Dark Matter Experiments - III

Maxime Pierre

BND Graduate School — Blankenberge 2024

Overview

Lecture 1 - Dark Matter Direct Detection part 1

- Direct Detection Principle
- Low-background Experiments
- Experimental Landscape

Lecture 2 - Dark Matter Direct Detection part 2

- Case Example: XENONnT
- Application to Neutrino Physics

Lecture 3 - Dark Matter Indirect Detection

Dark Matter Production

1 Dark Matter Indirect detection

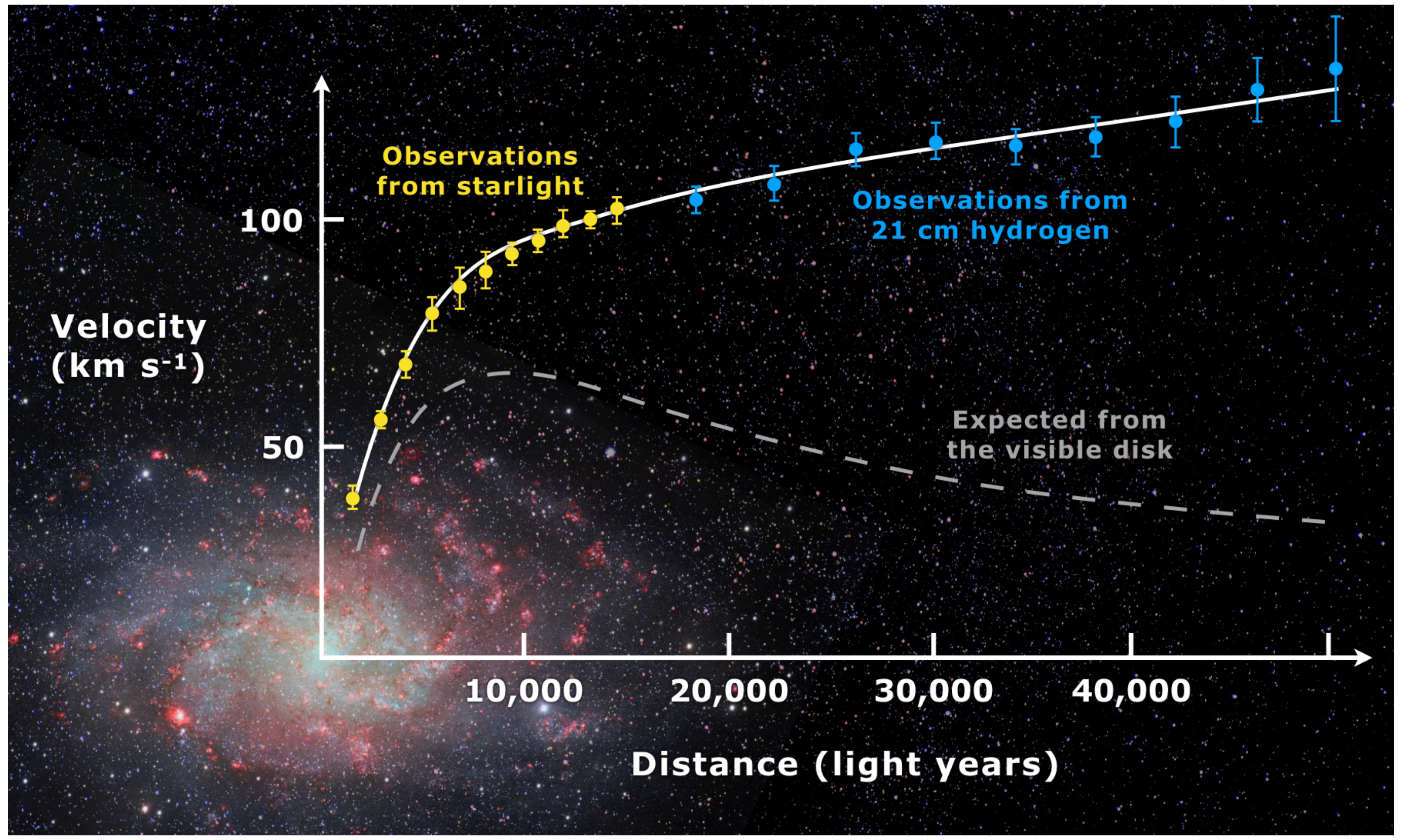
2 Dark Matter Production

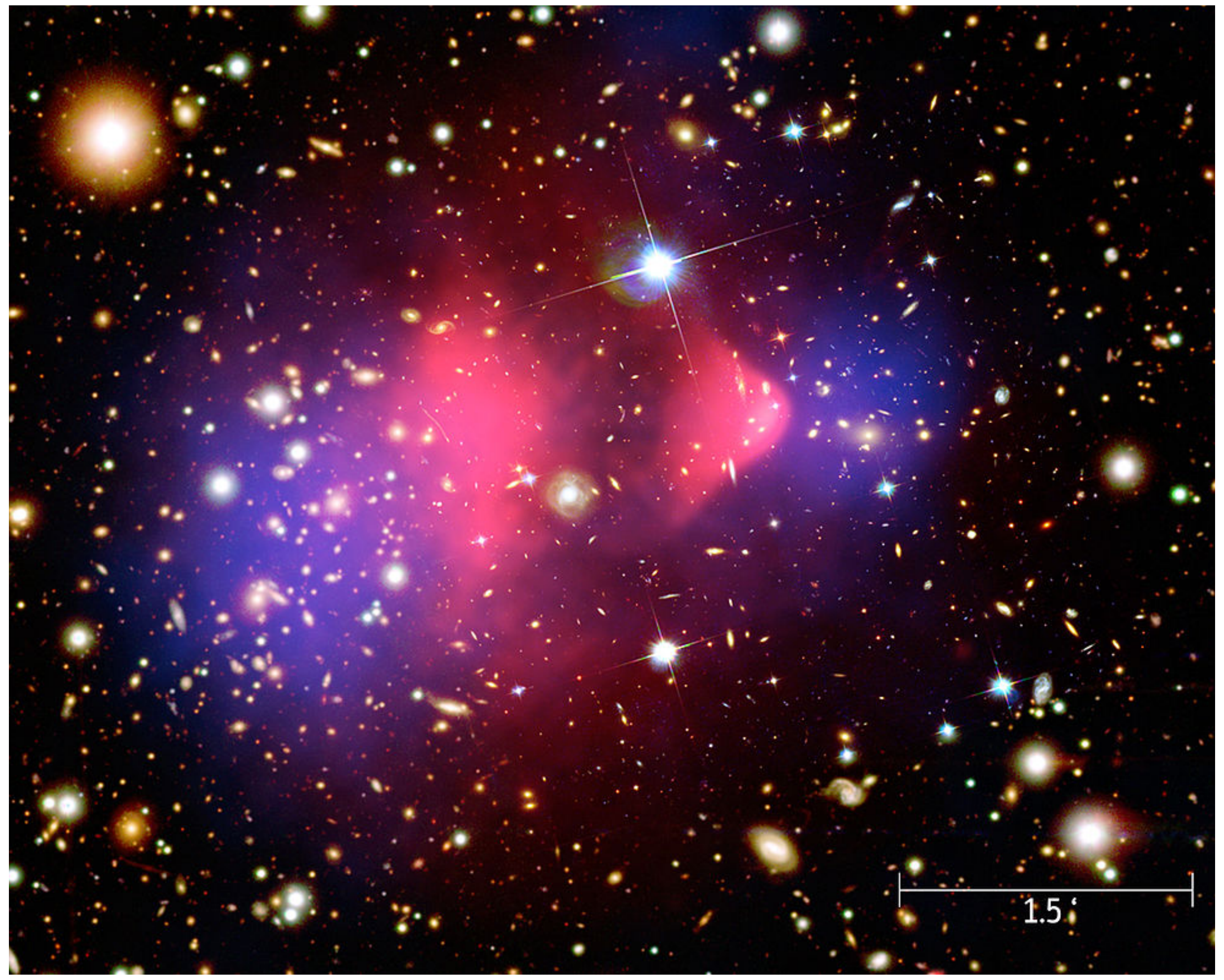
Dark Matter Indirect Detection

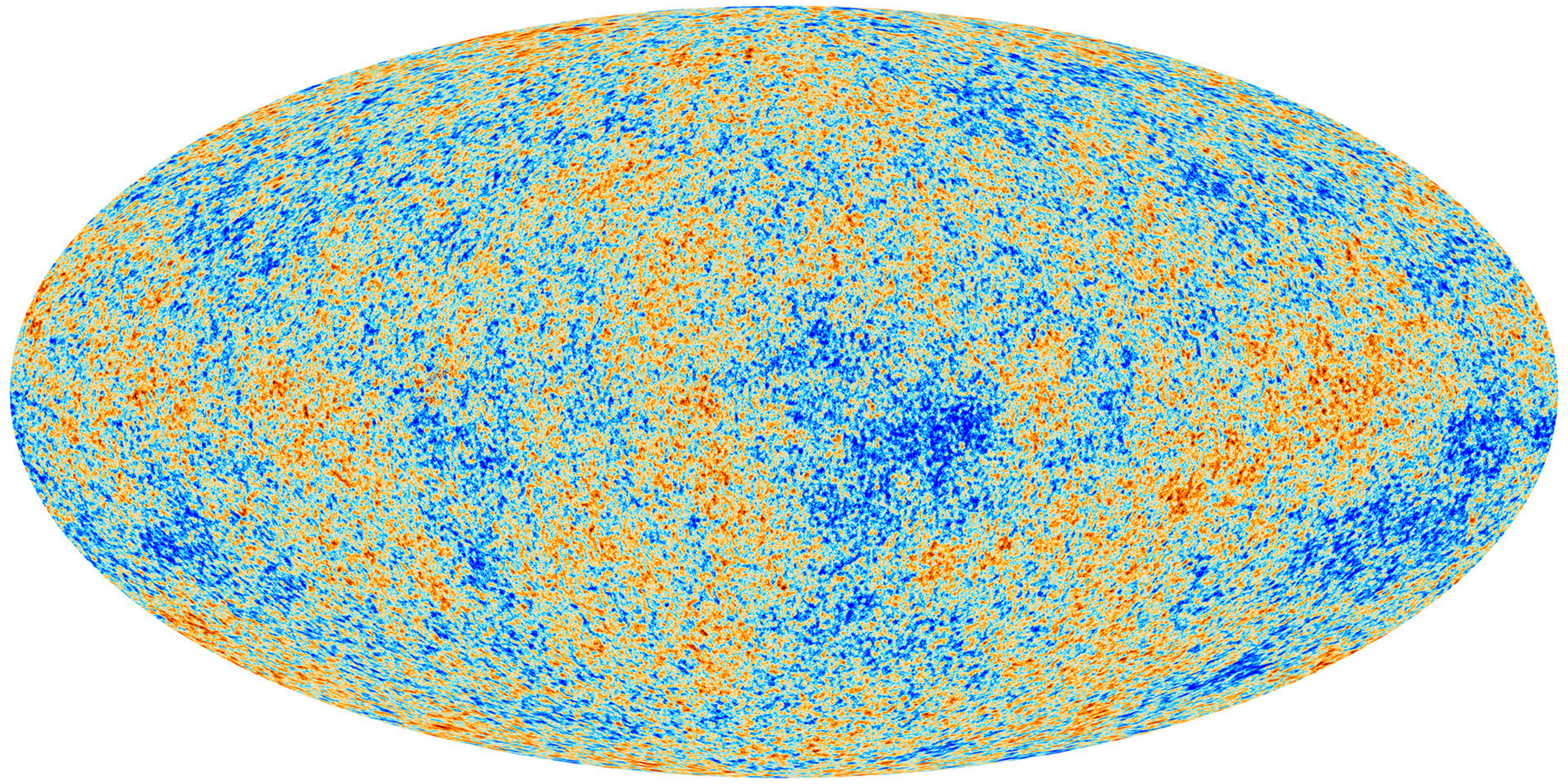
(For Dummies)

Concept of Indirect detection

Multiple Astrophysical evidences for the presence of DM





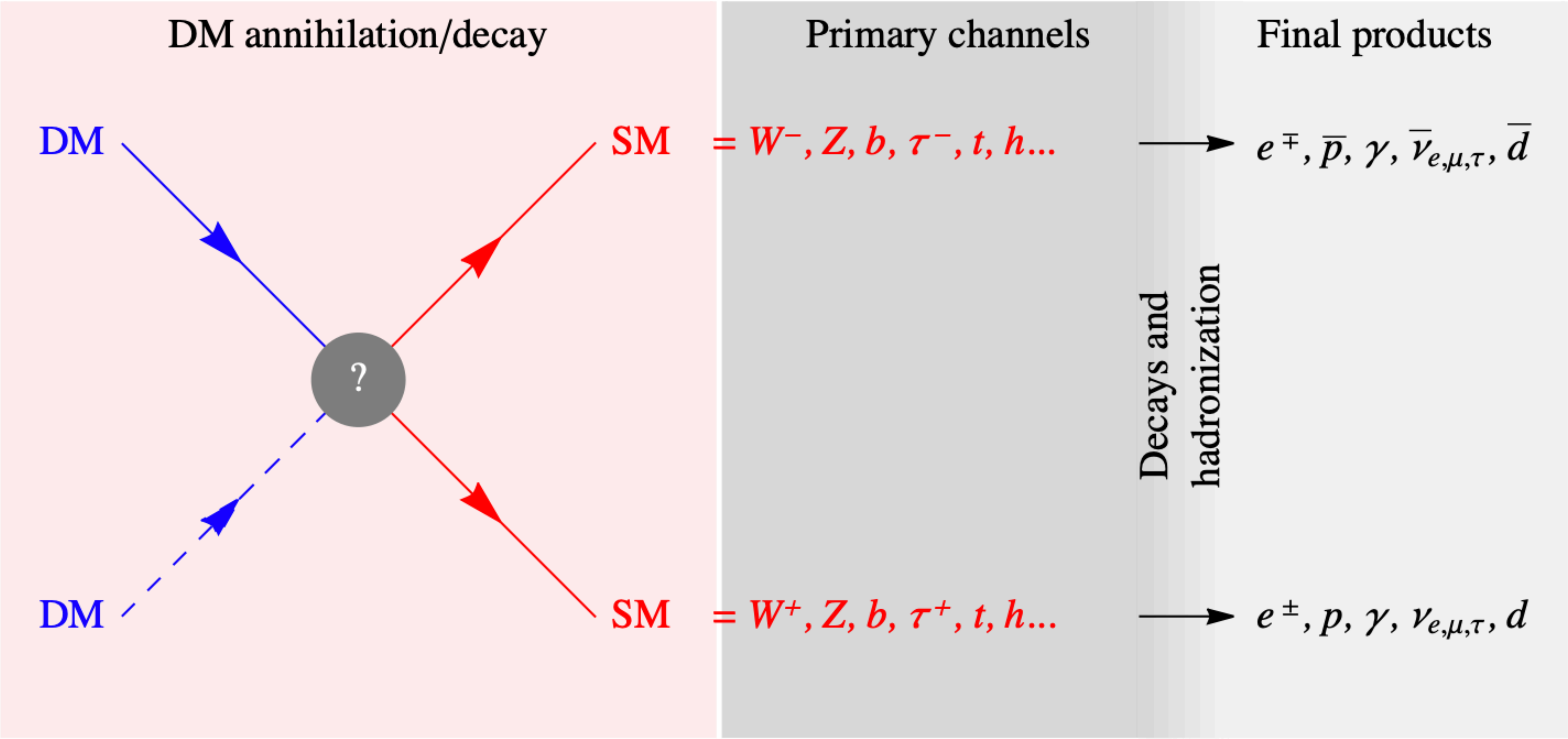


But more can be done: Astrophysics can also be used to constrain DM particle properties!

Concept of Indirect detection

Indirect DM Signature

- DM pair annihilation (or decay) resulting in measurable SM particles



arXiv:2406.01705

2-body primary channels

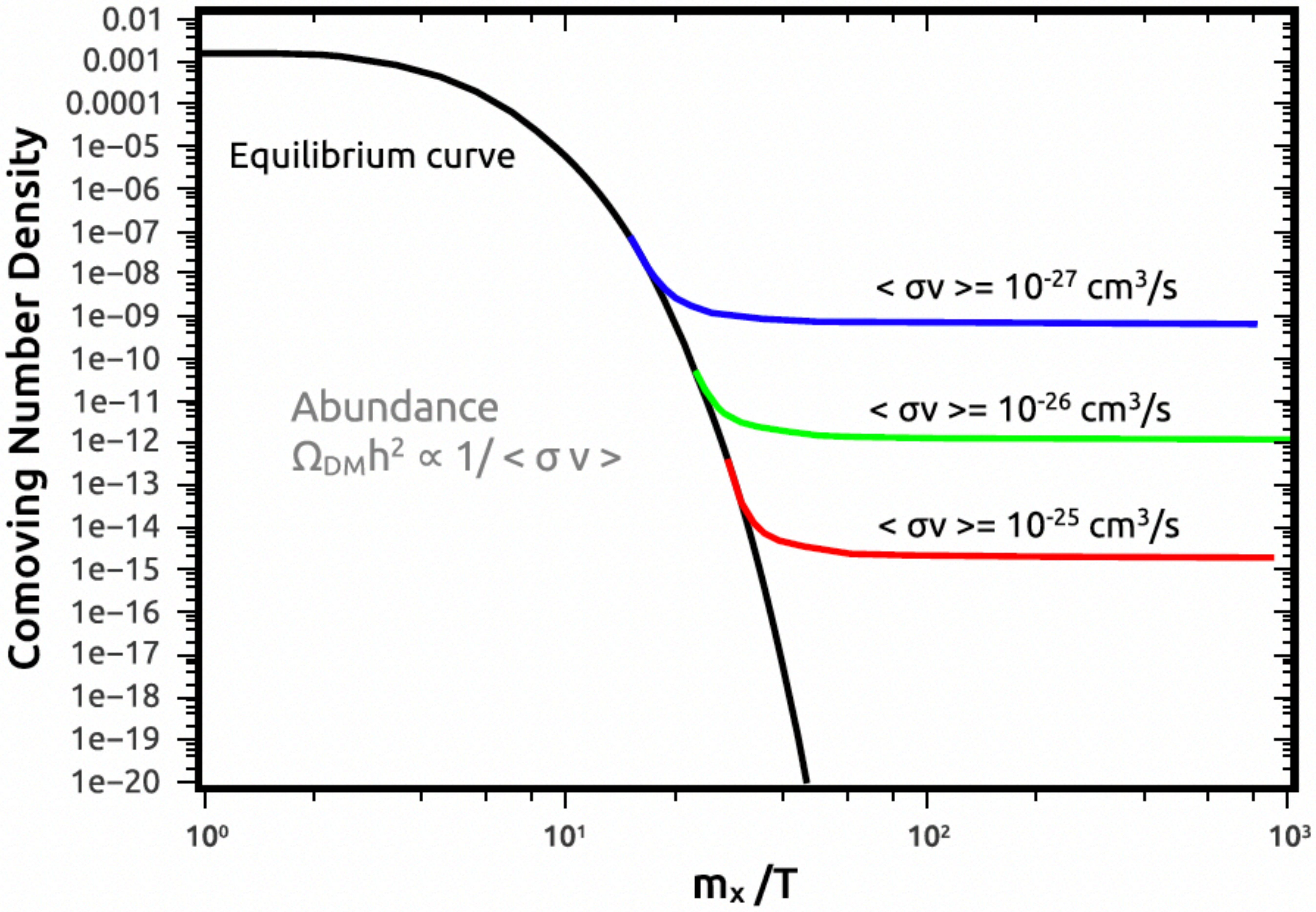
$e^+e^-, \mu^+\mu^-, \tau^+\tau^-, \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau,$

$q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}, \gamma\gamma, gg,$

W^+W^-, ZZ, hh

Concept of Indirect detection

Initial constrain from WIMP Miracle



G. Arcadi et al., Eur. Phys. J. C **78**, 203 (2018)

- WIMP production | freeze-out
- Observed relic DM density related to the annihilation cross section

$$\Omega_\chi \propto \frac{1}{\langle \sigma v \rangle_{\rm ann}} \sim \frac{m_\chi^2}{g_\chi^4}$$

Energy spectra at production

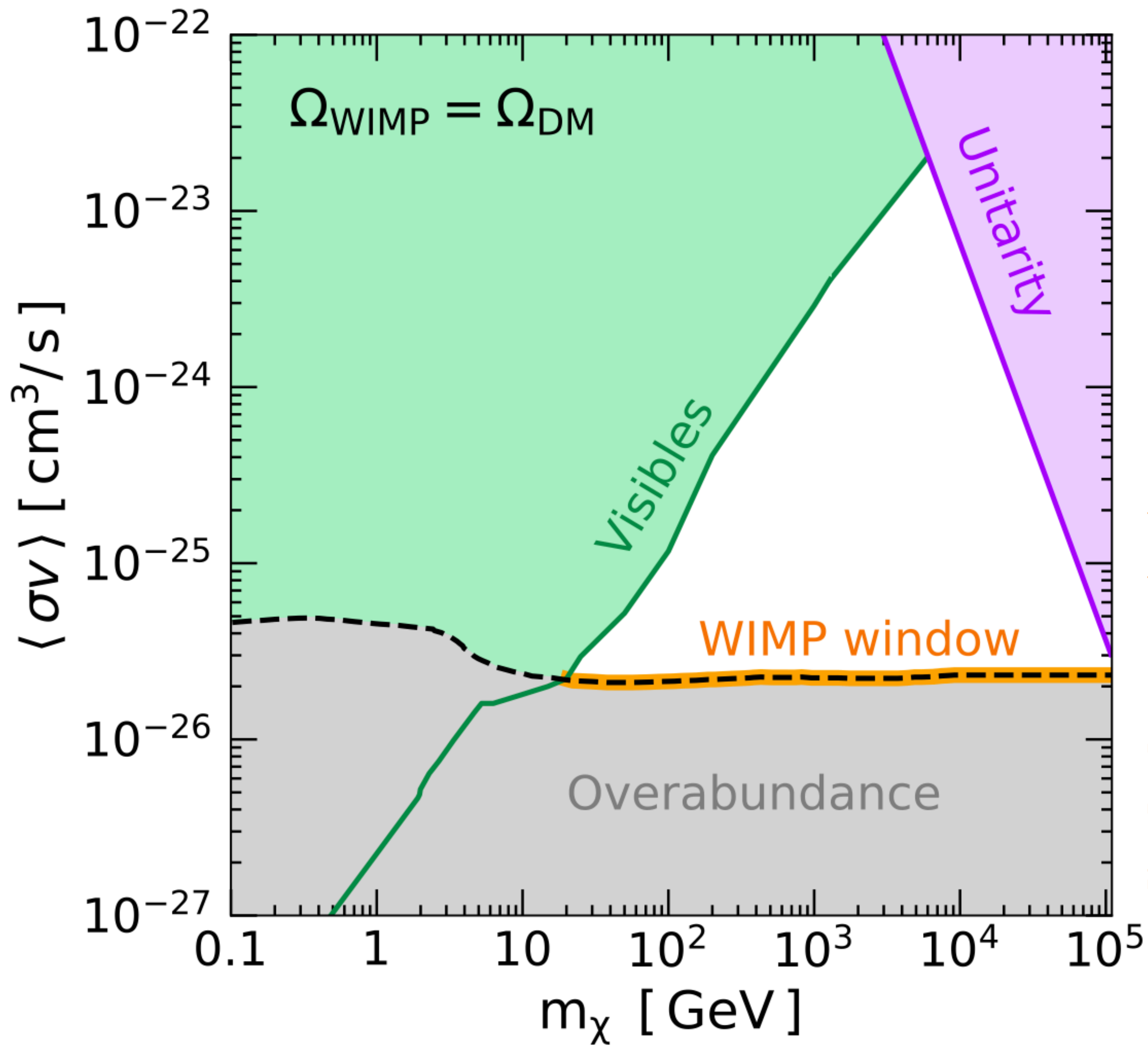
WIMP mass window

- Big Bang Nucleosynthesis

$$m_\chi > \mathcal{O}(1)\,\text{MeV}$$

- Constrain on WIMP mass from Unitarity limit (s-wave)

$$m_\chi < 100\,\text{TeV}$$



Phys. Rev. D **98**, 023016 (2018)

Indirect DM Messenger

Multiples channel (Multi-messenger) to probe indirect evidence of DM (signature)

- Indirect DM with cosmic rays
- Indirect DM with gamma rays
- Indirect DM with neutrinos
- DM in the stars?
- And many more…

My goal here, will be to present only a sub-set of the experiment looking for DM indirect detection via one of this channel. I might miss your favourite experiment in the process, sorry about that.

How to look for DM Ann. signature?

Solid angle in the sky

Branching Ratio

Differential energy spectrum for a primary channel i

DM density

$$\frac{d\phi(\Delta\Omega, E)}{dE} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle_{\text{ann}}}{2m^2}\sum_i B_r^i \frac{dN_i(E)}{dE} \times \int_{\Delta\Omega}\int_{\text{l.o.s}} \rho^2 \, dl \, d\Omega$$

Particle Physics

∑ Contribution from 2-body primary channels

Astrophysics (J-factor)

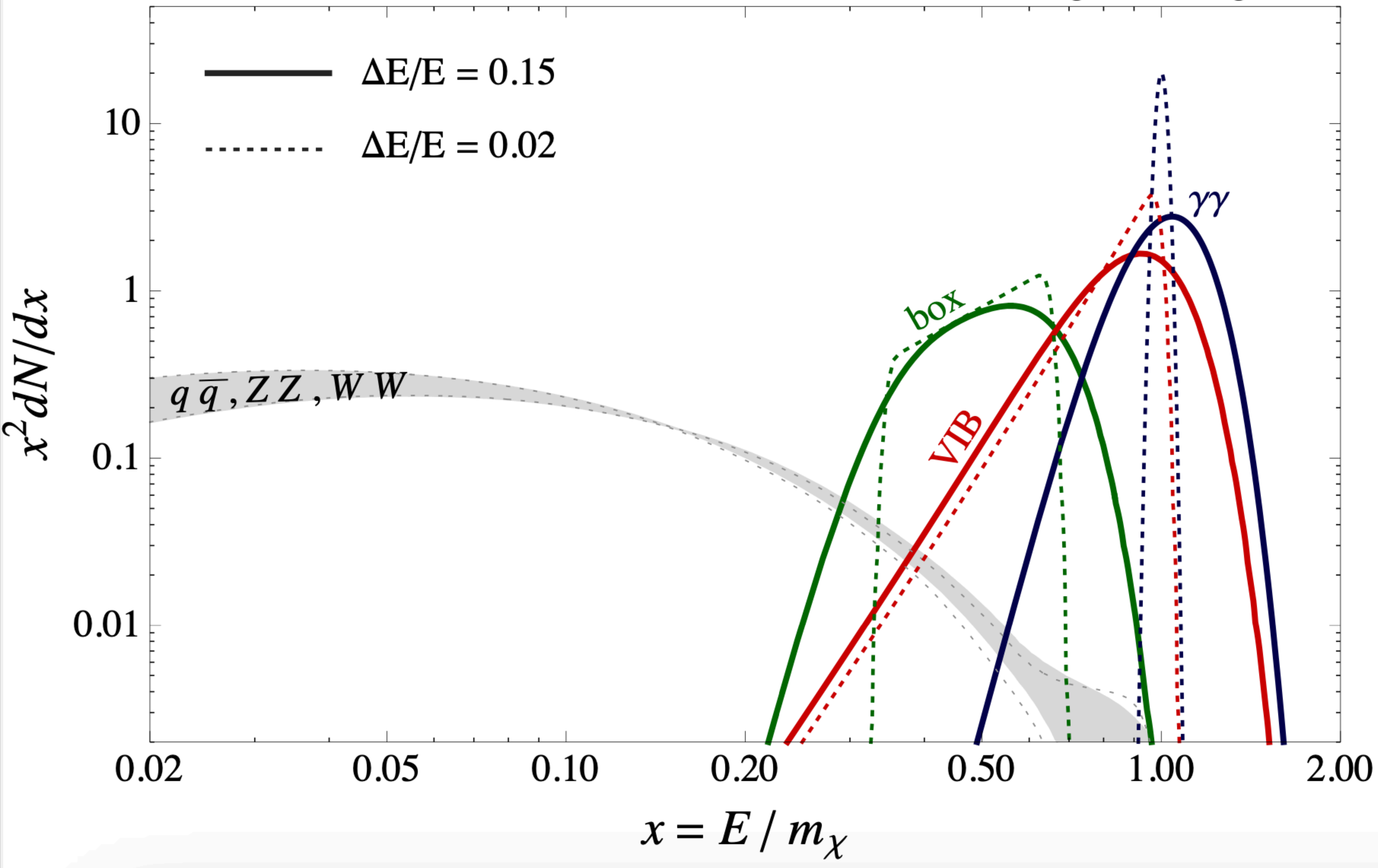
Account for the distribution of DM in the region of interest

- Estimate the differential flux of DM annihilation product (ɣ, 𝜈, …) on Earth from a region of interest in the sky. (More detail for ≠ product: arxiv.org:2406.01705)
- Measuring lower limit on flux → derive lower limit on annihilation cross-section

How to look for DM Ann. signature?

Initial slide from R. Laha

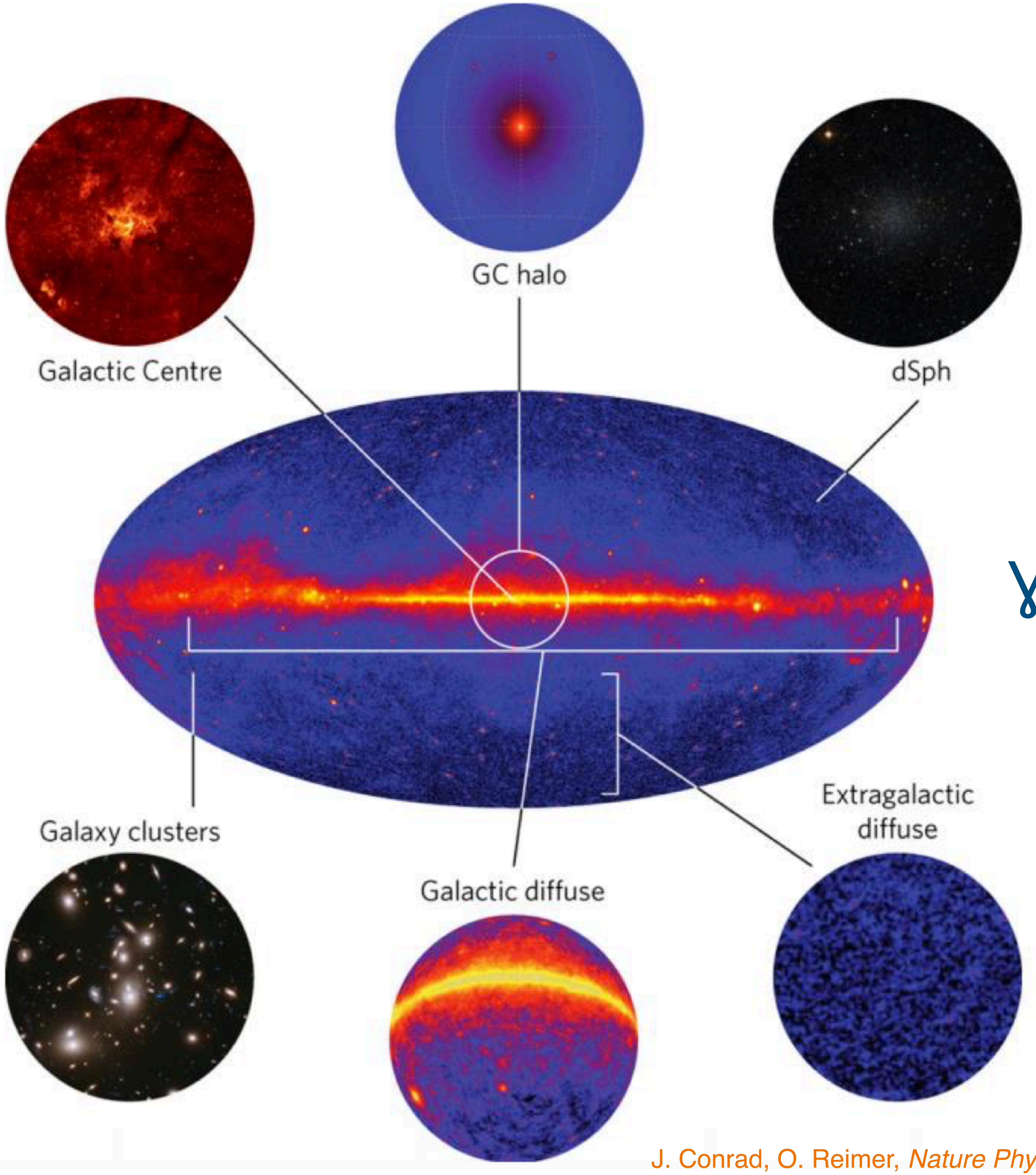
Bringmann & Weniger (2012)



- Different type of signal:
  - Continuum:
    $\chi\chi \to q\bar{q}, Z\bar{Z}, W^+W^-$
  - Box:
    $\chi\chi \to \phi\phi;\ \phi \to \gamma\gamma$
  - Virtual internal Bremsstrahlung:
    $\chi\chi \to \ell^+\ell^-\gamma$
  - Line:
    $\chi\chi \to \gamma\gamma$

Where to look for DM Ann. signature?

- Regions with large density of DM
- But signal/ratio is also important! (Low astrophysical background)



dwarf Spheroidal galaxies

ɣ-ray Sky

J. Conrad, O. Reimer, *Nature Phys* **13**, 224–231 (2017)

DM annihilation with gamma rays

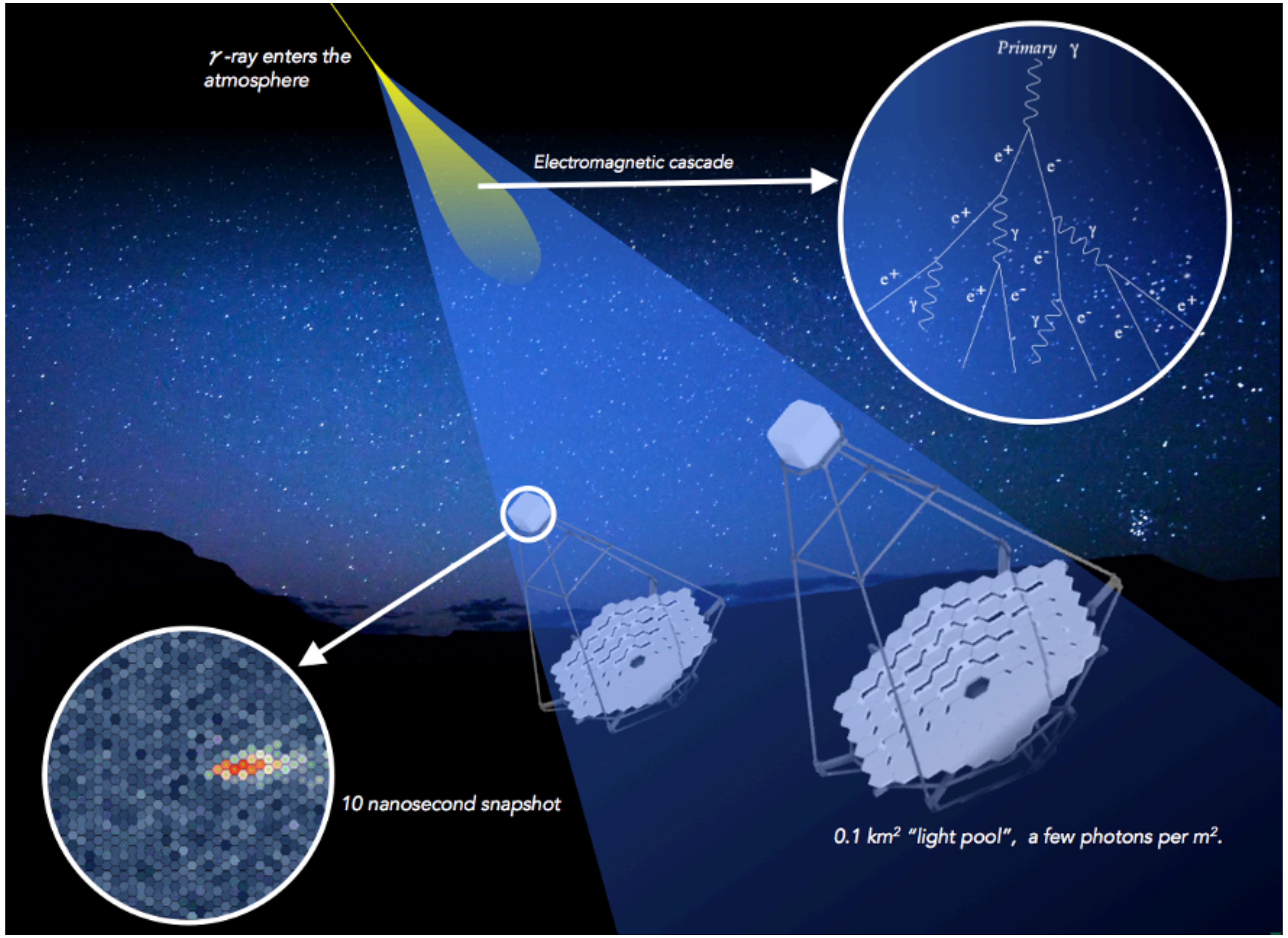
Different types of detectors for gamma rays:

- Spatial experiments (like FERMI, AMS-02)
- Imaging atmospheric Čerenkov telescopes (H.E.S.S., MAGIC, VERITAS, CTA,…)
- Air Čerenkov telescopes (HAWC, MILAGO,…)

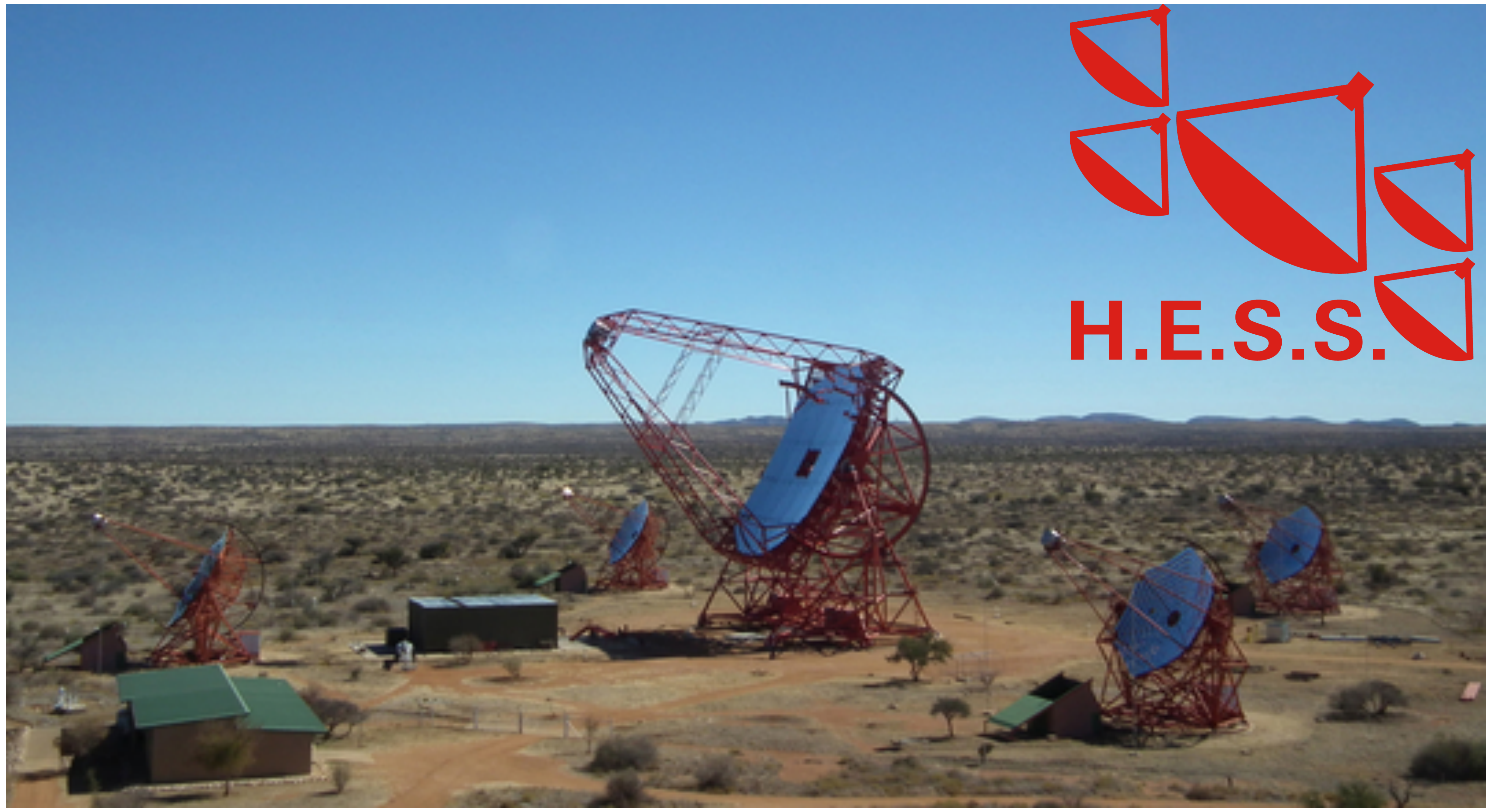
High Energy Stereoscopic System (H.E.S.S)

- Ground based IACT:
  - Energy range: 30 GeV - 100 TeV
  - Location: Namibia
  - Operating since 2003

Imaging Atmospheric Čerenkov Telescope



R. White (MPIK), K. Bernlohr (MPIK)/DESY.



Čerenkov Telescope Array (CTA)

- Ground based IACT:
    - Energy range*: 50 GeV - 50 TeV
    - Location: Paranal (Chile), La Palma (Spain)
    - Future Telescope - Improved E-resolution

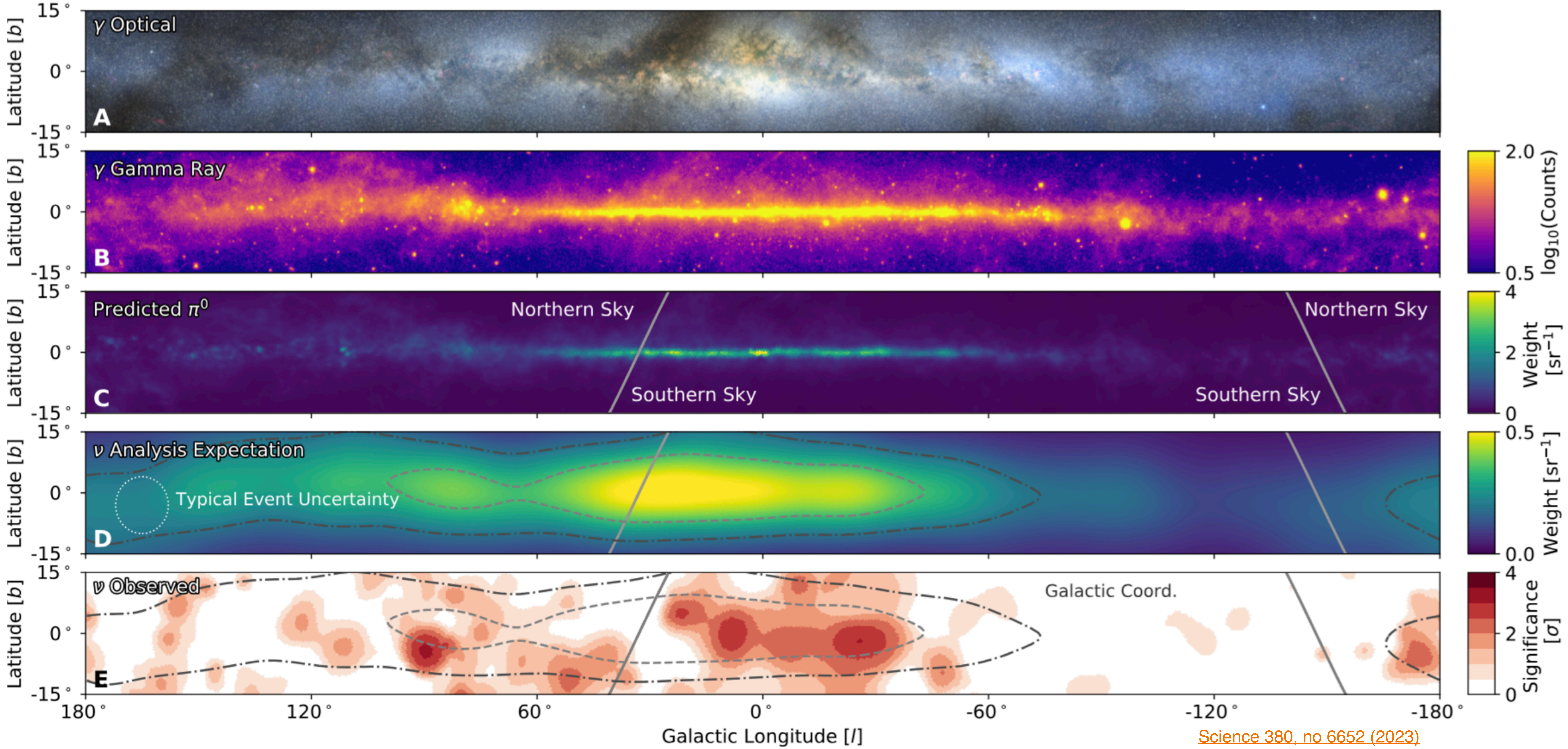
Gabriel Pérez Diaz (IAC)/Marc-André Besel (CTAO)/ESO/ N. Risinger (skysurvey.org)

DM annihilation with Neutrinos

Types of detectors for neutrinos:

- Large Underground/Under-Ice/Under-Sea Čerenkov detectors (IceCube, BAIKAL, ANTARES, Super Kamiokande, KM3NET*)
- Detect Shower of secondary particles (e.g. muons)

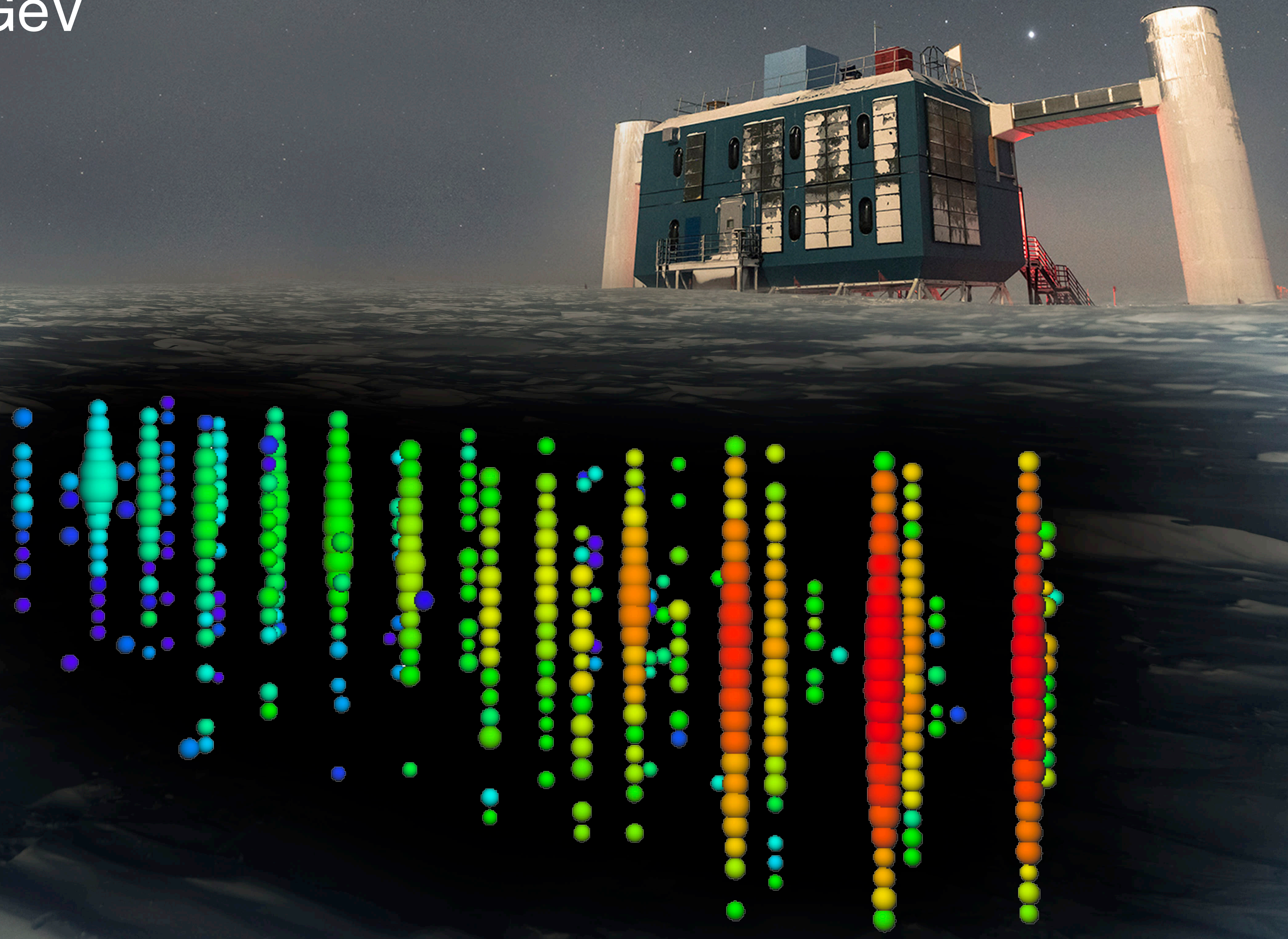
Multi-messenger Era



Science 380, no 6652 (2023)

Icecube

- Under-Ice Large Ċerenkov Telescope:
  - Energy range: > 100 GeV
  - Location: South Pole
  - Operating since 2005



Credit: IceCube Collaboration/NSF

Credit: KM3NET

- Under-Sea Large Ċerenkov Telescope:
  - Energy range: > 1 TeV
  - Location: ORCA (France) ARCA (Italy)
  - Under deployment

Credit: KM3NET

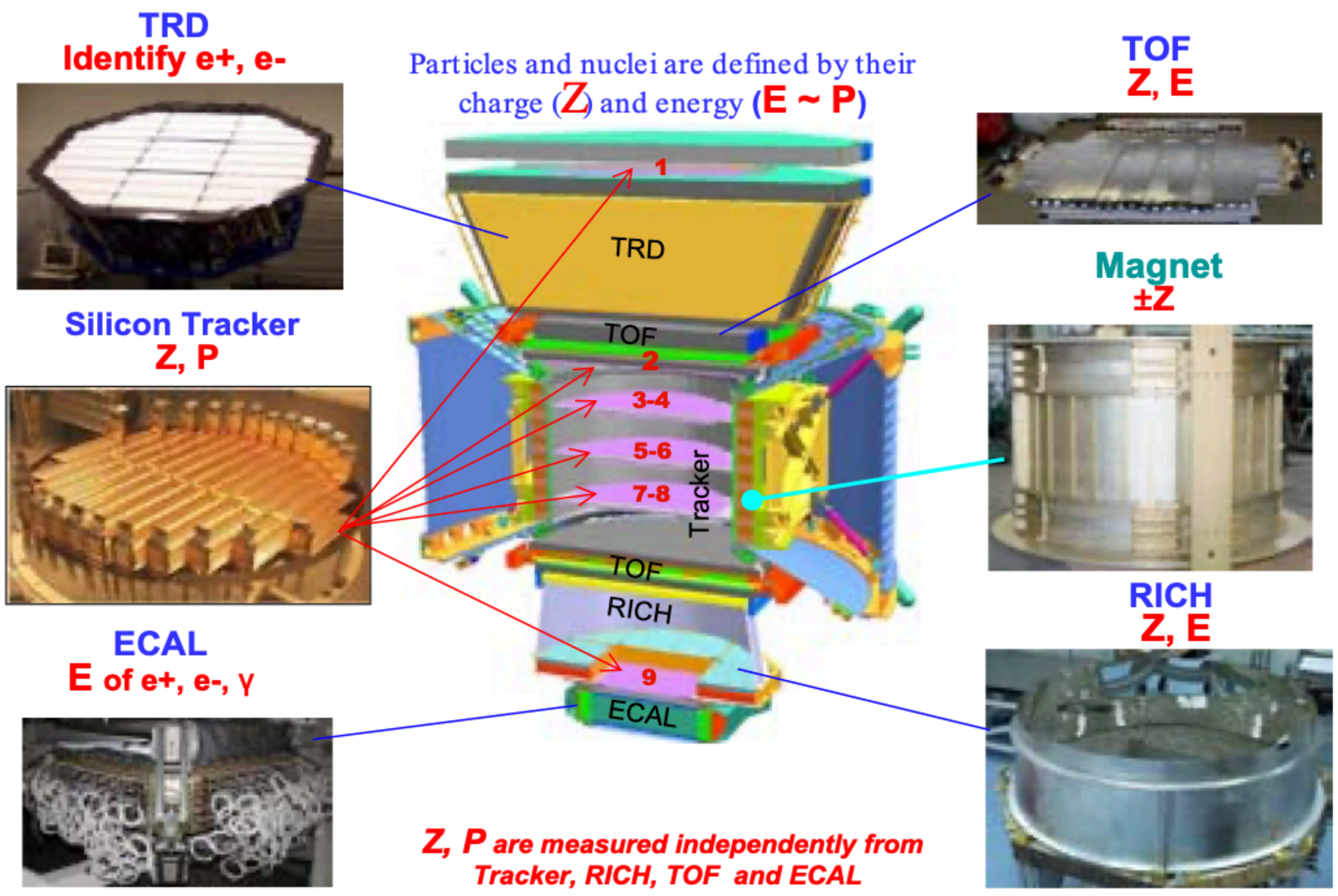
Types of detectors for Charged Cosmic Rays:

- Satellite (or spatial station) detectors, use magnetic field to distinguish between particles/anti-particles.
- Constrain from limited size

AMS-02

- Alpha Magnetic Spectrometer:
  - Energy range: 50 MeV - 2 TeV
  - Location: ISS (Space)
  - Operating since 2011

Multi-layer for Tracking & Calorimeter

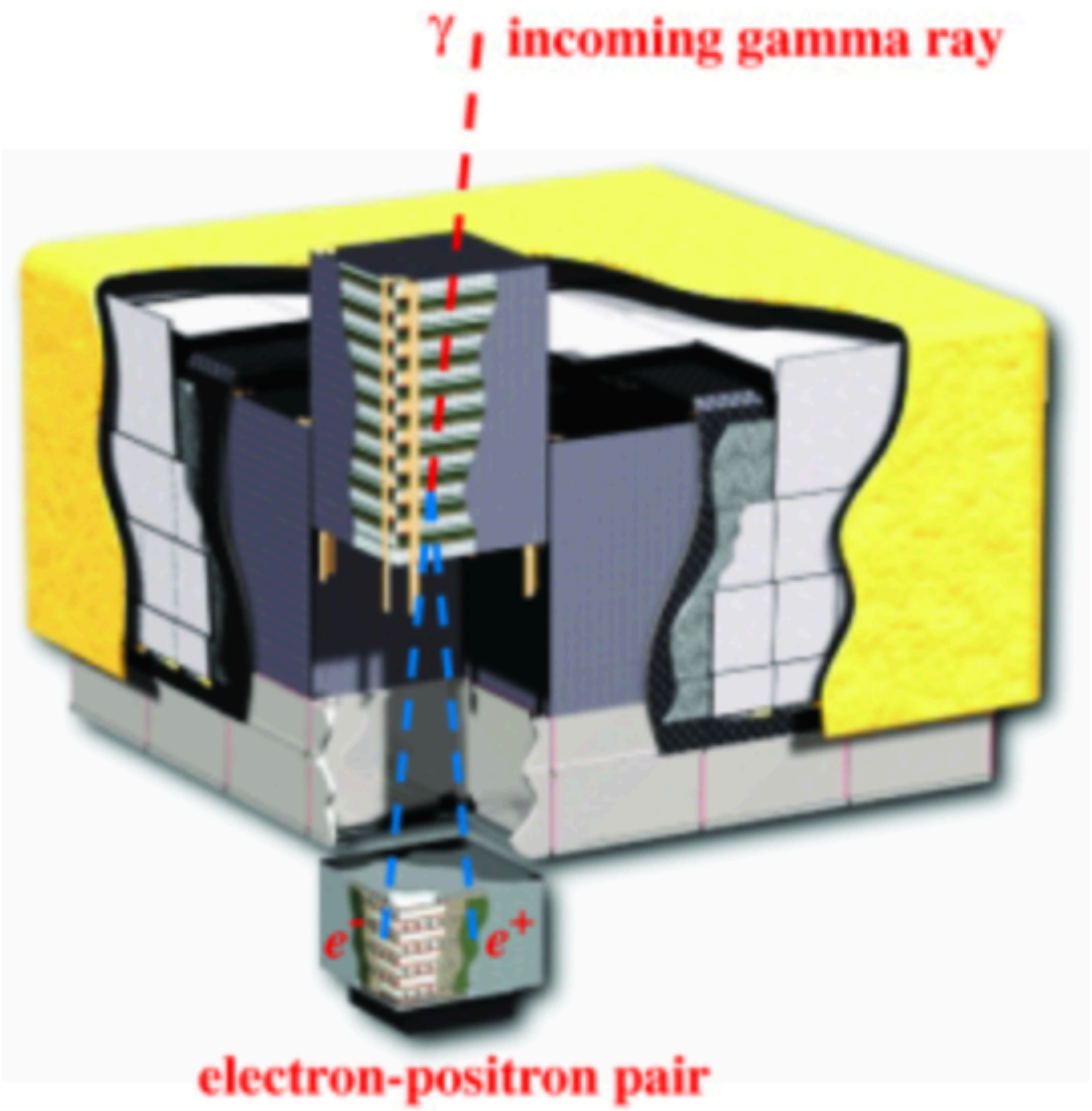


arXiv:1009.5349

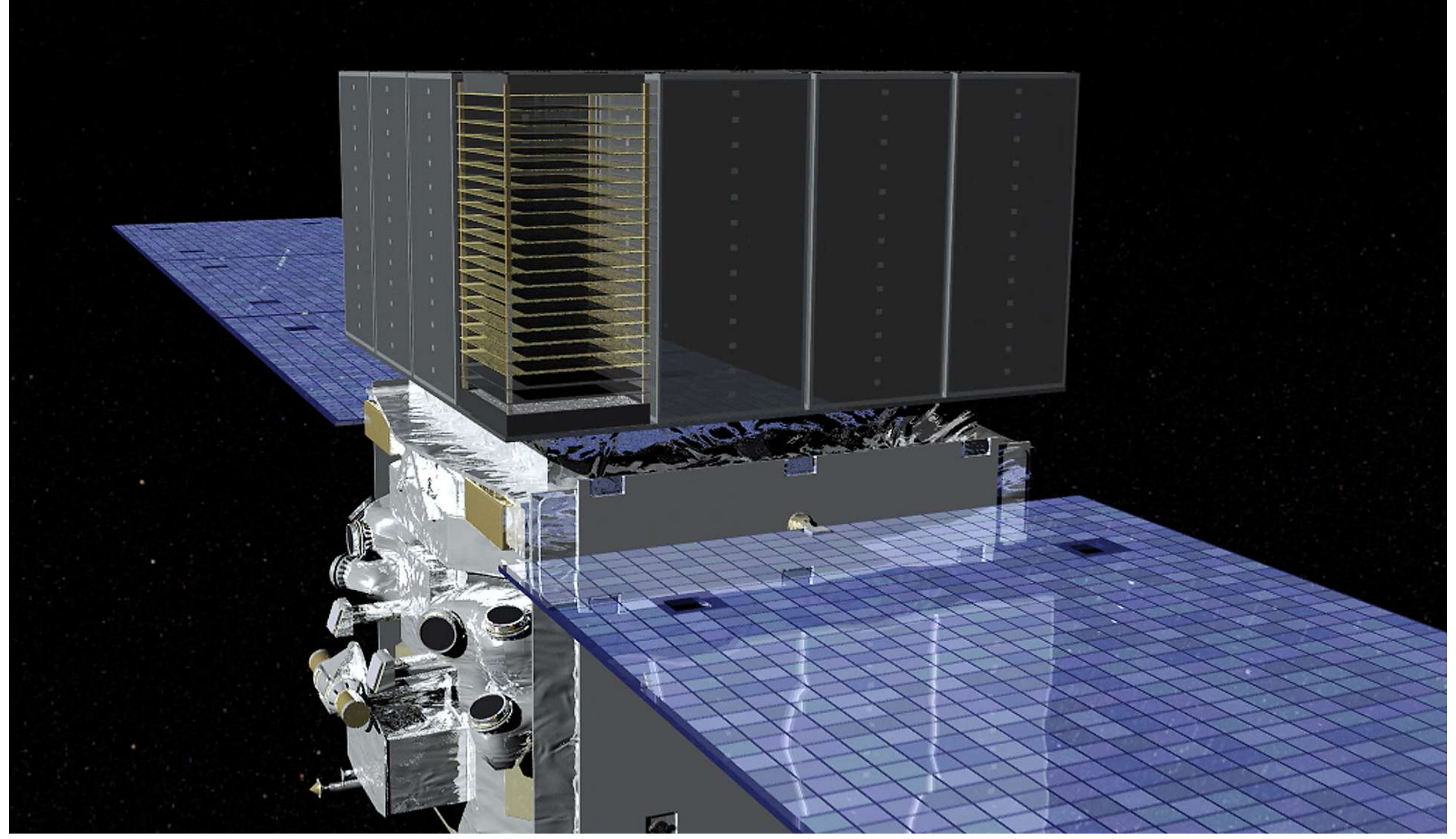
arXiv:2406.01705

Fermi - Large Area Telescope (Fermi-LAT)

- Gamma Ray Telescope
    - Energy range: 20 MeV - 500 GeV
    - Location: Space - Satellite
    - Operating since 2008
    - Can also detect charged cosmic rays using Earth magnetic field



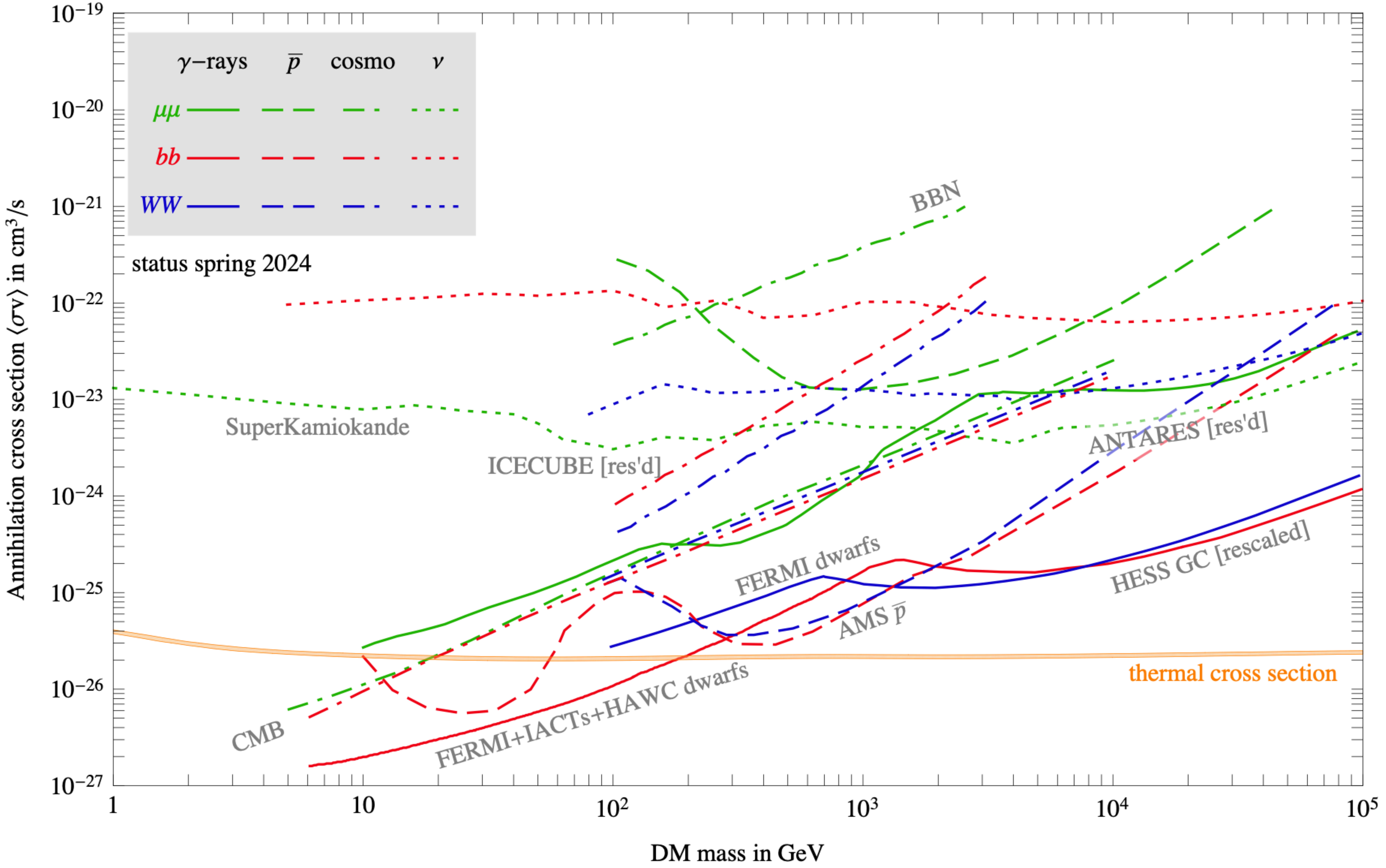
arXiv:0902.1089



Credit: Nasa/Goddard Space Flight Center Conceptual Image Lab

Indirect DM search status

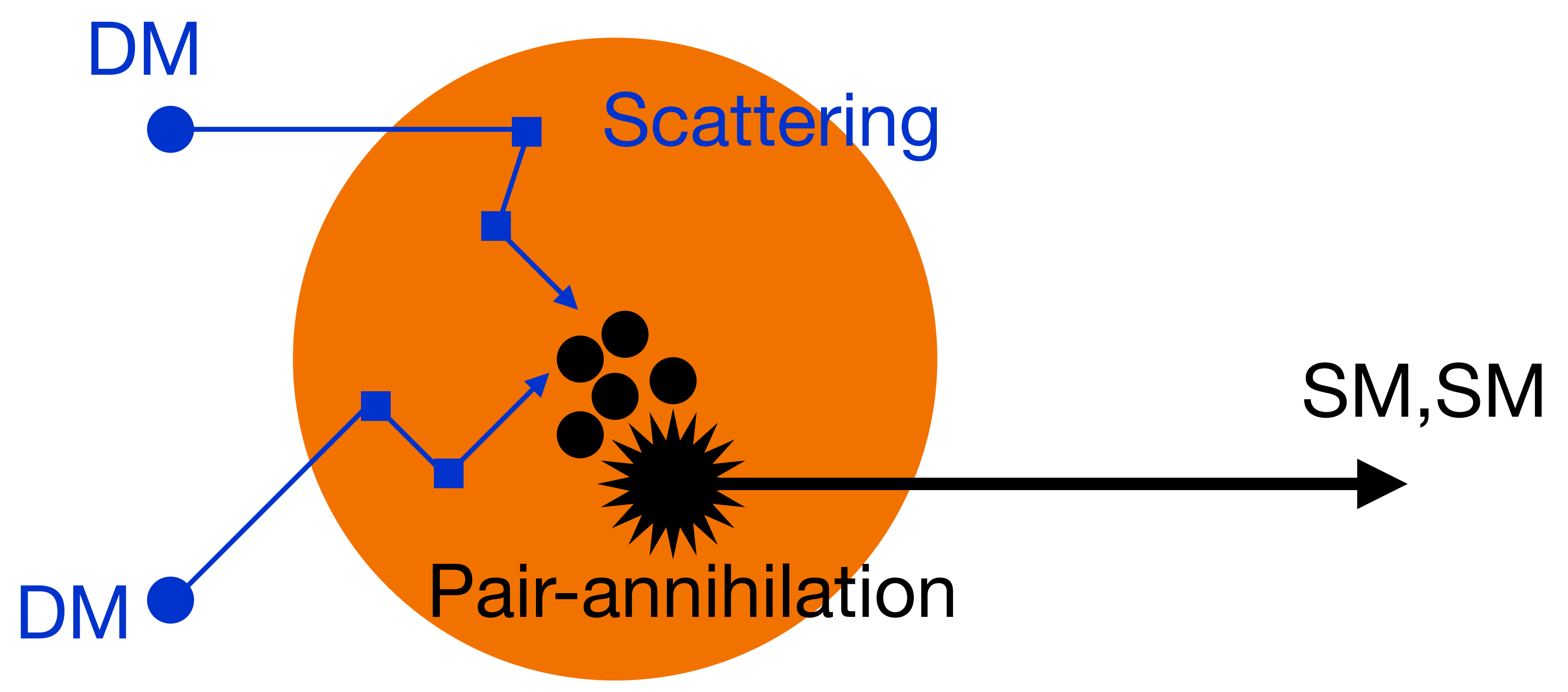
All Indirect Detection constraints



arXiv:2406.01705

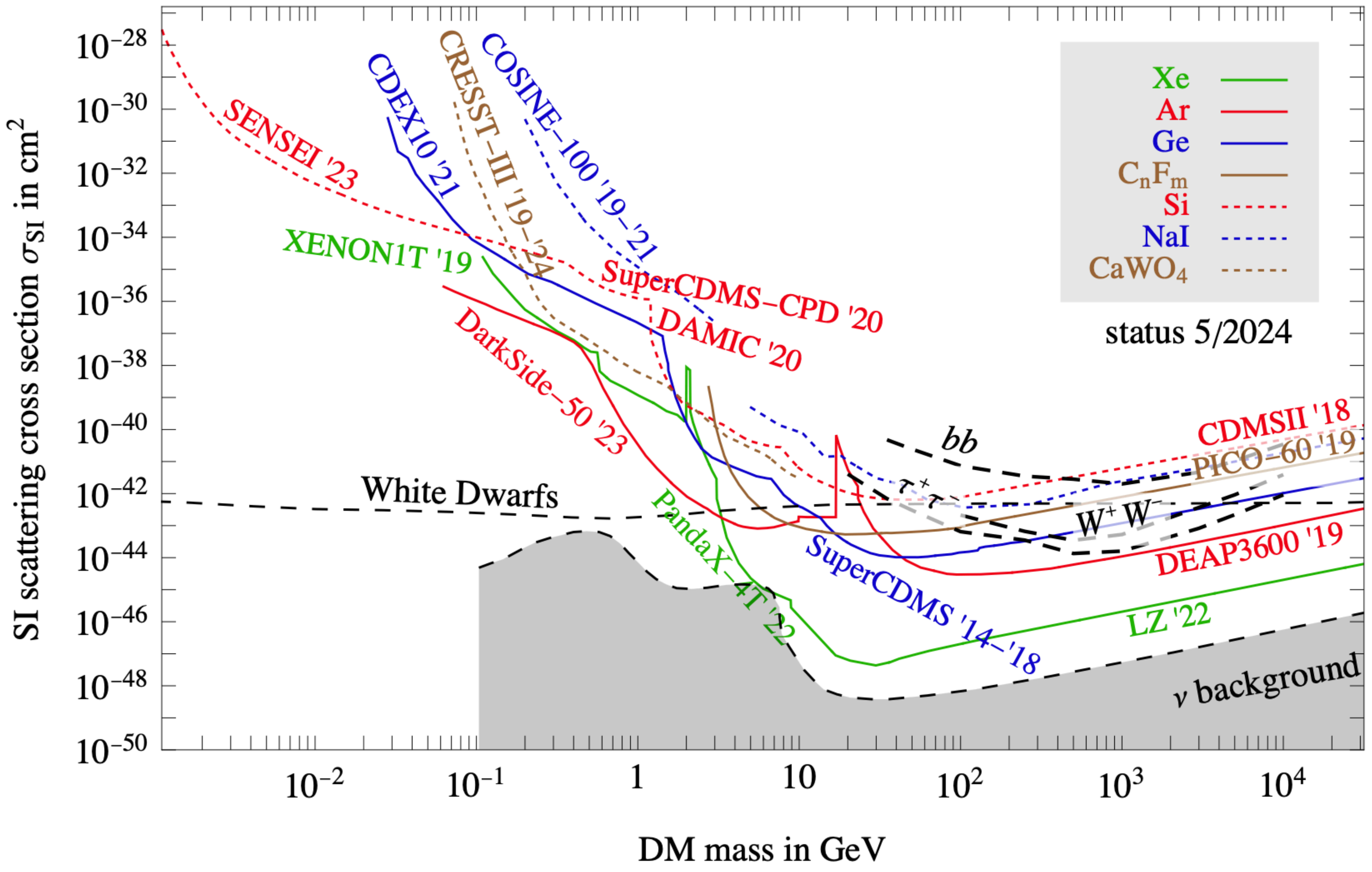
DM capture in Stars

- Sun | Neutron stars | White Dwarfs
  - DM loses energy by scattering in the star and get gravitationally bound to the star
  - Accumulation of DM → Annihilation
  - At equilibrium, relation between annihilation and capture rate
  - Can probe same quantity as DM direct detection experiment



Direct Detection constraints on SI scattering

arXiv:2406.01705



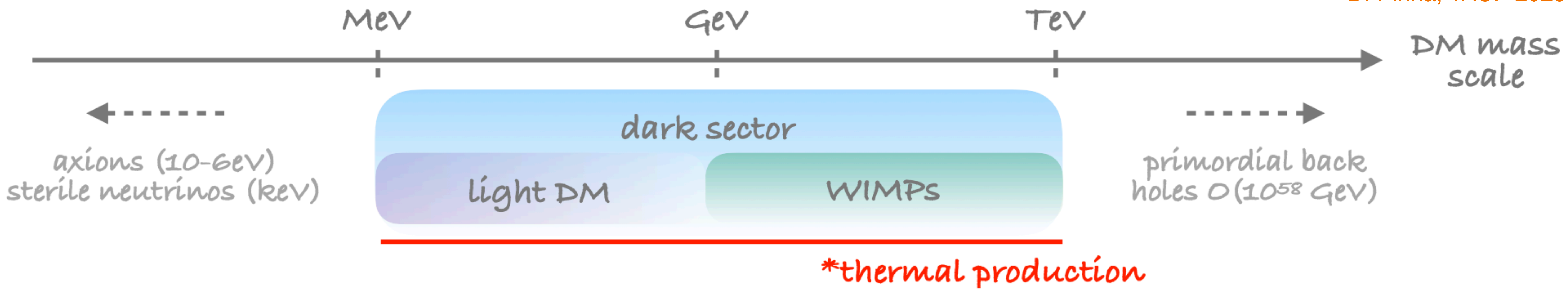
Dark Matter Production

(For Dummies)^2

Concept of DM Production

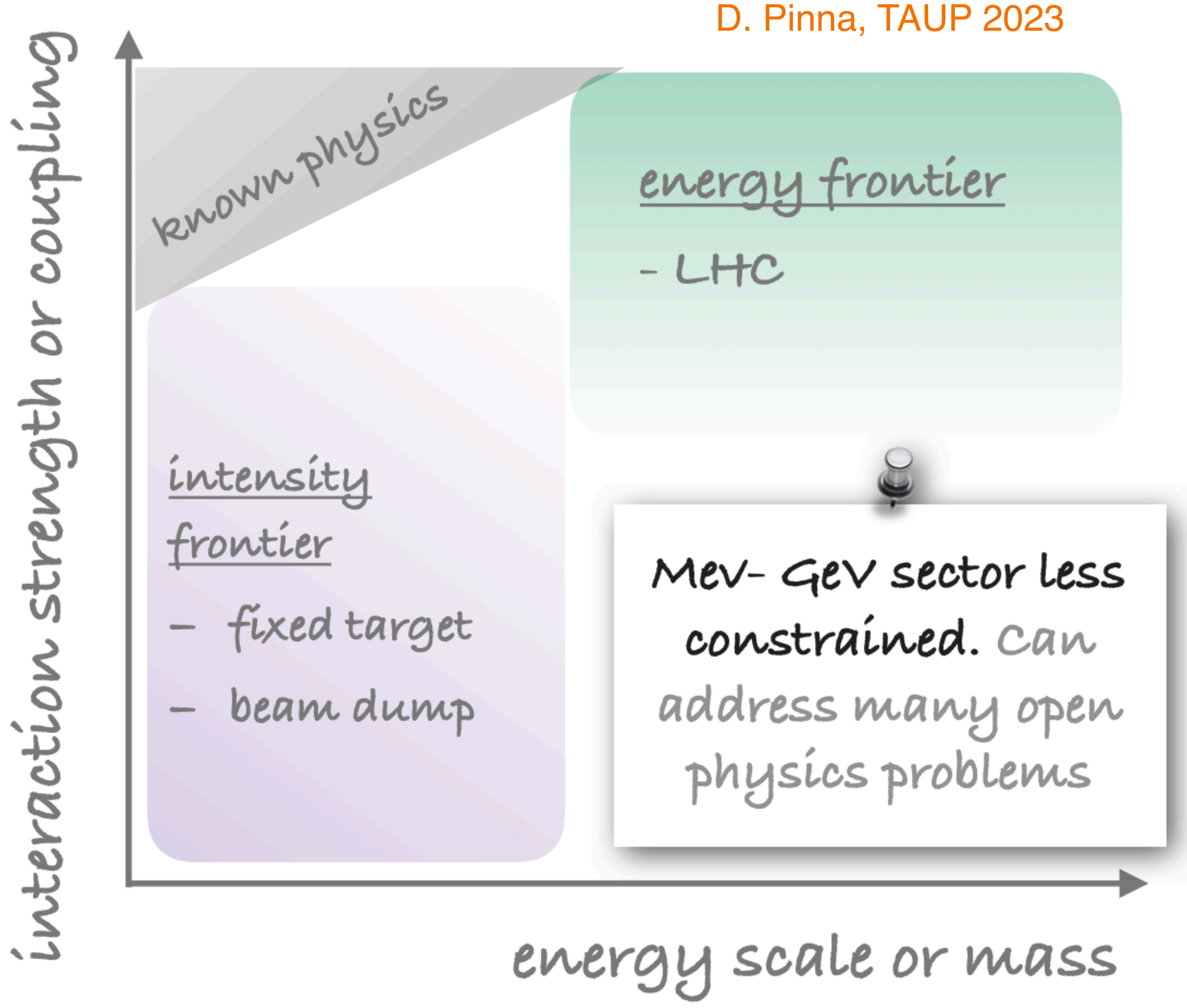
Probing the Dark Sector:

D. Pinna, TAUP 2023



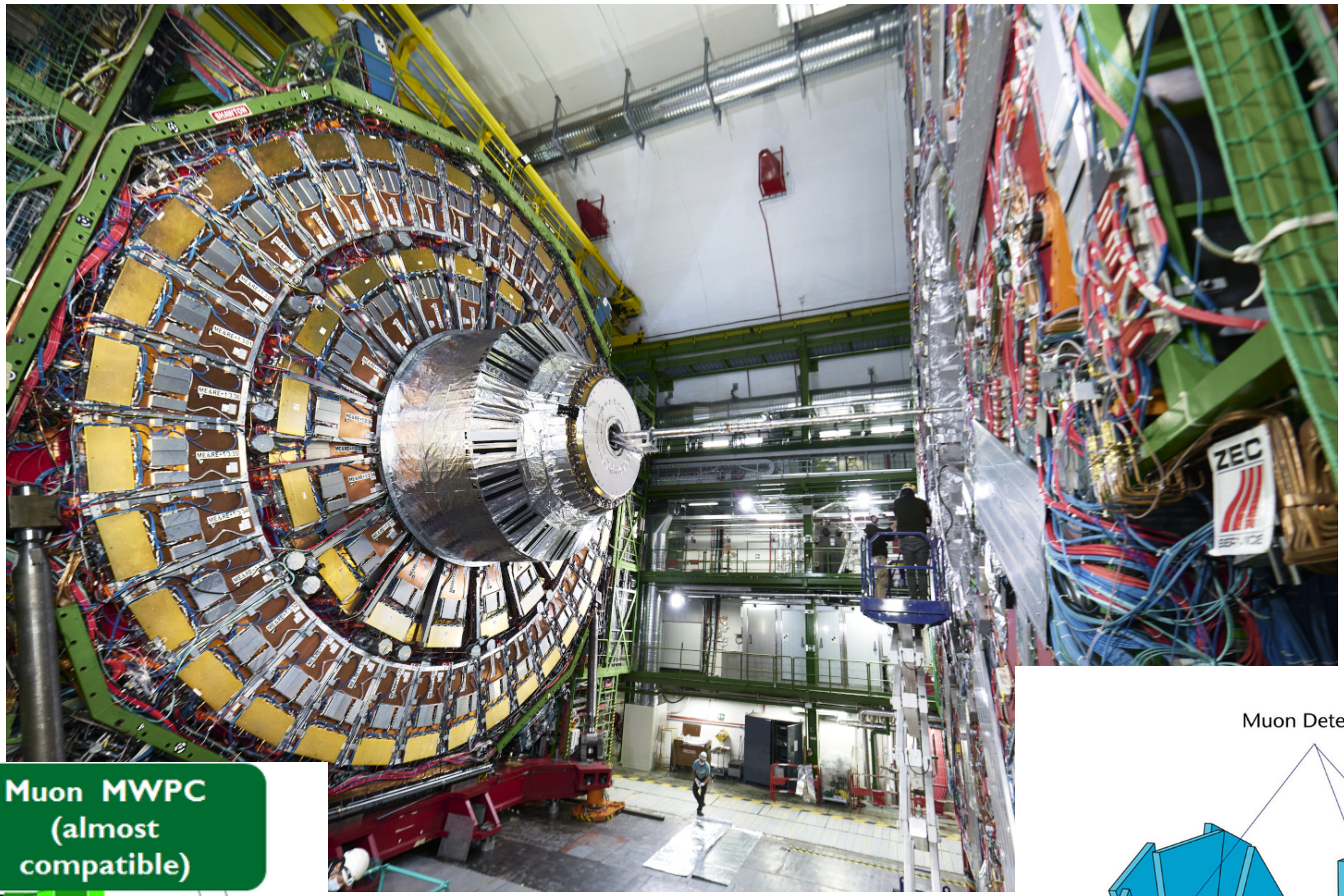
- Accelerators experiments (**Energy Frontier**)
  - Missing transverse momentum (MET)
  - Signature of Mediator (Resonance)
- Colliders experiments (**Intensity Frontier**)
  - Missing energy, momentum, or mass
  - Decay of Mediator or unstable DM particles

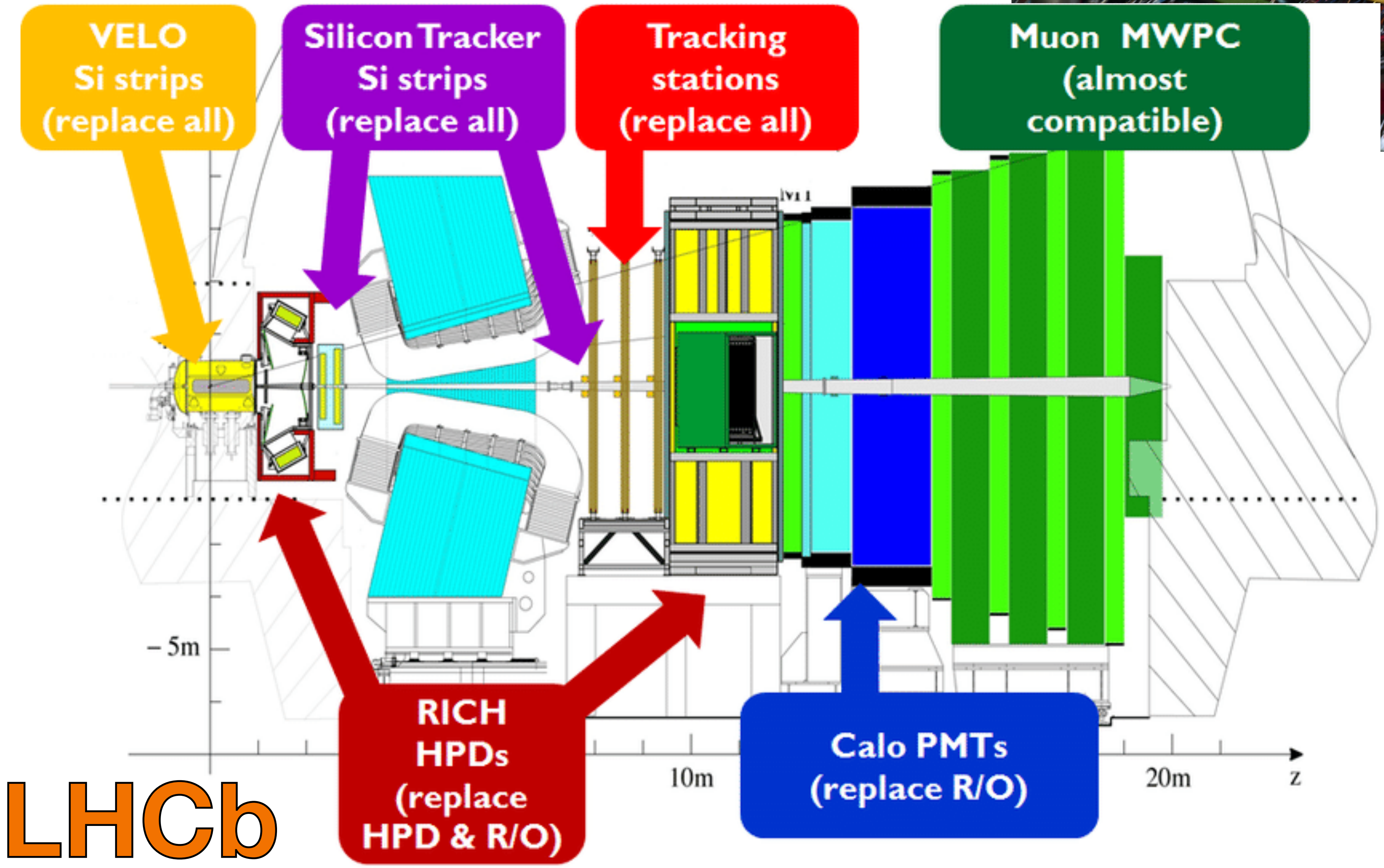
D. Pinna, TAUP 2023



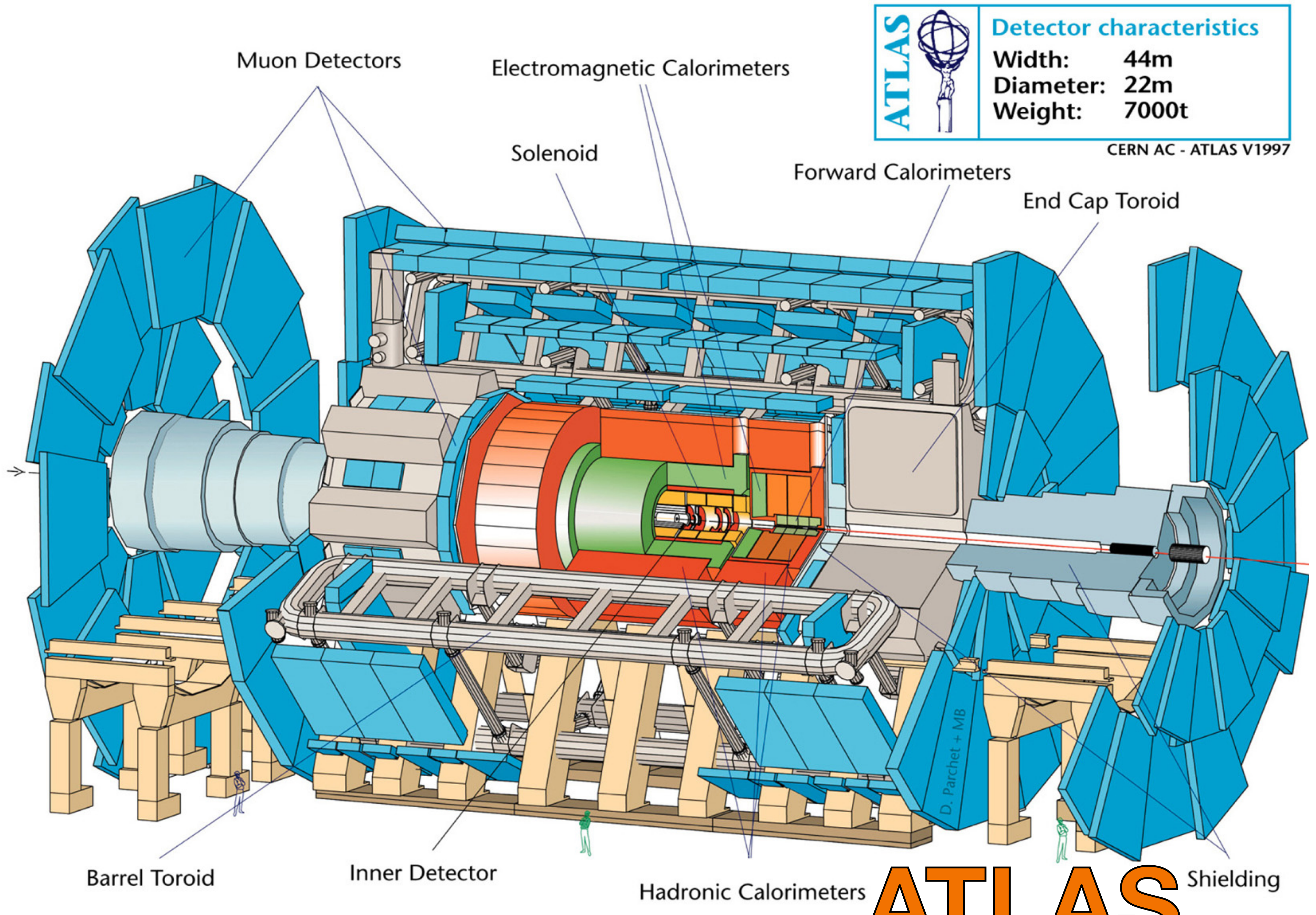
Experiments at LHC

CMS





LHCb



ATLAS

Collider experiments

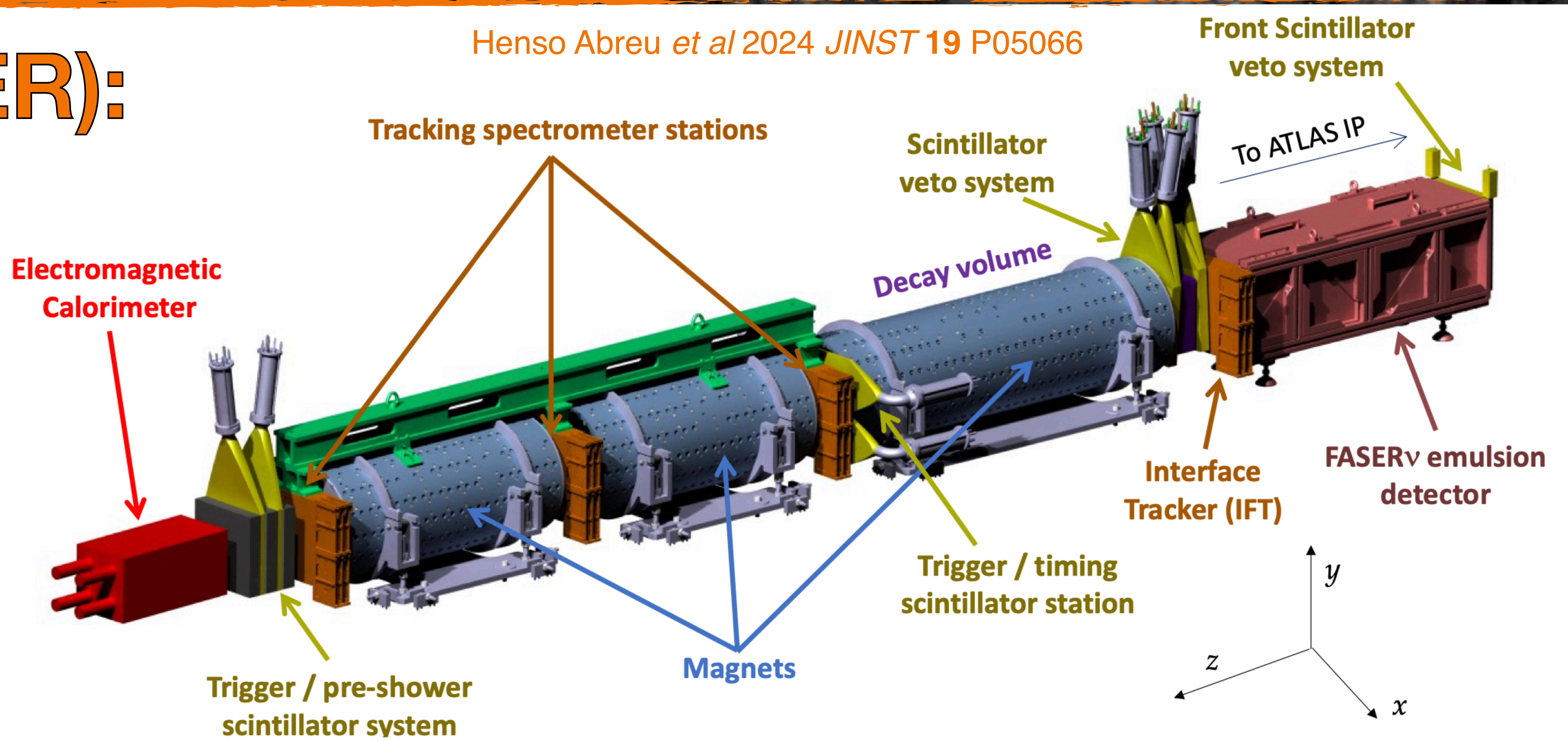
ForwArd Search ExpeRiment (FASER):

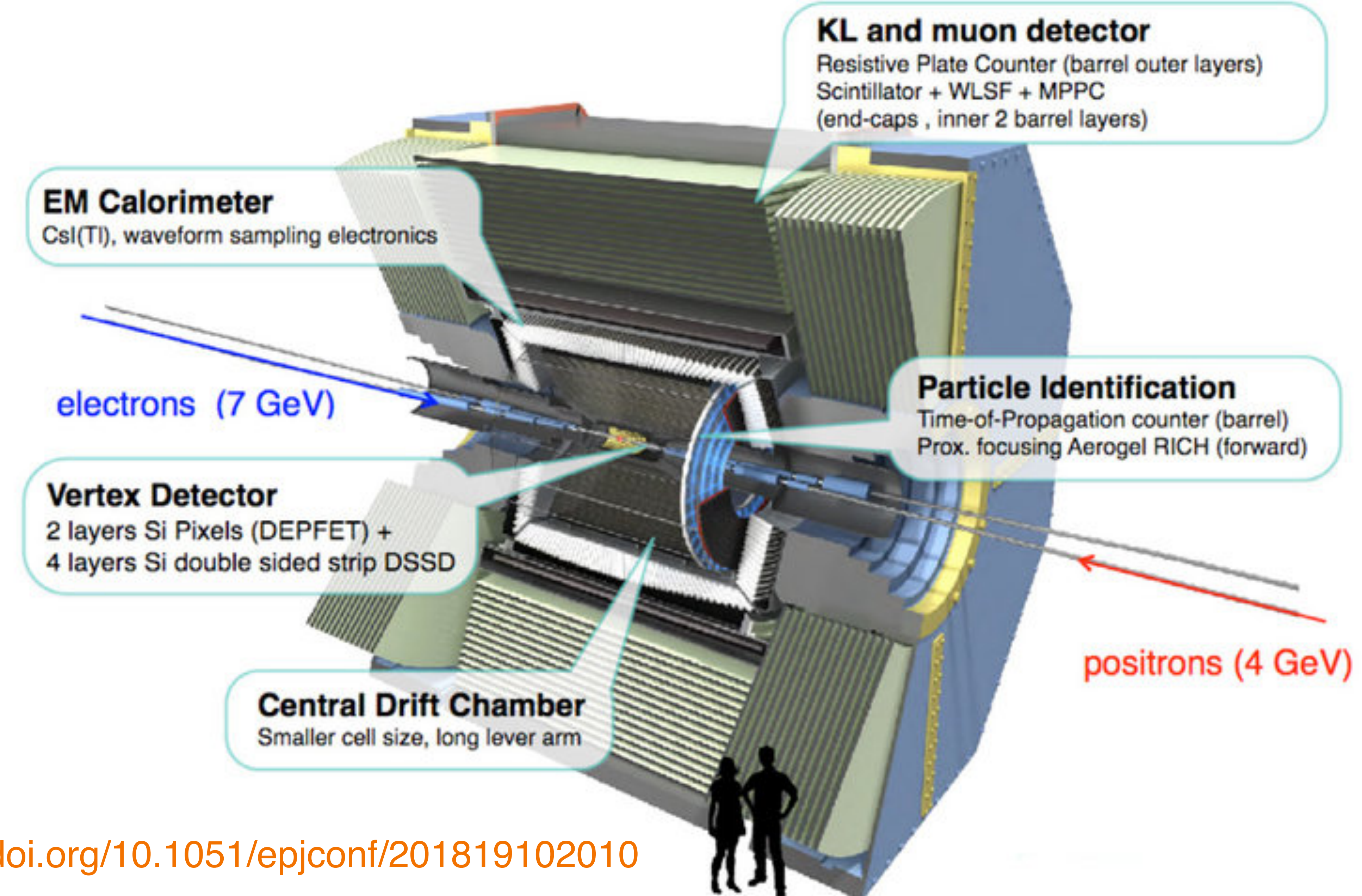
- Running at LHC, close to ATLAS Interaction point
- Look for light DM, like Axion-Like Particle (ALPs), Dark Photons.
- Neutrino as well

BELLE-2:

- Running at SuperKEKB, Japan
- Focus on flavour physics (B/D mesons, Tau lepton decays)
- Explore light DM (dark sector particles)

Henso Abreu *et al* 2024 *JINST* **19** P05066



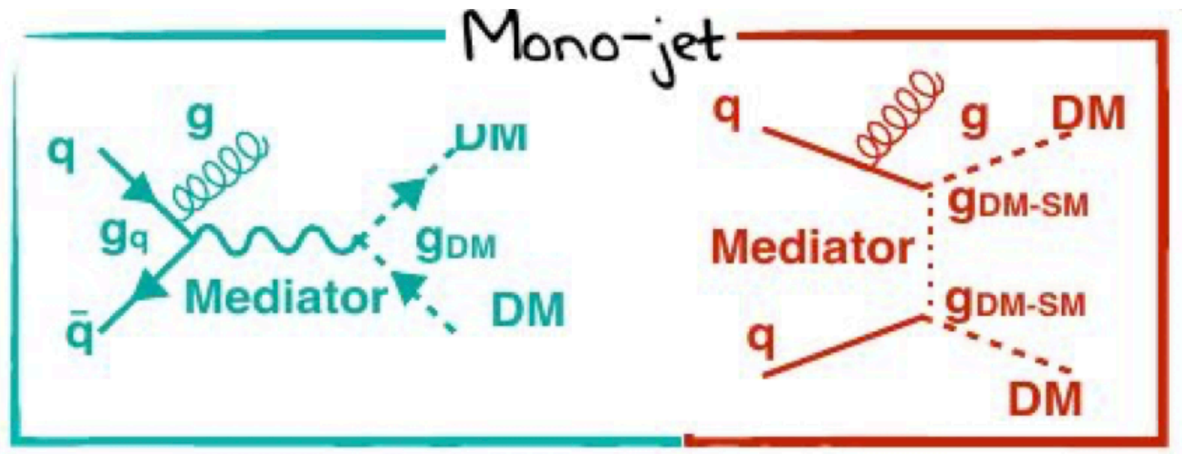


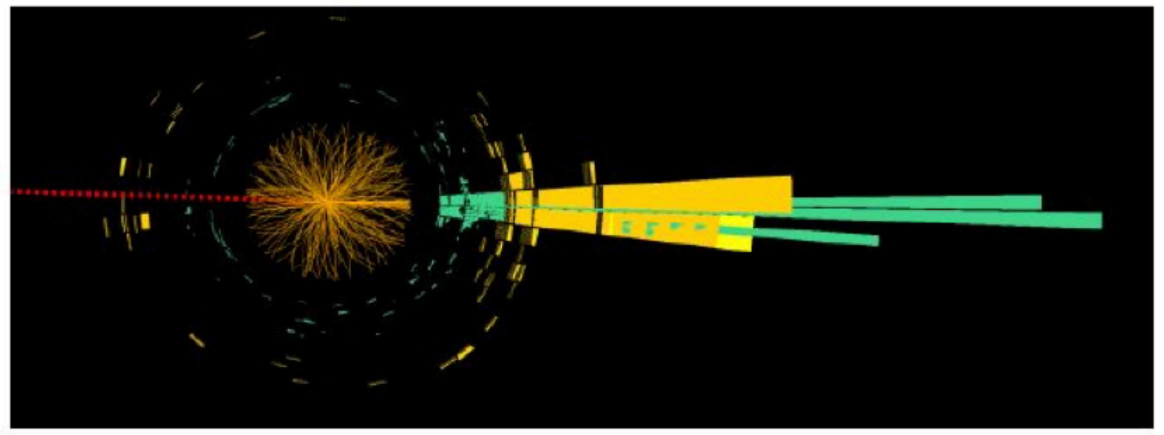
https://doi.org/10.1051/epjconf/201819102010

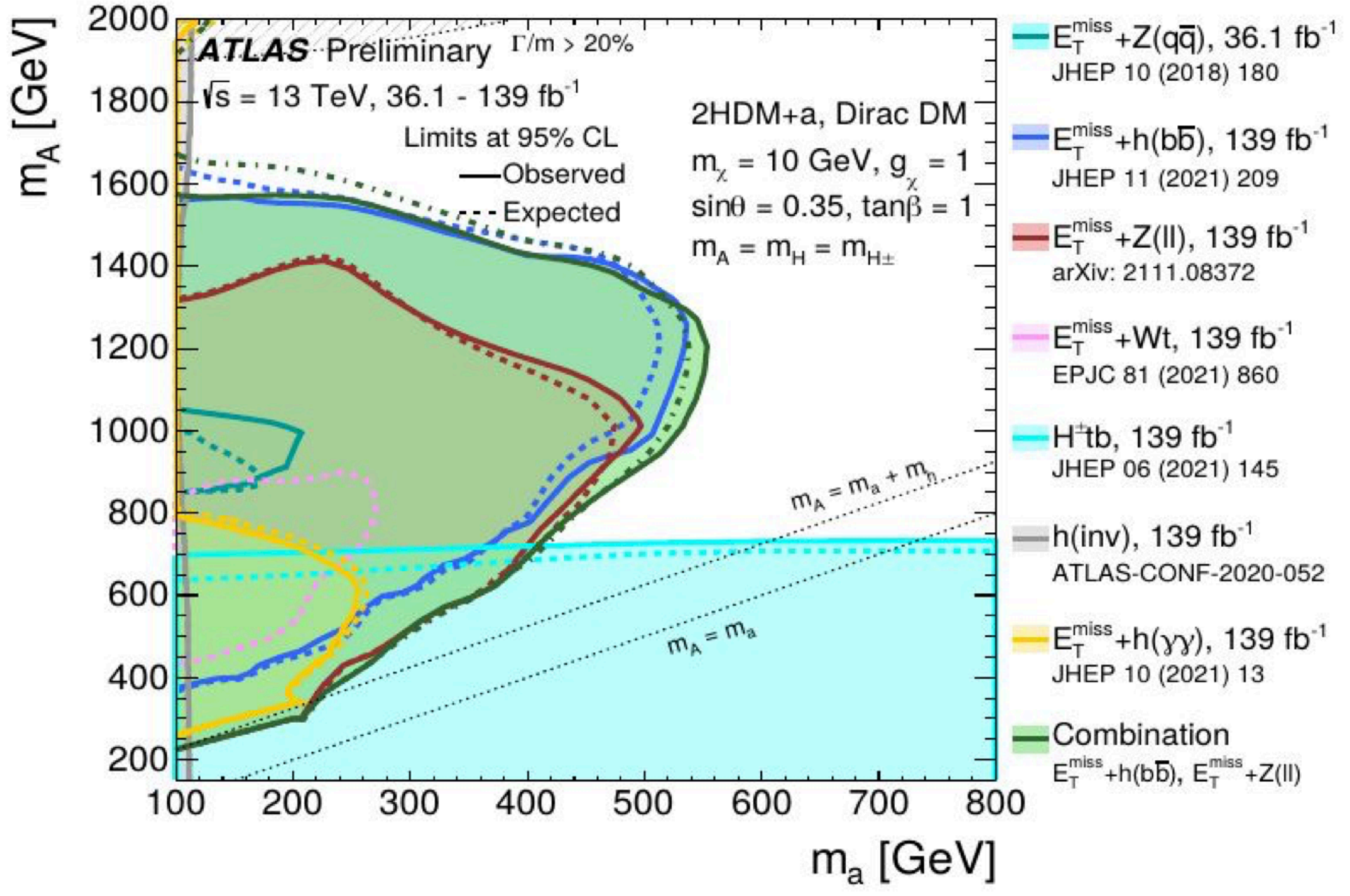
Credit Slide: Luca Scotto Lavina

Model-Dependent Results:

Example : monojet with P_T missing





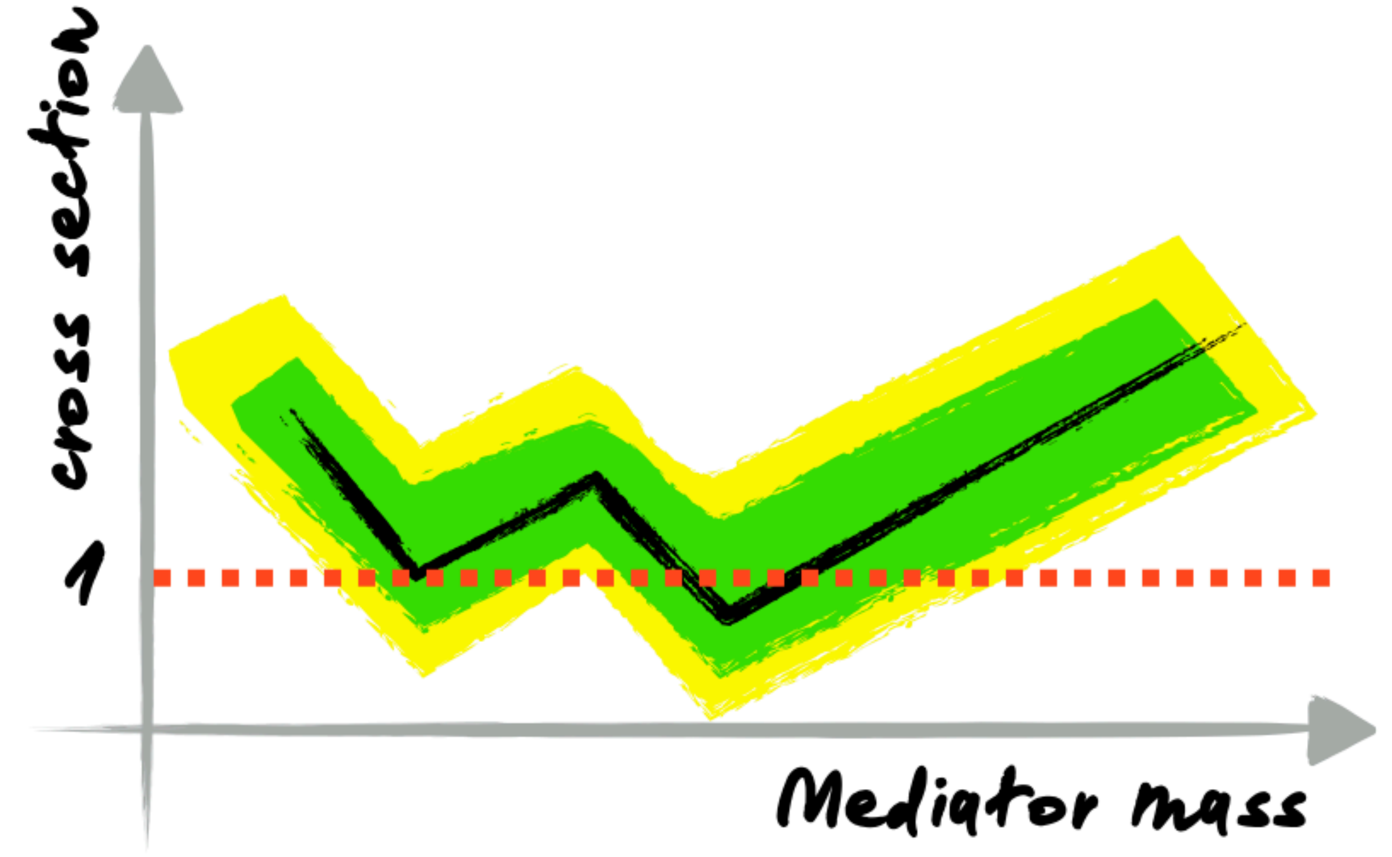


arXiv:2301.10141

Comparison with Direct Detection Results

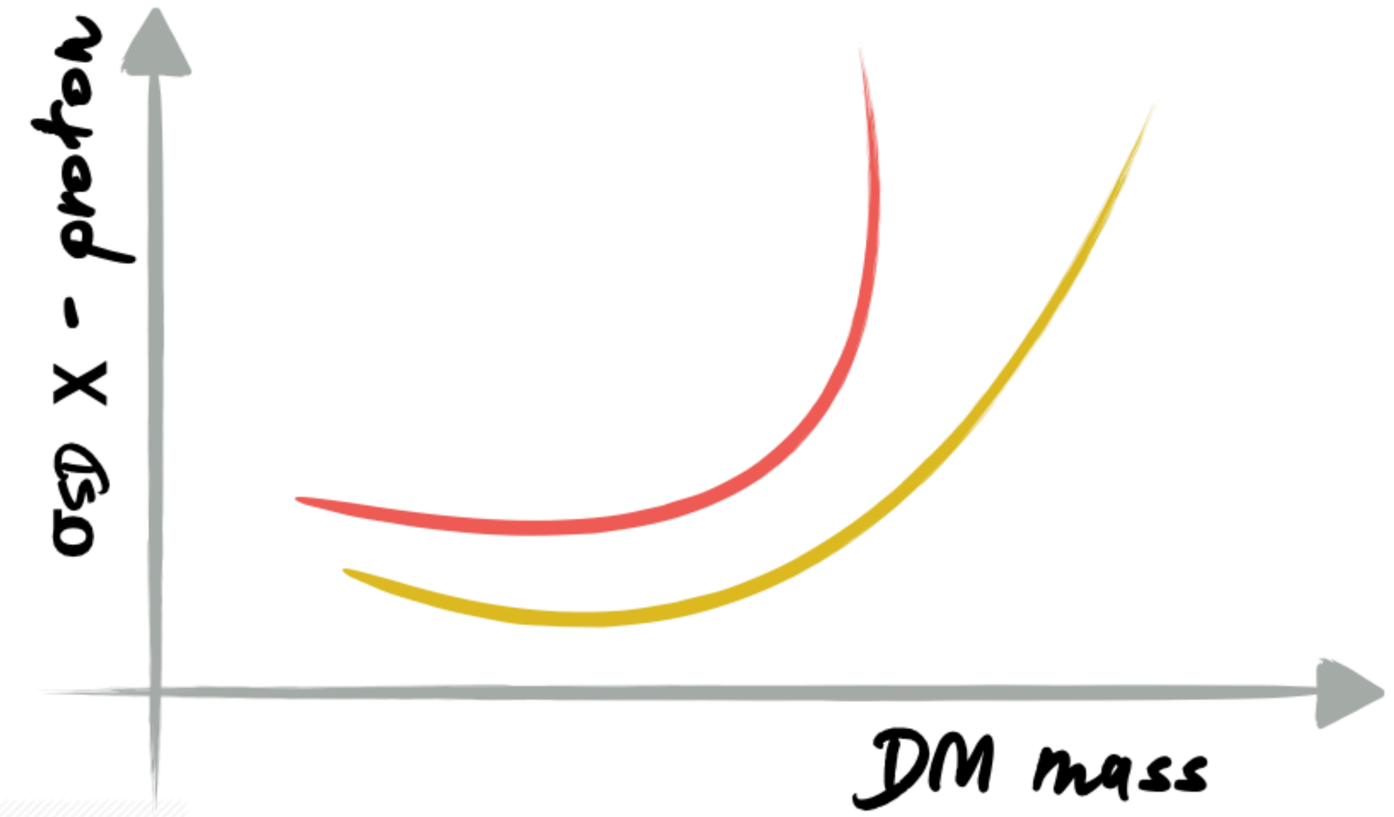
Credit Slide: Luca Scotto Lavina

Based on coupling assumptions:



Mediator mass

- Fix couplings
- Fix DM mass
- #% C.L. on production cross section ratio of mediators



DM mass

- Fix couplings
- Limits on spin χ-nucleon cross sections at # % C.L.
- Allow to compare collider searches with other experiments

Discovery potential depends on assumed interaction and couplings

Credit: F. Cirotto, Dark matter searches with the ATLAS detector