Direct and Indirect dark matter searches

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EPS-HEP 2019, Ghent, July 10-17, 2019.

towards a dark matter "problem"

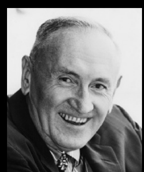
1904: Lord Kelvin applies gas theory to a system of stars held by gravity → the first concern about the existence stars too faint to be detected by telescopes: **"Many of our stars, perhaps a great majority of them, may be dark bodies"**

20's

Kapteyn and Oort carry out the first quantitative estimations on "dark matter" based on observational measurements of proper velocities of stars in the Milky Way.

But *dark matter* is still understood as **"extinguished stars, dark clouds, meteors, comets and so on"** (Knut Lundmark, 1930)

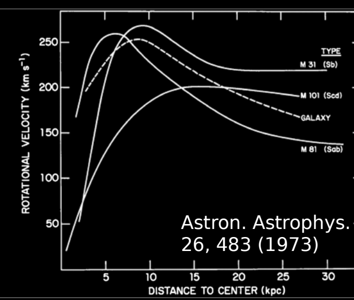
30's



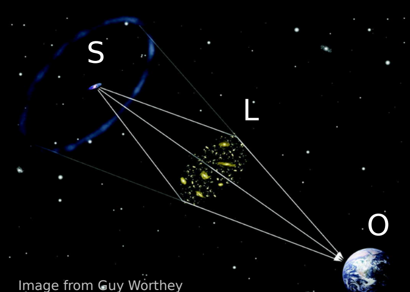
Fritz Zwicky measures redshift of galaxies in the Coma cluster and applies the virial theorem to measure the mass of the cluster: " … *the average density in the Coma system would have to be at least 400 times larger than that derived on the grounds of observations of luminous matter*"
Helv. Phys. Acta 6, 110–127 (1933)

70's

K. Freeman, K. Ford, V Rubin and many others: Explosion of measurements of rotation curves of galaxies thanks to new and precise spectroscopic techniques, both optical and in radio.



90's



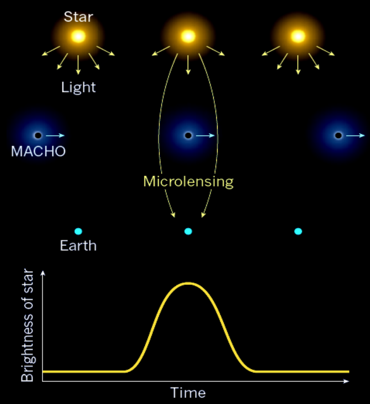
Gravitational lensing. Comparing M from gravitational lensing with the mass obtained from mass-to-light ratios, reveals the quantity of dark matter in the lensing object

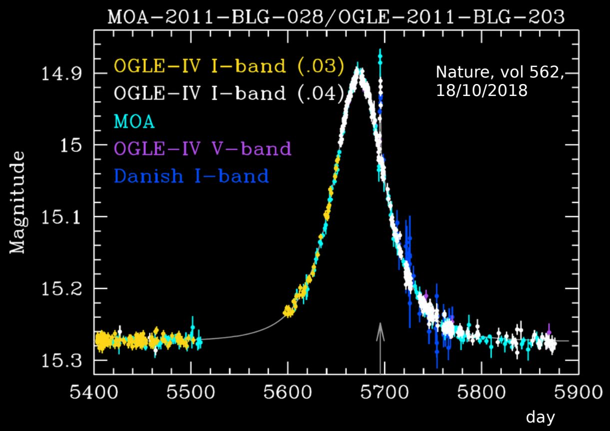
$$\alpha = \sqrt{\frac{4GM}{c^2}\frac{D_{SL}}{D_{OL}D_{OS}}}$$

Microlensing

(MACHO, EROS, OGEL ,Gaia)

amount of non-luminous objects at a few percent level





Microlensing

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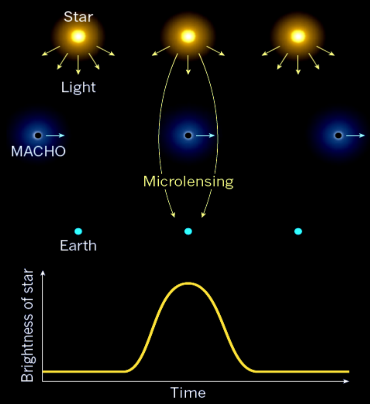
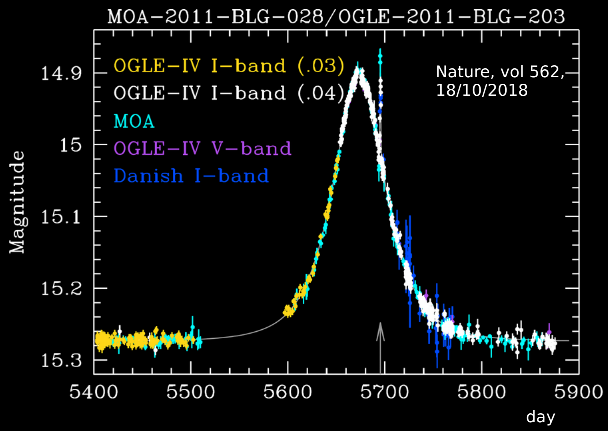
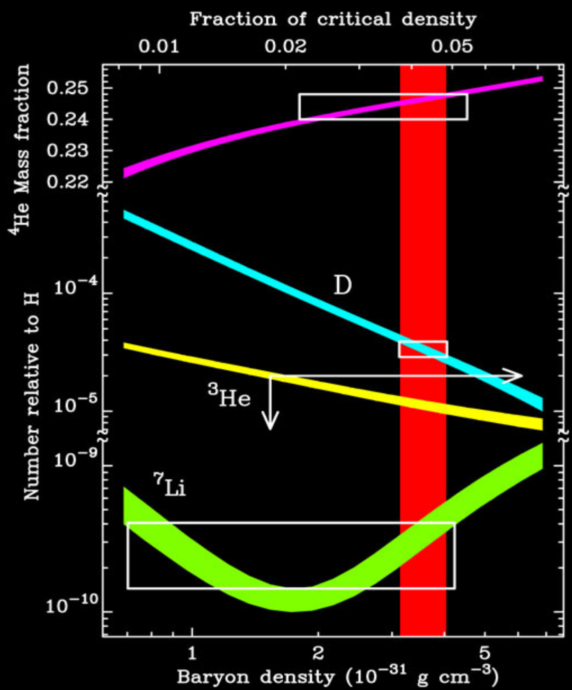
Big bang nucleosynthesis

very precise limit on amount of baryons in the Universe.







Microlensing

(MACHO, EROS, OGEL ,Gaia)

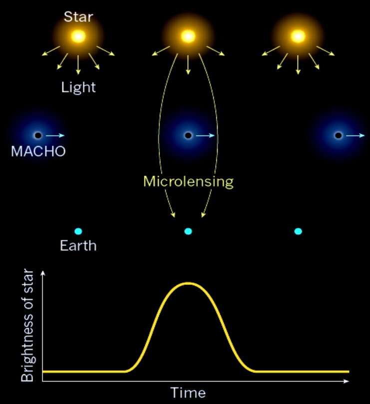
amount of non-luminous objects at a few percent level

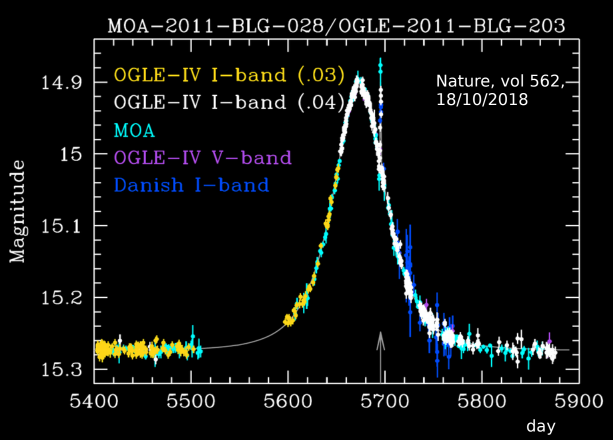
Big bang nucleosynthesis

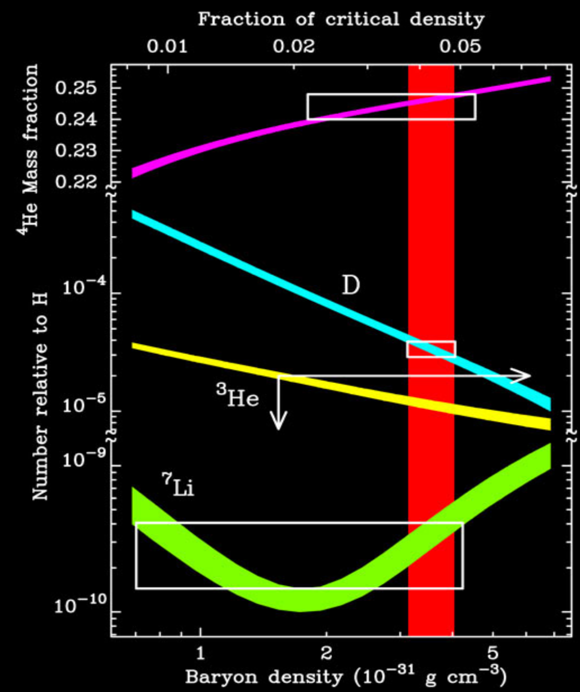
very precise limit on amount of baryons in the Universe.

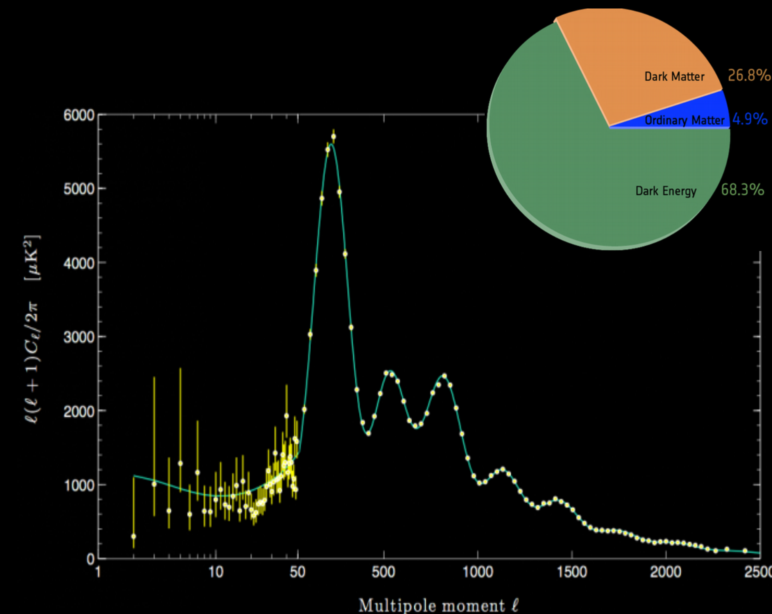
CMB data
(COBE, WMAP, Planck)

fit with DM and dark energy







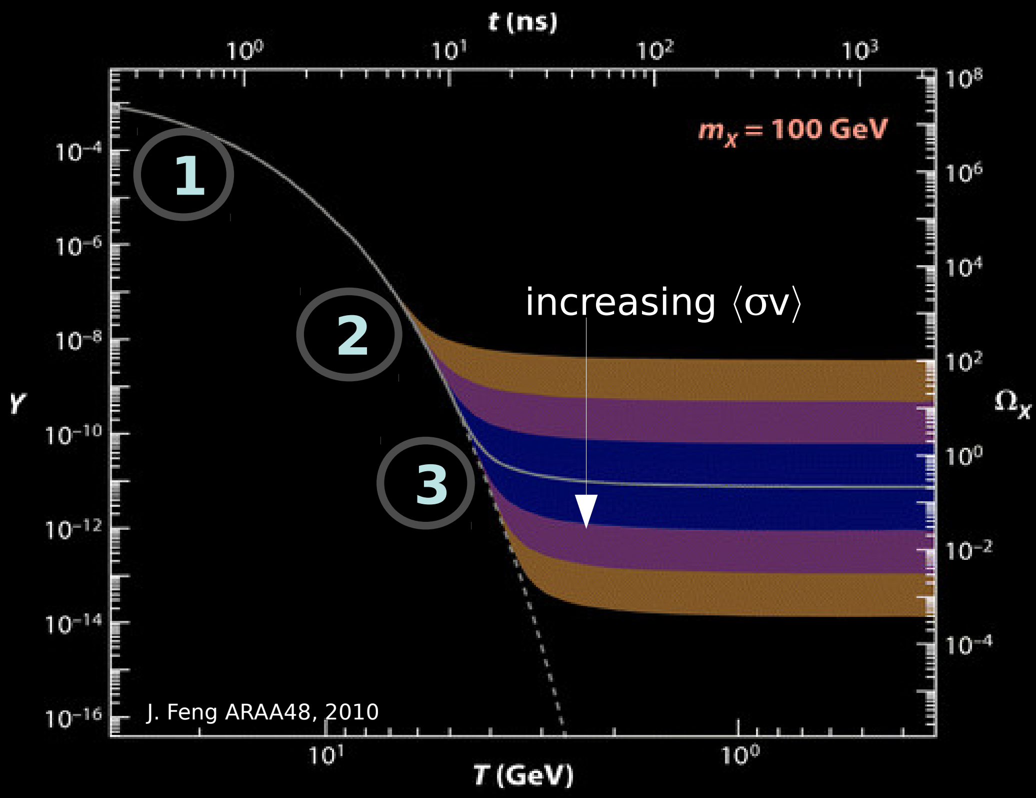


The easiest solution is to introduce a new particle species that must:

a) be heavy: we want it to play a role in gravitational structure formation

b) be weakly interacting: we do not want it to disturb the evolution of the Universe

c) be stable: its effects must perdure today



1 DM in themal equilibrium with matter

$$\chi\chi \Leftrightarrow SM\ SM$$

2 Universe expands, number density of χ decreases

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \langle\sigma v\rangle (n_{eq}^2 - n_\chi^2)$$

3 When $n_\chi \langle\sigma v\rangle \sim H$ annihilations stop

$$\Omega_\chi h^2 \sim \frac{10^{-26} cm^3/s}{\langle\sigma v\rangle}$$

J. E. Taylor, Advances in Astronomy. Volume 2011

Dark matter influences the development of the universe and ends up forming halos around galaxies → Λ Cold Dark Matter (ΛCDM) model

The ΛCDM needs:

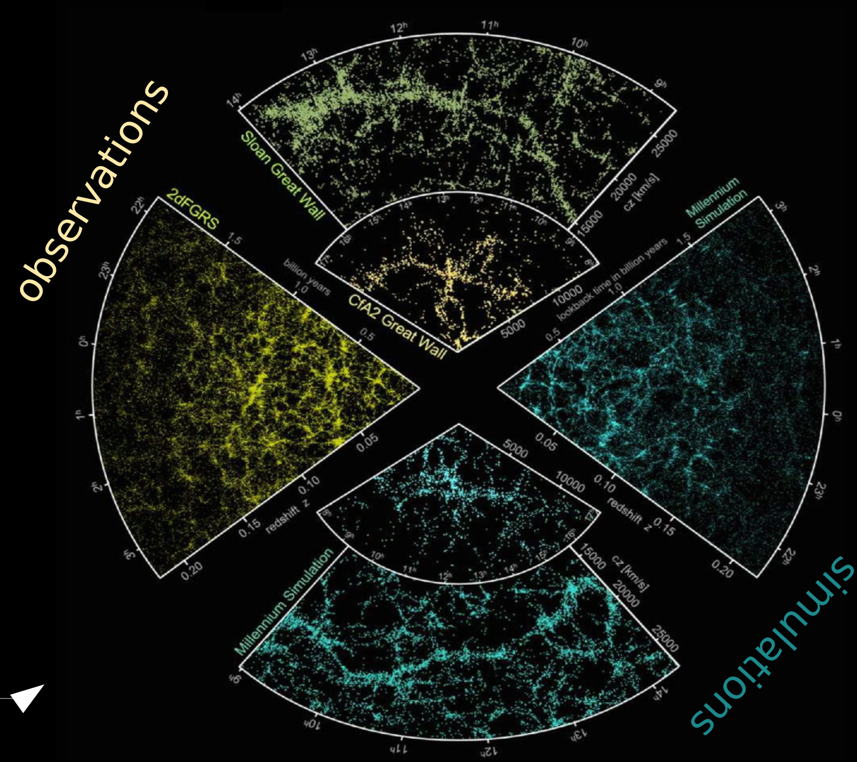
known elementary particles/forces (i.e. the SM)

weakly interacting, stable, cold dark matter candidate(s)

a cosmological constant

with these ingredients ΛCDM exactly predicts the grow of fluctuations into a large-scale structure of galaxies compatible with observations

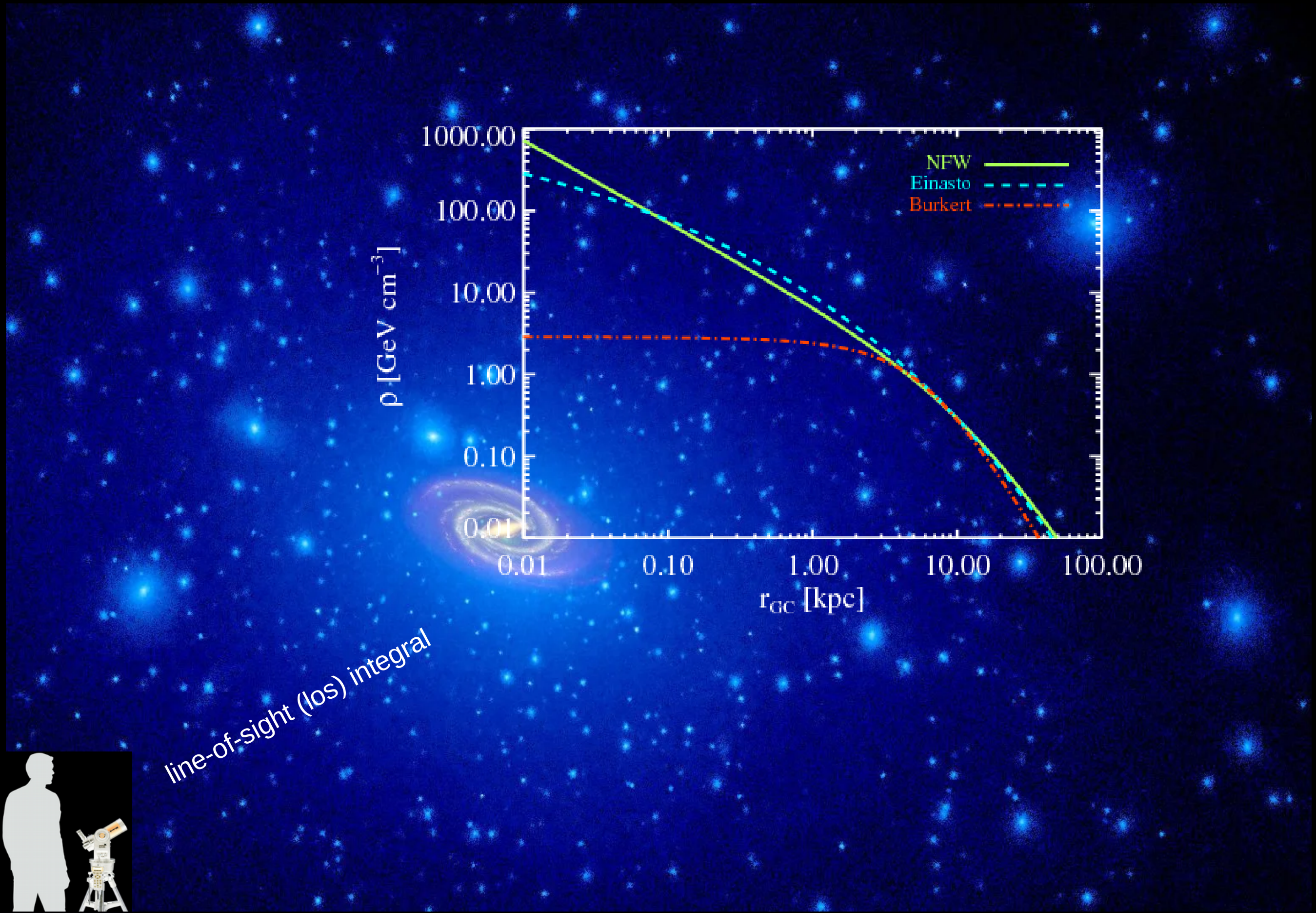
$\delta = (\rho - \bar{\rho})/\bar{\rho}$ + numerical simulations



We live in a poorly known, probably complex halo of dark matter

N-body simulations of galaxy formation tell us that DM halos are clumpy and they extend well beyond the visible galaxy

The interpretation of experimental results depends on the shape and structure of this halo

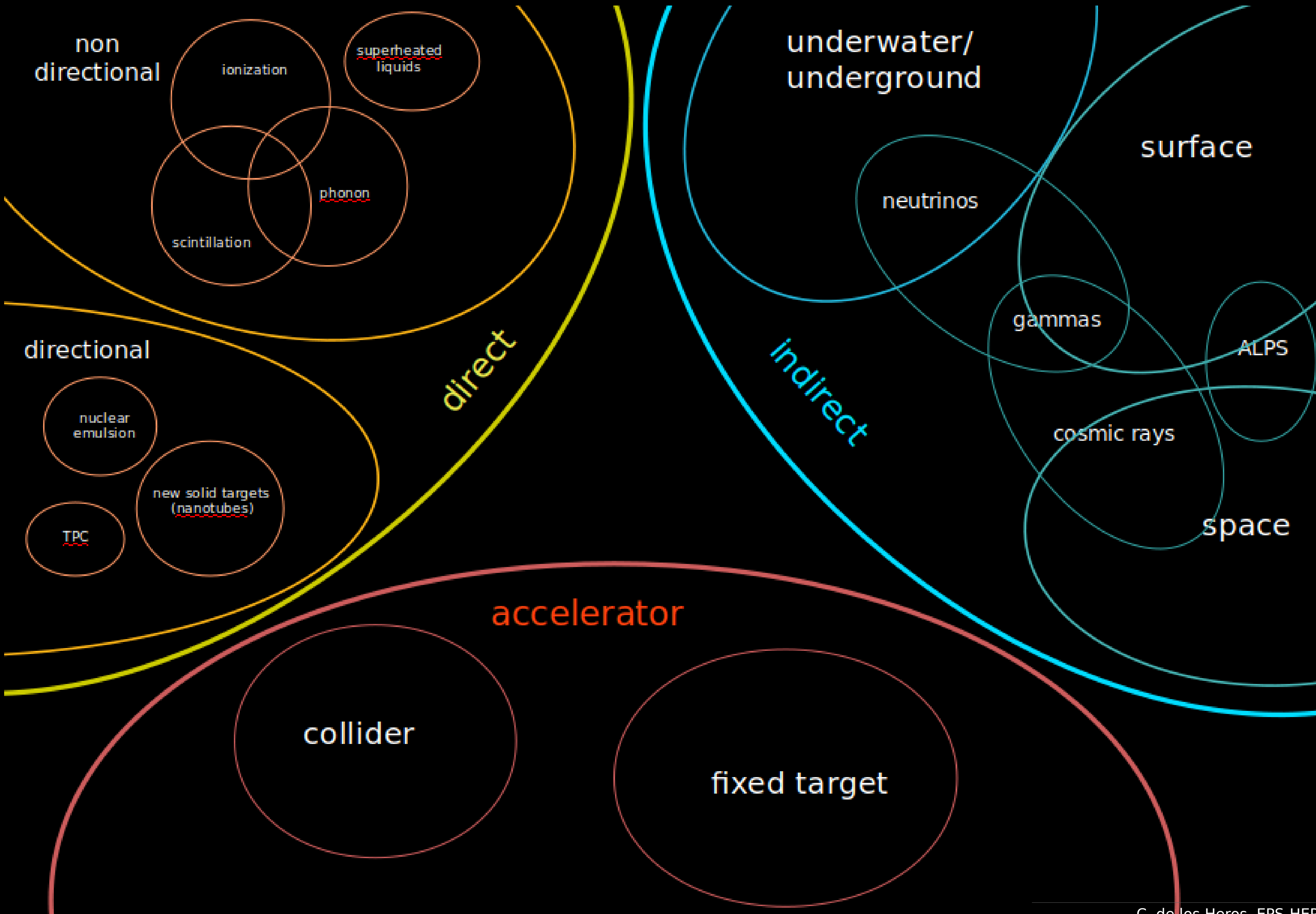


Dark matter density as a function of radius from the center of the galaxy

$$\rho_{DM}(r) = \rho_{smooth}(r) + \langle \rho_{subs}(r) \rangle$$

$$\rho_{smooth}(r) = \frac{\rho_o}{\left(\delta + \frac{r}{r_s}\right)^{\gamma} \cdot \left[1 + \left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}$$

experimental approaches to the search for dark matter



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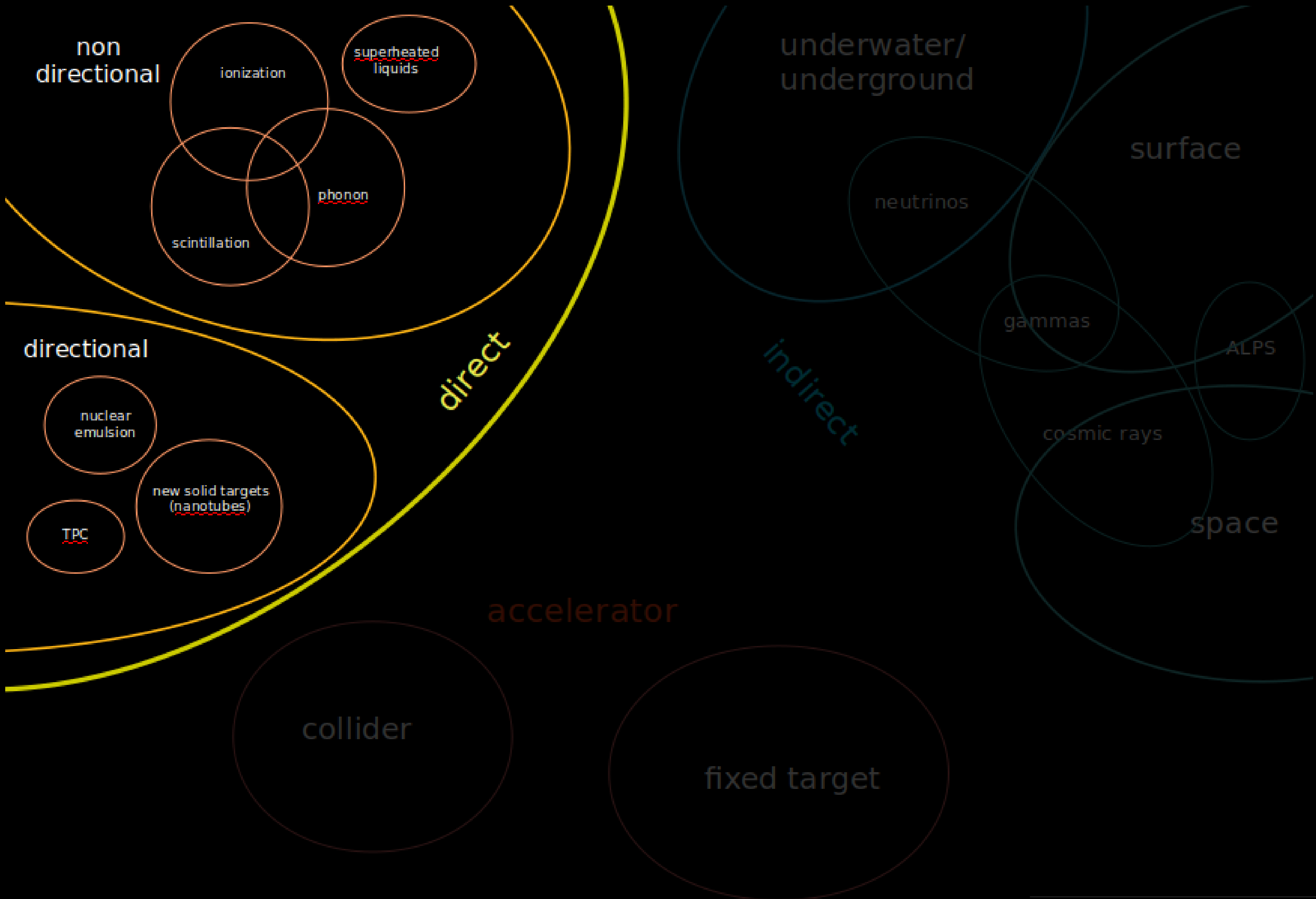
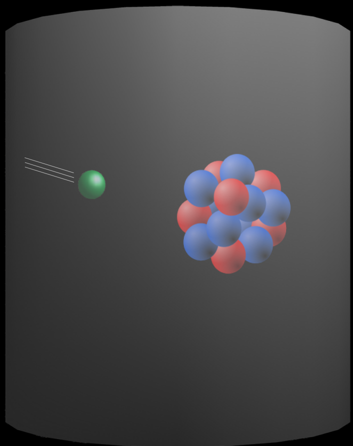
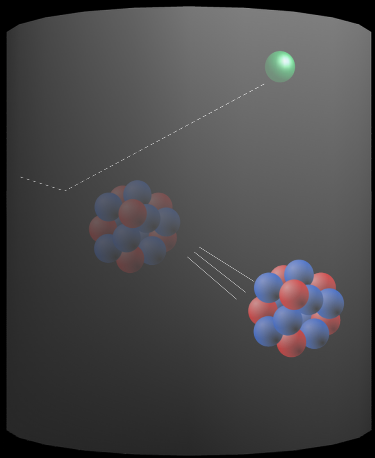


Look for nuclear recoils from DM-nucleus interactions in a suitable target





Number of recoils at the detector with a target m_A

$$\frac{dR}{dE}(E,t) = \frac{\rho_O}{m_\chi m_A}\int v \cdot f(v,t)\frac{d\sigma}{dE}(E,v)\, d^3 v$$

measure

particle physics

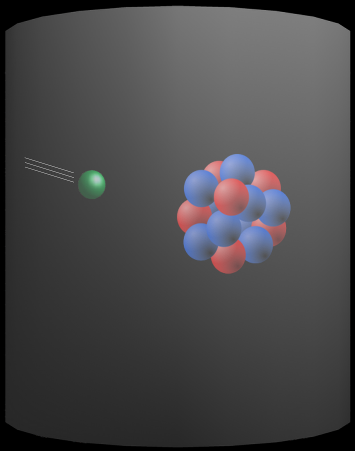
astrophysics

constrain (or discover)

$\underbrace{\hspace{4cm}}_{\text{external inputs}}$

Target choice (m_A) is important. Along with location is the only handle an experimentalist has on the above equation

Look for nuclear recoils from DM-nucleus interactions in a suitable target



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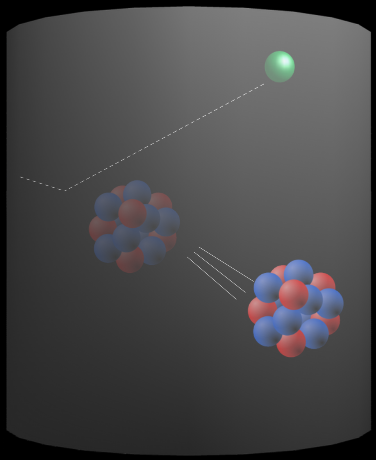
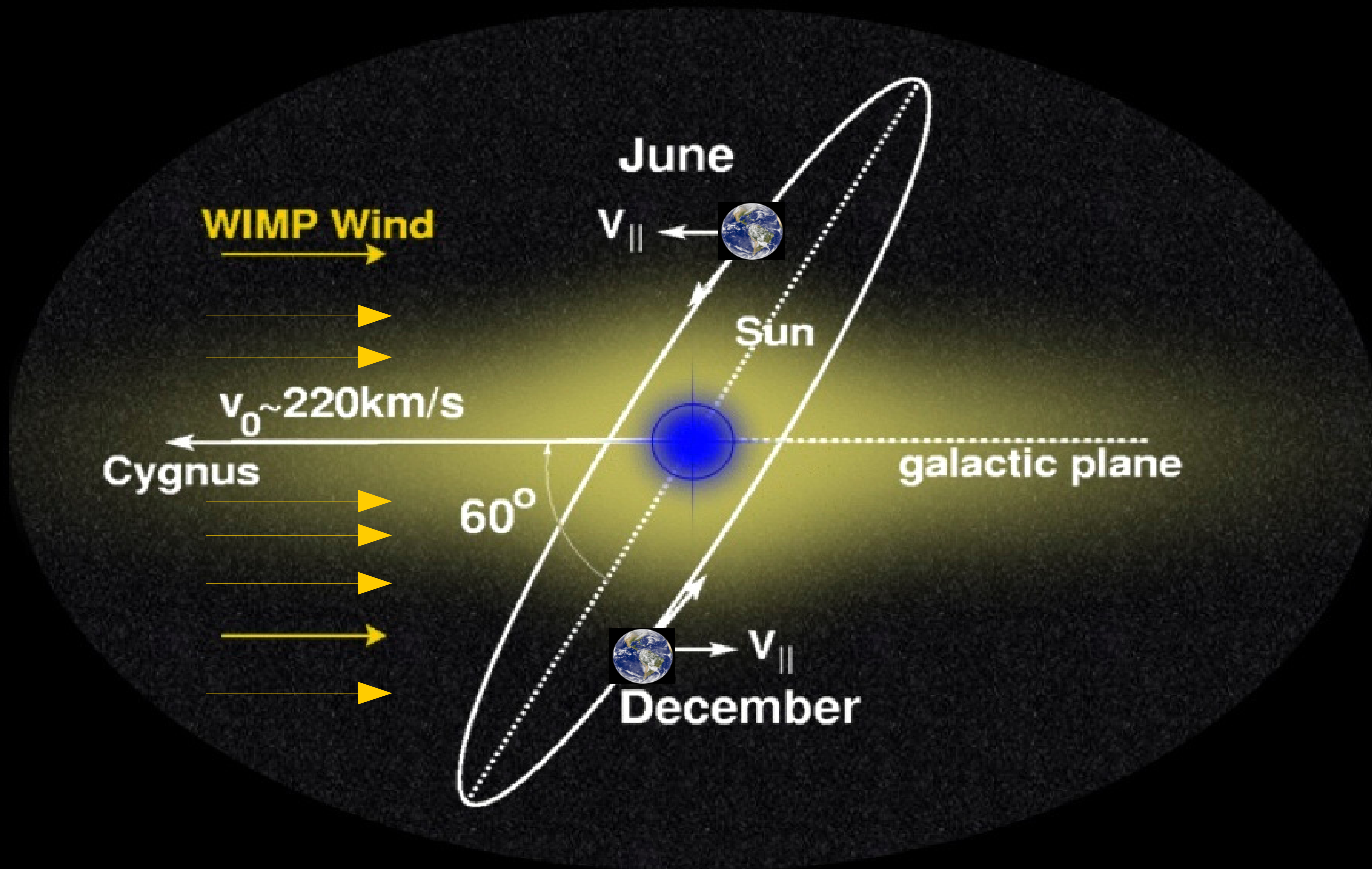


Backgrounds:

- ambient or detector radioactivity (neutrons, gammas…)
- neutrino elastic ν+e or coherent ν+A

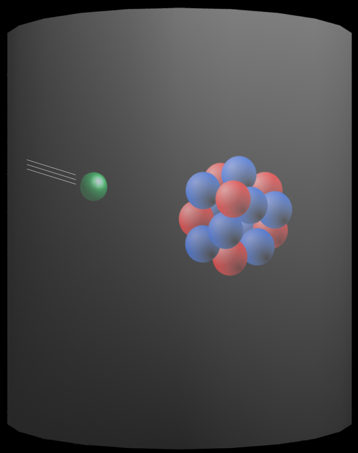
→ Need stable, radiopure, shielded detectors with an energy threshold of ~ keV



f(v,t) leads to an "annual modulation" in the recoil rate due to changes in the relative velocity between target and DM wind

A "daily modulation" is also possible for a detector placed at the right latitude

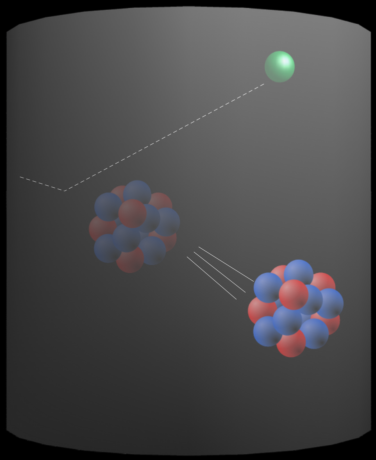
Look for nuclear recoils from DM-nucleus interactions in a suitable target



Number of recoils at the detector with a target m_A

$$\frac{dR}{dE}(E,t) = \frac{\rho_O}{m_\chi m_A} \int v \cdot f(v,t) \frac{d\sigma}{dE}(E,v)\, d^3 v$$

$$\Downarrow$$



σ

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

Coupling from scalar and vector part of the Lagrangian.

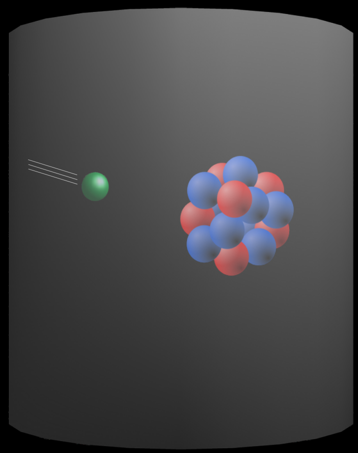
→Larger target nuclei the better

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

Coupling from axial-vector part of the Lagrangian.

→ Targets with large angular momentum favoured

Look for nuclear recoils from DM-nucleus interactions in a suitable target



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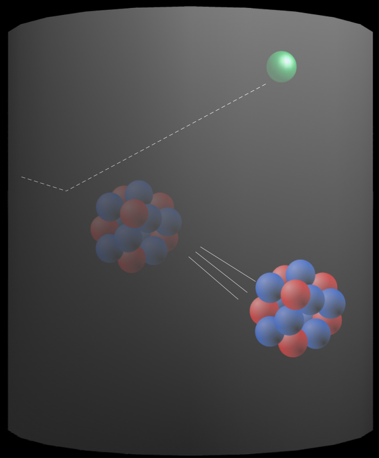

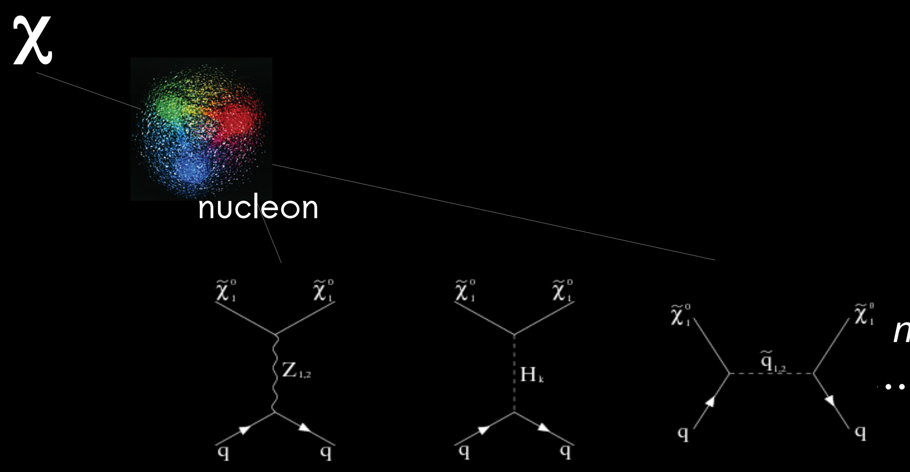

DM-nucleus cross section
=
DM-quark cross section
x
quark distribution inside nucleons
x
nucleon distribution in the target nuclei

Structure of the nucleon and target nucleus play an essential role in calculating and interpreting observables

Astropart.Phys.13:215-225 (2000), Astropart.Phys.18:205-211 (2002), Phys. Rev. D 77 (2008) 065026, JCAP11(2013)049, Phys. Rev. D 99, 055031 (2019) ...

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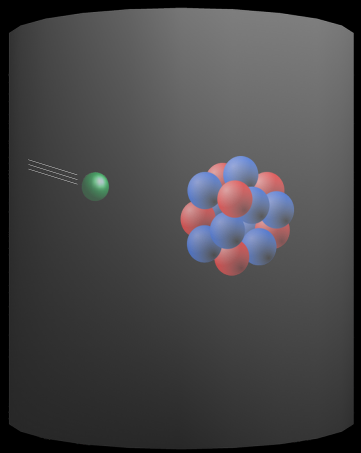

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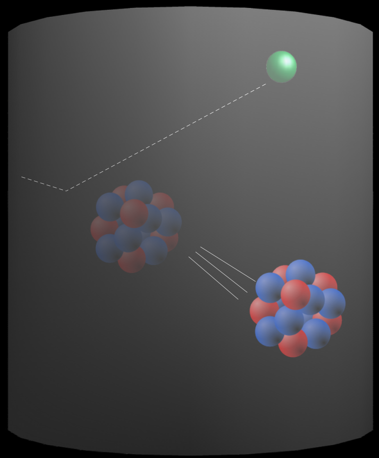
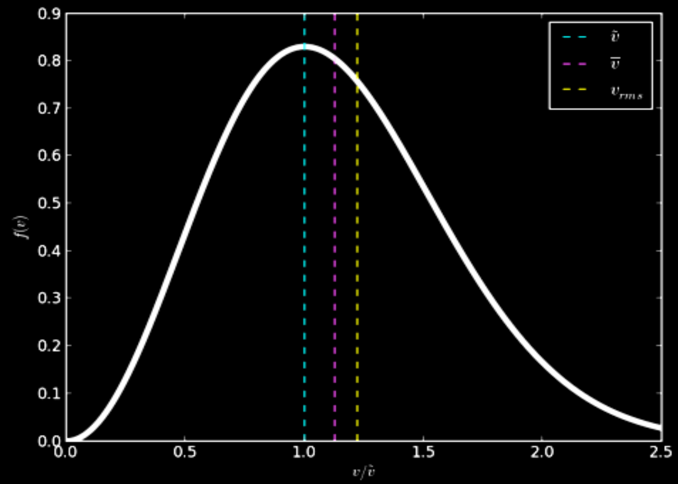
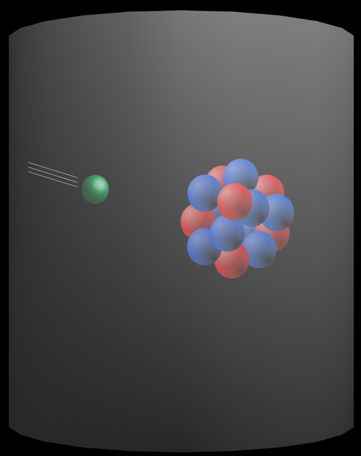
Velocity distribution of the DM particles in the halo: usually assumed Boltzmann





direct searches for dark matter

Look for nuclear recoils from DM-nucleus interactions in a suitable target



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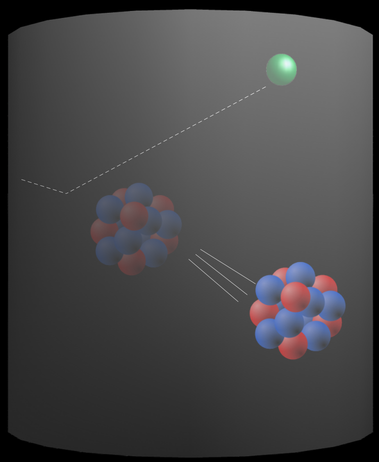
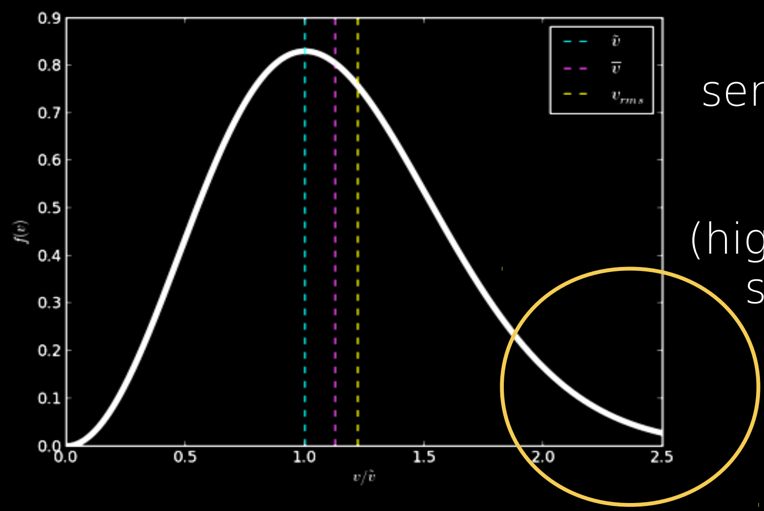
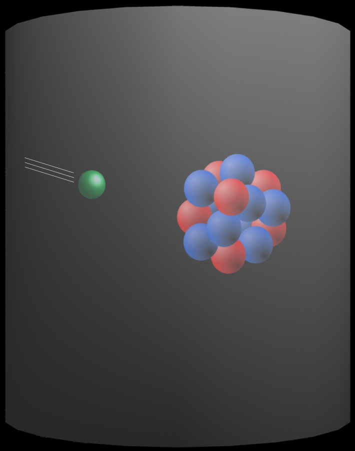




direct DM experiments sensitive to the high-velocity tail of the distribution

(high-energy particles produce stronger recoils in target)

Look for nuclear recoils from DM-nucleus interactions in a suitable target



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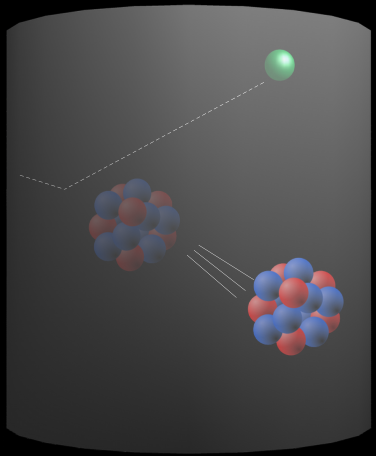
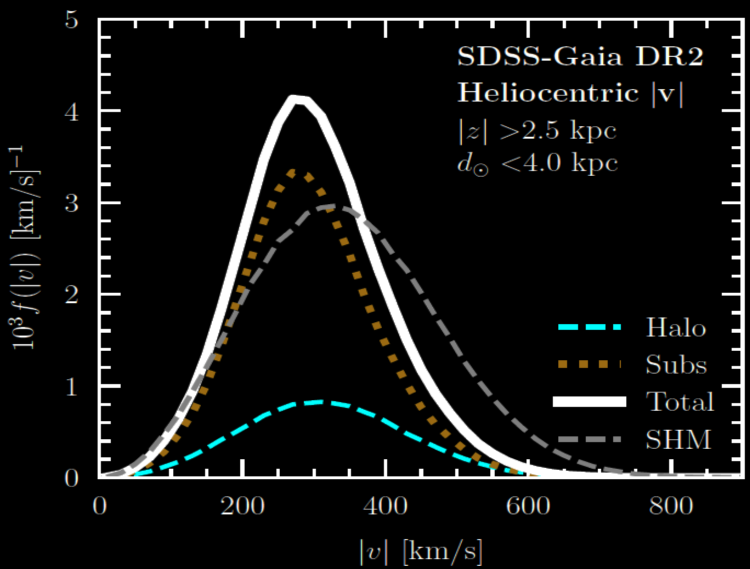
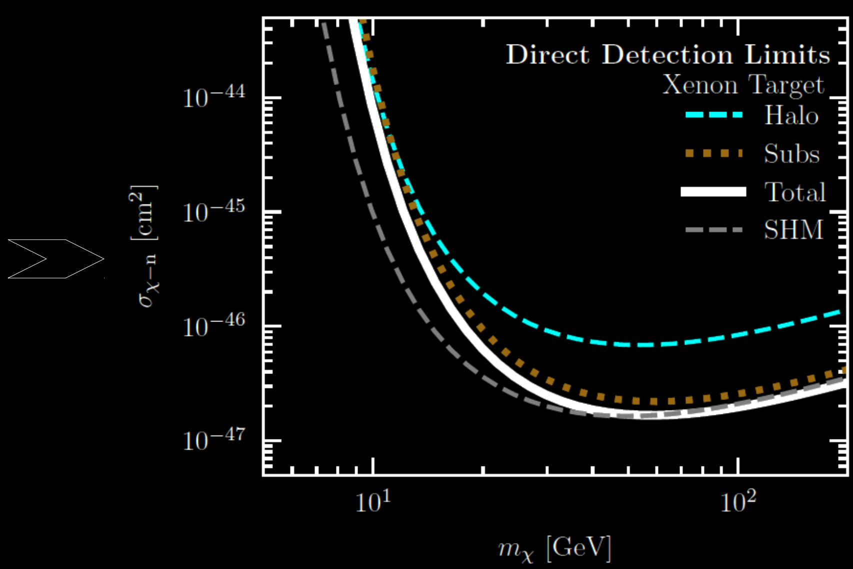
But: expected deviations from a pure Boltzmann distribution
(JCAP02(2010)030, arXiv:1807.02519, arXiv:1904.04781...)







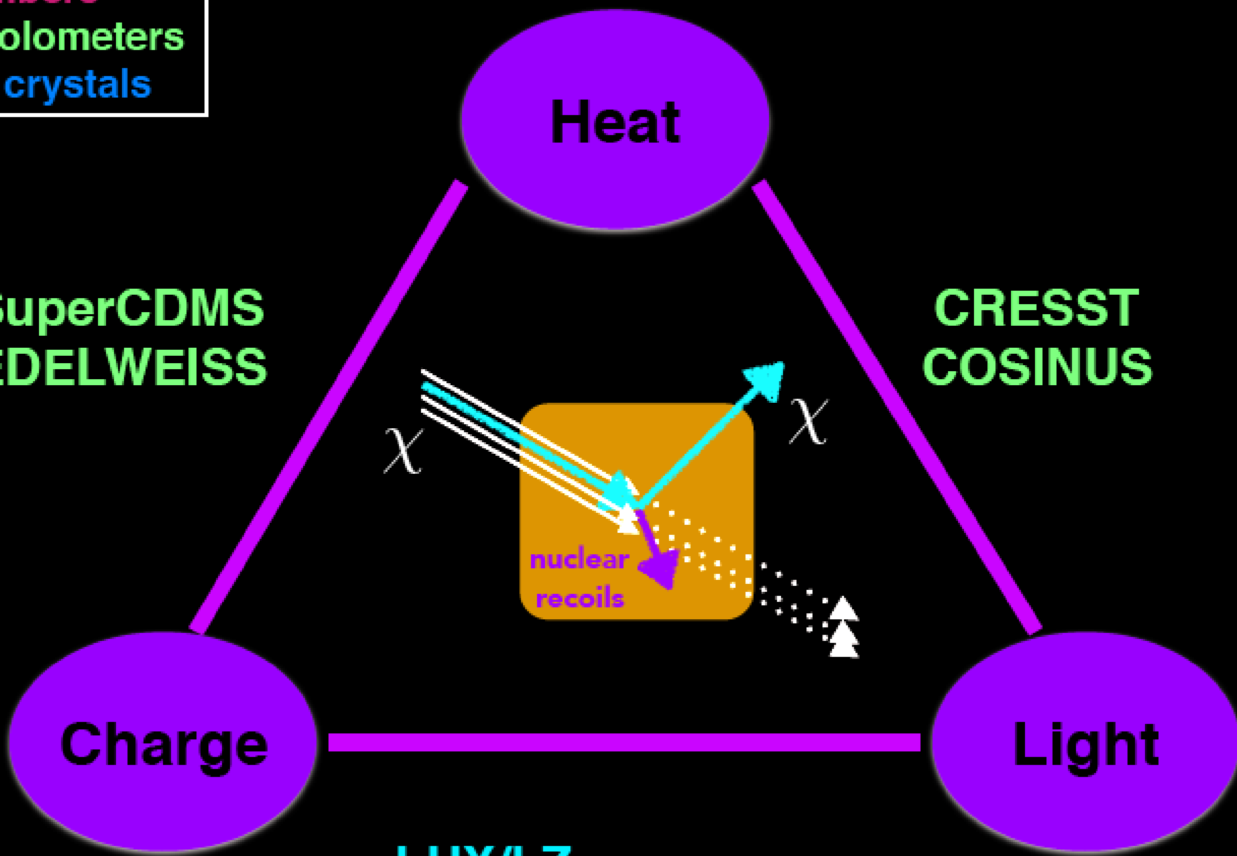
Direct Detection Techniques

(slide from M. Selvi)

(see also J. Phys. G43 (2016) no.1, 013001 and arXiv:1903.03026)

- Liquid argon
- Liquid xenon
- Directional detectors
- Low-threshold
- Bubble chambers
- Cryogenic bolometers
- Scintillating crystals

SIMPLE
PICASSO
COUPP
PICO



SuperCDMS
EDELWEISS

CRESST
COSINUS

CoGeNT
CDEX
DAMIC
SENSEI
NEWS-G
DRIFT
MIMAC
DMTPC

LUX/LZ
PandaX
XENON

ArDM
DarkSide

DAMA
DM-Ice
COSINE
SABRE
ANAIS
PICO-LON
DEAP
XMASS

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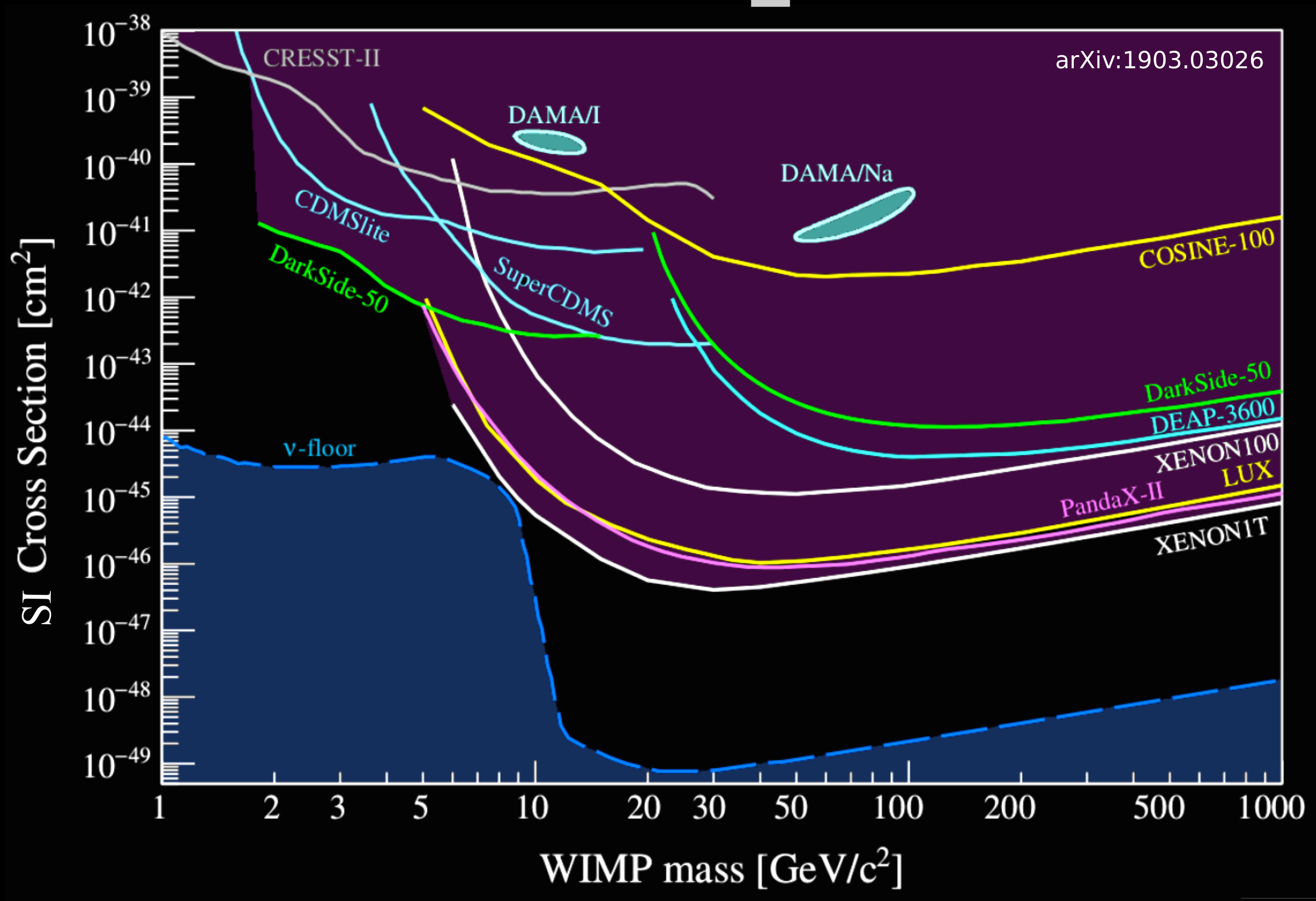

see paralell talks by
A. Brown (XENON)
T. Pollmann (DEAP)
A. Caminata (DarkSide)
K. Thieme (DAREWIN)
C. Hardy (PICO)

direct searches for dark matter: status

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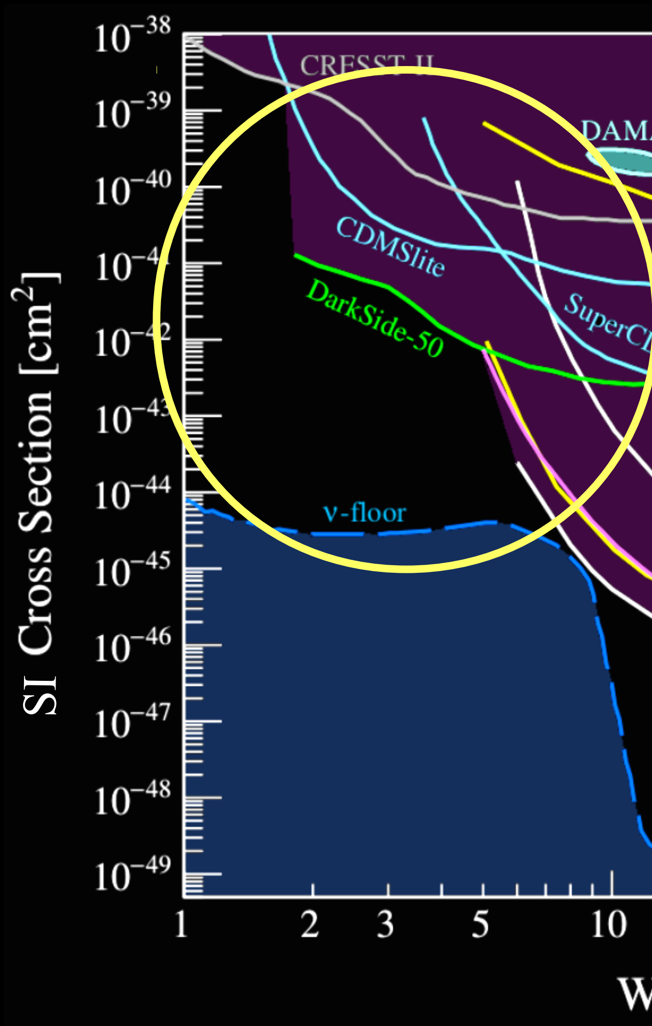
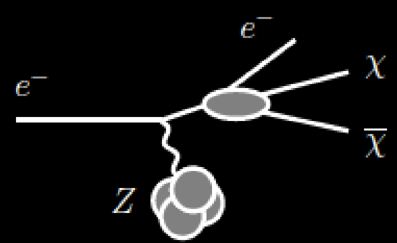


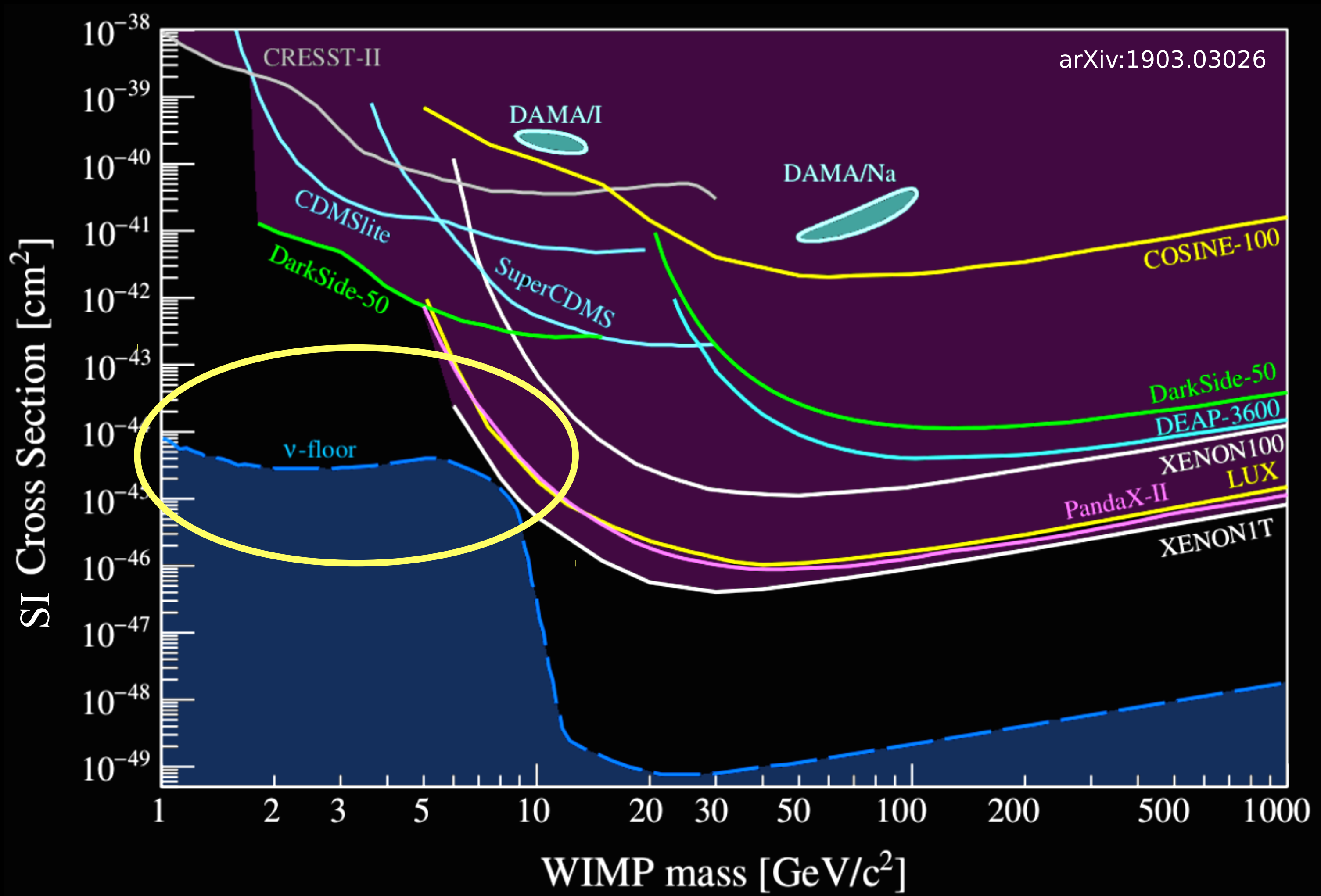
see paralell talks by
V. Dutta (LDMX)
J. Schieck (CRESST)

Current efforts concentrated on improving sensitivity to low-masses

- Lower thresholds in existing techniques and/or
- Add sensitivity to e$^-$ recoils and/or
- Production of DM in fixed target experiments, e.g.



For very low m_χ masses, coherent neutrino scattering on target nuclei can mimic a dark matter scattering signal → **neutrino "floor" (swampland?)**



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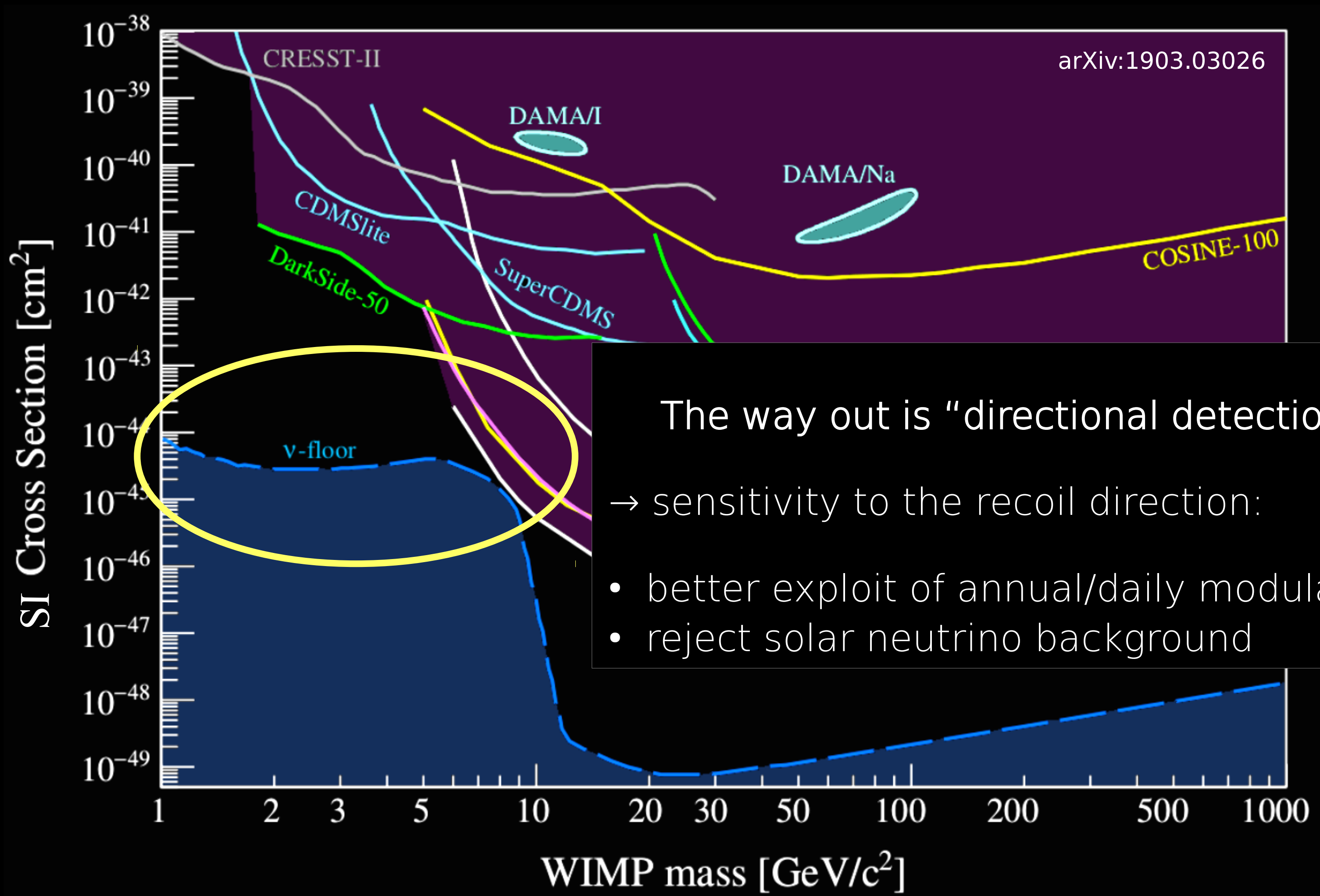

The way out is “directional detection”

→ sensitivity to the recoil direction:

- better exploit of annual/daily modulations
- reject solar neutrino background

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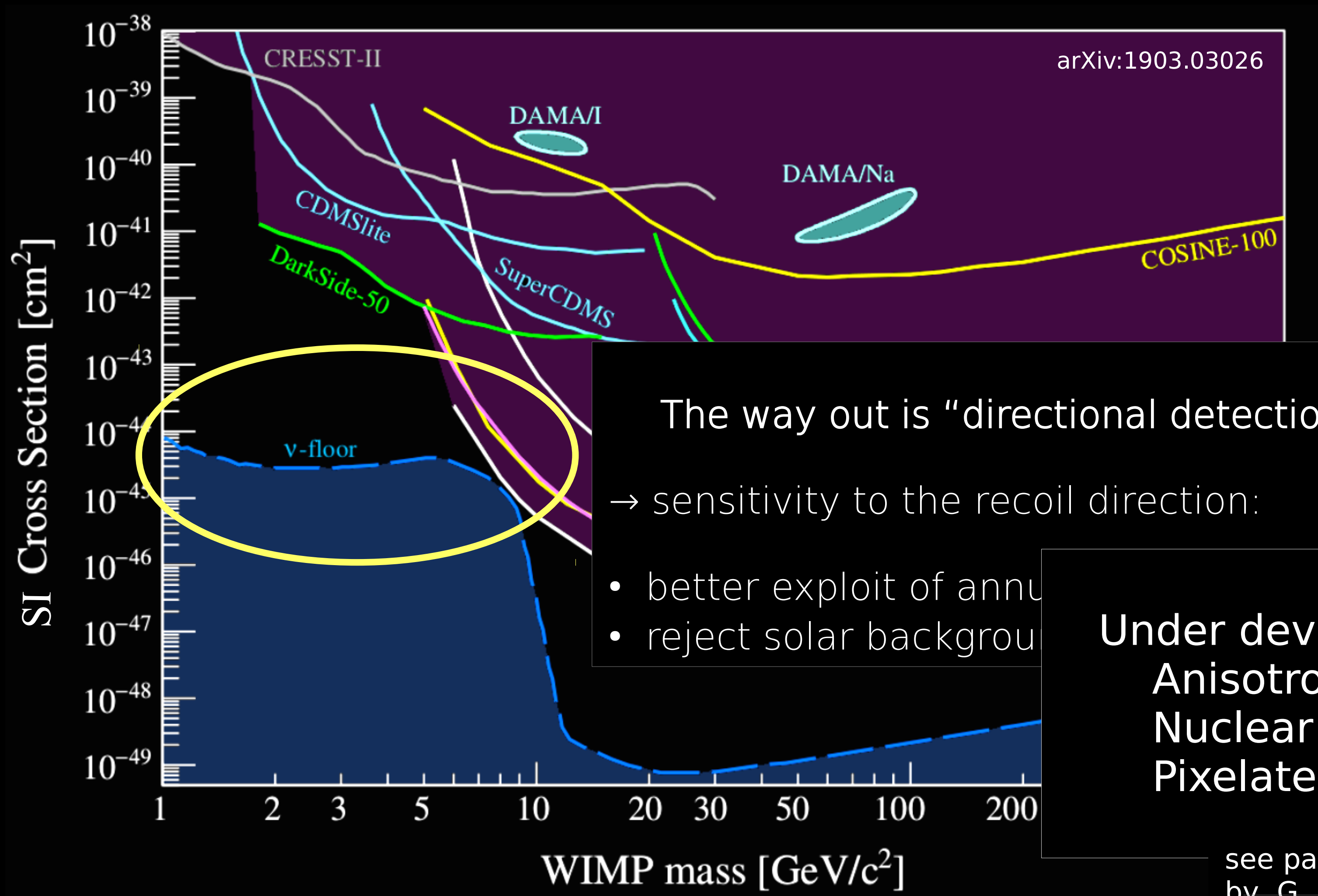


The way out is "directional detection"

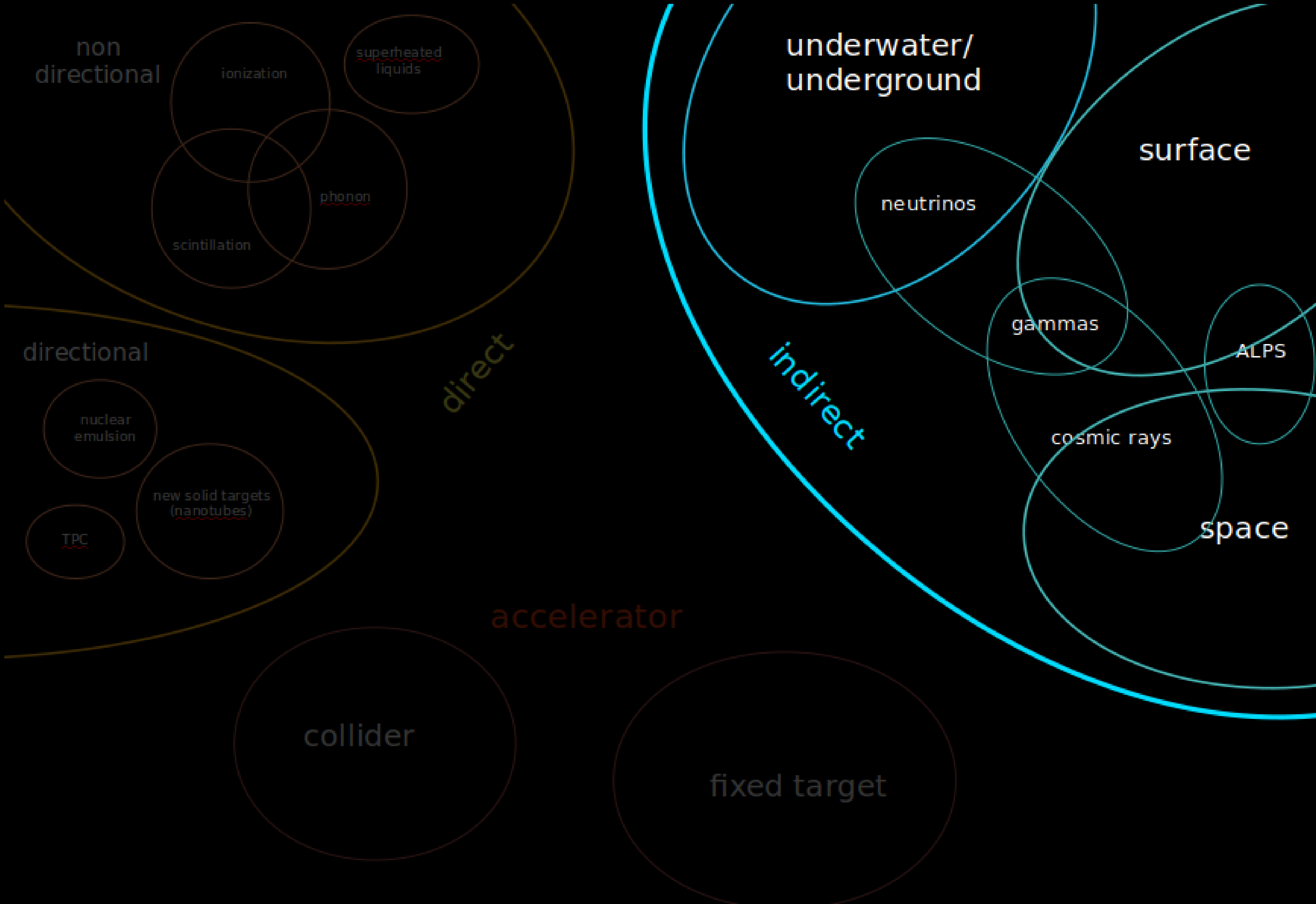
→ sensitivity to the recoil direction:

- better exploit of annu
- reject solar backgrou

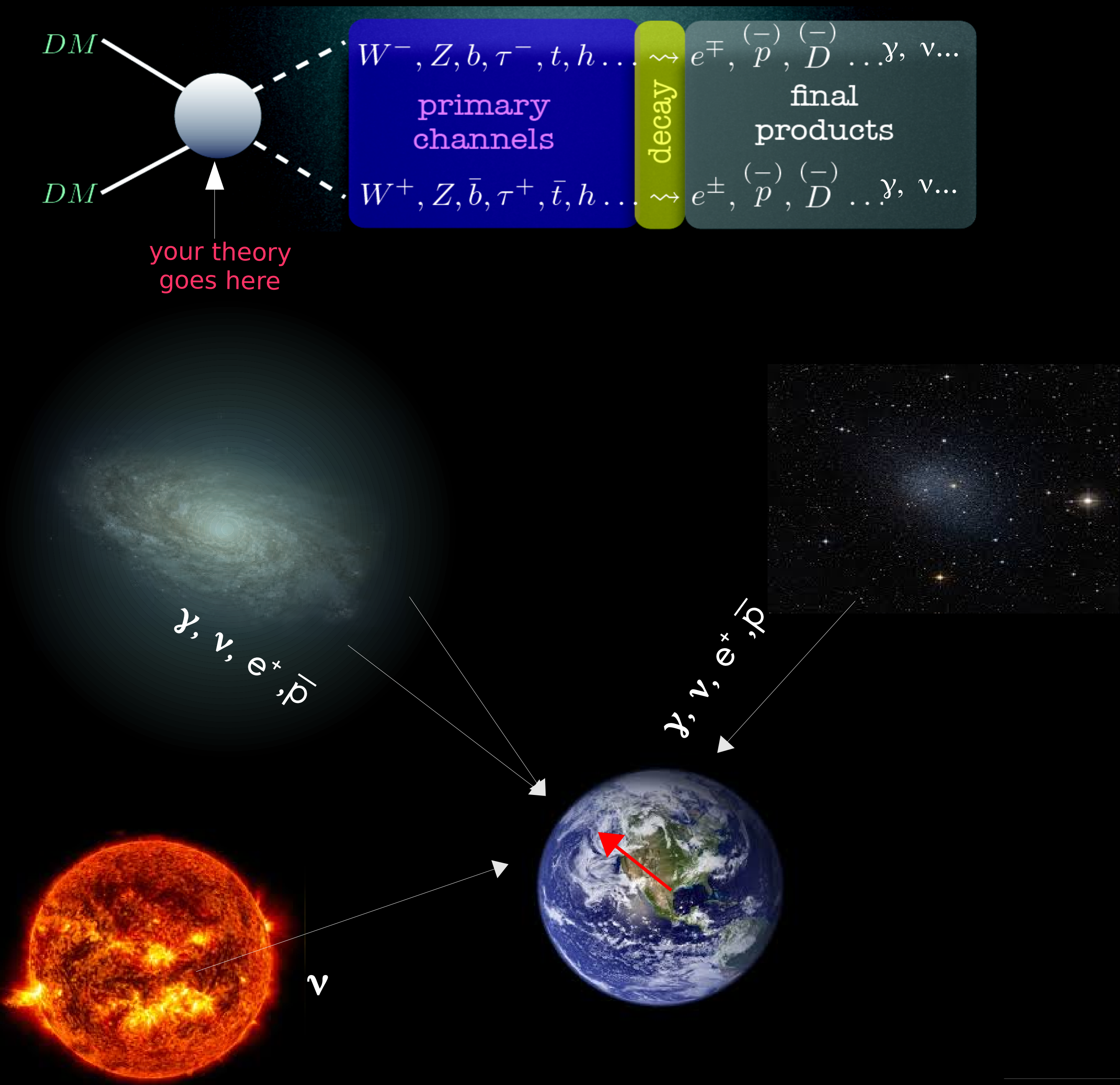
Under development:
Anisotropic targets
Nuclear emulsion
Pixelated TPCs

see paralell talk
by G. Galati

indirect searches for dark matter



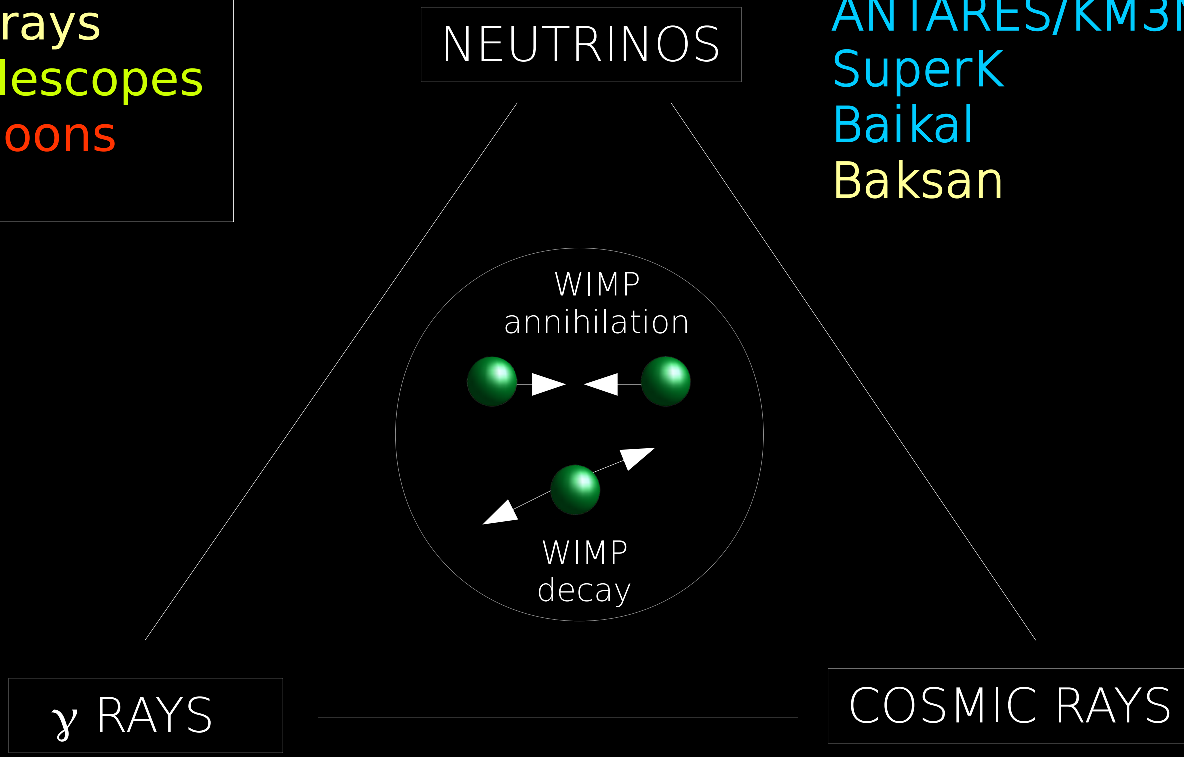
indirect searches for dark matter



indirect detection techniques

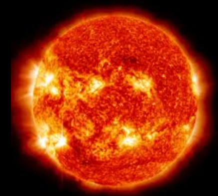
neutrino telescopes
air shower arrays
cherenkov telescopes
satellites/balloons

IceCube
ANTARES/KM3NET
SuperK
Baikal
Baksan



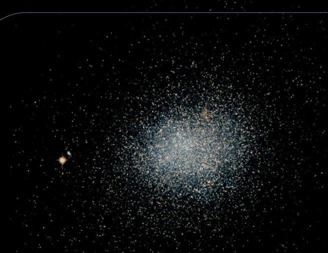
see paralell talks by
C. Armand (Fermi)
N. Zimmermann (AMS)
R. Munini (GAPS)

Fermi, Pamela, GAPS, AMS, ATIC, DAMPE, CALET
HESS, MAGIC, VERITAS
AUGER, HAWC, ALPACA, LHAASO



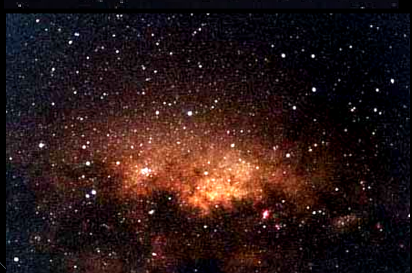
Sun

Earth



dwarf galaxies
&
distant galaxies

Galactic
Halo



Galactic
Center

probe spin-dependent and spin-independent DM-nucleon cross section, $\sigma^{SD}_{\chi-N}$ $\sigma^{SI}_{\chi-N}$

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\Gamma_A}{4\pi D^2}\frac{dN_\nu}{dE_\nu} \qquad (\Gamma_A \propto \sigma_{\chi N})$$

- complementary to direct detection
- different astrophysical uncertainties

probe velocity-averaged DM annihilation cross section $\langle\sigma_{Ann} v\rangle$

$$\frac{\Phi_x}{dE_x} = \frac{1}{4\pi}\frac{\langle\sigma_{\chi\chi} v\rangle}{2m_{DM}^2}\frac{dN_x}{dE_x}\int_{l.o.s.} \rho^2_{DM}(r)\, dr\, d\Omega$$

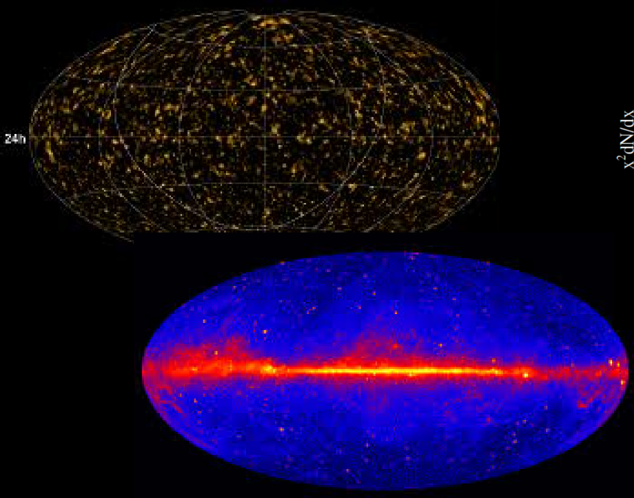
(x=ν, γ, CRs)

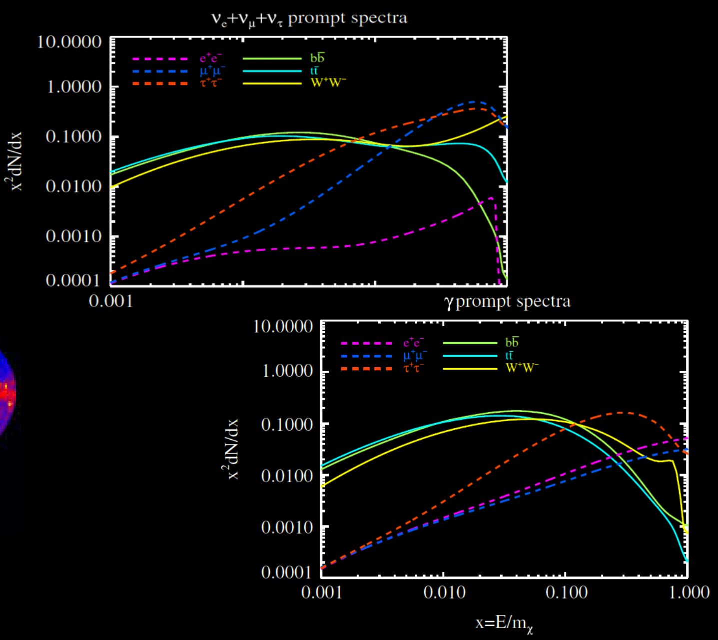
- shared astrophysical systematic uncertainties (halo profiles, galaxy structure...)
- probe different annihilation channels

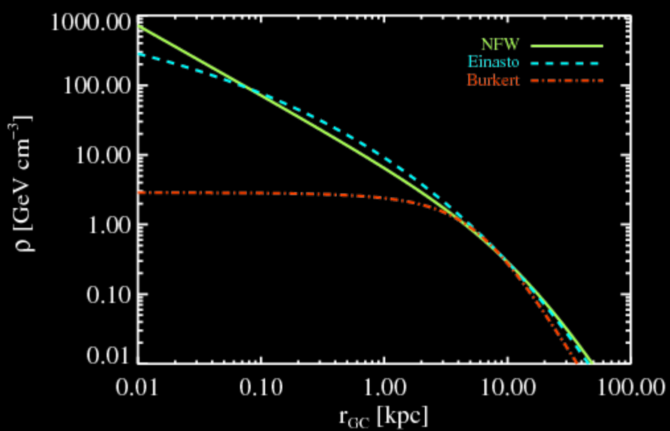
$$\frac{d\phi_i}{dE_i} = \frac{1}{4\pi}\frac{\langle\sigma_{ann} v\rangle}{2 m_{DM}^2}\frac{dN_i}{dE_i} \times \int_{l.o.s.} \rho_{DM}^2(r)\, dr\, d\Omega$$

($i=\nu,\gamma$,CR)

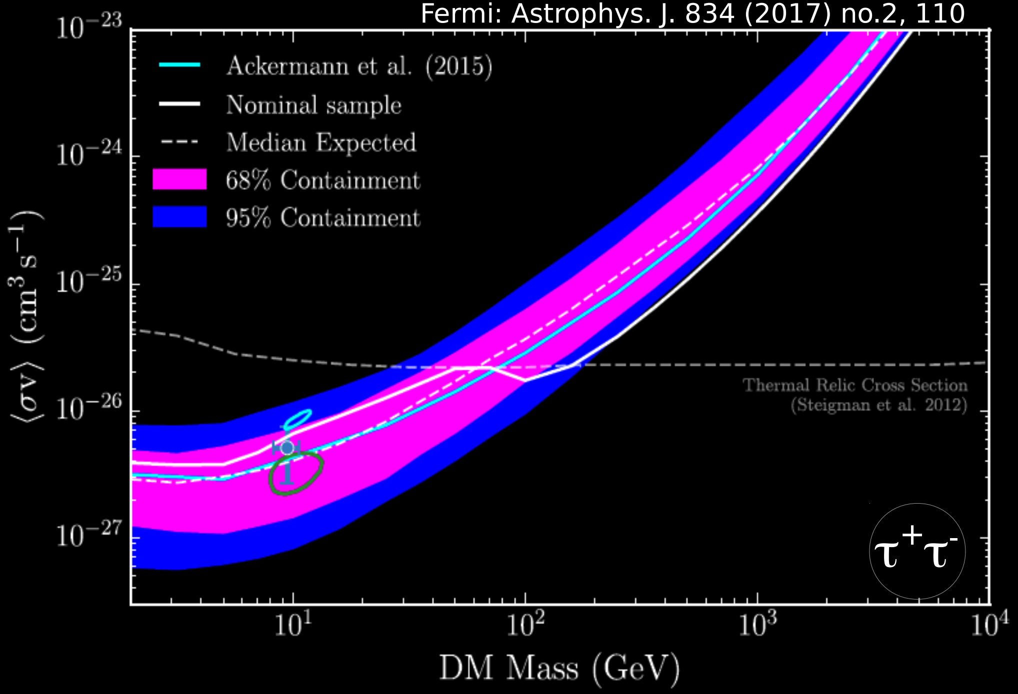
measure | **particle physics model** | **astrophysics**

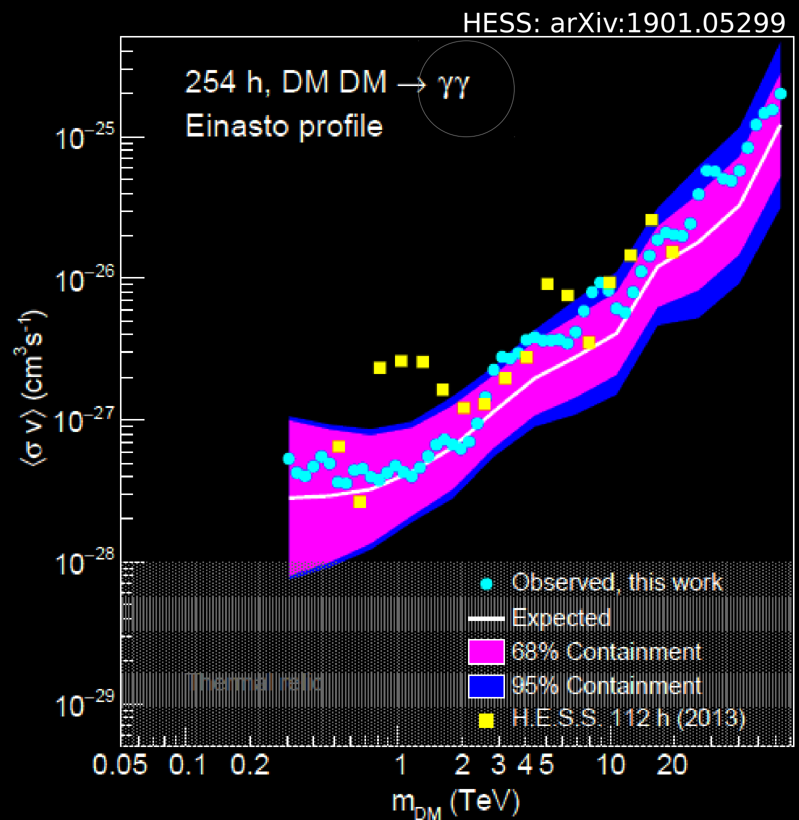






Example of recent results from space (Fermi) and ground (HESS)

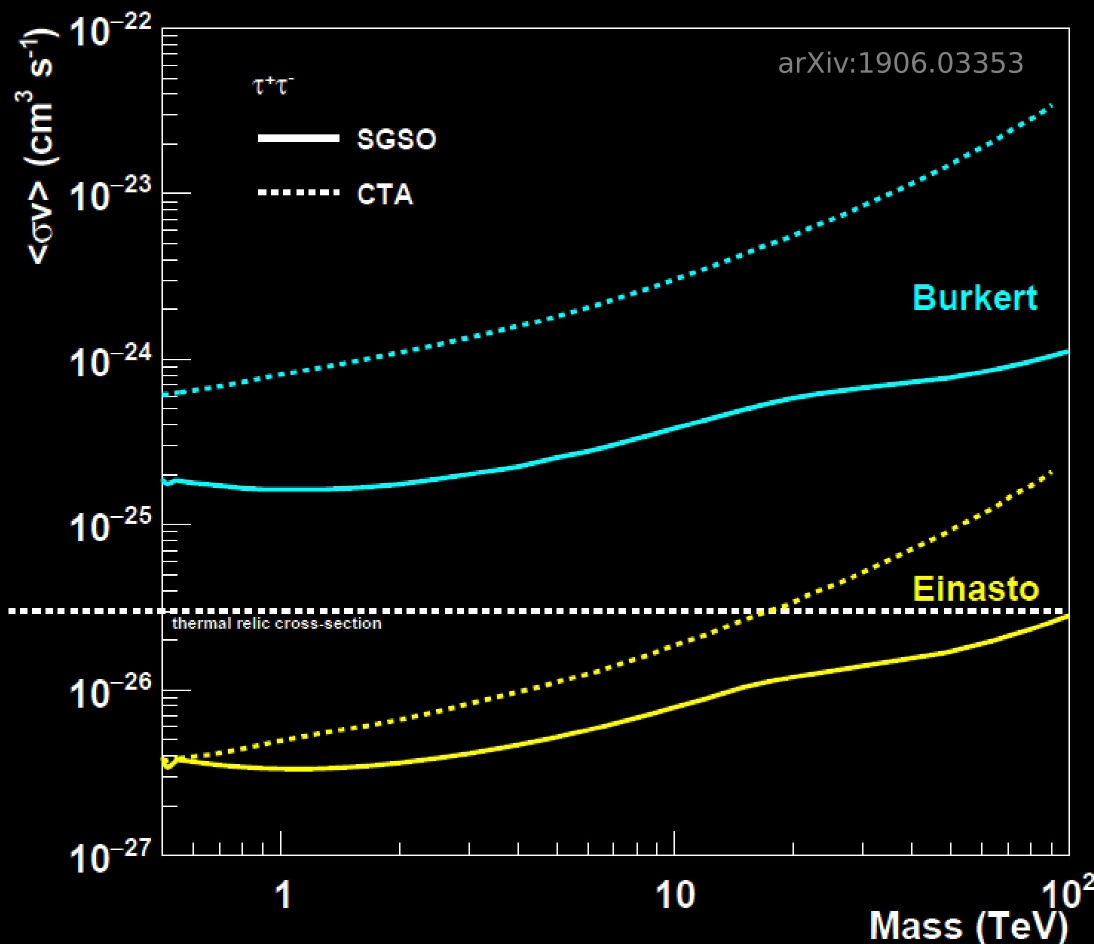




For fair comparison between experiments note that the same annihilation channel, source, DM density profile and J-factor calculation should be used.

Effect of the choice of halo model

$$\frac{d\phi_i}{dE_i} = \frac{1}{4\pi}\frac{\langle\sigma_{ann} v\rangle}{2 m_{DM}^2}\frac{dN_i}{dE_i} \times \int_{l.o.s.} \rho_{DM}^2(r)\, dr\, d\Omega$$



Effect of different choice of halo model

Recent AMS data confirms, and extends to 1 TeV, the positron excess (Phys. Rev. Lett. 122, 041102 (2019))

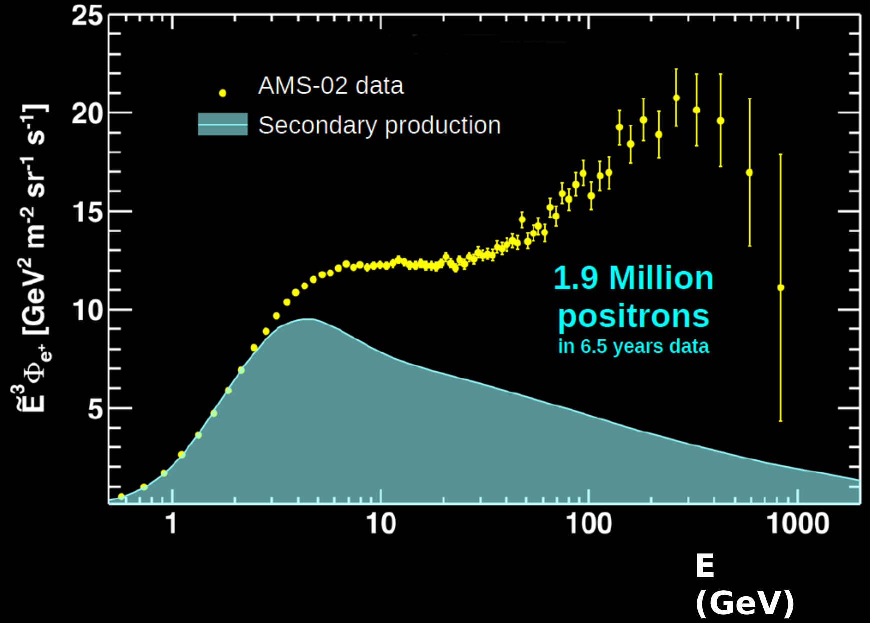
Spectrum compatible at > 4σ with a cut-off at 812 GeV

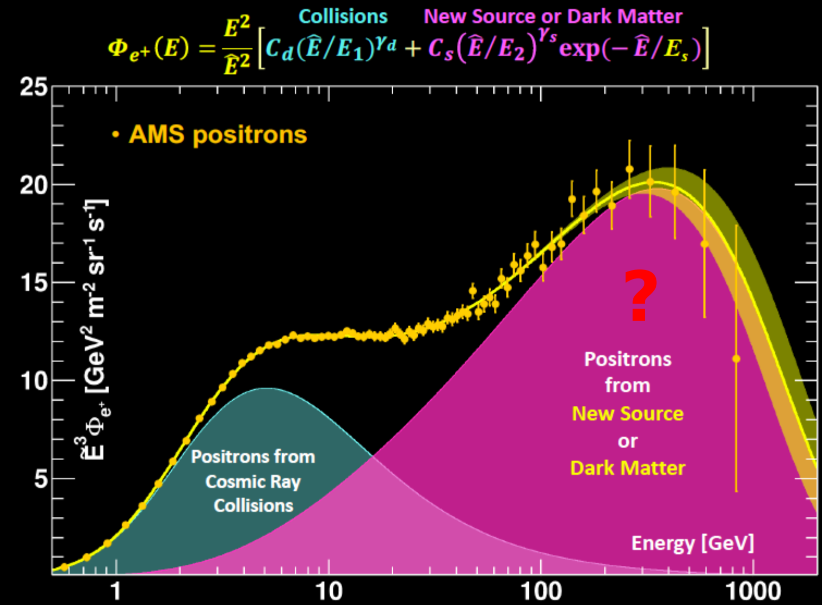
Both DM annihilations and conventional explanations (pulsar) possible

DM models need to be a bit contrived →

$\overline{\mathrm{p}}$ flux compatible with standard background (bar a recent claim of a $\overline{\mathrm{p}}$ excess @10 GeV Phys. Rev. Lett. 118, 191102 (2017))

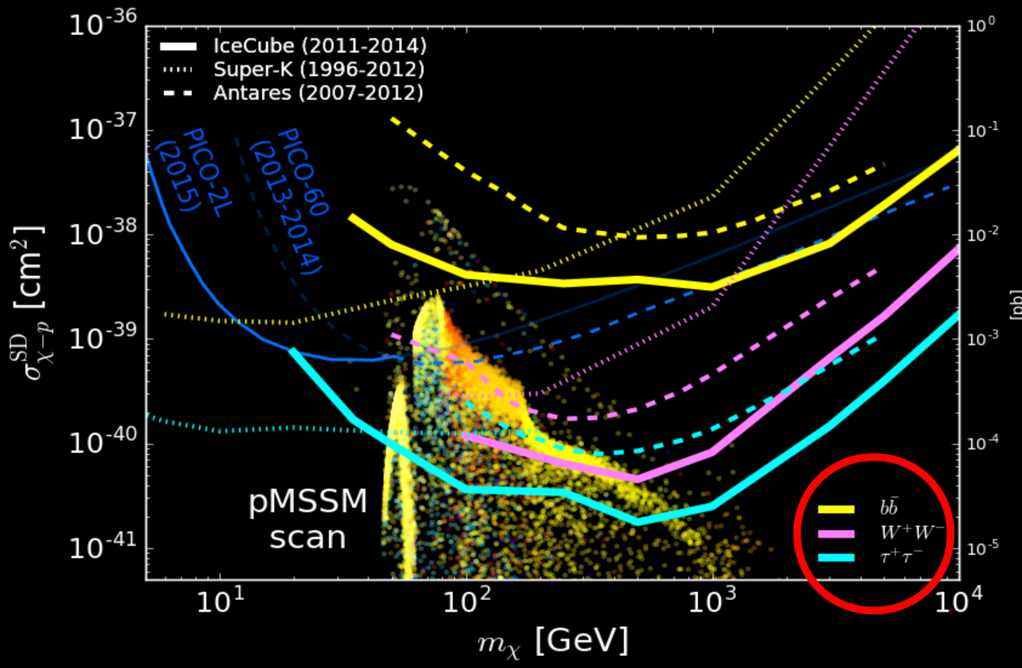
Need: complete antimatter picture ($\overline{\mathrm{He}}$, $\overline{\mathrm{d}}$) + spectrum beyond 1 TeV





From the Sun

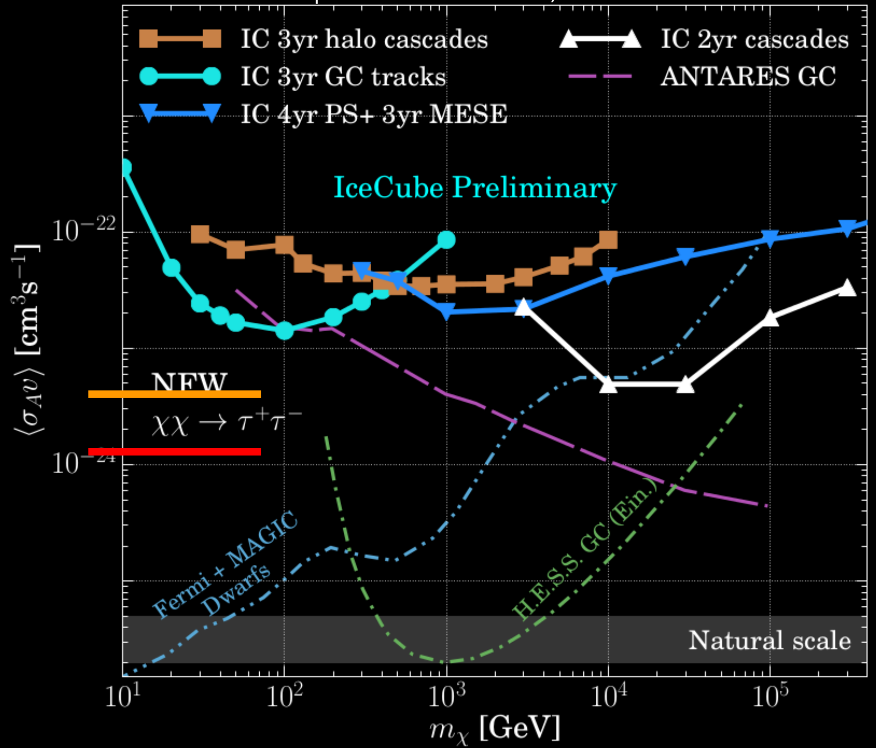
$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\Gamma_A}{4\pi D^2}\frac{dN_\nu}{dE_\nu} \propto \sigma_{\chi N}$$



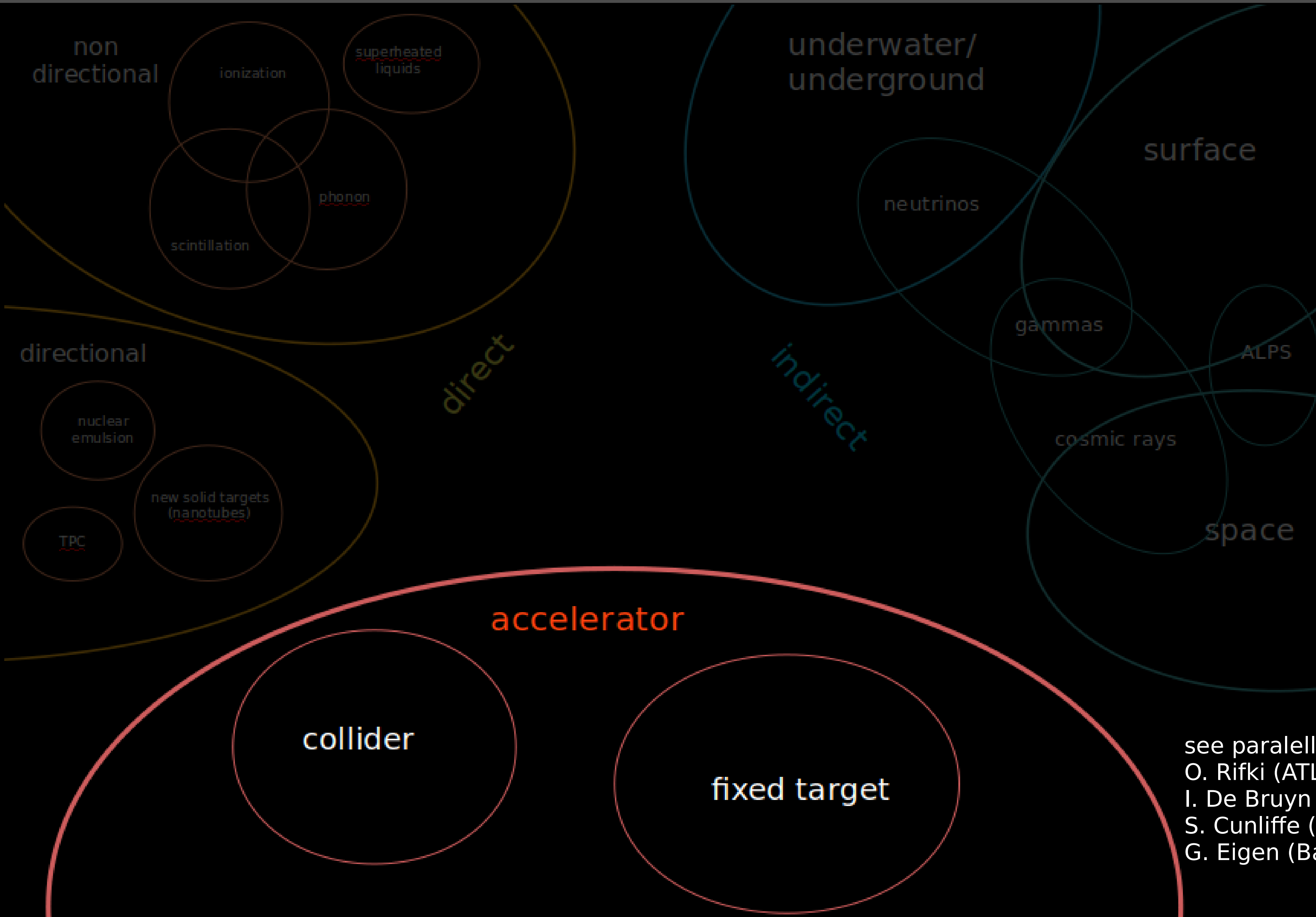
From galaxies

$$\frac{\Phi_x}{dE_x} = \frac{1}{4\pi}\frac{\langle\sigma_{\chi\chi} v\rangle}{2m^2_{DM}}\frac{dN_x}{dE_x}\int_{l.o.s.}\rho^2_{DM}(r)\,dr\,d\Omega$$

(see erratum to Phys. Lett. B, Volume 769, (2017) 249 for an updated ANTARES limit)



accelerator searches for dark matter

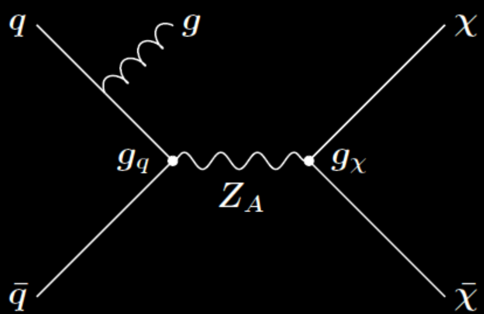


see paralell talks by
O. Rifki (ATLAS)
I. De Bruyn (CMS)
S. Cunliffe (Belle)
G. Eigen (BaBar)

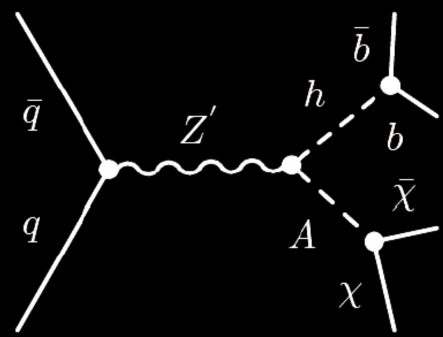
Really: searches for new particles

DM candidates = missing energy

Need to tag the event to trigger, e.g.,

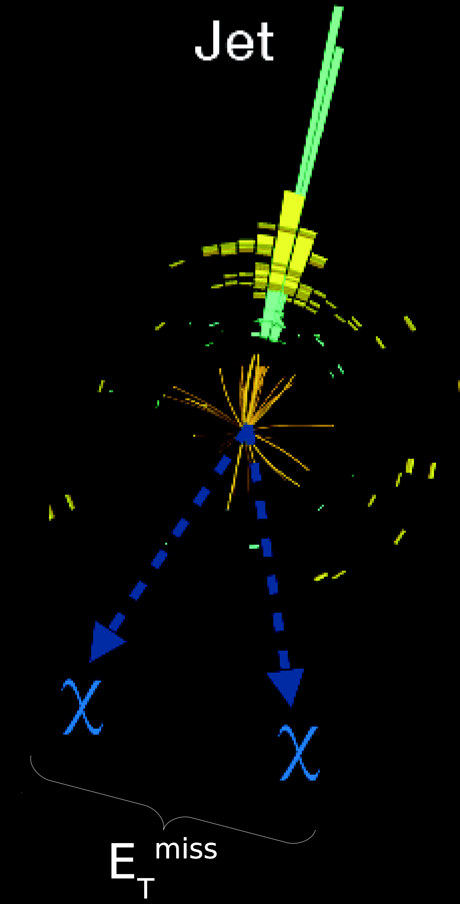


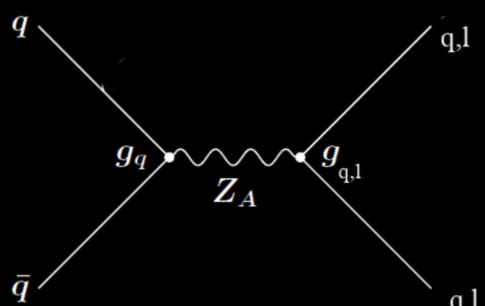
or



or

Jet + E_T^{miss}
Photon + E_T^{miss}
Z→ll + E_T^{miss}
V → qq + E_T^{miss}
h → bb + E_T^{miss}
top + E_T^{miss}
tt/bb + E_T^{miss}



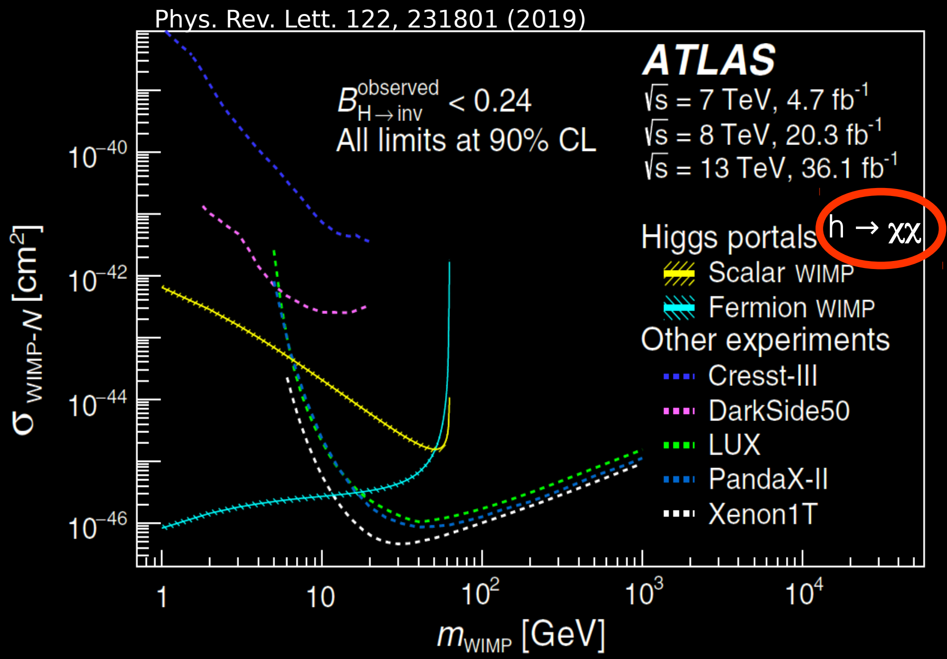


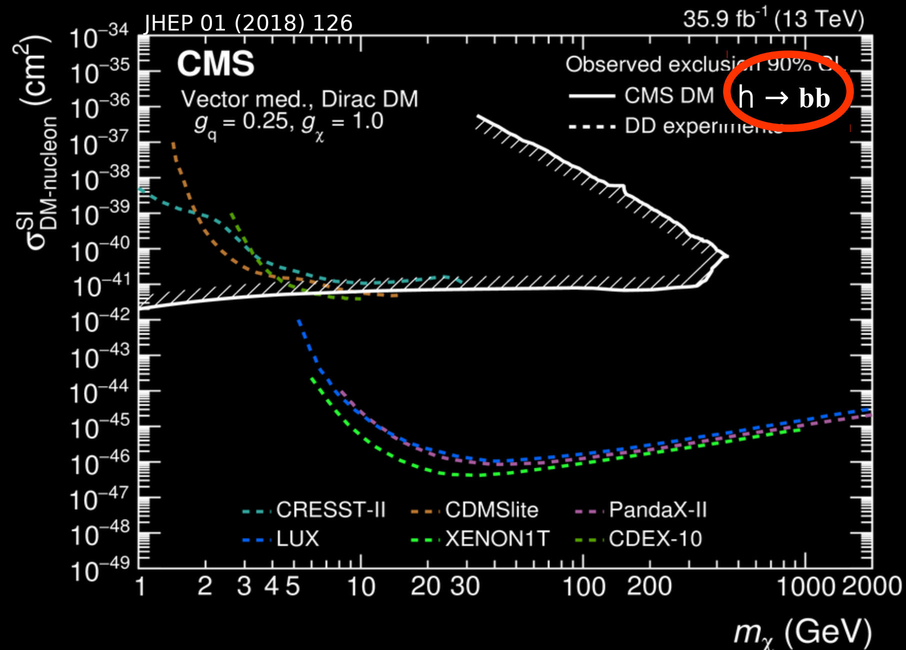
= resonance @ m_{ZA}

Results can be cast in terms of the $\sigma_{\text{DM-N}}$ Xsection to be able to compare with direct/indirect experiments

Many model dependencies:
comparisons must be made with care

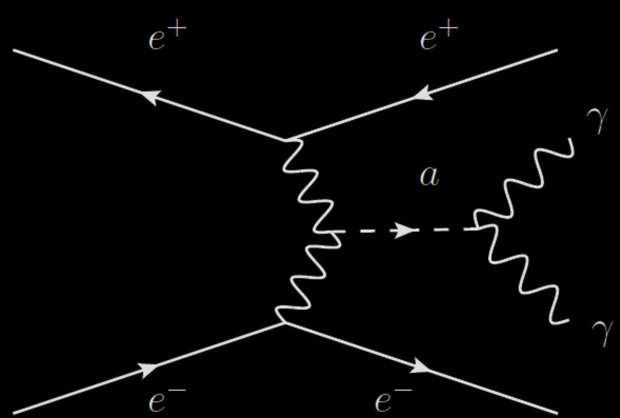
Accelerator competitive regions:
low mass DM, below a few GeV

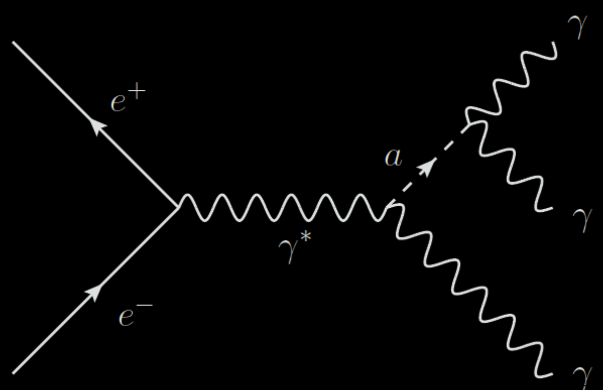


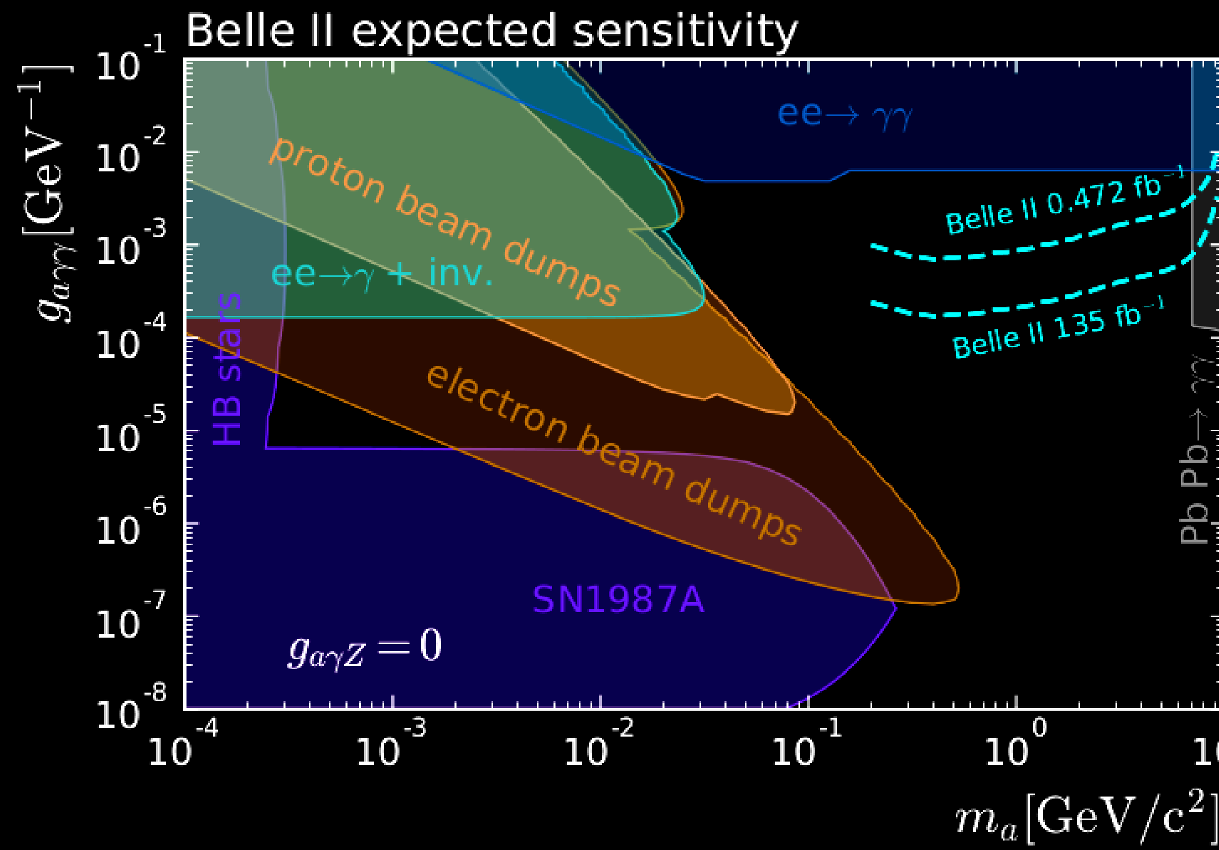


Cleaner environment in e+e- colliders

Competitive sensitivity to ALPS







outlook

- The search for dark matter is a complex, multidisciplinary endeavour

- Experimentally driven field, since many possibilities on its nature remain open

- After more than a decade of exploration, direct detection experiments are converging to a few established techniques, and collaborations joining efforts

- Next challenge for direct detection is lowering thresholds and coping with the neutrino swampland
  → promising R&D efforts in directional detection

- Indirect searches provide a complementary approach, subject to different systematics.

- Uncertainties from external inputs (astrophysics, nuclear physics…) play a determinant role in interpreting results

- Accelerator searches face the difficulty of model dependency and inability to determine the lifetime of a potential signal, but benefit from controlled environments and precision measurements

- Lively fixed target program at CERN, JLAB, FNAL and SLAC

- Is the dark sector really so simple as one stable particle, while the visible sector comprises several fundamental particles and families?
  → we need to avoid looking under the lamppost, and start considering more complex scenarios. Theory can lead in this respect

the end