

Dark Matter Search Experiments

Manfred Lindner

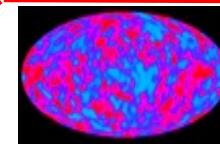


SUSY2023

17 - 21 July
University of Southampton
Southampton, UK

The XXX International Conference on Supersymmetry
and Unification of Fundamental Interactions (SUSY2023)

What are we looking for?



radiation: 0.005%



**chemical elements:
(not H & He) 0.025%**



stars: 0.8%



H & He: gas 4%

ν_e, ν_μ, ν_τ



neutrinos = CvB: 0.17%



black holes: PBH or LBH



dark matter: 26.8%
one component/cocktail?



dark energy: 68.3%

Potential Dark Matter Directions

Gravity

Modified GR

MOND
simple one
scale
modification
→ fails badly

Other
is the EP
fundamental or
effective?

BHs

today's BHs

a suitable
population
(mass,
number) of
primordial
black holes

Particles

BSM physics motivated ↔ SM problems

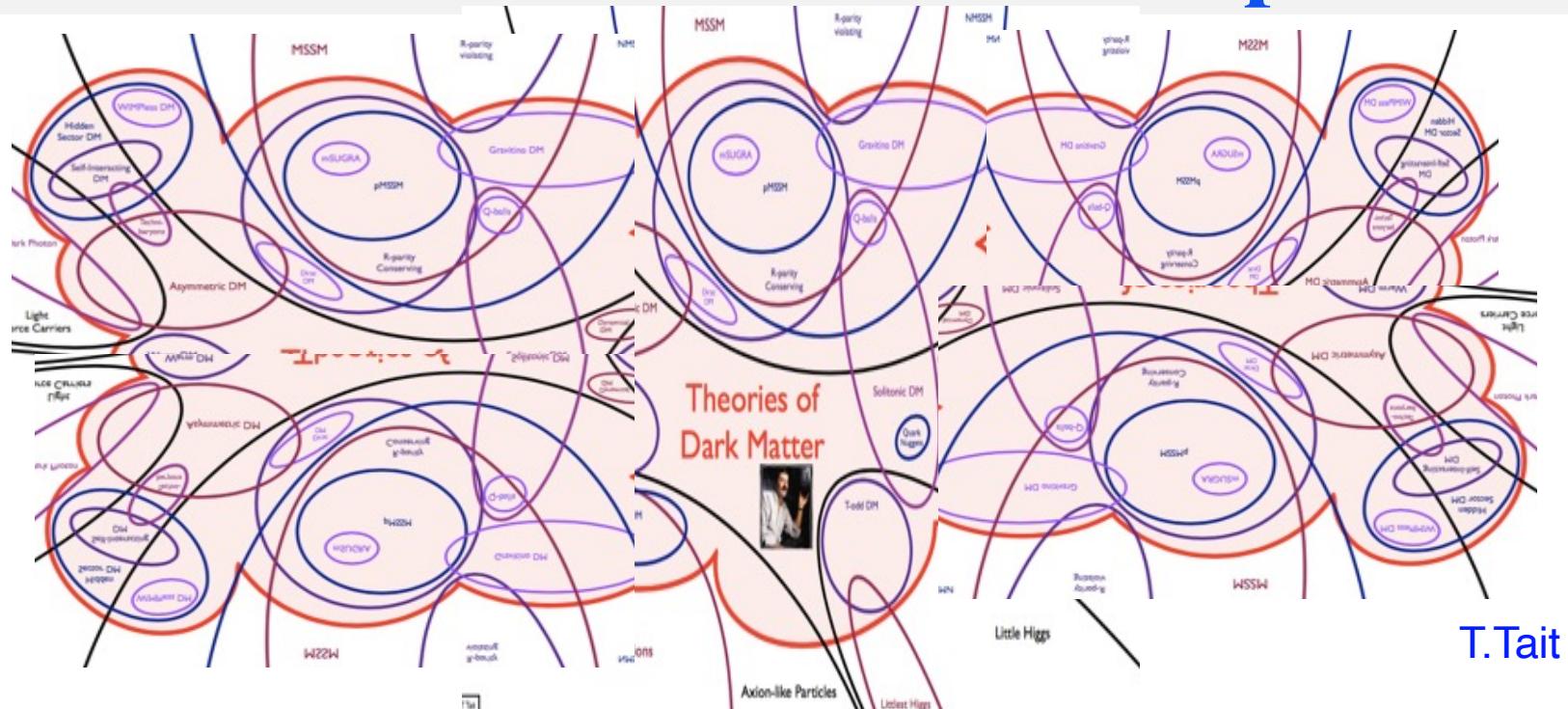
- neutrinos
- WIMPs:
neutralino
...
- axions
- sterile ν's
- ...

thermal production (WIMP miracle)
or non-thermal?

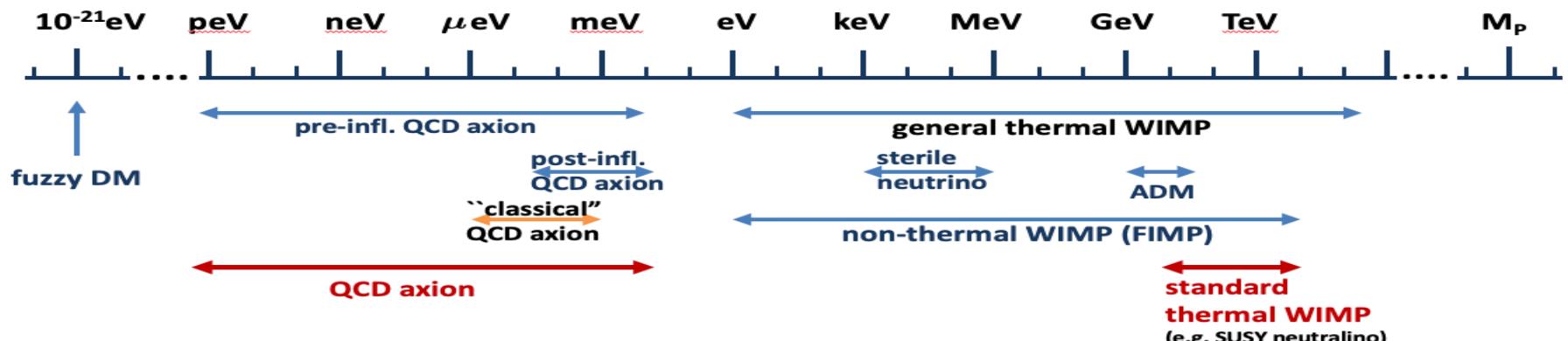
Models with correct abundance

- WIMPs
- dark photons
- ALPs
- other new
particles

Particle Dark Matter Options



- theory: any model that wasn't worked out so far...

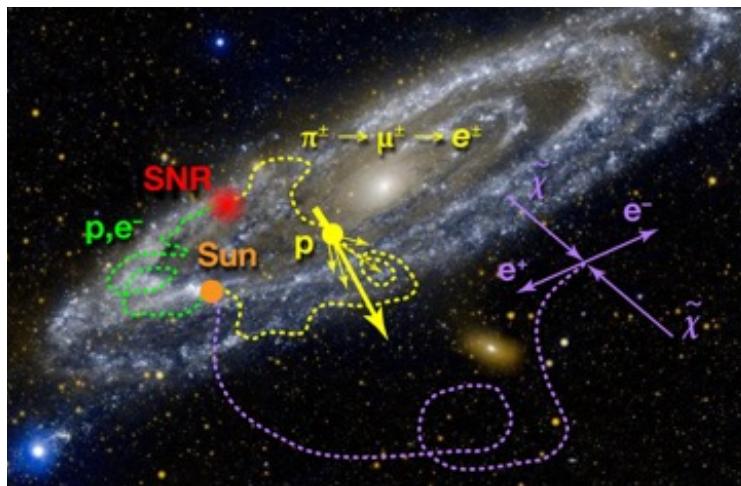


- experiment: cover unexplored mass / coupling space

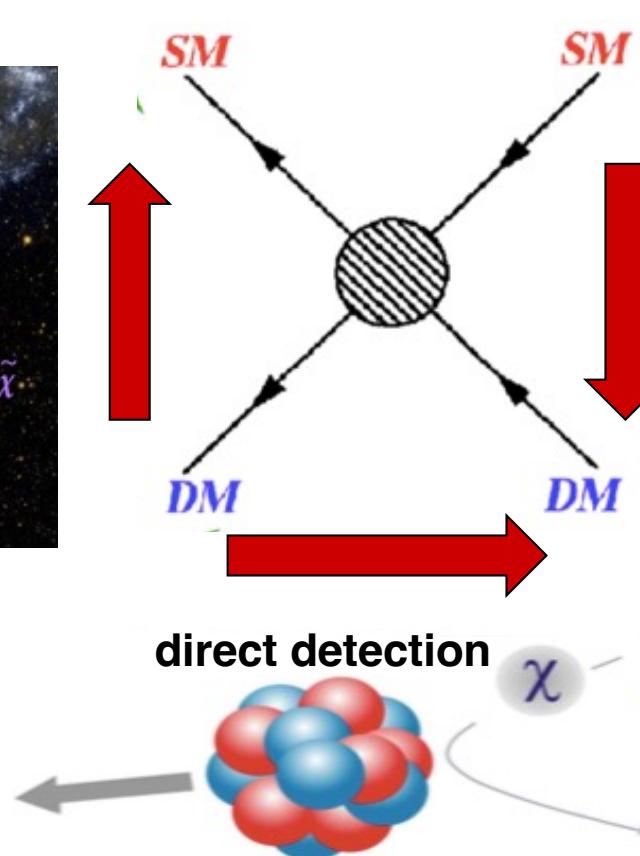
Option 1: WIMP Hunting

known Standard Model (SM) particles interact with WIMPs: **assumptions...**

indirect detection



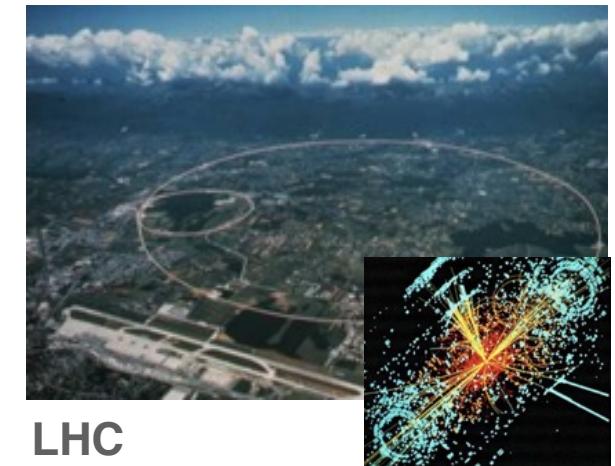
FERMI, PAMELA, AMS, HESS,
IceCube, CTA, HAWC...
astronomical uncertainties...
→ signal without doubt DM?



WIMP wind : ~232km/s from Cygnus

- modelling
- rare event backgrounds

colliders



LHC

may detect new particles, but
is it DM (lifetime, abundance)?

So far nothing seen...

- SUSY & higher scale
- other SB motivated WIMPs
- new ideas/candidates

Dark Matter Production at Colliders

DM particles: no EM interaction; carry energy & momentum

- no DM tracks in a detector
- missing energy

Two main approaches:

1) direct production of DM particles

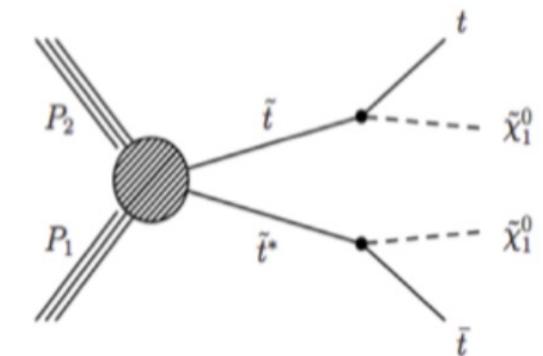
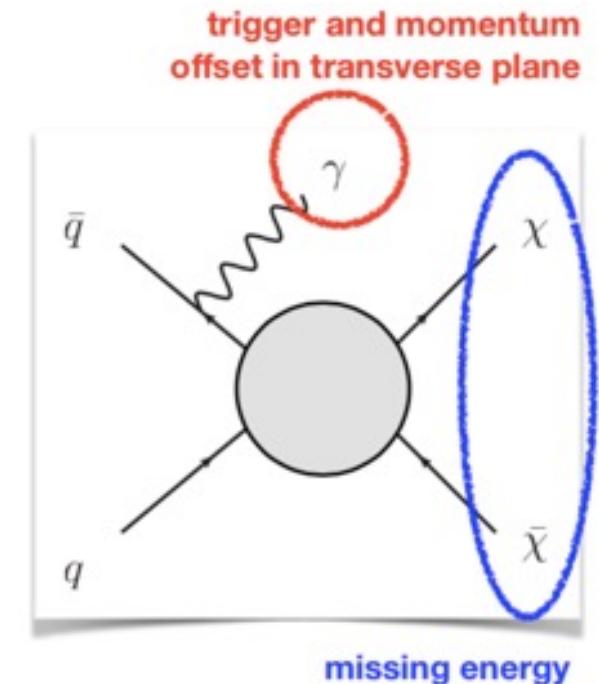
annihilation of standard model particles into a pair of DM particles

2) indirect production of DM particles

search for dedicated decay chains with DM-like particles using a dedicated model (e.g. SUSY)

Drawbacks:

- a signal does not guarantee a long life-time
- unrelated to DM density in the Universe



EFT Interpretation

For $q \ll \text{mediator mass } M_{\text{med}}$

→ Interaction described by M^* and m_{DM}

type of interaction → different operators

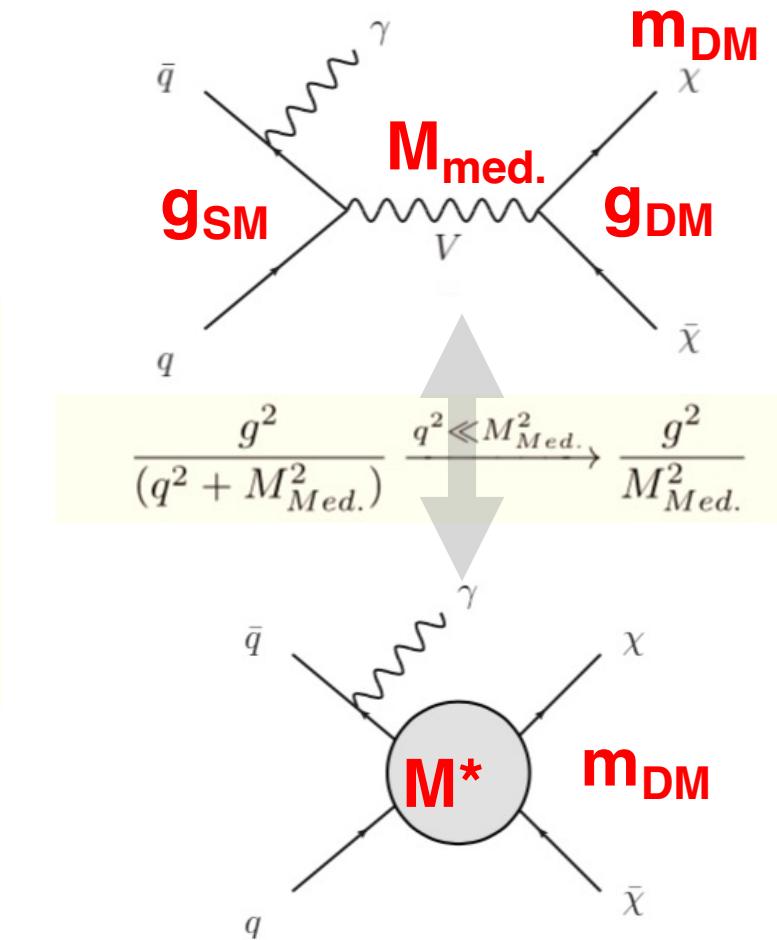
Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_*^3} \bar{\chi} \chi \bar{q} q$
D5	qq	vector	$\frac{1}{M_*^2} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_*^2} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu \gamma^\mu q$
D9	qq	tensor	$\frac{1}{M_*^2} \bar{\chi} \sigma^{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q$
D11	gg	scalar	$\frac{1}{4M_*^3} \bar{\chi} \chi \alpha_s (G_{\mu\nu}^s)^2$

D1, D5, D11 spin independent (SI), D8, D9 = SD

Mediator induces also SM → SM processes

→ LHC sets limits on $g_{\text{SM}}^2/M_{\text{med}}^2$ (mod. m_{DM})

→ Unless g_{SM} is tiny TeV-ish limits on M_{med} .



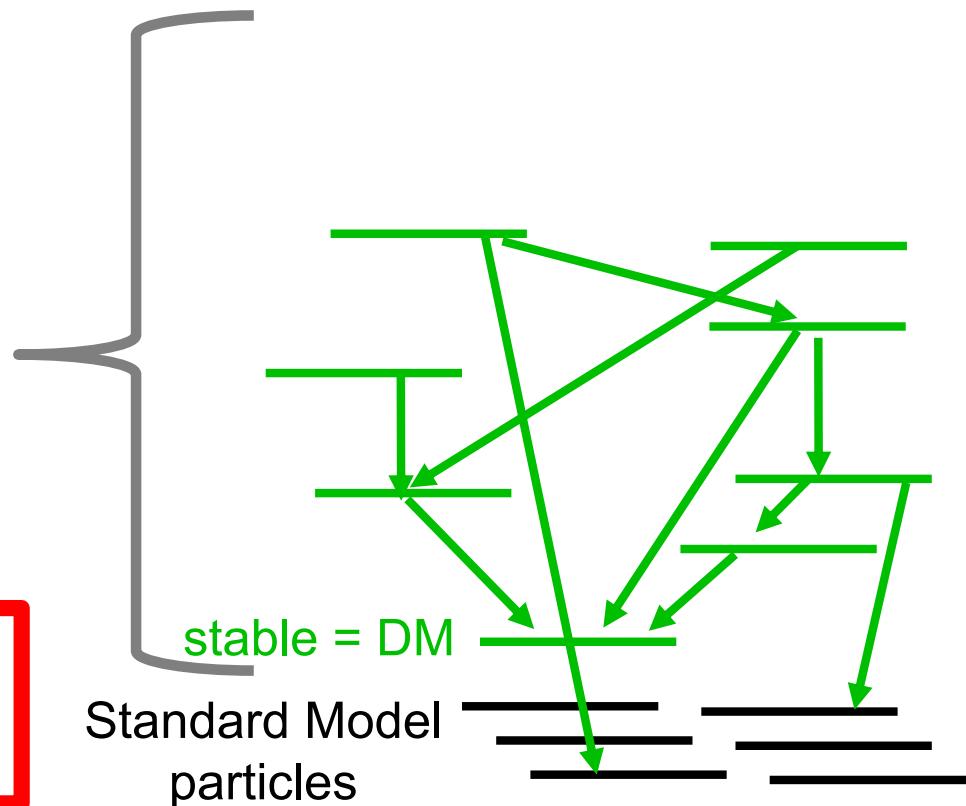
$g_{\text{DM}} = 1$ is an assumption → could be tiny → weaker DM limits

or a full model → more signatures/effects & constraints

DM motivated Extensions have other Consequences

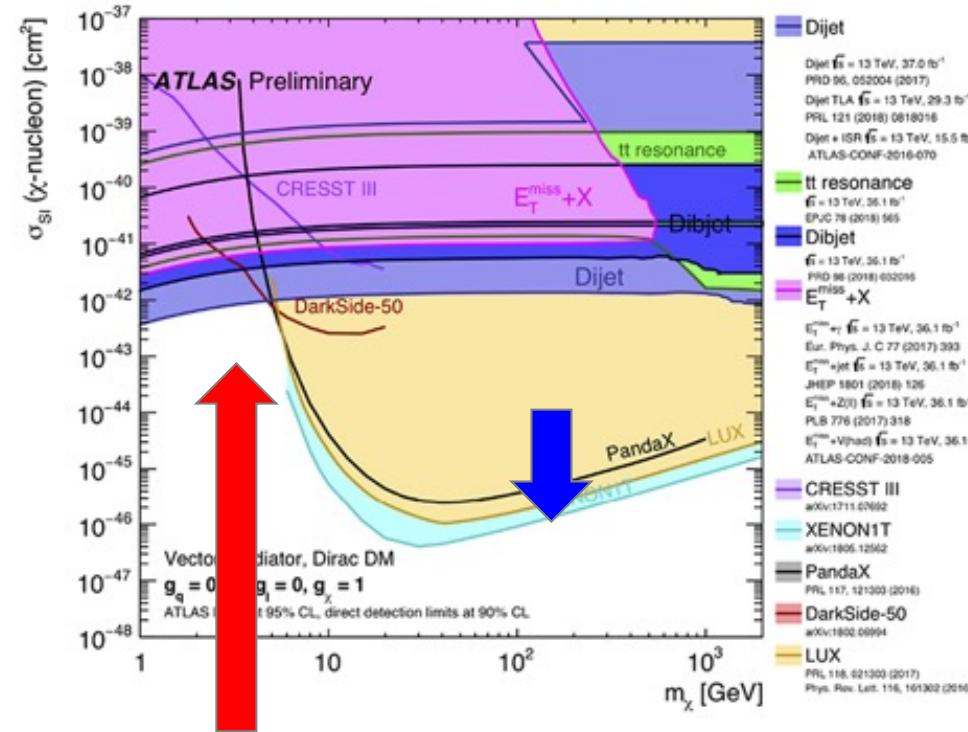
- More particles...
- All existing particles **produced** in Big Bang and later (decays, ...)
- Some particles may be stable
- Very long-lived due to **small parameters** → natural?
- Effects of unstable states +/- → on the early Universe
→ on collider physics

A full DM model usually affects many other observables!



Dark Matter at the LHC

- Generic signature
- Generic kinematics: weak dependence on WIMP mass for $m_{\text{DM}} \ll \text{beam energy}$

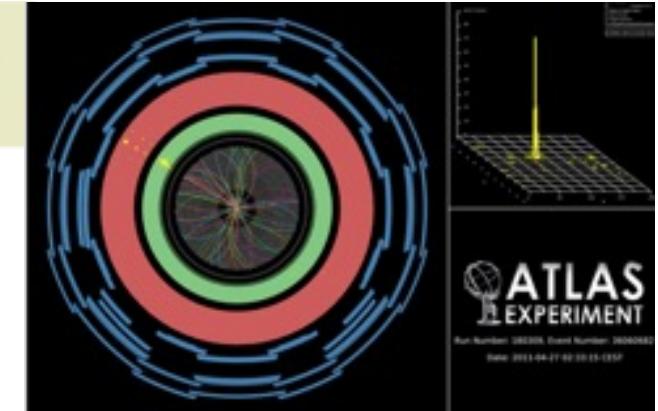


light WIMPs
 $\mathcal{L} \rightarrow$ timing

\leftrightarrow CRESST-III, SuperCDMS \rightarrow GeMMC

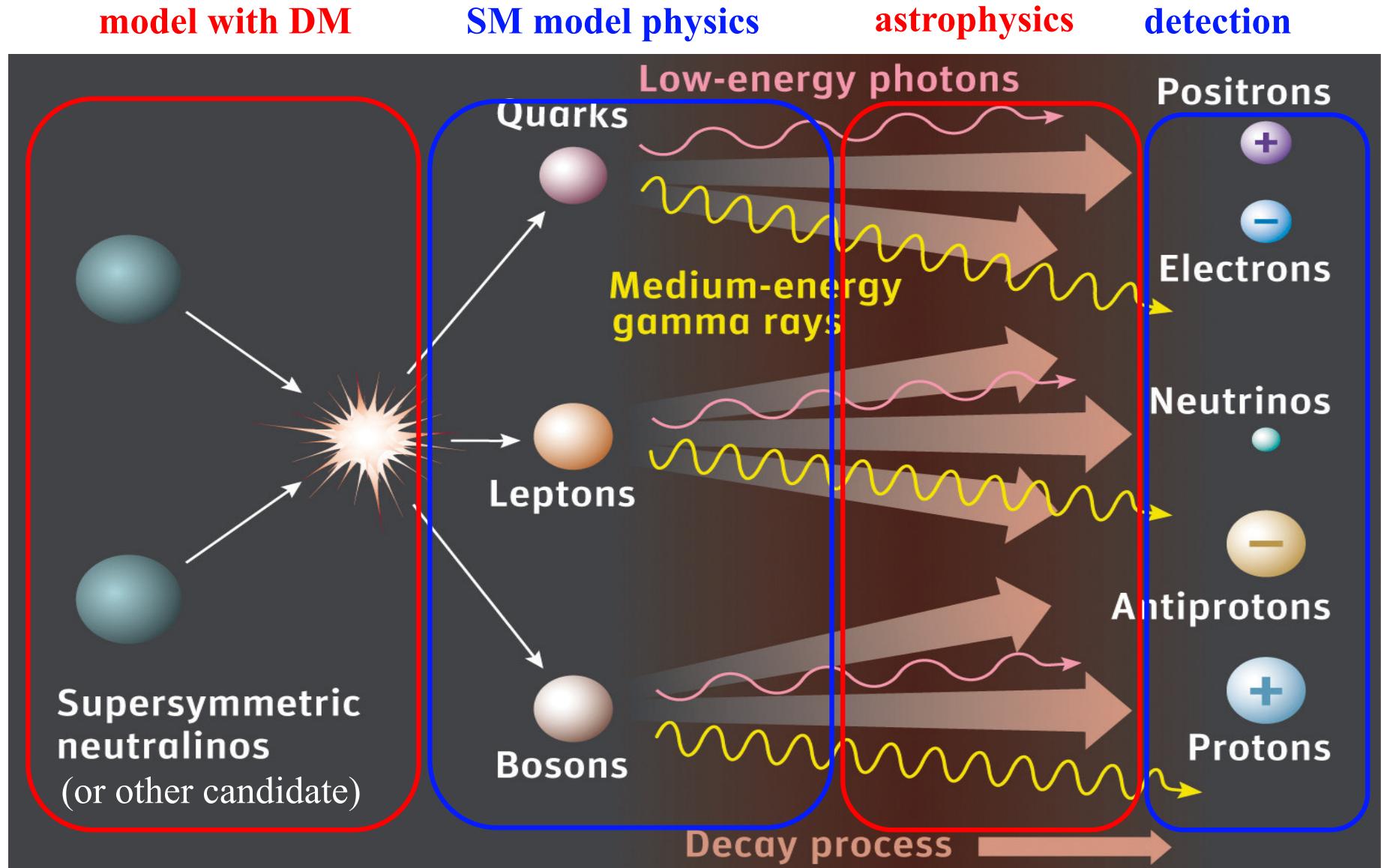
heavy WIMPs
 \rightarrow direct searches

$$pp \rightarrow \cancel{E}_T + X$$



- Life is more complex...
 - many conceivable candidates
 - detection efficiencies, ...
 - ➔ EFT or simplified models
 - =parametrization – not always appropriate
 - g_{DM} = assumptions *or* full model +...
- LHC:
 - can exclude DM candidates
 - can establish a candidate
 - does not test amount of DM in Universe long lived? abundance?

Indirect Detection



→ huge number of sources, reaction channels and detection techniques + decay channels

Challenges for Indirect Detection

Often large systematic uncertainties and backgrounds related to astrophysics and/or DM density profile

Complementary observations / analyses help to reduce uncertainties

→ **Strategies to minimize uncertainties:**

- look for low-background signals (e.g. monochromatic lines, anti-nuclei)
- focus on low- background regions (e.g. dwarf galaxies)

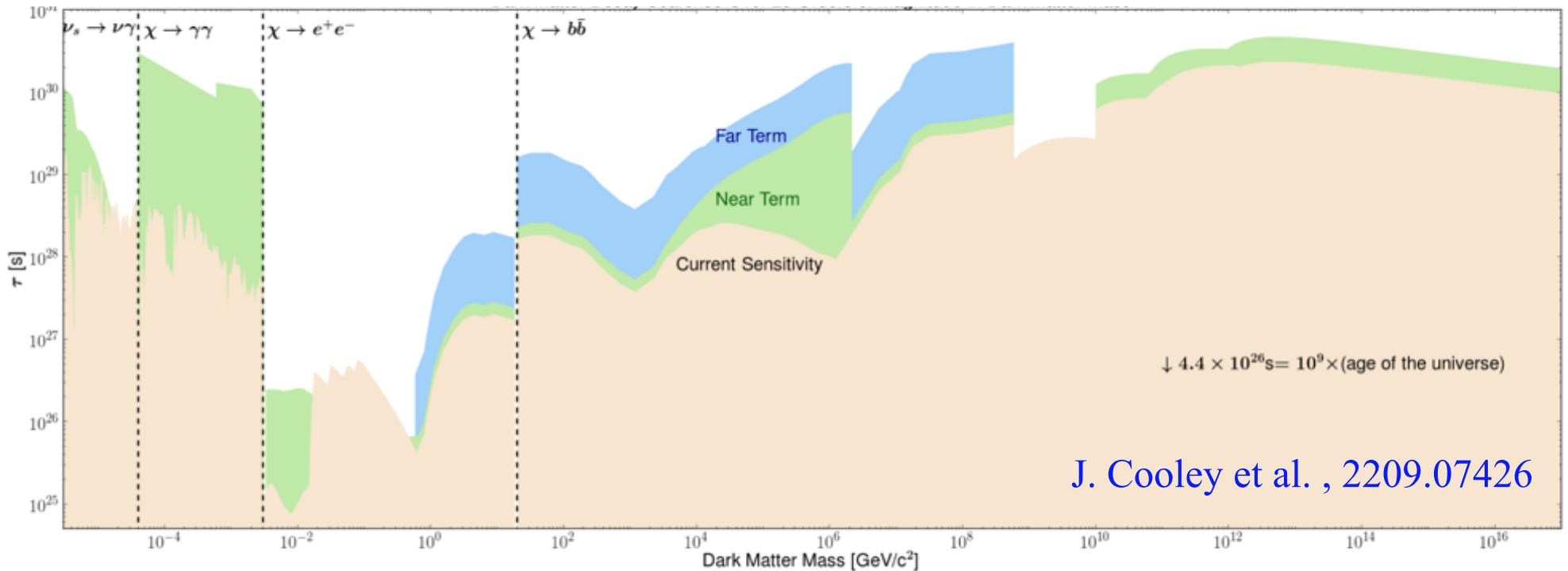
→ Can we be sure? Example: 3.5 keV **line** as a signal of keV sterile ν's

- Alternative explanation: atomic charge exchange reactions of electrons between S16 and H; flux fits plasma models ([L. Gu et al.](#))
- line also inconsistent with blanck sky observations ([Dessert et al.](#))

Other example: rising positron fraction, ...

Impressive Limits

Current and expected sensitivity to DM decay from cosmic-ray and γ -ray experiments



visible decays: → DM lifetime

- must be 8+ orders of magnitude longer than the age of the universe
- over 20+ orders of magnitude in mass

The Galactic Center Gamma Ray Excess

- A bright and highly statistically significant excess of γ -rays observed around the Galactic Center
- Difficult to explain with astrophysics
- Looks like the signal predicted from annihilating DM

Hooper, Goodenough (2009, 2010), Hooper, Linden (2011), Abazajian, Kaplinghat (2012), Gordon, Macias (2013), Daylan, et al. (2014), Calore, Cholis, Weniger (2014), Murgia, et al. (2015), Ackermann et al. (2017)

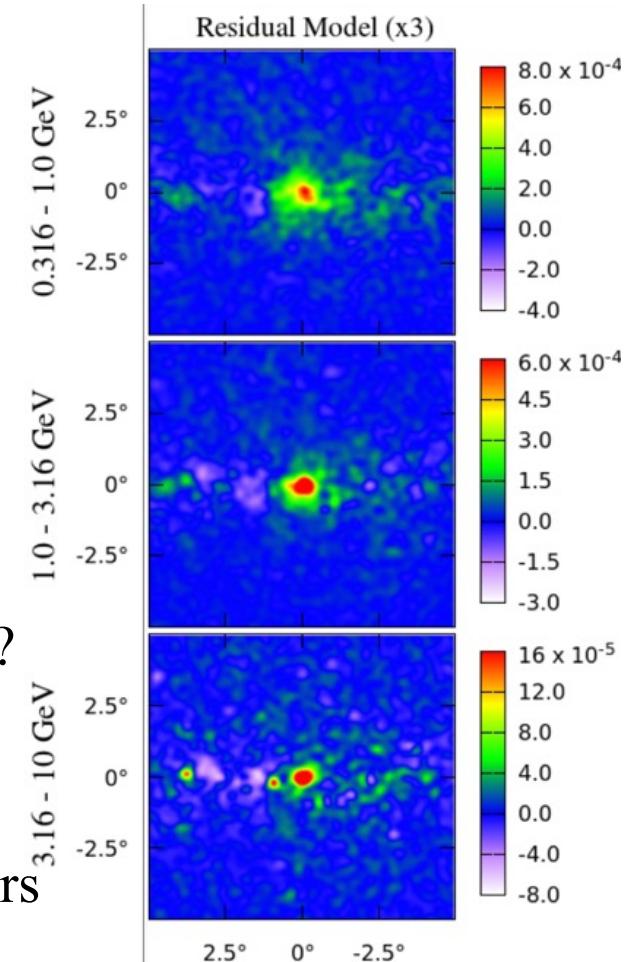
Explanation of the Excess:

- Annihilating dark matter?
- Large population of centrally located millisecond pulsars?

pulsars are spinning neutron stars

→ slow down and become faint

→ accretion from a companion star can spin-up dead pulsars



➔ plausible that large numbers of MSPs could exist near the Galactic Center

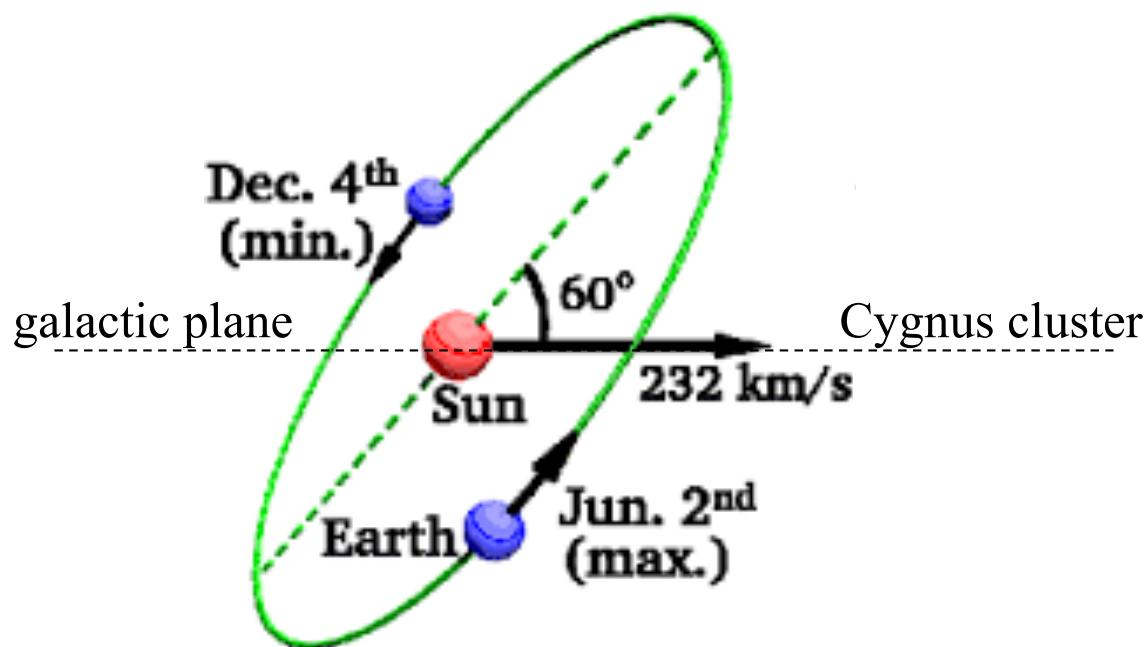
Direct Detection of the WIMP Wind

$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R) dv$$

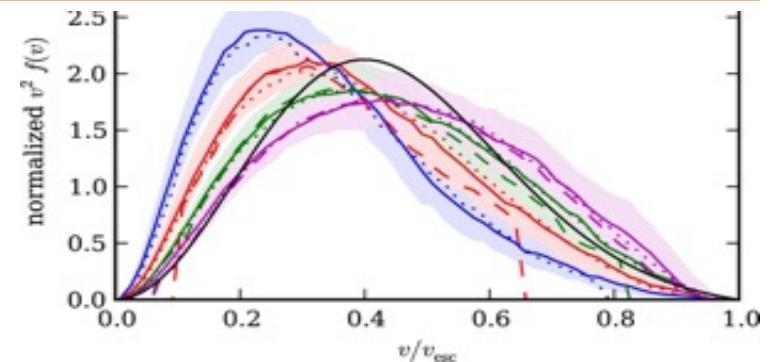
detector (mass, threshold, ...)

astrophysics

particle physics



uncertainties in DM halo modeling
→ affect all experiments ~same way



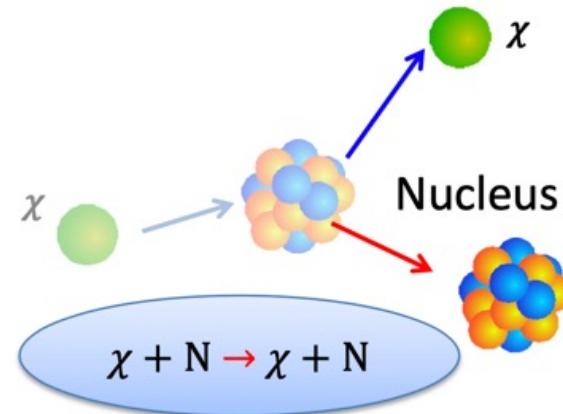
$$R_{\text{Sun}} \sim 8.5 \text{ kpc}$$

$$R_{\text{galaxy}} \sim 15 \text{ kpc}$$

$$R_{\text{halo}} \sim 300 \text{ kpc}$$

Direct Detection: Billard with invisible Balls

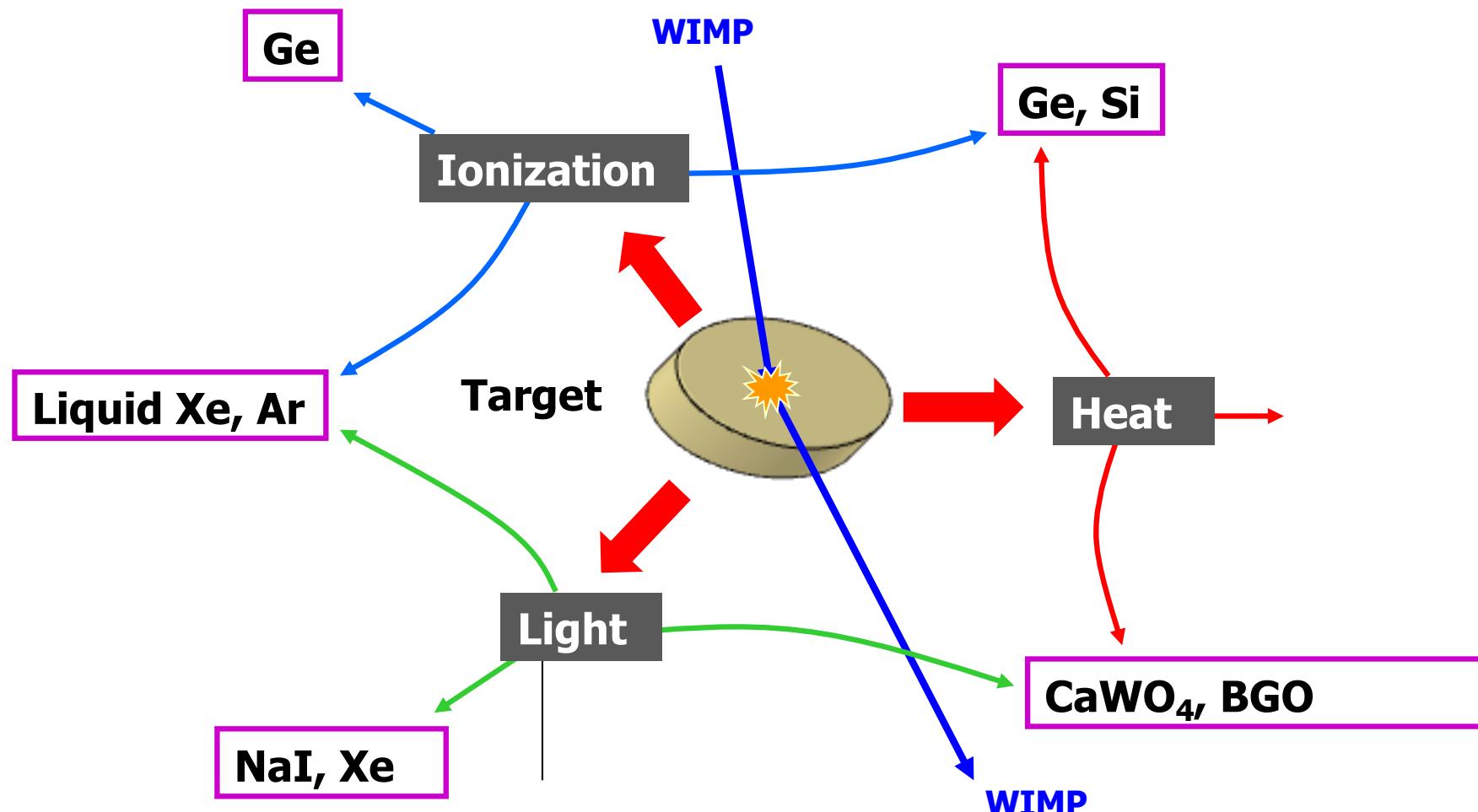
- WIMPs scatter off atoms in a detector → detect the signal...
- Maximal momentum transfer → $M_{\text{WIMP}} \sim M_{\text{atom}}$
Additionally: clean, transparent, high density, no free charges, ...
→ liquid Xenon (ca. -100 degree)
↔ rarest stable element



- 1) **Maximize signal**
 - many atoms
 - big detector
- 2) **Minimize background**
 - extreme low radioactive background requirements

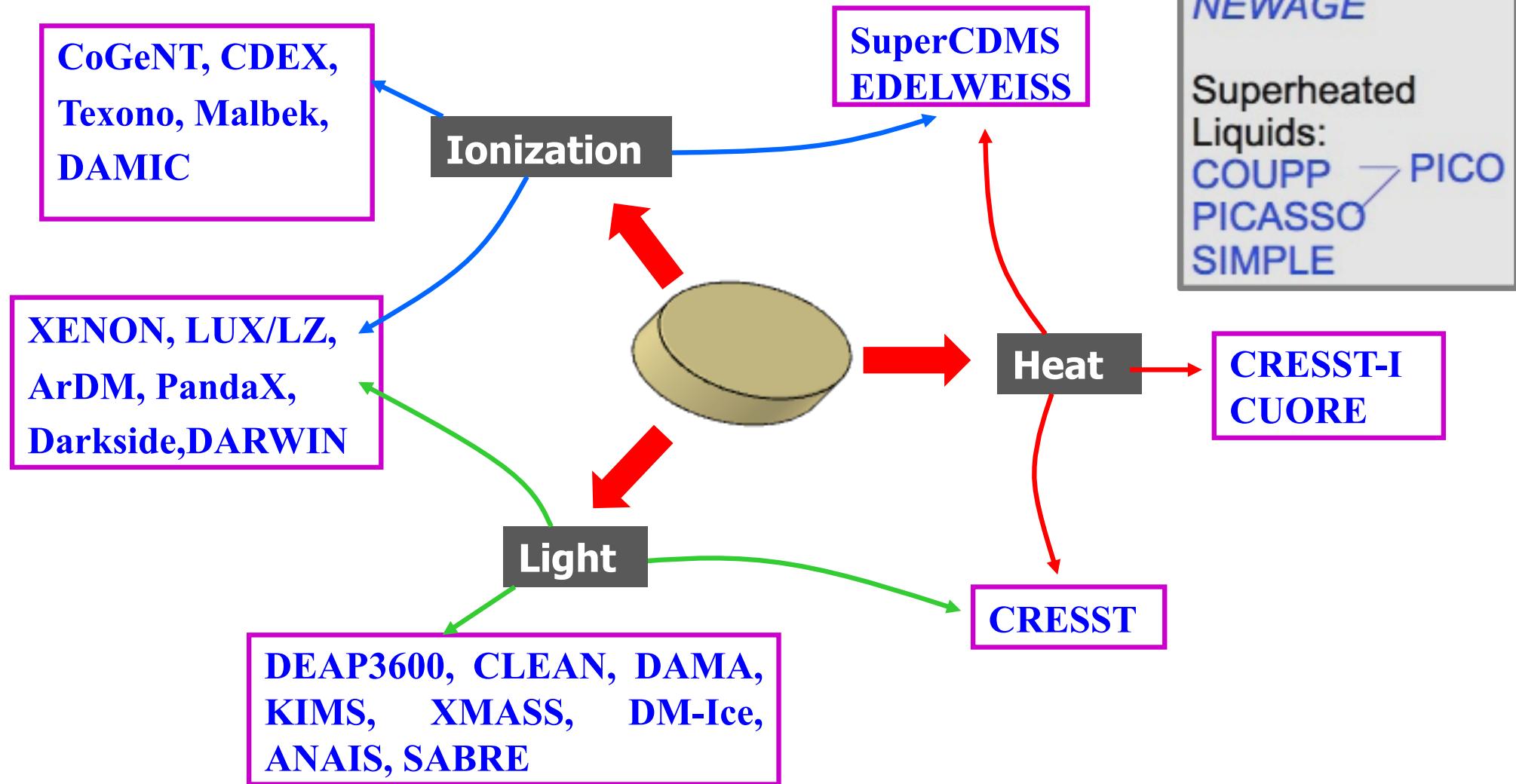
Direct Detection Techniques (WIMPs)

- Directly see what the Universe is made of
→ WIMP wind (~known flux) scatters on target atoms → signal...



Direct Detection Experiments

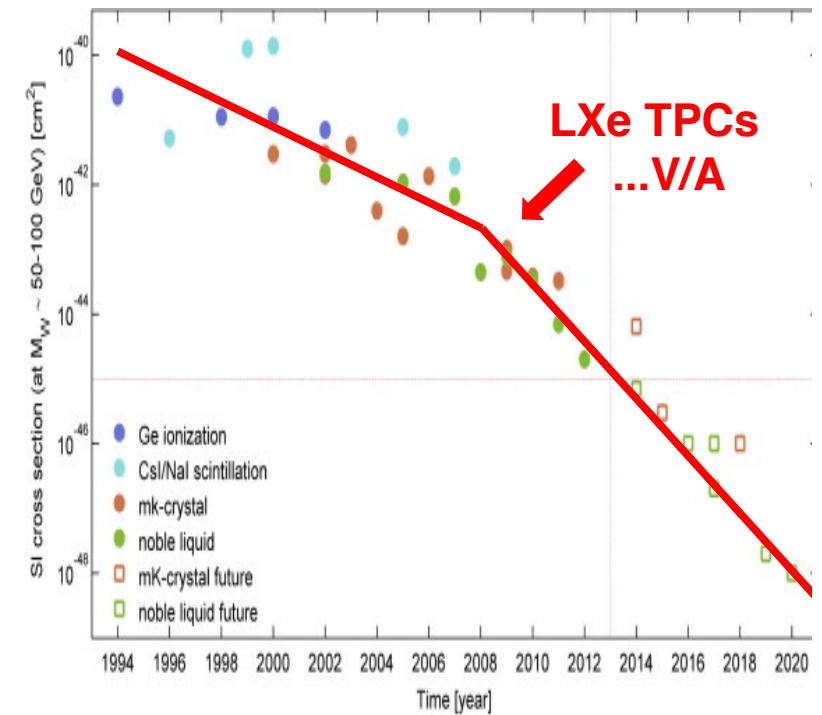
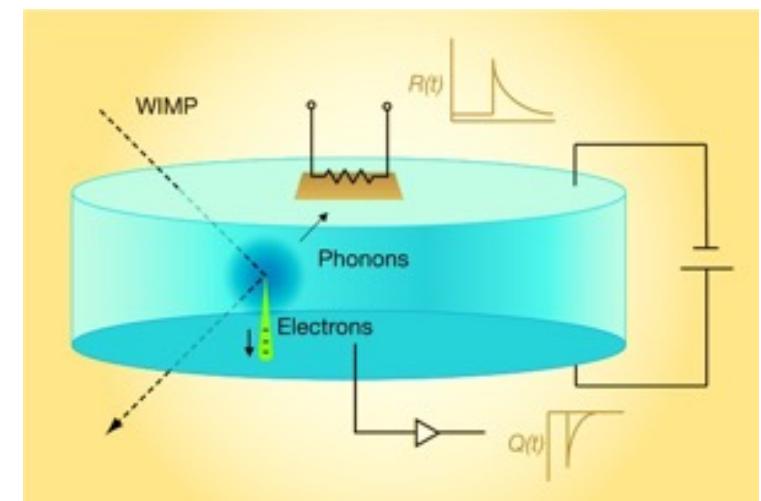
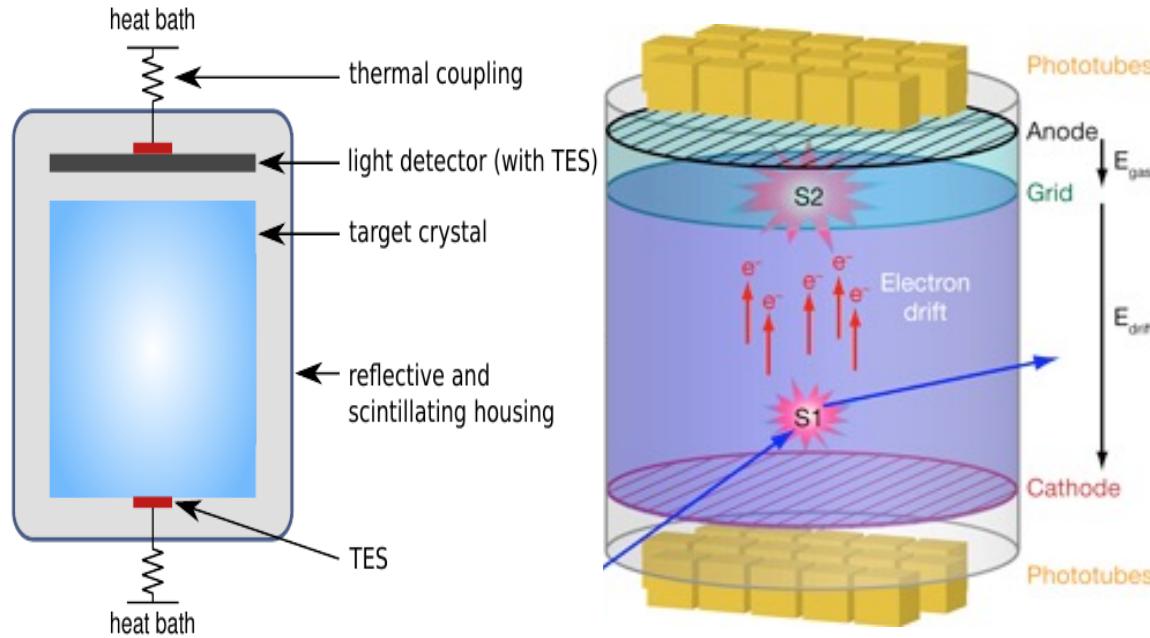
Detection methods: Crystals (NaI, Ge, Si),
Cryogenic Detectors, Liquid Noble Gases



Converting WIMP Scattering into Signals

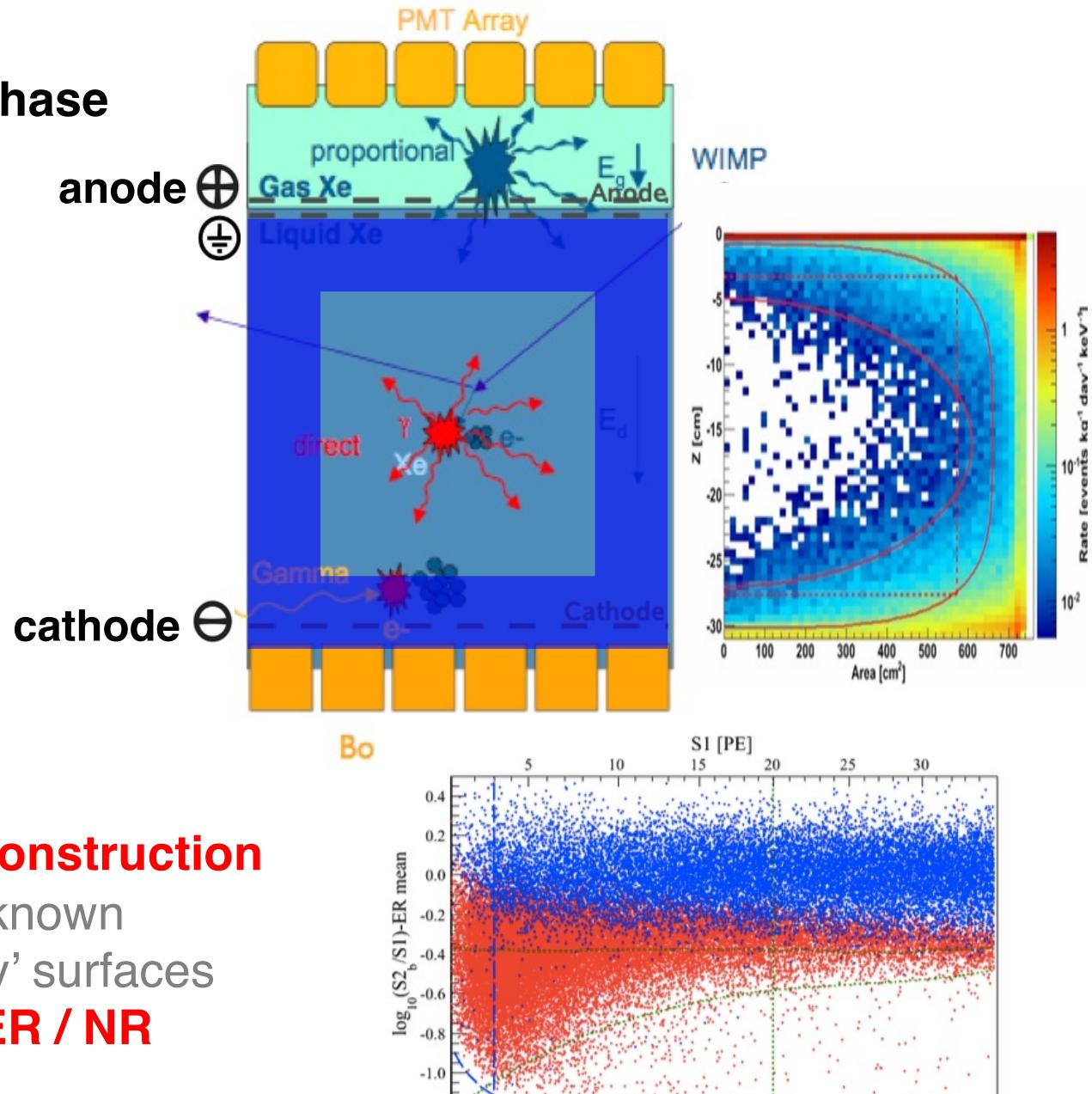
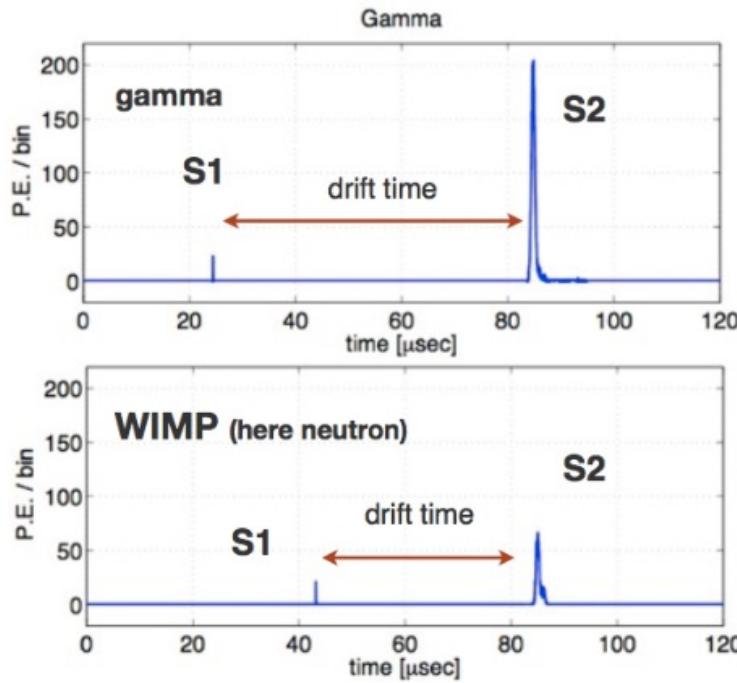
Light – ionization – heat: 3 examples

- **semiconductor Crystals (Ge)**
→ pulses
- **in crystals (e.g. CaWO₄)**
→ heat +light signal
- **liquid noble gases**
→ light and ionization @TPC



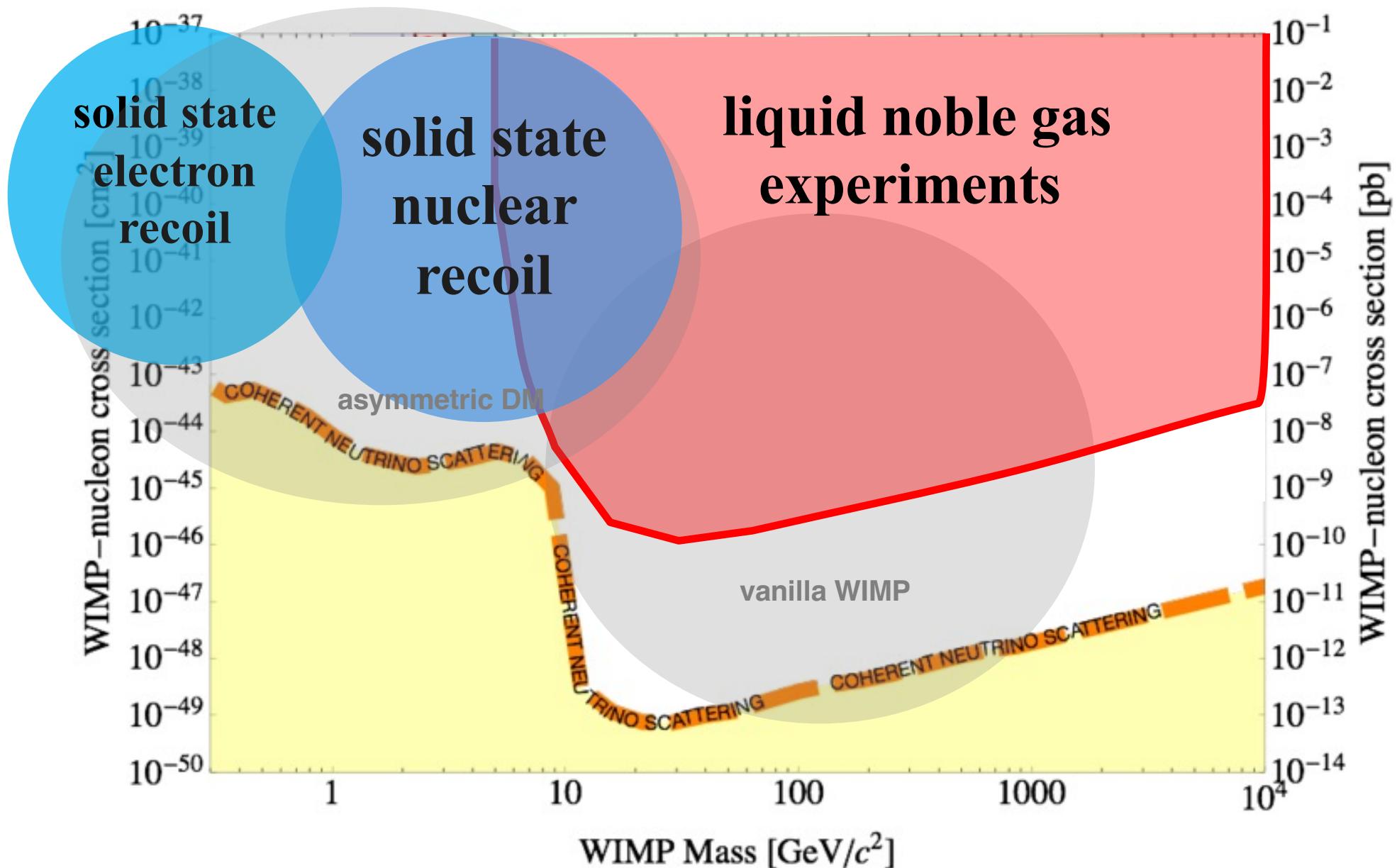
Powerful Devices: Dual-Phase TPCs

- 1) direct light signal → S1
- 2) drift of electrons to gas phase
- 3) 2nd light signal → S2

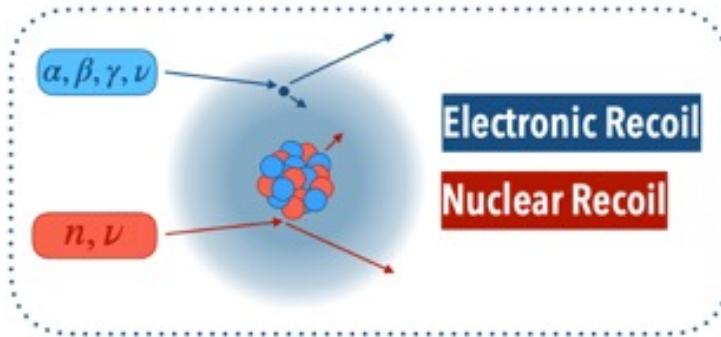


- excellent 3D position reconstruction
- fiducialization = exclude known backgrounds from 'dirty' surfaces
- S2/S1 discrimination of ER / NR

Were to find WIMPs generically



Dark Matter Detectors in UG Laboratories



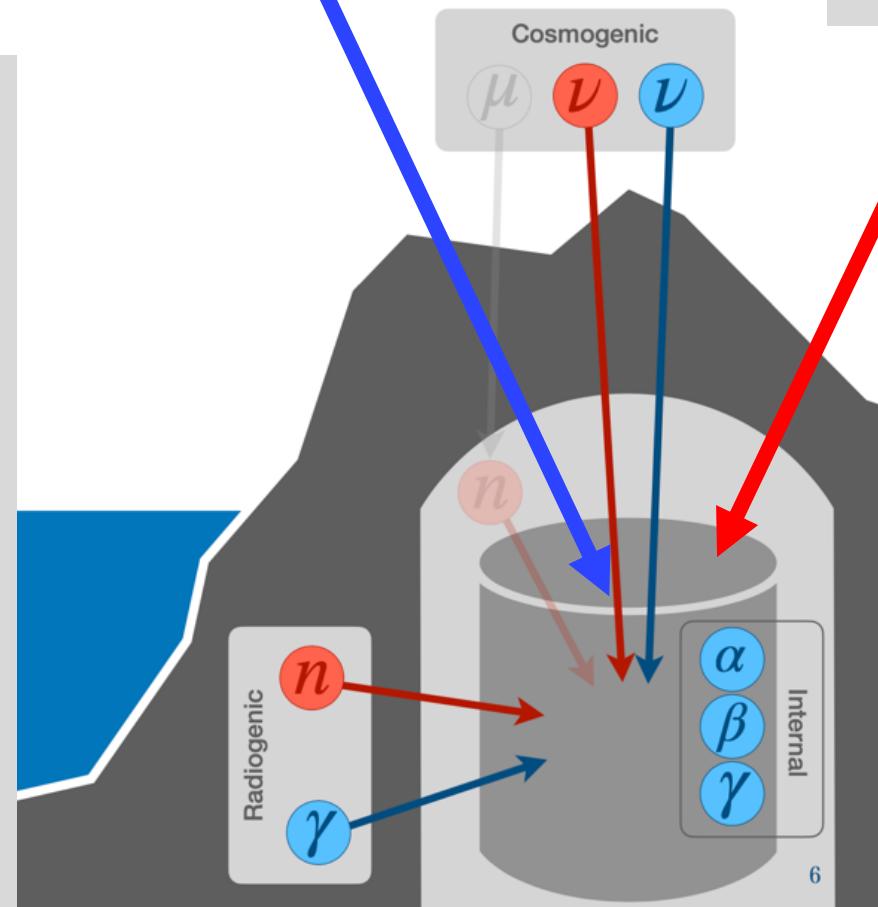
WIMPs
→ nuclear recoils

Sun:
- Neutrinos
- Axions ?
- ???

Background reduction

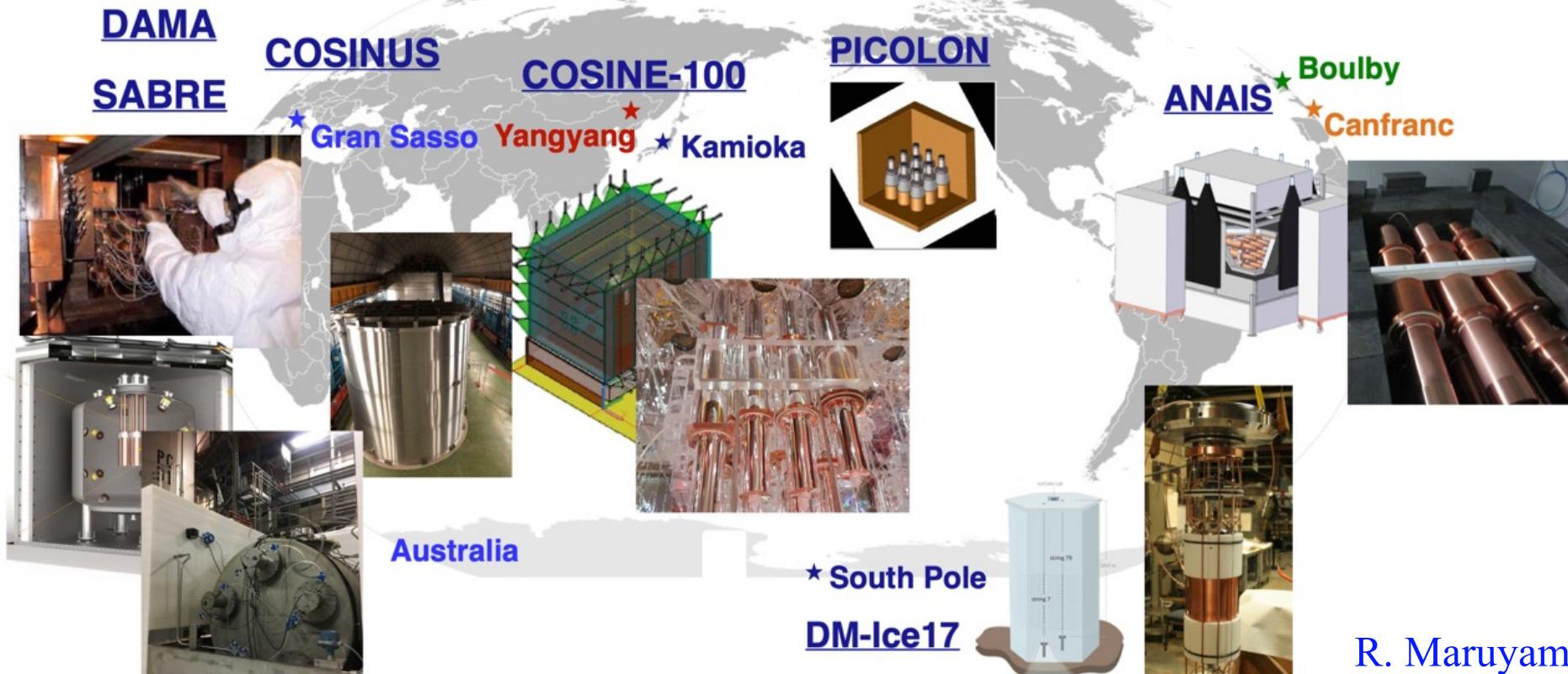
→ extremely challenging:

- material selection
- screening (γ , Rn, ...)
- graded shielding
 - deep underground
 - veto systems
 - water
- cryogenic distillation
- pulse shape analysis
- ...



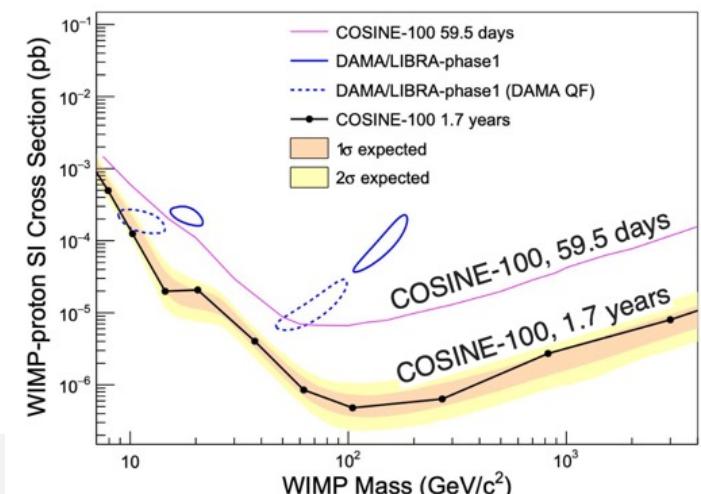
SM: too weak
→ should
not show up

Global Effort to Resolve DAMA (NaI)



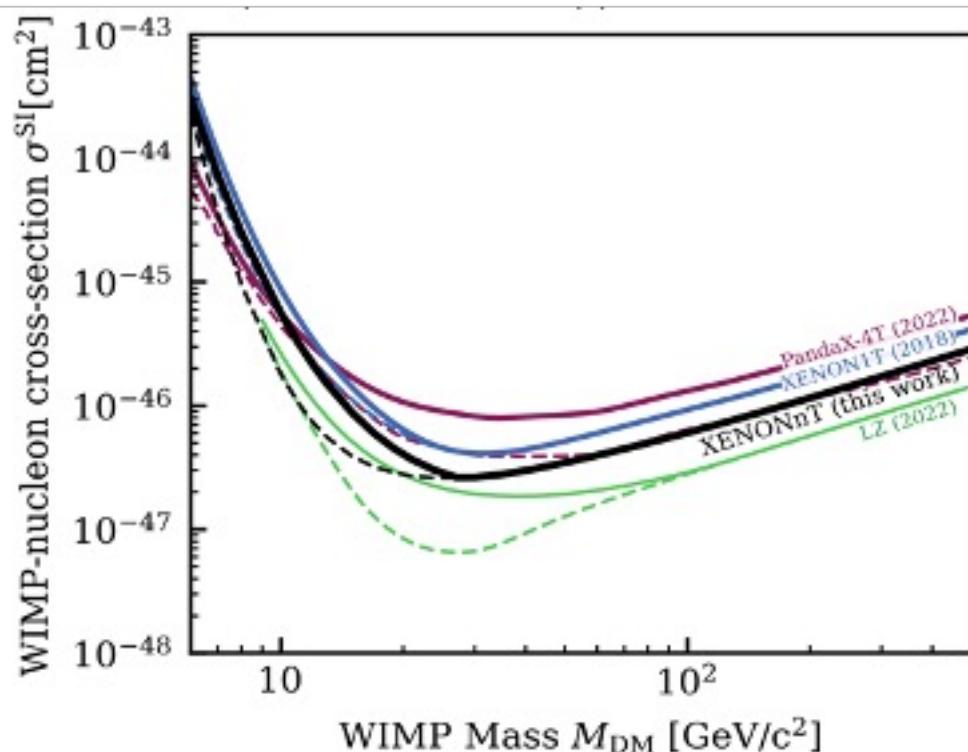
R. Maruyama

- **DAMA sees annual modulation**
- No signal from other direct detection experiments
- ANAIS-112 & COSINE-100 offer direct test
 - no clear observation of modulation
- However, no explanation for DAMA's signal
- Debates about binning induced modulation
 - more data



WIMP Results from LXe Experiments

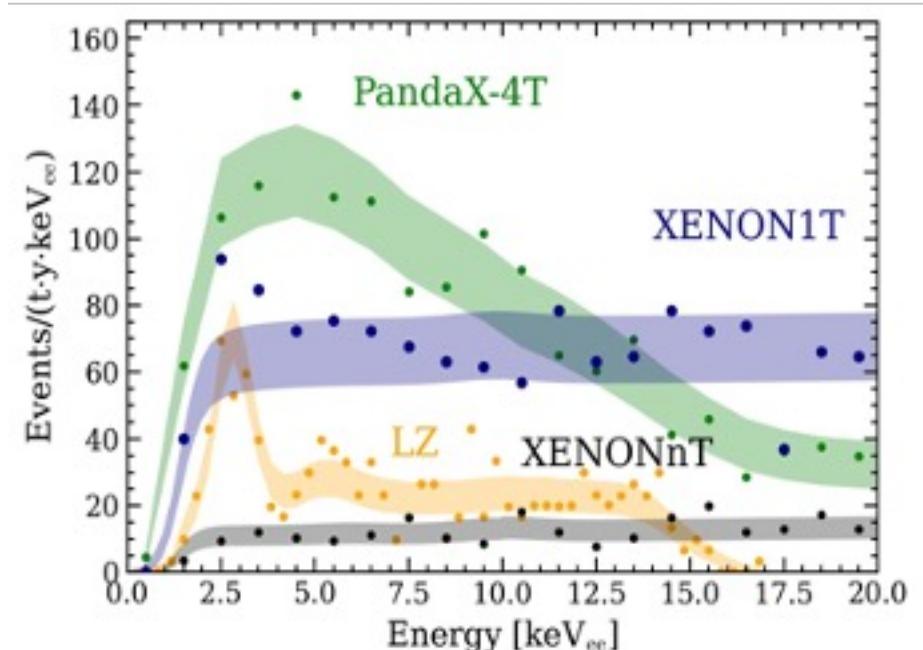
Spin-Independent cross section: Same conservative power-constraint applied to all results of all non-blind LXe experiments



LZ, arXiv:2207.03764

XENON1T, PRL 121, 111302 (2018)

PandaX-4T, PRL 127, 261802 (2021)



ER Background:

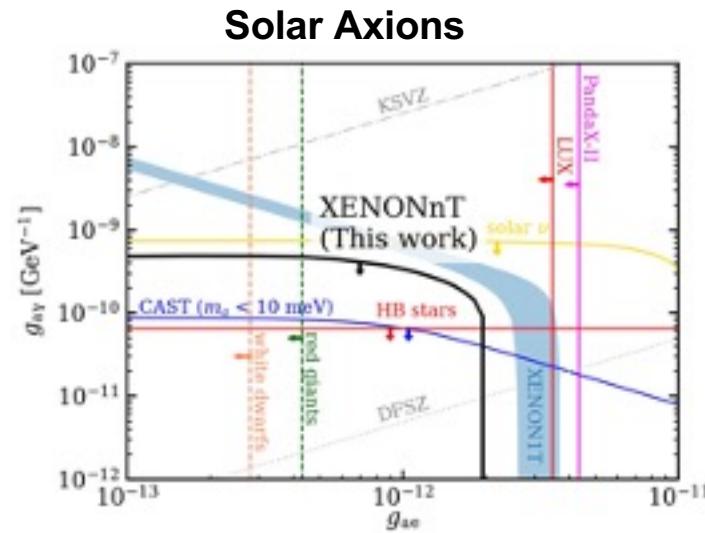
PandaX-4T PRL 129, 161804 (2022)

XENON1T PRD 102, 072004 (2020)

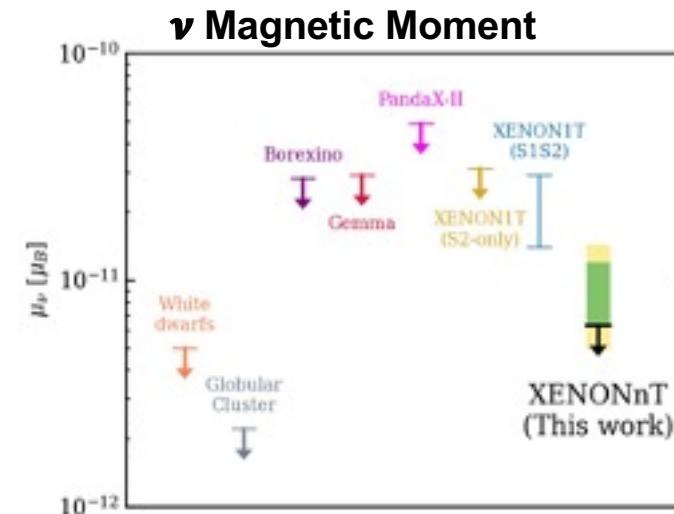
LZ arXiv:2207.03764

XENONnT PRL 129, 161805 (2022)

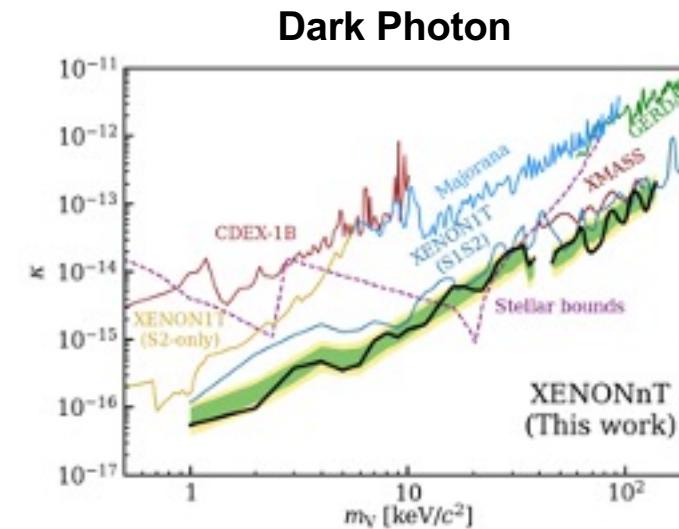
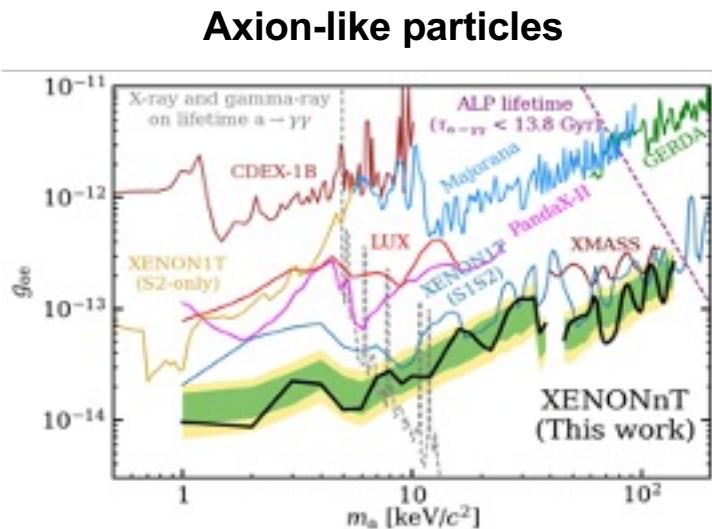
XENONnT Limits on New Physics



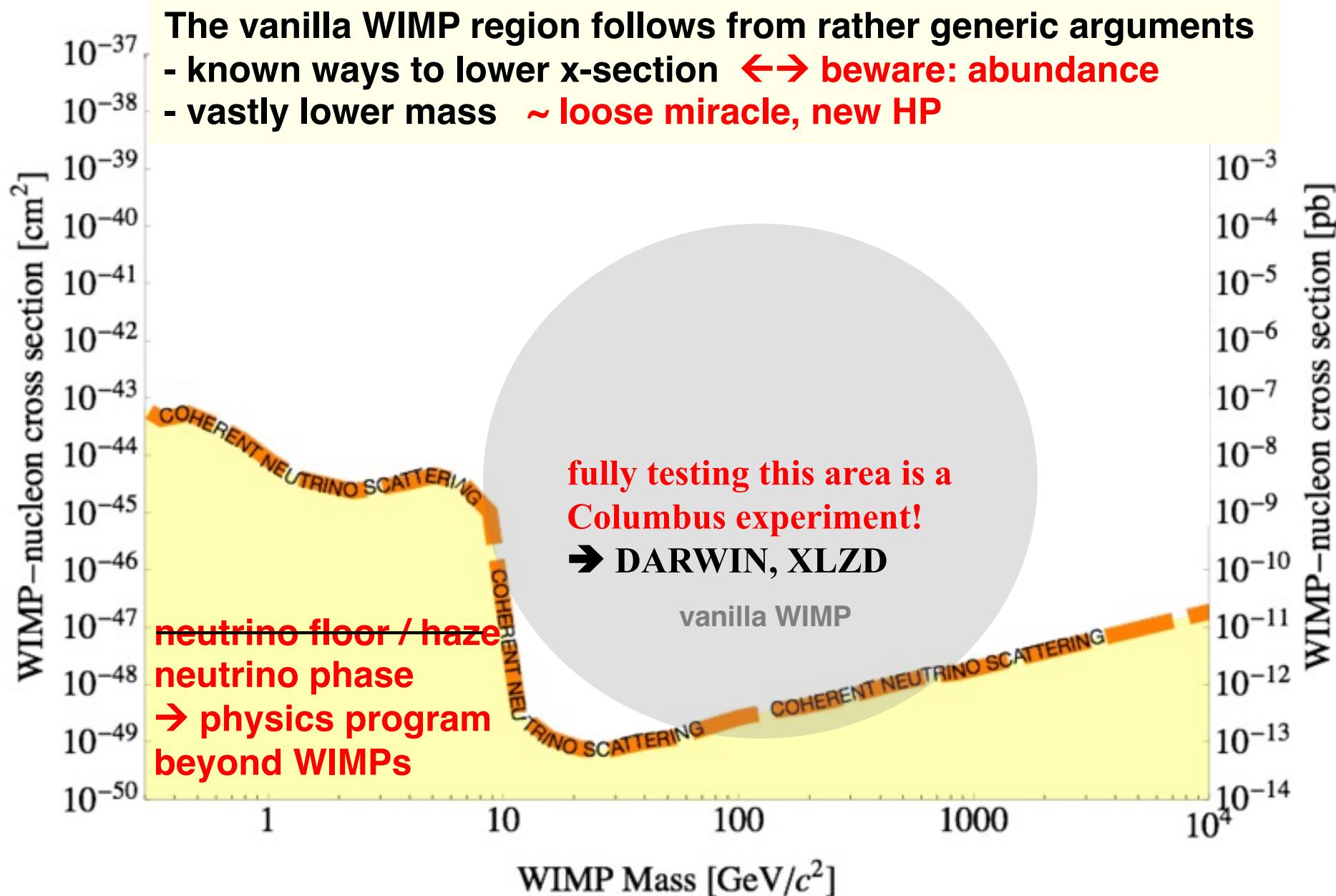
Limit on 14.4 keV peak for ^{57}Fe solar axions is < 20 events/(t^*y)



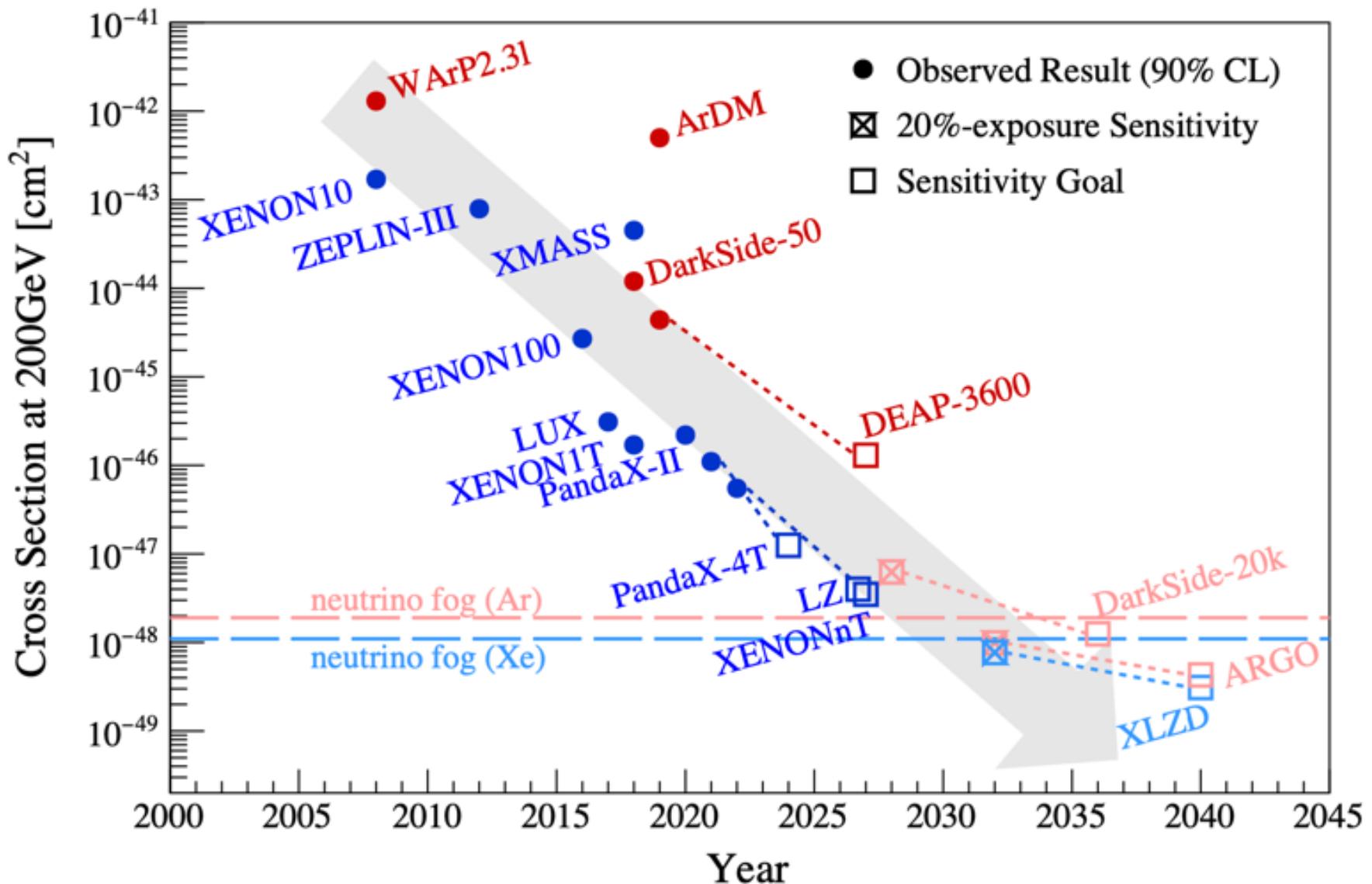
$\mu_\nu < 6.3 \cdot 10^{-12} \mu_B$, most stringent DD limit



The Future of Liquid Noble Gas Detectors



Sensitivity Development of Liquid Noble Gas TPCs

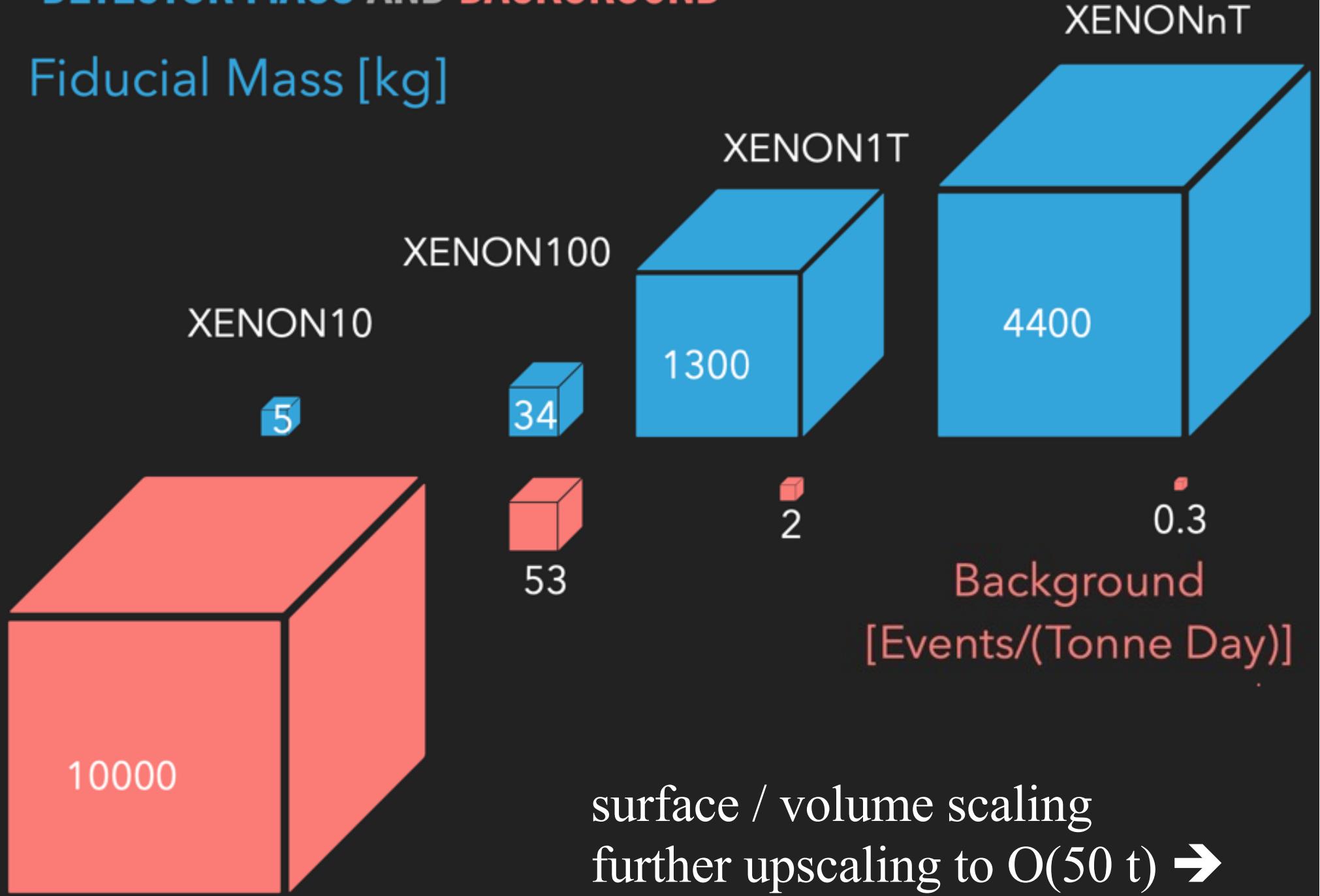


5+ orders of magnitude!

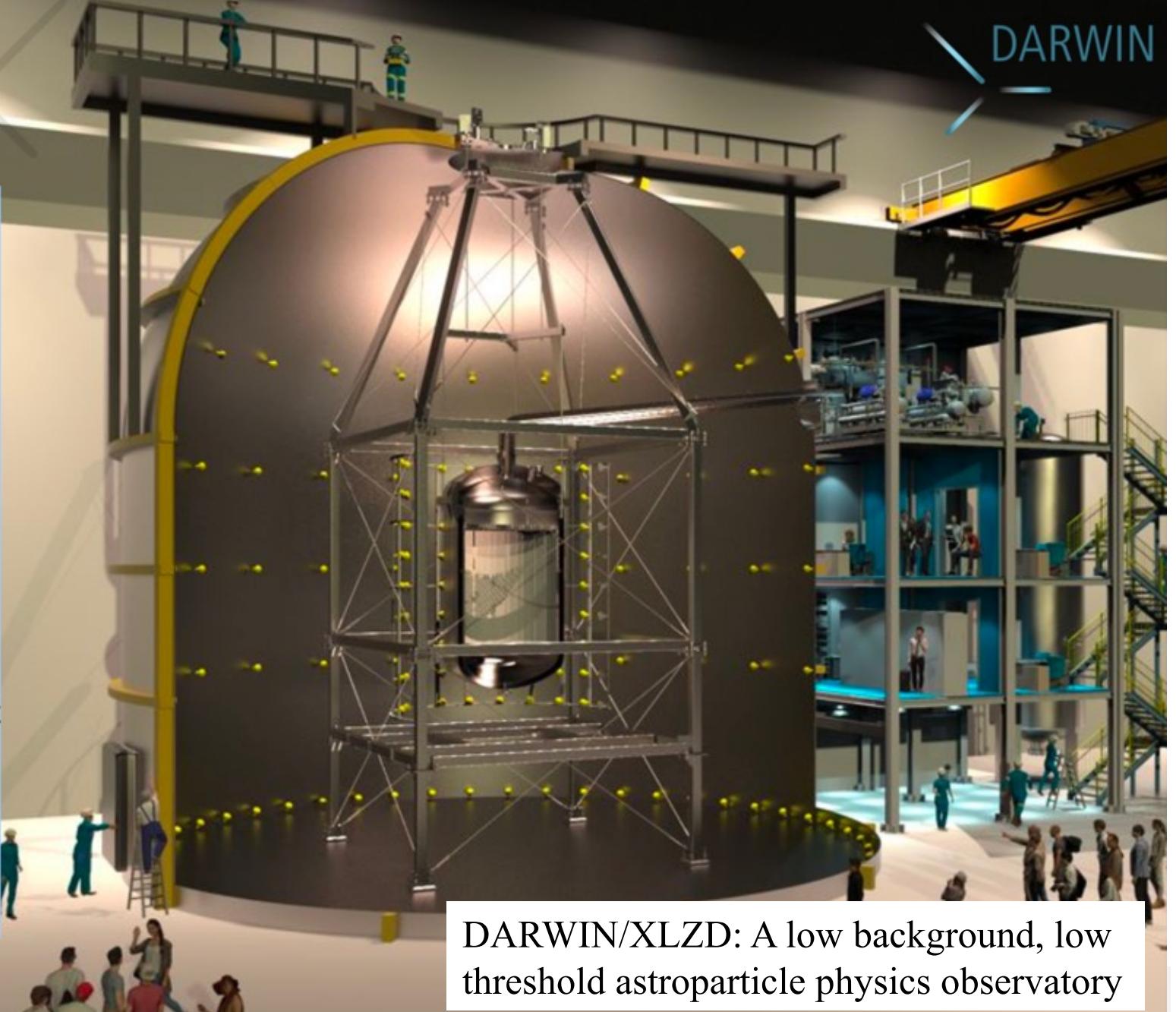
Cooley et al., 2209.07426

DETECTOR MASS AND BACKGROUND

Fiducial Mass [kg]



DARWIN / XLZD



The image shows a large, spherical detector housed within a multi-story industrial building. The detector is a dark sphere with a yellow ring at the top and bottom. A complex steel truss structure supports the sphere from below. Several workers in blue and green uniforms are visible around the detector, some on ladders and walkways. In the background, there are other industrial structures, pipes, and a crane. The word "DARWIN" is written in blue on the right side of the image.

XLD

Dark Matter (NR)
WIMPs (SI, SD, EFT)
low-mass NR
S2-only, Migdal
Planck-scale DM

Dark Matter (ER)
WIMP-e scattering
Annual Modulation
ALPs
Dark Photons

Neutrinos
CNNs
supernova neutrinos
solar neutrinos
neutrino magn. moment

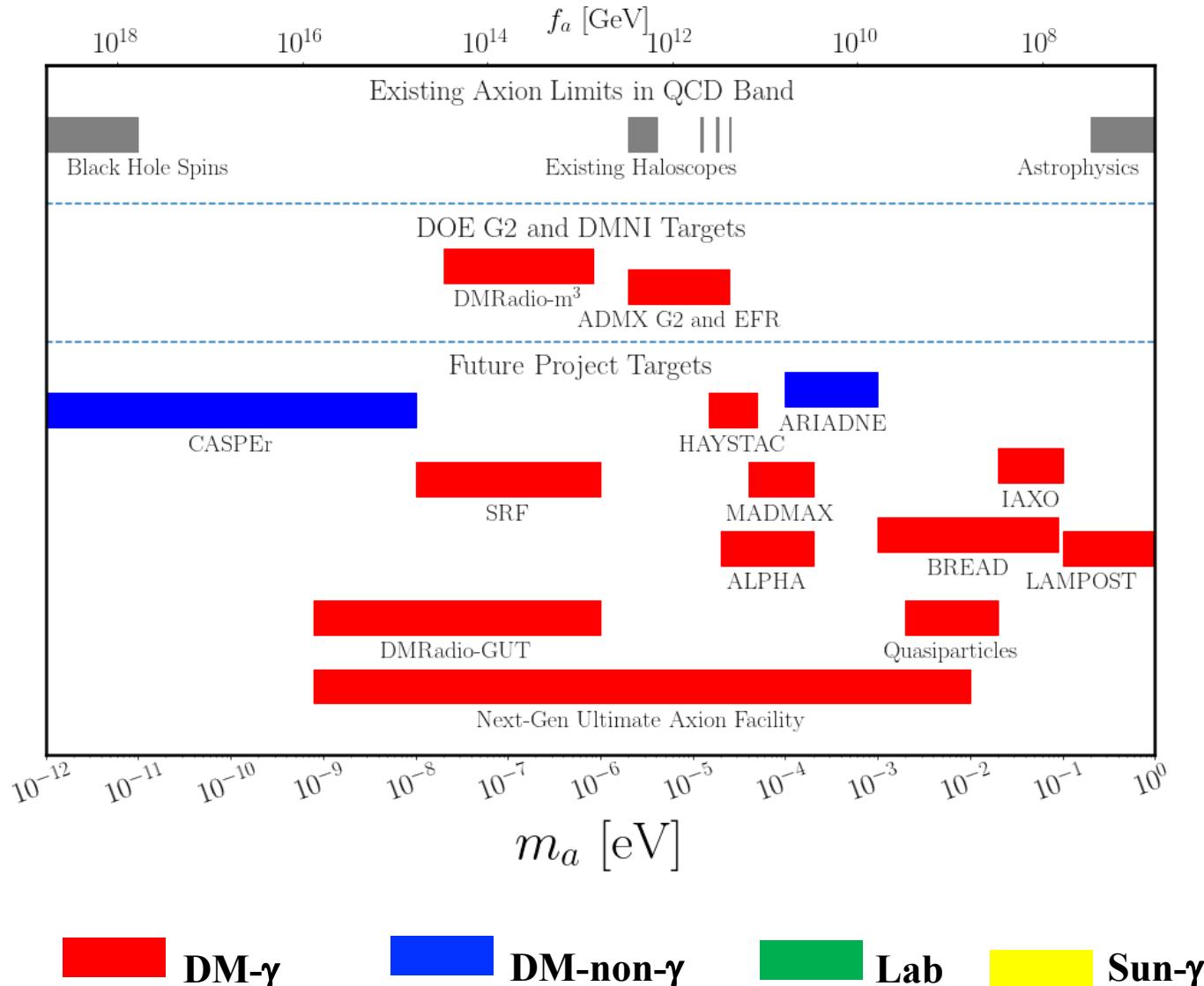
Rare nuclear decays
 $0\nu\beta\beta^{136}\text{Xe}$
 $0\nu / 2\nu\text{ECEC}^{124}\text{Xe}$

Solar Axions
... and even more!

DARWIN/XLZD: A low background, low threshold astroparticle physics observatory

Main Options 2: Axions (and ALPs)

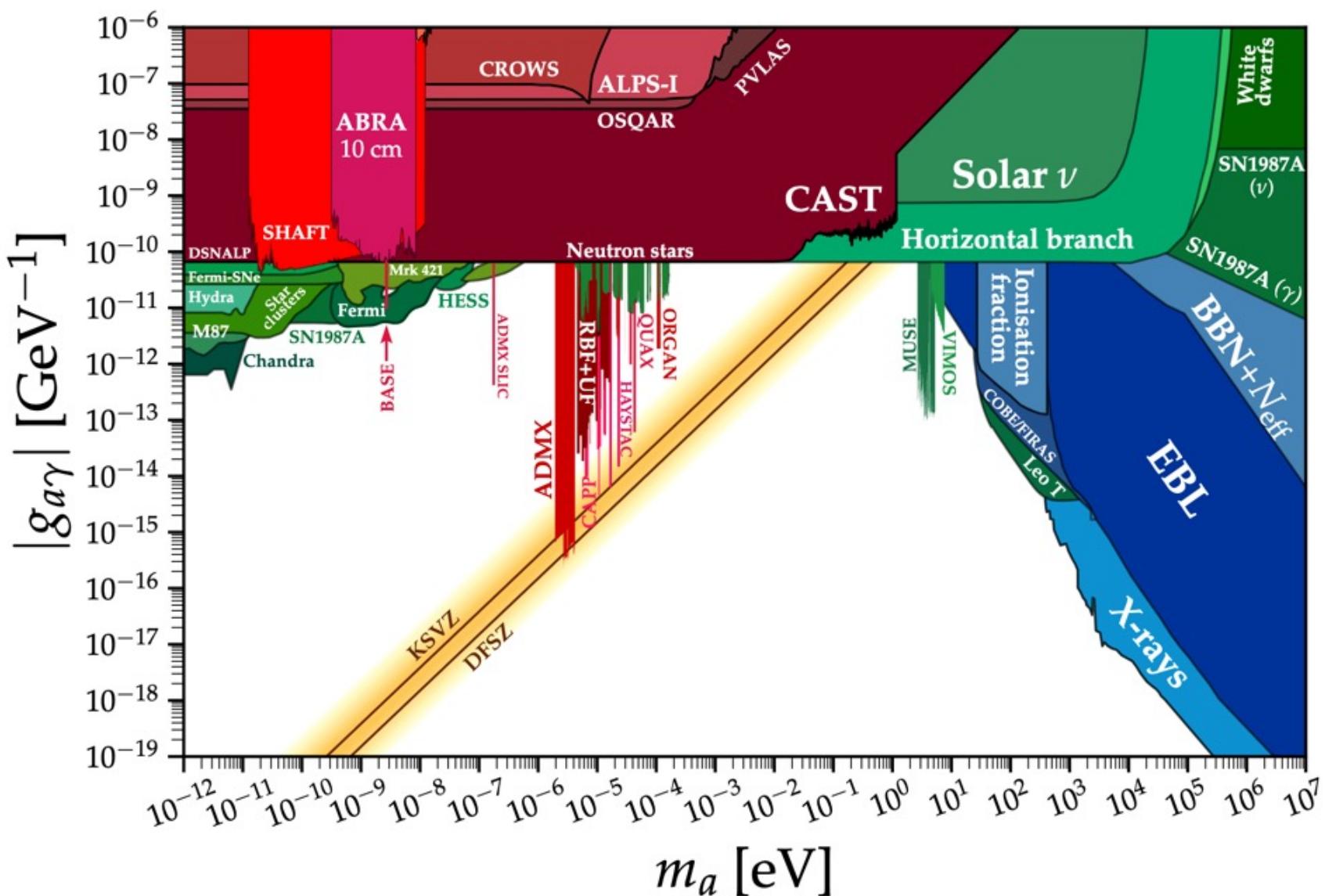
→ Motivated by the strong CP problem



Snowmass CF2 wave-like DM report

- a very active field
- many technologies
- new ideas
- axions & ALPs

Many Limits...



Interesting and important even if axions were not DM!

Main Options 3: keV Sterile Neutrinos

Active neutrinos as DM:

- primordial number density $n_\nu = 112 \text{ cm}^{-3}$ (per flavour)
- correct dark matter abundance requires
→ known neutrino masses are too small
→ active ν 's are hot DM ↔ problem: small scale structure

$$\sum m_\nu \sim 11 \text{ eV}$$

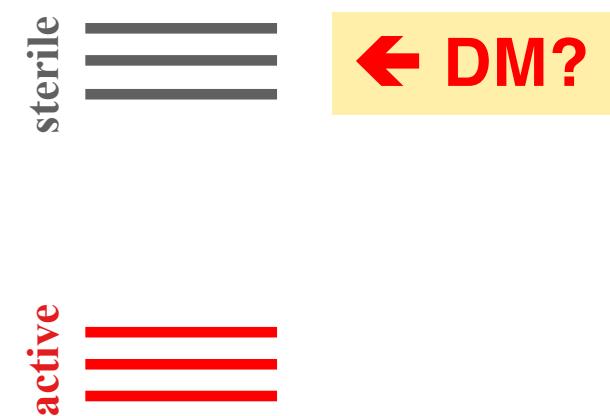
BUT: Neutrinos are Dark Matter even if they contribute only 0.5%

Sterile neutrinos as warm DM ↔ simplest explanation of ν masses

Quarks	Up-type Quarks			Down-type Quarks		
	Left: $\frac{2}{3}$ u Right: up	Left: $\frac{2}{3}$ c Right: charm	Left: $\frac{2}{3}$ t Right: top	Left: $-\frac{1}{3}$ d Right: down	Left: $-\frac{1}{3}$ s Right: strange	Left: $-\frac{1}{3}$ b Right: bottom
Leptons	$<0.0001 \text{ eV}$ ${}^0\nu_e$ Left: electron Right: sterile neutrino	$\sim \text{keV}$ ${}^0\nu_1$ Left: neutrino Right: neutrino	$\sim 0.01 \text{ eV}$ ${}^0\nu_\mu$ Left: muon neutrino Right: muon neutrino	$\sim \text{GeV}$ ${}^0\nu_2$ Left: neutrino Right: neutrino	$\sim 0.04 \text{ eV}$ ${}^0\nu_\tau$ Left: tau neutrino Right: tau neutrino	$\sim \text{GeV}$ ${}^0\nu_3$ Left: neutrino Right: neutrino
	0.511 MeV e Left: electron Right: electron	105.7 MeV μ Left: muon Right: muon	1.777 GeV τ Left: Right: tau			

add 3 right-handed singlets
→ see-saw mechanism

$$\begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^c \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$



Bounds for sterile Neutrino DM

Tremaine-Gunn bound \leftrightarrow violation of the Pauli exclusion principle
 \rightarrow minimal mass for fermionic dark matter $\sim 300 - 400$ eV

Lyman- α forest...

X-ray bounds...

too much DM...

too little?...

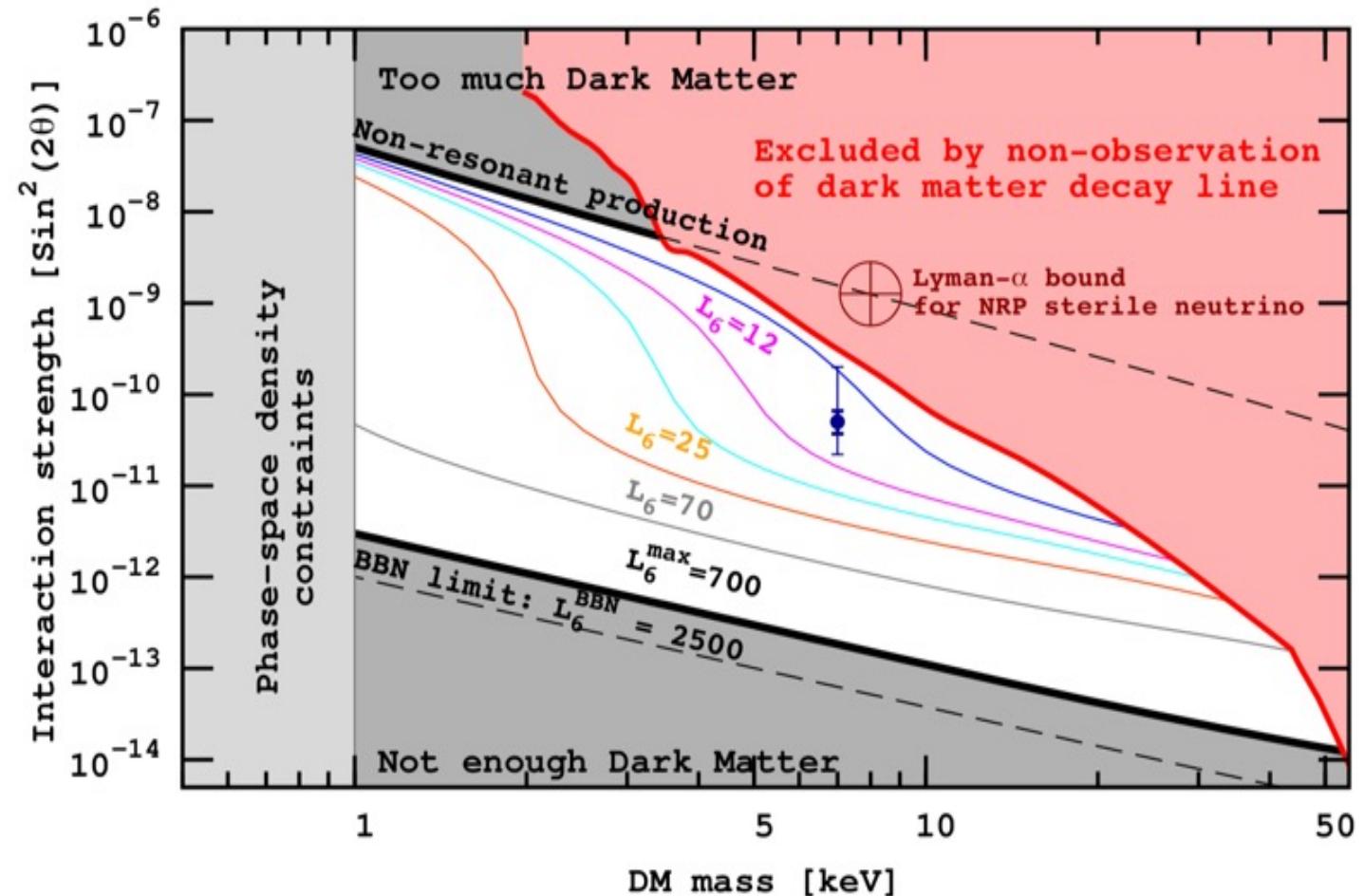
Claimed signal...

E. Bulbul et al.

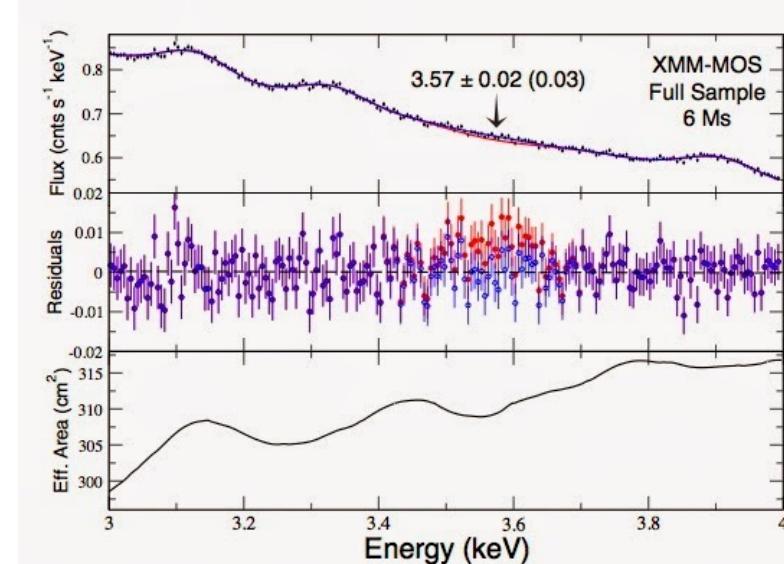
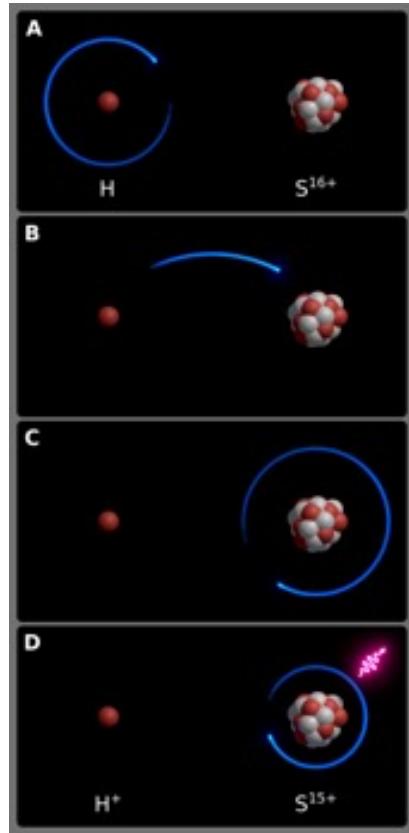
A. Boyarsky et al.

$\nu_s \rightarrow \nu_a + \gamma$

$\rightarrow \gamma$ line at
 $E = m_s/2 = 3.6$ keV



Parameters are in allowed window
 How robust is the signal?
 Other explanations?

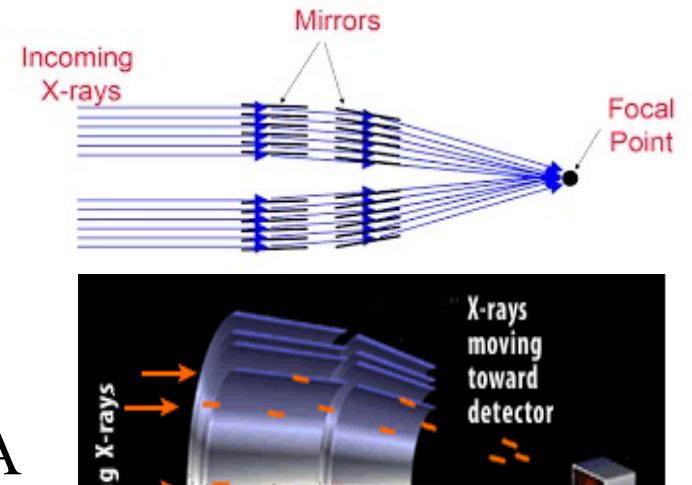


Alternative explanation:

Charge exchange reactions $H + S^{16+} \rightarrow H^+ + S^{15+} + \gamma$

[C. Sah et al. 1608.04751](#)

→ much harder to proof that a keV-ish line is from sterile neutrino decay



The bottom line:

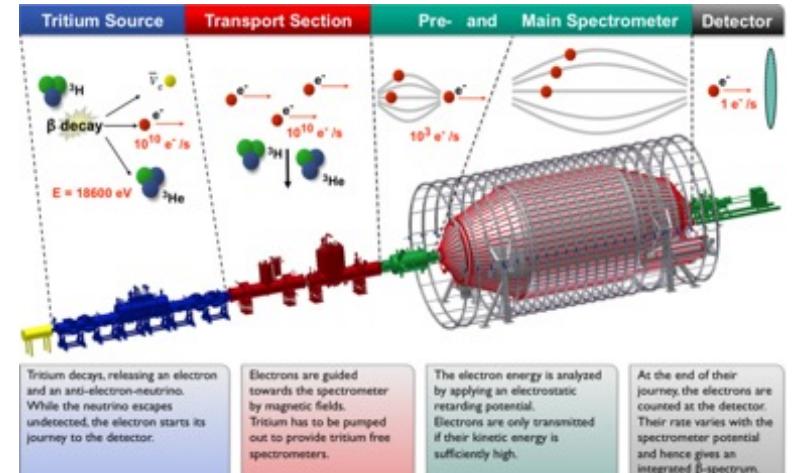
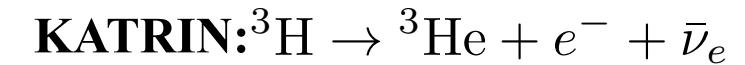
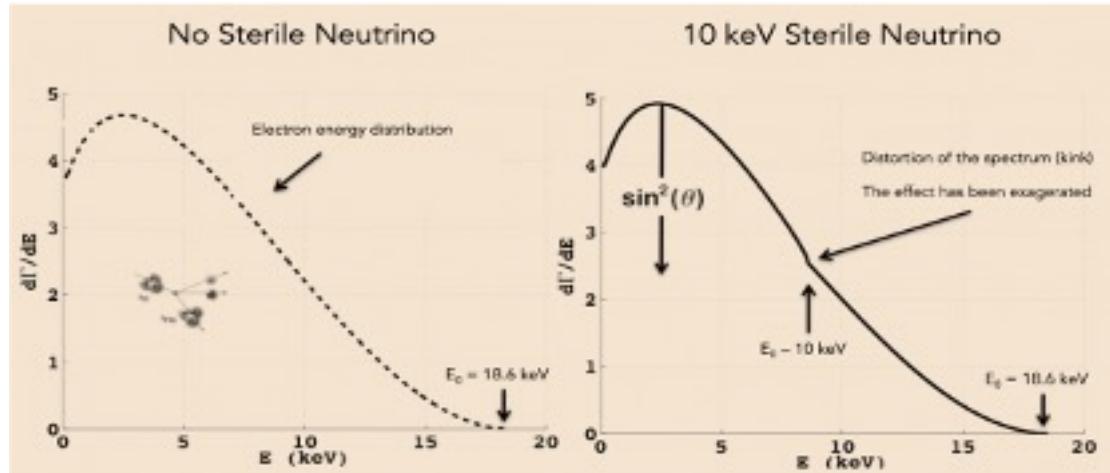
keV sterile neutrinos well motivated

All or part of the DM?

→ future experiments like XRISM, ATHENA

Laboratory Searches

→ look for effects in the endpoint of β -decay spectra

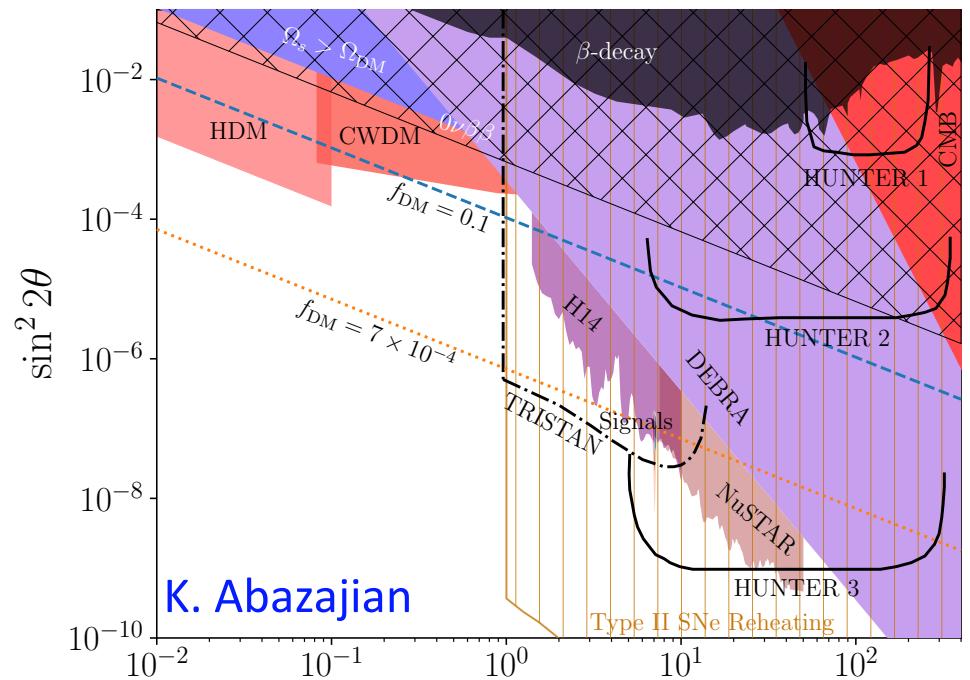


Now:

- bounds from various experiments

Future:

- TRISTAN (KATRIN upgrade)
- HUNTER
- ...



Conclusions

Dark Matter remains an extremely active and divers field

- New particles or gravitational effects or both?
 - Discussed main players: WIMPs, axions, sterile v's & technologies
 - ➔ Various “evidences” – be careful - so far no established signal
 - Many more theoretical DM options.... & many more technologies...
 - ➔ apologies for 1001 things that can not be touched in 25 minutes
- ➔ upscale powerful technologies! E.g. for direct detection:

LXe: XENON, LZ ➔ DARWIN / XLZD

LAr: Darkside 20k, ARGO

- ➔ develope all other and new technologies: We must stay open minded and be prepared for whatever explains DM

Large parts of expected parameter space already covered

➔ on-going/new/upcoming experiments have excellent potential