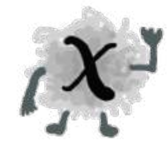
Neutrinos in dark matter experiments:
Friends or Foes?

DAVID G. CERDEÑO

Instituto de Física Teórica UAM-CSIC
Universidad Autónoma de Madrid
MultiDark Multimessenger Approach for Dark Matter Detection

I wanted this to be a talk on **Dark Matter**....



... a mysterious (and very abundant) new form of matter that does not emit or absorb light, and that challenges the Standard Model.

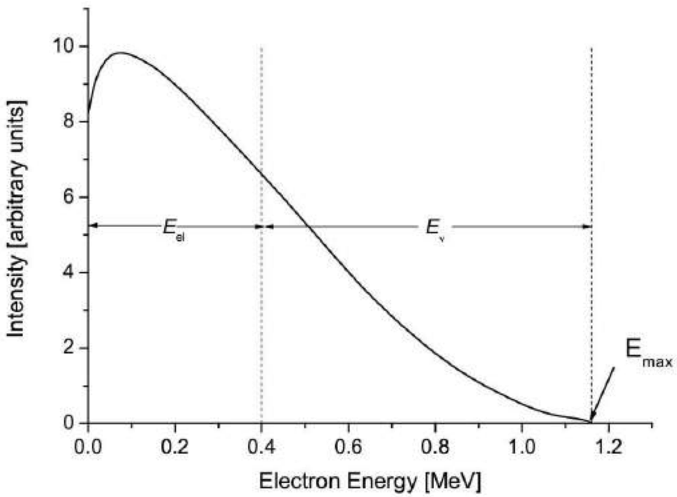
However, **neutrinos**  will get in the way...

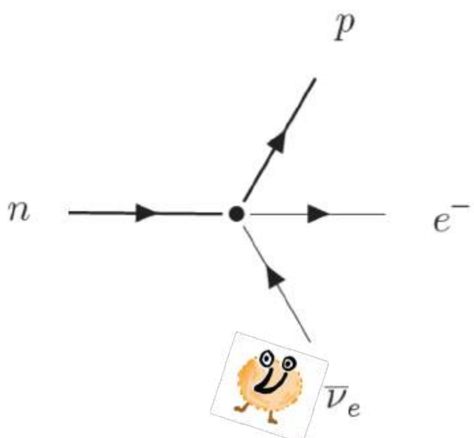
... and pose a challenge for direct dark matter detection experiments.

But this can be seen as an opportunity to study new neutrino physics with dark matter detectors.

Neutrinos have been with us for a long time

- Proposed in 1931 (Pauli) as a necessary invisible particle to explain the continuous spectrum of beta decays.





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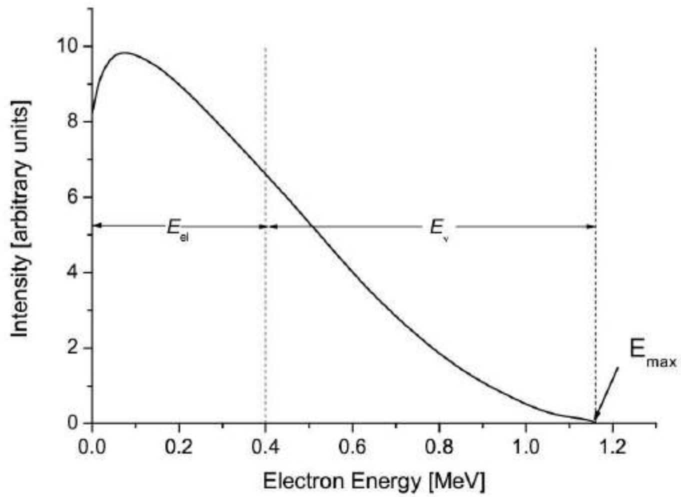
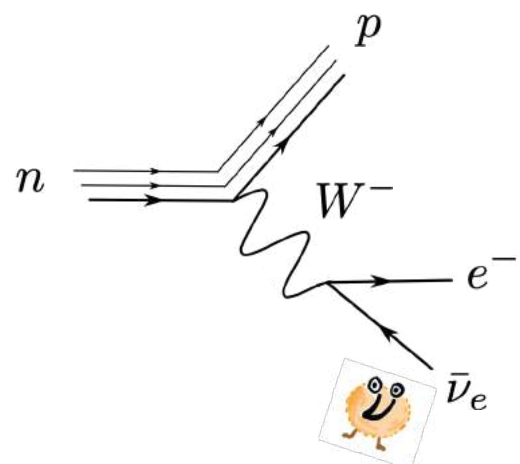
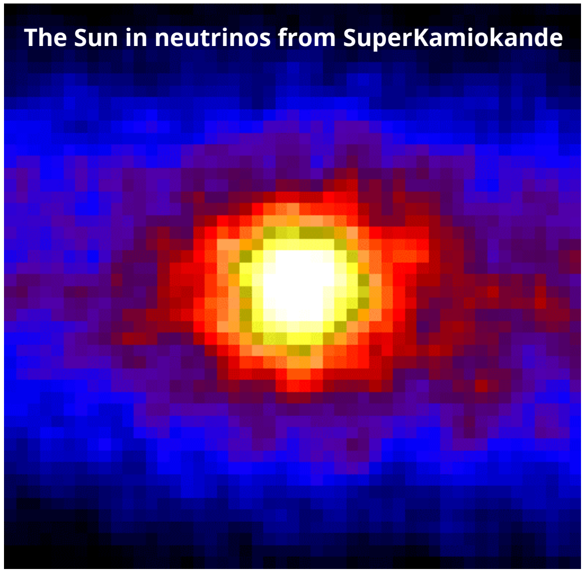


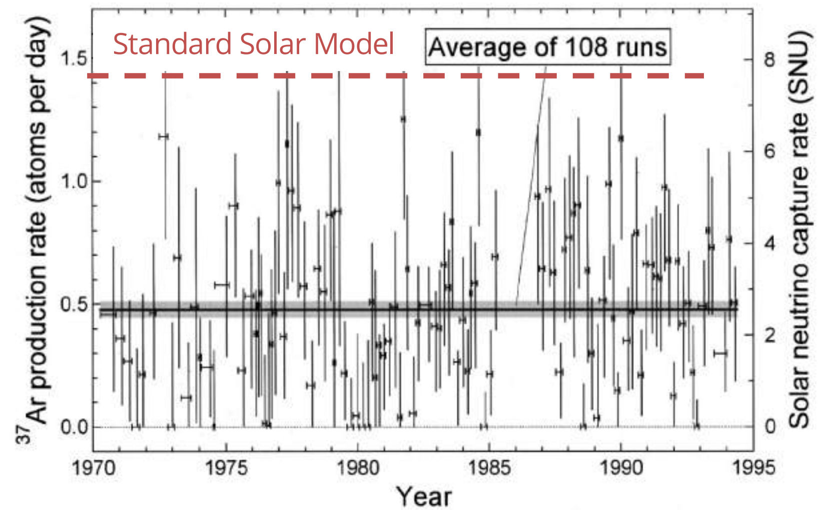


Incorporated in a Theory of Weak interactions (Fermi, 1934) – effective Electroweak Interactions (exchange of Z^0 and $W^\pm$ bosons)

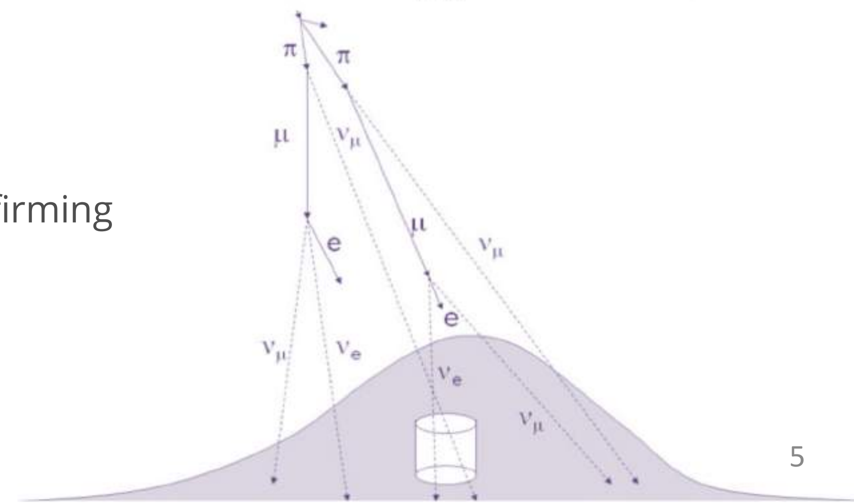

Observed 25 years later (Cowan, Reines) from nuclear reactor

- Produced in nuclear processes in the Solar interior (first observed at Homestake 1968) – but there were fewer than expected?





- And in the atmosphere from **cosmic rays**

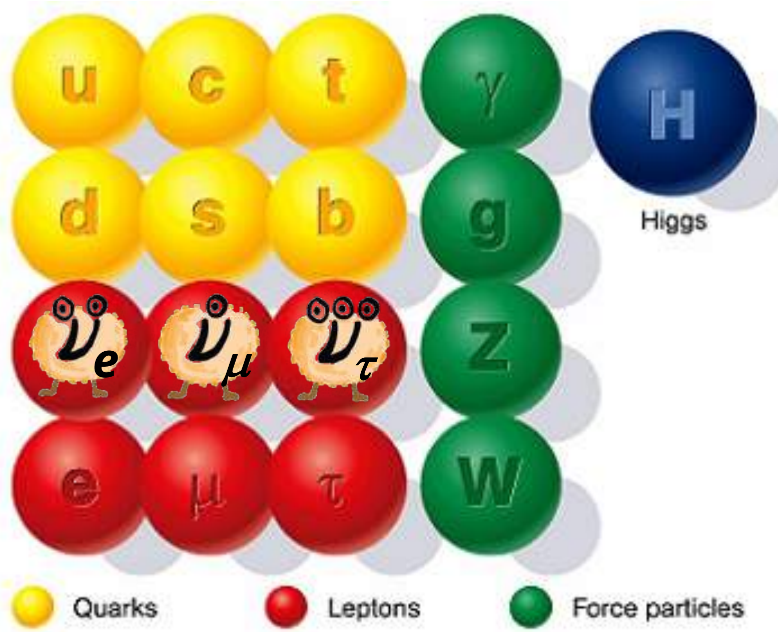


- Observed in Super Kamiokande (1998), confirming the fact that neutrinos oscillate.

  They must have a mass!

Neutrinos fit “nicely” in the Standard Model of particle physics

- Neutral fermion (spin 1/2)
- Feels only the Weak Force - *W* and *Z* bosons)
- They come in three generations (e, μ, τ)



But there are open questions that point to **new physics:**

- How do they get (such a tiny) mass?
- Are they Dirac or Majorana?
- Are there only three? (heavy sterile neutrinos?)
- Are they associated to other new particles?
- …

Dark Matter is much more exotic…

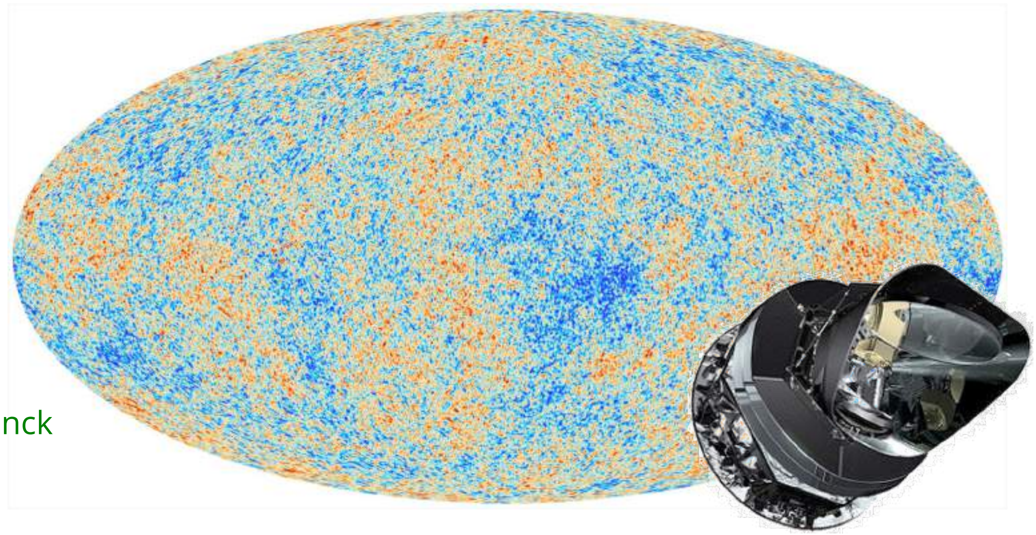
We have not seen it, but we feel its **gravitational** effect at all scales in the Universe

Clusters of galaxies

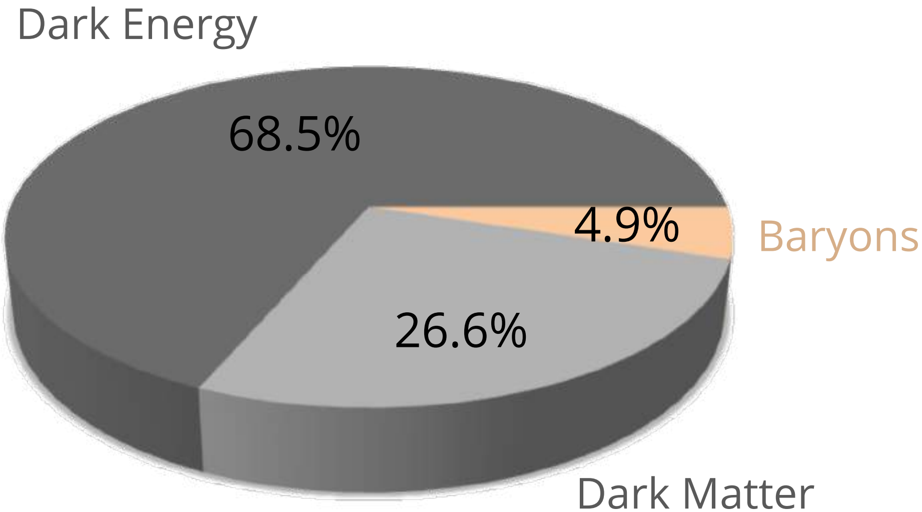
- Peculiar velocities and gas temperature
- Weak lensing
- Dynamics of cluster collision
- Filaments between galaxy clusters

Dark matter is fundamental to explain the filamentary structure of the Universe

Observations of the **Cosmic microwave Background** can be used to determine the components of our Universe



COBE, WMAP, Planck



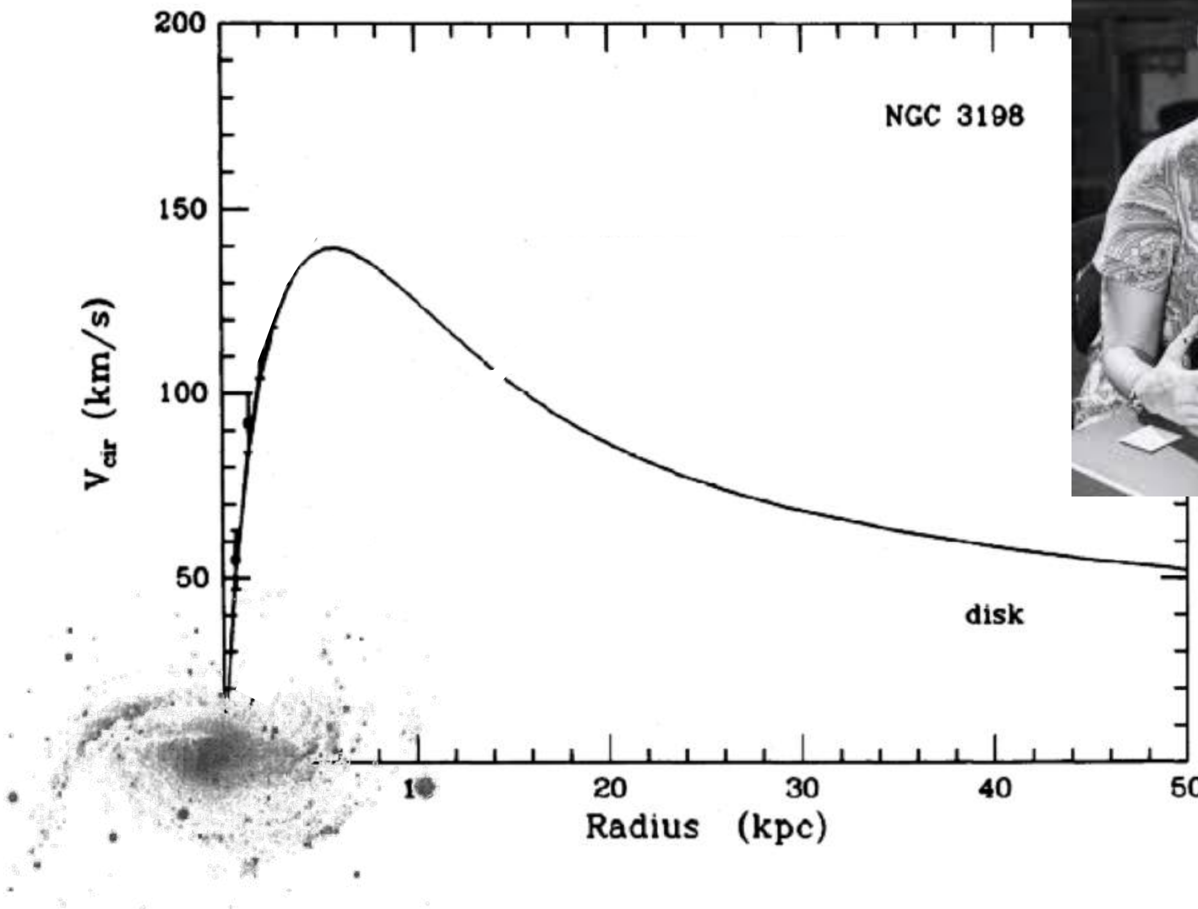
$$\Omega_\Lambda h^2 = 0.3116 \pm 0.009$$

$$\Omega_c h^2 = 0.1196 \pm 0.003$$

$$\Omega_b h^2 = 0.02207 \pm 0.00033$$

Planck 2013

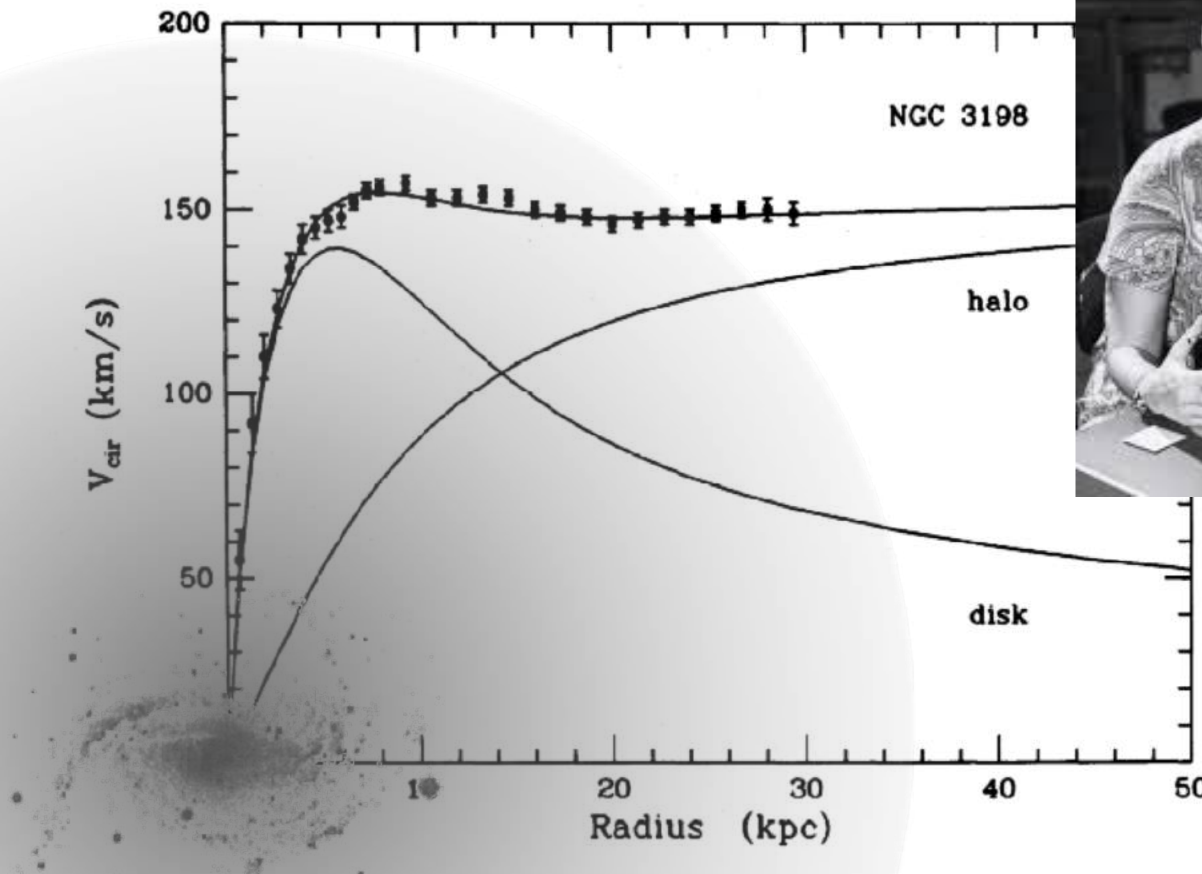
Dark Matter makes galaxies rotate **faster**



Vera Rubin

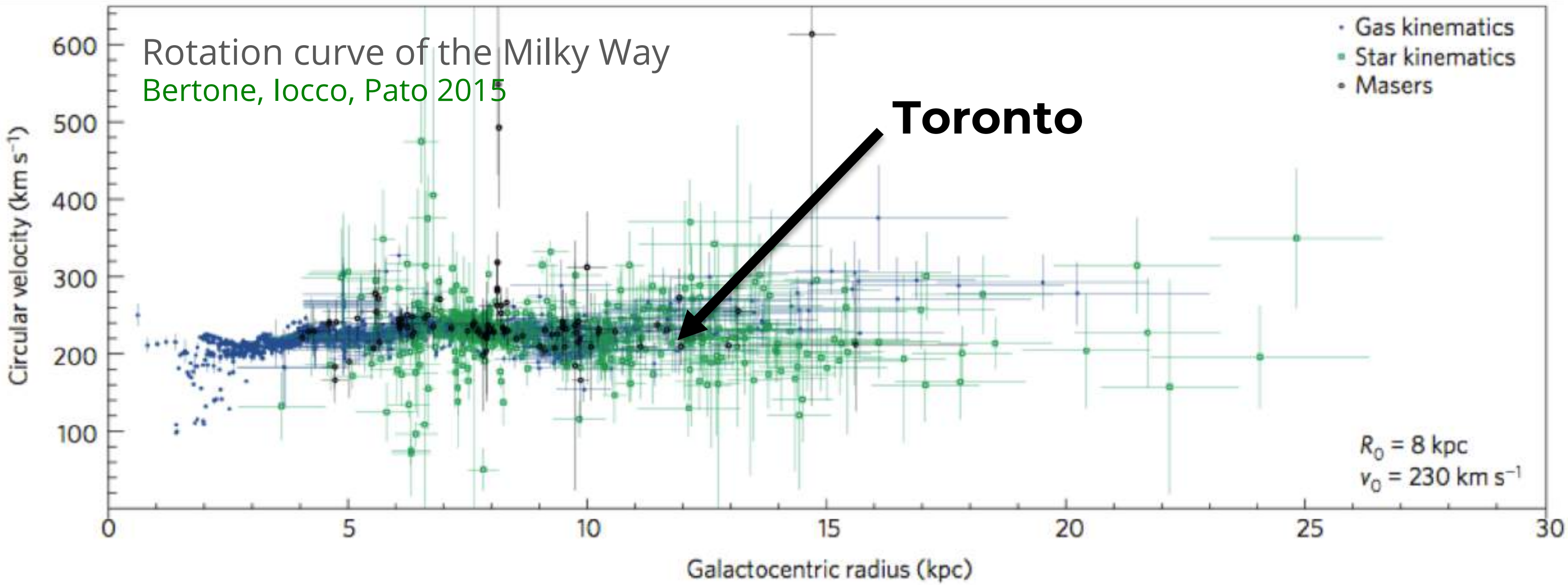
This confirms that there is (a lot of) **matter that we do not see**

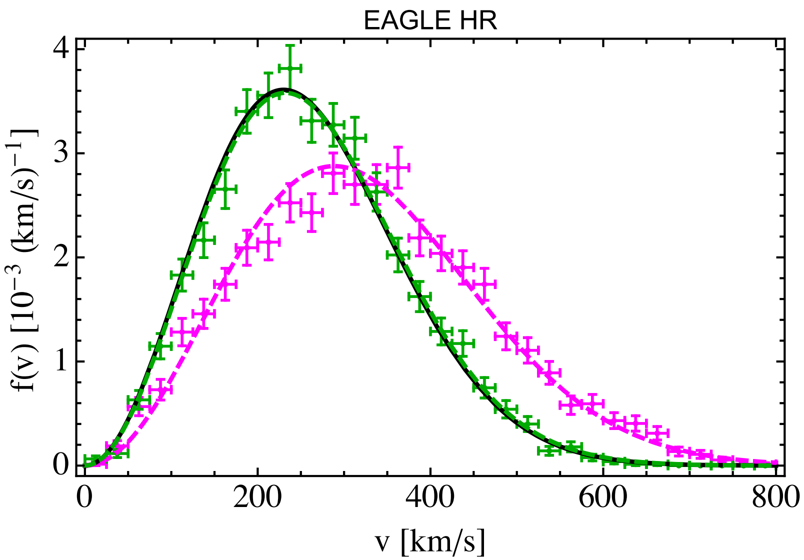
Dark Matter makes galaxies rotate **faster**



Vera Rubin

Galaxies are surrounded by a halo of DM ~ 80% - 90% of the total mass





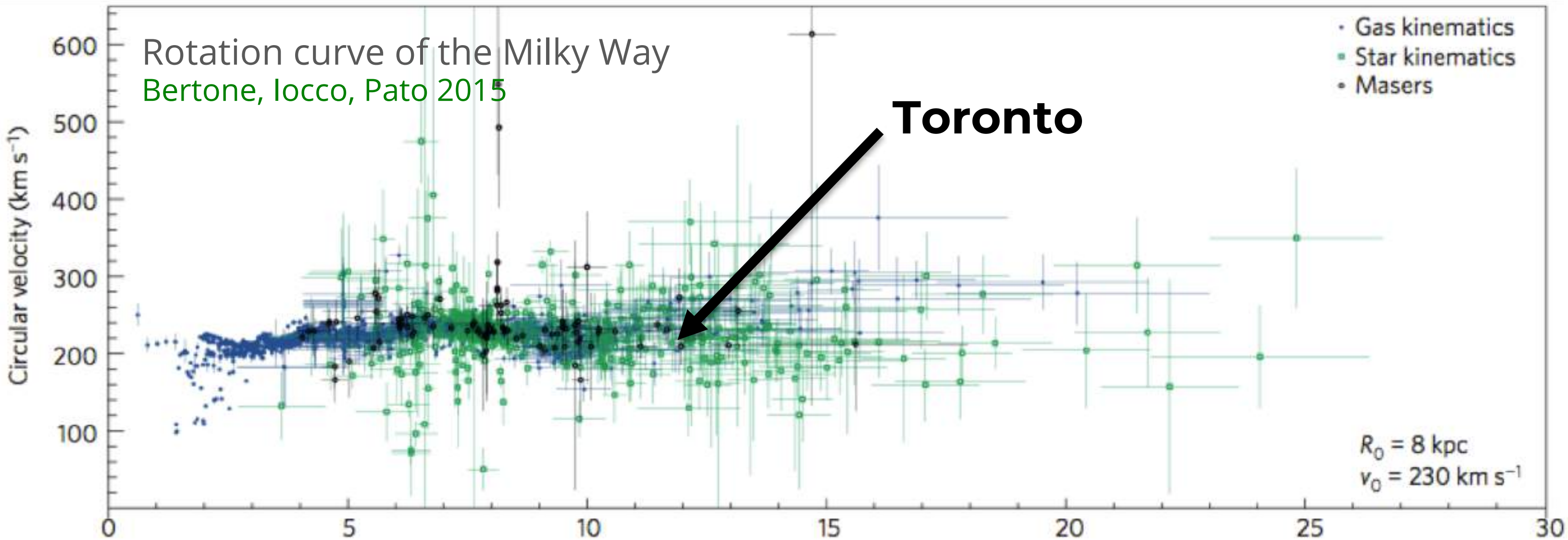
- local DM density

$$\rho_{DM}(R_0) \approx 0.4\ \mathrm{GeV/cm^3}$$

- Velocity distribution of DM particles

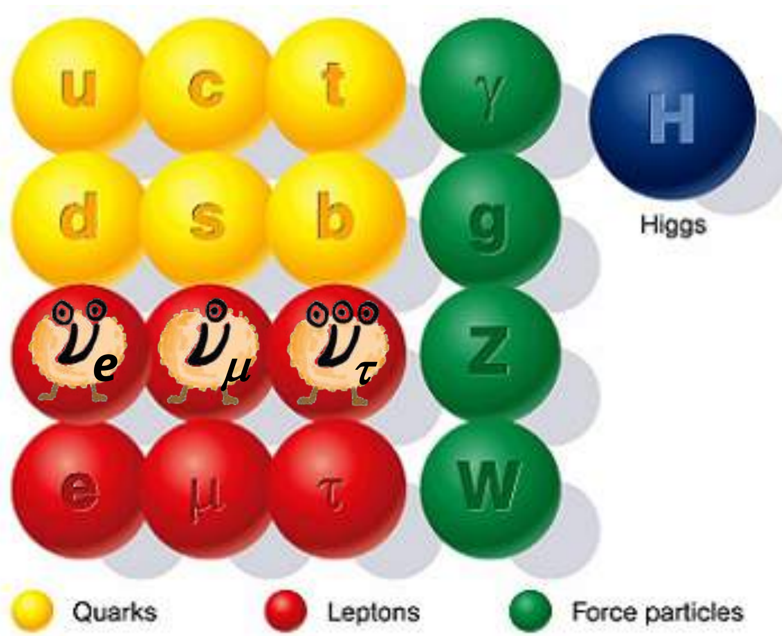
Maxwellian distribution is a good fit in the Milky Way
Uncertainty in astrophysical parameters

Bozorgnia et al. 1601.04707



Very few people know this, but the tiny pocket in our jeans is for carrying 10 GeV of dark matter

Dark Matter has no place in the Standard Model



The way that DM interacts (feels) the Standard Model is crucial to understand how it was formed in the Early Universe

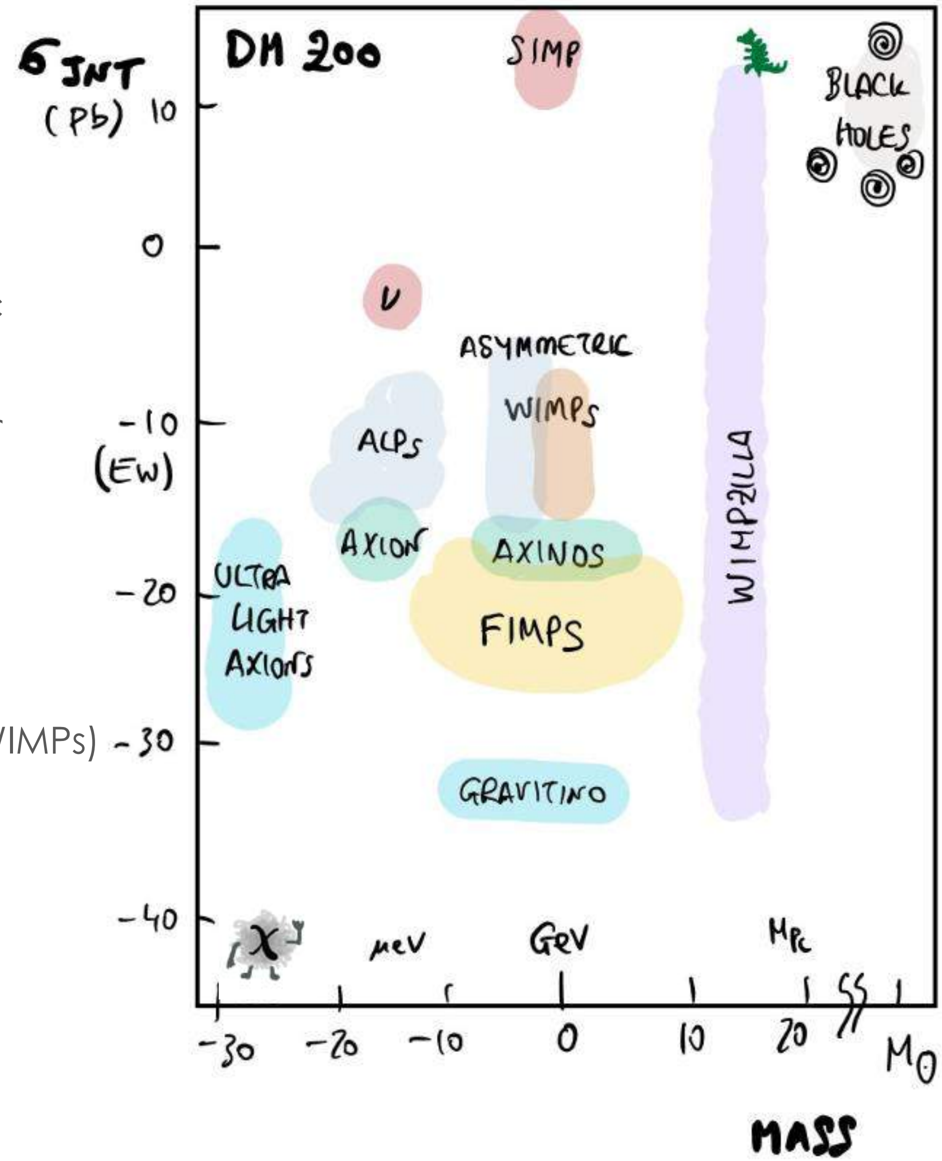
We don't know yet what DM is... but we do know many of its properties

Dark matter needs to be...

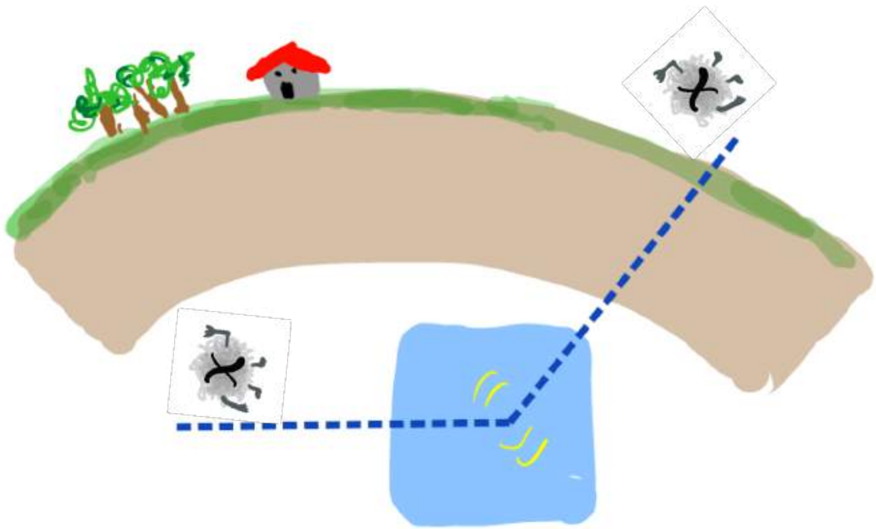
- Neutral
- Stable on cosmological scales
- Reproduce the correct relic abundanc
- Not excluded by current searches
- No conflicts with BBN or stellar evolutior

Many candidates in Particle Physics

- Axions
- Weakly Interacting Massive Particles (WIMPs)
- SuperWIMPs and Decaying DM
- Asymmetric DM
- SIMPs, CHAMPs, SIDMs, ETCs...



Direct detection experiments have become multifaceted probes of invisible sectors

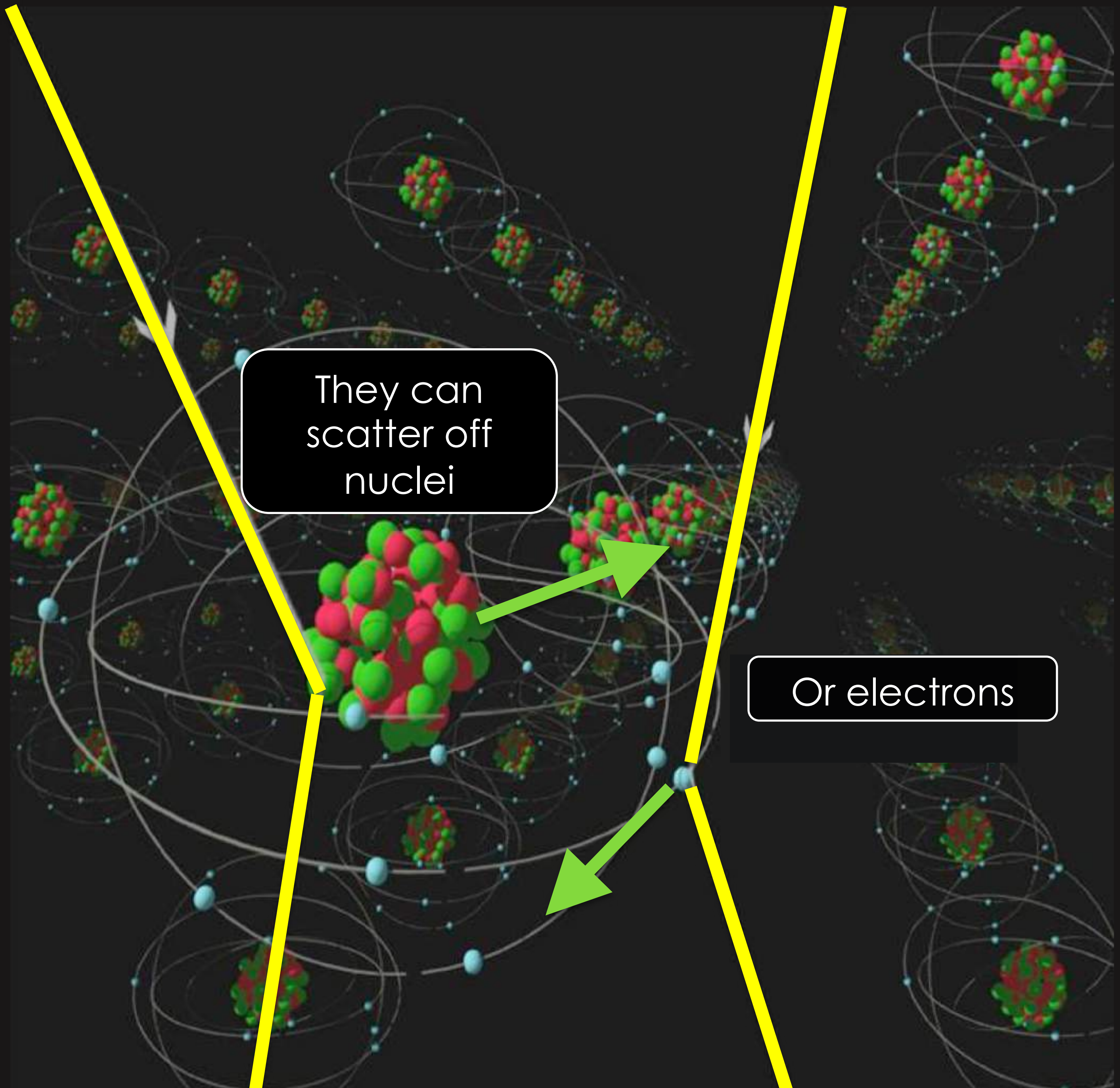


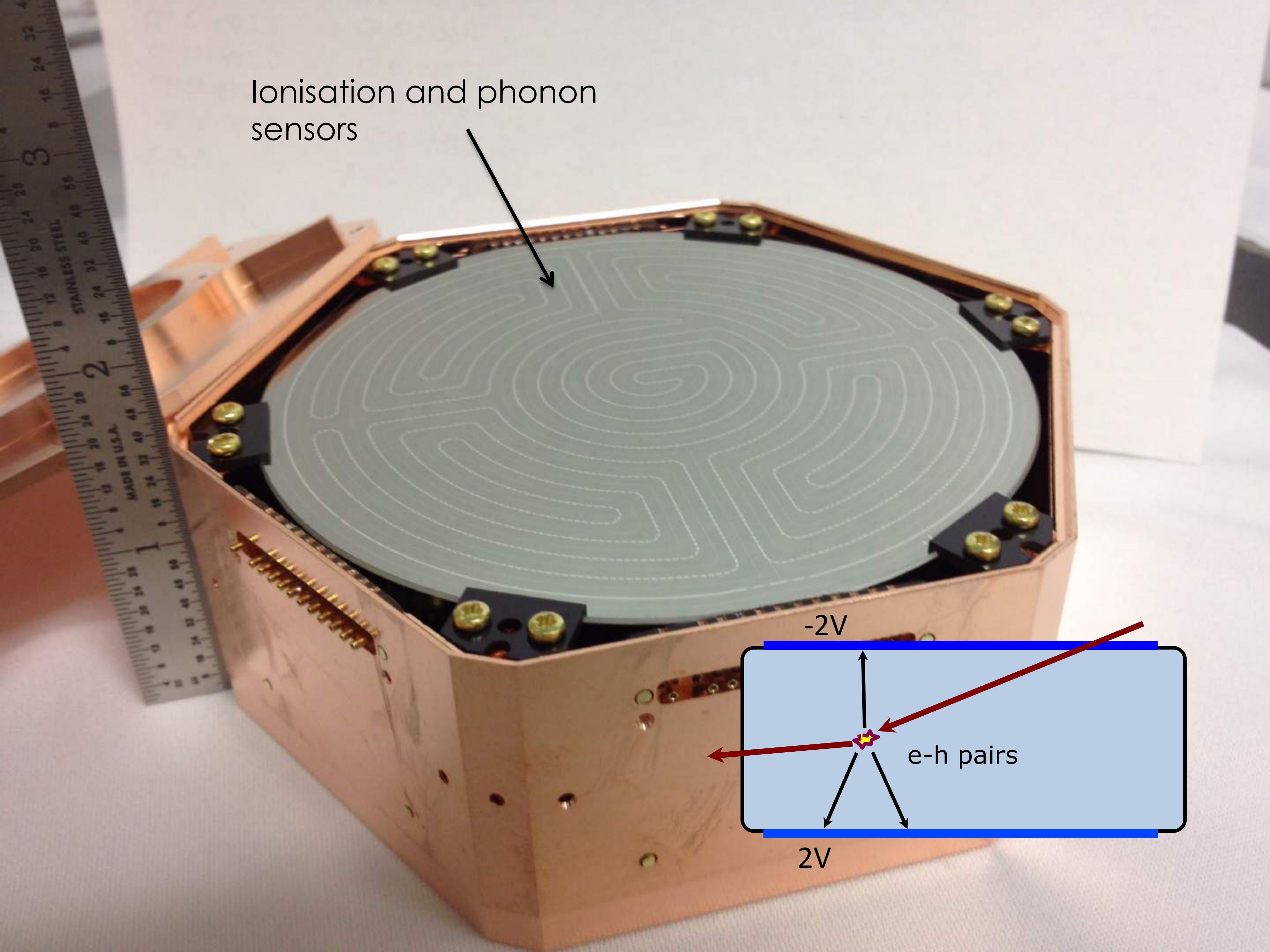
An **exotic particle** collides with **something** in an **underground** detector

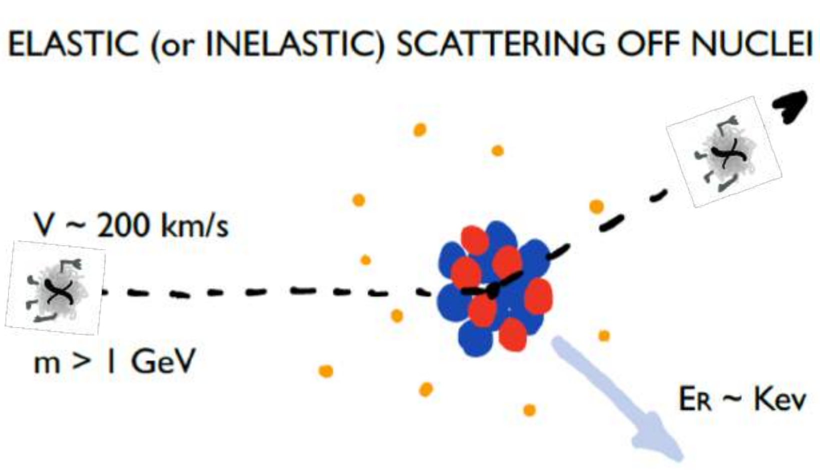
- WIMP – FIMP – ALP
- Neutrino
- Millicharged particle

- Nuclei
- electrons

- Some experiments run on surface


They can scatter off nuclei
Or electrons


Ionisation and phonon sensors
-2V
e-h pairs
2V



DIRECT DARK MATTER SEARCHES: What can we measure?

NUCLEAR SCATTERING

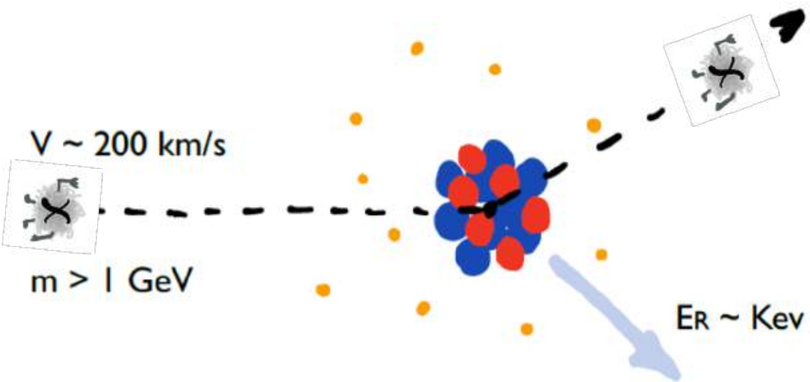
- "Canonical" signature
- Elastic or Inelastic scattering
- Sensitive to m >1 GeV

$$E_R = \frac{\mu_N^2 v^2 (1 - \cos\theta^*)}{m_N}$$

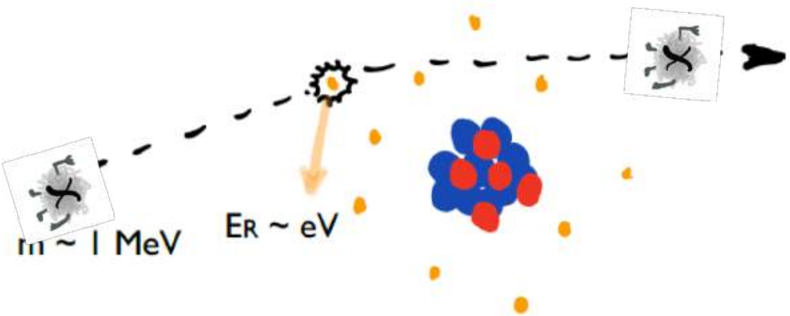
The scattering takes place in the non-relativistic limit. The nuclear (or electronic) recoil energy is a function of the mass of the DM particle.

Experiments are sensitive to energies ~ keV

ELASTIC (or INELASTIC) SCATTERING OFF NUCLEI



INELASTIC SCATTERING WITH ELECTRONS



$$E_R = \frac{\mu_e^2 \, v^2(1-\cos\theta^*)}{m_e}$$

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ELECTRON SCATTERING

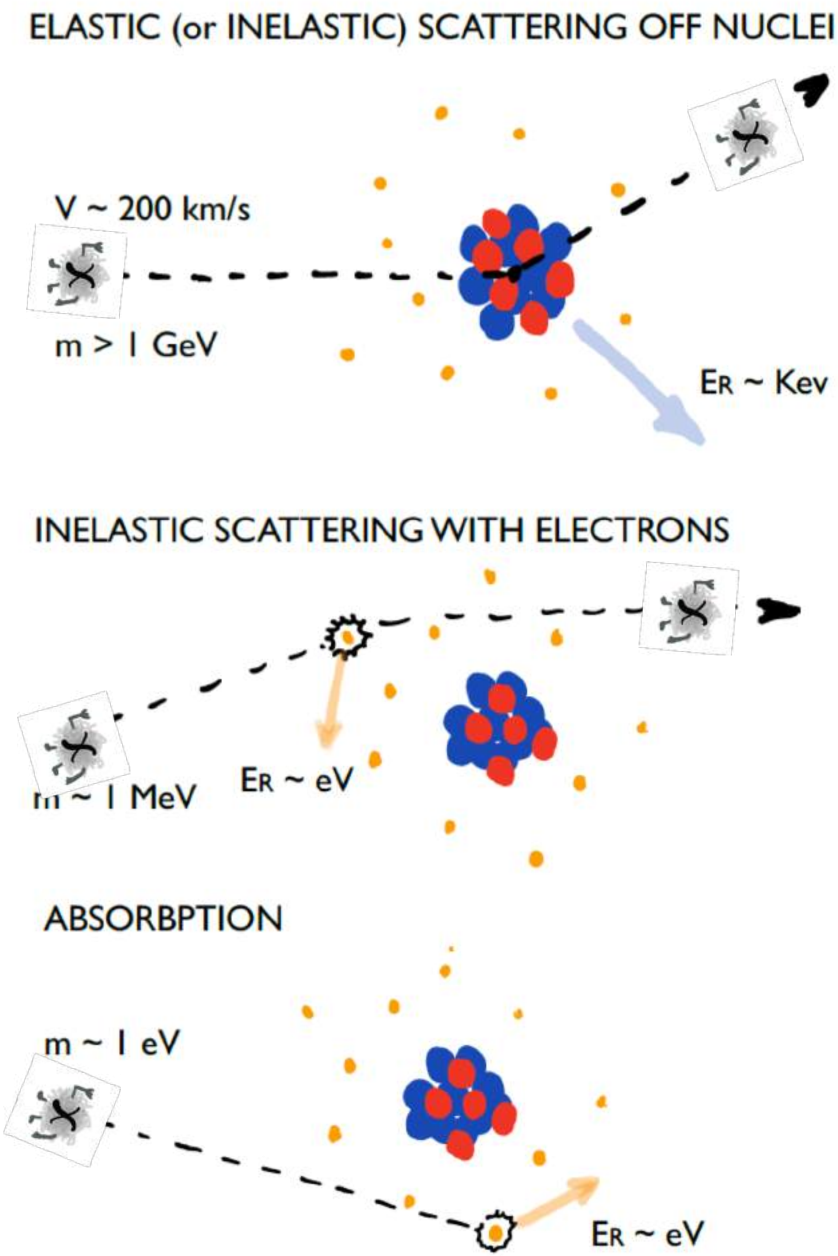
- Sensitive to light WIMPs

ELECTRON ABSORBPTION

- Very light (non-WIMP)

EXOTIC SEARCHES

- Axion-photon conversion in the atomic EM field
- Light Ionising Particles



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Conventional direct detection approach (WIMPs)

$$N = \int_{E_T} \epsilon \frac{\rho}{m_\chi m_N} \int_{v_{\min}} v f(\vec{v}) \frac{d\sigma_{WN}}{dE_R} d\vec{v}\, dE_R$$

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Particle (+ nuclear) Physics

The scattering cross section contains the details about the microphysics of the DM model

Traditionally, it has been split into two components: spin-dependent and -independent

$$\frac{d\sigma_{WN}}{dE_R} = \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SI} + \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SD}$$

These include nuclear form factors that encode the coherent scattering with the nucleus.

If nothing is found, we derive upper limits on the scattering cross section.

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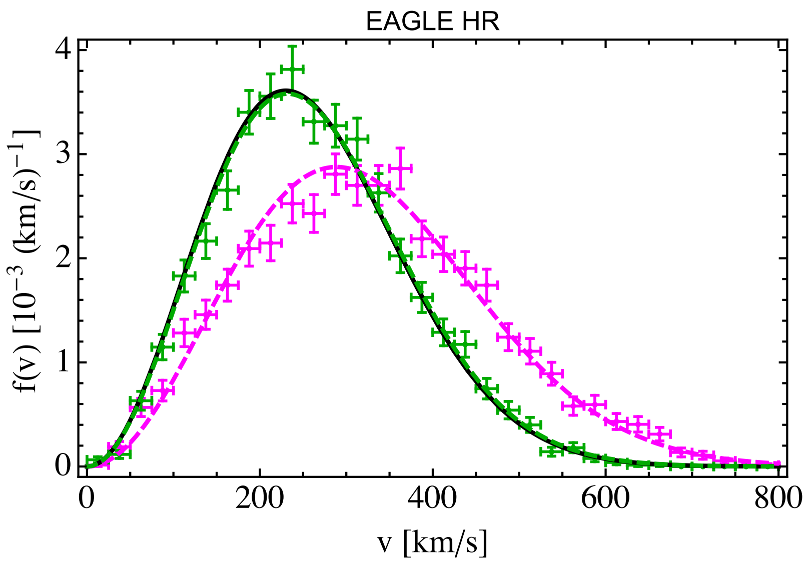
Astrophysics



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- Velocity distribution of DM particles

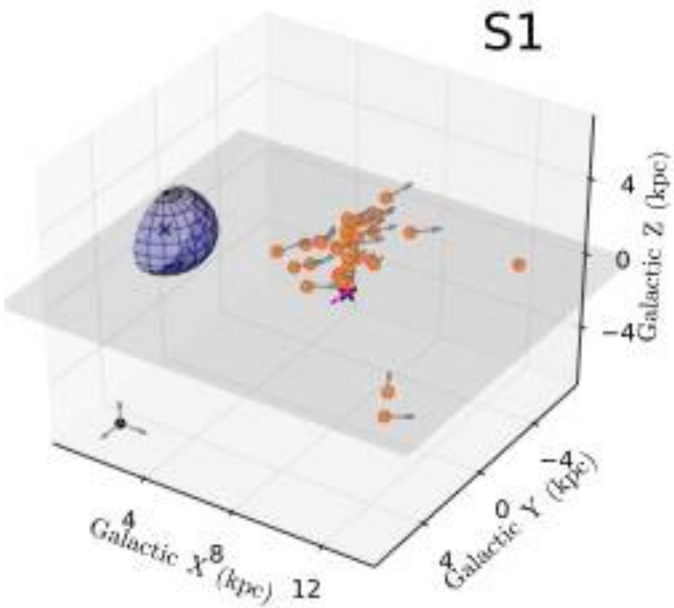
Maxwellian distribution is a good fit in the Milky Way

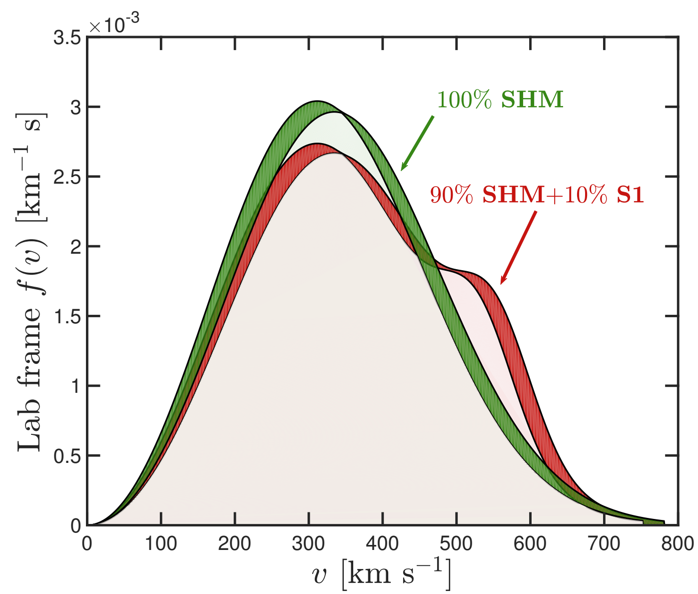
Bozorgnia et al. 1601.04707

There can be streams of Dark Matter

Using Gaia data, a stream of stars, S1, has been found in the Milky Way

If DM is also present in the stream it will modify the local velocity distribution function





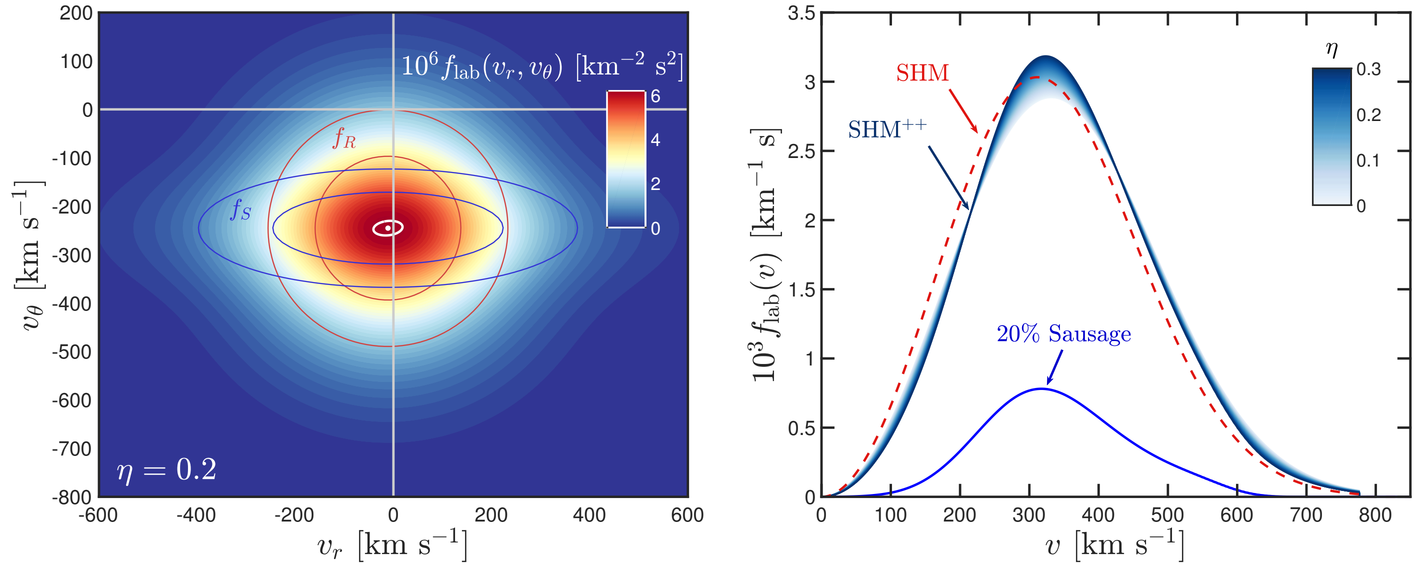
O'Hare, McCabe, Evans, Myeong, Berlokurov 1807.0900

A sausage in our Galaxy??

The DM (and stars) velocity distribution function is sensitive to the merging history.

Evans, et al. 2018

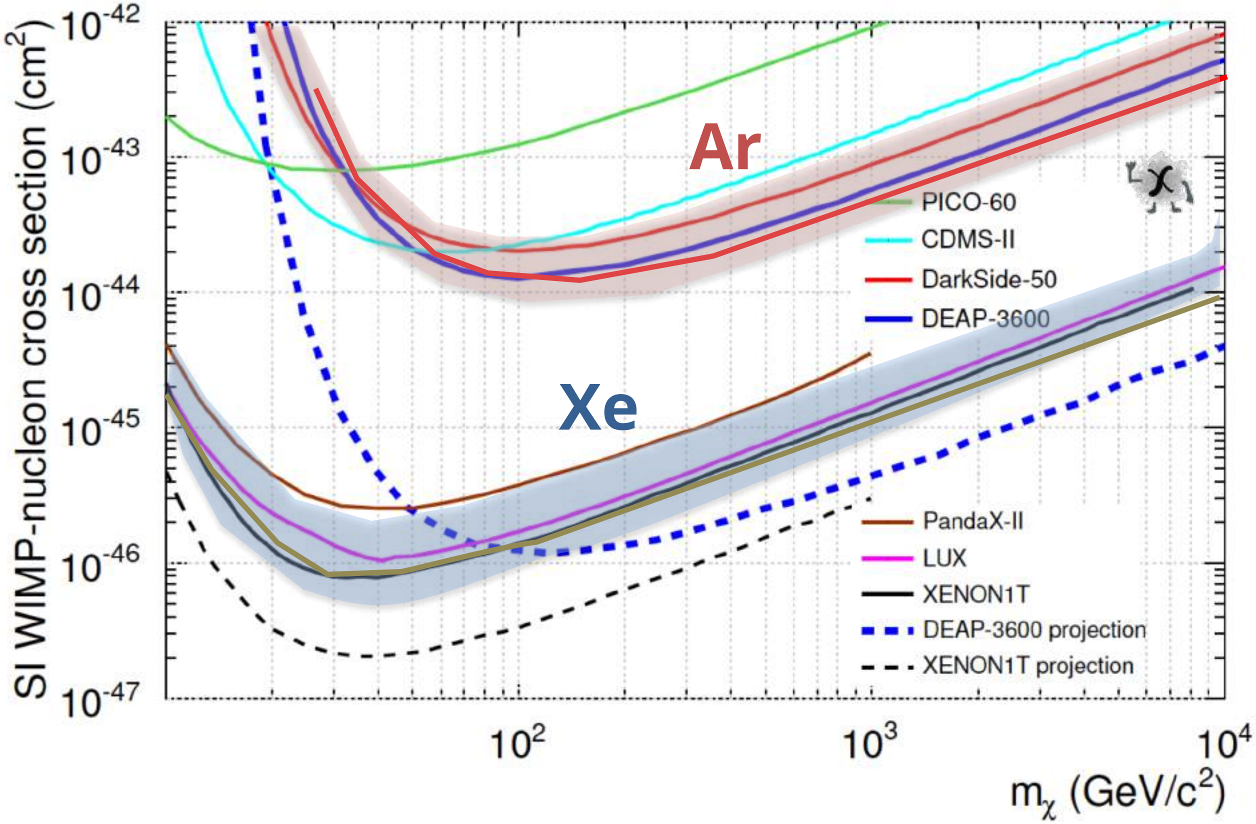
A head-on collision of the MW with a smaller object left a characteristic imprint in the angular and radial velocities (of stars).



Evans, O'Hare, McCabe 1810.11468

Constraints on the DM-nucleus scattering cross section

Single or double phase noble gas detectors excel in searches at large DM masses
XENON1T, LUX, Panda-X (Xe), DARKSIDE, DEAP (Ar)
Easily scalable



DARKSIDE 1802.07198
~10000 kg day

DEAP 1707.08042
9870 kg day

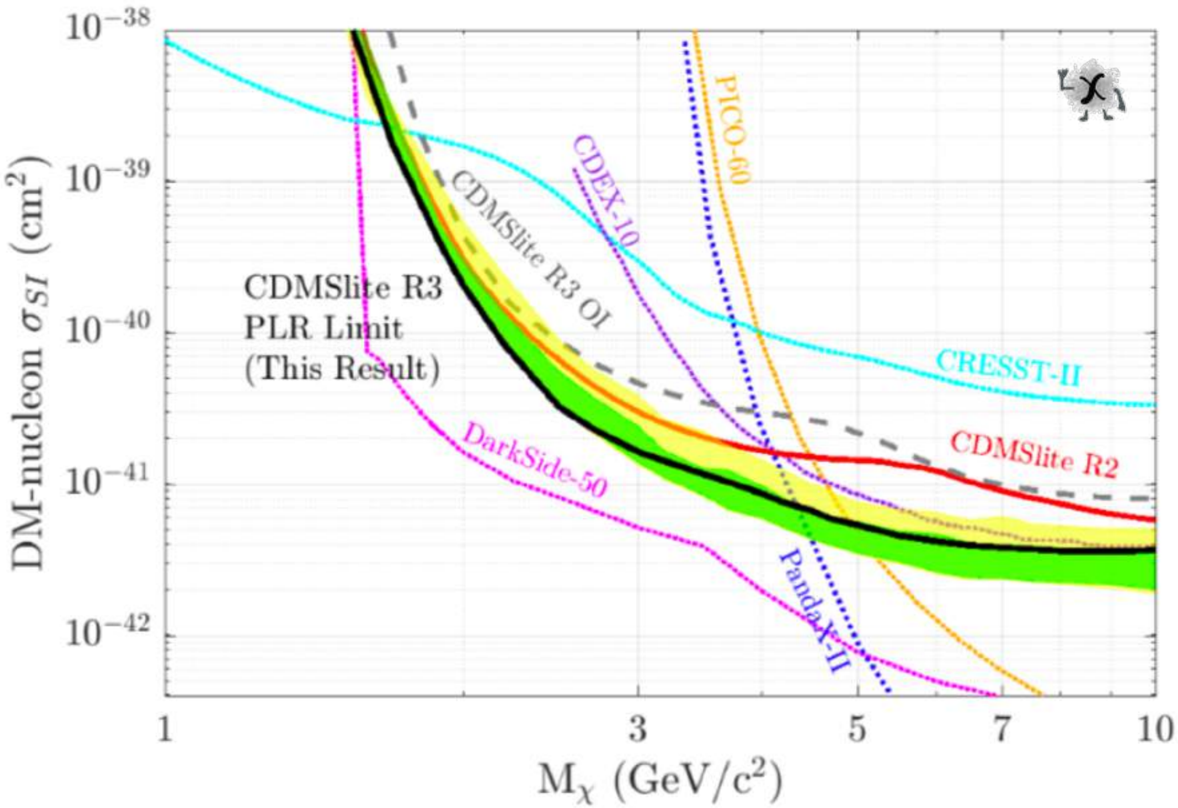
PANDAX 1708.06917
54000 kg day

LUX 1608.07648
33500 kg day

XENON1T 1805.12562
362000 kg day

Constraints on low-mass WIMPs

CDMSlite, SuperCDMS, Edelweiss, CDEX (Ge), CRESST ($CaWO_4$), NEWS-G (Ne) complete the search for WIMPs at low masses.
Low-threshold experiments (with smaller targets) are probing large areas of parameter space



Direct detection experiments will soon be able to detect a new source of background…

… neutrinos!

Coherent neutrino scattering

The de Broglie wavelength of neutrinos can exceed the radii of heavy nuclei for neutrino energies below ~100 MeV.

- Recently **observed SM phenomenon (COHERENT)**

  Extremely small cross section only within the reach of ultra-low background experiments.

- **Background** for DM experiments

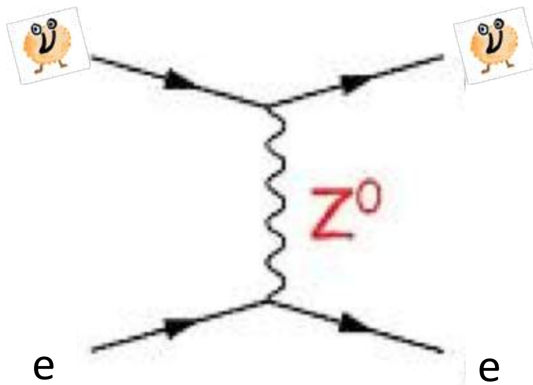
  - The signature is similar to that expected for a WIMP

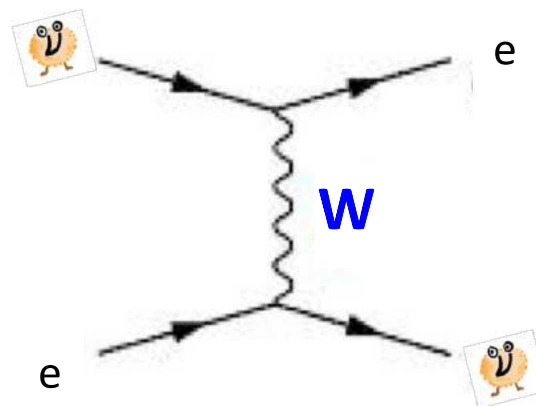
- It can give us access to **solar properties** (e.g., CNO neutrinos and solar metallicity)

- It can allow us to probe **new physics in the neutrino sector**

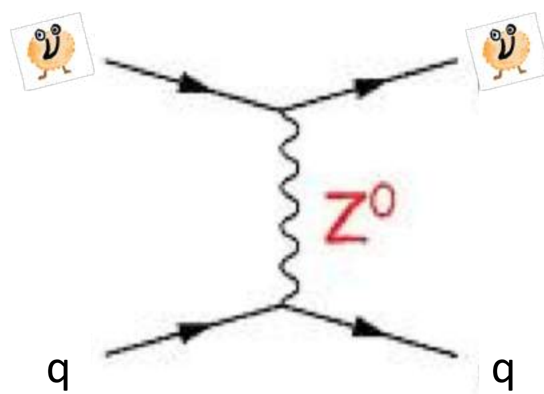
Neutrino scattering in a DM experiment

Exchange of W and Z bosons with electrons





Exchange of a Z boson with the nucleus



Neutrinos in direct detection experiments

$$N = \varepsilon\, n_T \int_{E_{\rm th}}^{E_{\rm max}} \sum_{\nu_\alpha} \int_{E_\nu^{\rm min}} \frac{d\phi_{\nu_e}}{dE_\nu}\, P(\nu_e \to \nu_\alpha)\, \frac{d\sigma_{\nu_\alpha T}}{dE_R}\, dE_\nu dE_R$$

Neutrino-Electron scattering (ER)

$$\frac{d\sigma_{\nu e}}{dE_R} = \frac{G_F^2 m_e}{2\pi}\left[(g_v + g_a)^2 + \quad (g_v - g_a)^2\left(1 - \frac{E_R}{E_\nu}\right)^2 + (g_a^2 - g_v^2)\frac{m_e E_R}{E_\nu^2}\right]$$

Coherent Neutrino-Nucleus scattering (NR)

$$\frac{d\sigma_{\nu N}}{dE_R} = \frac{G_F^2}{4\pi} Q_v^2 m_N \left(1 - \frac{m_N E_R}{2E_\nu^2}\right) F^2(E_R)$$

The form factor is the same as in WIMP-nucleus scattering.

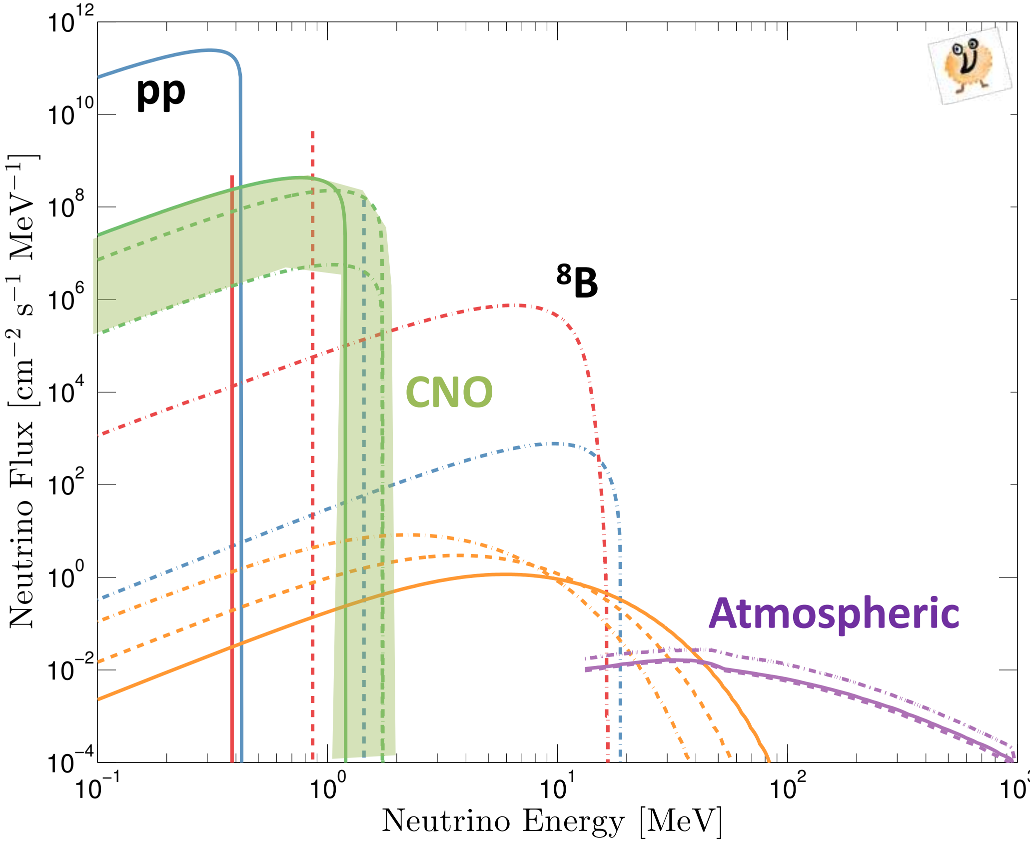
$$Q_v = N - (1 - 4\sin^2\theta_W)Z$$

Neutrino fluxes

- **Solar neutrinos**
  dominate at low energy – the leading contribution is the pp chain below 1 MeV

- **Diffuse Supernovae Background**
  relevant around ~20-50 MeV

- **Atmospheric neutrinos**
  contribute at higher energies but at a much smaller rate



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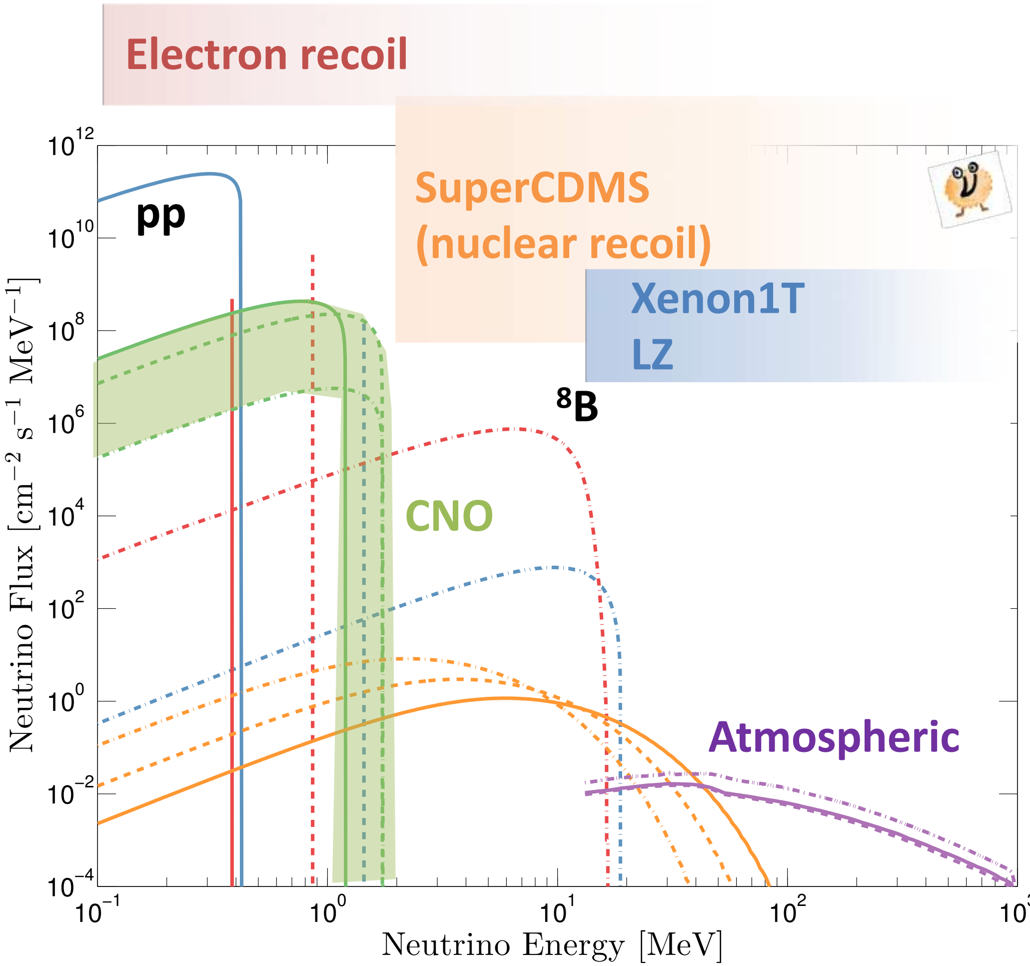


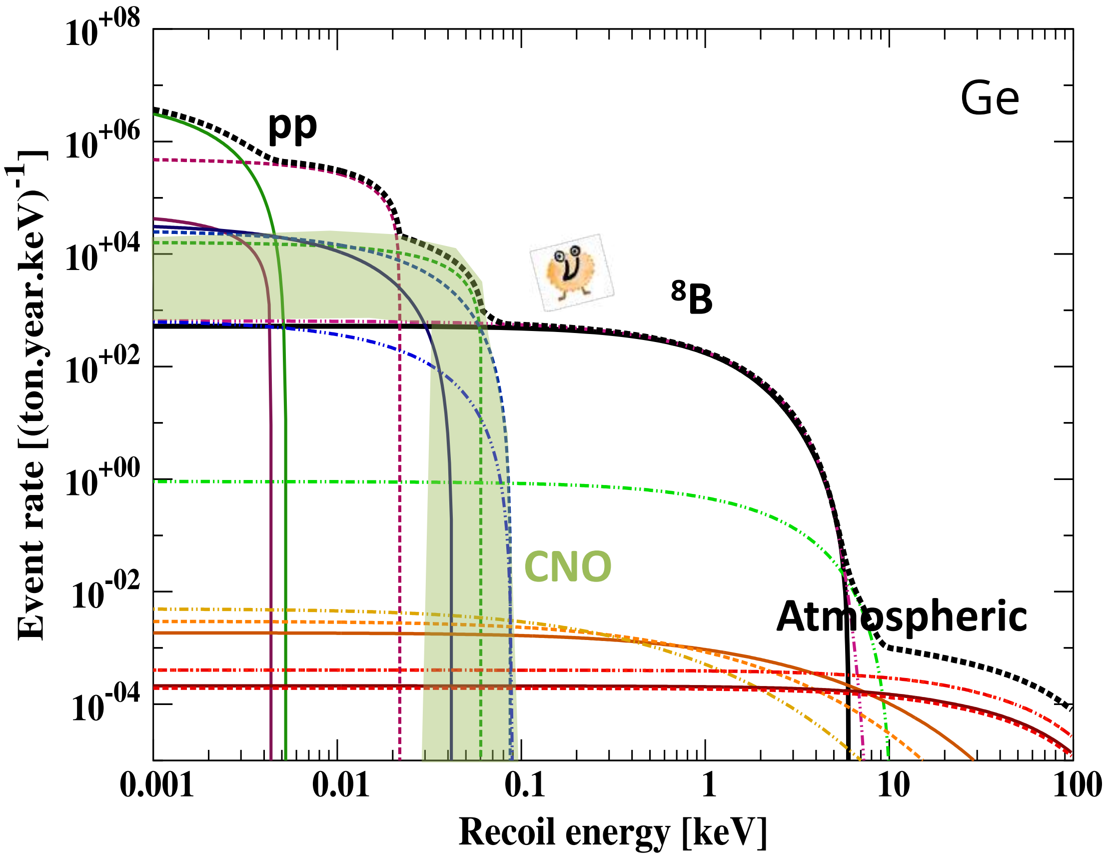
Experimental response to CNNS

Neutrinos would leave a characteristic energy spectrum in the detector.

This is a Standard Model prediction, so we know the rate.

Notice that to see **CNO** neutrinos, the experimental threshold must be really small!

Ruppin, Billard, Figueroa-Feliciano, Strigari 2014



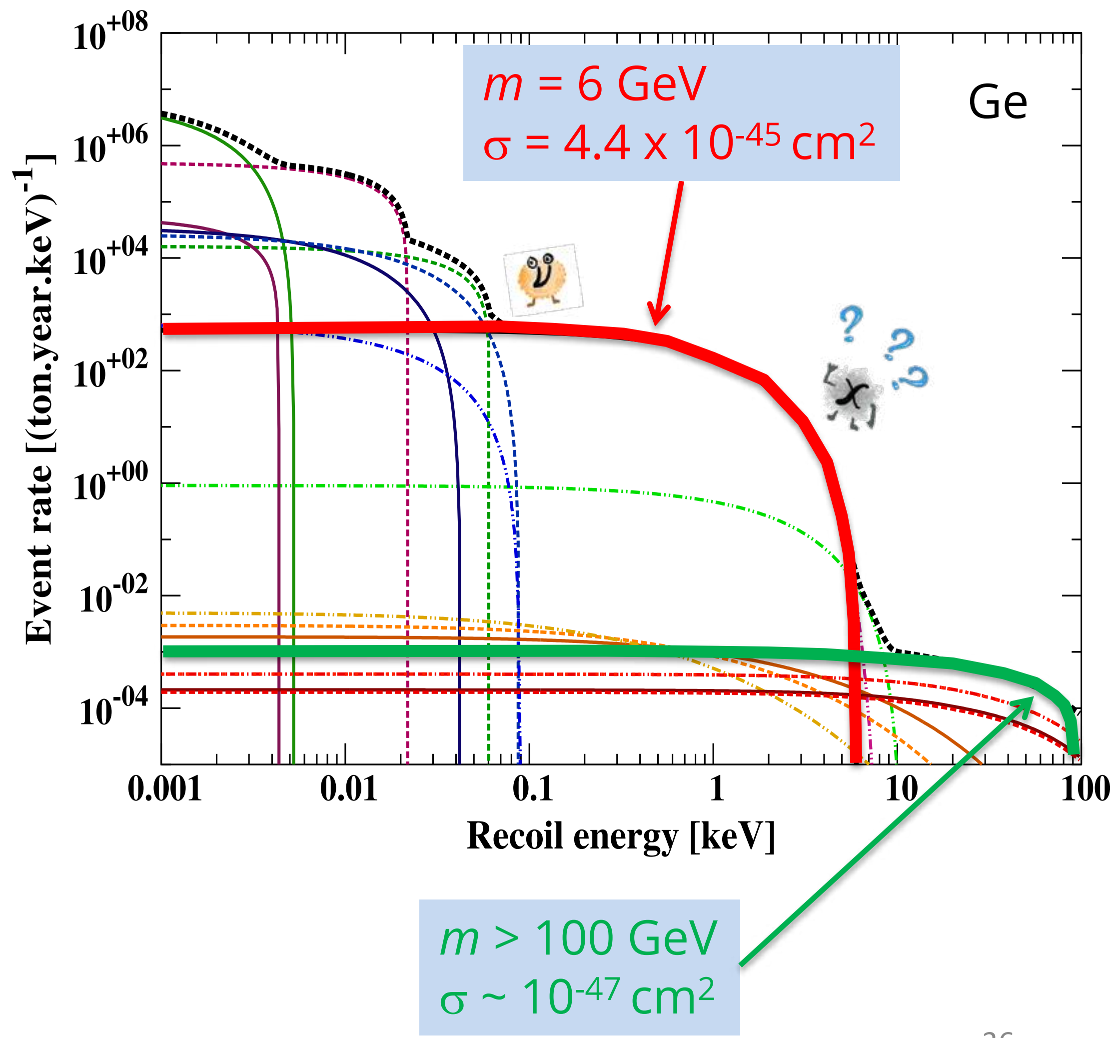
Experimental response to CNNS

Dark Matter particles would leave a very similar spectrum!!

(identical for some masses)

This poses a big problem if we want to detect DM!!

Ruppin, Billard, Figueroa-Feliciano, Strigari 2014

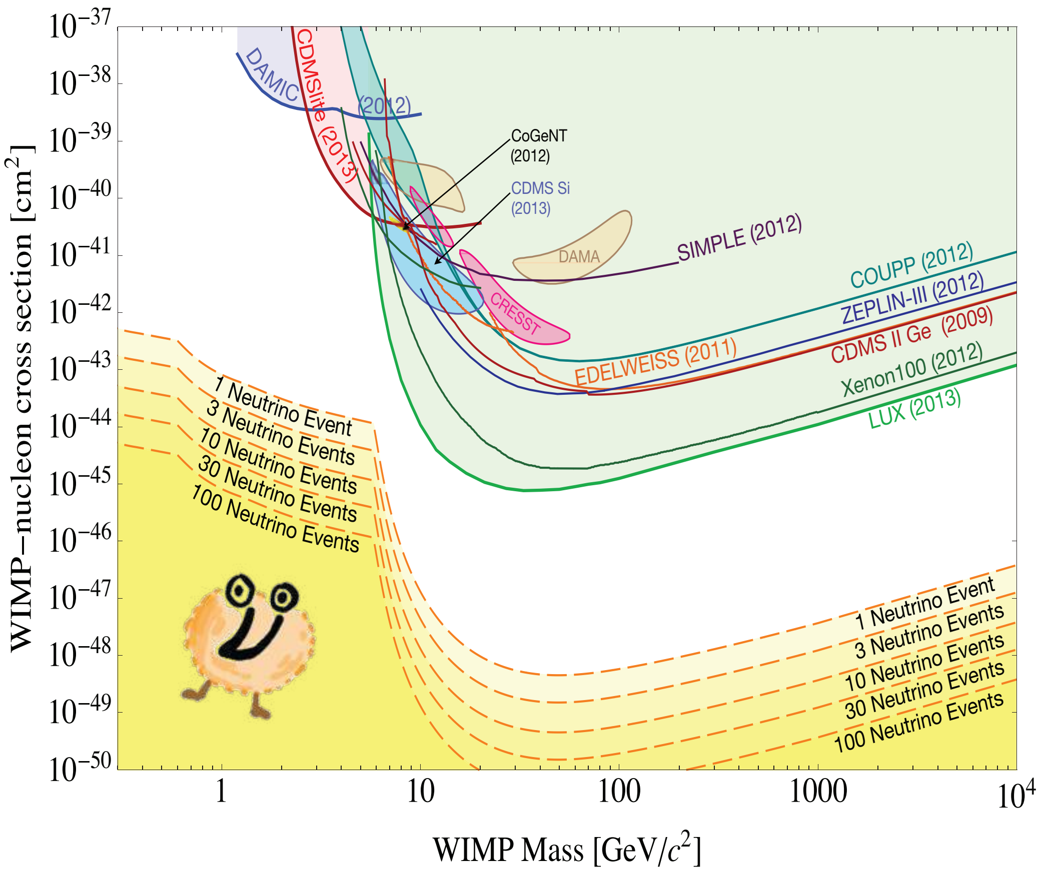


Neutrinos or Dark Matter??

Future dark matter experiments will be sensitive to this SM process, limiting the reach for DM searches (**Neutrino Floor**)

Going beyond the neutrino floor:

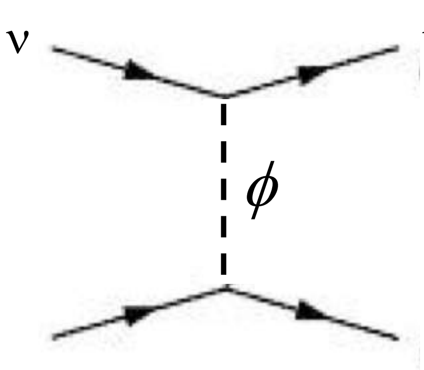
- Spectral analysis
- Annual modulation
  Billard et al. 1307.5458
  Davis 1412.1475
- Combination of complementary targets
  Ruppin et al. 1408.3581
- Directional detection
  Grothaus et al. 1406.5047
  O'Hare et al. 1505.08061



New physics in the neutrino sector can raise the neutrino floor

New neutrino physics can also alter the neutrino floor

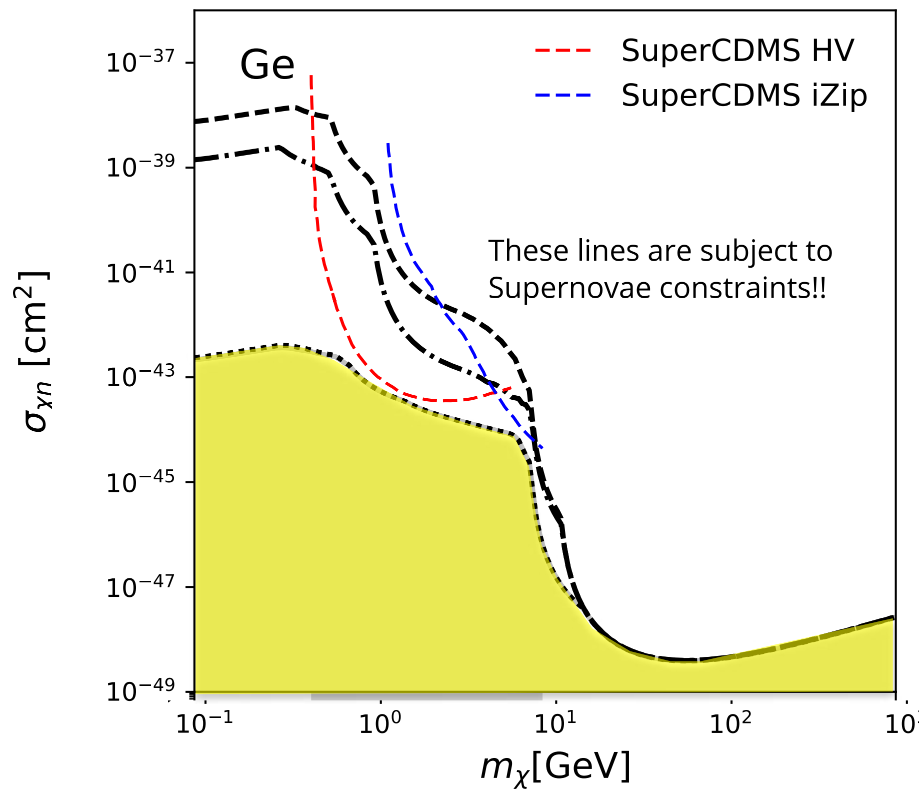
$$\mathcal{L} = -y_\nu \bar{\nu}_L^c \phi \nu_L - \sum_{f \neq \nu} y_f \bar{f} \phi f - \sum_{f \neq \nu} y_f^5 \bar{f} \phi i \gamma_5 f + \text{h.c.}\ ,$$



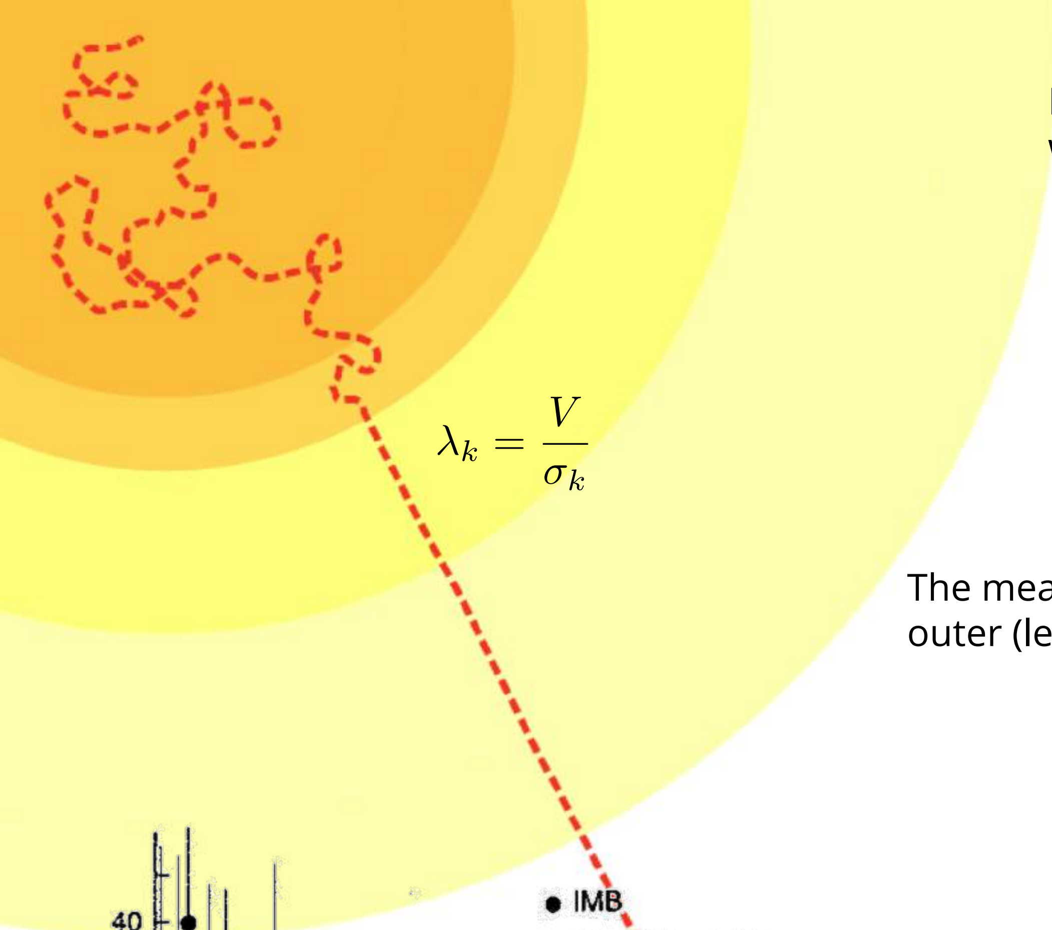
New light mediator, with mass m_ϕ

and couplings C_N

Boehm, DGC, Machado, Olivares, Reid 2018

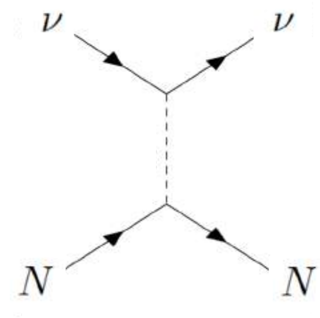


The neutrino floor can be **orders of magnitude** higher than in the SM



$$\lambda_k = \frac{V}{\sigma_k}$$

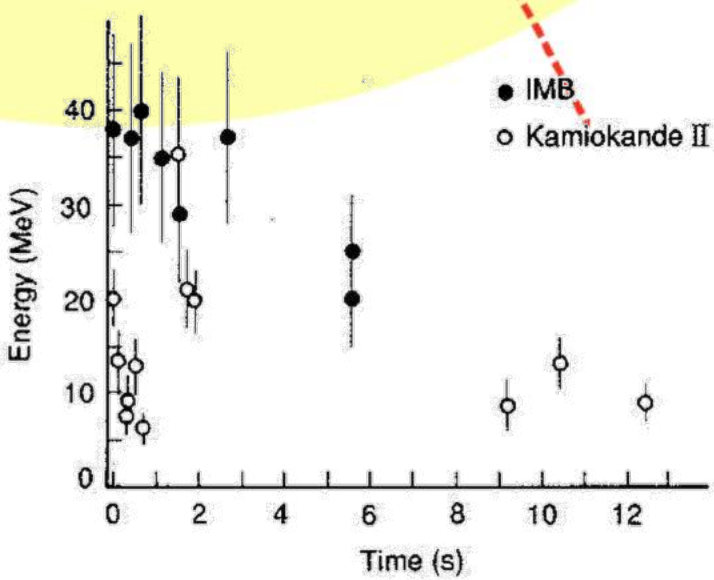
Neutrinos scatter off nucleons (n, p) on their way out of the proto Neutron Star



The mean free-path increases as we move towards outer (less dense – colder) layers

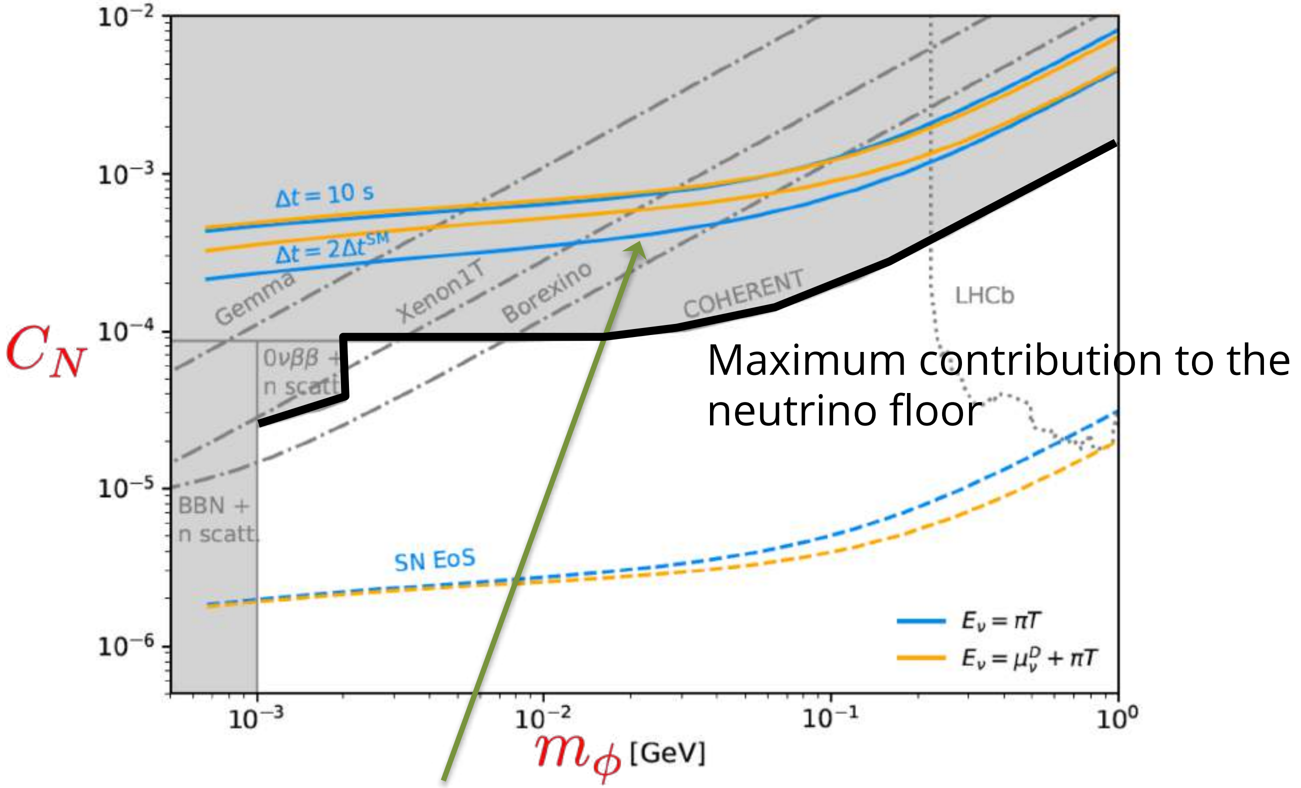
Neutrino diffusion time:

$$c\Delta t^{\nu(\bar{\nu})} = \sum_{k=1}^{n} \frac{R_k^2 - R_{k-1}^2}{\lambda_k^{\nu(\bar{\nu})}}$$



Observation of SN1987A suggests that these neutrinos are observed for $\Delta t \sim 10\ \mathrm{s}$

$$\mathcal{L} = -y_\nu \bar{\nu}_L^c \phi \nu_L - \sum_{f\neq\nu} y_f \bar{f}\phi f - \sum_{f\neq\nu} y_f^5 \bar{f}\phi i\gamma_5 f + \text{h.c.} \ ,$$



Neutrinos above this line take more than 10s to diffuse out of the SN.

DGC, Cermeño, Pérez-García, Reid (2021)

We included medium effects and the inner structure of the proto-NS

Direct detection can test models with new physics in the neutrino sector!

Muon anomalous magnetic moment

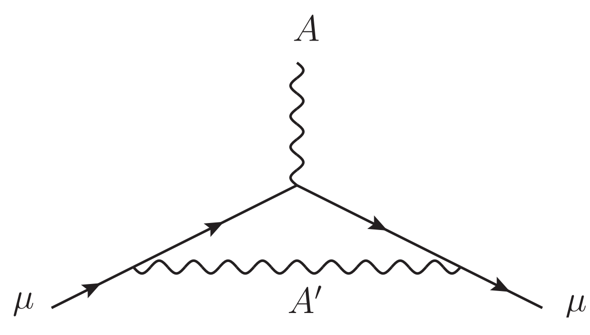
Different particle physics realisations have been proposed to account for the anomaly in $(g-2)_\mu$

He, Joshi, Lew, Volkas (1991)
Ma, Roy, Roy (2001)

$$a_\mu^{\mathrm{FNAL}} = 116\ 592\ 040(54) \times 10^{-11}$$

$$a_\mu^{\mathrm{SM}} = 116\ 591\ 810(43) \times 10^{-11}$$

A gauged $U(1)_{L_\mu - L_\tau}$ is an elegant solution: simple and anomaly free.



However, $(g-2)_\mu$ only probes the mediator coupling to muons – is there anyway that we can verify this solution?

Light vector mediator as a solution to $(g-2)_\mu$

The observed discrepancy in the muon anomalous magnetic moment can be explained by a gauged $U(1)_{L_\mu - L_\tau}$ model.

He, Joshi, Lew, Volkas (1991)
Ma, Roy, Roy (2001)

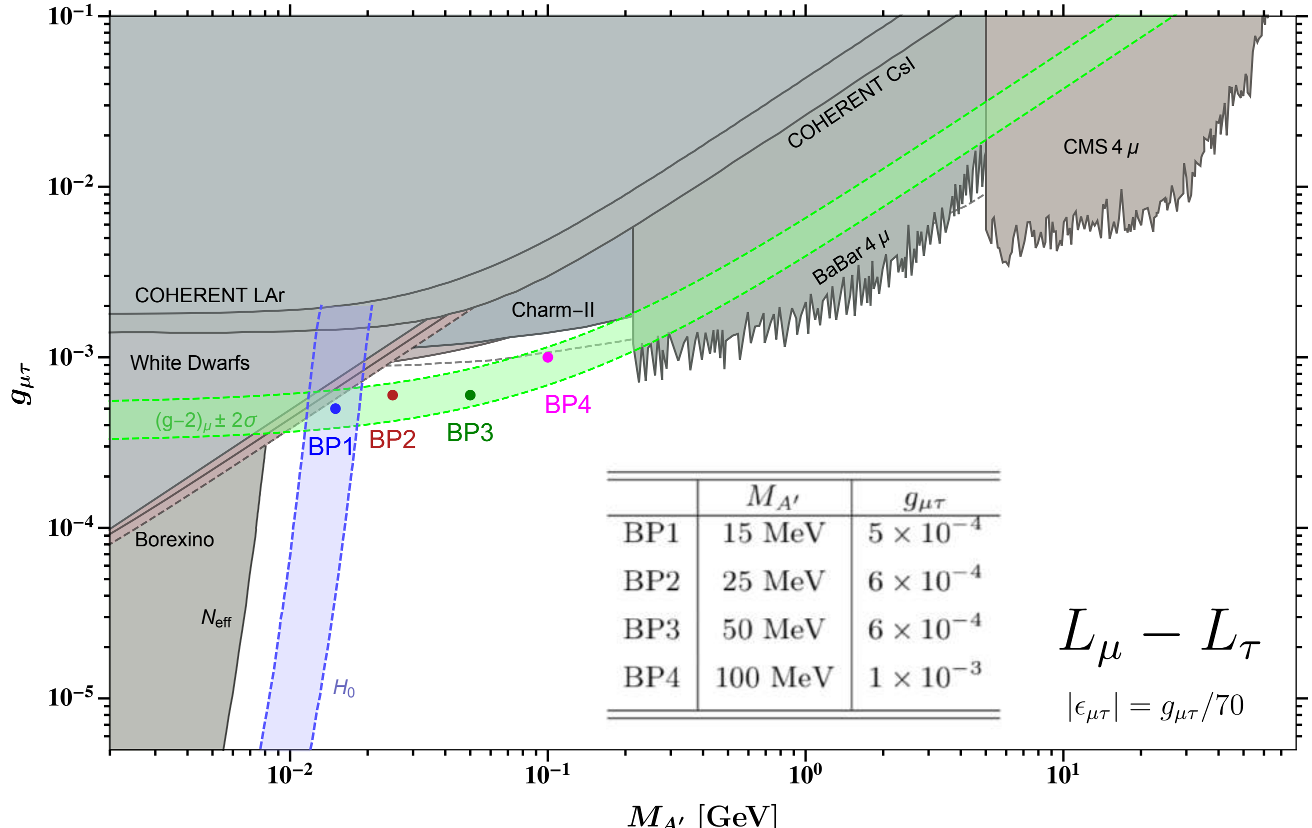
Could also account for an observed tension in the Hubble parameter

($\Delta N_{eff} = 0.4$)

Escudero et al. (2019)

Araki et al. (2013)

Amaral, DGC, Cheek, Foldenauer 2104.03297



	$M_{A'}$	$g_{\mu\tau}$
BP1	15 MeV	5×10^{-4}
BP2	25 MeV	6×10^{-4}
BP3	50 MeV	6×10^{-4}
BP4	100 MeV	1×10^{-3}

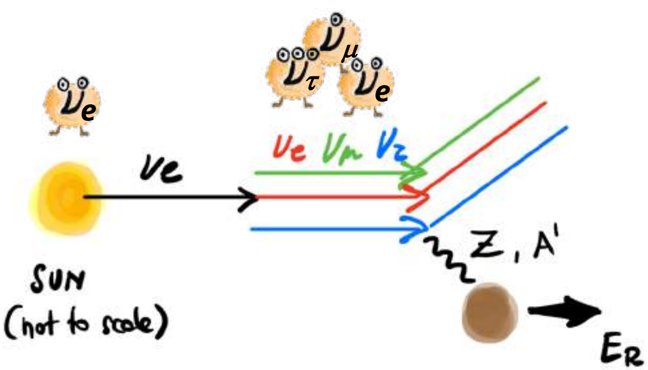
There is a set of **complementary** experiments suited for an independent test of the $(g-2)_\mu$ solution within muon-philic vector mediators **using neutrinos**.

- Fixed target experiments (NA64μ) **can measure the vector coupling to muons** (and the mediator mass)
- Coherent neutrino scattering at spallation sources **can help determining the kinetic mixing parameter** (and improve measurement of the mediator mass)
- Direct detection experiments **can measure the mediator coupling to taus**, effectively separating $U(1)_{L_\mu - L_\tau}$ from $U(1)_{L_\mu}$ at low mediator mass.

Neutrinos in direct detection experiments

$$N = \varepsilon\, n_T \int_{E_{\rm th}}^{E_{\rm max}} \sum_{\nu_\alpha} \int_{E_\nu^{\rm min}} \frac{d\phi_{\nu_e}}{dE_\nu}\, P(\nu_e \to \nu_\alpha)\, \frac{d\sigma_{\nu_\alpha T}}{dE_R}\, dE_\nu dE_R$$

$$\frac{\mathrm{d}\sigma_{\nu_\alpha N}}{\mathrm{d}E_R} = \frac{G_F^2\, M_N}{\pi}\left(1 - \frac{M_N\, E_R}{2E_\nu^2}\right) \times \left\{ \underbrace{\frac{Q_{\nu N}^2}{4}}_{\text{SM}} + \underbrace{\frac{g_x\, \epsilon_x\, e\, Z\, Q_{\nu_\alpha}^x\, Q_{\nu N}}{\sqrt{2}\, G_F\, (2M_N E_R + M_{A'}^2)} + \frac{g_x^2\, \epsilon_x^2\, e^2\, Z^2\, {Q_{\nu_\alpha}^x}^2}{2\, G_F^2\, (2M_N E_R + M_{A'}^2)^2}}_{\text{New physics}} \right\} F^2(E_R)$$



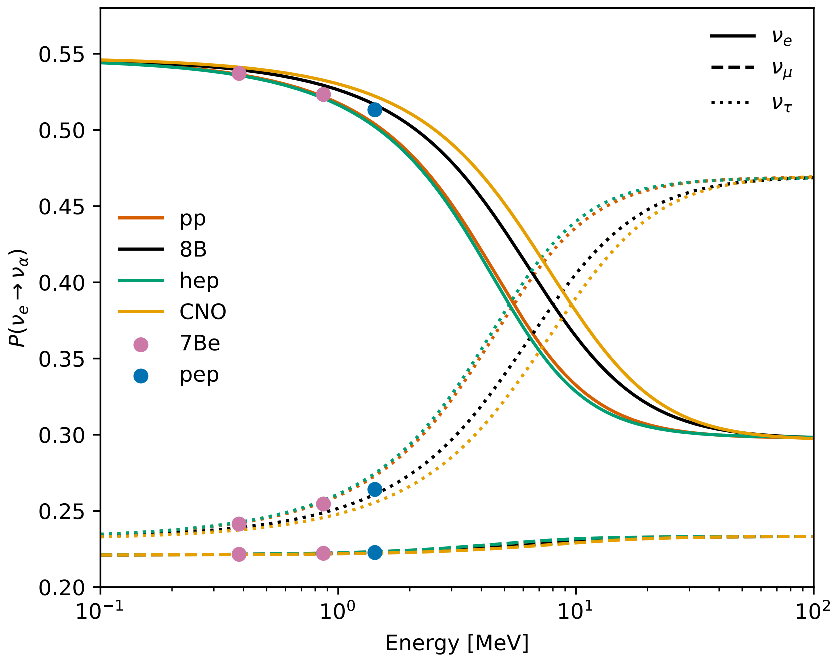
Because of neutrino oscillation, **there is a ν_τ flux**

The ν_τ and ν_μ contributions have **opposite signs**!

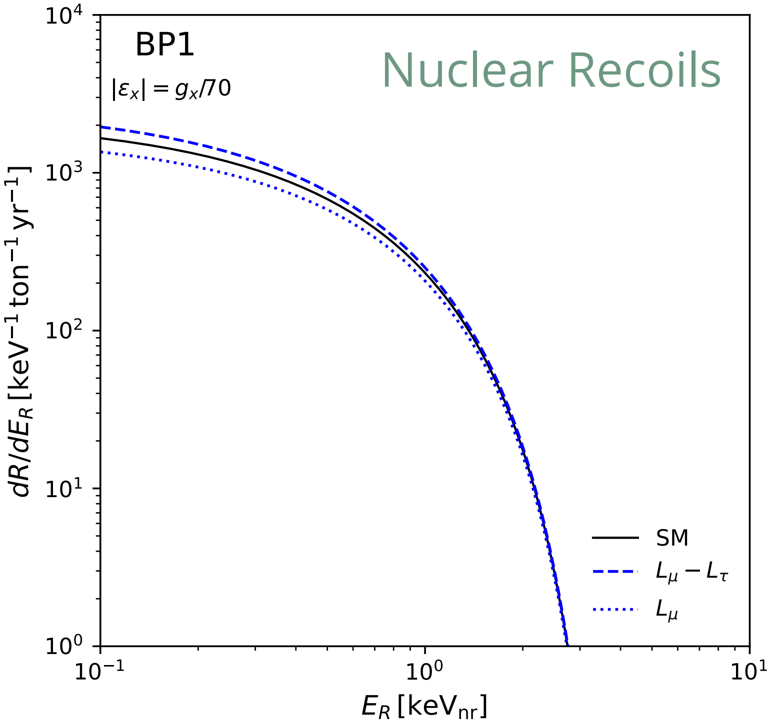
This does not happen for electron recoils

This results in a **positive** new physics contribution for $U(1)_{L_\mu - L_\tau}$

... and a **negative** contribution for a pure muon-philic model

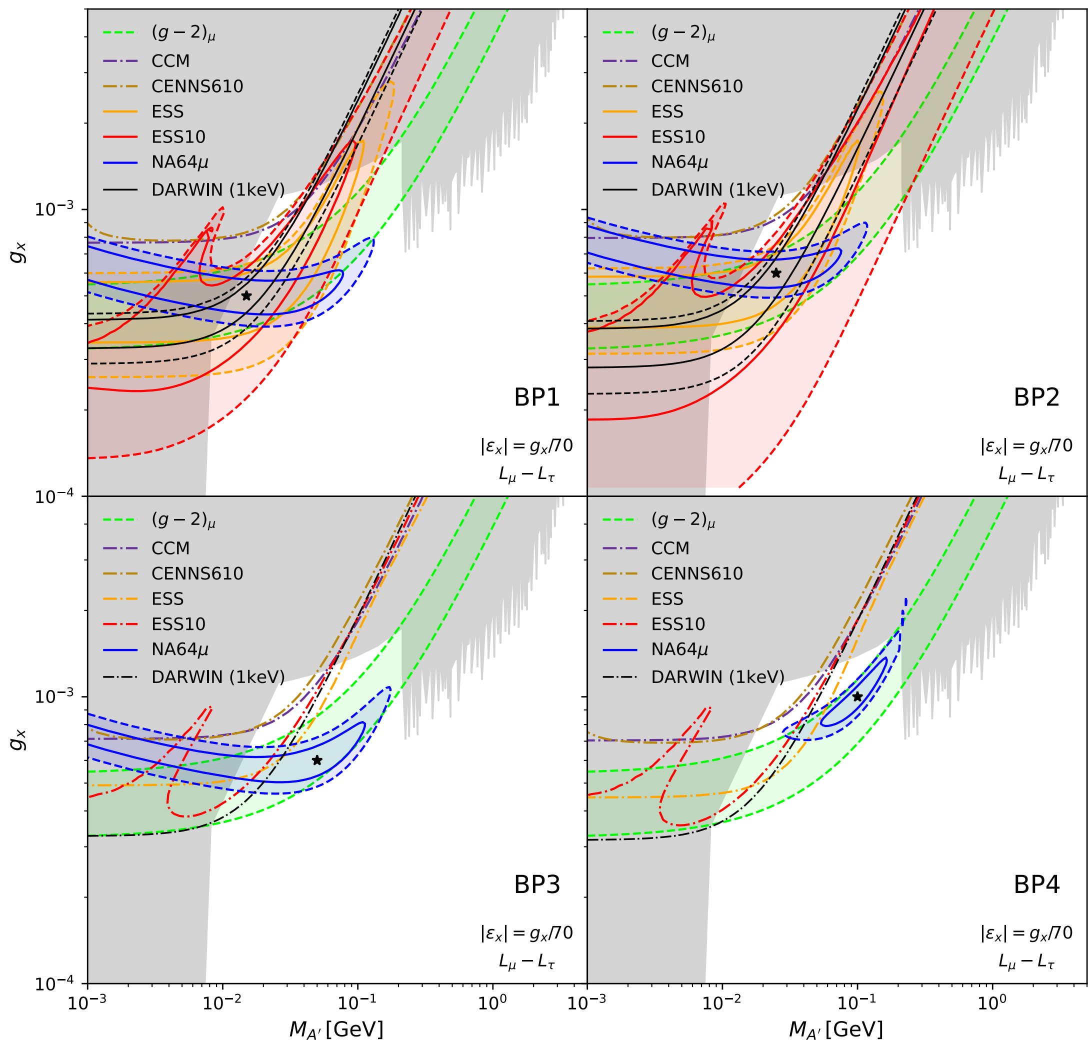


Amaral, DGC, Foldenauer, Reid JHEP 12 (2020) 155



(for electron recoils both contributions are positive)

Combining the information from direct detection, assuming the correct model, direct detection leads to a better reconstruction.



The whole area is inconsistent if the wrong model is assumed.

In conclusion…

Neutrinos are a challenge for direct dark matter detection:

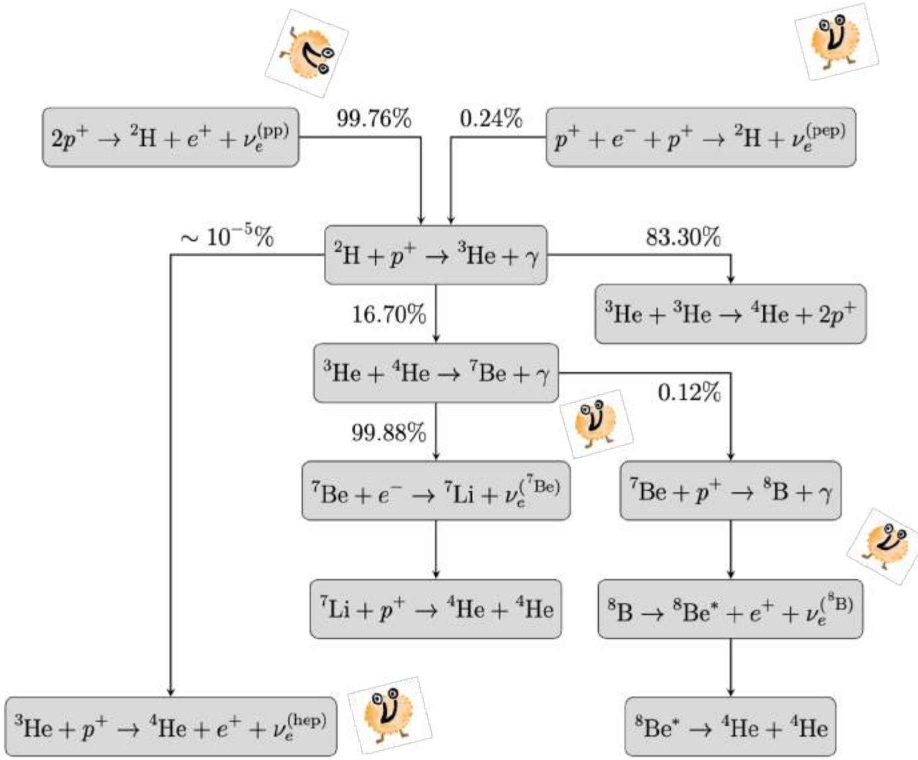
- They pose as dark matter and limit the experimental sensitivity (neutrino floor)
- New physics (light mediators) makes it worse!

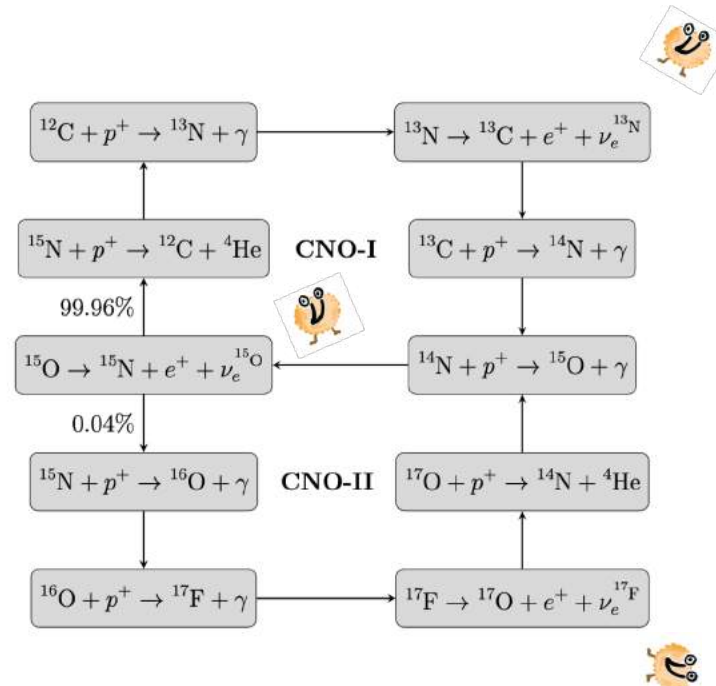
Dark matter detectors can study new physics in neutrinos!

- Searches for low-mass mediators complementary to other experiments
- Can probe the muon anomalous magnetic moment!

Neutrinos from the sun

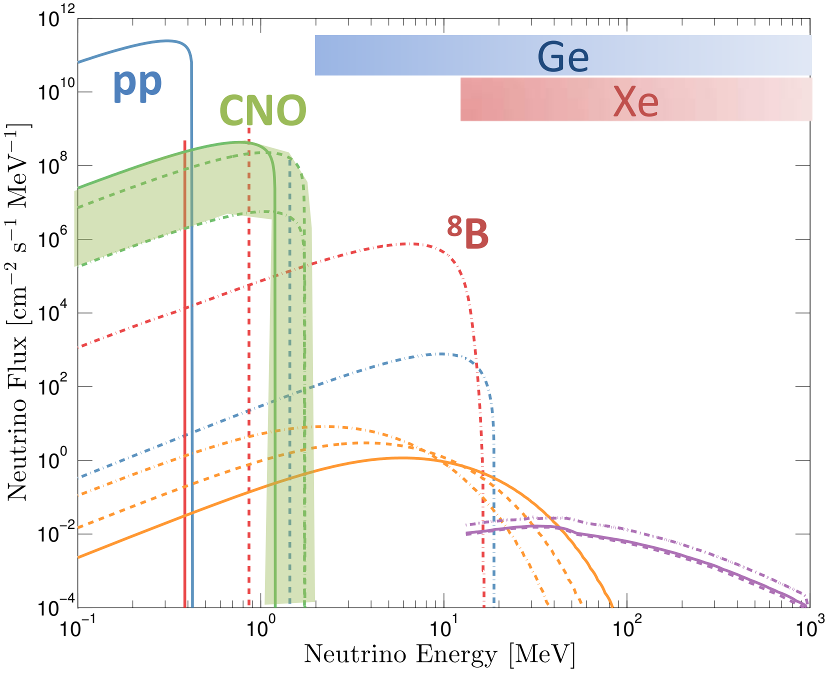
Solar neutrinos are produced in two main “chains”: pp and CNO (more sensitive to the metallicity of the Sun)



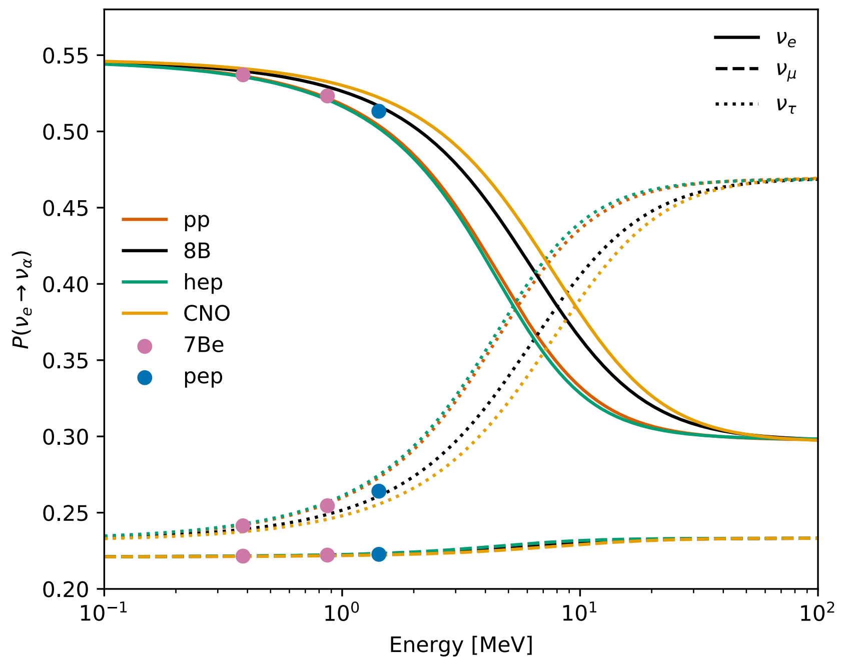


Solar neutrinos oscillate on their way to the Earth. The flux we see is composed of the three flavours.

$$\frac{\mathrm{d}\phi_{\nu_e}}{\mathrm{d}E_\nu}$$



$$P(\nu_e \to \nu_\alpha)$$



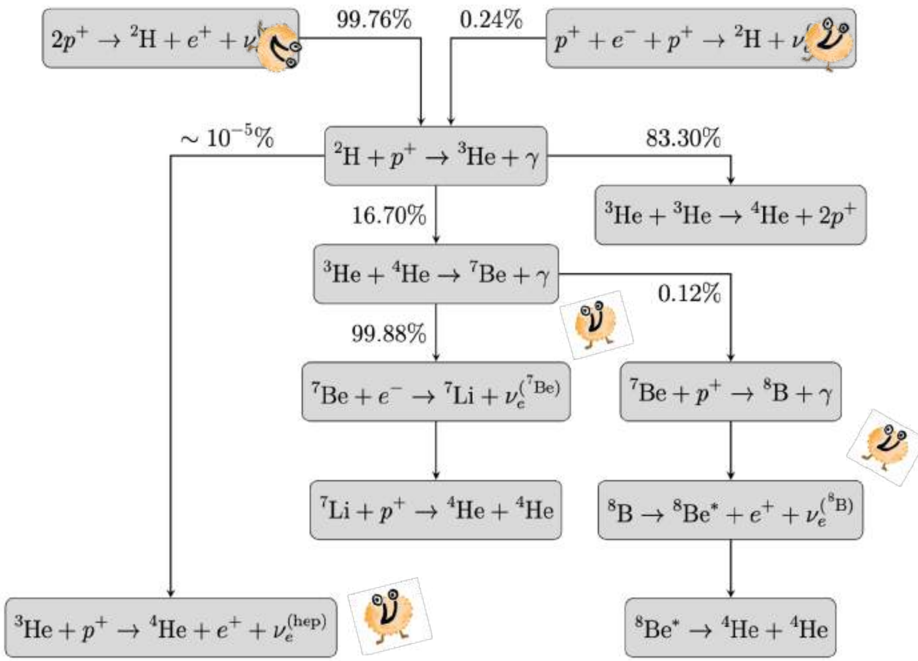
Amaral, DGC, Foldenauer, Reid 2006.11225

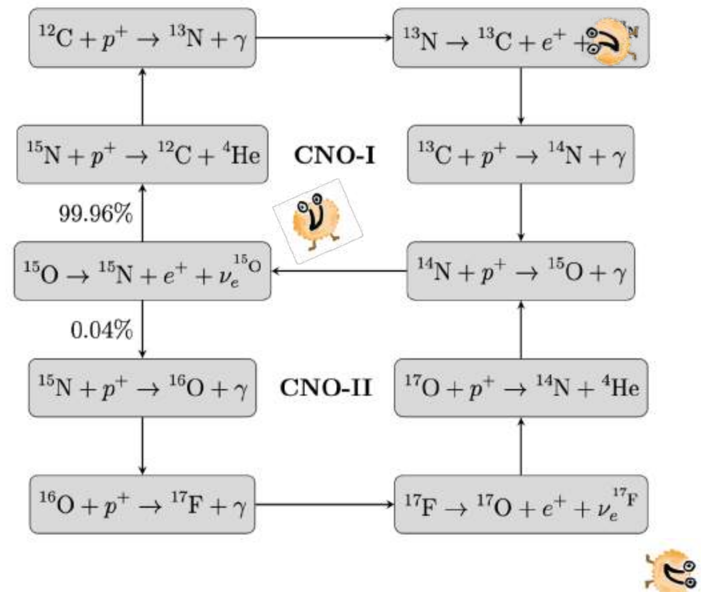
However, being more positive, this means that neutrinos can be studied in direct detection experiments!

- Complementary to dedicated neutrino experiments
- Implications for astrophysics and particle physics
- “For free” as a by-product of upcoming DM detectors

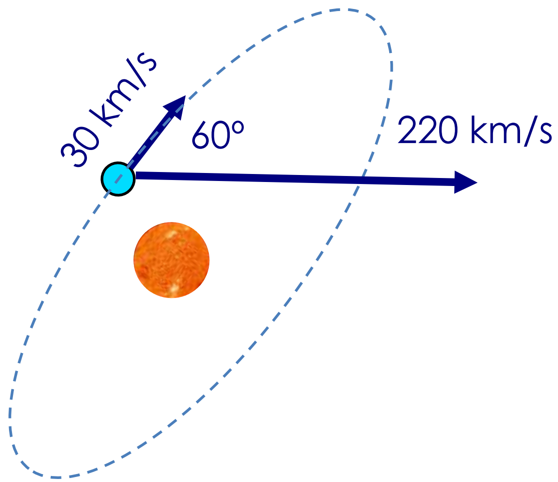
Measurement of CNO neutrinos

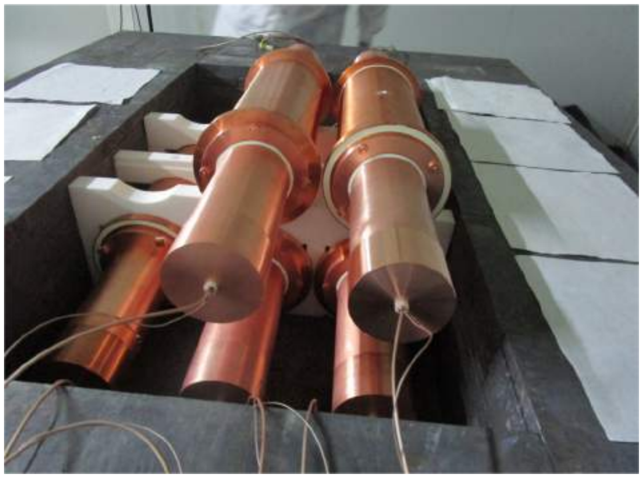
On Solar neutrinos

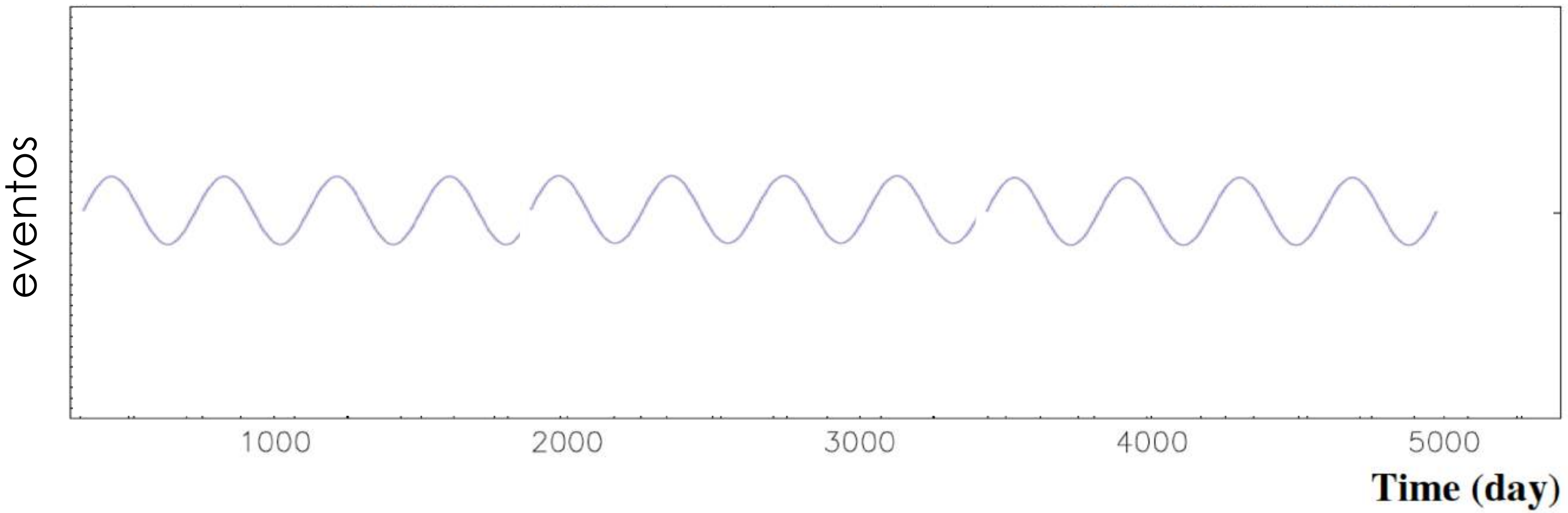




El experimento ANAIS ha buscado la modulación anual en la señal de materia oscura







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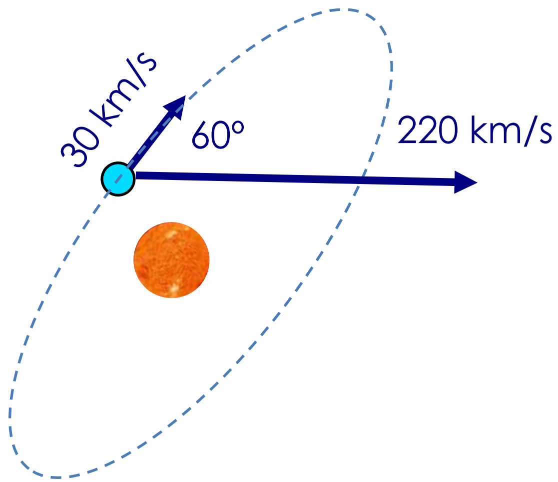
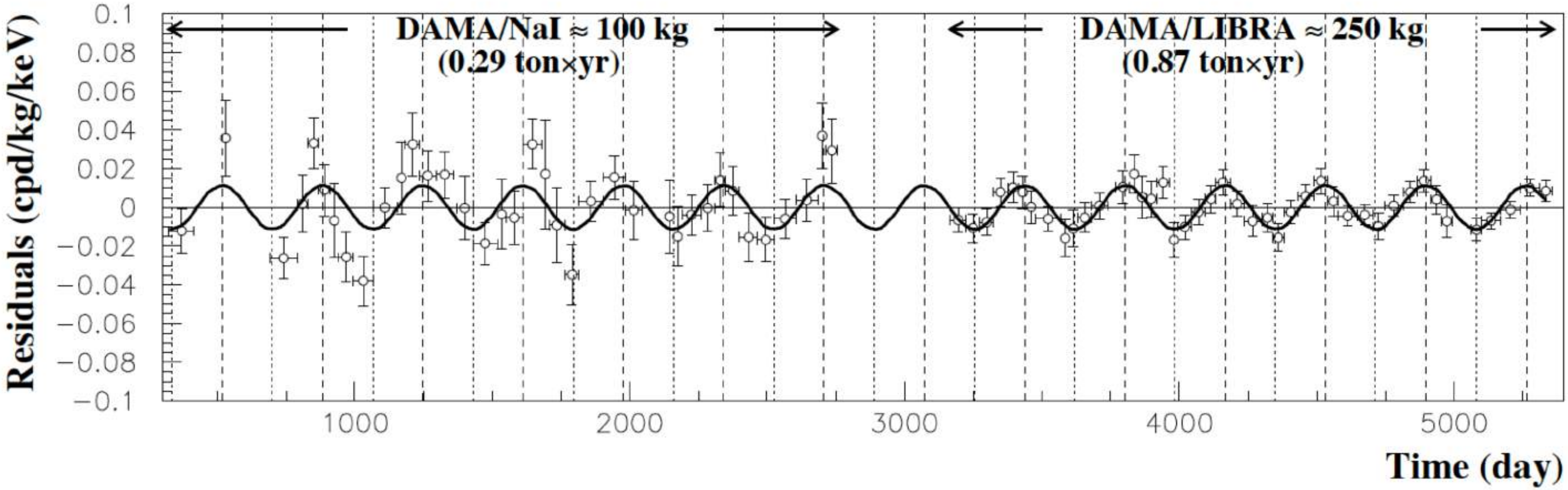


Desde el año 2000 había una possible observación del detector DAMA/Libra



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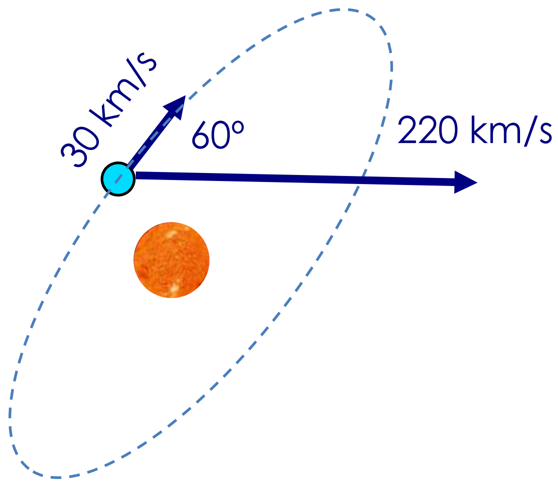

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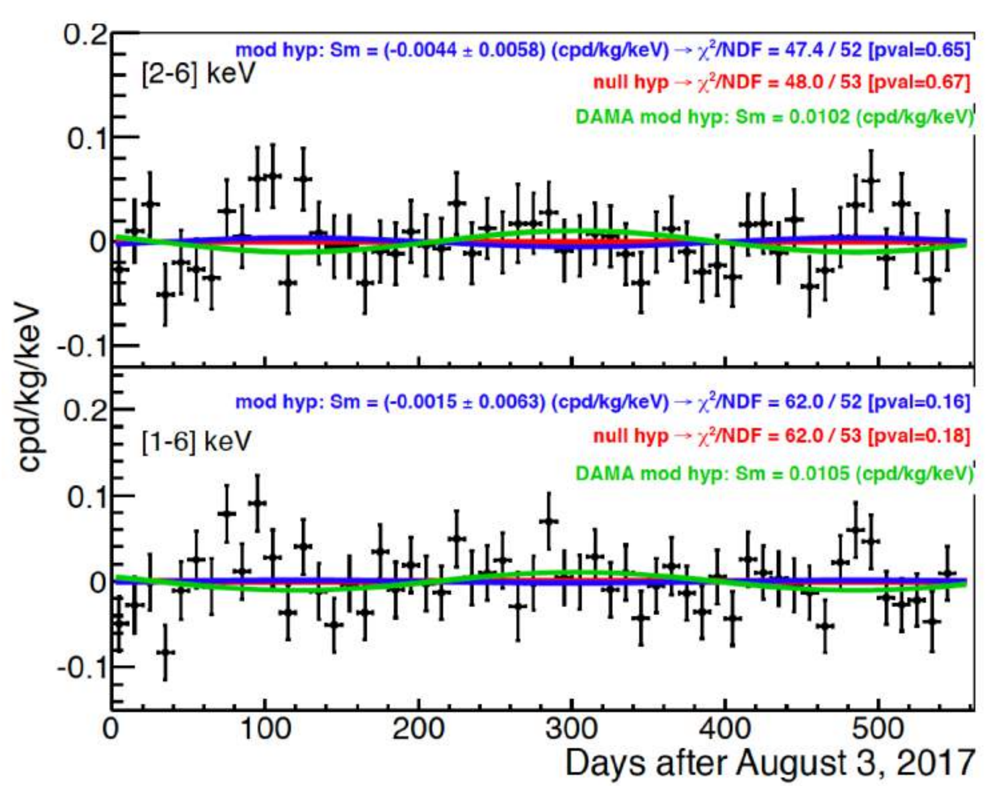
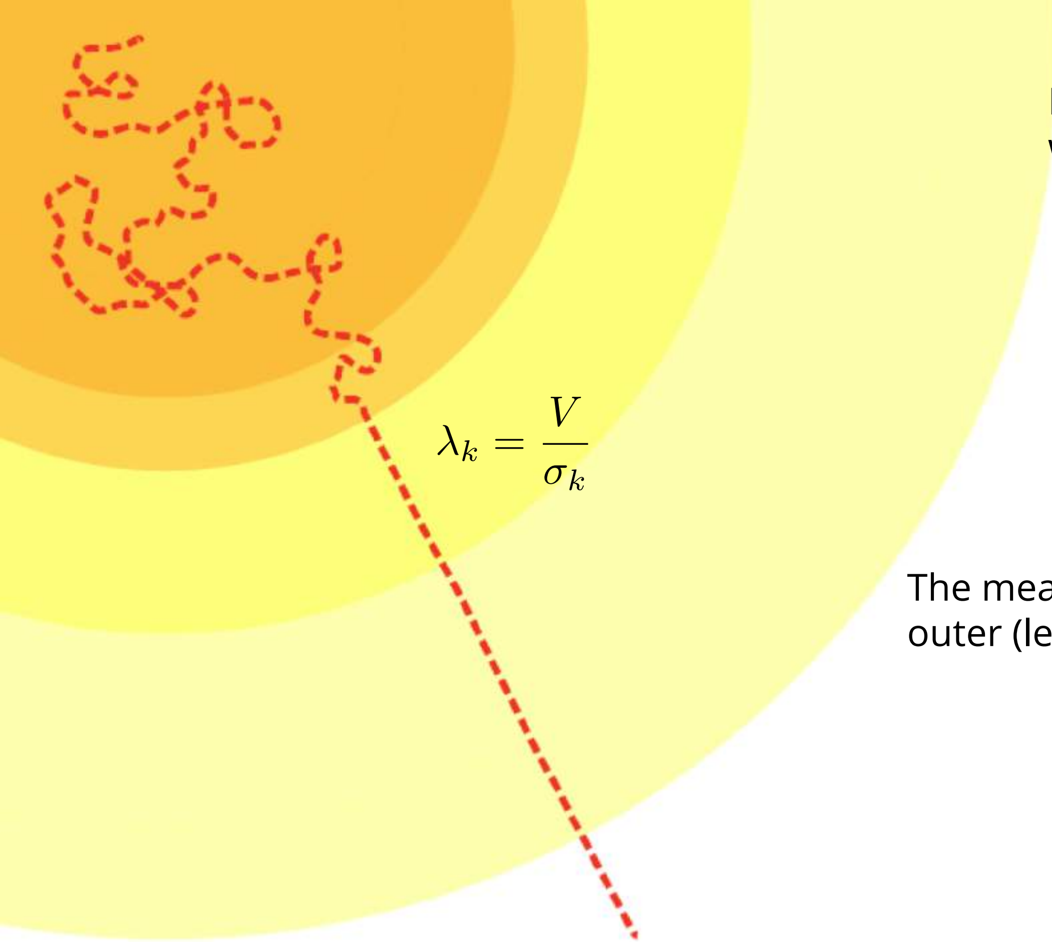


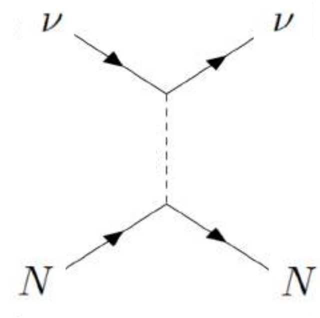
ANAIS no observa modulación.

Descarta la posibilidad de que esa señal sea Materia Oscura



$$\lambda_k = \frac{V}{\sigma_k}$$

Neutrinos scatter off nucleons (n, p) on their way out of the proto NS



The mean free-path increases as we move towards outer (less dense – colder) layers

Neutrino diffusion time:

$$c\Delta t^{\nu(\bar{\nu})} = \sum_{k=1}^{n} \frac{R_k^2 - R_{k-1}^2}{\lambda_k^{\nu(\bar{\nu})}}$$

Majorana Neutrinos

$t \sim 5$ s	R (km)	T (MeV)	$n_B(\mathrm{fm}^{-3})$	μ_n^* (MeV)	μ_p^* (MeV)	m_N^* (MeV)	λ^{SM} (m) $(E_\nu = \pi T)$	λ^{SM} (m) $(E_\nu = \mu_\nu^D + \pi T)$
$k=1$	5.0	25	0.5	509.9	381.1	256.2	0.71	0.34
$k=2$	7.5	28	0.4	514.3	395.4	310.8	0.52	0.29
$k=3$	10.0	32	0.3	541.0	435.5	395.4	0.36	0.25
$k=4$	12.5	25	0.15	665.9	587.1	599.3	0.77	0.58
$k=5$	15.0	10	0.05	831.9	787.0	805.3	4.1	4.1

$$\Delta t^{\mathrm{SM}} = 1.1 \ \mathrm{s}$$

$$\Delta t^{\mathrm{SM}} = 2.7 \ \mathrm{s}$$