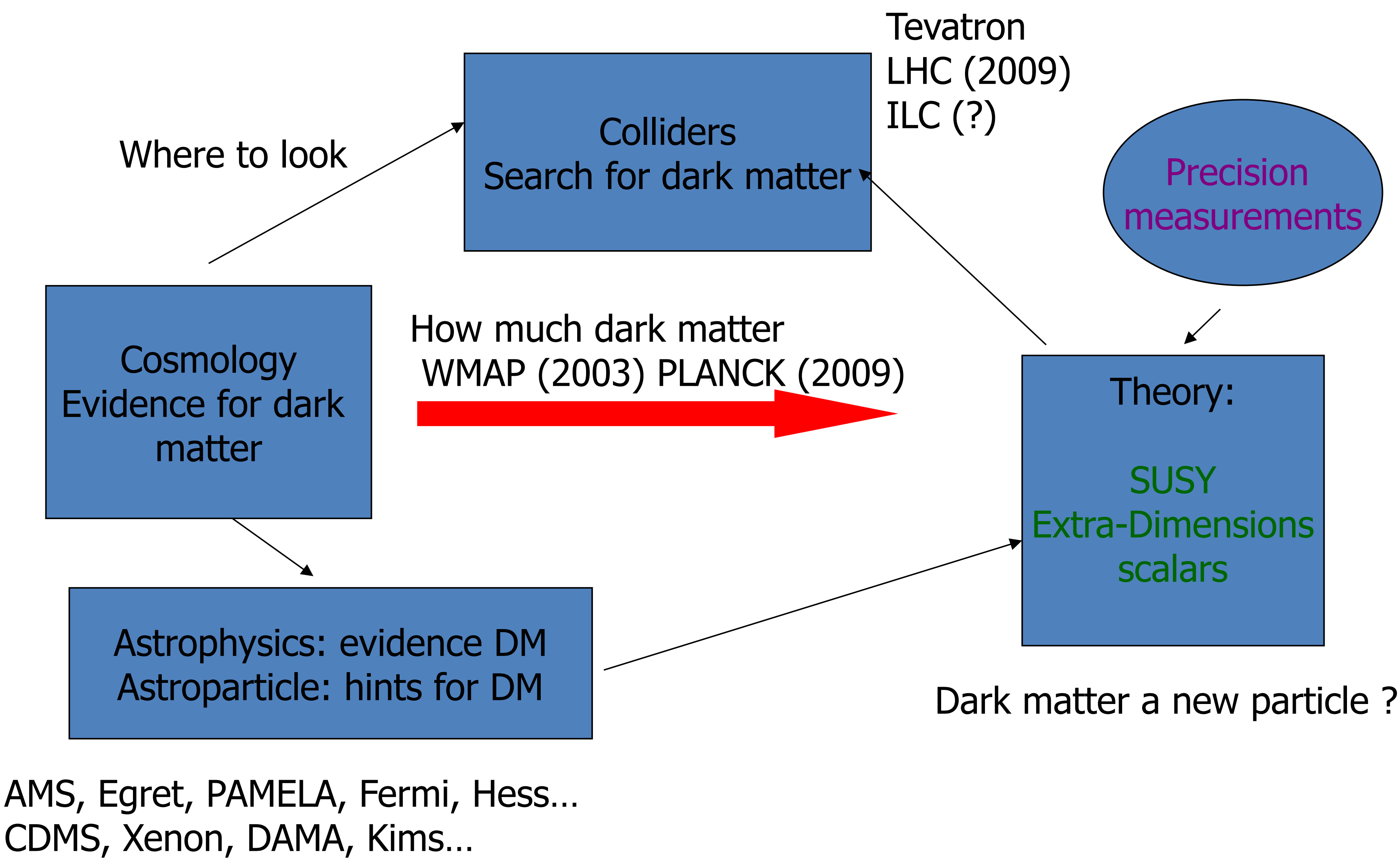
Searching for Dark matter

- Direct detection
  - Elastic scattering of WIMPs off nucleons in a large detector
  - Xenon, CDMS, Dama/Libra
- Indirect detection
  - WIMPs annihilation in galaxy, observe decay products
  - e, p, γ: Pamela, Fermi, Hess
  - Neutrinos: IceCube,Km3Net
- Collider searches
  - Indirect + Direct searches : Tevatron, LHC, ILC

Cosmology-(astro)particle-colliders



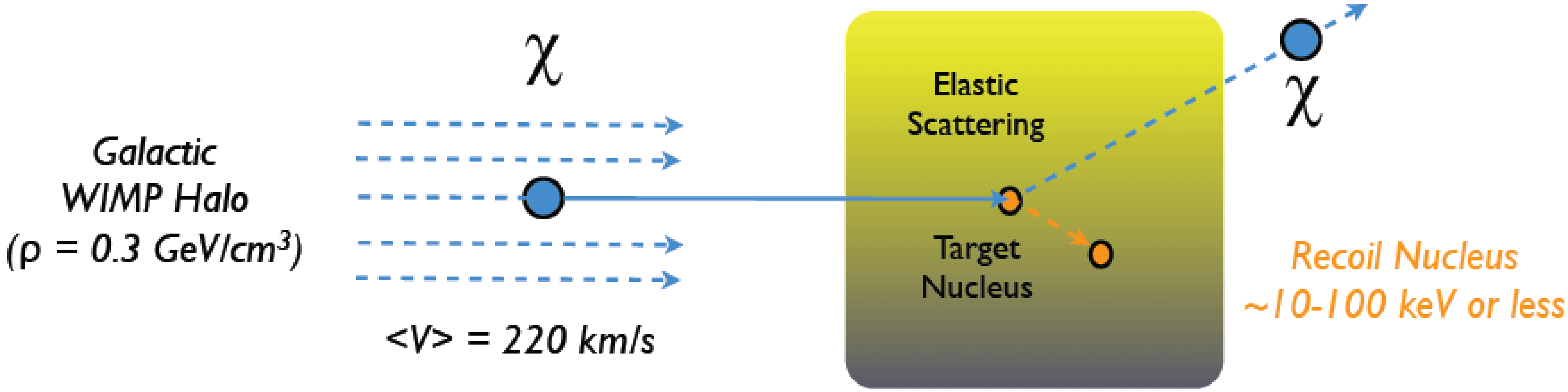
Direct detection

- Elastic scattering of WIMPs off nuclei in a large detector
- Measure nuclear recoil energy, E_R

- Best way to prove that WIMPs form DM

- Small transfer momentum – typically 100MeV
  - $E_R = q^2/2m_N$ q: transfer momentum
  - $E_R = \mu^2 v^2 (1-\cos\theta)/m_N$
  - $\mu = m_\chi m_N/(m_\chi + m_N)$: reduced mass
  - 100GeV WIMP, v=220km/s → $E_R < 27$keV

Direct detection



- Two types of scattering
  – Coherent scattering on A nucleons in nucleus, for spin independent interactions
    - Dominant for heavy nuclei
  – Spin dependent int – only one unpaired nucleon
    - Dominant for light nuclei

Steps to compute nucleus recoil energy

- Wimp-quark/gluon scattering: depend on particle physics model, compute from Feynman diagrams
- Relate WIMP-quark to WIMP-nucleon – quark coefficients in nucleons – determined from first principle + experiments
- WIMP-nucleon → WIMP nucleus : form factor
- Take into account velocity distribution of WIMP
- Recoil energy for WIMP scattering on nucleus

- Experimental results are presented in sigma WIMP-proton vs DM mass : easy comparison between exp.

WIMP- Nucleon amplitude

- For any WIMP, need effective Lagrangian for WIMP-nucleon amplitude *at small momentum*,
- Generic form for a Majorana fermion

$$\mathcal{L}_F = \lambda_N \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \psi_N + i\kappa_1 \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \gamma_5 \psi_N + i\kappa_2 \bar{\psi}_\chi \gamma_5 \psi_\chi \bar{\psi}_N \psi_N + \kappa_3 \bar{\psi}_\chi \gamma_5 \psi_\chi \bar{\psi}_N \gamma_5 \psi_N$$
$$+ \kappa_4 \bar{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \bar{\psi}_N \gamma^\mu \psi_N + \xi_N \bar{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \bar{\psi}_N \gamma^\mu \gamma_5 \psi_N$$

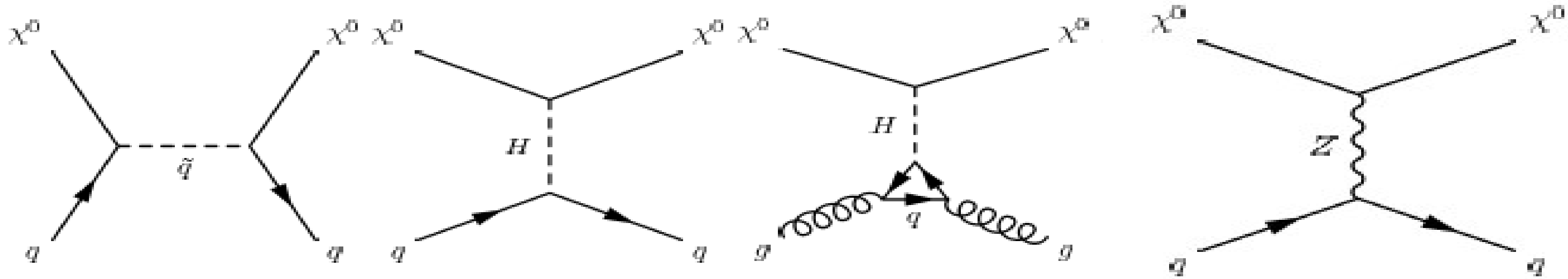
- For Majorana fermion only 2 operators survive at small q^2

- First need to compute the WIMP quark amplitudes
  - Computed from Feynman diagrams+ Fierz
  - depends on details of particle physics model
- Effective Lagrangian for WIMP-quark scattering has same generic form as WIMP nucleon

Direct detection

- Typical diagrams

- Higgs exchange often dominates



For Dirac fermions Z exchange contributes to SI and SD

Spin independent interactions

- The case of Majorana fermion

$$\mathcal{L}^{SI} = \lambda_N \overline{\psi}_\chi \psi_\chi \overline{\psi}_N \psi_N$$

- Matrix element squared

$$|A_N^{SI}|^2 = 64\,(\lambda_N M_\chi M_N)^2$$

- Summing over photons and neutrons

$$|A_A^{SI}|^2 = 64 M_\chi^2 M_A^2 (\lambda_p Z + \lambda_n (A - Z))^2$$

- Cross section for scattering on point like nucleons

$$\sigma_0^{SI} = \frac{4\mu_\chi^2}{\pi} (\lambda_p Z + \lambda_n (A - Z))^2 \qquad \mu_\chi = m_{\tilde{\chi}} M_A / (m_{\tilde{\chi}} + M_A).$$

WIMP-quark to WIMP-nucleon

- Coefficients relate WIMP-quark operators to WIMP nucleon operators
  - Scalar, vector, pseudovector, tensor
  - Extracted from experiments
  - Source of theoretical uncertainties
- Example , scalar coefficients, contribution of q to nucleon mass (heavy quark contribution expressed in terms of gluonic content)

$$\langle N | m_q \overline{\psi}_q \psi_q | N \rangle = f_q^N M_N$$

$$\lambda_{N,p} = \sum_{q=1,6} f_q^N \lambda_{q,p} \qquad f_Q^N = \frac{2}{27}\left(1 - \sum_{q \leq 3} f_q^N\right)$$

- Scalar coefficients extracted from ratios of light quark masses, pion-nucleon sigma term and σ_0 (size of SU(3) breaking effect)

$$\sigma_{\pi N} = m_l \langle p|\bar{u}u + \bar{d}d|p\rangle$$
$$\sigma_0 = m_l \langle p|\bar{u}u + \bar{d}d - 2\bar{s}s|p\rangle$$

- Large uncertainty in s-quark contribution

$$\sigma_{\pi N} = 55 - 73 \text{ MeV} \quad \text{and} \quad \sigma_0 = 35 \pm 5 \text{ MeV}$$

Nucleon	f_{Tu}	f_{Td}	f_{Ts} [24]	f_{Ts} [25]	f_{Ts} [20, 26]
n	0.023	0.034	0.08	0.14	0.46
p	0.019	0.041	0.08	0.14	0.46

- 2011: Lattice calculations give new estimates of those coefficients – get s-quark content lower than previously thought (~0.02)
- The value of the quark coefficient a large impact on the scattering rate - varying coefficients within the range above can in the MSSM lead to almost order of magnitude change in cross section
  - Bottino et al hep-ph/0010203, Ellis et al hep-ph/0502001

WIMP-nucleon to WIMP-nucleus

- To get rate as a function of the recoil energy must take into account nuclear form factor + velocity distribution
- Ignoring form factor effect expect isotropic scattering in CMS frame - - in lab frame for velocity v get constant distribution over recoil energy in interval 0<E<Emax

$$E_{max}(v) = 2\left(\frac{v^2\mu_\chi^2}{M_A}\right)$$

- For fixed v, recoil energy distribution

$$\frac{d\sigma_A^{SI}}{dE} = \sigma_0^{SI}\frac{\Theta(E_{max}(v) - E)F_A^2(q)}{E_{max}(v)} \qquad q = \sqrt{2EM_A}.$$

- F_A(q) : form factor (Woods-Saxon form factor)

$$F_A(q) = \int e^{-iqx}\rho_A(x)d^3x \qquad \rho_A(r) = \frac{c_{norm}}{1 + exp((r - R_A)/a)}$$

$$R_A = 1.23A^{\frac{1}{3}} - 0.6\mathrm{fm}$$

a=0.52fm (extracted from muon scattering data)

- DM have velocity distribution f(v)
- Integrating over incoming velocities -> distribution of number of events over the recoil energy

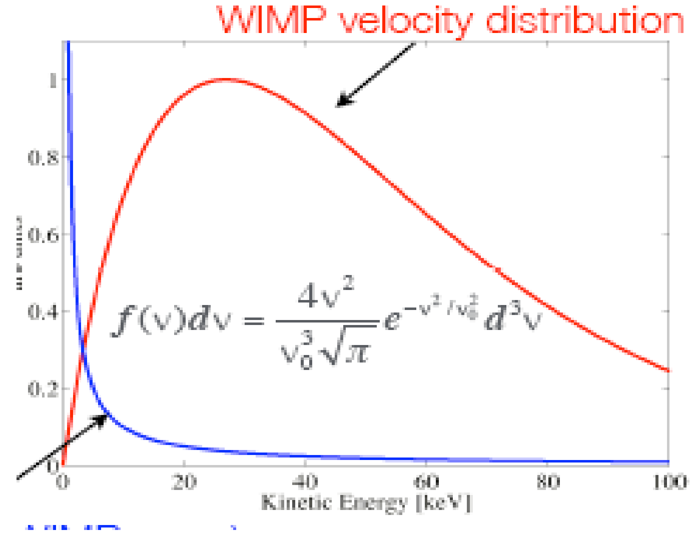
$$\frac{dN^{SI}}{dE} = \frac{2M_{det}t}{\pi}\frac{\rho_0}{M_\chi}F_A^2(q)\left(\lambda_p Z + \lambda_n(A-Z)\right)^2 I(E)$$

ρ_0: DM density near Earth

- M_{det}: detector mass
- T: exposure time

$$I(E) = \int_{v_{min}(E)}^{\infty}\frac{f(v)}{v}dv$$

$$v_{min}(E) = \left(\frac{EM_A}{2\mu_\chi^2}\right)^{1/2}$$



WIMP-nucleon to WIMP-nucleus

- Rates (SI and SD) depends on nuclear form factors and velocity distribution of WIMPs + local density

$$\frac{dN^{SI}}{dE} = \frac{2M_{det}t}{\pi}\frac{\rho_0}{M_\chi}F_A^2(q)\left(\lambda_p Z + \lambda_n(A-Z)\right)^2 I(E)$$

Nuclear form factors

Particle physics
+ quark content in nucleon

DM velocity distribution

$$I(E) = \int_{v_{min}(E)}^{\infty} \frac{f(v)}{v} dv$$

$$v_{min}(E) = \left(\frac{EM_A}{2\mu_\chi^2}\right)^{1/2}$$

Spin dependent

- Effective Lagrangian for Majorana fermion

$$\mathcal{L}^{SD} = \xi_N \overline{\psi}_\chi \gamma_5 \gamma_\mu \psi_\chi \overline{\psi}_N \gamma_5 \gamma^\mu \psi_N$$

$$|A_N^{SD}|^2 = 192(\xi_N S_N M_\chi M_N)^2$$

- Sum spin currents produced by p and n separately
- ψ_0 component vanish → 3dim vector current proportional to angular momentum
- $S_p=S_n=1/2$

$$\vec{J}_N^A = S_N^A \vec{J}_A / |J_A|$$

- Non trivial summation over spins

$$\sum_{s_\chi, s'_\chi} \sum_{s_A, s'_A} \sum_{1 \le k,l \le 3} < s_\chi | J_\chi^k | s'_\chi >< s'_\chi | J_\chi^l | s_\chi >< s_A | J_A^k | s'_A >< s'_A | J_A^l | s_A >$$

$$= \sum_{1 \le k,l \le 3} tr(J_\chi^k J_\chi^l) tr(J_A^k J_A^l) = (2J_\chi + 1) J_\chi (J_\chi + 1) \cdot (2J_A + 1) J_A (J_A + 1)/3$$

- After average over initial polar, $(2J\chi+1)(2J_A+1)$ cancels out

- WIMP-nucleus amplitude squared

$$|A^{SD}|^2 = 256\frac{J_A+1}{J_A}\left(\xi_p S_p^A + \xi_n S_n^A\right)^2 M_\chi^2 M_A^2$$

- Cross section at rest for point-like nucleus

$$\sigma_0^{SD} = \frac{\mu_\chi^2}{\pi}\frac{J_A+1}{J_A}\left(\xi_p S_p^A + \xi_n S_n^A\right)^2$$

- S_N^A are obtained from nuclear calculations or from simple nuclear model ~0.5 for nuclei with odd nb of p or n ~0 for even nuclei

Nucleus	$\langle S_p\rangle_{OGM}$	$\langle S_n\rangle_{OGM}$	$\langle S_p\rangle$	$\langle S_n\rangle$
^{19}F	0.46	0.0	0.415	−0.047
			0.368	−0.001
^{27}Al	0.25	0.0	−0.343	0.030
^{29}Si	0.0	0.15	−0.002	0.13
^{73}Ge	0.0	0.23	0.011	0.491
			0.030	0.378
^{93}Nb	0.36	0.0	0.46	0.08
^{131}Xe	0.0	−0.166	−0.041	−0.236

Axial vector quark coefficients

- Axial vector current counts the total spin of quarks and antiquarks in nucleon
- Operators for A-V interactions in nucleon related to those in quarks

$$\xi_{N,s} = \sum_{q=u,d,s} \Delta q^N \xi_{q,s} \qquad 2s_\mu \Delta q^N = \langle N|\overline{\psi}_q \gamma_\mu \gamma_5 \psi_q|N\rangle$$

- Δq^N extracted from lepton-proton scattering , in particular strange contribution to spin of nucleon (measured first by EMC) much larger than expected in naïve quark model

$$\Delta_u^p = 0.842 \pm 0.012, \quad \Delta_d^p = -0.427 \pm 0.013, \quad \Delta_s^p = -0.085 \pm 0.018$$

$$\Delta_u^n = \Delta_d^p, \quad \Delta_d^n = \Delta_u^p, \quad \Delta_s^n = \Delta_s^p$$

Dirac fermion

- Fermions

$$\mathcal{L}_F = \lambda_{N,e}\bar{\psi}_\chi\psi_\chi\bar{\psi}_N\psi_N + \lambda_{N,o}\bar{\psi}_\chi\gamma_\mu\psi_\chi\bar{\psi}_N\gamma^\mu\psi_N + \xi_{N,e}\bar{\psi}_\chi\gamma_5\gamma_\mu\psi_\chi\bar{\psi}_N\gamma_5\gamma^\mu\psi_N - \frac{1}{2}\xi_{N,o}\bar{\psi}_\chi\sigma_{\mu\nu}\psi_\chi\bar{\psi}_N\sigma^{\mu\nu}\psi_N$$

$$\lambda_N = \frac{\lambda_{N,e} \pm \lambda_{N,o}}{2} \quad \text{and} \quad \xi_N = \frac{\xi_{N,e} \pm \xi_{N,o}}{2}$$

- Vector current $\bar{\psi}_q\gamma_\mu\psi_q$ is responsible for the difference between χN and χN interactions. It counts the number of quarks minus antiquarks in the nucleon (valence quarks)
  - no uncertainties.

$$\lambda_{N,p} = \sum_{q=u,d} f^N_{V_q}\lambda_{q,p} \qquad f^p_{V_u} = 2,\ f^p_{V_d} = 1,\ f^n_{V_u} = 1,\ f^n_{V_d} = 2$$

Scalar and vector DM

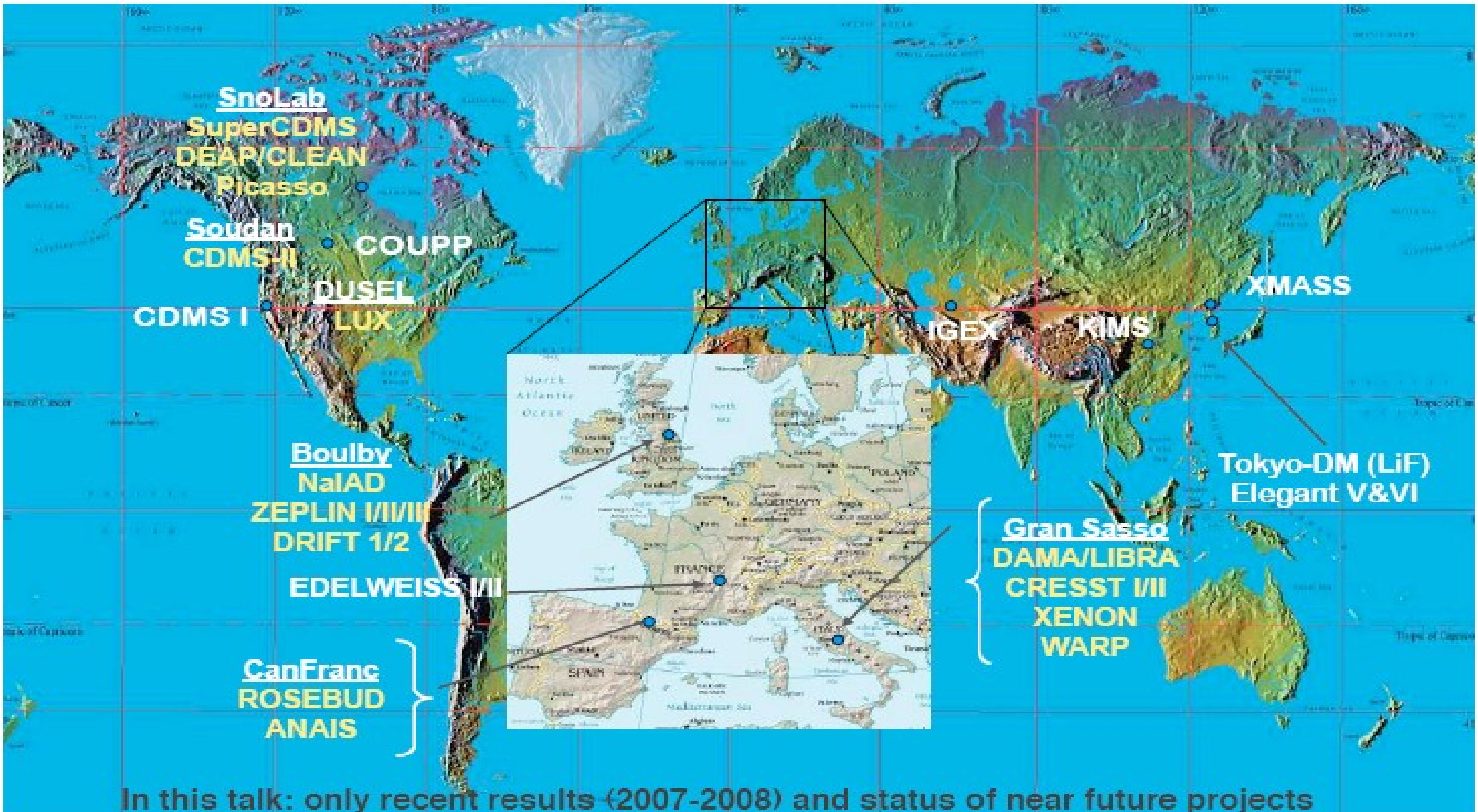
- Complex scalar
  - Only spin independent interactions

$$\mathcal{L}_S = 2\lambda_{N,e} M_\chi \phi_\chi \phi_\chi^* \bar{\psi}_N \psi_N + i\lambda_{N,o}(\partial_\mu \phi_\chi \phi_\chi^* - \phi_\chi \partial_\mu \phi_\chi^*) \bar{\psi}_N \gamma_\mu \psi_N$$

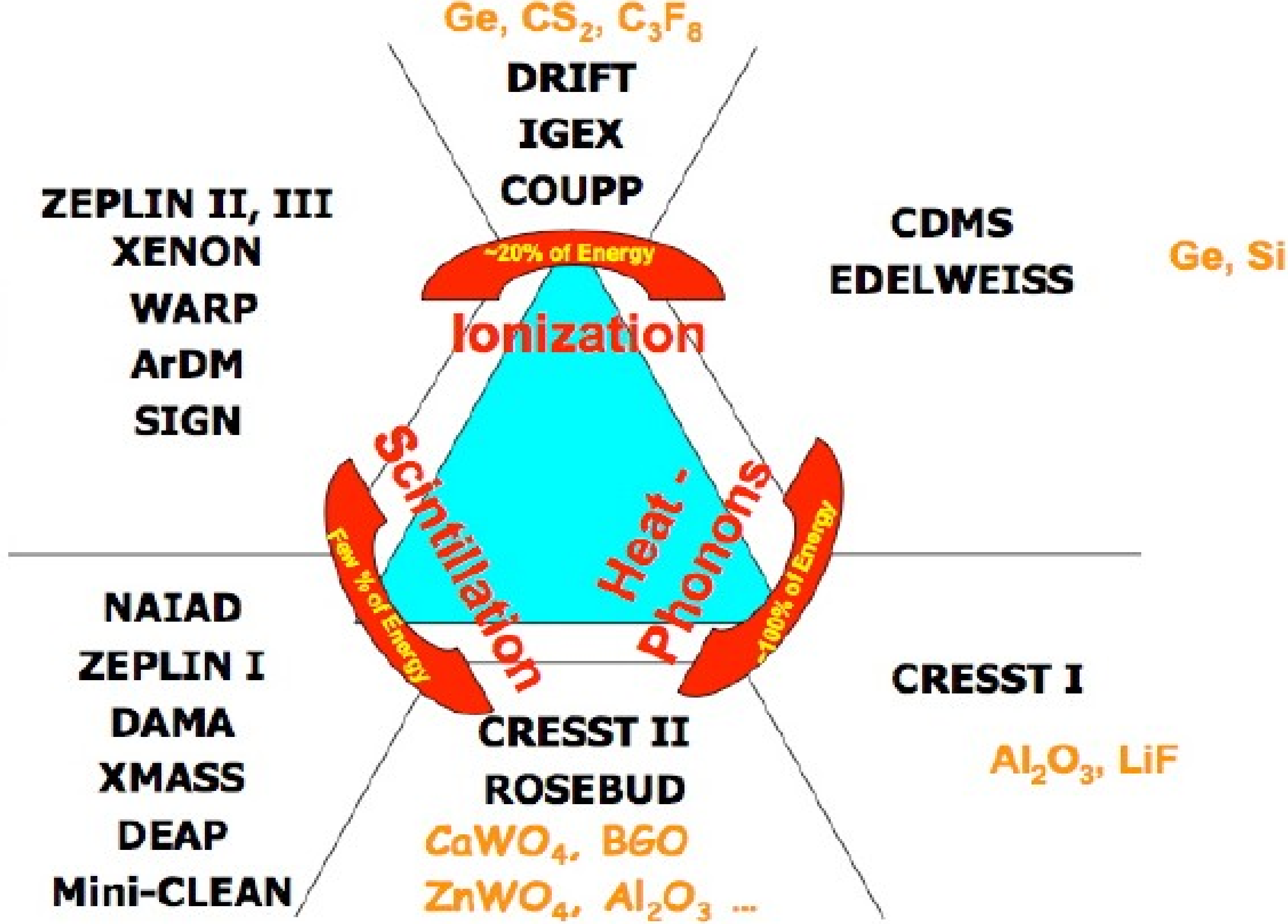
- Complex vector (SI and SD)

$$\begin{aligned}
\mathcal{L}_V &= 2\lambda_{N,e} M_\chi A_{\chi,\mu} A_\chi^\mu \overline{\psi}_N \psi_N + \lambda_{N,o} i (A_\chi^{*\alpha} \partial_\mu A_{\chi,\alpha} - A_\chi{}^\alpha \partial_\mu A_{\chi\alpha}^*) \overline{\psi}_N \gamma_\mu \psi_N \\
&+ \sqrt{6}\xi_{N,e}(\partial_\alpha A_{\chi\beta}^* A_{\chi\gamma} - A_{\chi\beta}^* \partial_\alpha A_{\chi\gamma}) \epsilon^{\alpha\beta\gamma\mu} \overline{\psi}_N \gamma_5 \gamma_\mu \psi_N \\
&+ i\frac{\sqrt{3}}{2}\xi_{N,o}(A_{\chi\mu} A_{\chi\nu}^* - A_{\chi\mu}^* A_{\chi\nu}) \cdot \overline{\psi}_N \sigma_{\mu\nu} \psi_N
\end{aligned}$$

World Wide Wimp searches



Direct Detection Techniques



Direct detection -results

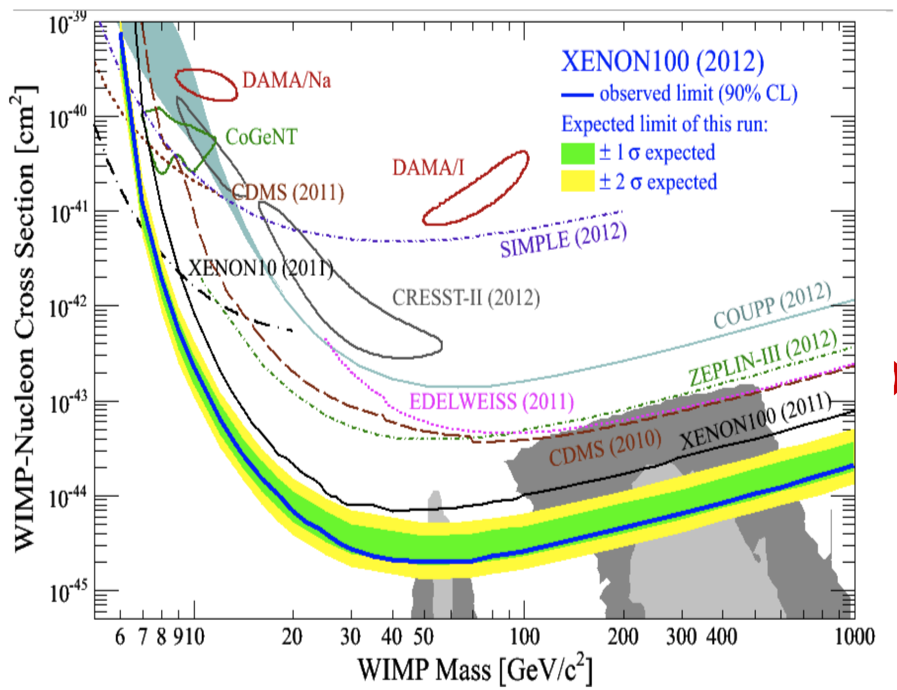
SI

- For easy comparison between experiments – extract $\sigma_{\chi p}$

$$\sigma_p^{SI} = \lim_{m_\chi \to \infty} \sigma\{m_N = m_p, m_\chi\}$$

- Assume velocity distribution

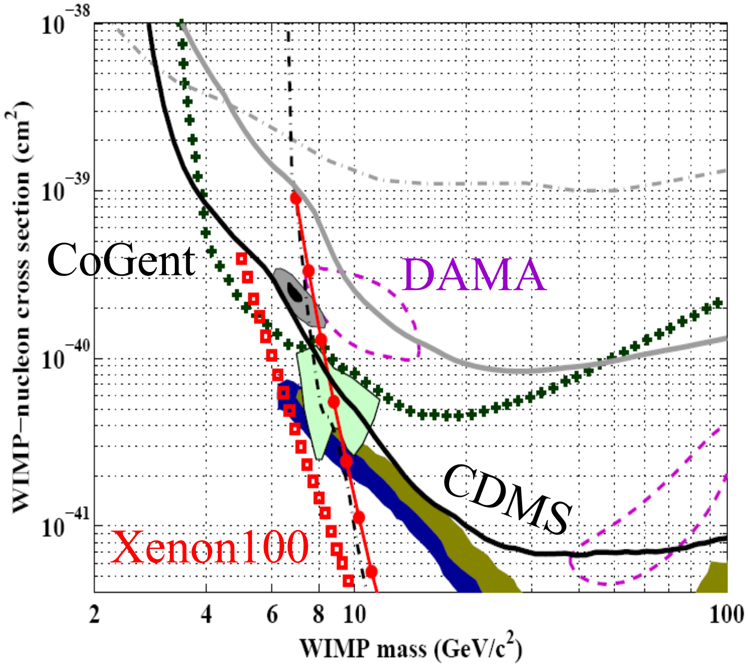
- Limits are improving every year
  - Best limits Xenon (2012)
  - DAMA confirm their annual modulation signal



Direct Detection

Akerib et al, CDMS, 1010.4290

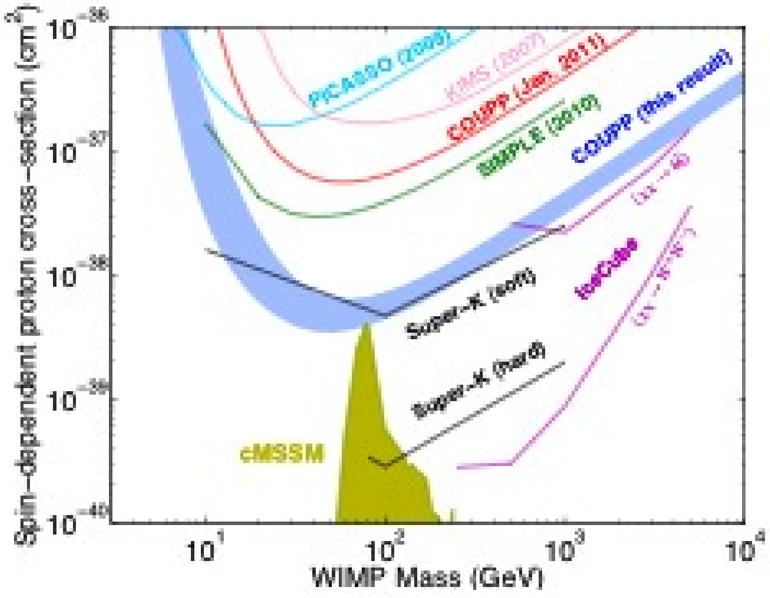
- DAMA : signal in annual modulation compatible with light DM (8.9σ)
- Recently CoGent, CDMS , CRESST also reported some signals compatible with 'light' DM
- Some of the favoured regions are excluded by Xenon10, Xenon100, CDMS
  - theoretical uncertainties



DM proton scattering cross section : experimental results

Spin dependent

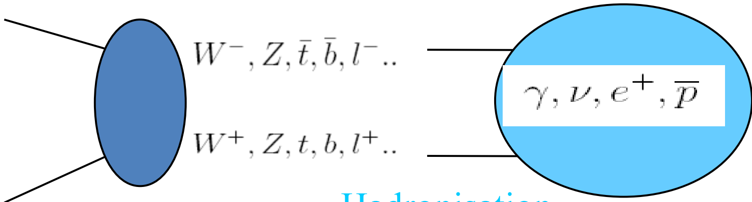
- Also KIMS 1204.2646



Coupp : 1204.3094

Indirect detection

- Annihilation of pairs of DM particles into SM : decay products observed



- Searches for DM in 4 channels
  - Antiprotons and
  - Positrons from galactic halo/center
  - Photons from galactic halo/center
  - Neutrinos from Sun

- Rate for production of e^+,p,γ
  - Dependence on the DM distribution (ρ) – not well known in center of galaxy

v=0.001c

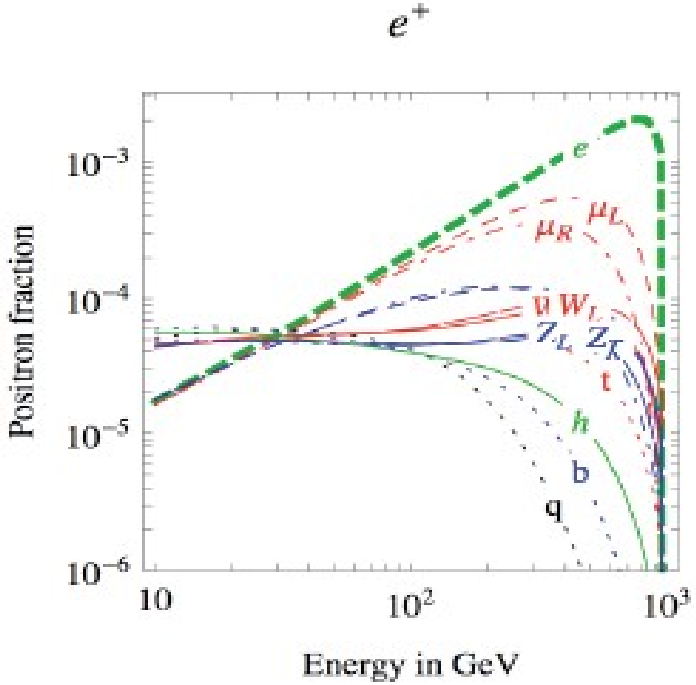
$$Q(x, \mathrm{E}) = \frac{<\sigma v>}{2}\left(\frac{\rho(\mathbf{x})}{m_\chi}\right)^2 \frac{dN}{dE}$$

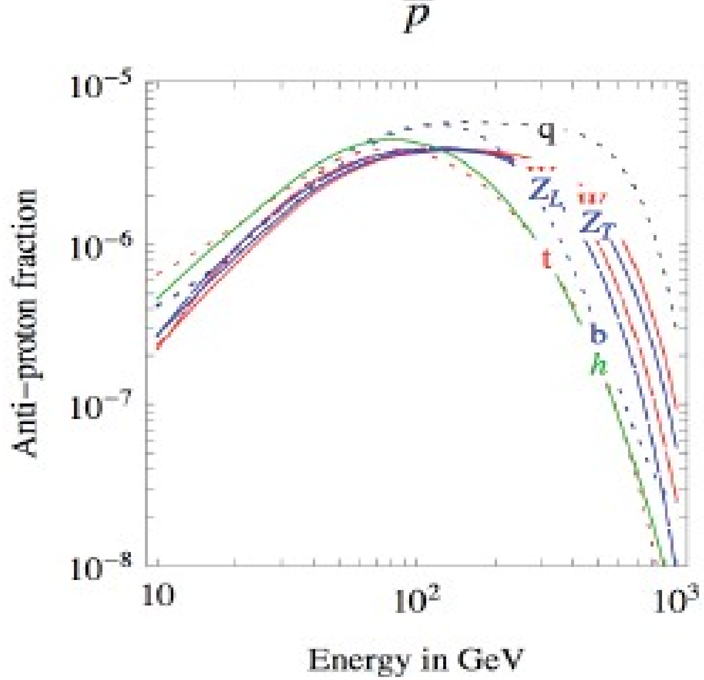
- Typical annihilation cross section at freeze-out

$$<\sigma v> = 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{sec}$$

dN/DE

- Spectrum depends
  - mass of DM
  - primary annihilation channels





Propagation of cosmic rays

- *For Charged particle spectrum detected different than spectrum at the source*

- Charged cosmic rays are deflected by irregularities in the galactic magnetic field
  - For strong magnetic turbulence, MC simulations show that effect similar to space diffusion

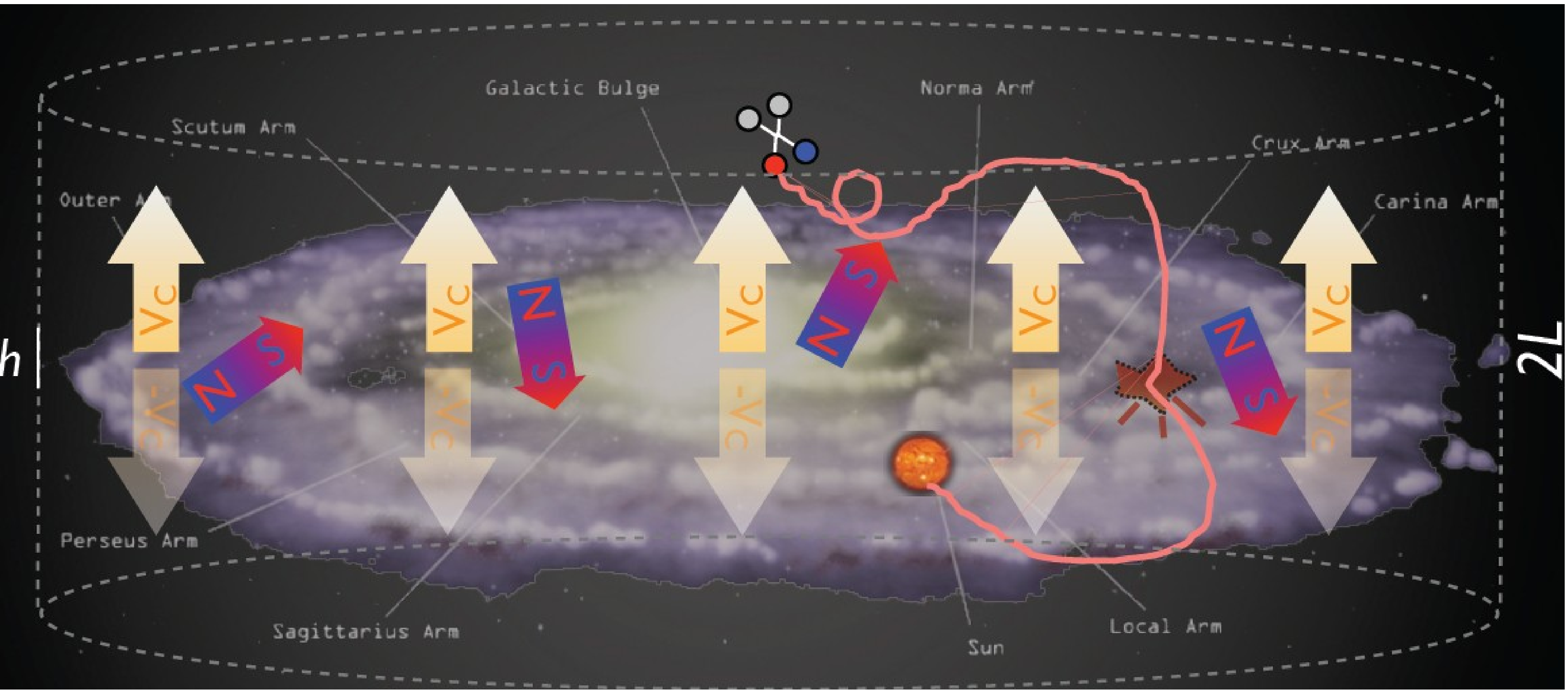
- Energy losses due to interactions with interstellar medium

- Convection driven by galactic wind

- Reacceleration due to interstellar shock wave

Antiprotons and positrons from DM annihilation in halo

M. Cirelli, Pascos2009



$$\frac{\partial N}{\partial t} - \nabla \cdot [K(\mathbf{x}, E)\, \nabla N] - \frac{\partial}{\partial E}[b(E)\, N] = q(\mathbf{x}, E)$$

diffusion — Energy losses — Source

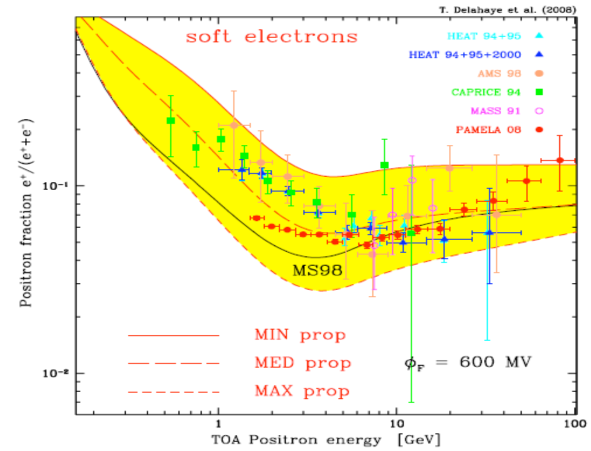
Indirect detection

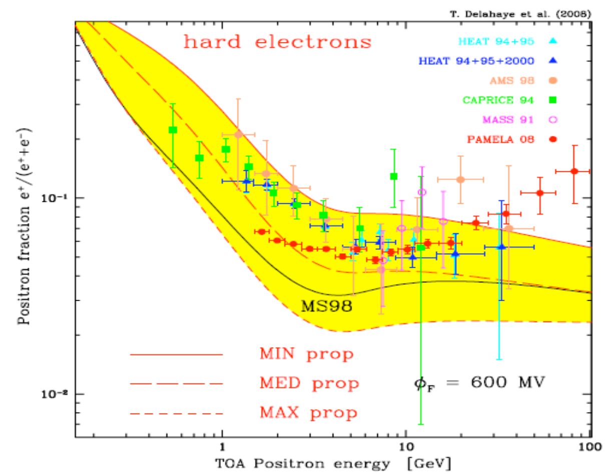
- For charged particles : solve propagation equation

$$\frac{\partial N}{\partial t} - \nabla \cdot [K(\mathrm{x}, E) \nabla N] - \frac{\partial}{\partial E}[b(E) N] = q(\mathrm{x}, E)$$

- Theoretical computation of spectrum of secondary charged particle and from DM annihilation
  - GALPROP – Strong and Moskalenko
  - T. Delahaye, P. Salati et al

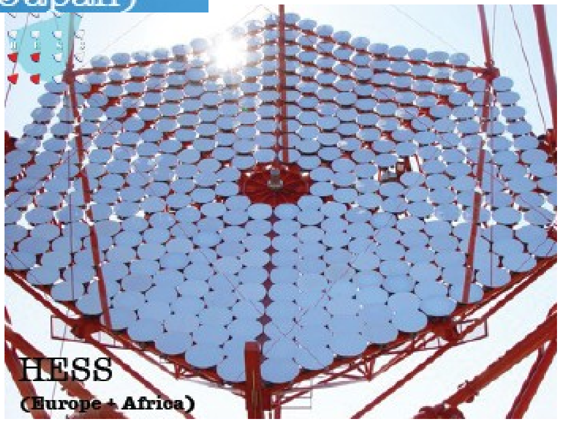
- Background spectrum
  - Astro sources: supernova explosions, interaction between cosmic ray nuclei in interstellar medium





Indirect DM searches

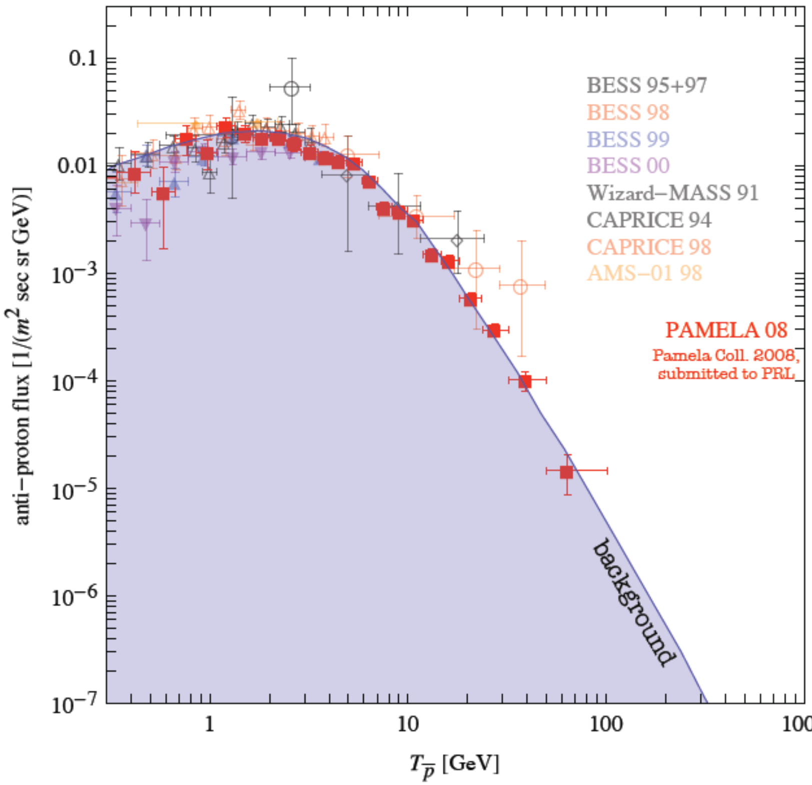
Payload for
Anti
Matter
Exploration and
Light nuclei
Astrophysics



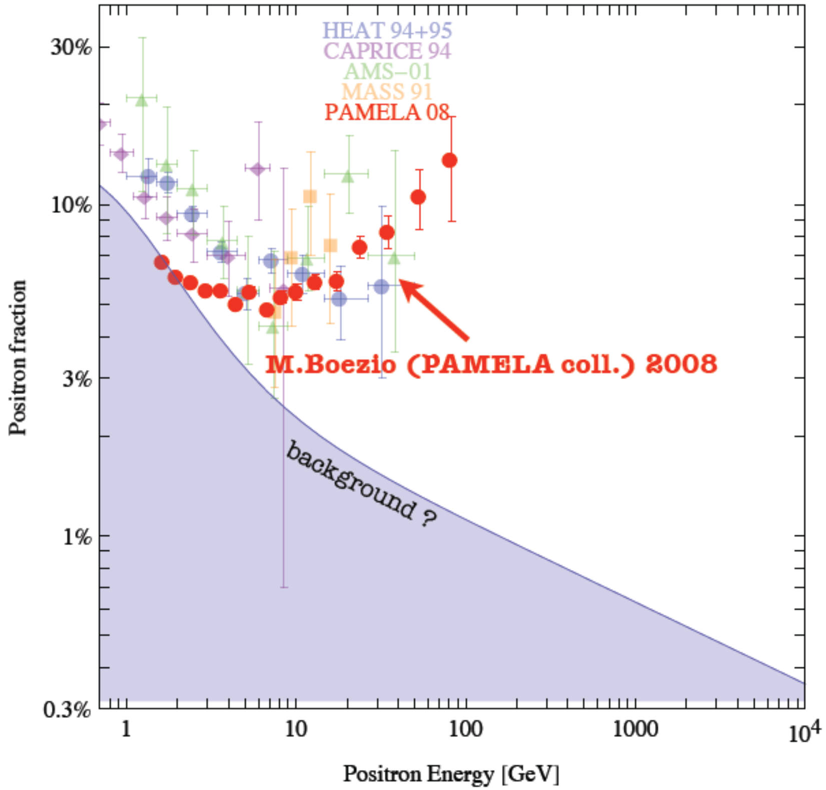
Ground base large array gamma ray telescope

PAMELA - results

Excess in positron fraction at high energies



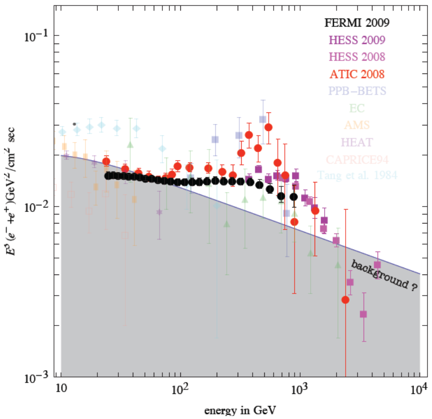
O. Adriani, 0810.4994



O. Adriani 0810.4995

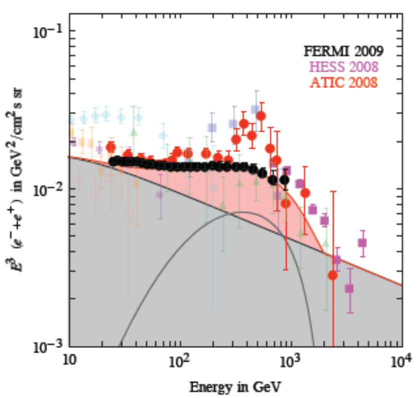
DM indirect detection

Fermi-LAT 0905.0025



- Results on *total* electron positron spectrum
  - Higher energies than PAMELA
  - Excess over background

- Fit Pamela, Fermi, Hess with e.g. heavy DM (2TeV) annihilating into taus

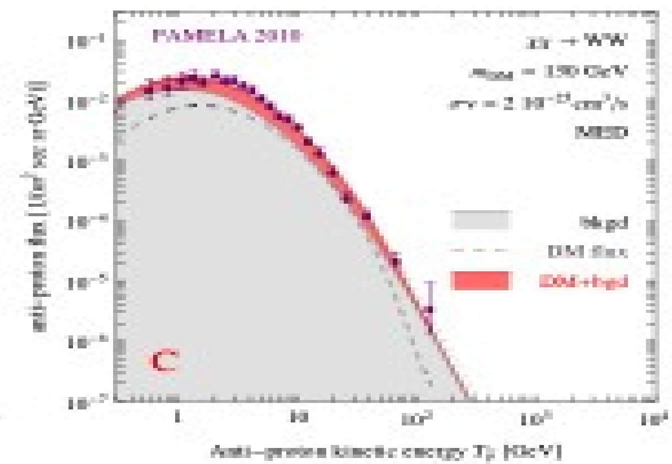


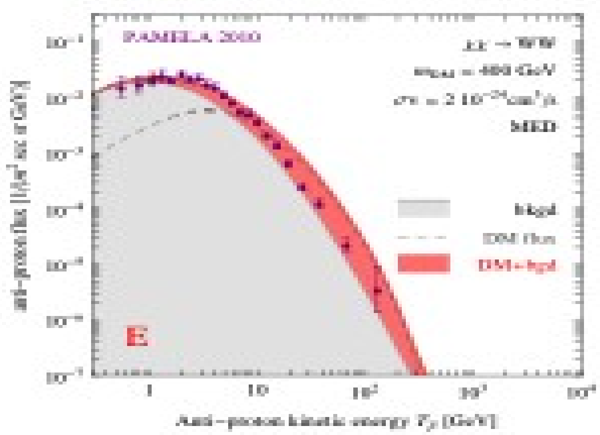
Strumia, Papucci.. arXiv:0905.0480

- Careful investigation of secondary spectrum
- Astro sources (pulsars) give similar signal

DM in antiprotons - example

WW channel





O. Adriani, 0810.4994

O. Adriani 0810.4995

Photons

- Flux calculation

$$\Phi_{\gamma,\nu} = \frac{1}{8\pi}\frac{<\sigma_{ann}v>}{m_\chi^2}\sum_{f.s.}\left(\frac{dN_{\gamma,\nu}}{dE}\right)_{f.s.}\int_{l.o.s.}\rho_s^2$$

- Photon production
  - In decay of SM particles
  - Monochromatic gamma rays ($\gamma\gamma$,γZ)
  - Internal bremsstrahlung

- Integral over line of sight depends strongly on the galactic DM distribution

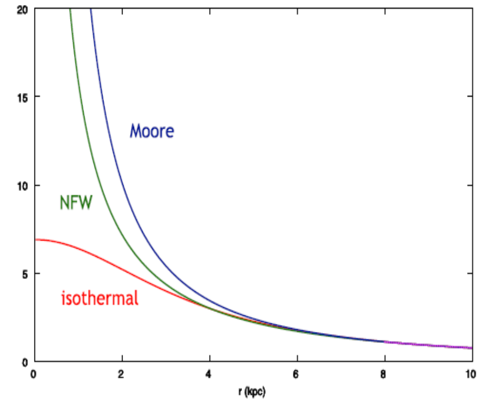
Dark matter profile

- Dark matter profile

$$\rho_s(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1+(r_\odot/a)^\alpha}{1+(r/a)^\alpha}\right]^{\frac{\beta-\gamma}{\alpha}}$$

$r_\odot = 8$ kpc

$\rho_\odot = 0.3$ GeV.cm^{-3}



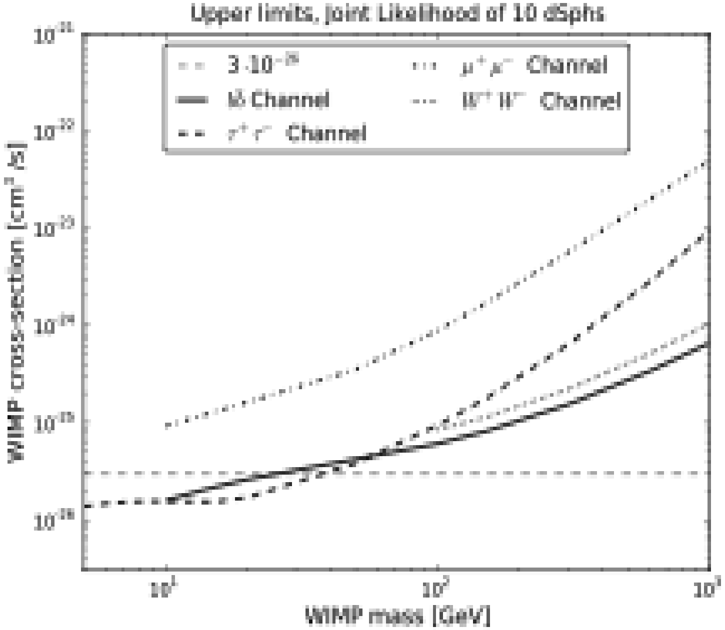
- N-body simluation

Halo model	α	β	γ	a (kpc)
Isothermal with core	2	2	0	4
NFW	1	3	1	20
Moore	1.5	3	1.5	28

- Different halo profile rather similar except in center of galaxy

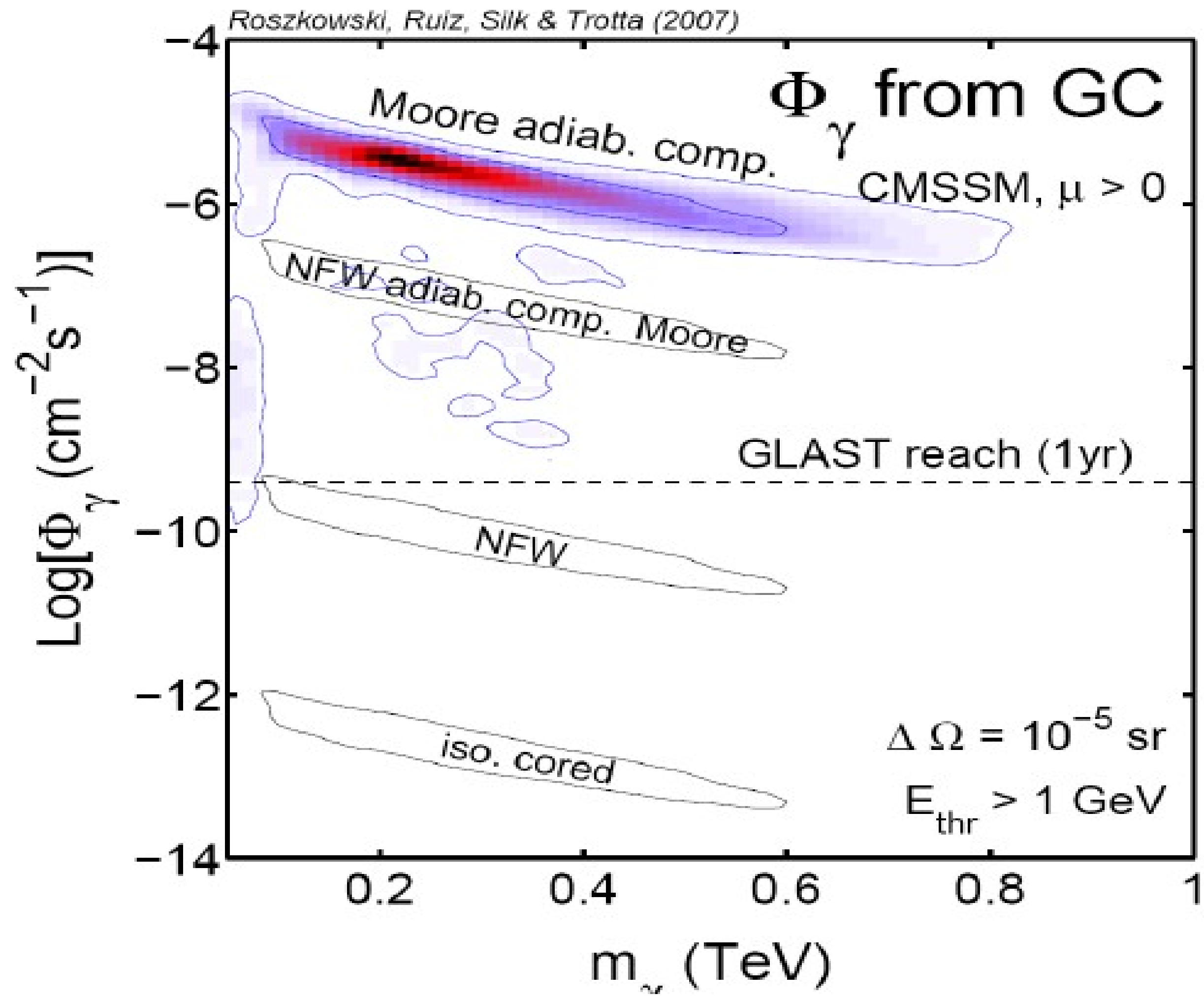
Photons from dwarf galaxies

- Dwarf galaxies are dominated by DM – good probe
- Not as strong dependence on the density profile (profiles differ strongly only in Galactic center)
- Fermi has derived limits on photon flux and DM cross section for different channels
- Low masses probe the relic density favoured value



Impact of DM profile on rate

A SUSY example



Summary

- A number of direct and indirect detection offer good prospects to probe dark matter (probe σv and M_{DM})
- Photons and antiprotons sensitive to light DM with expected cross section
- Direct detection can probe both SI and SD interactions in protons and neutrons using different detectors
- Already constrain some favoured models
- Theoretical uncertainties are important

•Hints of signals, not clear it is DM: DAMA, Pamela, Fermi gamma-ray line

- Extra notes
-

Velocity distribution of DM

- Nuclear recoil energy measured depends on WIMP velocity distribution in rest frame of detector→ distribution in rest frame of galaxy + Earth velocity in this frame
$$v_0 = 220 \pm 20 km/s$$
- Velocity of rotation in LSR
- Peculiar velocity of the Sun
- Earth velocity in Galactic frame: $v_1=v_0+v_{pec}+v_E$ (Earth in solar system)
$$\vec{v}_e = v_e\big(-\sin(2\pi t),\ \ \sin\gamma\cos(2\pi t),\ \ \cos\gamma\cos(2\pi t)\big)$$
- Velocity of DM particles on Earth=obtained from velocity of DM particles in Galactic Rest Frame
$$f(v) = \int \delta(v-|\vec{V}|)F_{GRF}(\vec{V}-\vec{v}_0-\vec{v}_{pec}-\vec{v}_e)d^3\vec{V}$$
- Mass Galaxy is fin $498 km/s < v_{max} < 608 km/s$ for which F =0 v>v

- Several DM velocity distribution, they are correlated with DM density distribution
- Simplest : isothermal sphere model

$$F_{GRF}(\vec{V}) \sim exp(-|\vec{V}|^2/\Delta V^2)\Theta(v_{max} - |\vec{V}|)$$

- Lead to

$$f(v) = c_{\text{norm}} \left[exp\left(-\frac{(v-v_1)^2}{\Delta V^2}\right) - exp\left(-\frac{min(v+v_1, v_{max})^2}{\Delta V^2}\right)\right]$$

$$\Delta V = v_0$$

- Note: Earth motion around Sun leads to 7% modulation effect of v_1 and to modulation of signal in DD experiments
- DM velocity distribution near the sun could be quite different