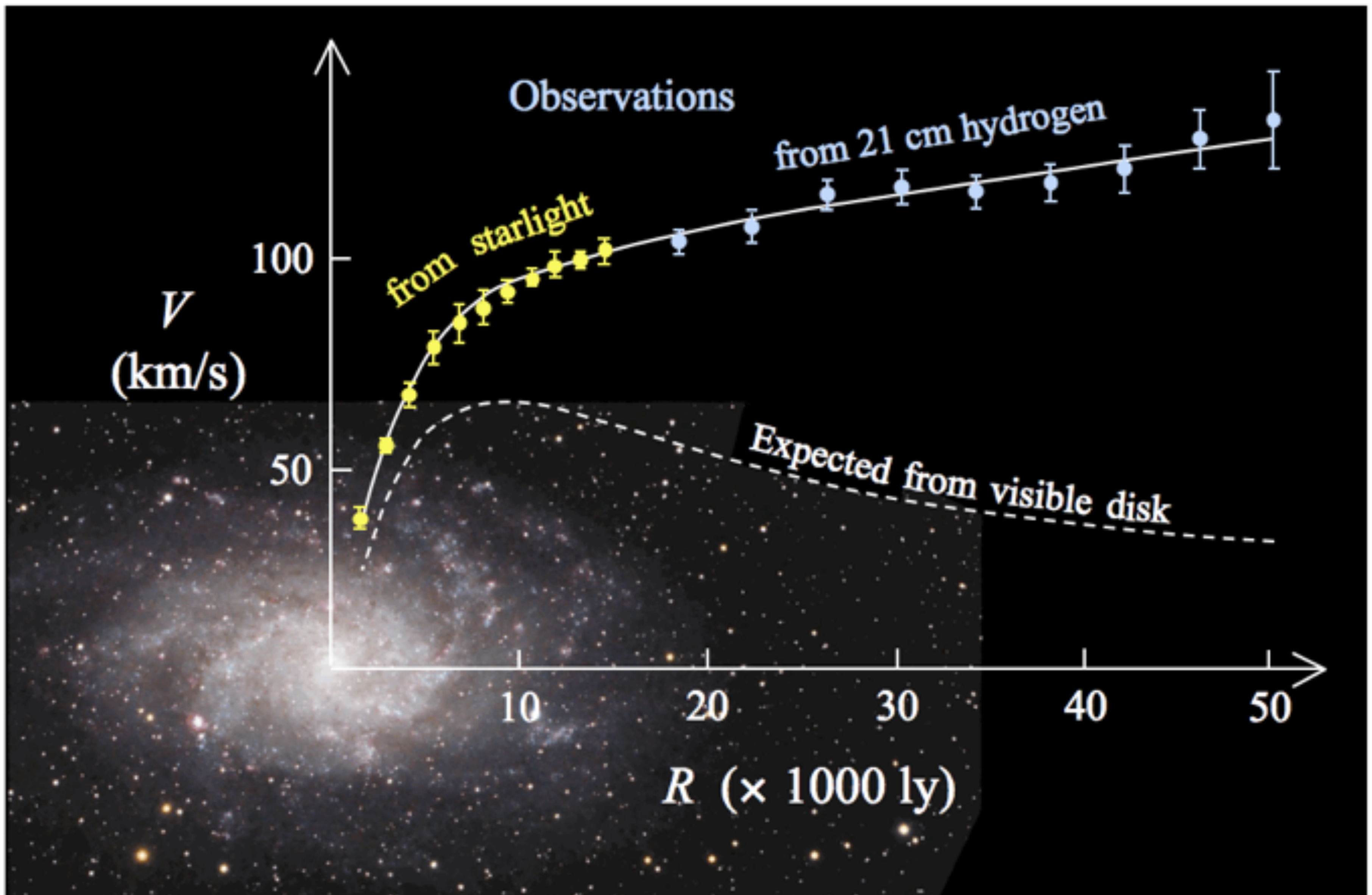
State-of-the art in the search of dark matter

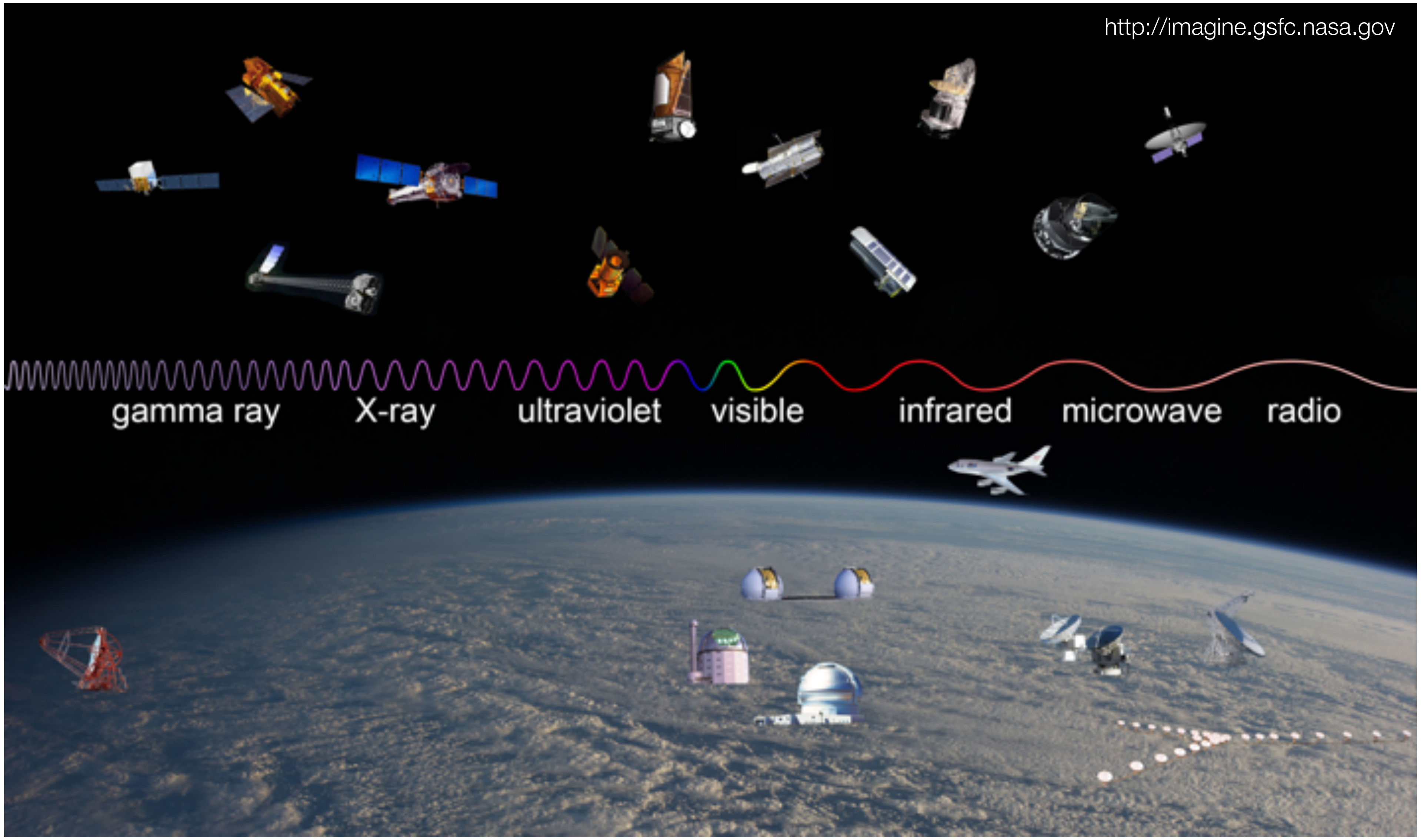


Marcello Messina
Columbia University

CYGNUS-TPC Kick off meeting, 07/04/2016, Frascati.

The nebulous band of the Milky Way

- With today's telescopes, we can observe the Milky Way (*and our Universe*) using light not only on the visible region, but in many different wavelengths
- **However, one of its major components - *the dark matter* - is not directly visible**



Dark matter: a brief history

- **1922: Jacobus 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: Jan 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)*

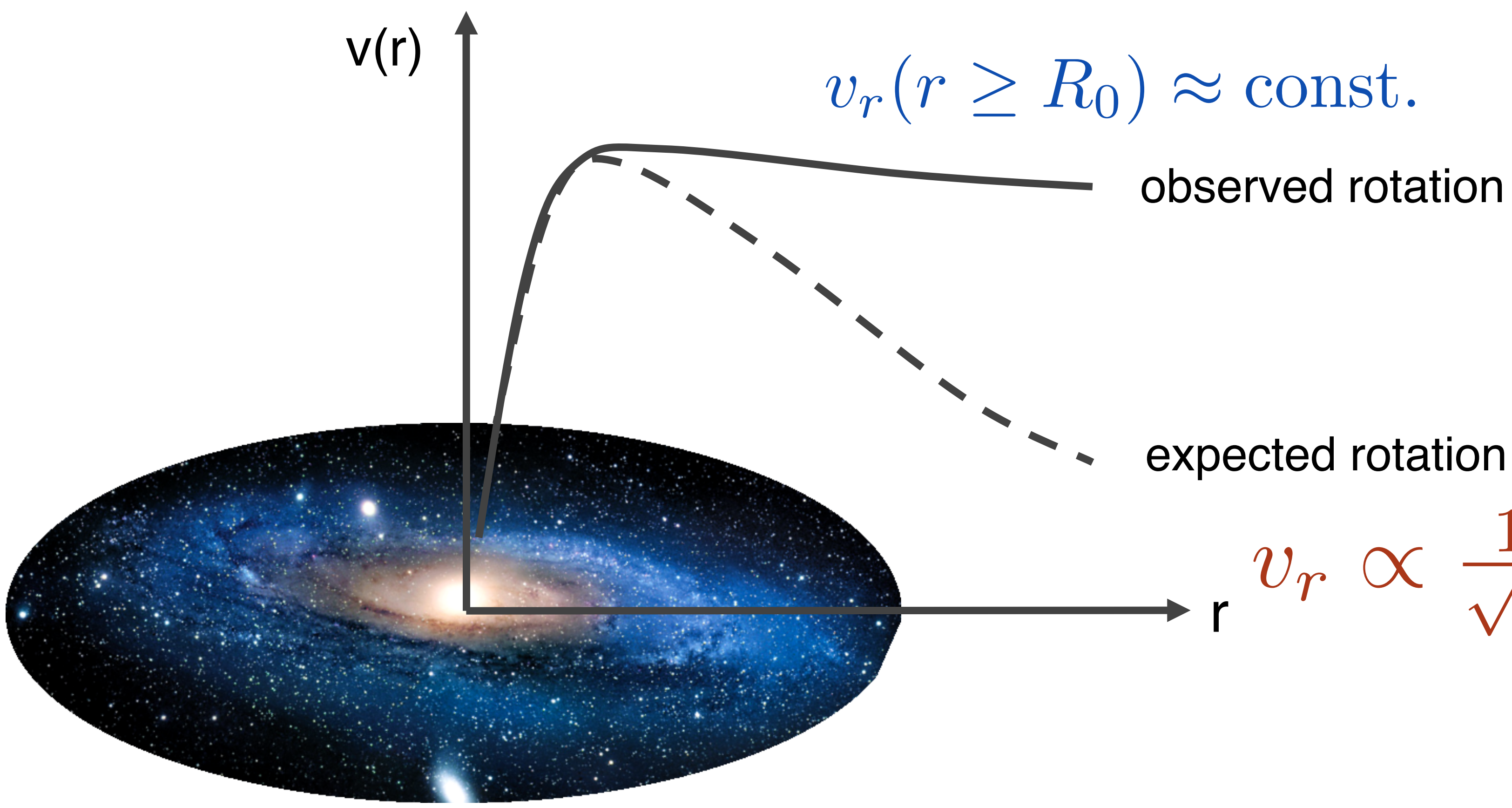
- **1933: F. Zwicky found *'dunkle Materie'* in the Coma cluster - *the redshift of galaxies were much larger than the escape velocity due to luminous matter alone***

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.

Dark matter: a brief history

- **1970s:** V.C. Rubin & W. Ford: flat optical rotation curves of spiral galaxies

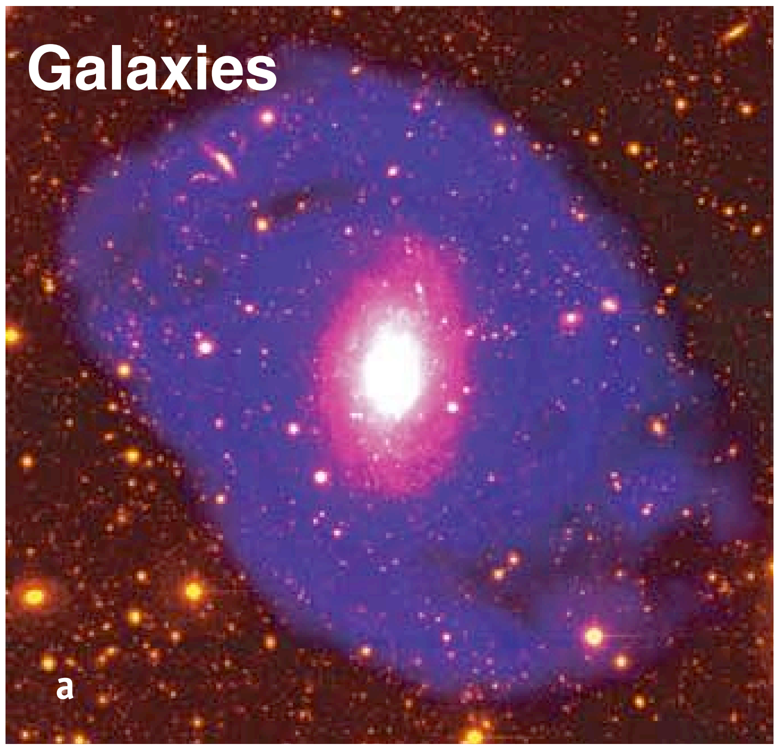


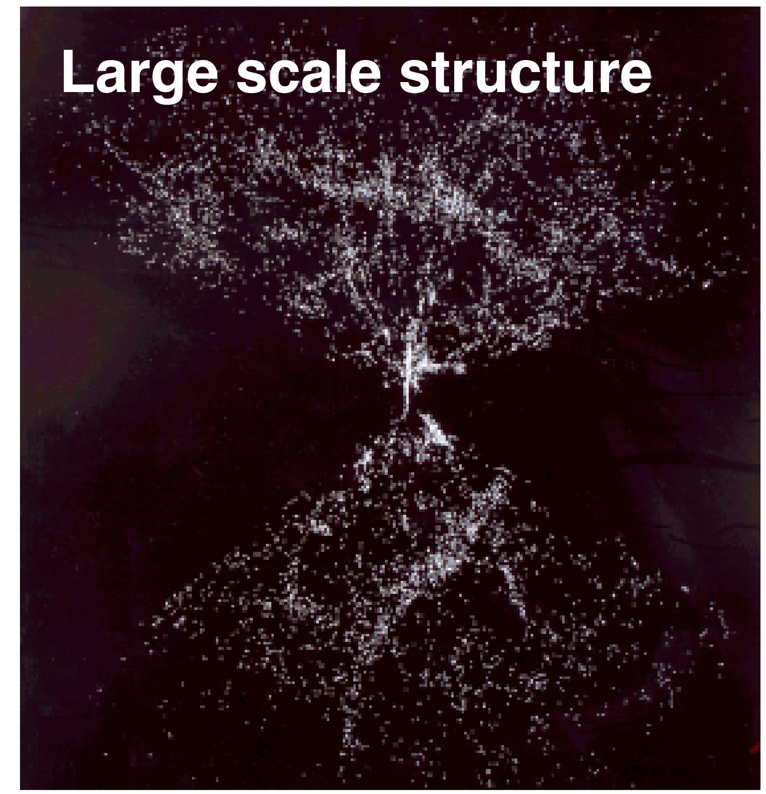
$$v_r(r \geq R_0) \approx \text{const.}$$

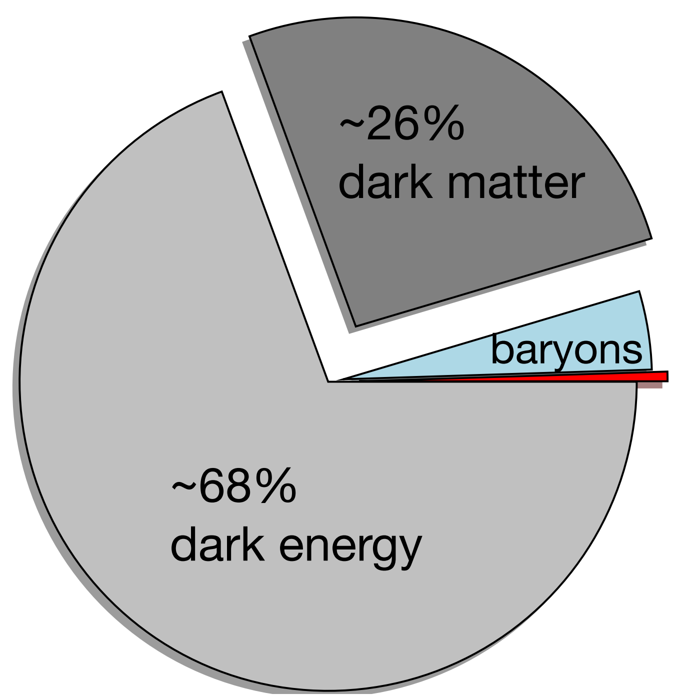
$$v_r \propto \frac{1}{\sqrt{r}}$$

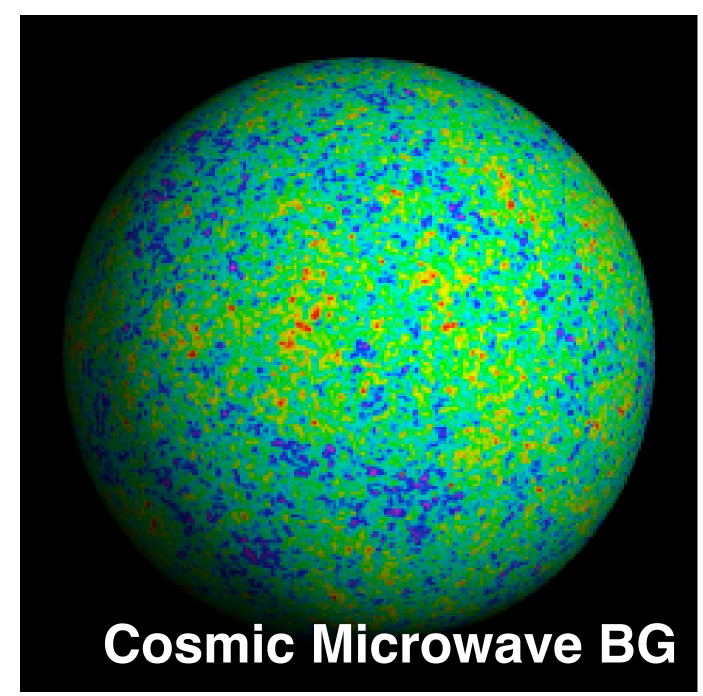
$$\Longrightarrow M_r \propto r$$

Our Universe today: apparently consistent picture from an impressive number of observations









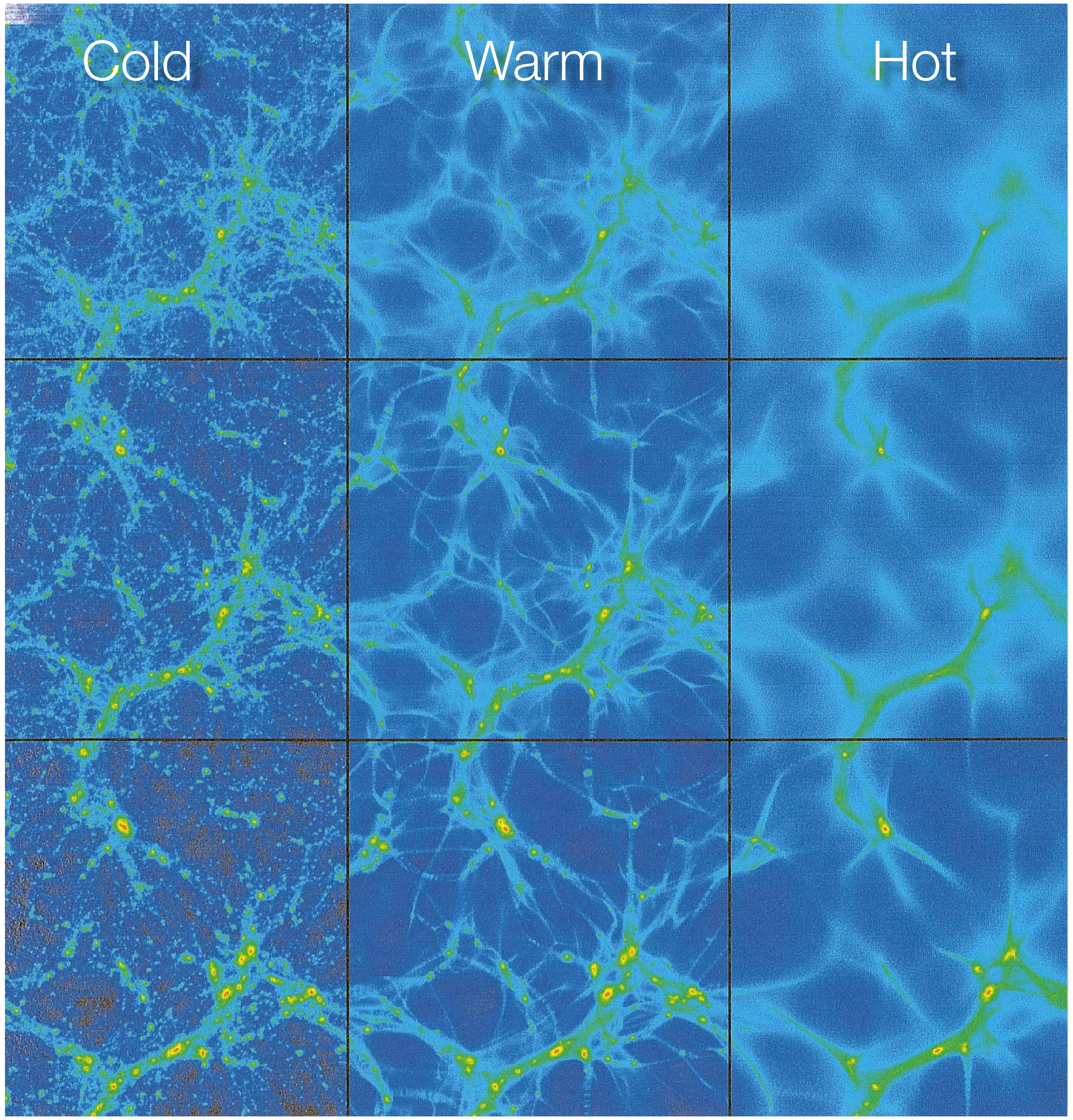
What do we know about the dark matter?

Exists today and in the early Universe

Constraints from astrophysics and searches for new particles:

- No colour charge
- No electric charge
- No strong self-interaction
- Was slow-moving (non-relativistic) as large-scale structures were forming

Stable, or very long-lived

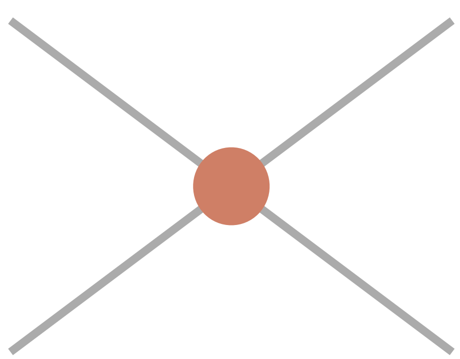


Probing dark matter through gravity

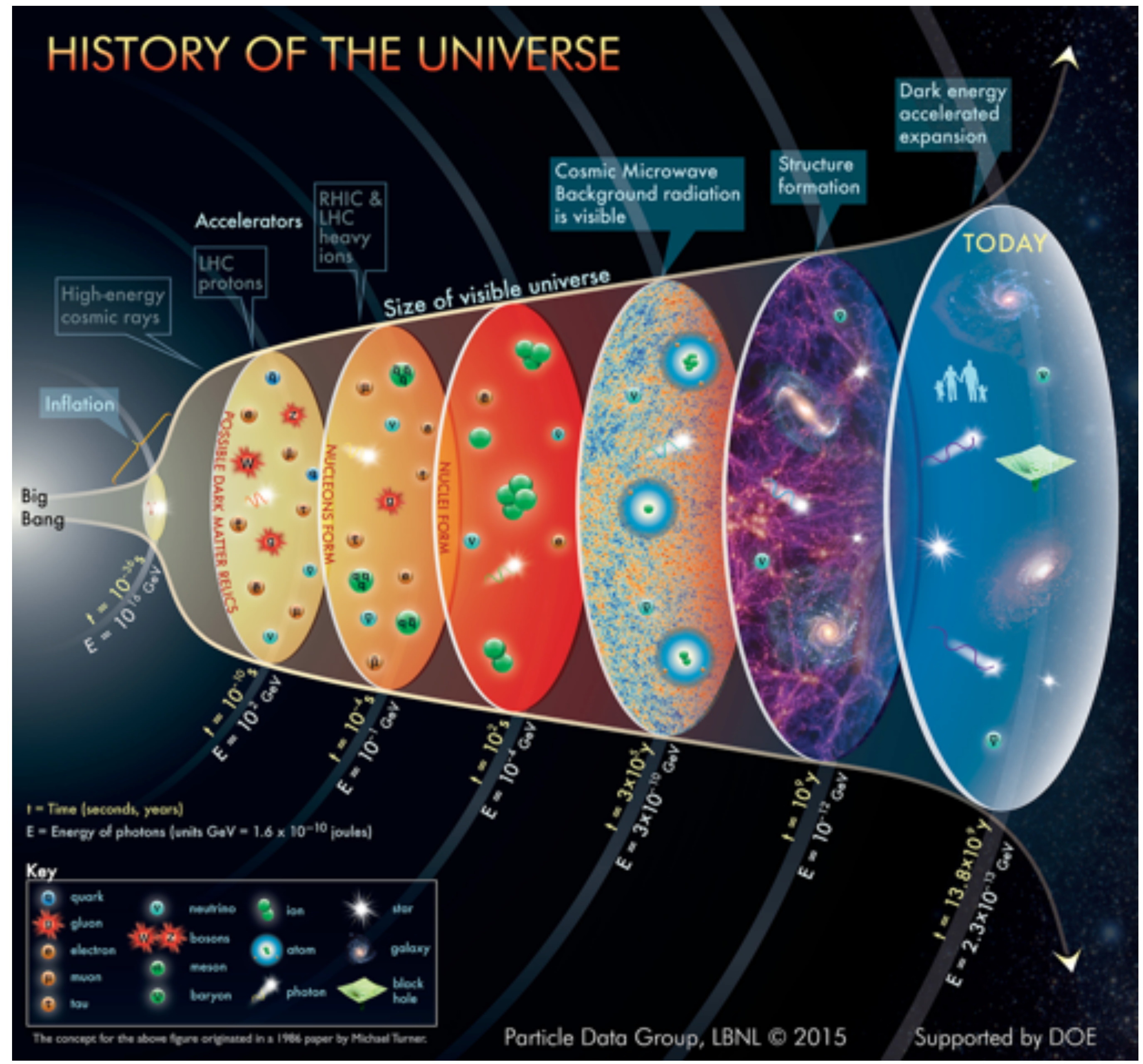
What could the dark matter be?

- Leading hypothesis: a 'thermal relic' from an early period in our Universe
- when the average temperature was $T \sim 10^{15}$ K ~ 100 GeV
- While no particle in the Standard Model is a viable candidate, our young Universe was hot enough to create new, massive particles:

quarks
leptons
photons
…

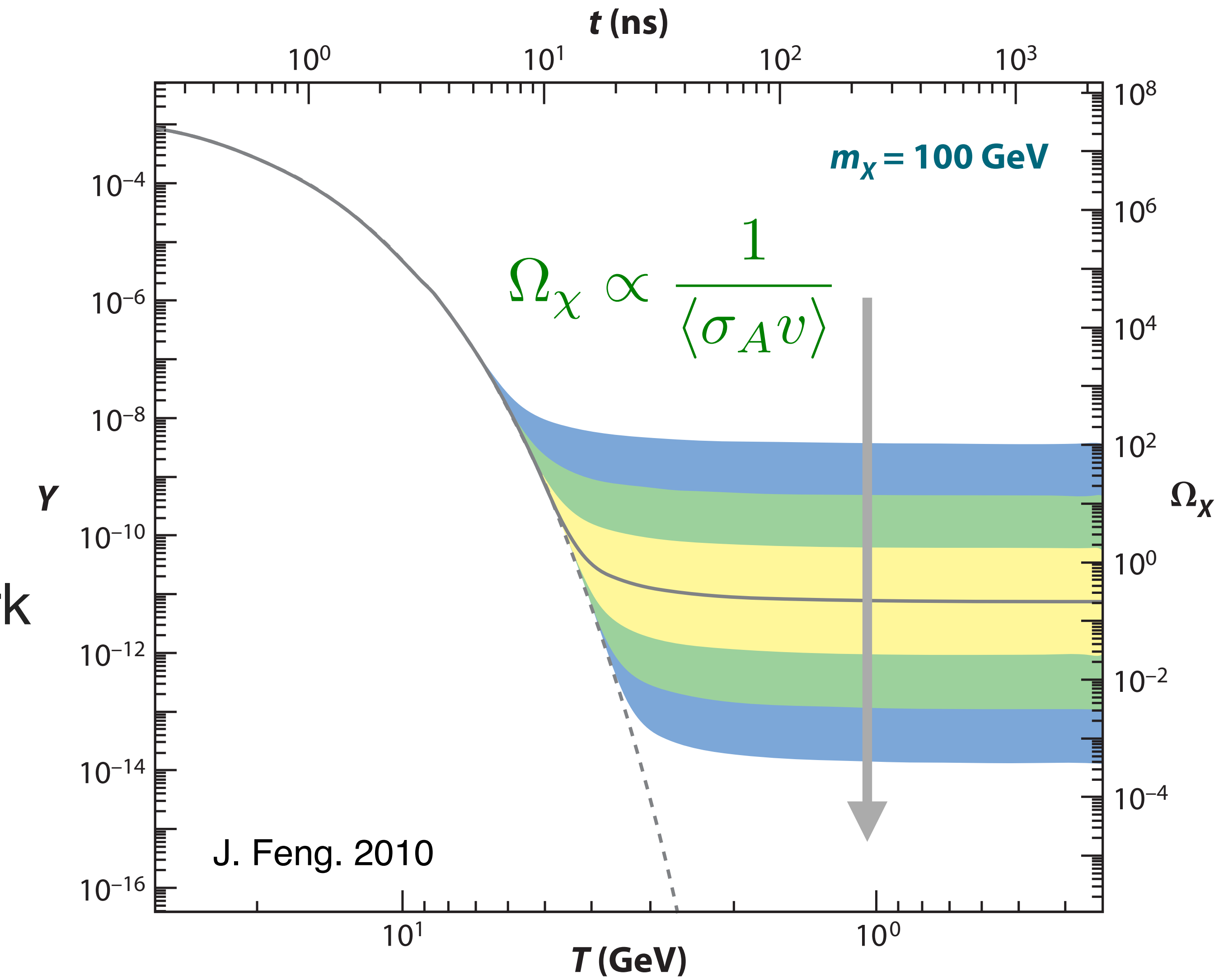


new
particles



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)*

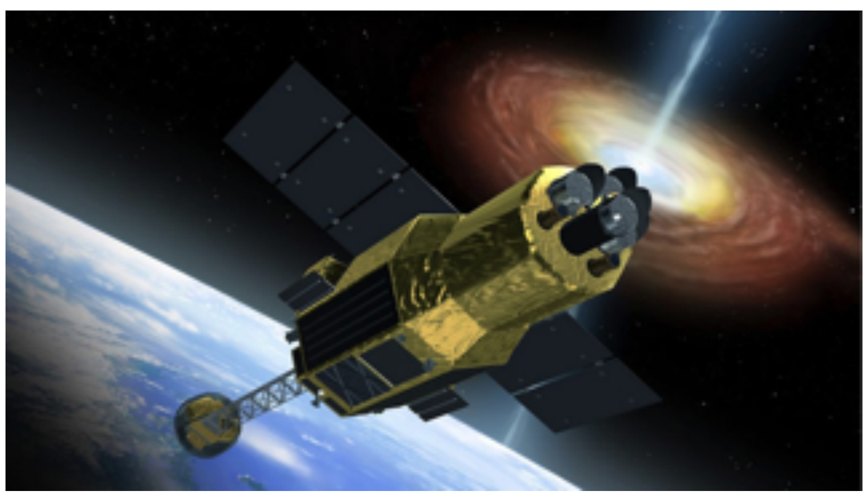


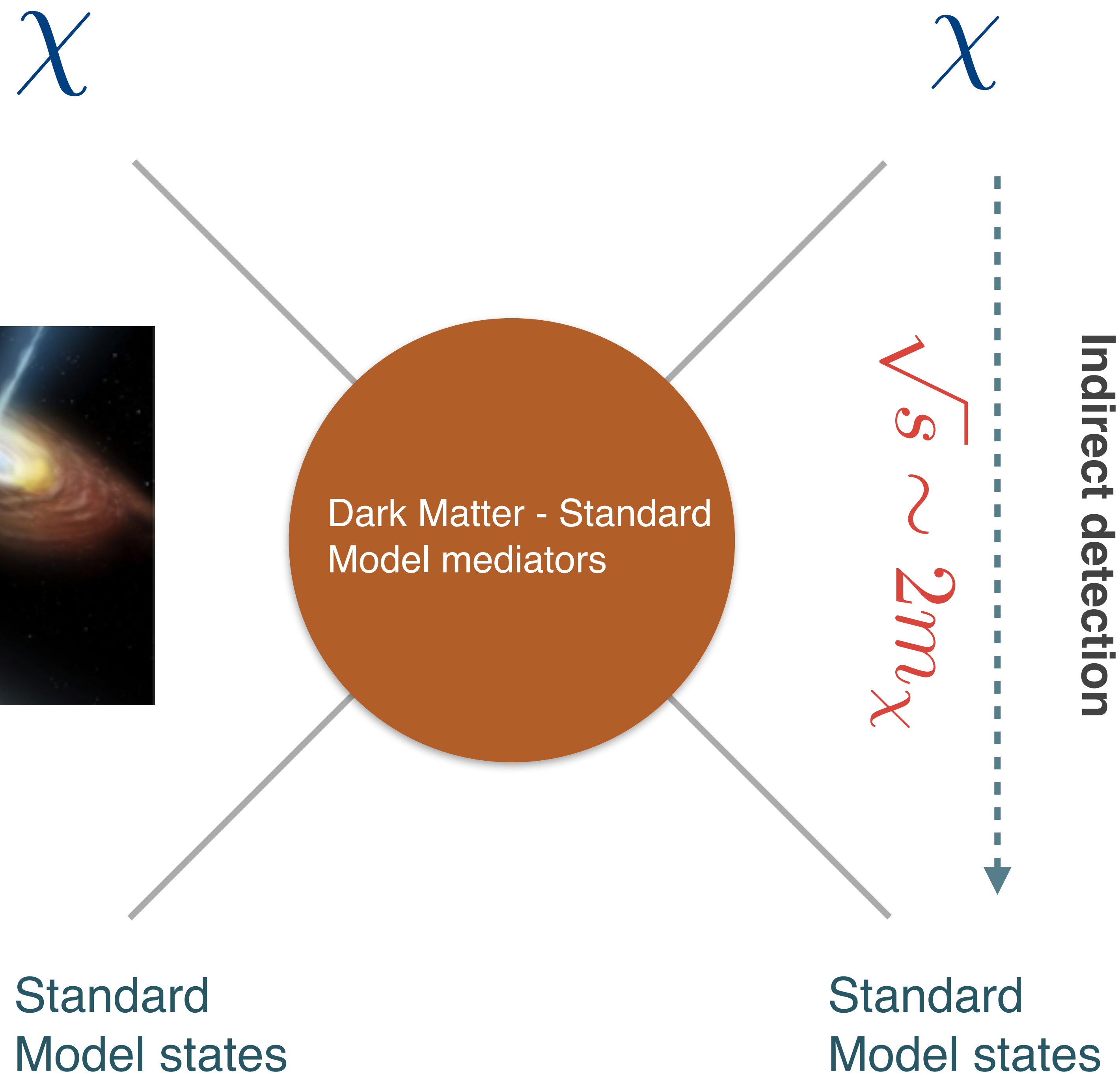
$$\Omega_\chi h^2 \simeq 3 \times 10^{-27} cm^3 s^{-1} \frac{1}{\langle \sigma_A v \rangle}$$

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

How do we search for WIMPs?

How do we search for WIMPs?





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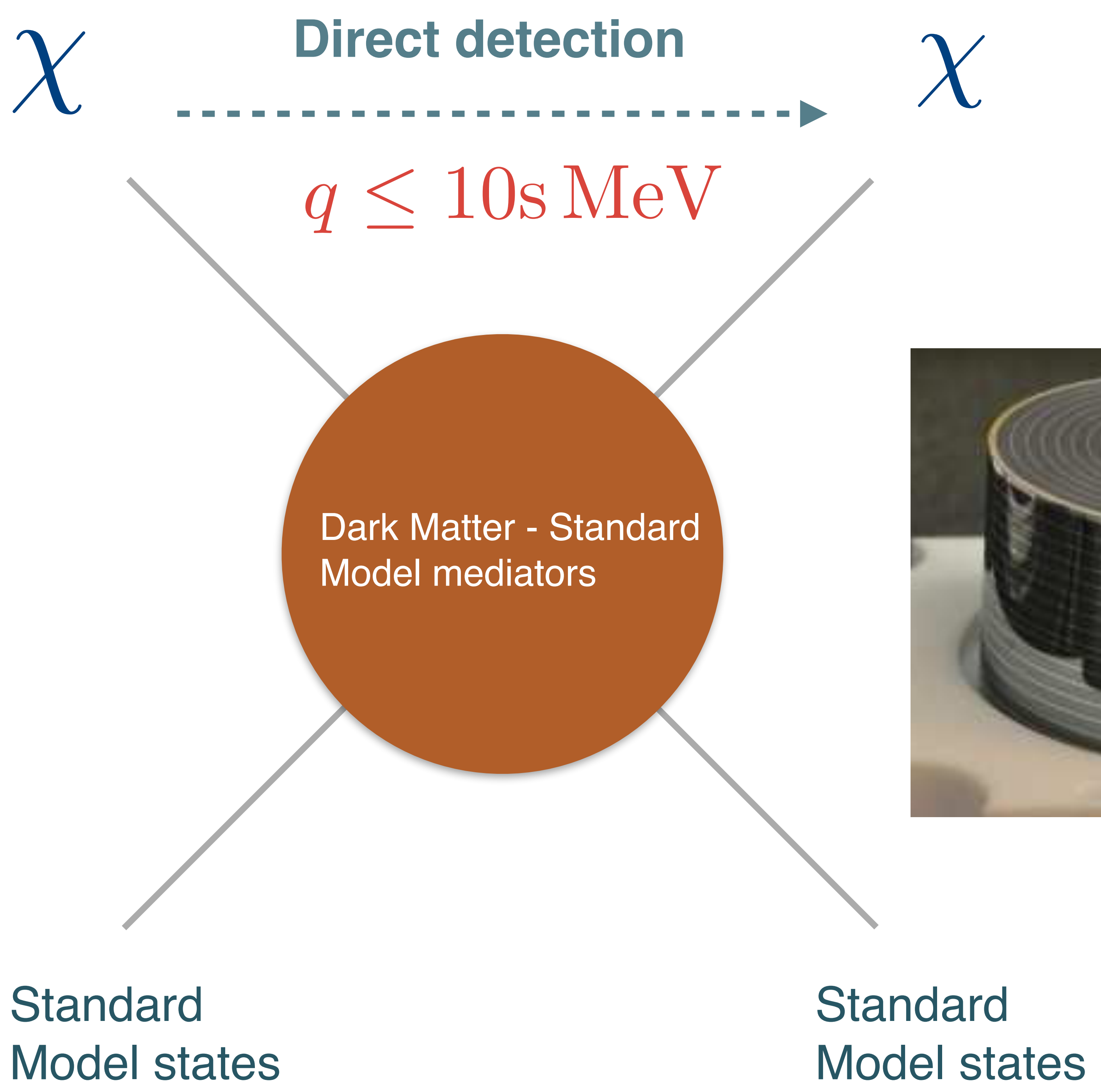
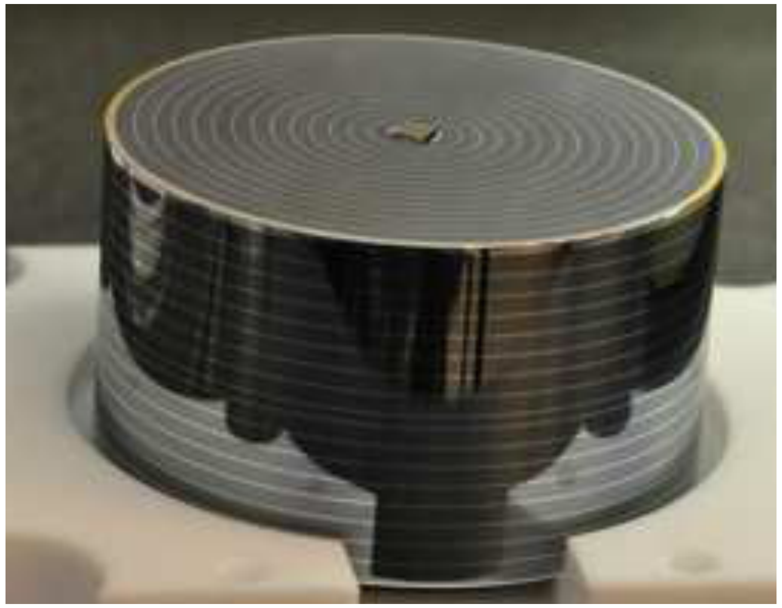
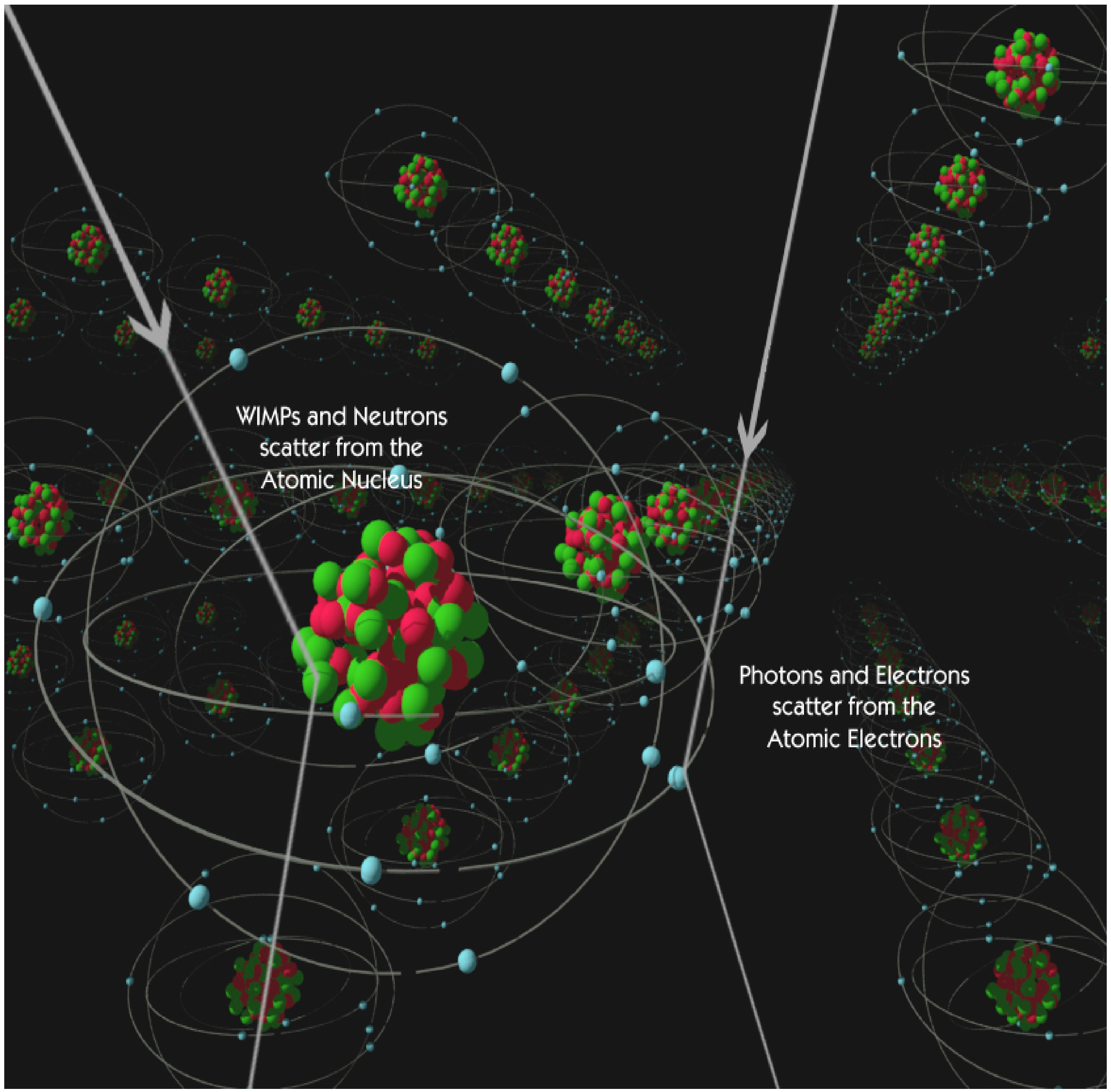
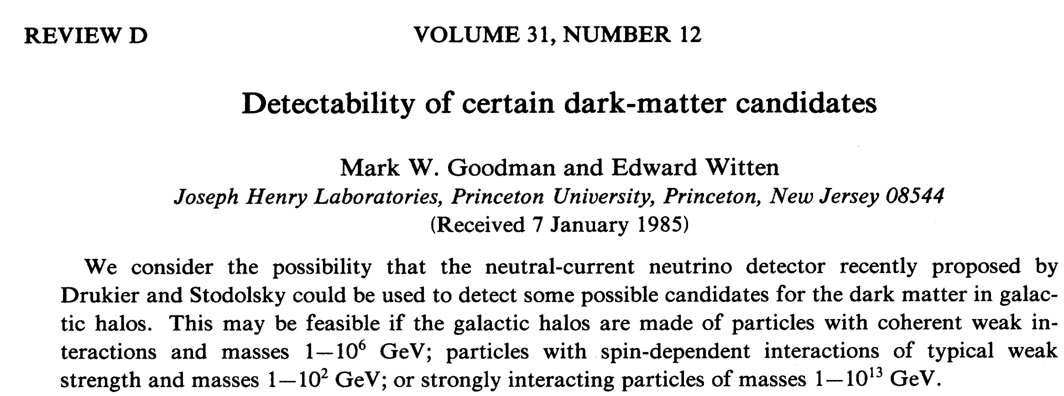




Direct detection principle



Collisions of invisibles particles with atomic nuclei



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

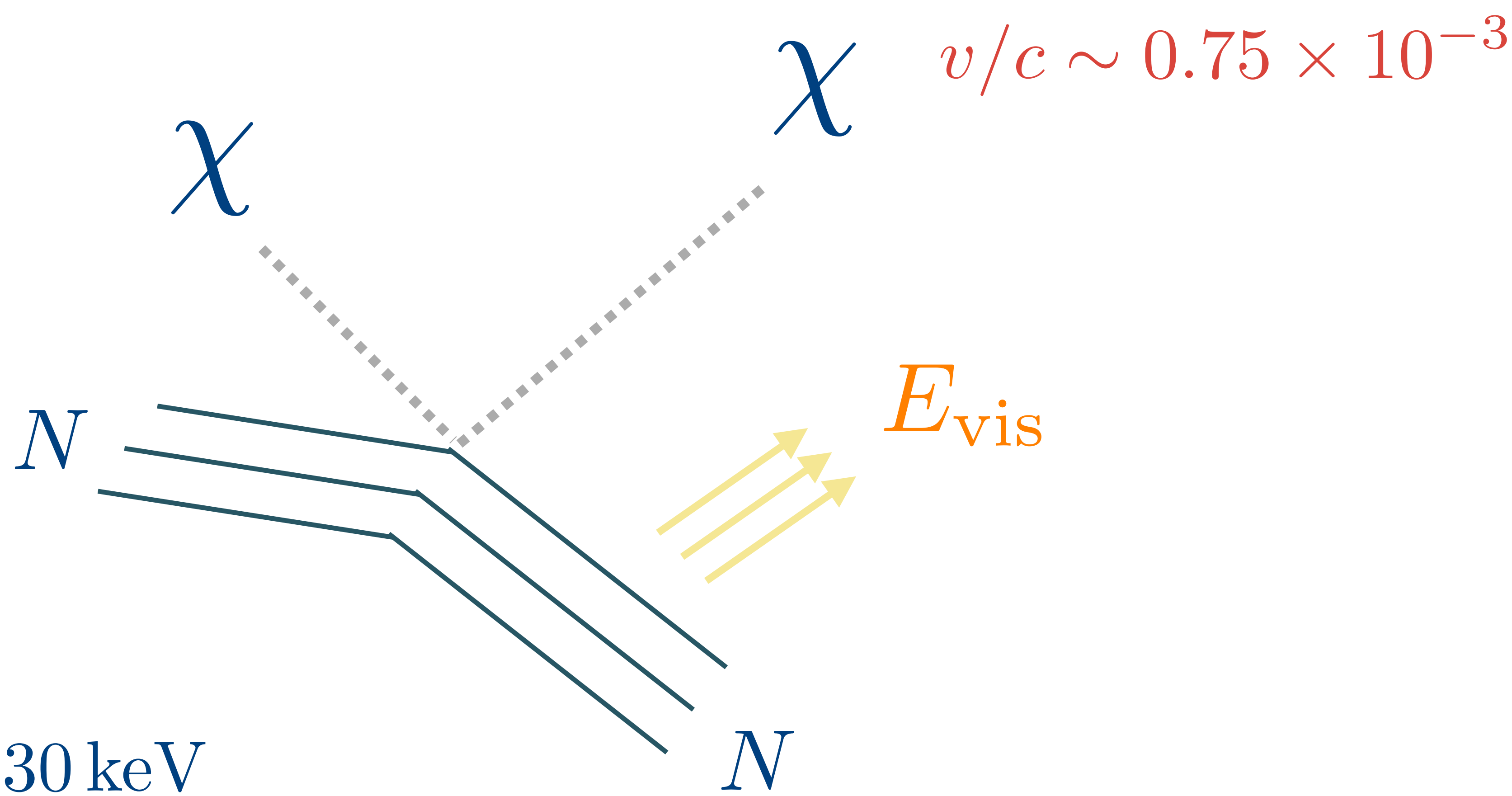
(Received 7 January 1985)

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.

Direct detection principle

Momentum transfer ~ few tens of MeV

Energy deposited in the detector ~ few keV - tens of keV



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

What to expect in a terrestrial detector?

$$R \sim N_N \times \frac{\rho_0}{m_W} \times \langle v \rangle \times \sigma$$

Detector physics

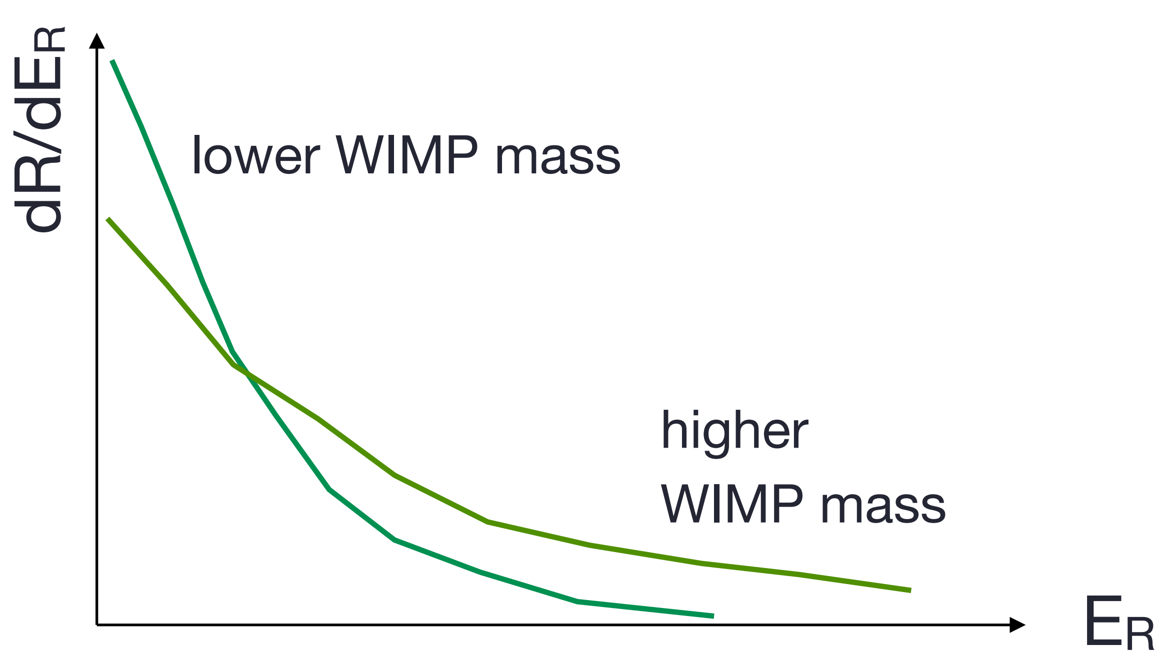
N_N, E_{th}

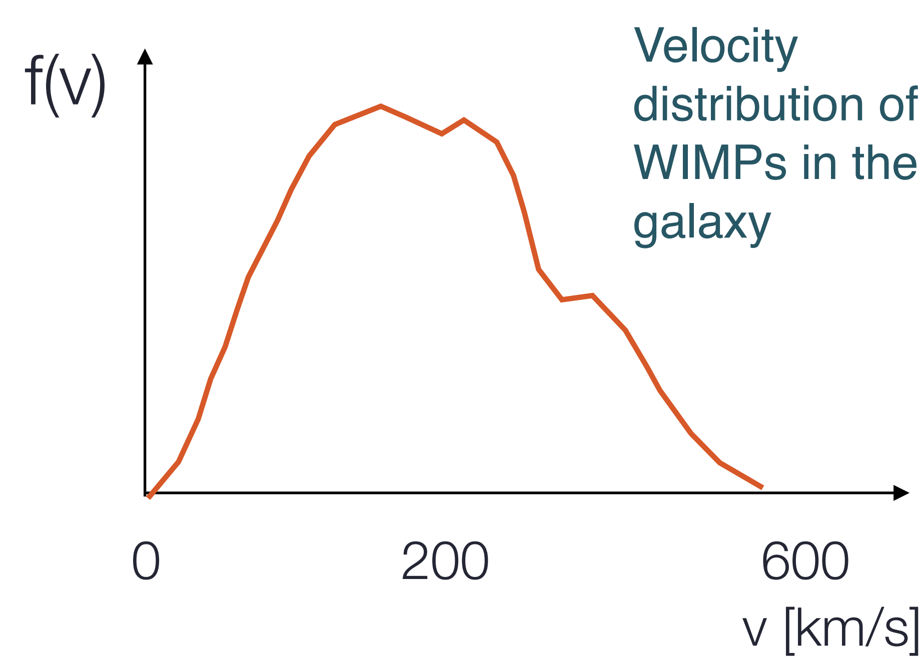
Particle/nuclear physics

$m_W, d\sigma/dE_R$

Astrophysics

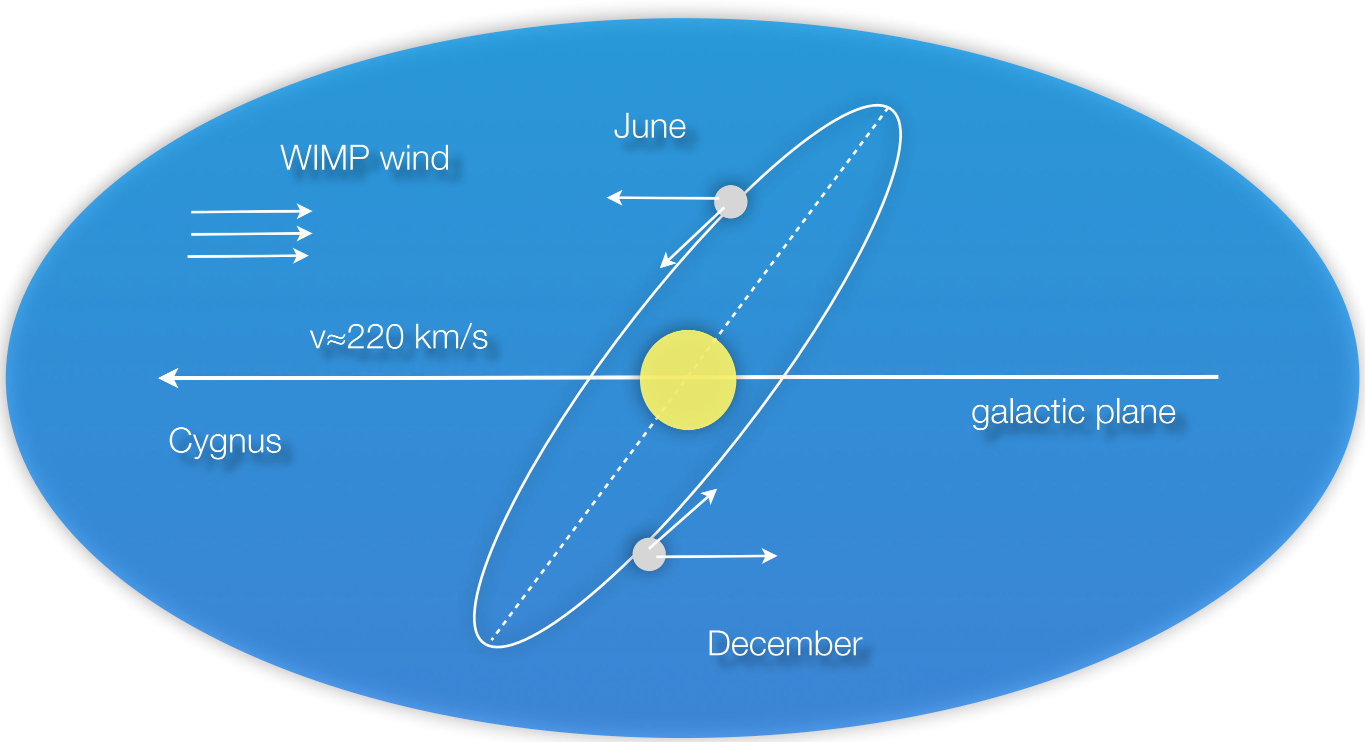
$\rho_0, f(v)$



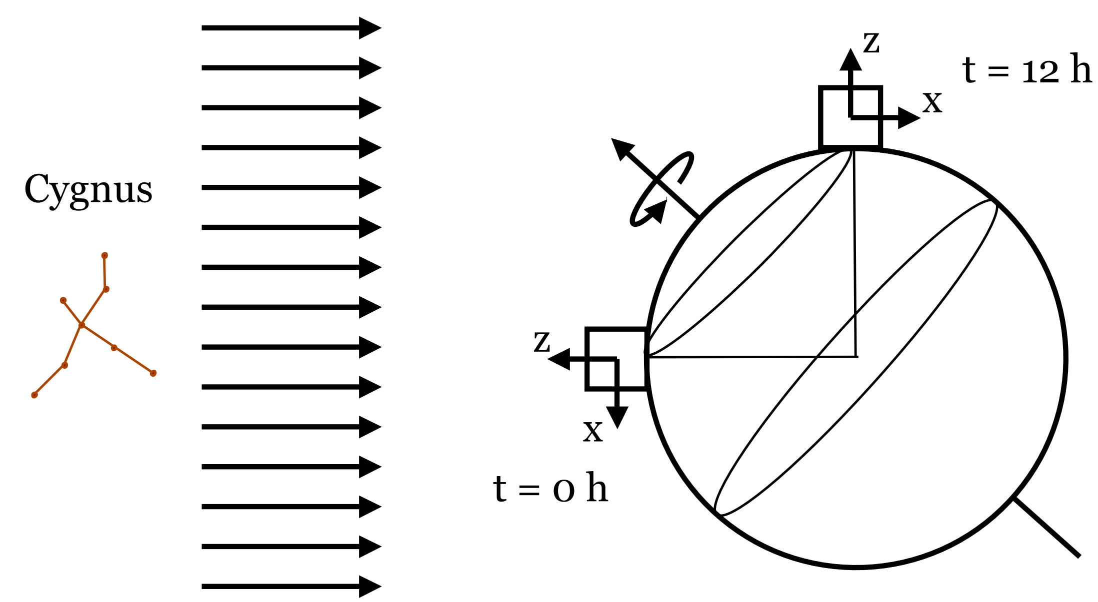


What we expect to measure

- **Rate and shape of nuclear recoil spectrum that depends upon the 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

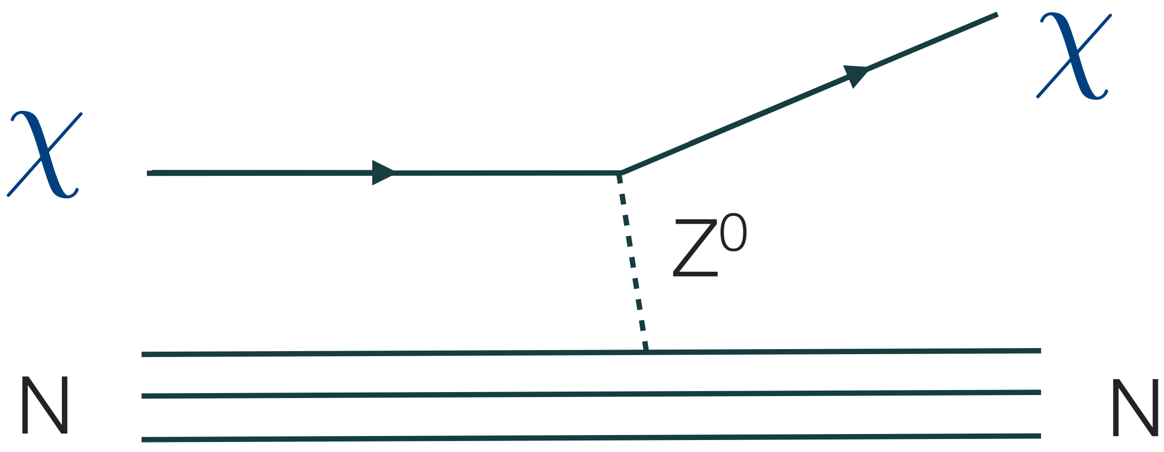


Drukier, Freese, Spergel, PRD 33,1986

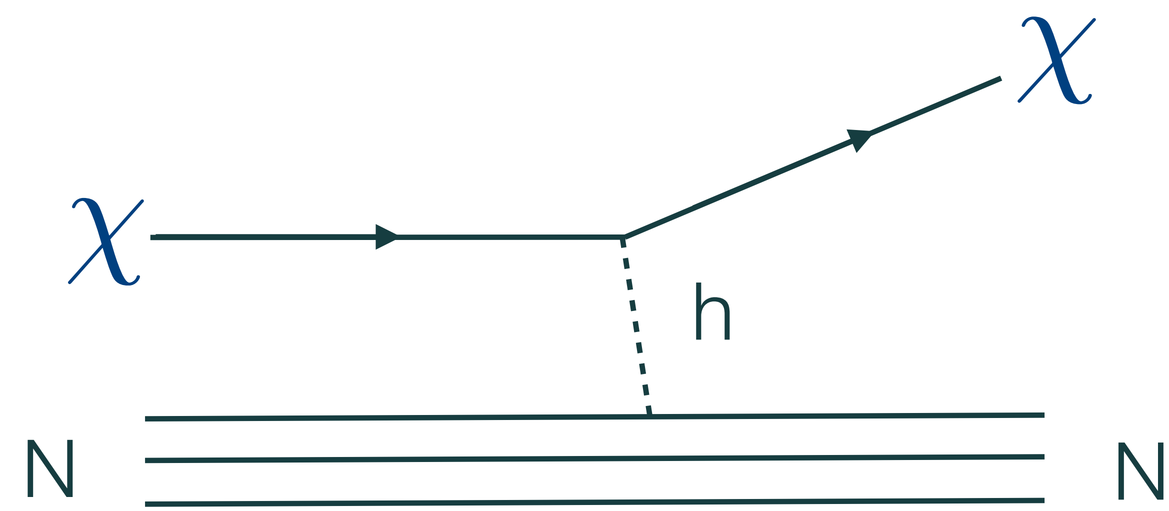


D. Spergel, PRD 36, 1988

Example cross sections



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



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

Scattering cross section on nuclei

- In general, interactions leading to WIMP-nucleus scattering are parameterized as:
  - **scalar interactions** (coupling to WIMP mass, from scalar, vector, tensor part of L)

$$\sigma_{SI} \sim \frac{\mu^2}{m_\chi^2}[Z f_p + (A - Z) f_n]^2$$

f_p, f_n: scalar 4-fermion couplings to p and n

=> nuclei with large A favourable (but nuclear form factor corrections)

  - **spin-spin interactions** (coupling to the nuclear spin J_N, from axial-vector part of L)

$$\sigma_{SD} \sim \mu^2 \frac{J_N + 1}{J_N}(a_p\langle S_p\rangle + a_n\langle S_n\rangle)^2$$

a_p, a_n: effective couplings to p and n; $\langle S_p \rangle$ and $\langle S_n \rangle$ expectation values of the p and n spins within the nucleus

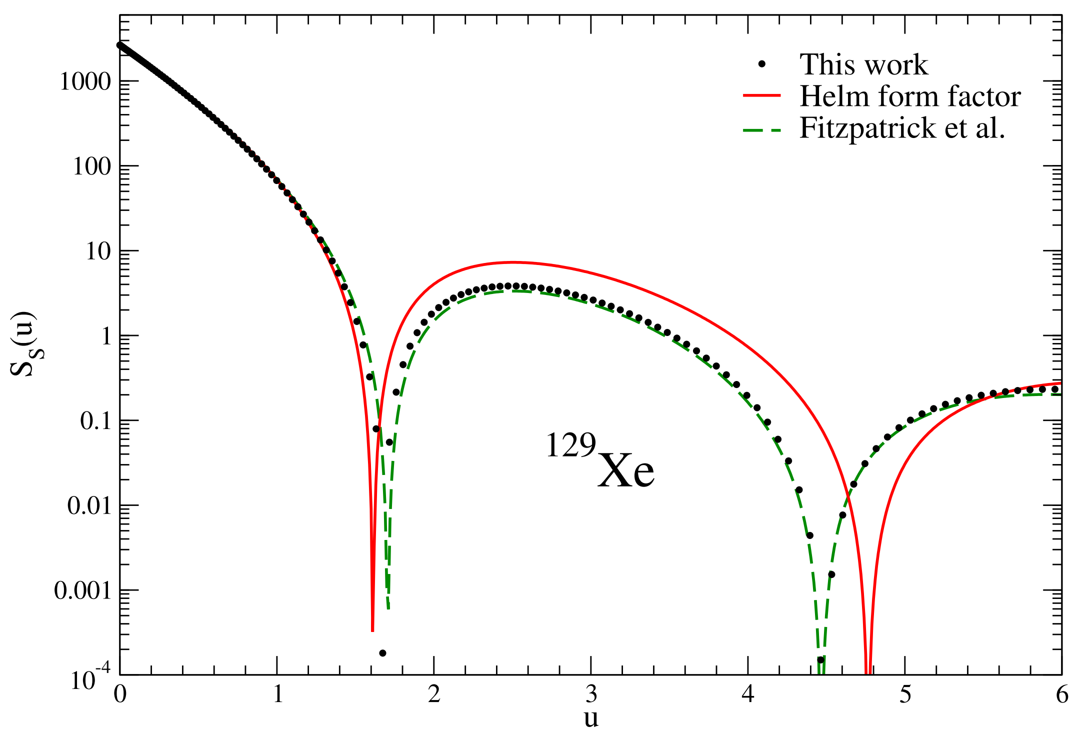
=> nuclei with non-zero angular momentum (corrections due to spin structure functions)

Form factor corrections

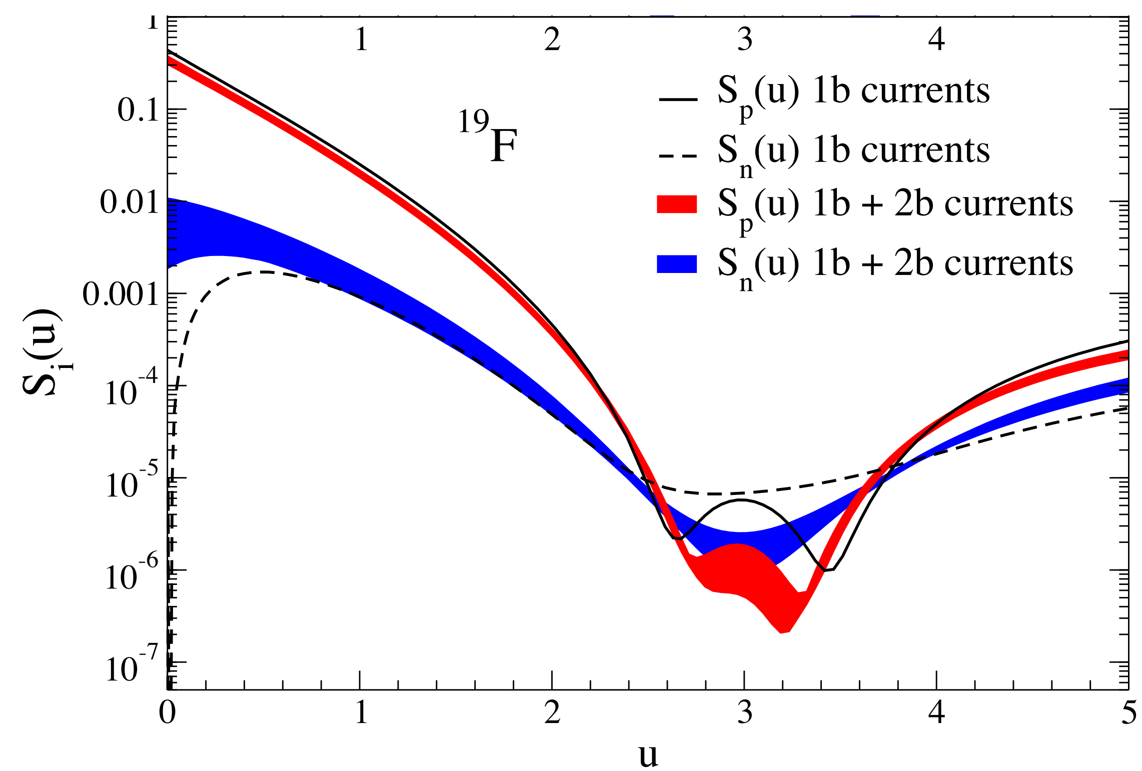
- Especially important for heavy WIMPs and/or nuclei and for WIMPs in the tail of the velocity distribution

$$\frac{d\sigma_{SI}}{dq^2} = \sigma_{0,SI} \times S_s(q)$$

$$\frac{d\sigma_{SD}}{dq^2} = \sigma_{0,SD} \times S_A(q)$$



L. Vietze et al., Phys.Rev. D91 (2015)

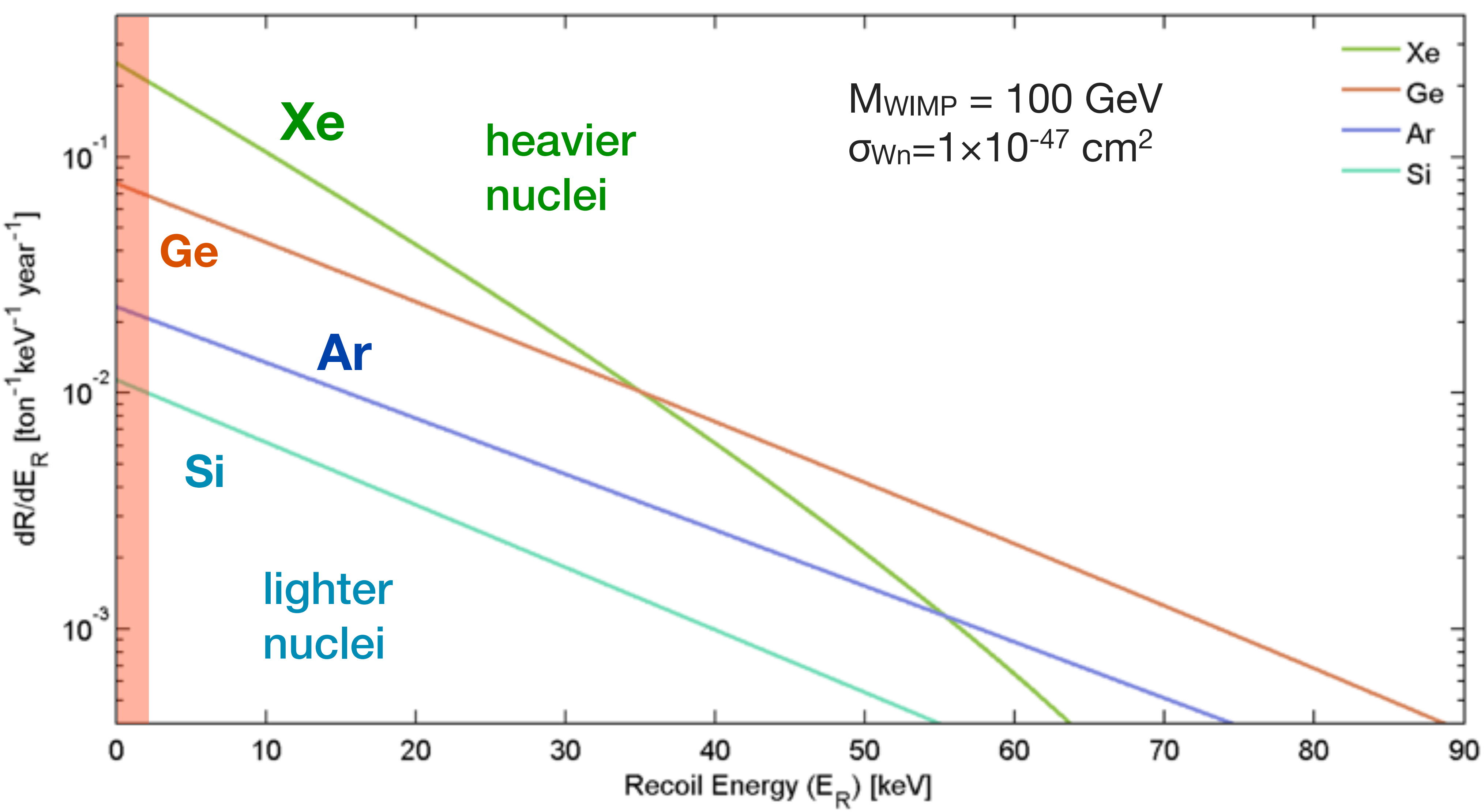


P. Klos et al., PRD 88 (2013)

$$u = q^2 b^2 / 2$$

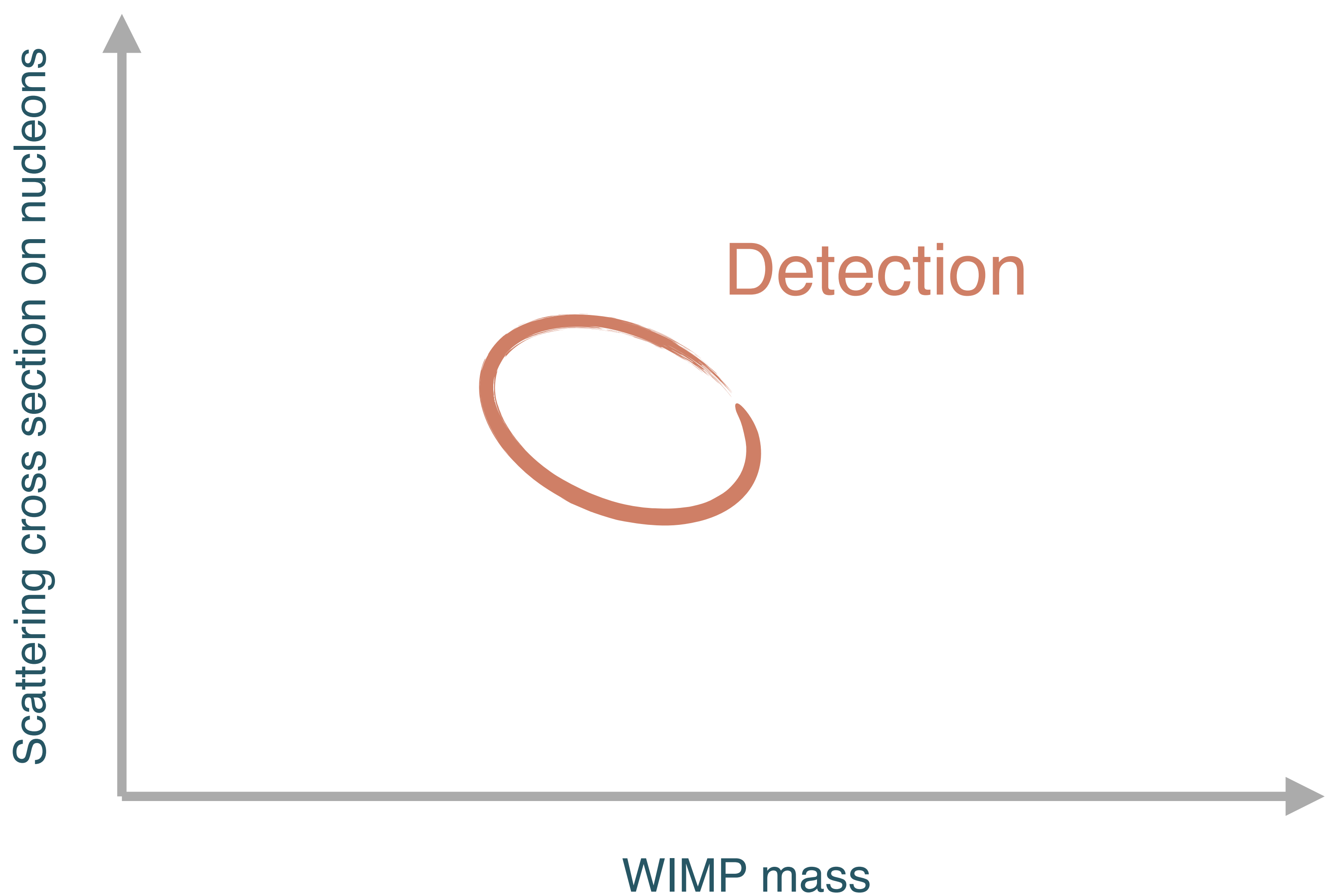
Putting it all together: interaction rates

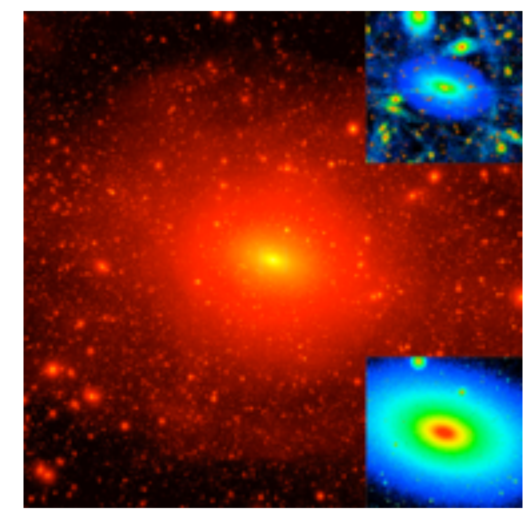
$$R \sim 0.13 \, \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\,\text{cm}^{-3}} \right]$$

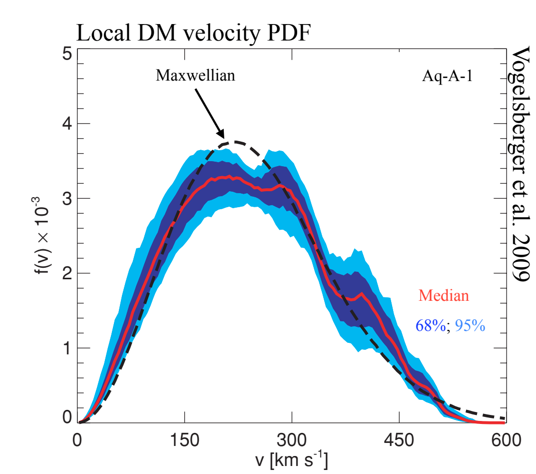


What can we learn about WIMPs?

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{v_{min}}^{v_{max}} dv\, f(v) v \frac{d\sigma}{dE_R}$$







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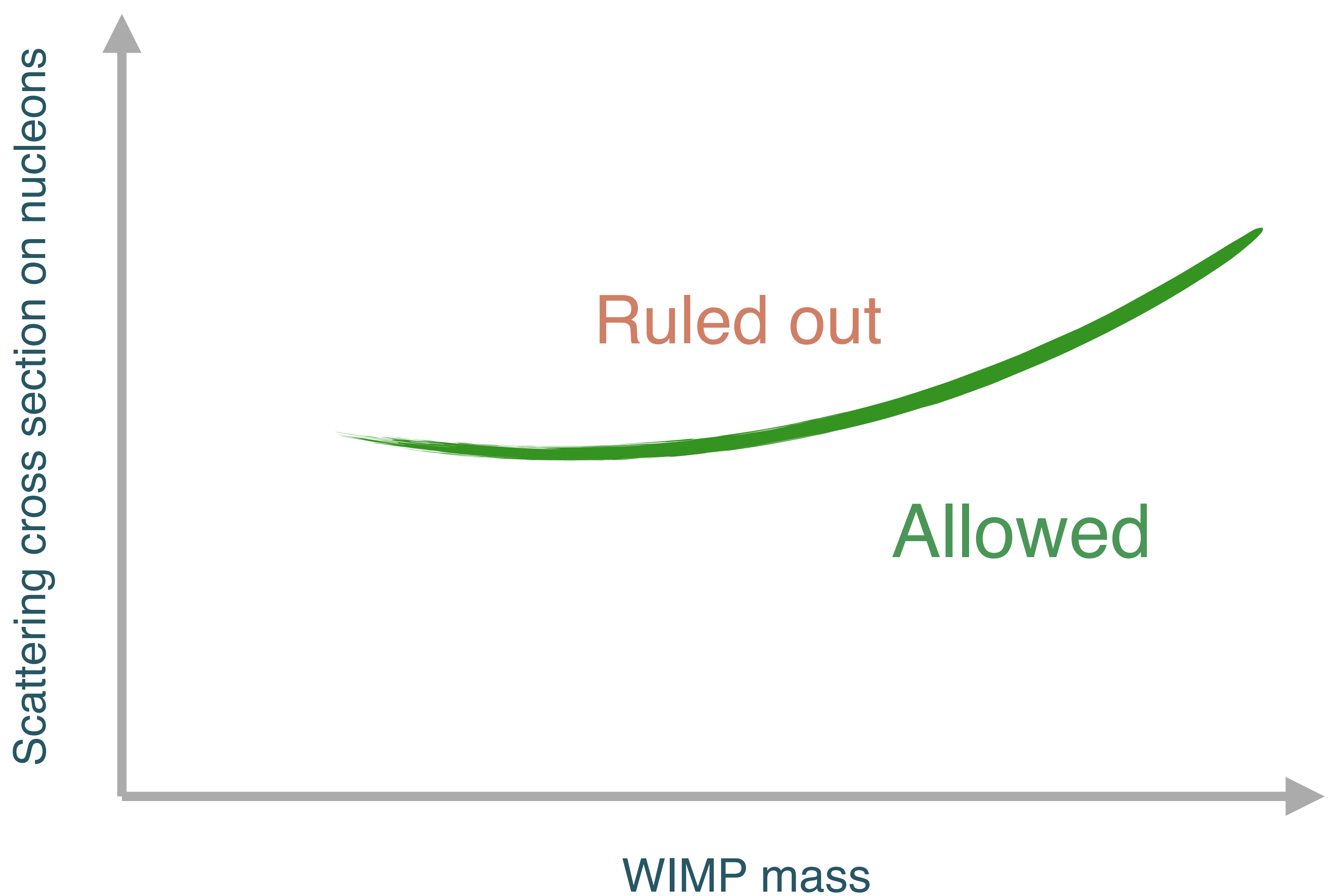
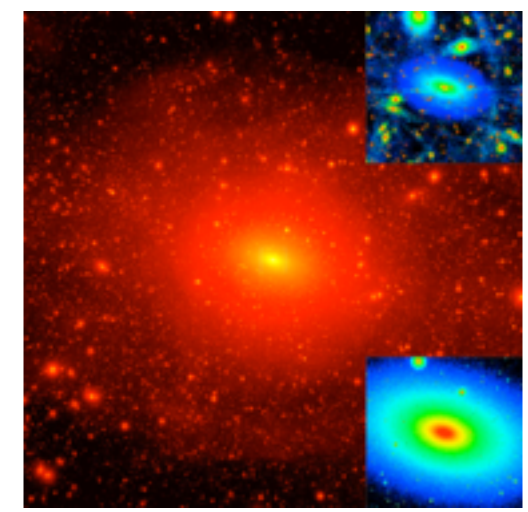
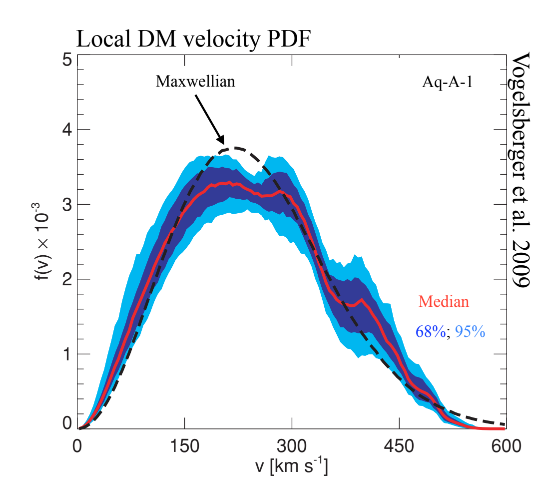
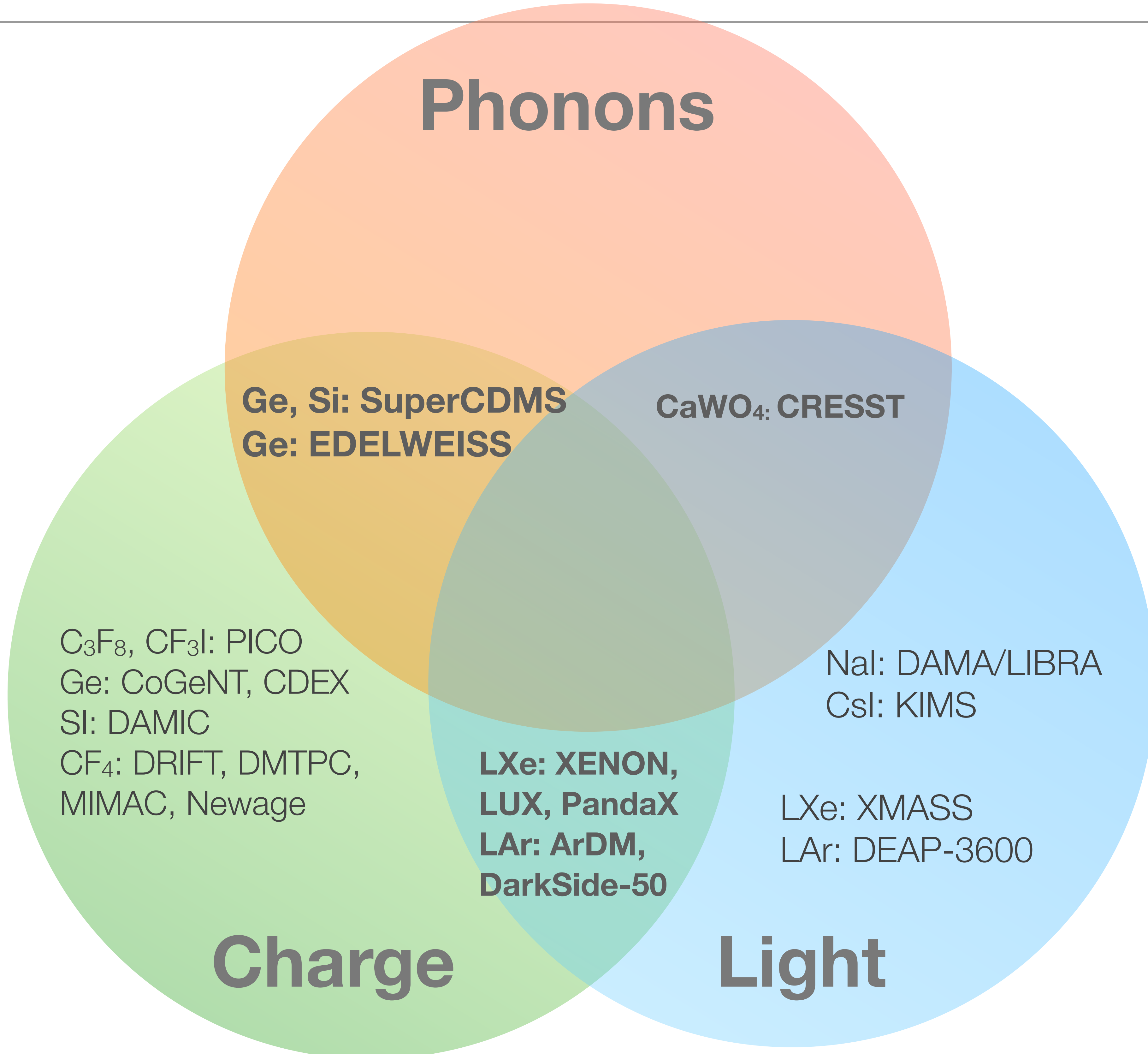


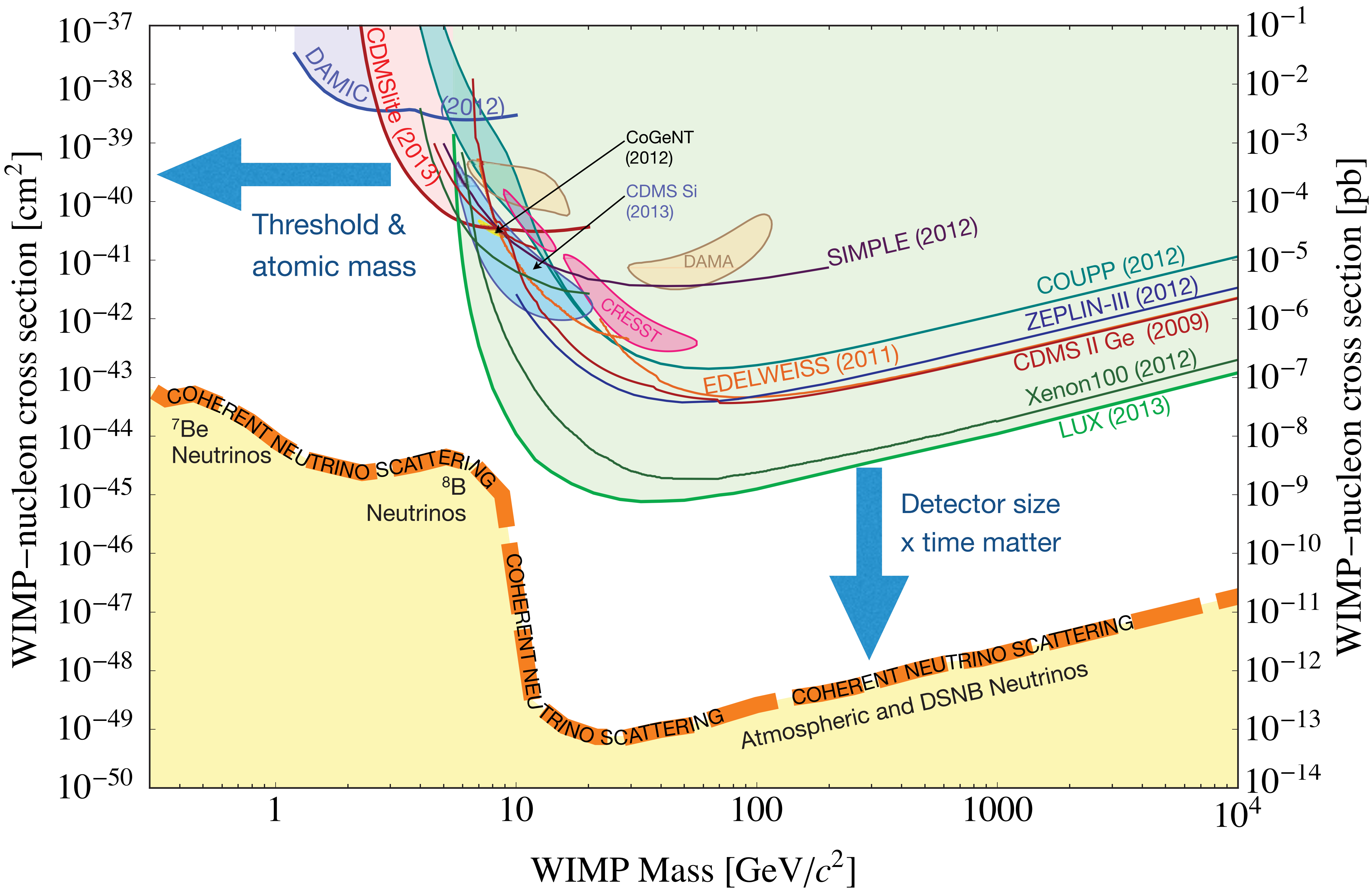




Direct dark matter detection zoo

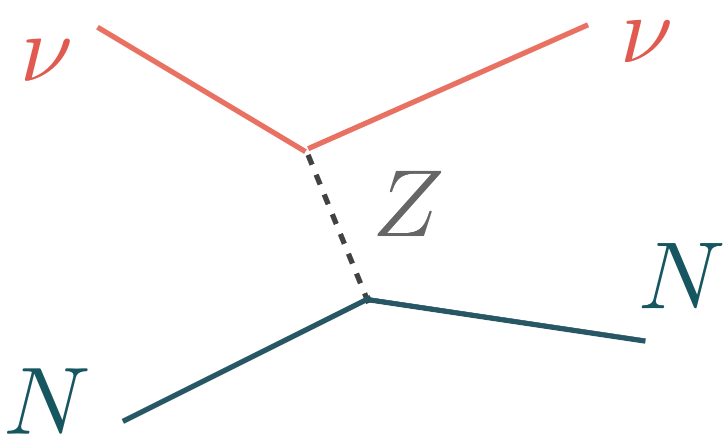


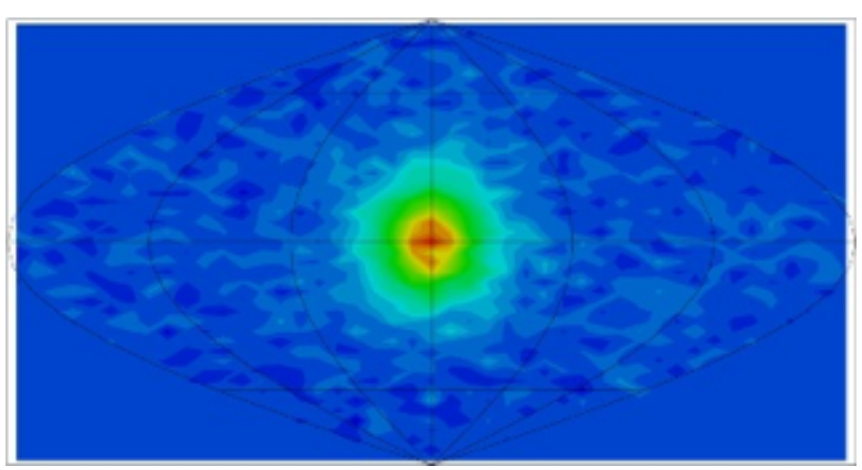
The WIMP landscape

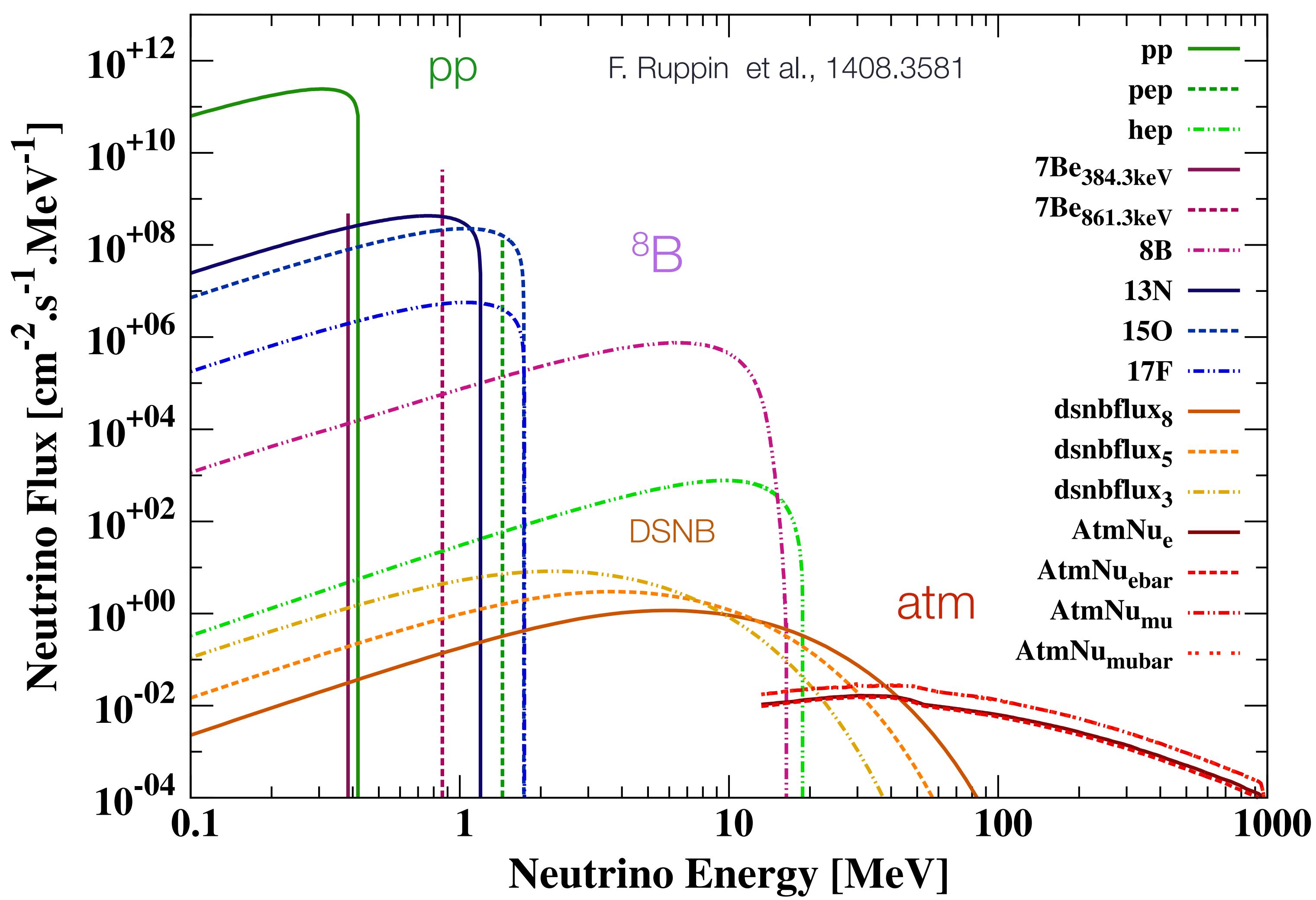


Backgrounds

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

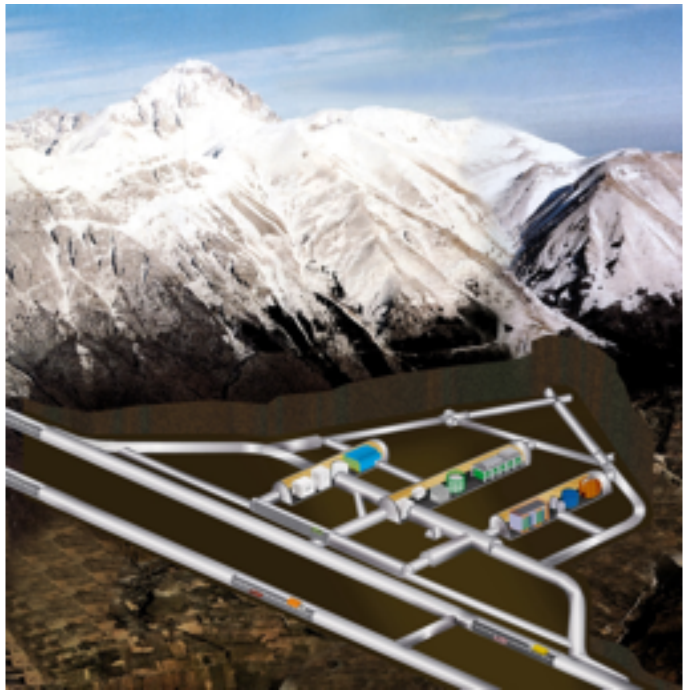




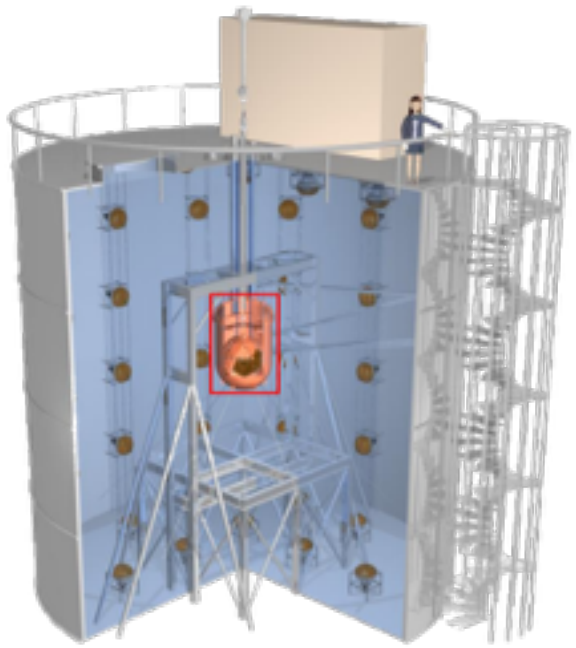


How to deal with backgrounds?

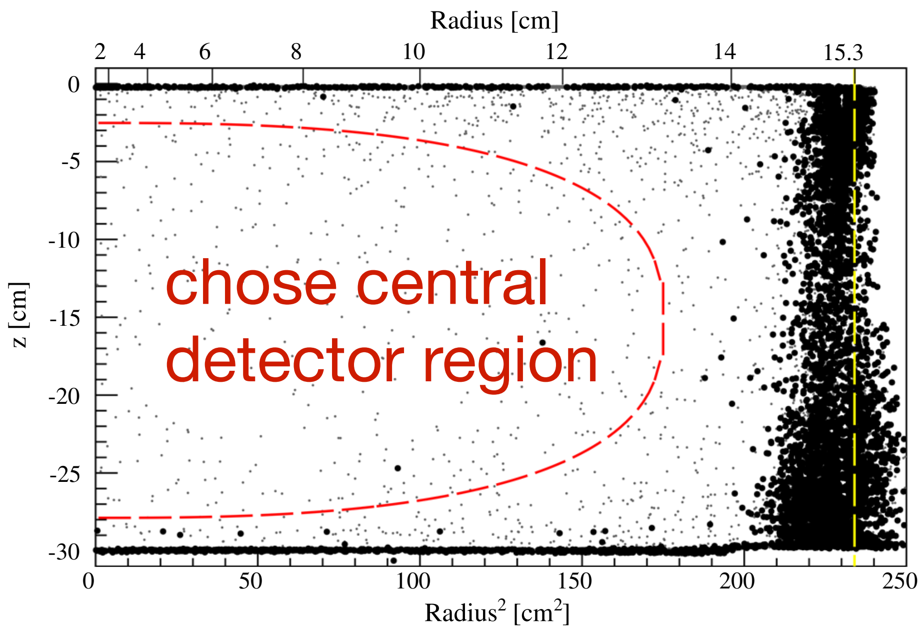
- Go deep underground



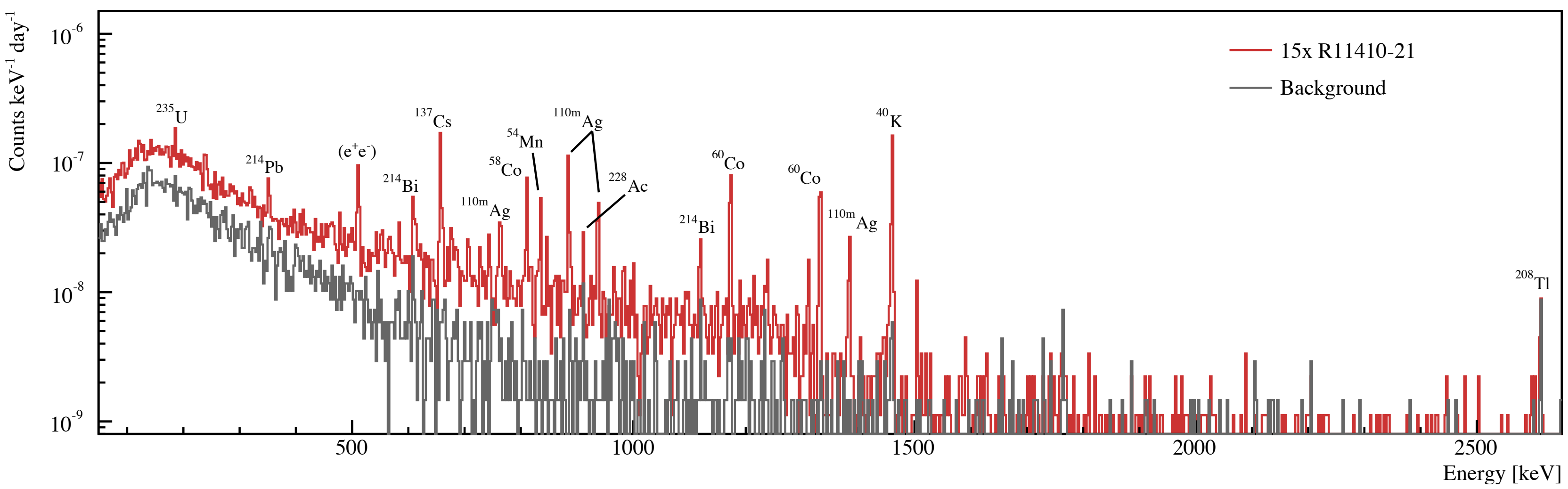
- Use active shields



- Fiducialize

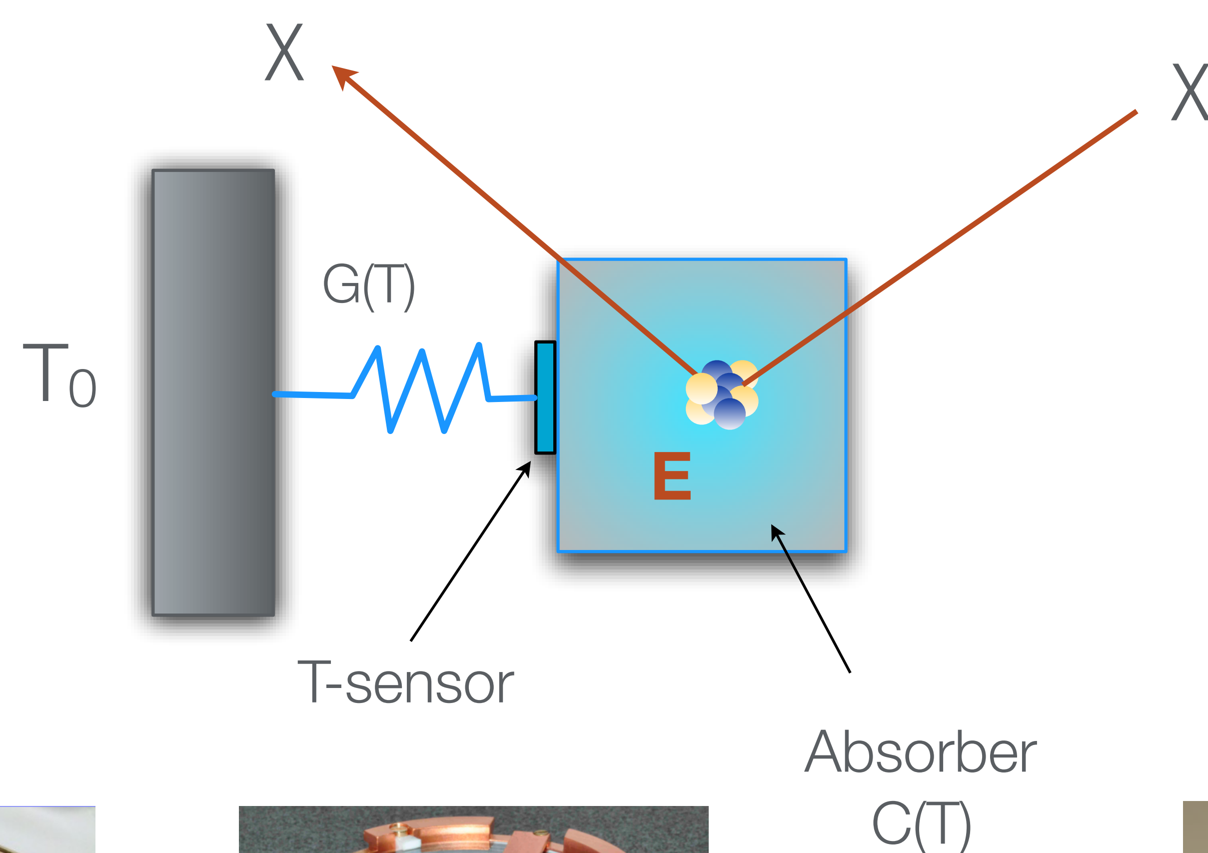


- Select low-radioactivity materials



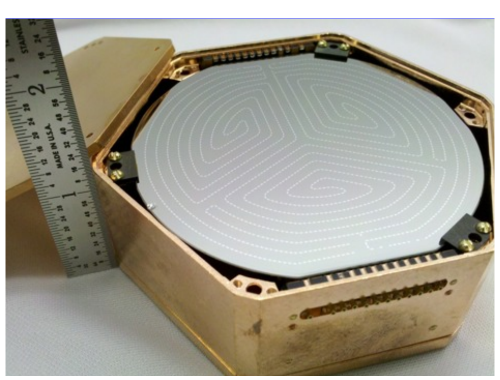
Cryogenic detectors at T ~ mK

- Detect a temperature increase after a particle interacts in an absorber
- Absorber masses form 100 g to 1.4 kg, TES (Transition-edge sensors) or NTD (neutron-transmutation-doped germanium sensors)

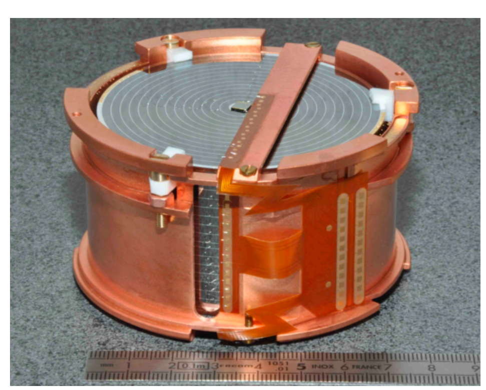


$$\Delta T = \frac{E}{C(T)} e^{-\frac{t}{\tau}}$$

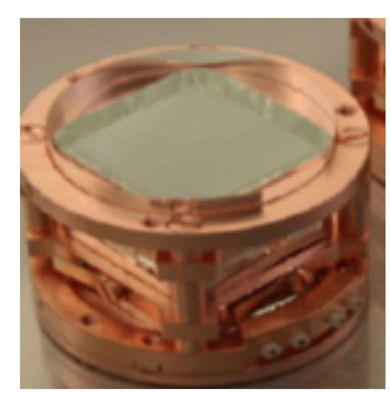
$$\tau = \frac{C(T)}{G(T)}$$



SuperCDMS: Ge, Si



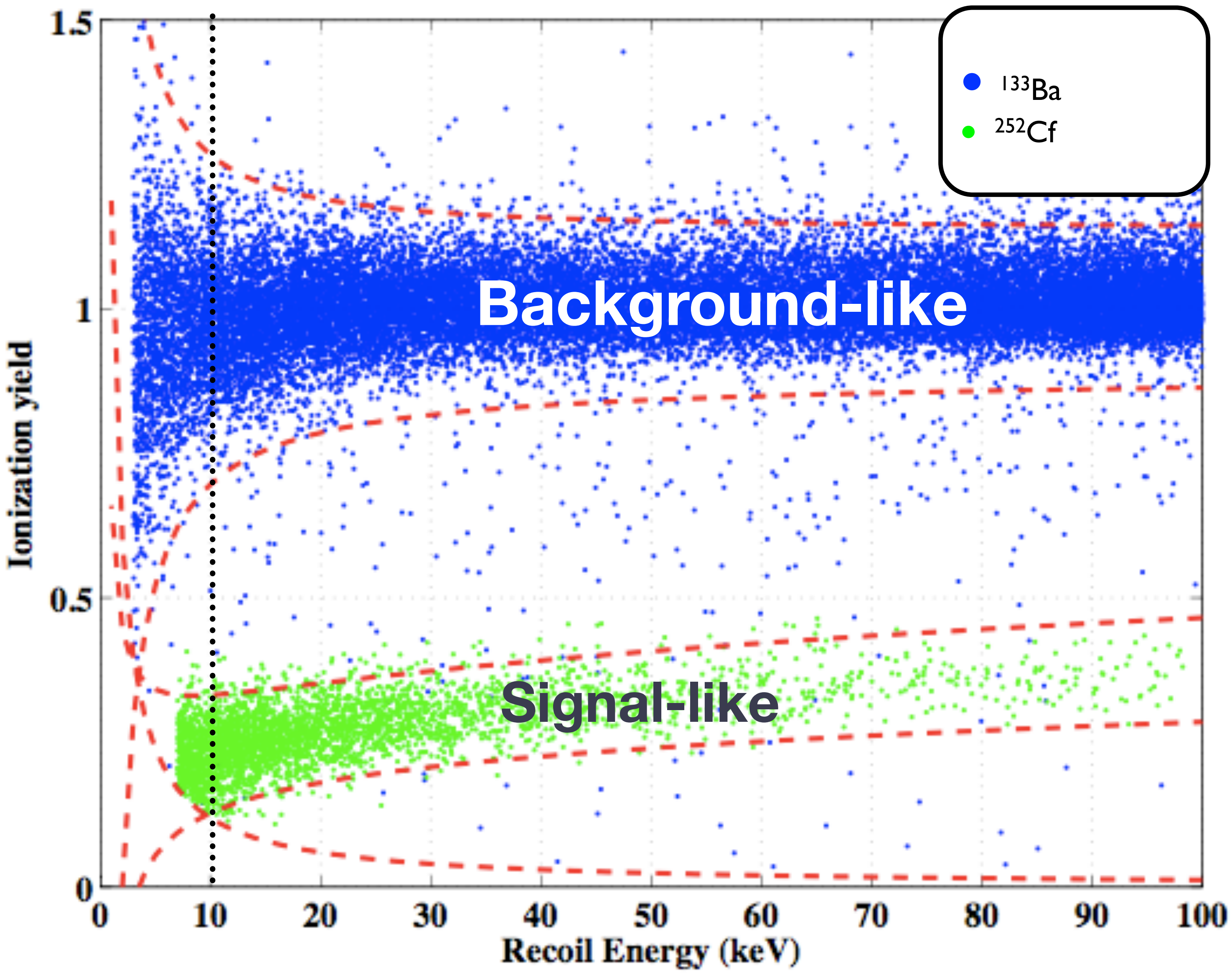
EDELWEISS-III (Ge)



CRESST ($CaWO_4$)

Cryogenic detectors at T ~ mK

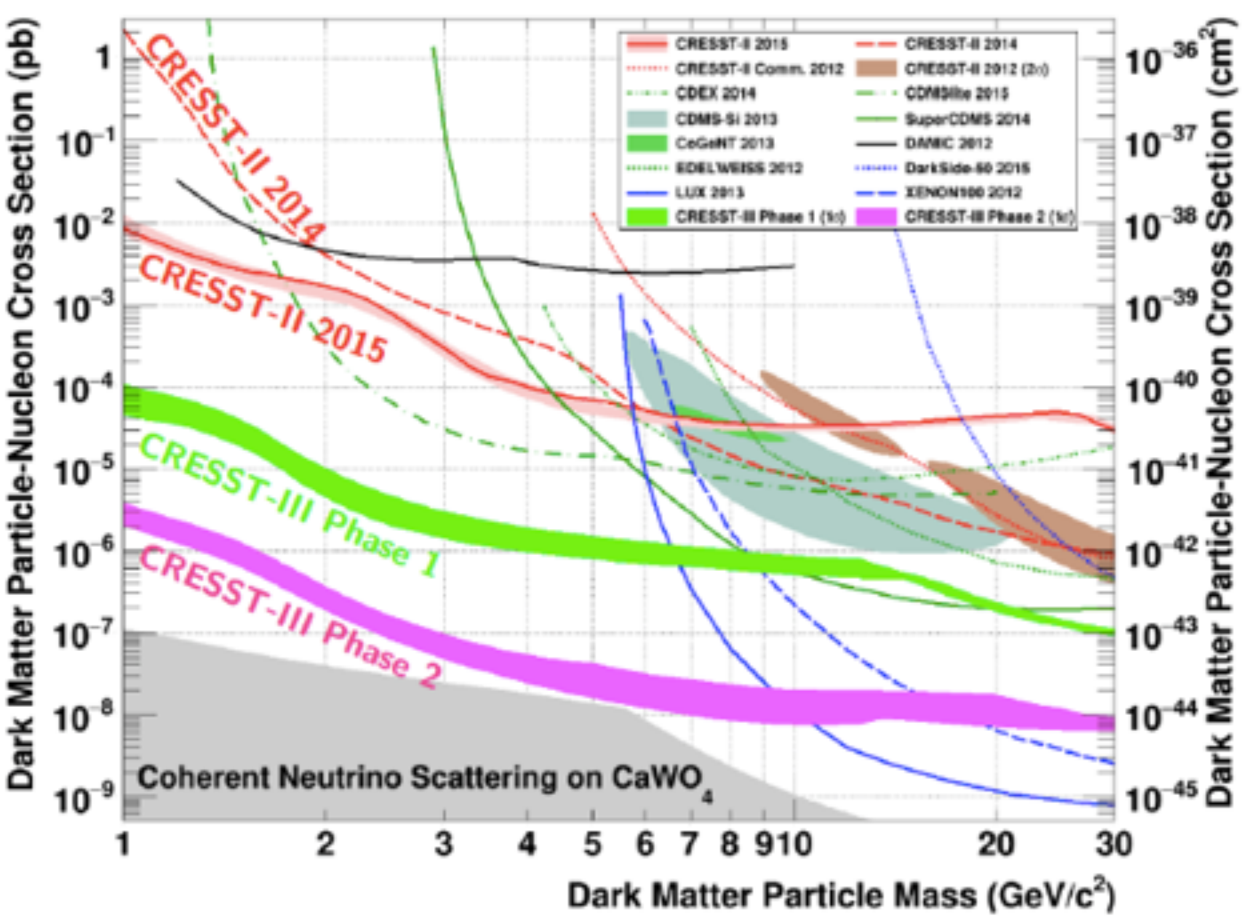
- Detect a temperature increase after a particle interacts in an absorber



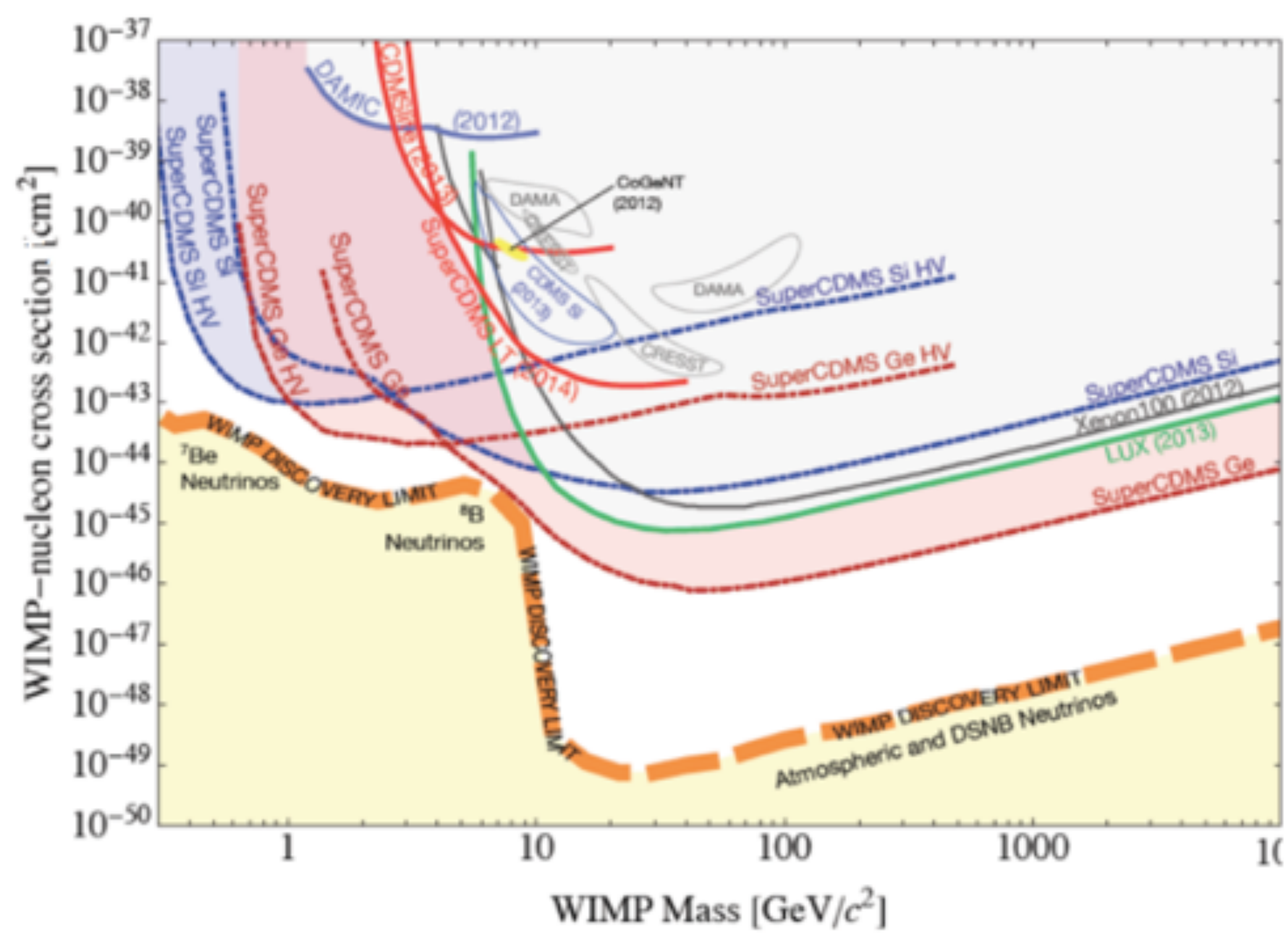
Cryogenic detectors at T ~ mK

- Goal: reach energy thresholds ≤ 100 eV
- **Probe low-mass WIMP region (sub-GeV to few GeV)**

CRESST-II and CRESST-III predictions



SuperCDMS and predictions

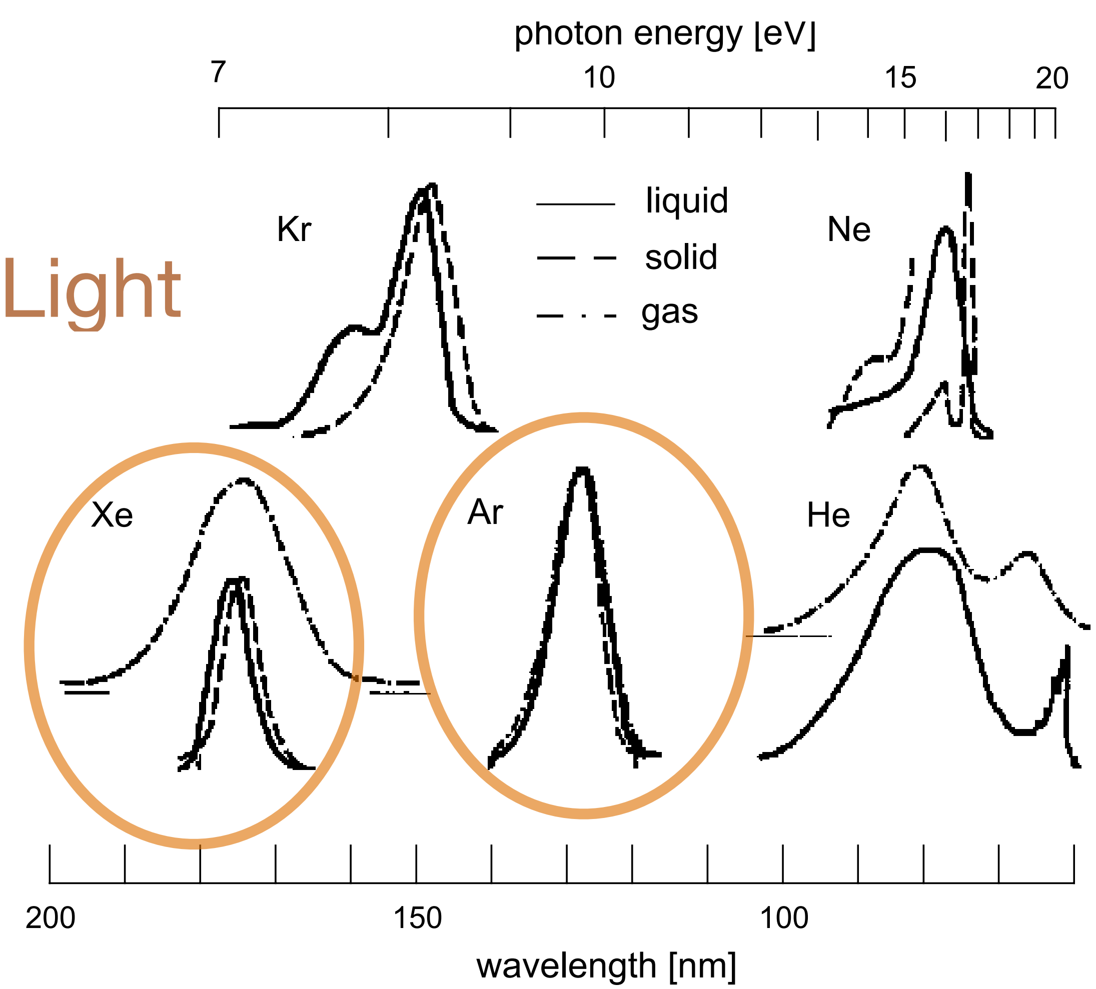


Liquefied noble gases

W. Ramsay: "These gases occur in the air but sparingly as a rule, for while argon forms nearly 1 hundredth of the volume of the air, neon occurs only as 1 to 2 hundred-thousandth, helium as 1 to 2 millionth, krypton as 1 millionth and xenon only as about 1 twenty-millionth part per volume.

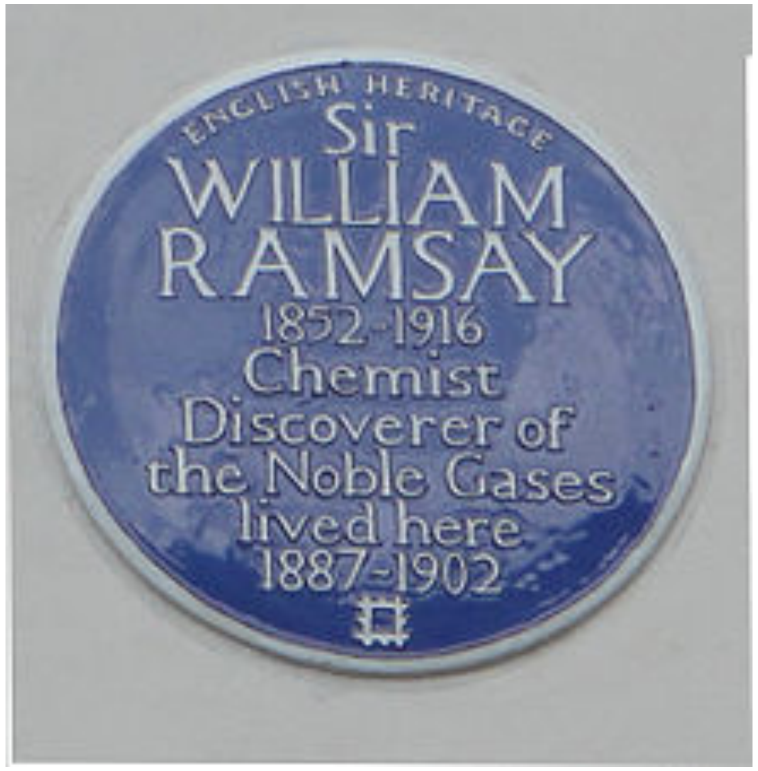
- **Argon ("the inactive one") , the Neon (the new one), Kripton (the hidden one) and the Xenon ("the strange one")**
- **High light and charge yield**

Light



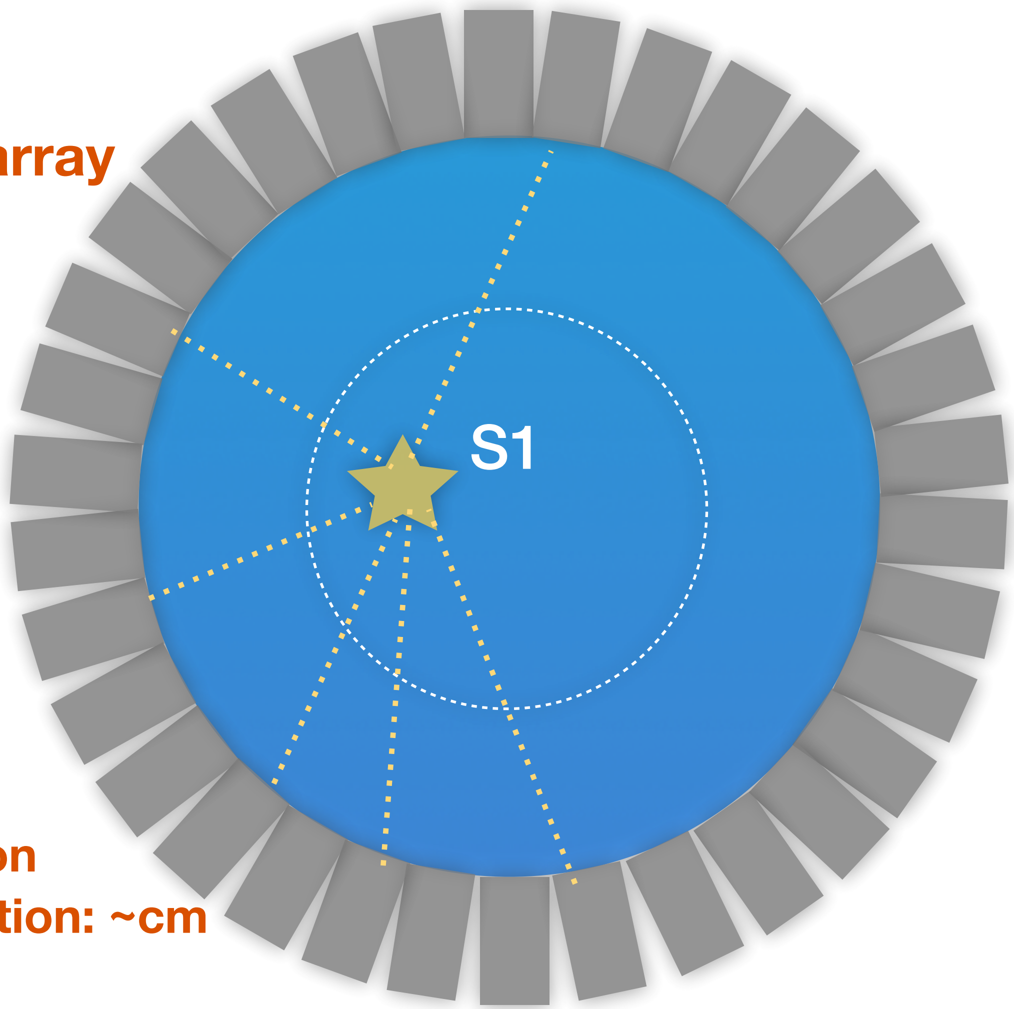
Noble gases: discovered by William Ramsay, student of
Bunsen and professor at UC London

1904 Nobel Prize in Chemistry



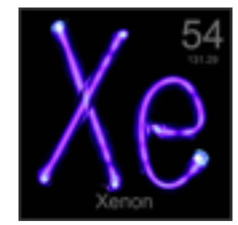
Single-phase noble liquid detectors

PMT array

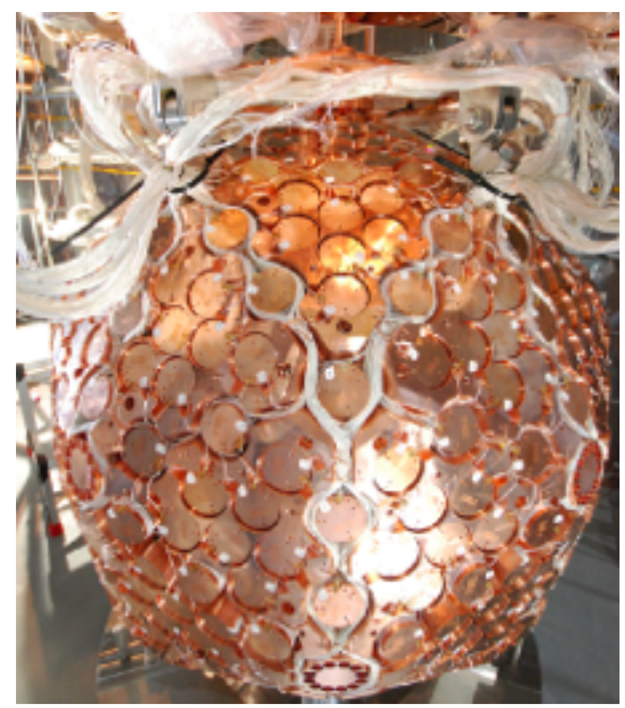


position
resolution: ~cm

+ PSD (mostly in LAr)

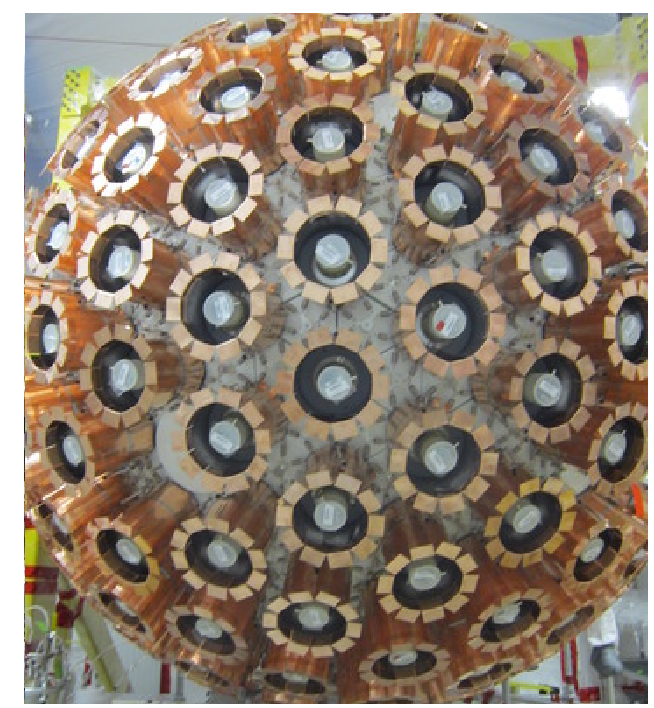


XMASS
at Kamioka, 832 kg



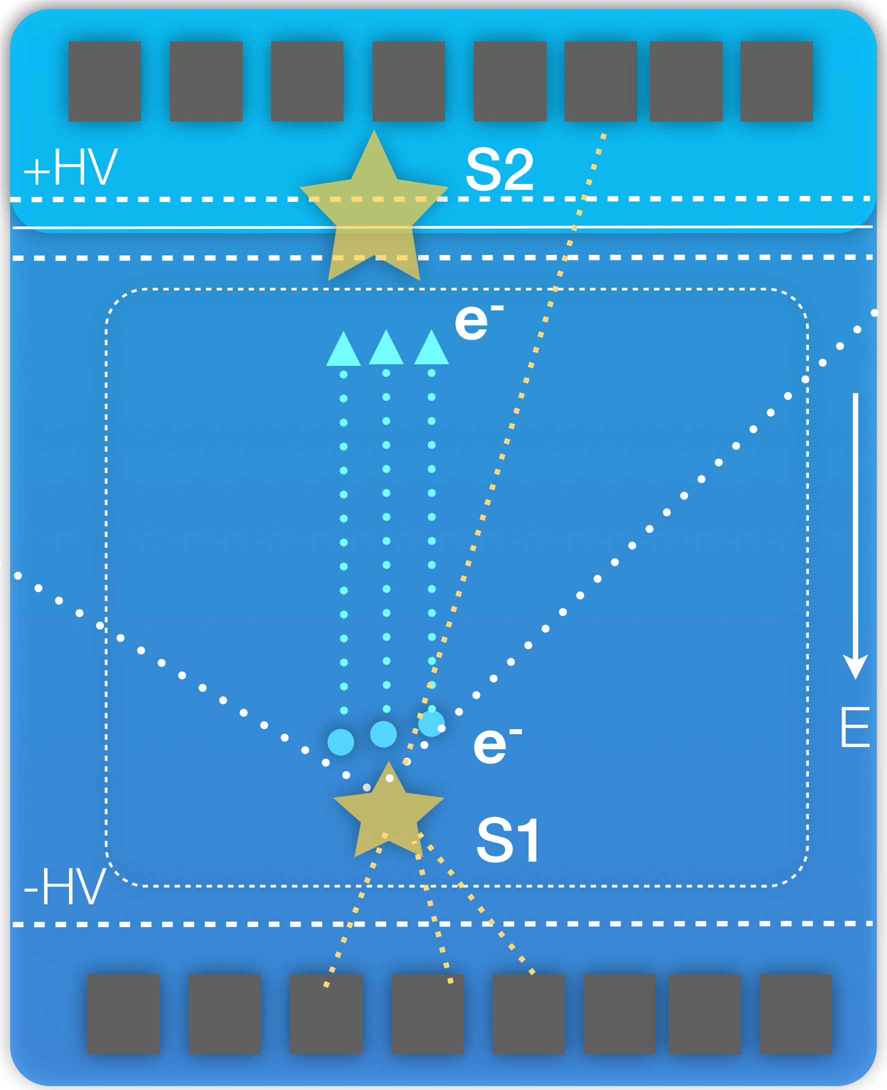
Running since 2013
Results in 2016

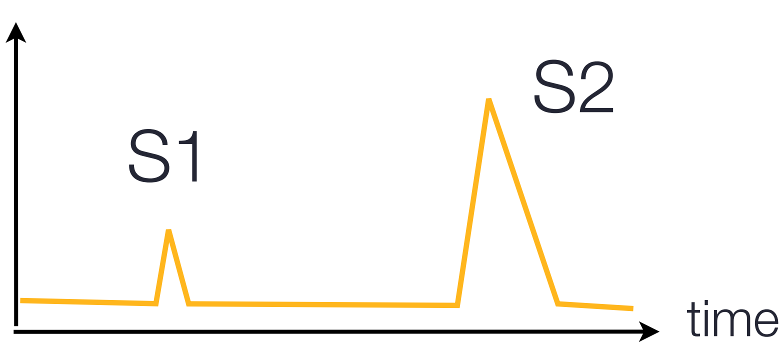
DEAP-3600
at SNOLAB, 3.6 t

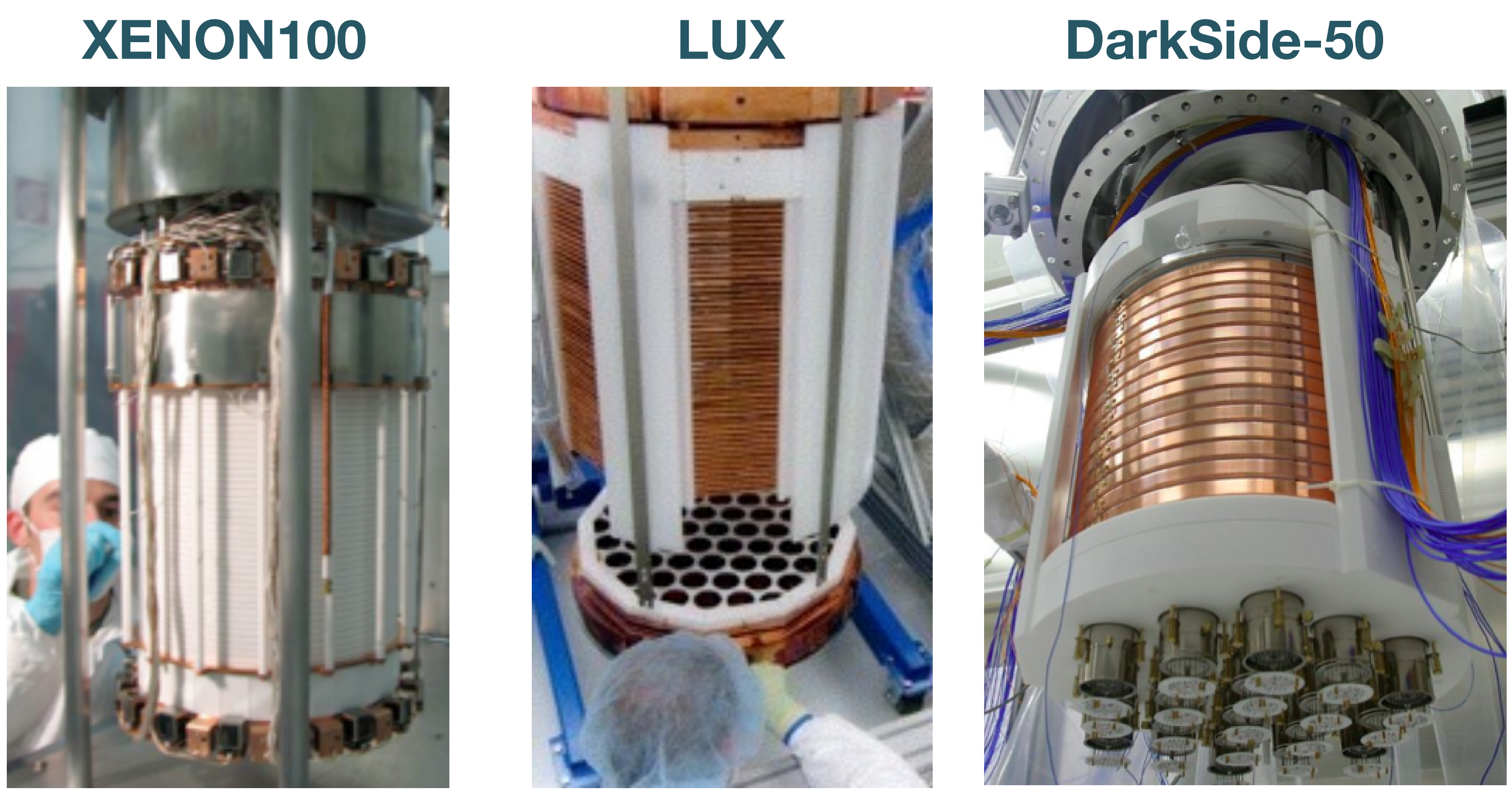


In commissioning
First results in 2016
1 x 10^{-46} cm^2 sensitivity

Dual-phase noble liquid detectors







Xenon

XENON100/1T at LNGS, LUX at SURF, PandaX at CJPL

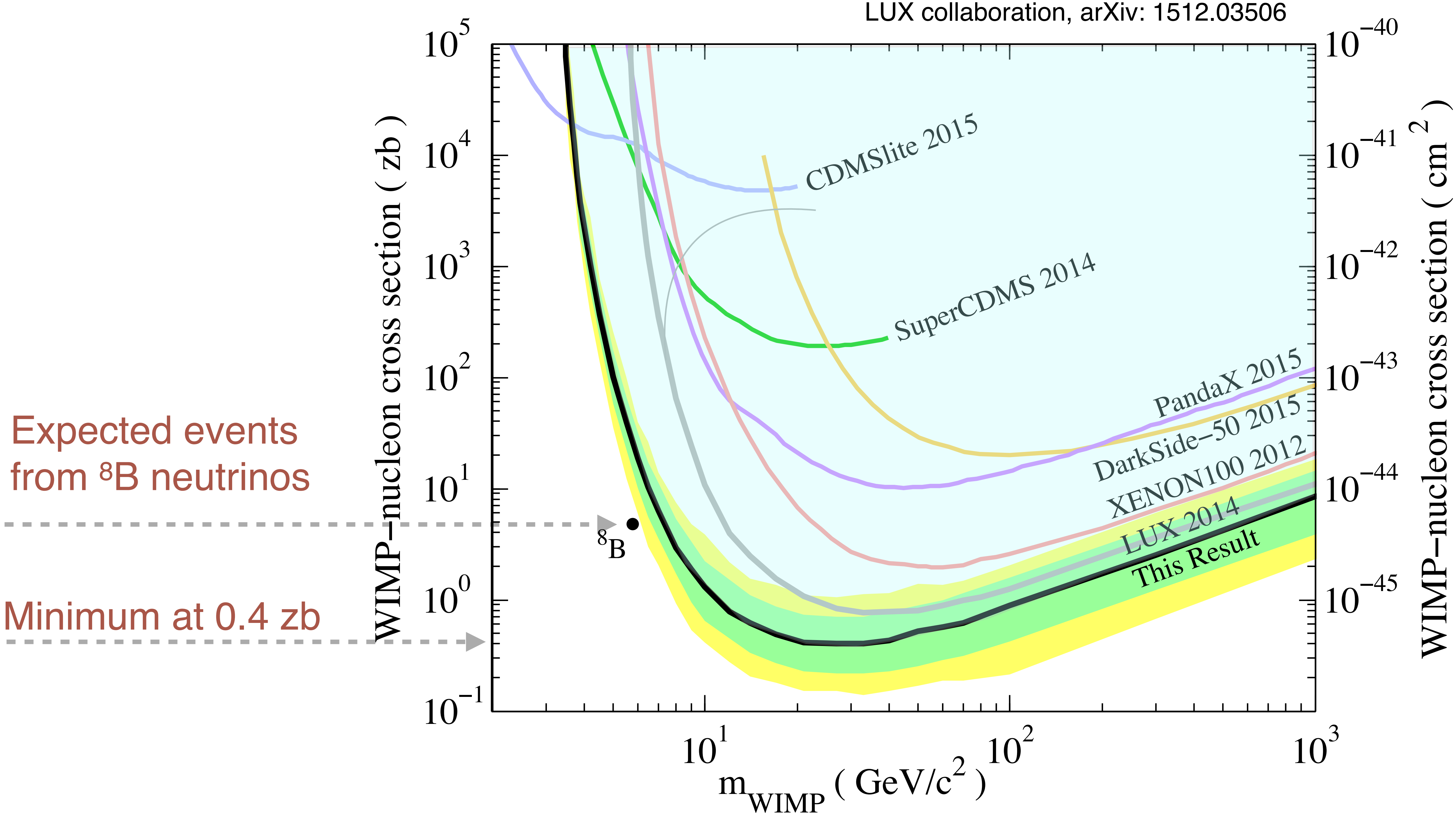
Argon

DarkSide-50 at LNGS, ArDM at Canfranc

Target masses between ~ 50 kg - 1 ton

Recent results: no evidence (yet) for WIMPs

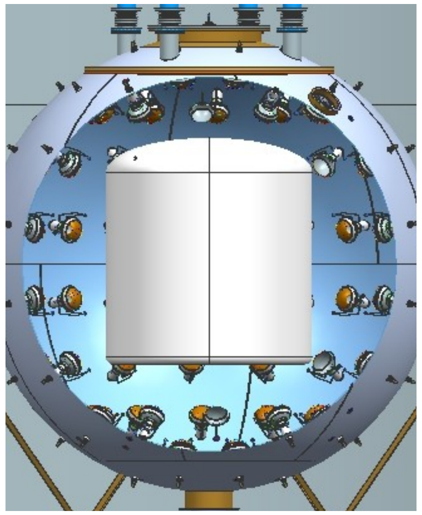
LUX collaboration, arXiv: 1512.03506



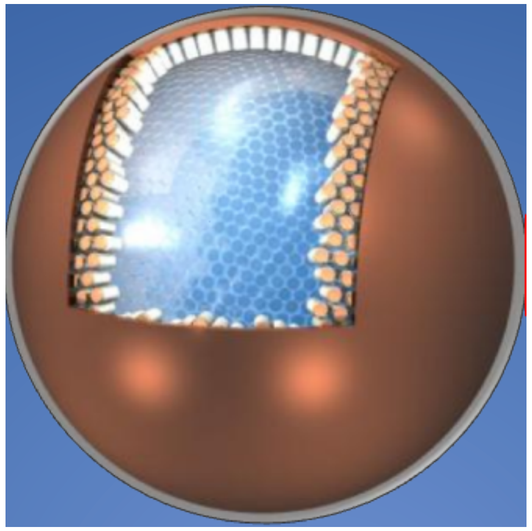
New and future noble liquid detectors

- Under commissioning: XENON1T (3.5 t LXe) at Gran Sasso
- Proposed LXe: LUX-ZEPLIN 7t, XENONnT 7t, XMASS 5t
- Proposed LAr: DarkSide 20 t, DEAP 50 t
- Design & R&D: DARWIN 50 t LXe; ARGO 300 t LAr

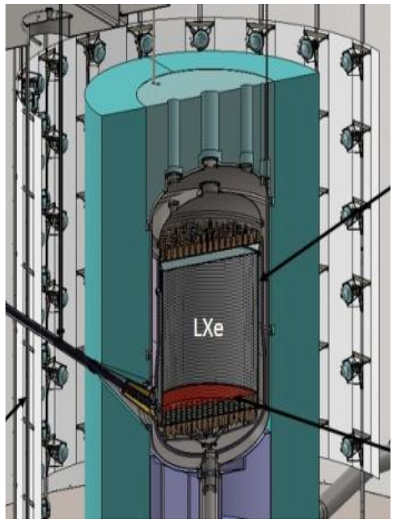
XENONnT: 7t LXe



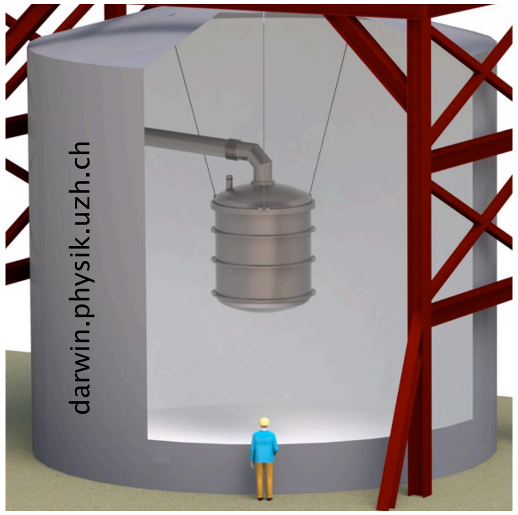
DarkSide: 20 t LAr



XMASS: 5t LXe



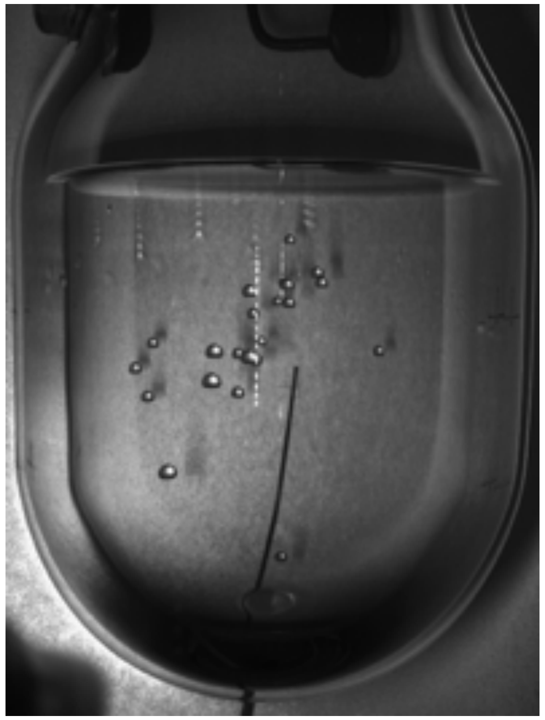
LZ: 7t LXe



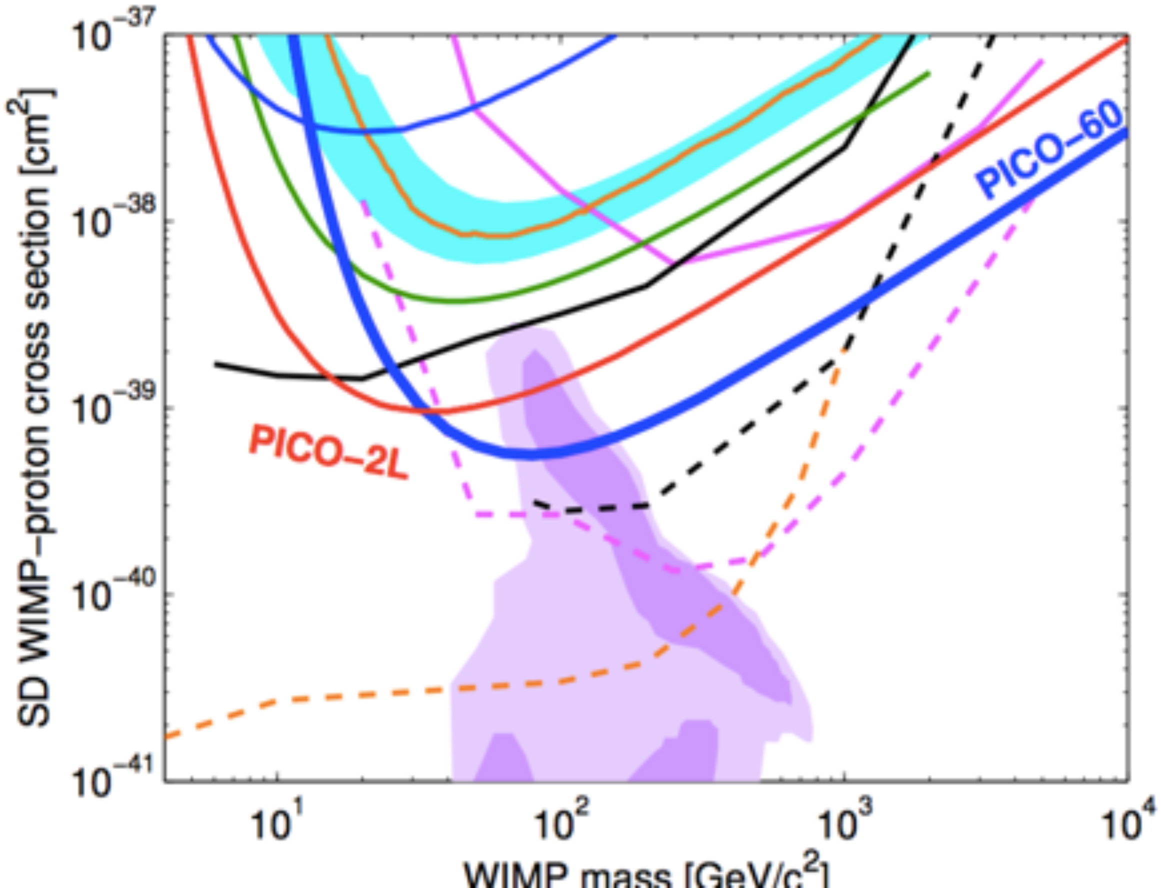
DARWIN: 50 t LXe

Bubble Cambers

- Detect single bubbles induced by dE/dx NRs in superheated liquid target:
  - acoustic and visual readout; measure integral rate above the threshold
  - large rejection factors (10^8-10^{10}) for MIPs, scalable to large masses
- PICO-2L (PICASSO+PICO), 2.9 kg C_3F_8 , target best for SD WIMP-proton search; PICO-60L published the first results in 2015 ; proposed PICO-250L at SNOWLAB
- MOSCA-B R&D ongoing at LNGS.



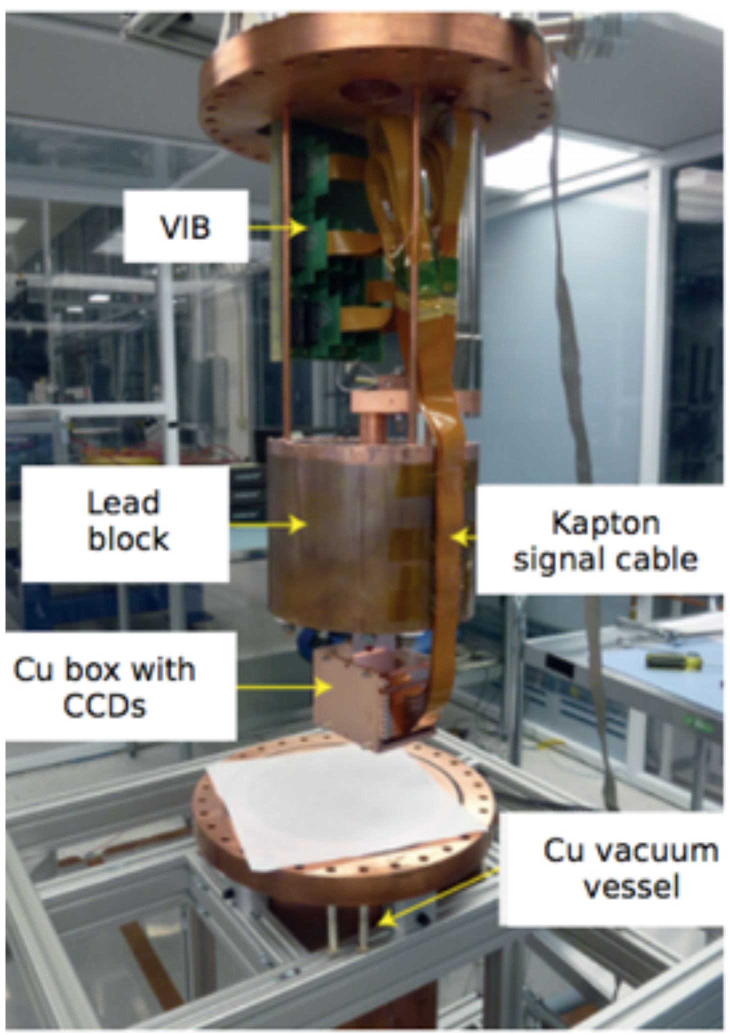
PICO-2L n calibration

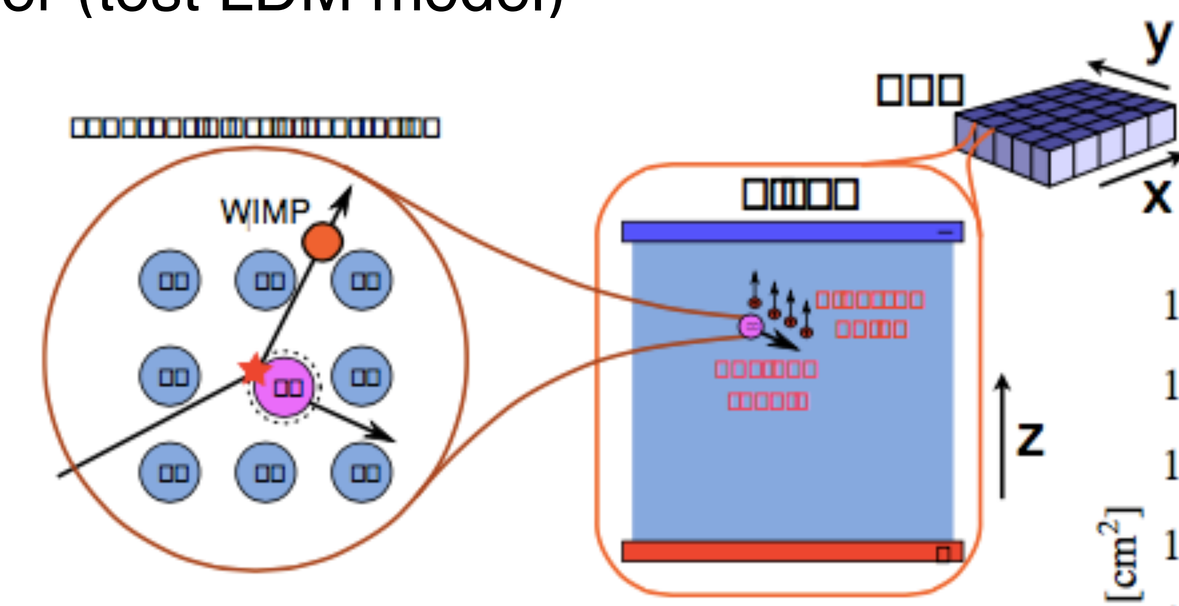


CCD Detector

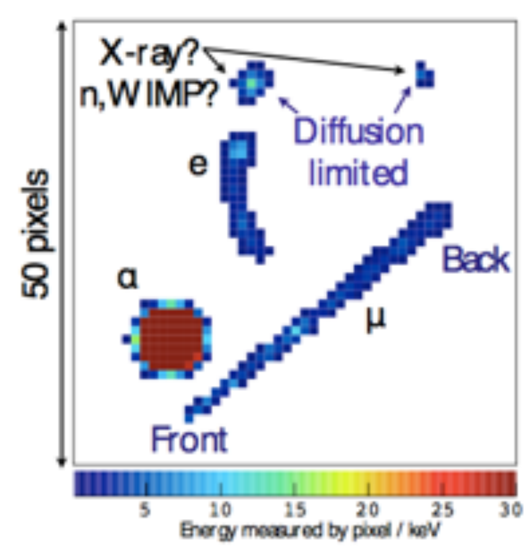
DAMIC at Snowlab

- CCD based experiment, 50 eV_{ee} energy threshold. 5.2 g per channel at 140 K
- DAMIC 100g is currently under commissioning at SNOWLAB
- Also look for DM e scatter (test LDM model)

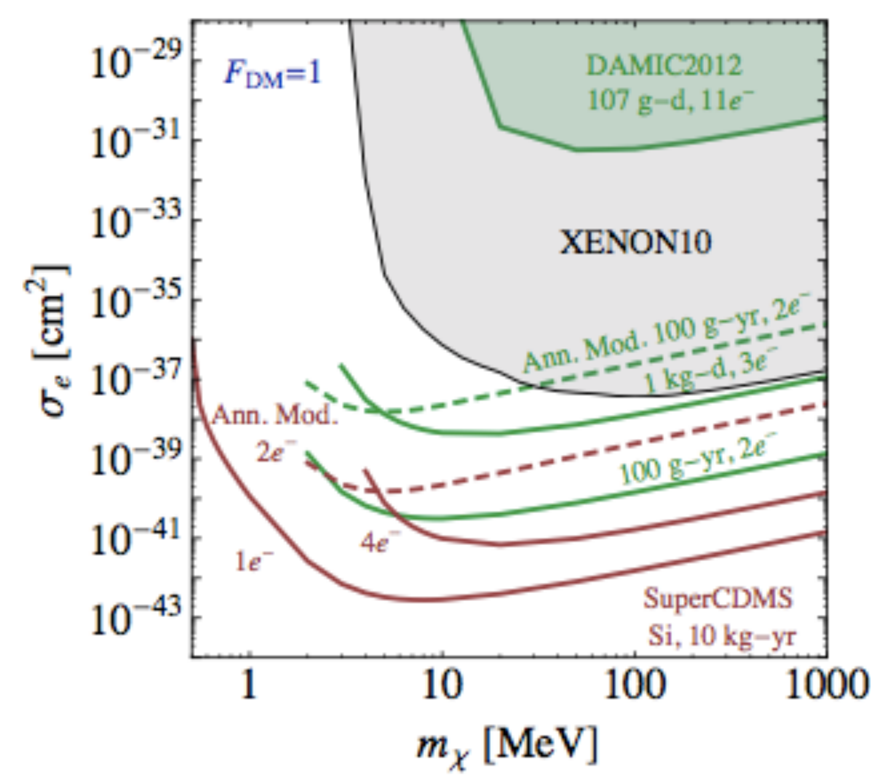




(b) WIMP detection in a CCD



(a) Portion of a DAMIC image



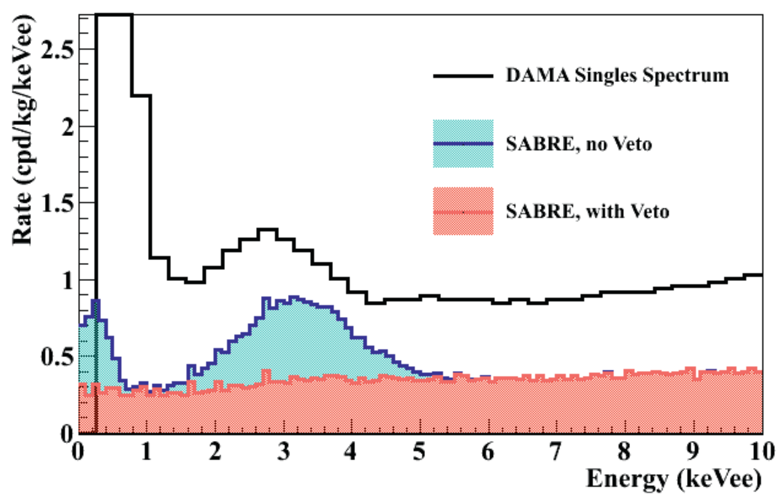
R. Essig et al., arXiv: 1509.01598

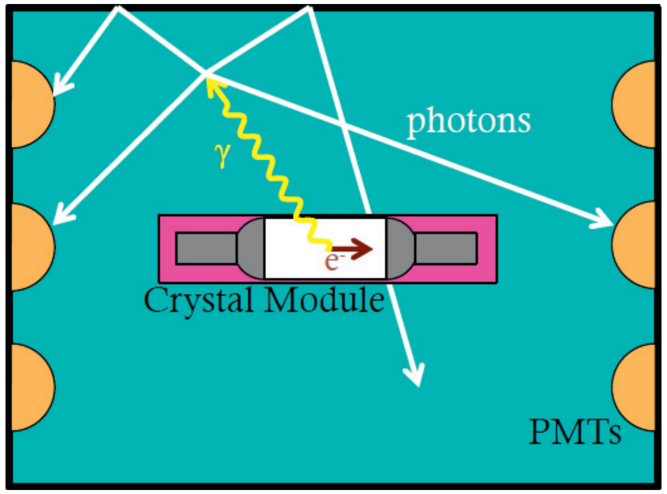
Scintillator crystals

DAMA/LIBRA annual modulation signal

- Period = 1 year, phase = June 2 ± 7 days; 9.3-sigma
- Results in tension with many WIMP searches
- Several experiments to *directly probe the modulation signal* with similar detectors (NaI, CsI): **SABRE, ANAIS, DM-Ice, KIMS**
- **"Leptophilic" models viable (until a few weeks ago…)**

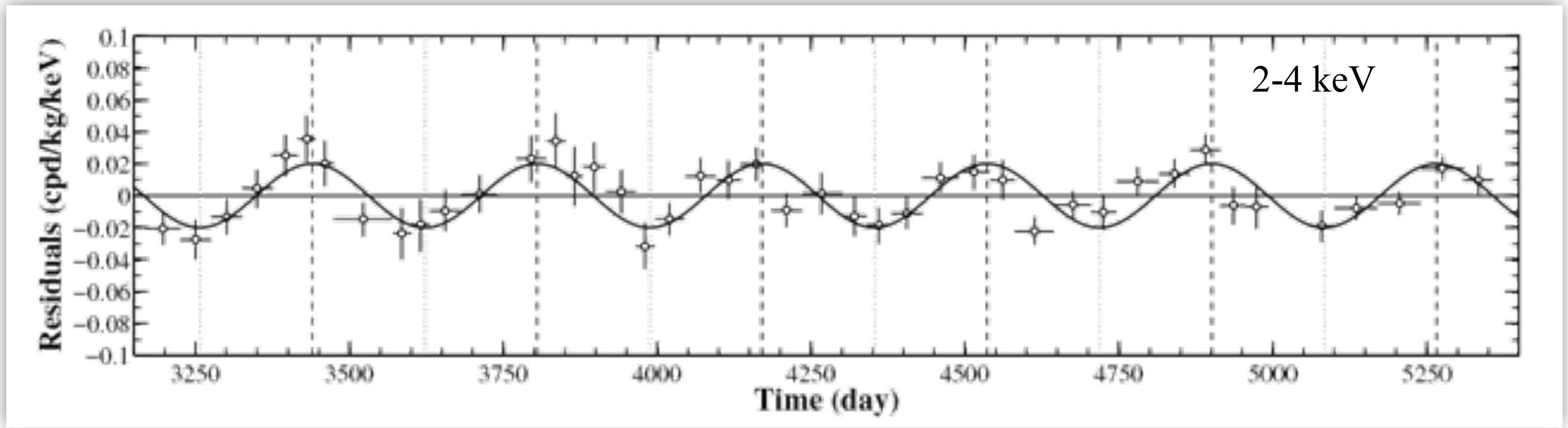
Emily Shields et al. / Physics Procedia 61 (2015) 169 – 178





SABRE, 50 kg NaI detectors

DAMA/LIBRA NaI: 2% annual modulation



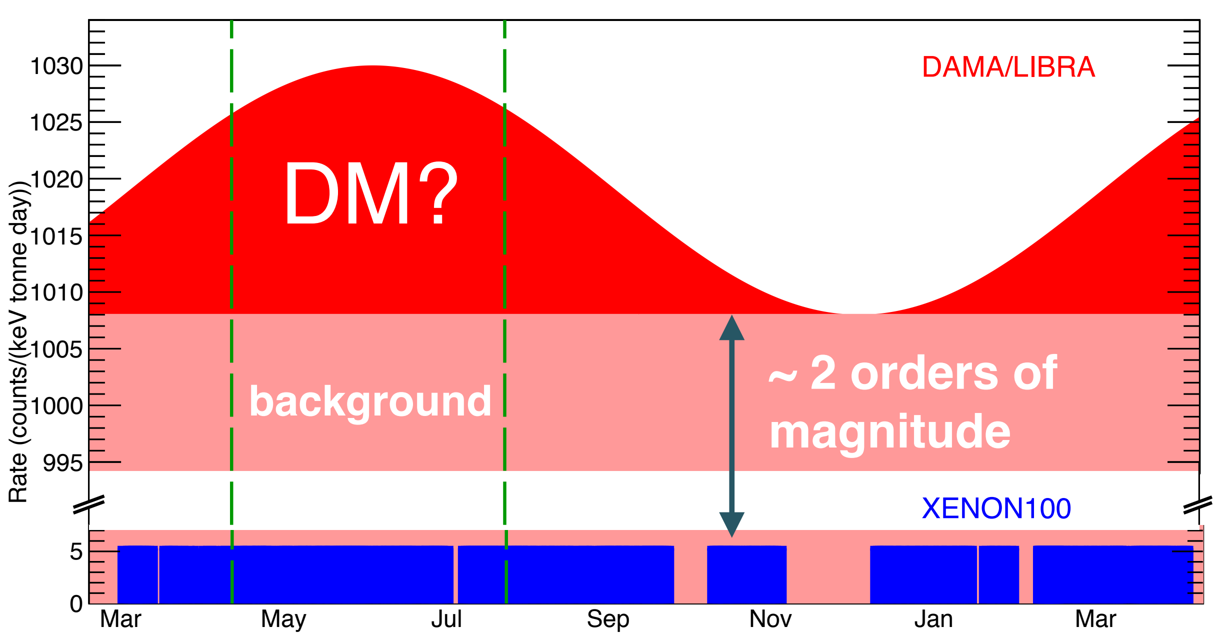
R. Bernabei et al, EPJ-C67 (2010)

New XENON100 results

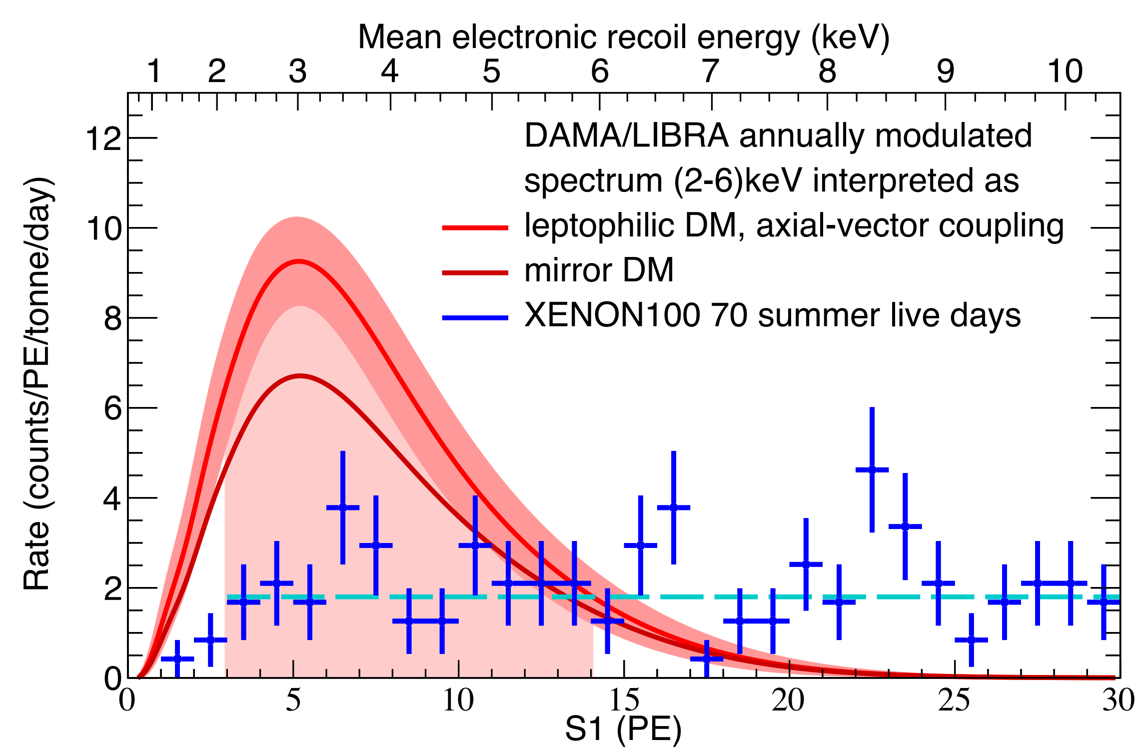
- Dark matter particles interacting with e^-
  - XENON100's ER background lower than DAMA modulation amplitude

  ➡ search for a signal above background in the ER spectrum

XENON collaboration, arXiv: 1507.07747, Science 349, 2015



Consider the 70 days with the largest signal

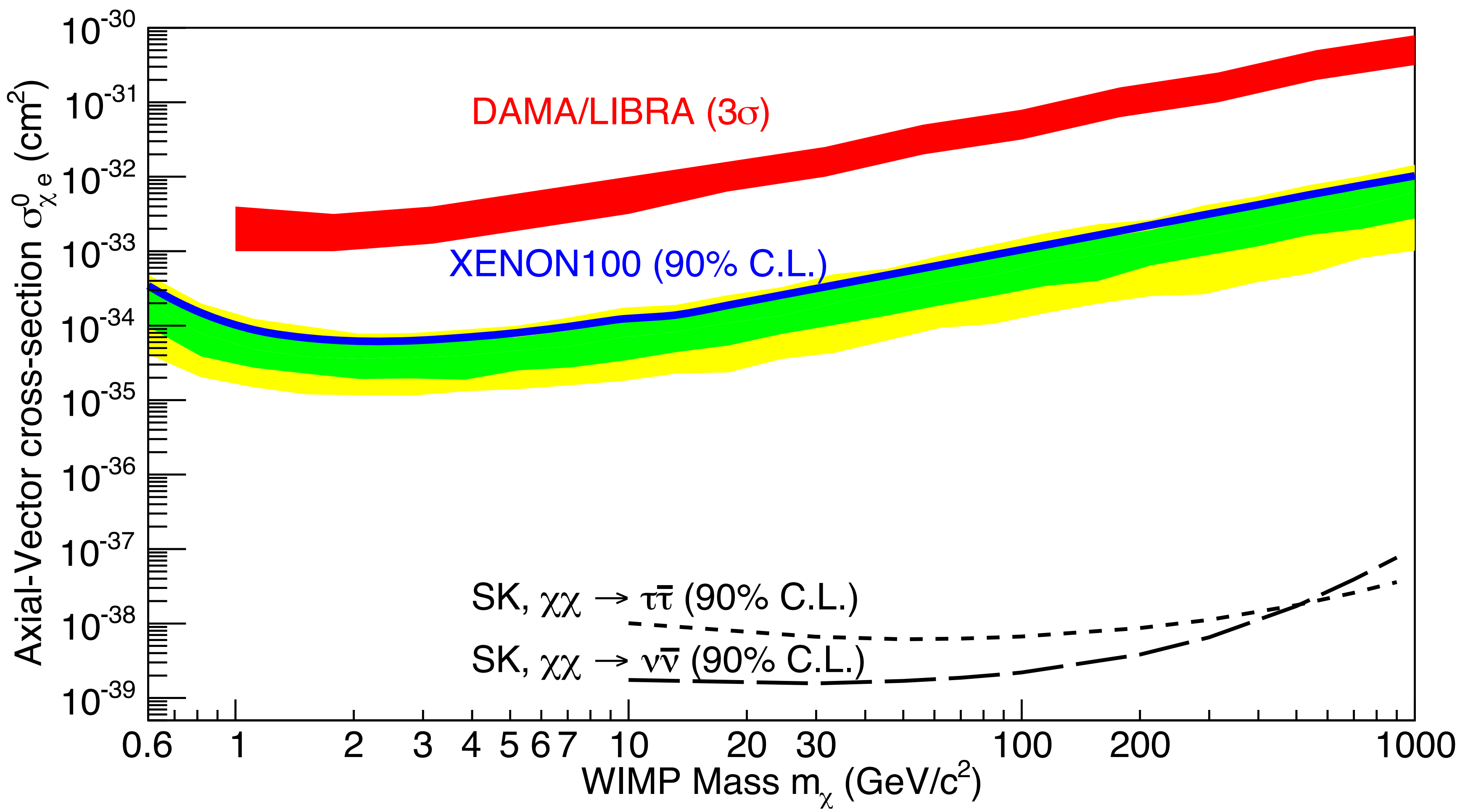


DAMA/LIBRA modulated spectrum as would be seen in XENON100 (for axial-vector WIMP-e^- scattering)

XENON100 excludes leptophilic models

- 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

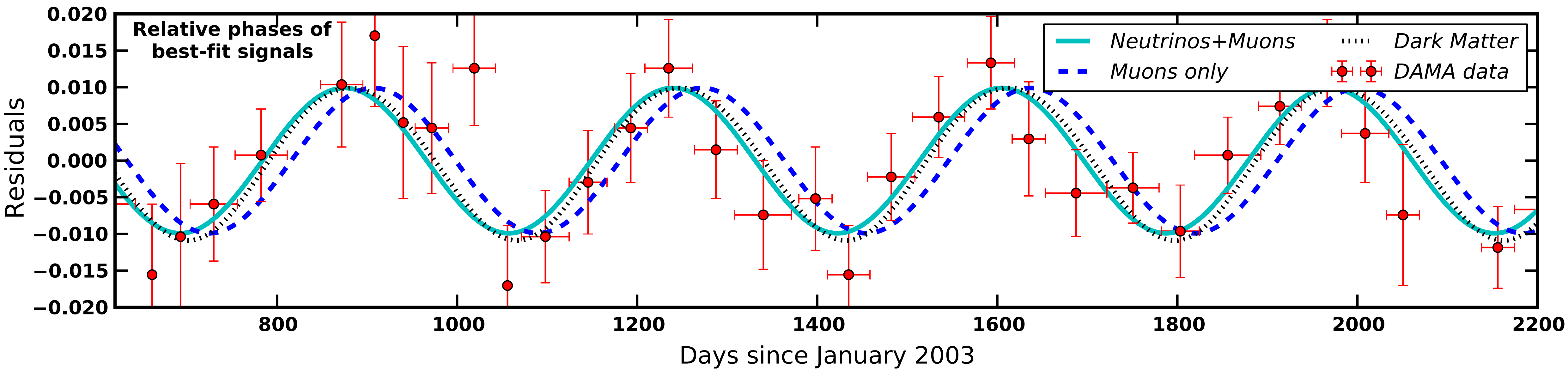


What is the origin of the DAMA signal?

Possible explanation: **a combination of neutrinos and muons**

Solar ^{8}B neutrino- and atmospheric muon-induced neutrons

Combined phase of muon and neutrino components: good fit to the data*

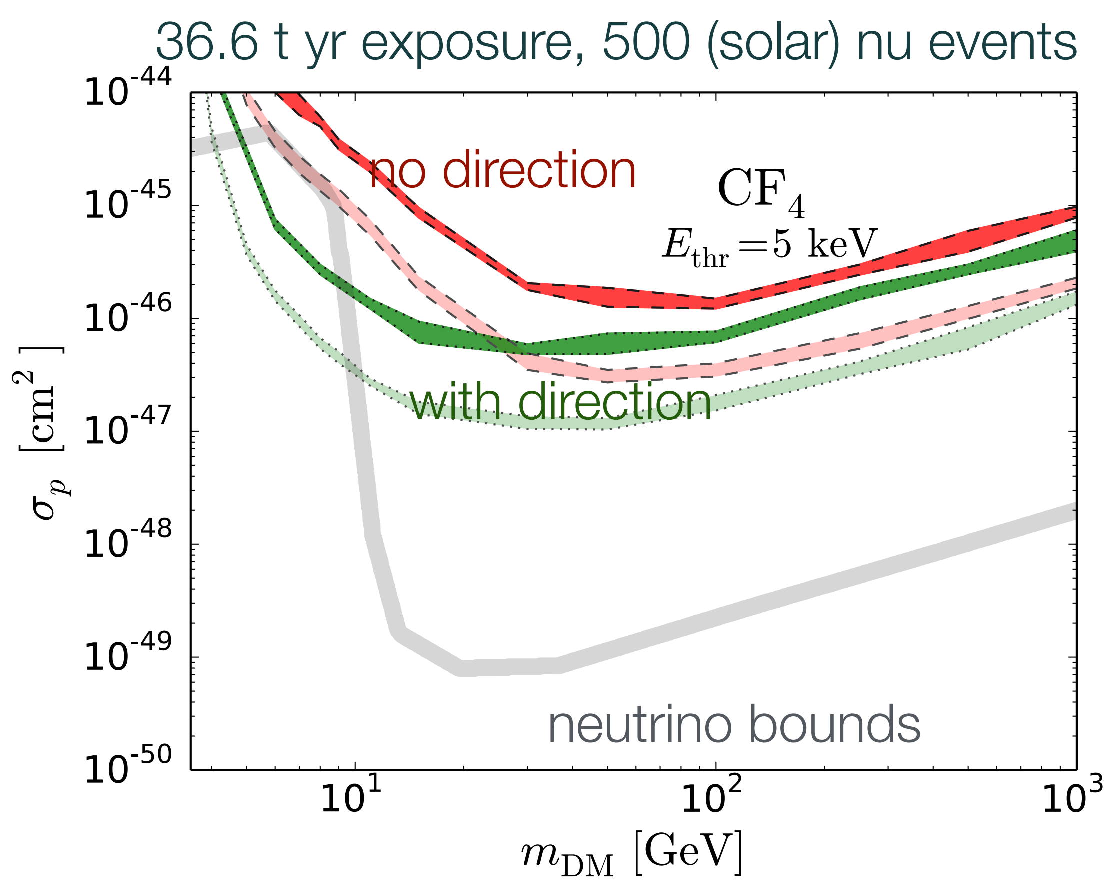


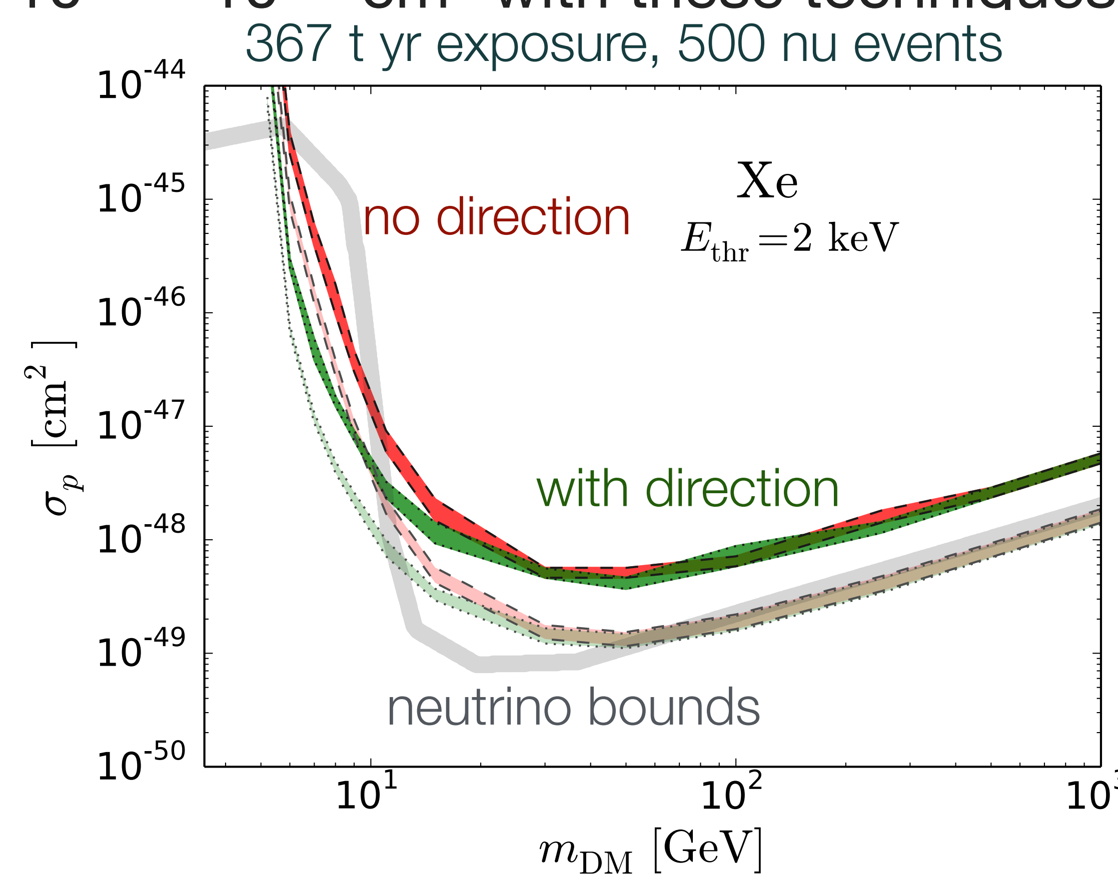
Jonathan Davis, PRL 113, 081302 (2014)

*Muons: flux correlated with T of atmosphere; period is ok but phase is 30 d too late
*Neutrinos: flux varies with the Sun-Earth distance; period is ok but phase peaks in early Jan

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



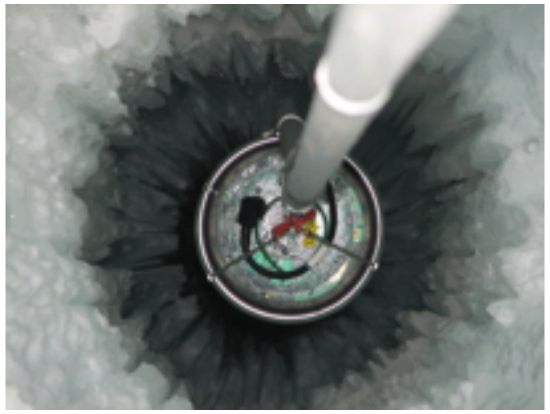


P. Grothaus, M. Fairbairn, J. Monroe, arXiv: 1406.5047

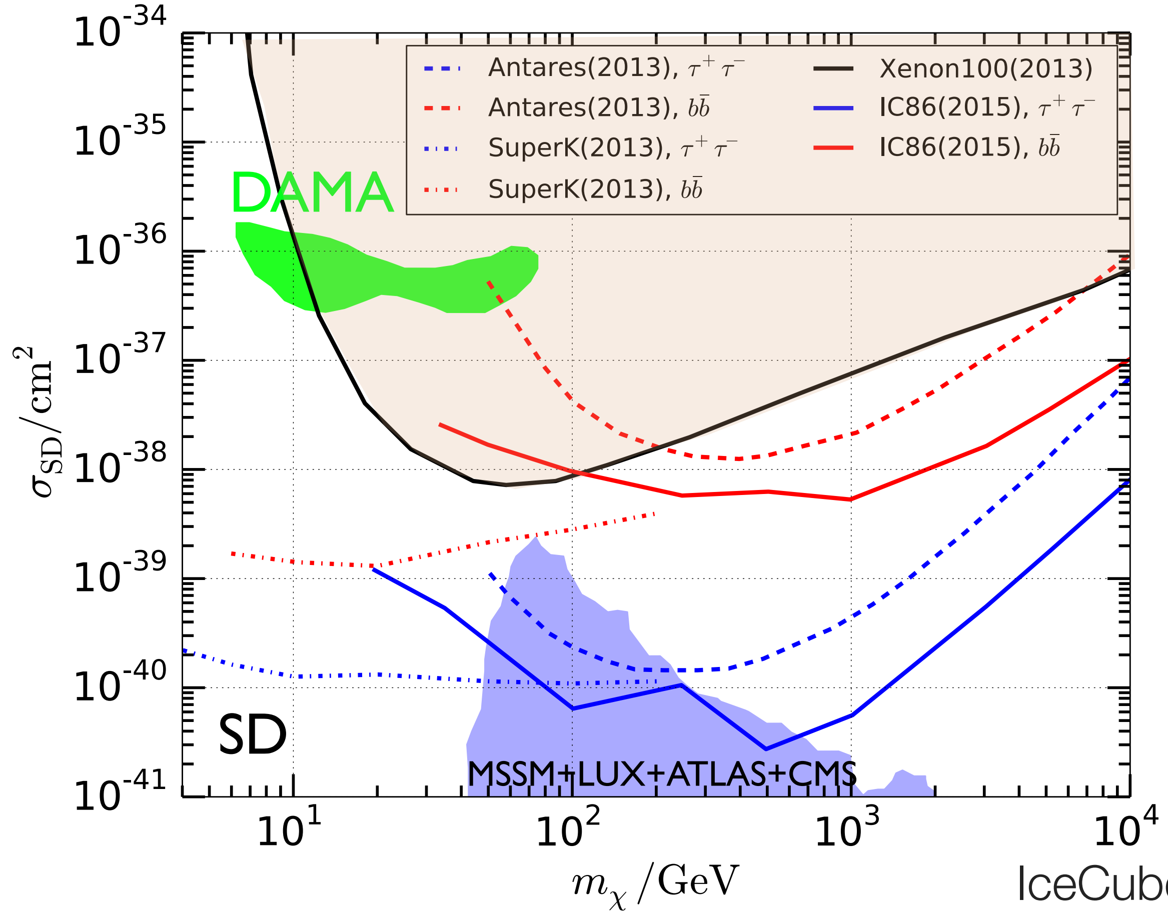
R&Ds are ongoing on DM directional measurements by exploiting features of the charge recombination in **Ar** and also extreme the spacial resolution in to the **Emulsions**

How do we compare with **indirect searches**?

- 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: WIMP-p; spin-dependent



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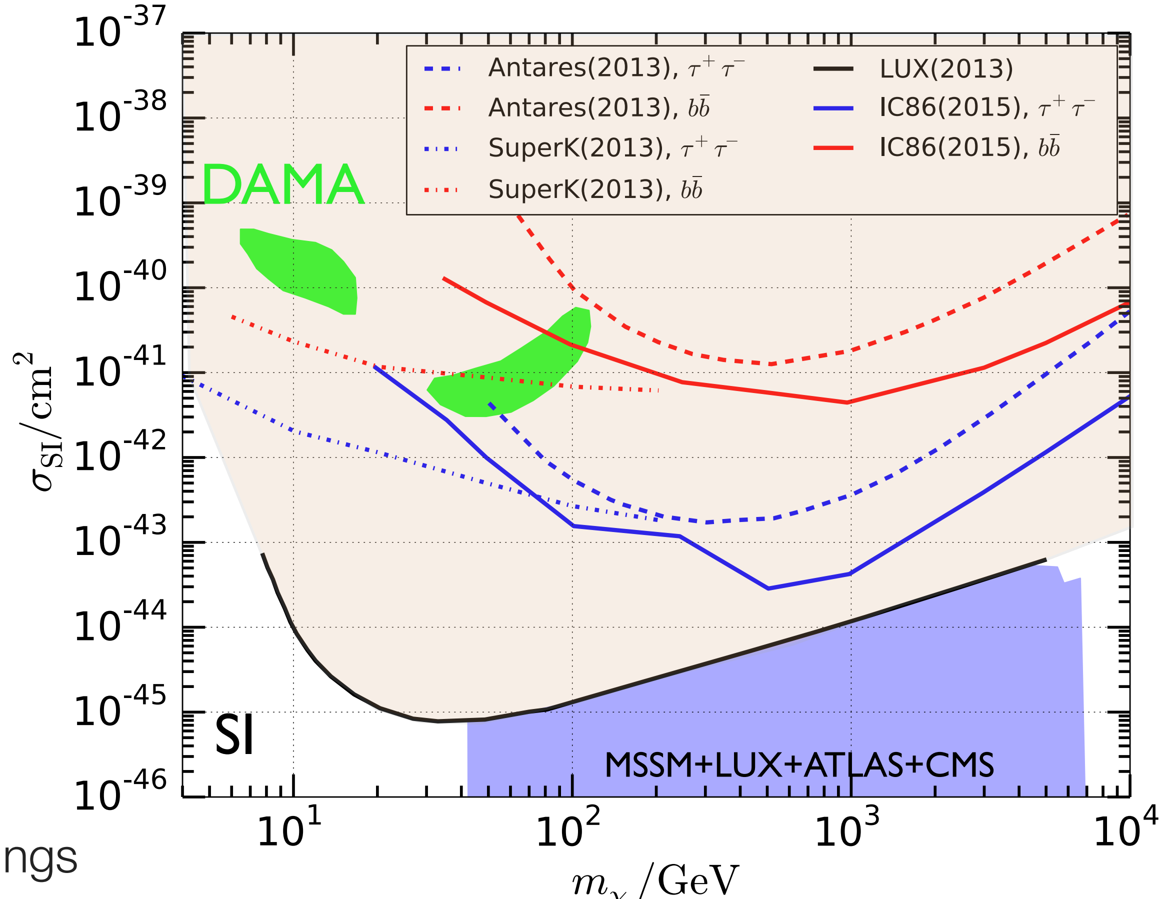
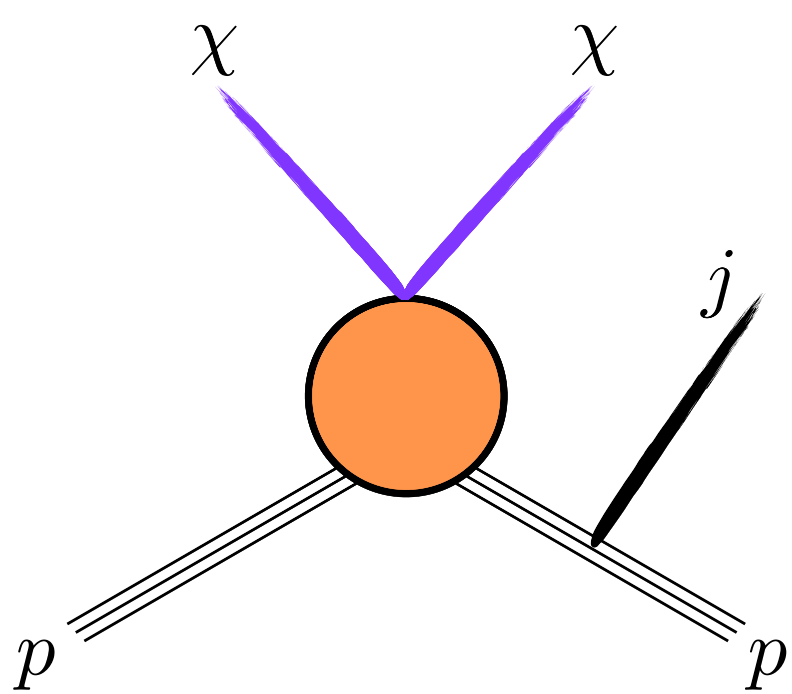


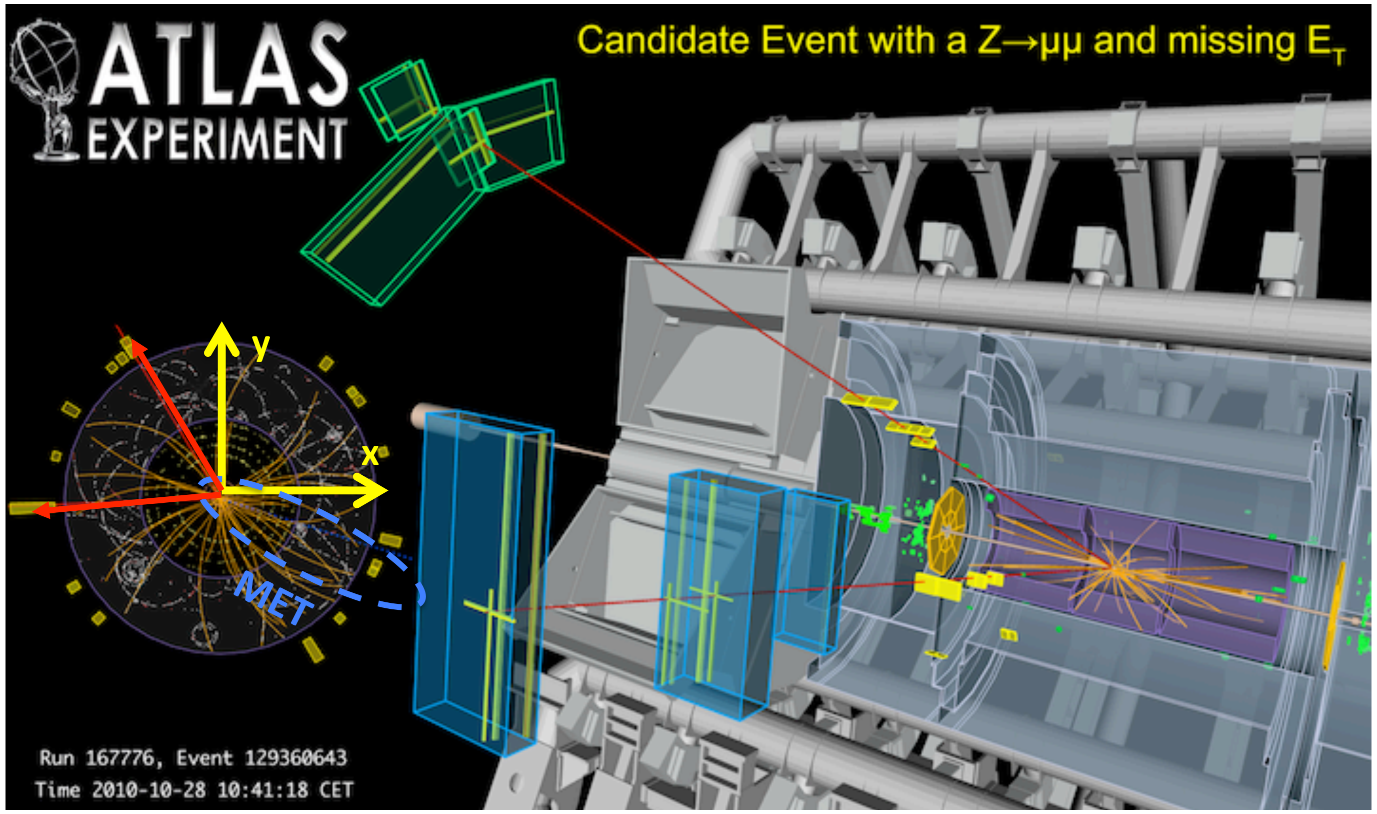
IceCube ICRC2015, 86 strings

Accelerator searches

- Dark matter particles can be directly produced in LHC collisions
- **Need visible particle in final state**



1 jet + missing energy



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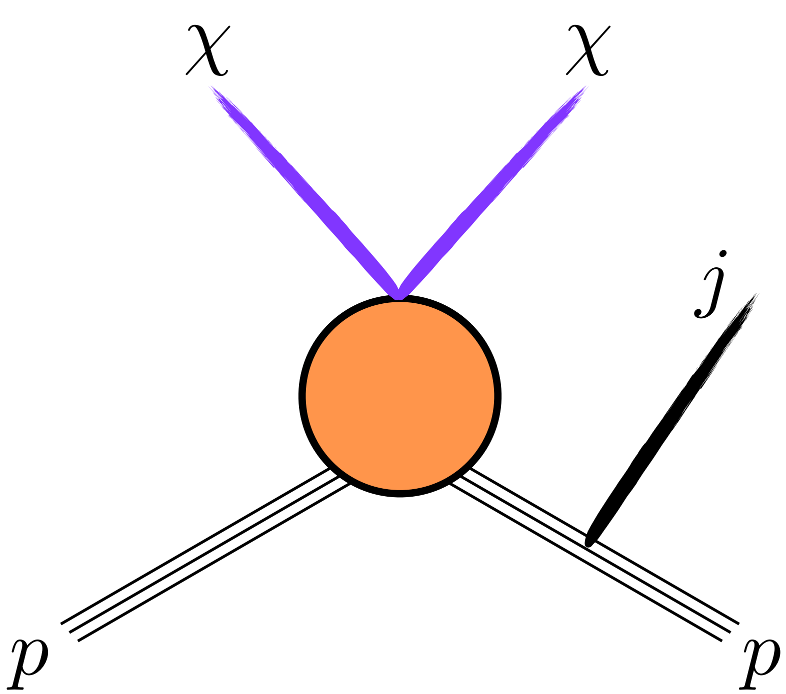
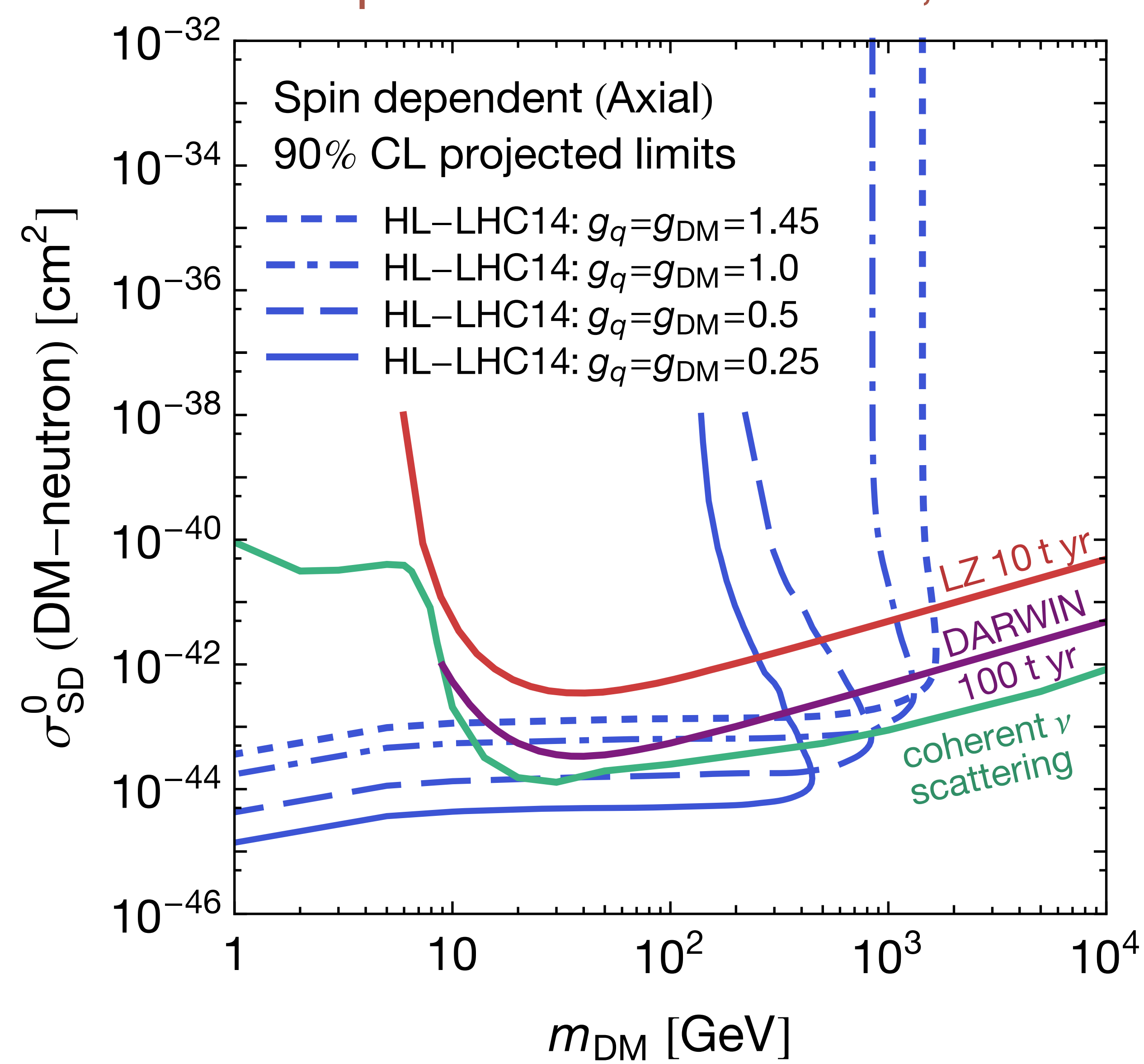


1 jet + missing energy

Expectations for LHC-14, SD



S. Malik et al., Phys. Dark Univ. 9-10 (2015) 51-58

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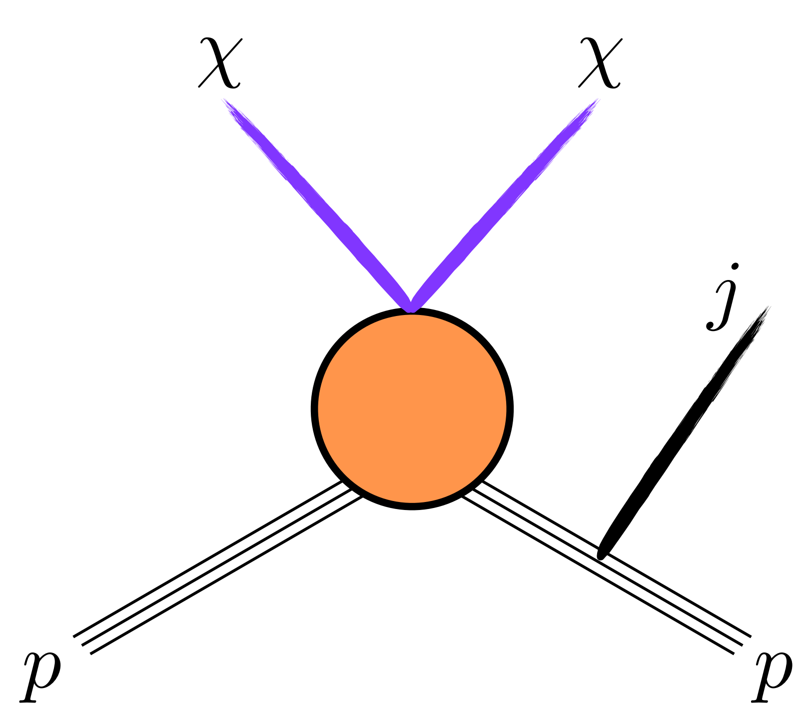
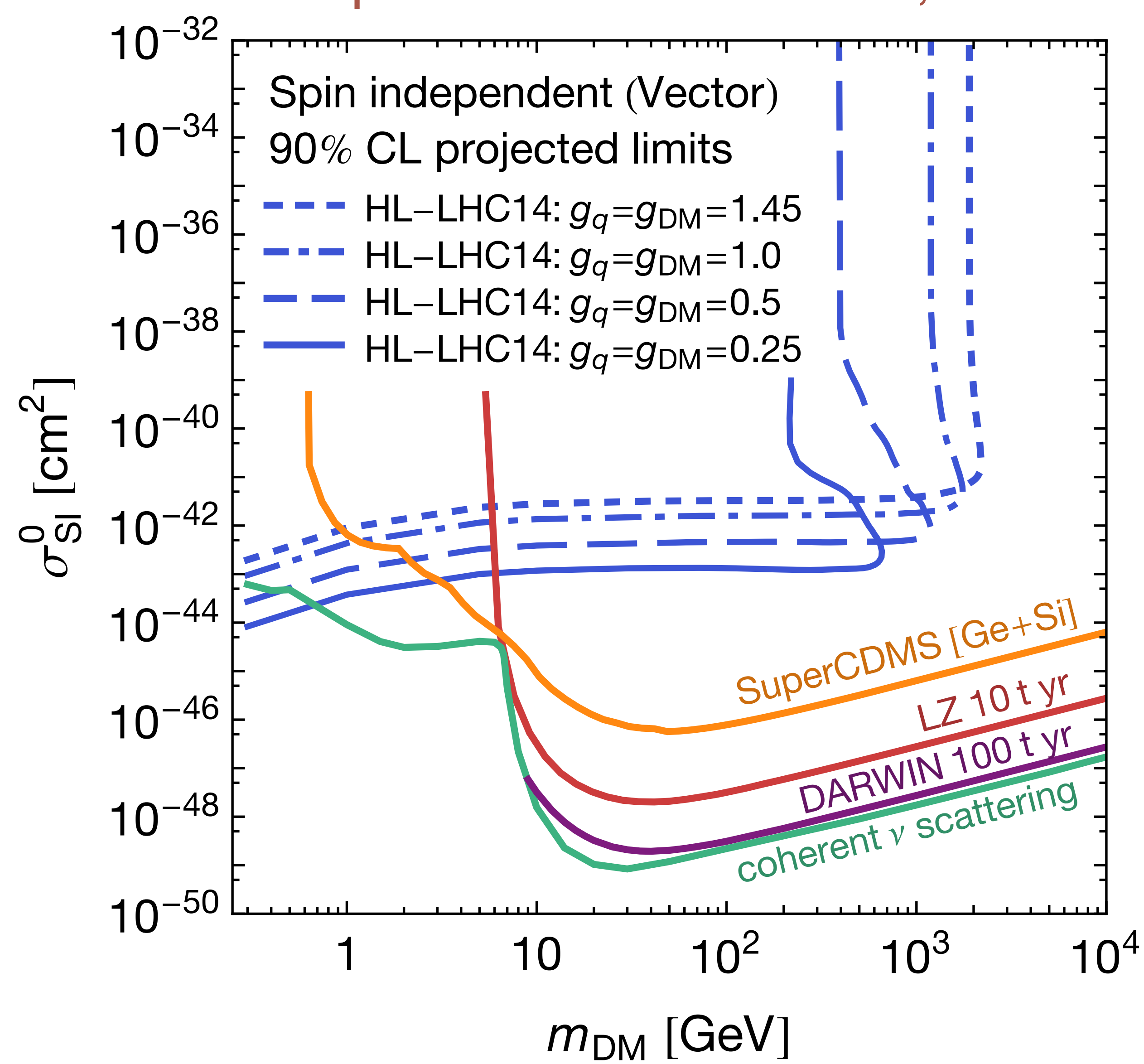


1 jet + missing energy

Expectations for LHC-14, SI



S. Malik et al., Phys. Dark Univ. 9-10 (2015) 51-58

Conclusions

Cold dark matter is a explanation for many cosmological & astrophysical observations

It could be made of WIMPs - thermal relics from an early phase of our Universe

- this hypothesis is testable: direct detection, indirect detection, accelerators

- so far, no convincing evidence of a dark matter particle was found

But: excellent prospects for discovery

direct detection: increase in WIMP sensitivity by 2 orders of magnitude in the next few years

reach neutrino background (measure neutrino-nucleus coherent scattering!) this/next decade

high complementarity with indirect & LHC searches