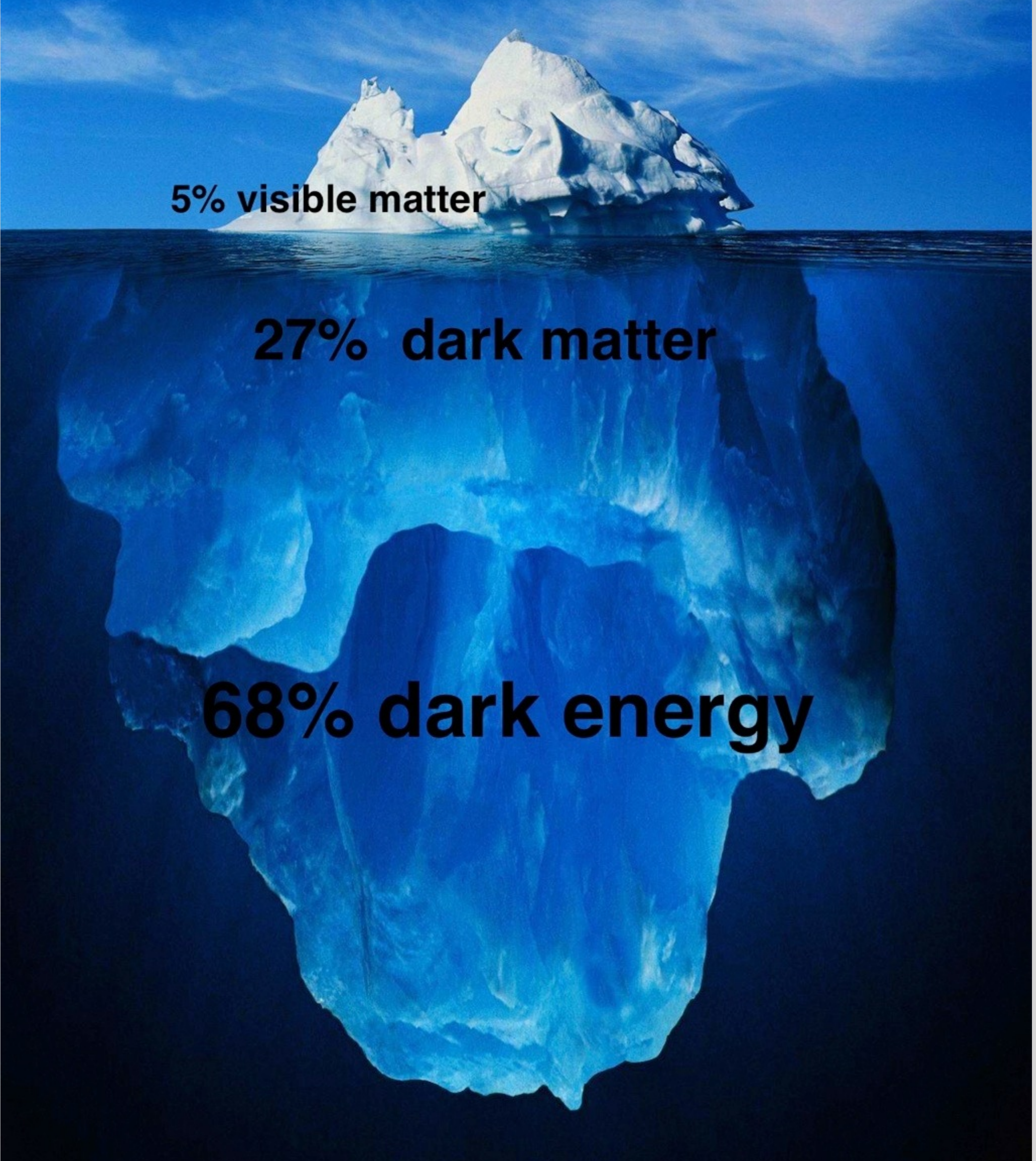
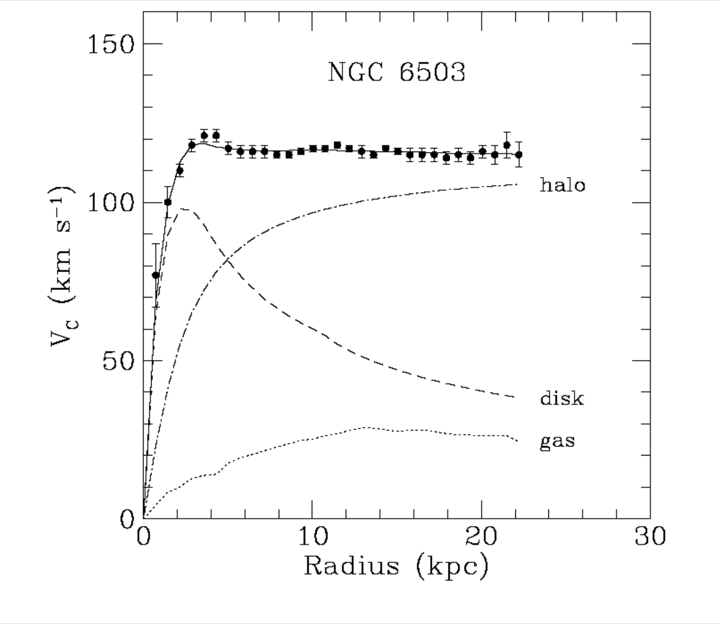
2021/06/07

2021 CAP Virtual Congress

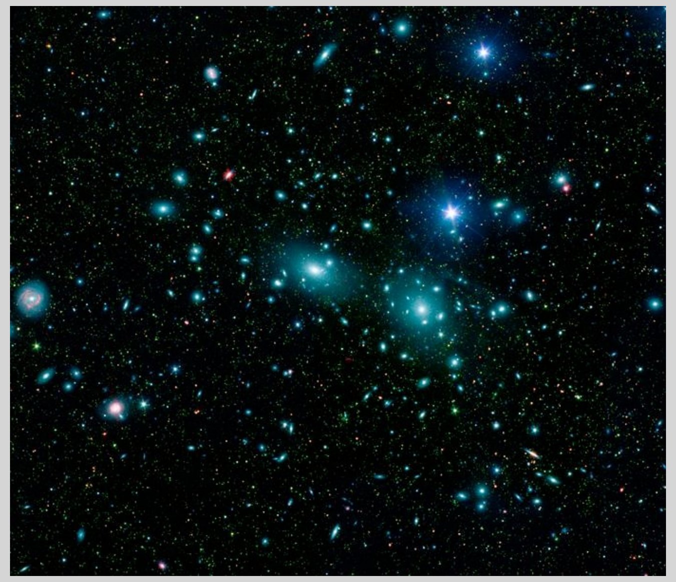
Challenges for Direct Dark Matter Detection Searches

Silvia Scorza



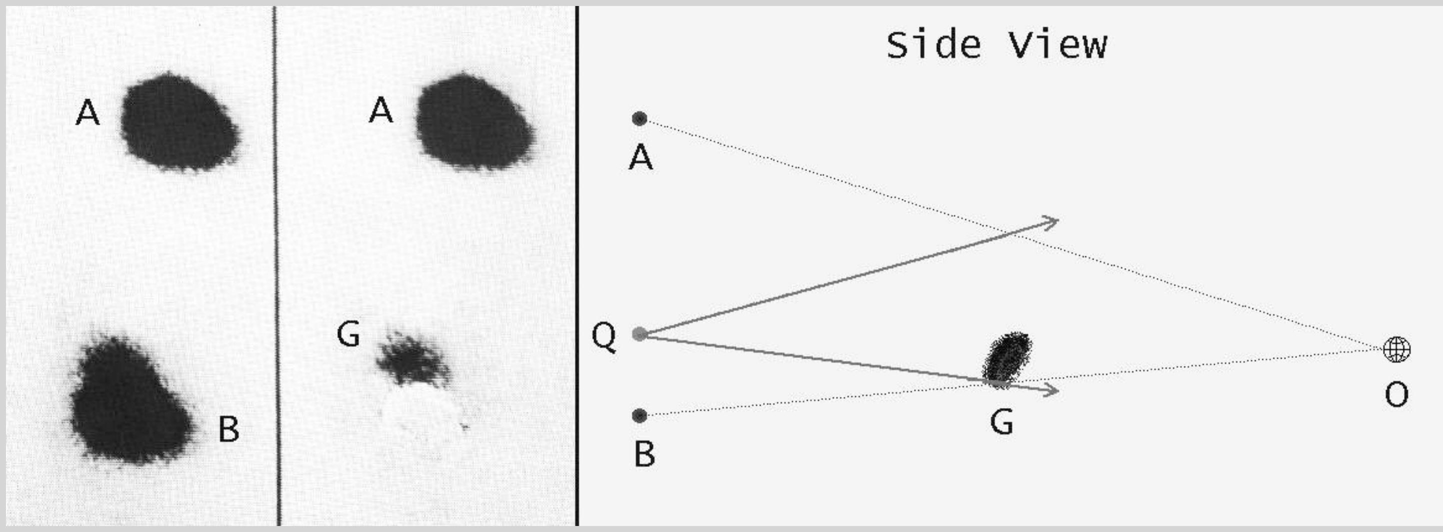


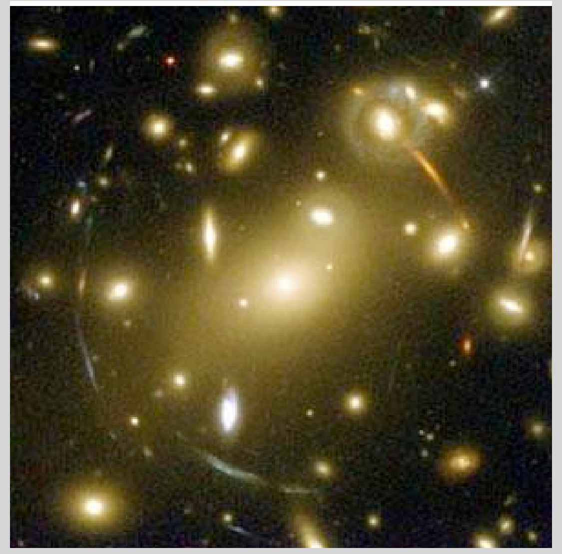
Rotation Curves



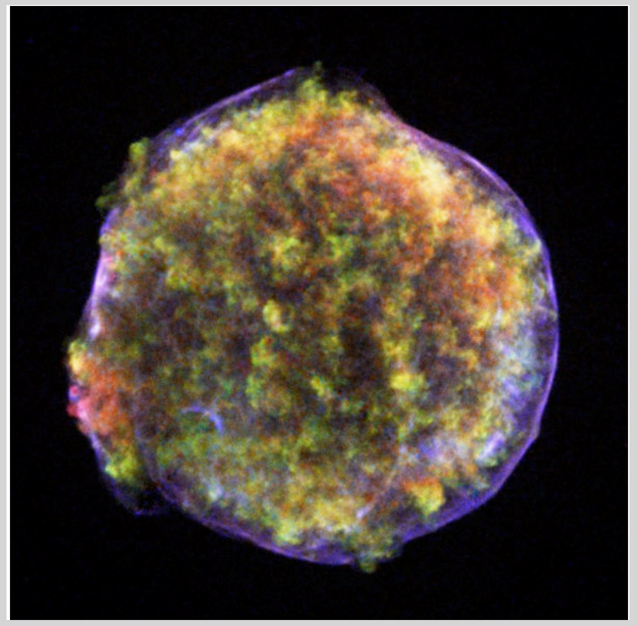
Motion of Galaxies in Clusters

Galaxy clusters

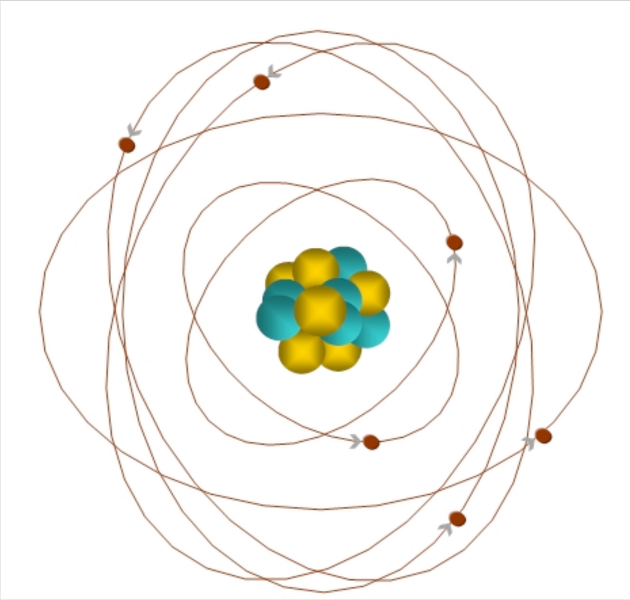




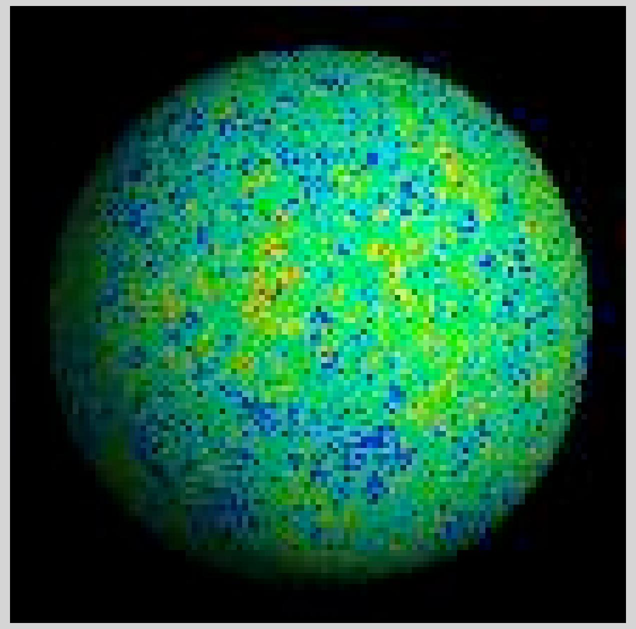
Gravitational Lensing



Supernovae Ia



Big Bang nucleosynthesis



Microwave background

Spin-independent cross section upper limits at 60 GeV WIMP mass

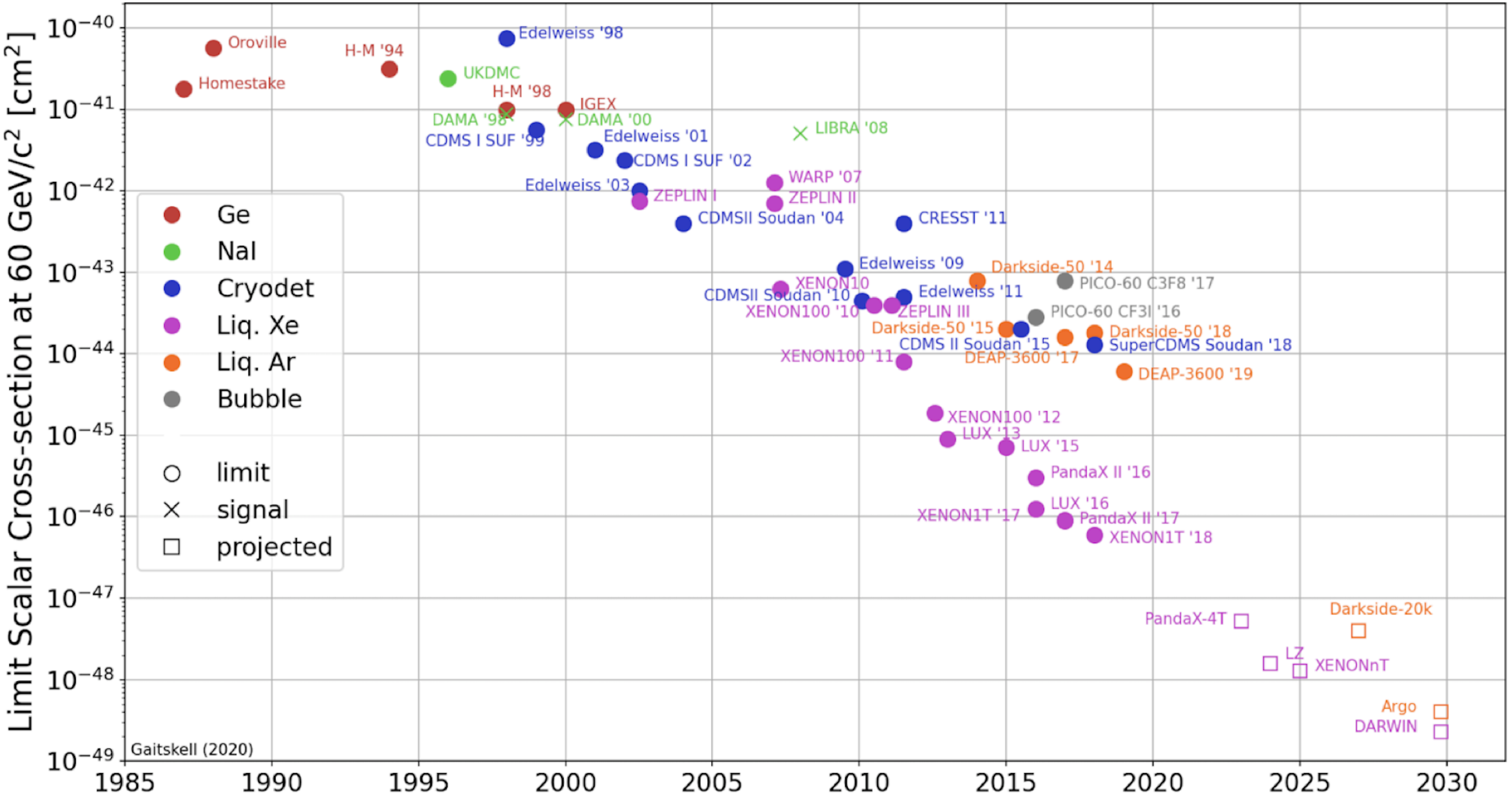
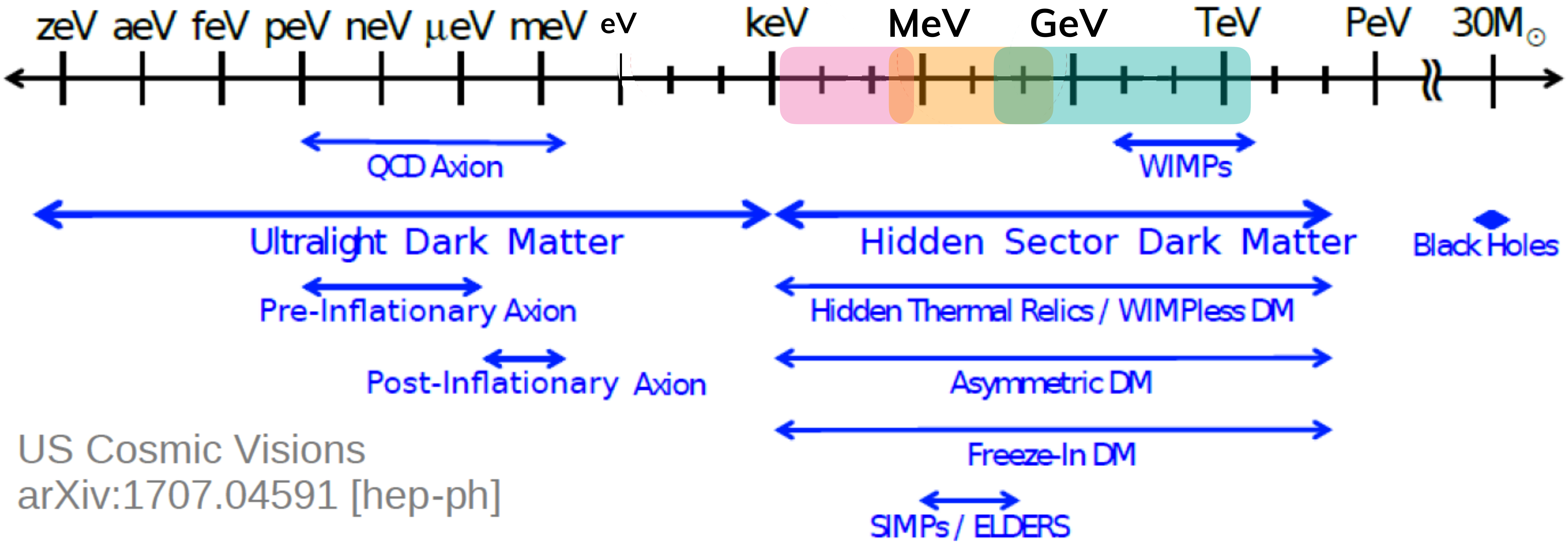


Figure: Rick Gaitskell, 2020

Dark Matter Candidate Scenario

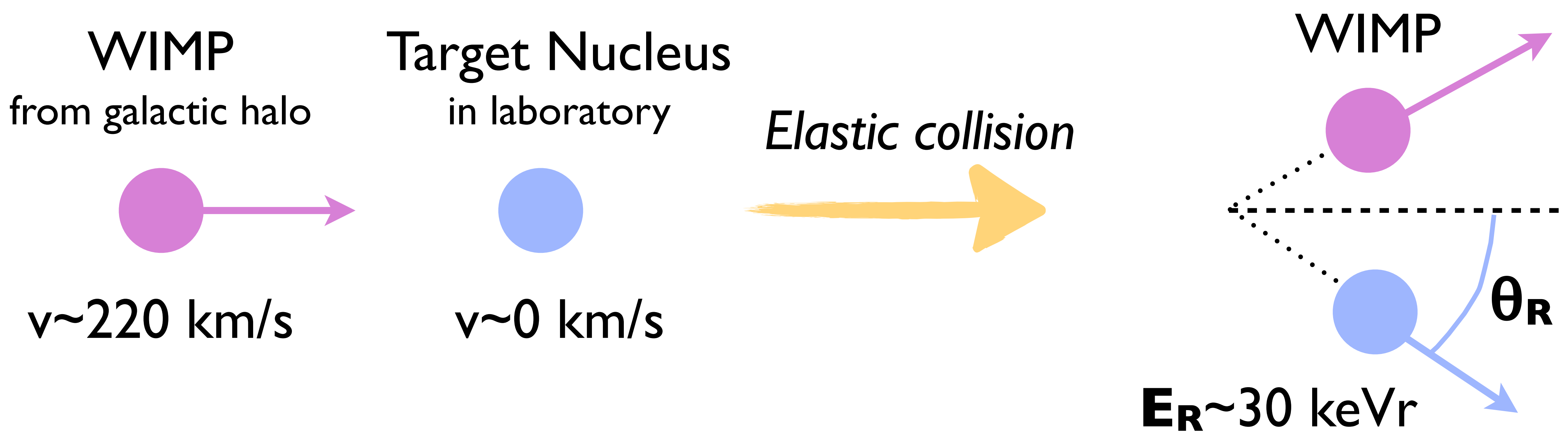
DM-nucleus scattering (nucelar recoil)
DM-electron scattering (electron recoil)
Absorption (electron recoil)



US Cosmic Visions
arXiv:1707.04591 [hep-ph]

Direct Detection Principle

Detection of the energy deposited due to elastic scattering off target nuclei



The Interaction Rate

Goodman & Witten (PRD 1985)

$$\frac{dR}{dE_r} = \frac{1}{2m_r^2}\frac{\sigma_0}{m_\chi} F^2(E_r) \rho_0 \int \frac{f(\vec{v})}{v} d^3v$$

Astrophysics
Nuclear physics
Particle physics

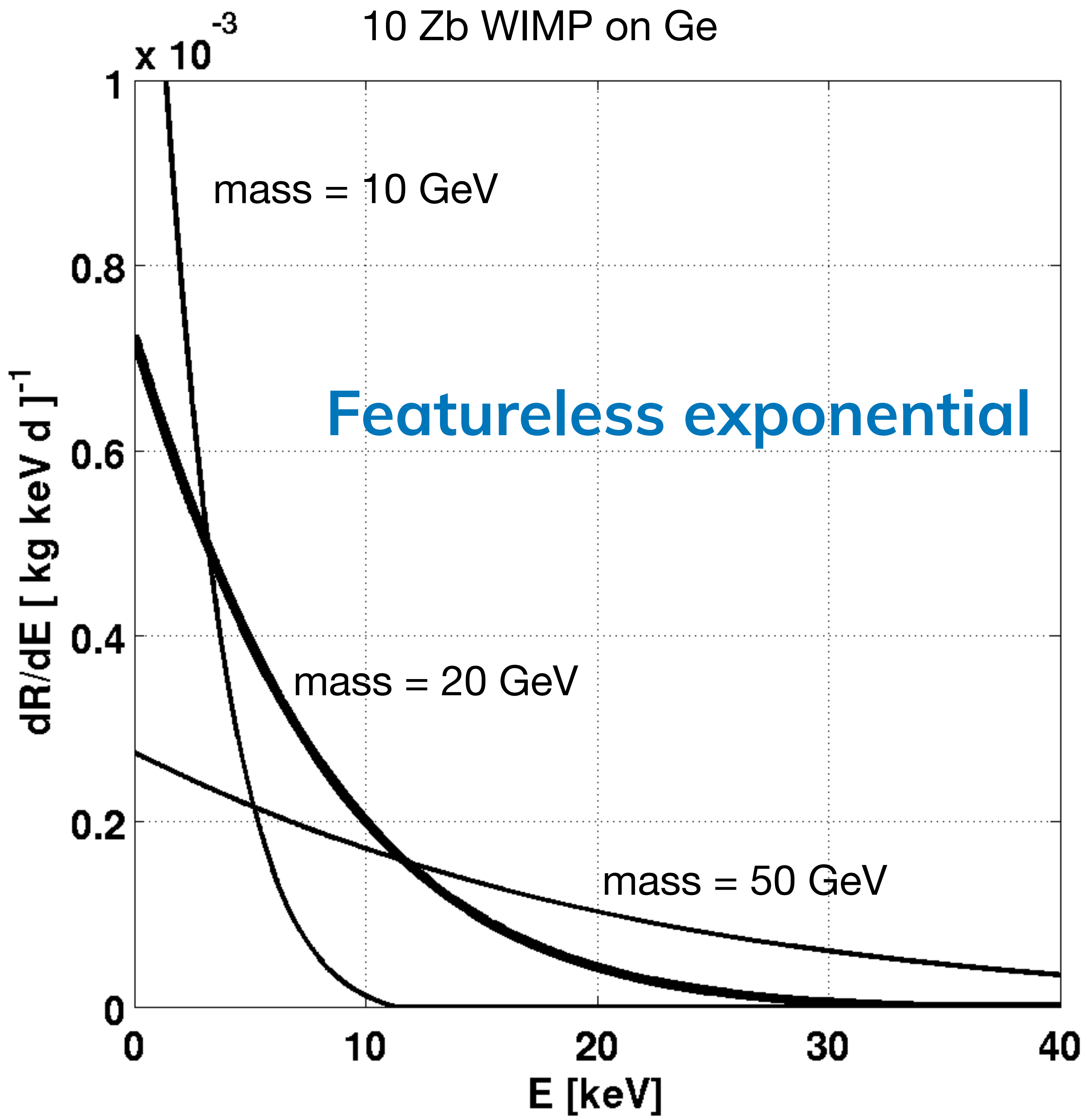
$F(E_R) \simeq \exp\left(-E_R\, m_N\, R_o^2/3\right)$ "form factor" (quantum mechanics of interaction with nucleus)

$m_r = \frac{m_\chi m_N}{m_\chi + m_N}$ "reduced mass"

$T(E_R) = \frac{\sqrt{\pi}}{2} v_o \int_{v_{\min}}^{\infty} \frac{f_1(v)}{v} dv$ integral over local WIMP velocity distribution

$v_{\min} = \sqrt{E_R\, m_N/(2m_r^2)}$ minimum WIMP velocity for given E_R

Direct Dark Matter Challenges



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Astrophysics

Nuclear physics

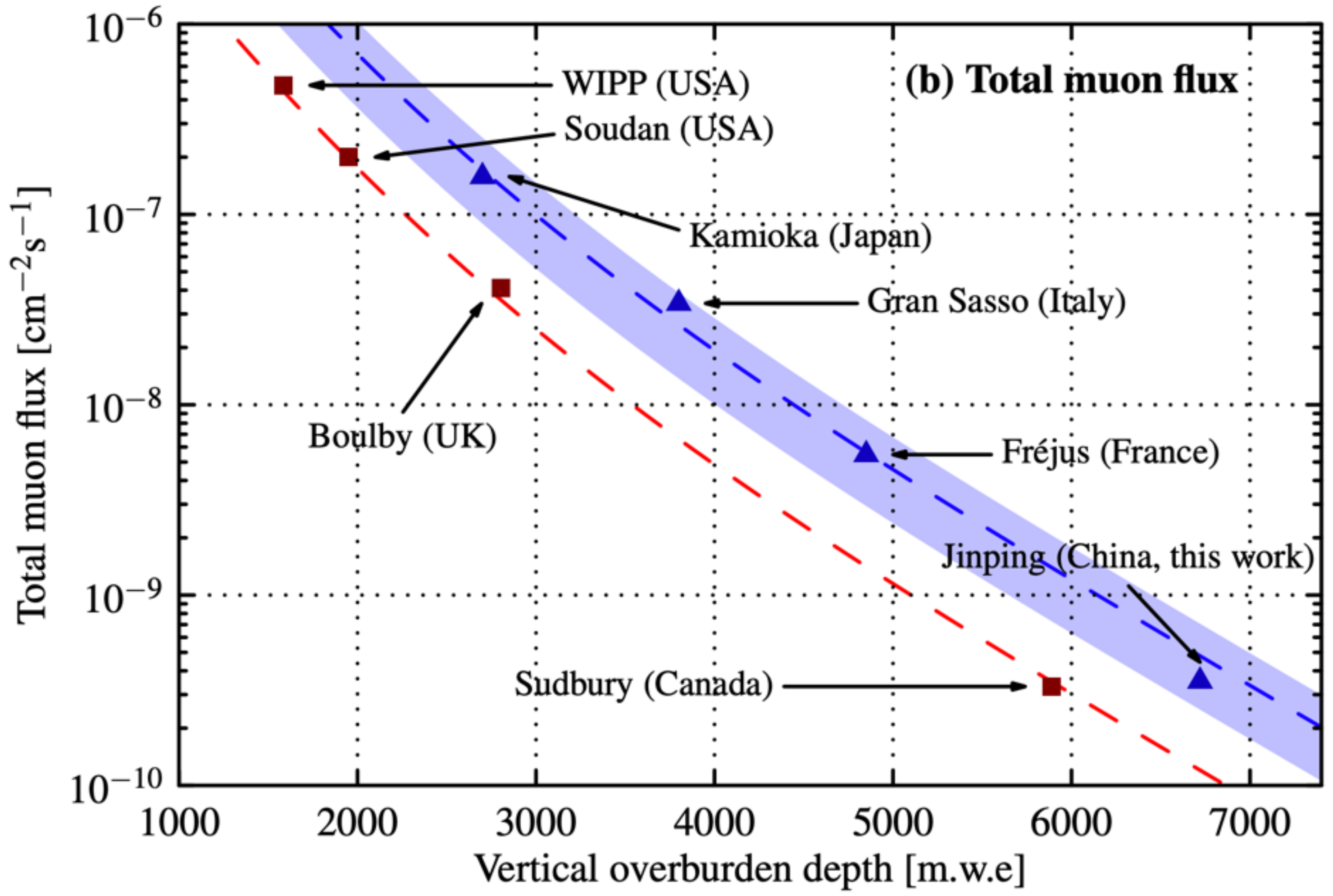
Particle physics

- **Low event rate:** *R < O(10) evts/ton/year*
- **Mean recoil energy:** ~ *O(10) keV*
- **Background reduction:** *active + passive*

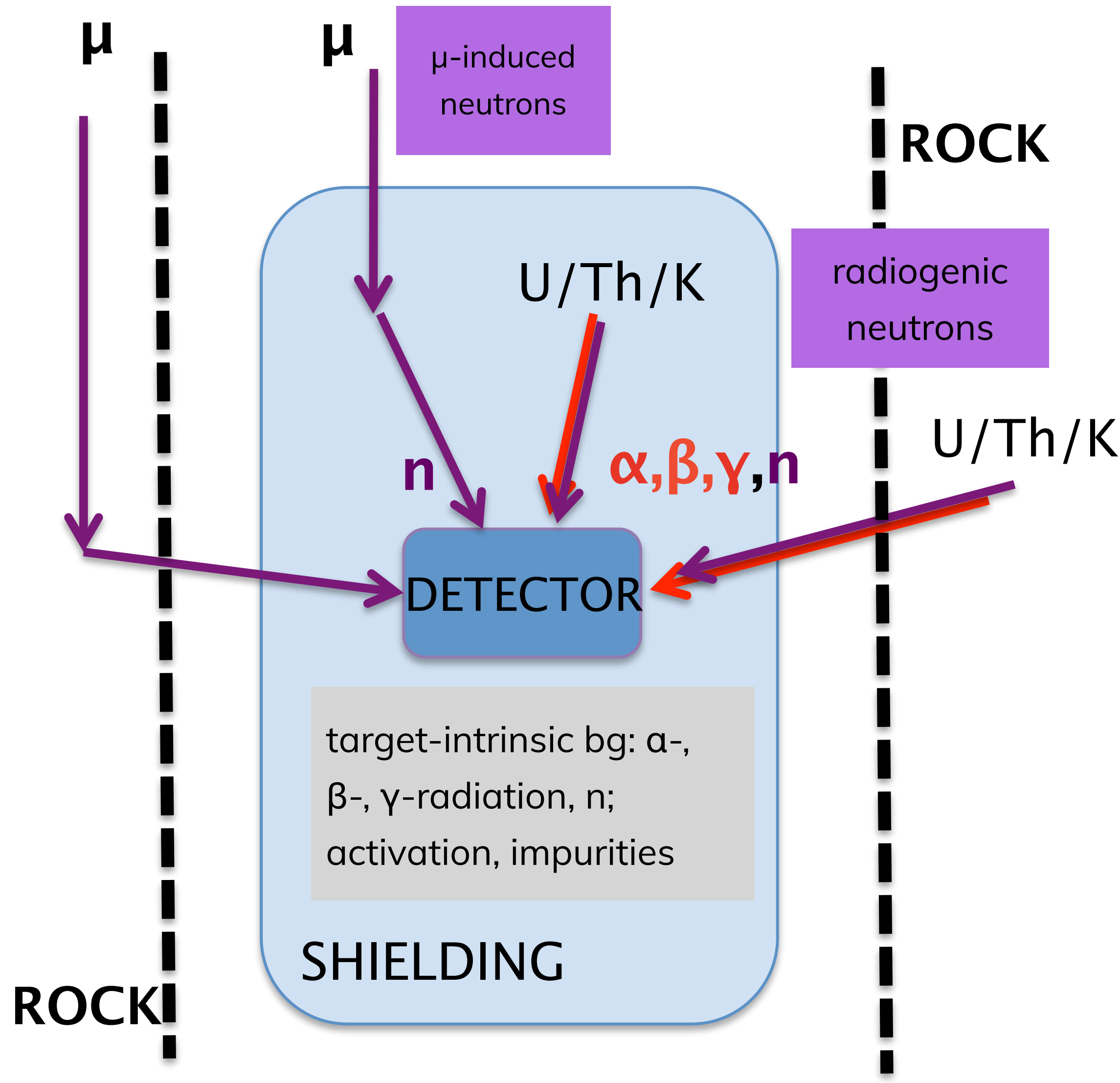
Direct DM Search Wishlist

- **Low** and **controlled** backgrounds
- **Discrimination** between signal and background
  - Simultaneous measurements of two signals allows ER/NR discrimination on an event-by-event basis
  - Detector technology background rejection and fiducialization
- **Large exposure** (*few events per ton-year*)
- **Low energy threshold**

Go deep underground
Fewer cosmic rays to produce neutrons.



Guo at al., arXiv:2007.15925v2



Passive/Active shielding
Reduce backgrounds from natural (^{238}U, ^{232}Th, ^{40}K) radioactivity

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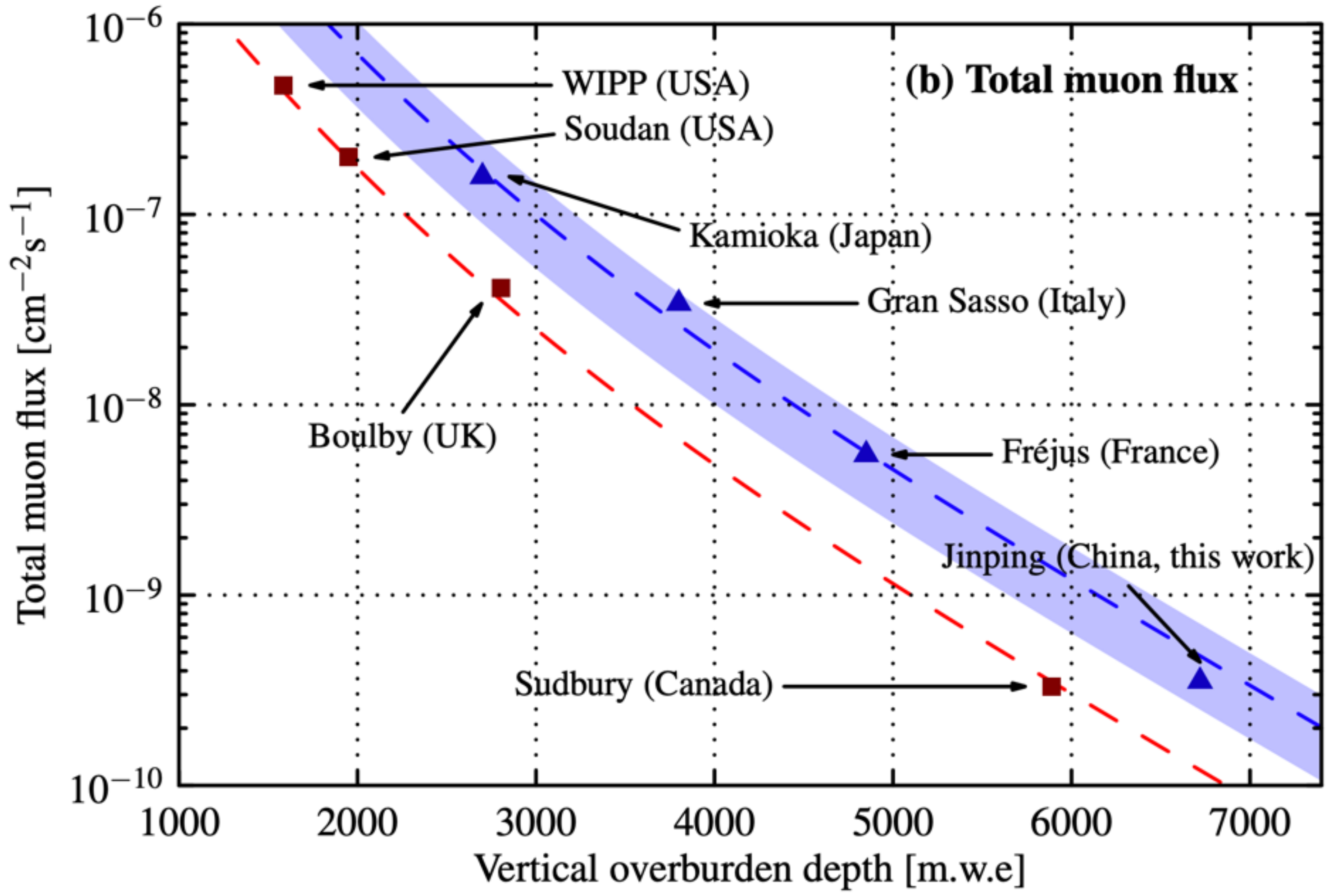
Background limit:

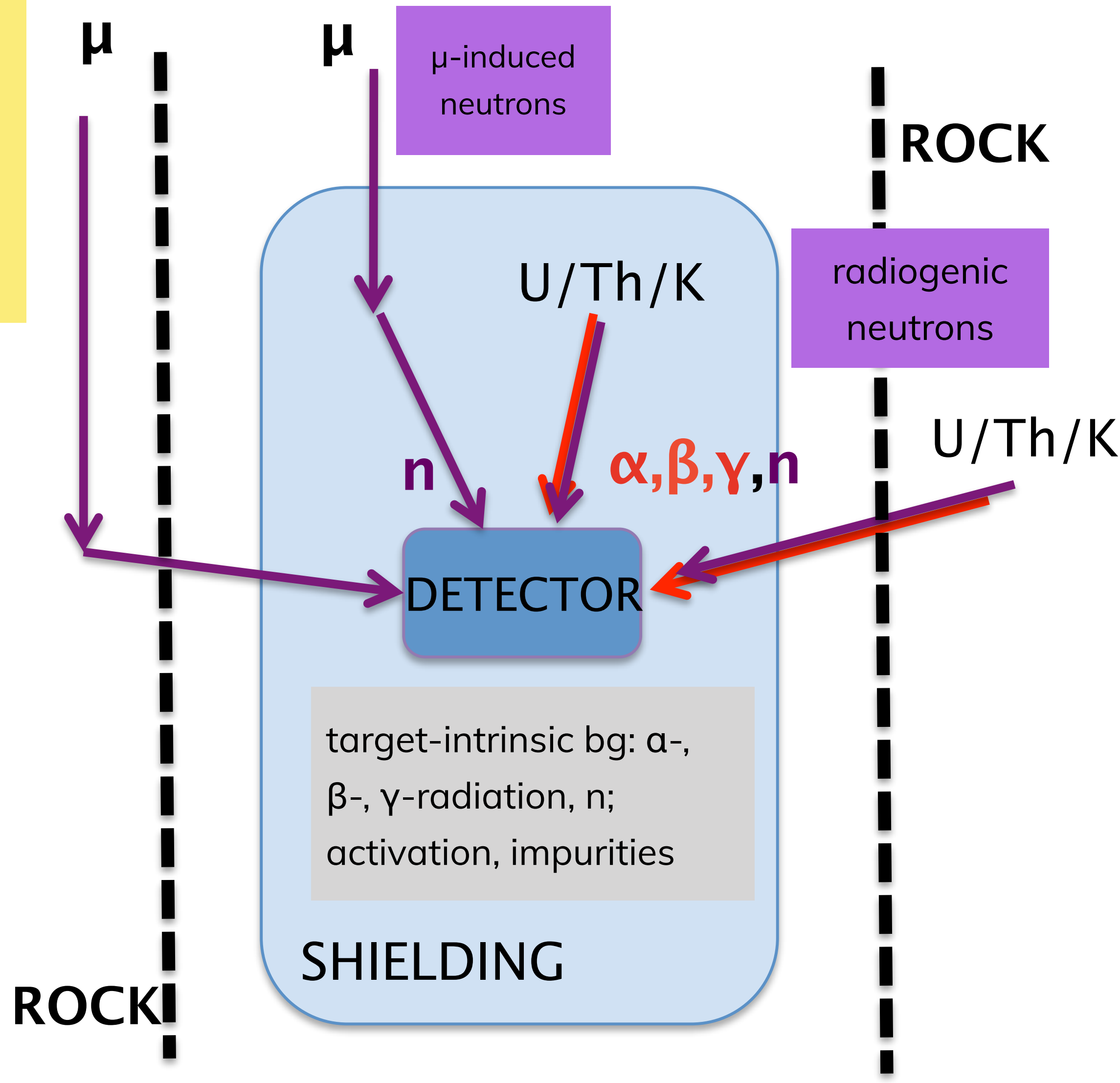
neutrino-nucleus scattering (solar, atmospheric and supernovae neutrinos)

Material screening and assay programme
Cleaning and purification techniques
Move underground detector fab and material purification

Go deep underground
Fewer cosmic rays to produce neutrons.



Guo at al., arXiv:2007.15925v2



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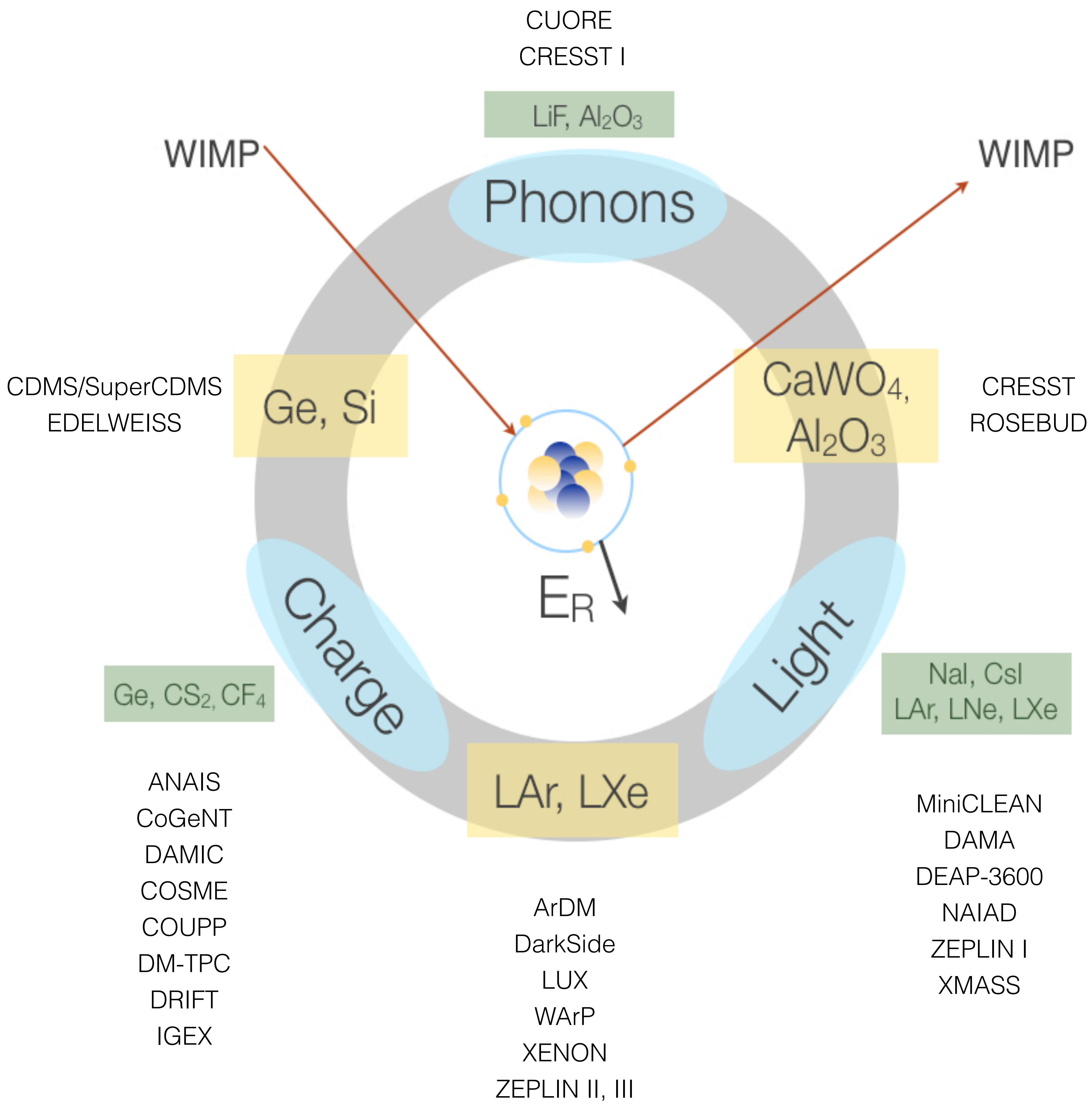

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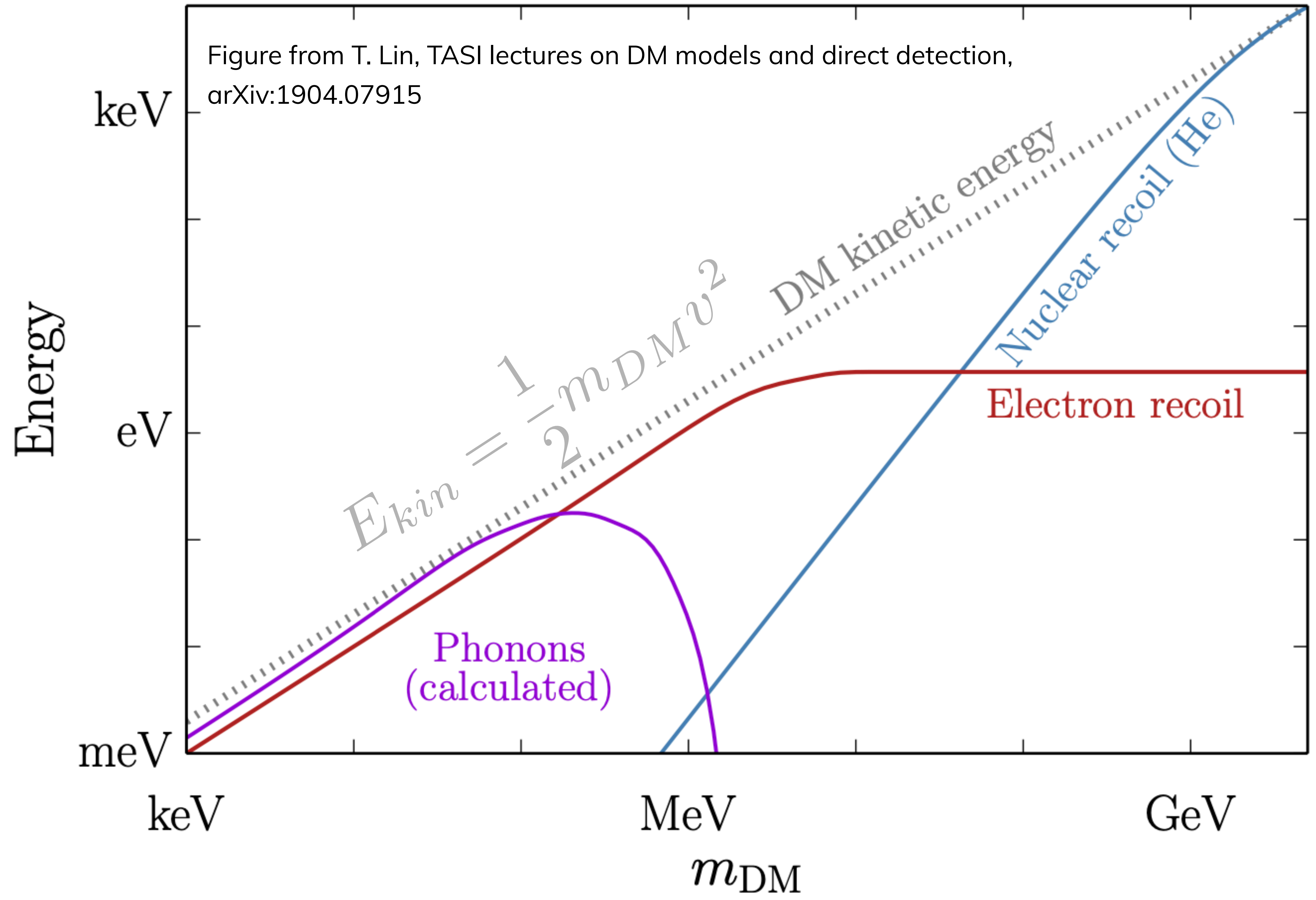
Transfer of DM kinetic energy inefficient when $M_n >> M_{DM}$ for elastic scatters



For DM masses below 100 MeV switch to DM-electron scattering searches

Direct DM Search Wishlist

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Particle Physics | Nuclear Physics | Astrophysics

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Interaction rate scales as $1/m_\chi$

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Interaction rate scales as $1/m_\chi$

Liquid noble experiments need 10 tons to get to 10^{-47} cm^2 at 100GeV

Solid-state experiments only needs 10kg to reach the same level at 100MeV

→ **energy sensitivity**

Direct DM Search Wishlist

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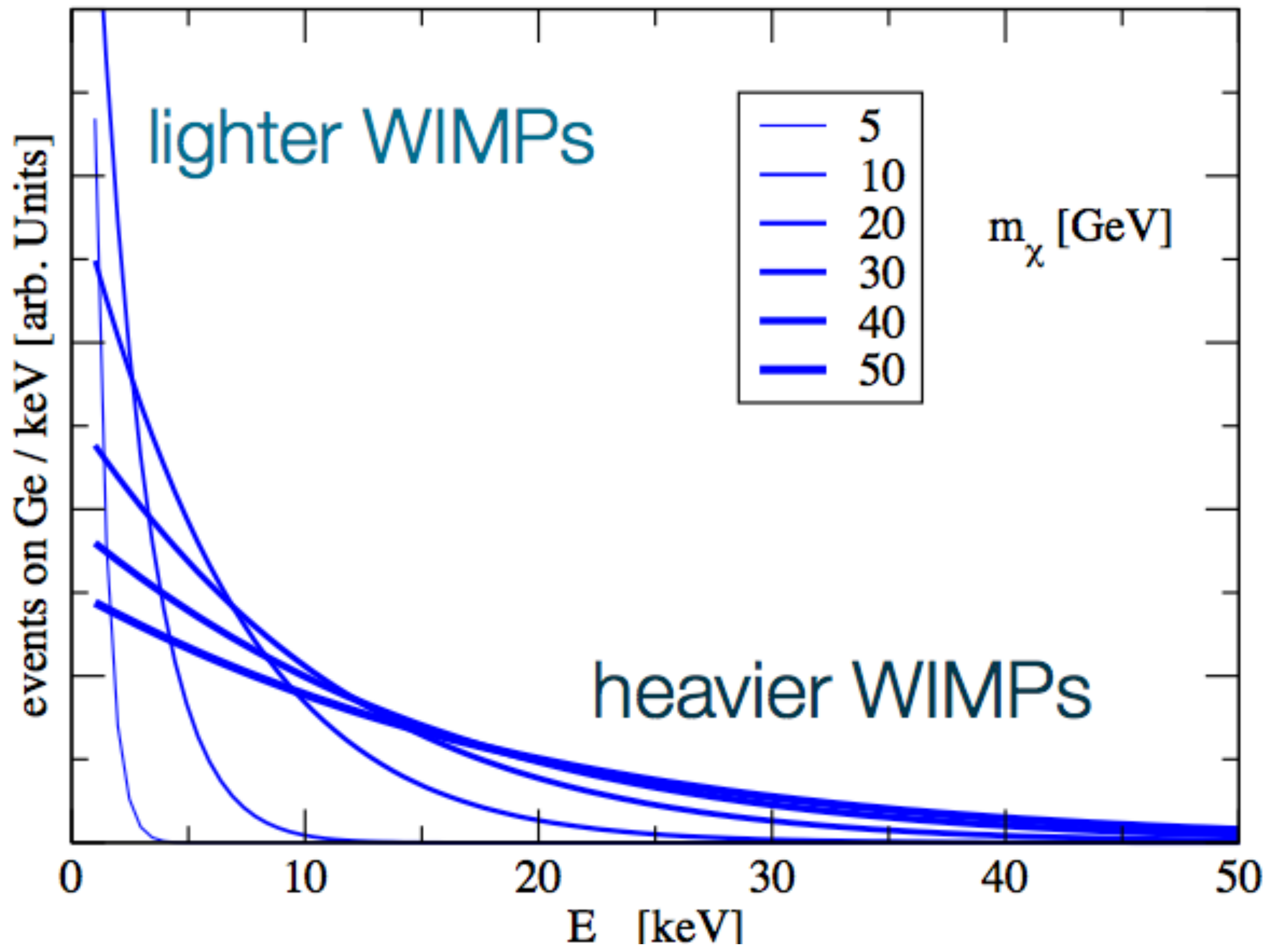
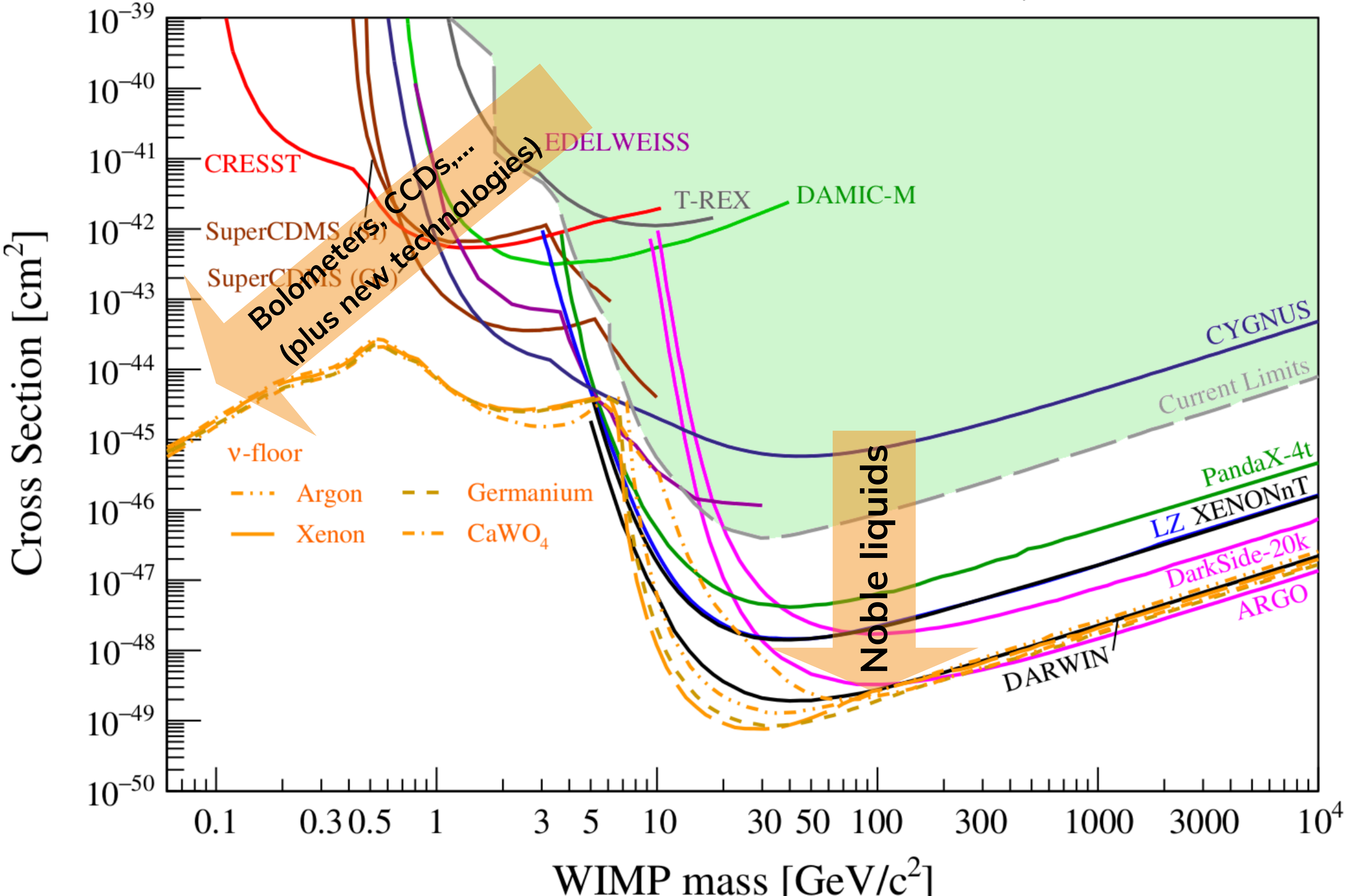


APPEC DM Report, arXiv:2104.07634

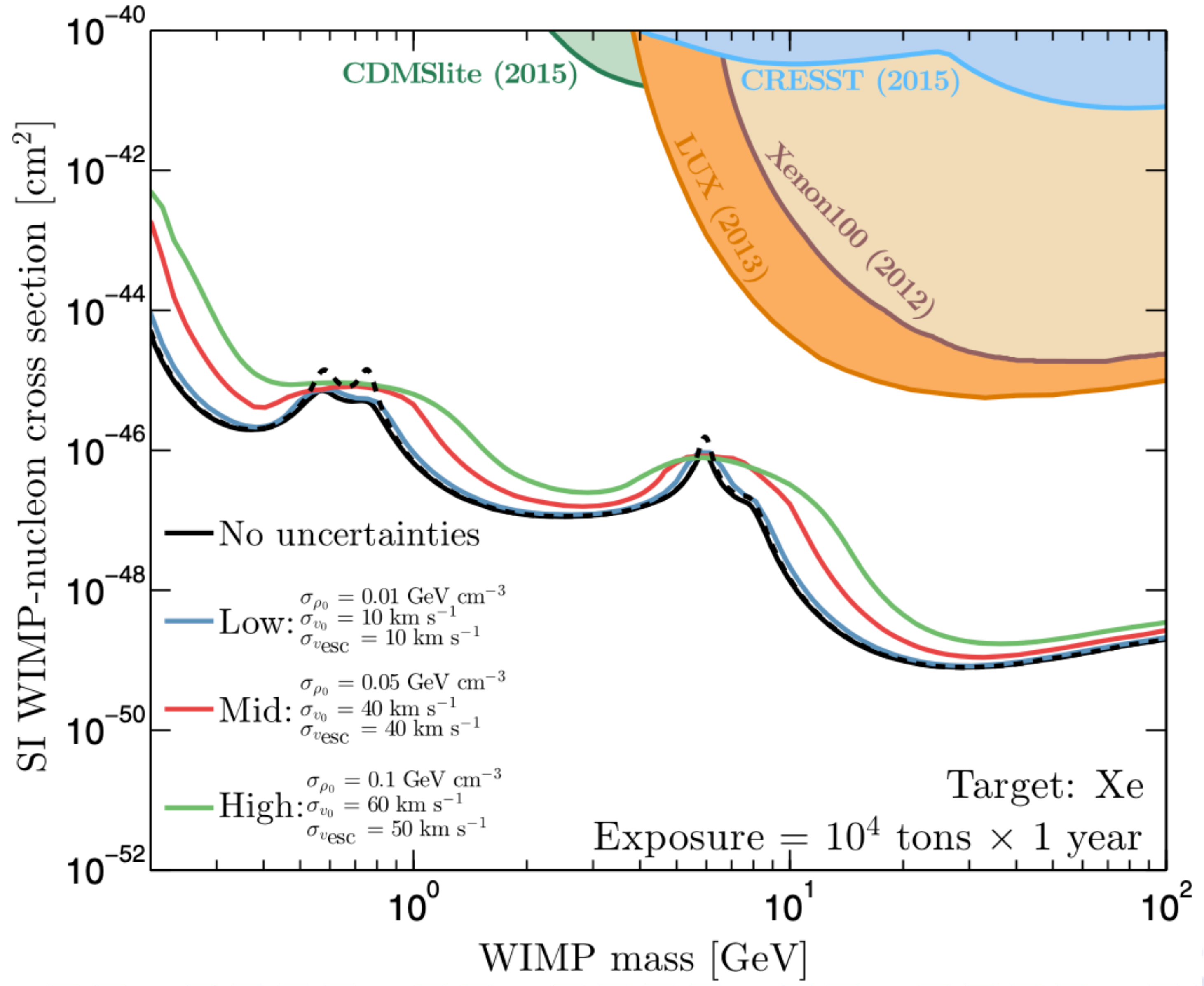


THE NEUTRINO FOG

The "**neutrino fog**" depends on:

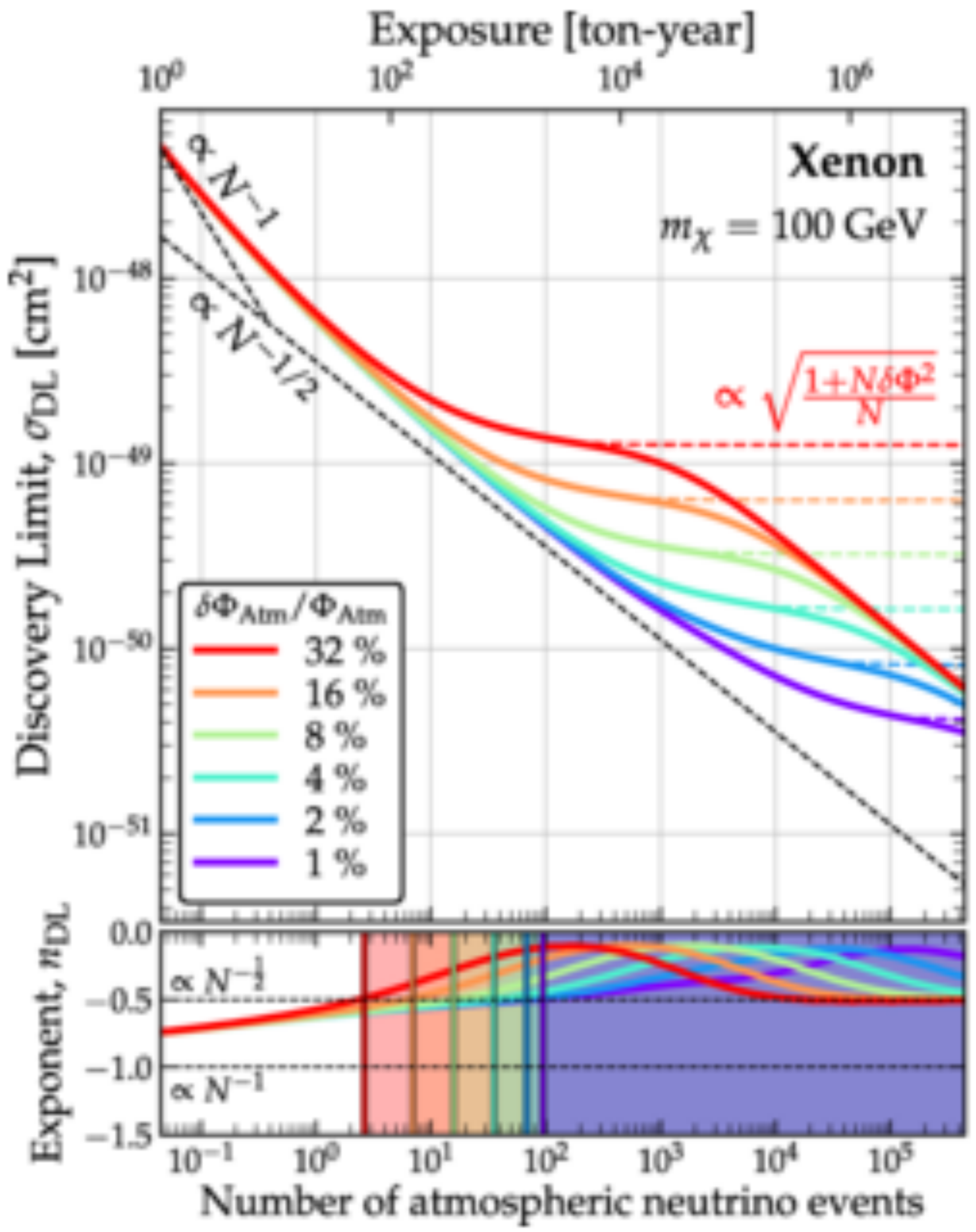
- systematic uncertainty in neutrino fluxes (~2% in 8B, ~20% for atmospheric neutrinos)
- nuclear and astro inputs for the DM signal

C. A. J. O'Hare PRD 94, 2016



Neutrino "floor" for 3 sets of 1-σ uncertainties on the local density, speed and escape velocity for a xenon target

C. A. J. O'Hare PRD 102, 2020



Discovery limit of a 100 GeV WIMP in an xenon target, as a function of the atm. neutrino event N and fract. uncertainty on the atm ν flux: δΦatm/Φatm

THE NEUTRINO FOG & BEYOND TECHNOLOGICAL CHALLENGES

Upscaling from 10s of kg to tonne scale (solid-state) and from tonne to 10s of tonne scale (noble liquids)

Solid-state

- Crystal growth and fabrication (underground);
- Operate large crystal arrays;
- Develop new ionisation and phonon sensors

Noble liquids

- Liquid target purification, depletion, cryogenic distillation, storage (underground)

Calibration techniques

THE NEUTRINO FOG & BEYOND BACKGROUND CHALLENGES

Reduce & model cosmogenic background

Reduce and predict in situ activation/production of cosmogenic isotopes underground

Construct Rn-free cleanrooms

Continuous cryogenic distillation & crystal growth underground

Understand neutrino backgrounds and uncertainties

Currently there is no way to distinguish between DM and CEvNS

- Add the directionality channel in current technology
- Dedicated CEvNS calibration using nuclear reactor

Data Interpretations

ASTROPHYSICS
LOCAL DARK MATTER DENSITY

Local measures: vertical kinematics of stars near Sun as ‘tracers’ of the gravitational potential

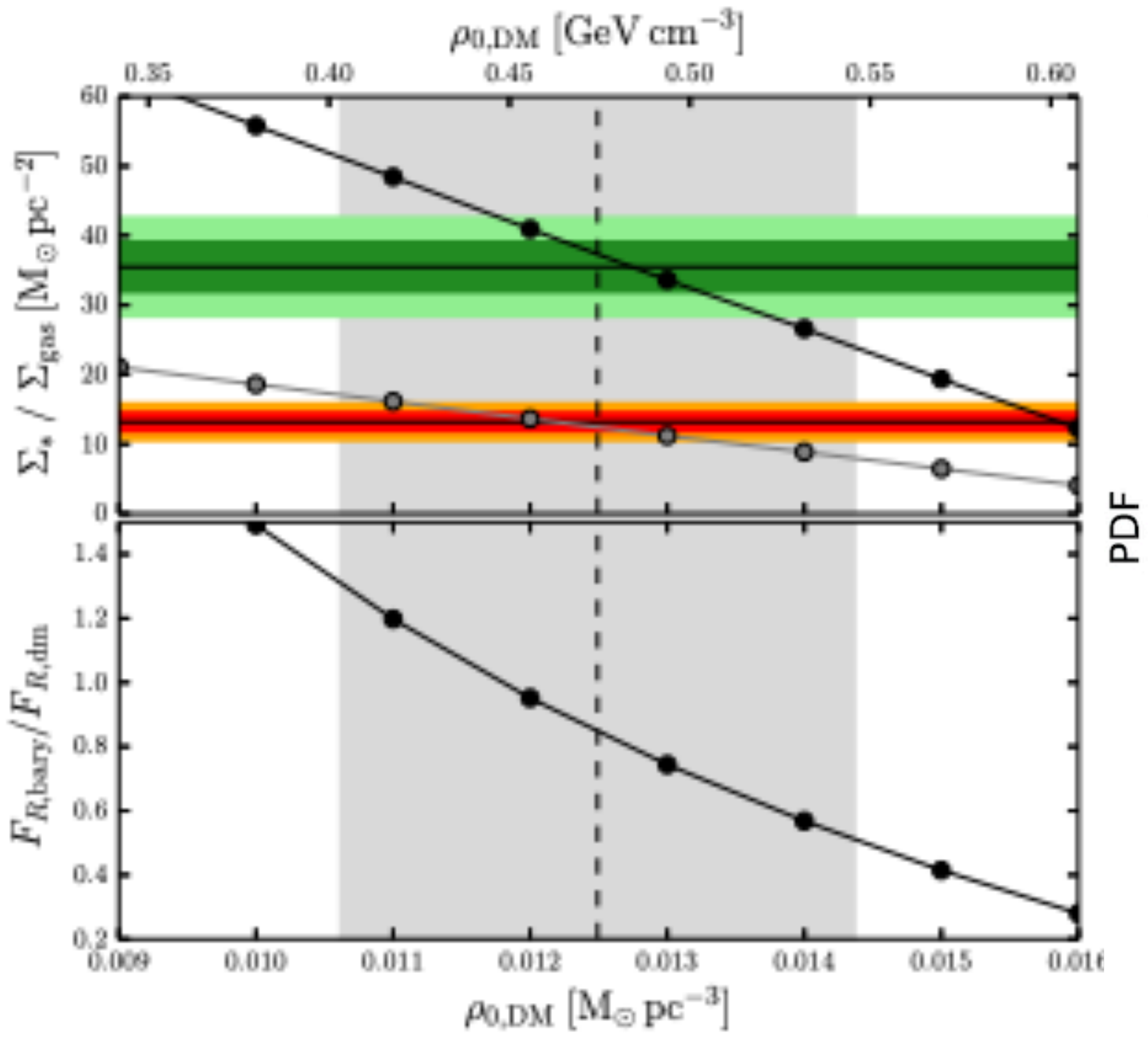
Global measures: extrapolate the density from Milky Way’s rotation curve derived from kinematic measurements of gas, stars

Major source of uncertainty: contribution of baryons (stars, gas, stellar remnants, …) to the local dynamical mass

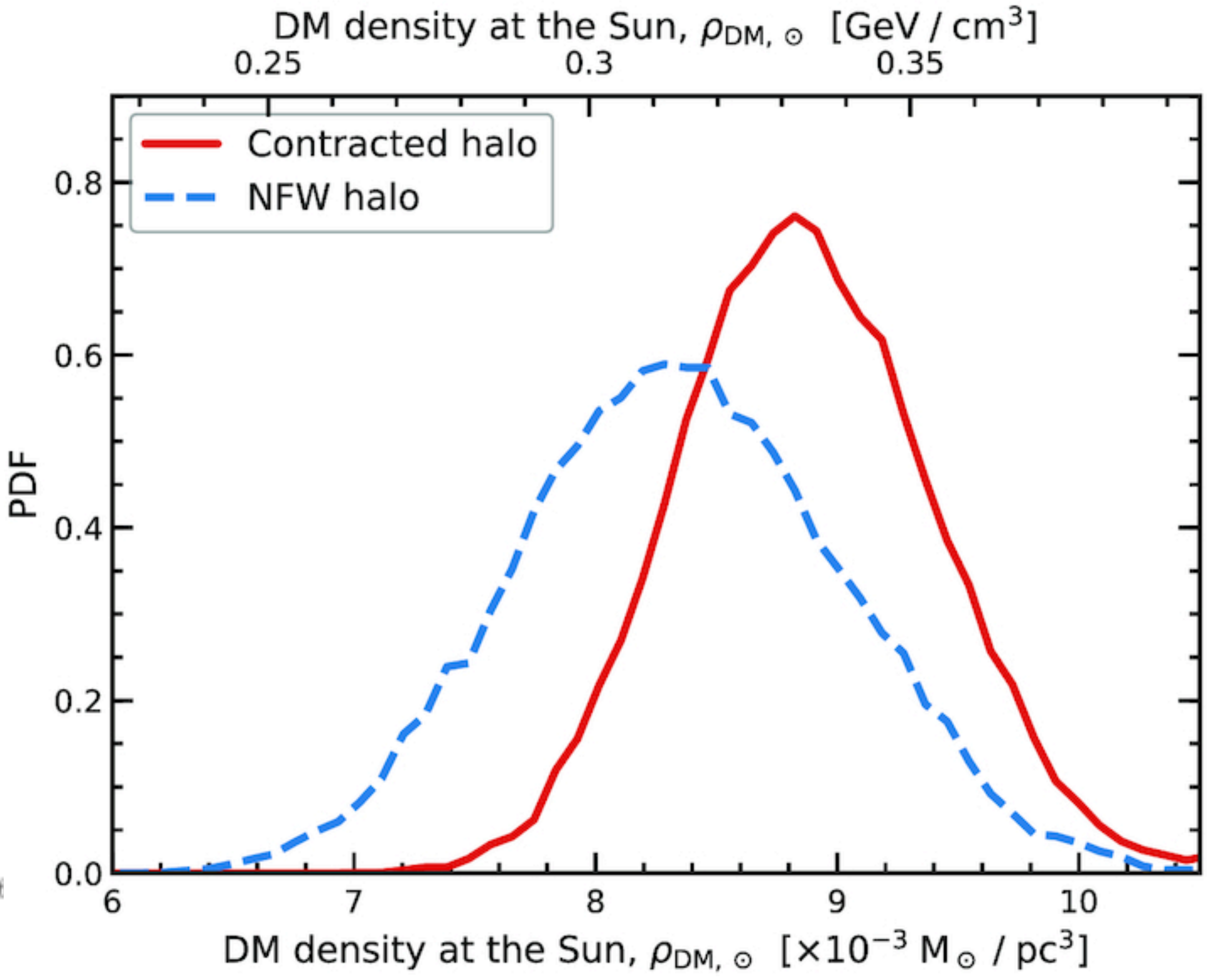
Direct detection rates:
- linear dependance on the local density;
- "canonical value" is 0.3 GeV/cm^3

Range of values in the literature: [0.2 - 0.6] GeV/cm^3

T. Piffl et al., MNRAS 445 (2015)



M. Cautun et al, MNRAS 494 (2020) 3, using Gaia DR2



ASTROPHYSICS

DARK MATTER VELOCITY DISTRIBUTION

Standard halo model (SHM): Maxwellian distribution (isotropic velocities)

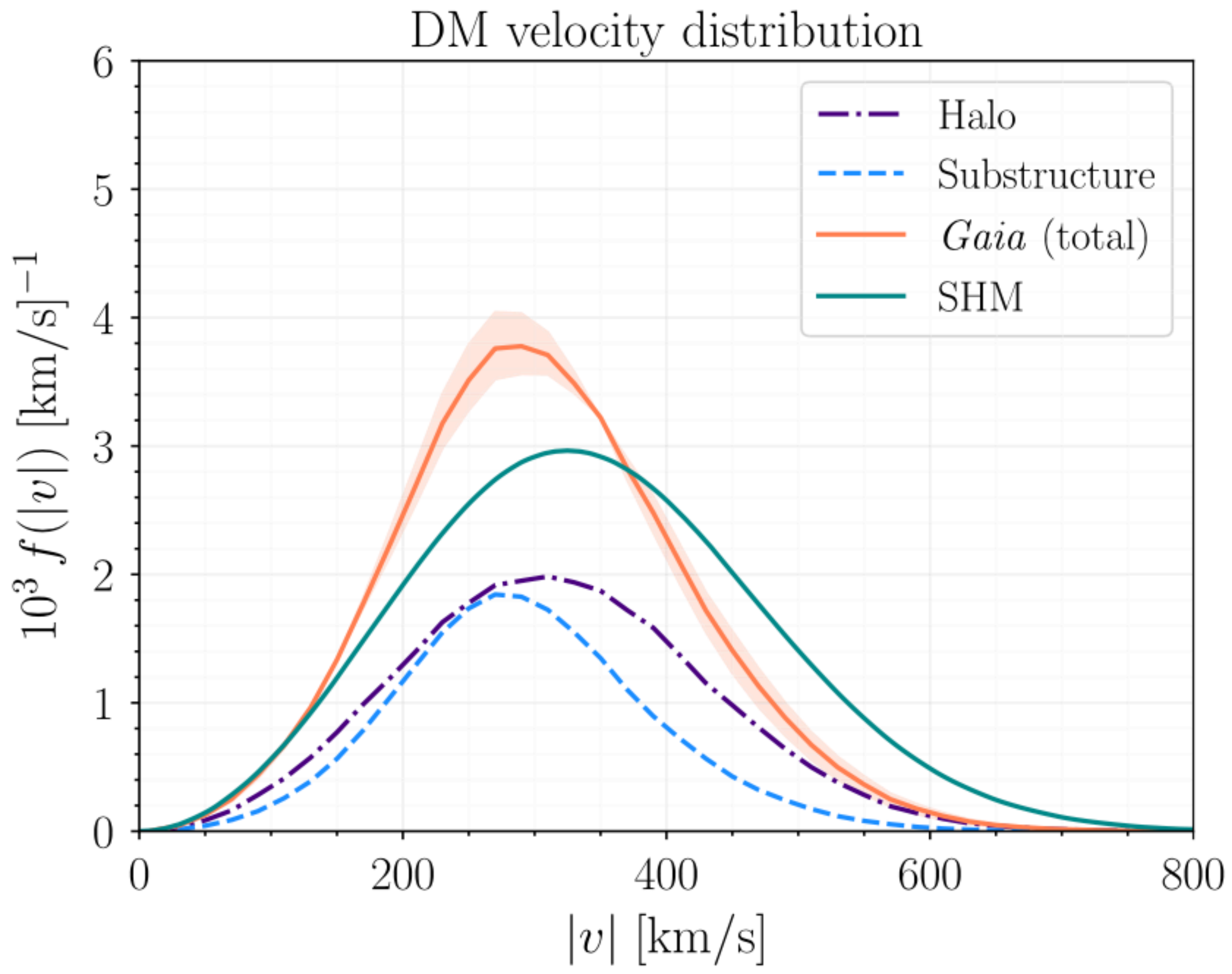
Determine f(v) from observation (e.g., motion of stars that share kinematics with DM)

Recent studies: deviations from SHM, due to anisotropies in the local stellar distribution (in Gaia data)

These arise from accretion events, see, e.g., the “Gaia-sausage” - one of the dominant merger in the solar neighbourhood

Effects for direct detection: escape speed, circular rotation speed; relevant mostly at low dark matter masses

Necib, Lisanti, Belorukov 2018, Evans, O’Hare, McCabe, PRD99, 2019; Buch, Fan, Leung, PRD101, 2020; and others



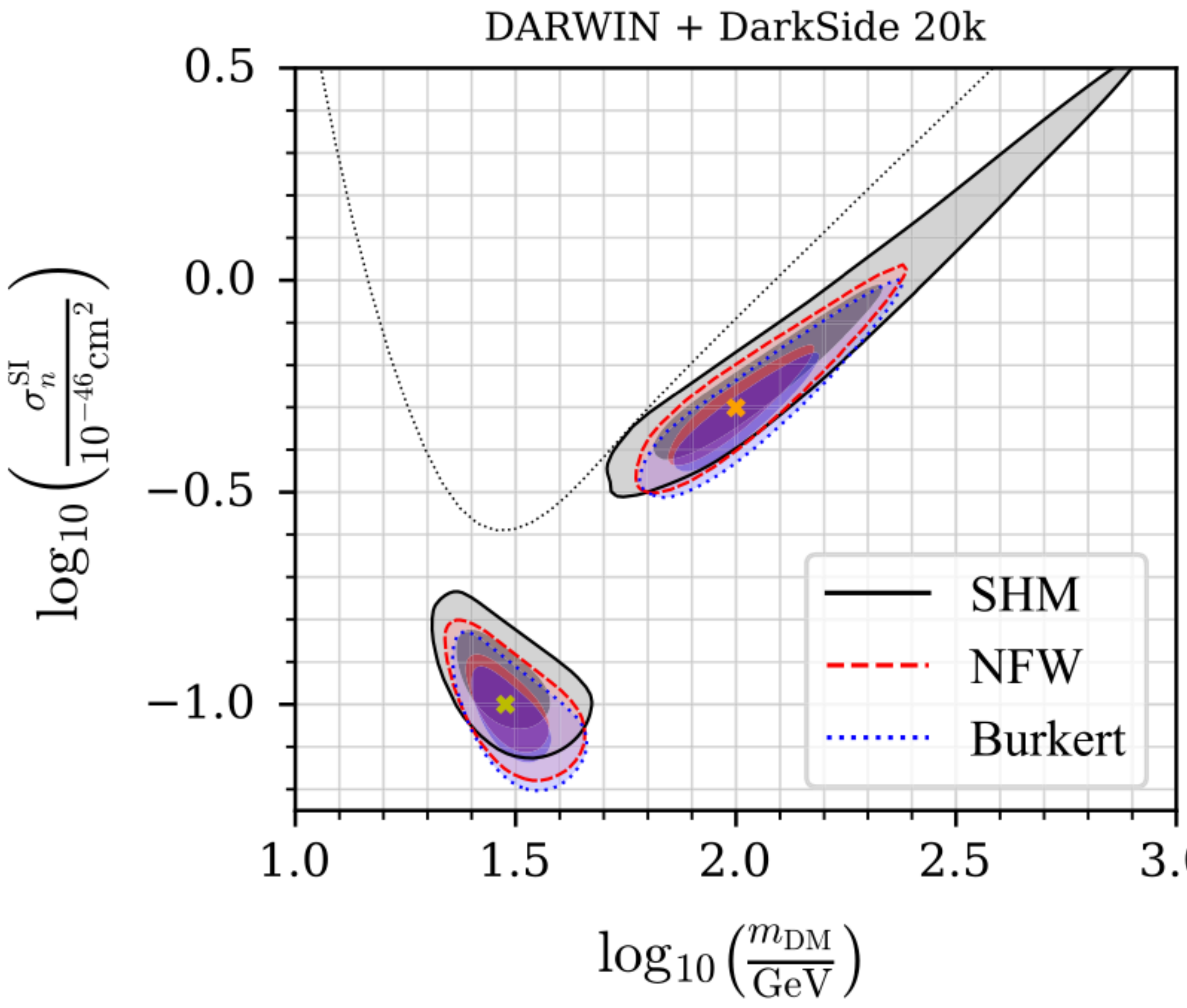
COMPARISON WITHIN DDM FIELD

HALO MODEL

SHM	Local DM density	ρ_0	0.3 GeV cm^{-3}
	Circular rotation speed	v_0	220 km s^{-1}
	Escape speed	v_{esc}	544 km s^{-1}
	Velocity distribution	$f_R(\mathbf{v})$	Eq. (1)
SHM^{++}	Local DM density	ρ_0	0.55 ± 0.17 Ge
	Circular rotation speed	v_0	233 ± 3 km s^{-1}
	Escape speed	v_{esc}	528^{+24}_{-25}
	Sausage anisotropy	β	0.9 ± 0.05
	Sausage fraction	η	0.2 ± 0.1
	Velocity distribution	$f(\mathbf{v})$	Eq. (3)

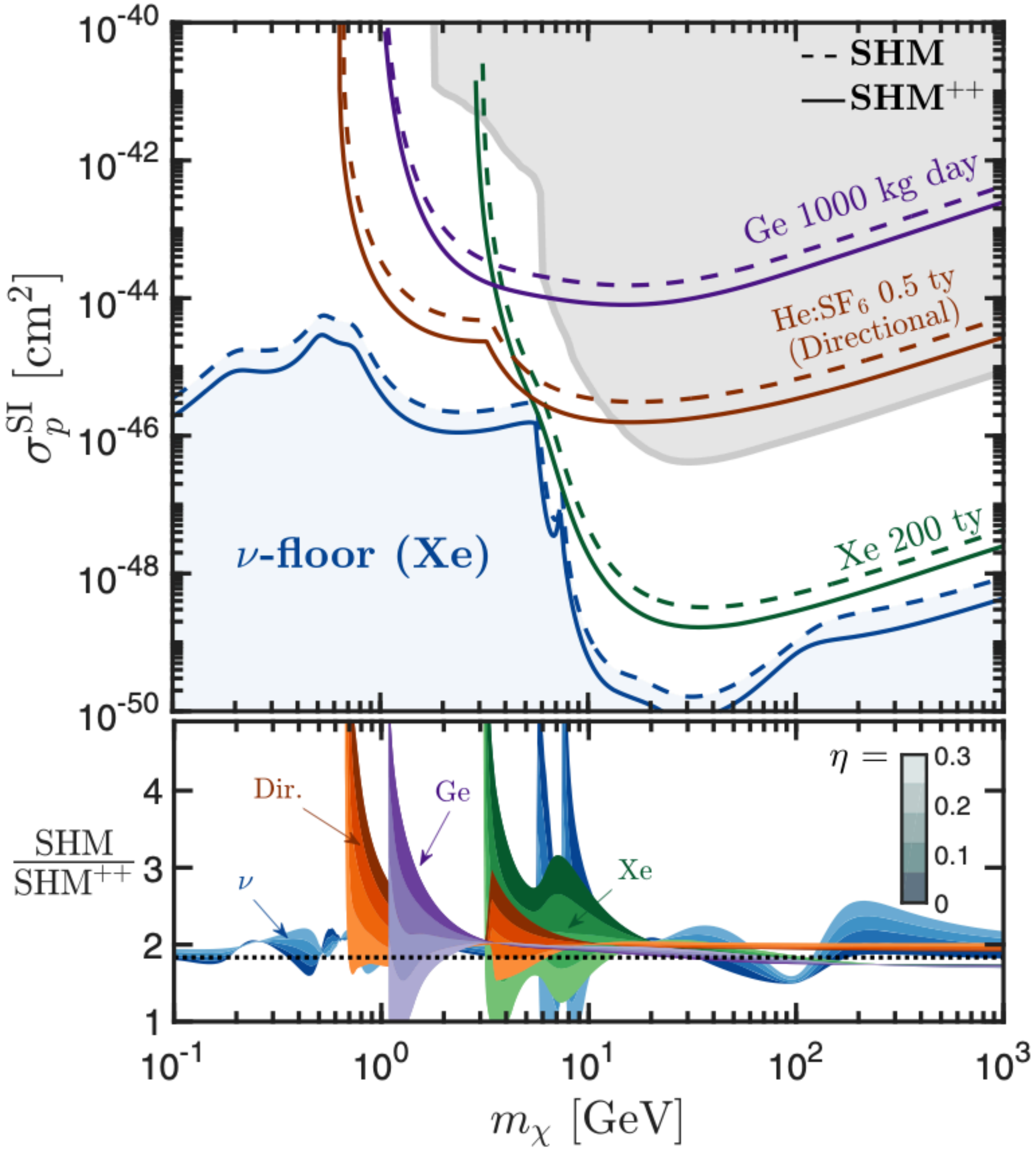
Which halo model to use?

- Impact on upper limit proposed in PRD99, 2019
- Influence the interpretation of results in case of a detection (PRD 102, 2020)



M. Petac, PRD 102, 2020, Reconstruction of DM mass and cross section: (30 GeV, 10^{-47} cm^2; 100 GeV, 5 x 10^{-47} cm^2)

Ewans, O'Hare, McCabe PRD 99, 2019, Impact of the halo model on upper limits



COMPARISON WITHIN DDM FIELD
STATISTICAL FRAMEWORK

Different approaches used by various collaboration (see, e.g., talks at PHYSTAT-DM 2019 https://indico.cern.ch/event/769726/overview)

New White Paper (arXiv: 2105.00599, emerged out of PHYSTAT-DM 2019)

- profile likelihood-based test statistics -> Likelihood Ratio (PLR) (following Cowan, Cranmer, Gross, Vitells, EPJ-C 71, 2011)
- to asses discovery significance & construct confidence intervals

See White Paper for full list of recommendations (also on astrophysical parameters & astrophysical

Recommended conventions for reporting results from direct dark matter searches

D. Baxter, I. M. Bloch, E. Bodnia, X. Chen, J. Conrad, P. Di Gangi, J. E. Y. Dobson, D. Durnford, S. J. Haselschwardt, A. Kaboth, R. F. Lang, Q. Lin, W. H. Lippincott, J. Liu, A. Manalaysay, C. McCabe, K. D. Mora, D. Naim, R. Neilson, I. Olcina, M.-C. Piro, M. Selvi, B. von Krosigk, S. Westerdale, Y. Yang, N. Zhou

PHYSTAT Dark Matter 2019

COMPARISON WITH OTHER FIELDS
SOFTWARE TOOLS

How to compare the data reliably with **accelerator searches** and **indirect detection**?

Simplified models; EFTs; UV complete models?

How to make the **underlying assumptions** transparent?

Which halo model, including new velocity substructures as revealed by Gaia data?

Software examples (C. Arina, Review on Dark Matter Tools, arXiv: 2012.09462):

- DarkSUSY 6, An Advanced Tool to Compute Dark Matter Properties Numerically, https://darksusy.hepforge.org (JCAP 1807, 2018)
- DarkBit, a GAMBIT module for computing dark matter observables and likelihoods (EPJ-C 77, 2017)
- MicrOMEGAs (https://lapth.cnrs.fr/micromegas/), Recasting DD limits (EPJ-C 81, 2021)


That's all Folks!