# The state-of-the-art in the search for dark matter

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Inaugural Zwicky Symposium
Braunwald, September 4, 2015

# Some (very brief) history

- 1922: J.C. Kapteyn coined the name *'dark matter'*, in studies of the stellar motion in our galaxy (he found that no dark matter is needed in the solar neighbourhood)
- 1932: J. Oort suggested that there would be more dark than visible matter in the vicinity of the Sun (later the result turned out to be wrong)
- **1933: F. Zwicky found *'dunkle Materie'* in the Coma cluster (the redshift of galaxies were much larger than the escape velocity due to luminous matter alone)**
- 1970: V.C. Rubin & W. Ford: flat optical rotation curves of spiral galaxies, 1978: Bosma, radio

from "Fritz Zwicky, Astrophysiker", Verlag NZZ

# Some (very brief) history

**Die Rotverschiebung von extragalaktischen Nebeln**

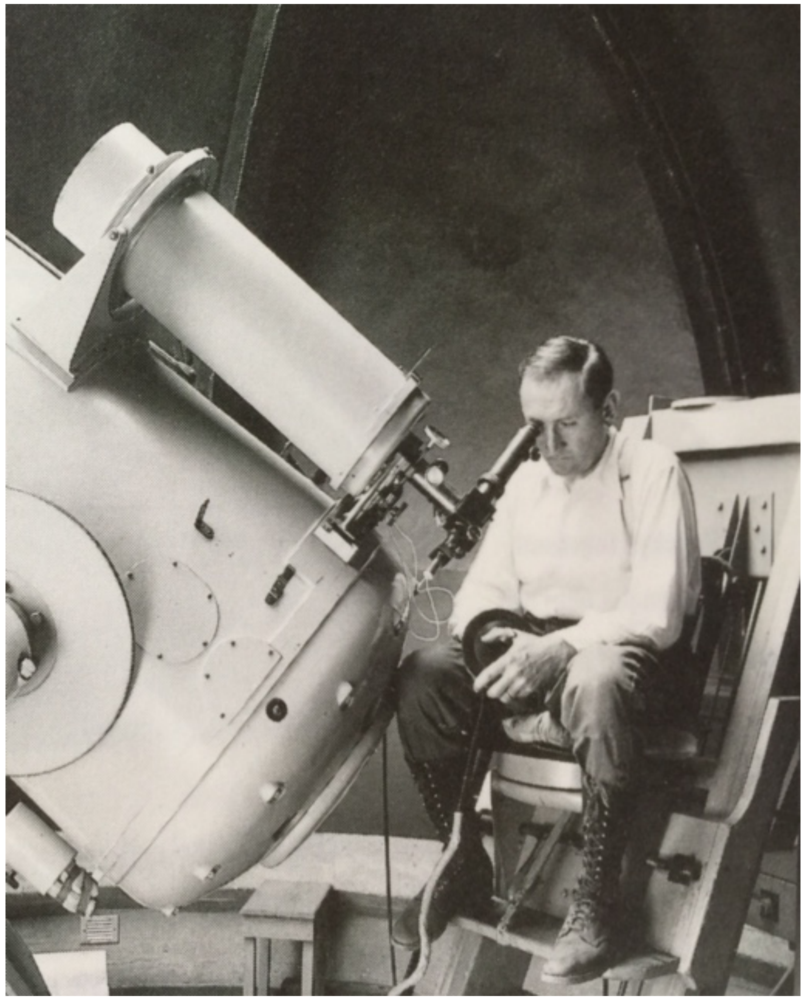
von **F. Zwicky.**

(16. II. 33.)

*Inhaltsangabe.* Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung dieses wichtigen Phänomens aufgestellt worden sind, werden kurz besprochen. Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Studium der durchdringenden Strahlung vøn Wichtigkeit zu werden verspricht.

Rotverschiebung extragalaktischer Nebel. 125

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.



from “Fritz Zwicky, Astrophysiker”, Verlag NZZ

# Some (very brief) history

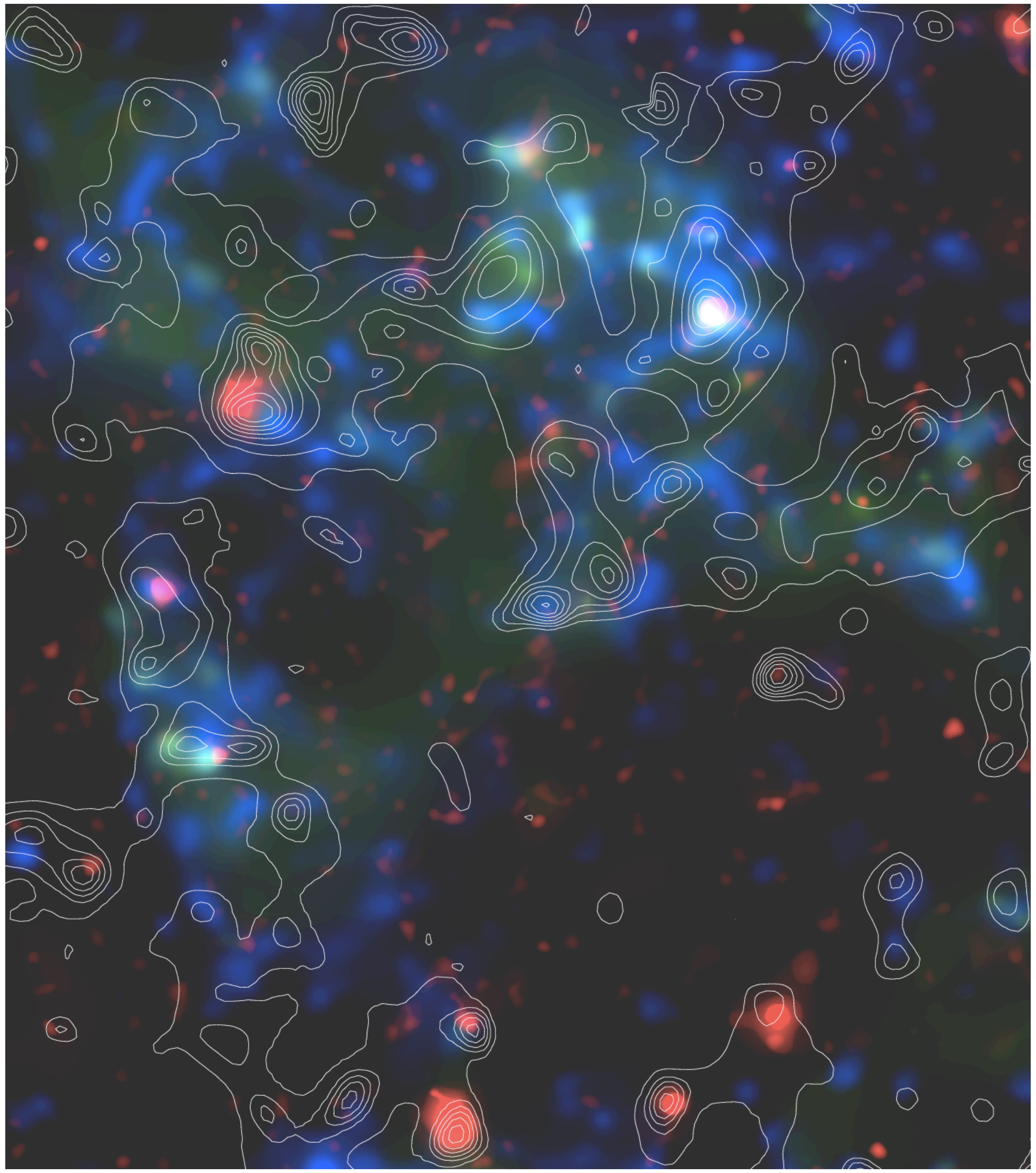
- 1973 - J. Ostriker & P. J. Peebles: numerical studies of the stability of galactic disks - more stable with dark halos
- 1977 - 1980 - S. White & M. Rees; Fall & G. Efstathiou: galaxy formation in massive halos
- 1979 - S.M. Faber & J.S. Gallagher: **"after reviewing all the evidence… the case for invisible mass in the Universe is very strong and getting stronger… we think it likely that the discovery of invisible matter will endure as one of the major conclusions of modern astronomy"**
- 1980s - D. Bond: hot, warm, cold dark matter
- 1981 - R. Sunyaev, Ya. Zeldovic et al: theory of hot dark matter, where light neutrinos make up most of dark matter (as purely baryonic adiabatic fluctuations were ruled out by upper limits on CMB anisotropies)
- 1983 - S. White, C. Frenk & M. Davis: HDM is ruled out based on simulations of nonlinear growth of structures (also, Tremaine-Gunn bound, 1979)
- 1985 first Lambda-CDM simulations…

# Today

The dark matter puzzle remains *fundamental*: dark matter leads to the formation of structure and galaxies in our universe

We have a standard model of CDM, from ‘precision cosmology’ (CMB, LSS): however, *measurement ≠ understanding*

**For ~85% of matter in the universe is of unknown nature**



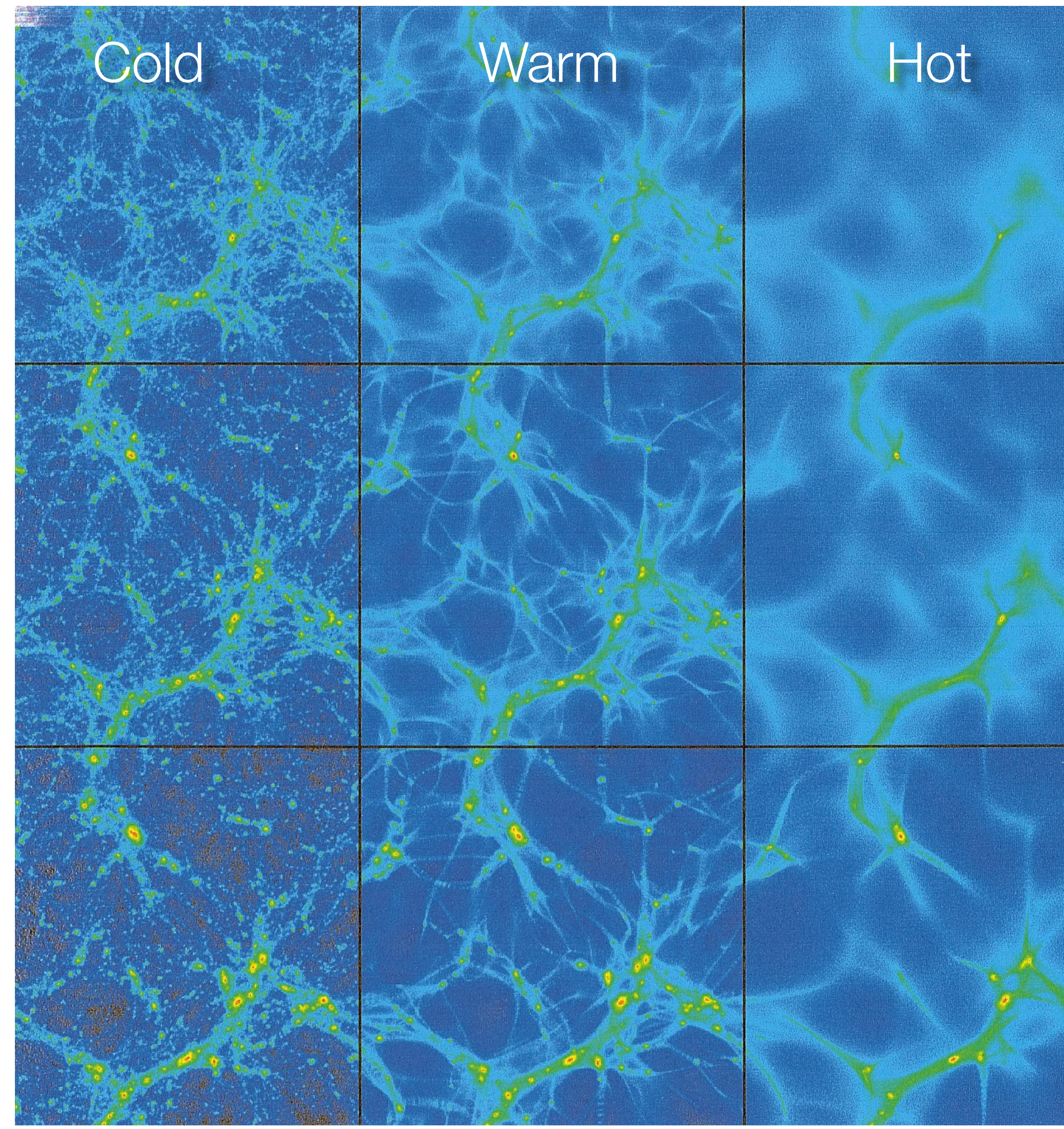
# What do we know about the dark matter?

So far, we mostly have “negative” information

**Constraints from astrophysics and searches for new particles:**

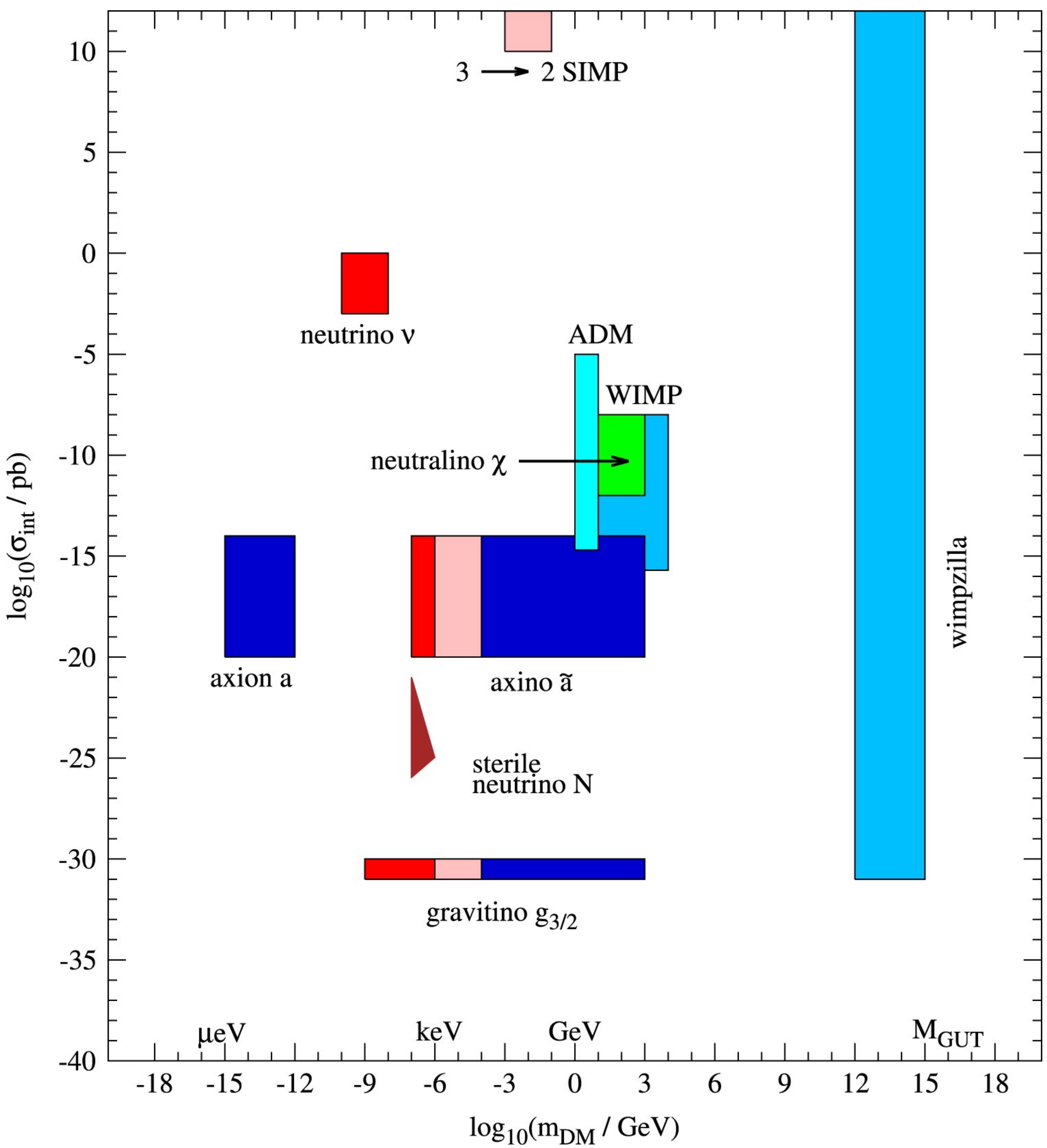
- No colour charge
- No electric charge
- No strong self-interaction

Stable, or very long-lived




**Probing dark matter through gravity**

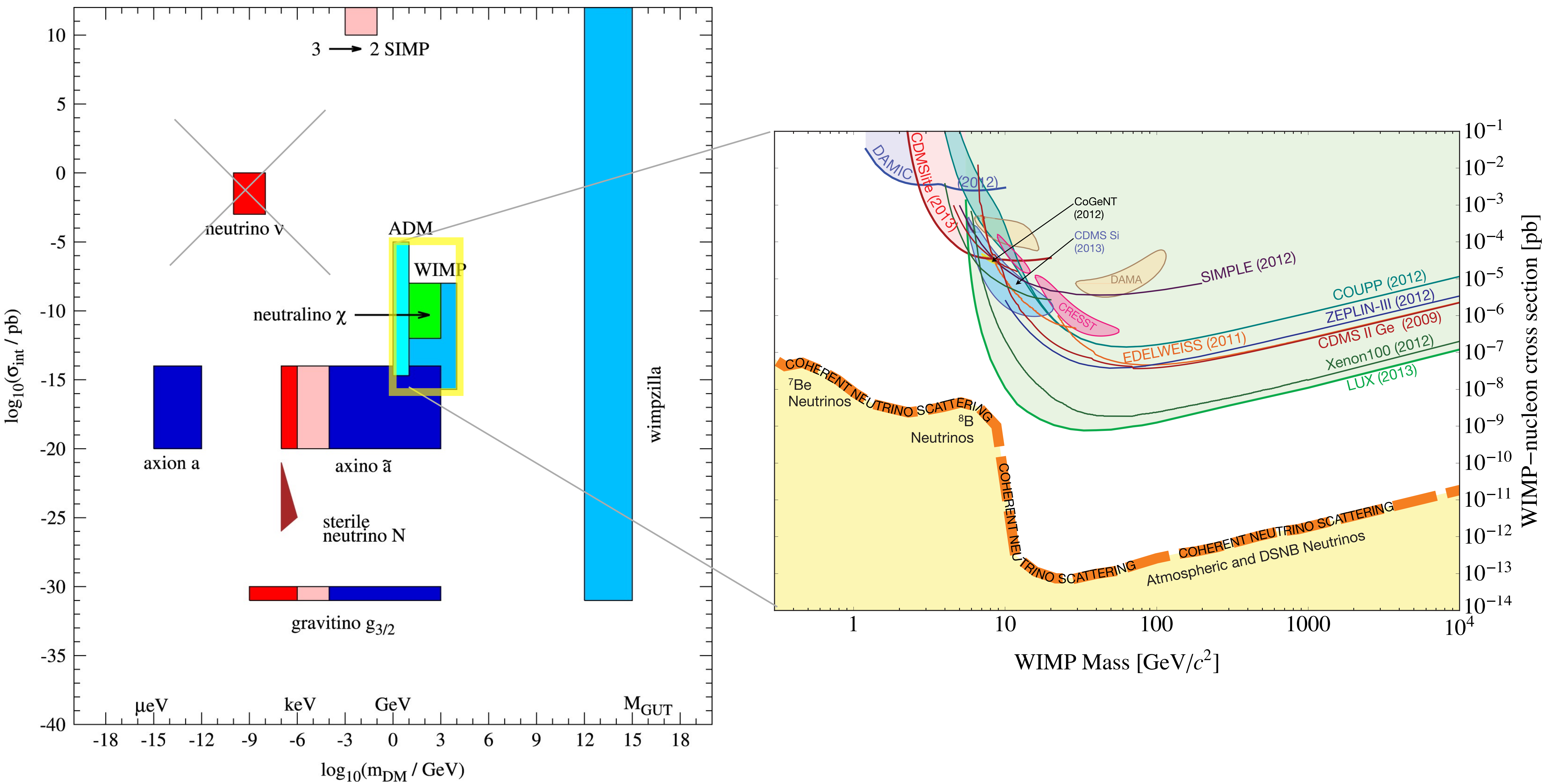
# Parameter space for searches




- **Masses & interaction cross sections span an enormous range**
- Most dark matter experiments optimised for WIMPs
- However also searches for axions, ALPs, SuperWIMPs, etc

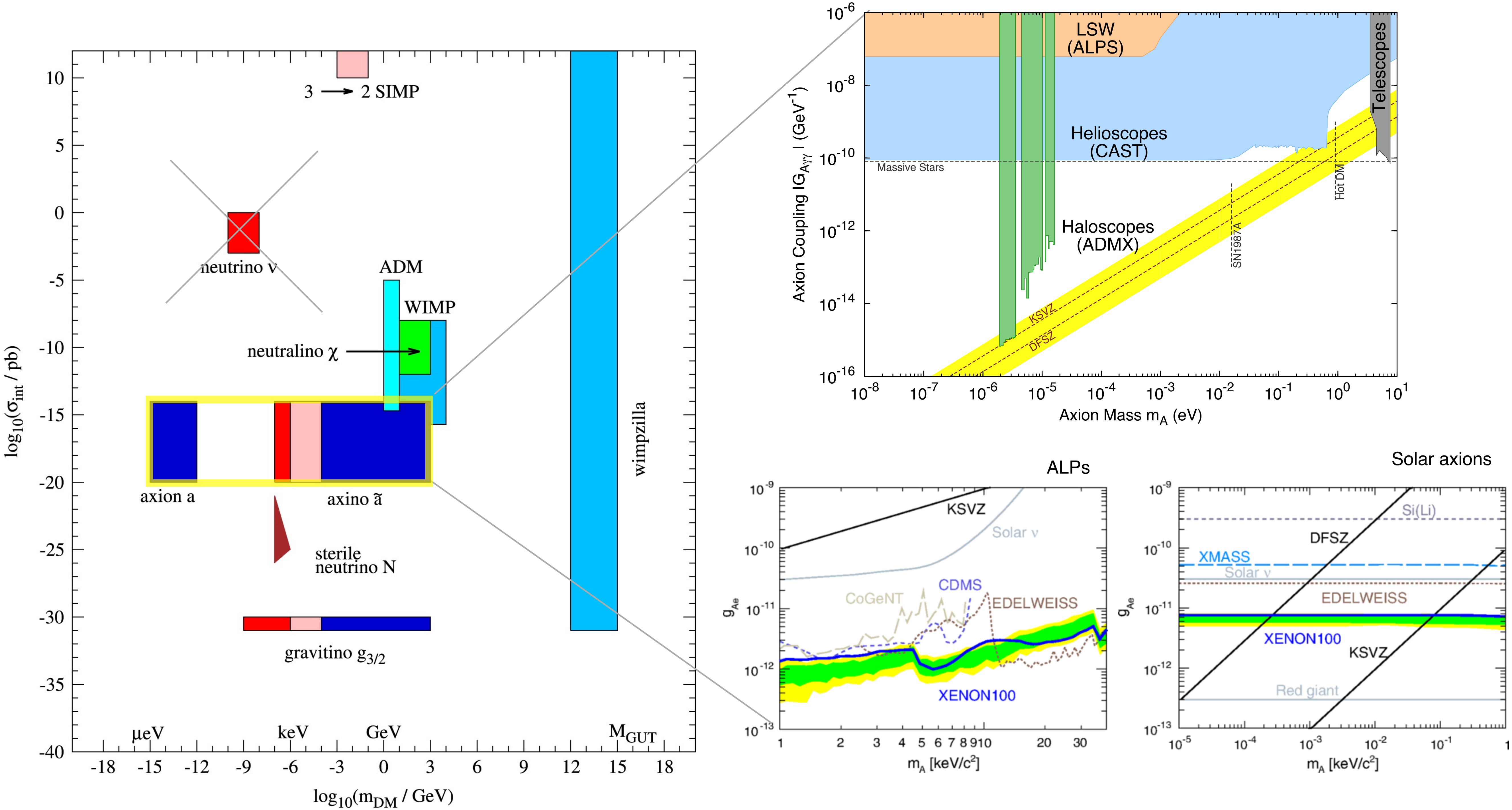
H. Baer et al., Phys. Rept. 555, 2014

# Parameter space for searches




H. Baer et al., Phys. Rept. 555, 2014

# Parameter space for searches




H. Baer et al., Phys. Rept. 555, 2014

Phys. Rev. D 90, 062009 (2014)

# Axions

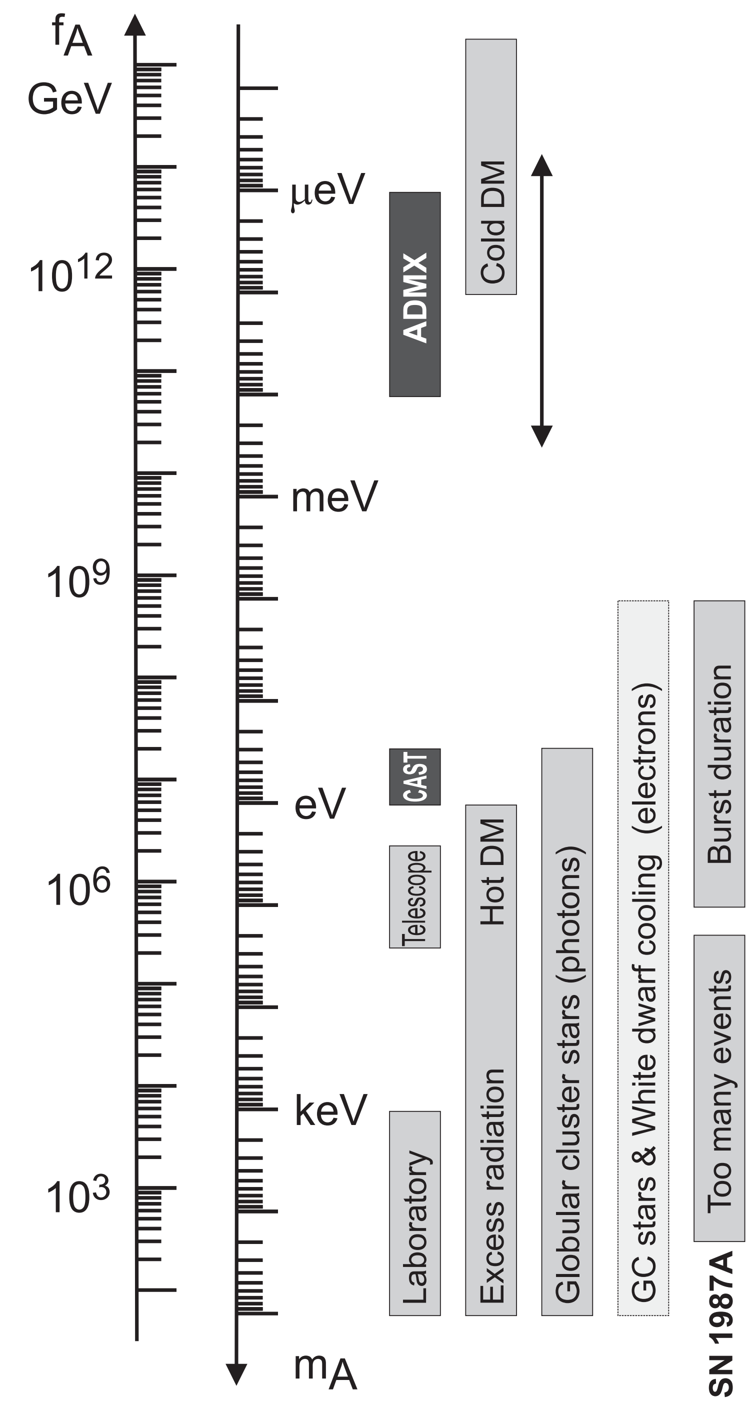
- Introduced by Peccei & Quinn as a solution to the strong CP problem: a global U(1) symmetry is spontaneously broken below an **energy scale $f_a$** (originally the weak scale $f_a \sim 200$ GeV $\sim f_{EW}$)
- Weinberg & Wilczek: PQ solution implies the existence of a light pseudoscalar, the axion
- **No axion detection so far; "invisible axion" models (with arbitrary large $f_a$) are still viable**

$$m_a \simeq 6 \cdot 10^{-6}\,\mathrm{eV}\,\frac{10^{12}\mathrm{GeV}}{f_a}$$

corresponds to the observed
dark matter density

- Constraints from astrophysics, cosmology & lab searches restrict the mass of a QCD dark matter axion to:

$$\sim 1\mu\mathrm{eV} \leq m_a \leq 3\,\mathrm{meV}$$



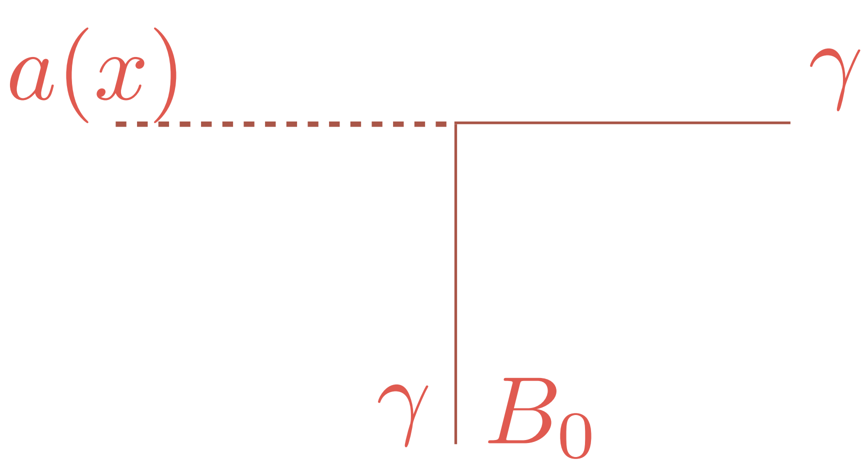
# Axion searches

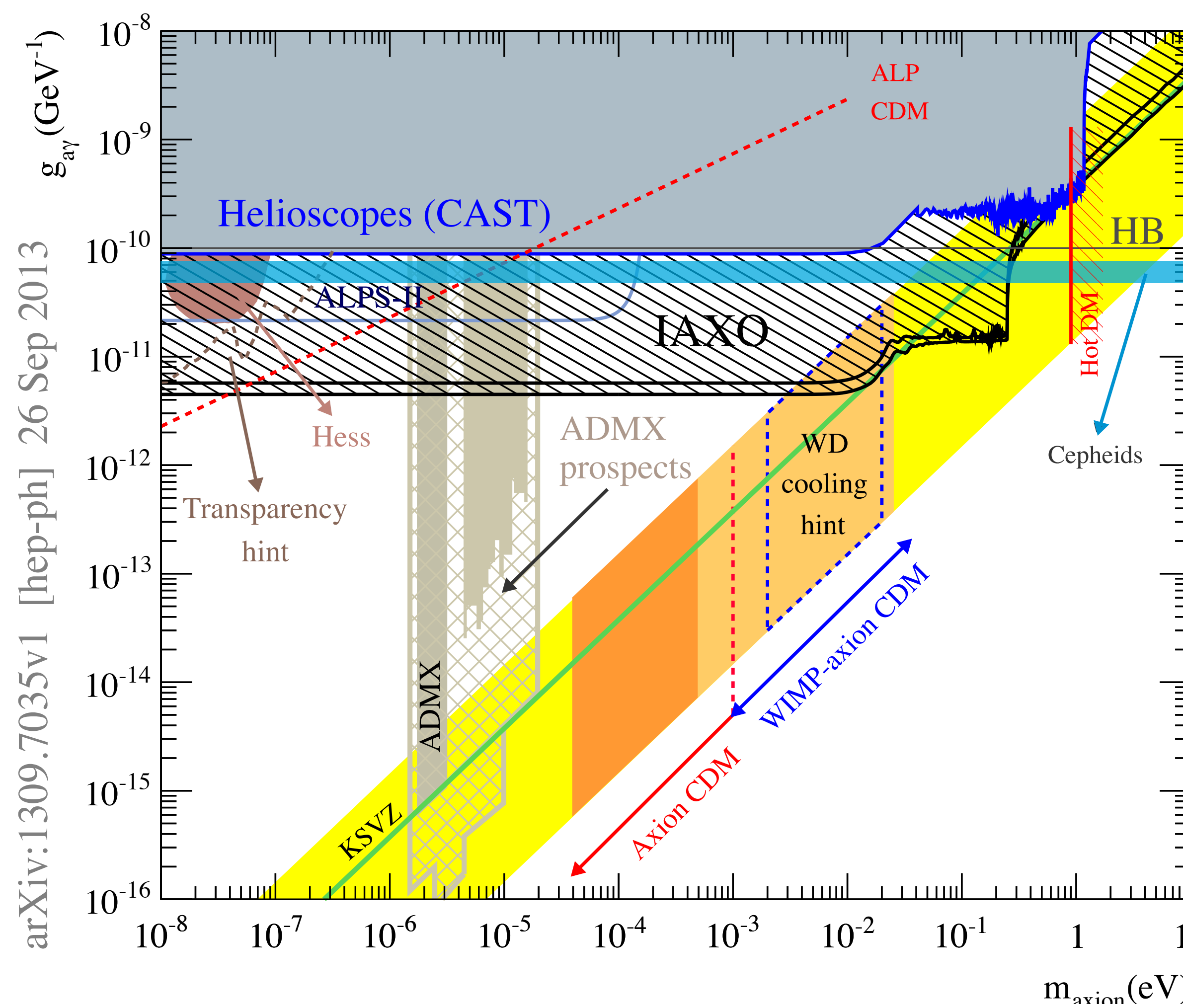
- **Mostly exploit the coupling to two photons** (also coupling to $e^-$, hadrons ~ $1/f_a$)

$$\mathcal{L}_{a\gamma\gamma} = -g_\gamma \frac{\alpha}{\pi}\frac{a(x)}{f_a}\vec{E}\cdot\vec{B} = -g_{\gamma\gamma}\vec{E}\cdot\vec{B}$$

0.36 (DFSZ) -0.97 (KSVZ)

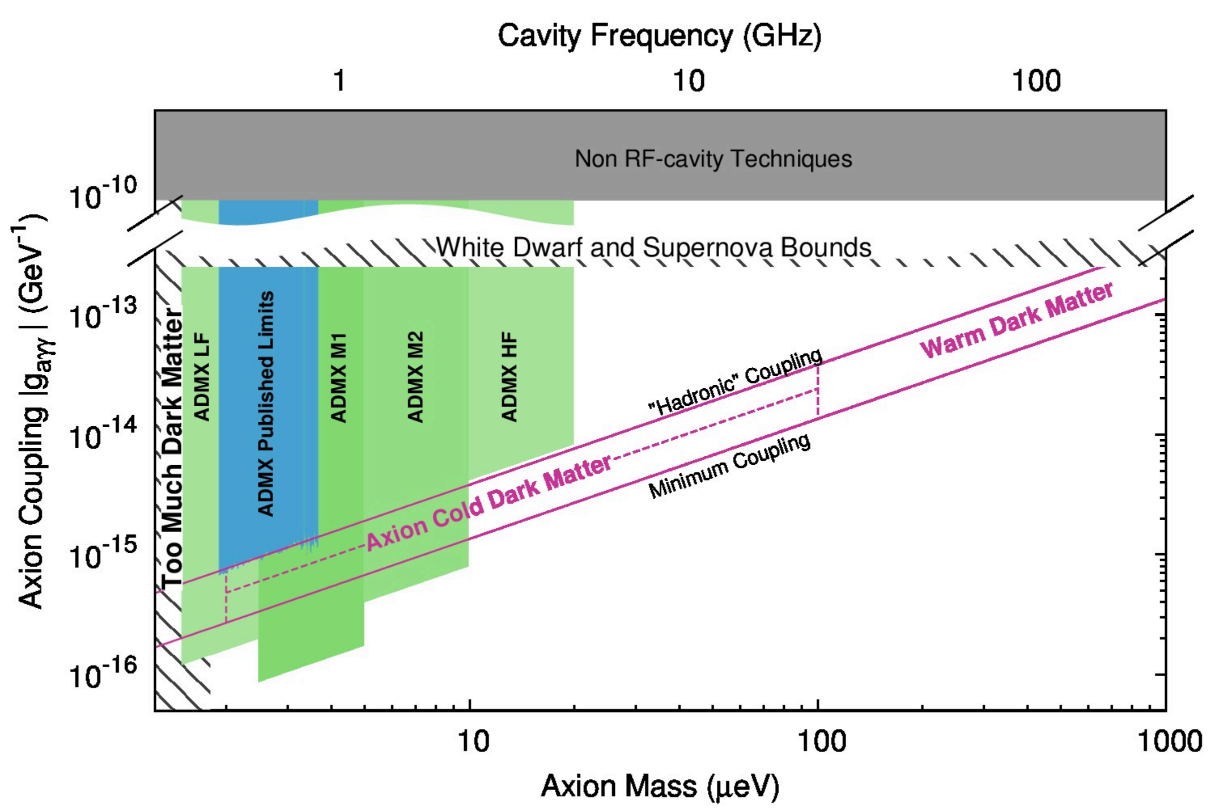
- This coupling is extremely weak, but the axion decay can be accelerated through a static, external magnetic field (inverse Primakoff effect)



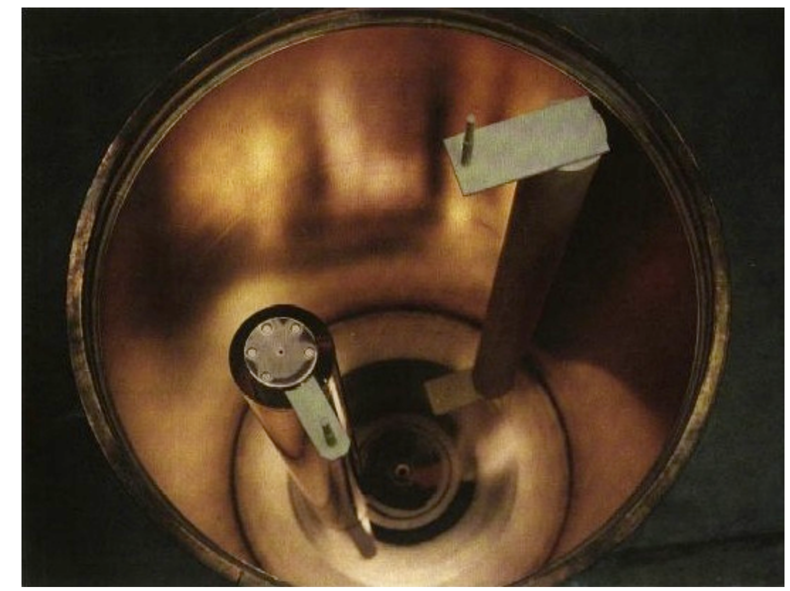



# The ADMS experiment

- Galactic axions convert into microwave photons inside a resonant cavity permeated by a strong magnetic field
- Noise reduction: dilution refrigerator (<100 mK) and SQUID amplifiers
- Search frequency range **0.5 - 2 GHz (2-8 μeV)**; construction & operation: 2015 - 2019
- ADMX-HF sister experiment: look at **4 - 6 GHz (16-24 μeV)**




Microwave cavity and tuning rods

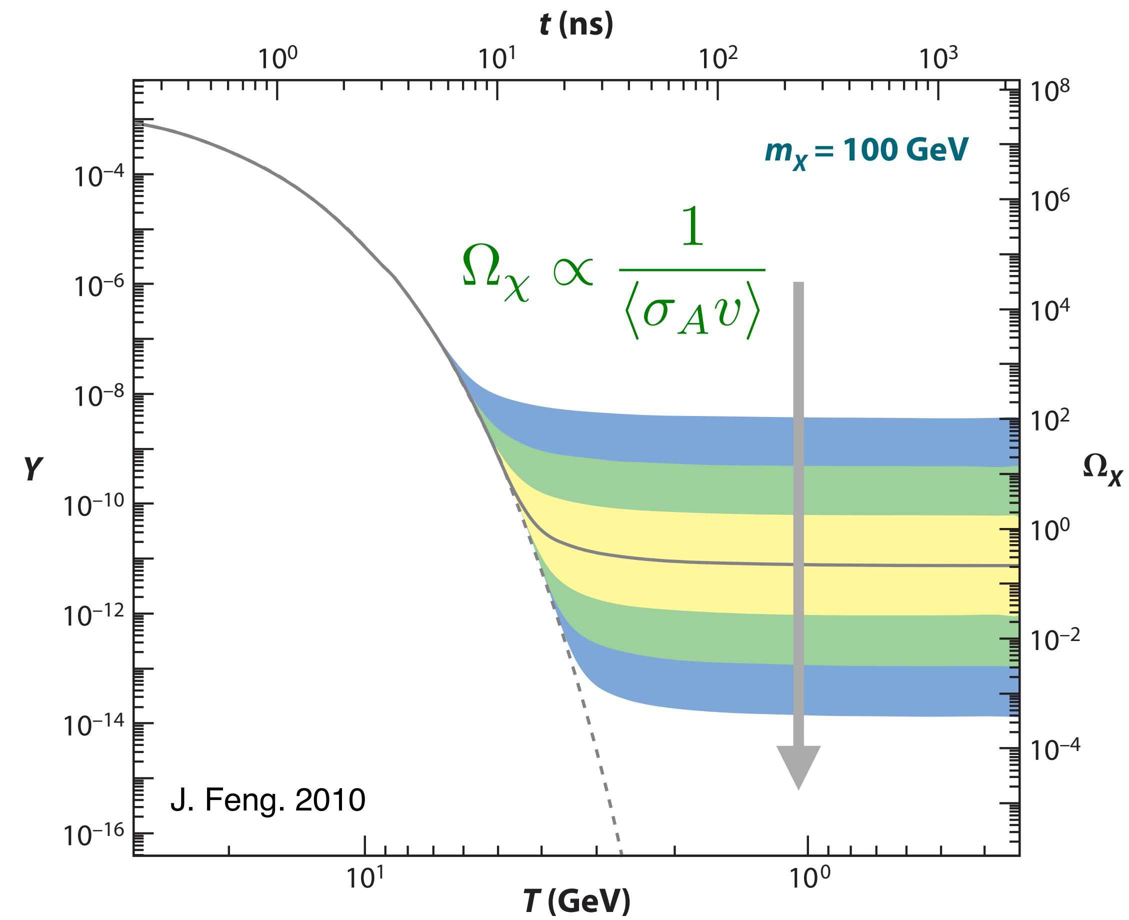


l = 1 m, d = 0.5 m; in an 8 Tesla SC magnet

Axion haloscope: Sikivie proposal, 1983

# Weakly Interacting Massive Particles

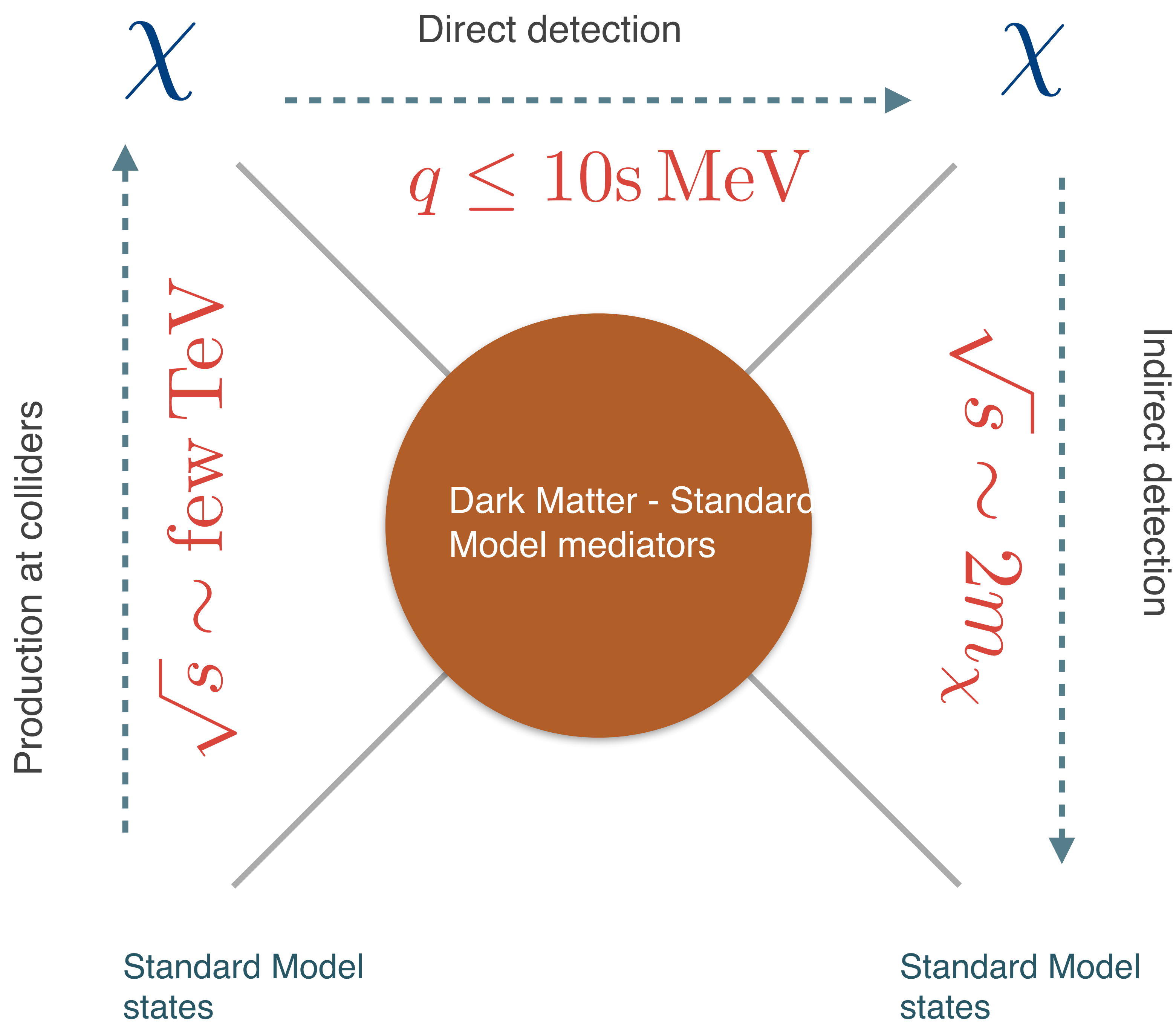
- **In thermal equilibrium in the early Universe**
- Freeze-out when annihilation rate drops below expansion rate and $M_{WIMP}$ > T ('cold')
- Their relic density can account for the dark matter if the annihilation cross section is weak (pb range)




$$\Omega_\chi h^2 \simeq 3 \times 10^{-27} cm^3 s^{-1} \frac{1}{\langle \sigma_A v \rangle}$$

$$\Omega_\chi h^2 = \Omega_{cdm} h^2 \simeq 0.1141 \Rightarrow \langle \sigma_A v \rangle \simeq 3 \times 10^{-26} cm^3 s^{-1}$$

# Three approaches to detect WIMPs



# Direct detection

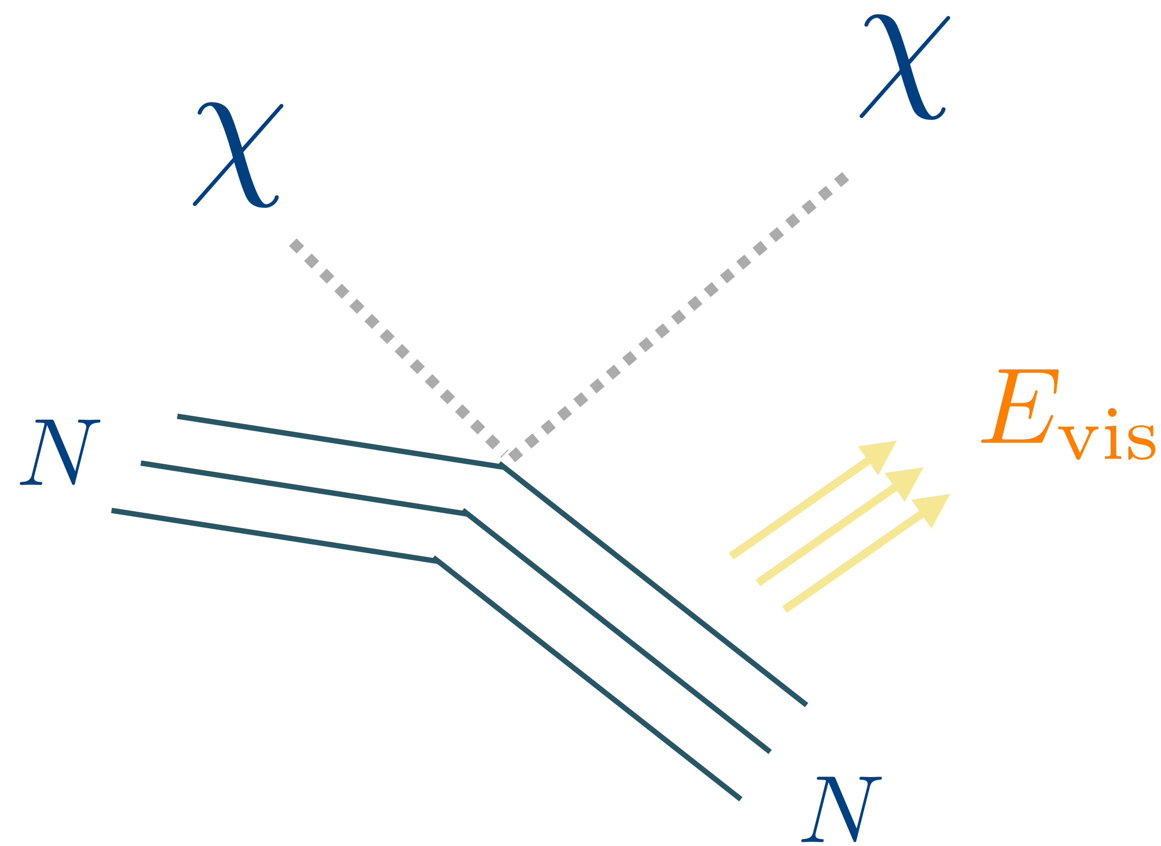
**Collisions of invisibles particles with atomic nuclei** => $E_{vis}$ (q ~ tens of MeV):

very low energy thresholds

ultra-low backgrounds, good background understanding (no "beam off" data collection mode), and particle ID

large detector masses

$$v/c \sim 0.75 \times 10^{-3}$$




REVIEW D VOLUME 31, NUMBER 12

**Detectability of certain dark-matter candidates**

Mark W. Goodman and Edward Witten
*Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544*
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

$$E_R = \frac{q^2}{2m_N} < 30\,\mathrm{keV}$$

# What to expect in a terrestrial detector?

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{\sqrt{(m_N E_{th})/(2\mu^2)}}^{v_{max}} dv f(v) v \frac{d\sigma}{dE_R}$$

**Astrophysics**

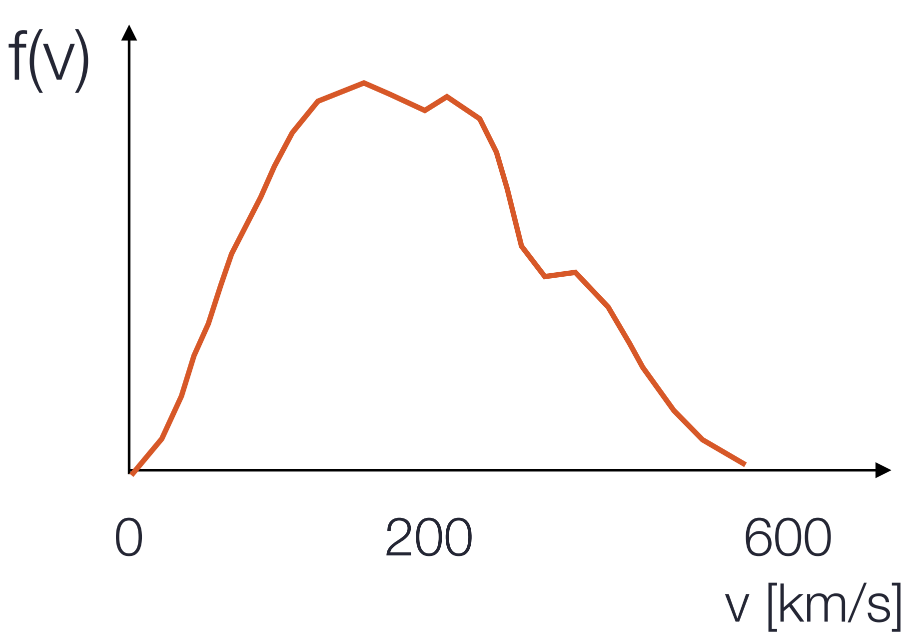
$\rho_0, f(v)$

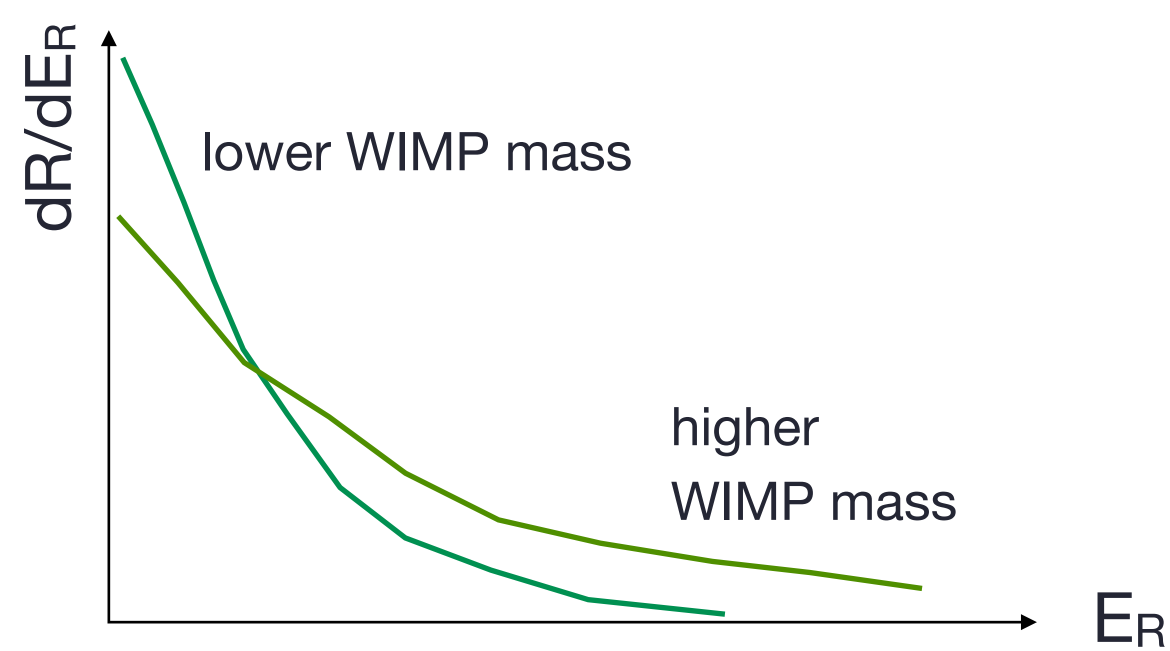
**Particle/nuclear physics**

$m_W, d\sigma/dE_R$

**Detector physics**

$N_N, E_{th}$



# Astrophysics

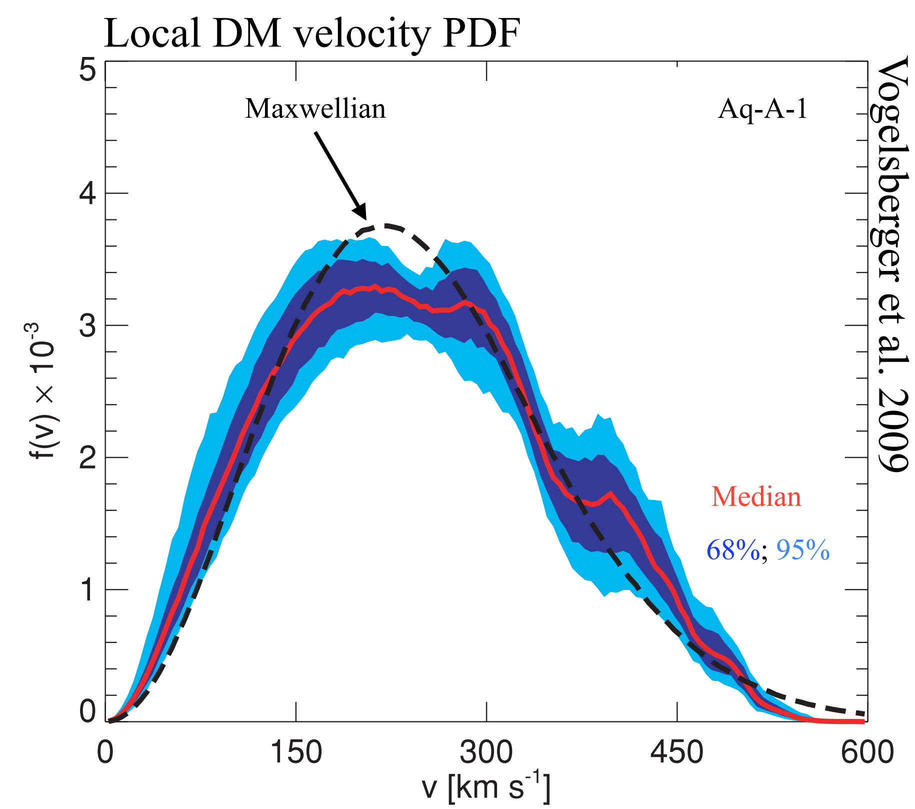
## Local density (at $R_0$ ~ 8 kpc)

**local measures** use the vertical kinematics of stars near the Sun as 'tracers' (smaller error bars, but stronger assumptions about the halo shape)

**global measures** extrapolate the density from the rotation curve (larger errors, but fewer assumptions)

**also:** modelling the phase space distribution over larger volumes around the solar neighbourhood

Velocity distribution of WIMPs in the galaxy



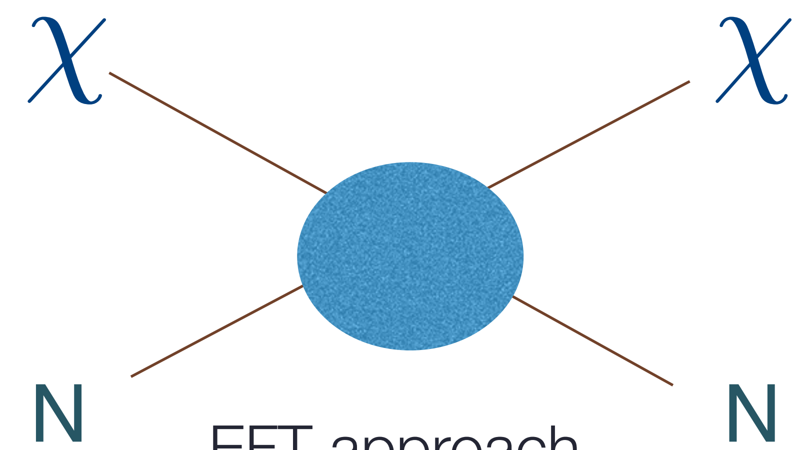

$$\rho(R_0) = 0.2 - 0.56\,\mathrm{GeV\,cm^{-3}} = 0.005 - 0.015\,\mathrm{M_\odot\,pc^{-3}}$$

Survey by J. Read, Journal of Phys. G41 (2014) 063101

=> **WIMP flux on Earth: ~$10^5$ $cm^{-2}s^{-1}$** ($M_W$=100 GeV, for 0.3 GeV $cm^{-3}$)

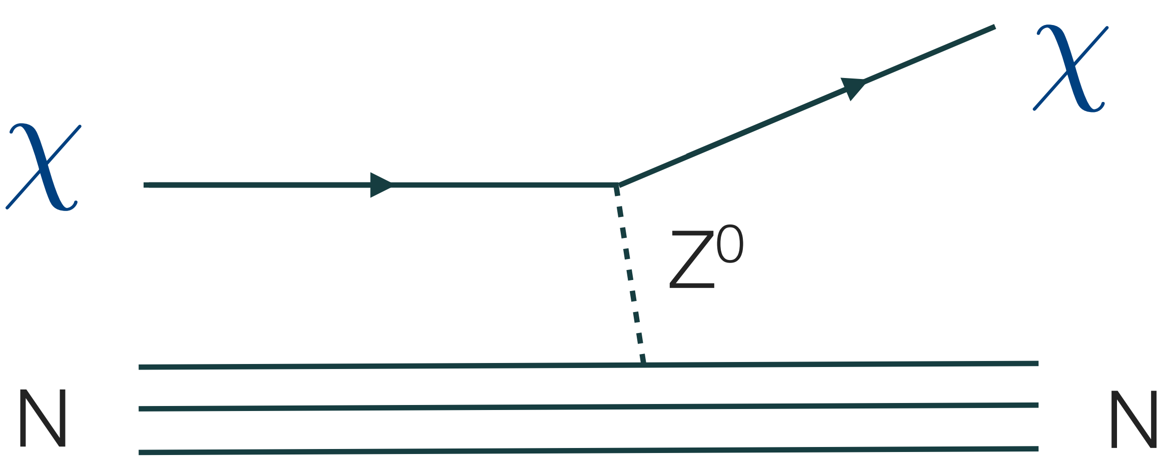
# Particle physics

- Use effective operators to describe WIMP-quark interactions
- Example: vector mediator $\mathcal{L}_\chi^{\text{eff}} = \frac{1}{\Lambda^2}\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$
- The effective operator arises from integrating out the mediator with mass M and couplings $g_q$ and $g_\chi$ to the quark and the WIMP:

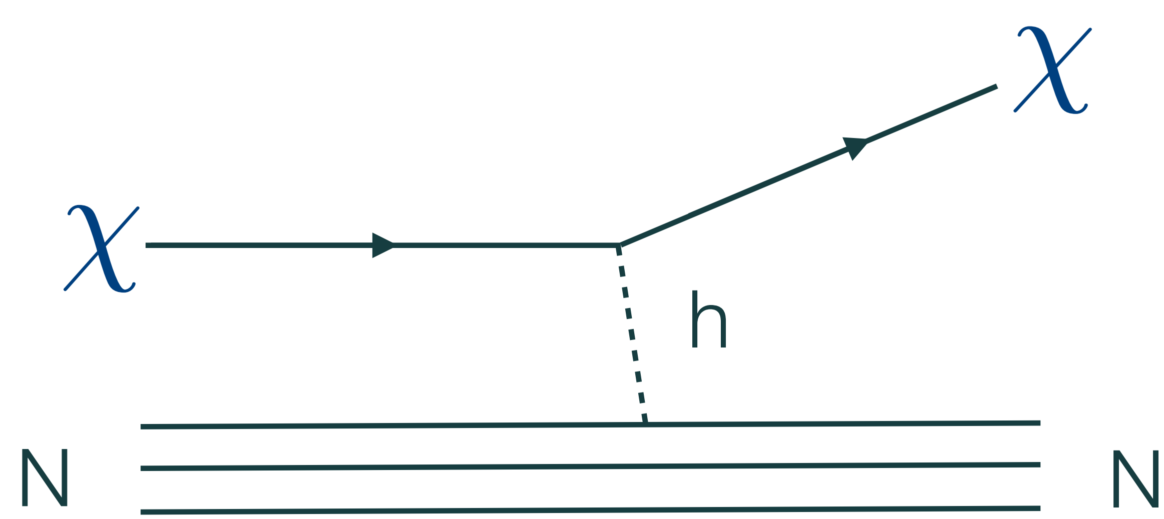



EFT approach (always valid for direct detection)

$$\Lambda = \frac{M}{\sqrt{g_q g_\chi}} \quad \Rightarrow \sigma_{\text{tot}} \propto \Lambda^{-4}$$




$$\sigma_0 \sim 10^{-39}\text{cm}^2$$

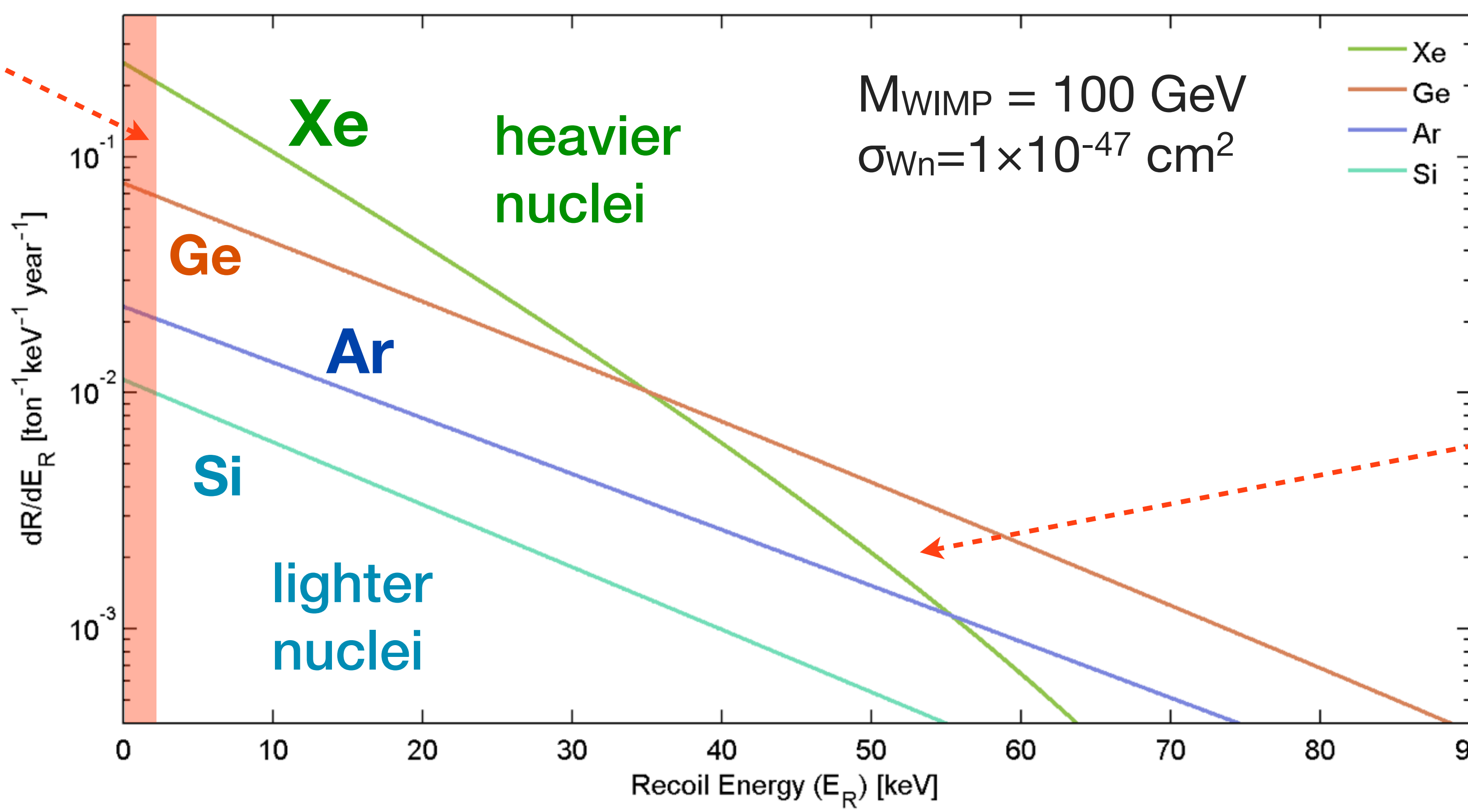



$$\sigma_0 \sim 10^{-44} - 10^{-47}\,\text{cm}^2$$

# Expected interaction rates

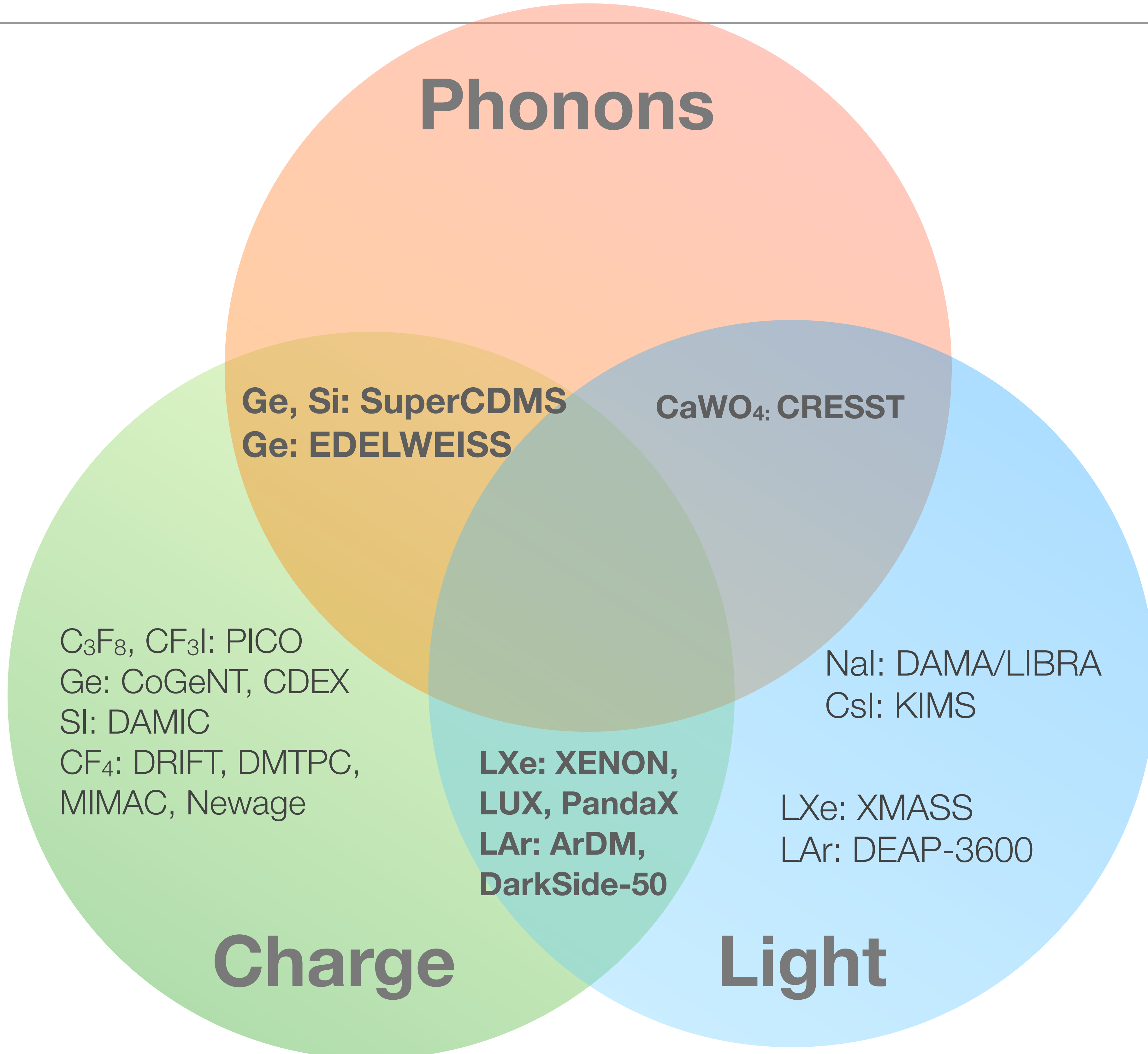
$$R \sim 0.13\ \frac{\text{events}}{\text{kg year}} \left[ \frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$

$$v_{min} = \sqrt{\frac{m_N E_{th}}{2\mu^2}}$$




$F^2(E_R)$

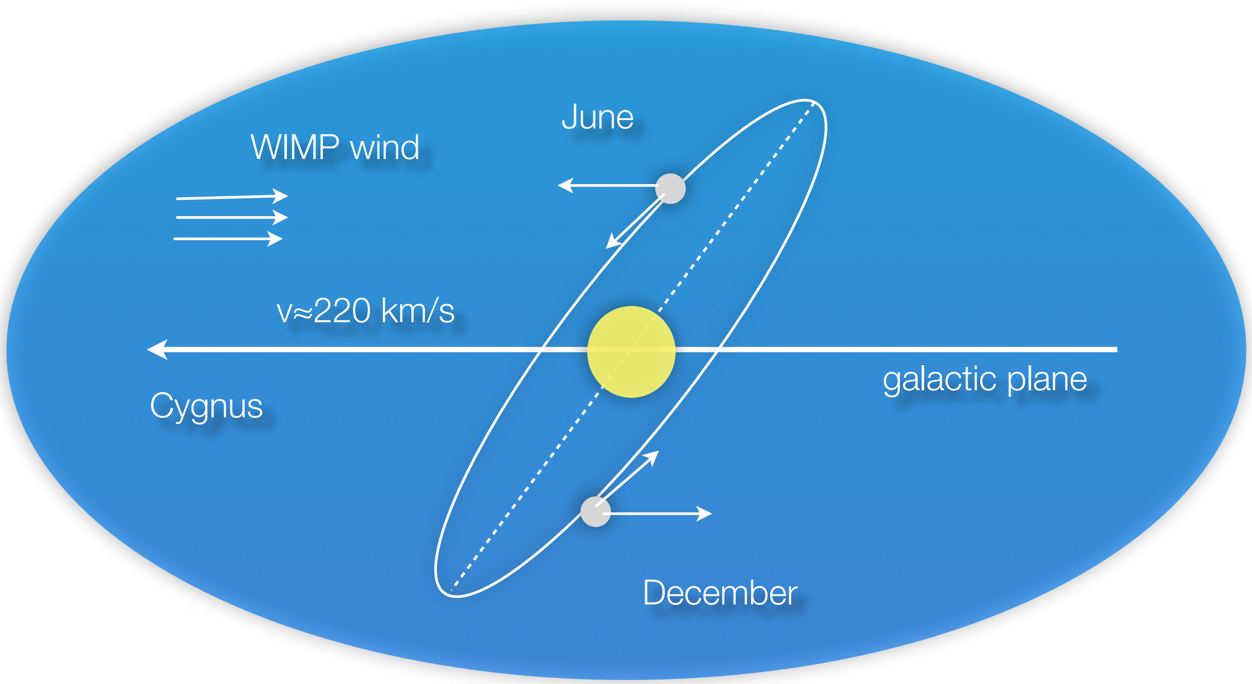
# Direct dark matter detection zoo



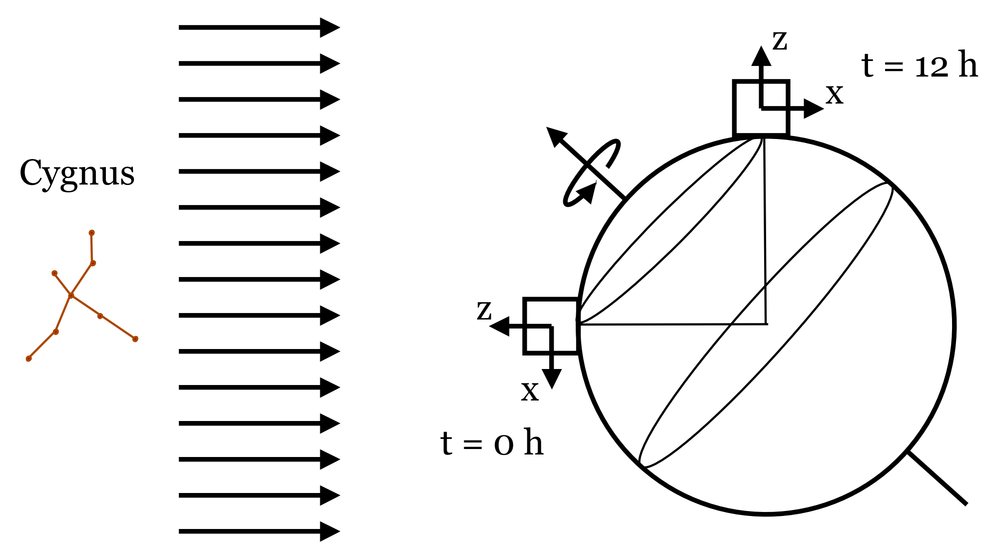
# Dark matter signatures

- Rate and shape of recoil spectrum depend on target material
- Motion of the Earth causes:
  - annual event rate modulation: June - December asymmetry ~ 2-10%
  - sidereal directional modulation: asymmetry ~20-100% in forward-backward event rate

Drukier, Freese, Spergel, PRD 33,1986

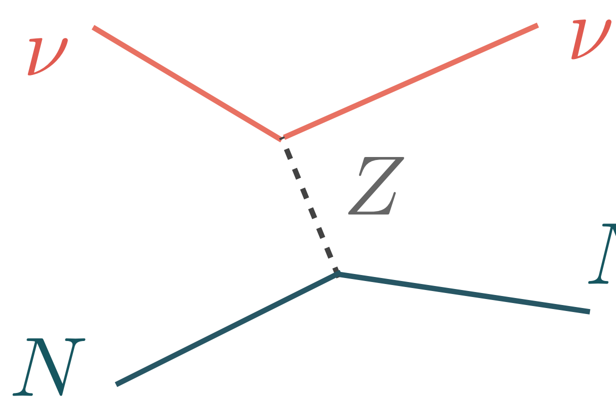


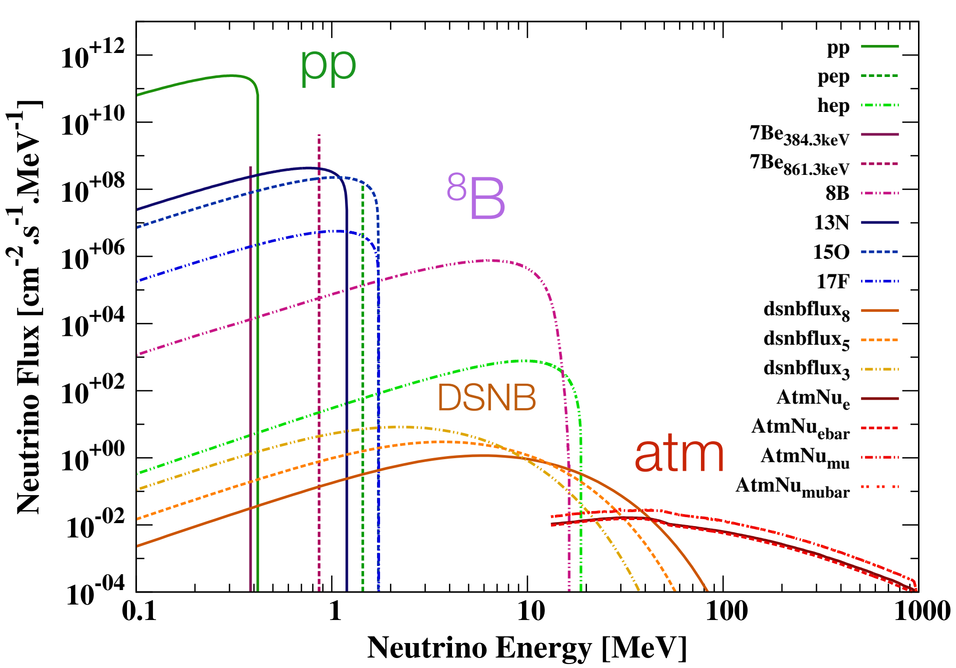

D. Spergel, PRD 36, 1988



# Expected backgrounds

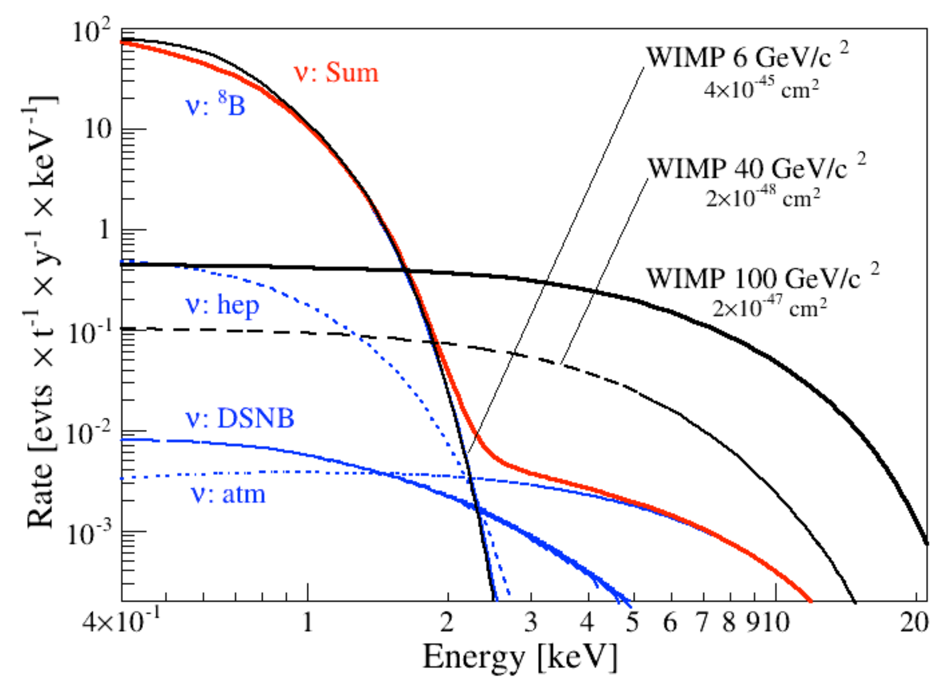
- Cosmic rays & cosmic activation of detector materials
- Natural ($^{238}$U, $^{232}$Th, $^{40}$K) & anthropogenic ($^{85}$Kr, $^{137}$Cs) radioactivity: $\gamma, e^-, n, \alpha$
- Ultimately: **neutrino-nucleus scattering (solar, atmospheric and supernovae neutrinos)**



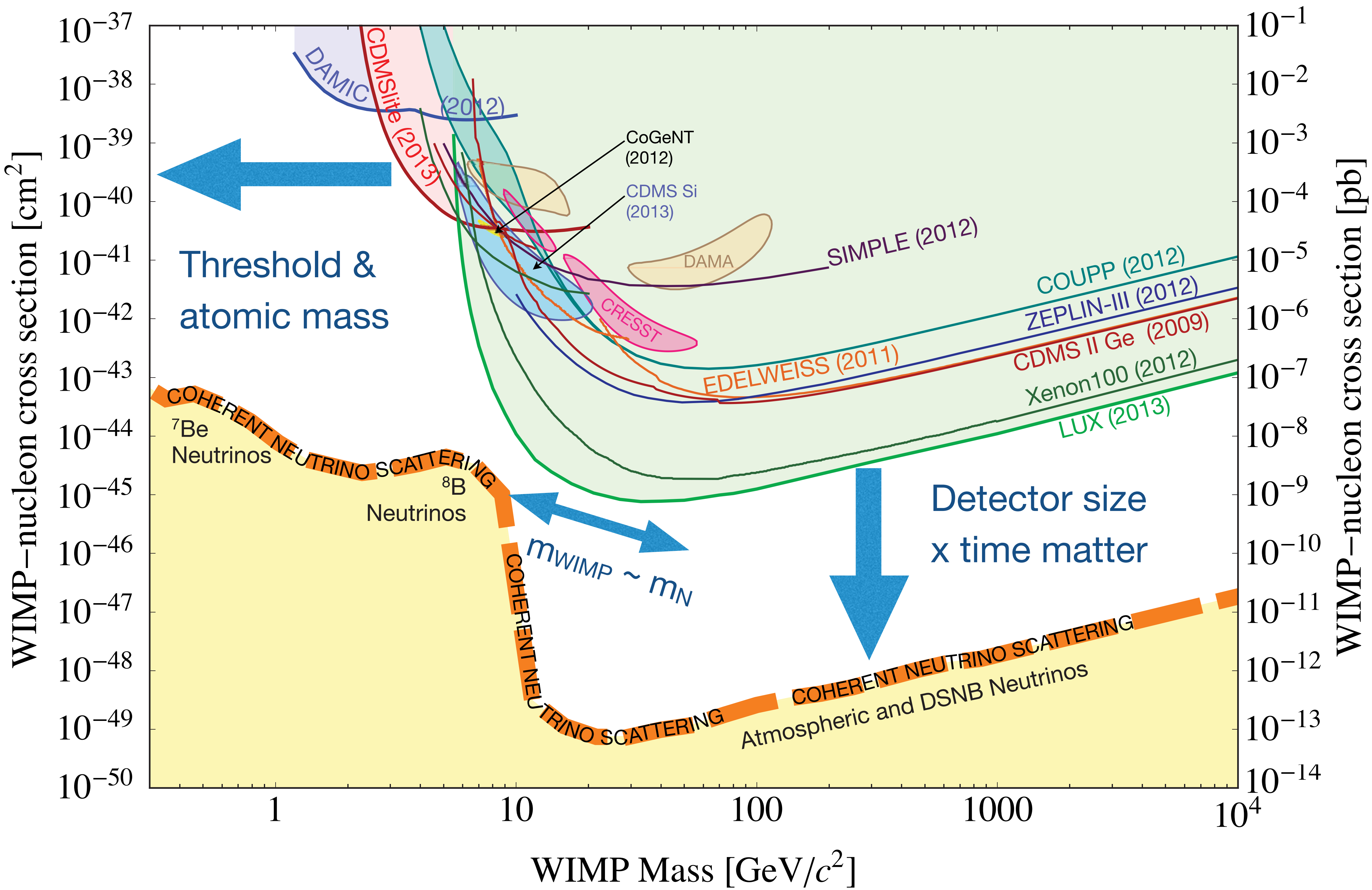

F. Ruppin et al., 1408.3581

$$\nu + N \longrightarrow \nu + N$$




LB et al., JCAP01 (2014) 044

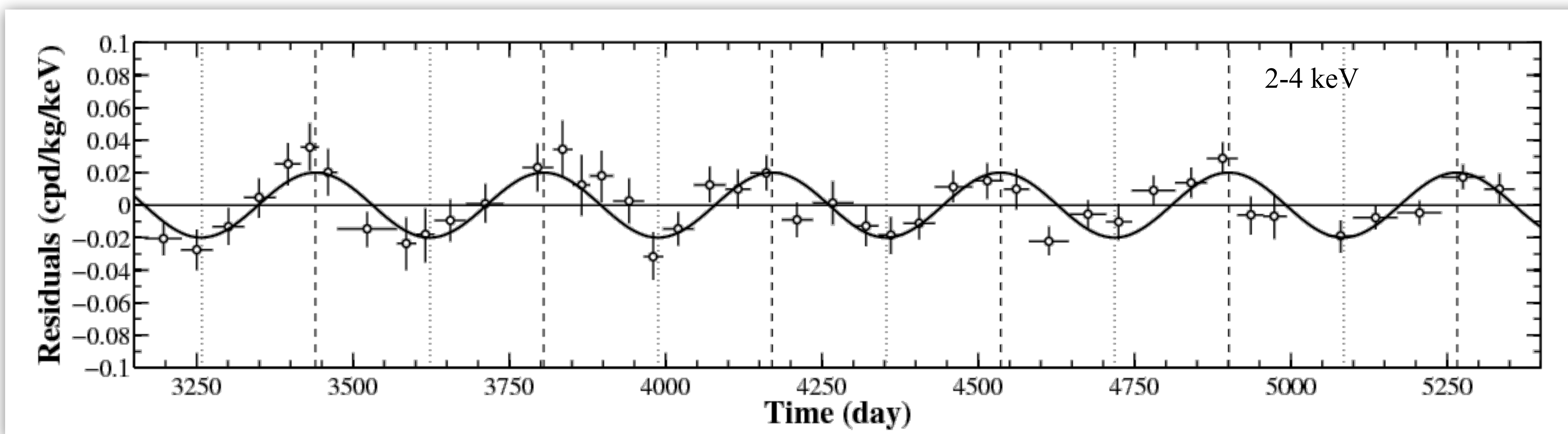
# The WIMP landscape today



# DAMA/LIBRA annual modulation signal

- Period = 1 year, phase = June 2 ± 7 days; 9.3-sigma
- Dark matter WIMP interpretation ruled out by many experiments
- Leptophilic models still viable (until a few days ago…)

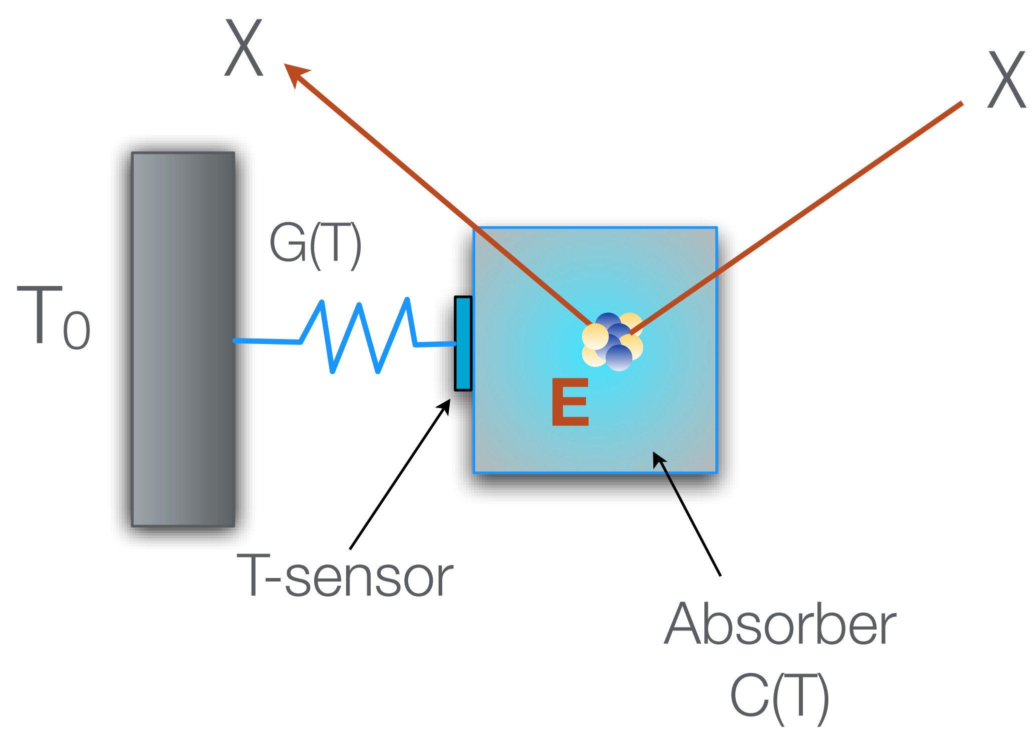
**DAMA/LIBRA NaI: 2% annual modulation**



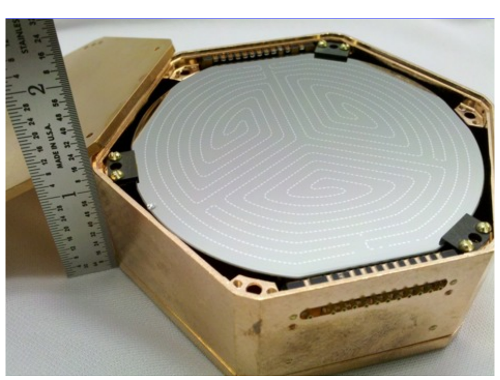

R. Bernabei et al, EPJ-C67 (2010)

# Cryogenic detectors at T ~ mK

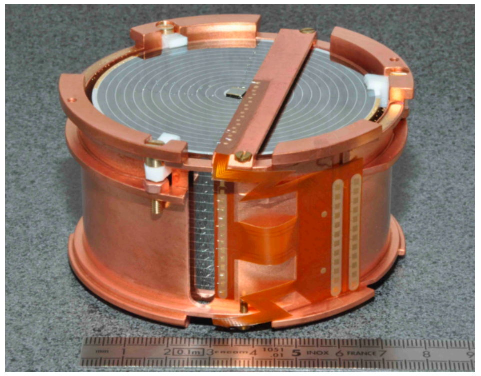
- Detect a temperature increase after a particle interacts in an absorber



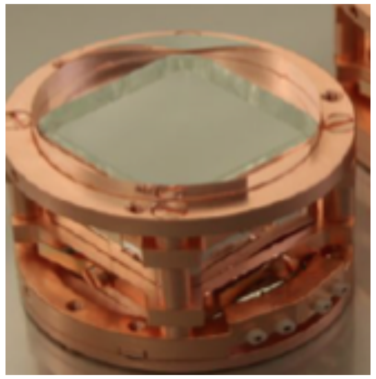

SuperCDMS: Ge, Si



EDELWEISS-III (Ge)

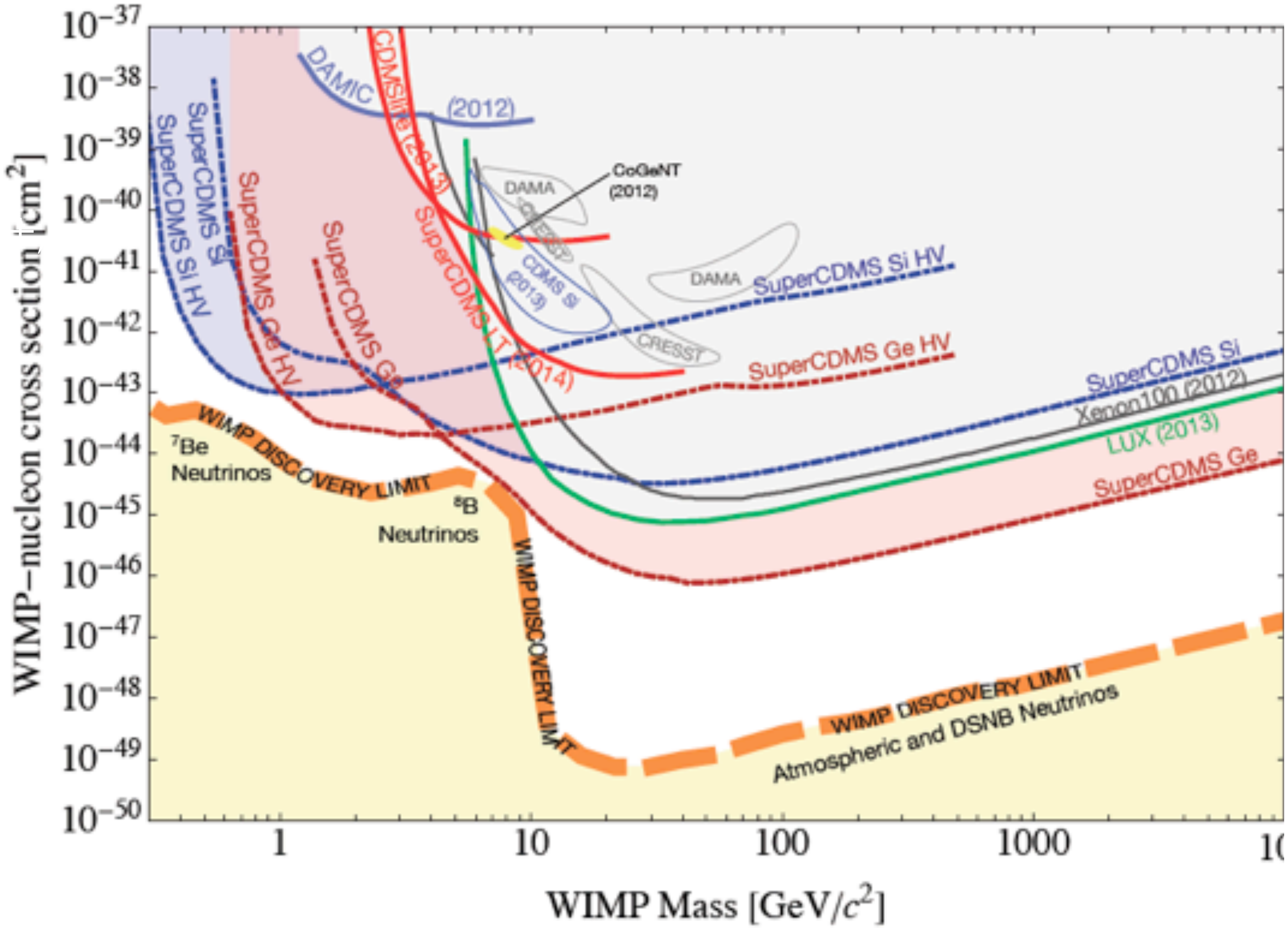


CRESST ($CaWO_4$)



# Cryogenic detectors at T ~ mK

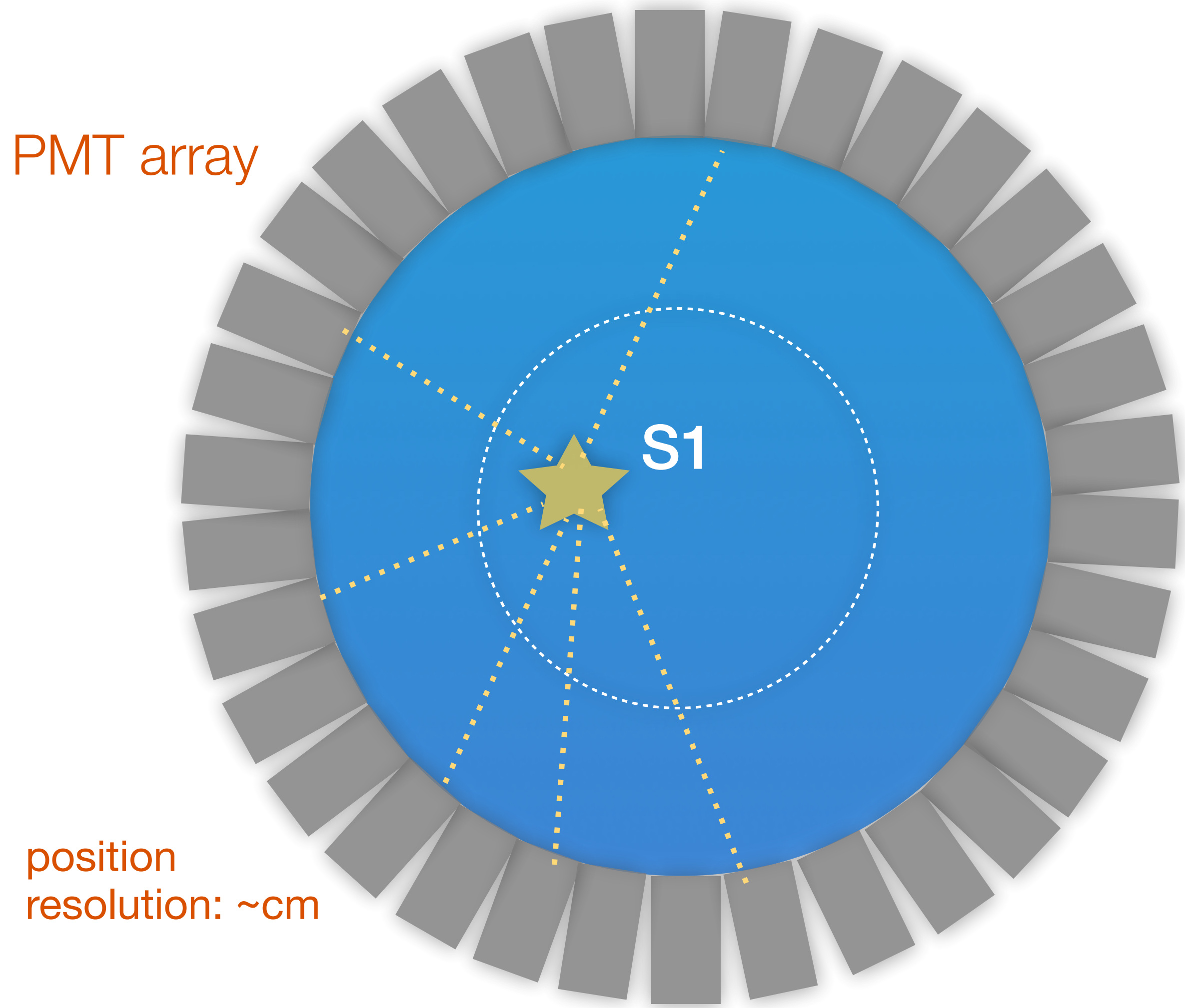
Probe low WIMP mass region



# Single-phase noble liquid detectors

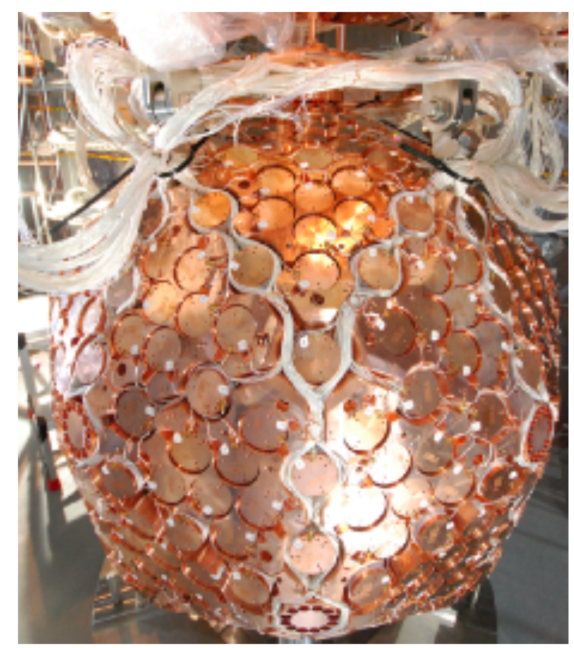
**Instrumented LAr or LXe volume**

Scintillation light in VUV region



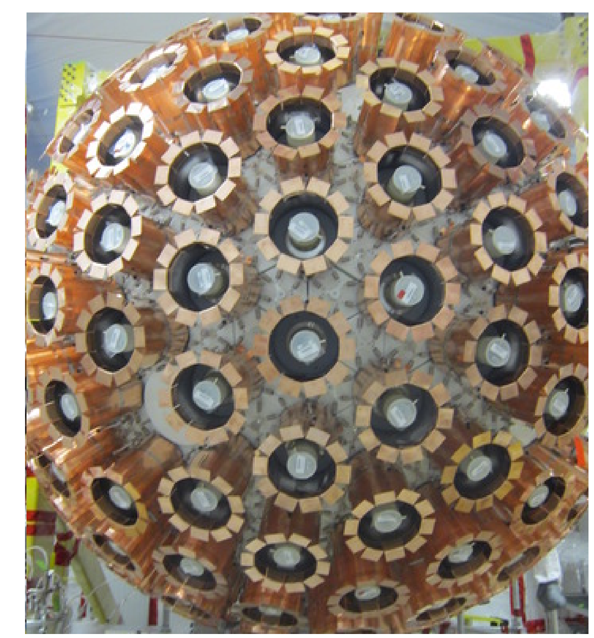


**LXe: XMASS**
**at Kamioka, 832 kg**



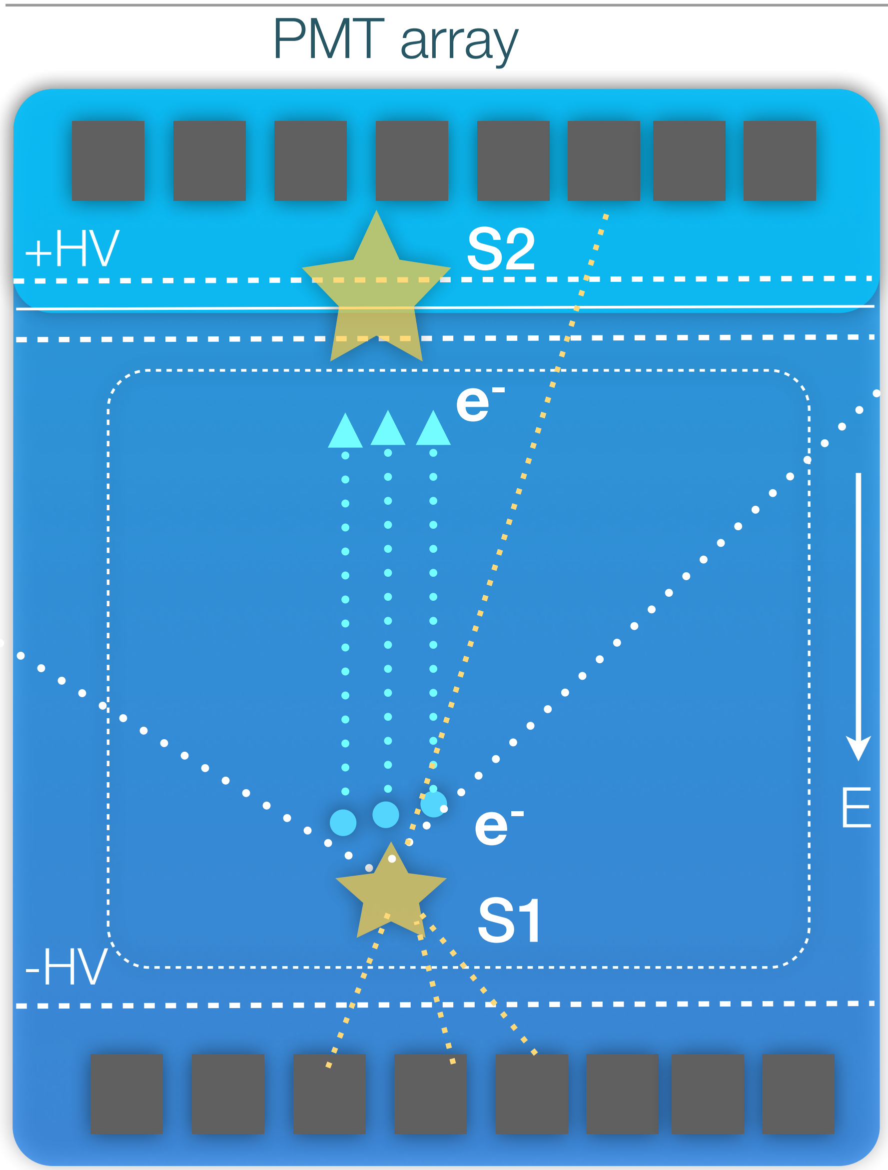
Running since 2013
Plans for 5 t detector

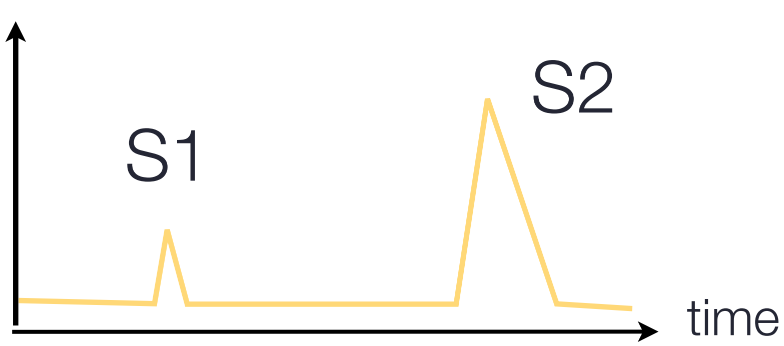
**LAr: DEAP-3600**
**at SNOLAB, 3.6 t**



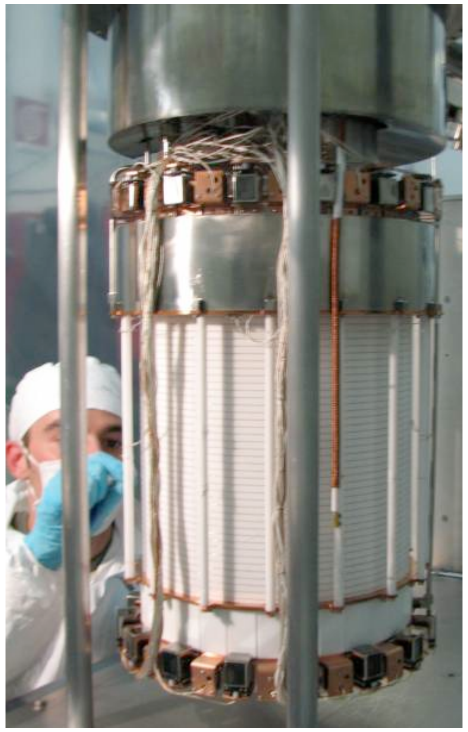
In commissioning
First results in late 2015
1 x $10^{-46}$ $cm^2$ sensitivity

# Dual-phase noble liquid detectors




**LXe: XENON100**



**LXe: LUX**

**LAr: DarkSide**

**LXe**
XENON100 at LNGS, LUX at SURF, PandaX at CJPL

**LAr**
DarkSide-50 at LNGS, ArDM at Canfranc

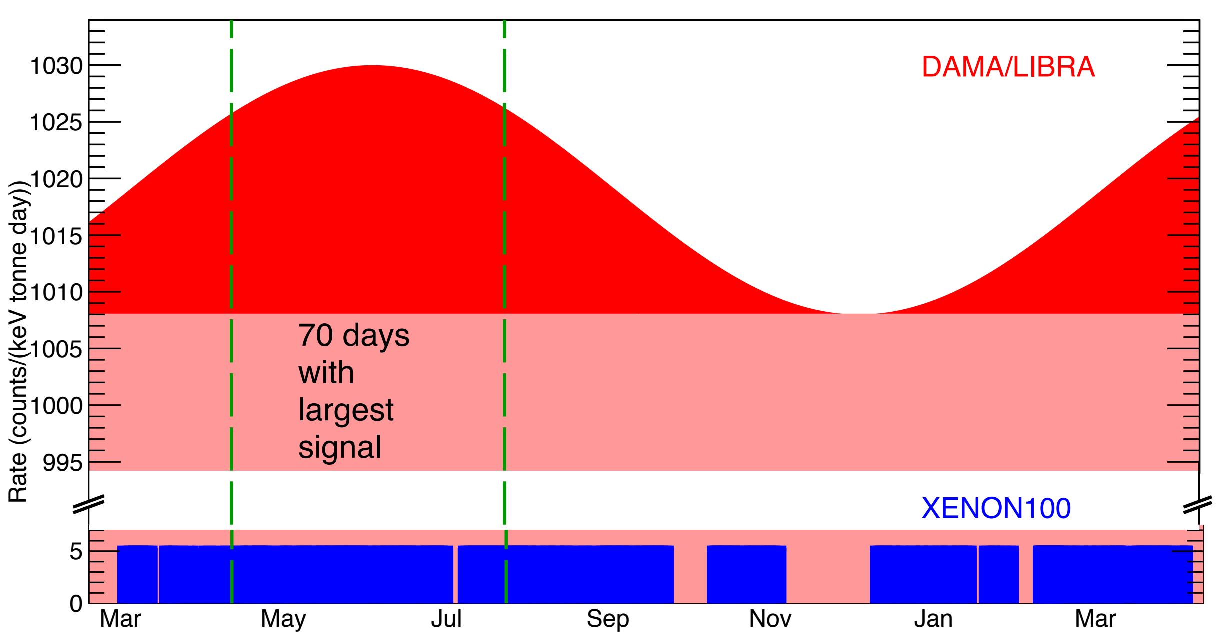
Target masses between ~ 50 kg - 1 ton

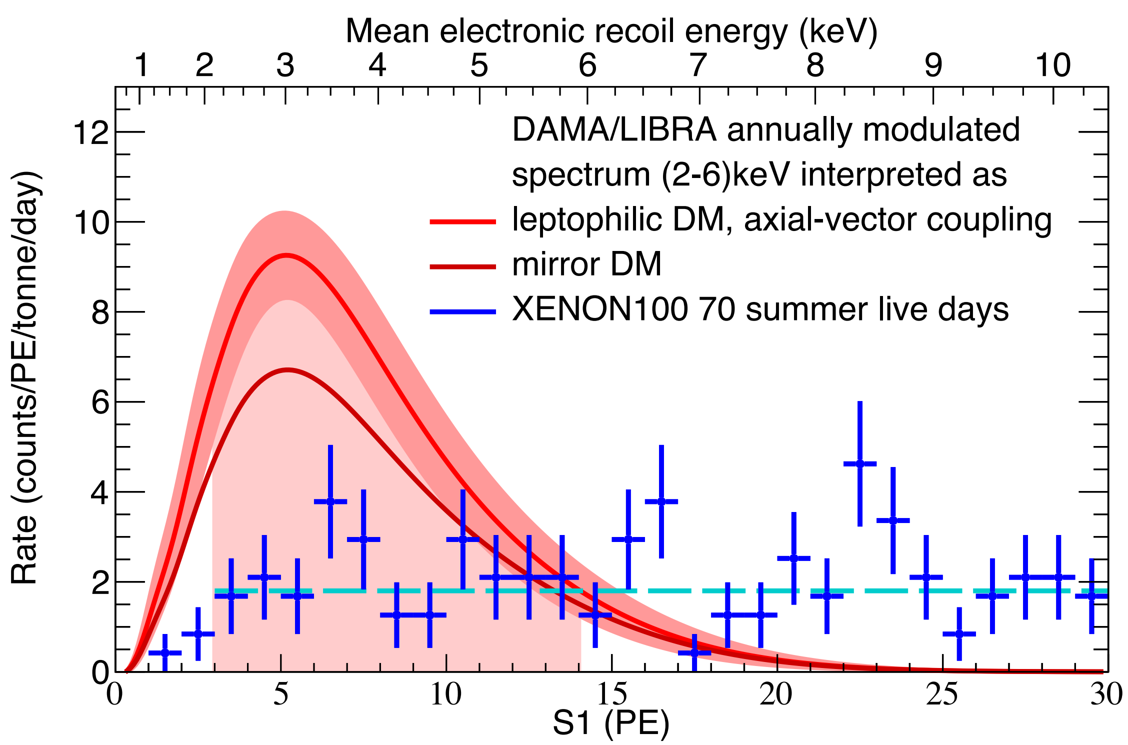
# New XENON100 results

- Dark matter particles interacting with $e^-$

1. search for periodic variations of the ER rate in the 2-6 keV region
2. search for a signal above background in the ER spectrum (use the average ER event rate)

**XENON collaboration, arXiv: 1507.07747, Science 349, 2015**




Consider the 70 days with the largest signal

DAMA/LIBRA modulated spectrum as would be seen in XENON100 (for axial-vector WIMP-$e^-$ scattering)

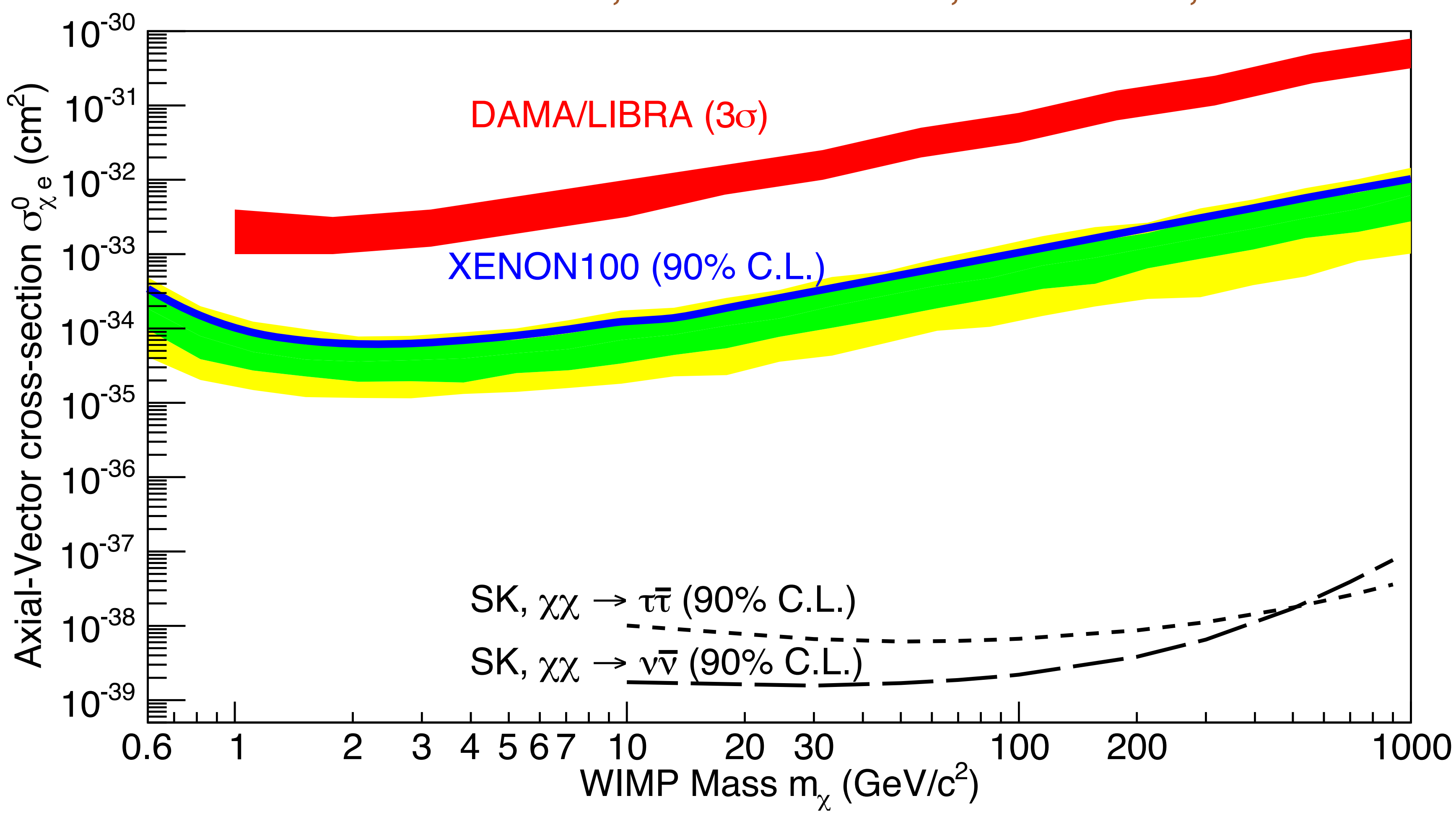
# New XENON100 results

- Dark matter particles interacting with $e^-$

  1. No evidence for a signal

  2. Exclude various leptophilic models as explanation for DAMA/LIBRA

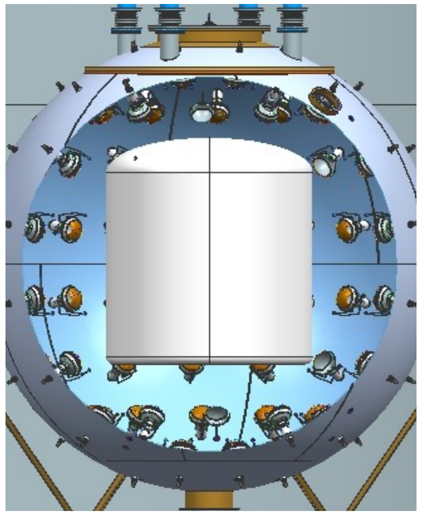
**XENON collaboration, arXiv: 1507.07747, Science 349, 2015**



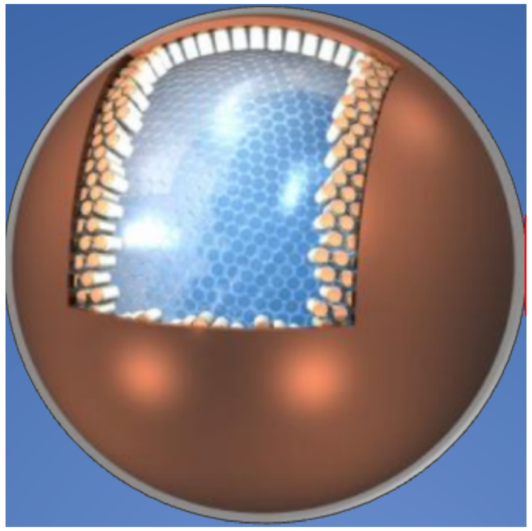
# Future noble liquid detectors

- Under construction: XENON1T/nT (3.3 t/ 7t LXe) at LNGS
- Proposed LXe: LUX-ZEPLIN 7t (approved), XMASS 5t LXe
- Proposed LAr: DarkSide 20 t LAr, DEAP 50 t LAr
- Design & R&D studies: DARWIN 30-50 t LXe; ARGO 150 t LAr

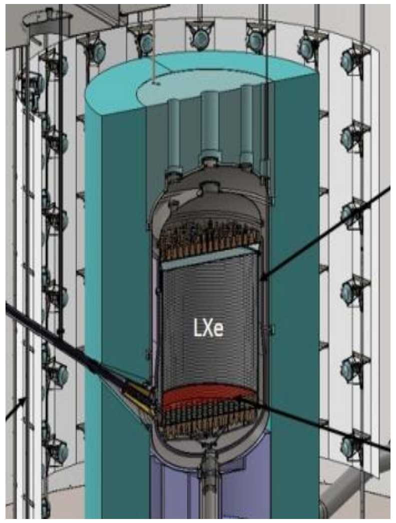
XENON1T: 3.3 t LXe



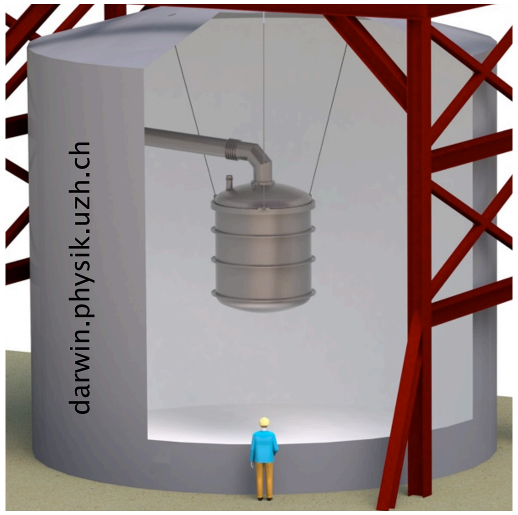
DarkSide: 20 t LAr



XMASS: 5t LXe



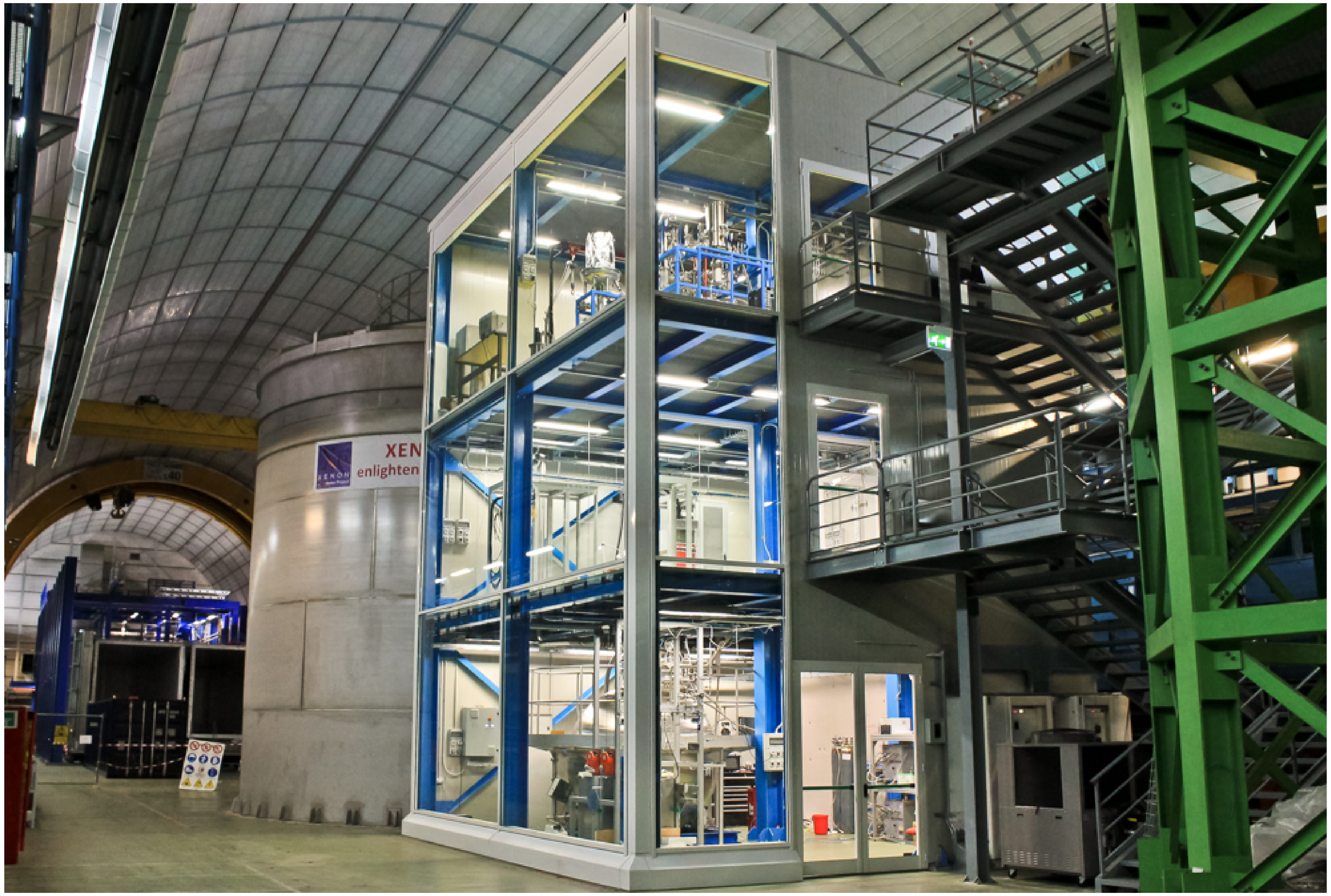

LZ: 7t LXe




DARWIN: 50 t LXe

# The XENON1T experiment

- Under construction at LNGS since autumn 2013; commissioning planned for late 2015
- Total (active) LXe mass: 3.3 t (2 t), 1 m electron drift, 248 3-inch PMTs in two arrays
- Background goal: 100 x lower than XENON100 ~ $5 \times 10^{-2}$ events/(t d keV)



# XENON1T: status of construction work

- Water Cherenkov shield built and instrumented
- Cryostat support, service building, electrical plant completed
- Several subsystems (cryostat, cryogenics, storage, purification, cables & fibres, pipes ) installed/ being tested underground

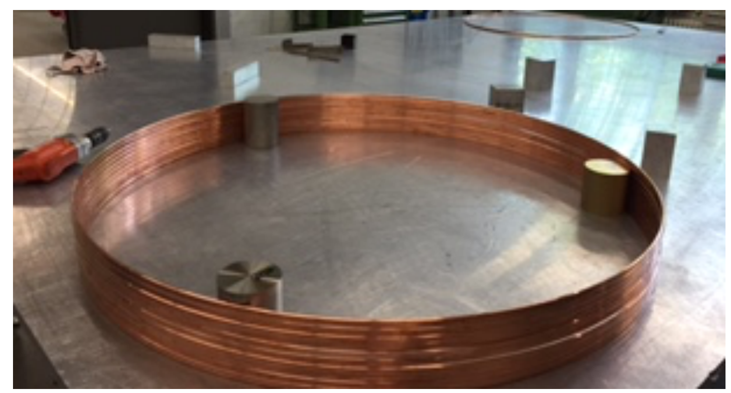


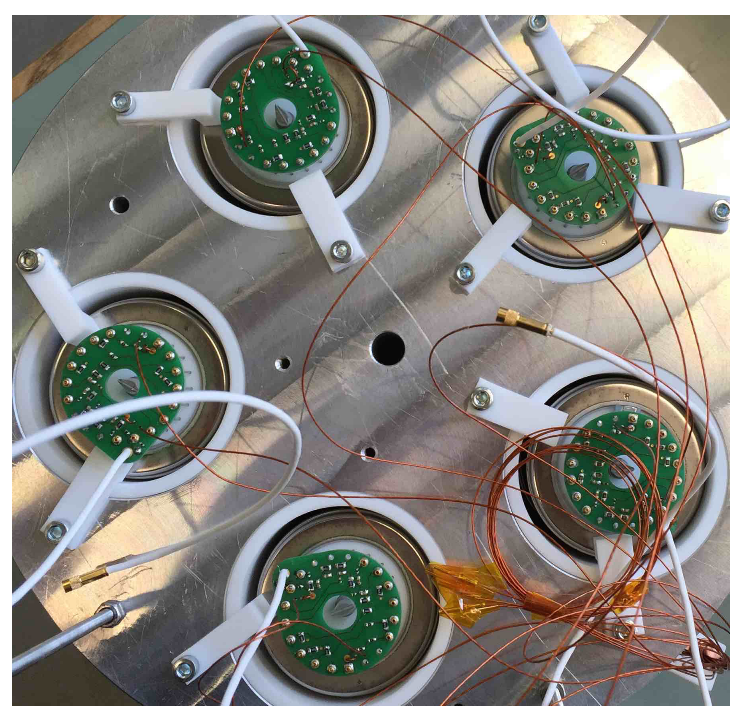


# The XENON1T inner detector

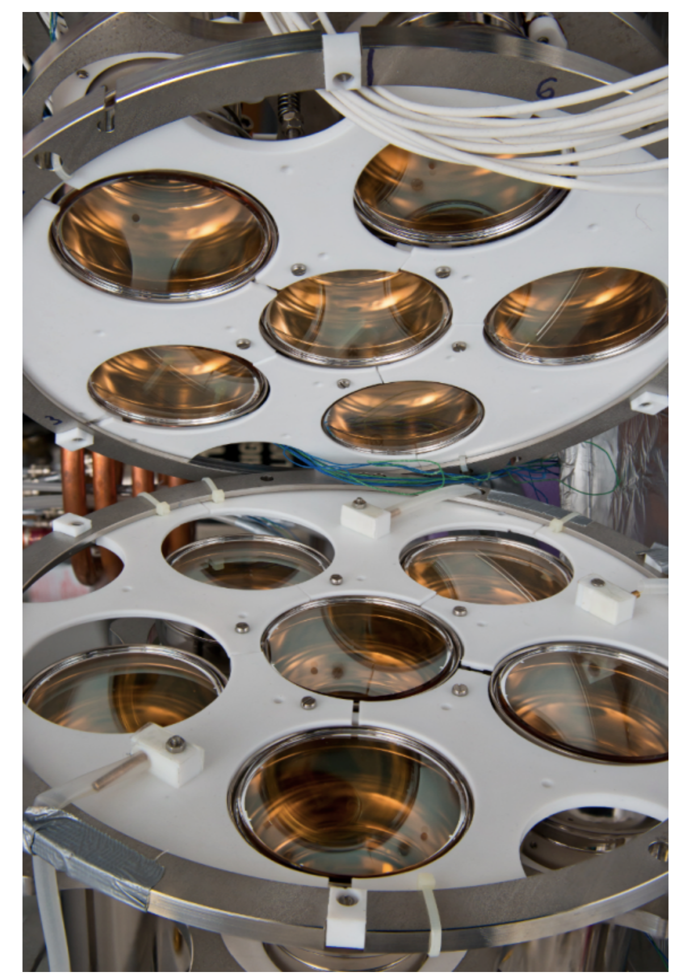
- PMTs are screened with HPGe, then tested in cold gas and - a subsample - in LXe
- TPC design is finalised, currently under prototyping, materials being screened

The TPC



PMT and final bases & cables tests in liquid xenon



PMT tests at -100 C

# The XENON1T inner detector

- PMTs are screened with HPGe, then tested in cold gas and - a subsample - in LXe
- TPC design is finalised, currently under prototyping, materials being screened

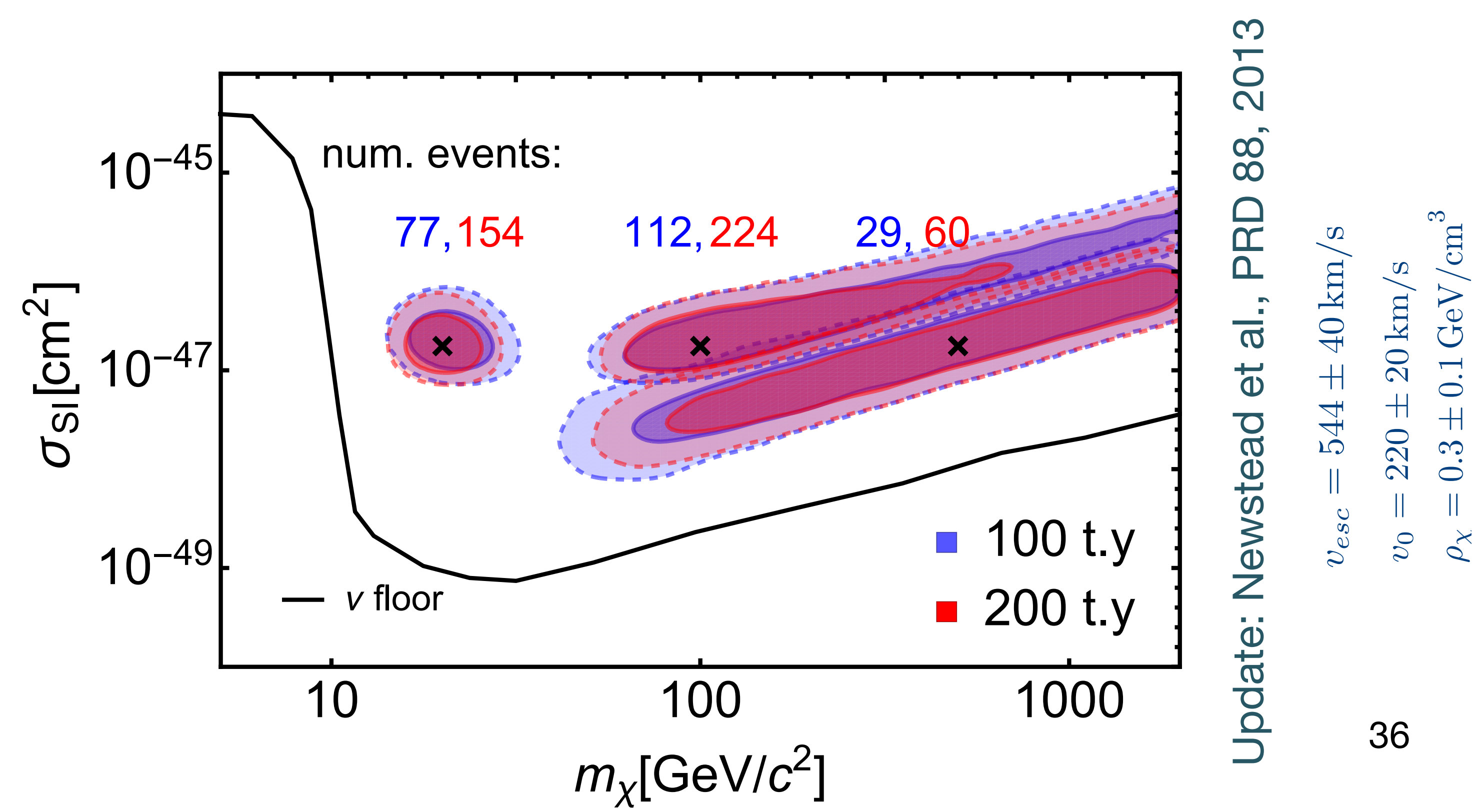
The TPC

Field cage tests at -100 C

# DARWIN - towards WIMP spectroscopy

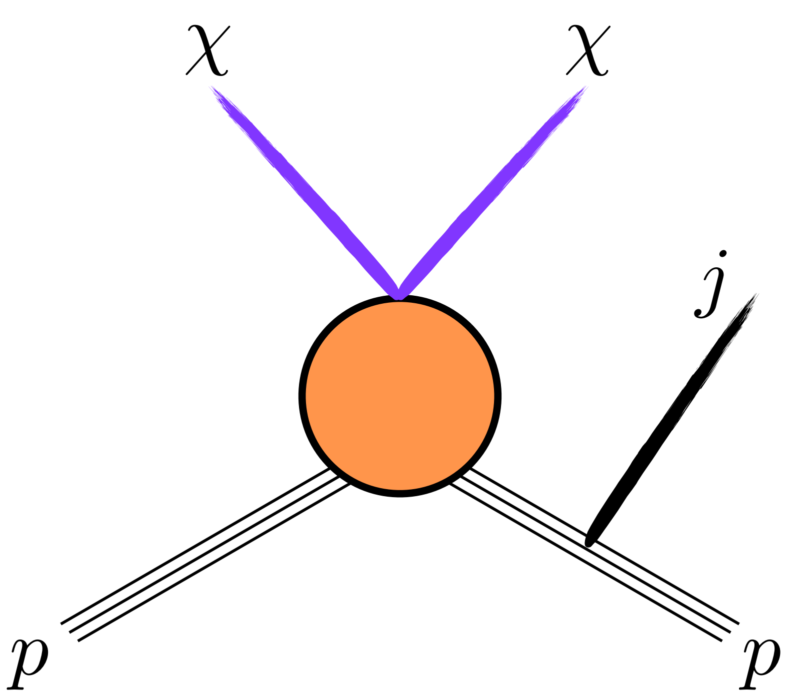

darwin-observatory.org arXiv:1506.08309

- Design study for 30-50 tons LXe detector
- Background goal: dominated by neutrinos
- Physics goal:
  - WIMP spectroscopy
  - many other channels (pp neutrinos, bb-decay, axions/ALPs, bosonic SuperWIMPs…)



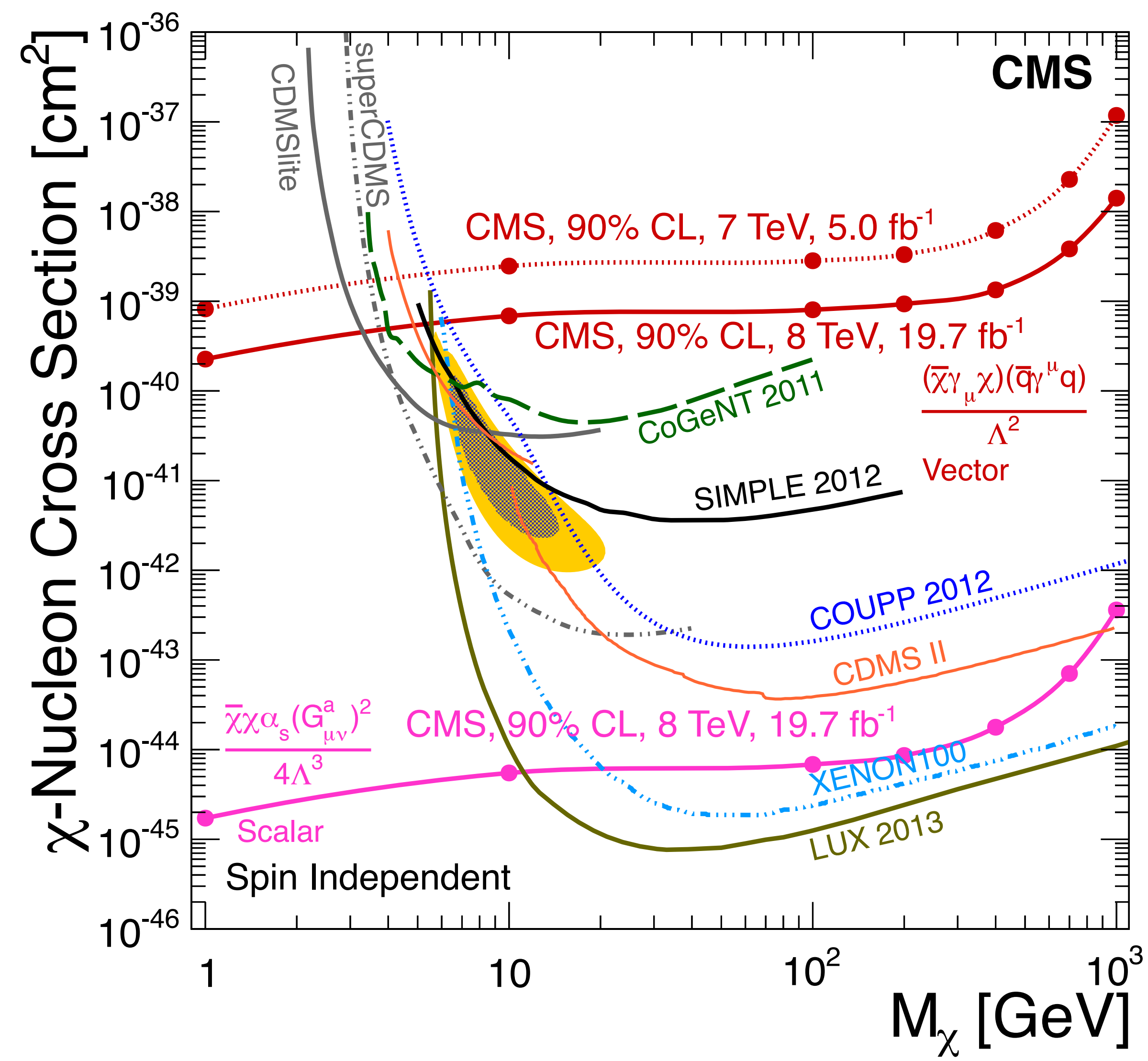
# Accelerator searches

- Dark matter particles can be directly produced in LHC collisions
- Mono-jet searches are particularly relevant




1 jet + missing energy

CMS Collaboration [1408.3583]

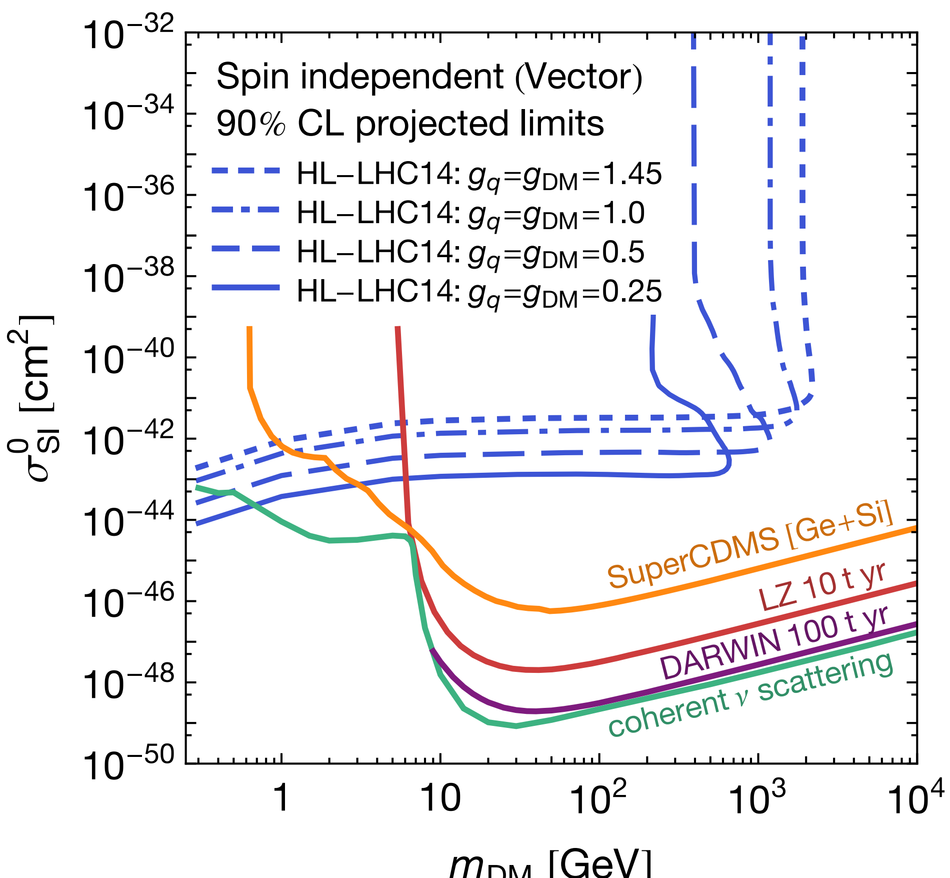


# Accelerator searches

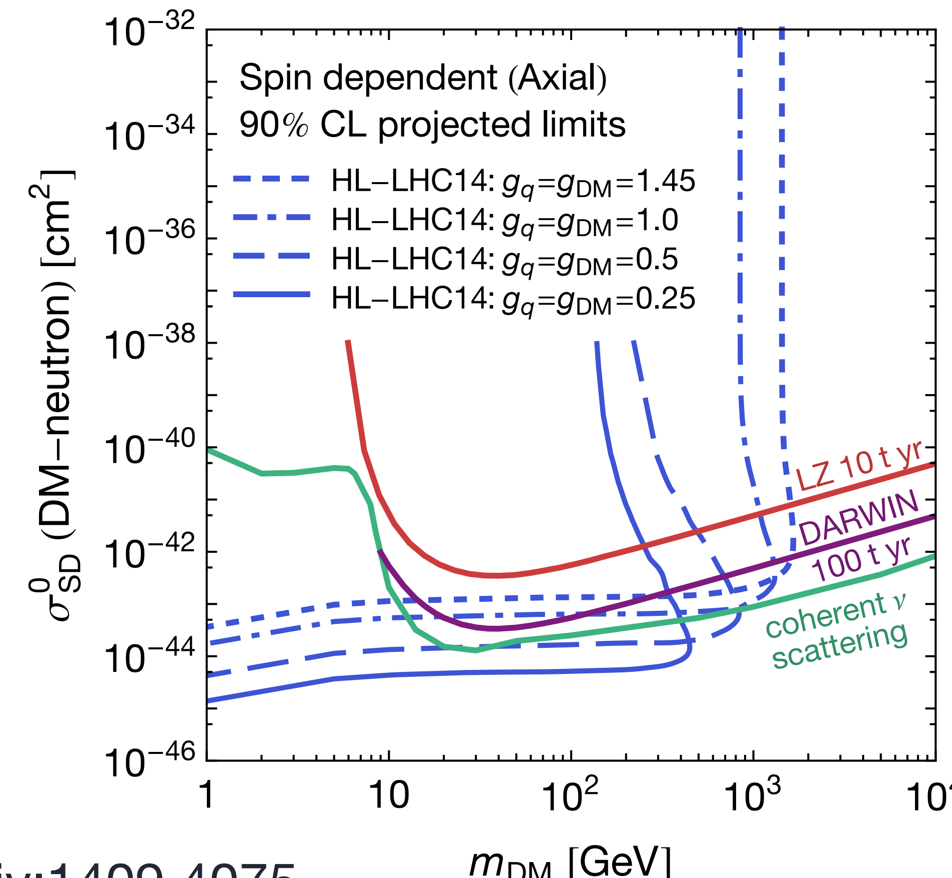
- Minimal simplified DM model with only 4 variables: $m_{DM}$, $M_{med}$, $g_{DM}$, $g_q$
- Here DM = Dirac fermion interacting with a vector or axial-vector mediator; equal-strength coupling to all active quark flavours

$$\sigma_{\mathrm{DD}} \propto \frac{g_{\mathrm{DM}}^2 g_q^2 \mu^2}{M_{\mathrm{med}}^4}$$

Spin independent




Spin dependent




S. Malik et al., arXiv:1409.4075

# Indirect detection

- Early universe: WIMPs are kept in equilibrium with SM particles via self-annihilation
- **Today: WIMPs expected to annihilate with the same cross section in regions where density is enhanced** $\Rightarrow \langle \sigma v \rangle \simeq 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$

$$\phi \propto n^2 \times \sigma$$

particle physics

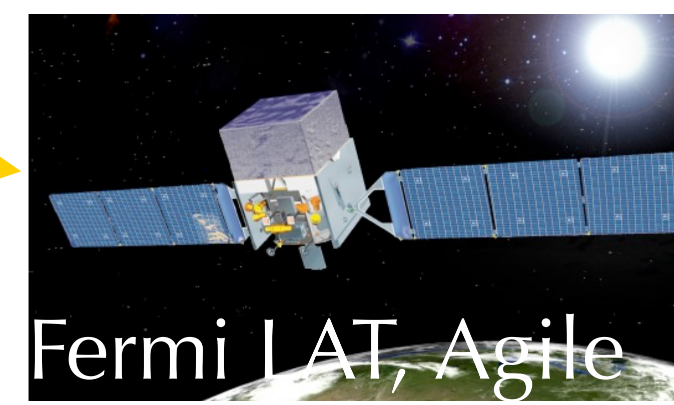
astrophysics

$\chi\bar{\chi}$

$\gamma$

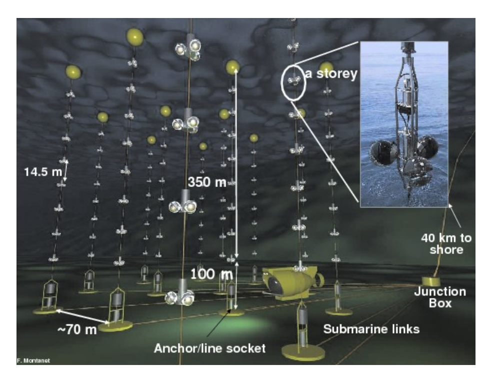
$\nu$

$e^+, e^-, p^+, p^-, \ldots$




+ ground based ACTs

AMS-02, PAMELA
CREAM




IceCube, Antares
KM3NET, SuperK

# Indirect detection goal

- Find an excess above the astrophysical background

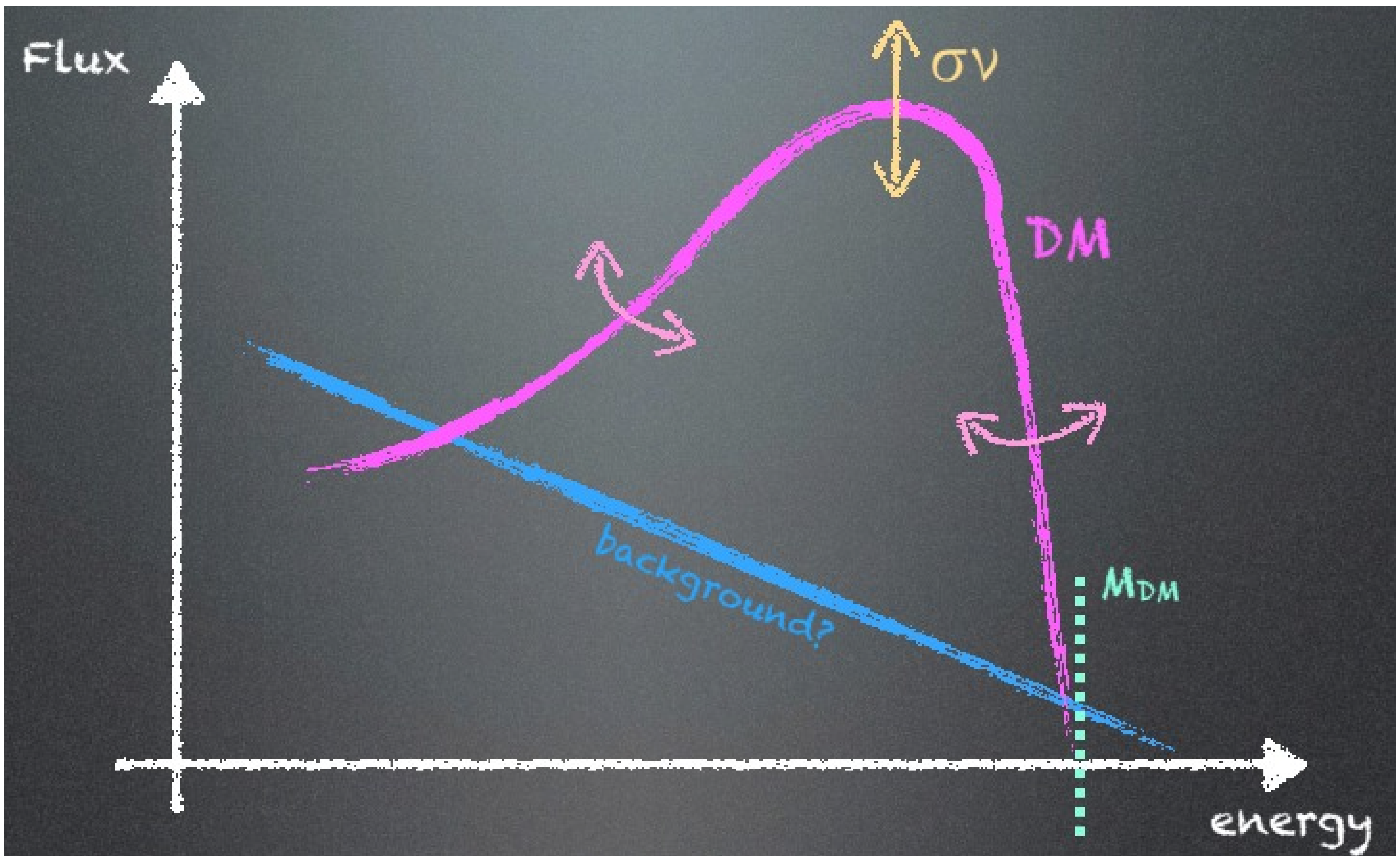
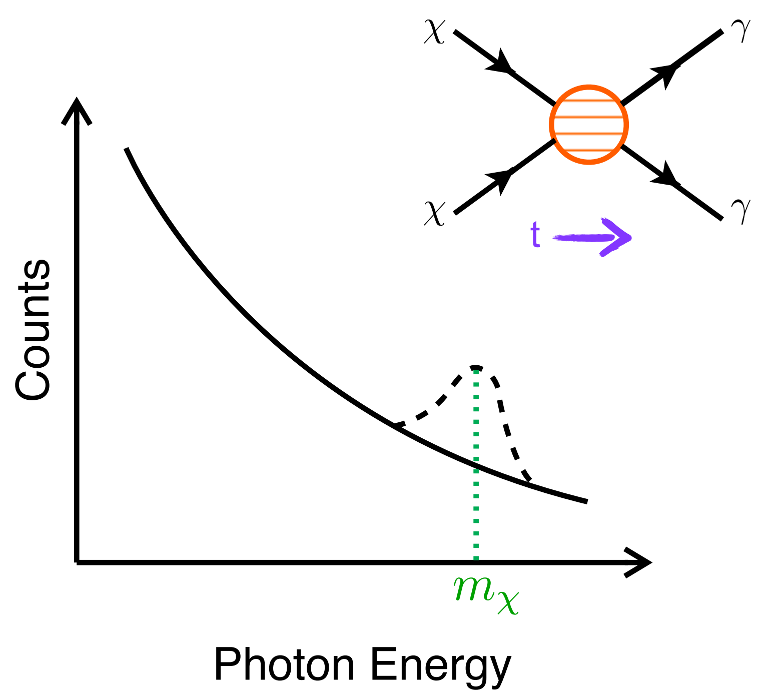


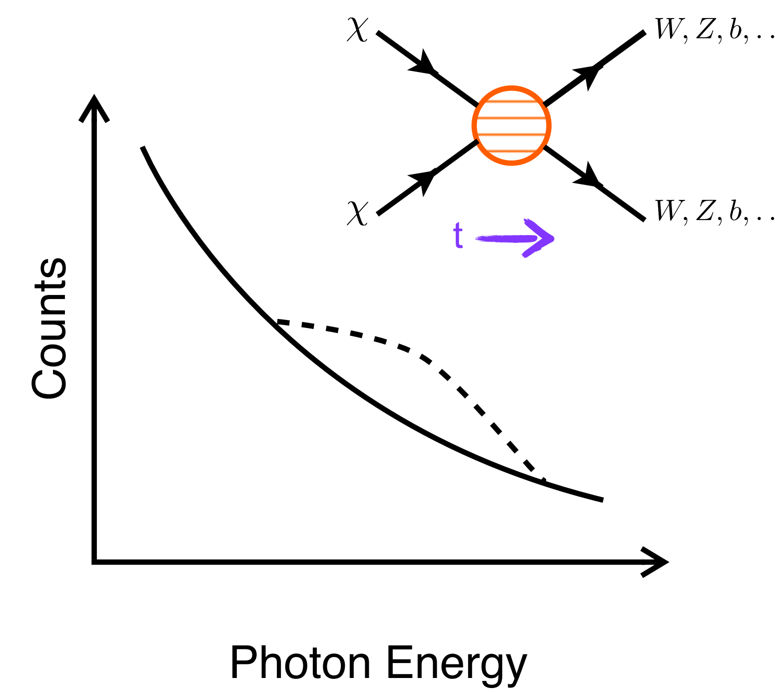

Figure by M. Cirelli

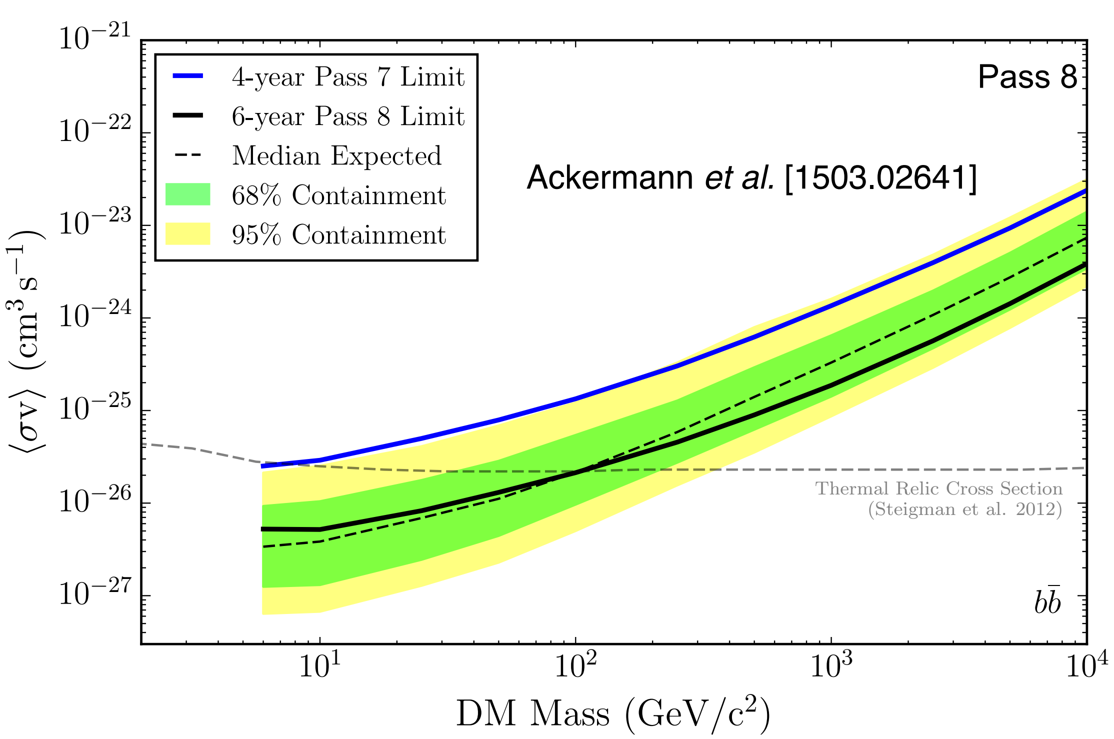
# Annihilation into photons

## Monochromatic




## Continuum



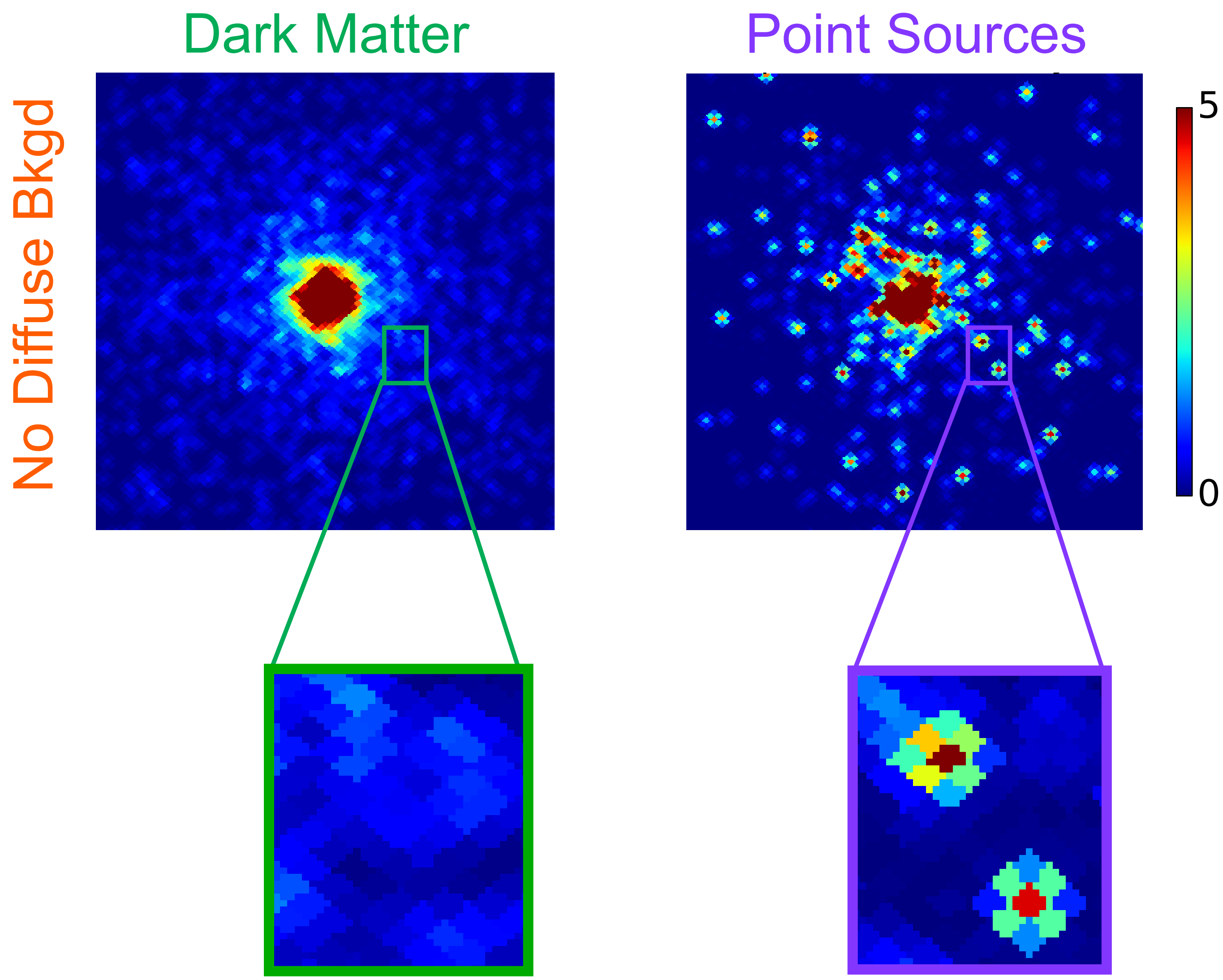




**FermiLAT: 6 years of data**

Search for gamma-ray emission from 15 dwarf spheroidal satellite galaxies

No signal; probing thermal relic annihilation cross section

# Gamma ray excess from Galactic Centre



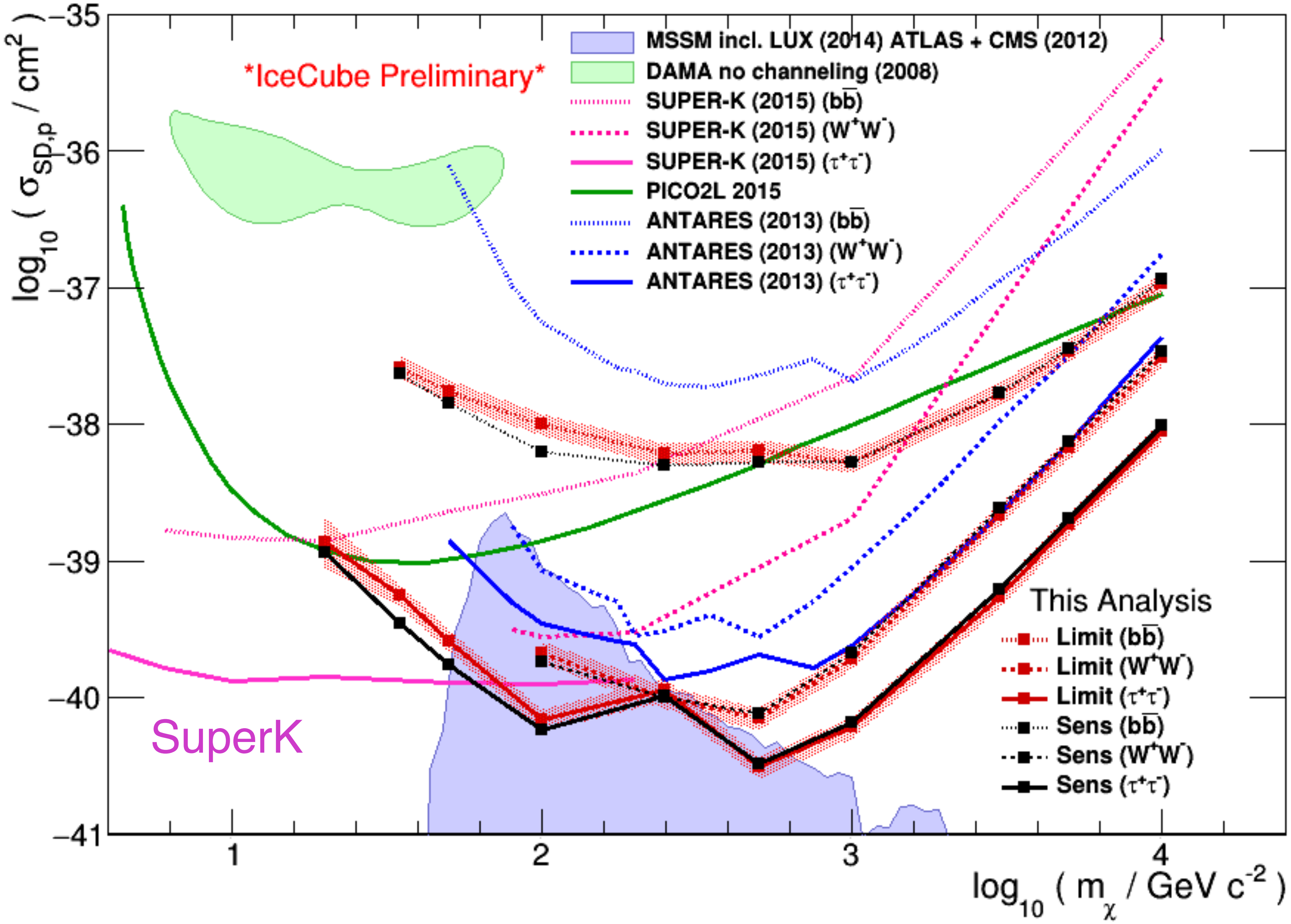

C. Weniger, SUSY 2015

| Channel | $\langle\sigma v\rangle$ $(10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1})$ | $m_\chi$ (GeV) | $\chi^2_{\mathrm{min}}$ | $p$-value |
|---|---|---|---|---|
| $\bar{q}q$ | $0.83^{+0.15}_{-0.13}$ | $23.8^{+3.2}_{-2.6}$ | 26.7 | 0.22 |
| $\bar{c}c$ | $1.24^{+0.15}_{-0.15}$ | $38.2^{+4.7}_{-3.9}$ | 23.6 | 0.37 |
| $\bar{b}b$ | $1.75^{+0.28}_{-0.26}$ | $48.7^{+6.4}_{-5.2}$ | 23.9 | 0.35 |
| $\bar{t}t$ | $5.8^{+0.8}_{-0.8}$ | $173.3^{+2.8}_{-0}$ | 43.9 | 0.003 |
| $gg$ | $2.16^{+0.35}_{-0.32}$ | $57.5^{+7.5}_{-6.3}$ | 24.5 | 0.32 |
| $W^+W^-$ | $3.52^{+0.48}_{-0.48}$ | $80.4^{+1.3}_{-0}$ | 36.7 | 0.026 |
| $ZZ$ | $4.12^{+0.55}_{-0.55}$ | $91.2^{+1.53}_{-0}$ | 35.3 | 0.036 |
| $hh$ | $5.33^{+0.68}_{-0.68}$ | $125.7^{+3.1}_{-0}$ | 29.5 | 0.13 |
| $\tau^+\tau^-$ | $0.337^{+0.047}_{-0.048}$ | $9.96^{+1.05}_{-0.91}$ | 33.5 | 0.055 |
| $[\mu^+\mu^-$ | $1.57^{+0.23}_{-0.23}$ | $5.23^{+0.22}_{-0.27}$ | 43.9 | $0.0036]_{\cancel{\mathrm{ICS}}}$ |

- Apparently consistent with dark matter annihilation
- But can also be explained by a population of unresolved point sources (for instance MSPs) -> use photon count statistics

# Annihilation into neutrinos

- High-energy neutrinos from WIMP capture and annihilation in the Sun (point-source)
- Sun is made of protons => strong constraints on SD WIMP-p interactions




IceCube collab.
86 strings
ICRC2015

# Annihilation into antiprotons

- $\bar{p}/p$ ratio measured by AMS-02
- Cosmic ray background uncertainties matter (cross section, primaries, propagation, …)

No excess above astrophysical background, when uncertainties are considered

AMS-02 CERN press release, 2015

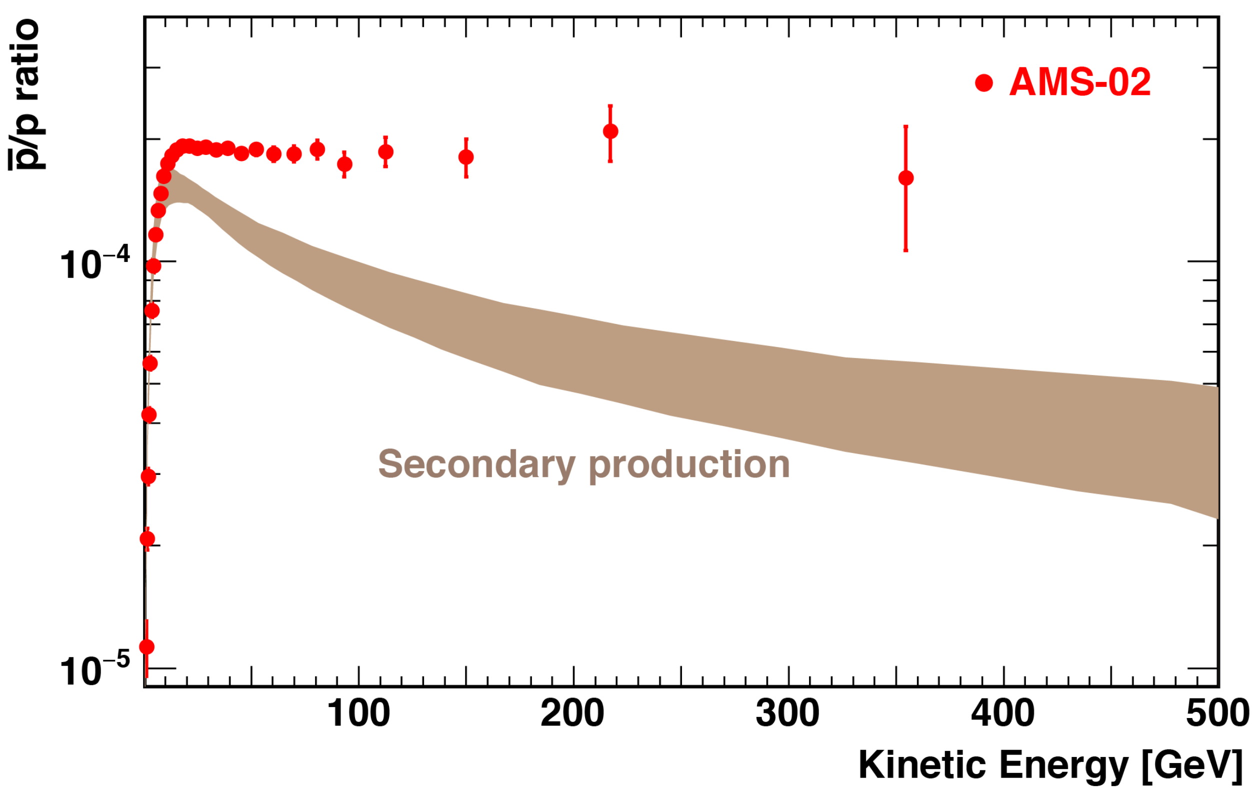
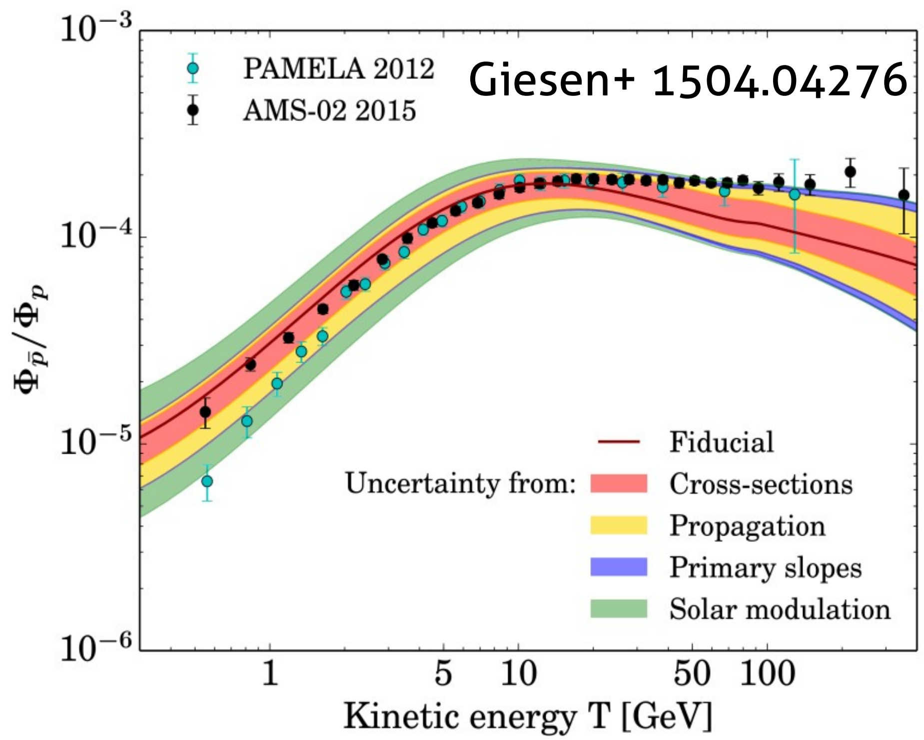
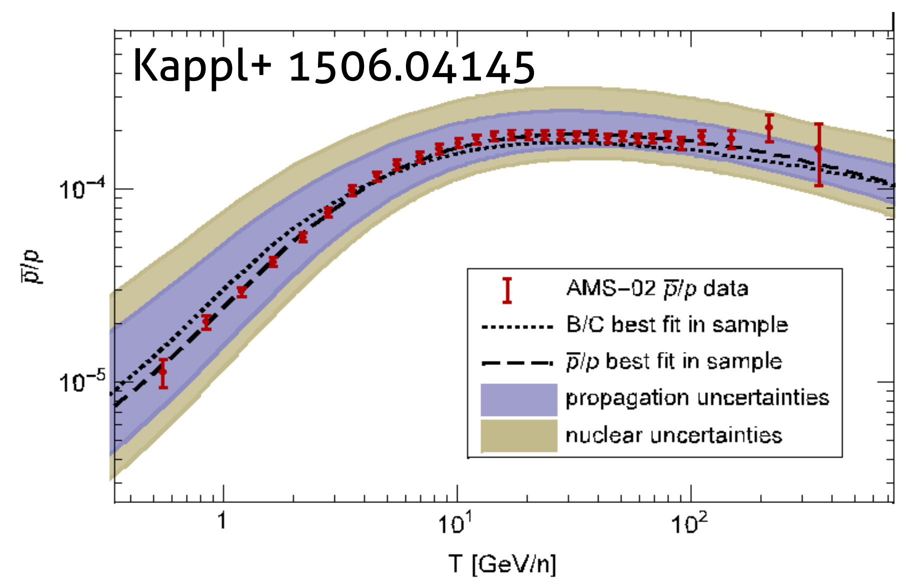



*Figure 1. Antiproton to proton ratio measured by AMS. As seen, the measured ratio cannot be explained by existing models of secondary production.*



# Conclusions

Dark matter detection experiments have reached tremendous sensitivities

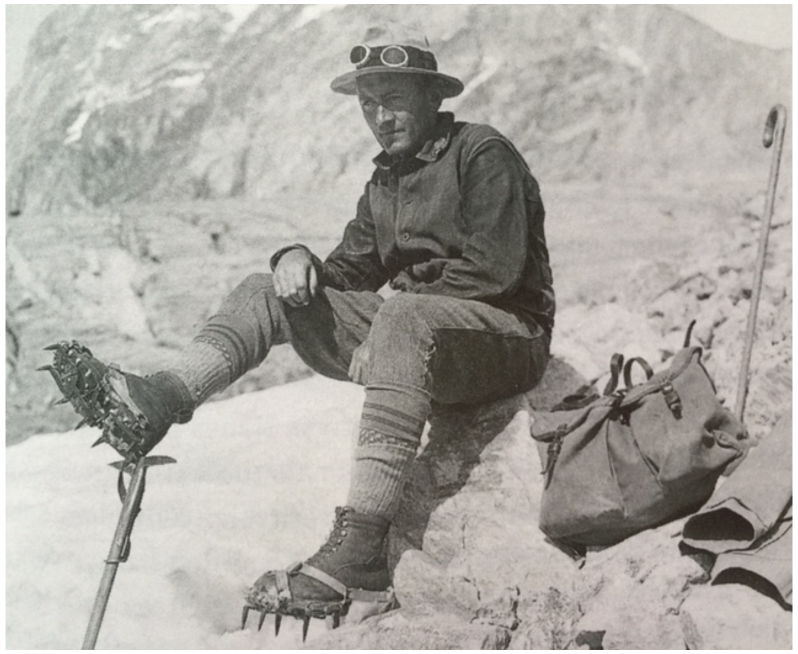
direct detection: probe cross sections down to $10^{-45}$ cm$^2$ at WIMP masses ~ 50 GeV

indirect detection: probe thermal relic annihilation cross section

searches are complementary with the LHC reach

& test various other particle candidates

Excellent prospects for discovery in the next years



from “Fritz Zwicky, Astrophysiker”, Verlag NZZ

Of course, “the probability of success is difficult to estimate, but if we never search, the chance of success is zero”

G. Cocconi & P. Morrison, Nature, 1959

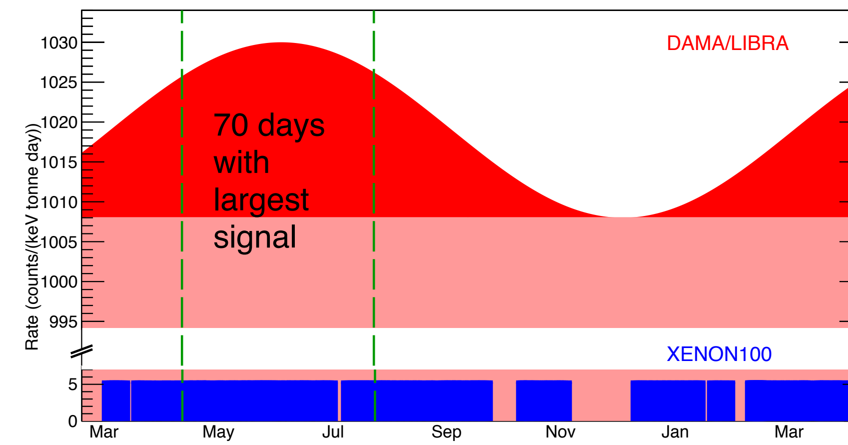
# The end

# New XENON100 results

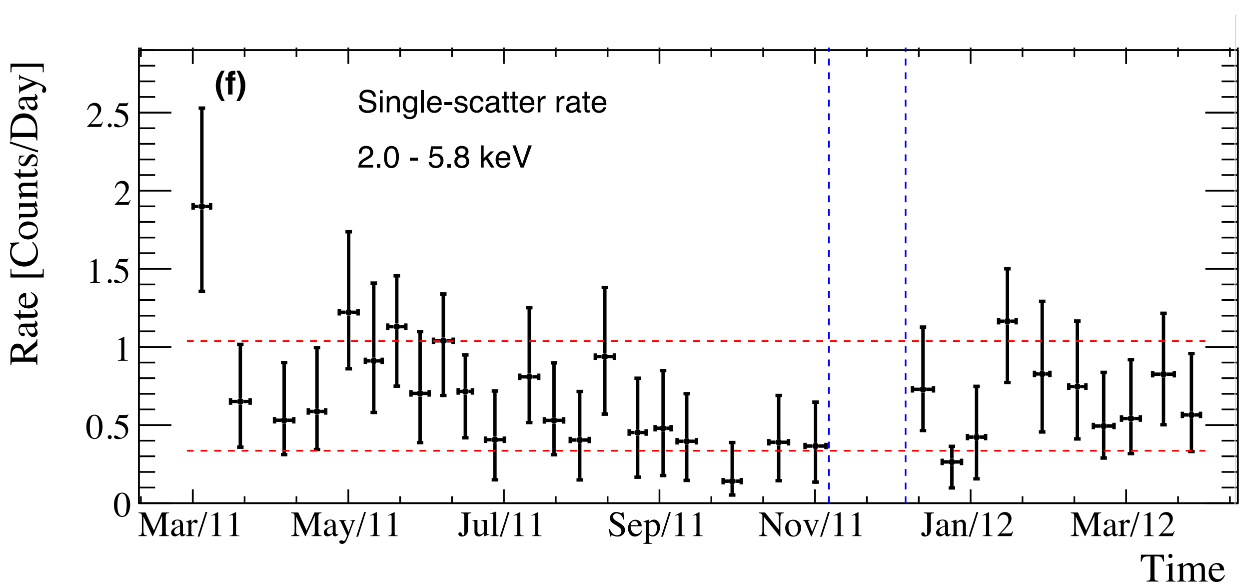
- Dark matter particles interacting with e⁻

    1. search for periodic variations of the ER rate in the 2-6 keV region

    2. search for a signal above background in the ER spectrum (use the average ER event rate)

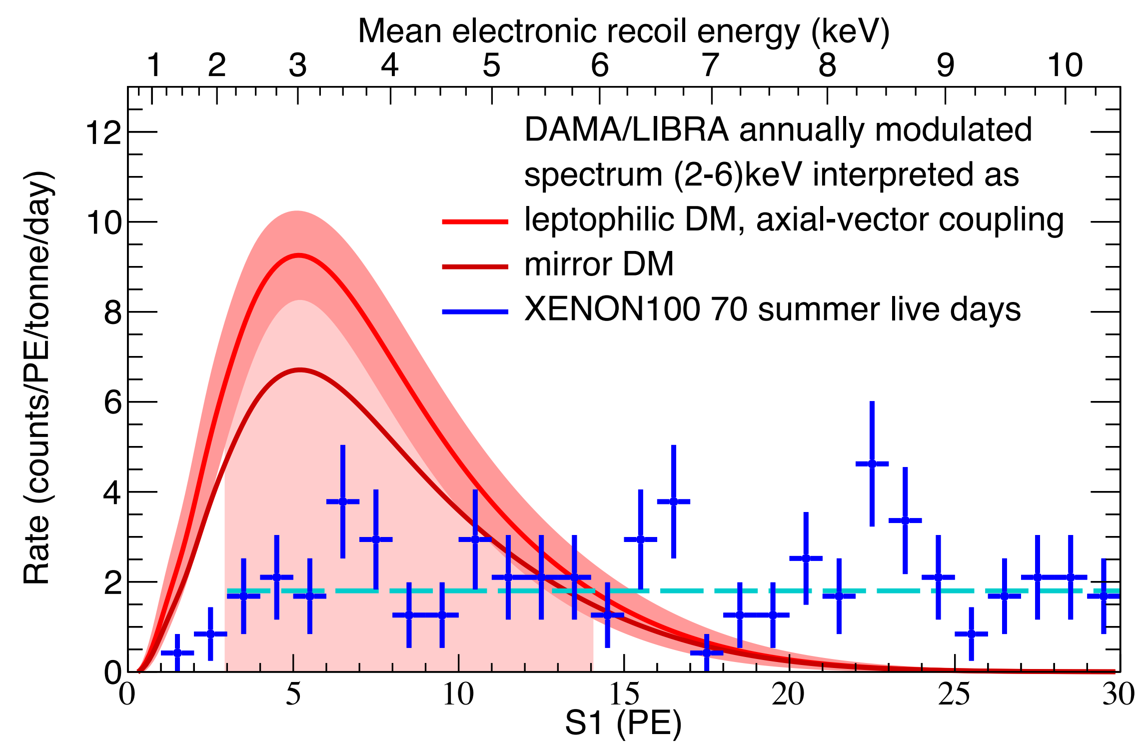



**1. XENON collaboration, arXiv: 1507.07748 (accepted in PRL)**




Electronic recoil event rate in 34 kg LXe for single-scatters versus time (many other detector parameters monitored as well)

**2. XENON collaboration, arXiv: 1507.07747 (accepted in Science)**




DAMA/LIBRA modulated spectrum as would be seen in XENON100 (for axial-vector WIMP-$e^-$ scattering)

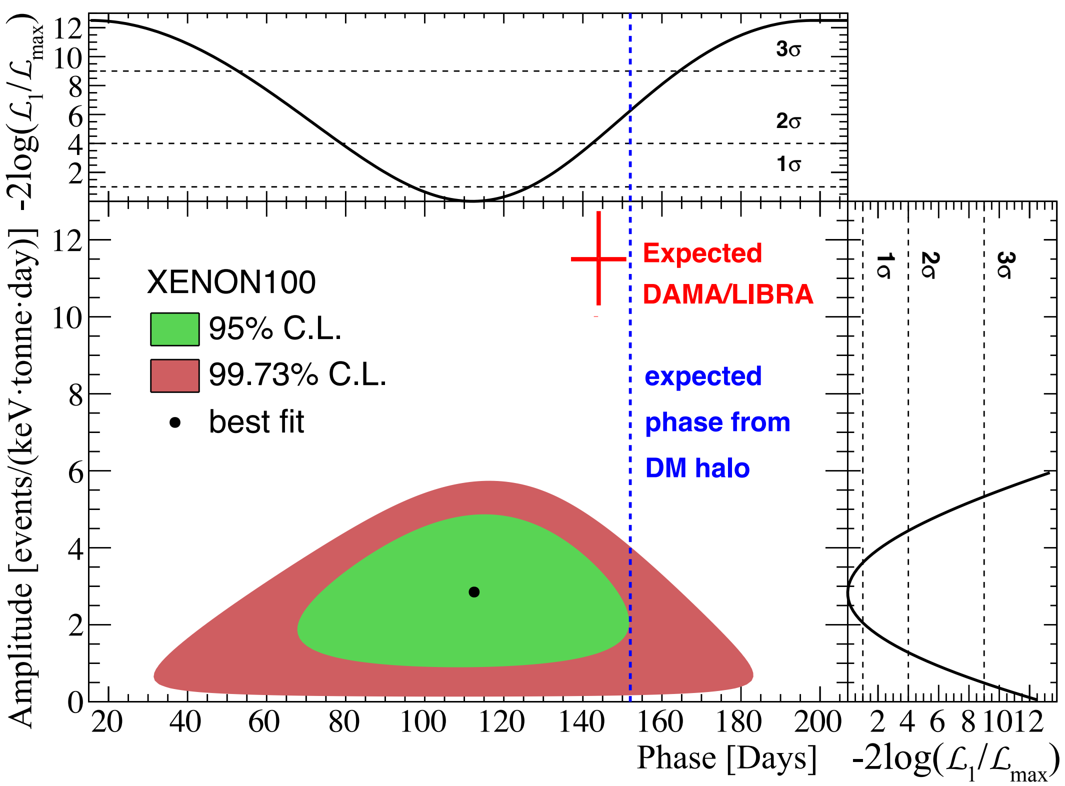
# New XENON100 results

- Dark matter particles interacting with $e^-$

1. search for periodic variations of the ER rate in the 2-6 keV region

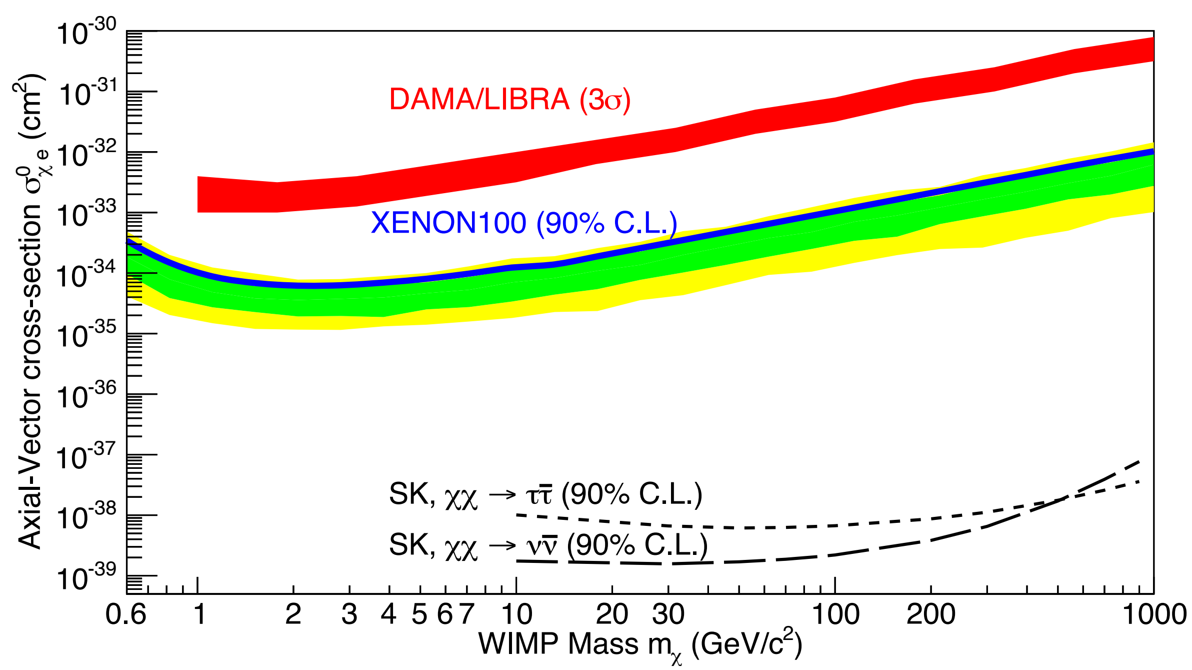
2. search for a signal above background in the ER spectrum (use the average ER event rate)

**1. XENON collaboration, arXiv: 1507.07748 (accepted in PRL)**




Disfavour interpretation of DAMA/LIBRA annual modulation signal as due to WIMP-e- axial-vector scattering ar 4.8 sigma

**2. XENON collaboration, arXiv: 1507.07747 (accepted in Science)**



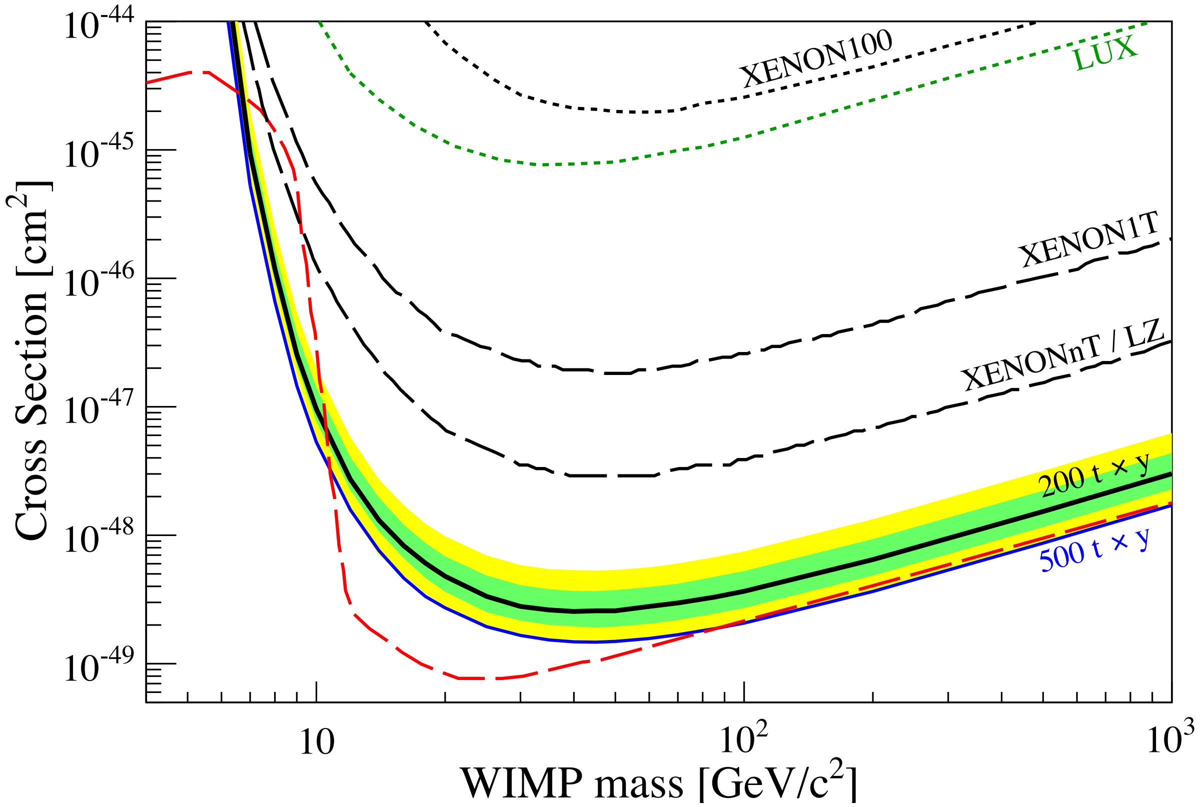

No evidence for a signal; exclude leptophilic models as explanation for DAMA/LIBRA

# DARWIN WIMP sensitivity

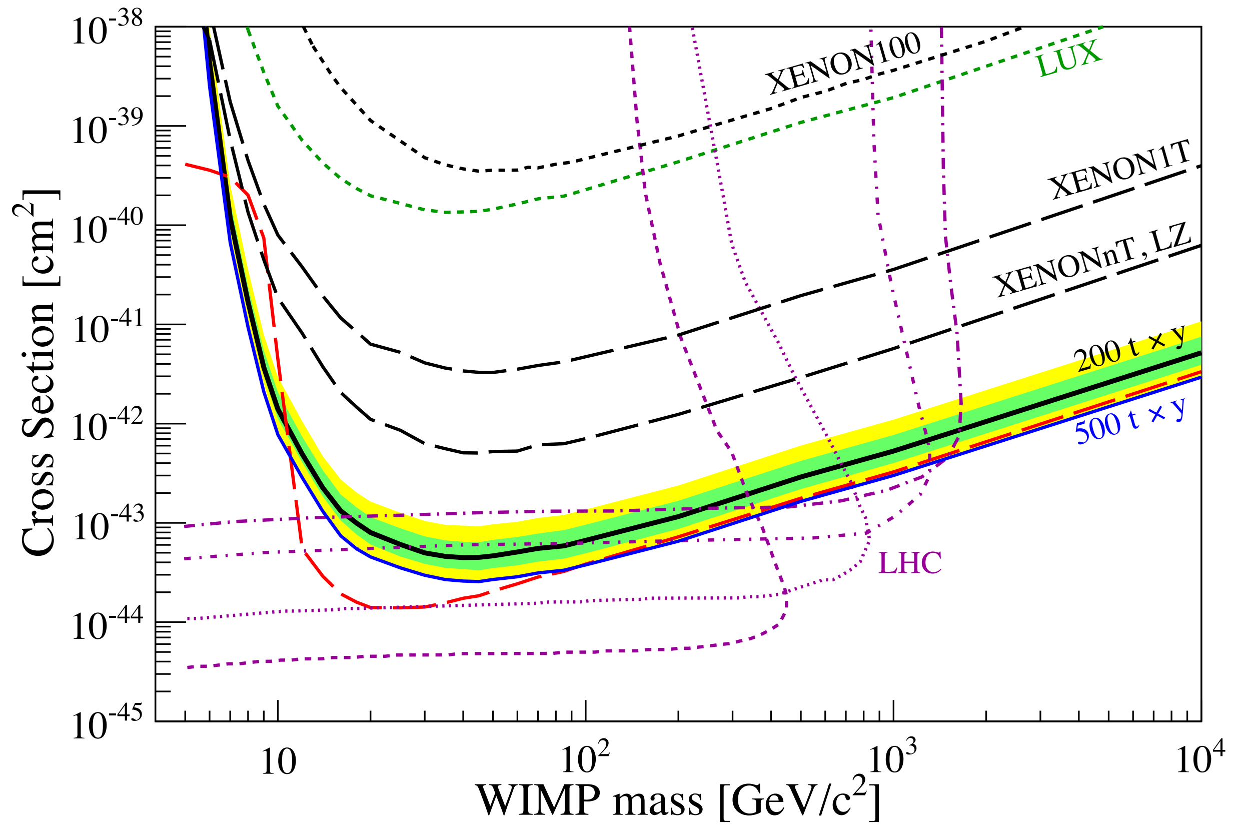
- E = [5-35] $keV_{nr}$

99.98% discrimination, 30% NR acceptance, LY = 8 pe/keV at 122 keV

Spin-independent



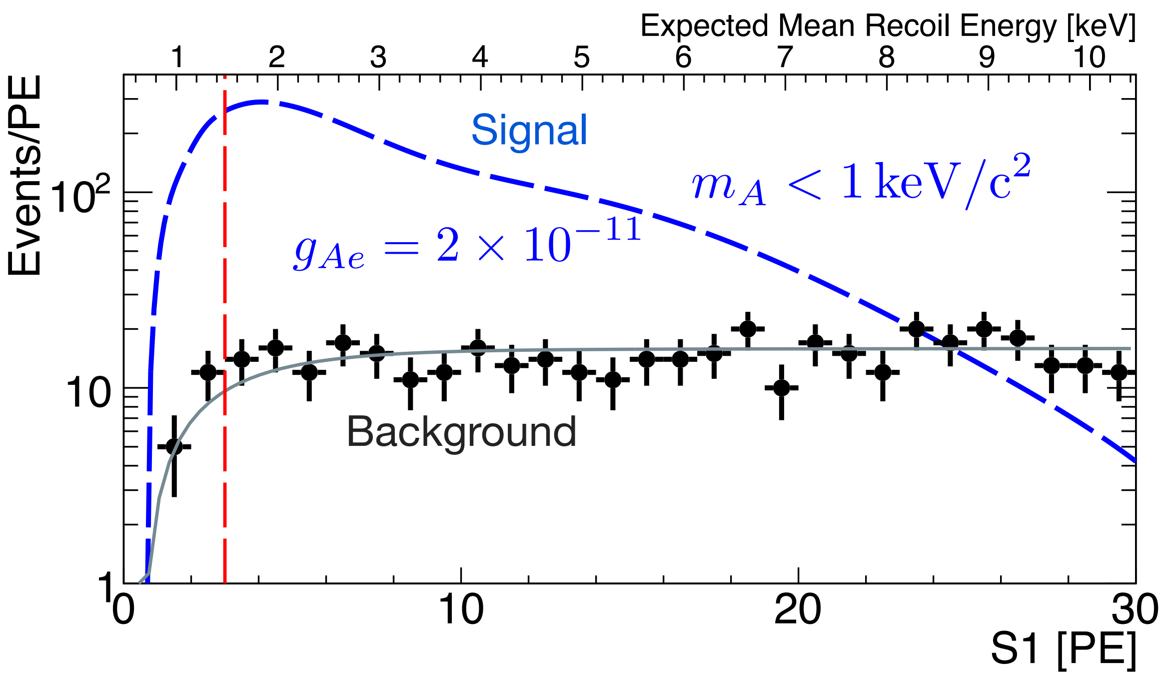

Spin-dependent

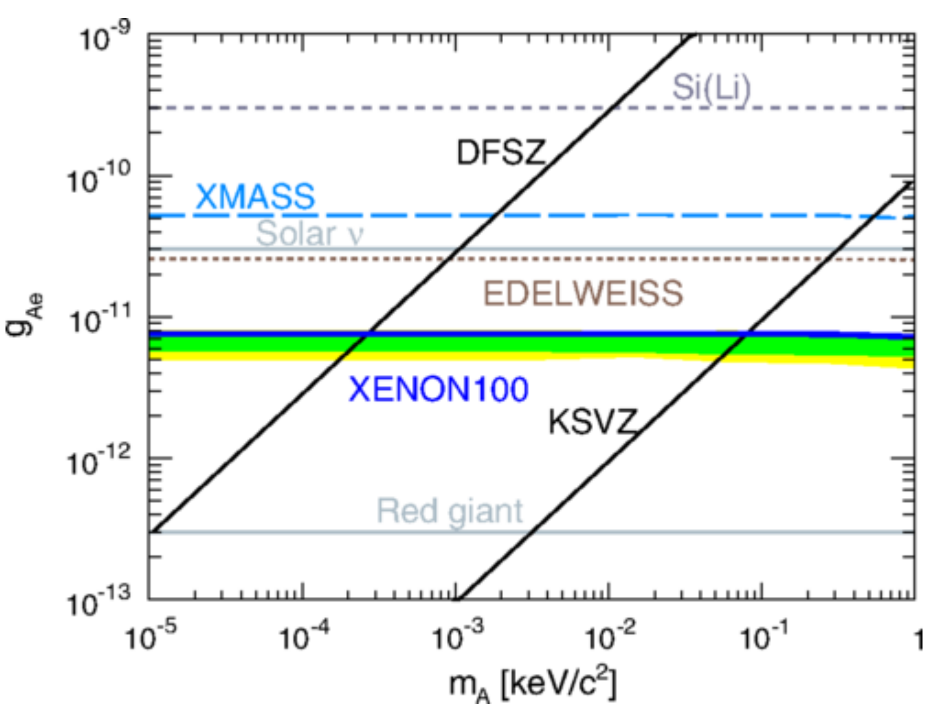



arXiv:1506.08309, JCAP 2015

Note: “nu floor” = 3-sigma detection line at 500 CNNS events above 4 keV

# Example: Solar axions with XENON100




Look for solar axions via their couplings to electrons, $g_{Ae}$, through the axio-electric effect

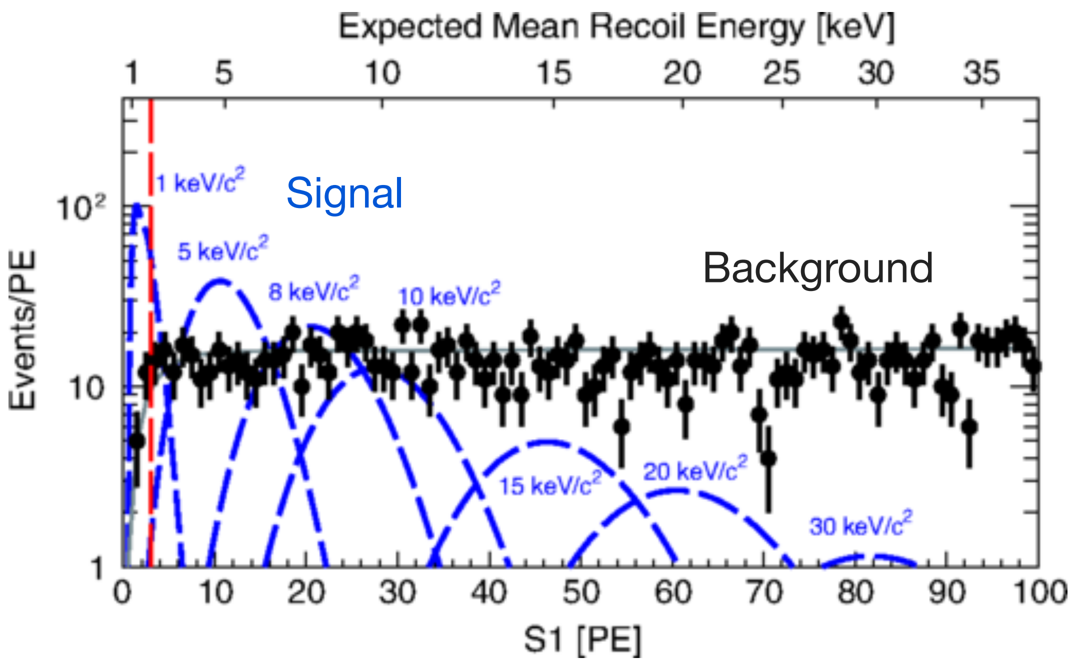
$$\sigma_{Ae} = \sigma_{pe}(E_A)\frac{g_{Ae}^2}{\beta_A}\frac{3E_A^2}{16\pi\alpha_{em}m_e^2}\left(1 - \frac{\beta_A^{2/3}}{3}\right)$$

$$\phi_A \propto g_{Ae}^2 \implies R \propto g_{Ae}^4$$

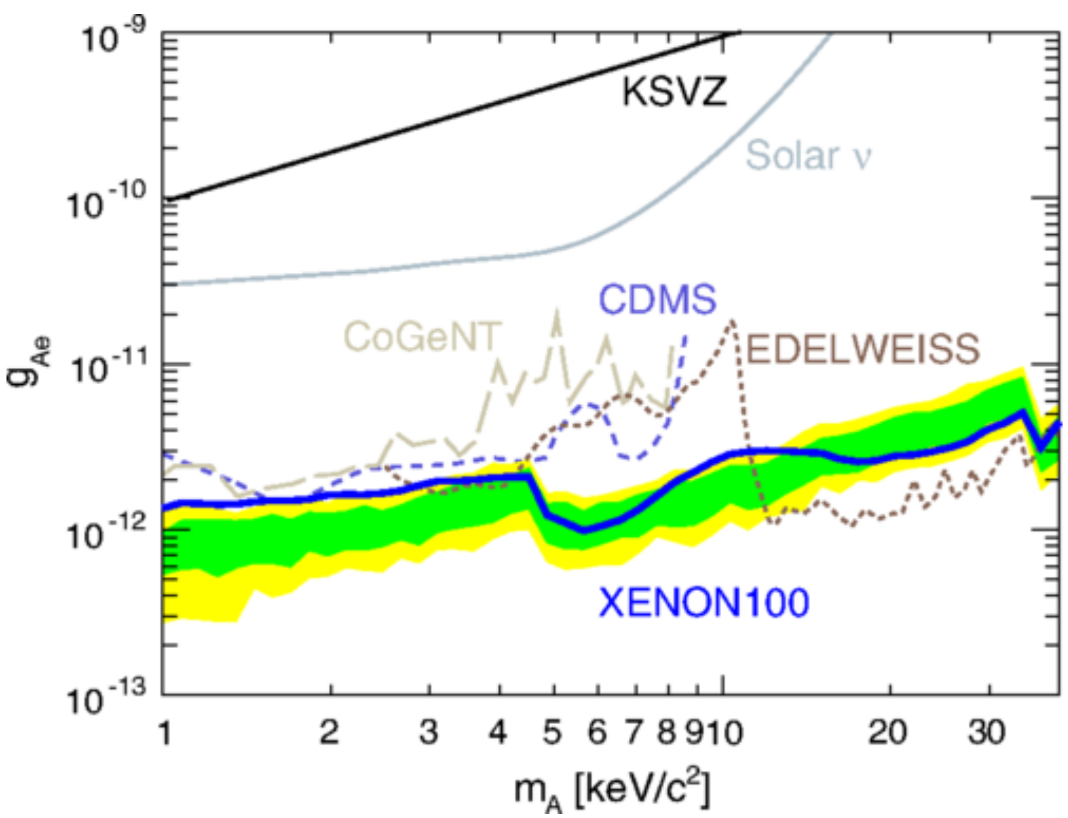
- XEON100: based on 224.6 live days x 34 kg exposure; using the electronic-recoil spectrum, and measured light yield for low-energy ERs (LB et al., PRD 87, 2013; arXiv:1303.6891)

XENON, Phys. Rev. D 90, 062009 (2014)

# Example: Galactic axion-like particles with XENON100




XENON, Phys. Rev. D 90, 062009 (2014)




Look for ALPs via their couplings to electrons, $g_{Ae}$, through the axio-electric effect

Expect line feature at ALP mass

Assume $\rho_0 = 0.3\,\mathrm{GeV/cm^3}$

$$\phi_A = c\beta_A \times \frac{\rho_0}{m_A}$$

$$R \propto g_{Ae}^2$$

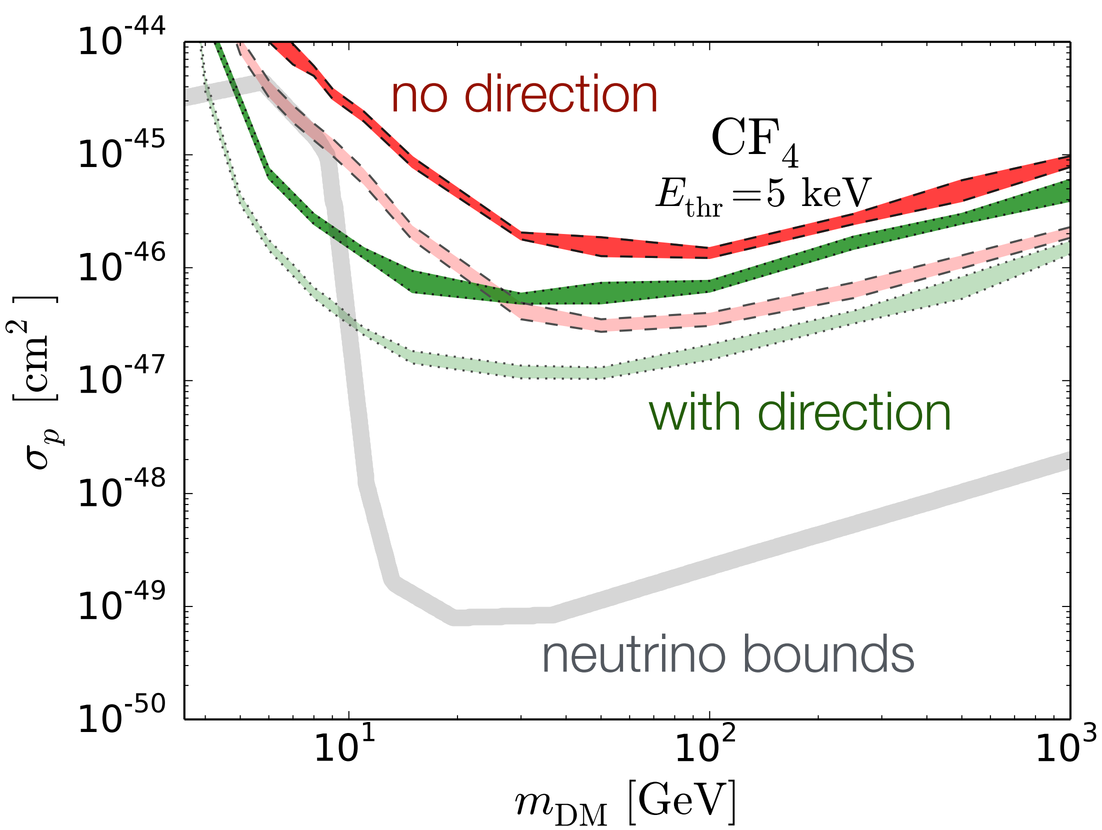
- XEON100: based on 224.6 live days x 34 kg exposure; using the electronic-recoil spectrum, and measured light yield for low-energy ERs (LB et al., PRD 87, 2013; arXiv:1303.6891)

XENON, Phys. Rev. D 90, 062009 (2014)

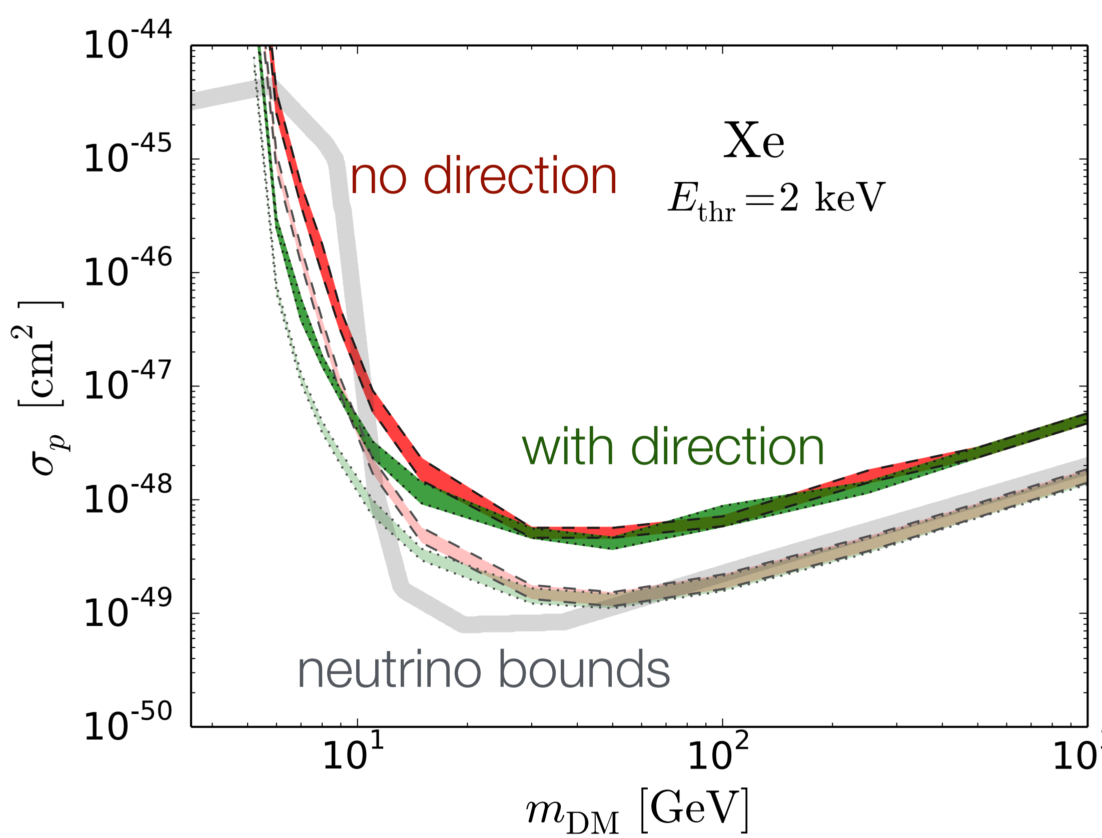
# Will directional information help?

- Yes, but mostly at low WIMP masses
- Directional detection techniques currently in R&D phase
- Would be very challenging to reach $10^{-48}$ - $10^{-49}$ $cm^2$ with these techniques

36.6 t yr exposure, 500 (solar) nu events




367 t yr exposure, 500 nu events




P. Grothaus, M. Fairbairn, J. Monroe, arXiv: 1406.5047