Lectures on selected topics in Astroparticle Physics:
Direct and Indirect Detection of
Particle (WIMP) Dark Matter

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Introduction

New discoveries in Micro-Universe $\Leftrightarrow$ New windows to the Macro-Universe

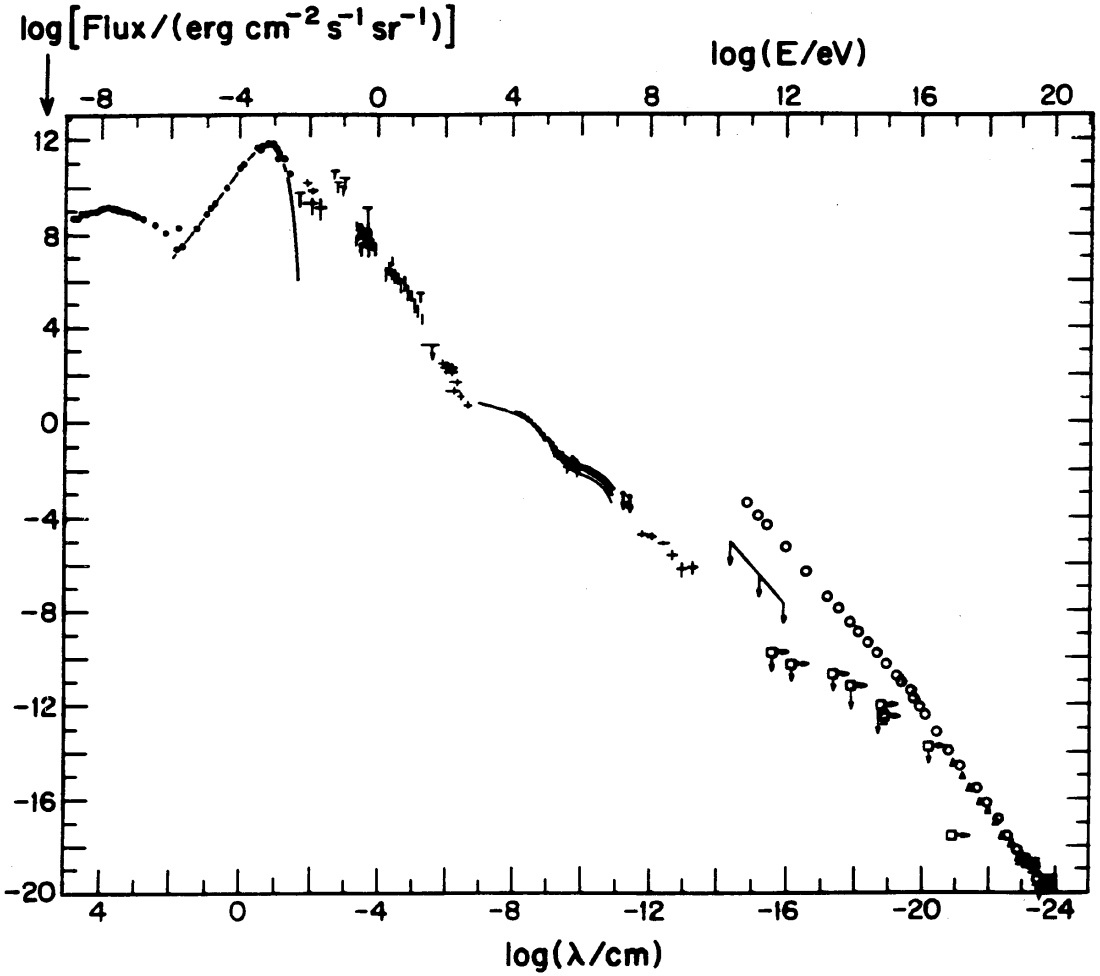
'Gravitational' (planetary) $\rightarrow$ 'Atomic' $\rightarrow$ 'Nuclear' $\rightarrow$ 'Particle'

Astrophysics

- solar $\nu \rightarrow \nu$ mass $\Rightarrow$ Physics beyond SM
- Dark Matter/Energy, CMBR anisotropy $\Rightarrow$ Physics beyond SM
- UHECR ($> 10^{11}$ GeV) $\rightarrow$??
- ...

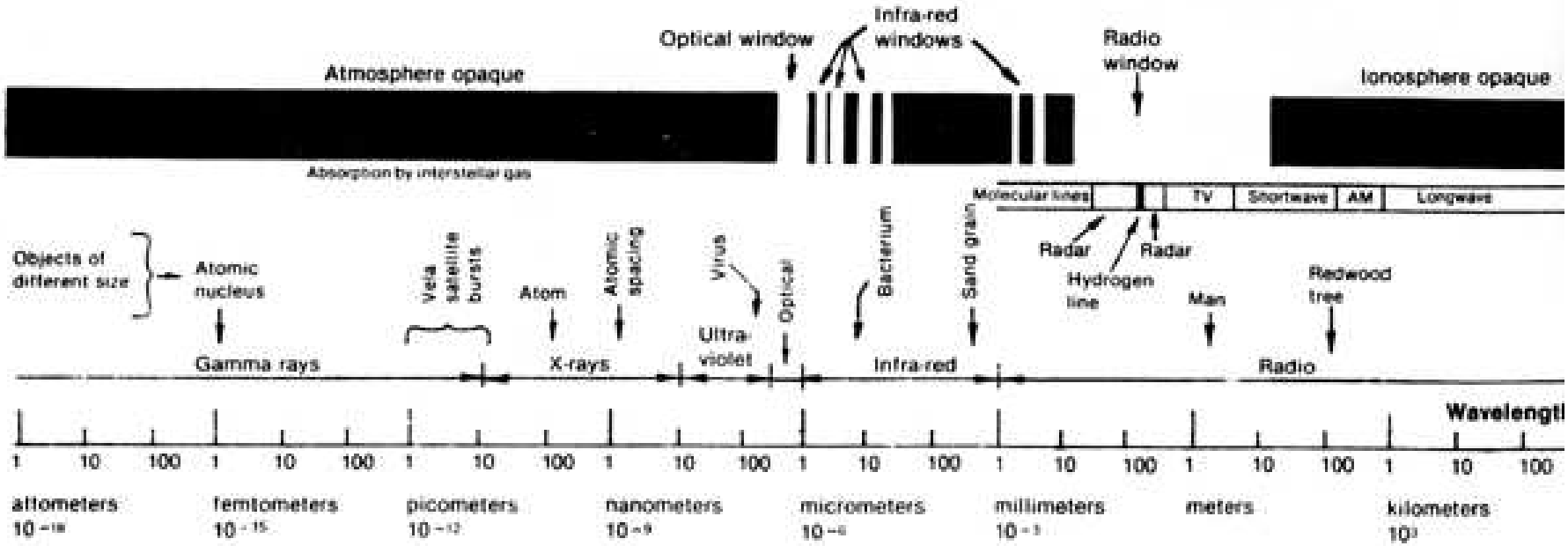
Physics beyond SM = SUSY ?, Extra Dimensions ?, ... ?

Cosmic Electromagnetic Radiation



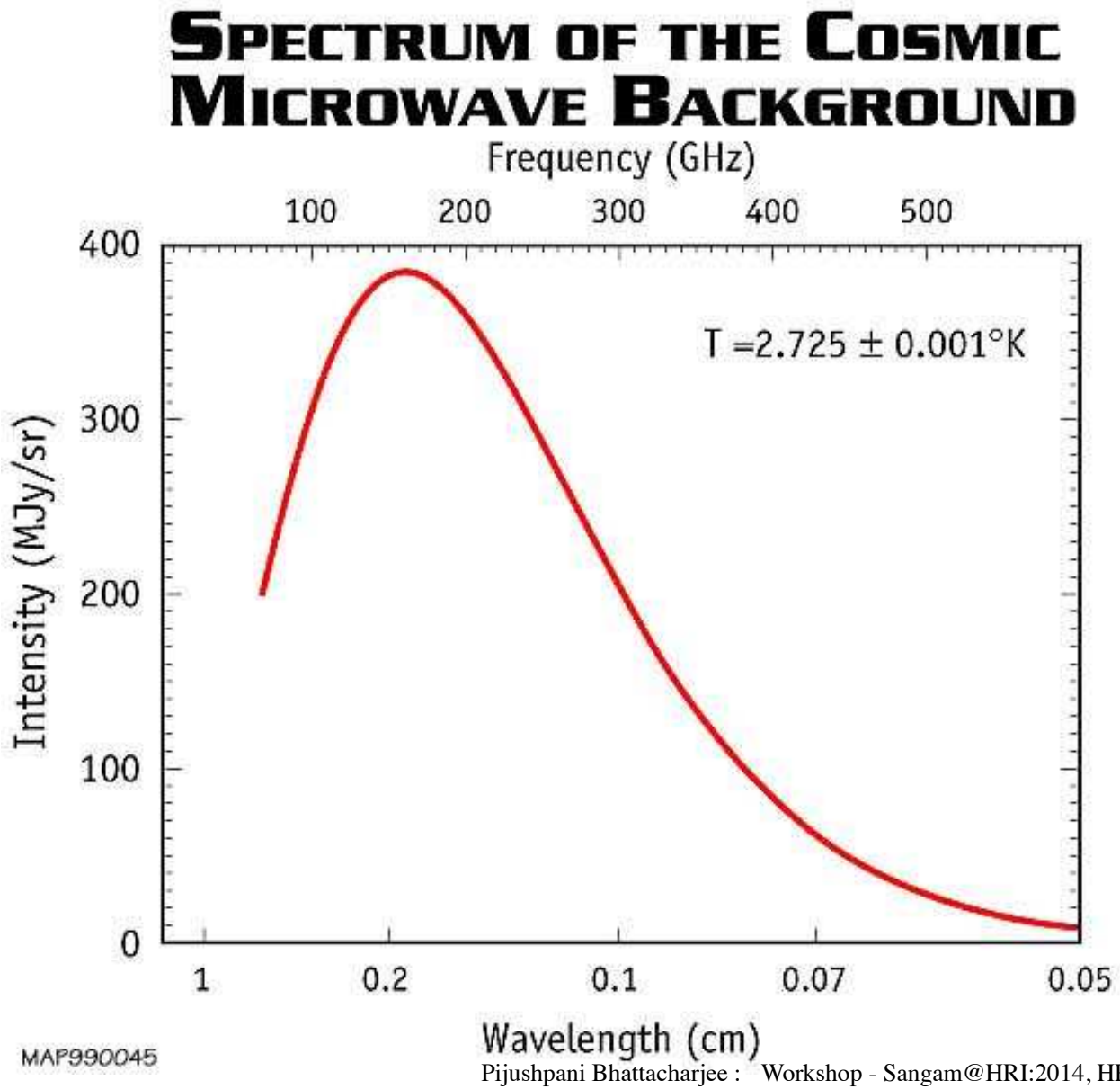
(Ressel & Turner)

Atmospheric Opacity

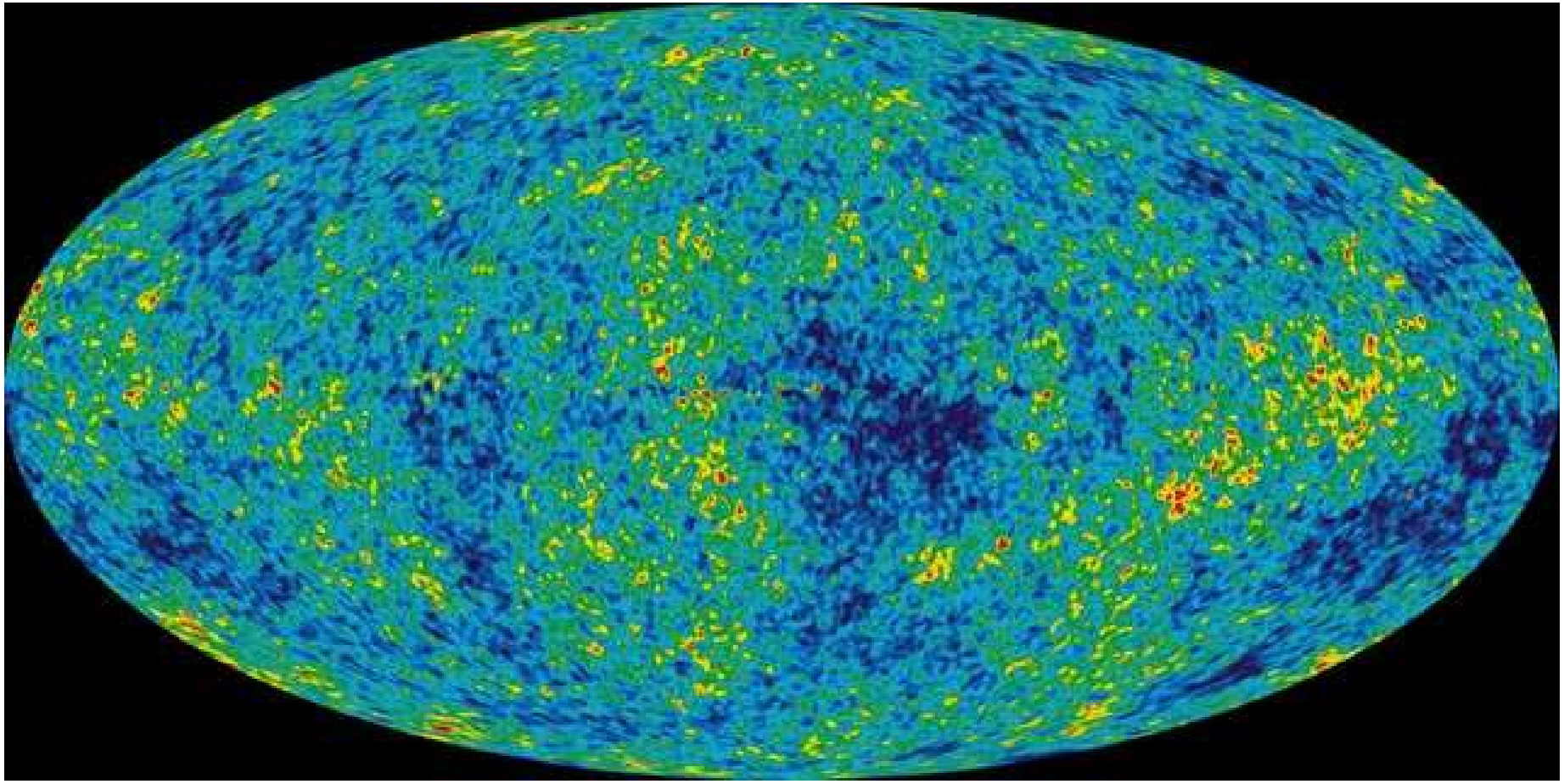


The electromagnetic spectrum with wavelength on a logarithmic scale from the shortest gamma rays to the longest radio waves. Wavelengths are expressed in metric units. The atmospheric opacity is shown at the top with the optical and radio windows in evidence.

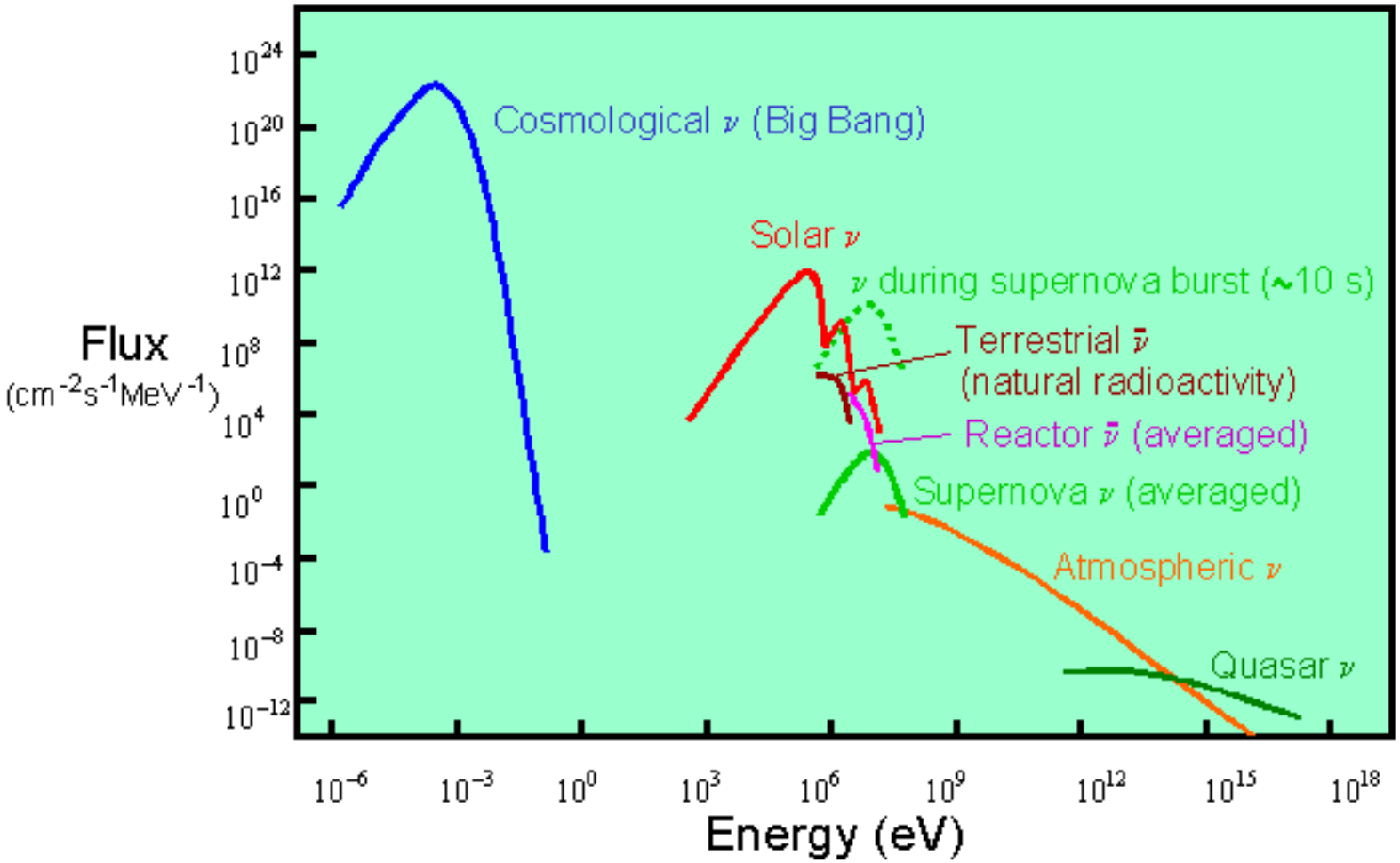
The Most Perfect Blackbody



CMBR Fluctuations



Neutrino Sky

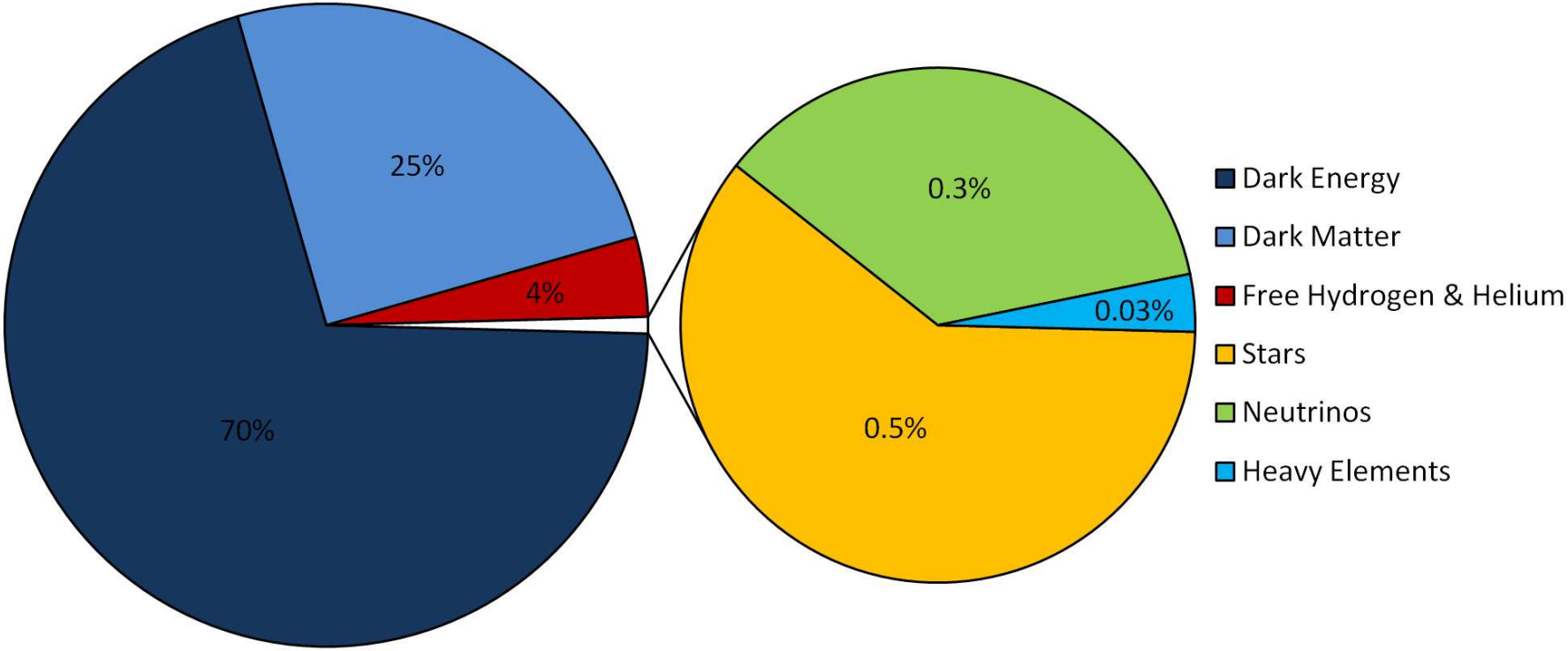


Flux on earth of neutrinos from various sources, in function of energy

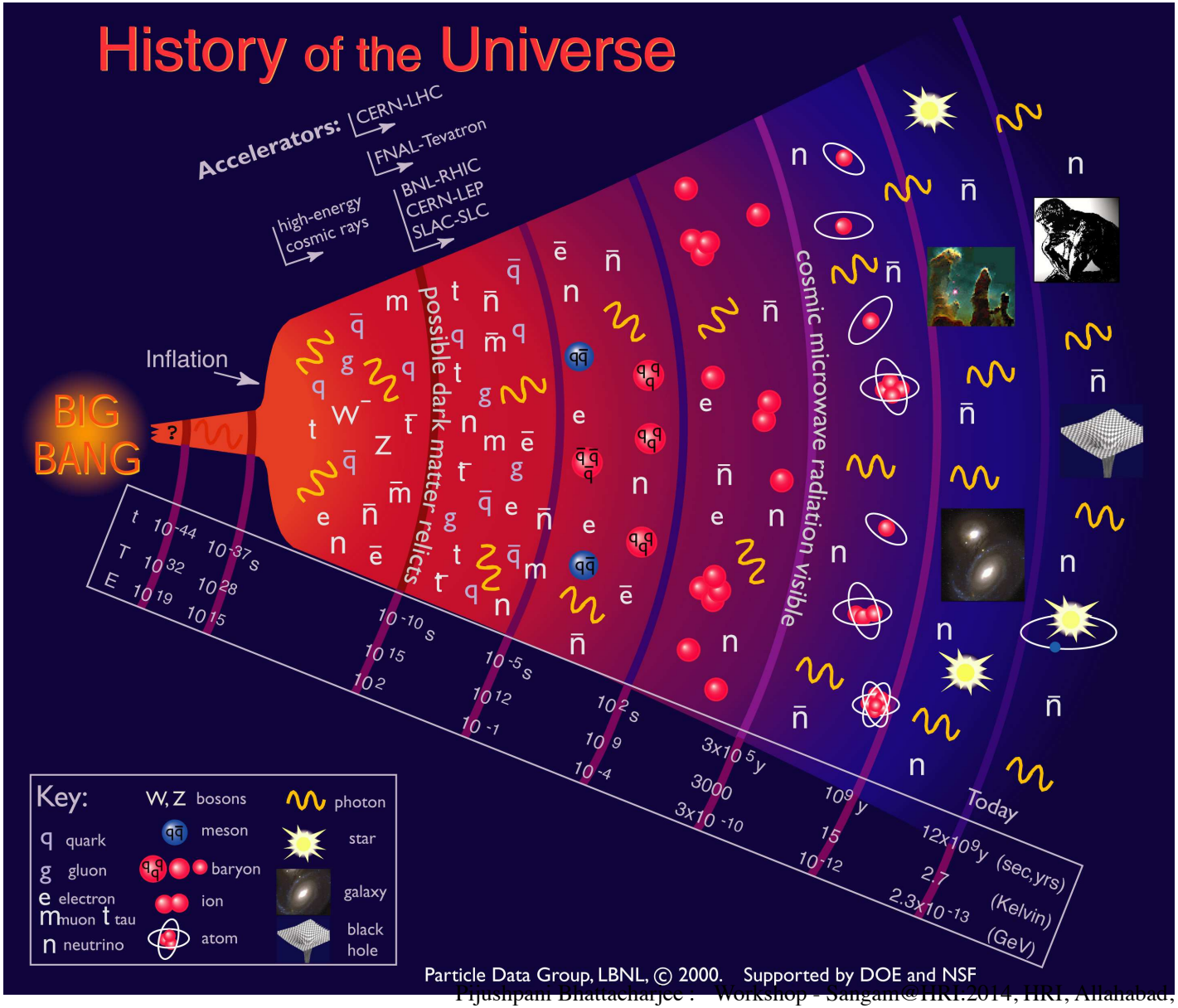
Outstanding Issues in Astroparticle Physics

- Origin of Matter-Antimatter Asymmetry
- Nature and origin of Dark Matter and Dark Energy
- Origin of the large-scale structure of the Universe
- Origin of the Ultra High Energy Cosmic Rays (UHECR)
- Nature of the "Central Engine" of Gamma Ray Bursts
- . . .

Contents of the Universe

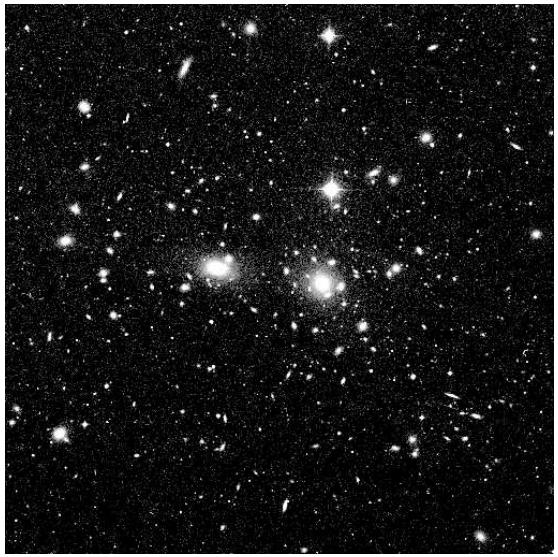


History of the Universe



Dark Matter

"Discovered" by Fritz Zwicky in 1933 : "Virial discrepancy" in the Coma cluster :



Coma Cluster

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

Measured $\langle v^2 \rangle^{\frac{1}{2}} \sim 1000\,\mathrm{km\,s^{-1}} \Rightarrow \langle \rho^{\mathrm{vir}}_{\mathrm{Coma}} \rangle \sim 400 \langle \rho_{\mathrm{visible}} \rangle$!!

— Radial velocities of galaxies in the Coma cluster are too large 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!).

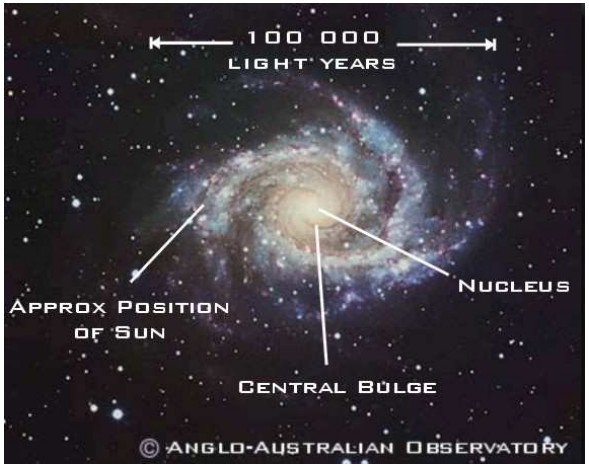
With $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, we get $\langle \rho^{\mathrm{vir}}_{\mathrm{Coma}} \rangle \sim 50 \langle \rho_{\mathrm{visible}} \rangle$

Rotation Curve of Spiral Galaxies and Dark Matter

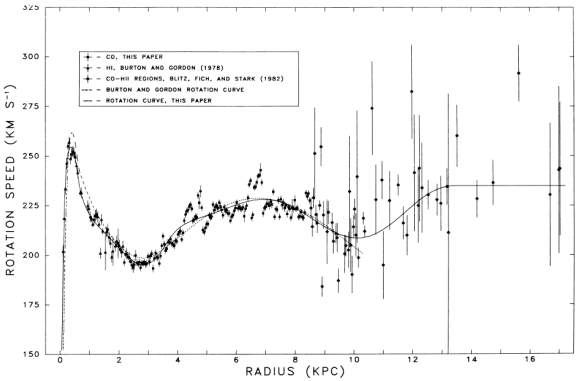
Galactic scale Dark Matter seriously studied only begining early 1970s: Vera Rubin: Rotation Curve of Spiral galaxies. Circular Rotation Speed: $v_c^2(R) = R\frac{\partial\phi}{\partial R} = G\frac{M(R)}{R}$

Rotation Curve of Milky Way

Vera Rubin

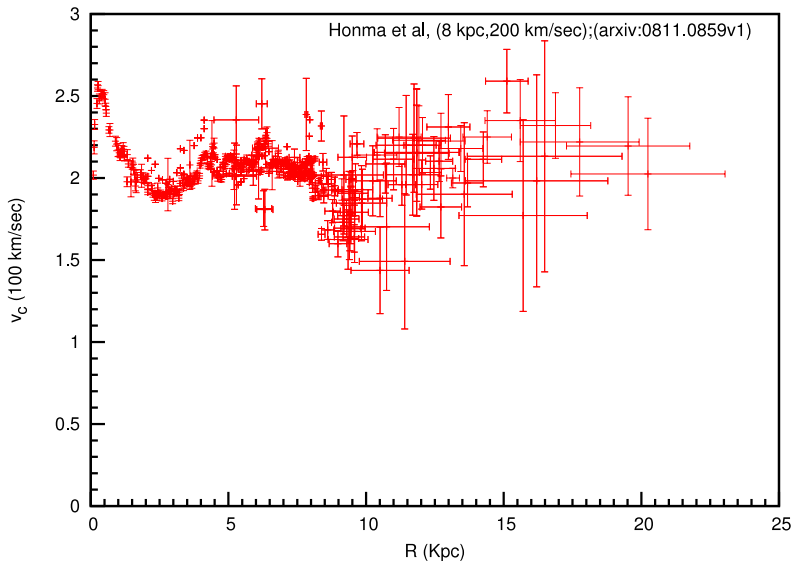


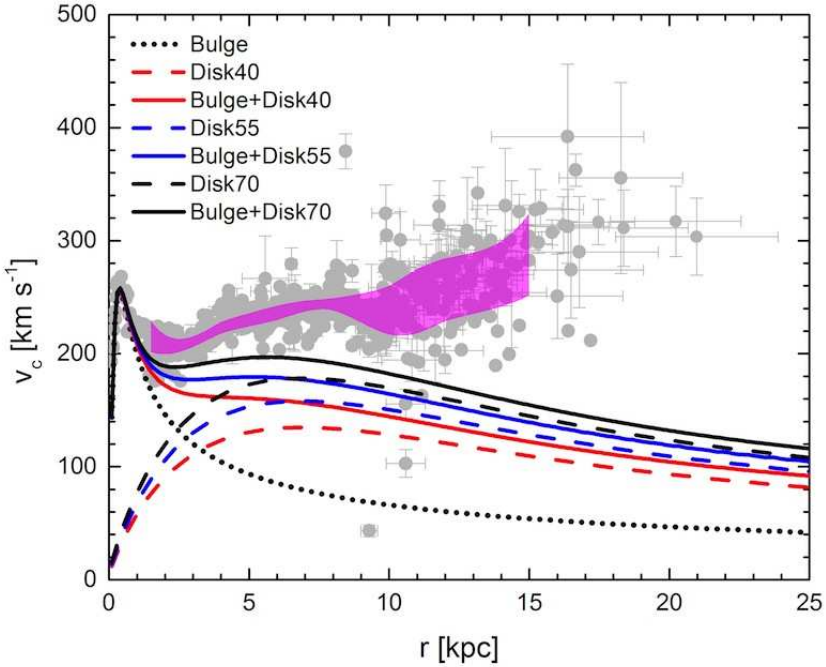
Milky Way



Clemens (1985)

Milky Way's Rotation Curve (to $\sim 20\,\mathrm{kpc}$)





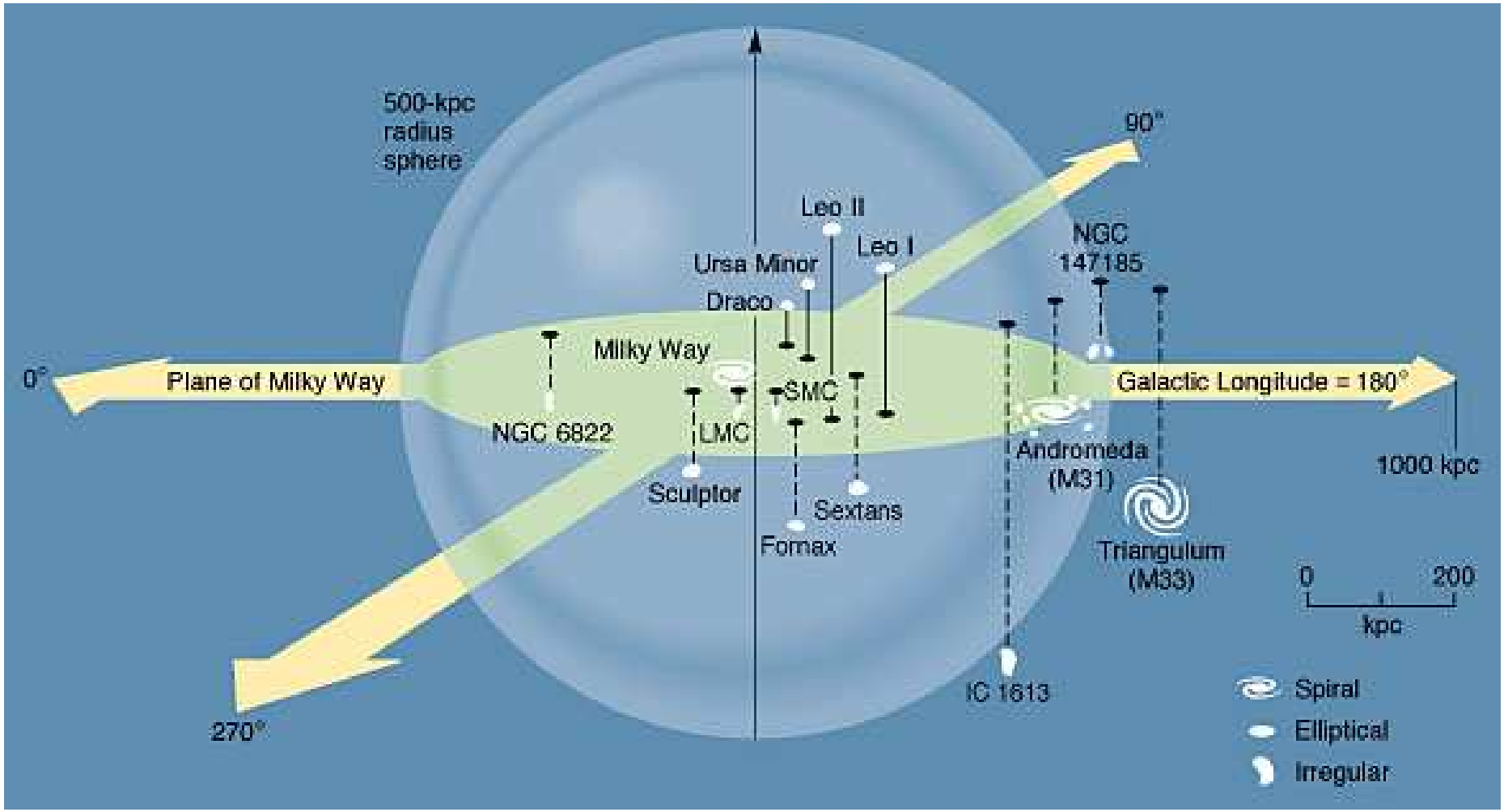
$R_0 = 8\,\mathrm{kpc}, V_0 = 200\,\mathrm{km\,s^{-1}}$

Honma et al, arXiv:0811.0859

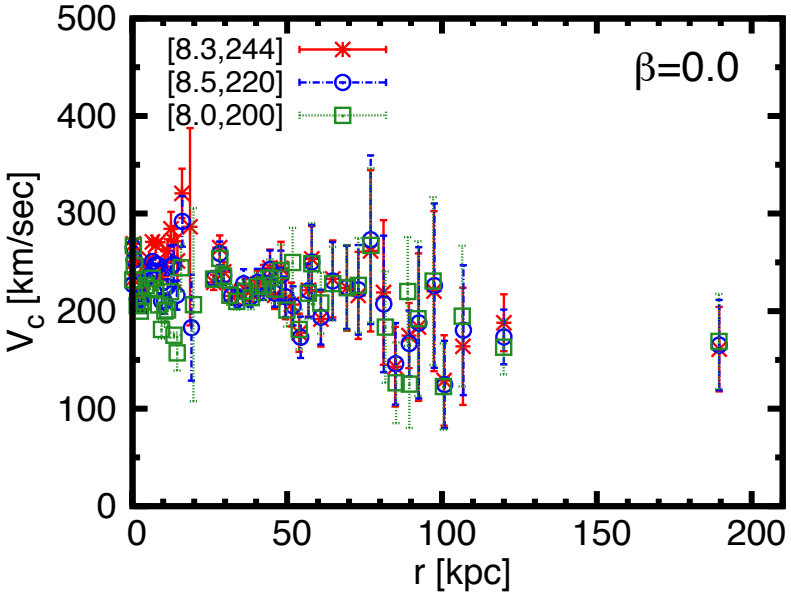
$R_0 = 8.3\,\mathrm{kpc}, V_0 = 240\,\mathrm{km\,s^{-1}}$

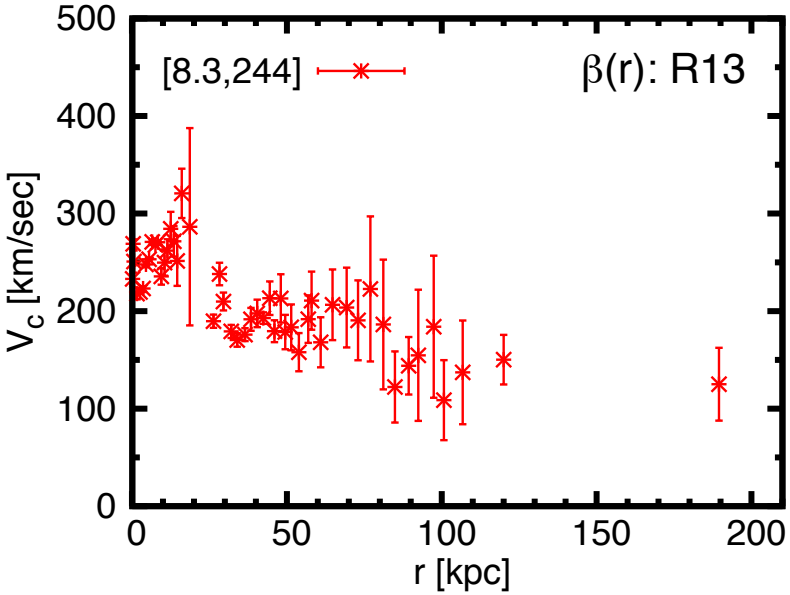
Burch & Cowsik, ApJ (2013) [arXiv:1306.1920]

The local group



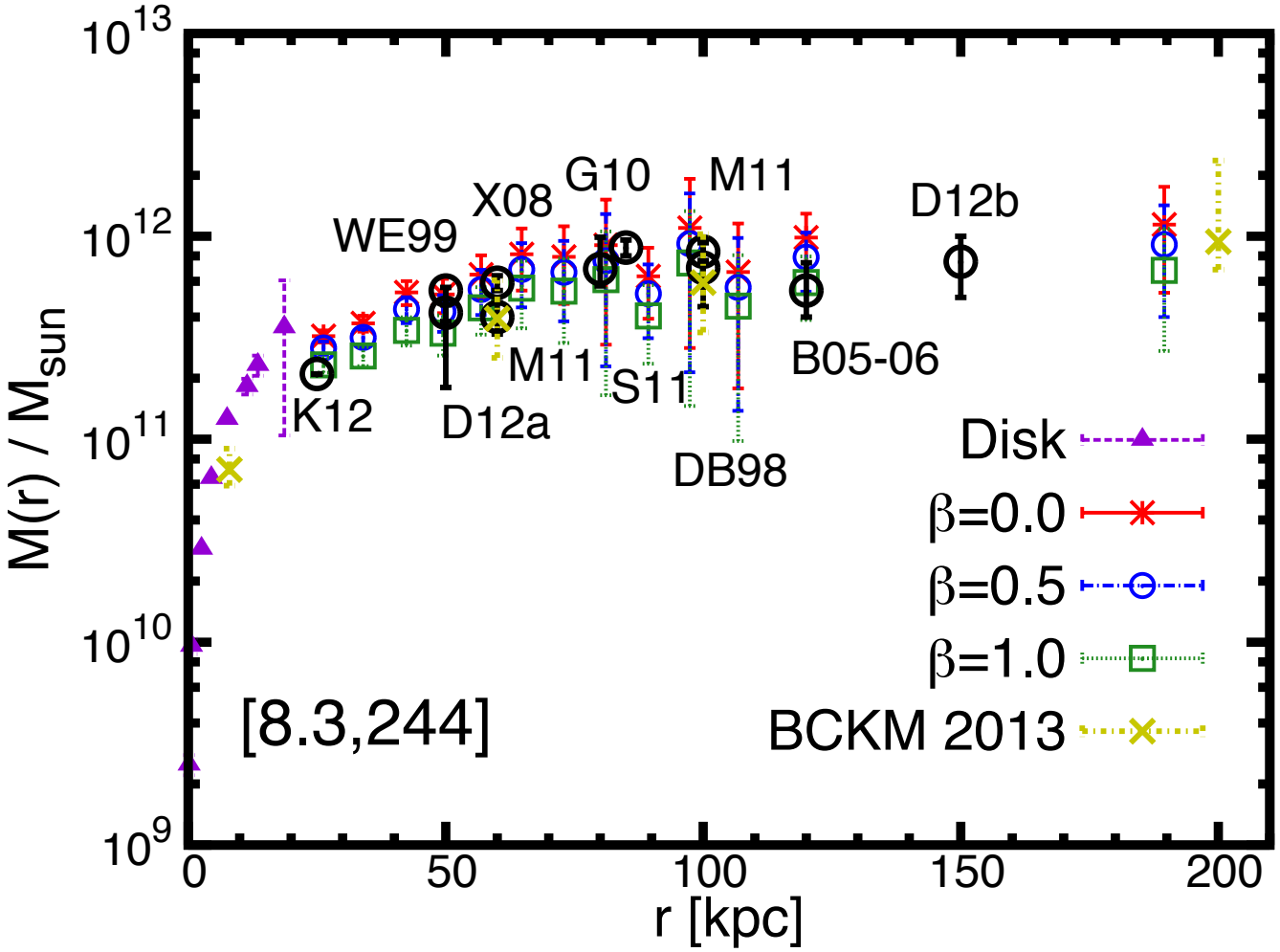
Milky Way's Rotation Curve (to $\sim 200\,\mathrm{kpc}$)



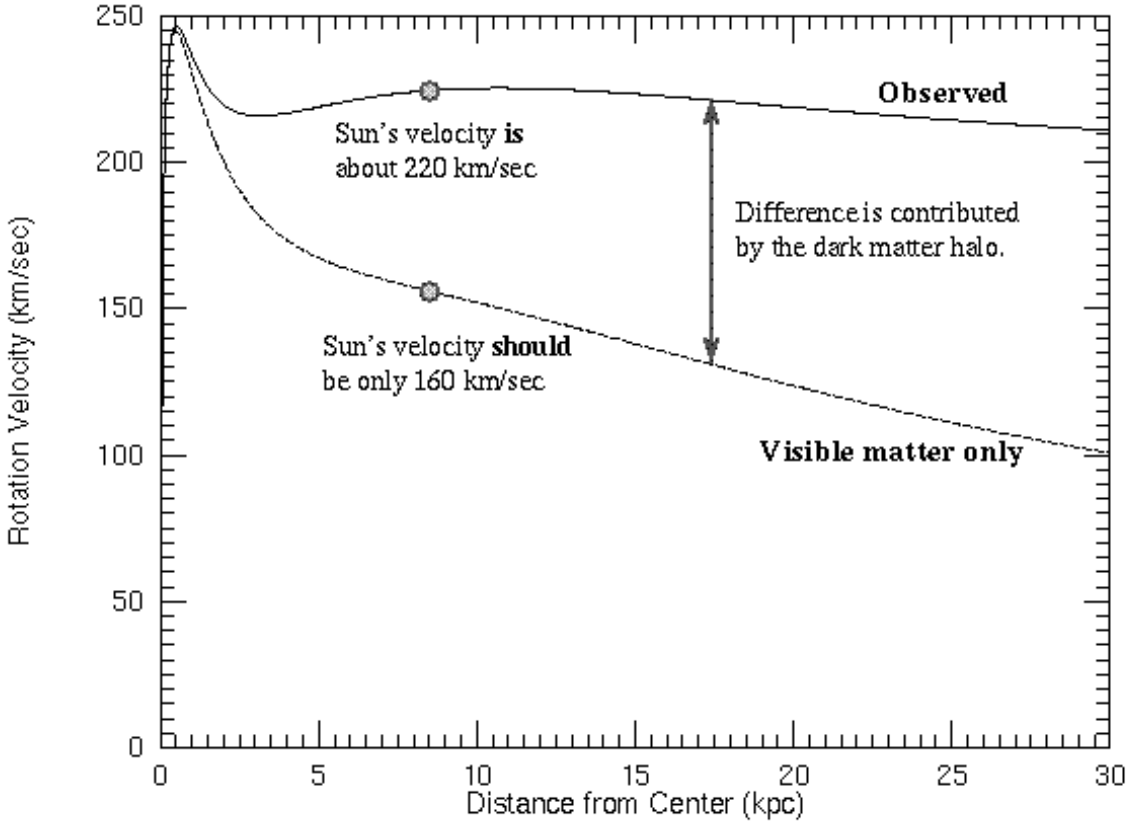


PB, S. Chaudhury & S. Kundu, ApJ (2014) [arXiv:1310.2659]

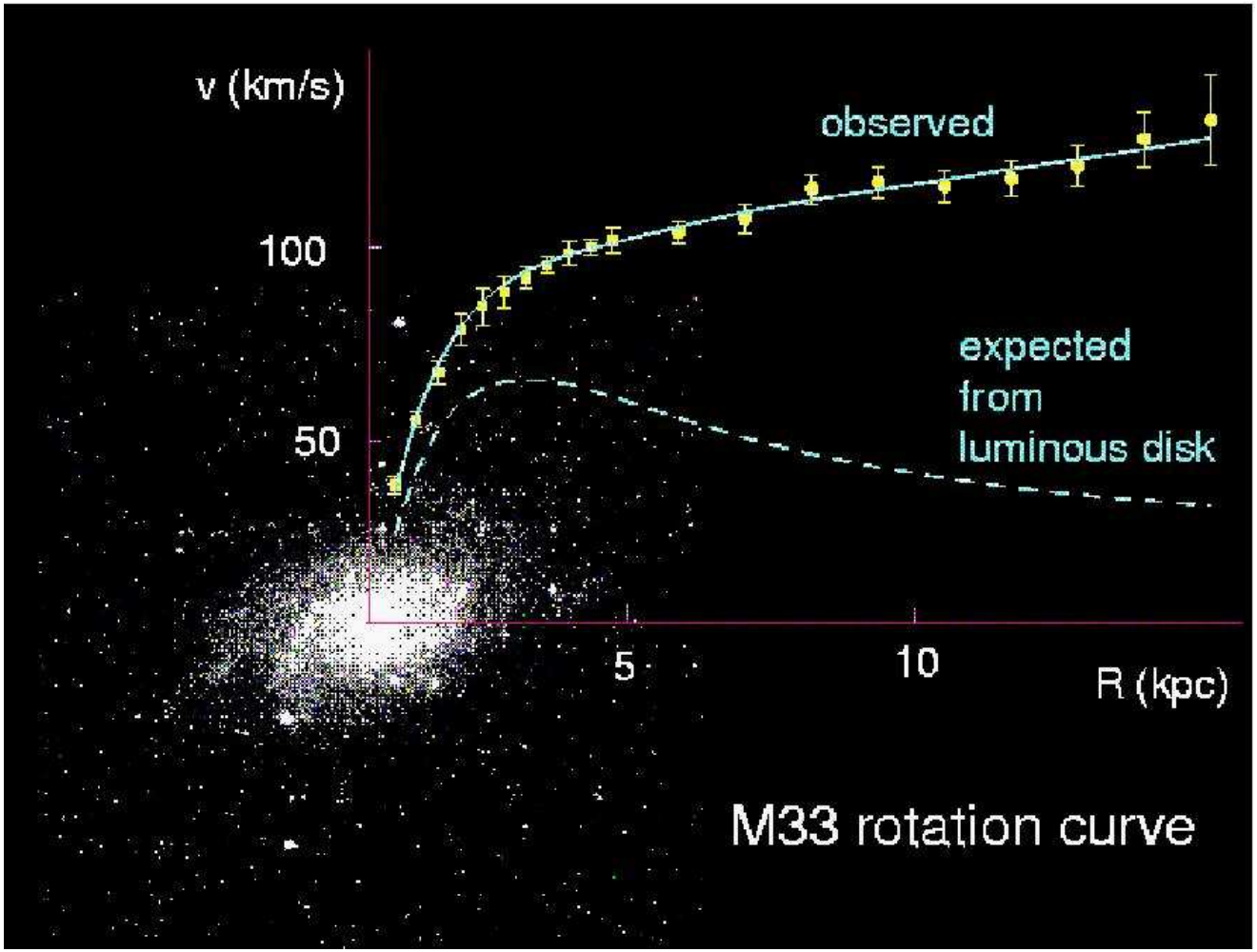
Mass of the Galaxy



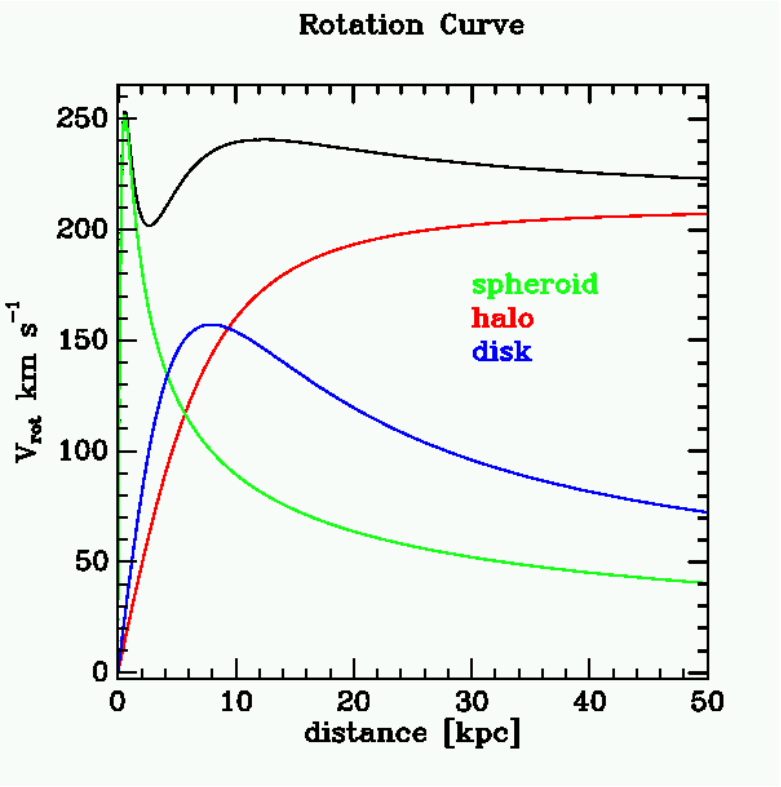
PB, S. Chaudhury & S. Kundu, ApJ (2014) [arXiv:1310.2659]



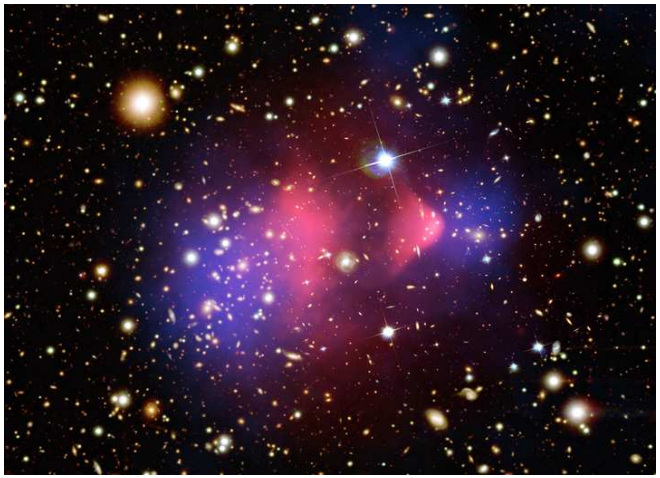
The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two curves is evidence for a **dark matter halo.**


v (km/s)
observed
100
50
expected
from
luminous disk
5
10
R (kpc)
M33 rotation curve

Mass Models : Dark Matter Halo



The Nature of Dark Matter

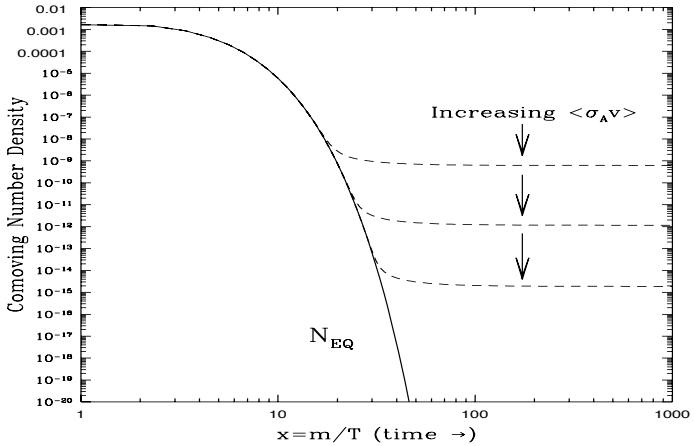


"Bullet Cluster"

- DM must be non-baryonic, dissipationless$\Rightarrow$ collisionless $\Rightarrow$ very weakly interacting
- Clustered on small (sub-galactic) scale $\Rightarrow$ Must be cold

$\Rightarrow$ Weakly Interacting Massive Particles

- In thermal equilibrium, $(n/s)^{\rm eq} \propto (m/T)^{3/2} e^{-m/T}$ $\Rightarrow$ negligible abundance today!
- But WIMPs can decouple ("freeze out") when $\Gamma_{\rm int} < H$ in the early universe and survive with $\Omega_{\rm WIMP} \propto \langle \sigma_{\rm ann} v \rangle^{-1}$ today.



WIMP abundance today:

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

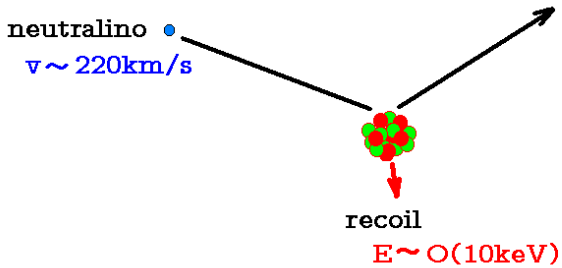
Typically, $\sigma \sim \alpha^2/\,\mathrm{m}_\chi \sim 10^{-8}\,\mathrm{GeV}^{-2} \sim 4 \times 10^{-36}\,\mathrm{cm}^2$ (with $\alpha \sim 10^{-2}$ $m_\chi \sim 100\,\mathrm{GeV}$), and $\langle v \rangle_f \sim 0.25c$. Also, $h \sim 0.7$.

Thus, if there is a WIMP, it is a natural DM candidate!

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

Also, WIMPs captured within astrophysical bodies would annihilate $\Rightarrow$ annihilation products (e.g., γ-rays, ν's) may be detectable. $\Rightarrow$ indirect detection through ν's from the Sun, γ-rays from Galactic Centre, dwarf Spheroidal galaxies, . . .

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

$$R \sim 2.7 \times 10^{-25}\,\mathrm{yr}^{-1} \left(\frac{\rho_\chi}{0.3\,\mathrm{GeV\,cm}^{-3}}\right) \left(\frac{100\,\mathrm{GeV}}{m_\chi}\right) \left(\frac{v}{300\,\mathrm{km\,s}^{-1}}\right) \left(\frac{\sigma_{\chi N}}{10^{-37}\,\mathrm{cm}^2}\right)$$

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

$$R_{\mathrm{total}} \sim 1.6\ \ \mathrm{events\,kg}^{-1}\,\mathrm{yr}^{-1} \left(\frac{100}{A}\right) \left(\frac{\rho_\chi}{0.3\,\mathrm{GeV\,cm}^{-3}}\right) \left(\frac{100\,\mathrm{GeV}}{m_\chi}\right) \left(\frac{v}{300\,\mathrm{km\,s}^{-1}}\right) \left(\frac{\sigma_{\chi N}}{10^{-37}\,\mathrm{cm}^2}\right)$$

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,

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

Direct detection: kinematics

Calculations . . .

Proper calculations :

Recoil energy: $E = (\mu^2 v^2/M)(1 - \cos\theta^*)$, 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 (typically measured in units of counts/day/kg/keV :

$\frac{\mathrm{d}R}{\mathrm{d}E} = \frac{\sigma(q)}{2\, m_\chi \mu^2}\, \rho\, \eta(E,t) \equiv$ Particle Physics $\otimes$ Astrophysics,

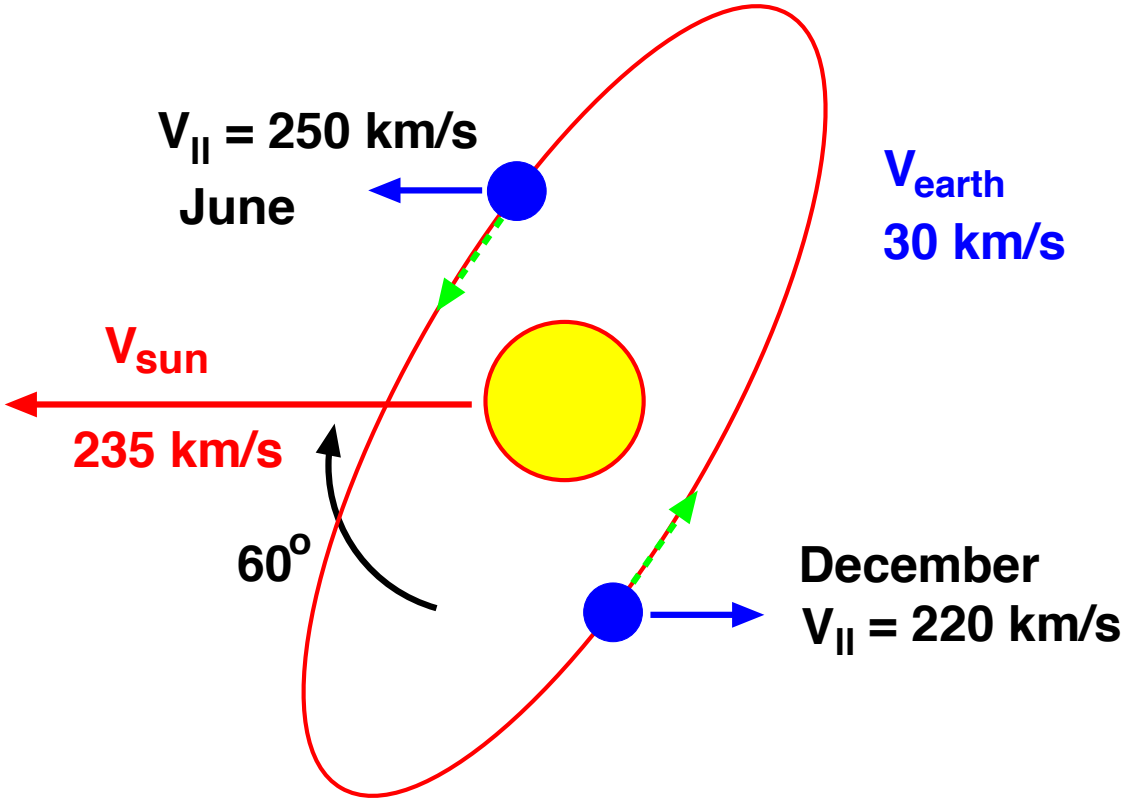
with $q = \sqrt{2ME} =$ nucleus recoil momentum, $\sigma(q) =$ WIMP-nucleus cross-section,

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

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

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

Modulation Signal



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

WIMP-nucleus effective cross sections

. . .

WIMP-Nucleus (Effective) Interactions

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

Form factor: loss of coherence

Coherence

WIMP-nucleon x-section

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

Spin-dependent (SD) Interaction:

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

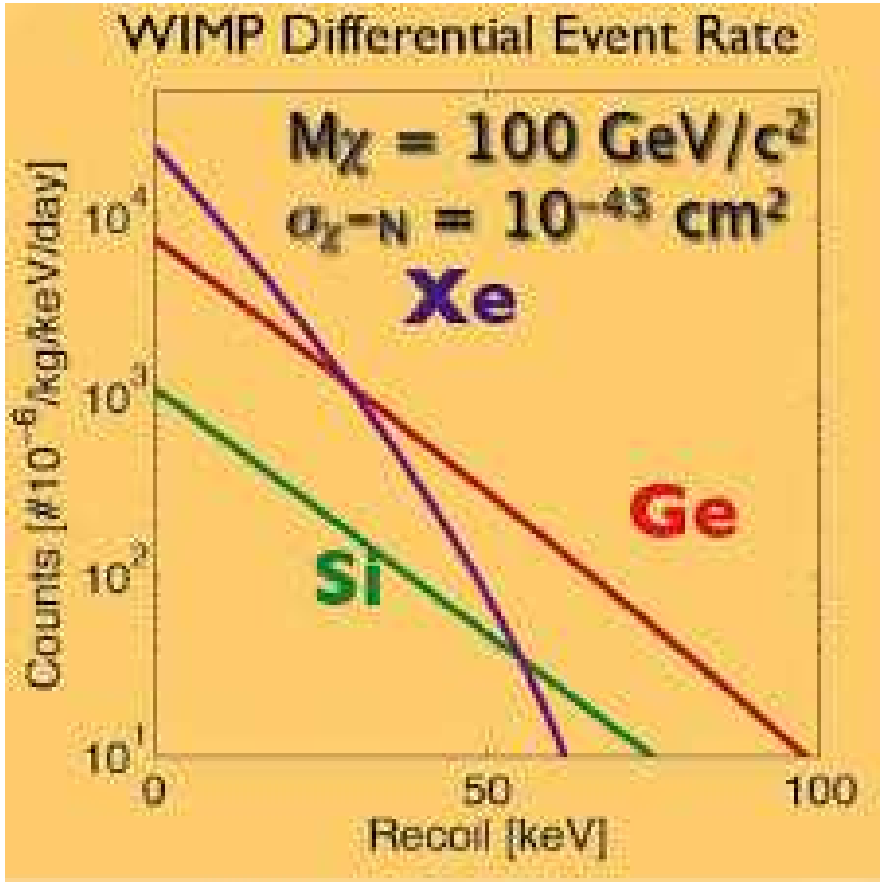
$$\Lambda = \frac{1}{J}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]$$

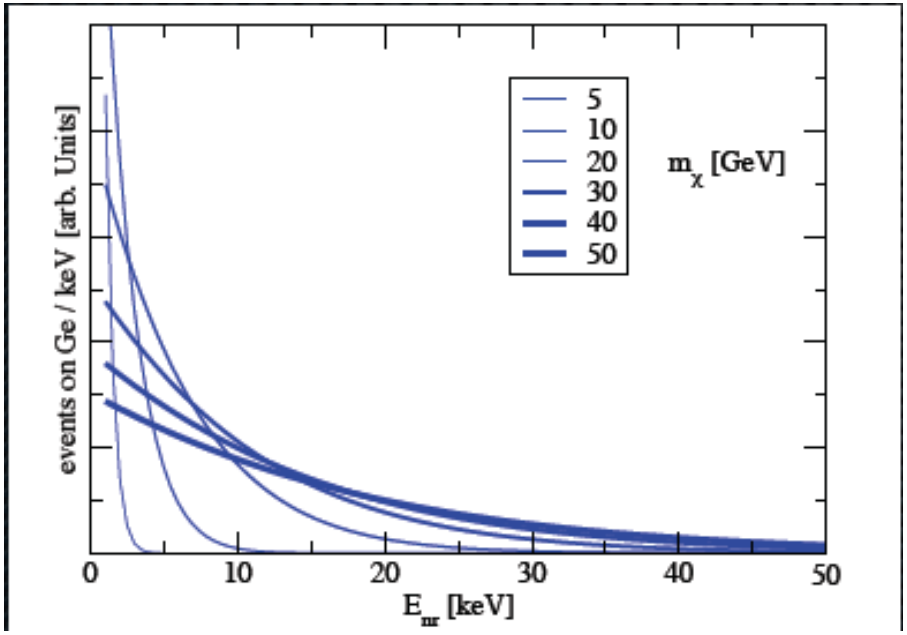
$$\langle S_{p,n}\rangle = \langle N|S_{p,n}|N\rangle$$

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

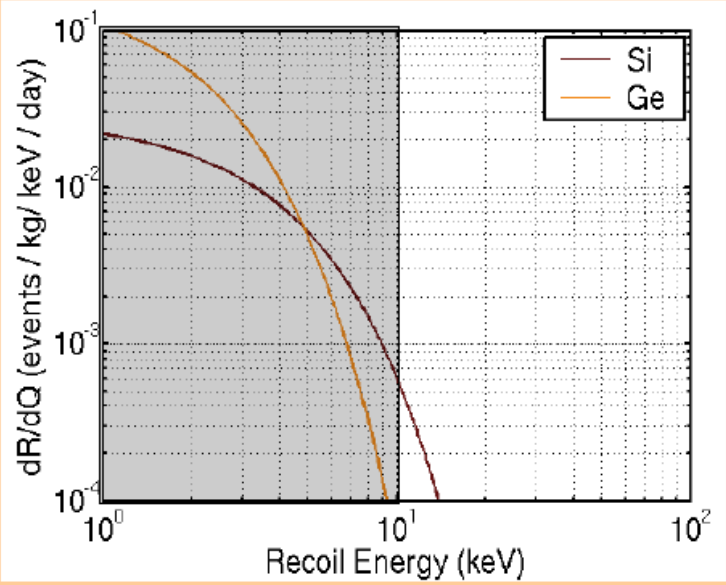
Nuclear Recoil Spectrum

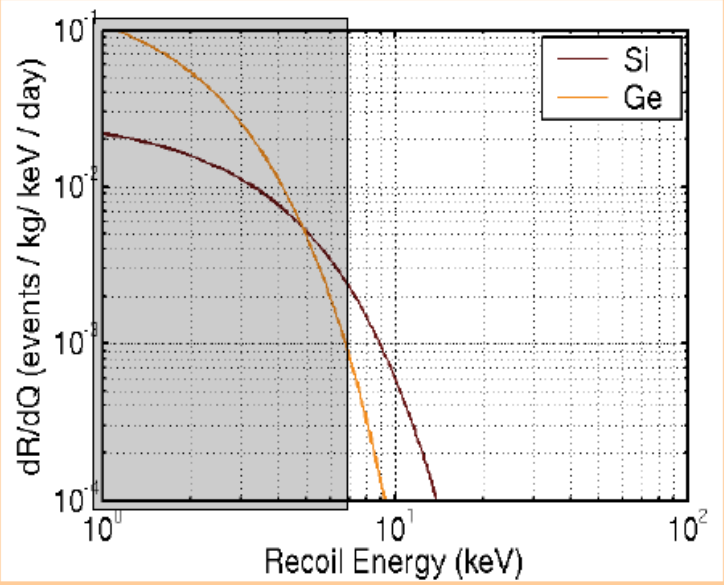




Low mass WIMP: Si vs Ge

m_WIMP=8 GeV





E_th = 10 keV

E_th = 7 keV

For low mass WIMPs, need lower threshold and lower target nucleus mass

Methods of detecting the nuclear recoil energy

- **Scintillation** : Recoil energy of nucleus taken up by electrons which radiate through scintillation detected by photomultiplier tubes..some part is lost as phonons. **[DAMA,XENON]**

Quenching: $E_{obs} = q \times E_r$

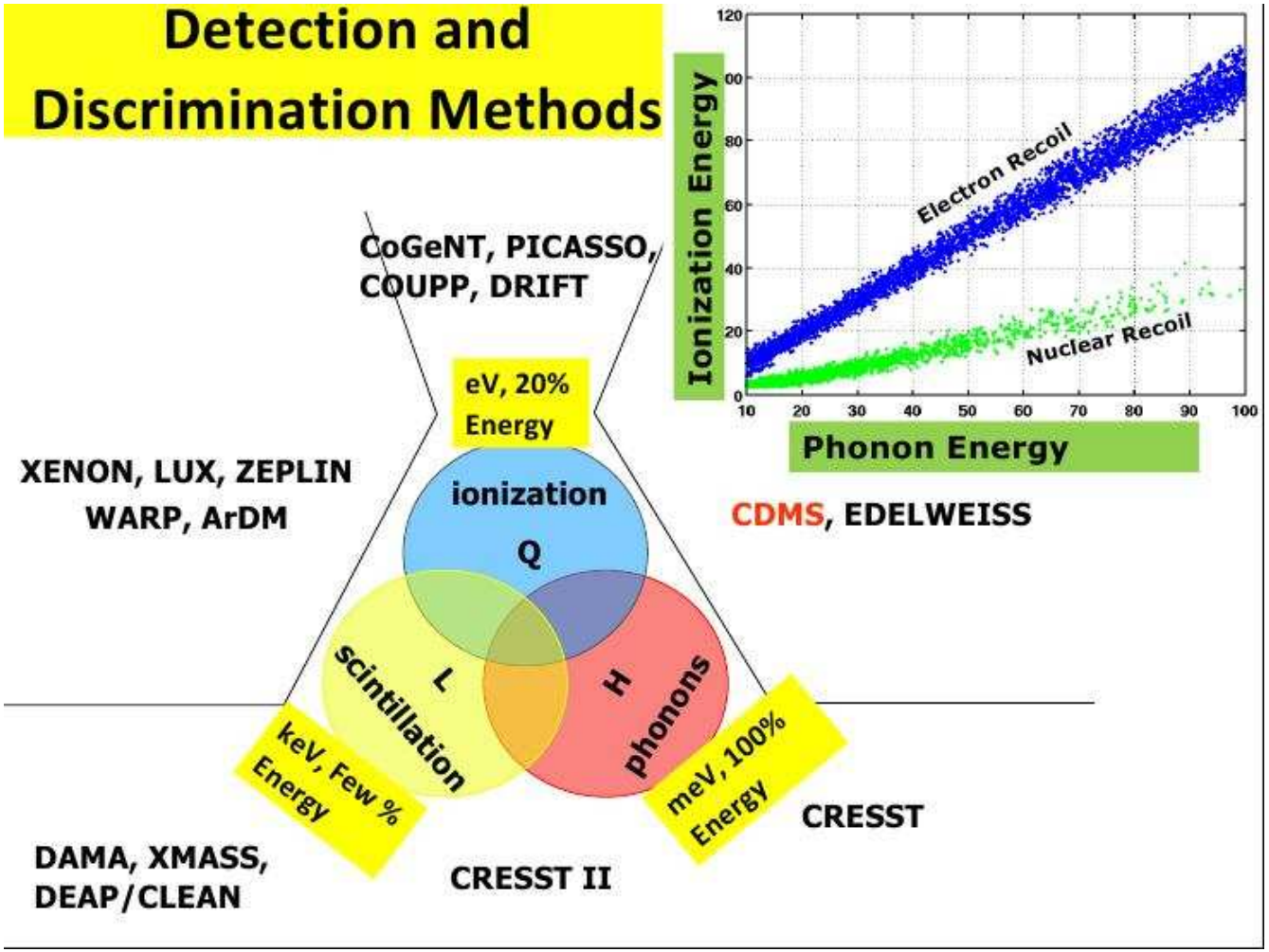
For some energies and incident angles:

q=1: Channeling [Drovyshevski,arxiv:0706.3095]

- **Ionization** : As the nucleus moves through the target mass it ionizes other target atoms and Electrostatic field detected.**[CDMS,XENON]**

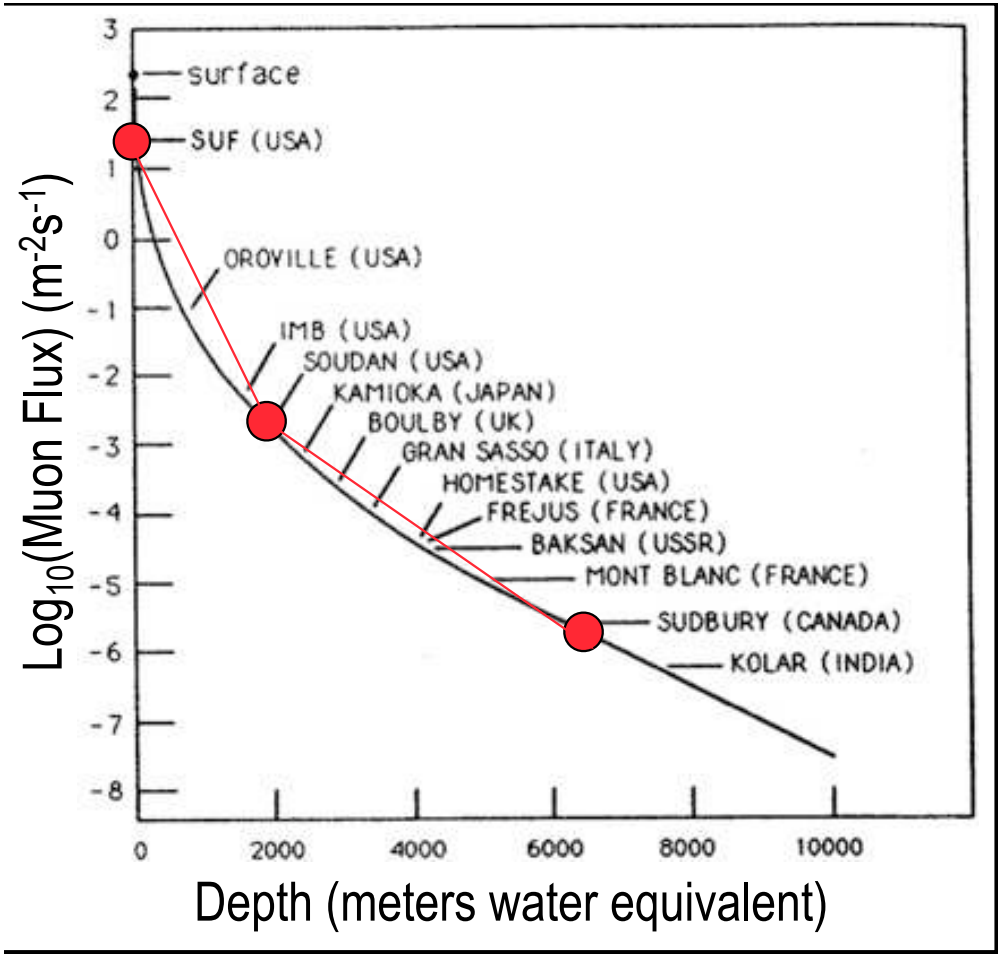
- **Phonons** : Detected by semiconductor and superconductor-junction sensors.

- **Heat** : Recoil energy is detected by change of semiconductor (doped Ge) resistance in a bolometer under cryogenic condition (<50 mK).**[CDMS,CRESST]**

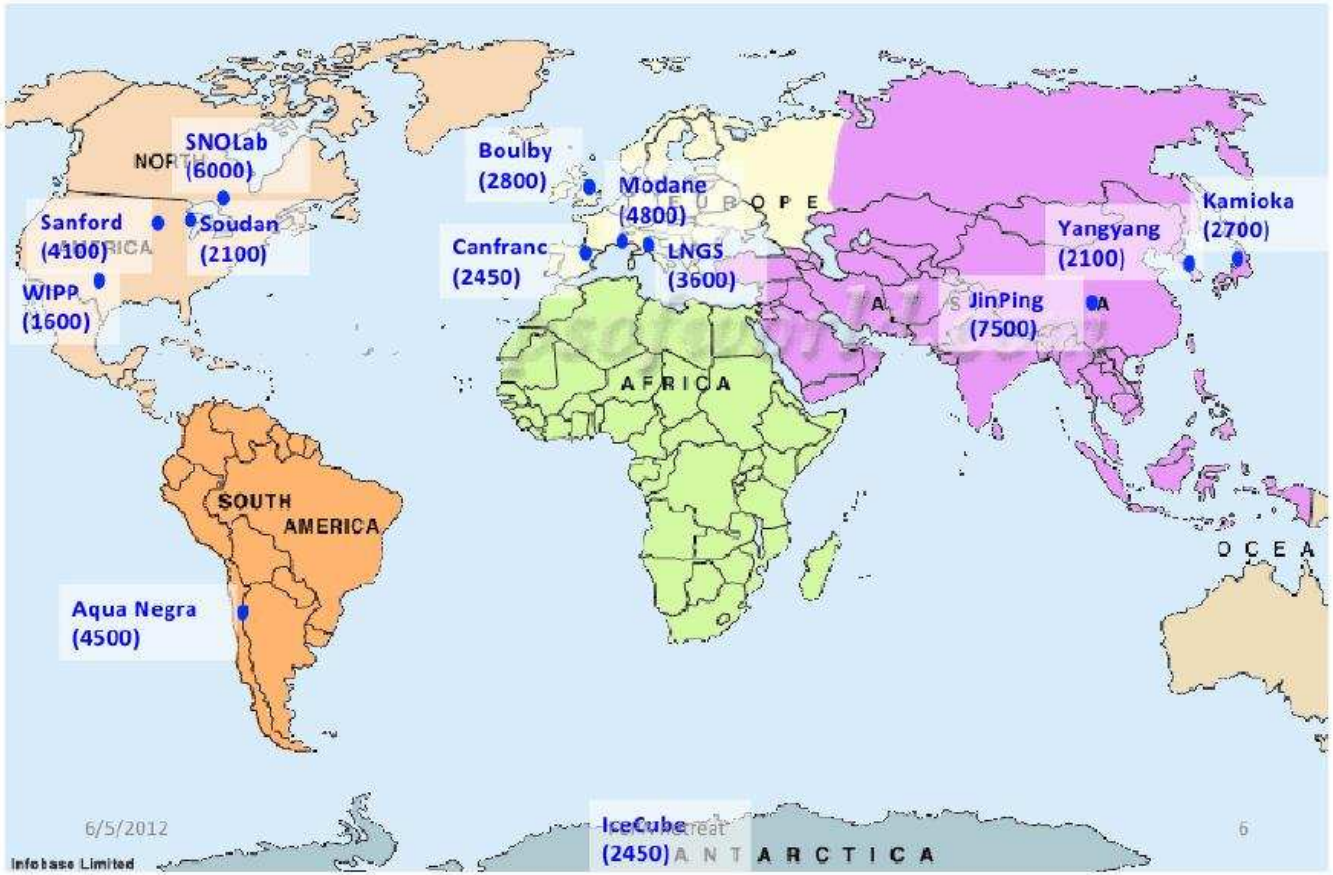

Detection and
Discrimination Methods
CoGeNT, PICASSO,
COUPP, DRIFT
eV, 20%
Energy
XENON, LUX, ZEPLIN
WARP, ArDM
ionization
Q
L
scintillation
H
phonons
keV, Few %
Energy
meV, 100%
Energy
CRESST
DAMA, XMASS,
DEAP/CLEAN
CRESST II
Ionization Energy
Electron Recoil
Nuclear Recoil
Phonon Energy
CDMS, EDELWEISS

(Source: CDMS)

Go underground to reduce the background :



Underground Laboratories



(From Dan Bauer 2012)

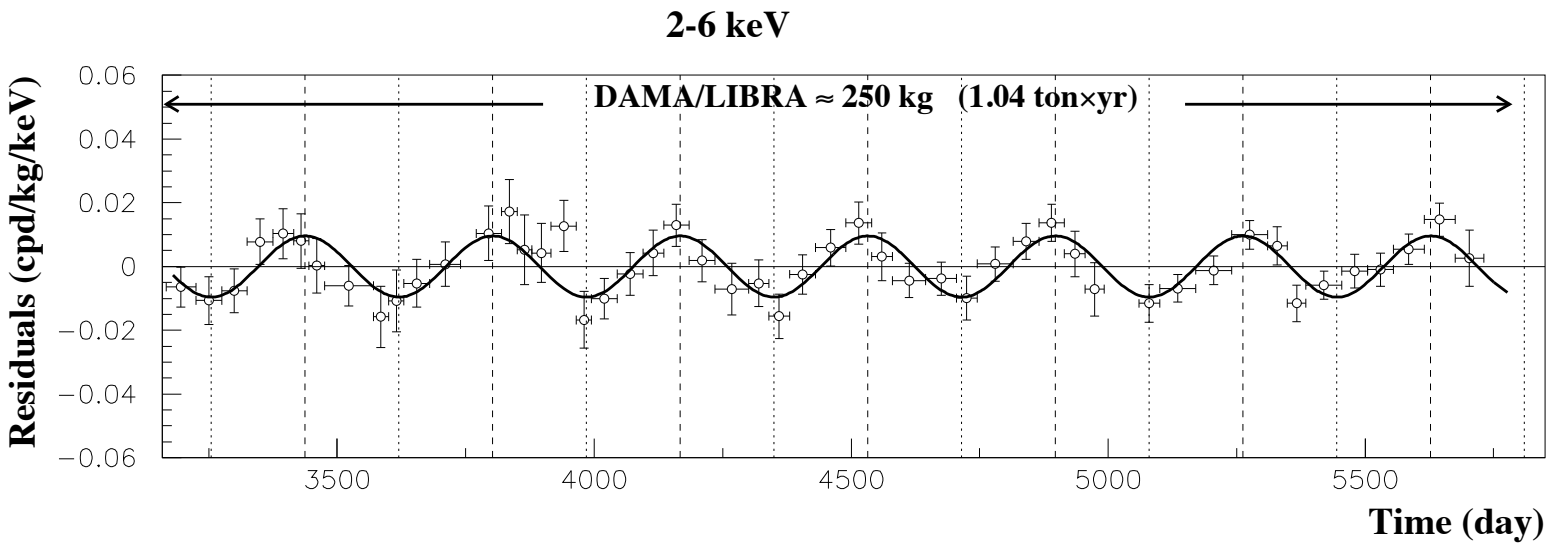
Direct Detection Technology Summary

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

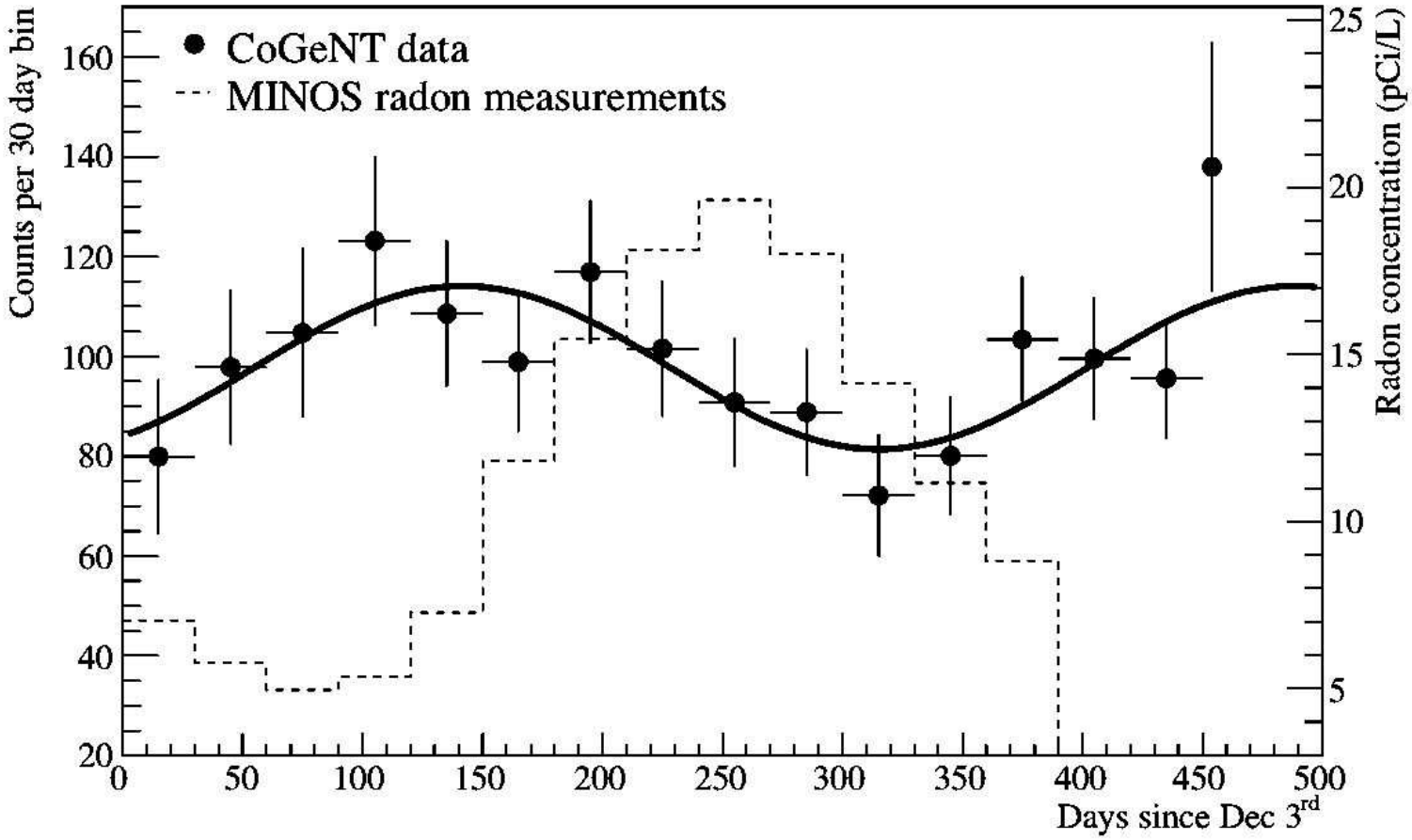
From Dan Bauer 2012

Annual modulation: Detection claim by DAMA/LIBRA Experiment



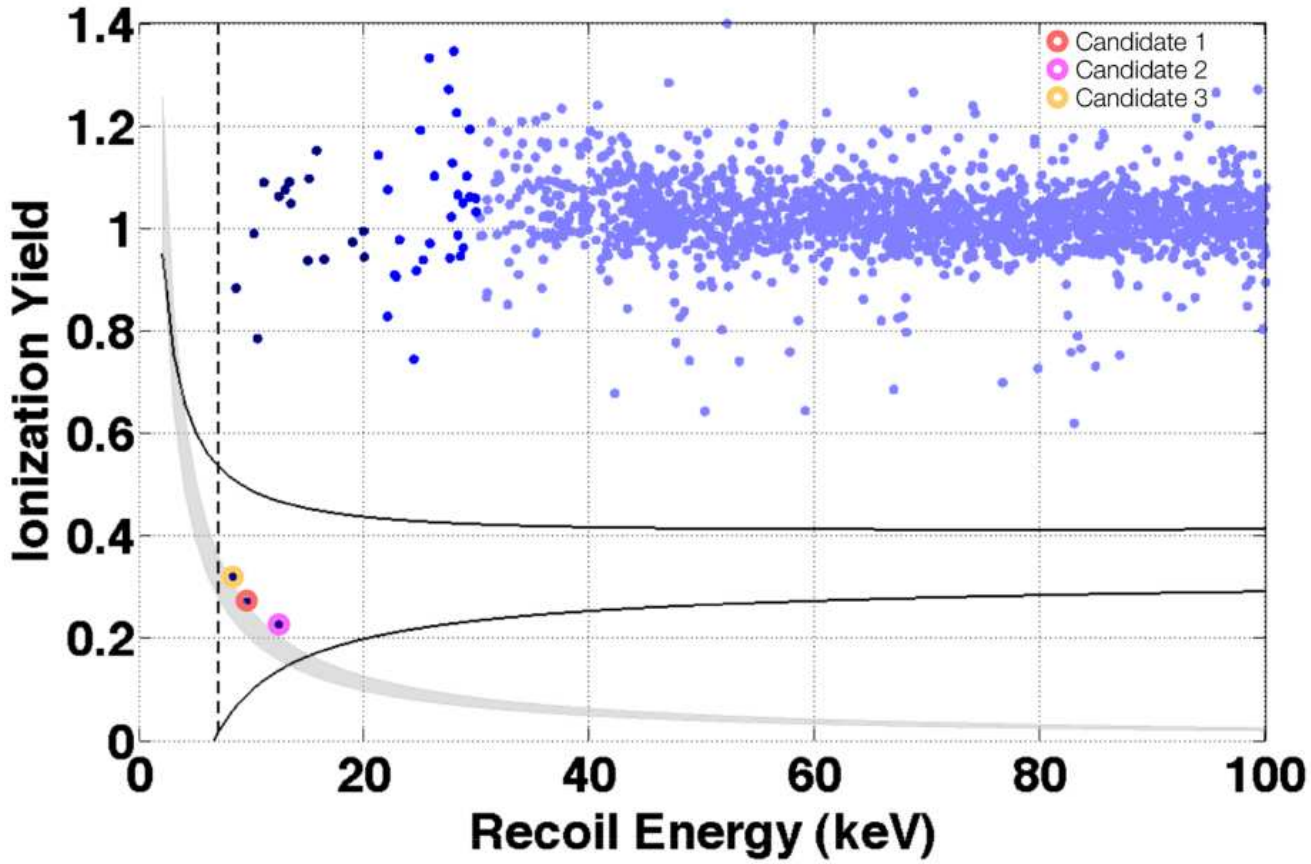
Temporal variation of single-hit event rate fitted with a sinusoidal curve: $A\cos\omega(t-t_0)$ with a period $T=\frac{2\pi}{\omega}=1$ yr, a phase $t_0=152.5$ day (June 2nd). The zero of the time scale is at January 1st of the first year of data taking of the former DAMA/NaI experiment. Dashed vertical lines: expected maximum (June 2nd). Dotted vertical lines: minimum. (Bernabei et al, arXiv:1308.5109)

Annual modulation in CoGeNT experiment



(Aalseth et al, arXiv:1208.5737

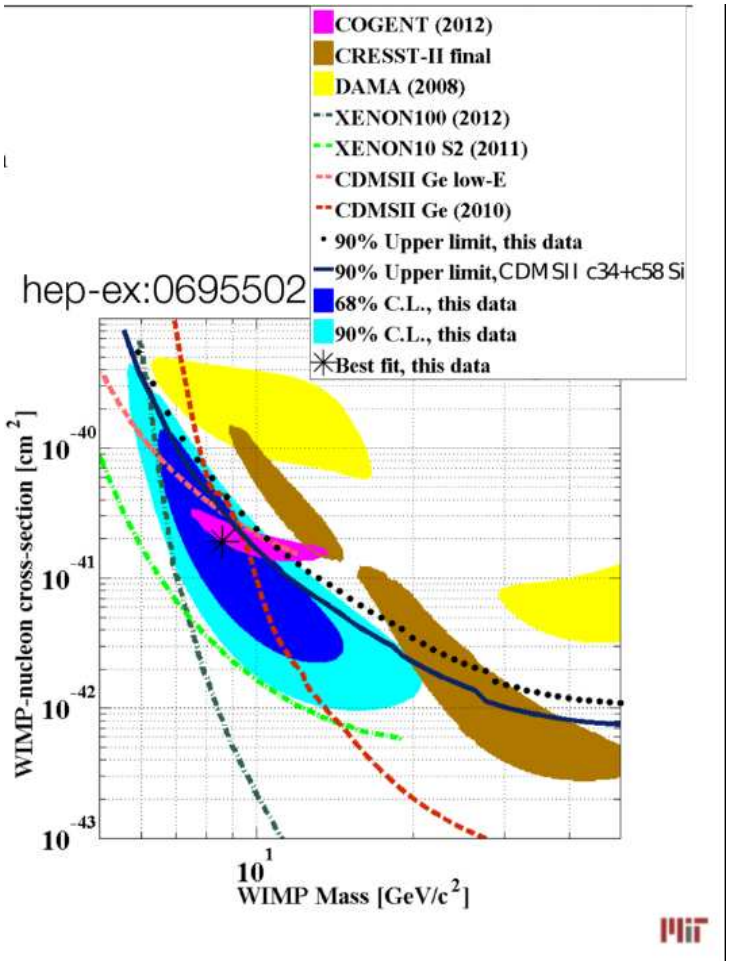
Direct Detection: CDMS Limits



Kevin A. McCarthy / APS April Meeting / 2013

140.2 kg. day of Si data (July 2007 – Sept 2008): 3 low-mass ($\sim$ 8.6 GeV) WIMP candidate events!

Exclusion Plot



From Kevin McCarthy, APS meeting, April'13

But ... new results from Large Underground Xenon (LUX) detector

First results from the LUX dark matter experiment at the Sanford Underground Research Facility

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(Dated: October 30, 2013)

The Large Underground Xenon (LUX) experiment, a dual-phase xenon time-projection chamber operating at the Sanford Underground Research Facility (Lead, South Dakota), was cooled and filled in February 2013. We report results of the first WIMP search dataset, taken during the period April to August 2013, presenting the analysis of 85.3 live-days of data with a fiducial volume of 118 kg. A profile-likelihood analysis technique shows our data to be consistent with the background-only hypothesis, allowing 90% confidence limits to be set on spin-independent WIMP-nucleon elastic scattering with a minimum upper limit on the cross section of 7.6×10^{-46} cm^2 at a WIMP mass of 33 GeV/c^2. We find that the LUX data are in strong disagreement with low-mass WIMP signal interpretations of the results from several recent direct detection experiments.

PACS numbers: 95.35.+d, 29.40.-n, 95.55.Vj
Keywords: dark matter, direct detection, xenon

LUX Exclusion Plot

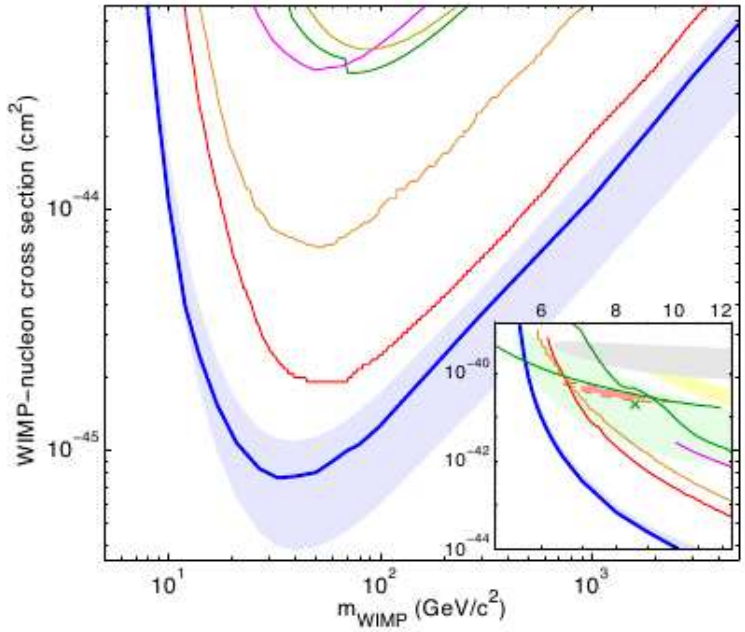
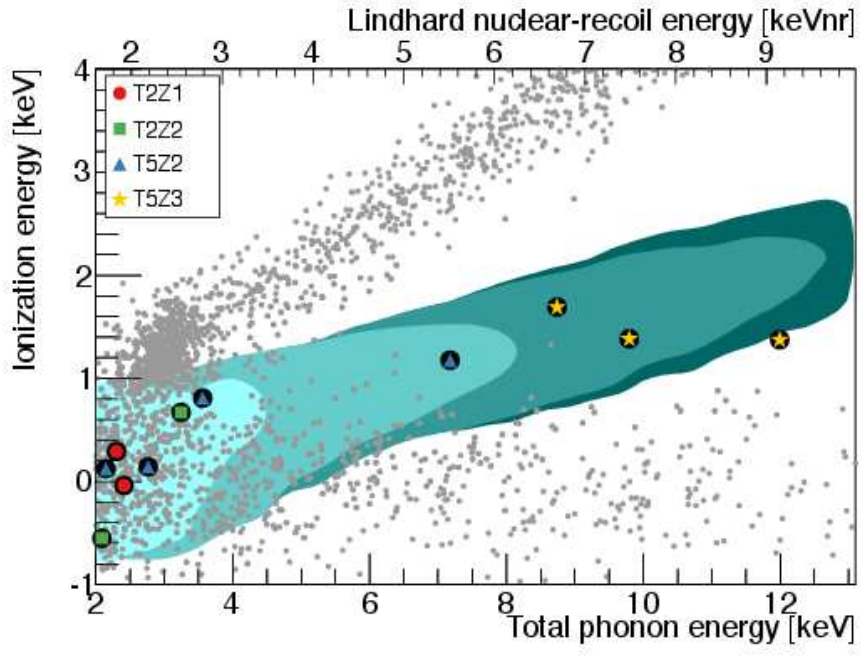


FIG. 5. The LUX 90% confidence limit on the spin-independent elastic WIMP-nucleon cross section (blue), together with the $\pm 1\sigma$ variation from repeated trials, where trials fluctuating below the expected number of events for zero BG are forced to 2.3 (blue shaded). We also show Edelweiss II [41] (dark yellow line), CDMS II [42] (green line), ZEPLIN-III [43] (magenta line) and XENON100 100 live-day [44] (orange line), and 225 live-day [45] (red line) results. The inset (same axis units) also shows the regions measured from annual modulation in CoGeNT [46] (light red, shaded), along with exclusion limits from low threshold re-analysis of CDMS II data [47] (upper green line), 95% allowed region from CDMS II silicon detectors [48] (green shaded) and centroid (green x), 90% allowed region from CRESST II [49] (yellow shaded) and DAMA/LIBRA allowed region [50] interpreted by [51] (grey shaded).

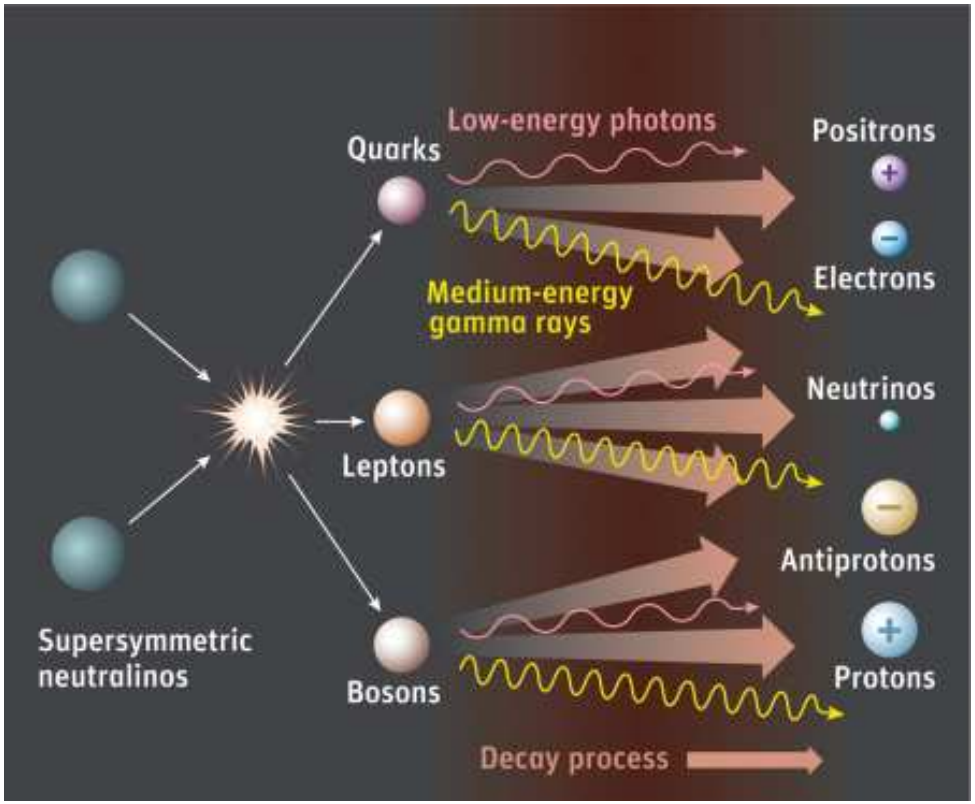
Latest SuperCDMS results



$\sigma^{\rm SI}_{\chi-n} < 1.2 \times 10^{-42} {\rm cm}^2$ at $m_\chi \sim 8$ GeV (But in tension with the results of LUX, CoGeNT, CDMS-Si, DAMA)

SuperCDMS collaboration: arXiv:1402.7137

Indirect Detection: WIMP annihilation



AMS-2 positron excess, Fermi γ rays from dwSph, Galactic center, ...

Astrophysical issues

Expected number of events in direct detection (DD) or indirect detection (ID) experiments, and thus the interpretation of the results of these experiments, depend upon the density and velocity distribution of the WIMPs in the Galaxy.

$$\begin{array}{lcl} \text{No. of events (DD or ID)} & \equiv & \text{Particle Physics} \otimes \text{Astrophysics} \\ & & \downarrow \qquad\qquad \downarrow \\ & & (m_\chi\,, \sigma_{\chi N}) \otimes (\rho_{\mathrm{DM},\odot}\,, f(\mathbf{v})) \\ & & \downarrow \qquad\qquad \downarrow \\ & & \text{e.g., LHC} \otimes \text{Galactic Dynamics (e.g., rot. curve)} \end{array}$$

- Need to fix Astrophysics to extract particle physics of DM (m_χ , σ).
- Use the observed rotation curve data of the Galaxy to determine the phase space DF of DM particles, i.e., $\rho_{\mathrm{DM},\odot}$, $f(\mathbf{v})$.
- Galactic rotation curve near solar location is significantly influenced by visible matter.
- Self-consistent approach: Determine the DF of the DM particles by self-consistently including the effect of known visible matter (VM) such that together (DM+VM) they give a good fit to the observed rotation curve data.

Astrophysical Issues contd. . . .

- For drawing conclusions from the results of any direct or indirect detection experiments, we need to specify $\rho_{\mathrm{DM},\odot}$ and $f(u)_{\odot}$, both of which are *a priori* unknown.
- Determine $\rho_{\mathrm{DM},\odot}$ and $f(u)_{\odot}$ from the relevant observational data pertaining to our Galaxy $\Rightarrow$ Rotation curve data, data on the dynamics of satellites of Milky Way, . . .
- Need to start at the level of the Phase Space Distribution Function (DF), $f(\mathbf{x}, \mathbf{u})$, of WIMPs in the Galaxy.

- Theoretically expected DF: a quasi-Maxwellian

Violent relaxation: [Lynden-bell (1967)]

Phase space distribution of collisionless systems

- Assume Dark Matter consists of WIMPs

$\Rightarrow$ Phase space DF satisfies collisionless Boltzmann (Vlasov) equation (CBE),

$$\frac{df}{dt} \equiv \frac{\partial f}{\partial t} + \boldsymbol{v}.\boldsymbol{\nabla} f - \boldsymbol{\nabla}\Phi.\frac{\partial f}{\partial \boldsymbol{v}} = 0\,.$$

Jeans Theorem: *Any steady-state solution of the CBE depends on the phase-space coordinates only through integrals of motion in the galactic potential, and any function of the integrals yields a steady-state solution of the CBE.*

Simplest choice: $f(\mathbf{x},\mathbf{v}) = f(E)$, with $E = \Phi + \frac{1}{2}v^2$.

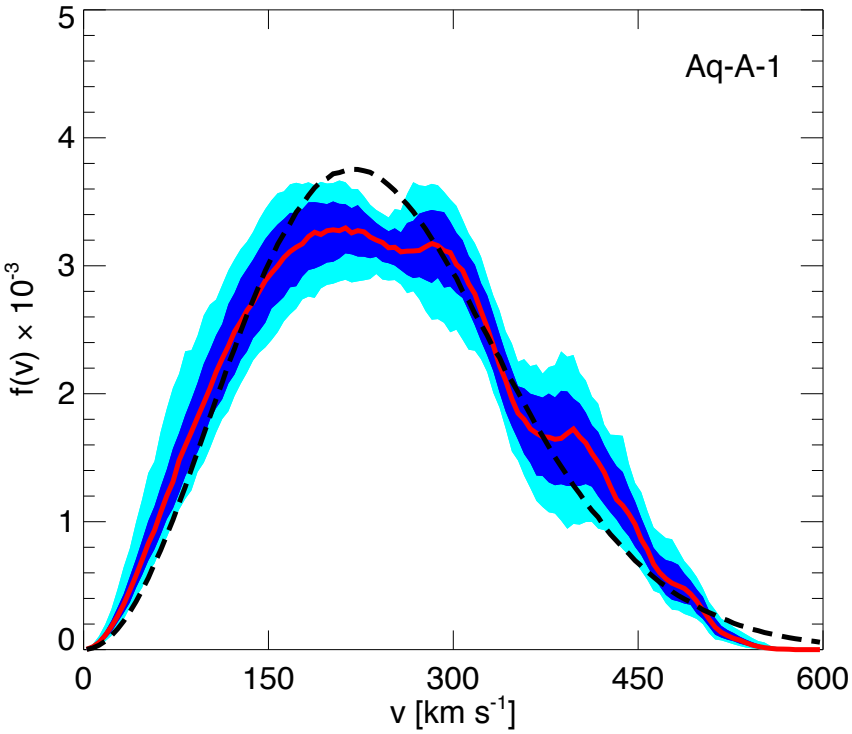
Isothermal DF:

$$f(\mathbf{x},\mathbf{v}) = \frac{\rho_0}{(2\pi\sigma^2)^{\frac{3}{2}}} \exp\left[-E/\sigma^2\right] \ ,$$

with $\langle v^2 \rangle = 3\sigma^2$ and boundary condition $\Phi(0) = 0$, so that

$\rho(\mathbf{x}) = \int f(\mathbf{x},\mathbf{v}) d^3\mathbf{v} = \rho_0 \exp\left[-\Phi(\mathbf{x})/\sigma^2\right]$, and $\nabla^2\Phi = 4\pi\rho_0 \exp\left[-\Phi(\mathbf{x})/\sigma^2\right]$.

DM Velocity Distribution: Simulations



(From Vogelsberger et al, arXiv:0812.0362)

The velocity distribution can be described by a “quasi-Maxwellian".

Also, the possibility of a "DM thick disc"

The 'Standard halo model'

Local WIMP velocity distribution, in the Galactic rest frame, is taken as Maxwellian (isotropic isothermal sphere):

$$
\begin{aligned}
f^{\rm G}(\mathbf{v}) &= N\left[\exp\left(-|\mathbf{v}|^2/v_{\rm c}^2\right) - \exp\left(-v_{\rm esc}^2/v_{\rm c}^2\right)\right] & |\mathbf{v}| < v_{\rm esc}\,, \\
f^{\rm G}(\mathbf{v}) &= 0 & |\mathbf{v}| > v_{\rm esc}\,,
\end{aligned}
$$

where N is a normalization factor, $v_{\rm c} \approx 220\,{\rm km\,s^{-1}}$ and $v_{\rm esc} \approx 730\,{\rm km\,s^{-1}}$ are the local circular and escape speeds respectively.

Usual fiducial value for the local WIMP density, $\rho_\chi = 0.3\,{\rm GeV\,cm^{-3}}$.

For an isothermal gravitating sphere, $\langle v^2\rangle^{1/2} = \sqrt{\frac{3}{2}}v_{c,\infty}$.
With $v_{c,\infty} = v_{c,\odot} = 220\,{\rm km\,s^{-1}}$, one has $\langle v^2\rangle^{1/2} = 270\,{\rm km\,s^{-1}}$.

Standard Halo Model $\equiv$ Maxwellian velocity distribution with $\rho_{{\rm DM},\odot} = 0.3\,{\rm GeV/\,cm^3}$ and $\langle v^2\rangle^{1/2}_{{\rm DM},\odot} = 270\,{\rm km\,s^{-1}}$.

- Cosmological density: $\rho_{\rm DM}^{\rm cos} \sim 10^{-6}\,{\rm GeV/\,cm^3}$
- Need $\rho_{{\rm DM},\odot}$, $f(v_{\rm DM})_\odot$
- Typically, one assumes isothermal dist. : $f(v) \propto exp(-v^2/\sigma^2)$
- For isothermal dist., $\rho_{{\rm DM},\odot} \sim (0.2-0.4)\ {\rm GeV/\,cm^3}, \sigma \sim \sqrt{\frac{3}{2}} v_\infty$. Assuming flat rot courve $v_\infty = v_{{\rm rot},\odot} \approx 220\,{\rm km\,s^{-1}}$, one gets $\sigma \approx 270\,{\rm km\,s^{-1}}$. Too simplistic!
- Also, isothermal model has infinite mass: Need to truncate it self-consistently, else not a solution of CBE.
- DM at solar neighborhood strongly influenced by Galactic processes. Galactic dynamics at solar location dominated by visible matter, not DM. Need to self-consistently include the effects of visible matter to determine $\rho_{{\rm DM},\odot}$ and $f(v_{\rm DM})_\odot$, i.e.,

  $\nabla^2 \Phi_{\rm DM} = 4\pi \rho_{\rm DM}(0) \exp\left[-\left\{\Phi_{\rm DM} + \Phi_{\rm vis}\right\}/\sigma^2\right]$. with

  $\nabla^2 \Phi_{\rm vis} = 4\pi \rho_{\rm vis}^{\rm obs}$.

Truncated Isothermal – "King model"

Isothermal model has divergent total mass, $M(r) \propto r$ as $r \to \infty$. Need to self-consistently truncate it.

$$f(x,v) \equiv f(\varepsilon) = \begin{cases} \rho_1 (2\pi\sigma^2)^{-3/2} \left(e^{\varepsilon/\sigma^2} - 1\right) & \text{for } \varepsilon > 0\,, \\ 0 & \text{for } \varepsilon \leq 0\,, \end{cases} \tag{1}$$

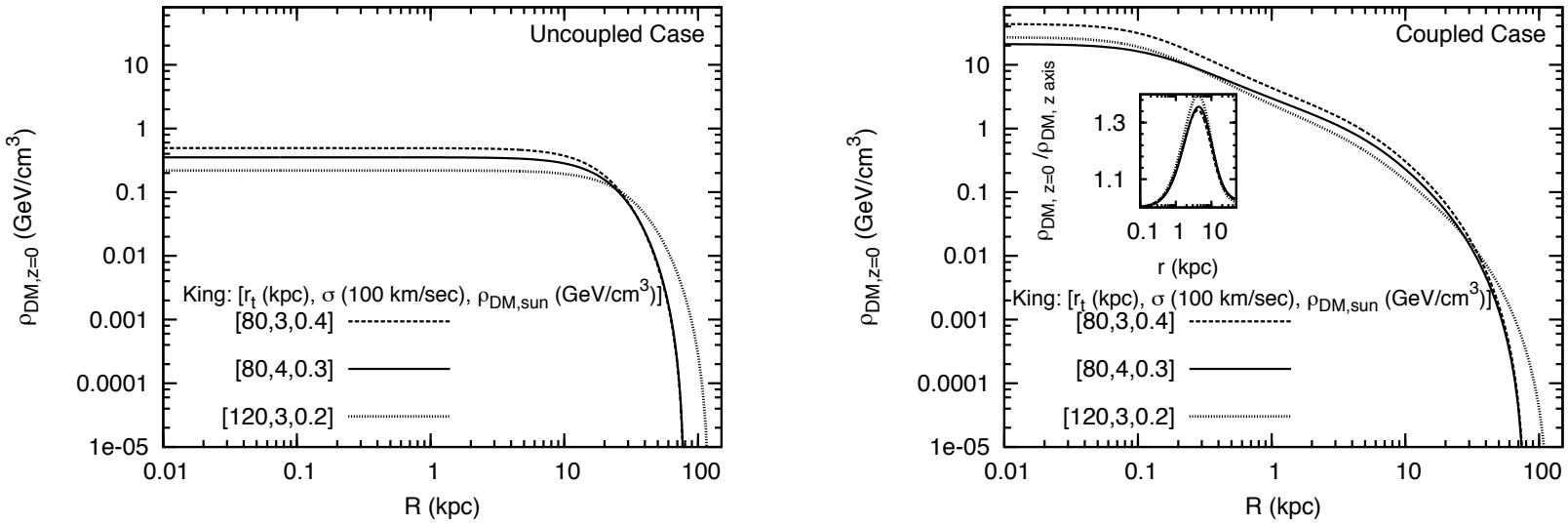
with $\varepsilon \equiv \phi_0 - (\frac{1}{2}v^2 + \phi)$, and $\phi = \phi_{\rm vis} + \phi_{\rm DM} \equiv \phi_{\rm total}$.
$\nabla^2 \phi_{\rm DM}(R,z) = 4\pi G \rho_{\rm DM}(R,z)$, $\nabla^2 \phi_{\rm vis}(R,z) = 4\pi G \rho_{\rm vis}(R,z)$.

$\rho_{\rm DM} \equiv \rho_{\rm DM}[\phi_{\rm vis} + \phi_{\rm DM}] = \int f \; d^3v$. Note Self-consistency.

Three parameters: ρ_1, σ and ϕ_0.
$\rho_{\rm DM}$ vanishes at $r = r_t$ where $\varepsilon = 0$.

Three "measurable" parameters of the model:
$\rho_{\rm DM,\odot} = \rho_{\rm DM}(R = R_0, 0)$, $\langle v^2 \rangle^{1/2}_{\rm DM,\odot} = \langle v^2 \rangle^{1/2}_{\rm DM}(R = R_0, 0)$ and r_t.

Self-consistent DM Density Profile

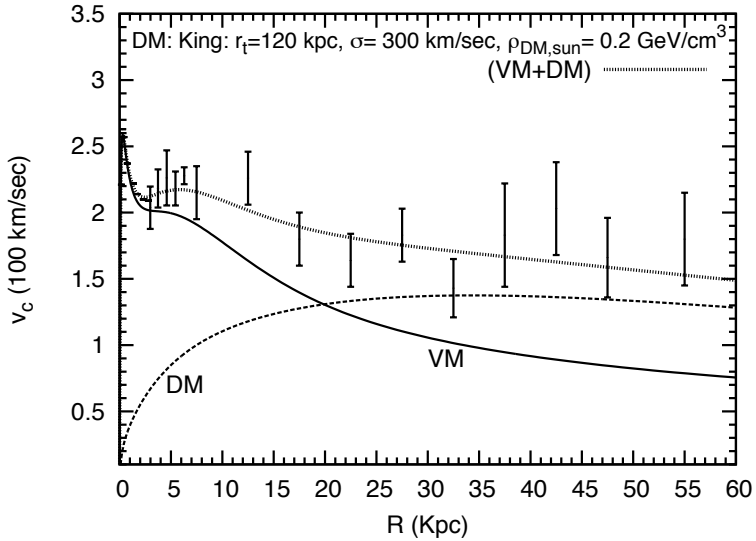


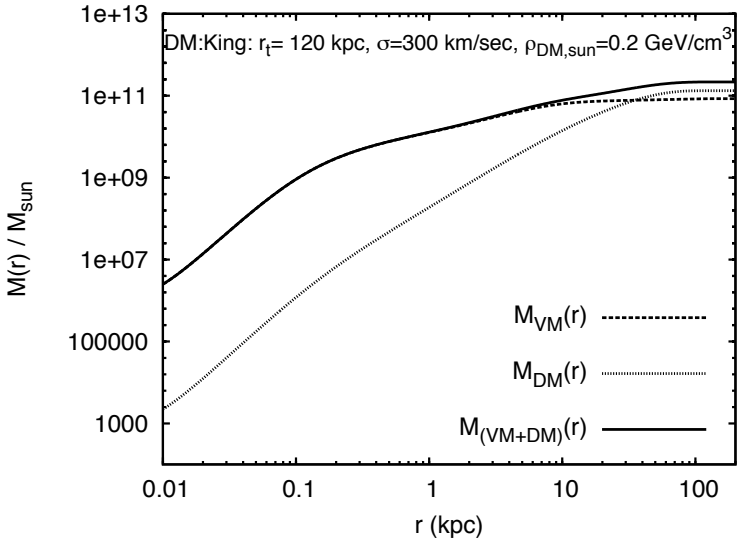
(S. Chaudhury, PB, R. Cowsik, JCAP (2010)) Visible matter "pulls in" the DM; DM density profile made steeper with enhanced density in the inner Galaxy

$\Rightarrow$ Impact on DM annihilation signals from the Galaxy Centre region

Rotation Curves for Truncated Isothermal Models

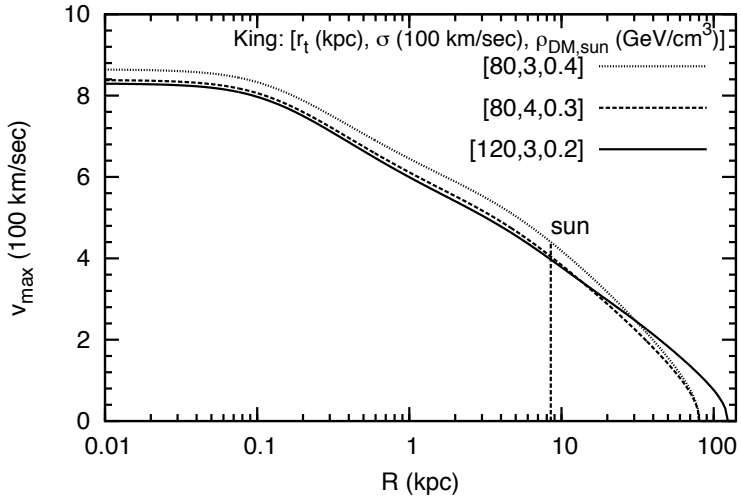
$$v_c^2(R) = R\frac{\partial\phi}{\partial R}(R,0) = R\frac{\partial}{\partial R}\left[\phi_{\rm DM}(R,0) + \phi_{\rm vis}(R,0)\right] .$$

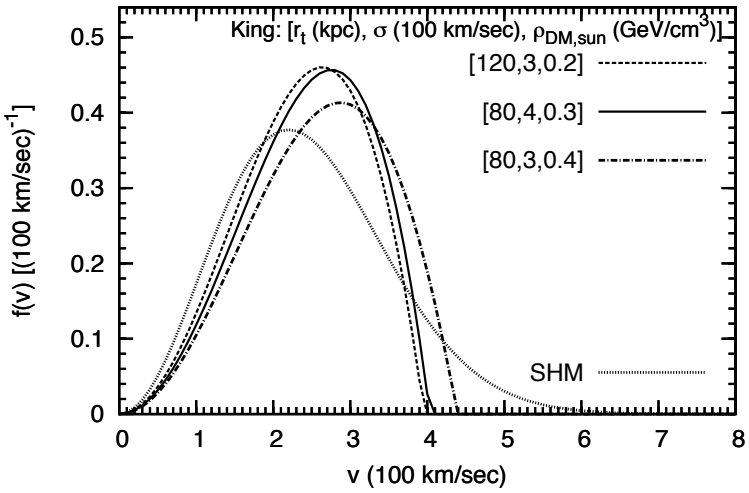




New rotation curve data out to 60 kpc (Xue etal (2008) is used.

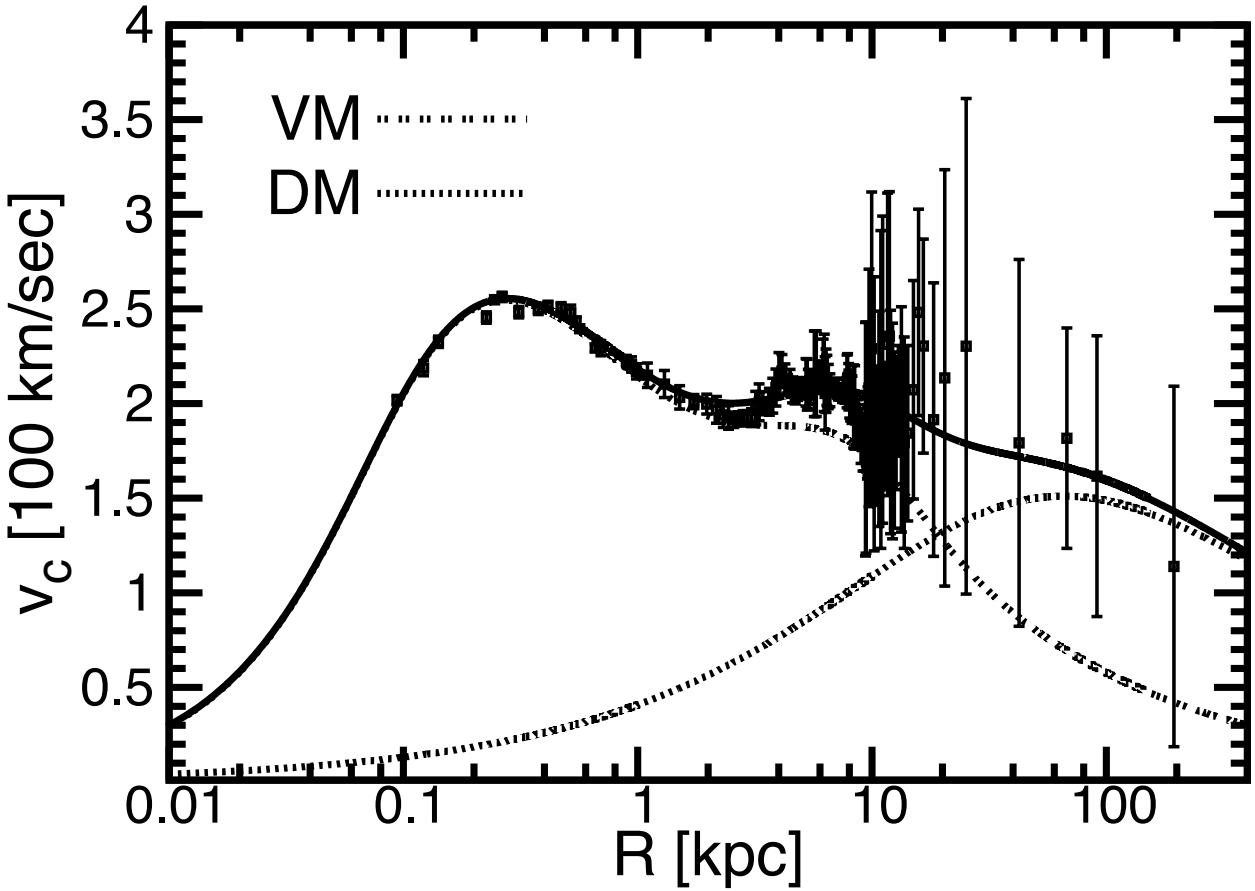
Self-consistent DM Velocity Distribution





Non-Maxwellian velocity distribution; cutoff speed determined self-consistently

More from Rotation Curve



Rotation curve with best-fit values of DM and VM parameters. Data are from Y. Sofue, PASJ **64** (2012) 75; arXiv:1110.4431.

(PB, S.Chaudhury, S. Kundu, S. Majumdar, PRD (2013))

Dark Matter parameters

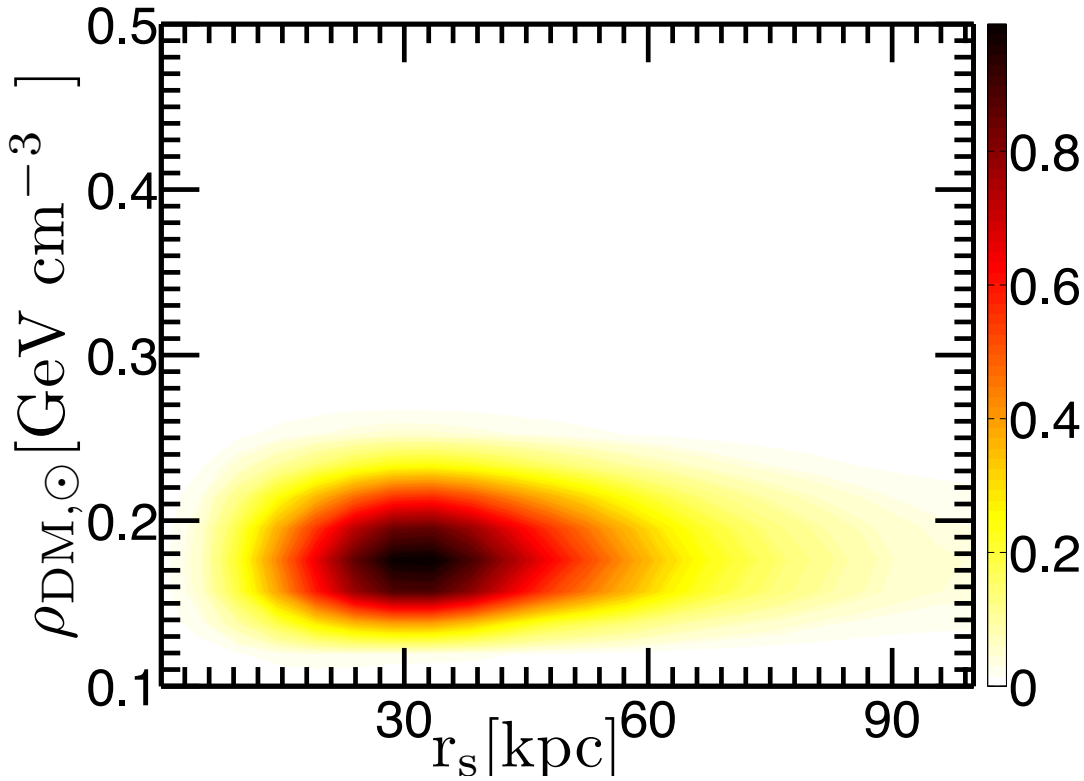
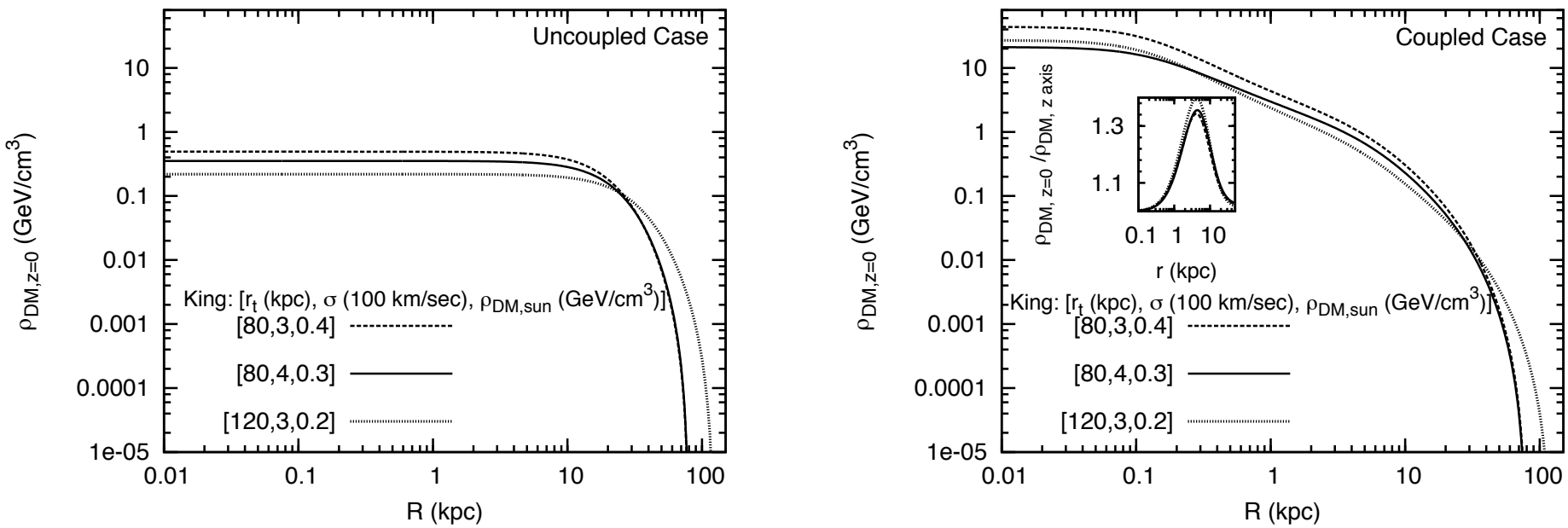


Figure 1: The 2D posterior probability density function for Dark Matter parameters $(r_s - \rho_{\mathrm{DM},\odot})$, marginalized over the visible matter parameters.

(PB, S.Chaudhury, S. Kundu, S. Majumdar, PRD (2013))

Self-consistent DM Density Profile



(S. Chaudhury, PB, R. Cowsik, JCAP (2010))

Visible matter "pulls in" the DM; DM density profile made steeper with enhanced density in the inner Galaxy

⇒ Impact on DM annihilation signals from the Galaxy Centre region

Dark Matter VDF

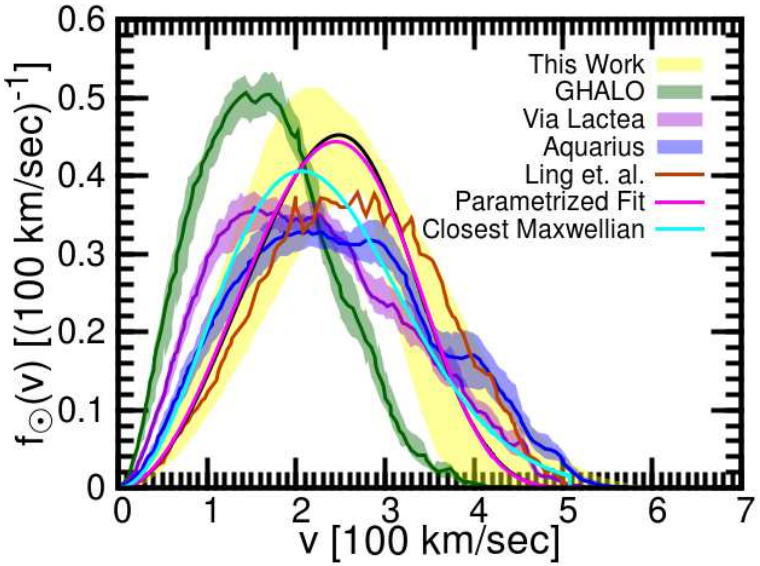


Figure 2: Normalized local speed distribution, $f_\odot(v)$, corresponding to the most-likely set of values of the Galactic model parameters determined from fit to rotation curve data, and its uncertainty band (shaded) corresponding to the 68% C.L. upper and lower ranges of the Galactic model parameters.

Best-fit (non-Maxwellian) speed distribution: $f_\odot(v) \approx 4\pi v^2 \left(\xi(\beta) - \xi(\beta_{\rm max})\right)$, where $\xi(x) = (1+x)^k \, e^{-x^{(1-k)}}$, $\beta = v^2/v_0^2$, $\beta_{\rm max} = v_{{\rm max},\odot}^2/v_0^2$, $v_0 = 339\,{\rm km\,s^{-1}}$ and $k = -1.47$.

(PB, S.Chaudhury, S. Kundu, S. Majumdar, PRD (2013))

Impact on WIMP Direct Detection

Recoil spectrum: $\frac{d\mathcal{R}}{dE_R}(E_R,t) = \frac{\sigma(q^2=2m_N E_R)}{2m_\chi \mu^2}\rho_\chi g(E_R,t)\,,$

with $\mu = m_\chi m_N/(m_\chi + m_N) =$ reduced mass, and

$$g(E_R,t) = \int_{u>u_{\rm min}(E_R)}^{u_{\rm max}(t)} \frac{d^3\mathbf{u}}{u} f_\odot\left(\mathbf{u}+\mathbf{v}_{\rm E}(\mathbf{t})\right)\Theta(u_{\rm max}-u_{\rm min})\,,$$

$\mathbf{u}$ (with $u = |\mathbf{u}|$)= relative velocity of the WIMP with respect to the detector at rest on Earth

$\mathbf{v}_{\rm E}(\mathbf{t}) =$ time-dependent velocity of the Earth relative to the Galactic rest frame.

$u_{\rm min}(E_R) = \left(m_N E_R/2\mu^2\right)^{1/2} =$ minimum WIMP speed required for producing a recoil energy E_R of the nucleus,

$u_{\rm max}(t) =$ lab frame (time-dependent) maximum WIMP speed corresponding to $v_{\rm max} = \sqrt{2\Psi}$ (defined in the Galactic rest frame).

Can show that $g(E_R,t)$ is a monotonically decreasing functiion of E_R, and thus takes its largest value at $E_R = E_{\rm th}$.

The lowest WIMP mass that can be probed by a given experiment:

$m_{\chi,\rm min} = m_N\left[\left(2m_N(v_{\rm max,\odot}+v_{\rm E})^2/E_{\rm th}\right)^{1/2}-1\right]^{-1}.$

Define $\zeta \equiv g(E_R = E_{\rm th})/g_{\rm Maxwell}(E_R = E_{\rm th})$

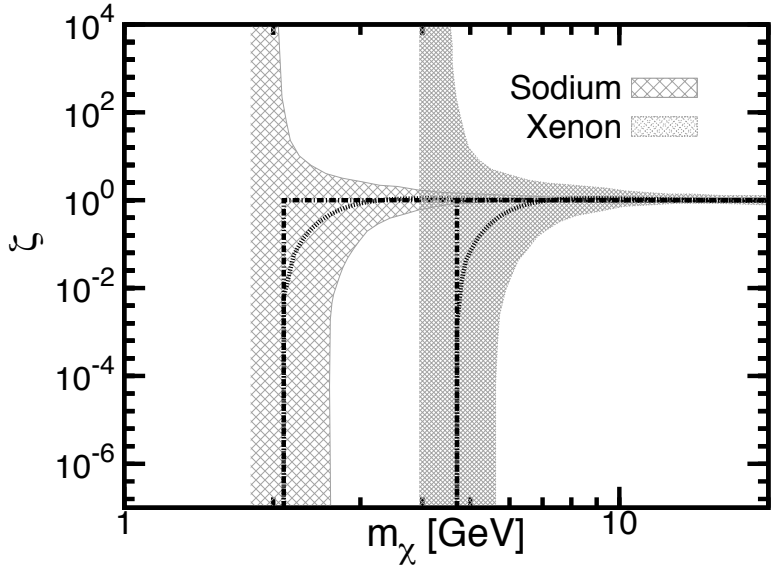


Figure 3: The ratio ζ for most-likely $f_\odot(v)$, with $E_{\rm th} = 2\,{\rm keV}$. The shaded bands correspond to the uncertainty bands of $f_\odot(v)$ from rotation curve. The calculations are for 2nd June, when the Earth's velocity in the Galactic rest frame is maximum.

Effect of departure from Maxwellian VDF is important for low m_χ

$\zeta \sim 10^{-2}$ at $m_\chi = m_{\chi,\rm min}$!

(PB, S.Chaudhury, S. Kundu, S. Majumdar, PRD (2013))

Summarizing . . .

- WIMPs are natural candidates for the Dark Matter in the Universe.
- Direct Detection experiments have already achieved sensitivity at the level of $\sim 10^{-9}$pb for SI WIMP-nucleus cross section. Some kinds of WIMPs may be close to detection, if they are there!
- Expected number of events in direct detection experiments depends on $\rho_{\mathrm{DM},\odot}$ and $f(v)_{DM,\odot}$. Must determine these parameters from observational data (e.g., Rotation Curve) by self-consistently including the gravitational effects of the visible matter.
- DM DVF is in general non-Maxwellian, and effect of departure from Maxwellian VDF is important for low-mass WIMPS — Maxwellian overestimates VDF at both high and low-velocity ends.
- Properly determined VDF will impact the interpretation of positron excess etc., from WIMP annihilation (Sommerfeld enhancement etc.).

Dark Matter search initiatives in India

PICASSO/PICO @ SNOLAB: Mainly sensitive to spin-dependent interactions

(mini)-DINO@ (Jaduguda)-INOLab: Mainly sensitive to spin-independent interactions