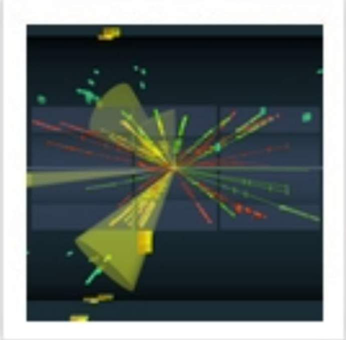

CENTRO DE CIENCIAS
DE BENASQUE
PEDRO PASCUAL

TAE 2023 - International Workshop on High Energy Physics

Sep 03 - 16, 2023

Dark Matter

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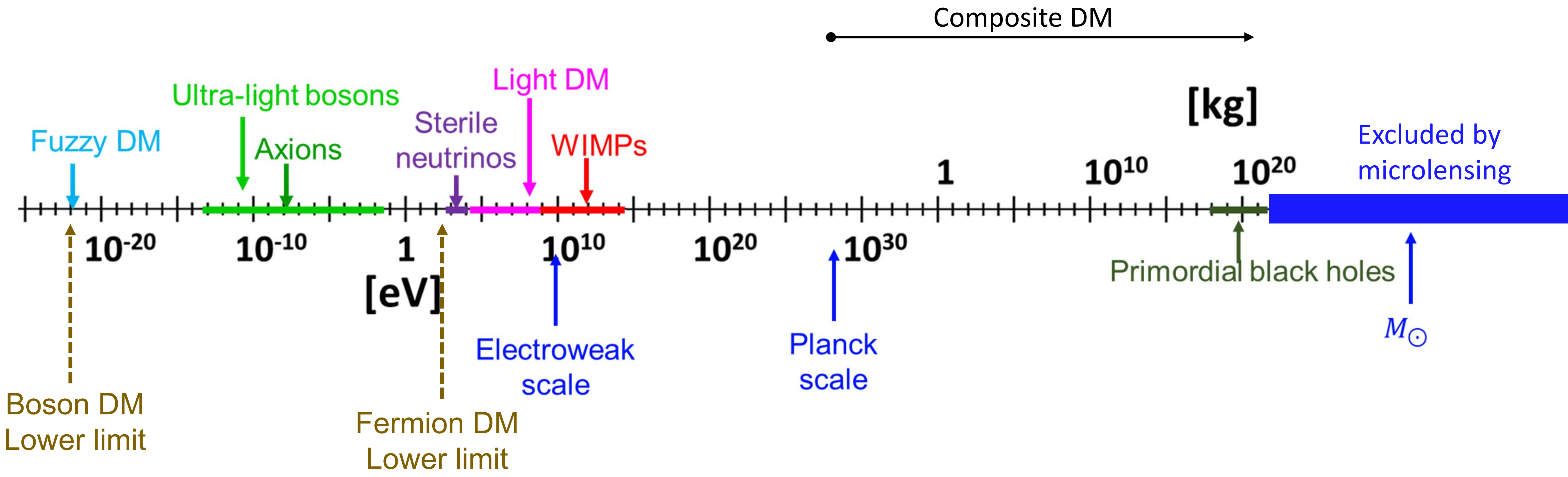
Centro de Astropartículas y
Física de Altas Energías
Universidad Zaragoza

Lecture III

Dark Matter (WIMPs & light DM) detection

How to detect DM?



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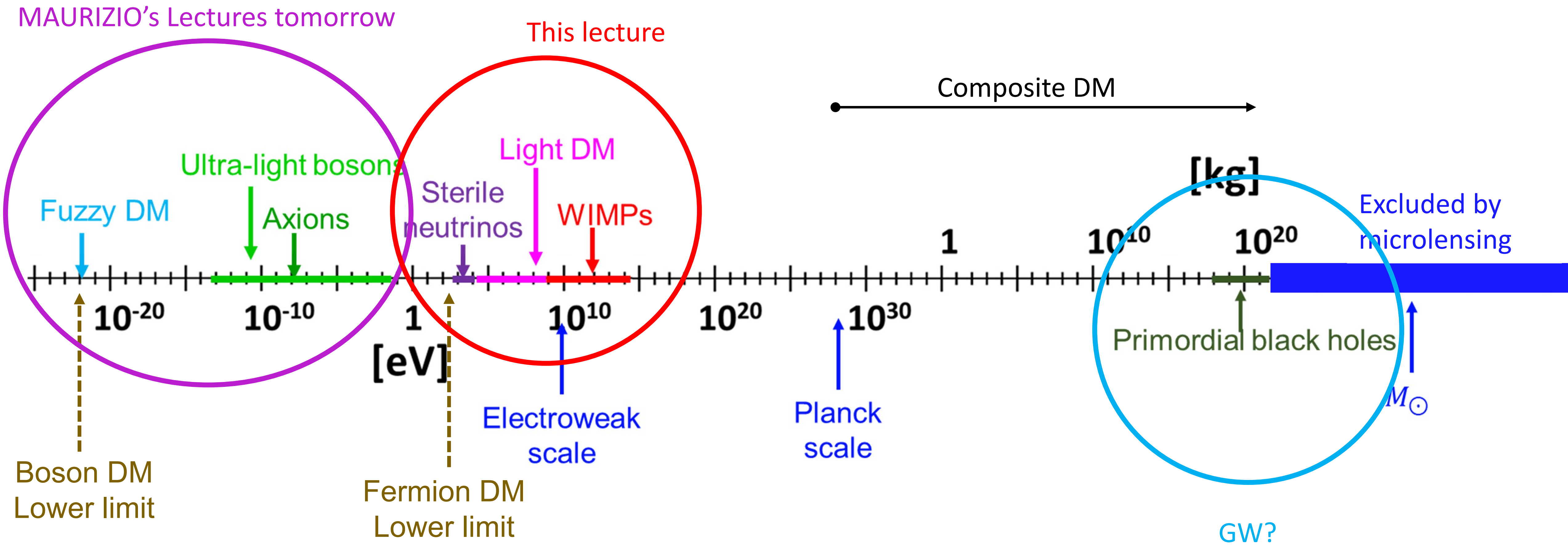

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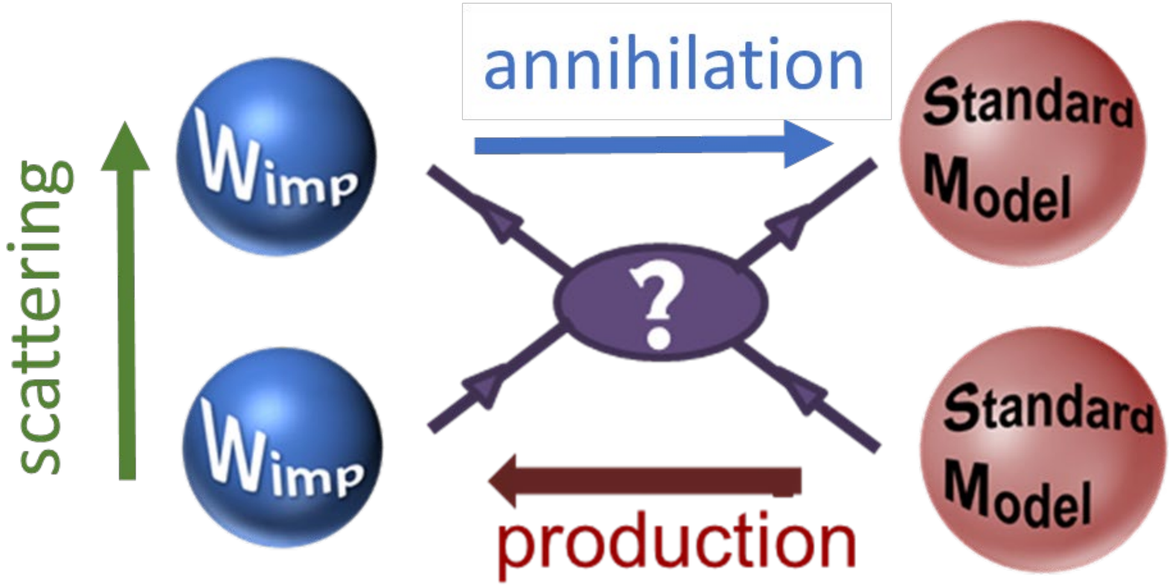

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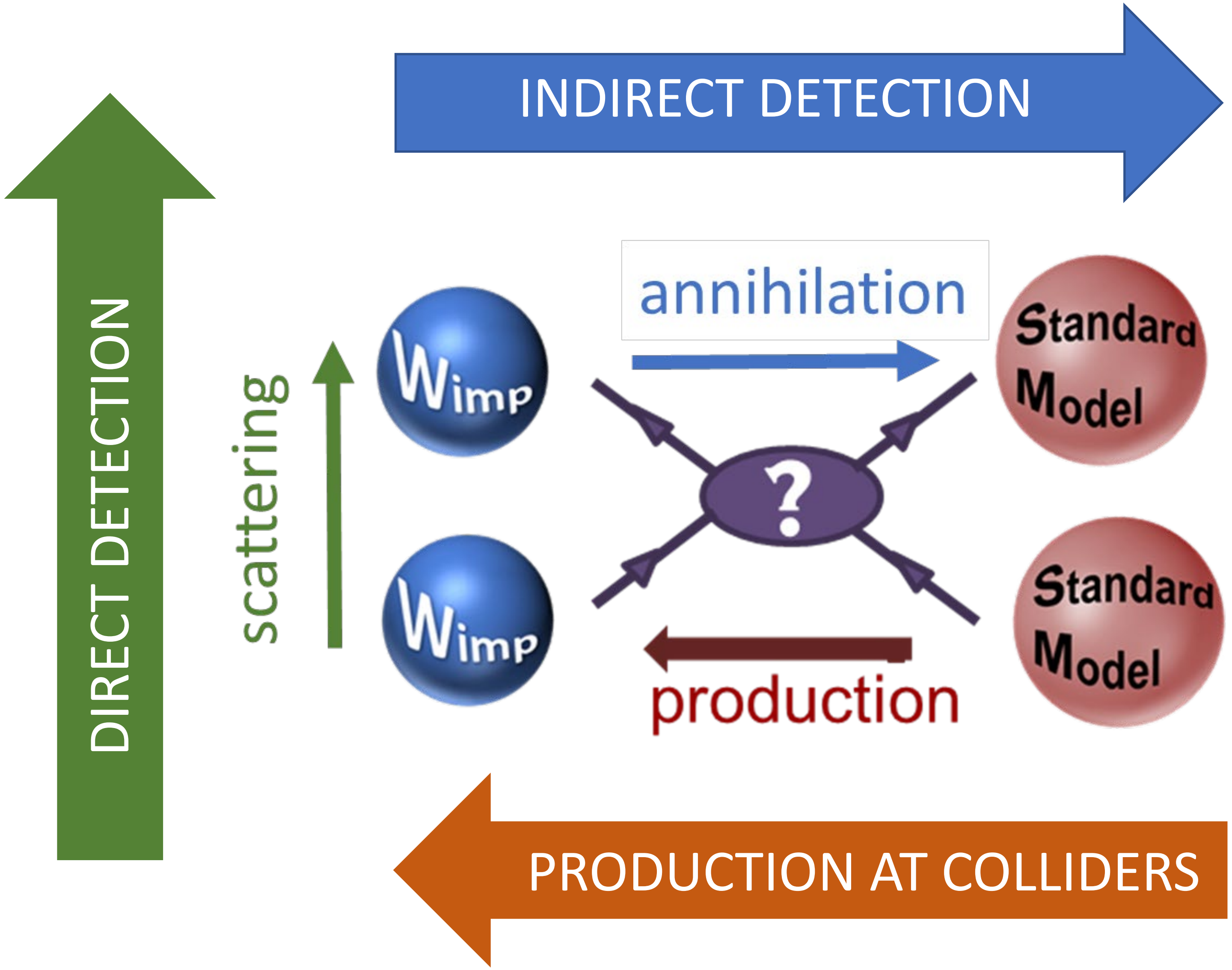

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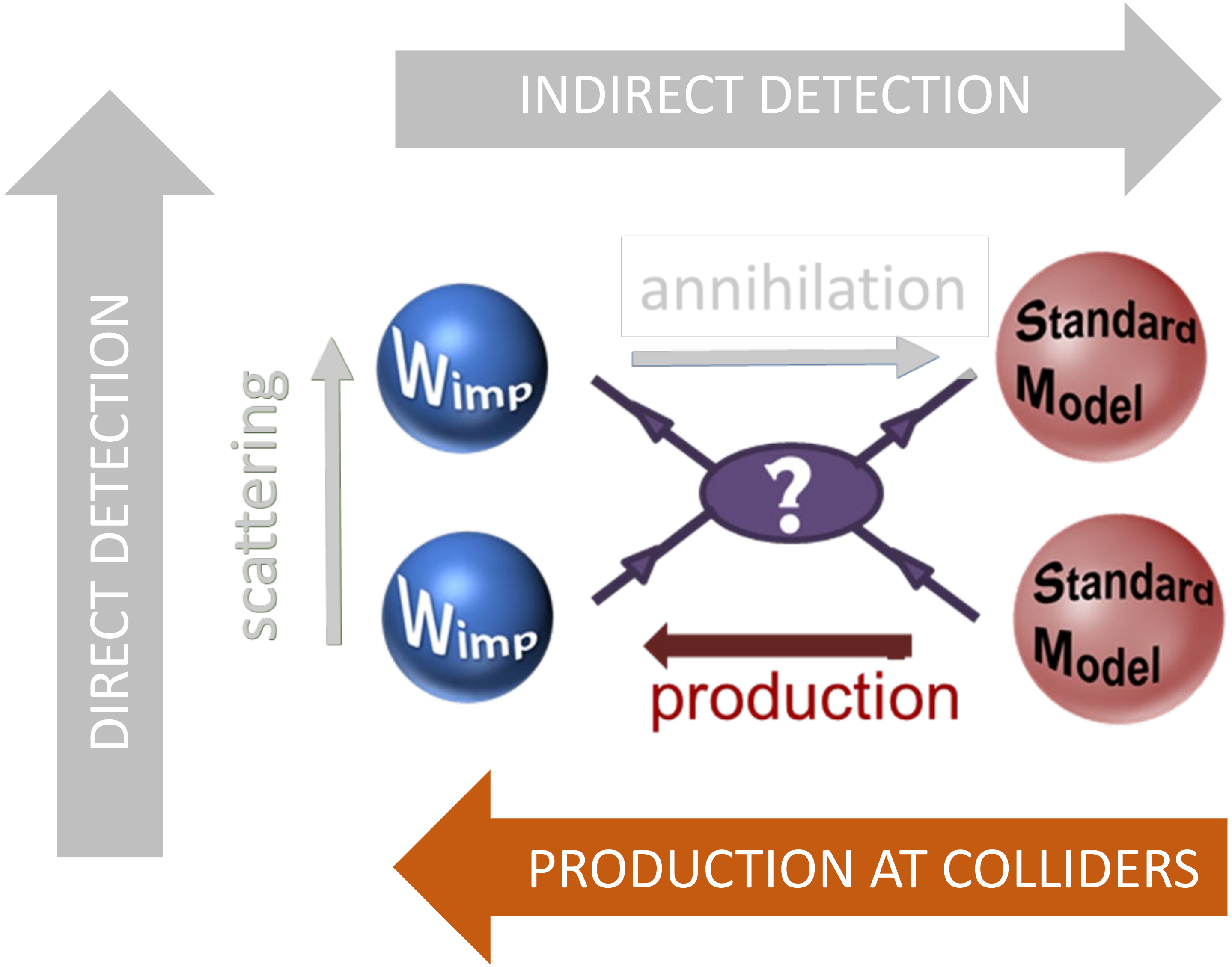


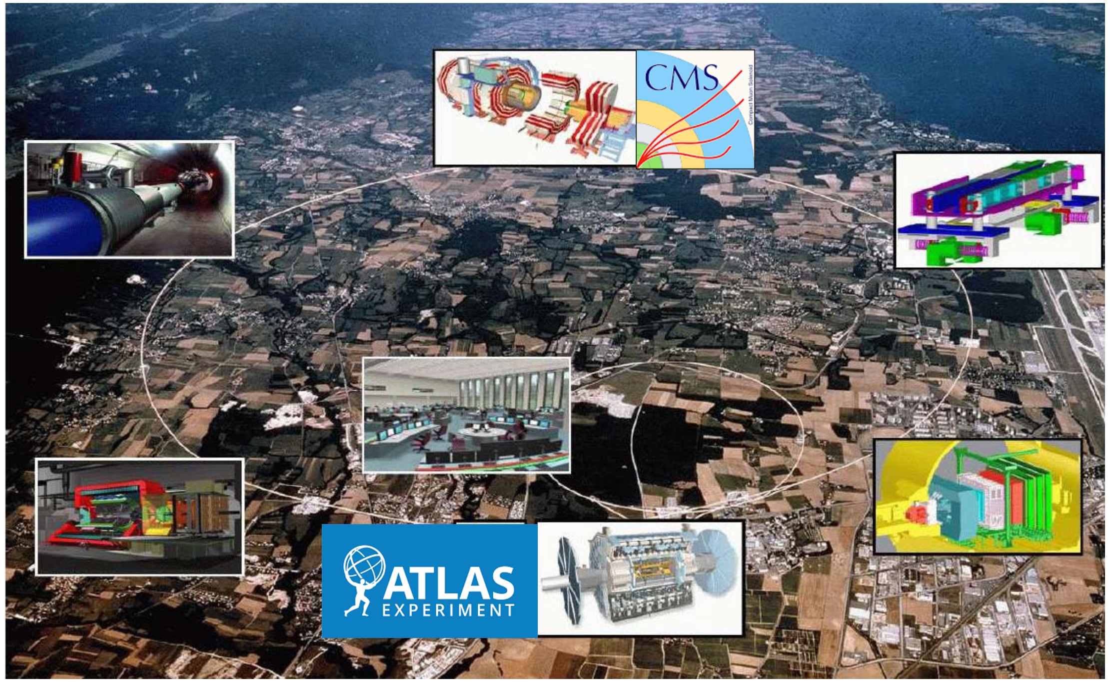
INDIRECT DETECTION

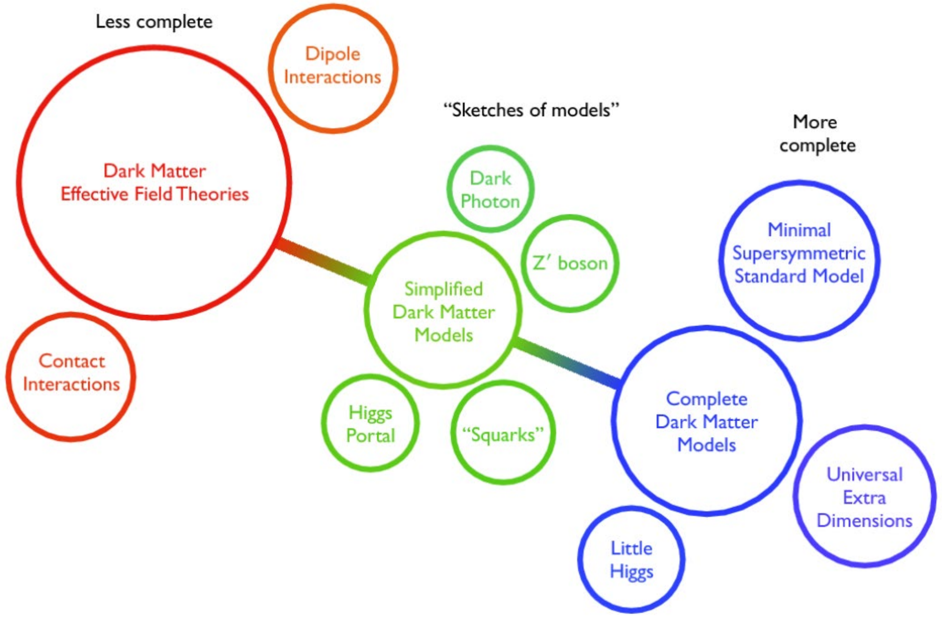
DIRECT DETECTION

PRODUCTION AT COLLIDERS

Production at colliders

- If we assume that DM couple sufficiently strongly to the SM (as freeze-out suggest) we can probe it at colliders
- DM searches at the LHC fully underway!
- How to predict the signals and interpret the results? Three approaches:
    1. EFT approach
    2. Dark Matter Simplified Models
    3. Complete models (e.g. SUSY)





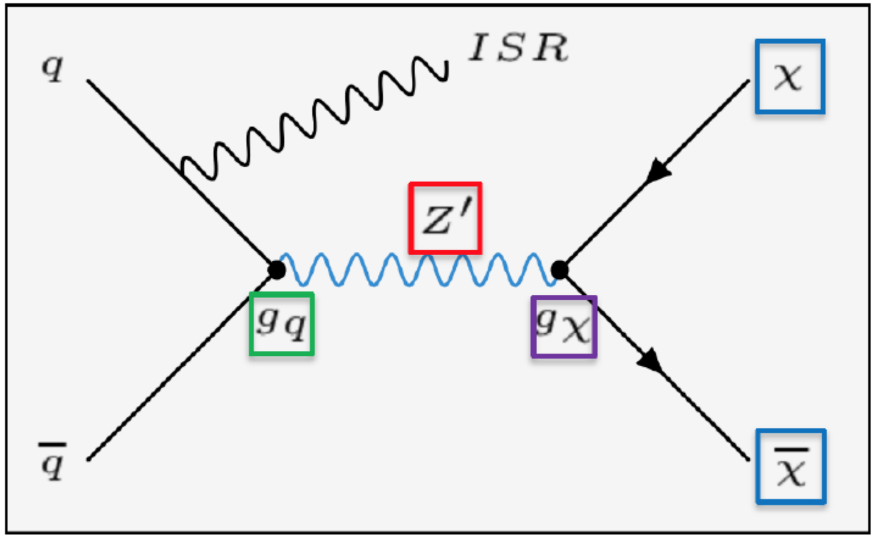
DM simplified models

Simple picture introducing a new mediator

4 tunable parameters

1.	M_{med}	Mediator mass
2.	M_χ	Dark matter mass
3.	g_q	Mediator's coupling to SM quarks
4.	g_χ	Mediator's coupling to dark matter

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}\mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu} - \overset{1.}{\boxed{\frac{1}{2}m_{\mathcal{A}}^2 \mathcal{A}_\mu \mathcal{A}^\mu}} + \overset{2.}{\boxed{\bar\chi(i\gamma^\mu\partial_\mu - m_\chi)\chi}} - \sum_q \overset{3.}{\boxed{g_q \mathcal{A}_\mu \bar q\gamma^\mu(\gamma^5)q}} - \overset{4.}{\boxed{g_\chi \mathcal{A}_\mu\bar\chi\gamma^\mu(\gamma^5)\chi}}$$



4 model flavors
- vector
- axil vector
- scalar
- pseudoscalar

[taken from C. Freer '22]

Phys. Dark Univ. 26 (2019) 100371

DM simplified models

Caveat: DM is non-interacting with our detector!!: We need some object to trigger or otherwise we will lose these events

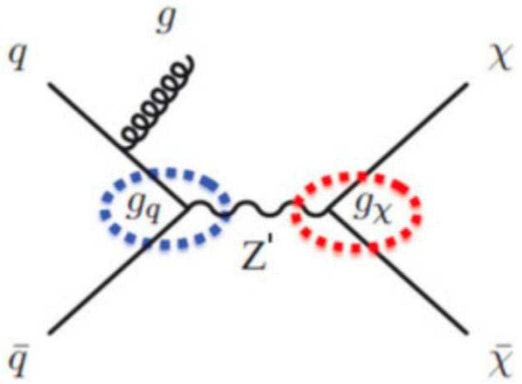
Option (a) (Mono-X)

include ISR particle which we can trigger on

Missing transverse momentum from DM

Searches:

- MonoZ
- MonoPhoton
- MonoJet/MonoV(hadronic)
- Monotop
- MonoHiggs
- tt+DM/
- bb+DM
- …



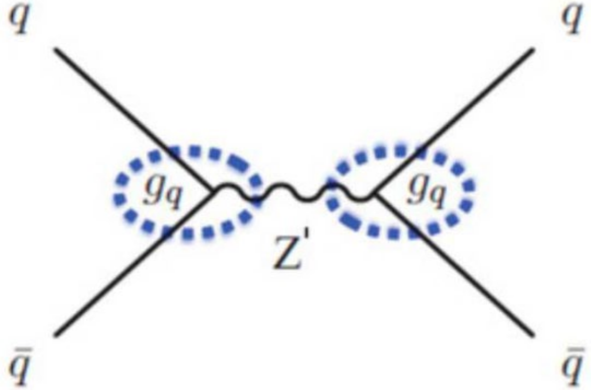
Option (b) (Mediator)

if the mediator can couple with SM then it can decay into SM

Can trigger on Z’ decay products (fully SM)

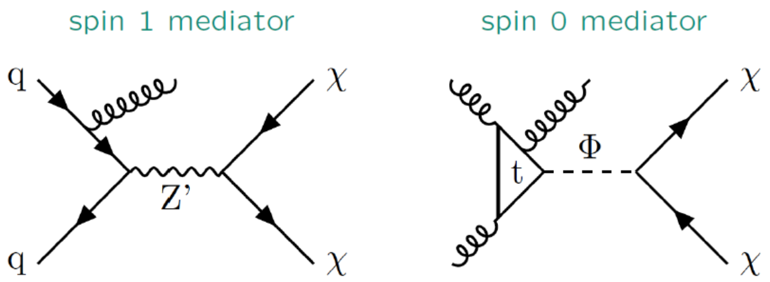
Searches:

- Dilepton resonance
- Boosted dijet
- Dijet w/ btag
- Dijet w/ ISR
- Dijet
- tt/bb resonance
- …



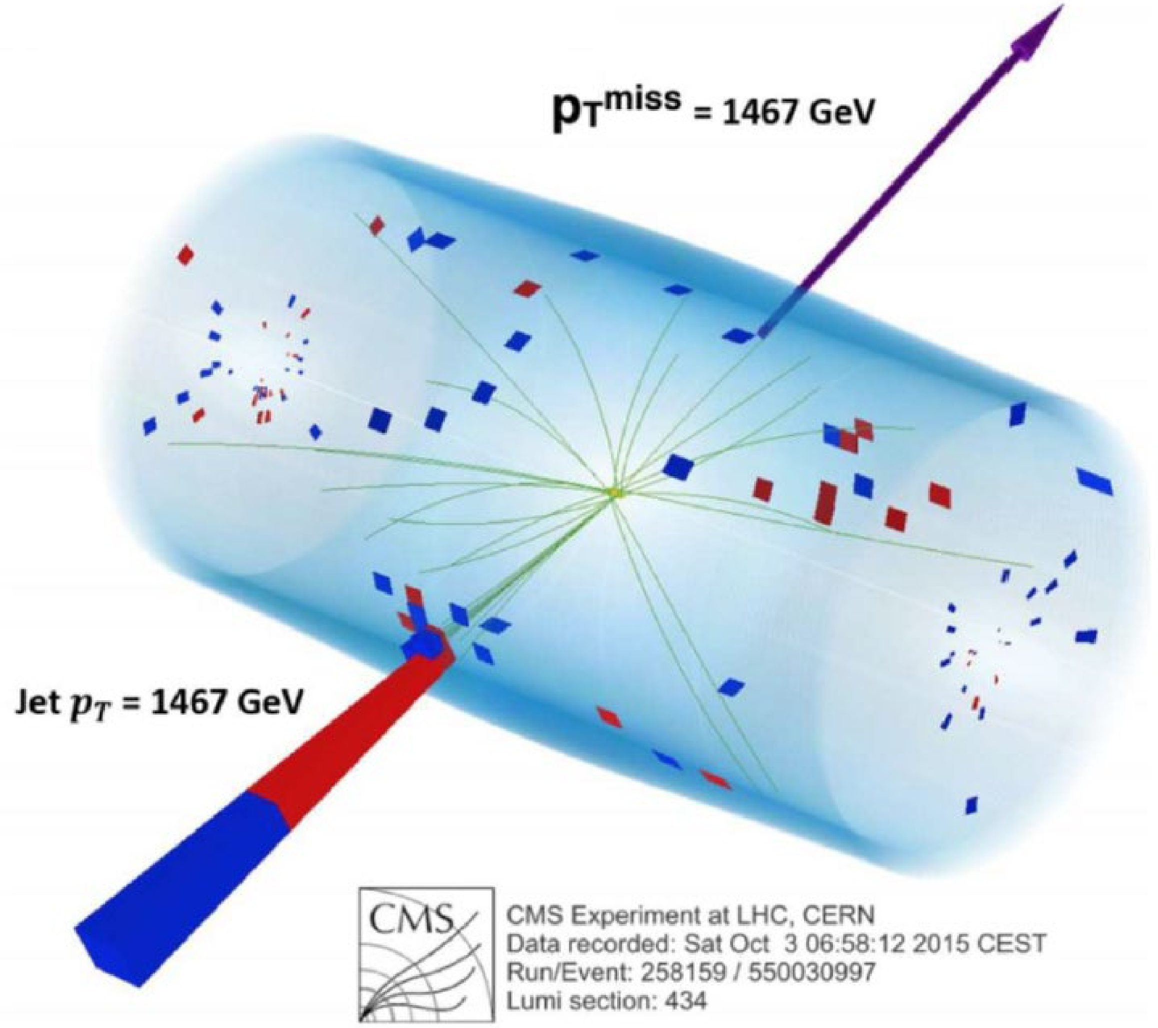
How does it look in the detector

Example:



Experimental signatures:

- Energetic jet
- Large missing transverse momentum

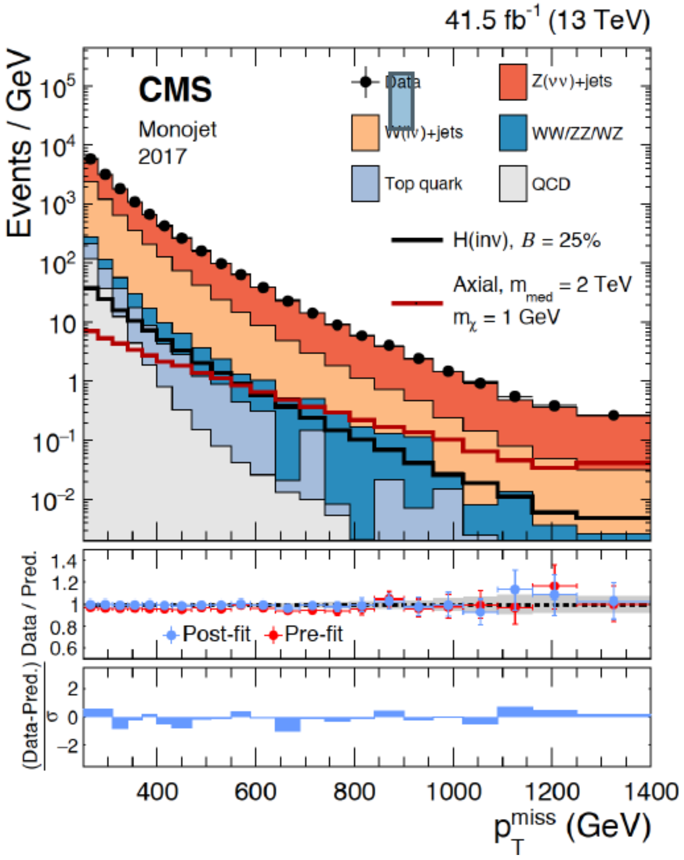


Example: experimental results

$g_q = 0.25,\ g_{\mathrm{DM}} = 1$

CMS collaboration, “Search for new particles in events with energetic jets and large missing transverse momentum in proton-proton collisions at $\sqrt{s}$ = 13 TeV” , JHEP 11 (2021) 153 [2107.13021]

Number of events with p_T^{miss}



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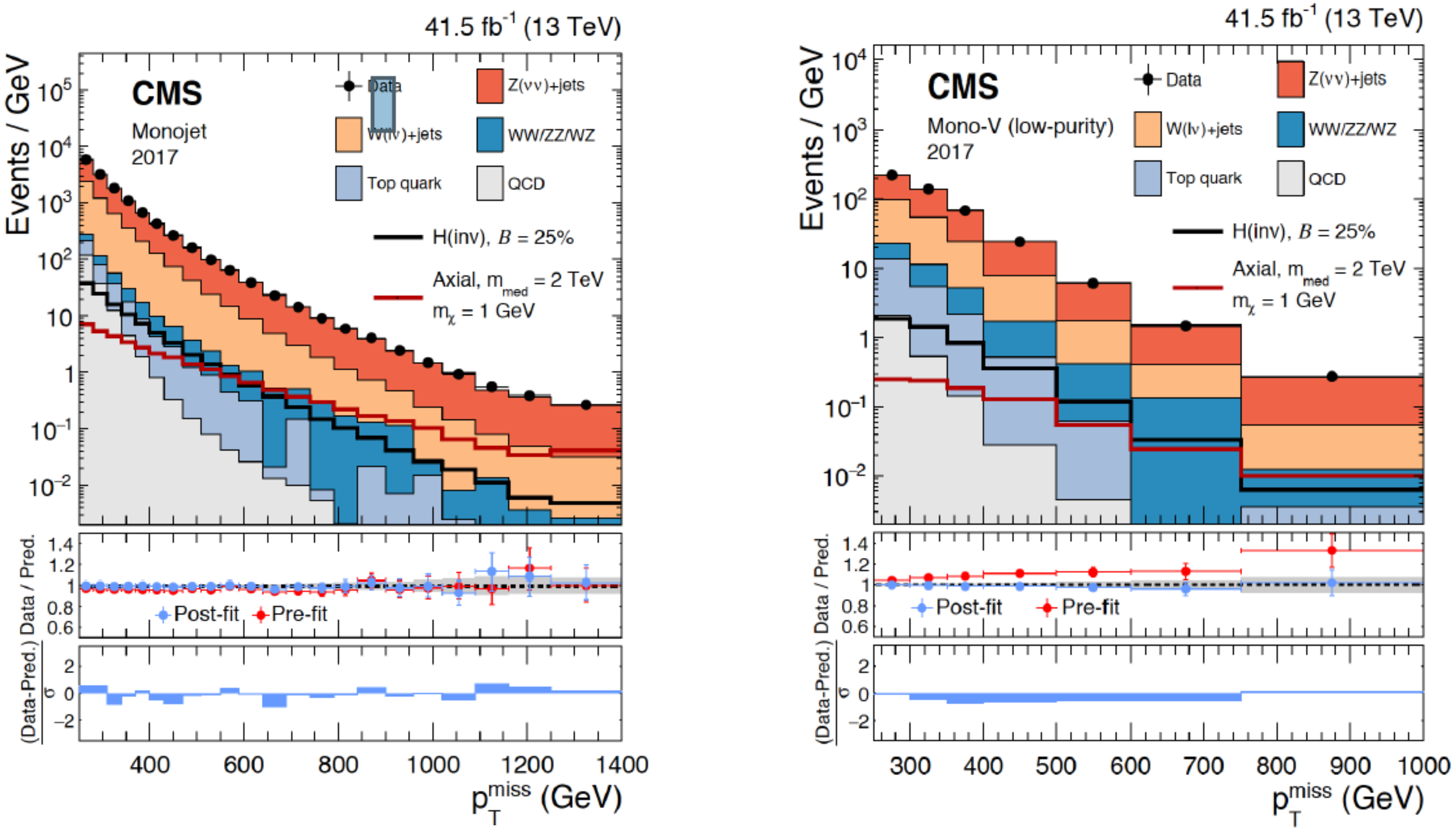
Number of events with p_T^{miss}

+ stronger requirements on the jets



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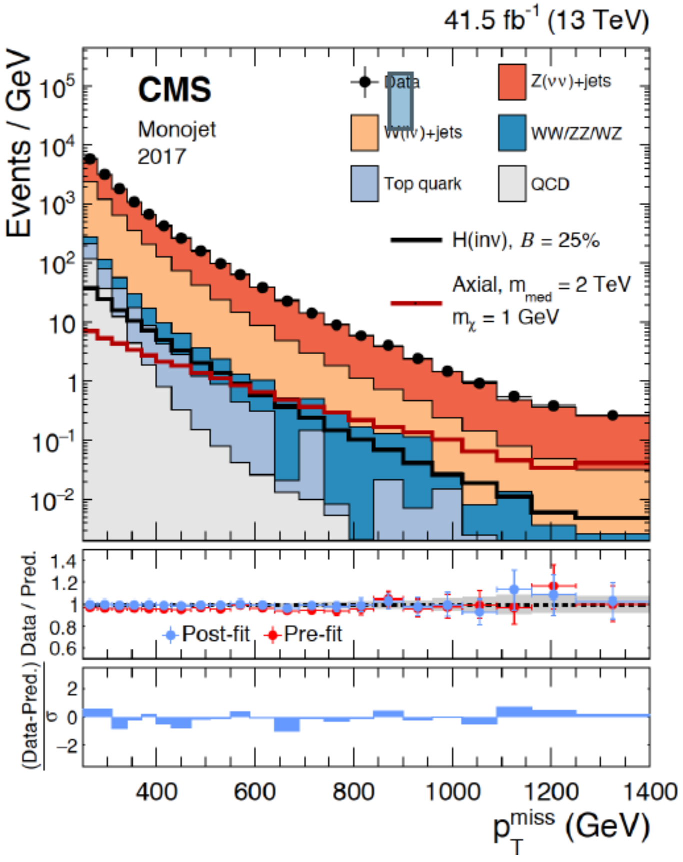
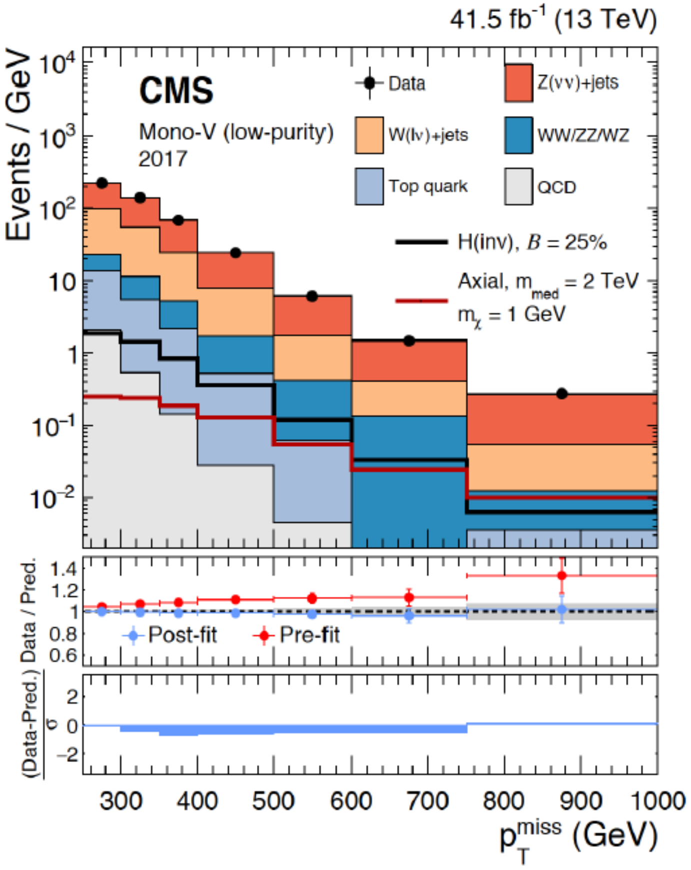
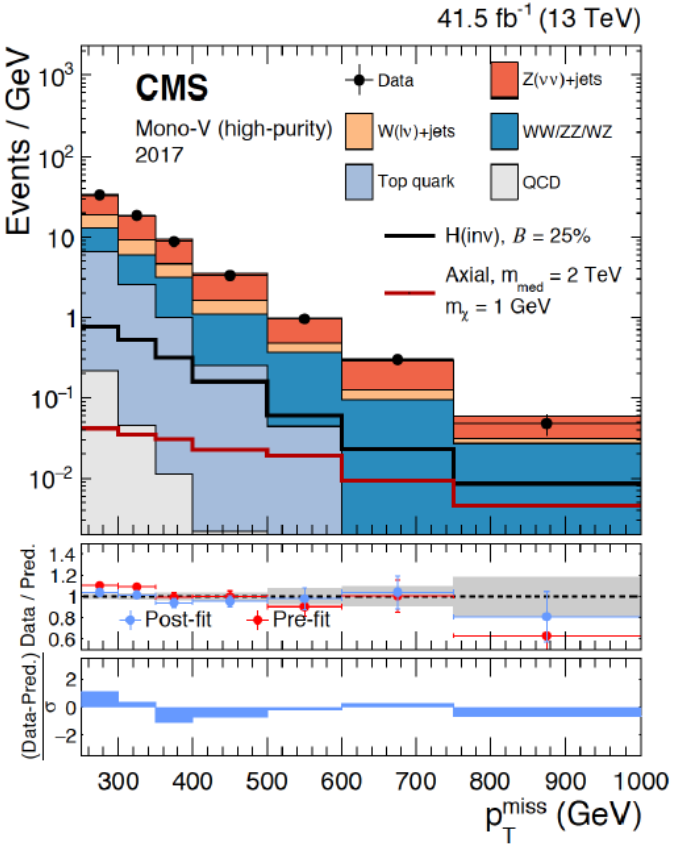


+ stronger requirements on the jets



+ even stronger requirements on the jets



Example: experimental results

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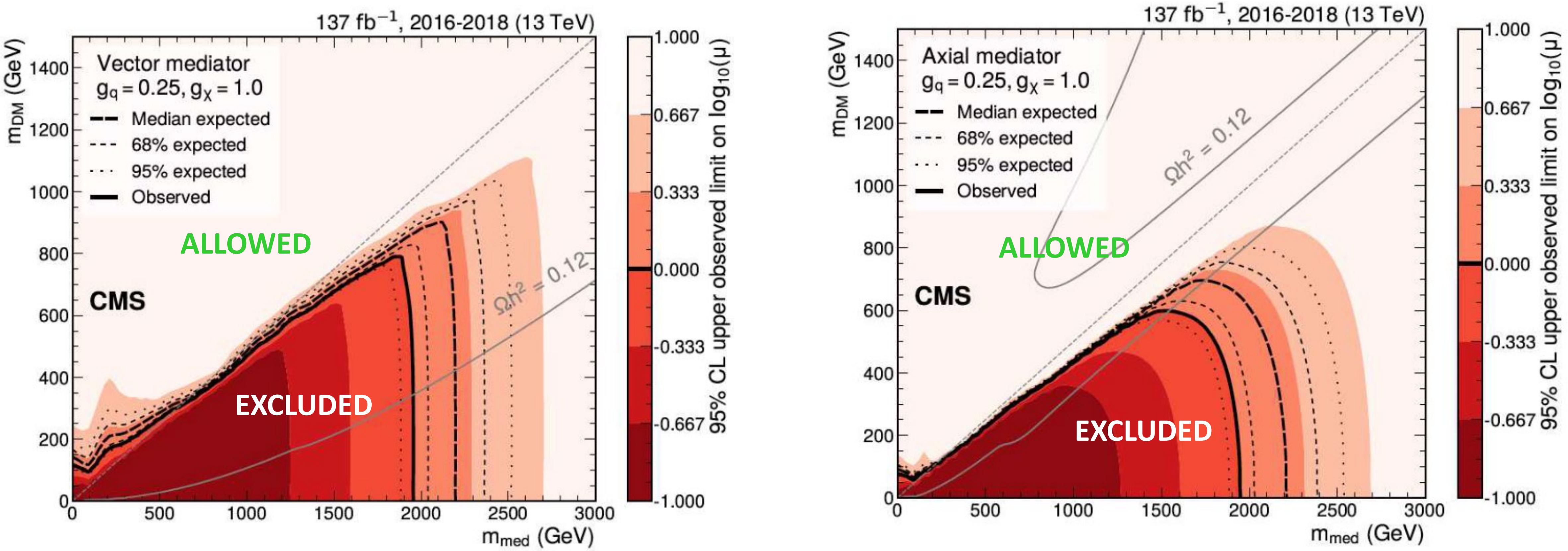
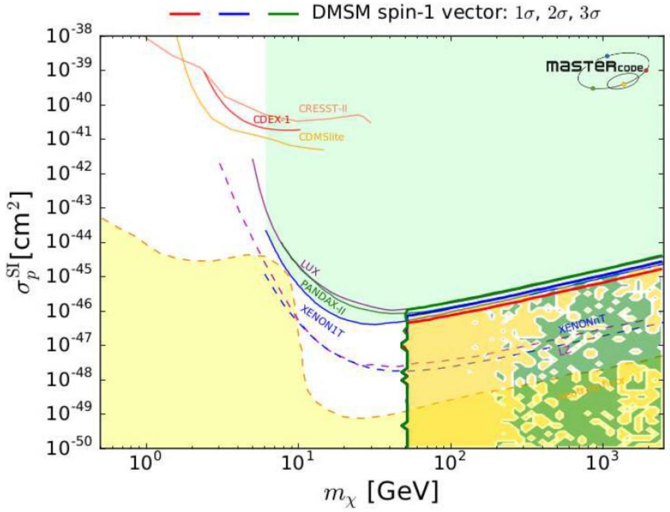


Up to now, no excess found → exclusion limits for models / parameters combinations (but theory space is enormous)

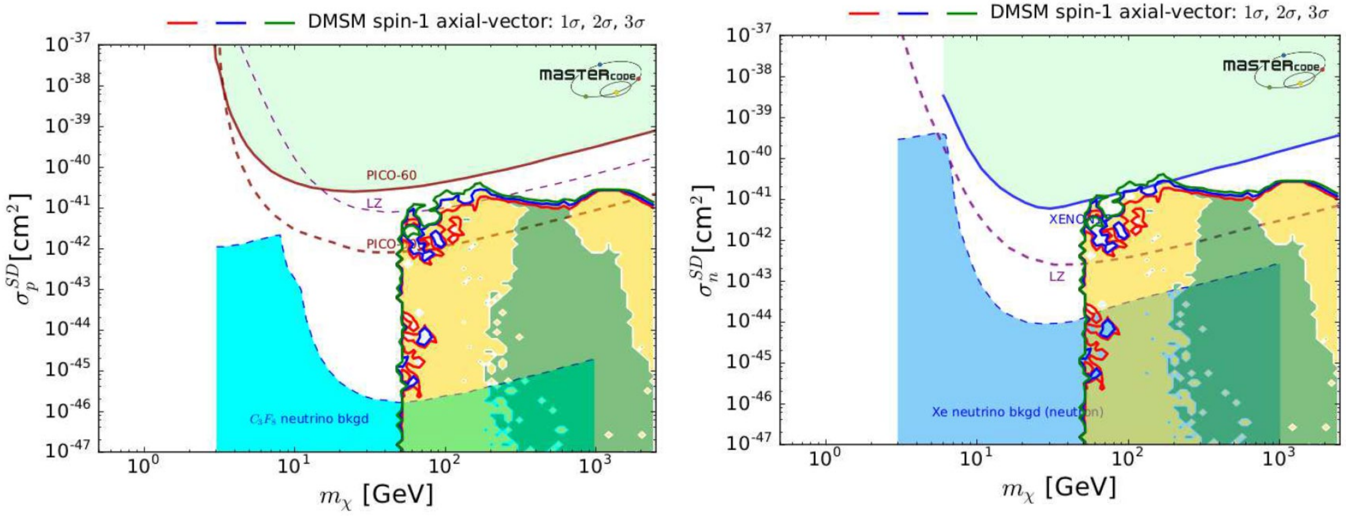
Production at colliders

With a more global analysis, one can determine an overall preferred DM parameter space (also for complete models)

vector mediator



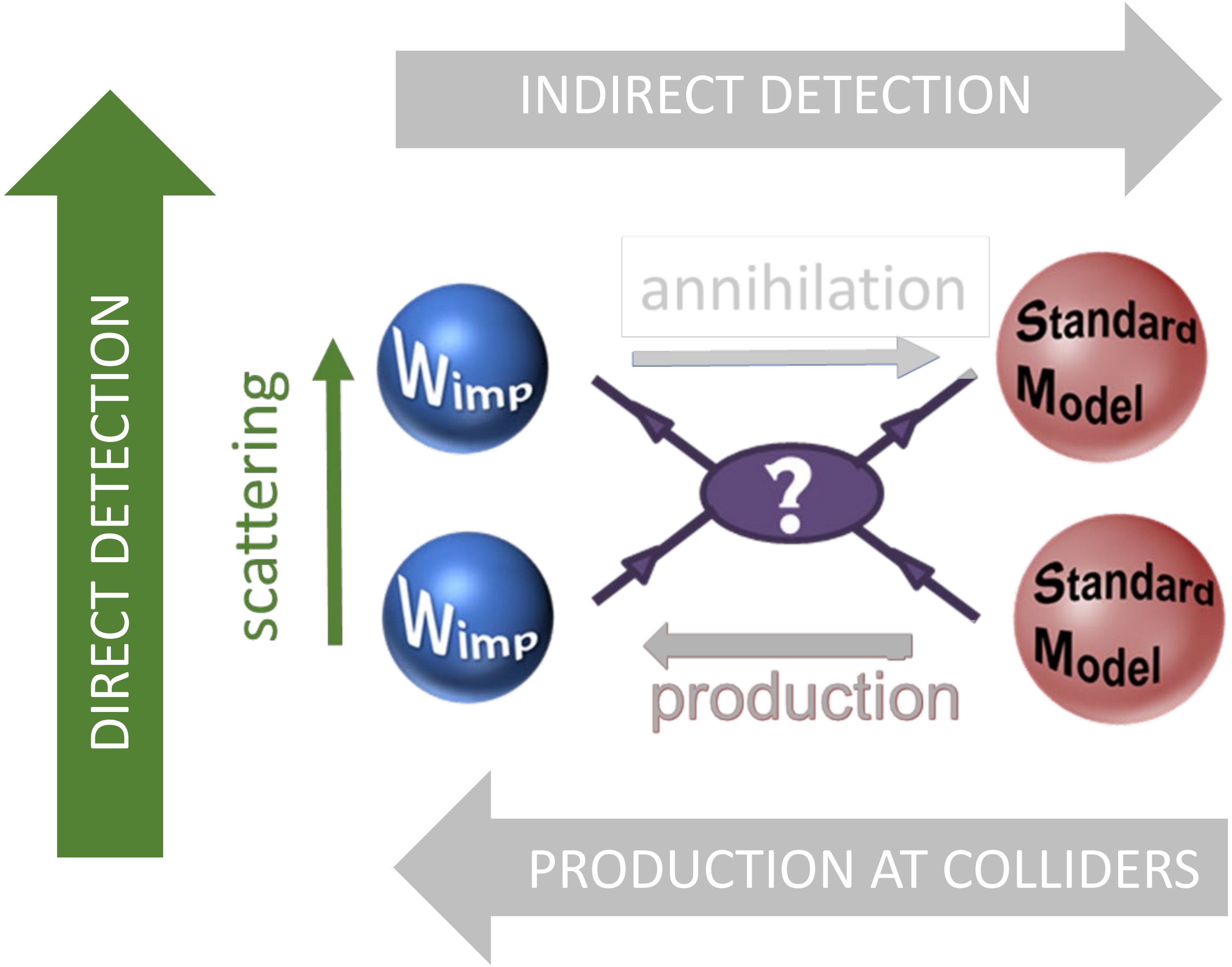
Axial-vector mediator



Some take-home messages:

- LHC has complementary sensitivity to other searches (DD and ID)
- DM searches at the LHC fully underway
- No hints of DM so far showing up but still < 10% of total expected LHC data analysed

How to detect DM?



INDIRECT DETECTION

DIRECT DETECTION

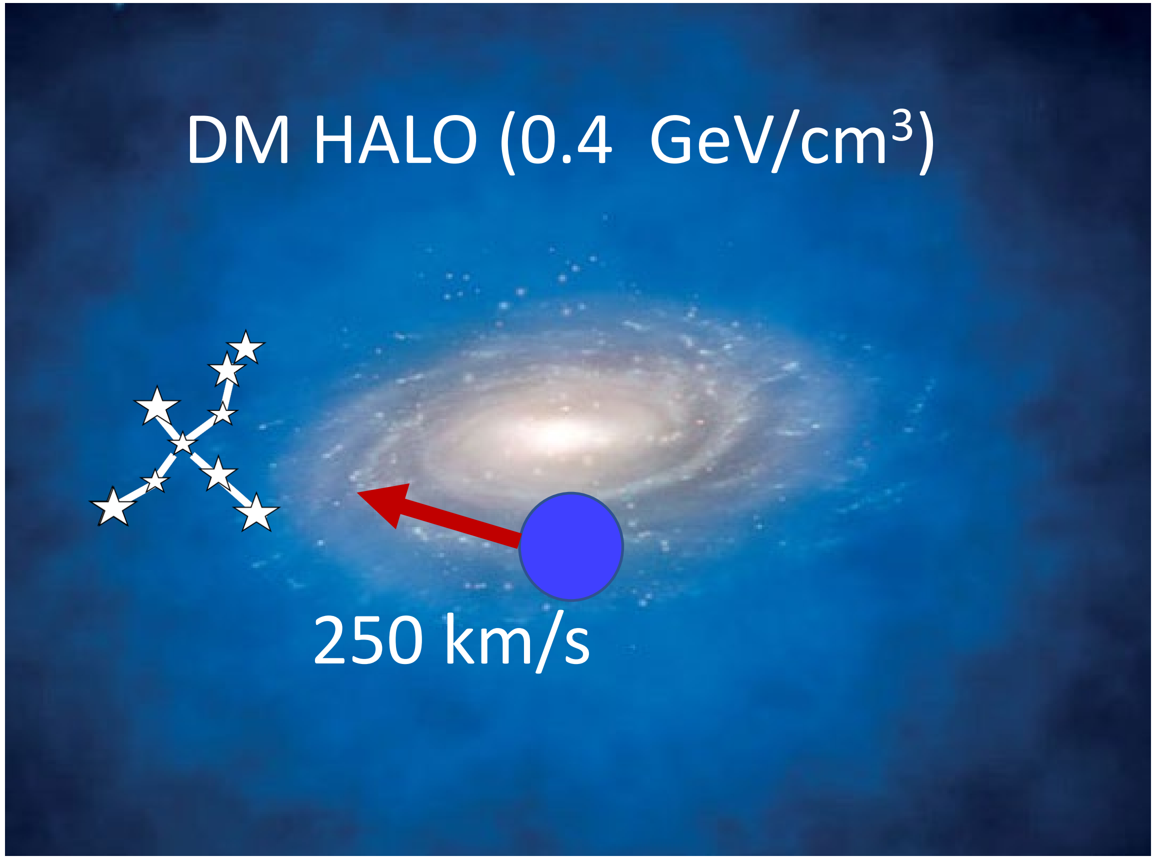
scattering

annihilation

production

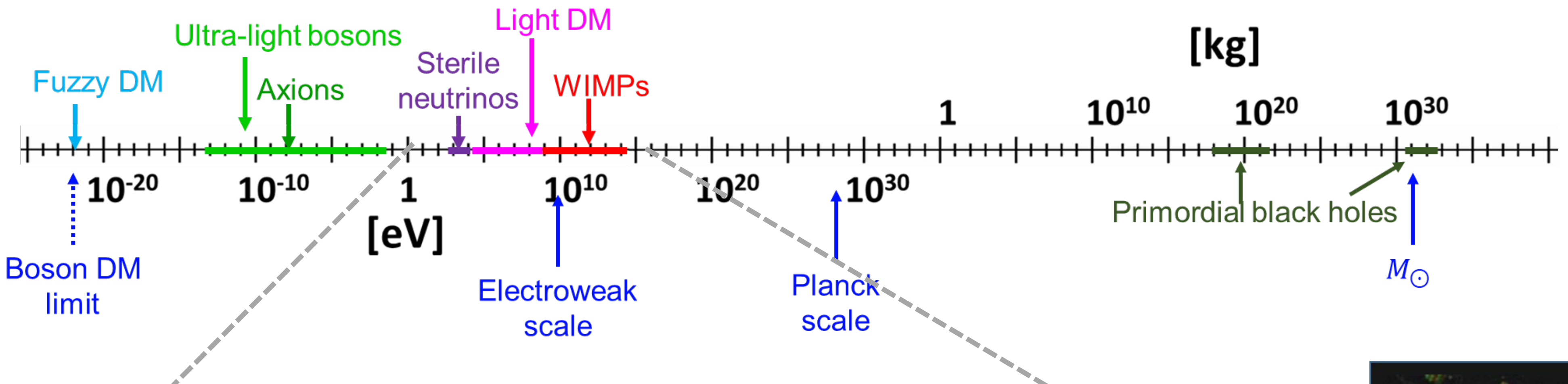
PRODUCTION AT COLLIDERS

Dark Matter direct detection



$$\phi = \frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}\langle v\rangle = 10^5\,\frac{\mathrm{part}}{\mathrm{cm}^2\times s}\left(\frac{100\ \mathrm{GeV}}{m_\chi}\right)\left(\frac{\rho}{0.4\ \mathrm{GeV/cm}^3}\right)\left(\frac{v}{250\ \mathrm{km/s}}\right)$$

Direct detection: mass ranges & interactions



Fuzzy DM

Ultra-light bosons

Axions

Sterile neutrinos

Light DM

WIMPs

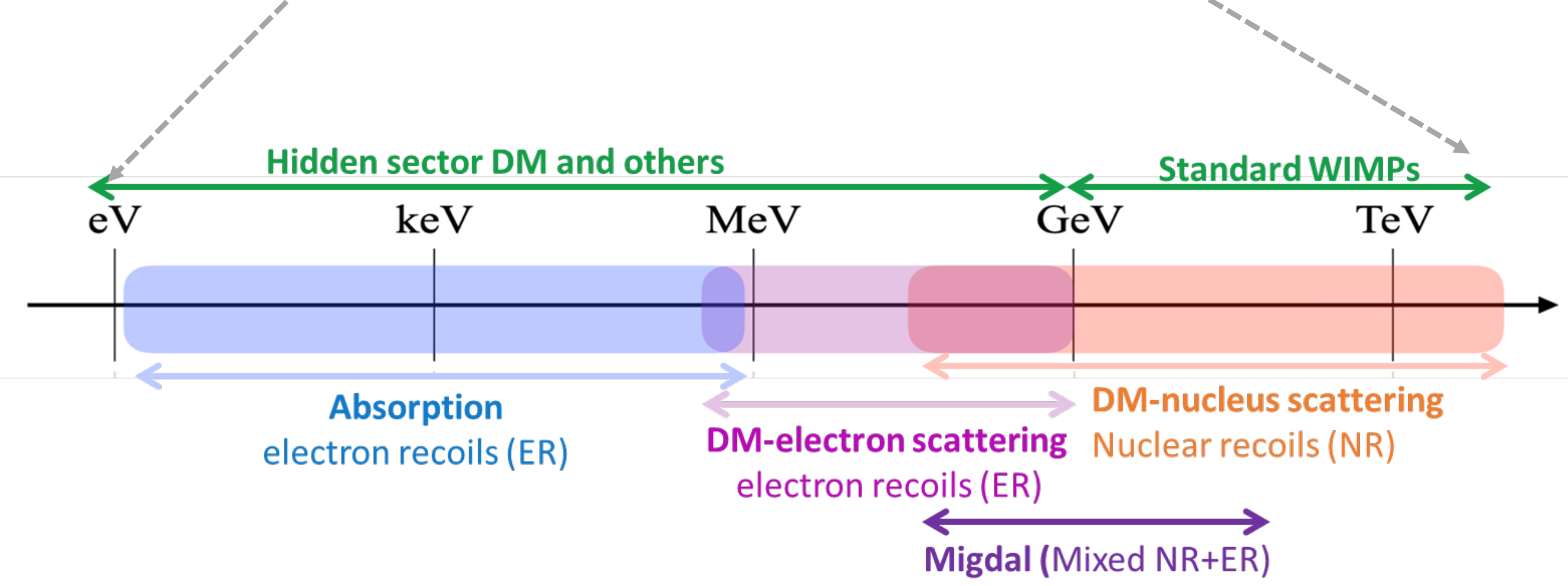
Boson DM limit

Electroweak scale

Planck scale

Primordial black holes

$M_\odot$



Hidden sector DM and others

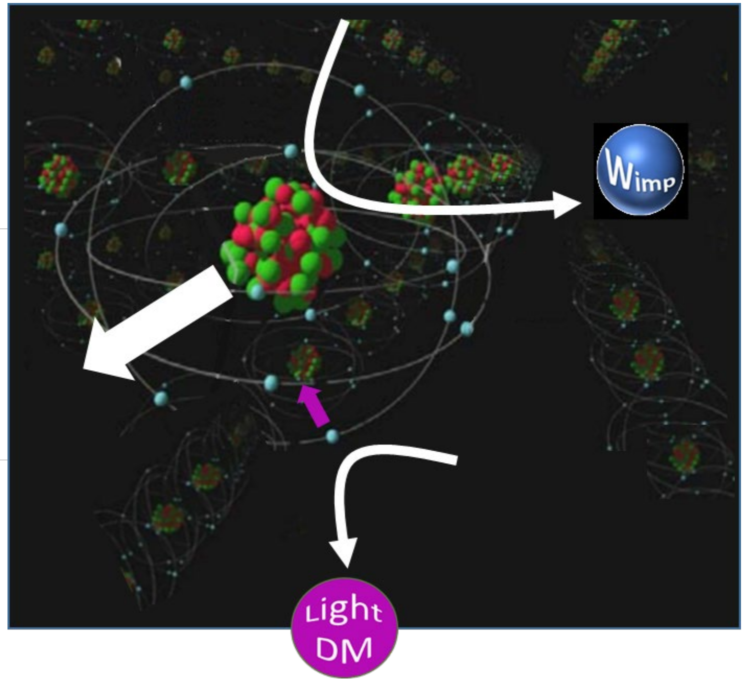
Standard WIMPs

Absorption
electron recoils (ER)

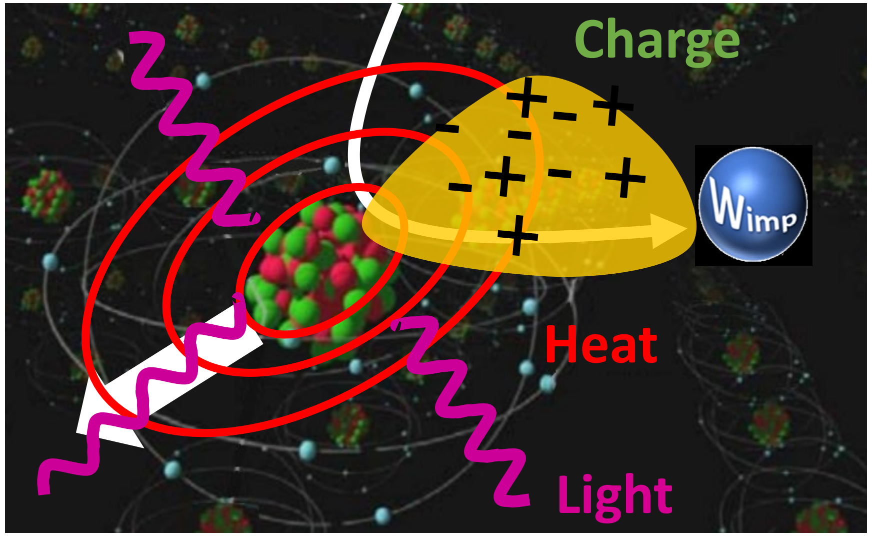
DM-electron scattering
electron recoils (ER)

DM-nucleus scattering
Nuclear recoils (NR)

Migdal (Mixed NR+ER)



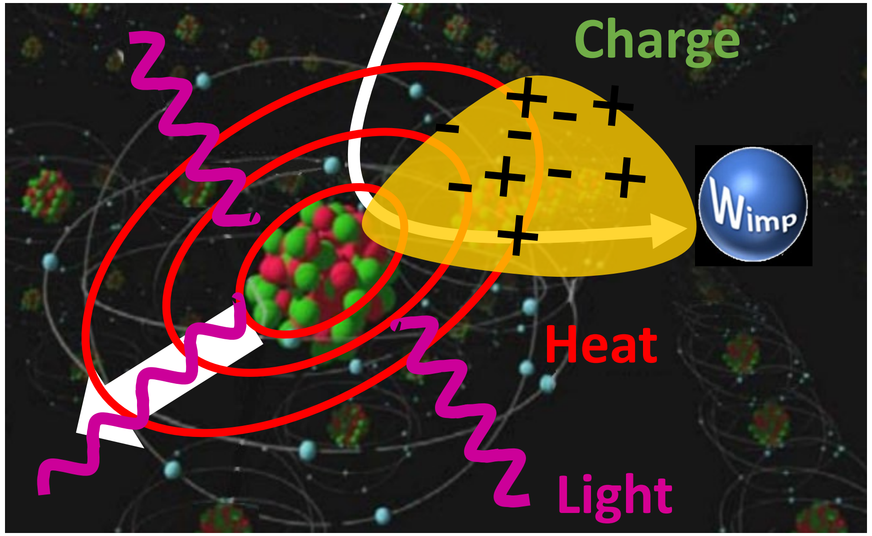
DM direct detection



$$\boxed{R \approx N_T \times \phi_{DM} \times \sigma}$$

$$\left.\begin{aligned}
&\phi_{DM} \sim 10^4 - 10^6\ \mathrm{s^{-1}\ cm^{-2}}\\
&N_T \sim \frac{10^3 \times \mathrm{N_A}}{\mathrm{A}}\ \text{nuclei/kg}\\
&\sigma \sim \sigma_{weak} \sim 10^{-40}\ \mathrm{cm^2}
\end{aligned}\right\} \quad \text{1 c/kg/y} - \text{1 c/ton/y}$$

DM direct detection



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DM local density

DM velocity distribution in detector's frame

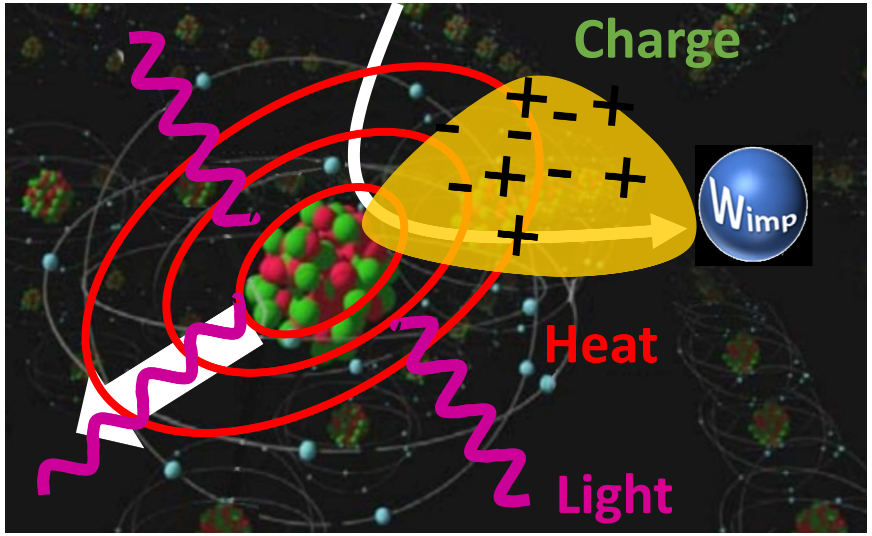
$$\boxed{\frac{dR}{dE_R} = \frac{M_{det}\rho_\chi}{2 m_\chi \mu_{\chi N}^2} \sigma^0 F^2(q) \int_{v_{min}}^{v_{esc}} \frac{f(v,t)}{v} d^3\boldsymbol{v}}$$

DM mass

scattering cross section

where $v_{min} = \sqrt{\frac{E_R m_N}{2\mu_{\chi N}^2}}$

DM direct detection



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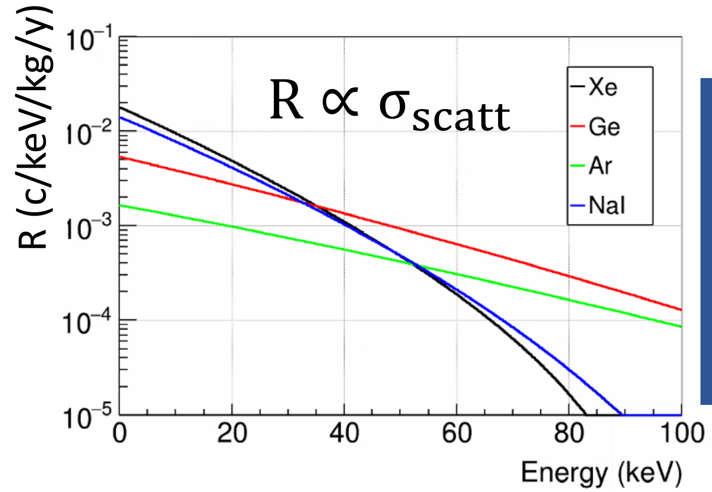


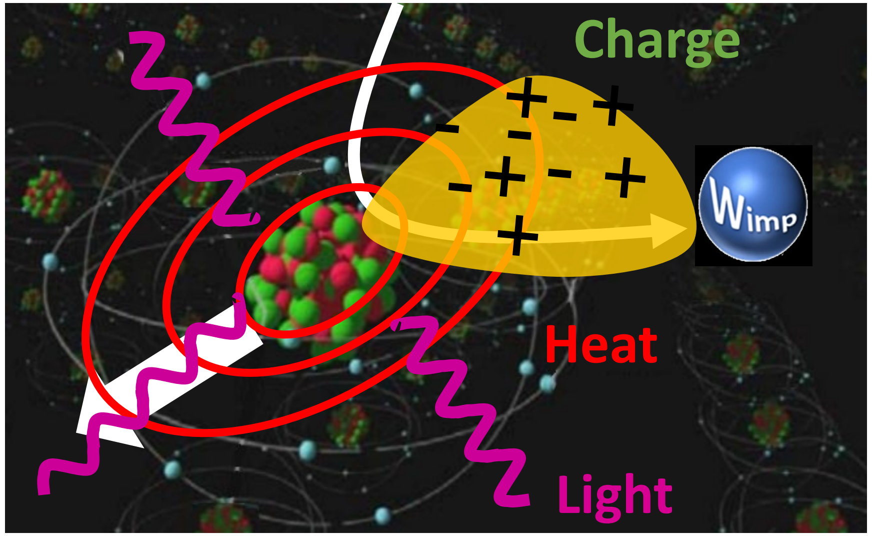
Few counts per kgxyear!

Energy O(10keV)

No distinctive signatures

Target dependent

DM direct detection



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DM local density

DM velocity distribution in detector's frame

$$\frac{dR}{dE_R} = \frac{M_{det}\rho_\chi}{2 m_\chi \mu_{\chi N}^2}\sigma^0 F^2(q)\int_{v_{min}}^{v_{esc}}\frac{f(v,t)}{v}d^3\boldsymbol{v}$$

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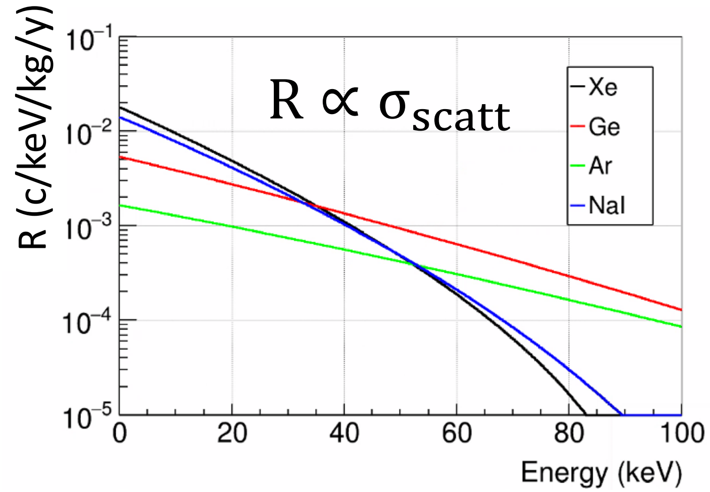


Experimental requirements

- **Ultra low background**
- **low energy threshold O(1-10 keV)**

Desiderata:

- Distinctive signatures: **annual modulation, directionality**

Spin independent / spin dependent couplings

As we have seen, there is a variety of well motivate DM candidates. **How they couple to the SM is model dependent**.

Hypothesis: very heavy mediator-particles (i.e., contact interaction):

$$(\bar{\chi}\Gamma\chi)(\bar{\psi}\Gamma'\psi)$$

In general, scalar, vector and axial-vector lead to the highest event rates. The **axial-vector current becomes an interaction between the quark spin and the WIMP spin**, while the vector and tensor currents assume the same form as the scalar interaction. So generically**, only two cases need to be considered**:

1. the scalar (**spin independent**) interaction. Signal adds coherently ∝ A^2 (additional assumption: same coupling for p & n) (**typically dominates).**
2. the **spin-spin interaction** (the WIMP couples to the spin of the nucleus) (**depend only on the unpaired nucleons)**

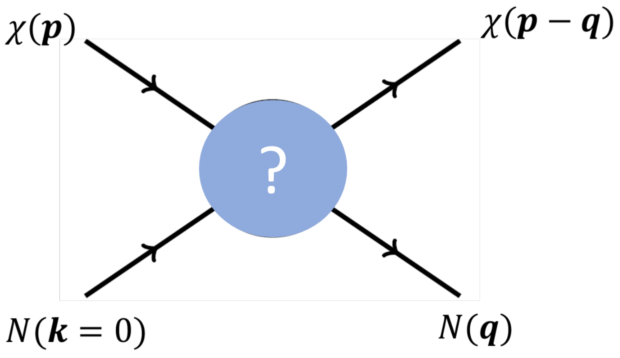
$$\sigma^0 F^2(q) = \sigma^0_{SI} F^2_{SI}(q) + \sigma^0_{SD} F^2_{SD}(q)$$

$$\sigma^0_{\mathrm{SI}} = \frac{A^2 \mu^2_{\chi N}}{\mu^2_{\chi n}} \sigma_{\mathrm{SI}} \qquad \sigma^0_{\mathrm{SD}} = \frac{\mu^2_{\chi N}}{\mu^2_{\chi n}} \sigma_{\mathrm{SD}} \frac{4}{3} \frac{J+1}{J} \frac{1}{\bar{a}^2} \left[\langle S_p \rangle a_p + \langle S_n \rangle a_n\right]^2 \qquad \sigma^p_{\mathrm{SD}} = \sigma_{\mathrm{SD}} \frac{a_p^2}{\bar{a}^2} \qquad \sigma^n_{\mathrm{SD}} = \sigma_{\mathrm{SD}} \frac{a_n^2}{\bar{a}^2}$$

WIMP parameter space: $(m_\chi, \sigma_{SI}, \sigma^p_{SD}, \sigma^n_{SD})$

A more general approach: EFT

Following an effective filed theory analysis (EFT) the various possible 4-point interactions can be described by a number of operators, assuming a heavy mediator (contact interaction) and nonrelativistic, **independent of underlying high-energy models**.



$$\mathcal{L}_{\text{int}}(\vec{x}) = c\Psi^*_\chi(\vec{x})\mathcal{O}_\chi\Psi_\chi(\vec{x})\Psi^*_N(\vec{x})\mathcal{O}_N\Psi_N(\vec{x}),$$

$$\mathcal{O}_1 = 1_\chi 1_N$$

SI

$$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$

SD

$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$

$$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right] \cdot \left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$

$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$

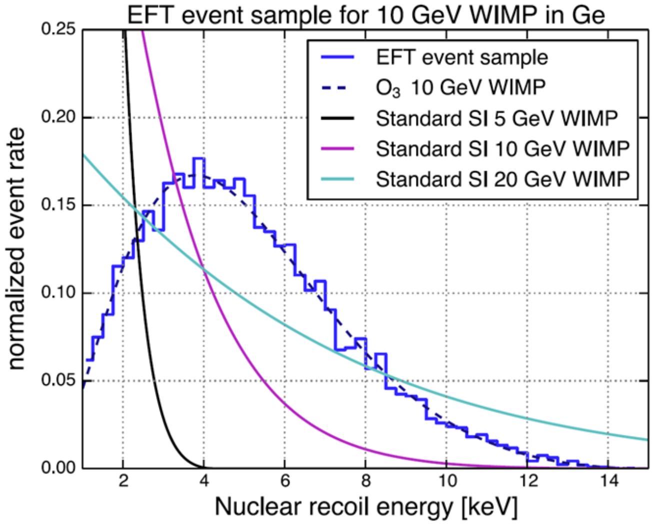
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp\right]$$

$$\mathcal{O}_{13} = i\left[\vec{S}_\chi \cdot \vec{v}^\perp\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \vec{v}^\perp\right]$$

$$\mathcal{O}_{15} = -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$$



$$\mathbf{v}_\perp = \mathbf{v} + \frac{\mathbf{q}}{2\mu_n}$$: Hermitian "transverse" velocity operator

Design of a DM DD experiment

$$\frac{dR}{dE_R} = \frac{M_{det}\rho_\chi}{2m_\chi\mu_{\chi N}^2}\sigma^0 F^2(q)\int_{v_{min}}^{\infty}\frac{f(v,t)}{v}d^3\boldsymbol{v}$$

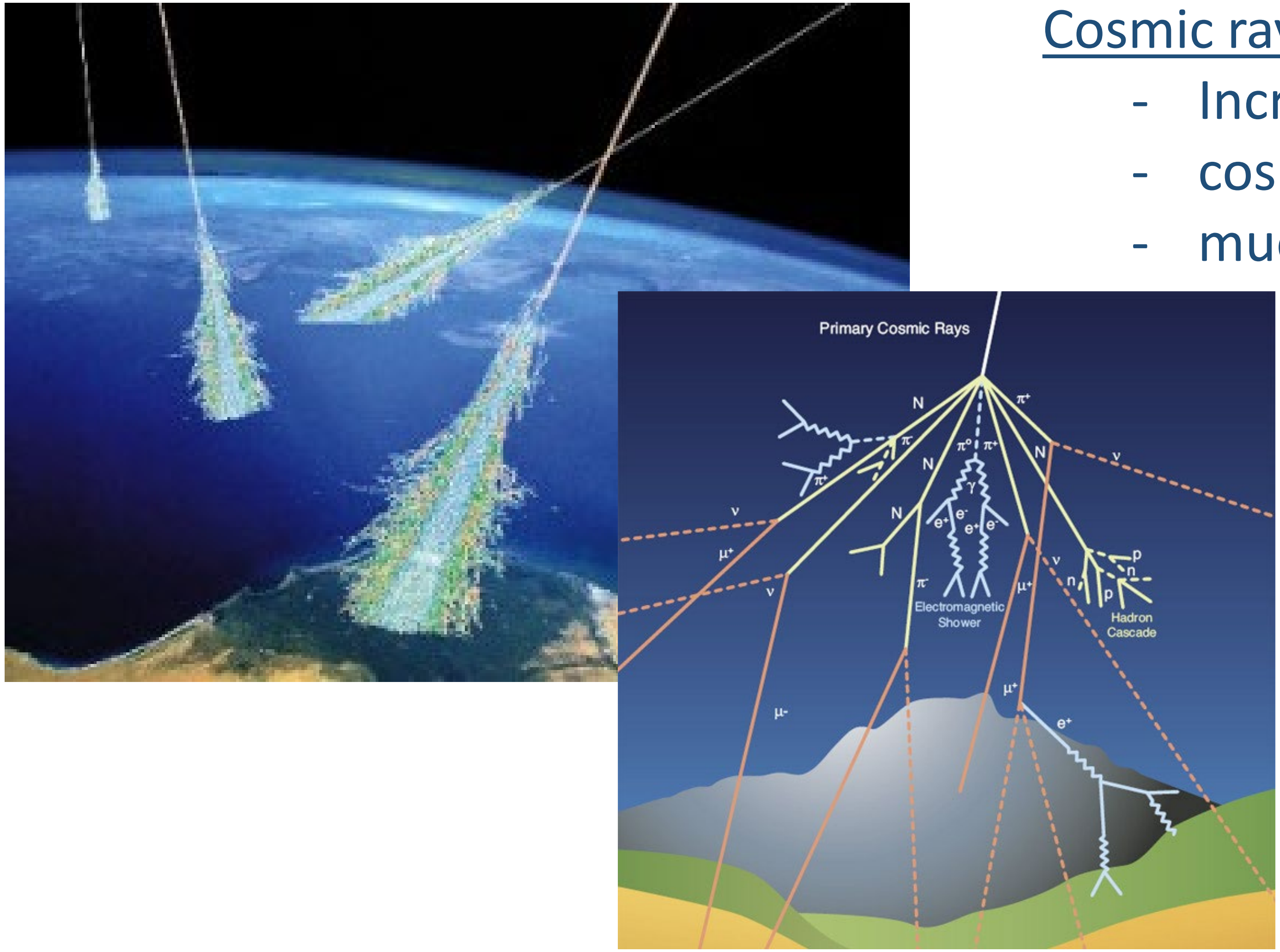
$$v_{min} = \sqrt{\frac{E_R m_N}{2\mu_{\chi N}^2}}$$

We need a particle detector with

- Large exposure (mass × time)
- High A for SI coupling, $m_\chi \sim 10 - 1000$ GeV
- Low A for light Wimps ($O(\mathrm{GeV})$)
- Isotopes with $J \neq 0$ for SD
- **Low energy threshold**
- good efficiency in the low energy region
- good knowledge of the detector response to NR (quenching factors)
- **ultra-low background at low energy for NR → particle discrimination!**

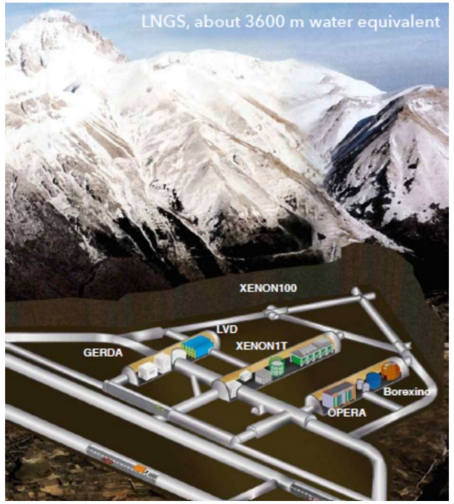
Note: Energy resolution is not a “must”. Some DM DD experiments are not even able to determine the energy of the recoil!

Backgrounds: cosmic rays



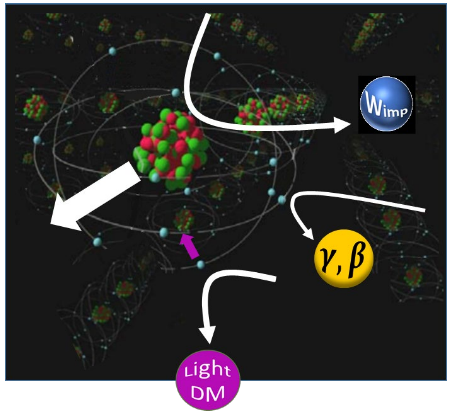
Cosmic ray-induced muons

- Increase the counting rate
- cosmogenic activation of materials
- muon-induced neutrons

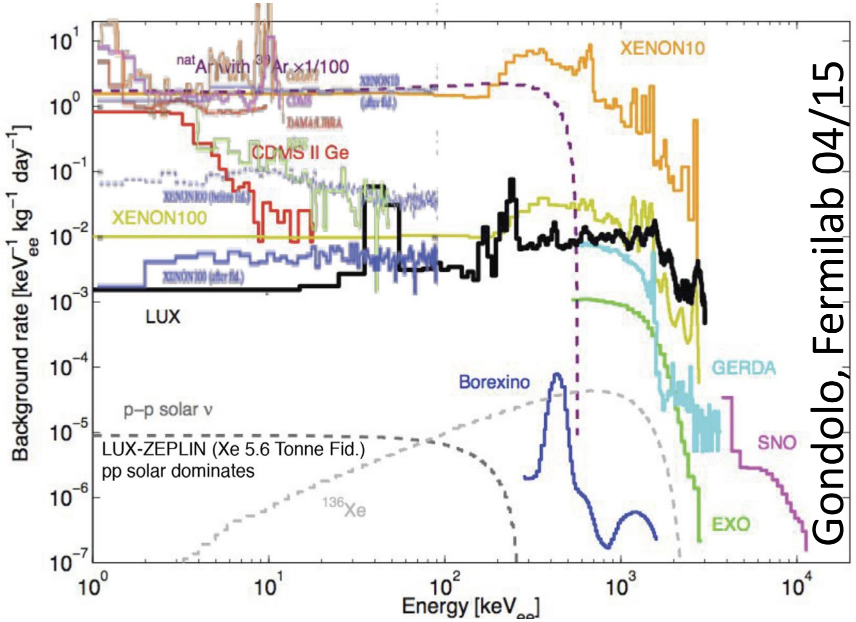


Go underground!

Backgrounds



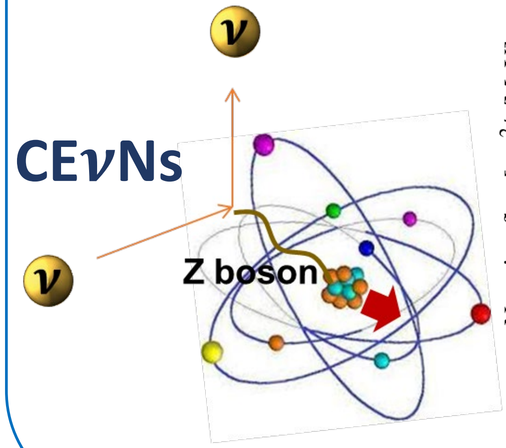
α, β, γ	material selection, shielding, **particle discrimination techniques**
$n\,N \rightarrow n\,N$	most critical (mimic WIMP signal). Shielding, active rejection (multiplicity)
$\nu\, e^- \rightarrow \nu\, e^-$	ultimate background for ER recoils
$\nu\, N \rightarrow \nu\, N$ (CEνNs)	ultimate background for WIMP search **(neutrino ~~floor~~ → fog)**

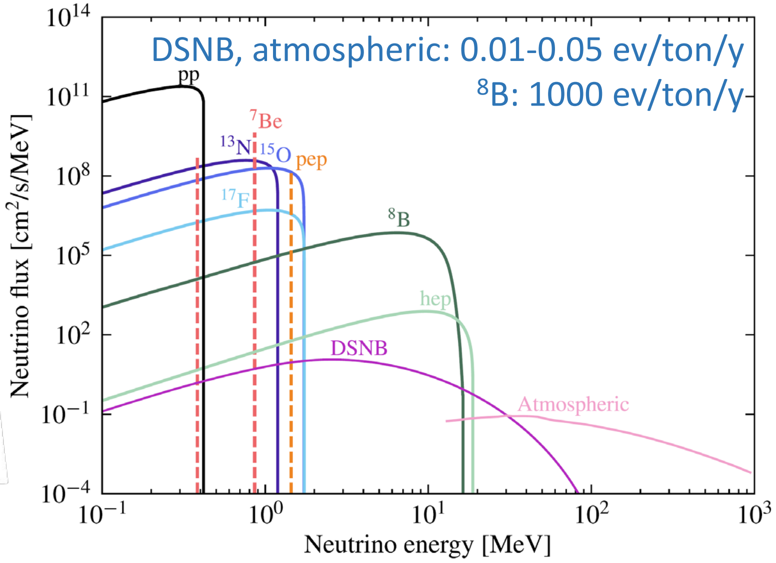


Gondolo, Fermilab 04/15

^{8}B, DSNB and atmospheric neutrinos produce nuclear recoil that cannot be distinguished from WIMP signals!

CEνNs

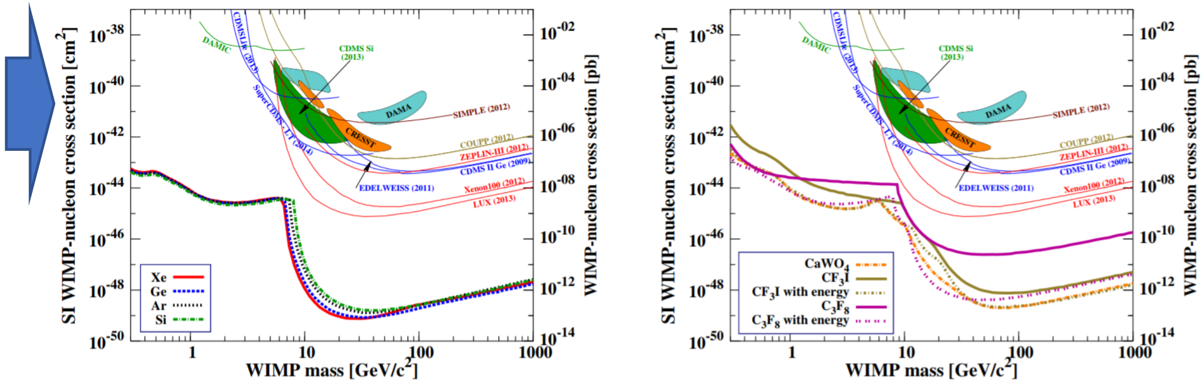




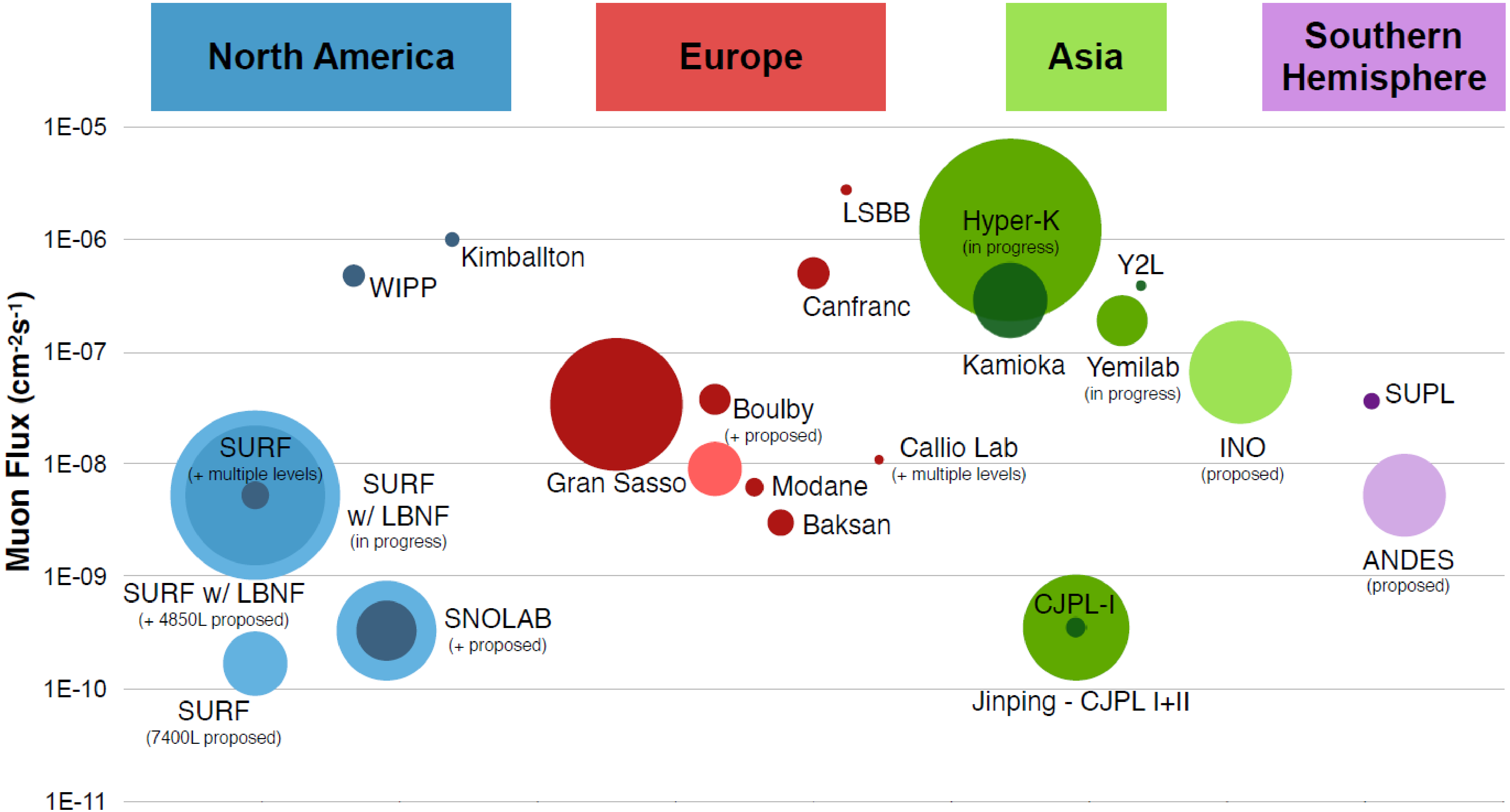
DSNB, atmospheric: 0.01-0.05 ev/ton/y

^{8}B: 1000 ev/ton/y

the sensitivity of the experiments does not evolve as in a bkg free experiment, but much slower → lower limit in achievable cross-section (neutrino floor)



Underground laboratories



J. Heise, arXiv:2203.08293

Underground DD searches

SURF
LUX / LZ

SNOLAB
Pico
Deap-3600
Super-CDMS
News-G
Damic
Sensei

ANDES

Boulby
Drift/Cygnus

Canfranc
Anais-112
Trex

Modane
Edelweiss
News-G
Damic-M

LNGS
Dama/Libra
Cresst
Xenon
DarkSide
Sabre-north
Cosinus

Baksan

INO

Yemilab

Y2L
Cosine-100

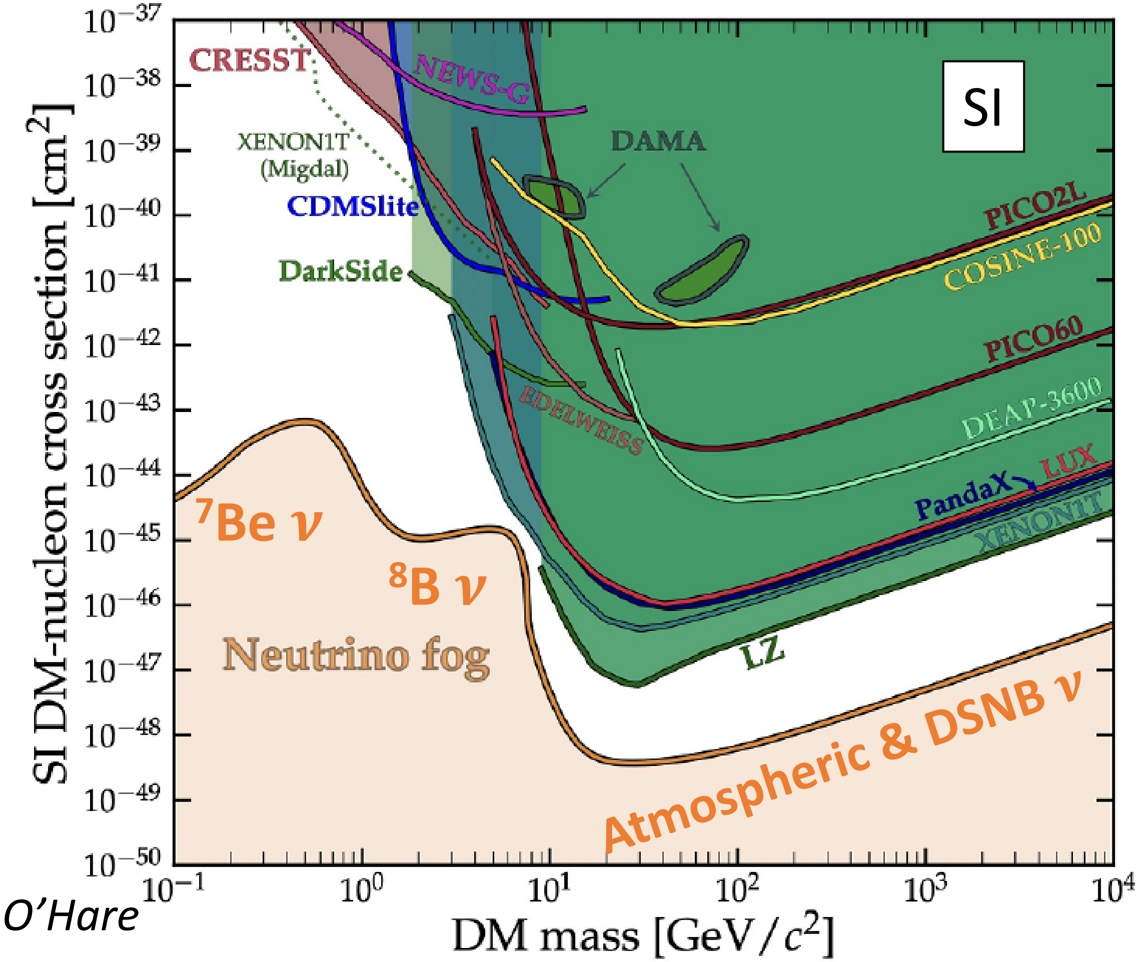
CJPL
PandaX
CDEX

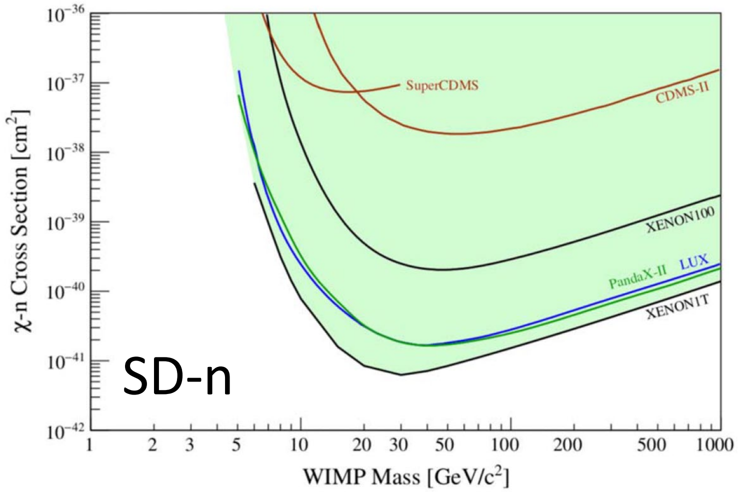
Kamioka
Xmass
Newage
Picolon

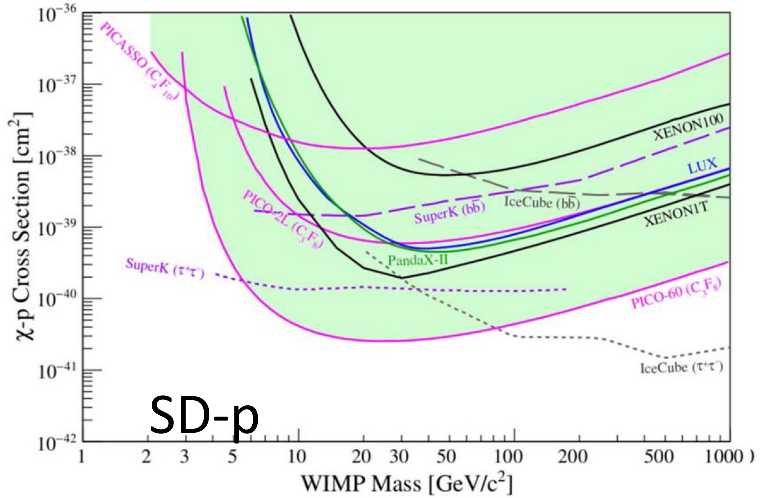
SUPL
Sabre-south

Experimental sensitivity @ 2023

- Exclude WIMPs that would produce a measurable rate over known backgrounds
- Assuming WIMPs coupling only spin-independent (SI) or only spin-dependent to neutrons (SD-n) or protons (SD-p)



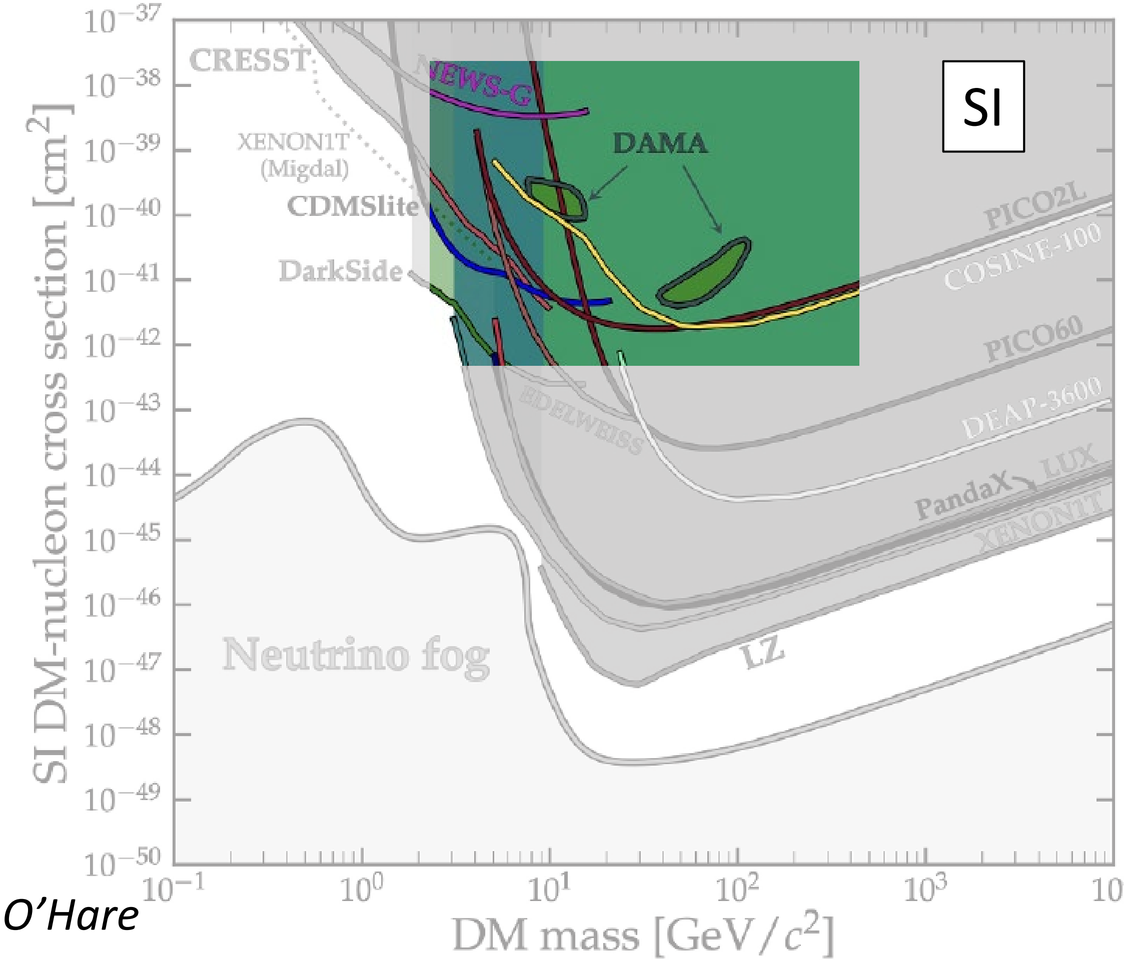




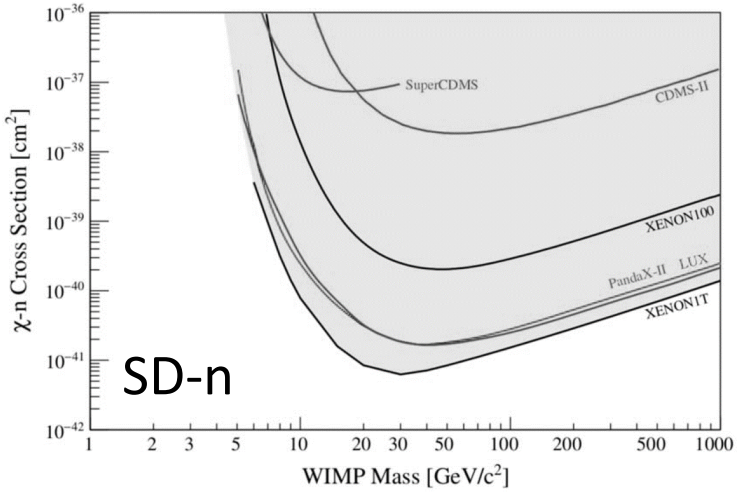
Credit: Ciaran O'Hare

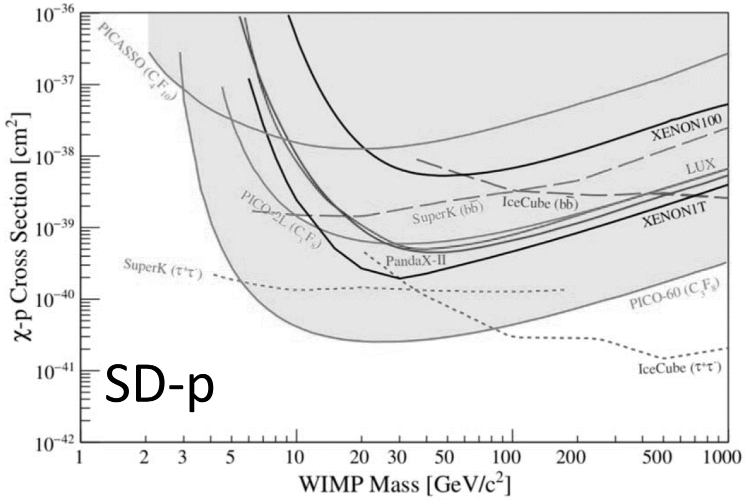
The DAMA/LIBRA annual modulation signal

Only one positive signal (surviving for more than 20 years…)

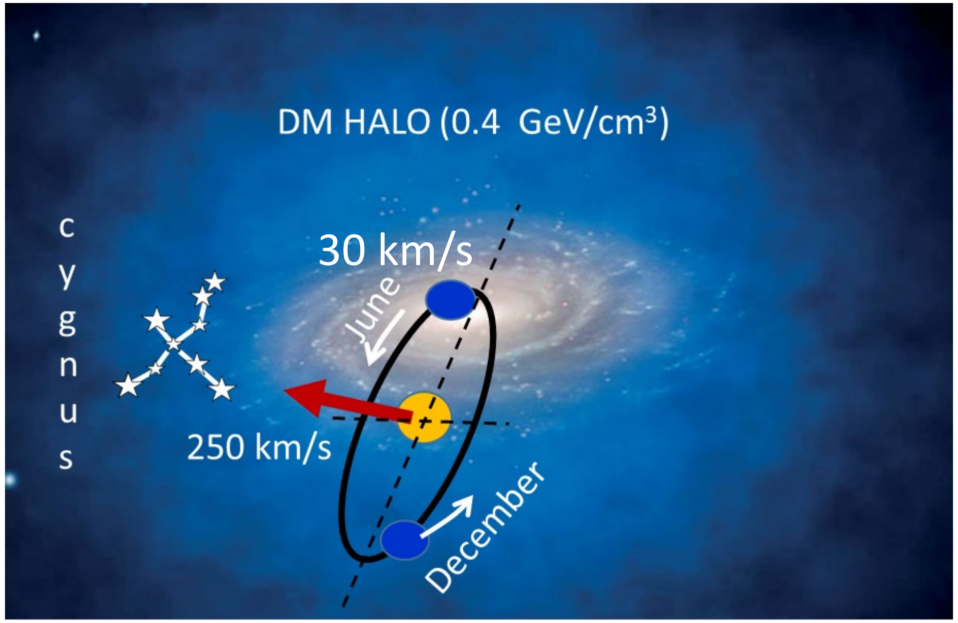


Credit: Ciaran O'Hare

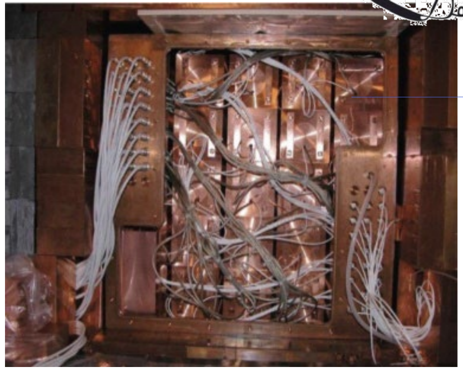




The DAMA/LIBRA annual modulation signal



LABORATORI NAZIONALI DEL GRAN SASSO



DAMA / NaI (1995-2002)

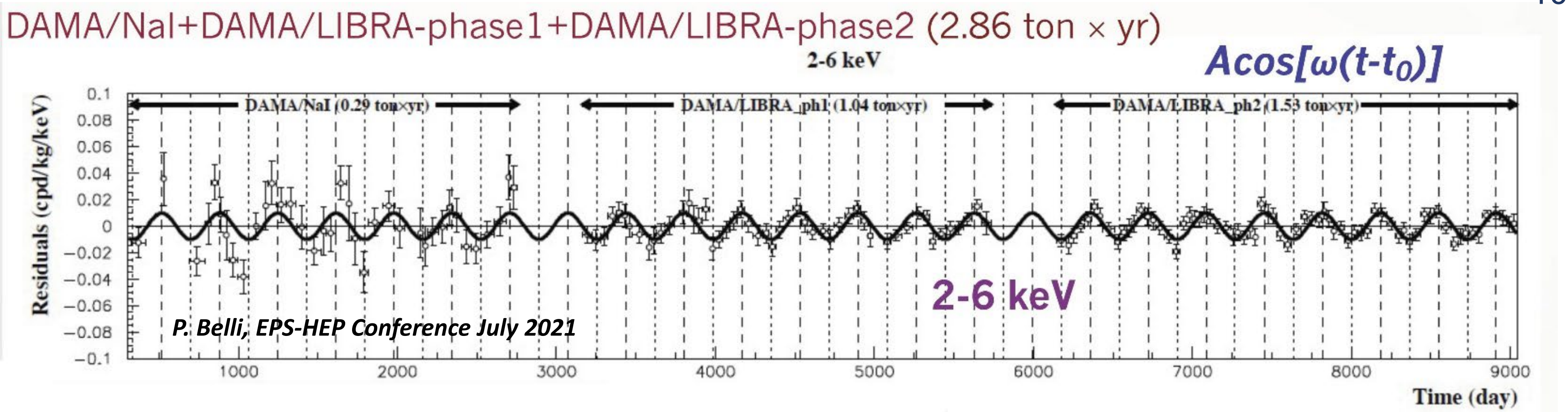
- 100 kg NaI(Tl) scintillators
- Eth = 2 keVee
- 7 annual cycles

DAMA / LIBRA ph1 (2003-2010)

- 250 kg NaI(Tl) scintillators
- Eth = 2 keVee
- 7 annual cycles

DAMA / LIBRA ph2 (2011-today)

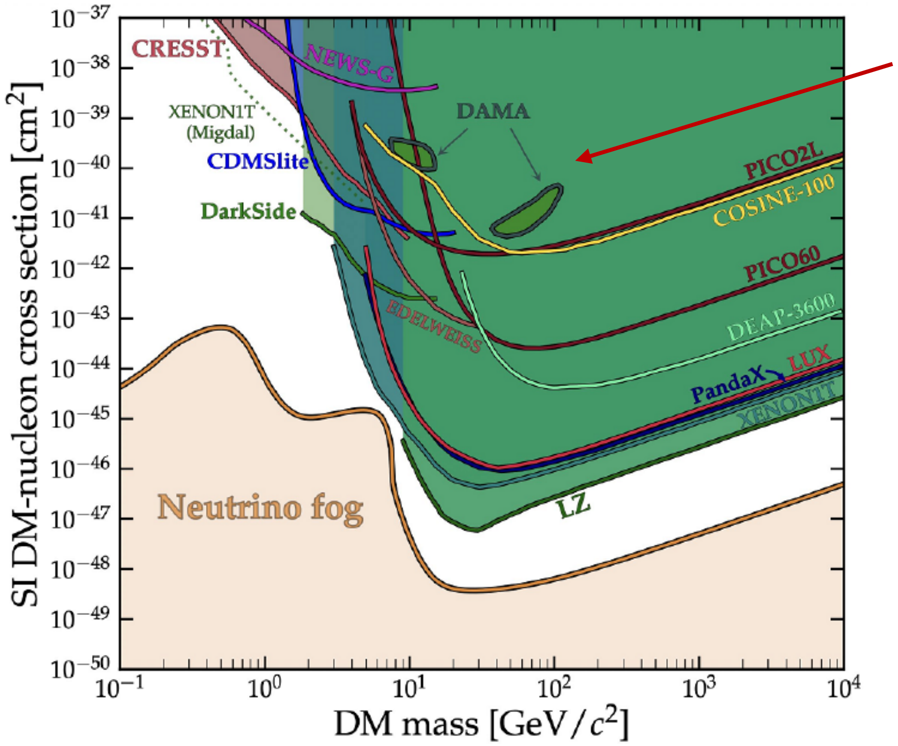
- 250 kg NaI(Tl) scintillators
- Eth = 1 keVee
- 10 annual cycles



P. Belli, EPS-HEP Conference July 2021

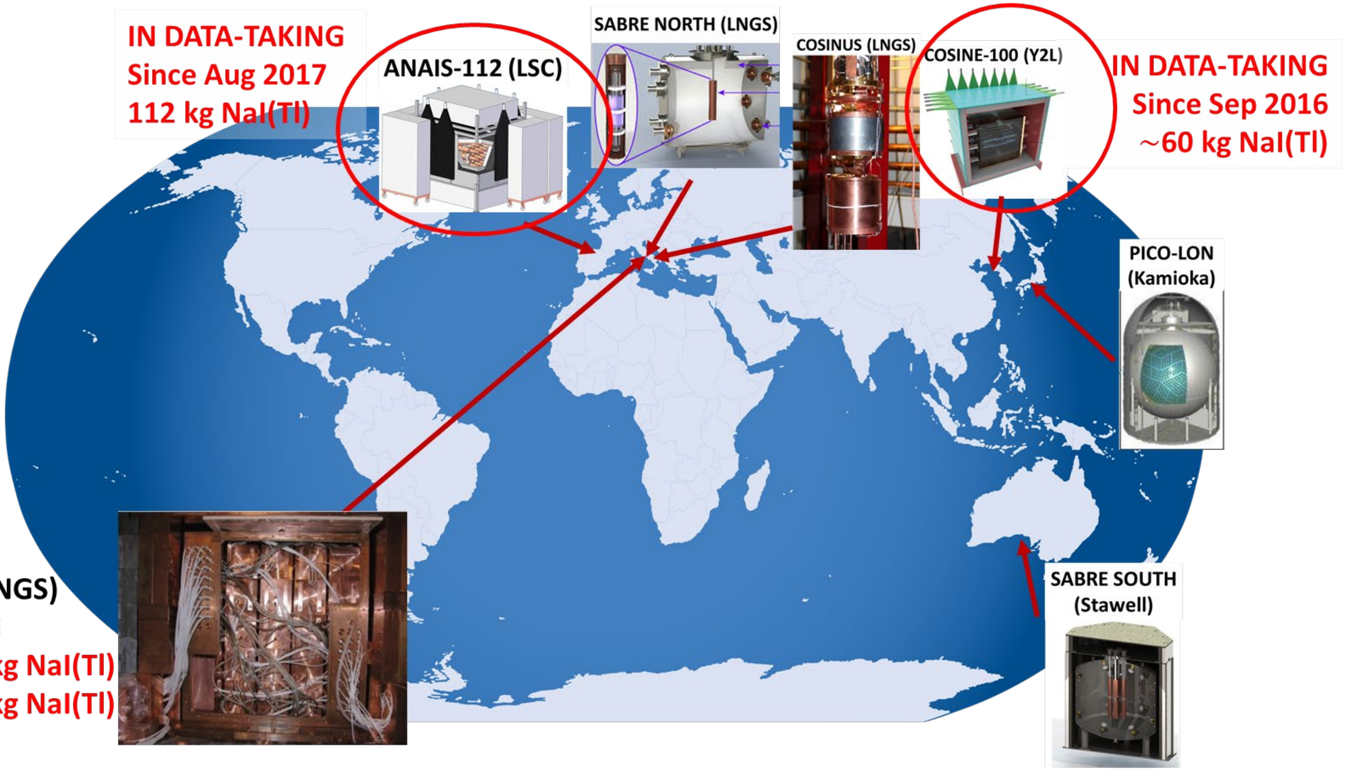
DAMA clearly sees an annual modulation at 13.7σ C.L.

Testing the DAMA/LIBRA signal



The parameter’s region singled out by DAMA/LIBRA is excluded by many DM experiments, but **this comparison is model dependent**.

To avoid any model dependence: USE NaI(Tl)



IN DATA-TAKING
Since Aug 2017
112 kg NaI(Tl)

ANAIS-112 (LSC)

SABRE NORTH (LNGS)

COSINUS (LNGS)

COSINE-100 (Y2L)

IN DATA-TAKING
Since Sep 2016
~60 kg NaI(Tl)

PICO-LON (Kamioka)

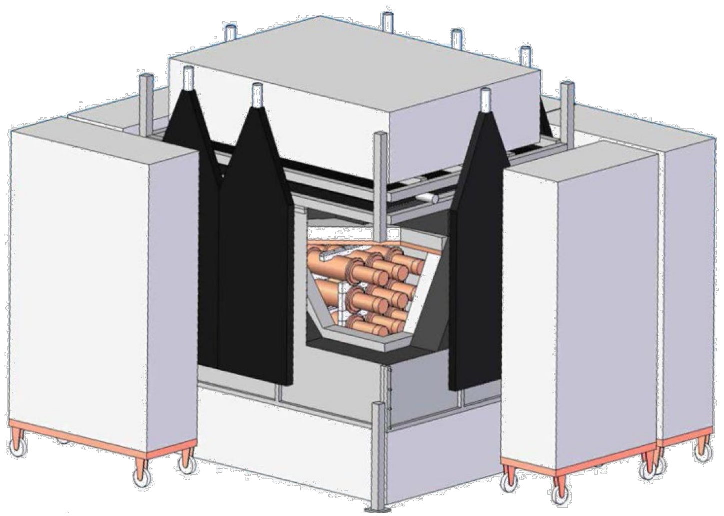
SABRE SOUTH (Stawell)

DAMA/LIBRA (LNGS)
IN DATA-TAKING
Since 1995 100 kg NaI(Tl)
Since 2003 250 kg NaI(Tl)

ANAIS-112 vs DAMA/LIBRA

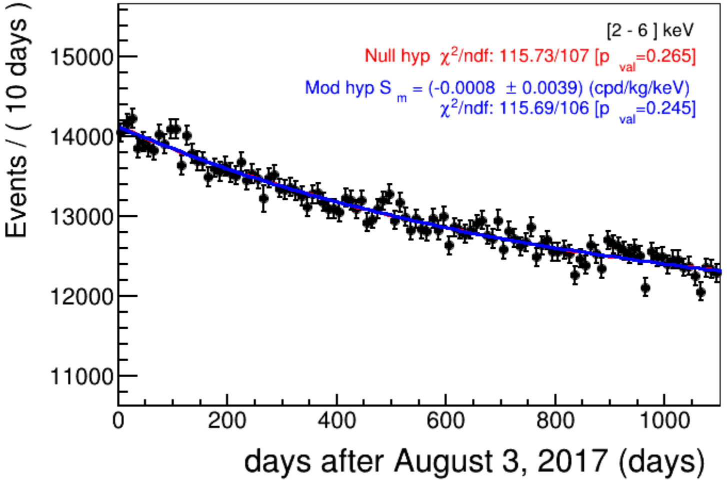
ANAIS-112: First model independet test of the DAMA/LIBRA signal (same target and technique)

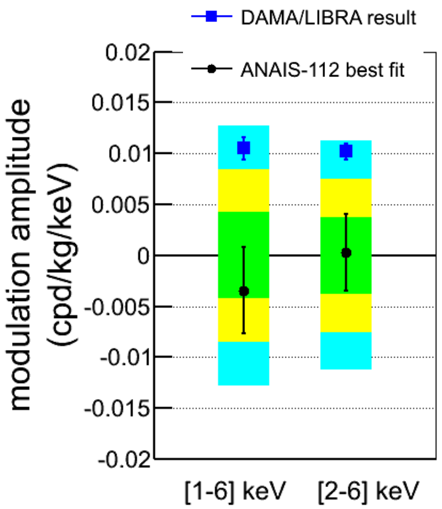
112 kg NaI(Tl) scintillators
@ Canfranc Underground Laboratory
In data-taking since August 2017
1 keVee energy threshold
Background @ ROI x3 DAMA/LIBRA



3 years results

PRD 103, 102005 (2021)



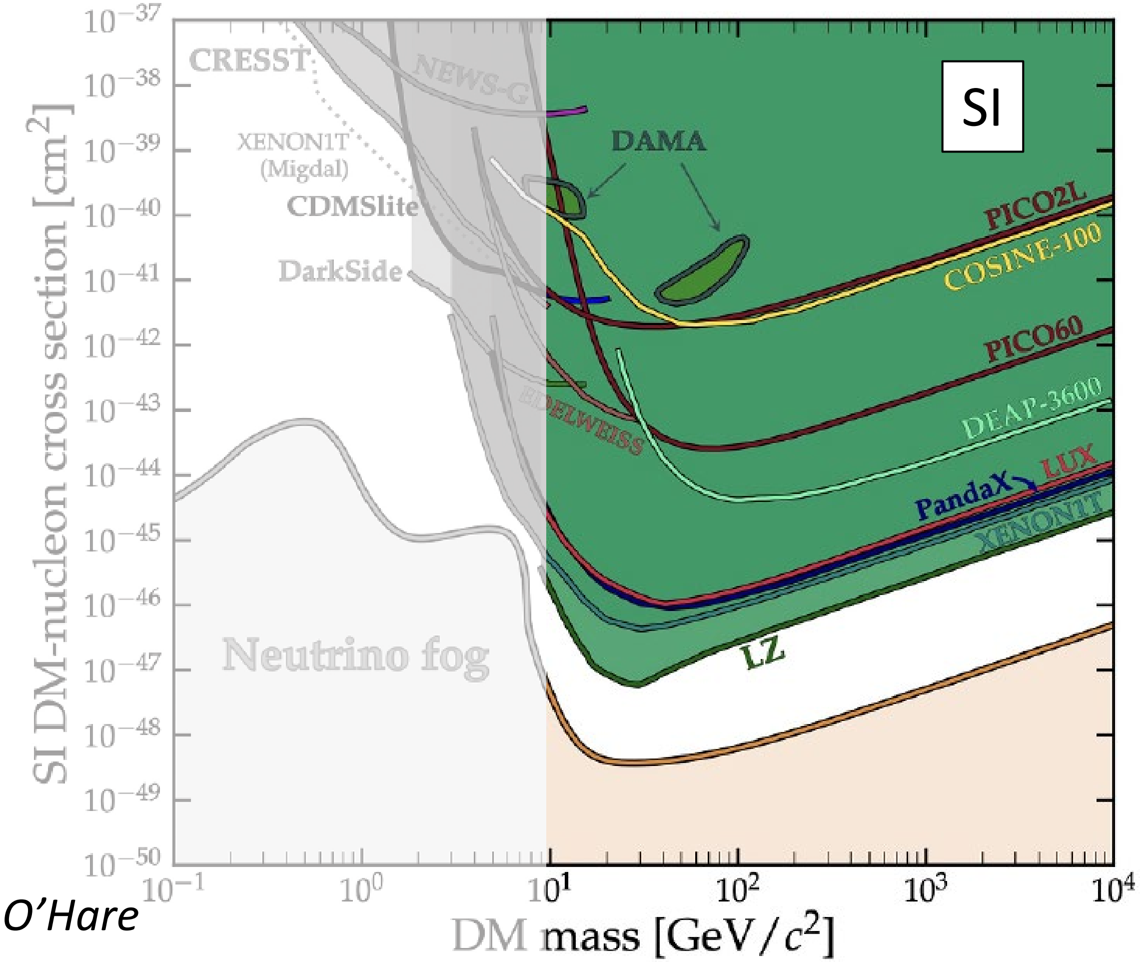


Best fit incompatible with DAMA/LIBRA at 3.3 (2.6) σ

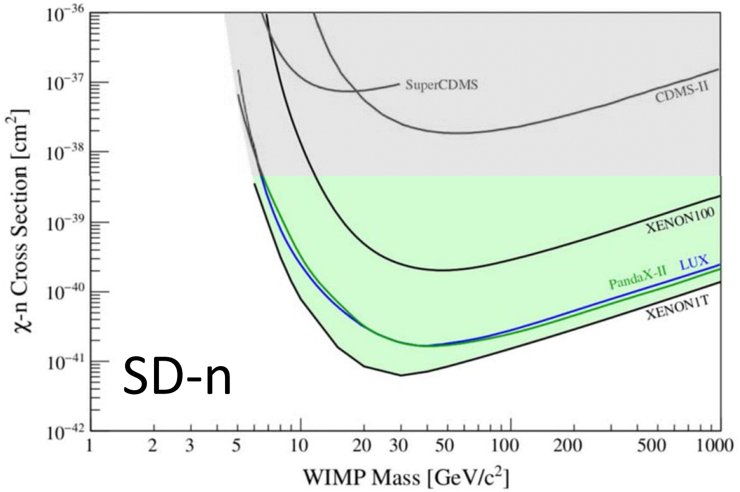
Current sensitivity: 2.5-2.7σ

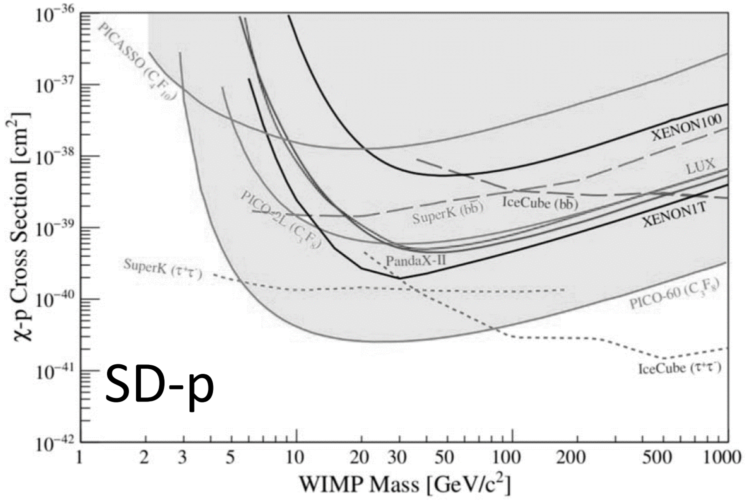
High WIMP mass

- Double-phase noble elements TPC: Lux/LZ, PandaX, Xenon, DarkSide
- noble liquid (single pase): Deap, XMass

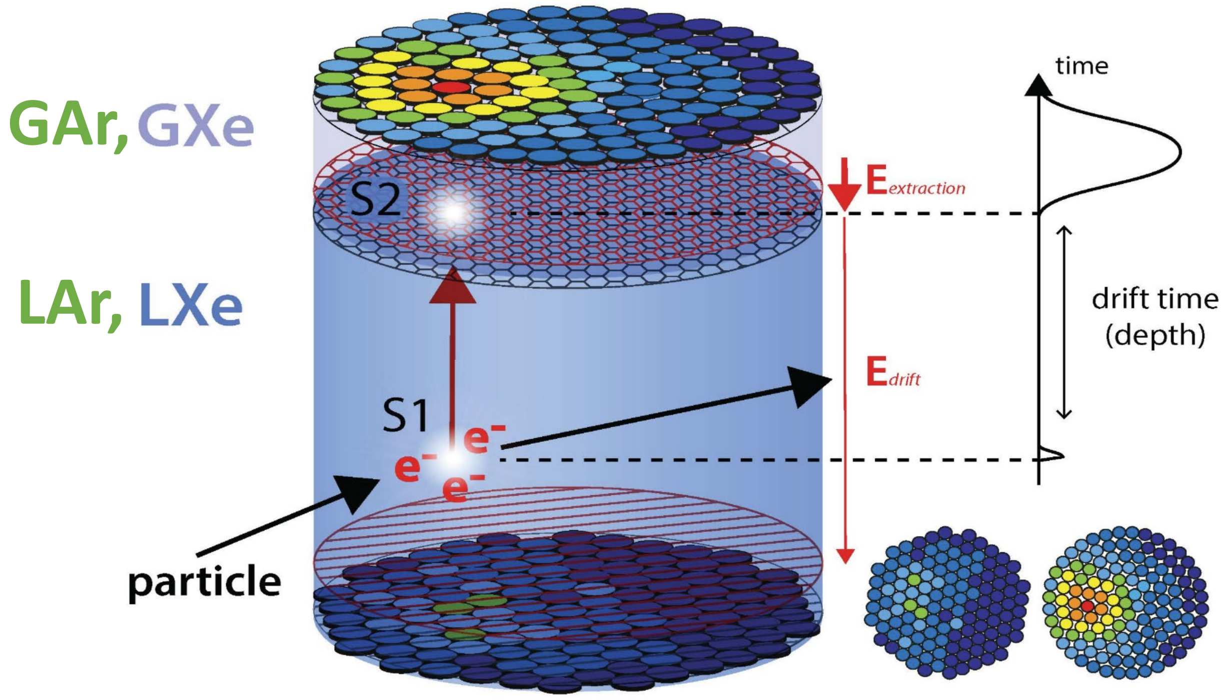


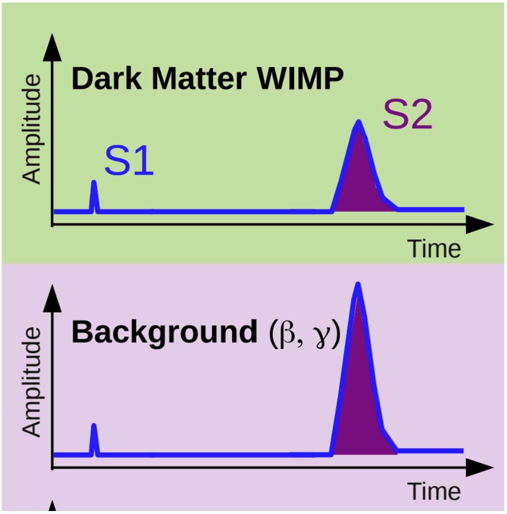
Credit: Ciaran O'Hare





Double-phase noble elements TPC (light + charge)



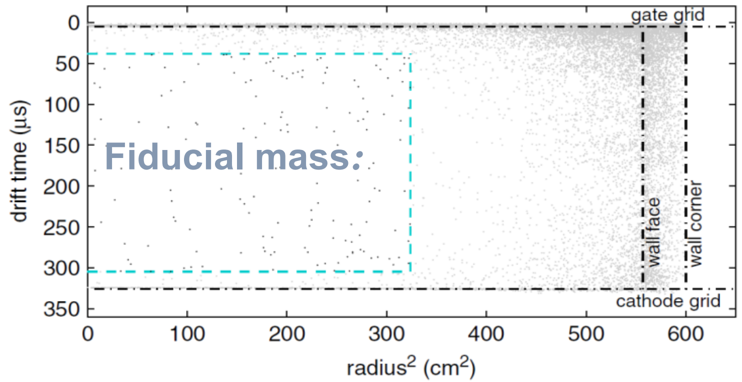


The ratio S1/S2 is different for nuclear recoils (WIMPs) or electron recoils (background)

Reconstruction of the hit position

- Top/bottom photomultipliers → (x, y)
- Drift time → z

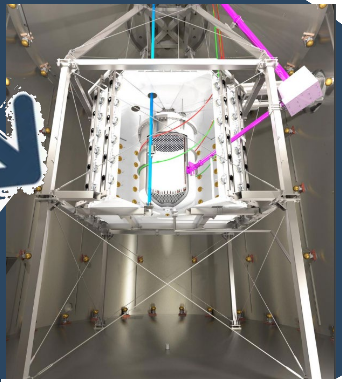
→ fiducialization (use only the inner (cleaner) part)



- ER Background rejection
- Fiducialization
- Possibility to reduce the threshold working only with charge readout (no bkg discrimination!)

Present and future of noble-TPCs

Xenon 1T
(1 ton LXe)
(decomissioned)



Xenon nT
(5.9 ton LXe)
STARTED IN 2021

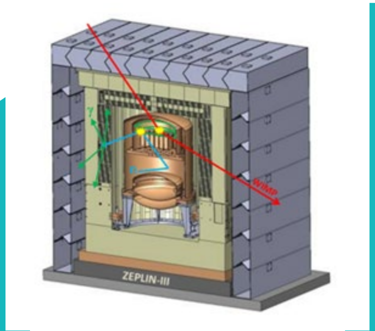
PANDAX-4T
(4 ton LXe)
STARTED IN 2021

DarkSide-50
(50 kg LAr)
(decomissioned)

Deap-3600
(3.6 ton LAr)

Ar

ArDM (1 ton LAr)
(decomissioned)

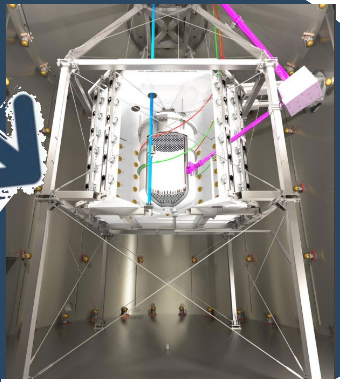


ZEPLIN-III
(6 kg LXe)
(decomissioned)

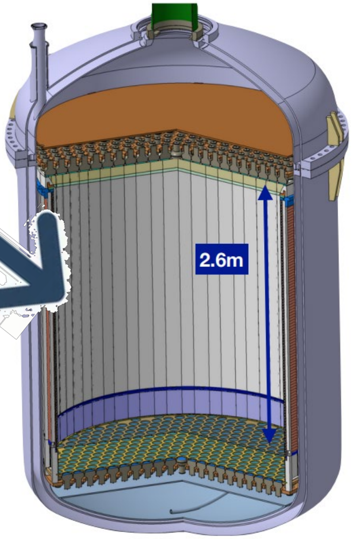
LUX
(100 kg LXe)
(decomissioned)

Present and future of noble-TPCs

Xenon 1T
(1 ton LXe)
(decomissioned)



Xenon nT
(5.9 ton LXe)
STARTED IN 2021



Future: DARWIN
(50 ton LXe)

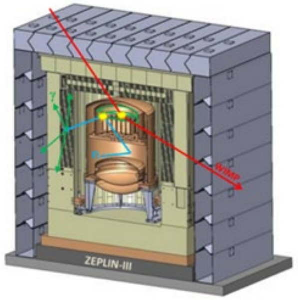
PANDAX-4T
(4 ton LXe)
STARTED IN 2021

Ar

Deap-3600
(3.6 ton LAr)

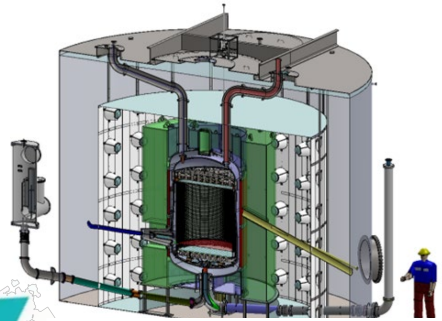
DarkSide-50
(50 kg LAr)
(decomissioned)

ArDM (1 ton LAr)
(decomissioned)

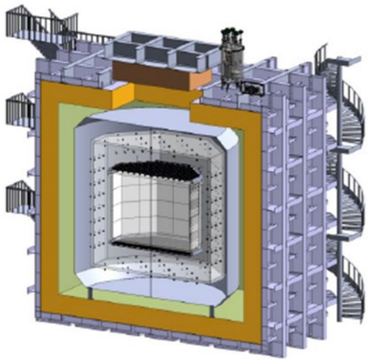


ZEPLIN-III
(6 kg LXe)
(decomissioned)

LUX
(100 kg LXe)
(decomissioned)



LZ @ SURF
(7 ton-fiducial LXe)
STARTED IN 2021

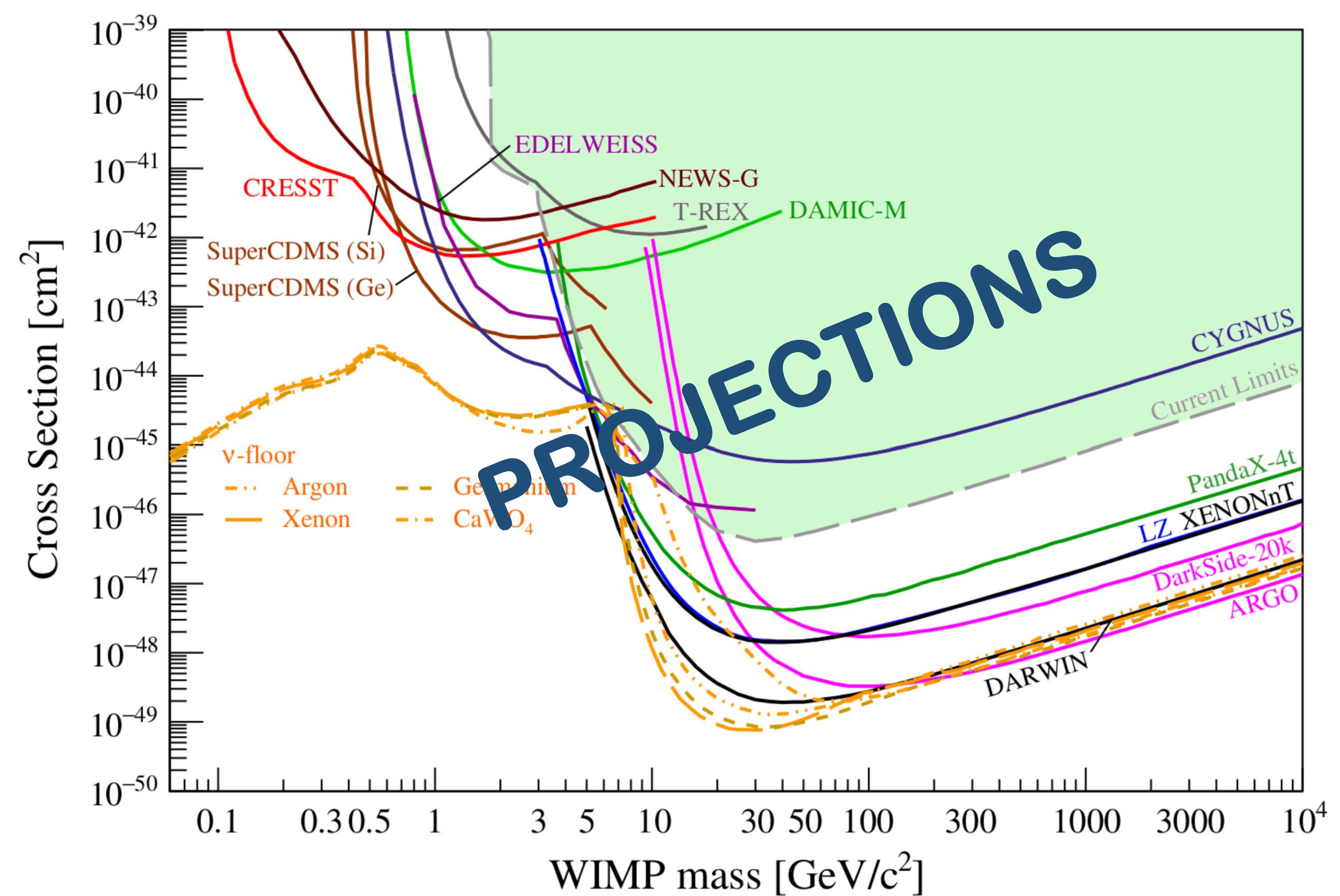


DarkSide-20k (in construction @ LNGS)
(50 ton LAr , 20 ton fiducial)

Present and future of noble-TPCs

Ar

Xenon 1T
(1 ton LXe)
(decomissioned)



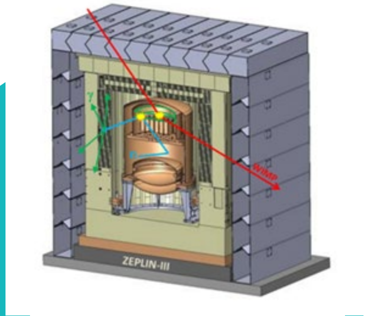
PROJECTIONS

DarkSide-50
(50 kg LAr)
(decomissioned)

ap-3600
ton LAr)

Ar

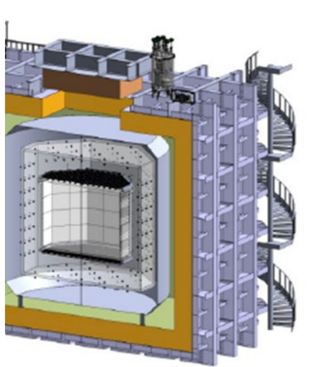
ArDM (1 ton LAr)
(decomissioned)



ZEPLIN-III
(6 kg LXe)
(decomissioned)

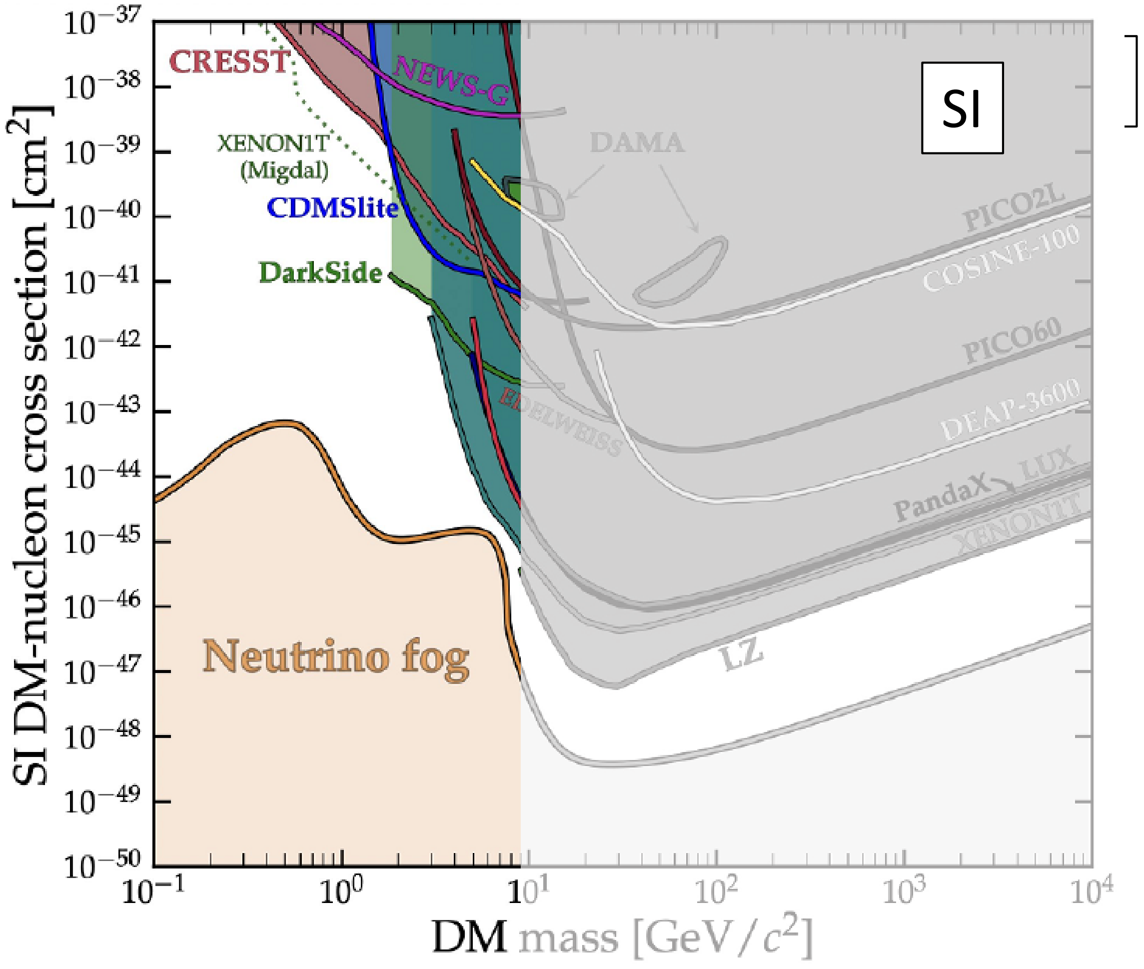
(100 kg LXe)
(decomissioned)

LZ (in construction @ SURF)
(7 ton-fiducial LXe)



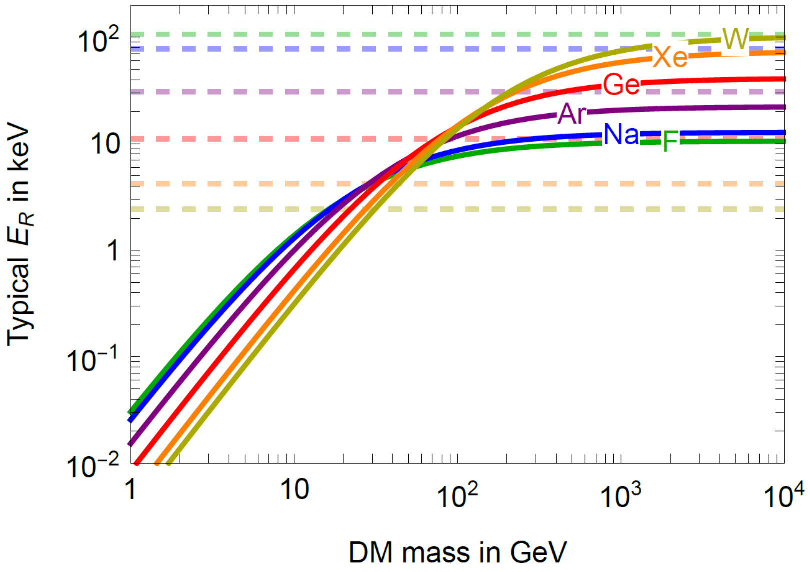
DarkSide-20k (in construction @ LNGS)
(50 ton LAr , 20 ton fiducial)

Low WIMP mass (<10 GeV)



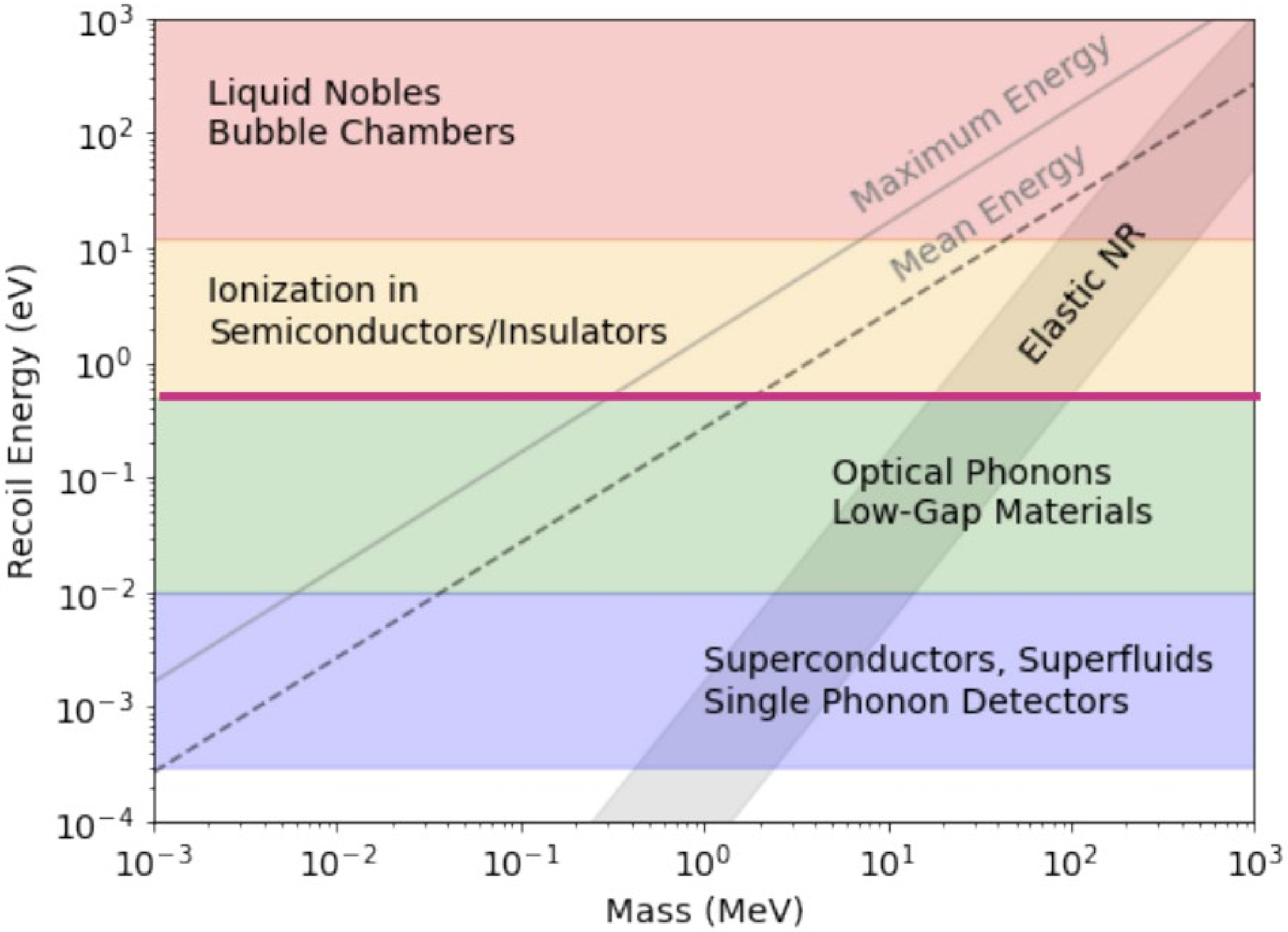
Credit: Ciaran O'Hare

A very low energy threshold is needed to explore the low-mass region



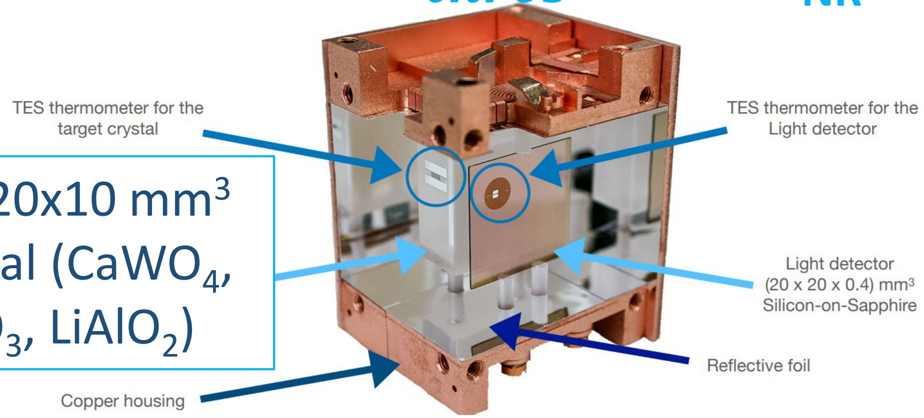
- **Cryogenic detectors: Edelweiss, CRESST, SuperCDMS**
- **CCds: Damic, Sensei**
- **High-pressure gas chambers: News-G**

DM-e scattering



Cryogenic detectors & p-type Ge for low-mass WIMPs

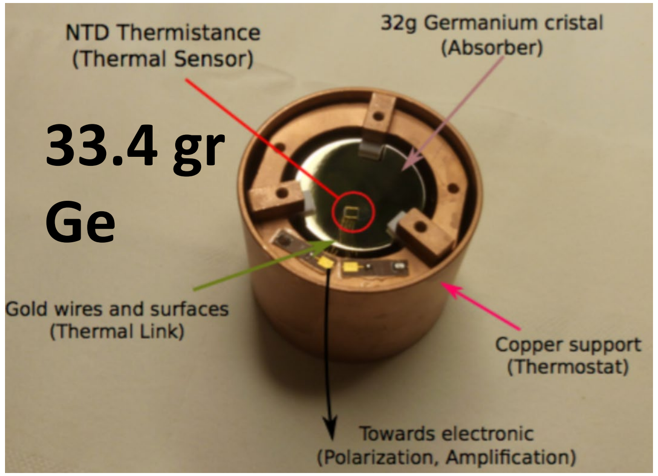
CRESST: E_{thres}= 30 eV$_{NR}$



20x20x10 mm^3 cristal (CaWO$_4$, Al$_2$O$_3$, LiAlO$_2$)

PRD 100 (2019) 102002

EDELWEISS: E_{thres}= 6 eV$_{ee}$



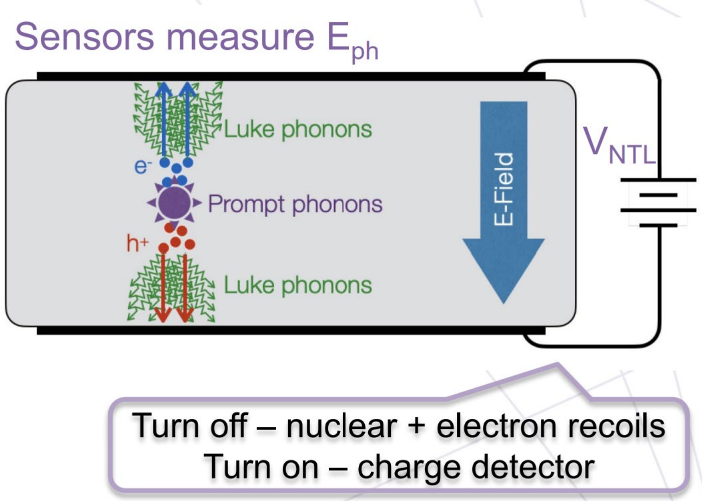
33.4 gr Ge

PRL 125 (2020) 14, 141301

CDMSLite E_{thres} = 70 eV

600 gr SuperCDMS detectors operated at high voltage → Neganov-Trofimov-Luke (NTL) amplification

PRD 99 (2019) 062001



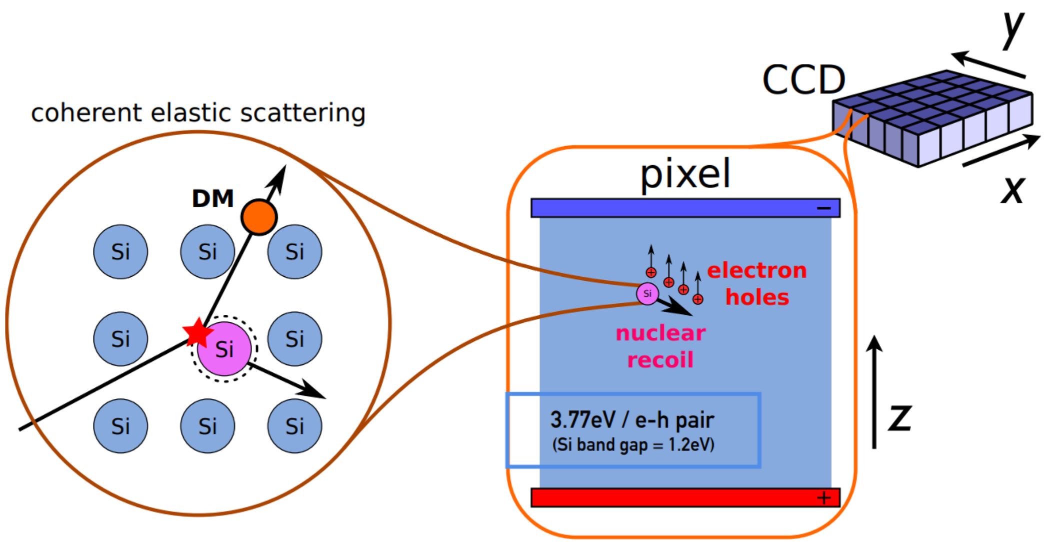
Turn off – nuclear + electron recoils
Turn on – charge detector

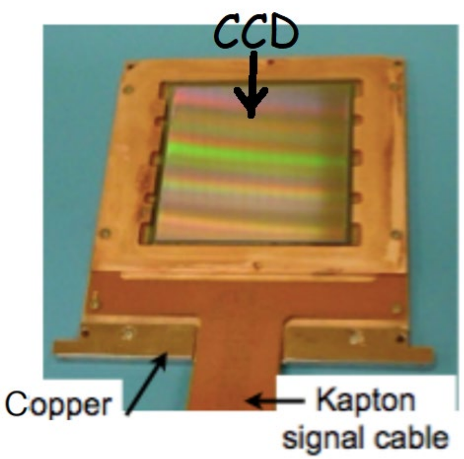
CDEX E_{thres} = 160 eV

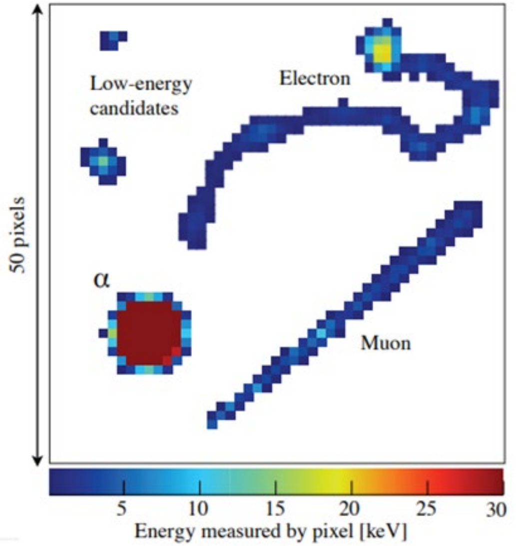
~1 kg p-type point contact Ge

PRL 123 (2019) 161301

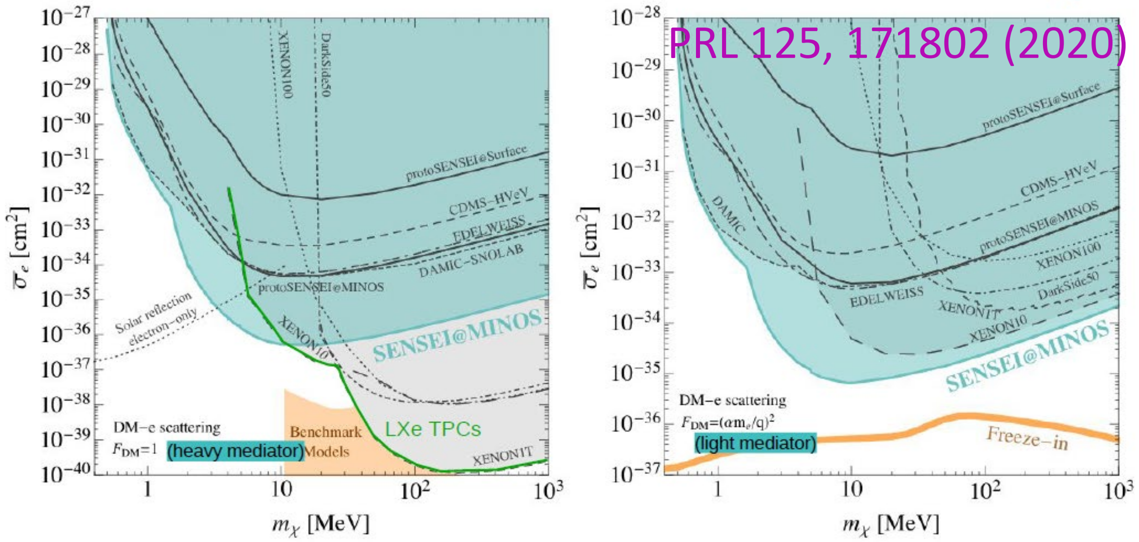
CCDs for low-mass & e^- scatteting: DAMIC, Sensei







WIMP–e^- scattering



DAMIC @ SNOLAB: 42 gr Si (7 CCDs), Eth = 50 eV
Future: DAMIC-M (LSM) (1 kg)

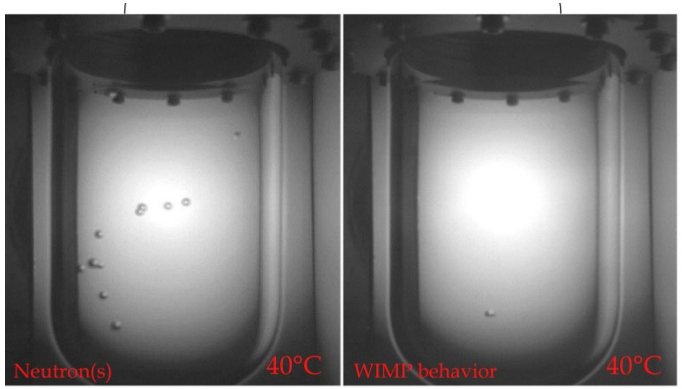
SENSEI @ MINOS: ~2 gr Si-CCD, Eth few eV
Future: 100 gr @ SNOLAB

OSCURA (O(10) kg), in development

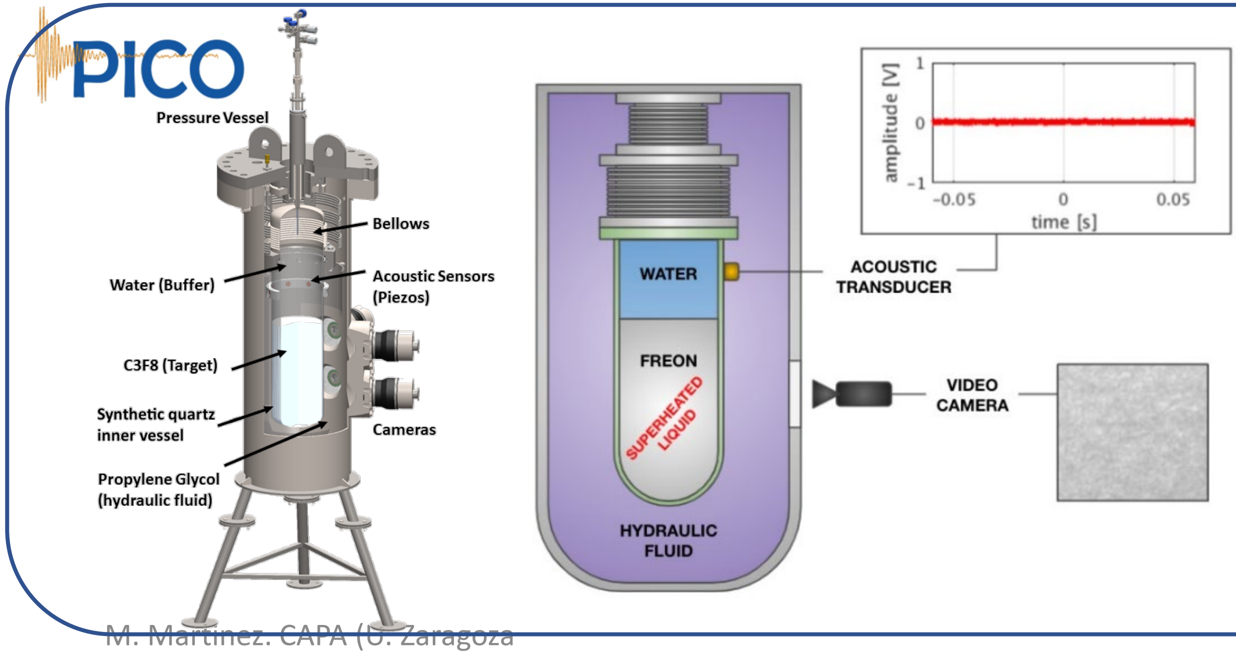
Bubble chambers for SD-p

Best DD SD-p limits come from bubble chambers experiments that use targets with F (highest sensitivity to SD WIMP-proton couplings)

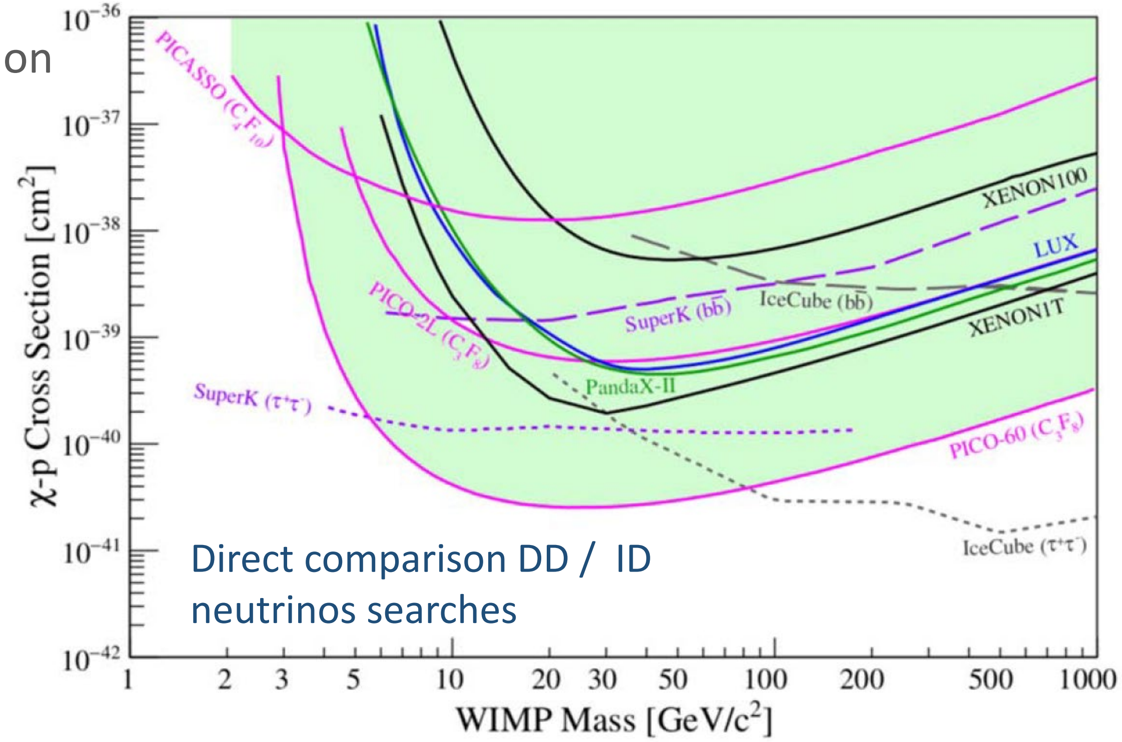
2-4 GeV: PICASSO (3 kg C_4F_{10})
Astropart. Phys. 90 (2017) 85
5-100 GeV: PICO-60 (52 kg C_3F_8)
PRD 100 (2019), 2 022001
> 100 GeV: Icecube ($\tau^+\tau^-$)



- Freon in metastable superheated state
- Tune the chamber to be unresponsive to most backgrounds. Only recoiling nuclei produce bubbles!
- Tune the chamber to set a nucleation energy threshold



Alphas are 4x louder than neutrons!

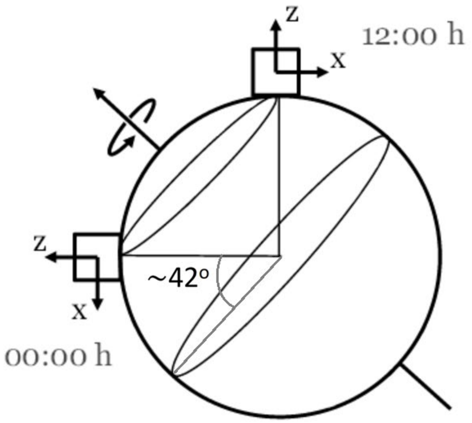


Direct comparison DD / ID neutrinos searches

Beyond the neutrino floor: directionality

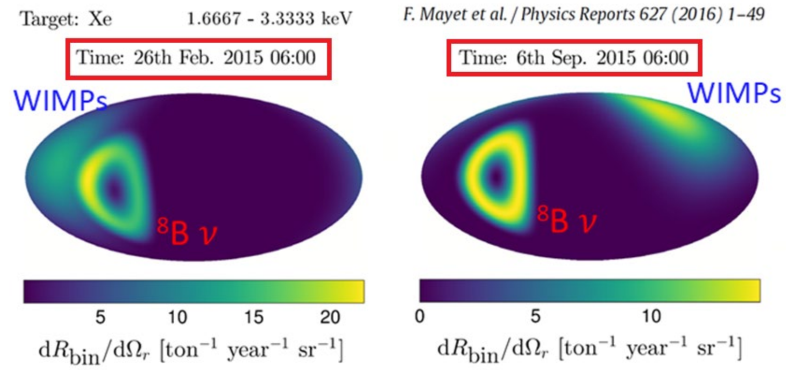
The Earth experiences a wind of DM particles apparently coming from Cygnus. The scattering is not isotropic in the galaxy frame → **FORWARD / BACKWARD ASYMMETRY**

Annual modulation: 2-10% effect
Forward-backward asymmetry: 20-100% effect

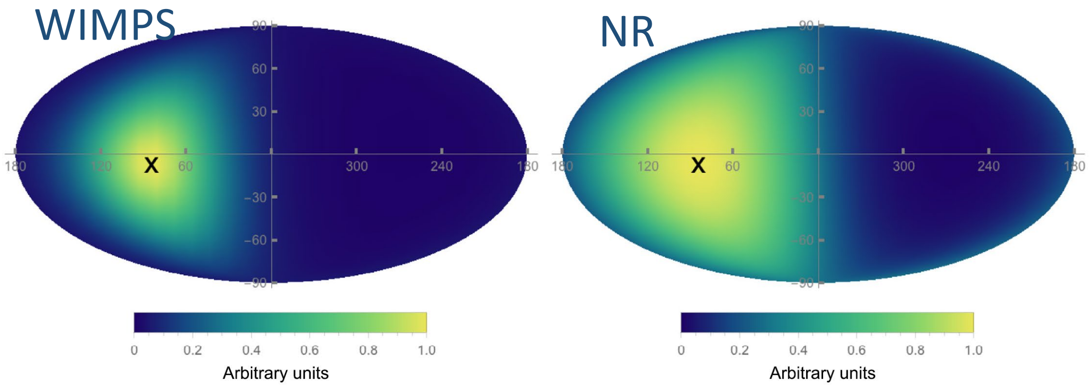


mean recoil direction oscillates due to the rotation of the Earth

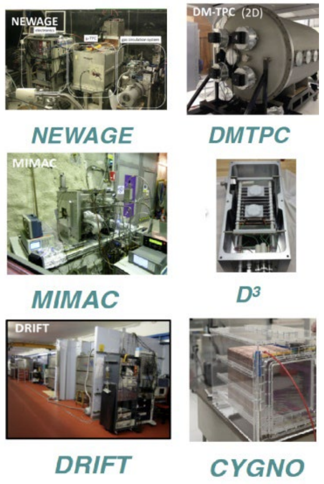
In general, can reject solar neutrinos



F. Mayet et al. / Physics Reports 627 (2016) 1–49



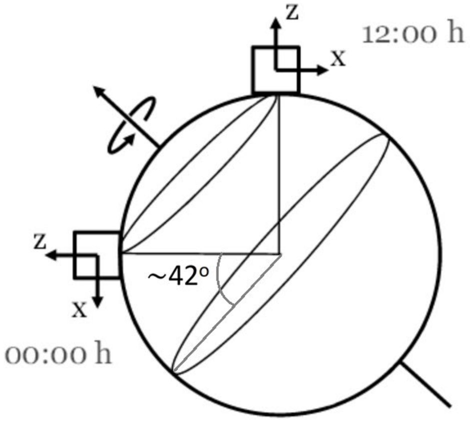
Name	Technology	Dim	Status
NEWAGE	Gas TPC, strip readout	3d	Running underground
DRIFT	Gas TPC, NID, wire readout	1.5d	Running underground
MIMAC	Gas TPC, strip readout	3d	Ran underground, scaling up
DMTPC	Gas TPC, optical readout	2d	Ran underground, scaled up, stopped
D³ / Hawaii R&D	Gas TPC, pixel readout	3d	Prototypes evaluated, ran aboveground
New Mexico R&D	Gas TPC, NID, optical	2d	Prototypes evaluated
LEMON, ORANGE, INITIUM, CYGNO	Gas TPCs, CMOS + PMT optical readout	3d	Prototypes evaluated, funded to scale up
NEWSdm	Nuclear Emulsions	2d	Prototyping / going underground
PTOLEMY	Graphene	2d	Prototyping / going underground



Beyond the neutrino floor: directionality

The Earth experiences a wind of DM particles apparently coming from Cygnus. The scattering is not isotropic in the galaxy frame → **FORWARD / BACKWARD ASYMMETRY**

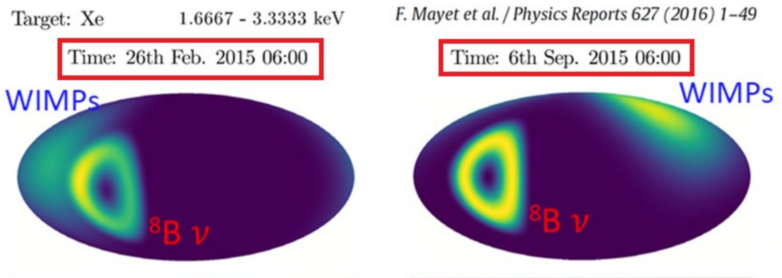
Annual modulation: 2-10% effect
Forward-backward asymmetry: 20-100% effect

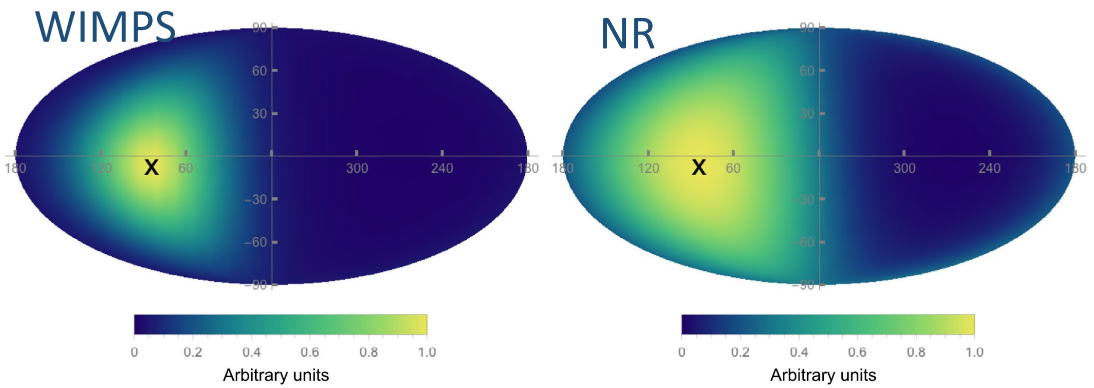


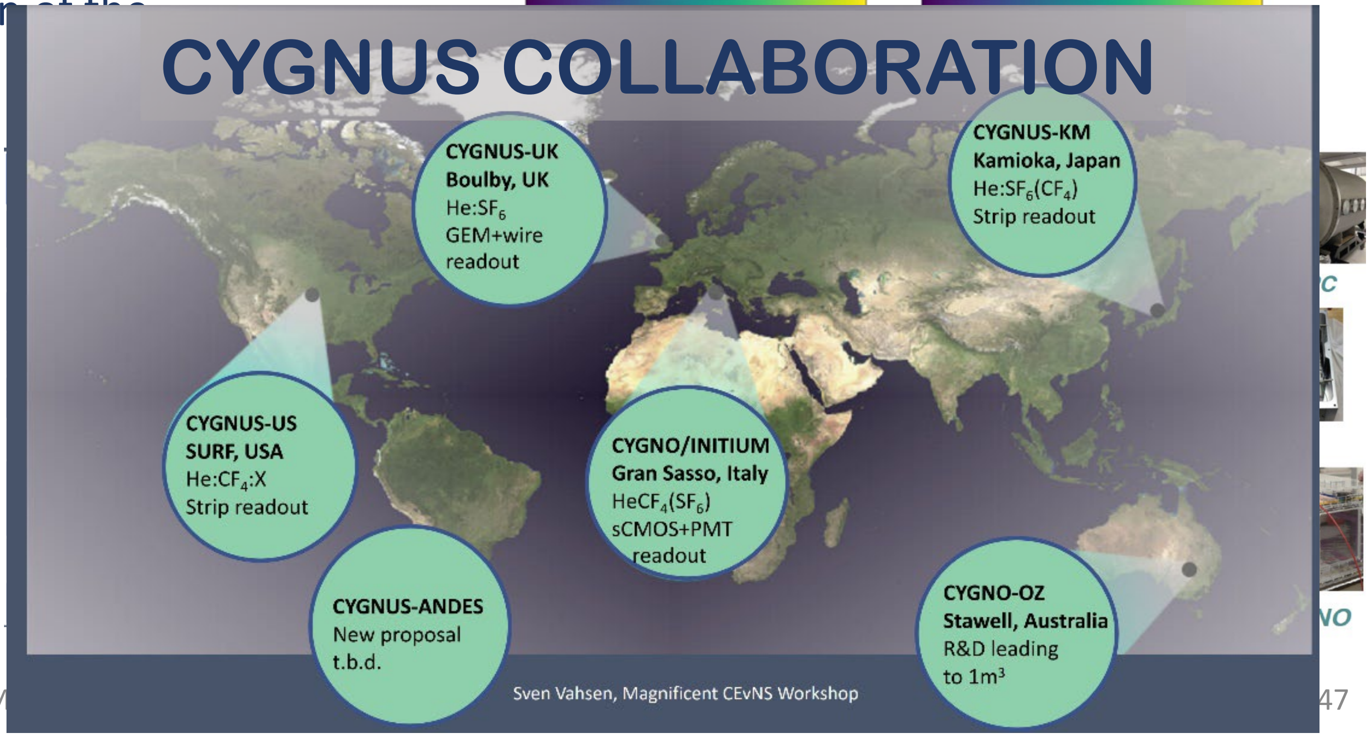
mean recoil direction oscillates due to the rotation of the Earth

In general, can reject solar neutrinos

F. Mayet et al. / Physics Reports 627 (2016) 1–49







CYGNUS COLLABORATION

CYGNUS-UK
Boulby, UK
He:SF$_6$
GEM+wire readout

CYGNUS-KM
Kamioka, Japan
He:SF$_6$(CF$_4$)
Strip readout

CYGNUS-US
SURF, USA
He:CF$_4$:X
Strip readout

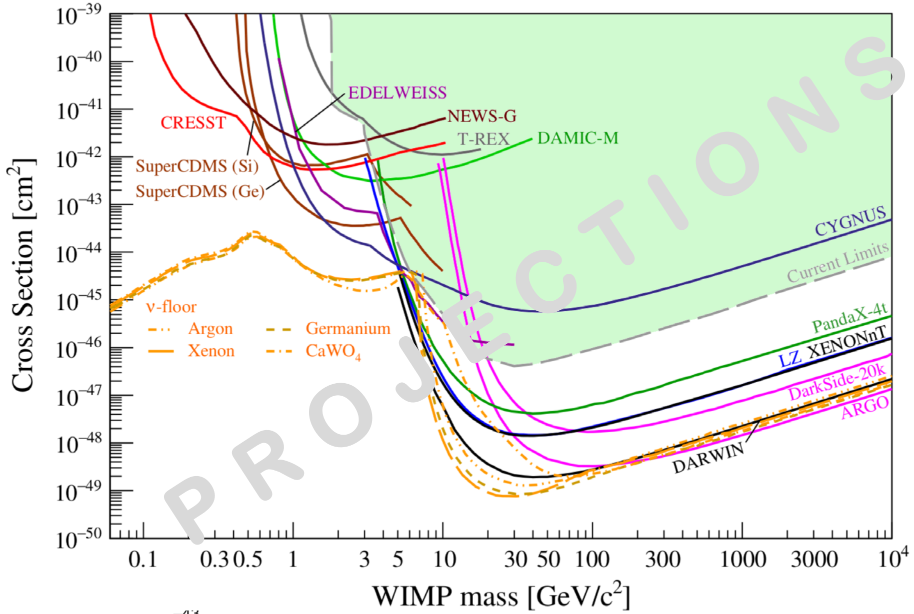
CYGNO/INITIUM
Gran Sasso, Italy
HeCF$_4$(SF$_6$)
sCMOS+PMT readout

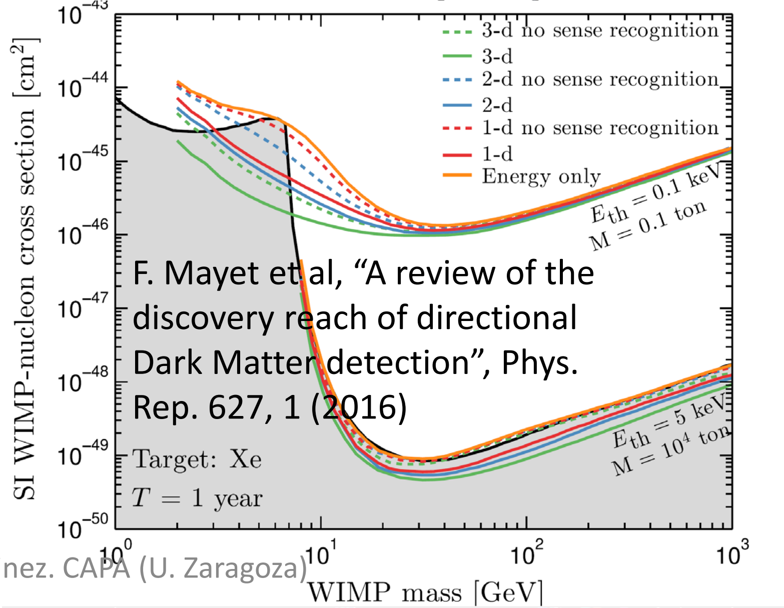
CYGNUS-ANDES
New proposal
t.b.d.

CYGNUS-OZ
Stawell, Australia
R&D leading to 1m^3

Sven Vahsen, Magnificent CEvNS Workshop

Outlook & prospects

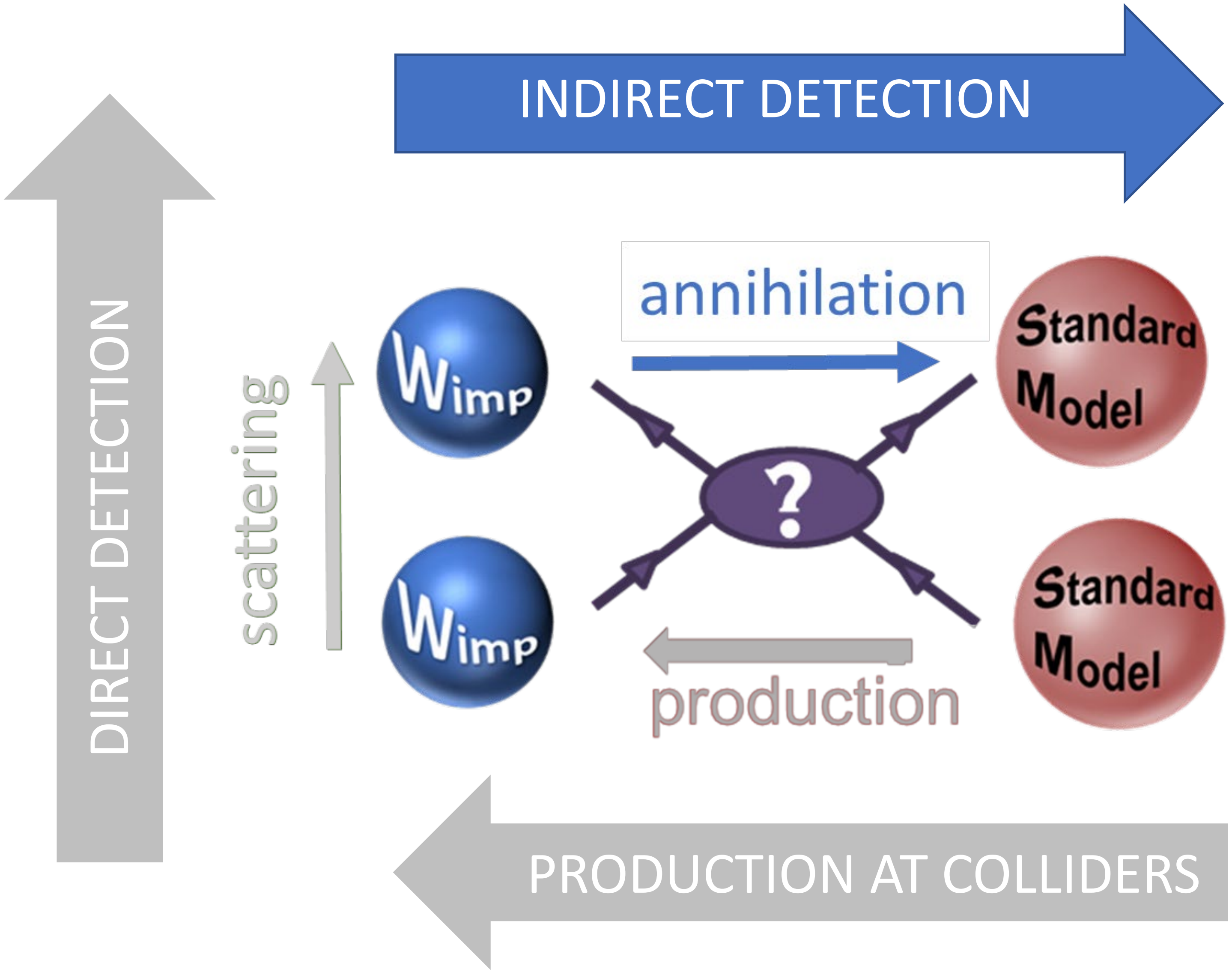




F. Mayet et al, "A review of the discovery reach of directional Dark Matter detection", Phys. Rep. 627, 1 (2016)

- World-wide effort to detect DM "directly". No signal by now
  - DAMA/LIBRA positive signal not confirmed at almost 3σ by ANAIS-112/COSINE-100 experiments
- Xe & Ar multi-ton experiments planned to reach the neutrino floor in the next decade
- Many new ideas/experiments to explore DM scenarios in the GeV (NR), MeV (ER), keV down to eV (absorption) regions
- Beyond the neutrino fog? Directionality? → CYGNUS collaboration

How to detect DM?



INDIRECT DETECTION

DIRECT DETECTION

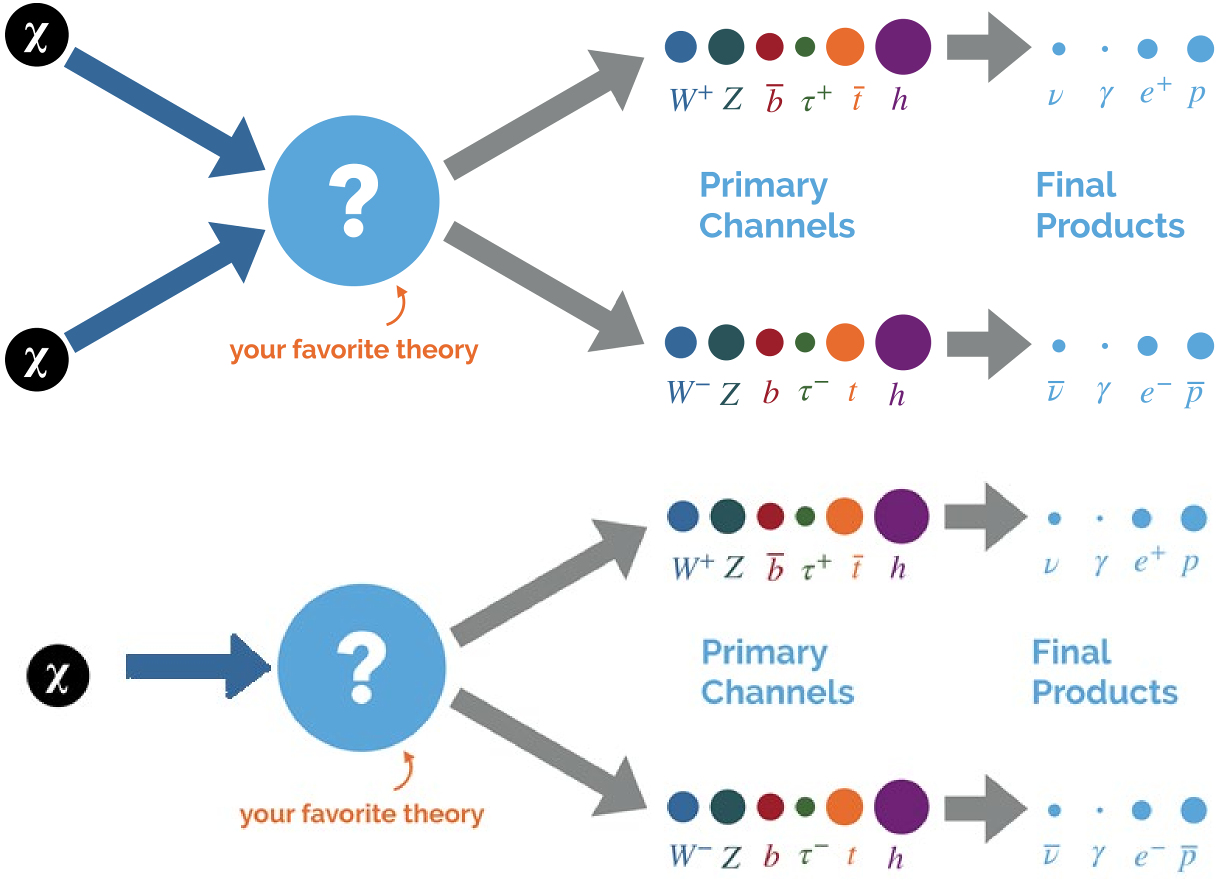
PRODUCTION AT COLLIDERS

scattering

annihilation

production

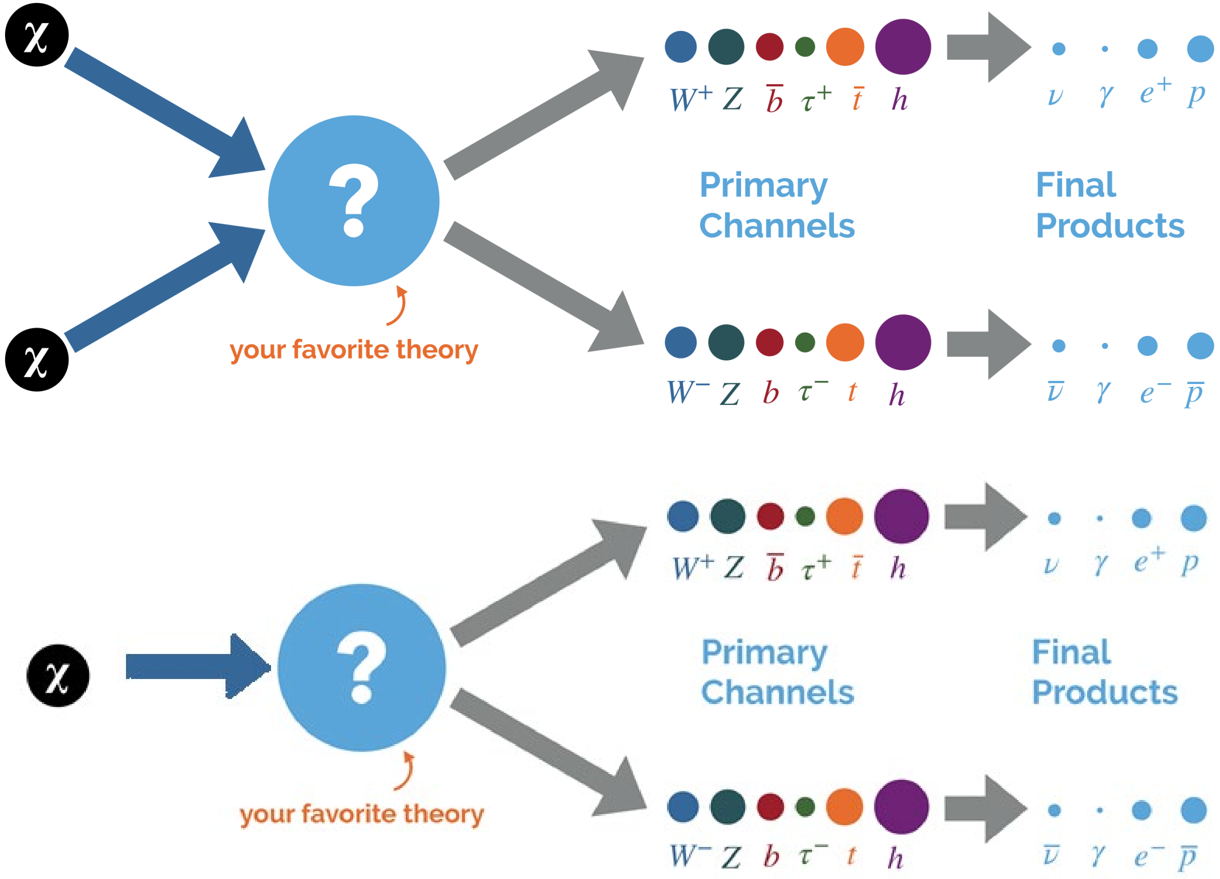
DM annihilation / decay



How much energy is dumped into the different particles depends on the annihilation channel & energy

Juan A. Aguilar, Dark Ghost 2022

DM annihilation / decay



3 kind of searches:

antimatter(*)

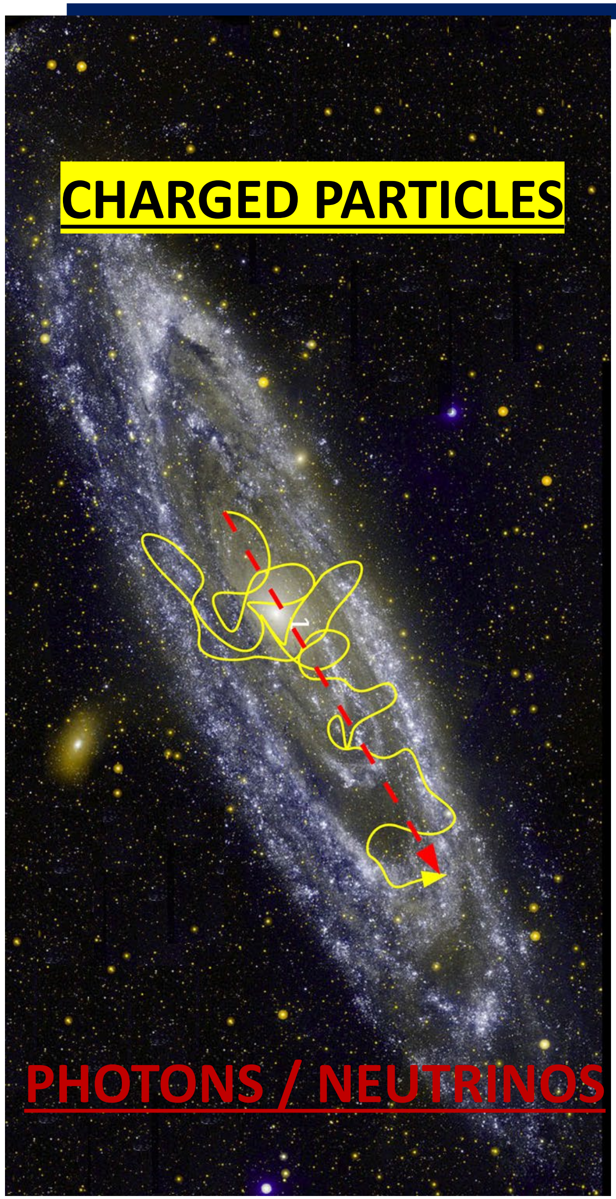
gammas

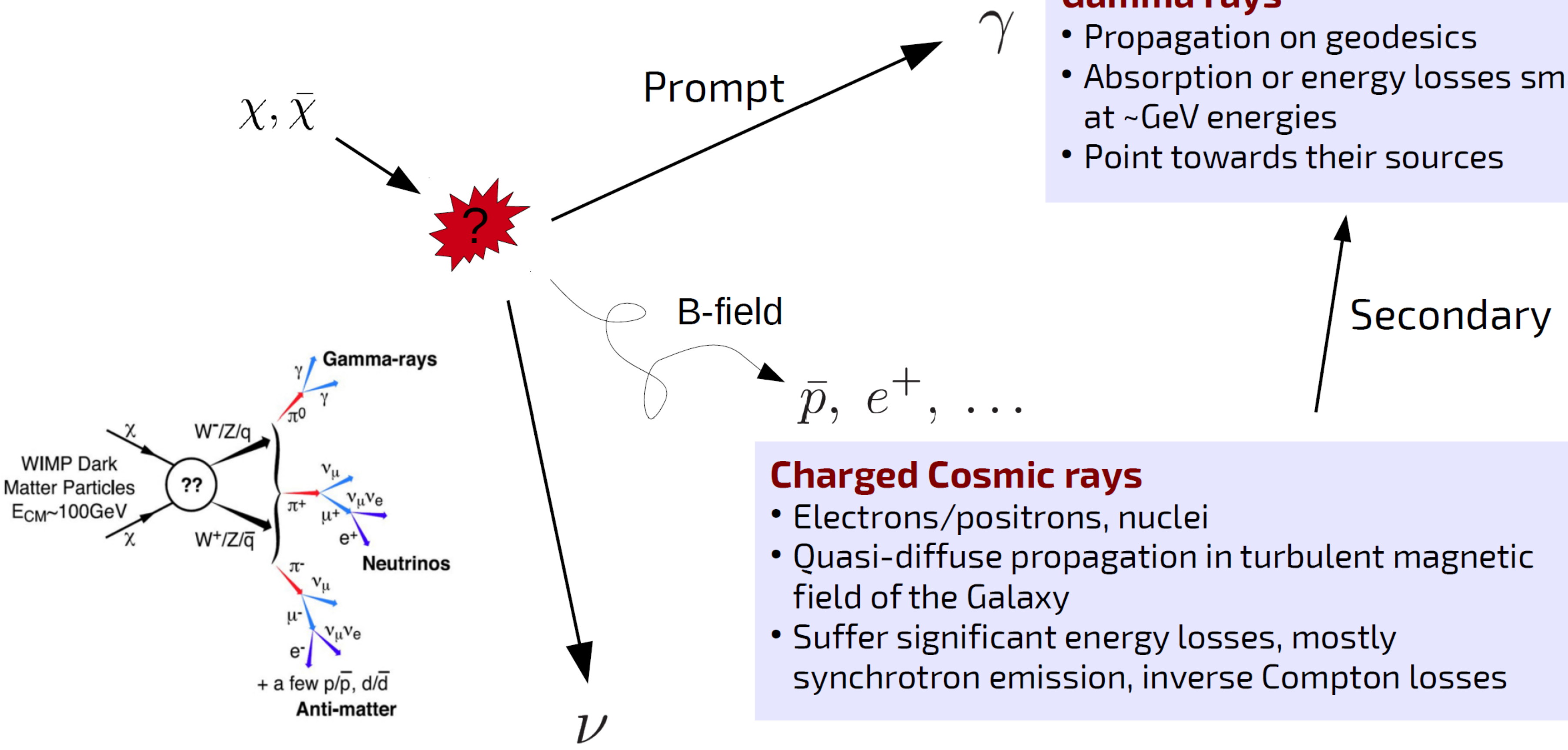
neutrinos

How much energy is dumped into the different particles depends on the annihilation channel & energy
(*) expected background is much lower for antimatter than for matter (but not negligible: positrons and antiprotons are produced through cosmic-ray collisions in the Galaxy)

Juan A. Aguilar, Dark Ghost 2022

Products propagation





Gamma rays
- Propagation on geodesics
- Absorption or energy losses small at ~GeV energies
- Point towards their sources

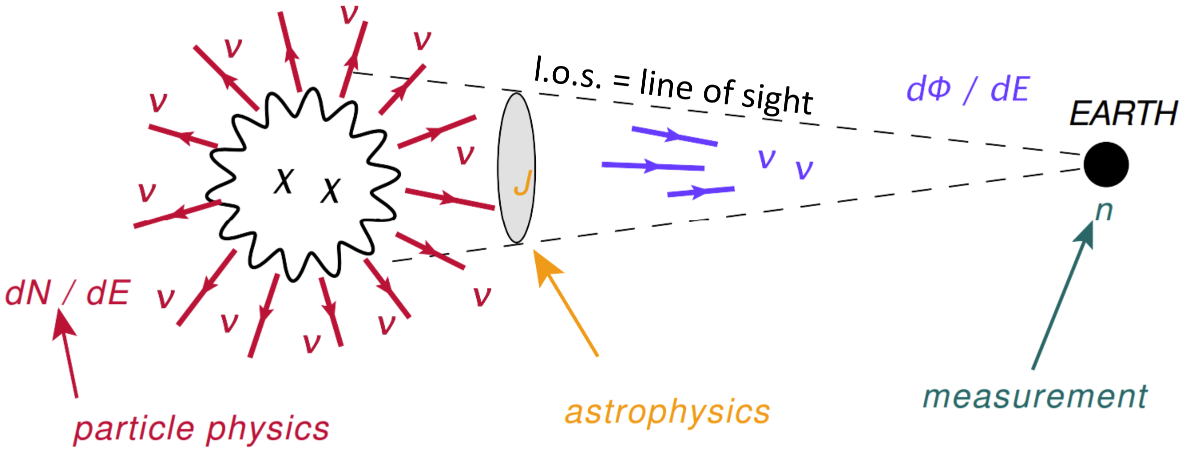
Charged Cosmic rays
- Electrons/positrons, nuclei
- Quasi-diffuse propagation in turbulent magnetic field of the Galaxy
- Suffer significant energy losses, mostly synchrotron emission, inverse Compton losses

Neutrinos
- Geodesics
- Very hard to measure
- Can escape from the core of dense stellar objects

Gammas/neutrinos flux @ Earth

Annihilation

$$\frac{d\Phi}{dE} = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\overset{\text{spectrum}}{\frac{dN}{dE}}\;\overbrace{\int_0^{\Delta\Omega} d\Omega \int_{l.o.s} \rho_\chi^2(r(s,\Psi,\theta))ds}^{\text{J-factor}}$$



Particle physics

Astrophysics

depends on the
density profile!
Common choice: NFW

Decay

$$\frac{d\Phi}{dE} = \frac{1}{4\pi}\frac{1}{m_\chi\tau_\chi}\frac{dN}{dE}\int_0^{\Delta\Omega} d\Omega \int_{l.o.s} \rho_\chi(r(s,\Psi,\theta))ds$$

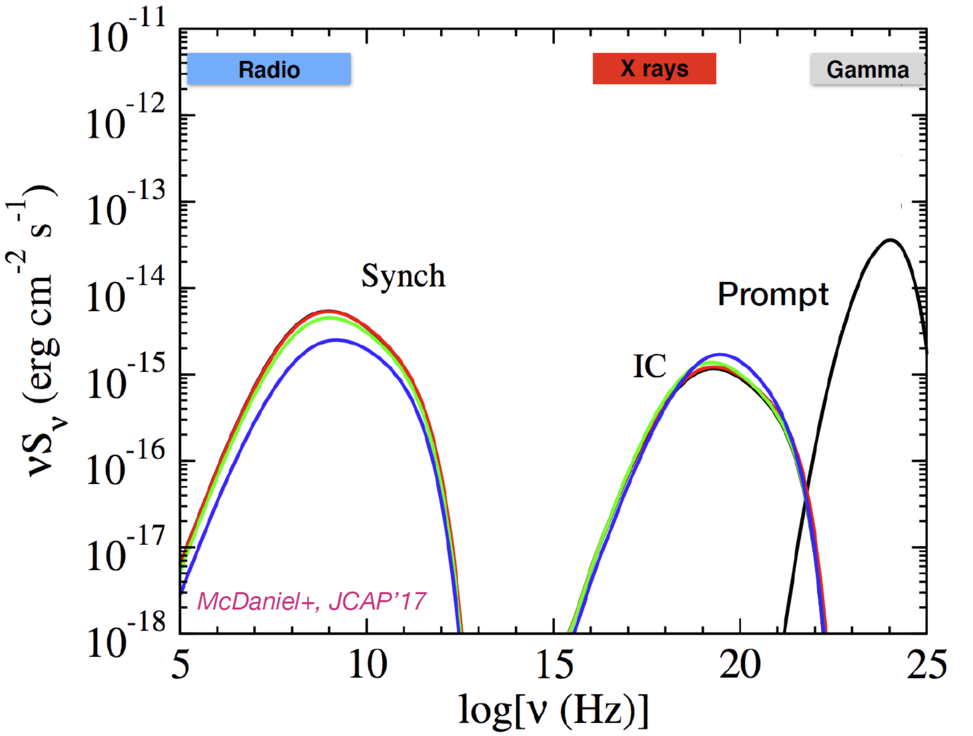
Adapted from Juan A. Aguilar & R. Gozzini, Dark Ghost 2022

Secondary emission

“Secondary” radiative emission induced by leptonic particles interacting with the environment

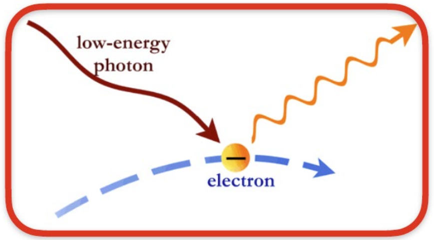
Charged particles from DM annihilation can also give rise to *secondary* photons, due to upscattering of ambient photons from starlight or the CMB, and synchrotron radiation from high-energy charged particles propagating in a magnetic field.

F. Calore, TAUP22

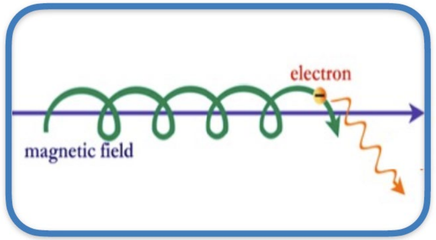


Example: Annihilation into b-quarks; m_{DM} = 100 GeV

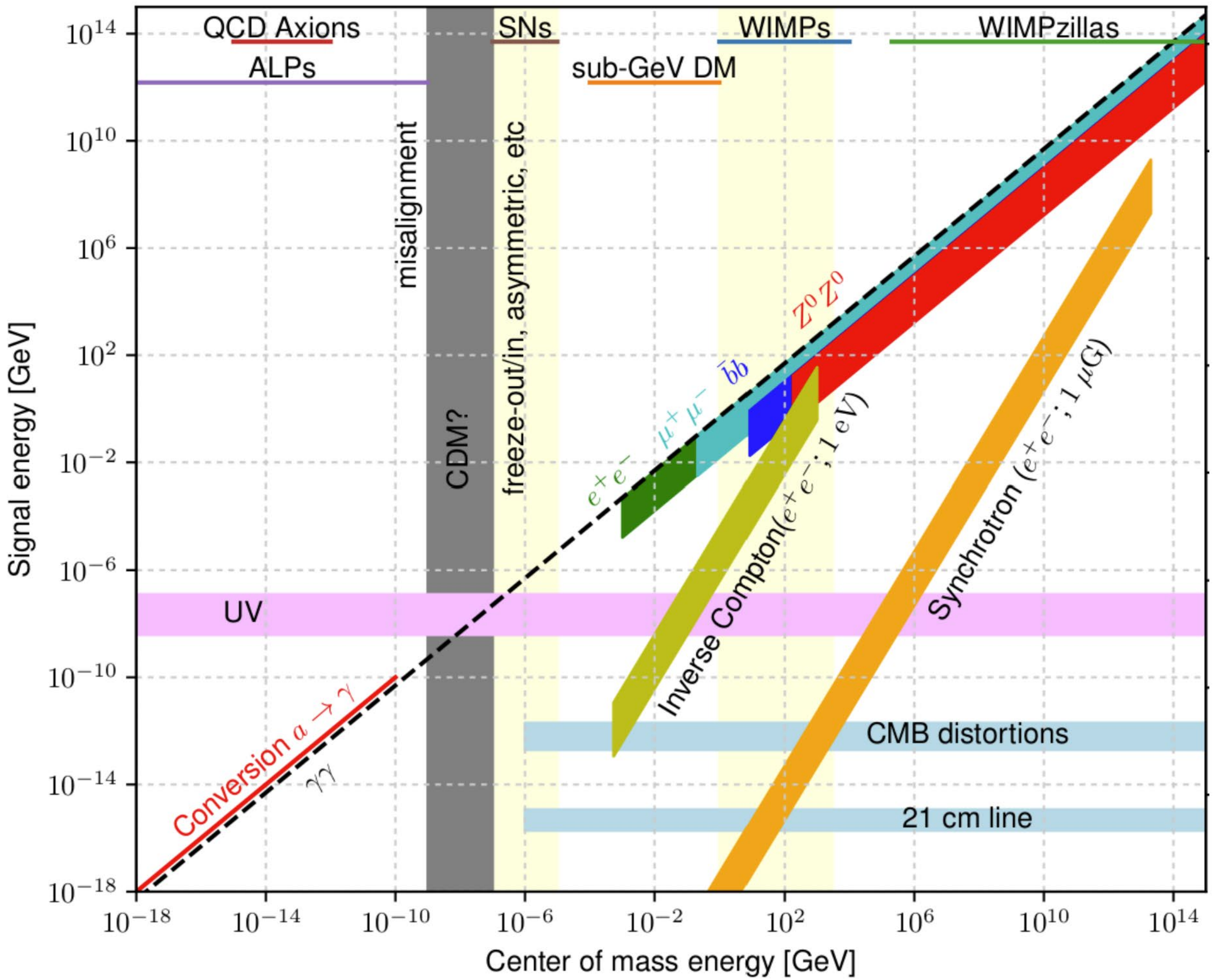
Inverse Compton scattering



Synchrotron emission



Relevant radiation mechanisms



CSW, in prep

UHECRs

Gamma rays &
Cosmic rays

X rays

UV

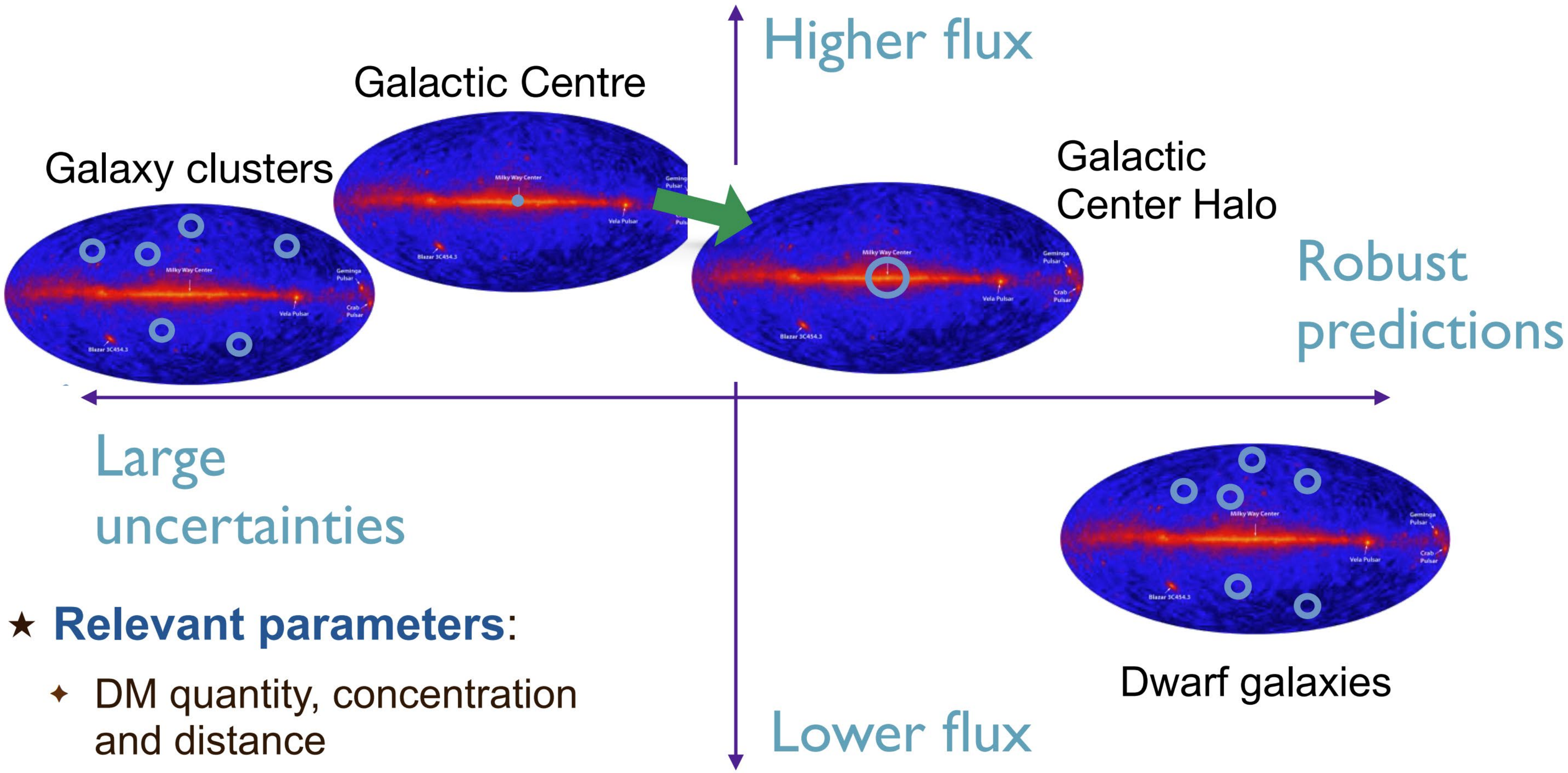
Optical/IR

CMB

Radio

1 Sep 2017 C. Weniger - Indirect DM searches

Sources for gamma ray searches



Higher flux

Galactic Centre

Galaxy clusters

Galactic Center Halo

Robust predictions

Large uncertainties

Dwarf galaxies

Lower flux

★ **Relevant parameters**:

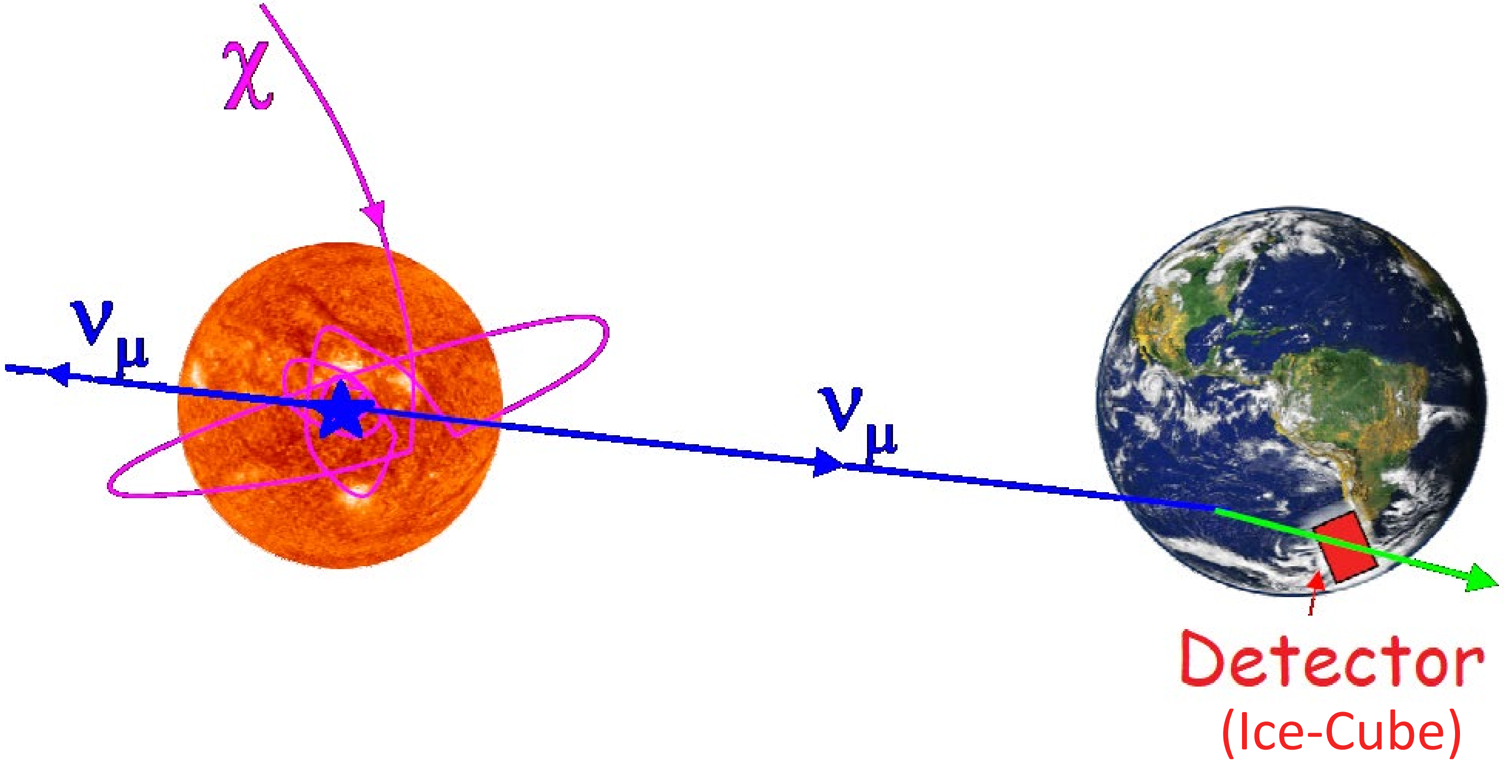
- DM quantity, concentration and distance
- Uncertainties
- Astrophysical background

J. Rico, Dark Ghost 2022

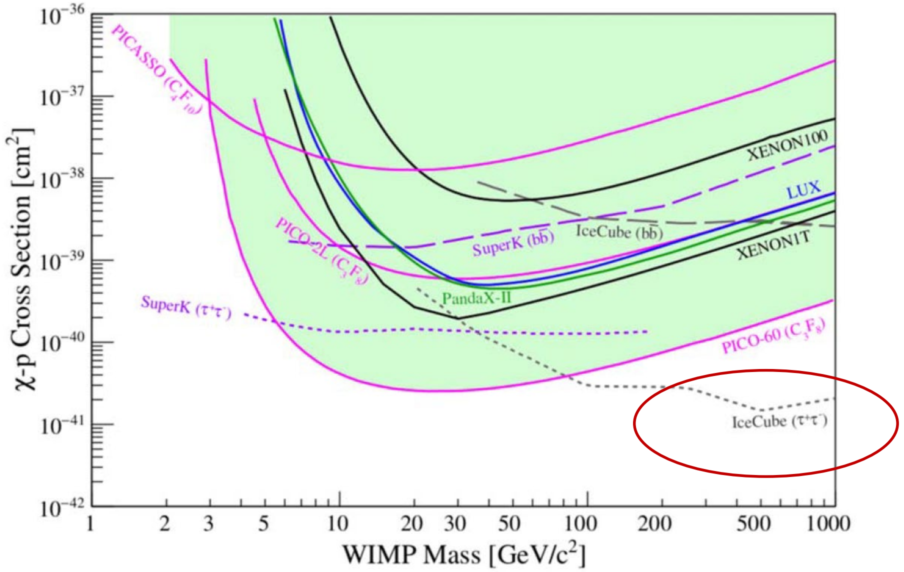
Sources (neutrinos)

Neutrino telescopes can also search for DM annihilation in the galactic center, but the most promising searches are for DM annihilation in the Sun

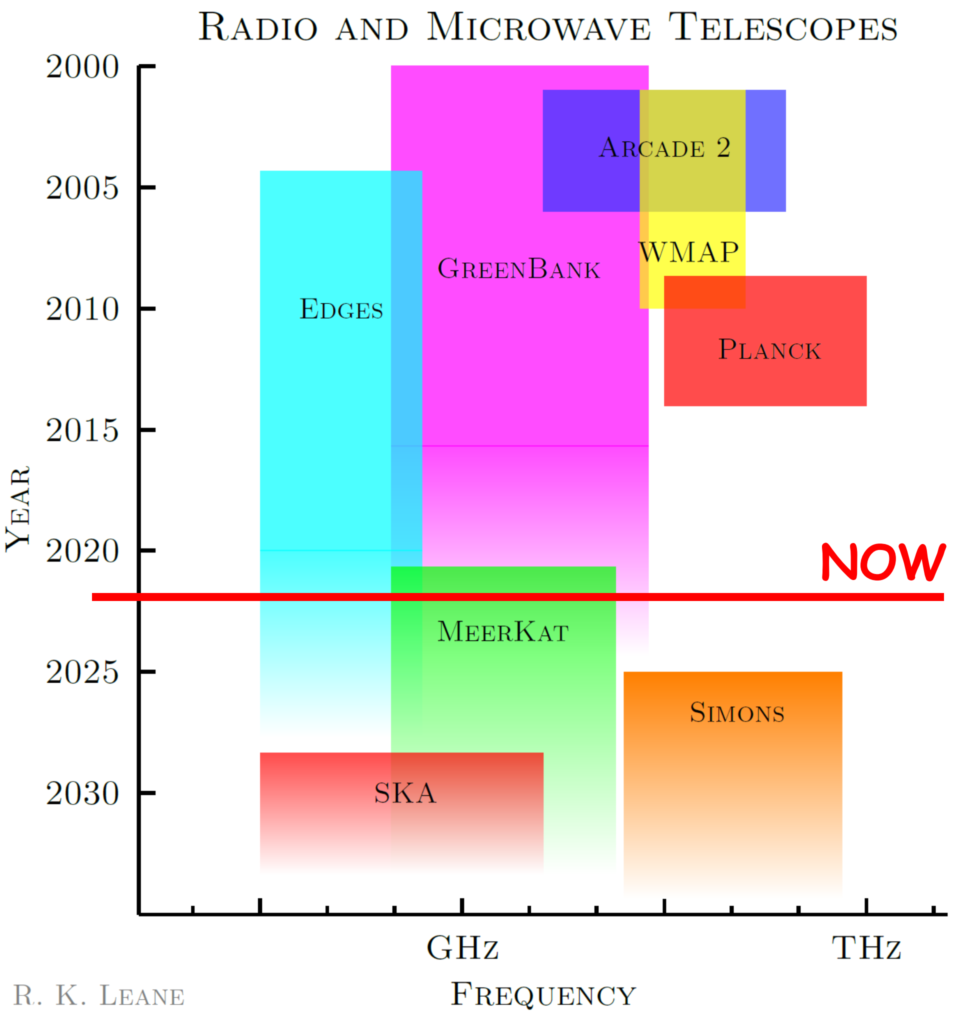
DM can be trapped in the Sun and annihilate. Only neutrinos can scape, and they would be a very clear signal of DM

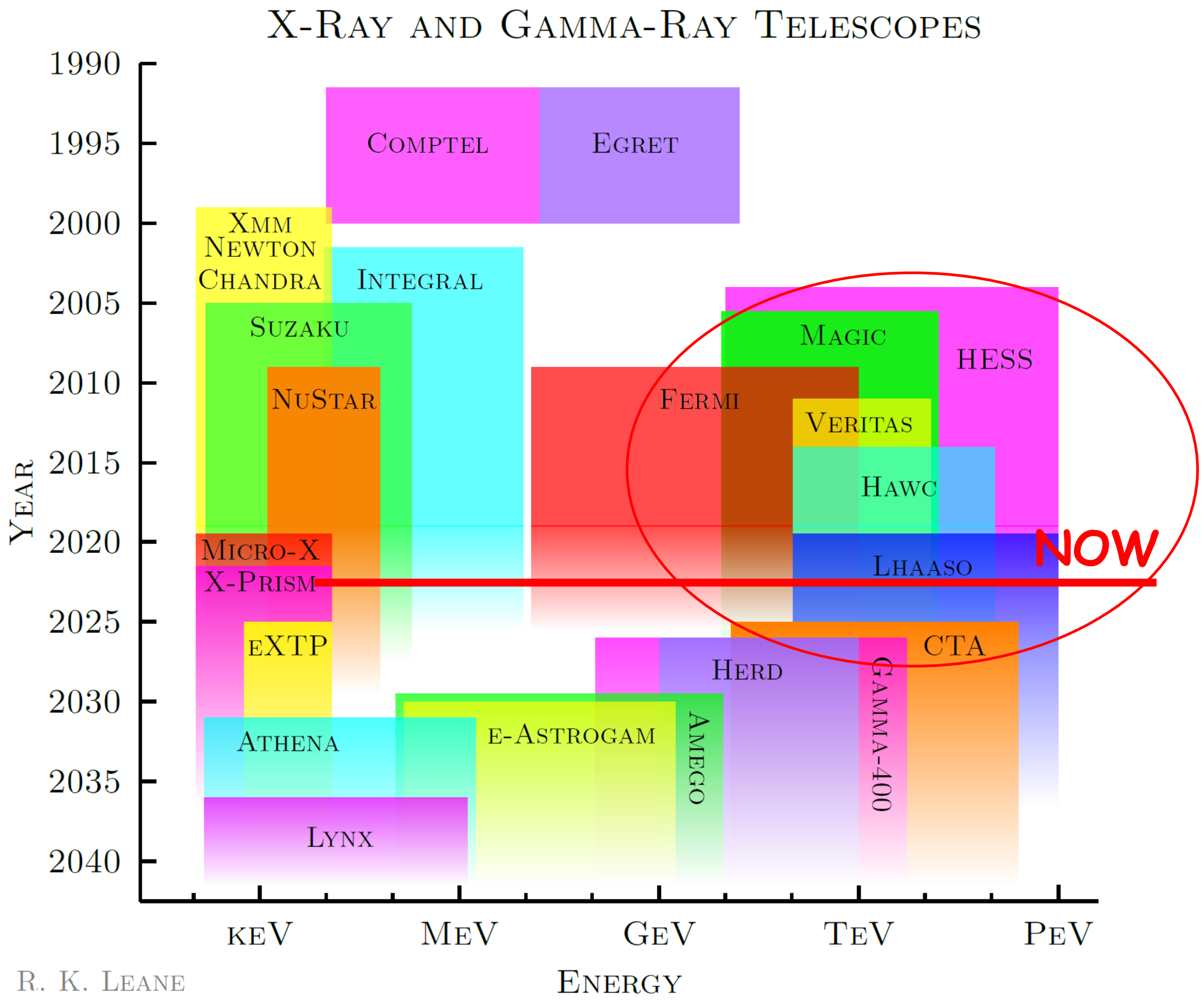


To calculate the annihilation rate, one assumes equilibrium with capture probability → related to σ_{scatt}, same cross section as for direct detection



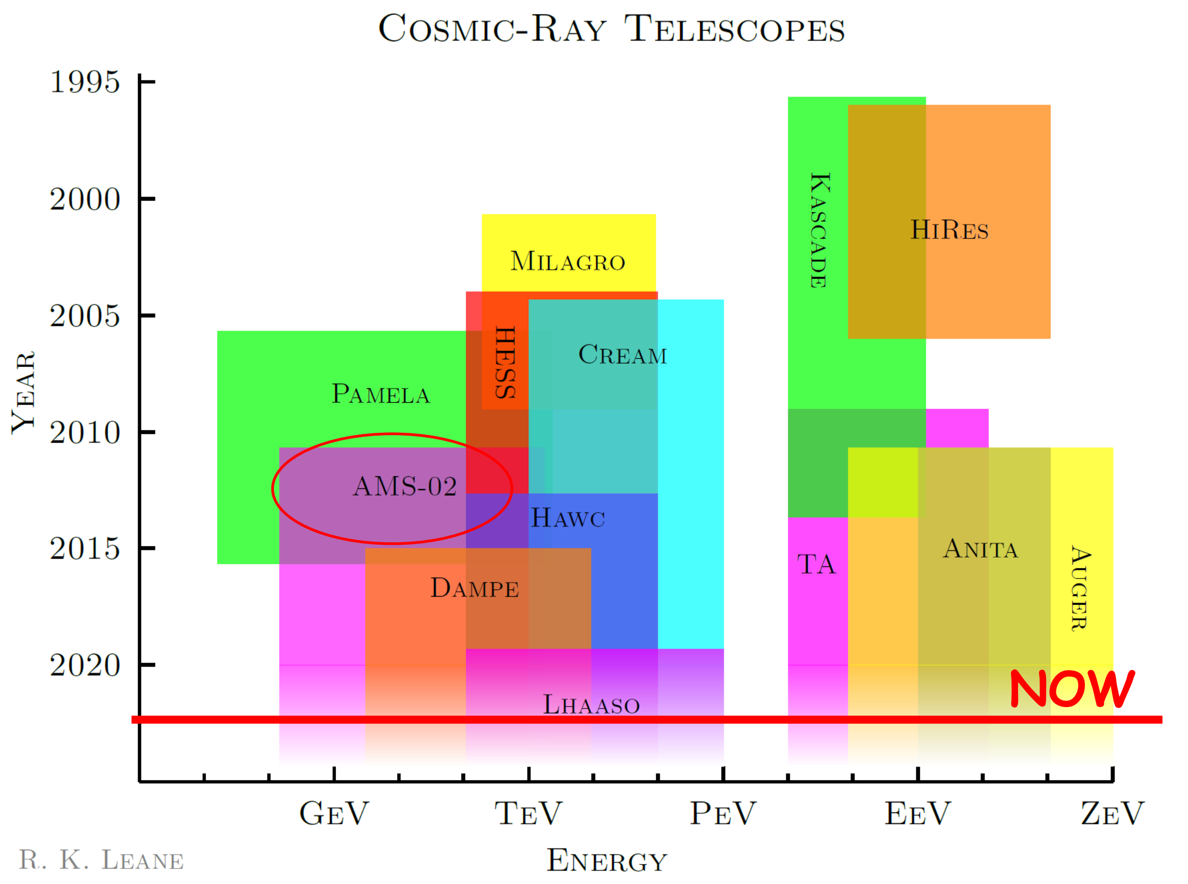
DM ID experiments: radio, microwave, x-ray, $\gamma's$

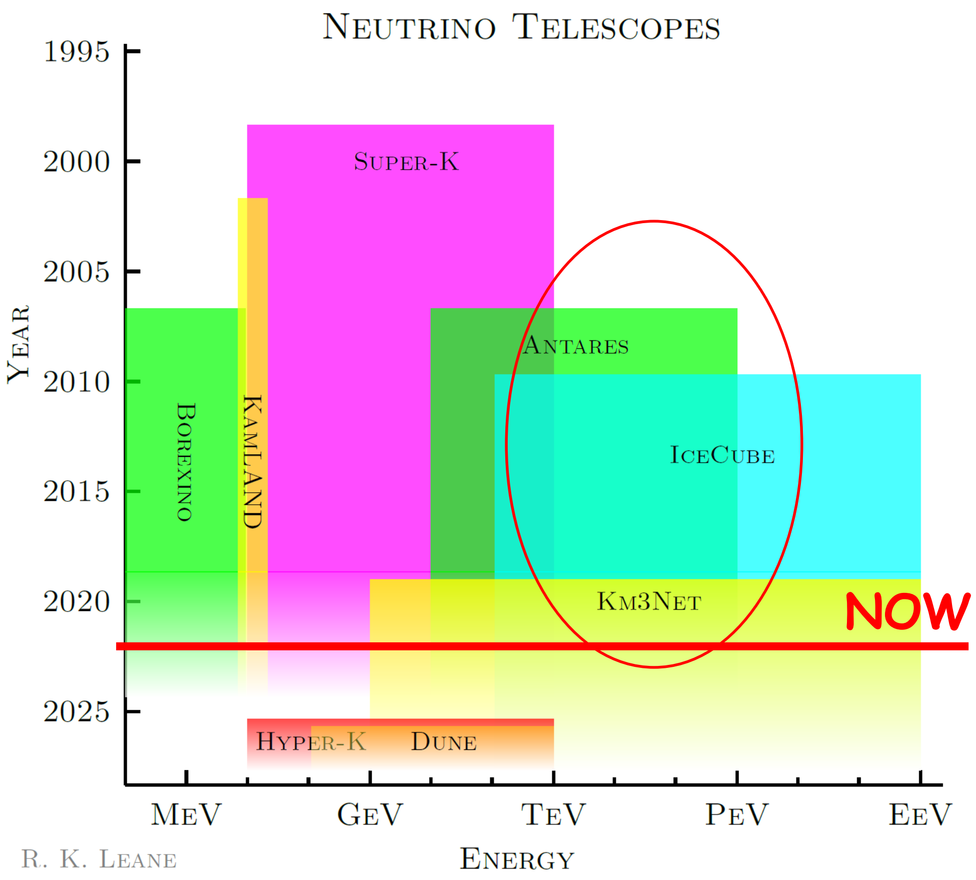




Slatyer'21

Cosmic rays and neutrino telescopes

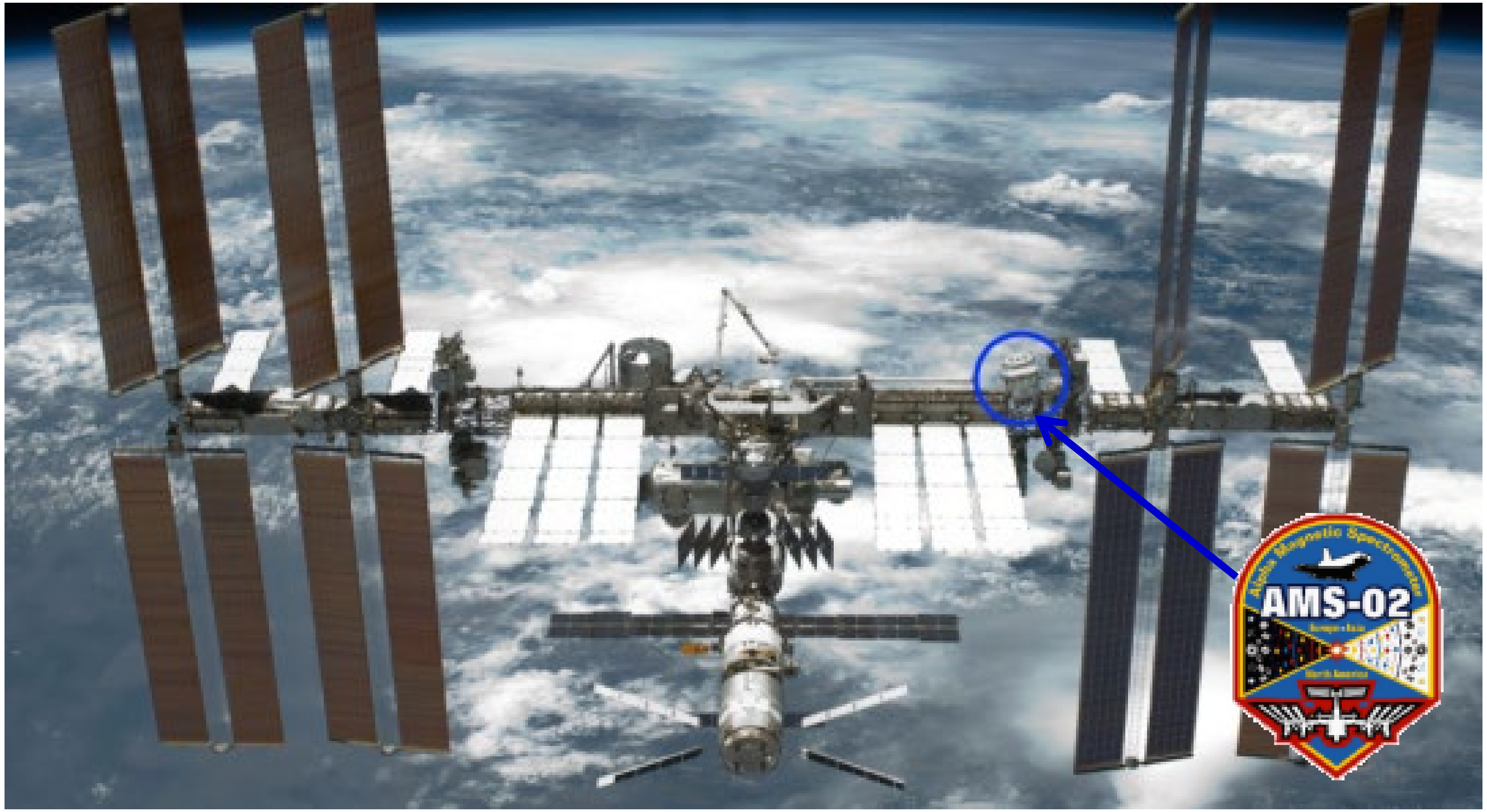


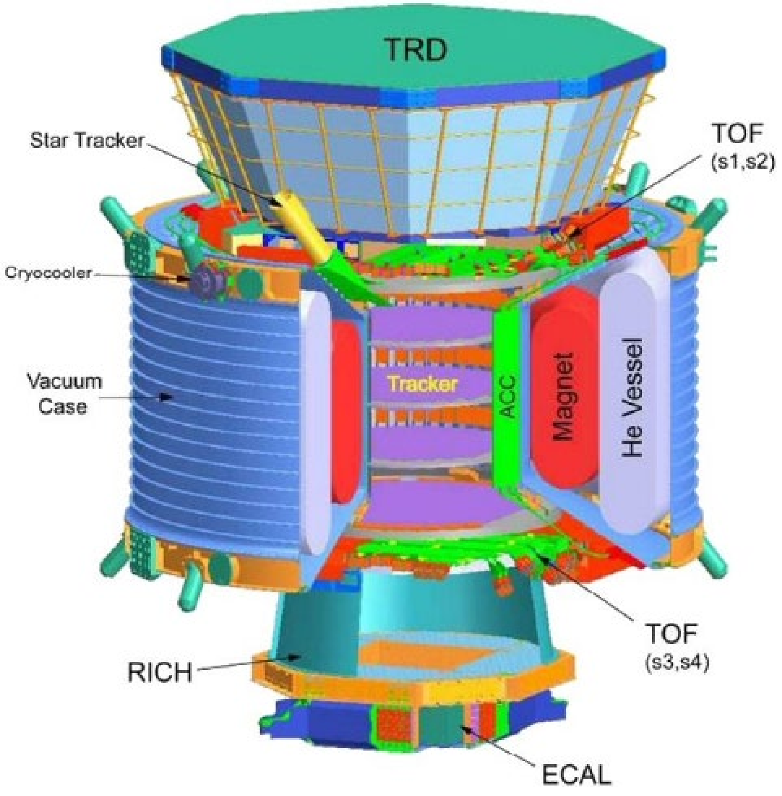


Slatyer'21

Antimatter: AMS02

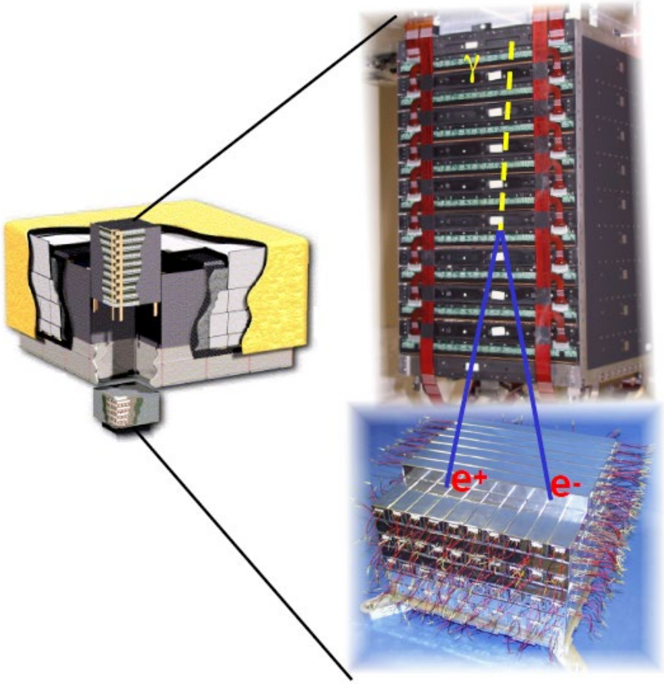
Alpha Magnetic Spectrometer (AMS-02), a detector operating on the **International Space Station** (**ISS**).





Gammas from the space: FermiLAT

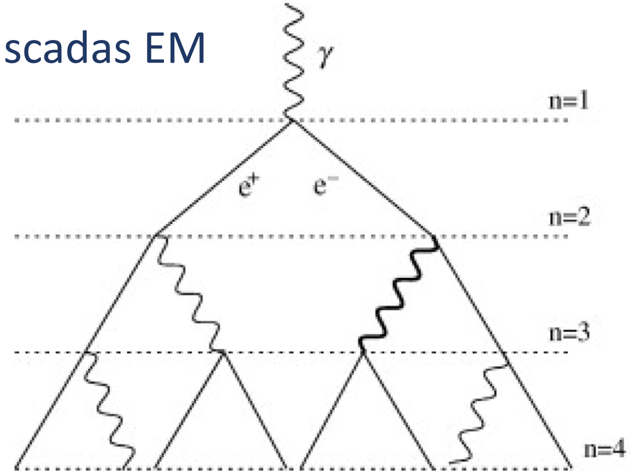
- **Space-borne telescope**:
  - Operating since August 2008
  - Anti-coincidence shield + tracker + calorimeter
- Almost **background free**
- **Energy range** 100 MeV - 300 GeV
- **Energy resolution**: 10-15%
- **Angular resolution**: ~1º(0.1º) @ 1 (100) GeV
- **Field of view**: 2.4 sr (1/5 of sky)
- **Full sky survey** every 2 orbits (~3 hours)
- **~100% duty cycle**

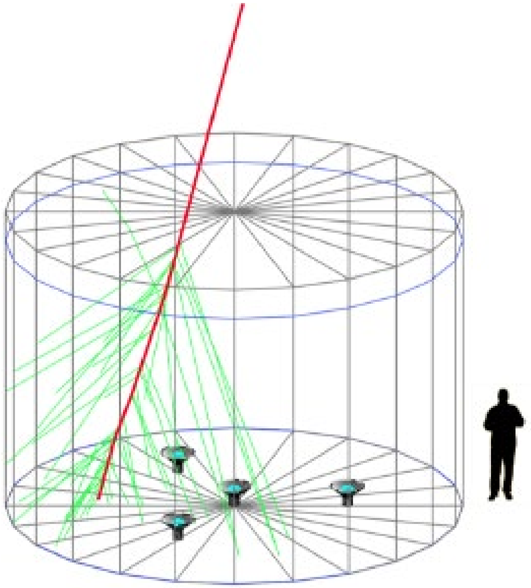


J. Rico, Dark Ghost 2022

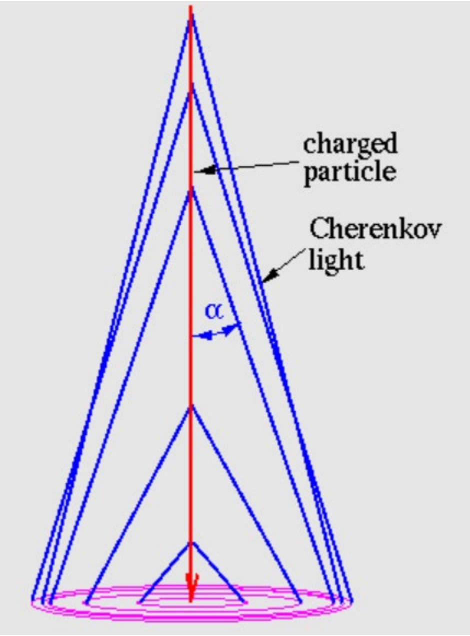
High energy gammas: HAWC & LHASO

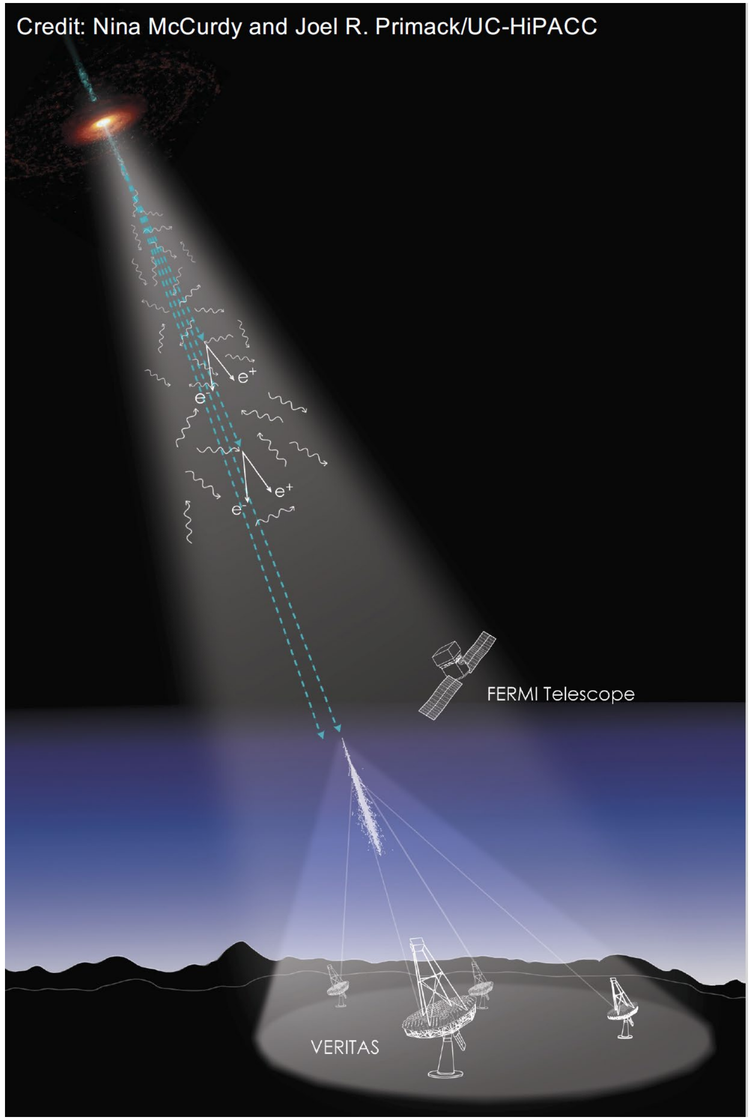
Cascadas EM





High energy gammas : Atmospheric Cherenkov telescopes

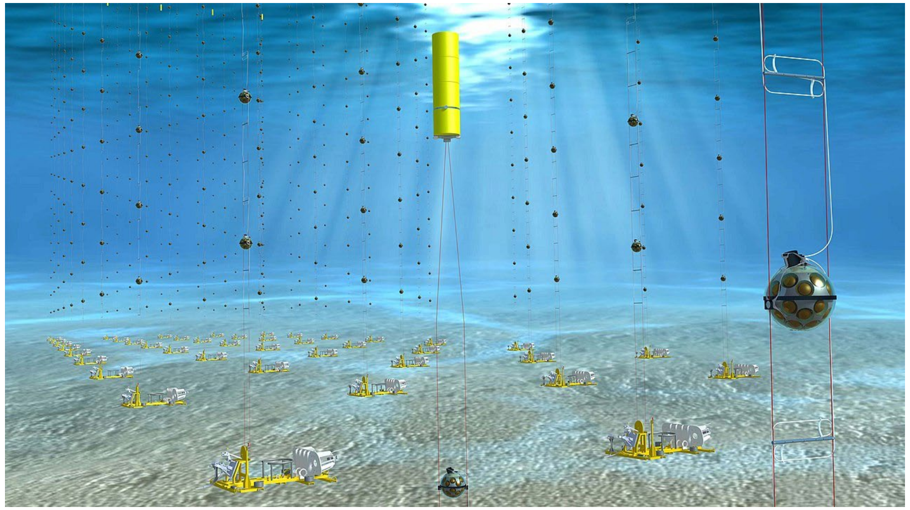


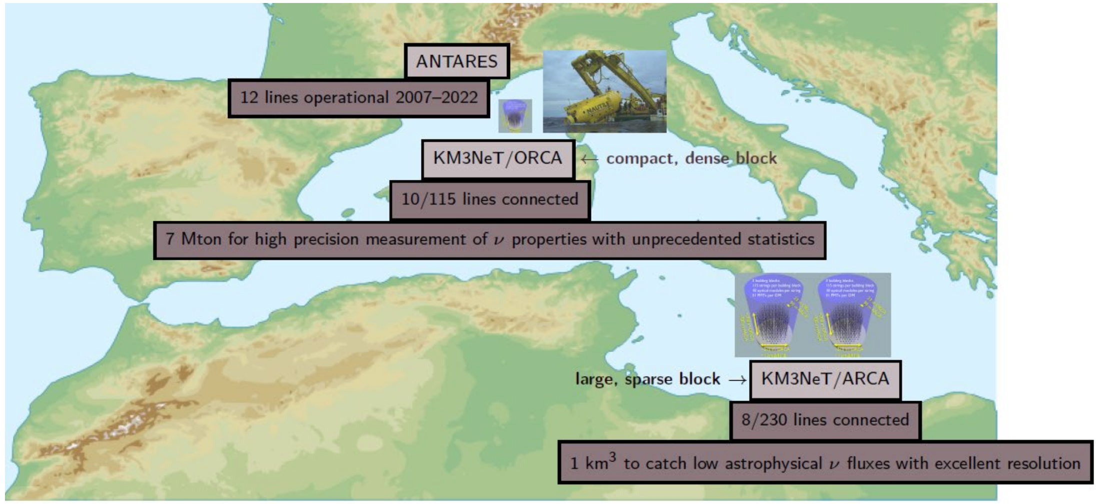

Credit: Nina McCurdy and Joel R. Primack/UC-HiPACC

FUTURE: CTA

Neutrinos: ICE-cube / Km3net

Km3net (Under Mediterranean See)




ANTARES

12 lines operational 2007–2022

KM3NeT/ORCA ← compact, dense block

10/115 lines connected

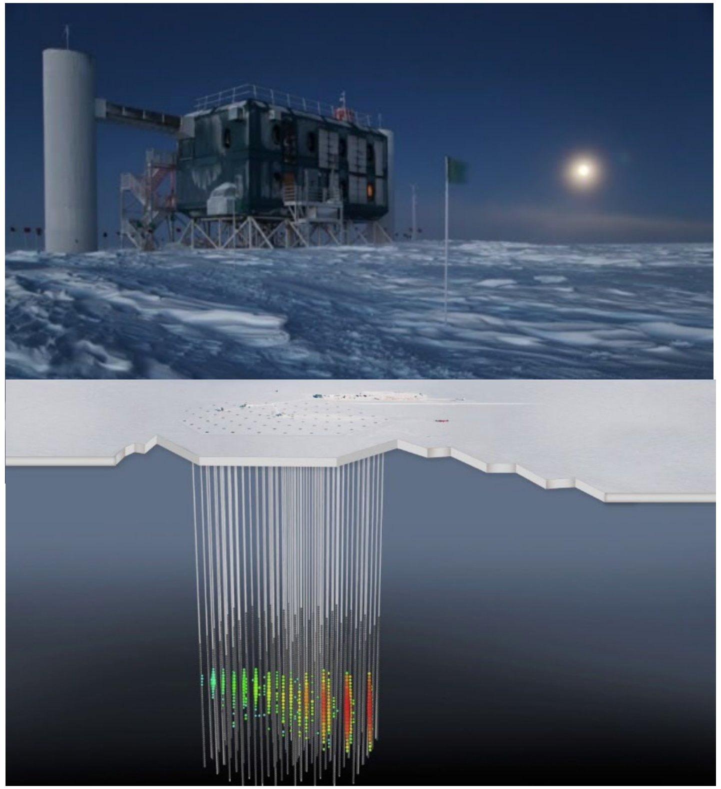
7 Mton for high precision measurement of ν properties with unprecedented statistics

large, sparse block → KM3NeT/ARCA

8/230 lines connected

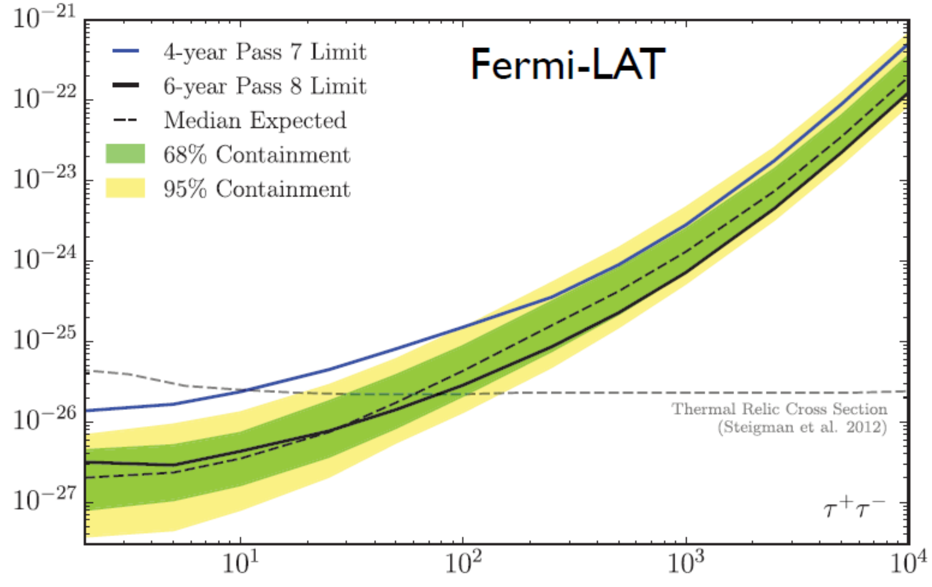
1 km^3 to catch low astrophysical ν fluxes with excellent resolution

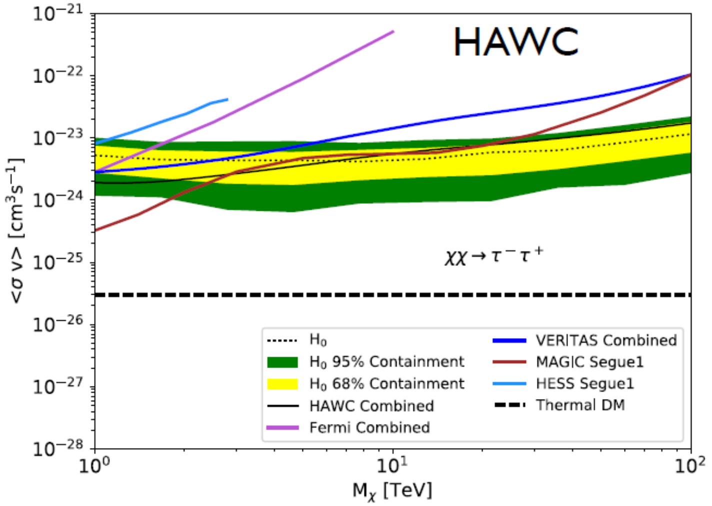
ICECUBE (South Pole)



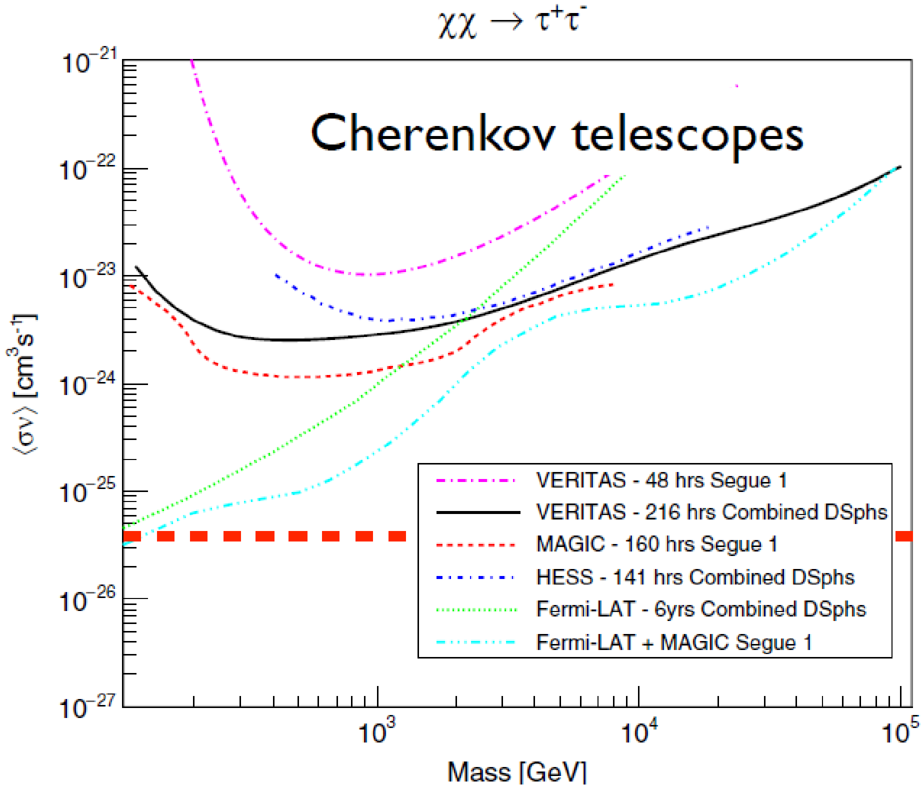
Limits from dwarf spheroidal galaxies

Ackermann at al. PRD89(2014)042001





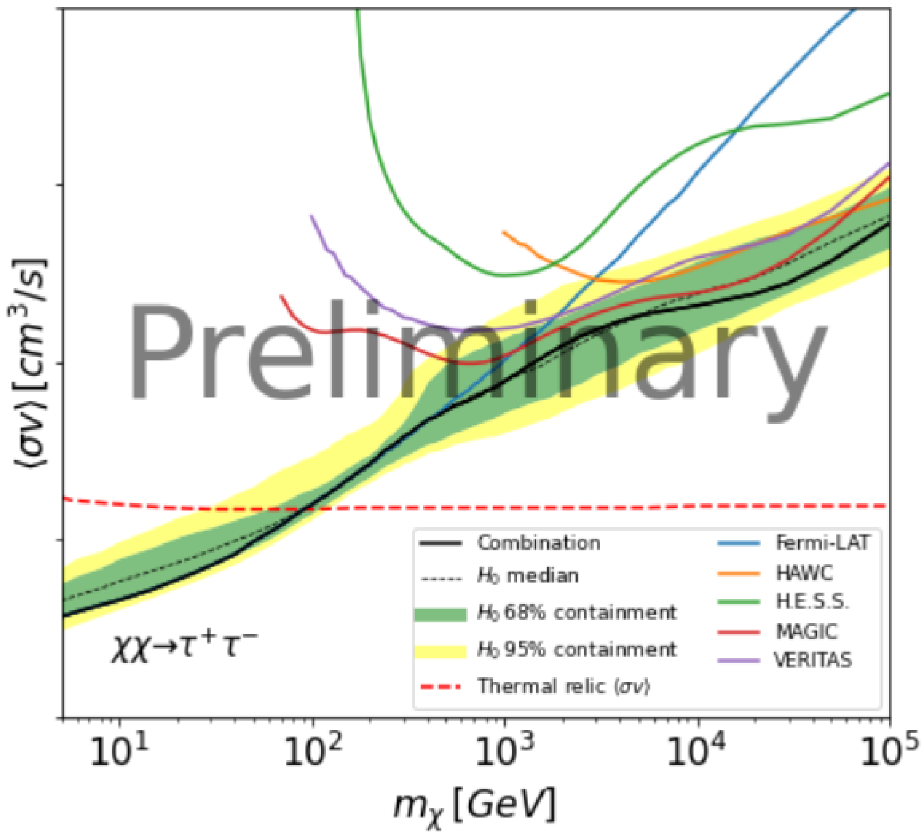
Albert et al.ApJ853(2018)154



Archambault et al. PRD95(2017)082001

Combined analysis: The Glory Duck project

dSph	Instrument[s]
Boötes I	VERITAS, HAWC, Fermi,
Canes Venatici I	HAWC, Fermi
Canes Venatici II	HAWC, Fermi
Carina	HESS, Fermi
Coma Berenices	MAGIC, HESS, HAWC, Fermi
Draco	MAGIC, VERITAS, HAWC,
Fornax	HESS, Fermi
Hercules	HAWC, Fermi
Leo I	HAWC, Fermi
Leo II	HAWC, Fermi
Leo IV	HAWC, Fermi
Leo T	Fermi
Leo V	Fermi
Sculptor	HESS, Fermi
Segue 1	MAGIC, VERITAS, HAWC,
Segue 2	Fermi
Sextans	HAWC, Fermi
Ursa Major I	HAWC, Fermi
Ursa Major II	MAGIC, HAWC, Fermi
Ursa Minor	VERITAS, Fermi

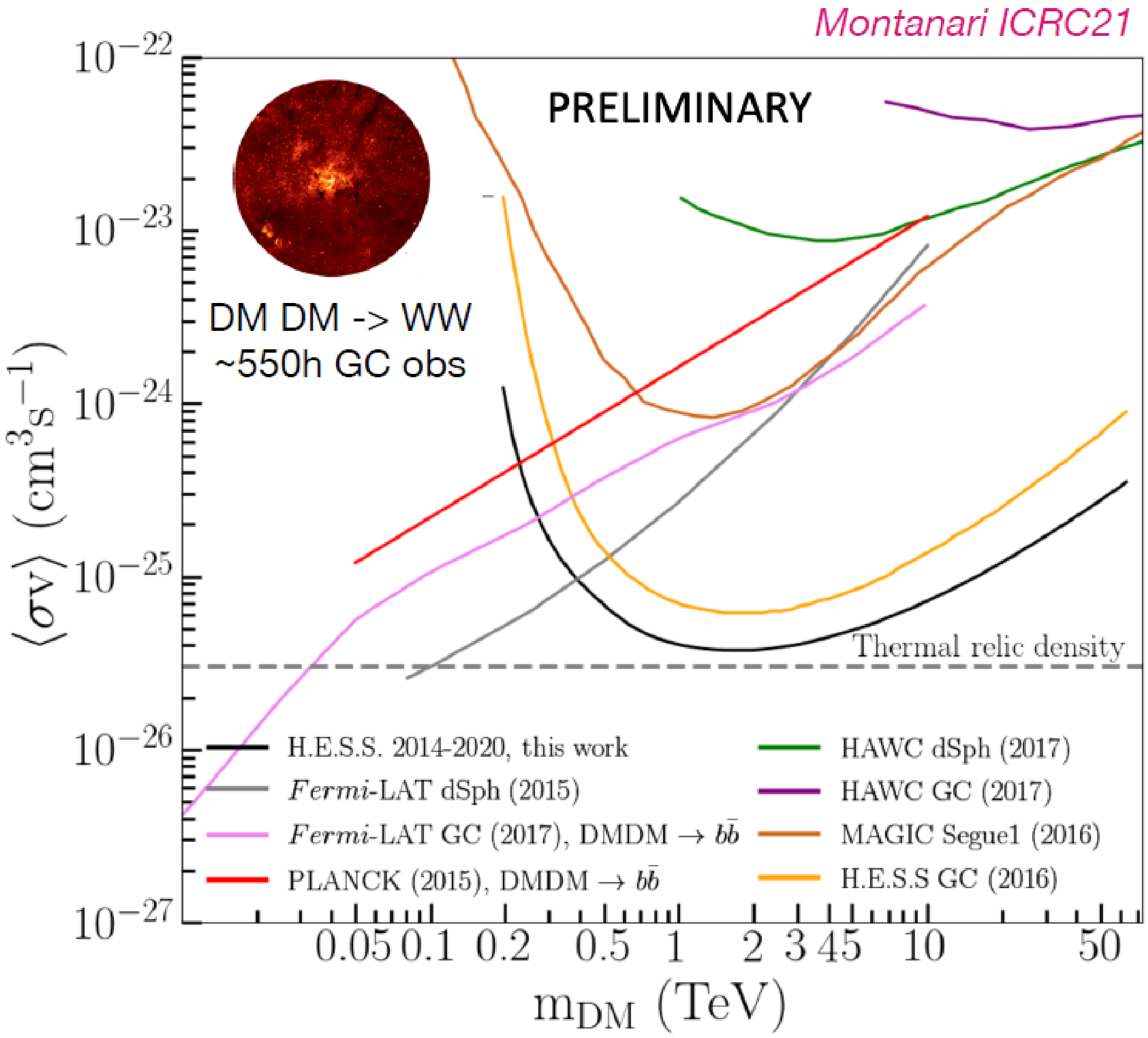


PoS ICRC2021 (2021) 528

GLORY DUCK

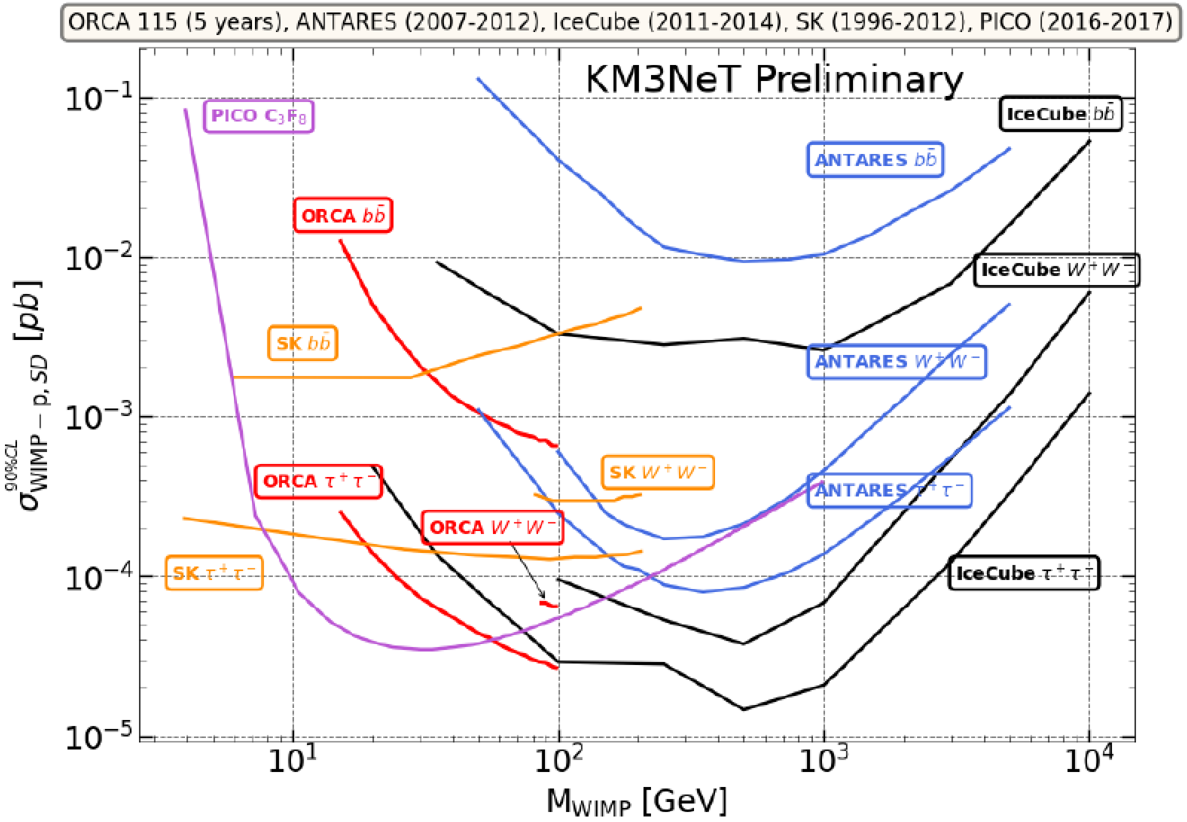
J. Rico, Dark Ghost 2022

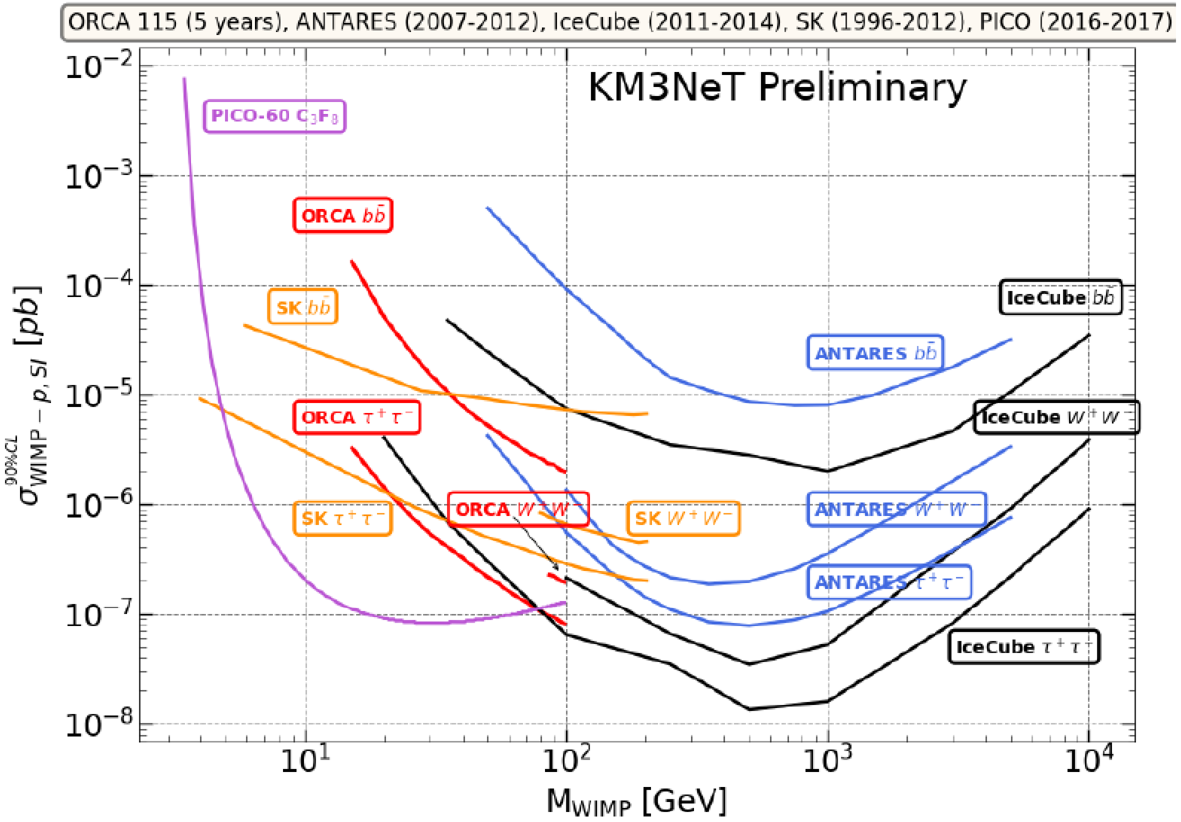
Limits from the galactic center



Neutrinos from the Sun

→ **Limits to the scattering cross-section (SD, SI), directly comparable with DD limits**



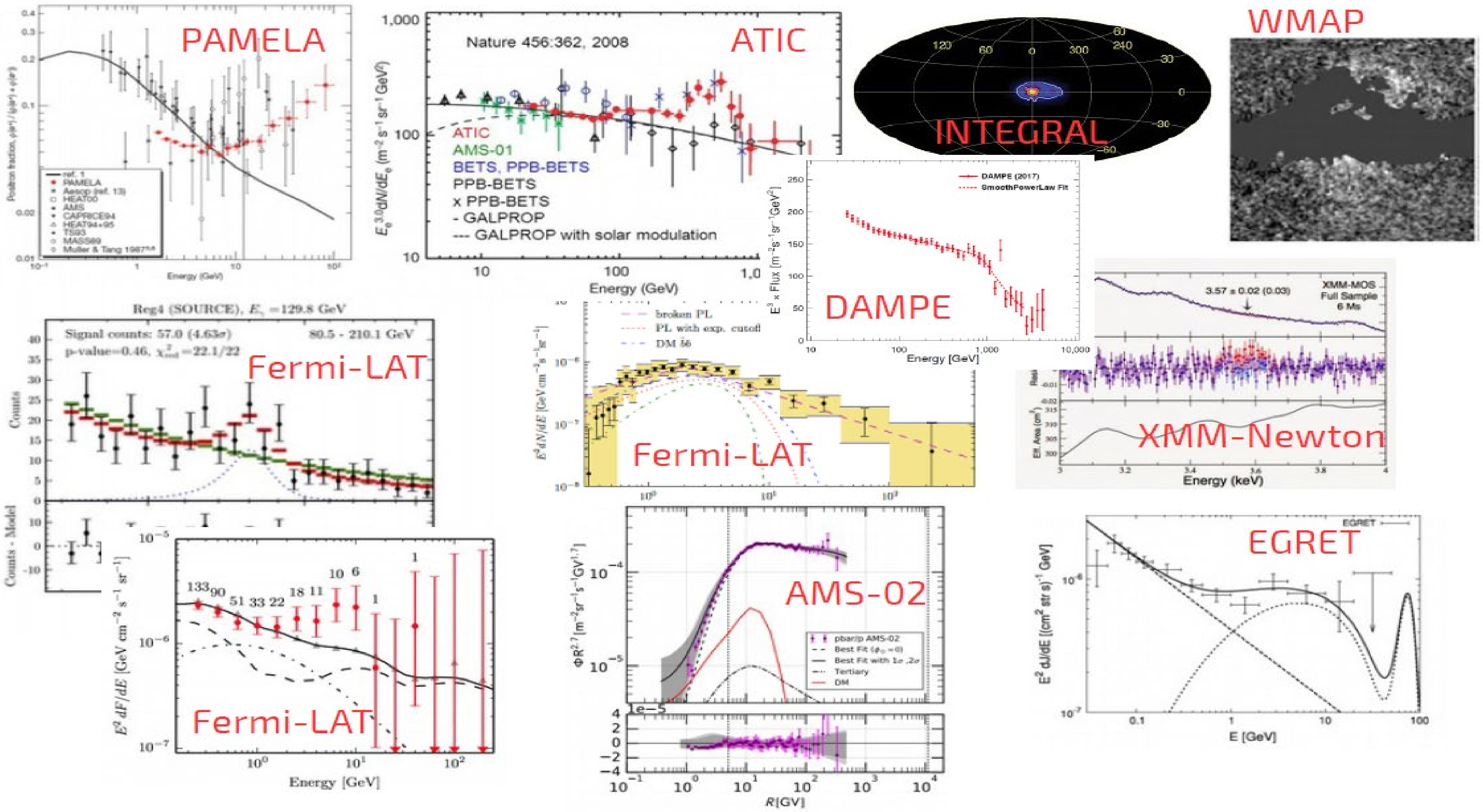


R. Gozzini, Dark Ghost 2022

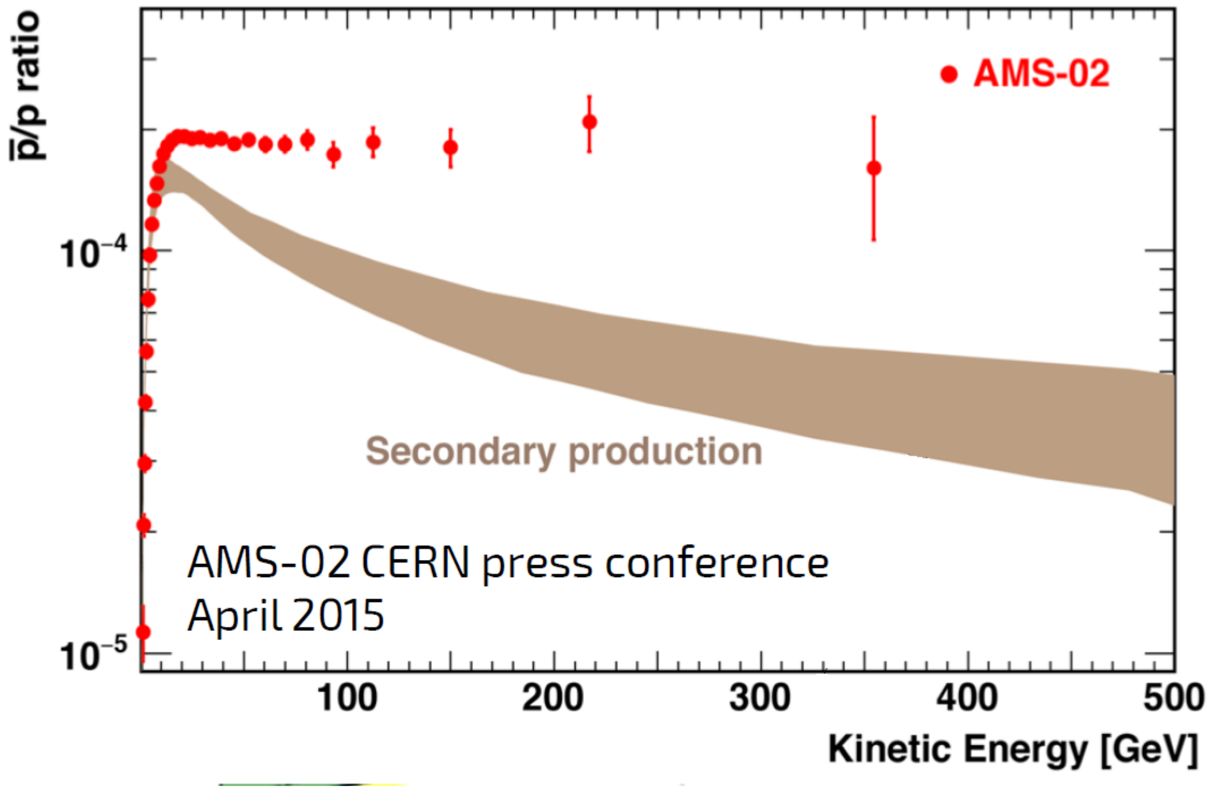
(NOTE: Orca limits are projections)

Some signal claims

C. Weniger, ATI PhD school, UCLA 2018



The AMS-02 antiproton excess

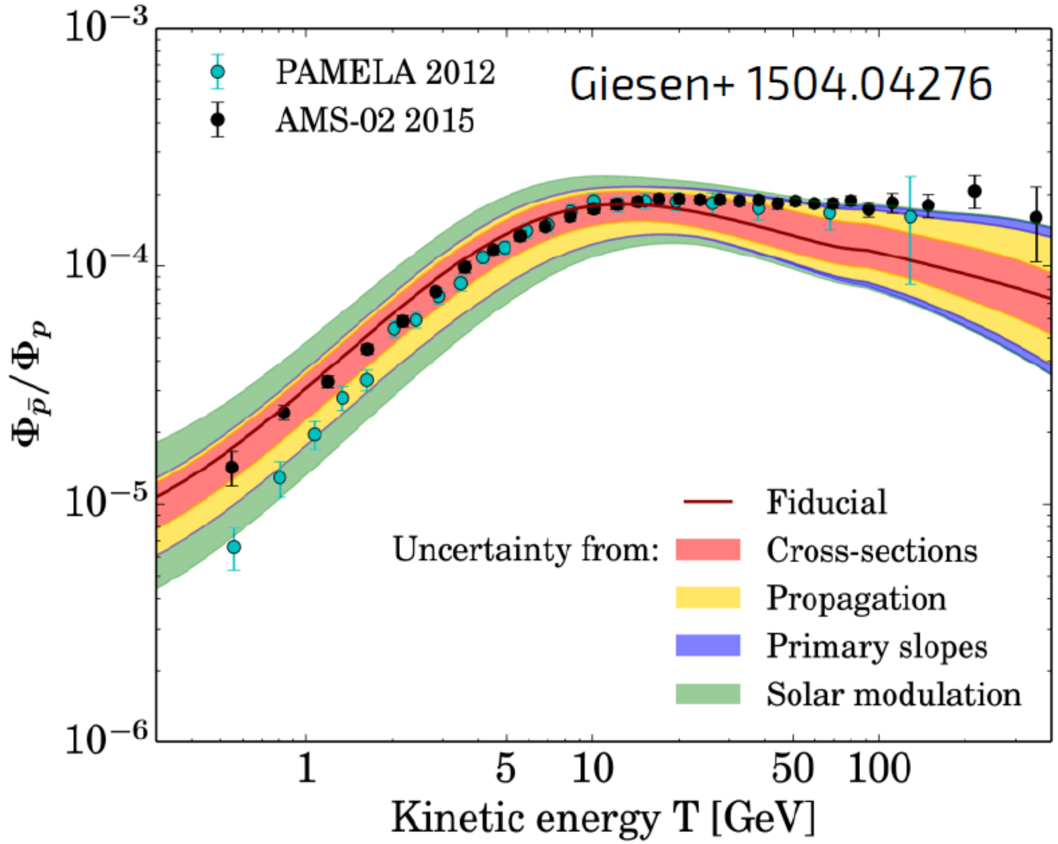


AMS-02 CERN press conference
April 2015

But this plot does not take into account all the present uncertainties

CURRENT SITUATION:

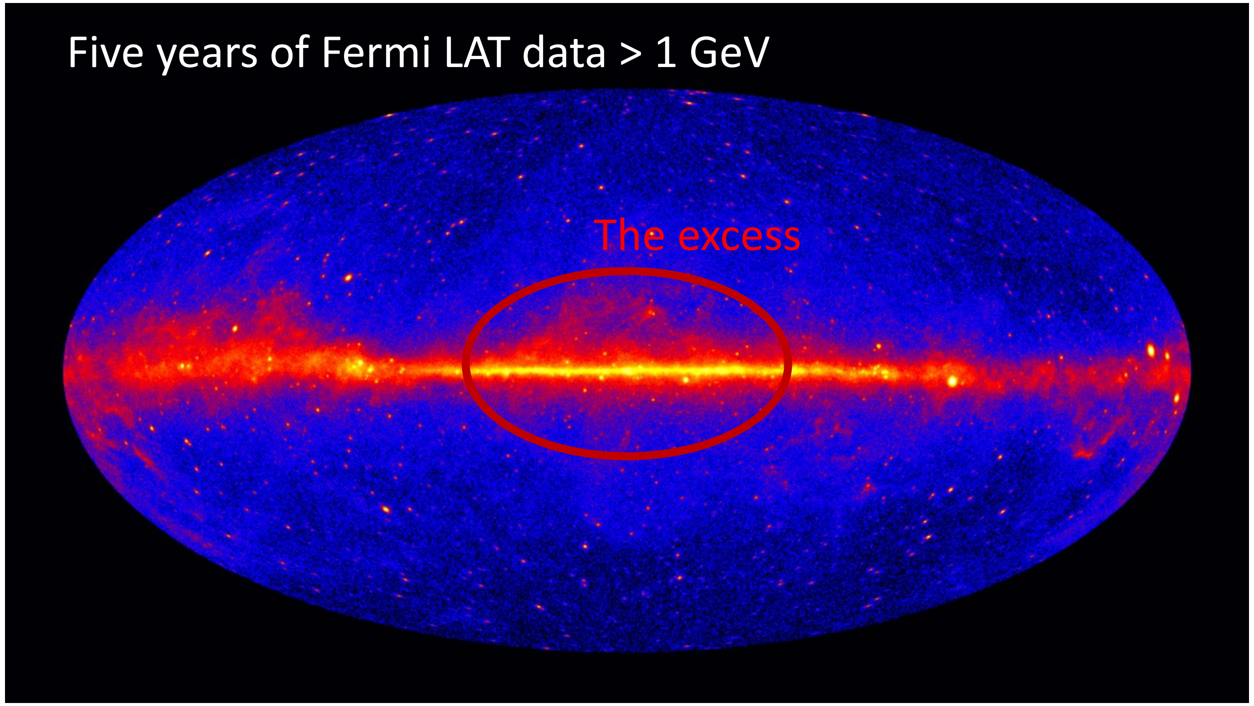
No excess observed above astrophysical background, when all uncertainties are taken into account → Only upper limits



Giesen+ 1504.04276

C. Weniger, ATI PhD school, UCLA 2018

The Galactic Center GeV Gamma-Ray Excess



Papers that looked at data

- Goodenough & Hooper, arXiv:0910.2998
- Vitale & Morselli, 2009
- Hooper & Goodenough, Phys. Lett. B697 (2011) 412
- Hooper & Linden, Phys. Rev. D84 (2011) 123005
- Boyarsky, Malyshev & Ruchayskiy, Phys. Lett. B705 (2011) 165
- Abazajian & Kaplinghat, PRD 86 (2012) 083511
- Hooper & Slatyer, Phys. Dark Univ. 2 (2013) 118
- Gordon & Macias, Phys. ReV. D88 (2013) 083521
- Macias & Gordon, PRD 89 (2014) 063515
- Abazajian, Canac, Horiuchi, Kaplinghat, Phys. Rev. D90 (2014) 023526
- Cholis, Evoli, Calore, Linden, Weniger, Hooper, JCAP 1512 (2015) 12
- Calore, Cholis & Weniger, JCAP 1503 (2015) 038
- Zhou, Liang, Huang, Li, Fan, Chang, Phys. Rev. D91 (2015) 123010
- Gaggero, Taoso, Urbano, Valli & Ullio, JCAP 1512 (2015) 056
- Daylan, Finkbeiner, Hooper, Linden, Portillo et al., Physics of Dark Universe 12 (2016) 1
- De Boer, Gebauer, Neumann, Biermann, arXiv:1610.08926 (ICRC 2016 proceedings)
- Huang, Ensslin & Selig, JCAP 1604 (2016) 030
- Carlson, Linden, Profumo, Phys. Rev. D94 (2016) 063504
- Bartels, Krishnamurthy, Weniger, Phys. Rev. Lett. 116 (2016) 5
- Macis, Gordon, Crocker, Coleman, Paterson, arXiv:1611.06644
- Lee, Lisanti, Safdi, Slatyer, Xue, Phys. Rev. Lett. 116 (2016) 5
- Ajello et al. 2016, Astrophys. J. 819, 44
- Ackermann et al., 2017, Astrophys. J. 840, 43
- Ajello et al., 2017, arXiv:1705.00009 (+ a few that I must have missed)

Excess is likely DM
Excess is there
Excess is likely not DM
Excess is not there

+ hundreds of DM theory papers

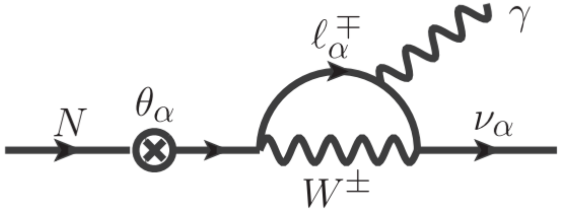
C. Weniger, ATI PhD school, UCLA 2018

The GeV excess is there, but is it a DM signal? Today, the leading explanations for this Galactic Center Excess are:

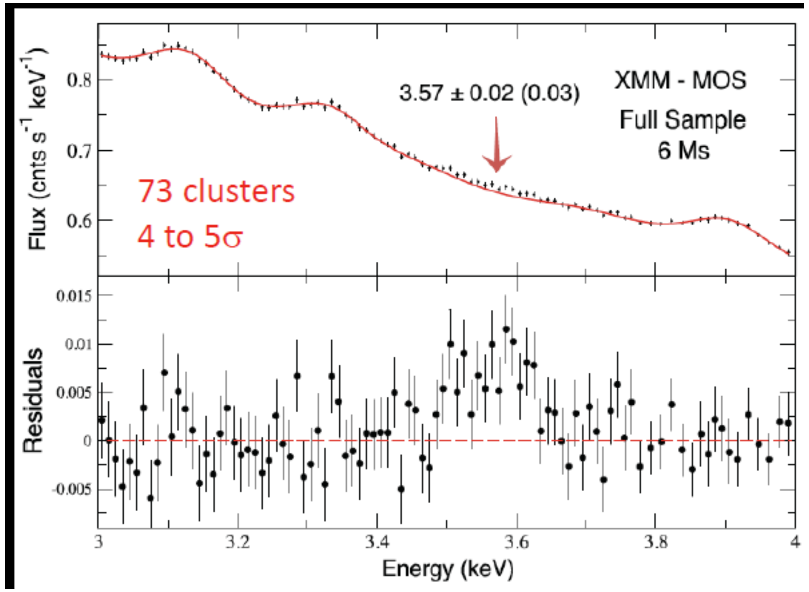
- a new population of millisecond pulsars
- annihilating dark matter.

7 keV sterile neutrino

- Xray DATA from XMM-Newton, Chandra, Fermi-GBM, ….
- Excess at 3.5 keV
- Posible explanation: decay of a 7 keV sterile neutrino

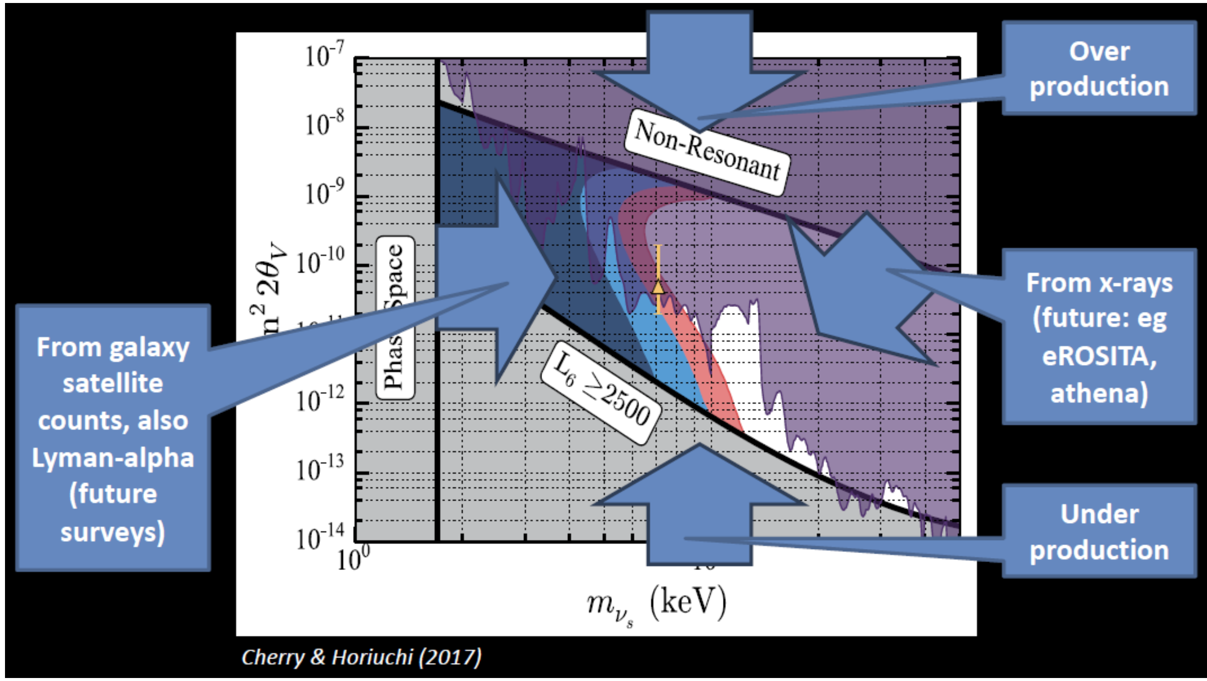


$$E_\gamma = m_s/2$$



Bulbul et al. (2014), Boyarsky et al (2014), many subsequent studies

Status: Signal strongly constrained!



Over production

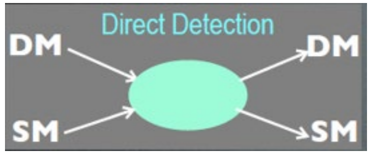
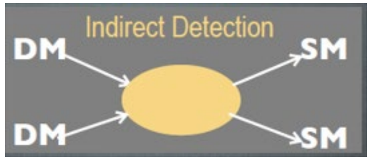
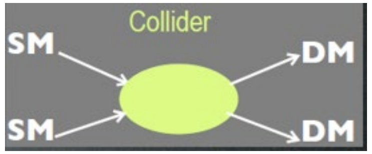
From x-rays (future: eg eROSITA, athena)

From galaxy satellite counts, also Lyman-alpha (future surveys)

Under production

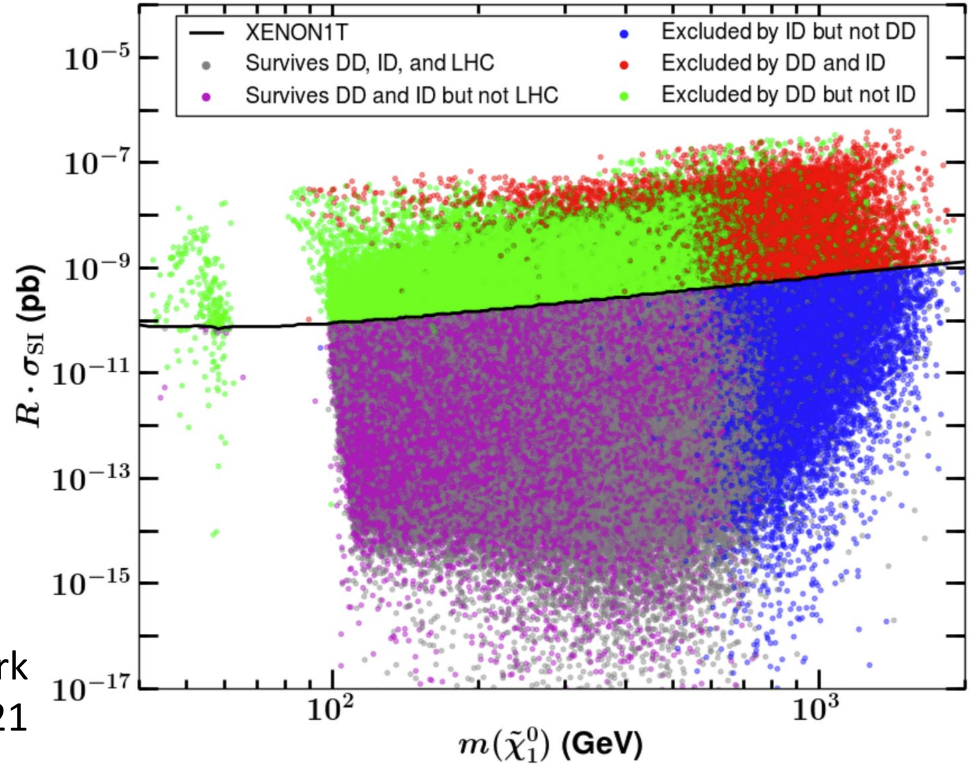
Cherry & Horiuchi (2017)

Complementarity of DM searches

			
REGIMES:	$q \sim$ few KeV	$\sqrt{s} \sim 2\, m_\chi$	$\sqrt{s} \sim$ few TeV
σ INVOLVED:	σ_{scatt}	$\langle \sigma_{ann} v \rangle$	σ_{prod}

Adapted from M. Cirelli

- The 3 searches are complementary
- The comparison is not direct, but we need a DM model



M. Cahill-Rowley et al. “Complementarity and Searches for Dark Matter in the pMSSM”, arXiv:1305.6921

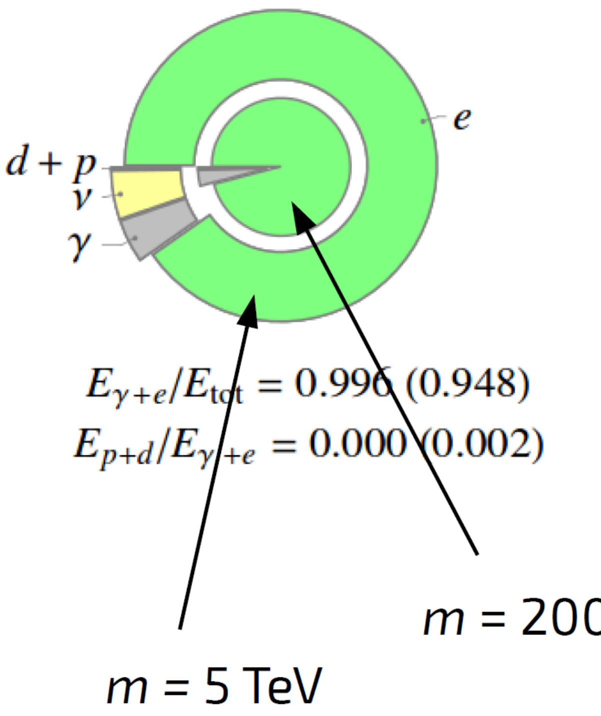
Backup

Distribution of final states

How much energy is dumped into the different particles depends on the annihilation channel

Leptonic channels

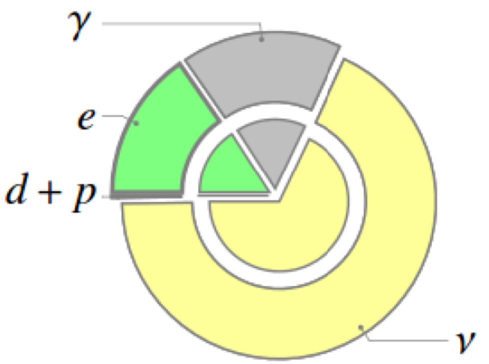
$DM\,DM \to e_L^- + e_L^+$



$E_{\gamma+e}/E_{\rm tot} = 0.996\ (0.948)$

$E_{p+d}/E_{\gamma+e} = 0.000\ (0.002)$

$DM\,DM \to \tau_L^- + \tau_L^+$

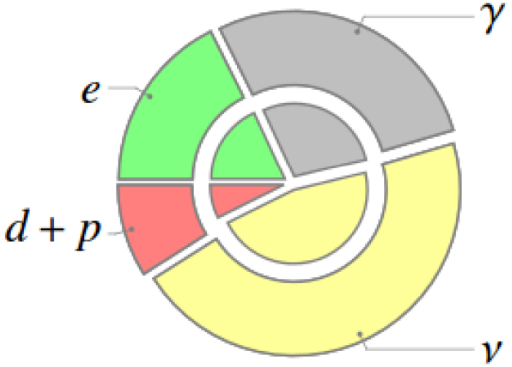


$E_{\gamma+e}/E_{\rm tot} = 0.320\ (0.318)$

$E_{p+d}/E_{\gamma+e} = 0.001\ (0.007)$

Hadronic channel

$DM\,DM \to b+b$



$E_{\gamma+e}/E_{\rm tot} = 0.462\ (0.454)$

$E_{p+d}/E_{\gamma+e} = 0.159\ (0.198)$

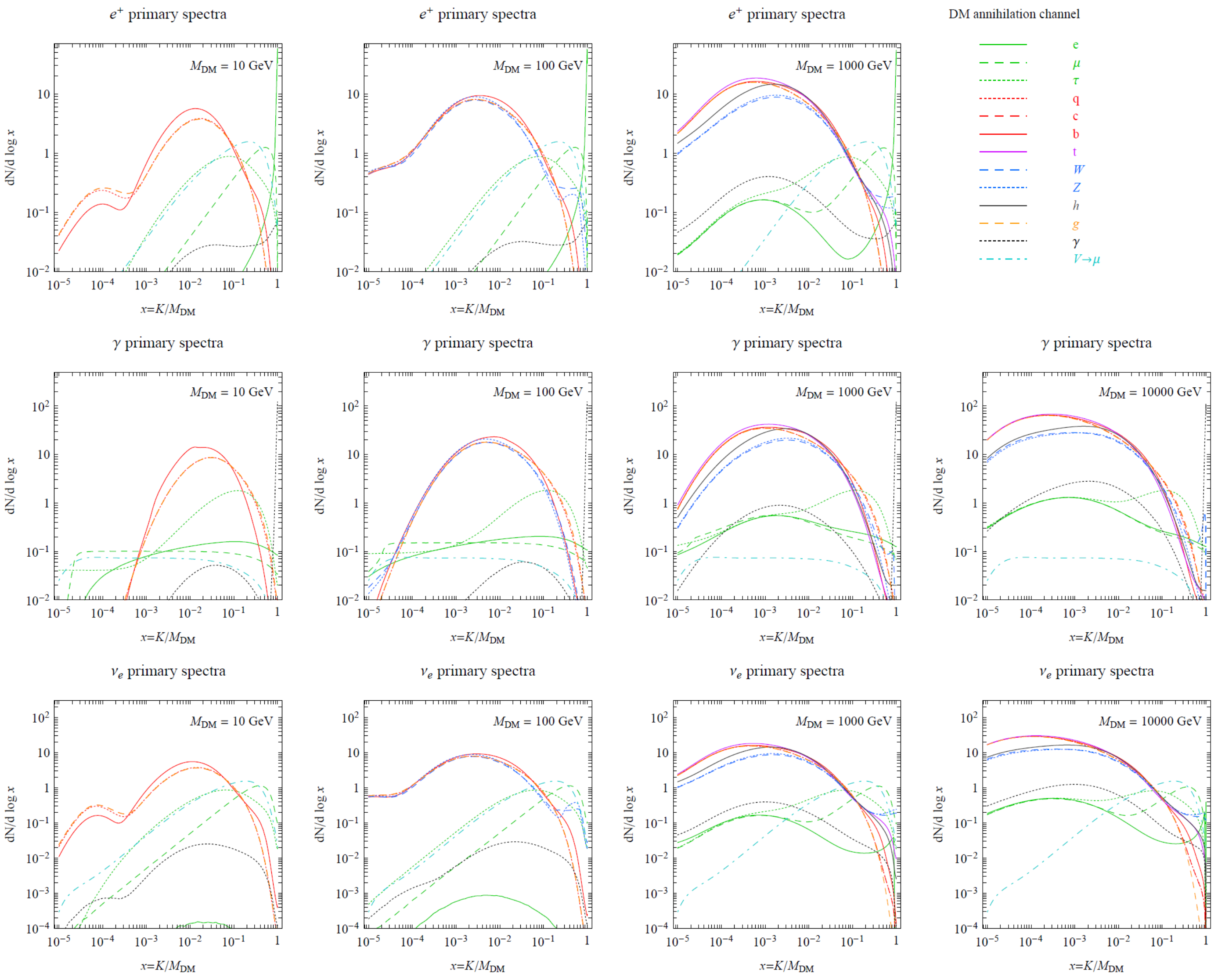
Cirelli et al. (2010) "PPPC4DMID"

Primary spectra

e^+

γ

ν

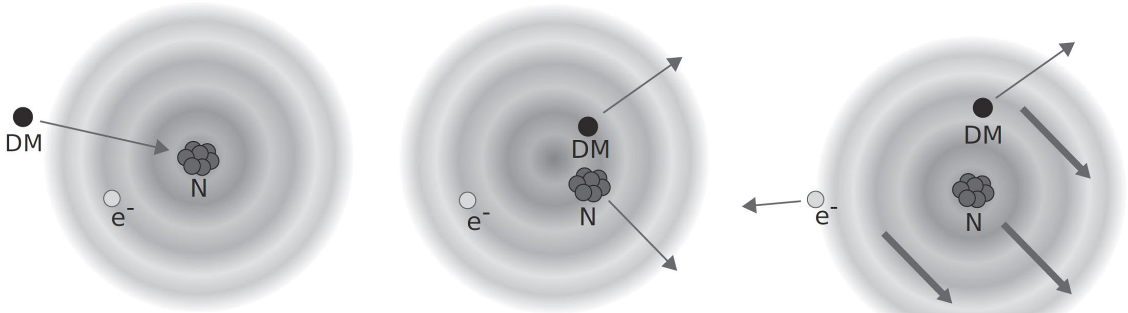


M. Cirelli et al, *"PPPC 4 DM ID: A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection"*, JCAP **1103**, 051 (2011) [1012.4515]

Migdal effect

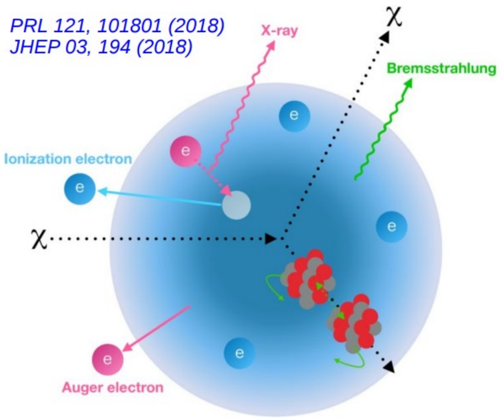
In our “naïve” picture of the WIMP scattering off nuclei we have made the implicit assumption that the electron cloud of the recoiling atom instantly follows the nucleus, so that ionization/excitation are only produced subsequently, as the recoiling atom collides with surrounding atoms.

However, it is known From neutron-nucleus scattering experiments that the sudden acceleration of a nucleus after a collision leads to excitation and ionization of the atomic electrons. The origin is found in the nucleus/electronic cloud dynamics:



M. J. Dolan, “Directly Detecting Sub-GeV Dark Matter with Electrons from Nuclear Scattering”, Phys.Rev.Lett. 121, 101801 (2018) [arXiv:1711.0990

Migdal approximation: the electron cloud of the atom does not change during the nuclear recoil



PRL 121, 101801 (2018)
JHEP 03, 194 (2018)

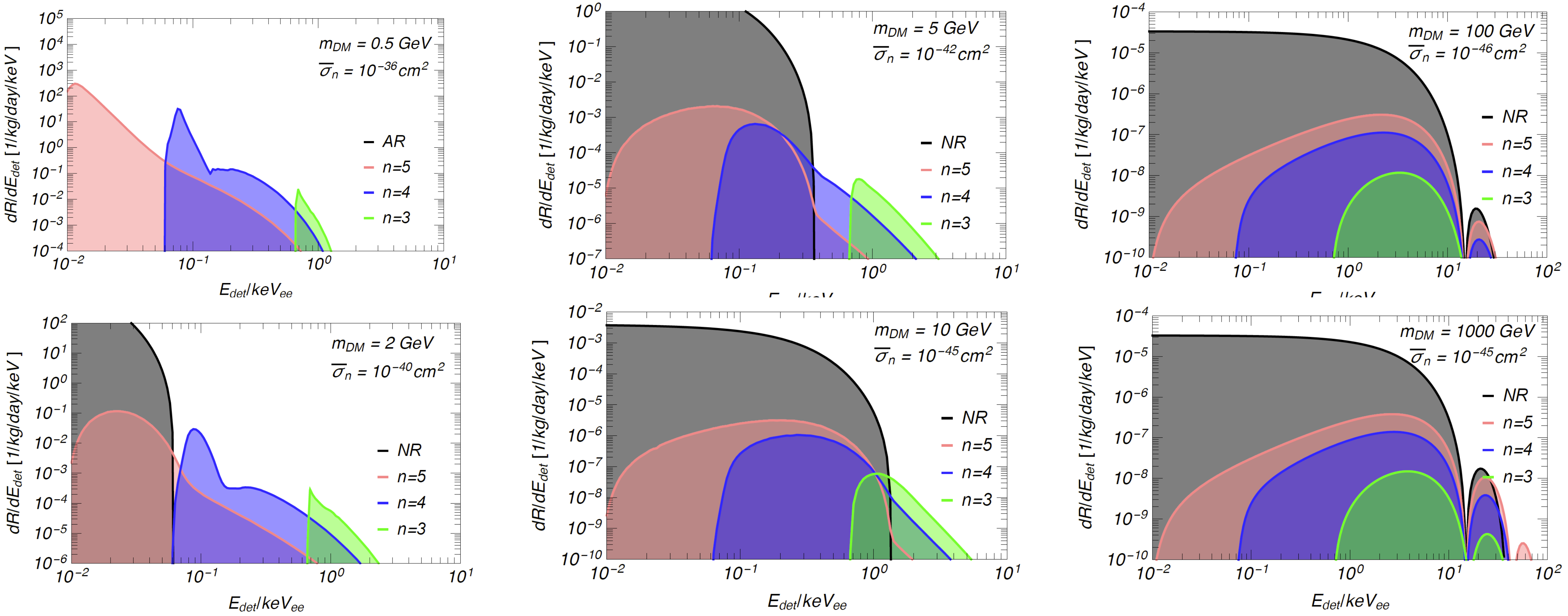
In the Migdal approximation, immediately after the collision the nucleus moves relative to the surrounding electron cloud. The electrons eventually catch up with the nucleus, but individual electrons can be “lost”, leading to ionization of the recoiling atom

The “Migdal effect” provides an additional signal which is larger than the normal one for low mass DM.

Caveat: It has not been observed yet, by now it is only a hypothesis!

Migdal effect “predictions”

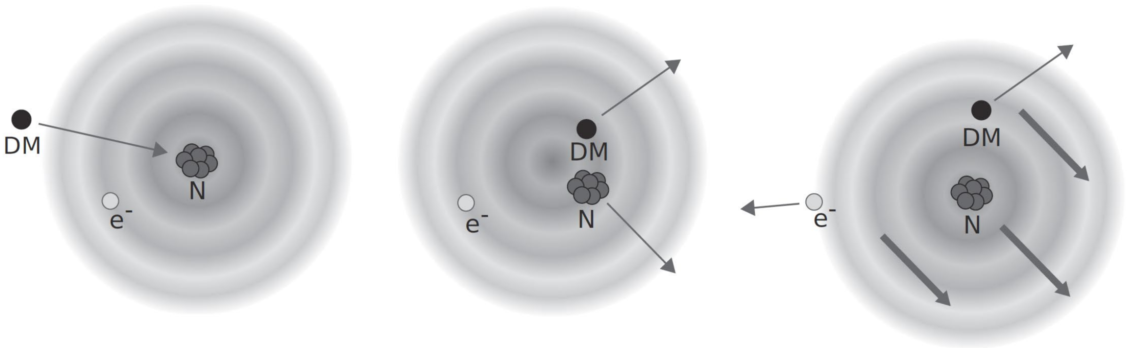
M. Ibe et al, “Migdal effect in dark matter direct detection experiments”, JHEP03(2018)194 [1707.07258]



“We showed that the ionization signals through the Migdal effect provide new detection channels for light dark matter with a mass in the GeV range. Since such signals are eliminated as background events in the conventional analysis of the dual-phase experiments, different analyses are required to cover such signals.“

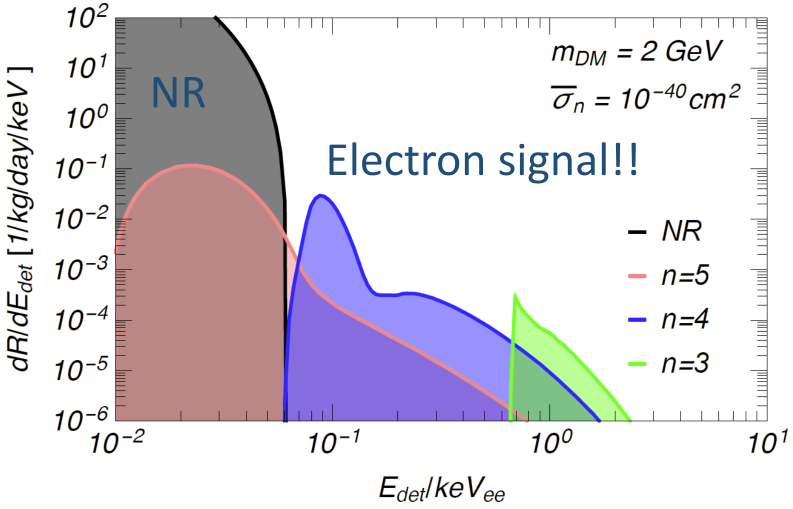
Migdal effect

M. J. Dolan, "Directly Detecting Sub-GeV Dark Matter with Electrons from Nuclear Scattering", Phys.Rev.Lett. 121, 101801 (2018) [arXiv:1711.09906]

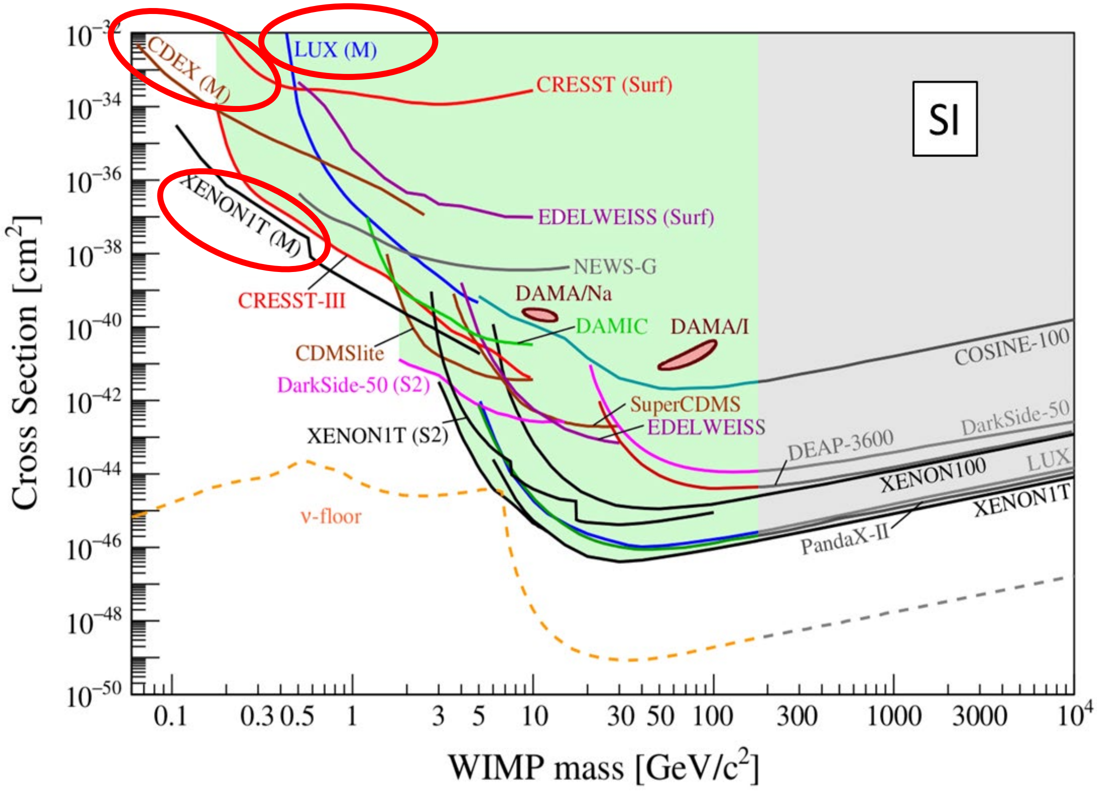


Migdal approximation: immediately after the collision the nucleus moves relative to the surrounding electron cloud. The electrons eventually catch up with the nucleus, but individual electrons can be "lost", leading to ionization of the recoiling atom

New detection channels (e-) for light dark matter with a mass in the GeV range.



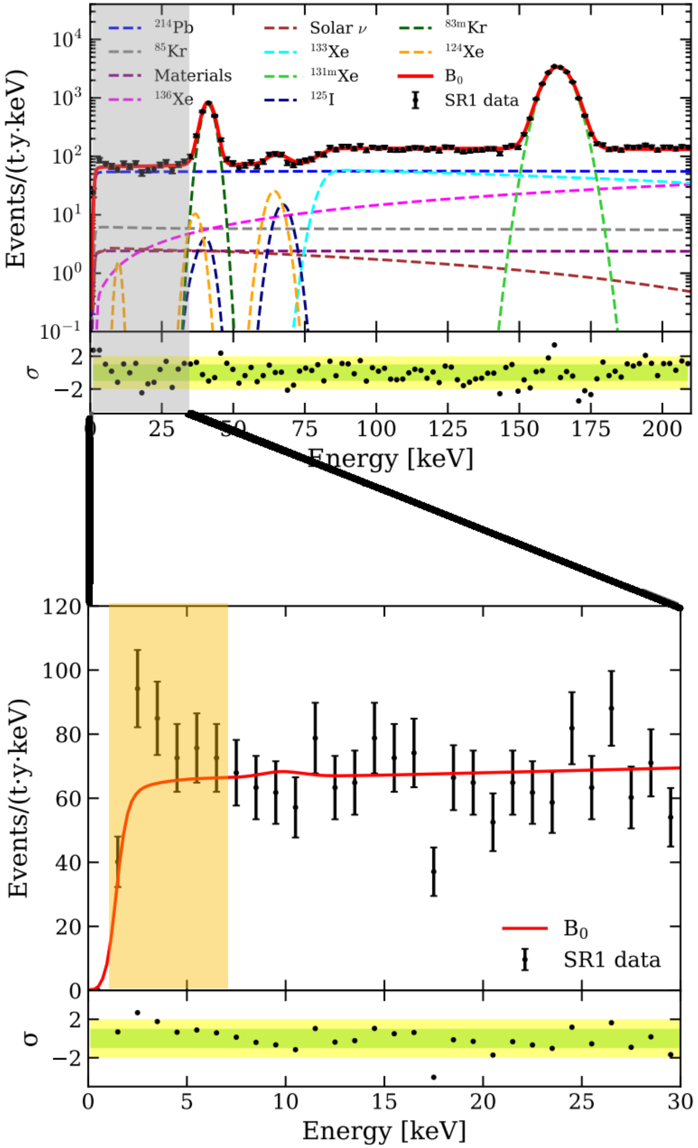
CAVEAT: EFFECT NOT YET PROVED EXPERIMENTALLY!! (but maybe will be proved son by the **MIGDAL** collaboration)



M. Ibe et al, "Migdal effect in dark matter direct detection experiments", JHEP03(2018)194 [1707.0725

Xenon1T electronic excess

PRD 102, 072004 (2020)



No electron recoil discrimination

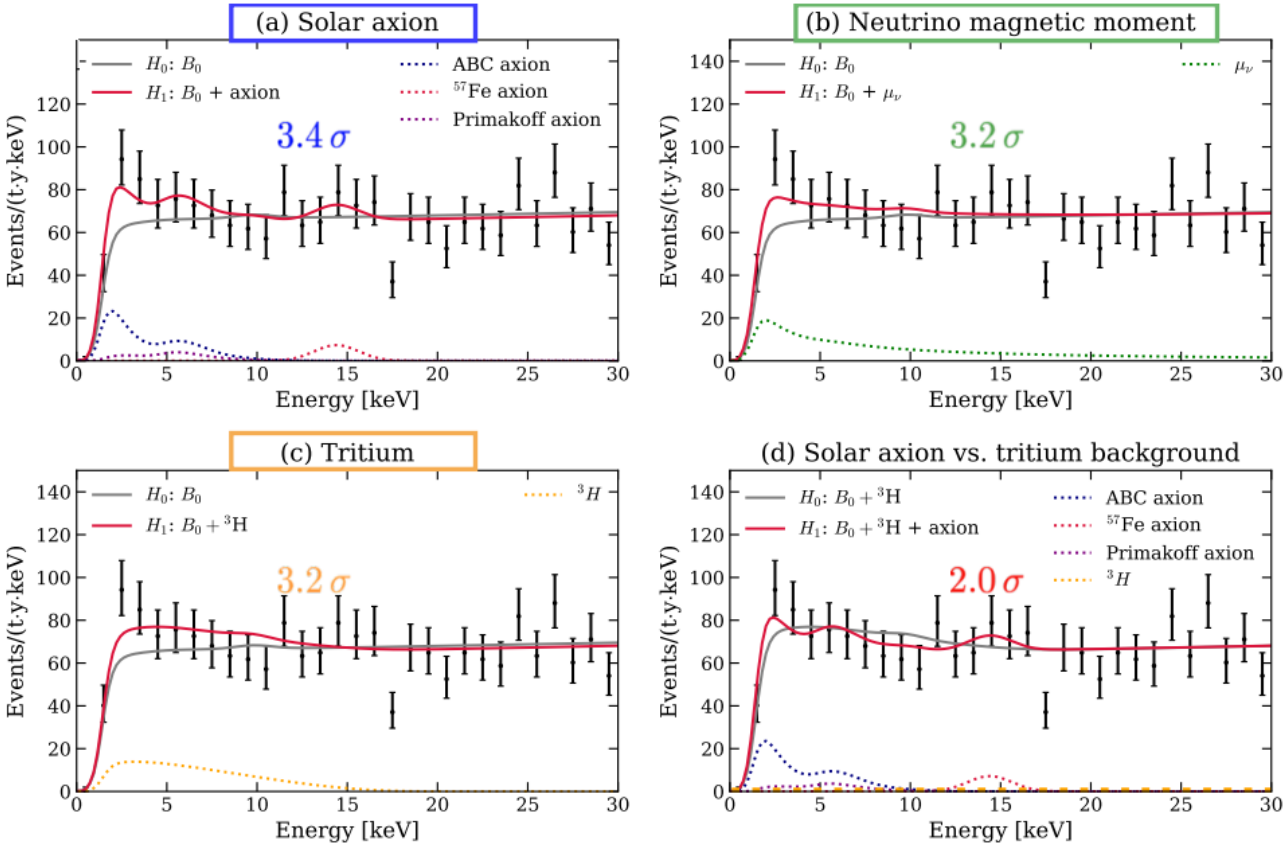
Background-only Fit

From 1-7keV:

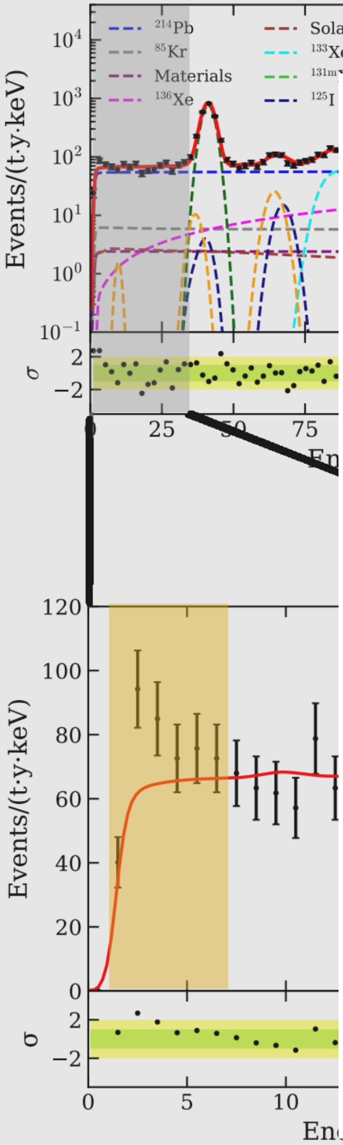
expected: 232

Observed: 285

Possible explanations:

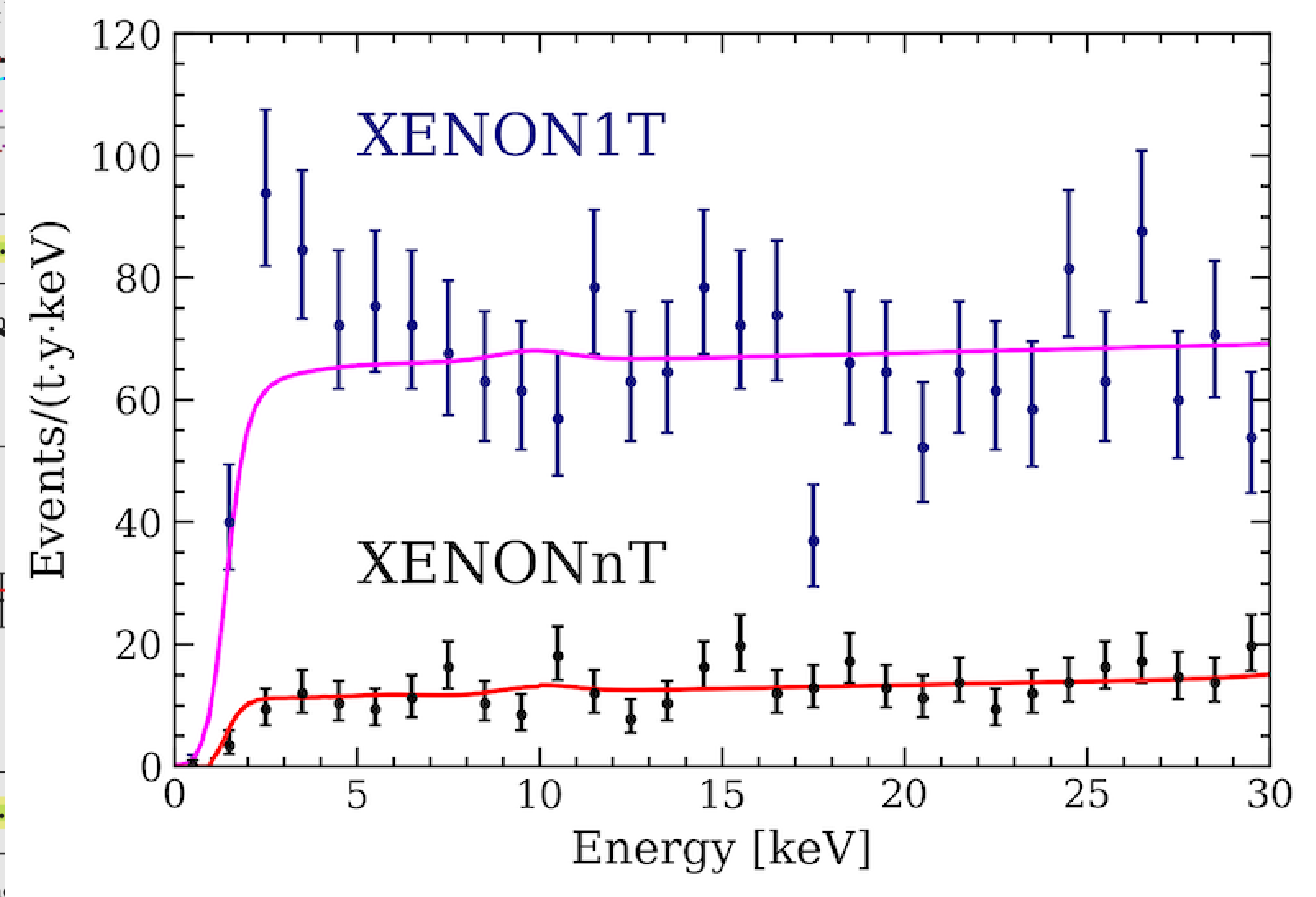


Xenon1T electronic excess not confirmed by XENONnT



No electron

Phys.Rev.Lett. 129 (2022) 16, 161805



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