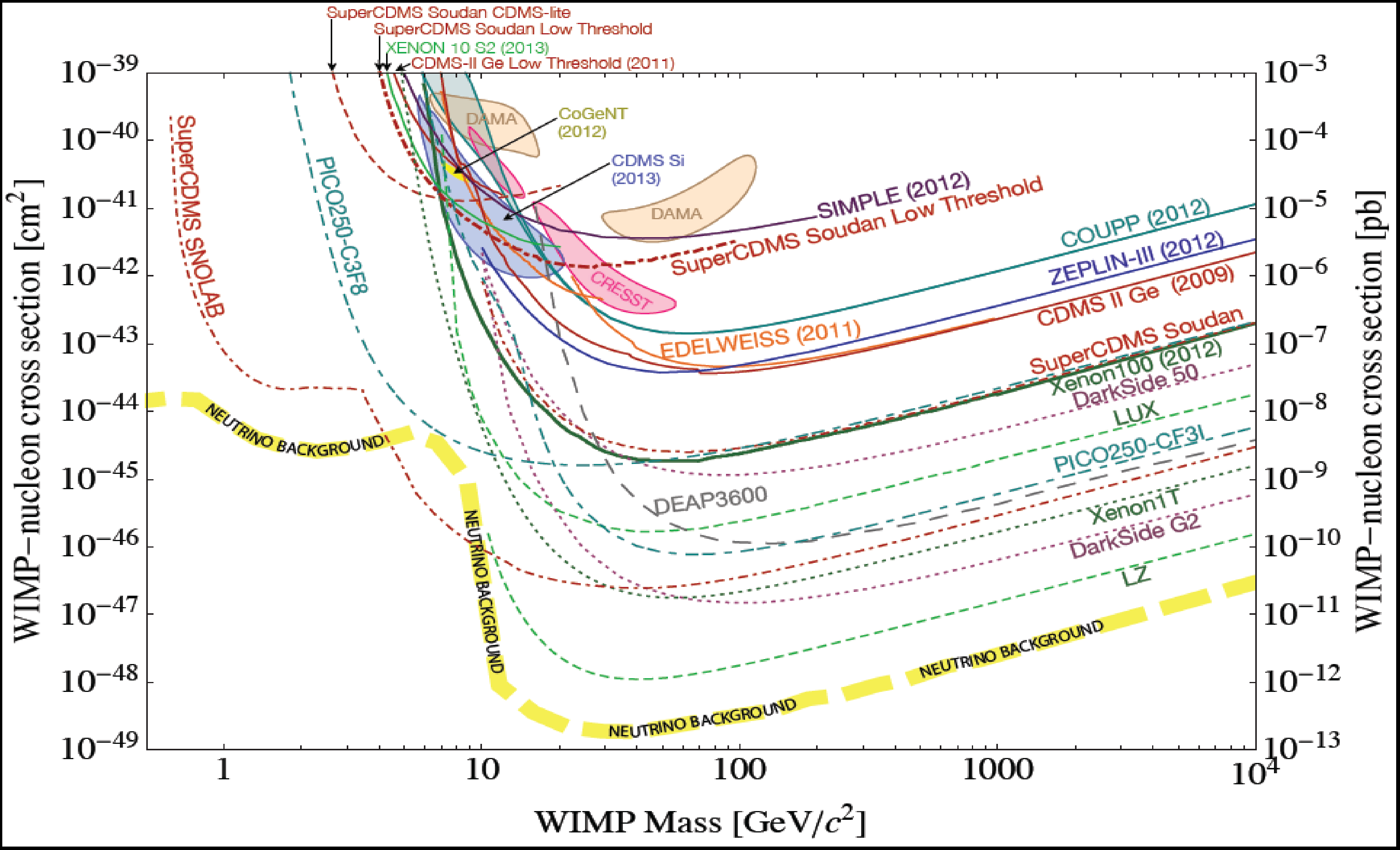


Fig. 9. Annual modulation observed by DAMA NaI and DAMA/LIBRA experiments with recoil energy between 2-6keV. The amplitude is (0.0129 ± 0.0016) cpd/kg/keV against an overall background counting rate of about 1 cpd/kg/keV (corresponding to a relative amplitude of about 1.3 ± 0.1 %). The phase is 144 ± 8 days, with maximum in early June. Details can be found in [108].

Recently, CoGeNT experiment has also claimed detecting an annual modulation in their data

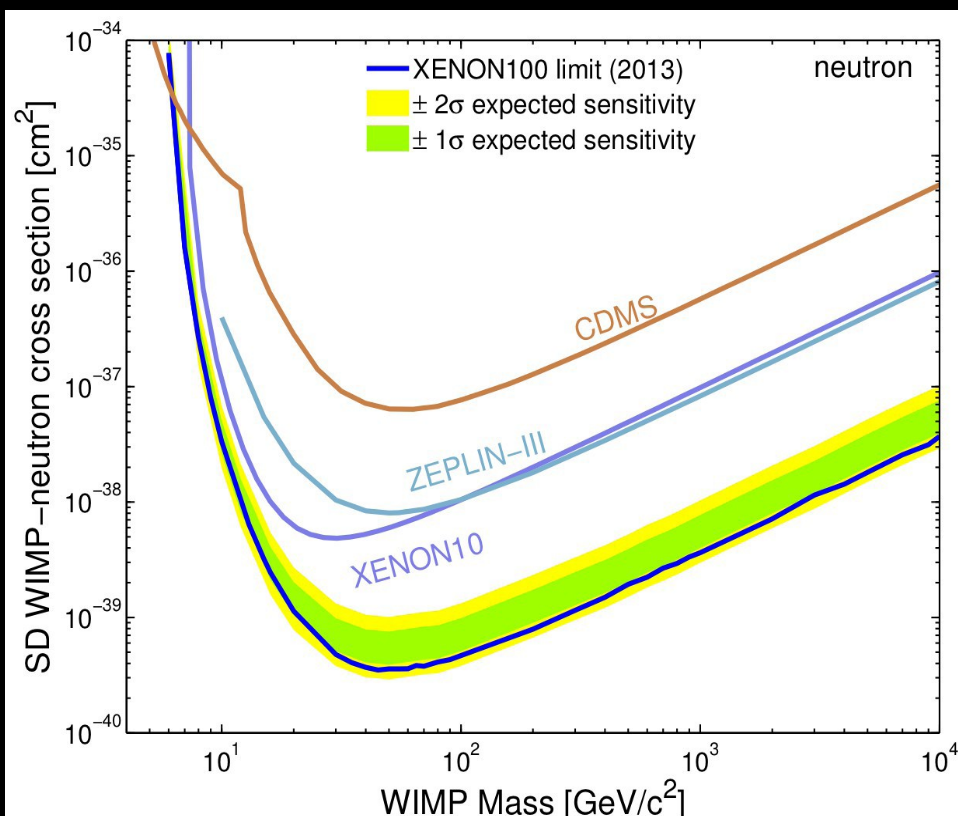
Exclusion Curves (spin-independent interaction)



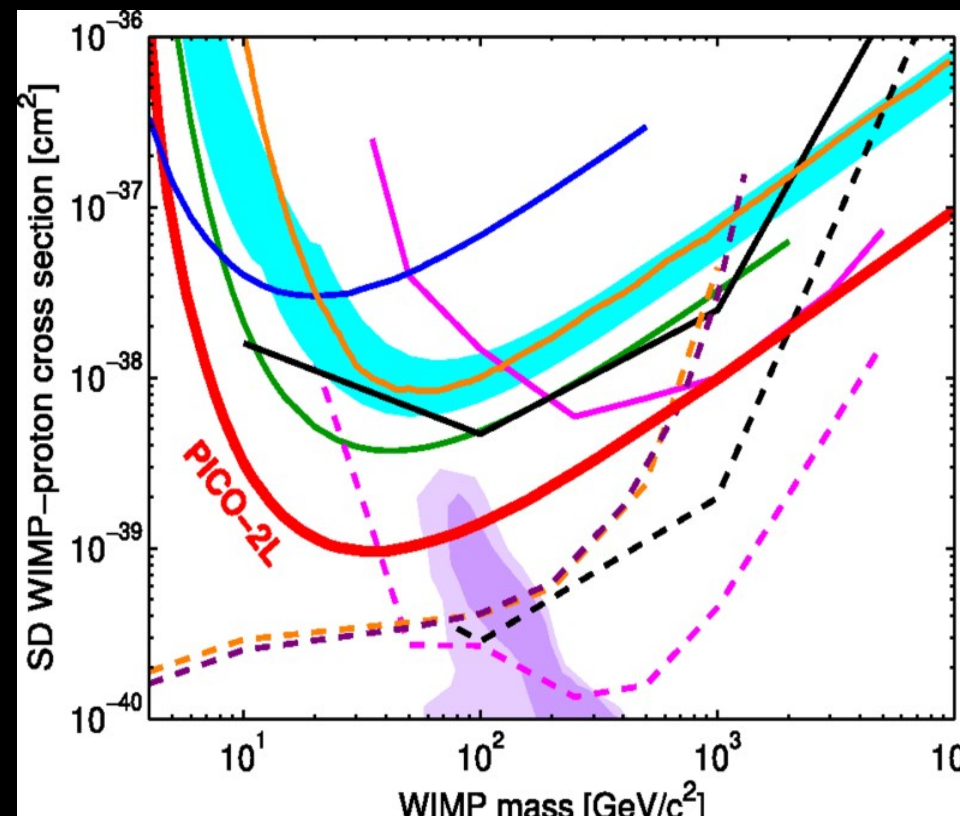
P. Cushman et al, arXiv:1310.8327

Exclusion Curves: Spin-dependent interactions

Aprile et al (XENON100) 2013



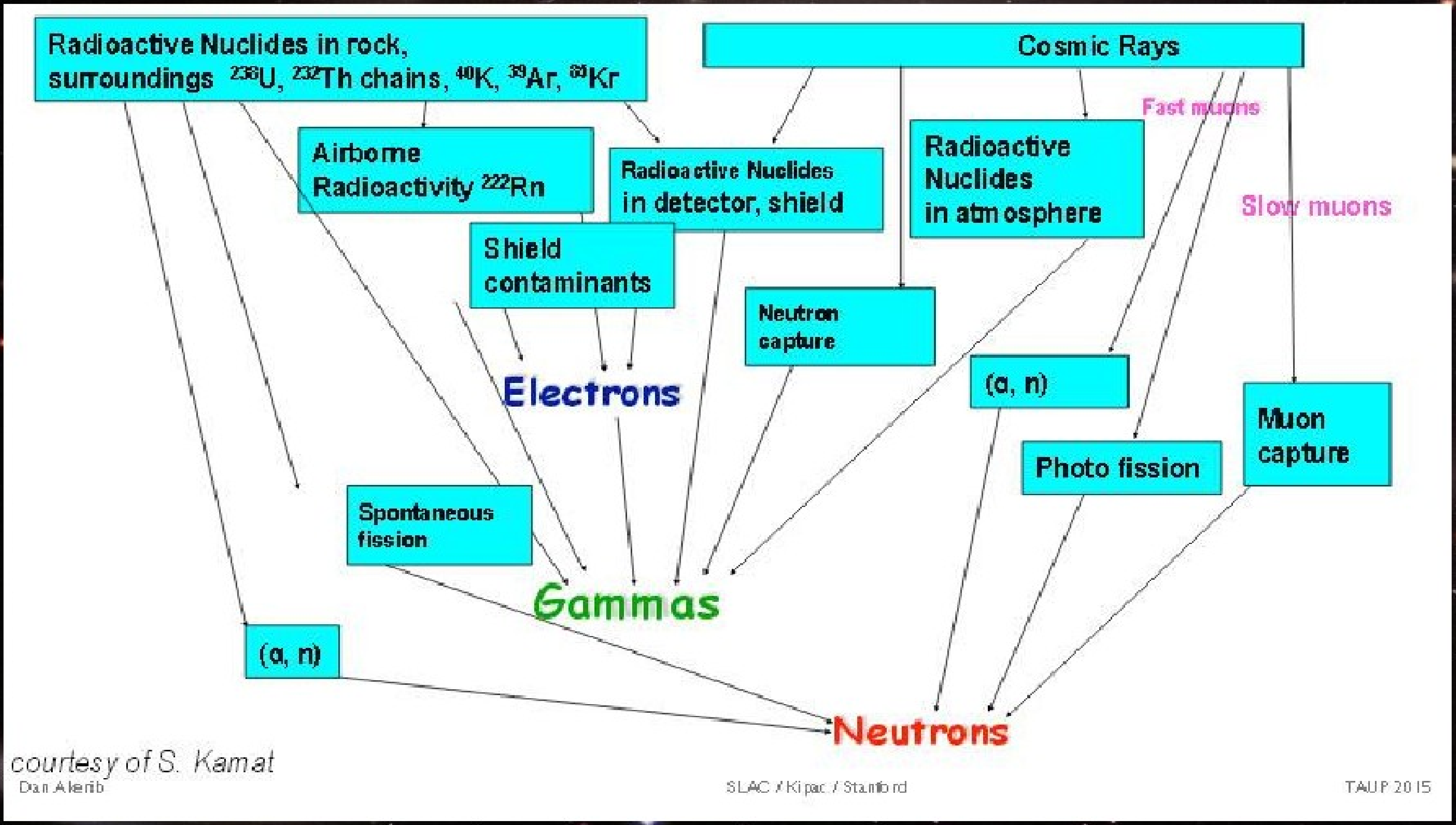
Amole et al (PICO) PRL 2015



(SINP)

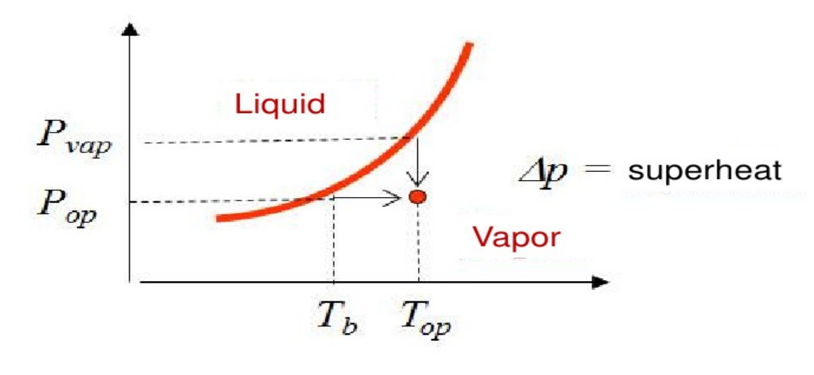
Detecting WIMPS means fighting Backgrounds !

WIMP scatters (< 1 evts /100 kg/ 100 day) swamped by backgrounds (> 10^{6-7} evts/kg-d)



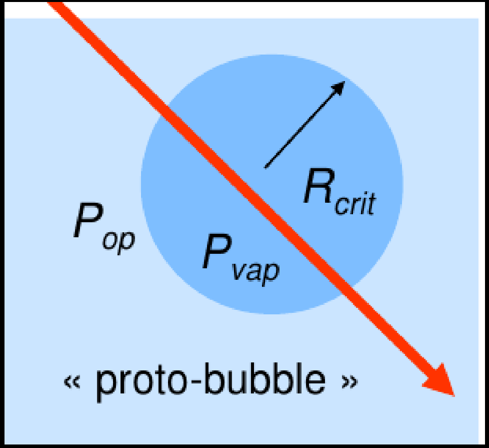
Viktor Zacek (AAPCOS-2015, SINP)

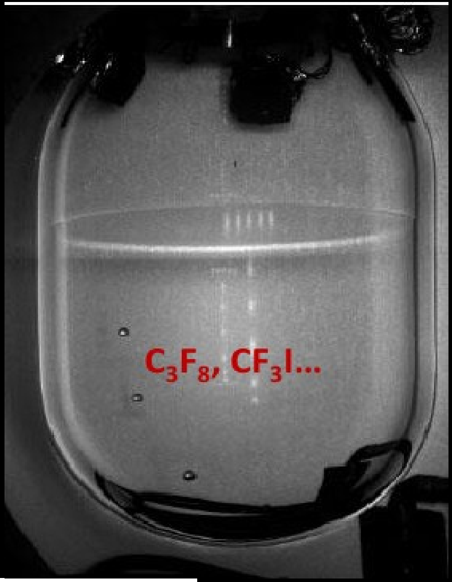
Superheated Liquid as a threshold detector for WIMPs



Bubble chamber principle: (D. Glaser, 1952)

- $E_{dep} < E_{thr}$ within R_{crit} → proto-bubble collapses
- $E_{dep} > E_{thr}$ within R_{crit} → irreversible bubble expansion!





$$E_{dep} = \frac{dE}{dx} \cdot R_{crit} \geq E_{thr}$$

Surface tension

$$R_c = \frac{2\sigma}{\Delta p} \qquad E_{thr} = 4\pi R_c^2 \left(\sigma - T \frac{\partial \sigma}{\partial T} \right) + \frac{4}{3} R_c^3 \rho_v h$$

Crit. Radius — Surface energy — Latent heat

Threshold energy *E_{thr}* is set by varying (T_{op}, P_{op})

Works at room temperature!

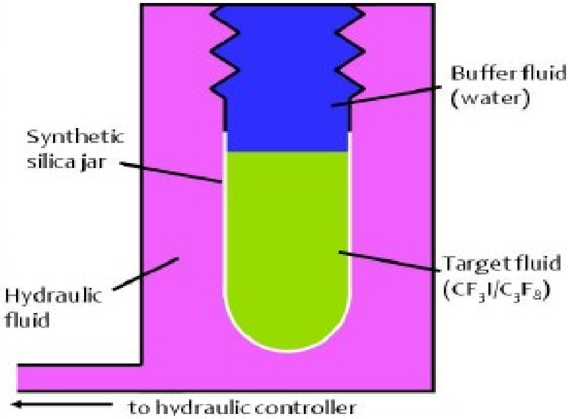
Fluids of choice: Fluorinated halocarbons → SD, SI

- C_4F_{10}, C_5F_{12}, C_3F_8, CF_3I, ... (right surface tension)
- But in principle any liquid

Spin Independent Interactions

Spin Dependent Interactions

Technical Realizations

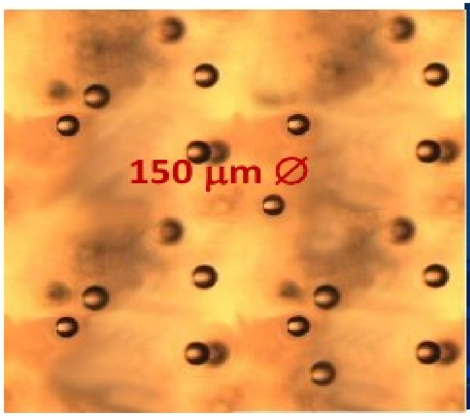


Bubble chambers

Acoustic & optical read out

Droplet detectors

Acoustic read out



Condensation chambers "Geyser"

Acoustic & optical read out

Viktor Zacek

Fluorine – good for spin-dependent WIMP search

Isotope	Spin	Unpaired	λ^2
^{7}Li	3/2	p	0.11
^{19}F	1/2	p	0.863
^{23}Na	3/2	p	0.011
^{29}Si	1/2	n	0.084
^{73}Ge	9/2	n	0.0026
^{127}I	5/2	p	0.0026
^{131}Xe	3/2	n	0.0147

$$\sigma = \frac{32 G_F^2 m_r^2}{\pi} \underbrace{\frac{J+1}{J}\left[a_p \langle s_p \rangle + a_n \langle s_n \rangle\right]^2}_{\lambda^2}$$

- Fluorine one of the more favourable targets

Courtesy: Tony Noble

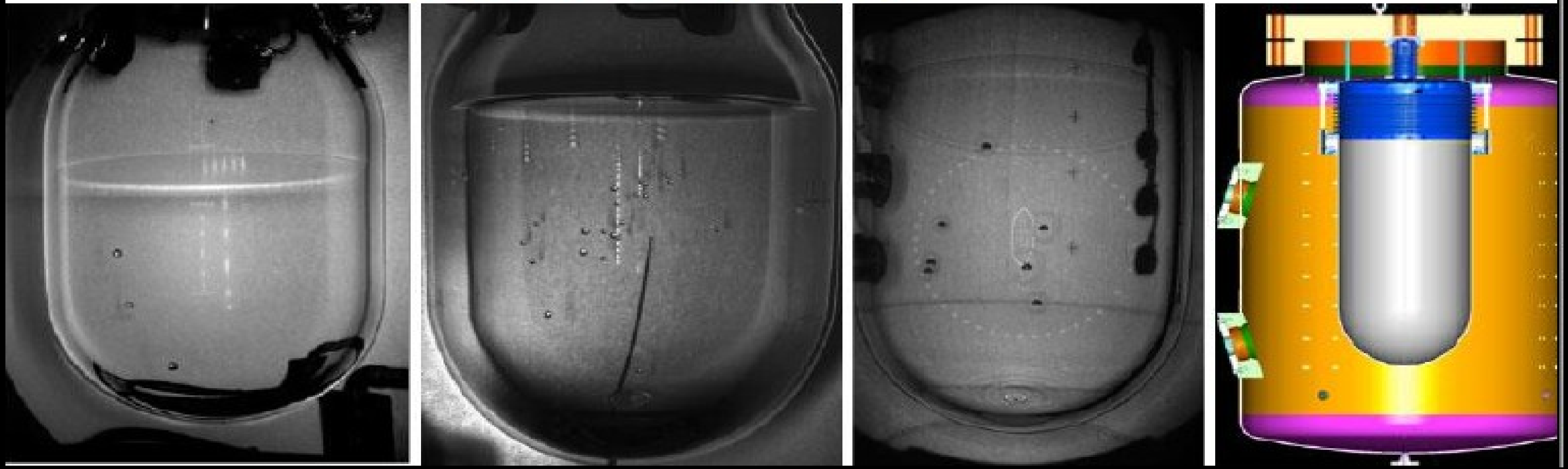
PICO

Merger of PICASSO and COUPP Collaborations

Queen's, Valencia, PNNL, Northwestern, Saha, FNAL, Toronto, Chicago, Montreal, Laurentian, SNOLAB, Alberta, Mexico, Drexel

- Develop the BC technology with the ultimate goal of building a **tonne scale detector** at SNOLAB
- Fully explore the **Spin-Dependent** sector with F-loaded targets and particular sensitivity to **low mass WIMPs**
- Exploit the **multi target** capacity of this approach (C_3F_8, CF_3I...)

PICO 2L → PICO 60 L → PICO 250 L



PICO Collaboration

Queen's University

C. Amole, M. Besnier, G. Caria, A. Kamaha, A. Noble, T. Xie

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

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Pacific Northwest NATIONAL LABORATORY

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P. Bhattacharjee, M. Das, S. Seth

Fermilab

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I. Lawson, E. Vázquez Jáuregui

VirginiaTech

D. Maurya, S. Priya

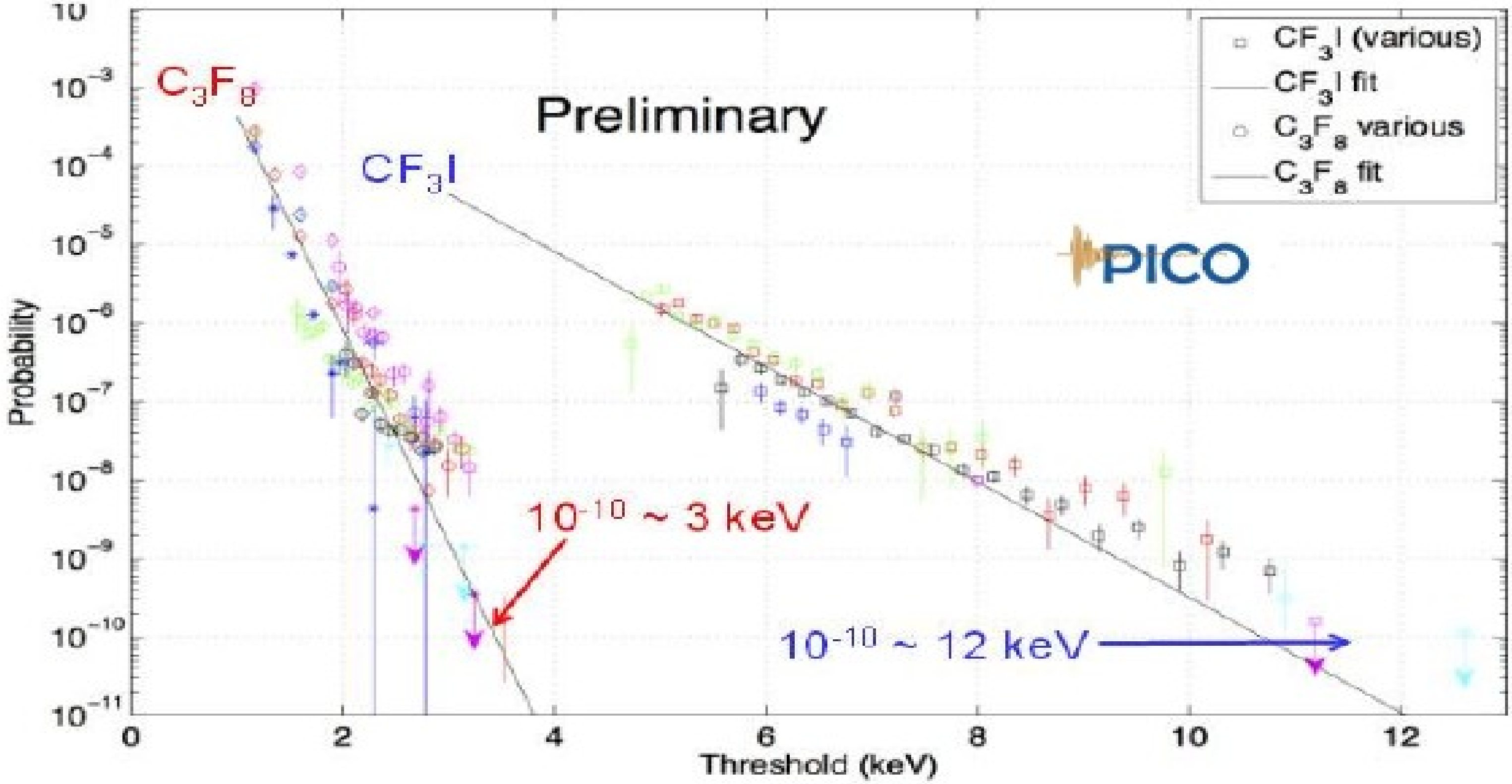
CosPA November 13th, 2013
Russell Neilson, University of Chicago

2

Superheated Liquids and Gamma Rejection

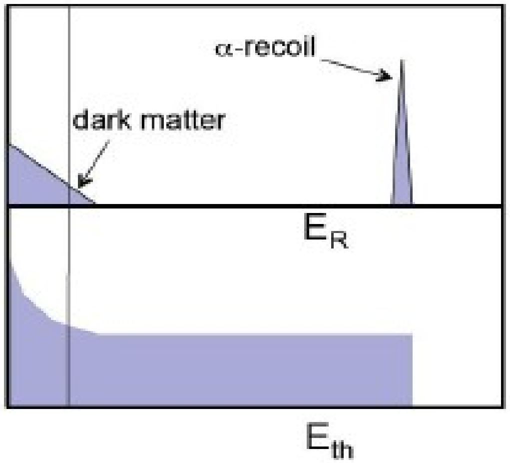
$$E_{dep} = \frac{dE}{dx} \cdot R_{crit} \geq E_{thr}$$

Can set superheat parameters (T, P) such that detector is blind to electronic recoils



10^{-10} rejection or better!

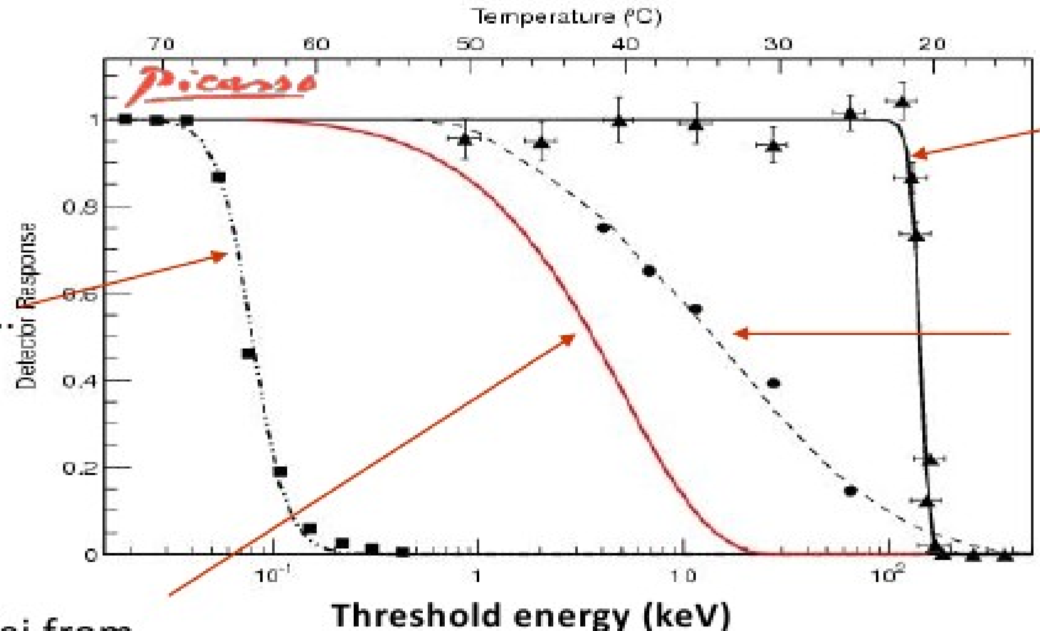
Viktor Zacek (PICASSO/PICO)



Particle Responses

Threshold device with integrating response

$$R(T,P) = \int_{E_{th}}^{\infty} \frac{dN}{dE_R} \, dE_R$$



α-response

γ's from ^{22}Na, ^{60}Co..

Neutrons from AcBe source (data + MC)

Recoil nuclei from 50 GeV /c² WIMP

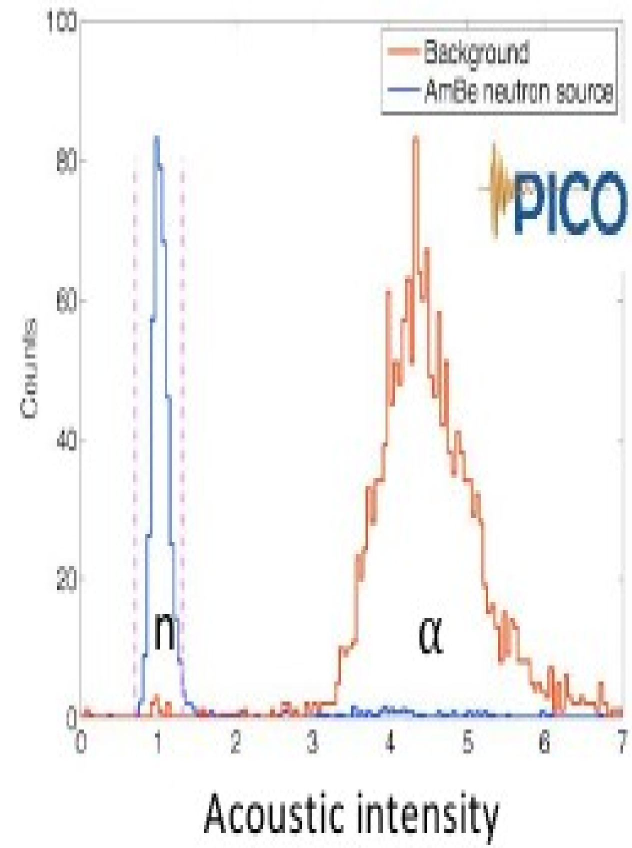
Any α is counted along with DM candidates!

Viktor Zacek

Acoustic Alpha Discrimination

Discovery of acoustic discrimination against alphas by PICASSO (Aubin et al, New J. Phys 10:103017, 2008)

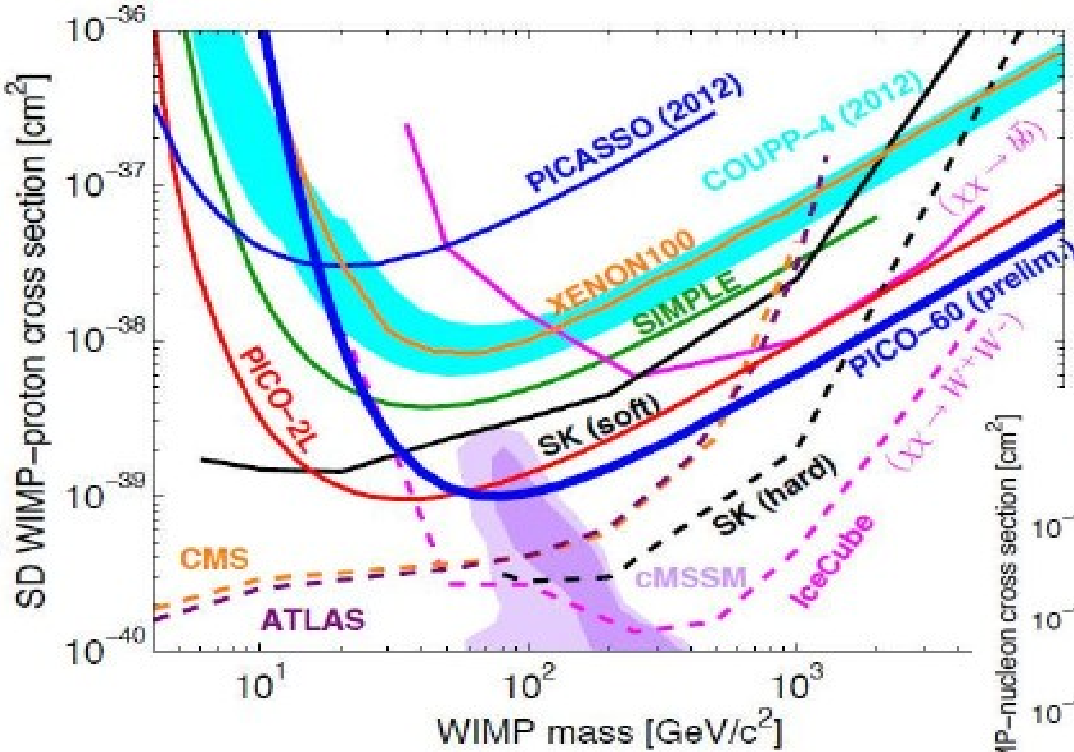
- Alphas deposit energy over tens of microns
- Nuclear recoils deposit theirs in tens of nanometers
- Alphas are several times louder !
- Alpha rejection> 98.2%



Viktor Zacek

PICO 2L @ SNOLAB – Run1

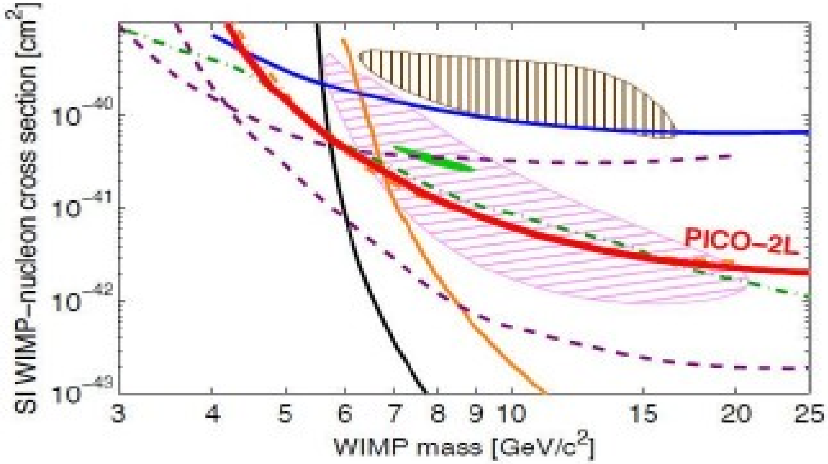
C. Amole et al.: Phys. Rev. Lett. 114, 231302 (2015)



- 212 kgd exposure of C_3F_8
- 4 thresholds (3 – 8 keV)
- 12 anomalous nucl. recoil events
- Timing not random!
- Rejected by optim. interval analysis

No DM signal detected!

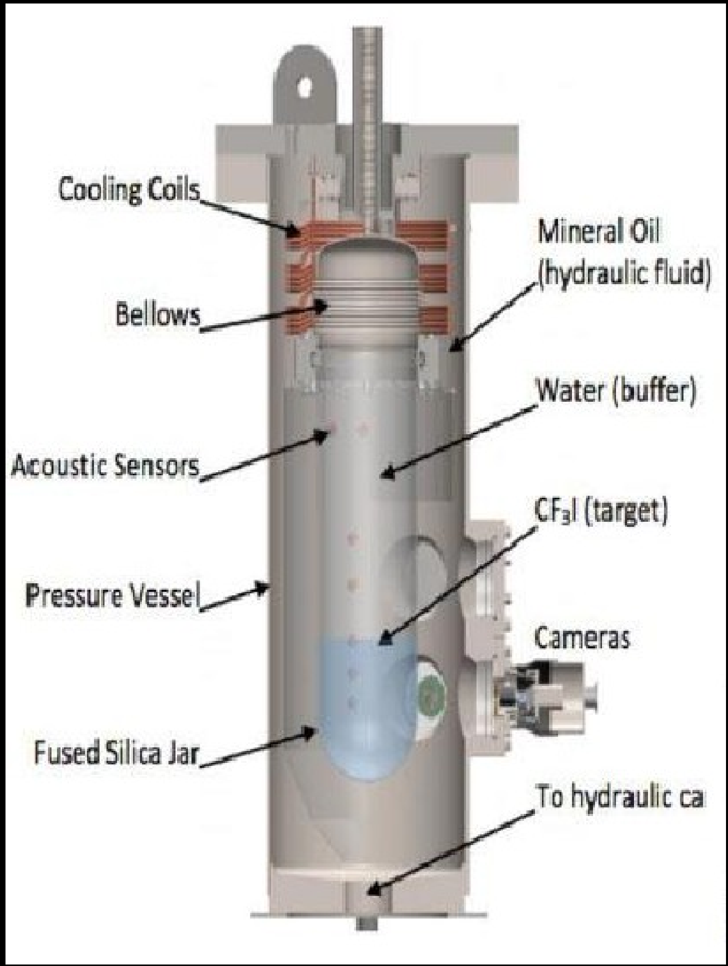
World best Spin Dependent WIMP-proton limits for direct detection!



Spin Independent results challenge signal claims!

Courtesy: Viktor Zacek (PICASSO/PICO)

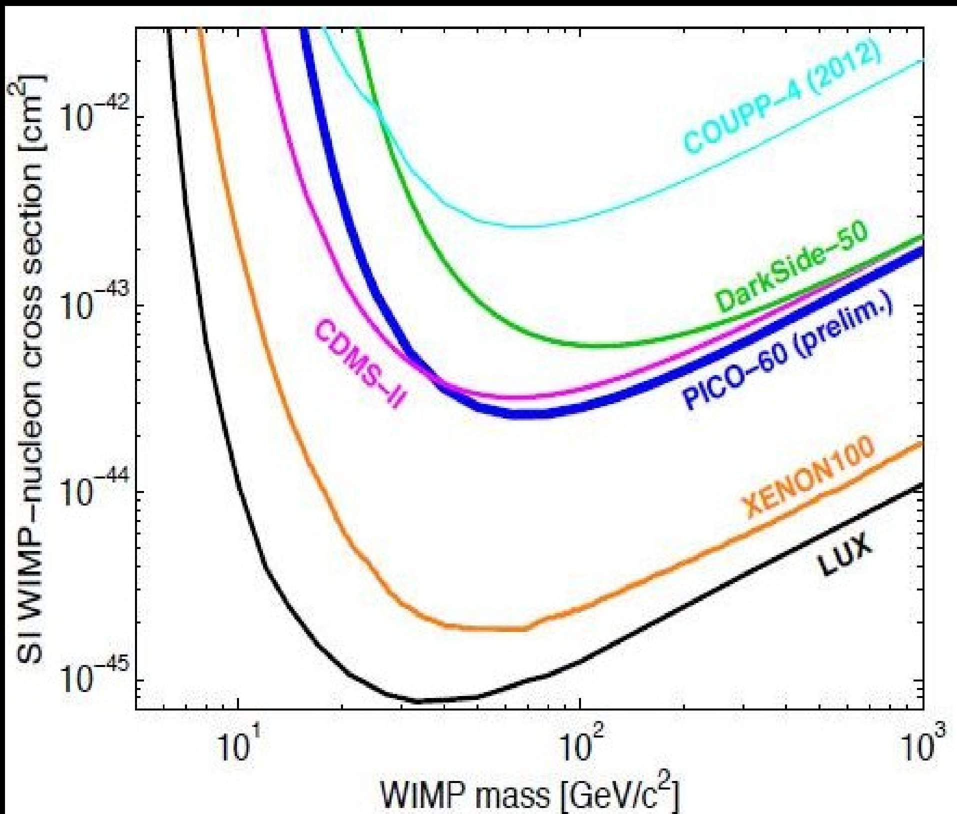
PICO 60 CF_3I @ SNOLAB

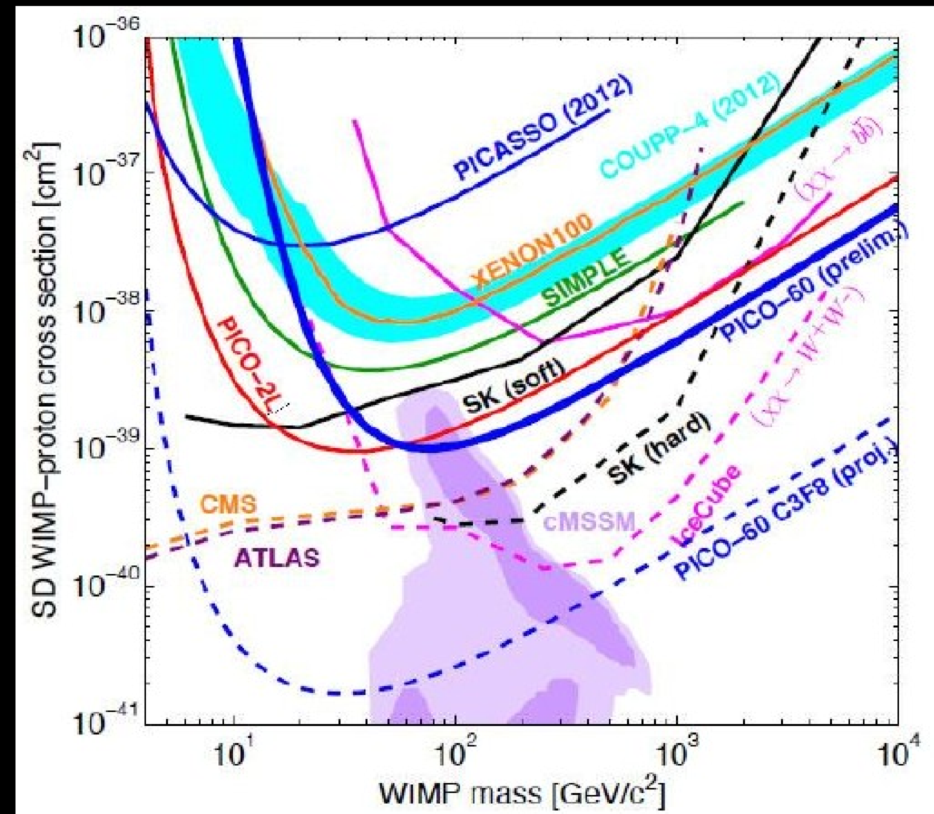


- Largest ever Bubble Chamber for DM search
- 36.8 kg (18.4 Litre) of CF3I
- 3415 kg-days of exposure (between June'13 and May'14

No DM candidates after cuts!

PICO-60 (CF3I) Bubble Chamber @SNOLAB

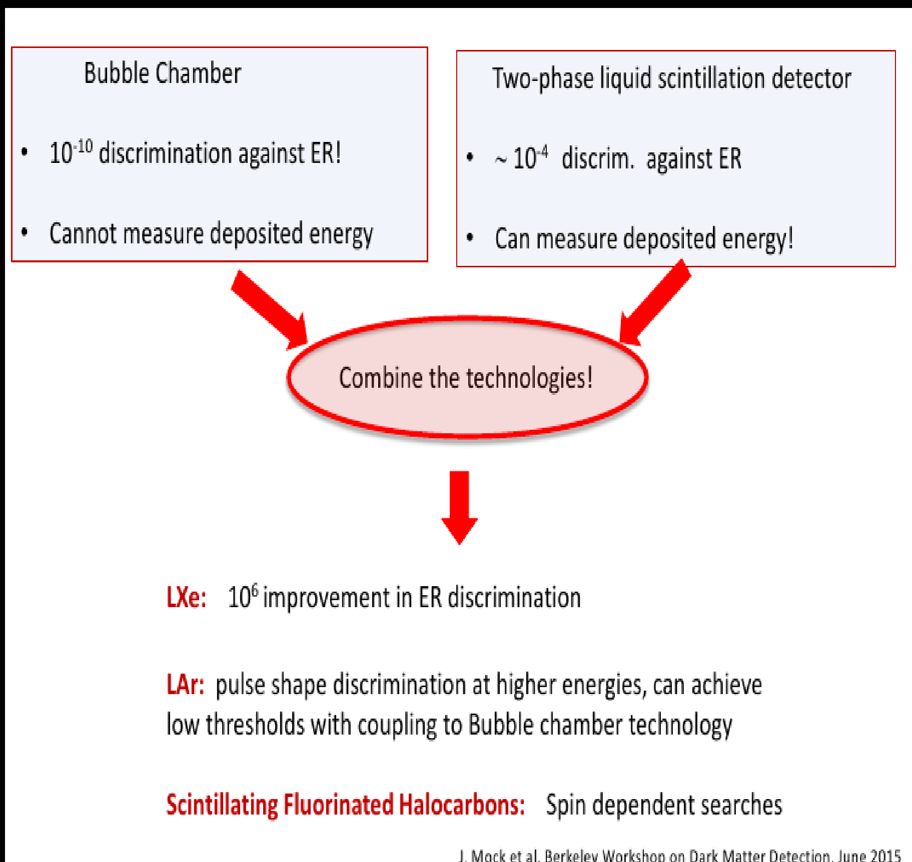


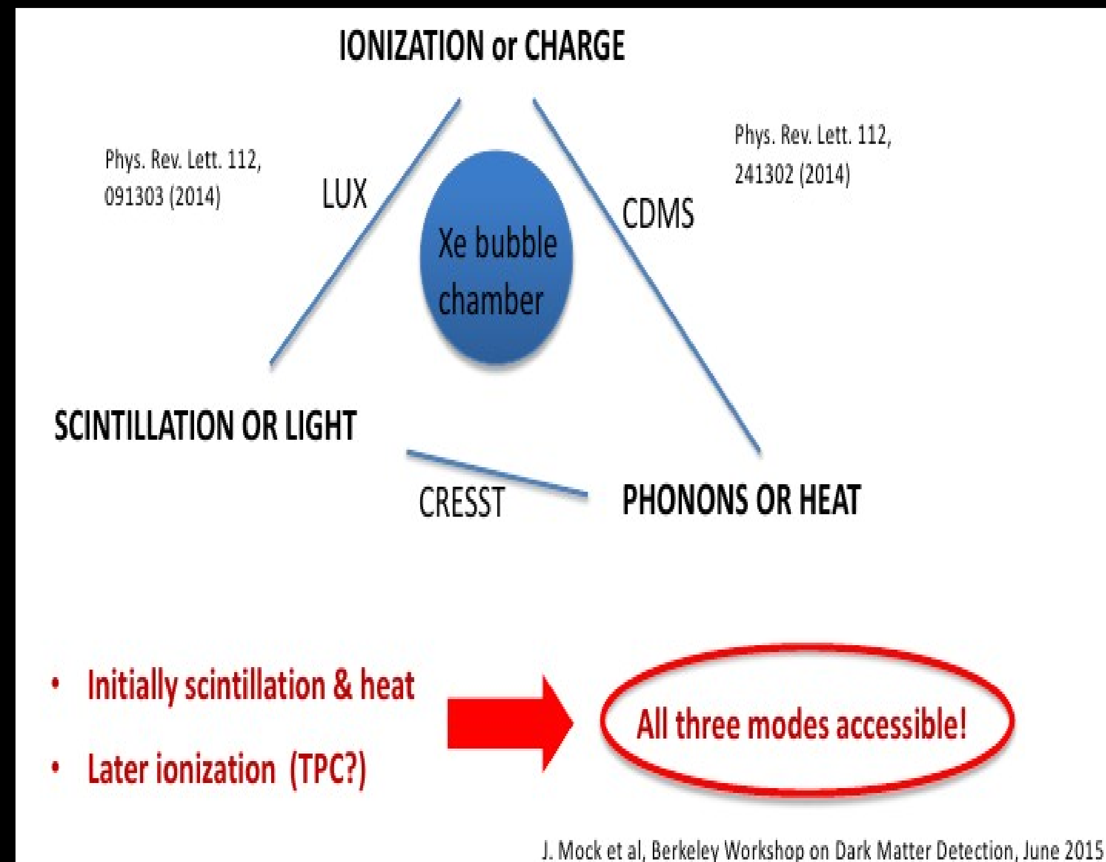


PICO collaboration (arXiv:1510.07754v2)

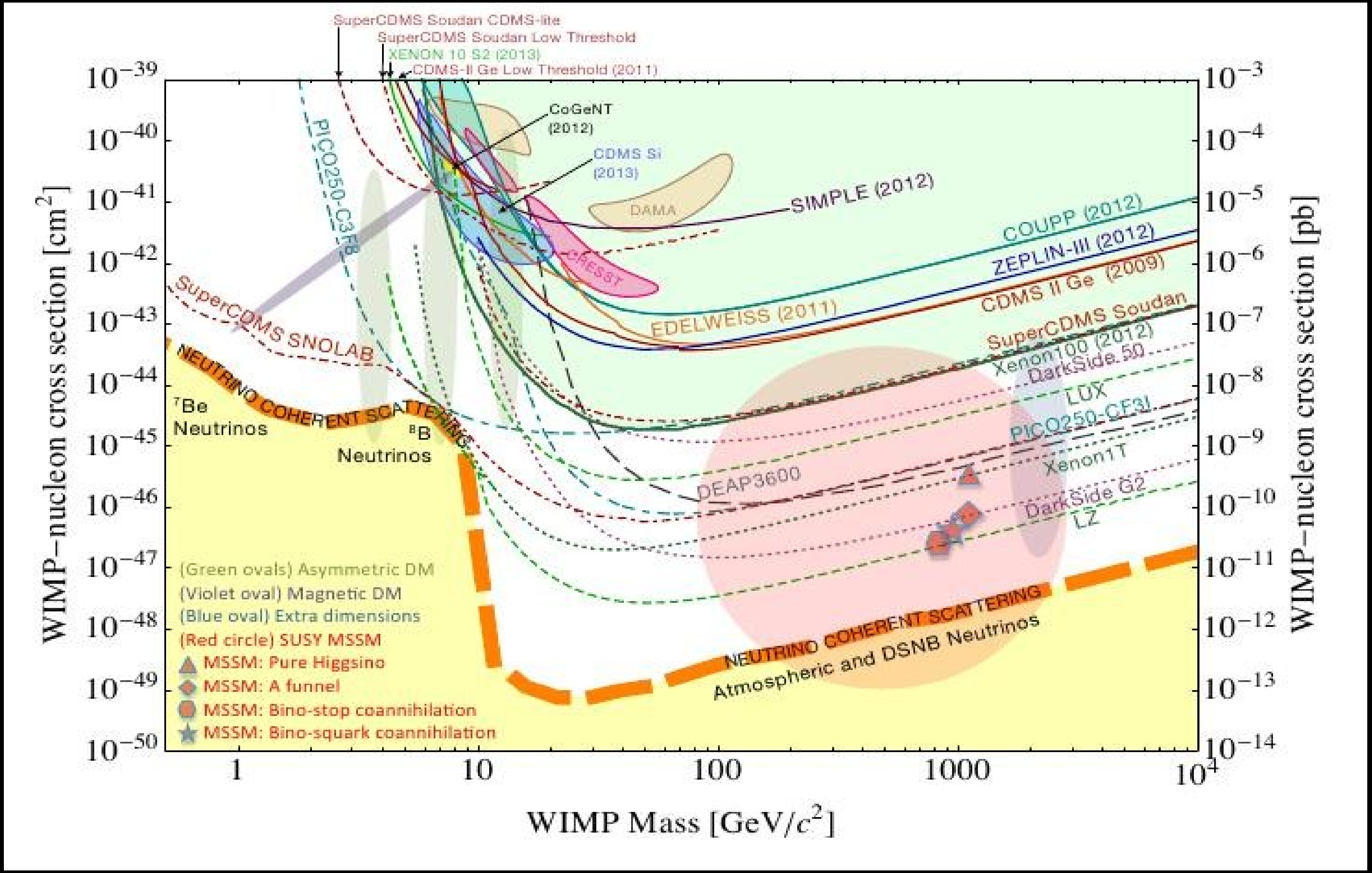
Looking Ahead on Bubble Chambers DM Detection

The Scintillating Bubble Chamber!





Ultimate Background: The Neutrino "Floor"



Cushman et al, arXiv:1310.8327

DM detectors will start detecting astrophysical neutrinos through Coherent Neutrino-Nucleus Elastic Scattering (SM process)!

Detecting SN neutrino with DM detectors

OBSERVING SUPERNOVA NEUTRINO LIGHT CURVE IN ... PHYSICAL REVIEW D **89,** 013011 (2014)

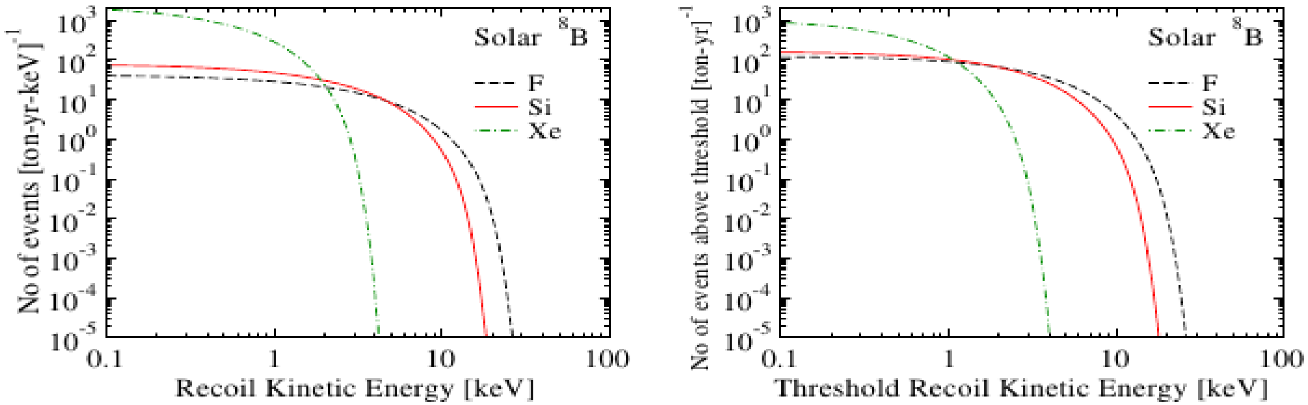


FIG. 1 (color online). Left: Recoil energy spectra (differential event rate as a function of recoil nucleus kinetic energy) for ^8B solar neutrinos in a dark matter detector with three different target materials, namely, ^{19}F, ^{28}Si and ^{131}Xe. Right: The integral recoil energy spectra (total event rate above a threshold recoil energy) as a function of the threshold recoil energy of the detector.

CHAKRABORTY, BHATTACHARJEE, AND KAR PHYSICAL REVIEW D **89,** 013011 (2014)

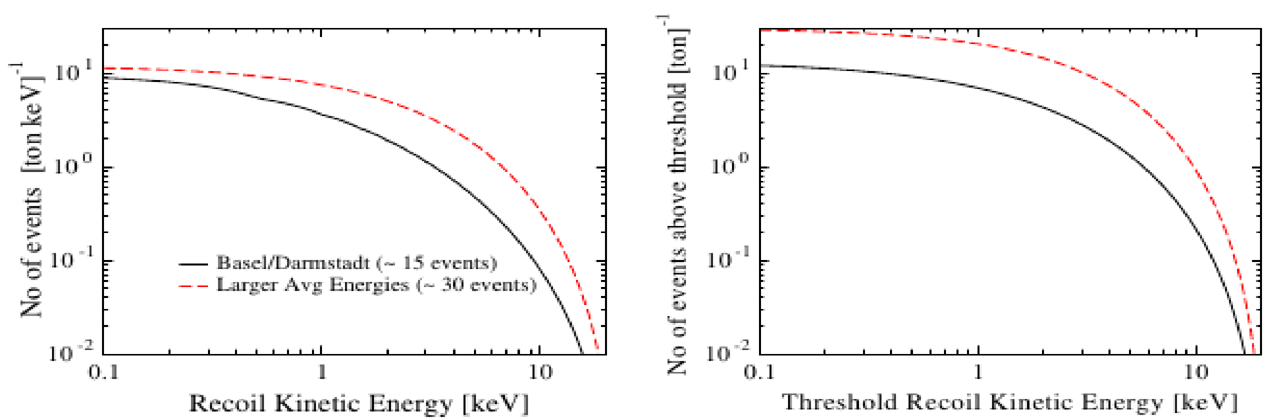
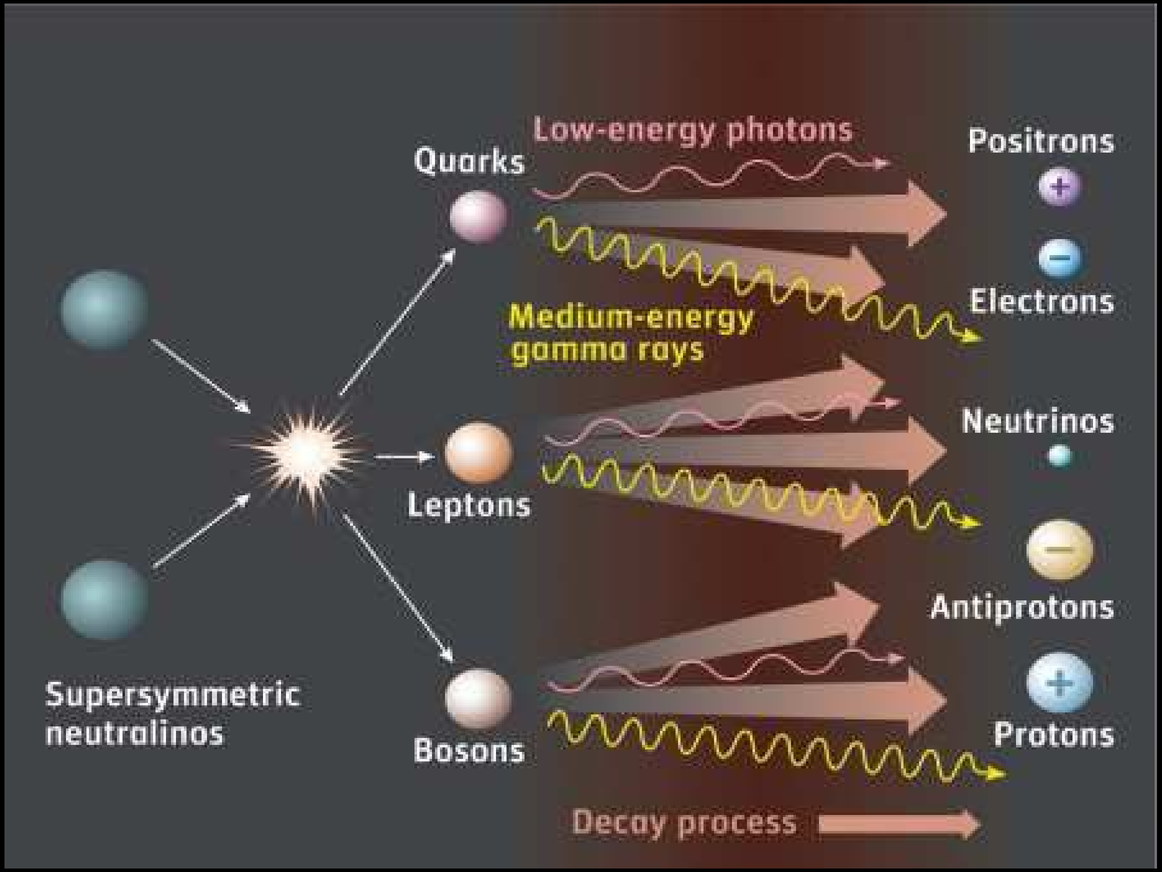


FIG. 5 (color online). Recoil energy differential spectra (left) and integral spectra as a function of the threshold recoil energy (right) for SN neutrinos in a 1-ton Xe detector. Curves are shown for the Basel/Darmstadt SN model as well as for another SN model with average energies of ν_e, $\bar{\nu}_e$ and ν_x equal to 10, 12 and 18 MeV, respectively, both for a SN at a distance of 10 kpc from the Earth.

INDIRECT DETECTION

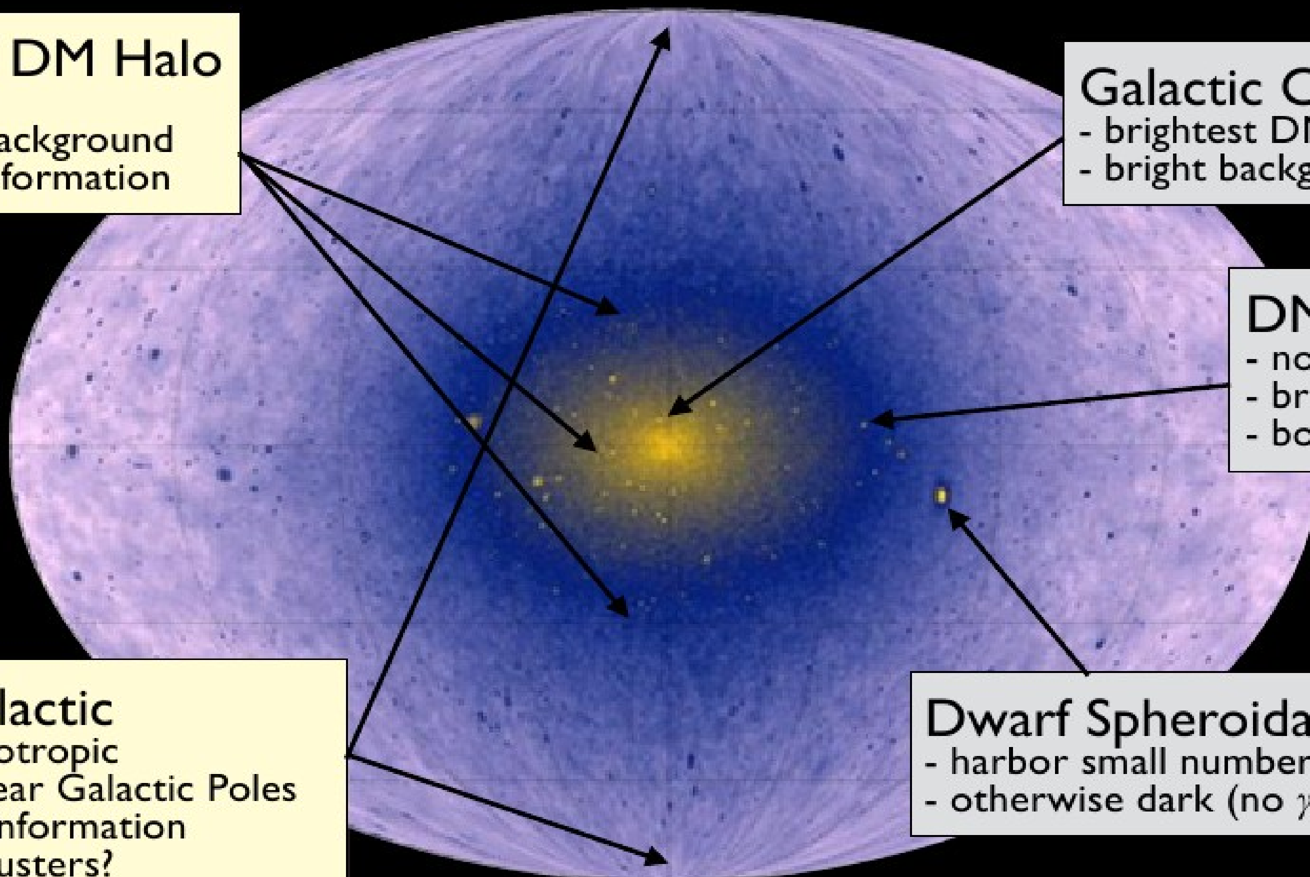


AMS-02: Positron excess in Galactic CR
FERMI-LAT: Gamma rays from WIMP annihilation in dwarf Spheroidal satellites of Milky Way
Super-K, ICECUBE: Neutrinos from WIMP annihilation in Sun
…

Gamma-rays from WIMP annihilation

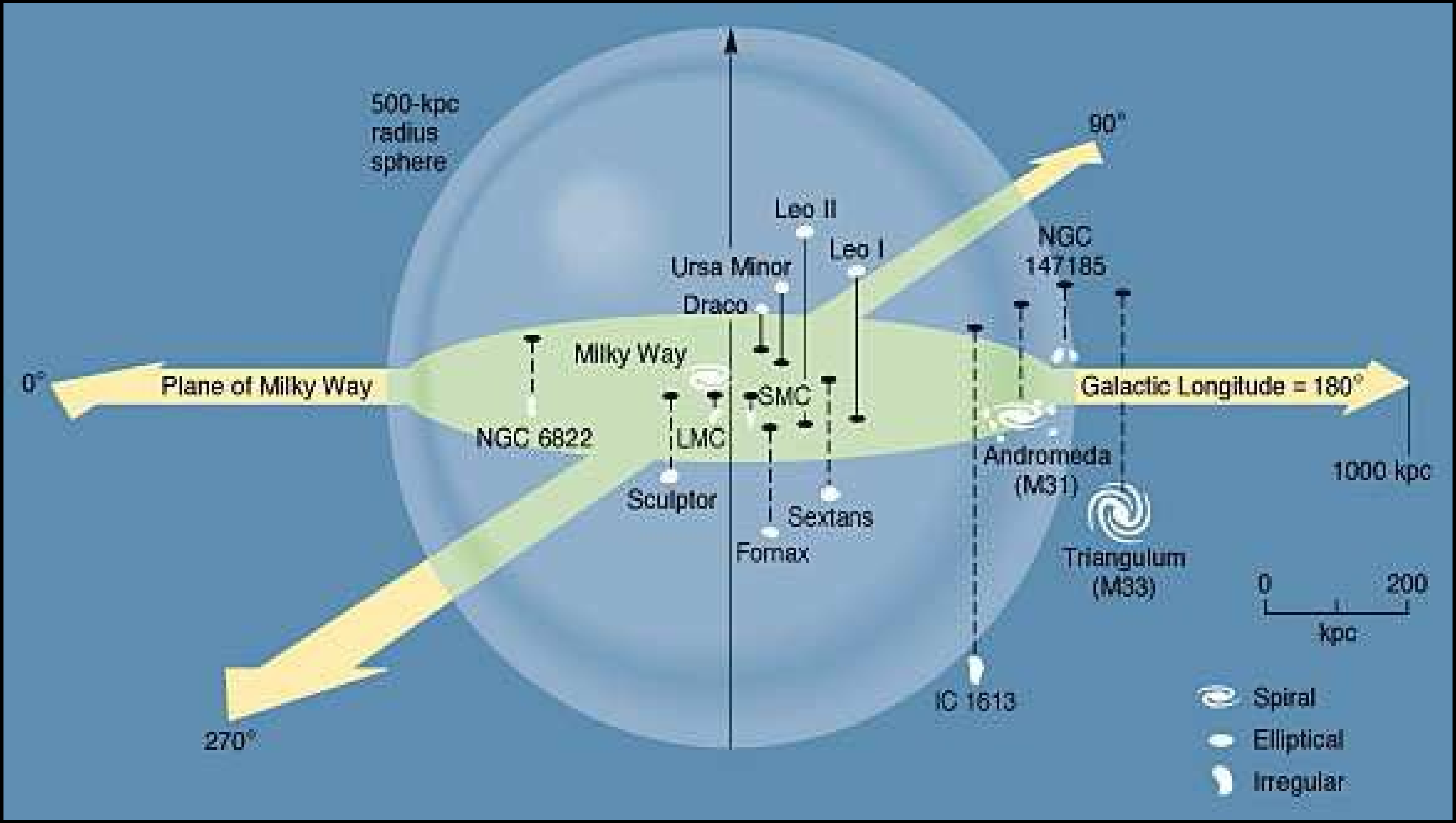
annihilation $$\frac{d^2\phi}{d\Omega\, dE} = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \times \int_{\text{l.o.s}} \rho^2\, ds$$

J factor



Kuhlen, Diemand, Madau 2007

Milky Way's dwSphs



Constraints on WIMP annihilation from gamma rays from Milky Way's dSphs

PRL 115, 231301 (2015) PHYSICAL REVIEW LETTERS week ending 4 DECEMBER 2015

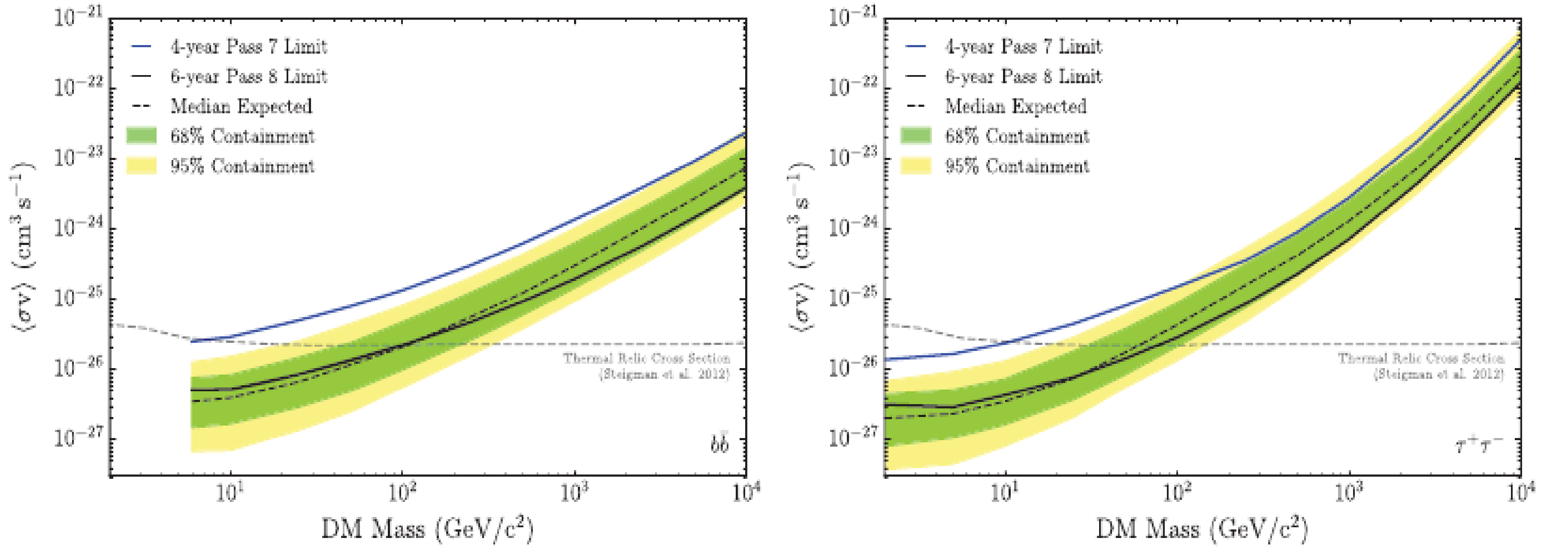
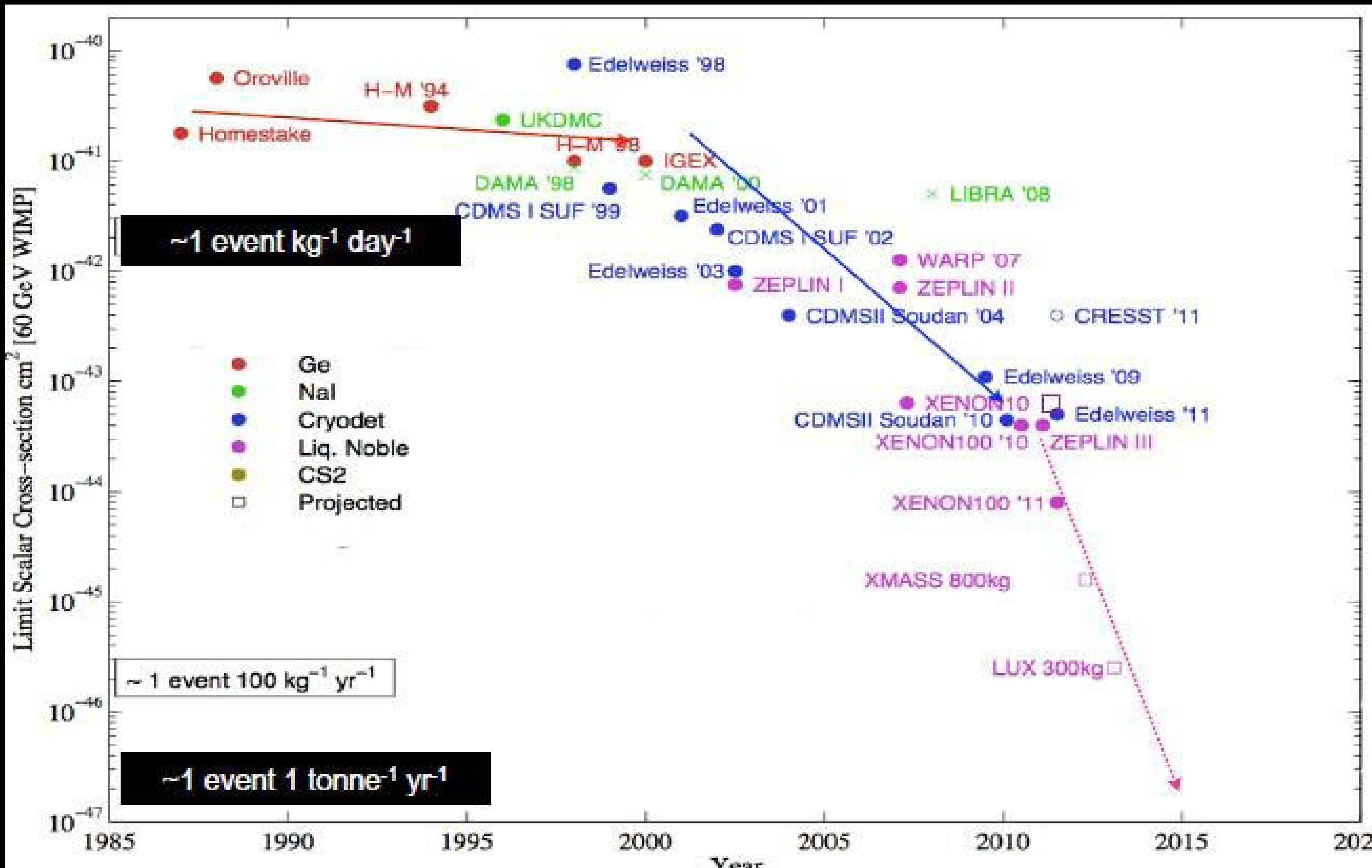


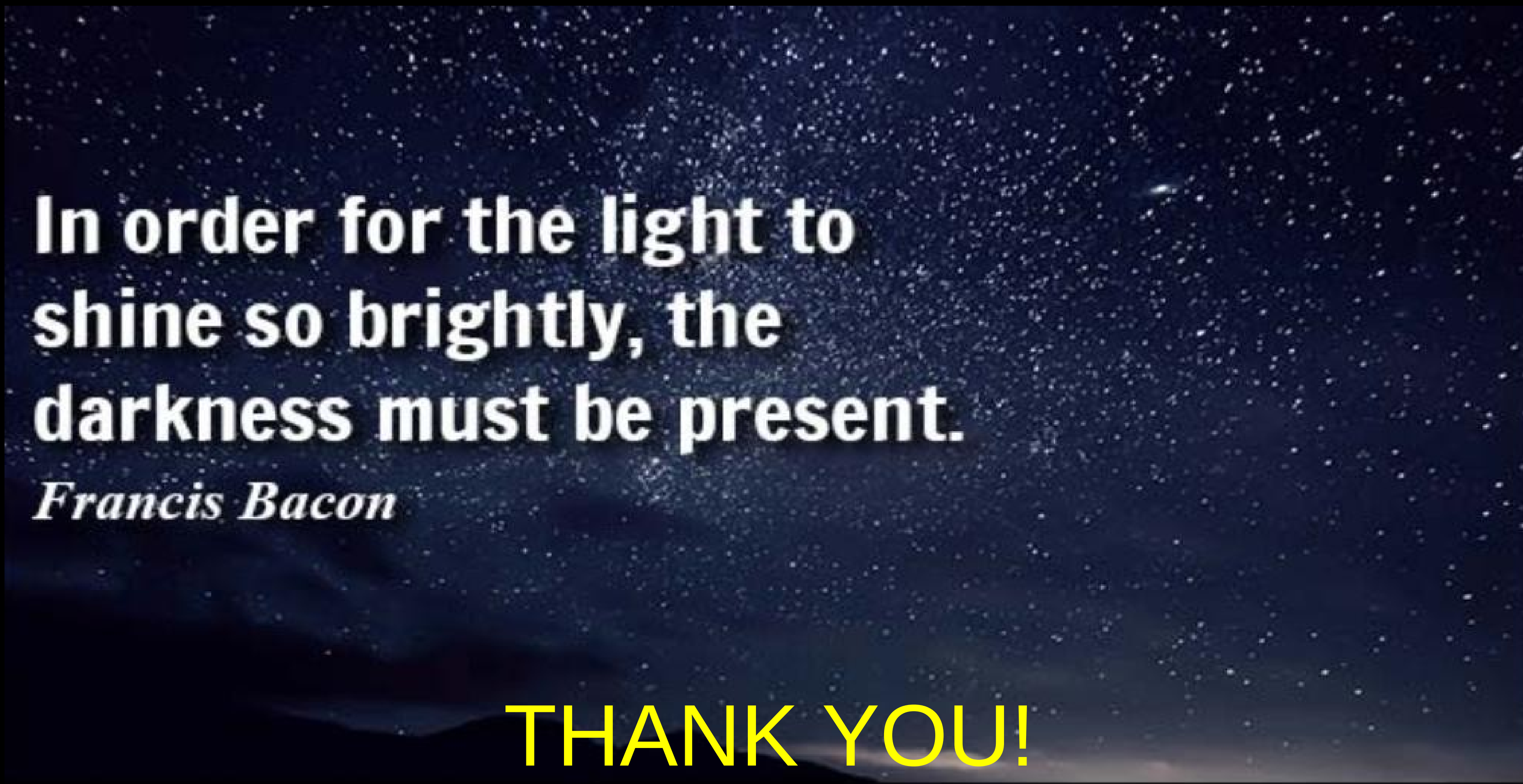
FIG. 1 (color). Constraints on the DM annihilation cross section at the 95% CL for the $b\bar{b}$ (left) and $\tau^+\tau^-$ (right) channels derived from a combined analysis of 15 dSphs. Bands for the expected sensitivity are calculated by repeating the same analysis on 300 randomly selected sets of high-Galactic-latitude blank fields in the LAT data. The dashed line shows the median expected sensitivity while the bands represent the 68% and 95% quantiles. For each set of random locations, nominal J factors are randomized in accord with their measurement uncertainties. The solid blue curve shows the limits derived from a previous analysis of four years of PASS7 REPROCESSED data and the same sample of 15 dSphs [13]. The dashed gray curve in this and subsequent figures corresponds to the thermal relic cross section from Steigman *et al.* [5].

Fermi-LAT collaboration (Dec 2015)

Wither WIMP Direct Detection?



Courtesy: Viktor Zacek (adapted from R. Gaitskell)


In order for the light to
shine so brightly, the
darkness must be present.
Francis Bacon

THANK YOU!