20 July 2012
Dark Attack 2012, Ascona

Long range forces in Direct DM searches

University of Southern Denmark

Paolo Panci

CP^3 - Origins
Particle Physics & Origin of Mass

based on:
N. Fornengo, P. Panci, M. Regis
PRD84 115002, [arXiv:1108.4661]

Plan of the Talk

- quick introduction of the experimental landscape

  - main uncertainties (astrophysics, experimental side, nature of interaction)

- modification of the allowed regions & constraints compare to the 'standard' picture due to a long range interaction

- complementary constraints on the mass of the new U(1) boson coming from DM self interaction & DM halo ellipticity

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Dark Matter Detection

- direct detection
  - DAMA/Libra, CoGeNT, CRESST.... (Xenon, CDMS, Edelweiss....)
- production at colliders
  - LHC
- indirect detection
  - γ from ann/dec in Galactic Center or halo and from synchrotron emission
    - FERMI, radio telescopes....
  - e^+ from ann/dec in Galactic Center or halo
    - PAMELA, FERMI, HESS, AMS-II, balloons....
  - $\bar{p}$ from ann/dec in Galactic Center or halo
  - $\bar{d}$ from ann/dec in Galactic Center or halo
    - AMS-II, GAPS....
  - $\bar{\nu}, \nu$ from ann/dec in Galaxy and massive bodies
    - SuperK, Icecube....

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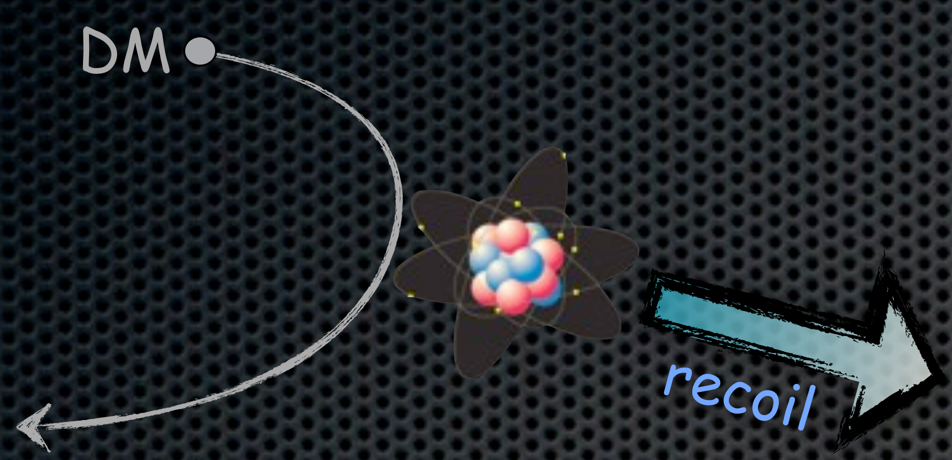
Direct Detection: Overview

aim at detecting the nuclear recoil possibly induced by:



- elastic scattering:

$$\chi + \mathcal{N}(A,Z)_{\rm rest} \to \chi + \mathcal{N}(A,Z)_{\rm recoil}$$

- inelastic scattering:

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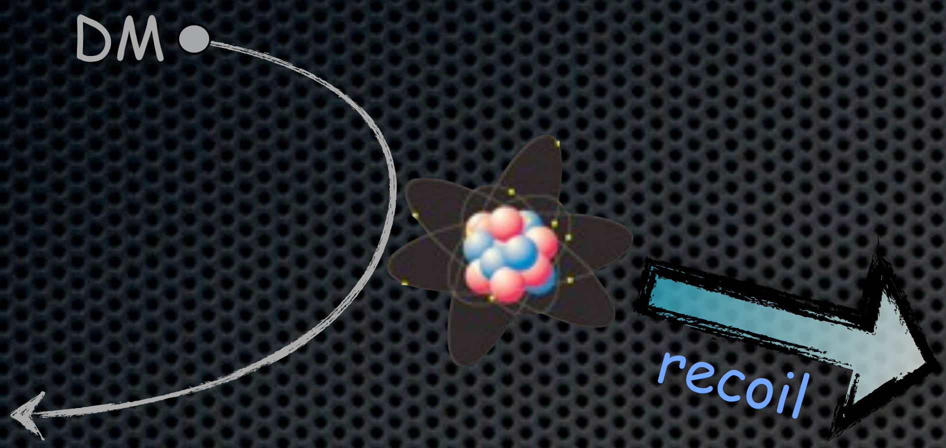

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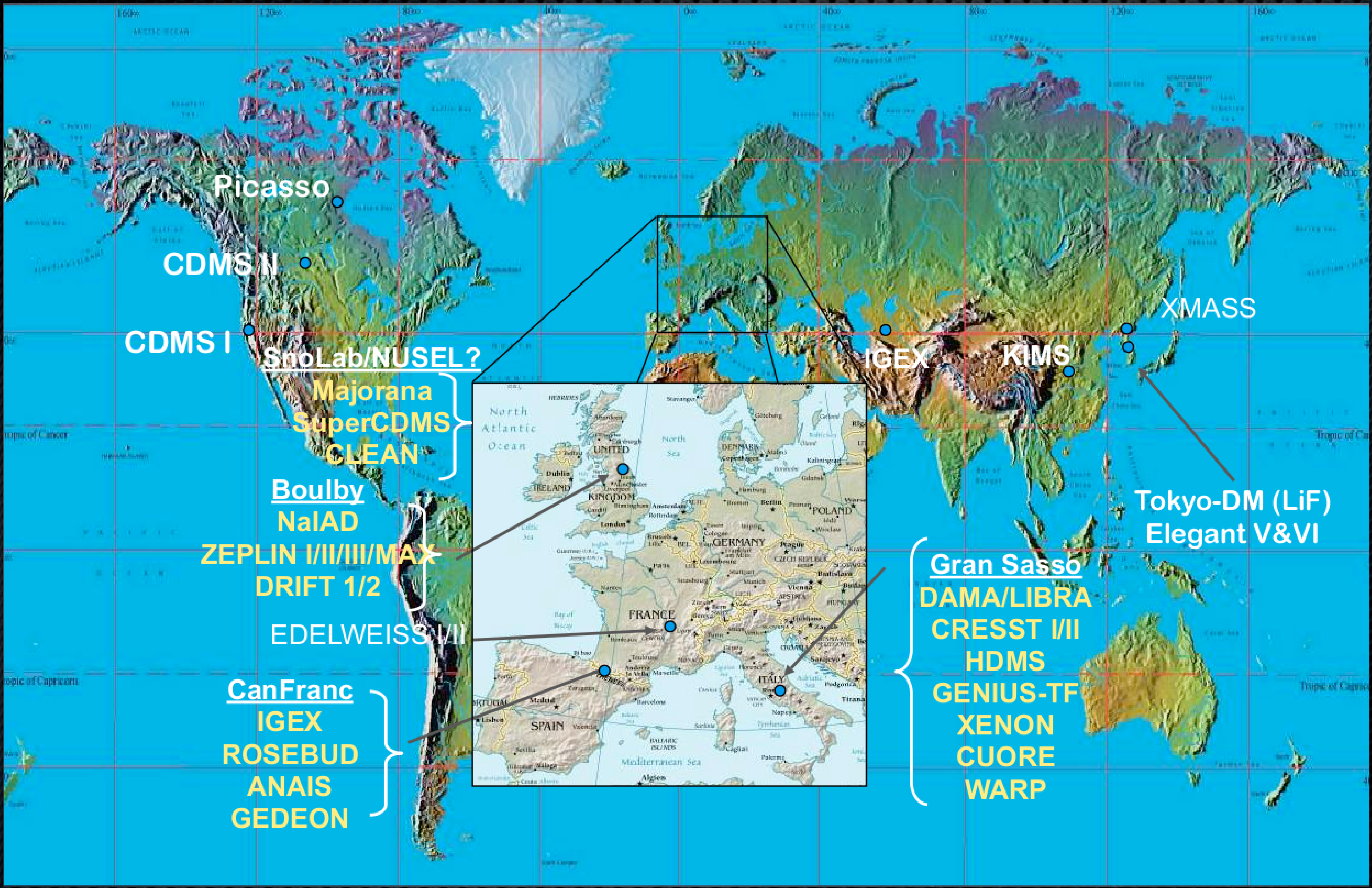
DM signals are very rare events (less then 1 cpd/kg/keV)

Experimental priorities for DM Direct Detection:

- ✓ the detectors must work deeply underground in order to reduce the background of cosmic rays
- ✓ they use active shields and very clean materials against the residual radioactivity in the tunnel (γ, α and neutrons)
- ✓ they must discriminate multiple scattering (DM does not scatter twice in the detector)

World Wide DM Searches



World Wide DM Searches

no discrimination between EM and nuclear recoil signals

DAMA

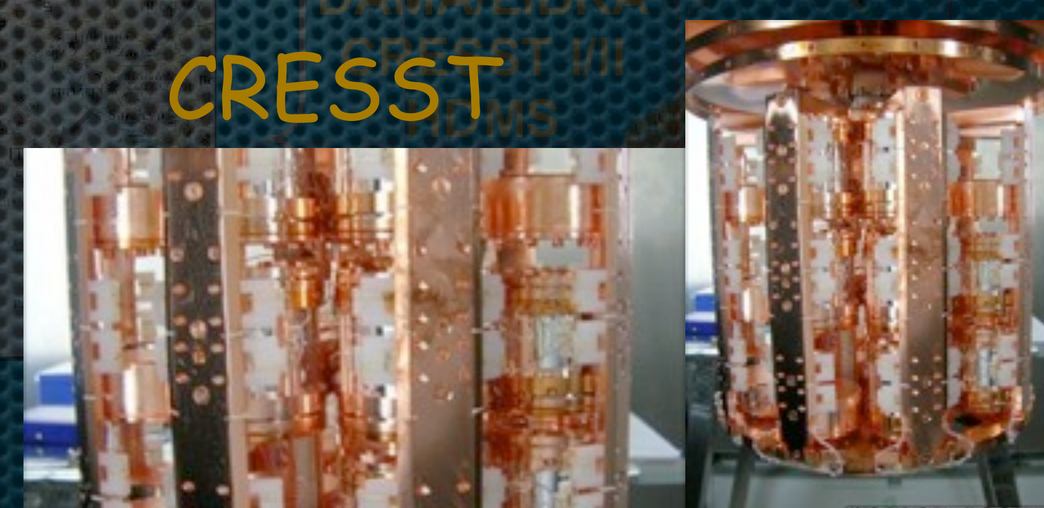
CoGeNT

discrimination between EM and nuclear recoil signals

XENON

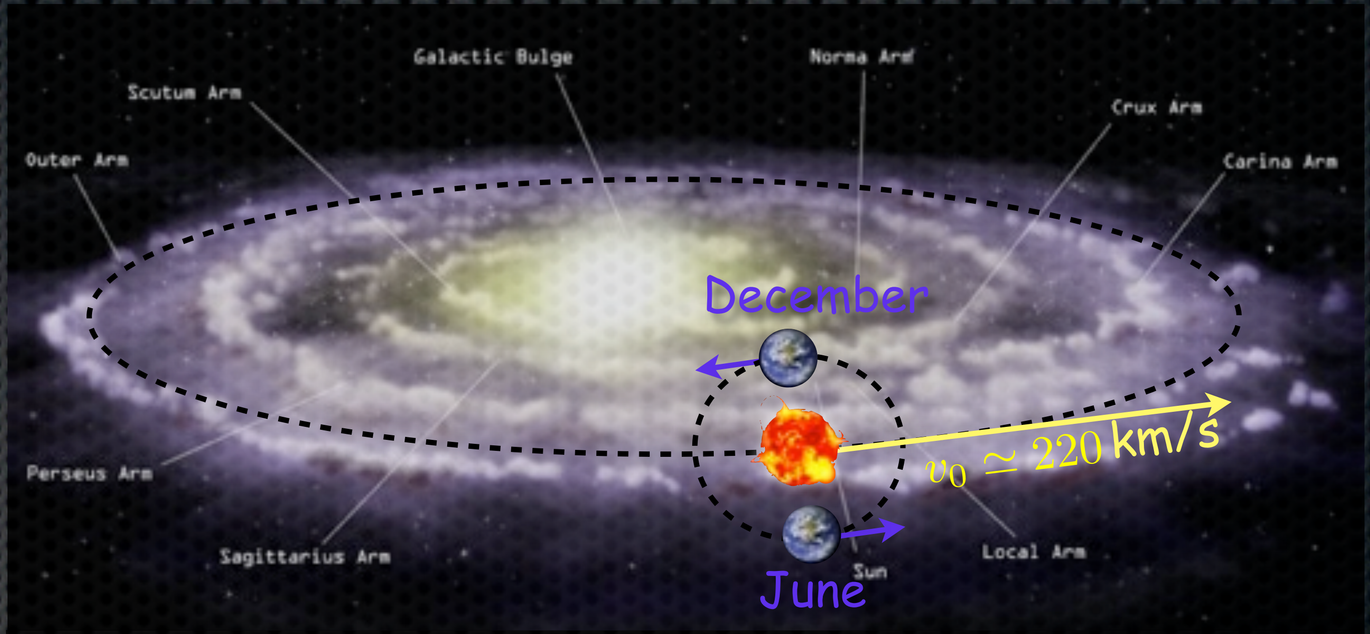
CDMS

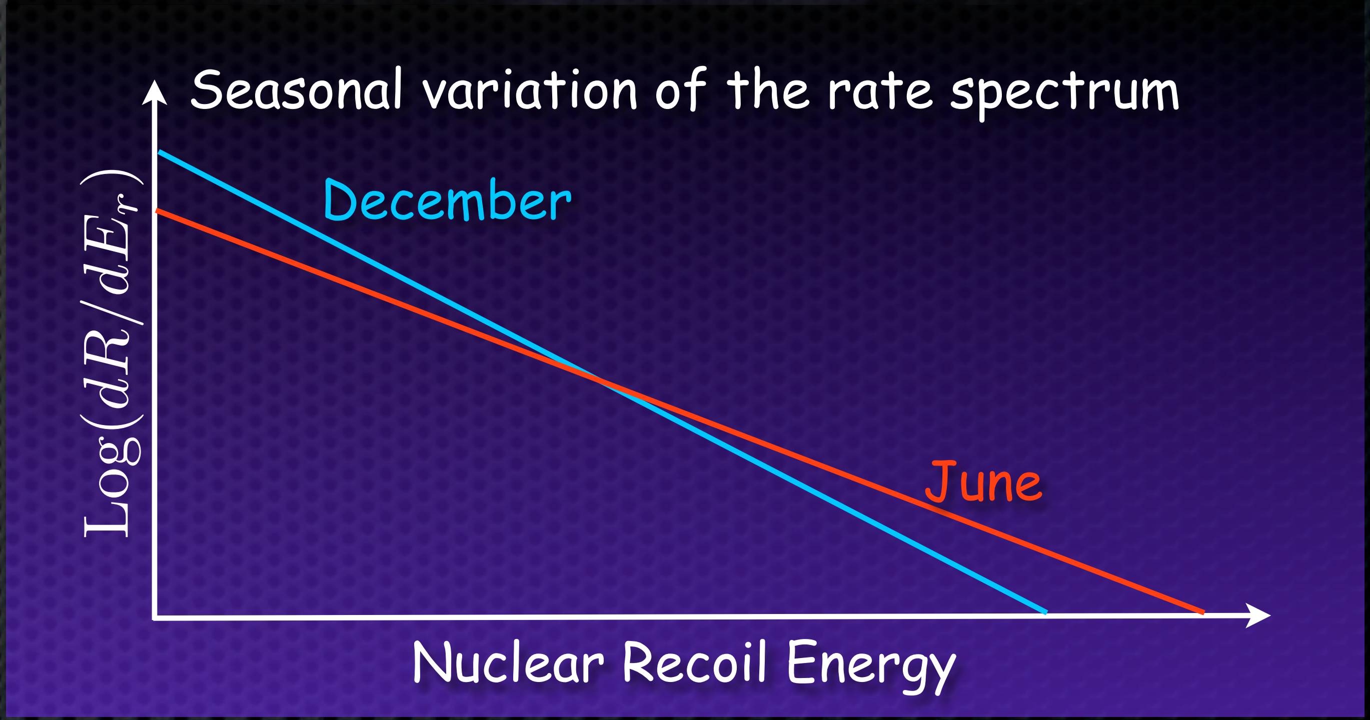
CRESST



Model Independent Signature

- if DM exists we expect annual modulation
- DAMA and CoGeNT do not distinguish between EM and nuclear recoil signals, but infer DM from annual modulation





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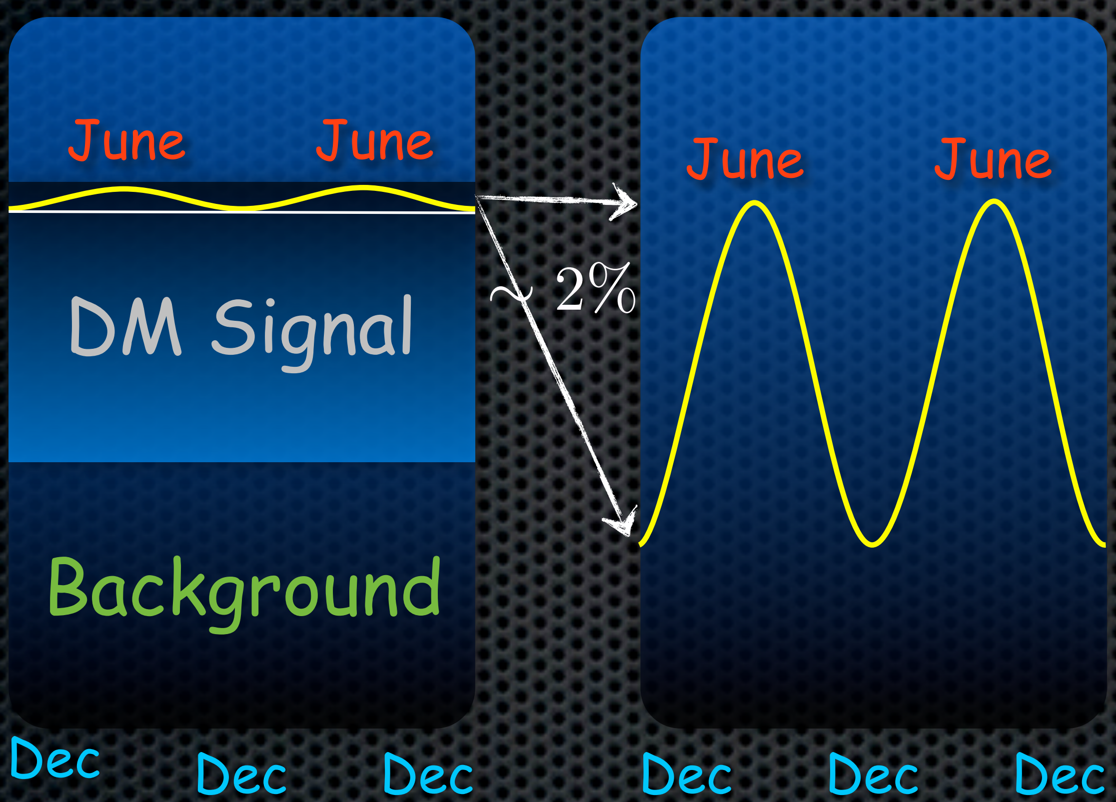
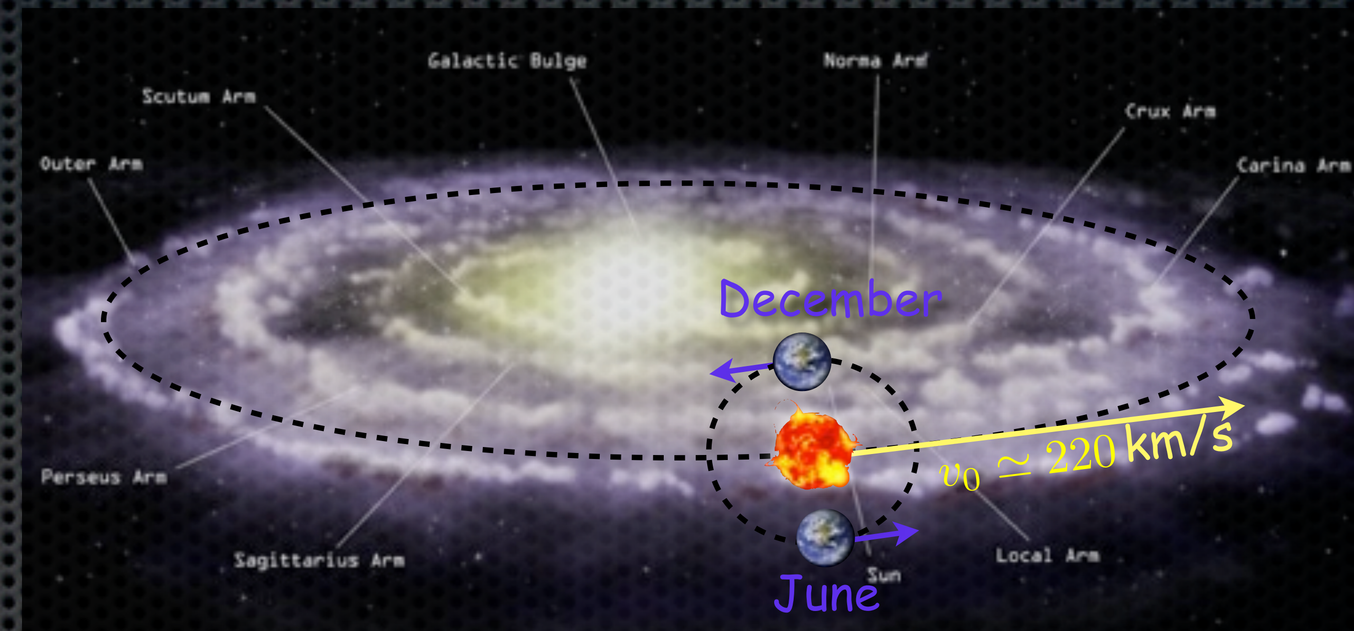
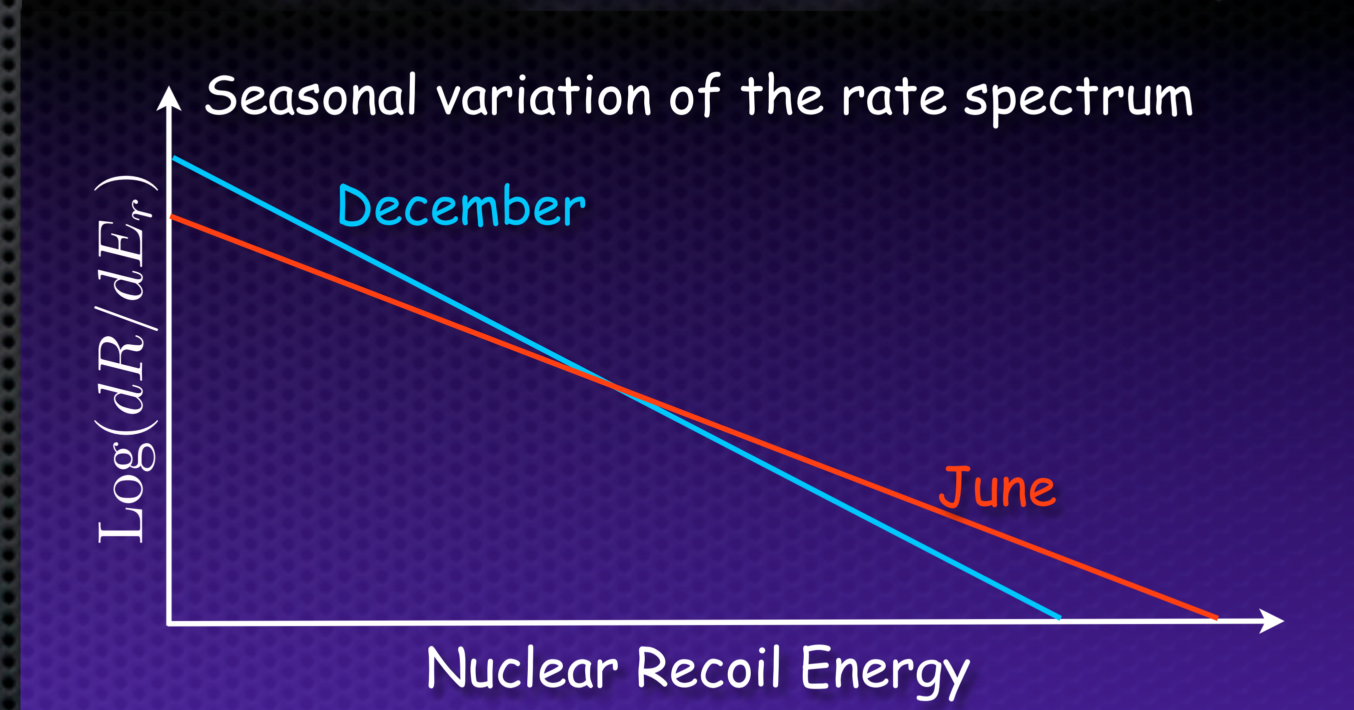
MODULATION



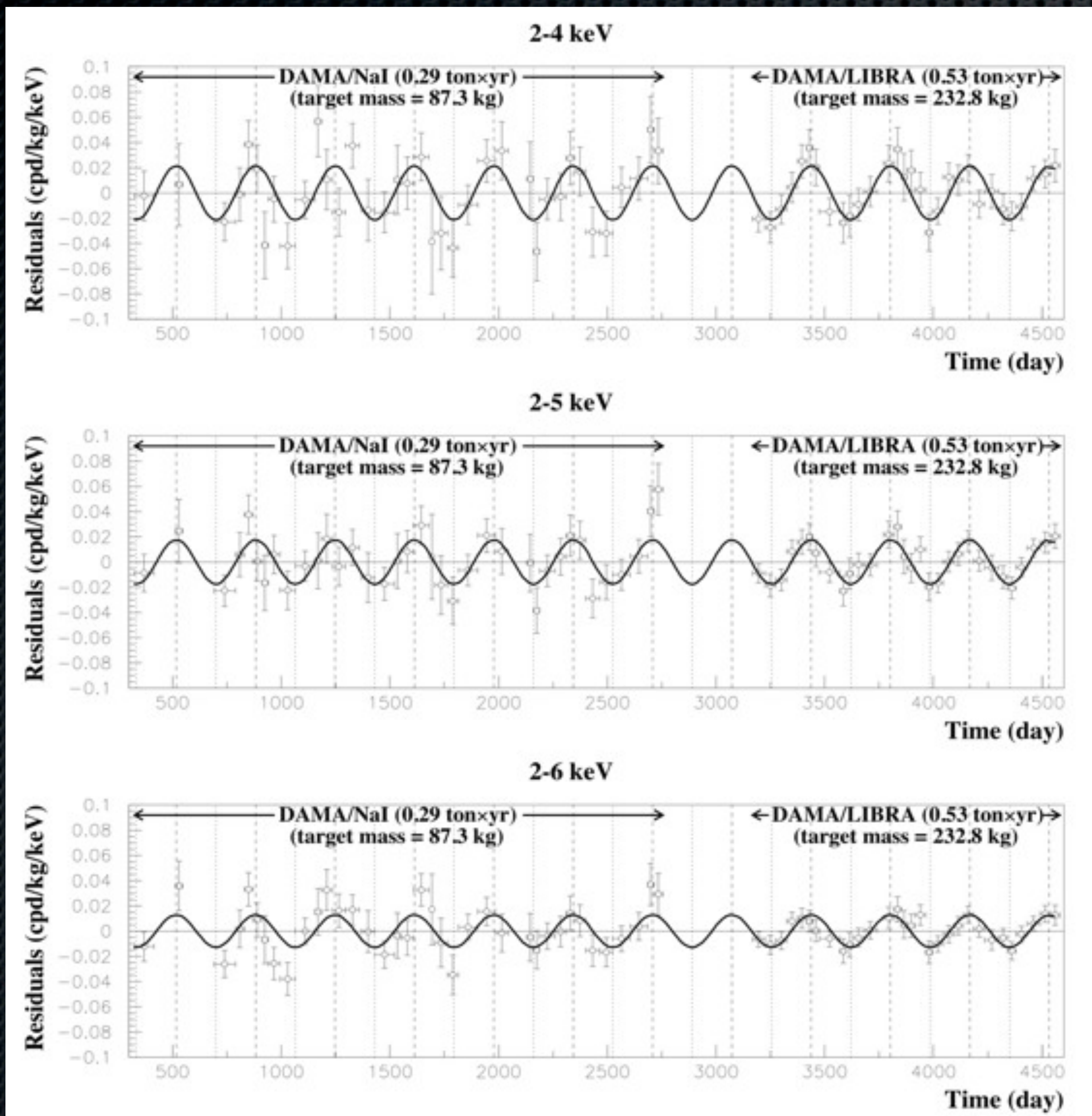




- DAMA and CoGeNT look for the small annual modulation of the sum of the DM signal and the background

DAMA: Results

A clear annual modulation is present



R.Bernabei et al. (2008)

Fitted with: $S_{\rm m} \cos(t/\tau + \phi)$

$$S_{\rm m} = 0.0223 \pm 0.0027 \text{ cpd/kg/keV}$$
$$\tau = 0.996 \pm 0.002 \text{ year}$$
$$\phi = 138 \pm 7 \text{ days} \simeq 2^{\rm nd} \text{ June}$$

with significance 8.3 σ CL

$$S_{\rm m} = 0.0178 \pm 0.0020 \text{ cpd/kg/keV}$$
$$\tau = 0.998 \pm 0.002 \text{ year}$$
$$\phi = 145 \pm 7 \text{ days} \simeq 2^{\rm nd} \text{ June}$$

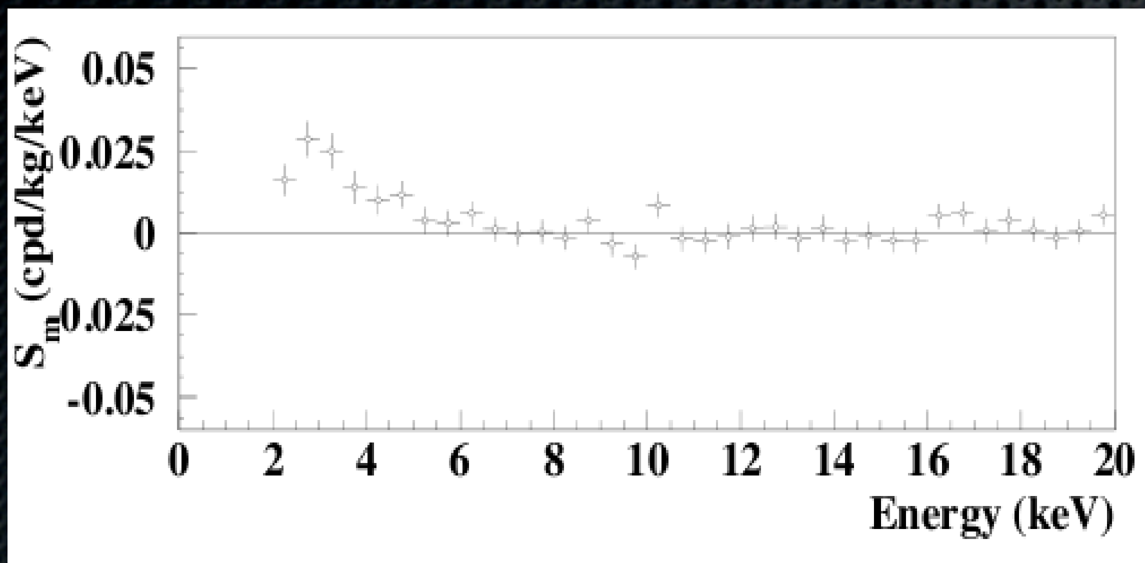
with significance 8.9 σ CL

$$S_{\rm m} = 0.0131 \pm 0.0016 \text{ cpd/kg/keV}$$
$$\tau = 0.998 \pm 0.003 \text{ year}$$
$$\phi = 144 \pm 8 \text{ days} \simeq 2^{\rm nd} \text{ June}$$

with significance 8.2 σ CL

DAMA: Results

Spectrum of the modulated signal



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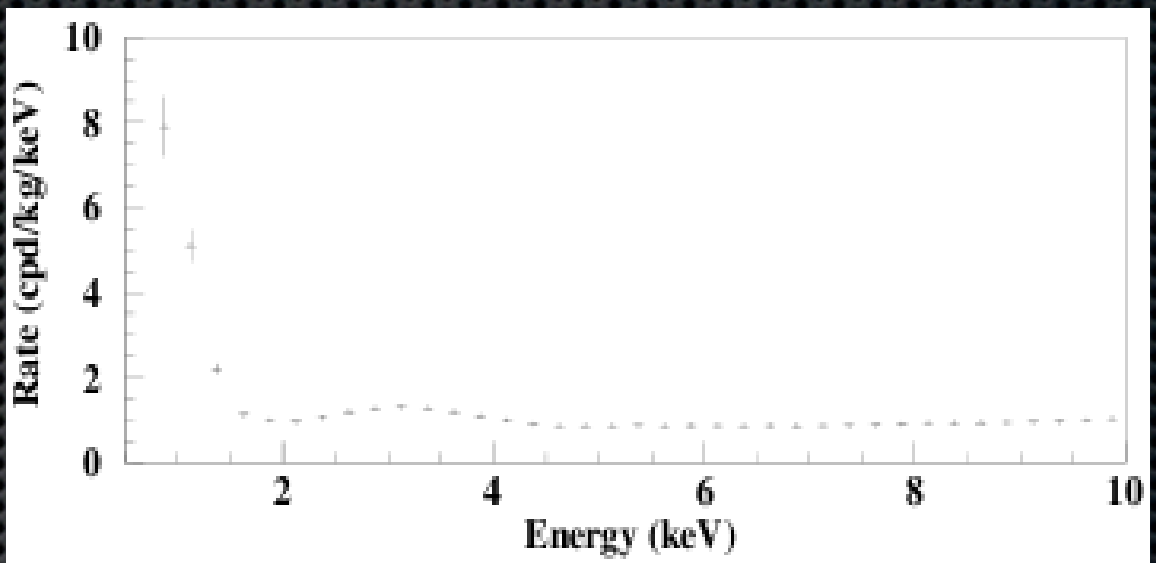
Spectrum of the total rate



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Bottom line: the modulation is only visible at low energy (from 2 to 6 keVee)

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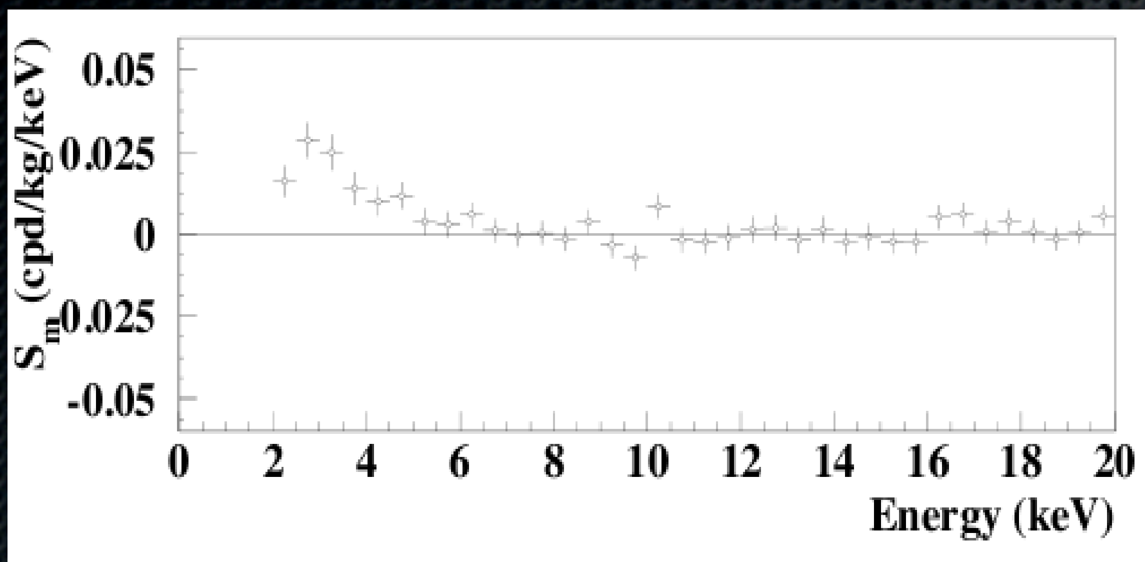

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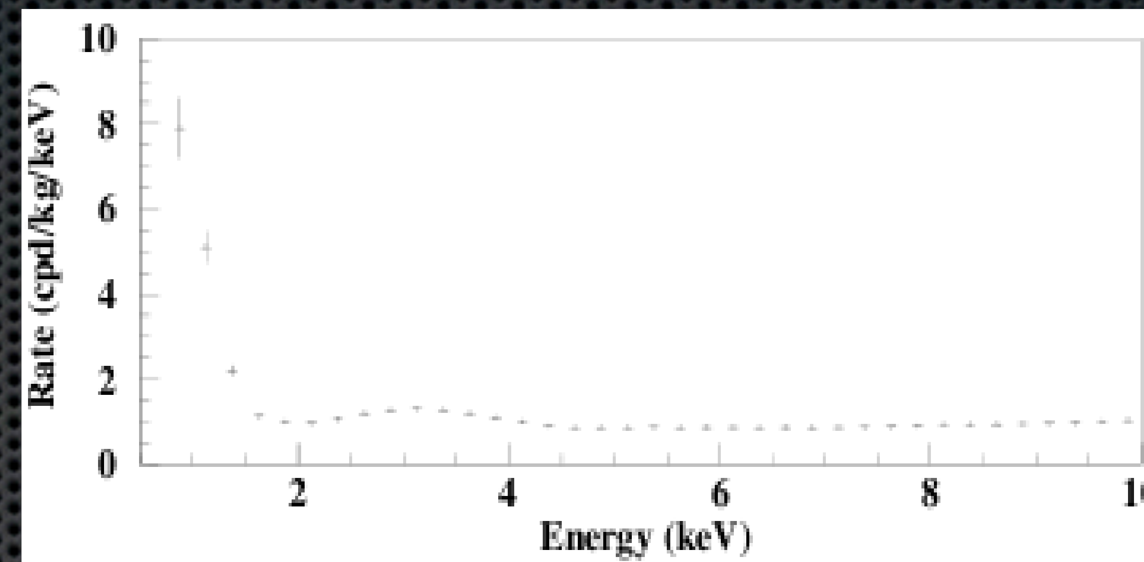

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Comparison with the DAMA datasets

- ✔ one has to compare the theoretical modulated signal with the experimental one in the energy bins of interest, without exceed the total rate

Rate of Nuclear Recoil

$$\frac{dR}{dE_{\rm r}}(v_{\rm E}(t), E_{\rm r}) = N_{\mathcal{N}}\, n_\chi \int_{v_{\rm min}(E_{\rm r})}^{v_{\rm esc}} d^3v\, v\, f_v(\vec{v}, \vec{v}_{\rm E}(t))\, \frac{d\sigma(v, E_{\rm r})}{dE_{\rm r}} F^2(E_{\rm r})$$

- $N_{\mathcal{N}}$: total number of target nuclei
- $n_\chi = \rho_\odot/m_\chi$: local DM number density
- $v_{\rm esc}$: DM escape velocity in the Milky Way (450 - 650 km/s)
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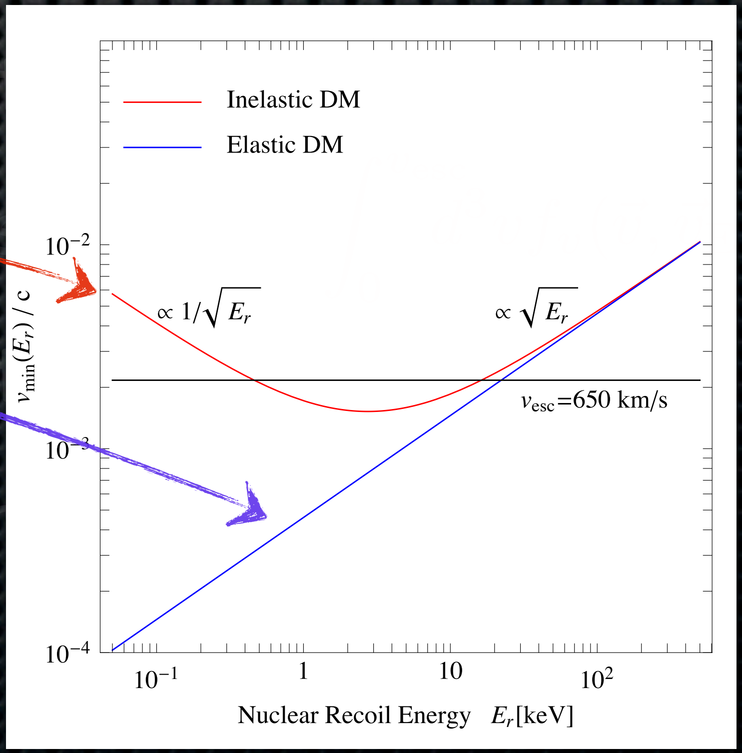
$$v_\mathrm{min}(E_\mathrm{r}) = \begin{cases} \sqrt{\dfrac{m_\mathrm{T}\, E_\mathrm{r}}{2\,\mu_{\chi\mathrm{T}}^2}} \\ \sqrt{\dfrac{m_\mathrm{T}\, E_\mathrm{r}}{2\,\mu_{\chi\mathrm{T}}^2}} \left(1 + \dfrac{\mu_{\chi\mathrm{T}}\,\delta}{m_\mathrm{T}\, E_\mathrm{r}}\right) \end{cases}$$



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$$|\vec{v}_{\rm E}(t)| = v_\odot + v_\oplus \cos(\gamma) \cos[2\pi(t-\phi)/\tau]$$

$v_\odot \simeq 232$ km/s: drift velocity of the Sun

$v_\oplus \simeq 30$ km/s: Earth's orbital velocity

$\gamma \simeq 60^\circ$: inclination of the Earth's orbital plane

$v_\oplus \cos(\gamma) \simeq 15$ km/s

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since $v_\odot \gg v_\oplus \cos(\gamma)$:

$\Delta v = v_\odot/(v_\oplus \cos\gamma) \simeq 0.02$

$$\frac{dR}{dE_R} \simeq \left.\frac{dR}{dE_R}\right|_{v_{\rm E}=v_\odot} + \frac{\partial}{\partial v_{\rm E}}\left.\frac{dR}{dE_R}\right|_{v_{\rm E}=v_\odot} \Delta v \cos\left[2\pi(t-\phi)/\tau\right]$$

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size of the modulated signal

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Comparison with the Experimental Rate

$$\frac{dR}{dE_{\rm det}}(E_{\rm det}) = \int dE'\, \mathcal{K}(E_{\rm det}, E') \sum_{i=\rm Nucleus} \frac{dR_i}{dE_{\rm r}}\left(E_{\rm r} = \frac{E'}{q_i}\right)$$

takes into account the response and energy resolution of the detector

runs over the different species in the detector (eg DAMA and CRESST are multiple-target)

quenching factor: accounts for the partial recollection of the released energy

Rate: Uncertainties

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Theoretical Motivations

Mirror World

- based on the gauge group $\mathcal{G} = \mathcal{G}_{\rm SM} \otimes \mathcal{G}'_{\rm SM}$, which consists on an exact duplicate of SM particles and interactions
  see eg: Lee and Yang, Phys.Rev104,254 (1956), Okun et al., Yad.Fiz3,1154 (1966)
- if mirror baryons are interpreted as DM candidates
  see eg: Z.Berezhiani et al., Phys.LettB375,26 (1996), & Phys.LettB503,362 (2001)
- it is possible an interaction via renormalizable M-O photon kinetic mixing between the two sectors
  see eg: Holdom, Phys.LettB166,196 (1986), R.Foot, Phys.LettB503,355 (2001)

$$\mathcal{L}_{\rm int} = \epsilon/2\, F^{\mu\nu} F'_{\mu\nu},$$

$$\begin{cases} F_{\mu\nu} & \text{: field strenght tensor for O-electromagnetism} \\ F'_{\mu\nu} & \text{: field strenght tensor for M-electromagnetism} \end{cases}$$

Other Models

see eg: N.Arkani-Hamed, Phys.RevD79,015014 (2009), "A Theory of Dark Matter"

- the dark sector and the nuclei interact through the mixing of a massive dark photon and the ordinary one

Differential Cross Section

Yukawa potential:

$$V(r) = (\alpha_{\rm SM}\alpha_{\rm dark})^{\frac{1}{2}}\,\frac{\epsilon Z\, Z'}{r}\,e^{-m_\phi r},$$

fine structure constant of the DS

- Z' : DM charge
- ϵZ : effective charge of the target
- m_ϕ: dark photon mass

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differential cross section:

$$\frac{d\sigma(v,E_{\mathrm{r}})}{dE_{\mathrm{r}}} = \frac{m_{\mathcal{N}}}{2\mu_{\chi \mathrm{p}}^2}\frac{1}{v^2} A^2 \boxed{\sigma^{\mathrm{p}}_{\phi\gamma}} F^2_{\mathrm{SI}}(E_{\mathrm{r}})\Theta(E_{\mathrm{r}})$$

Normalize total cross section:

$$\boxed{\sigma^{\mathrm{p}}_{\phi\gamma}} = \frac{16\pi\epsilon^2 Z'^2\alpha_{\mathrm{SM}}\alpha_{\mathrm{dark}}}{\tilde{m}_\phi^4}\mu_{\chi\mathrm{p}}^2 \simeq \left(\frac{\epsilon}{10^{-4}}\right)^2\left(\frac{Z'}{1}\right)^2\left(\frac{\alpha_{\mathrm{dark}}}{\alpha_{\mathrm{SM}}}\right)\left(\frac{\mu_{\chi\mathrm{p}}}{1\ \mathrm{GeV}}\right)^2 10^{-38}\mathrm{cm}^2$$

with $\tilde{m}_\phi = 1$ GeV

$$\Theta(E_{\mathrm{r}}) = \left(\frac{Z}{A}\right)^2\left(\frac{\tilde{m}_\phi^2}{2m_{\mathcal{N}}E_{\mathrm{r}} + m_\phi^2}\right)^2$$

DM only couples with protons

square of the momentum transferred

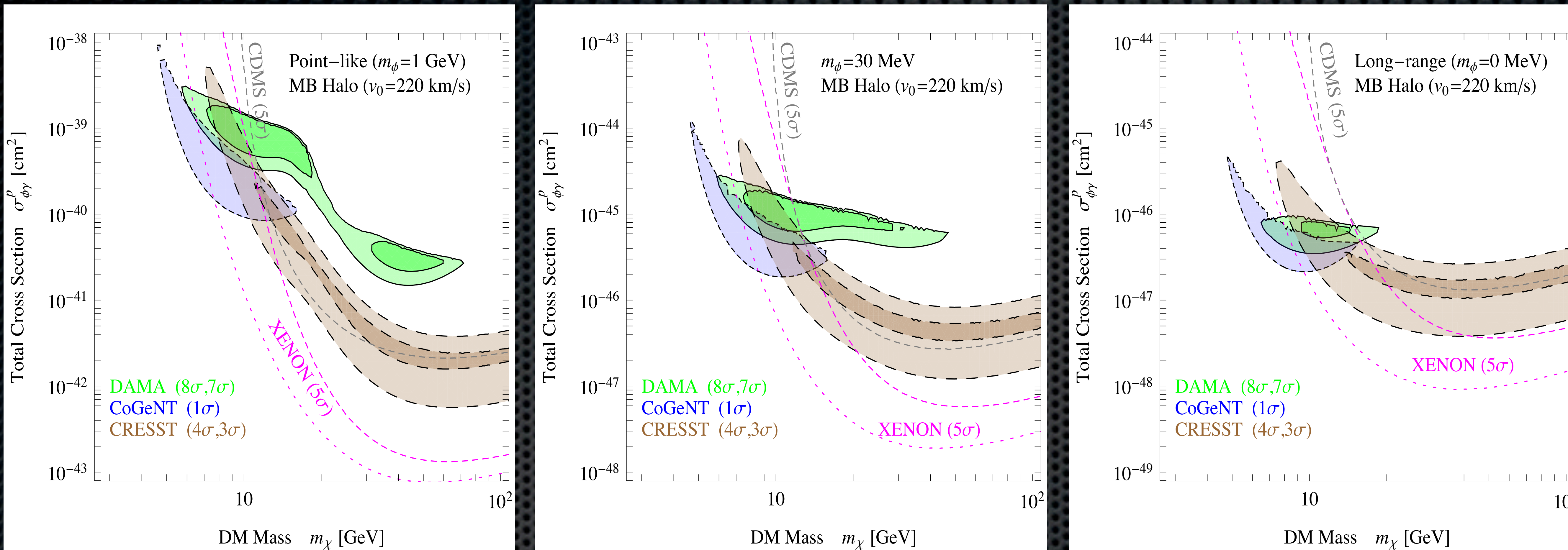
Contact type: $m_\phi \gg q = \sqrt{2m_{\mathcal{N}}E_r}$

$$(Z/A)^2\cdot(\tilde{m}_\phi/m_\phi)^4$$

Rutherford like: $m_\phi \ll q = \sqrt{2m_{\mathcal{N}}E_r}$

$$(Z/A)^2\cdot \tilde{m}_\phi^4/(2m_{\mathcal{N}}E_{\mathrm{r}})^2 \propto 1/E_{\mathrm{r}}^2$$

Allowed Regions & Constraints



for XENON100 we adopt two approaches:

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i) dotted magenta lines: constraints computed with the nominal values of the threshold and $\mathcal{L}_{\rm eff}$.

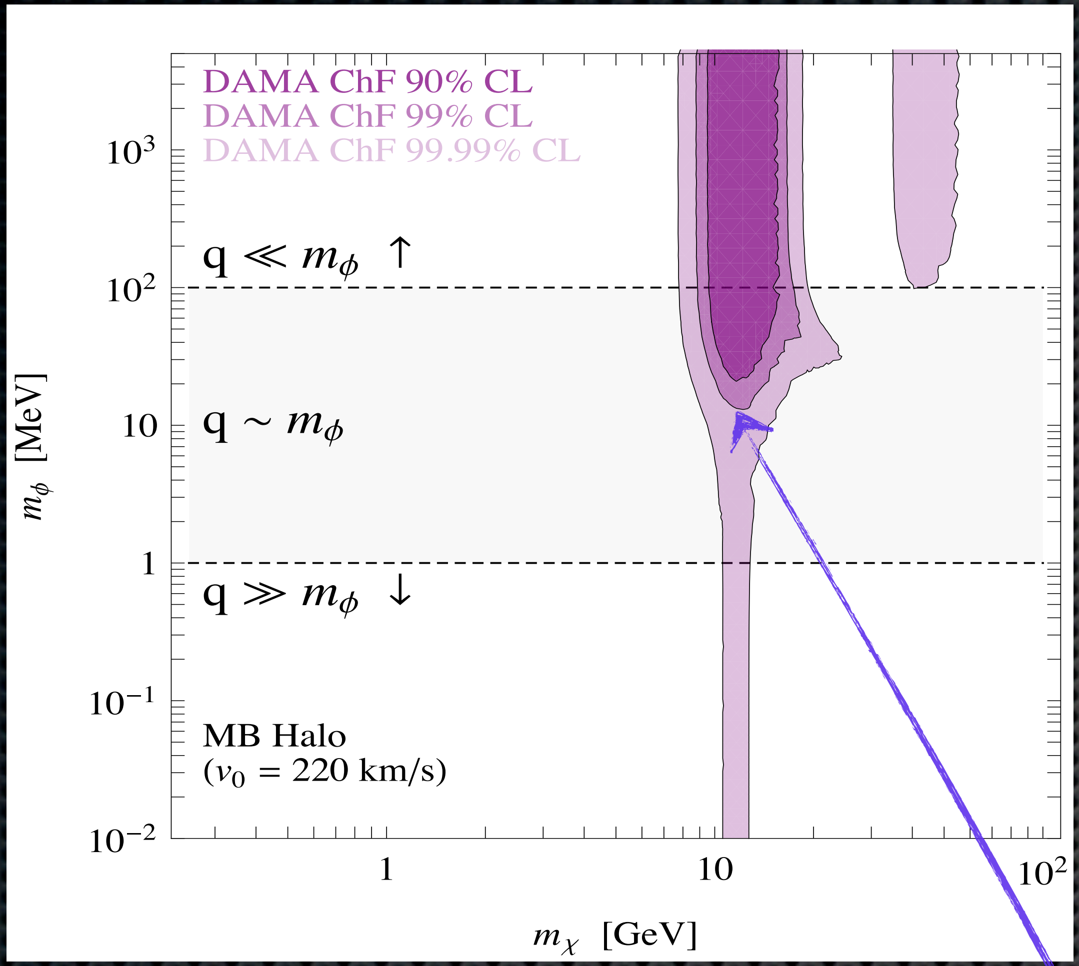
ii) dashed magenta lines: constraints computed with a threshold of 8 PHE in order to determine a situation which is nearly indepedent on the knowledge of $\mathcal{L}_{\rm eff}$ and the statistical distribution of events close to the threshold.

related discussion in eg: J.Collar, arXiv:1106.0653

Bottom line: going to long range interaction, a large overlap between DAMA, CoGeNT and CRESST is observed.
<u>The significance of the DAMA region get lower.</u>

Constraints on m_φ and ε

DAMA total Rate:



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the DAMA total rate put a 99% CL lower bound on the mass of the dark photon around 10 MeV.

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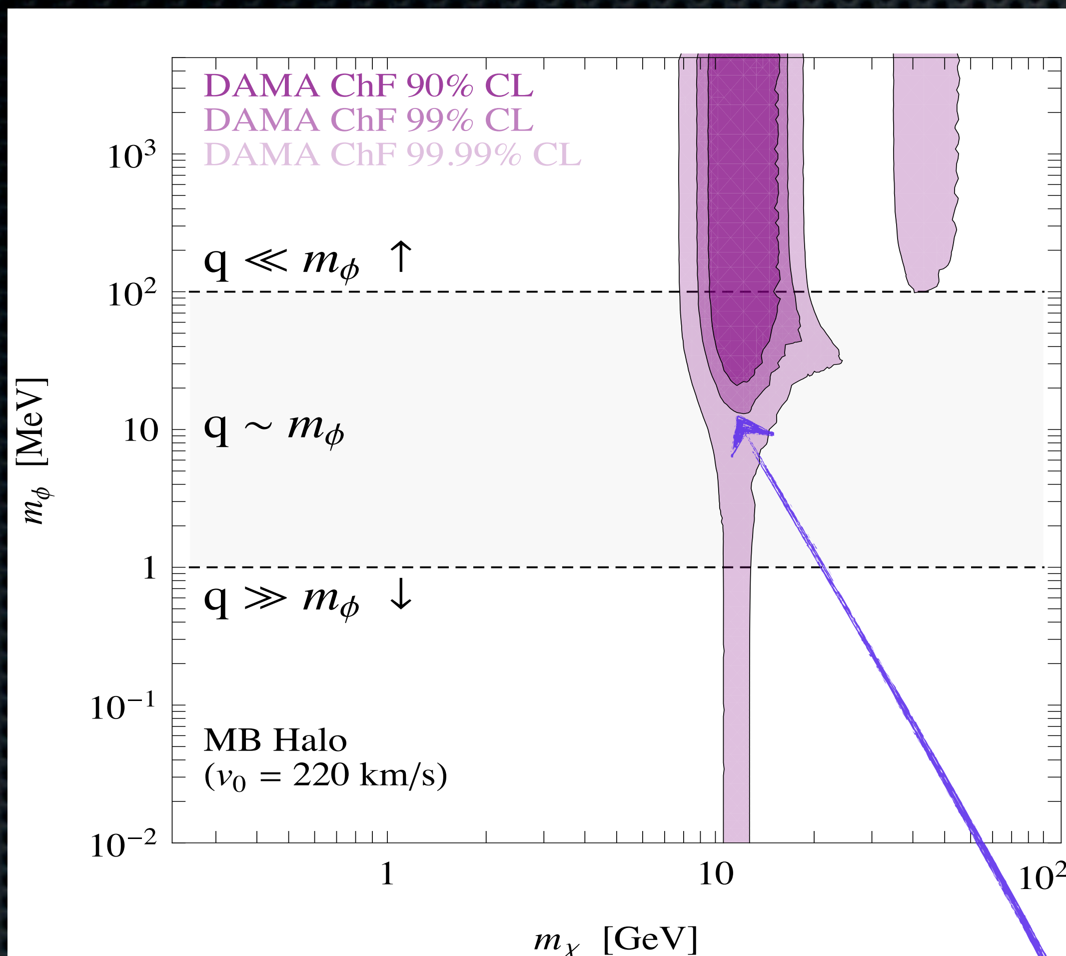

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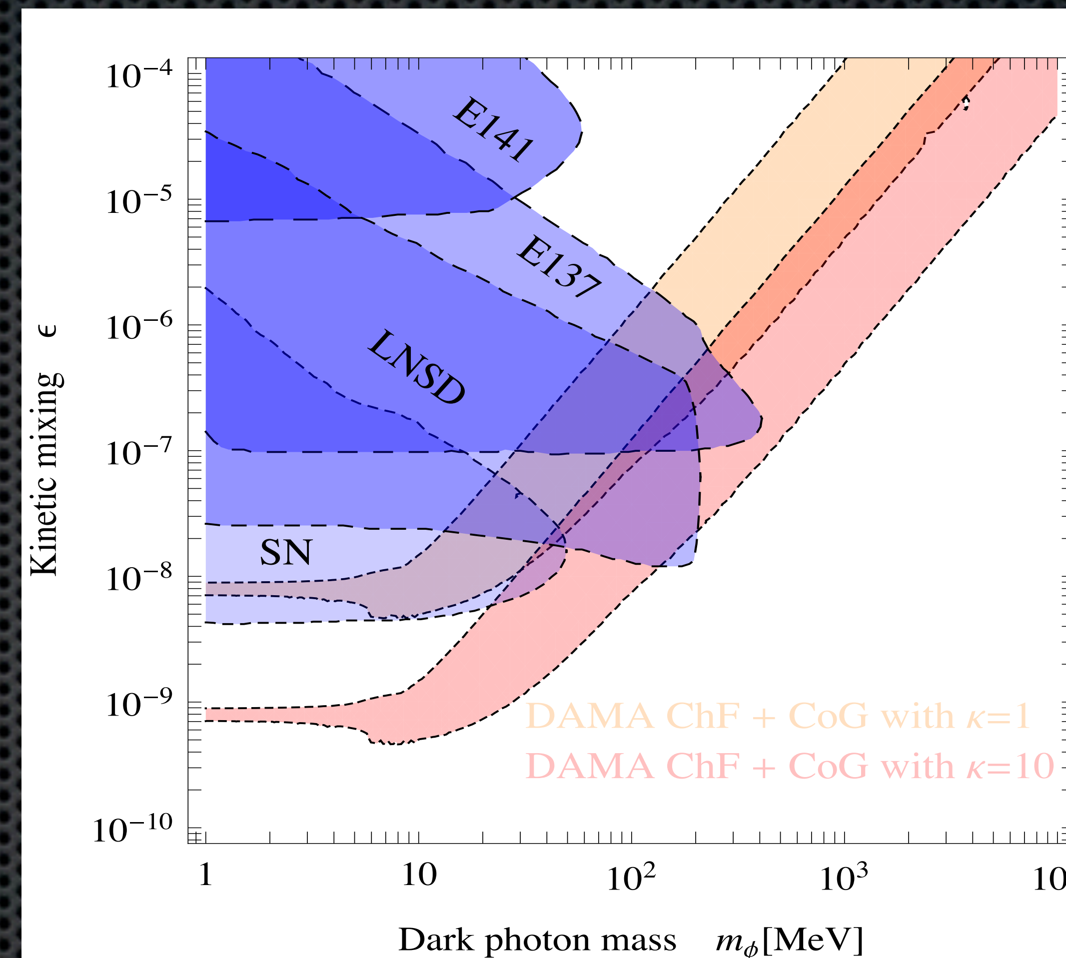
Bounds in the (ε, m_φ) plane:



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- constraints dependent on ϵ, m_ϕ while independent on Z', $\alpha_{\rm dark}$.

$$k = Z' \sqrt{\alpha_{\rm dark}/\alpha_{\rm SM}}$$

- sym. case (k=1): $m_\phi \gtrsim 100$ MeV
- asym. case (k=10): unbounded

Constraints on m_φ and ε

Constraints from DM self-interaction:

- dependent on Z', $\alpha_{\rm dark}$, m_ϕ, while independent on ϵ.

weighted cross section for self interaction:

$$\sigma_{\rm av} = \int d^3v_1 d^3v_2 f(v_1) f(v_2) \int d\Omega \frac{d\sigma}{d\Omega}(1-\cos\theta)$$

$\sigma(v_{\rm rel})$: for long range, the DM self interaction is analogous to a screened Coulomb scattering with plasma.

Bullet Cluster Bound

$\sigma_{\rm av}/m_\chi \lesssim 1.25~{\rm cm}^2/{\rm g}$ implies

$m_\phi \gtrsim (1, 20)~{\rm MeV~~for}~k = (1, 10)$

bullet Cluster

Constraints from the observation of the DM halo ellipticity:

- dependent on Z', $\alpha_{\rm dark}$, m_ϕ, while independent on ϵ.

relaxation time into a spherical configuration:

$$\tau_{\rm r} = 1/\int d^3v_1 d^3v_2 f(v_1) f(v_2) v_{\rm rel}\sigma(v_{\rm rel})(v_{\rm rel}/v_0)^2$$

$\tau_{\rm r}$ must be bigger than the age of the virialized object

- ellipticity of galaxy cluster halo: m_ϕ unbounded
- ellipticity of dwarf galaxy halo: $m_\phi \gtrsim 100~{\rm MeV}$

Conclusions

- we have discussed the possible indication of a signal in direct DM experiments due a mechanism of interaction between DM particle and target nuclei of a long range type.
- we have seen that this is a viable mechanism which is able to increase the overlap among positive results experiments in direct detection searches.
- in particular it should be interesting to study the formation of virialized objects in presence of long range forces in the DS since they predict a quite large space dependent self interaction that could help the formation of DM density profiles core.