

Dark Matter Experiments - III

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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

New indication for DM?

Axions

Lecture 3 - Dark Matter Indirect Detection

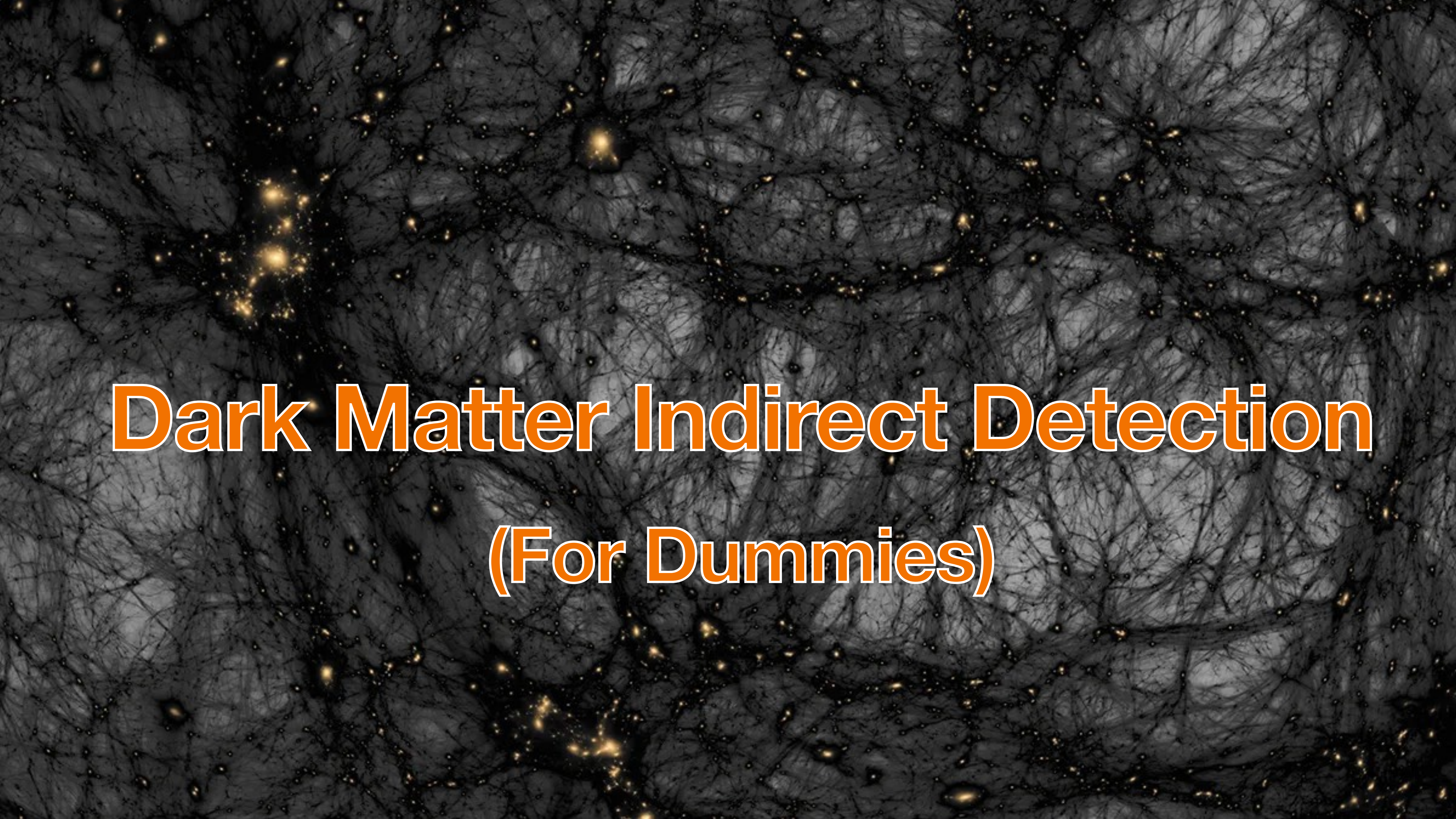
Dark Matter Production

1

Dark Matter Indirect detection

2

Dark Matter Production

The background of the slide is a detailed visualization of the cosmic web, showing a complex network of dark matter filaments and galaxy clusters. Numerous bright yellow and orange points, representing galaxies, are scattered throughout the dark, textured fabric of the universe.

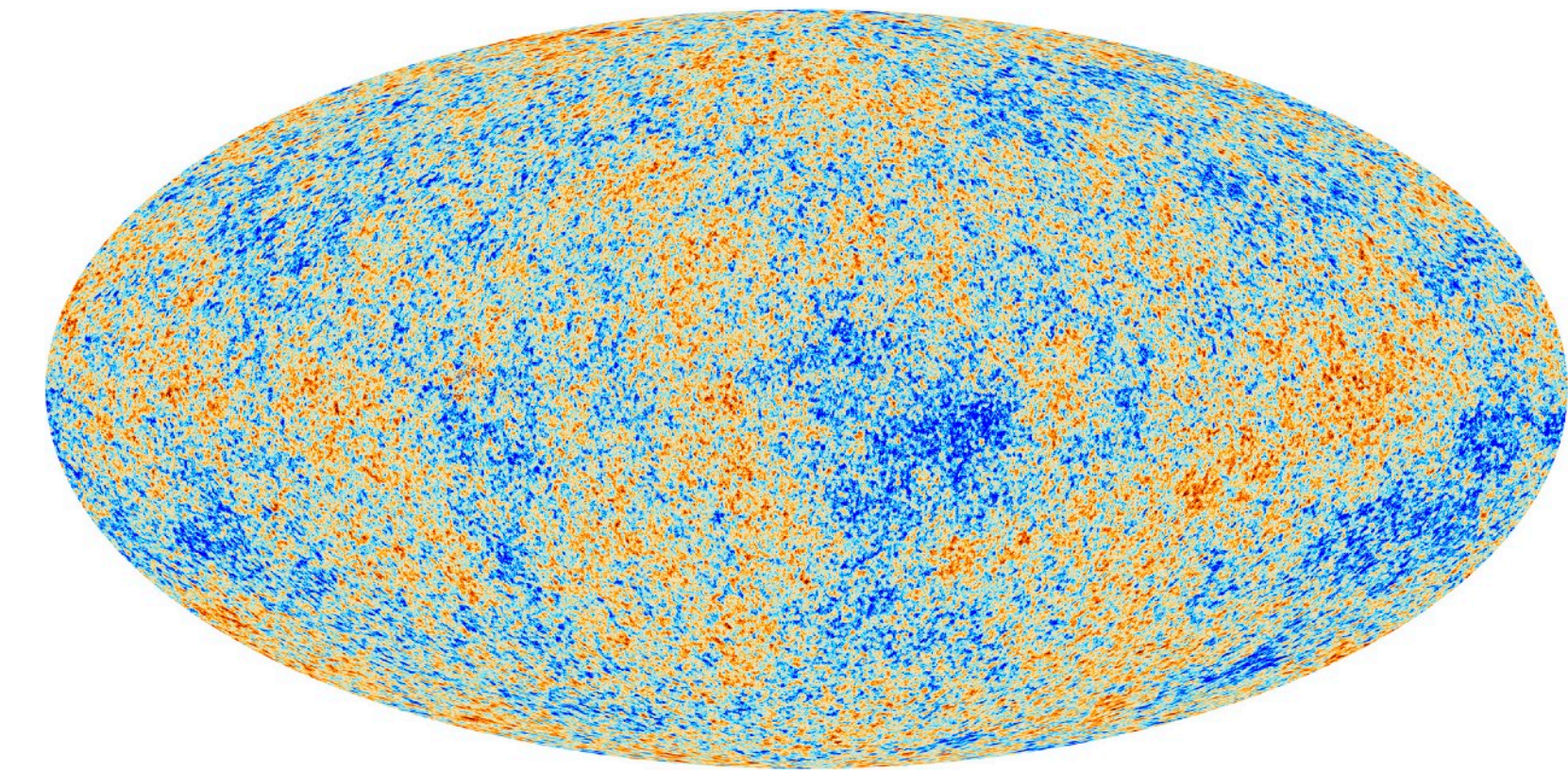
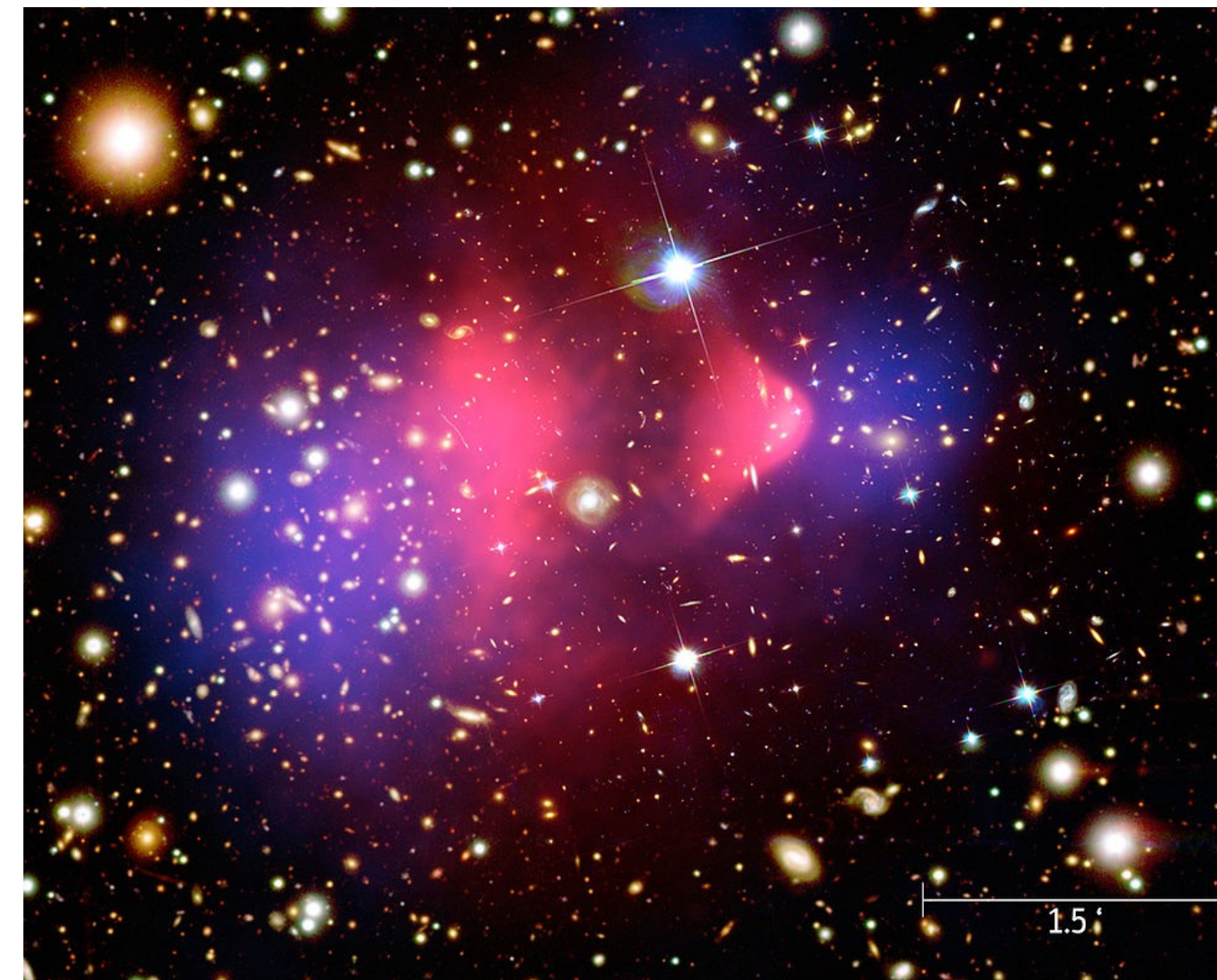
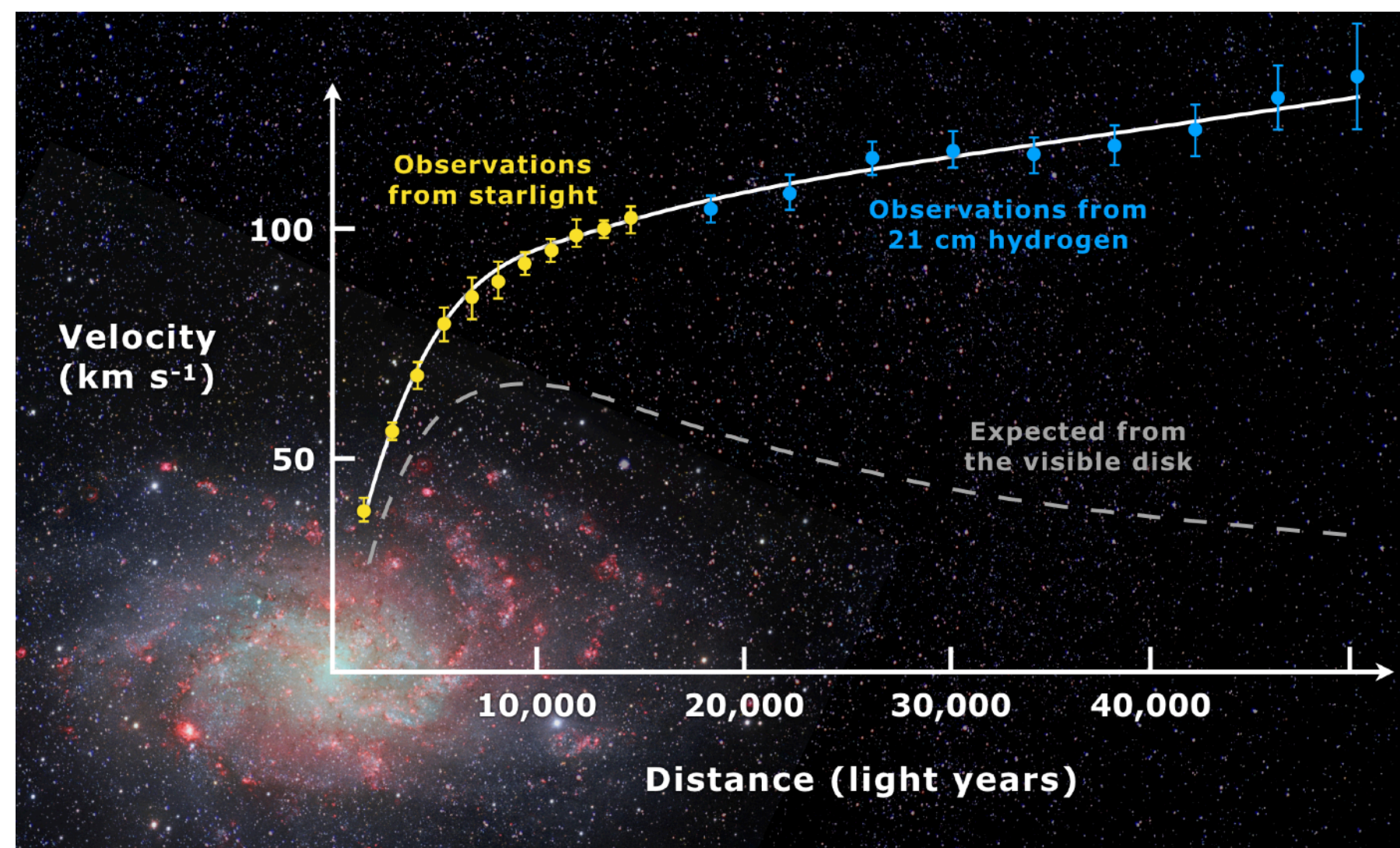
Dark Matter Indirect Detection

(For Dummies)

Concept of Indirect detection

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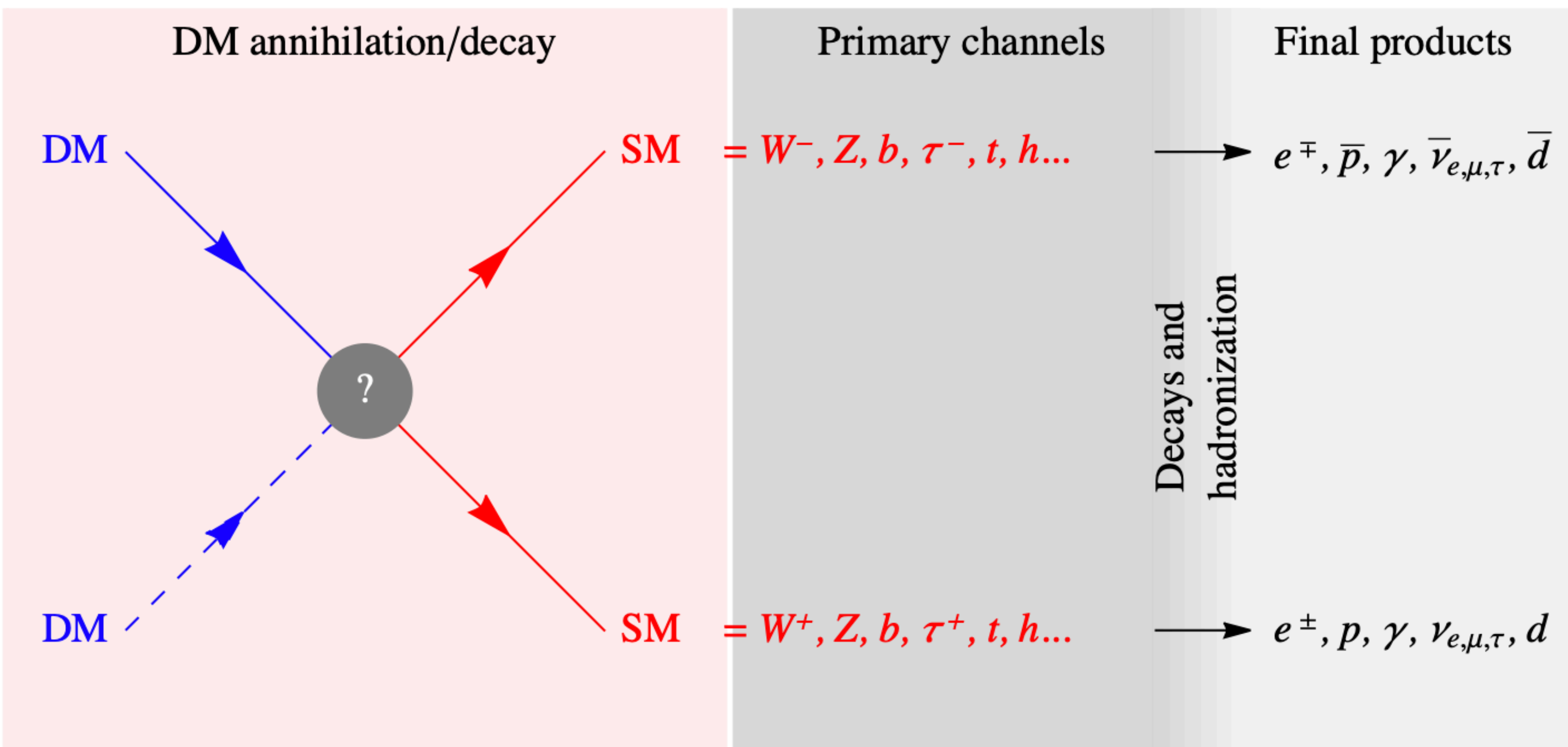
Multiple Astrophysical evidences for the presence of DM



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

Indirect DM Signature

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



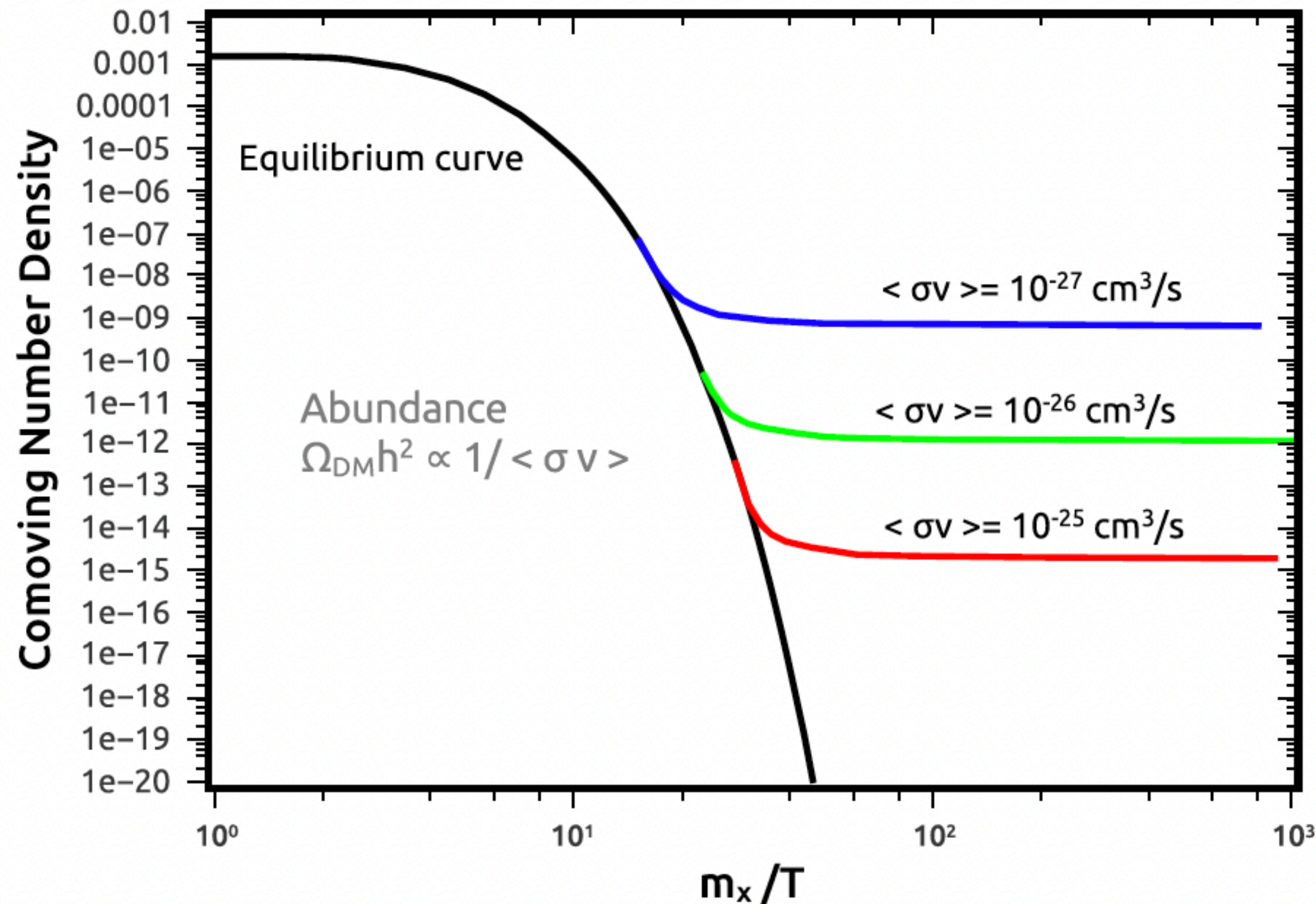
2-body primary channels

$e^+e^-, \mu^+\mu^-, \tau^+\tau^-, \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau,$
 $q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}, \gamma\gamma, gg,$
 W^+W^-, ZZ, hh

Concept of Indirect detection

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Initial constrain from WIMP Miracle



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

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

Allowed Annihilation Mass range

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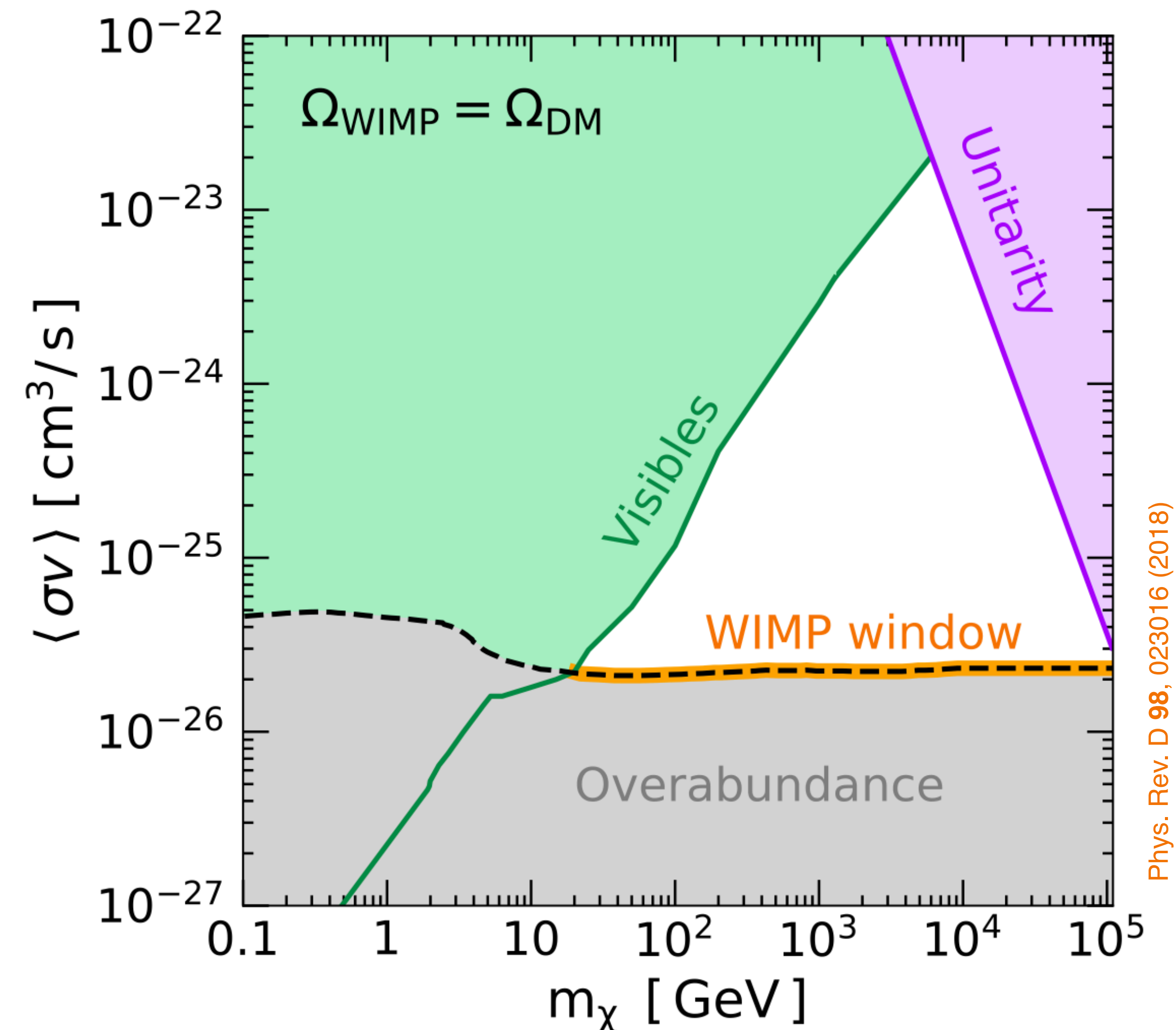
WIMP mass window

- ✦ Big Bang Nucleosynthesis

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

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

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



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?

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Solid angle in the sky

Branching Ratio

Differential energy spectrum for a primary channel i

DM density

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

$\sum$ Contribution from 2-body primary channels

Account for the distribution of DM in the region of interest

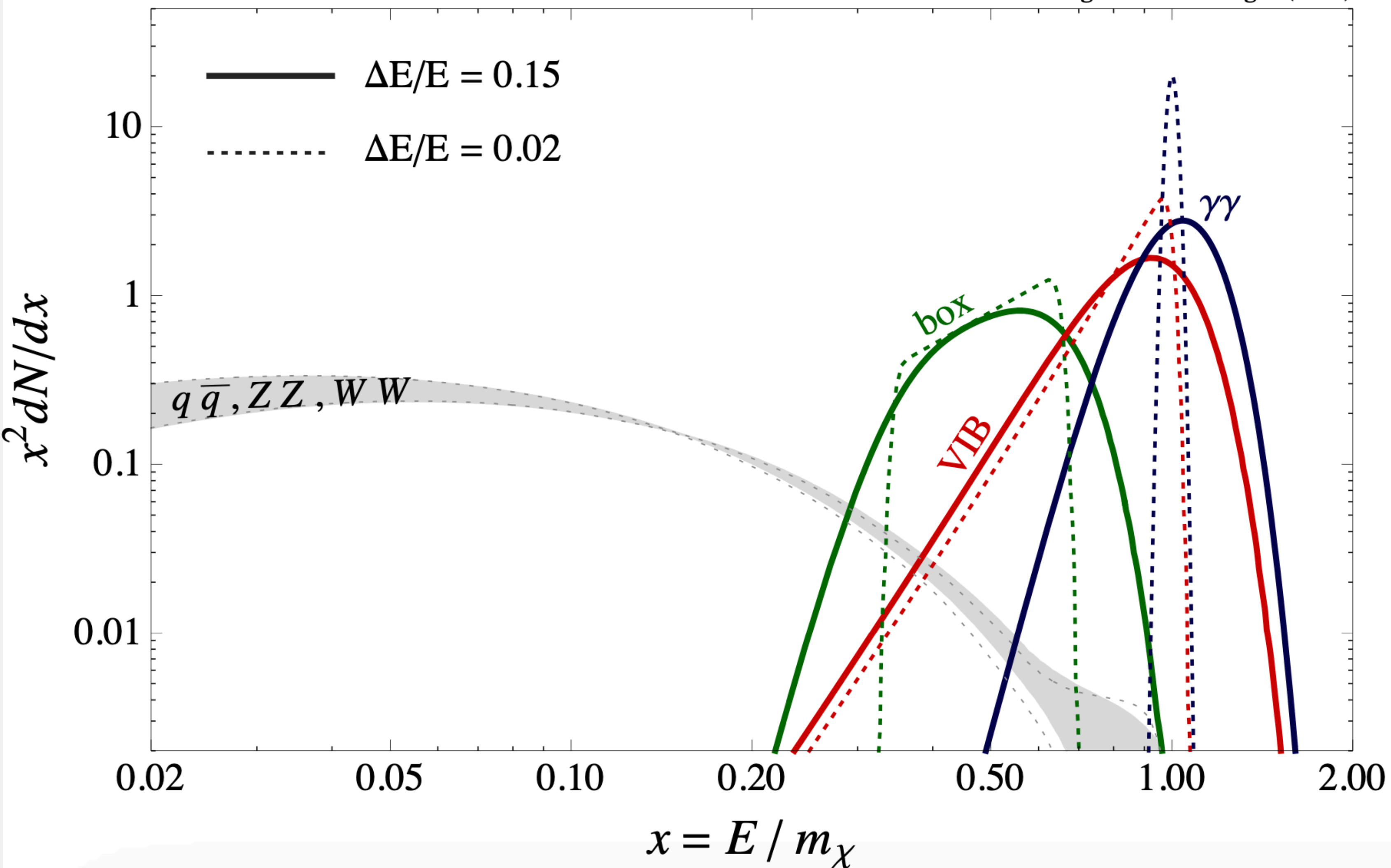
- ✦ Estimate the **differential flux** of DM annihilation product ($\chi, \nu, \dots$) on Earth from a region of interest in the sky. (More detail for $\neq$ product: [arxiv.org:2406.01705](https://arxiv.org/abs/2406.01705))
- ✦ Measuring upper limit on flux $\rightarrow$ derive upper limit on annihilation cross-section

How to look for DM Ann. signature?

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Initial slide from R. Laha

Bringmann & Weniger (2012)



✦ Different type of signal:

► Continuum:

$$\chi\chi \rightarrow q\bar{q}, Z\bar{Z}, W^+W^-$$

► Box:

$$\chi\chi \rightarrow \phi\phi; \phi \rightarrow \gamma\gamma$$

► Virtual internal Bremsstrahlung:

$$\chi\chi \rightarrow \ell^+\ell^-\gamma$$

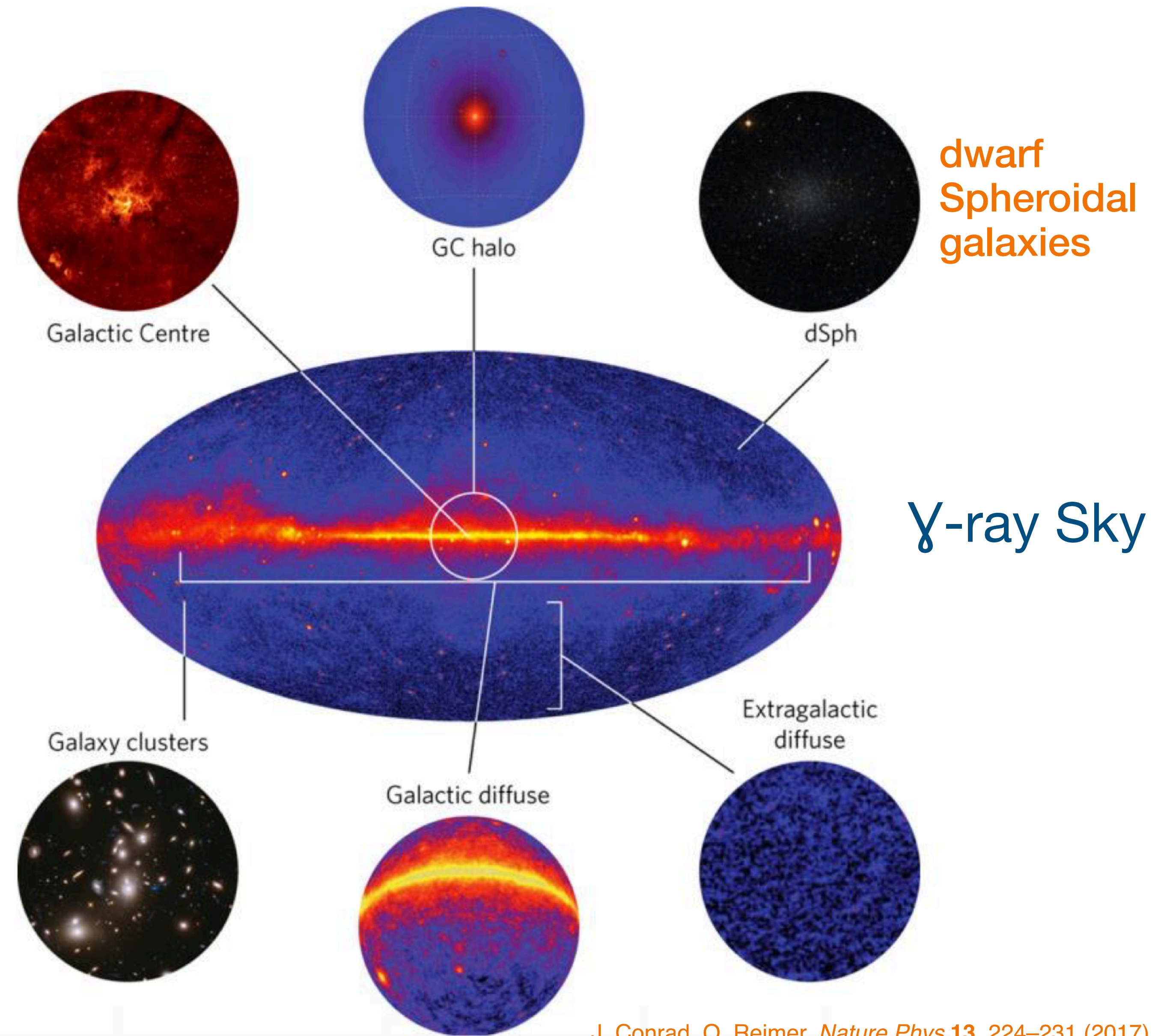
► Line:

$$\chi\chi \rightarrow \gamma\gamma$$

Where to look for DM Ann. signature?

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



Different types of detectors for gamma rays:

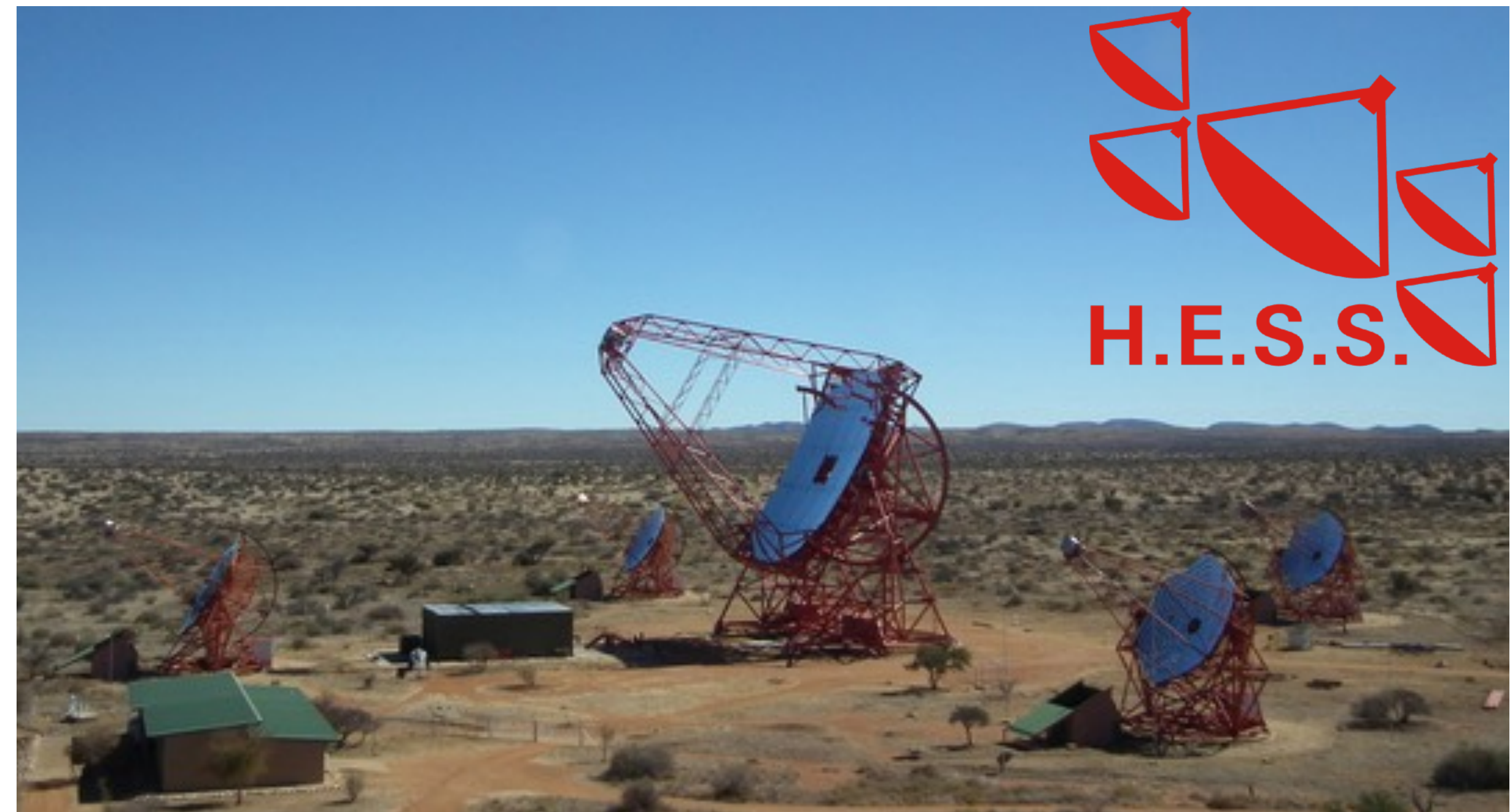
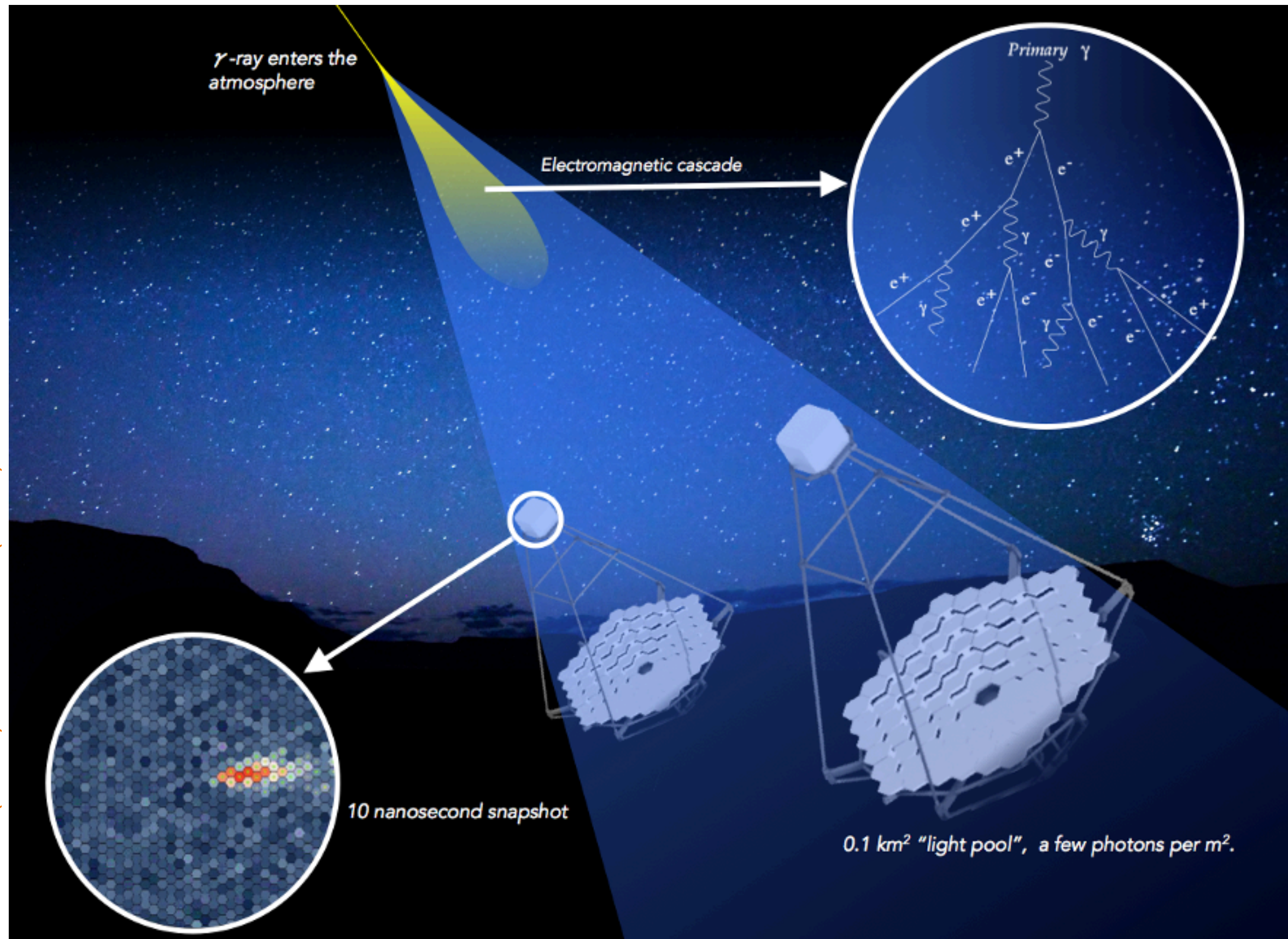
- ✦ Spatial experiments (like FERMI)
- ✦ Imaging atmospheric Čerenkov telescopes (H.E.S.S., MAGIC, VERITAS, CTA,...)
- ✦ Water Čerenkov telescopes (HAWC, MILAGRO,...)

High Energy Stereoscopic System (H.E.S.S.) 14

✦ Ground based IACT:

- ▶ Energy range: 30 GeV - 100 TeV
- ▶ Location: Namibia
- ▶ Operating since 2003

Imaging Atmospheric Čerenkov Telescope

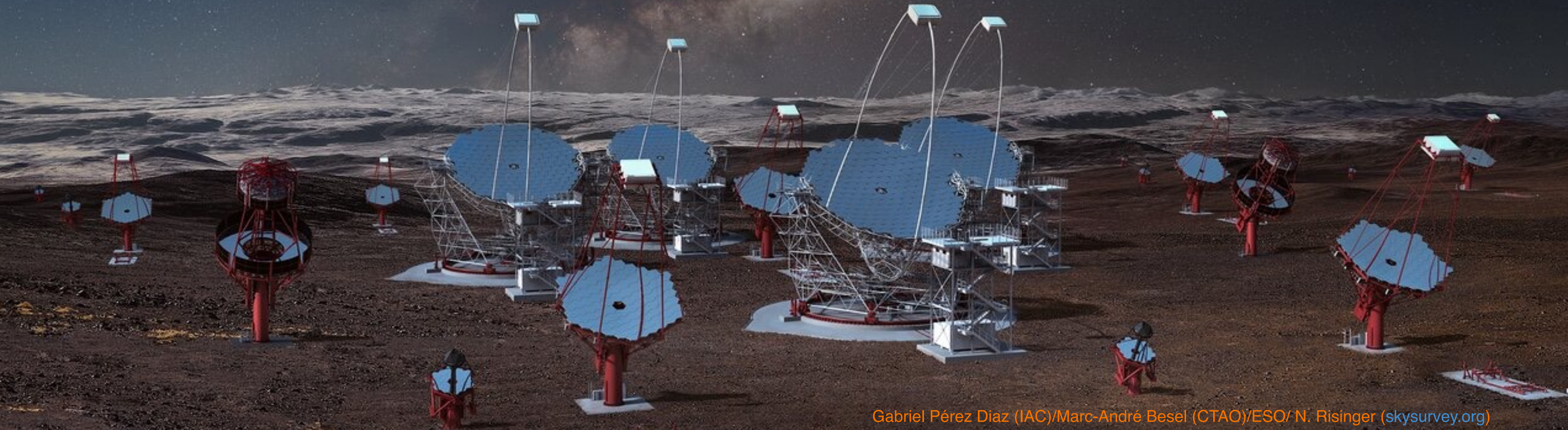


Čerenkov Telescope Array (CTAO)

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✧ Ground based IACT:

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

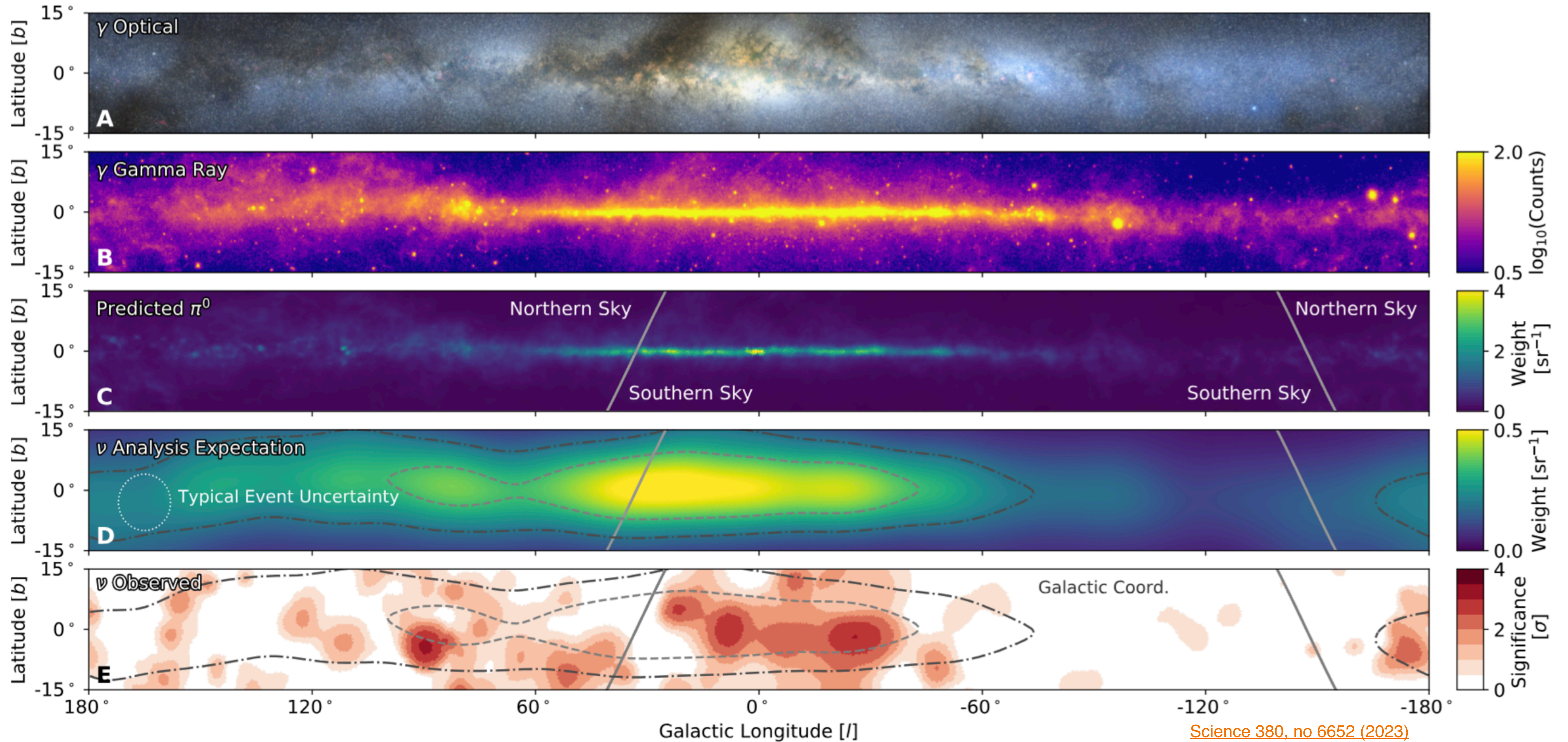


Types of detectors for neutrinos:

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

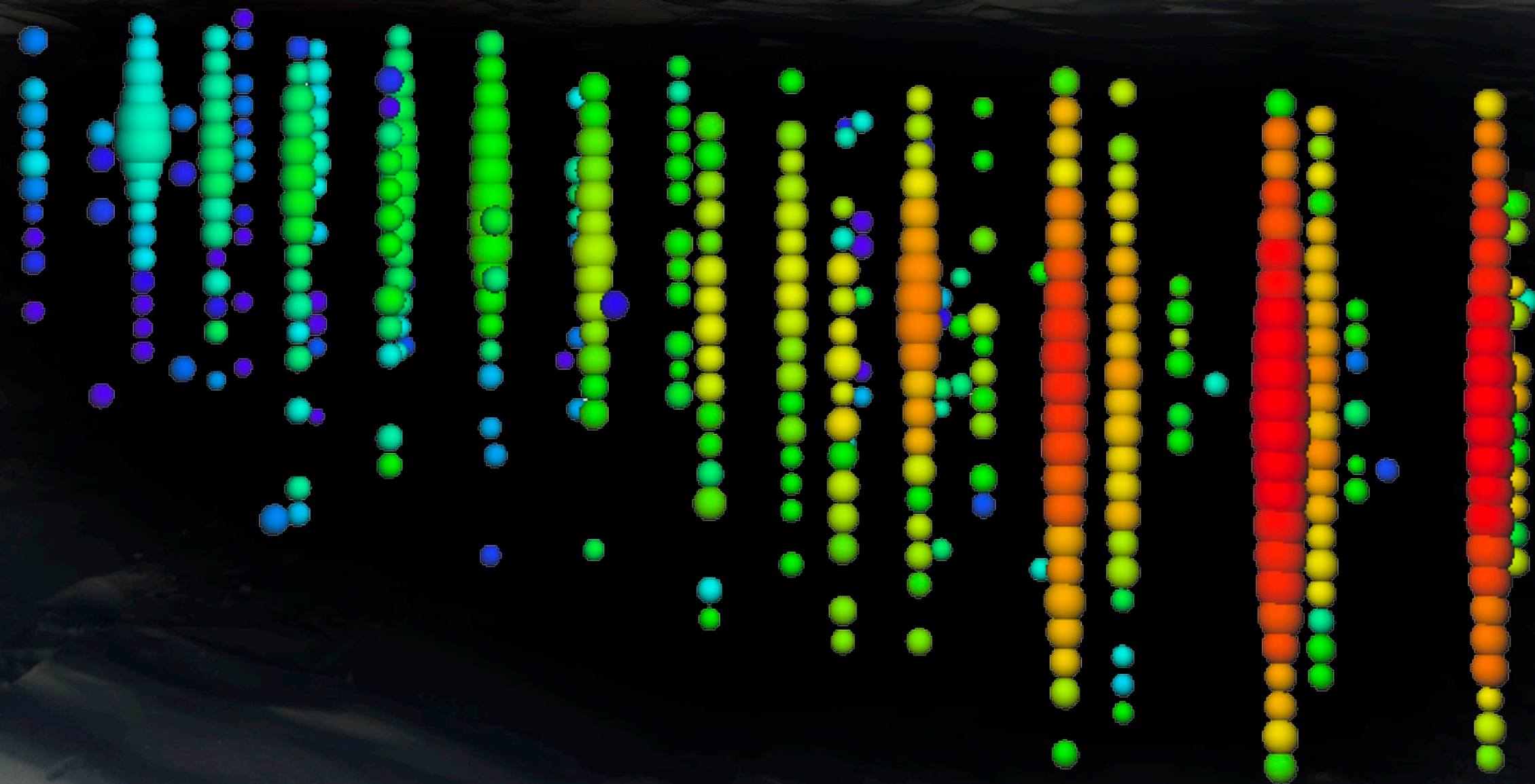
Multi-messenger Era

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✧ Under-Ice Large Čerenkov Telescope:

- ▶ Energy range: > 100 GeV
- ▶ Location: South Pole
- ▶ Operating since 2005



Credit: KM3NET

✦ Under-Sea Large Čerenkov Telescope:

- ▶ Energy range: $> 1 \text{ TeV}$
- ▶ Location: ORCA (France) ARCA (Italy)
- ▶ Under deployment



Credit: KM3NET

DM annihilation with Charged Cosmic Rays 20

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

✦ Alpha Magnetic Spectrometer:

Multi-layer for Tracking & Calorimeter

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

TRD
Identify e^+ , e^-

Particles and nuclei are defined by their charge (Z) and energy ($E \sim P$)

TOF
 Z, E

Magnet
 $\pm Z$

Silicon Tracker
 Z, P

ECAL
 E of e^+ , e^- , γ

Z, P are measured independently from Tracker, RICH, TOF and ECAL

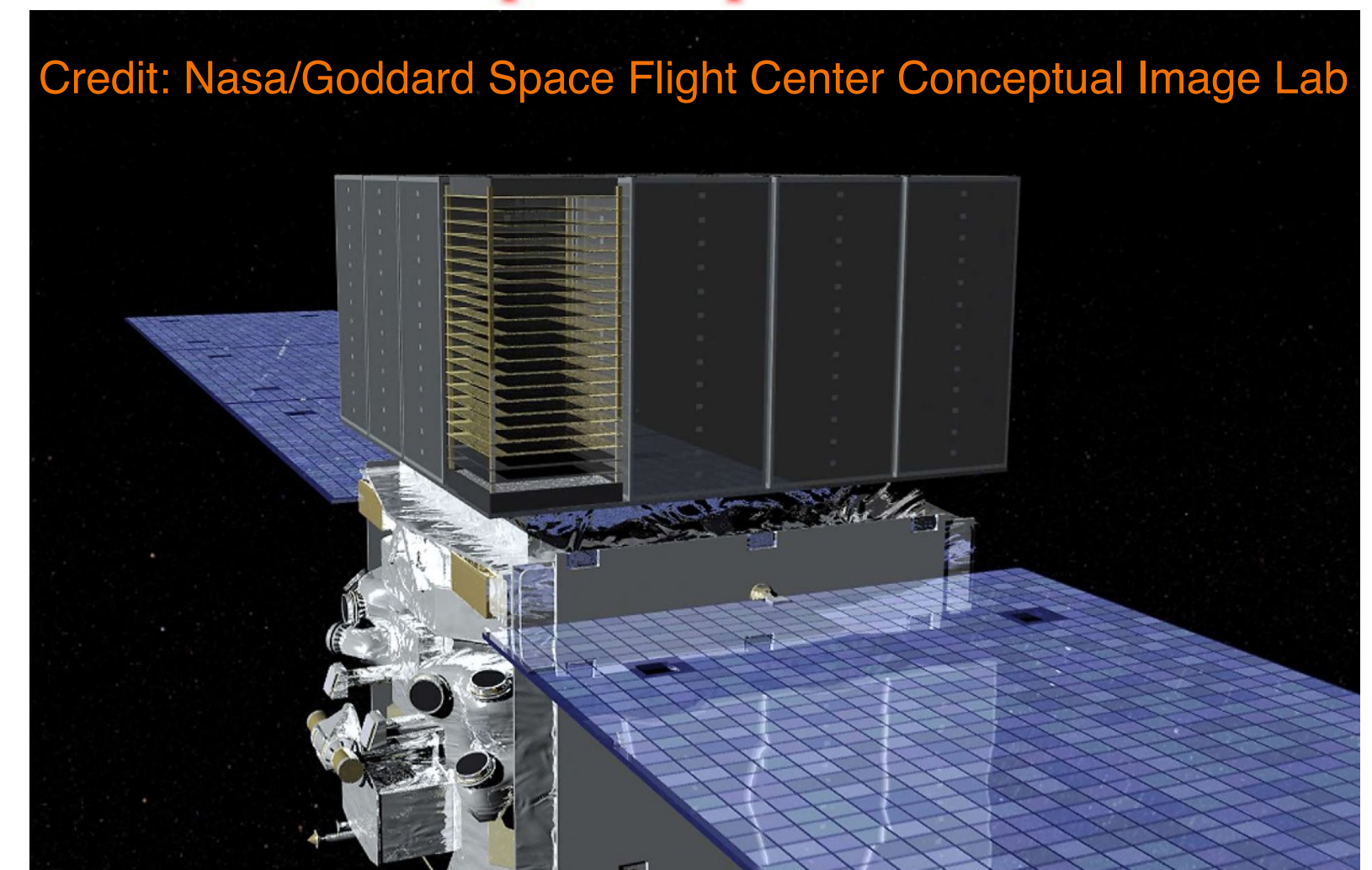
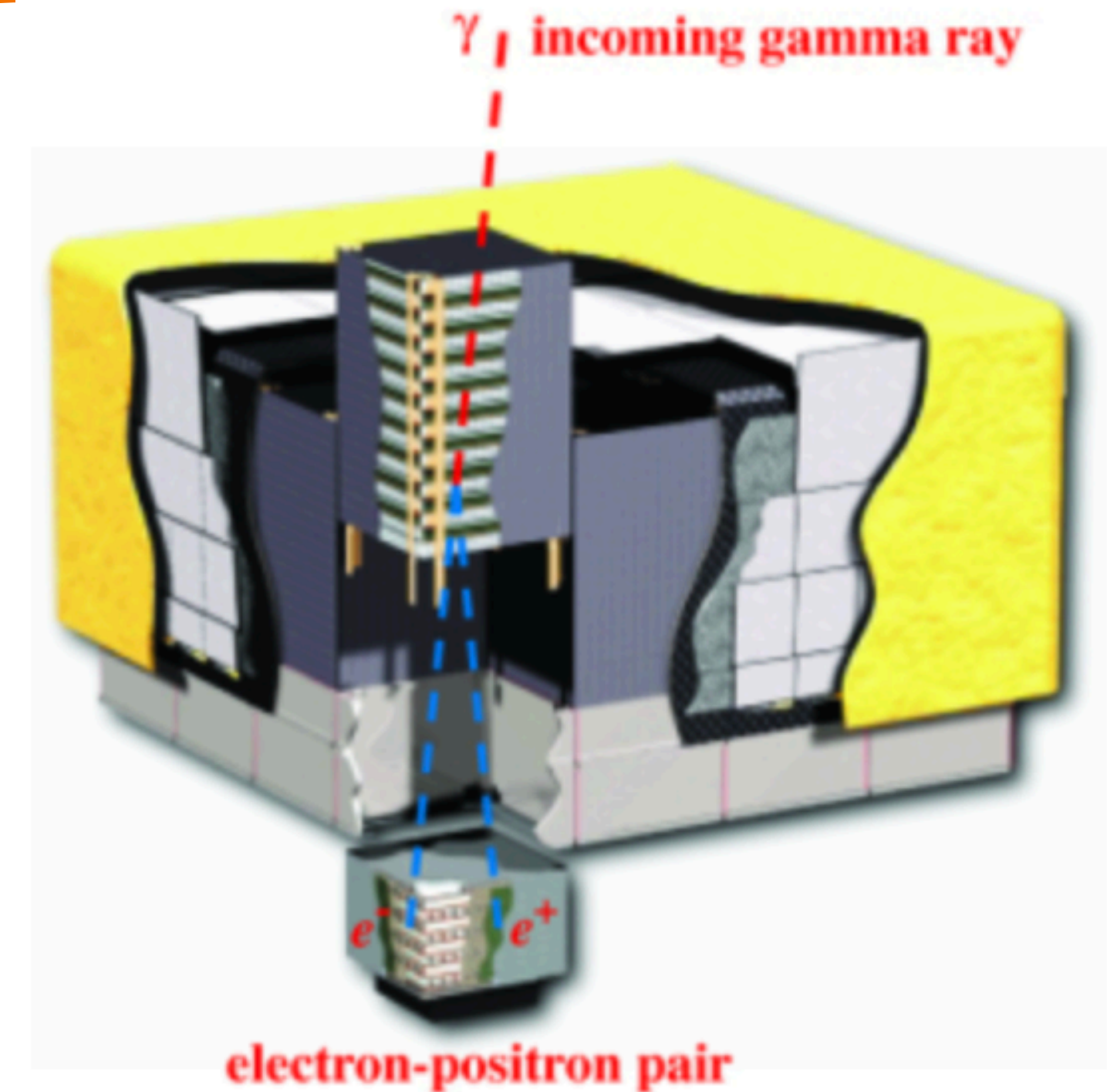
RICH
 Z, E



Fermi - Large Area Telescope (Fermi-LAT) 22

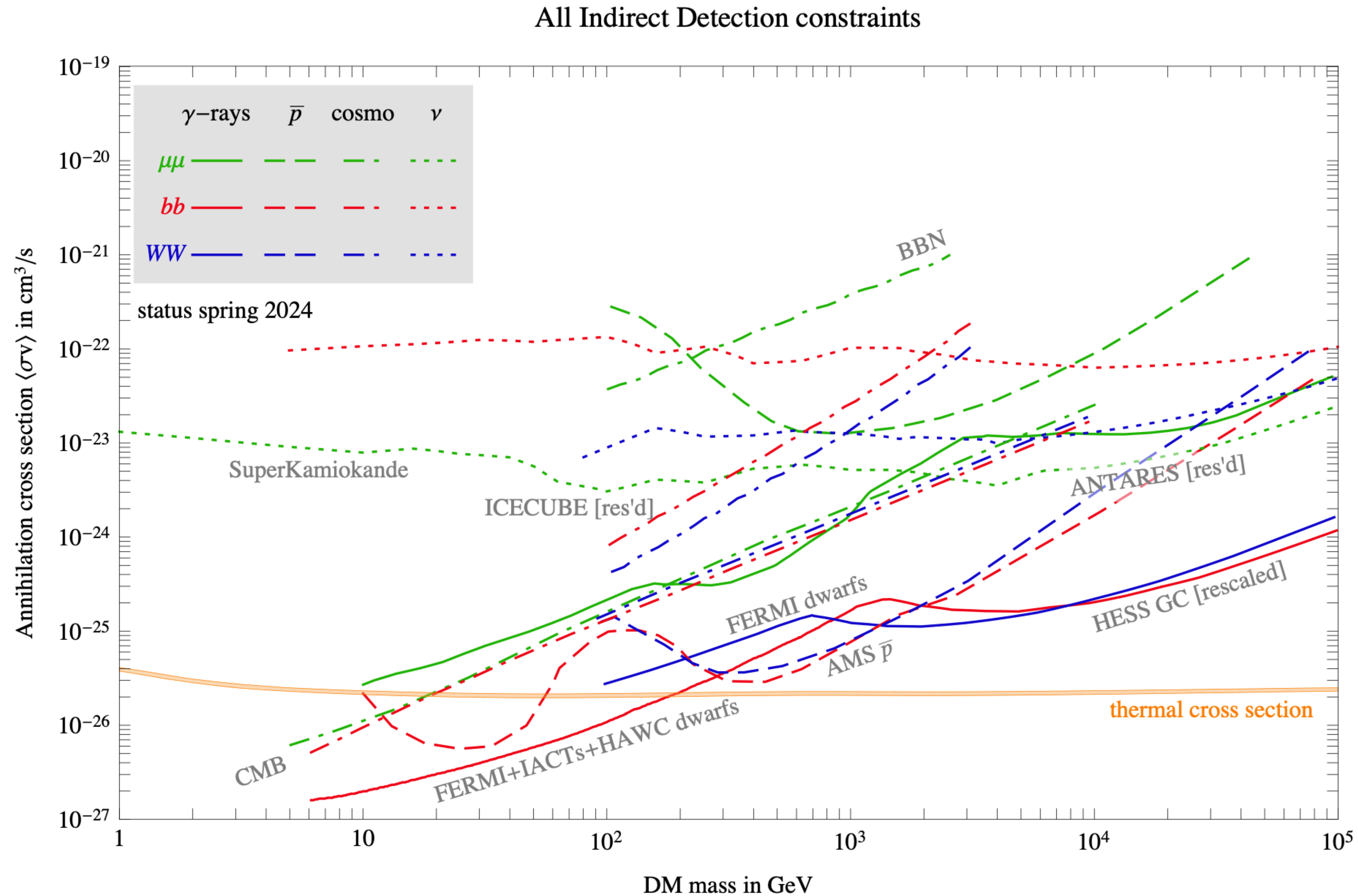
✧ Gamma Ray Telescope

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



Indirect DM search status

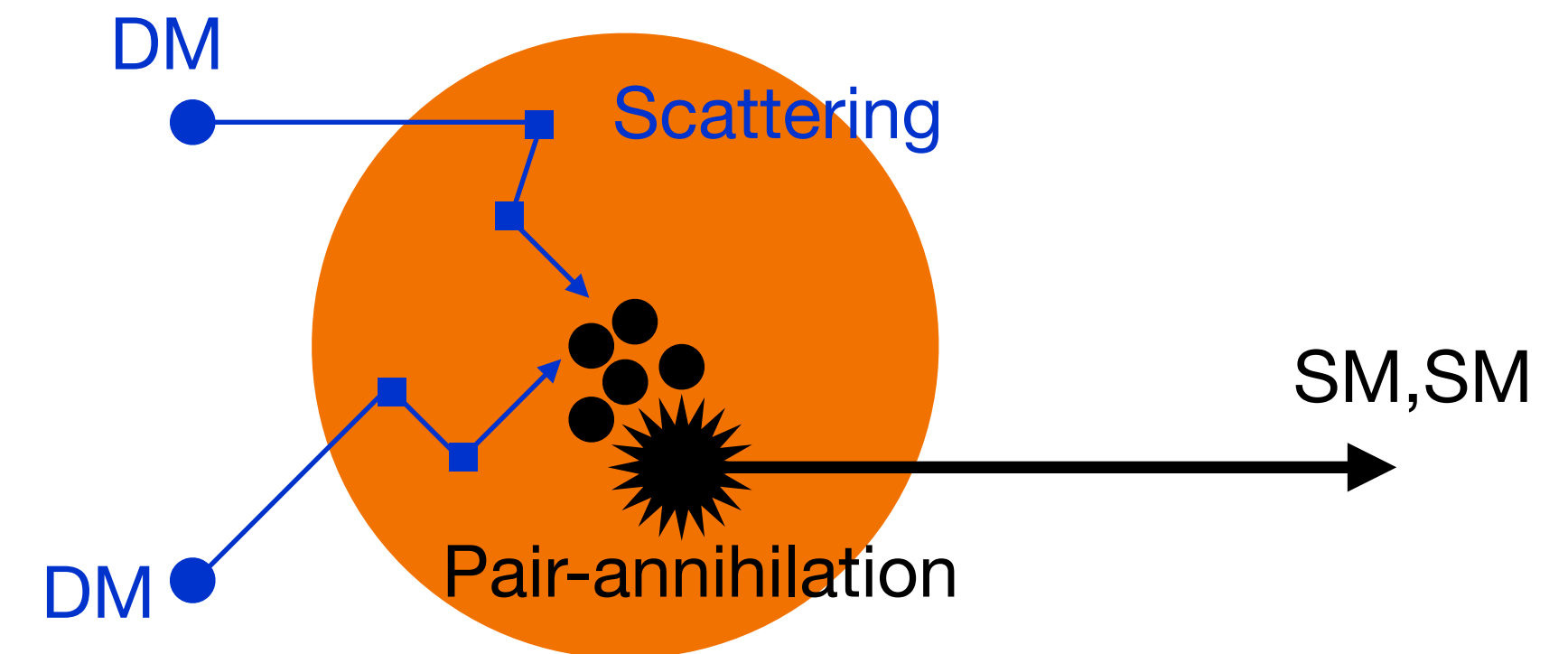
23



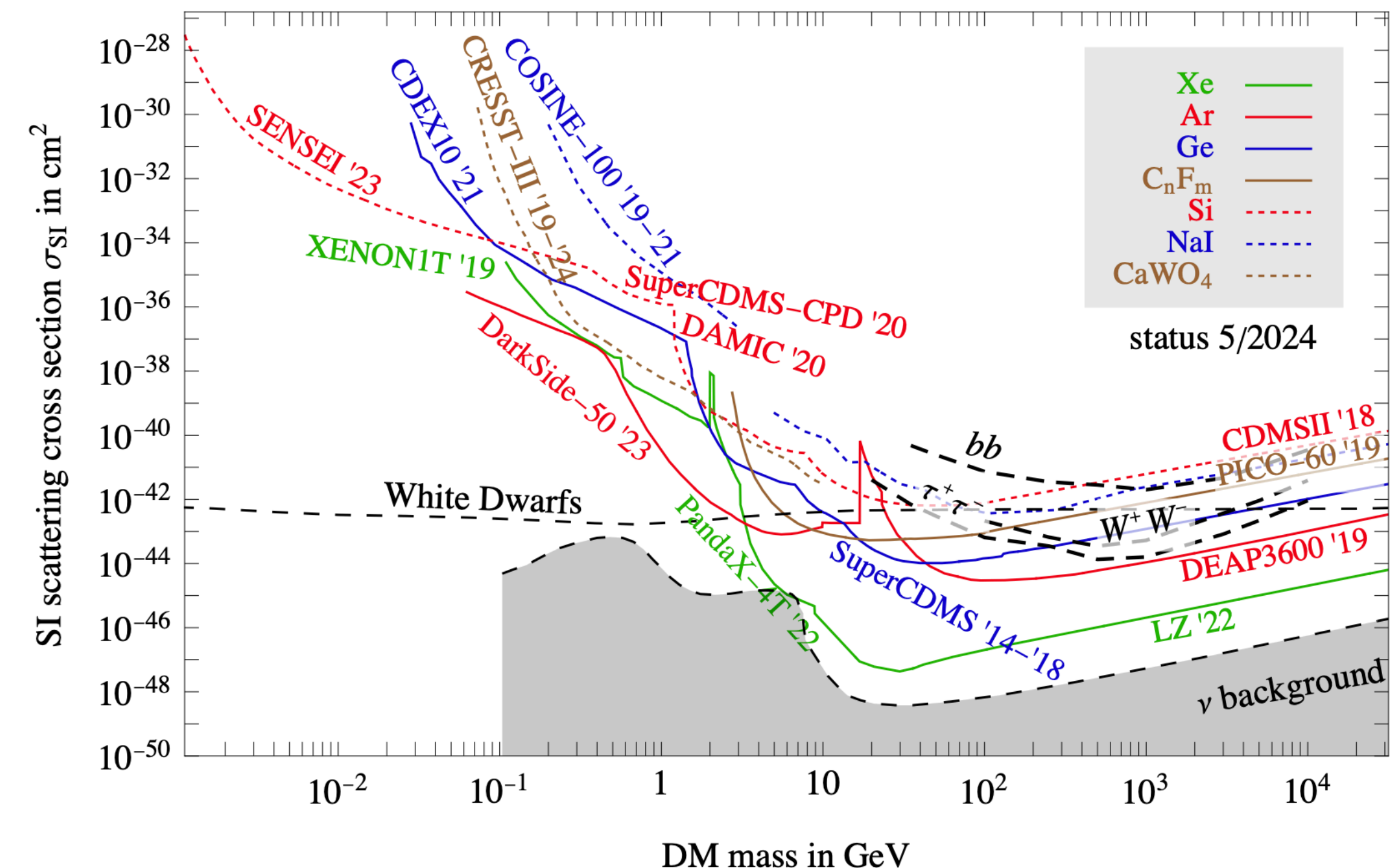
arXiv:2406.01705

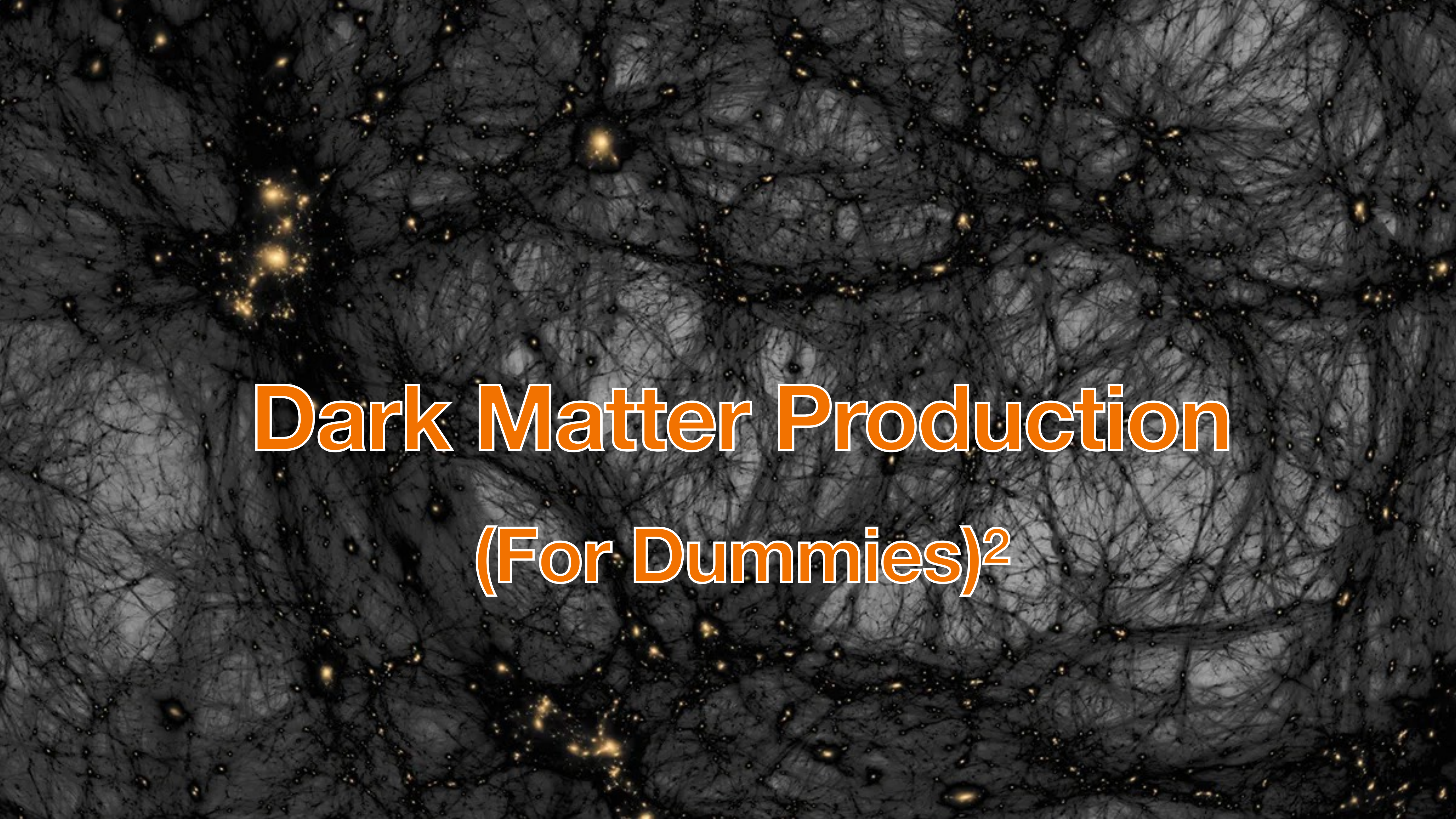
✦ Sun | Neutron stars | White Dwarfs

- ▶ 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](https://arxiv.org/abs/2406.01705)

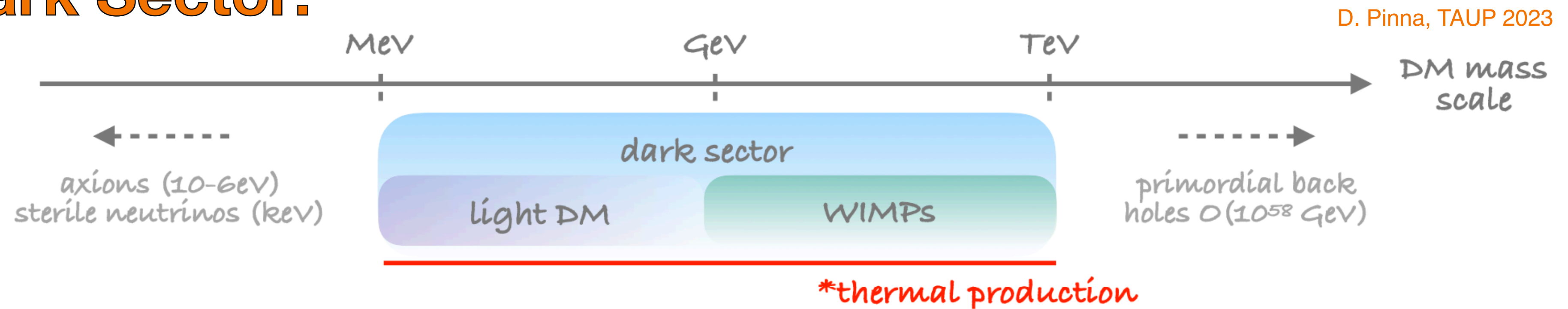


A visualization of the cosmic web, showing a complex network of dark matter filaments and clusters of galaxies. The background is dark with numerous small, bright yellow and orange points representing galaxies, connected by a dense web of thin, dark lines.

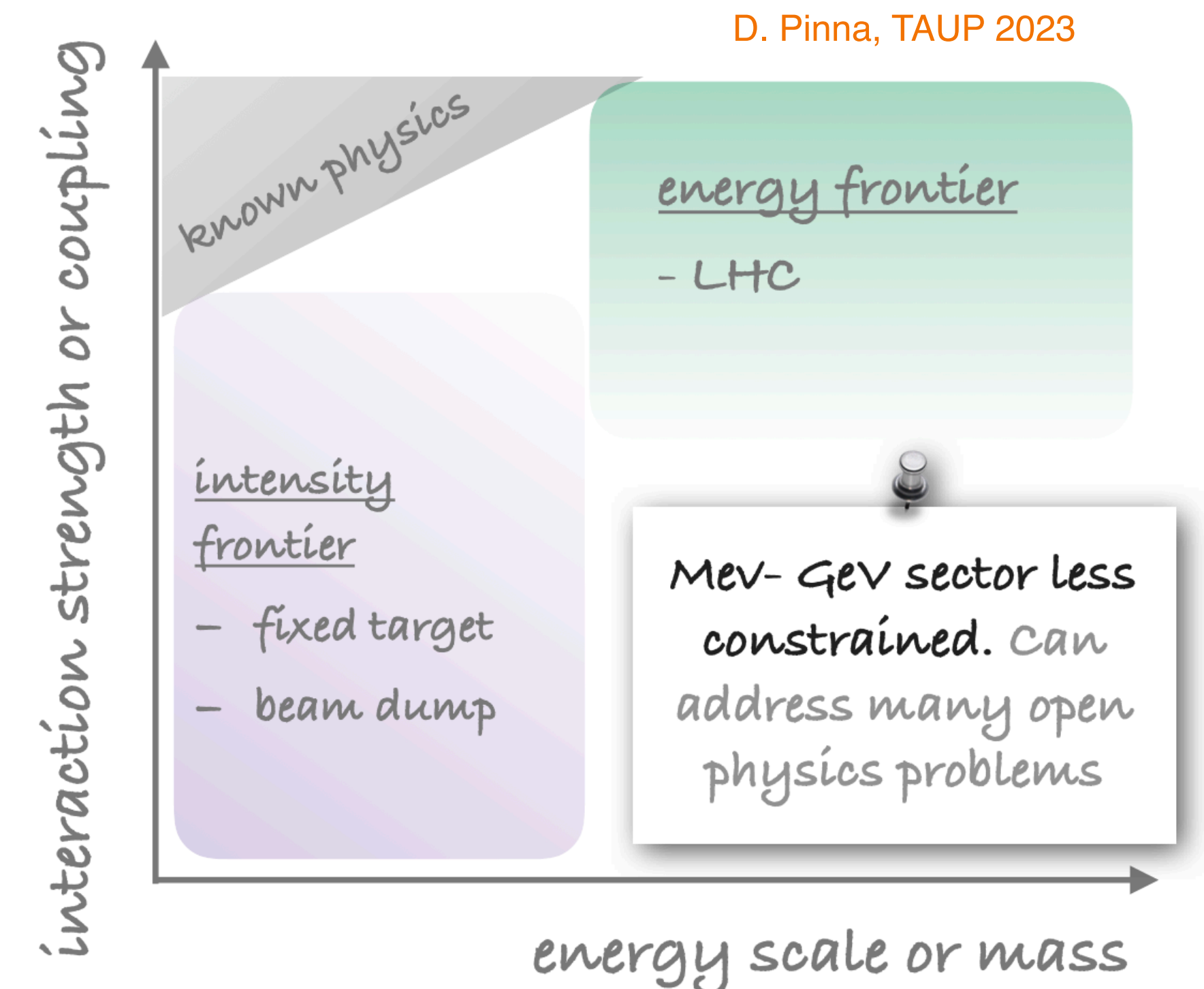
Dark Matter Production

(For Dummies)²

Probing the Dark Sector:

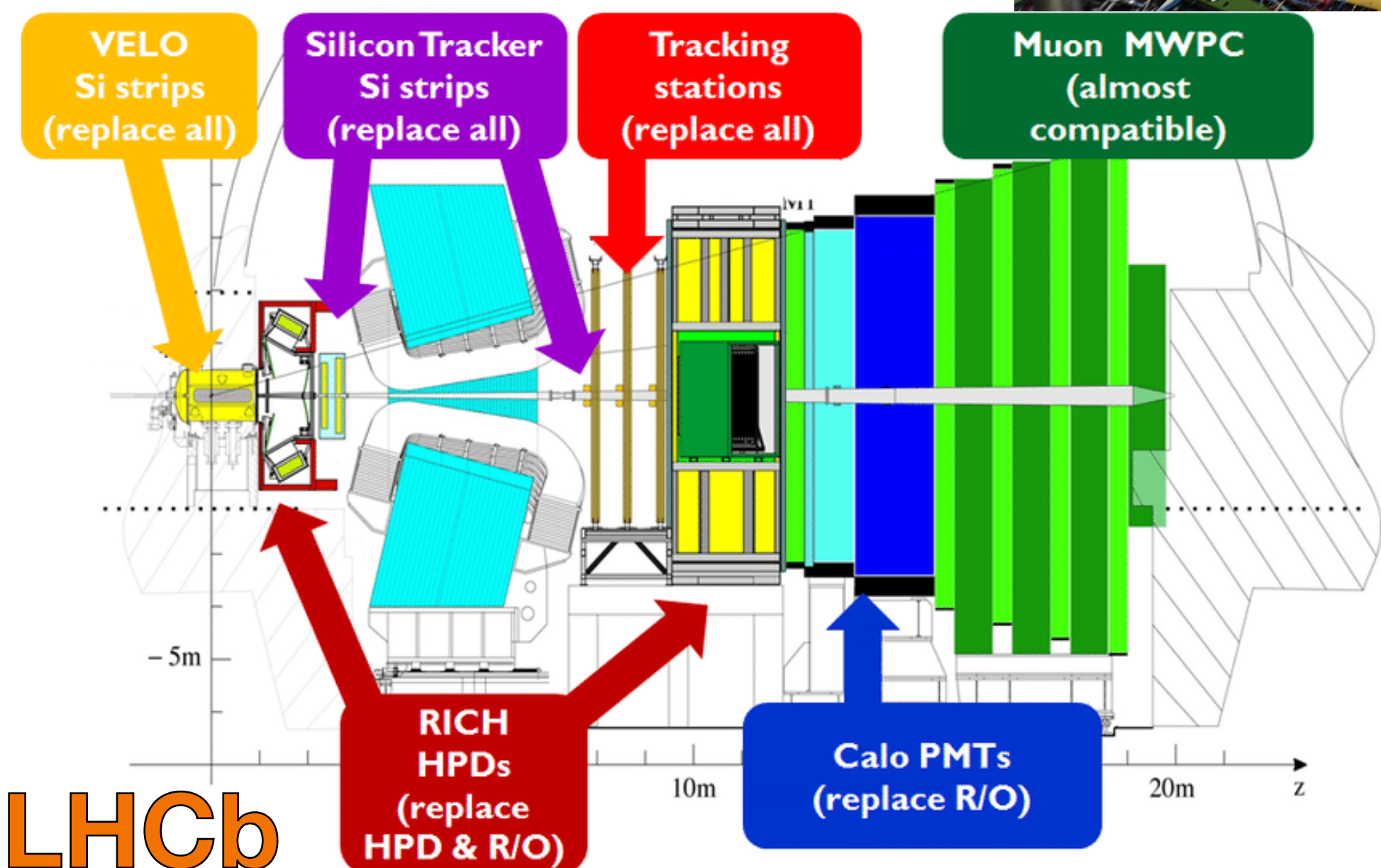
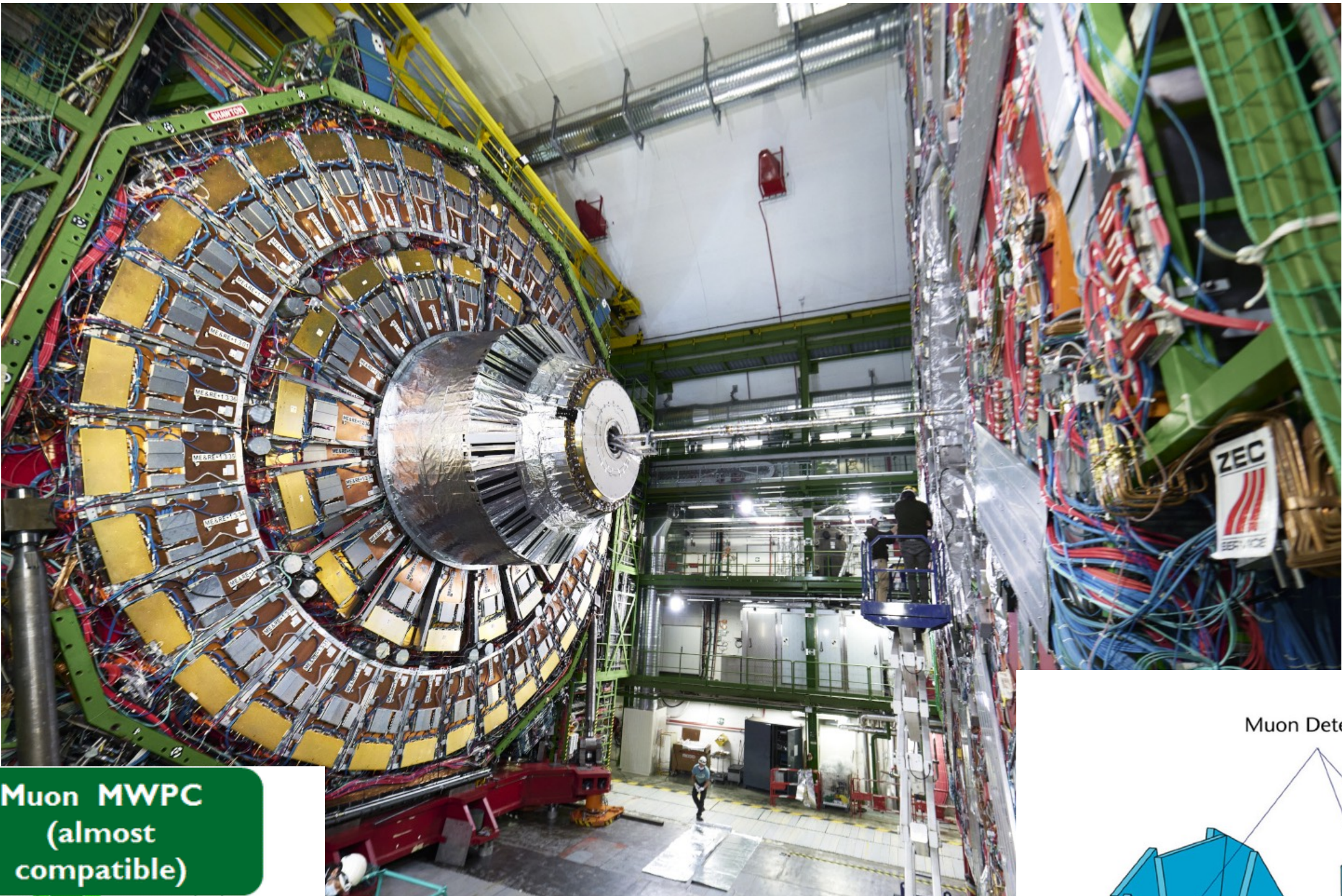


- ✦ Colliders experiments (**Energy Frontier**)
 - ▶ Missing transverse momentum (MET)
 - ▶ Signature of Mediator (Resonance)
- ✦ Accelerators experiments (**Intensity Frontier**)
 - ▶ Missing energy, momentum, or mass
 - ▶ Decay of Mediator or unstable DM particles

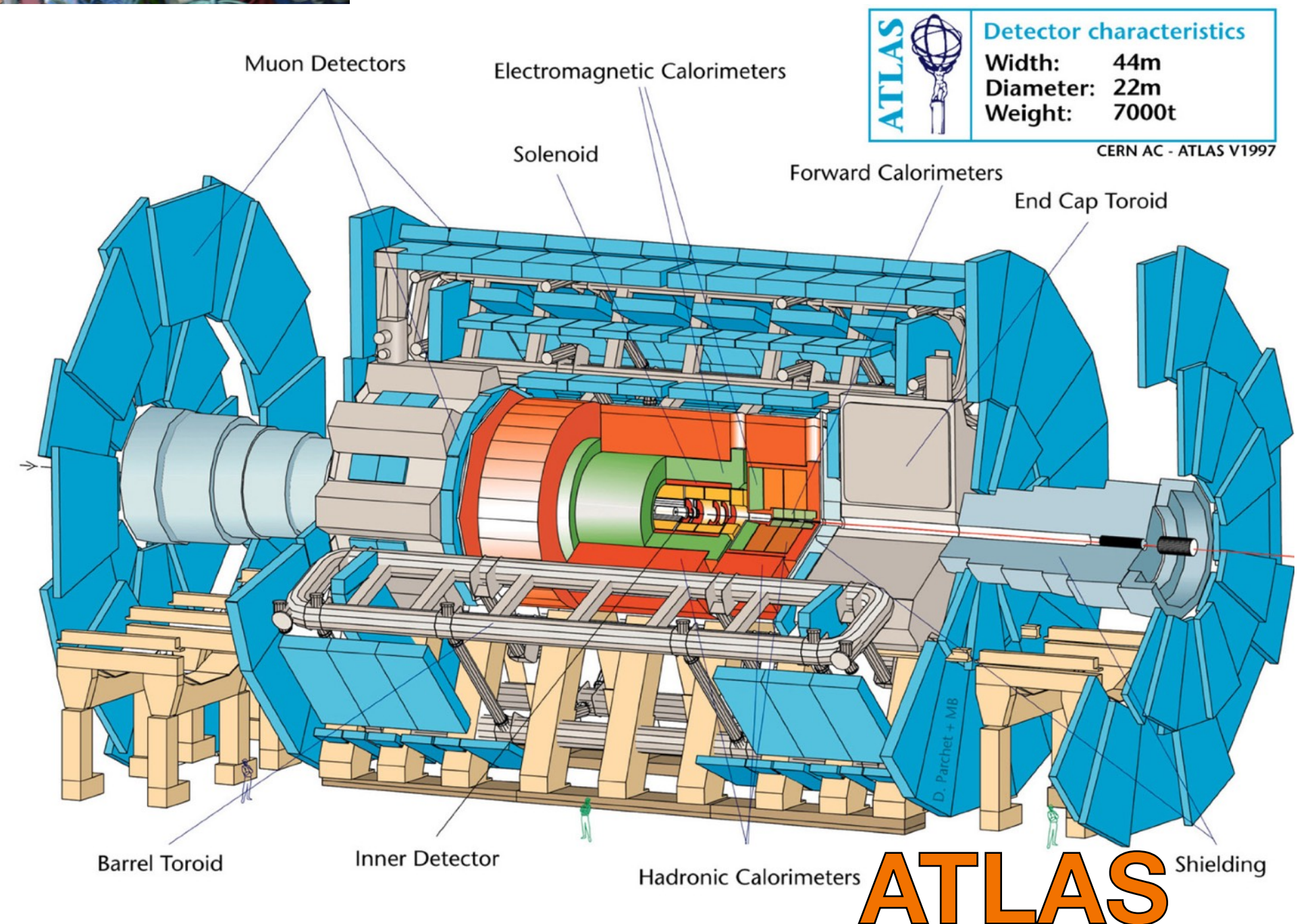


Experiments at LHC

CMS



LHCb



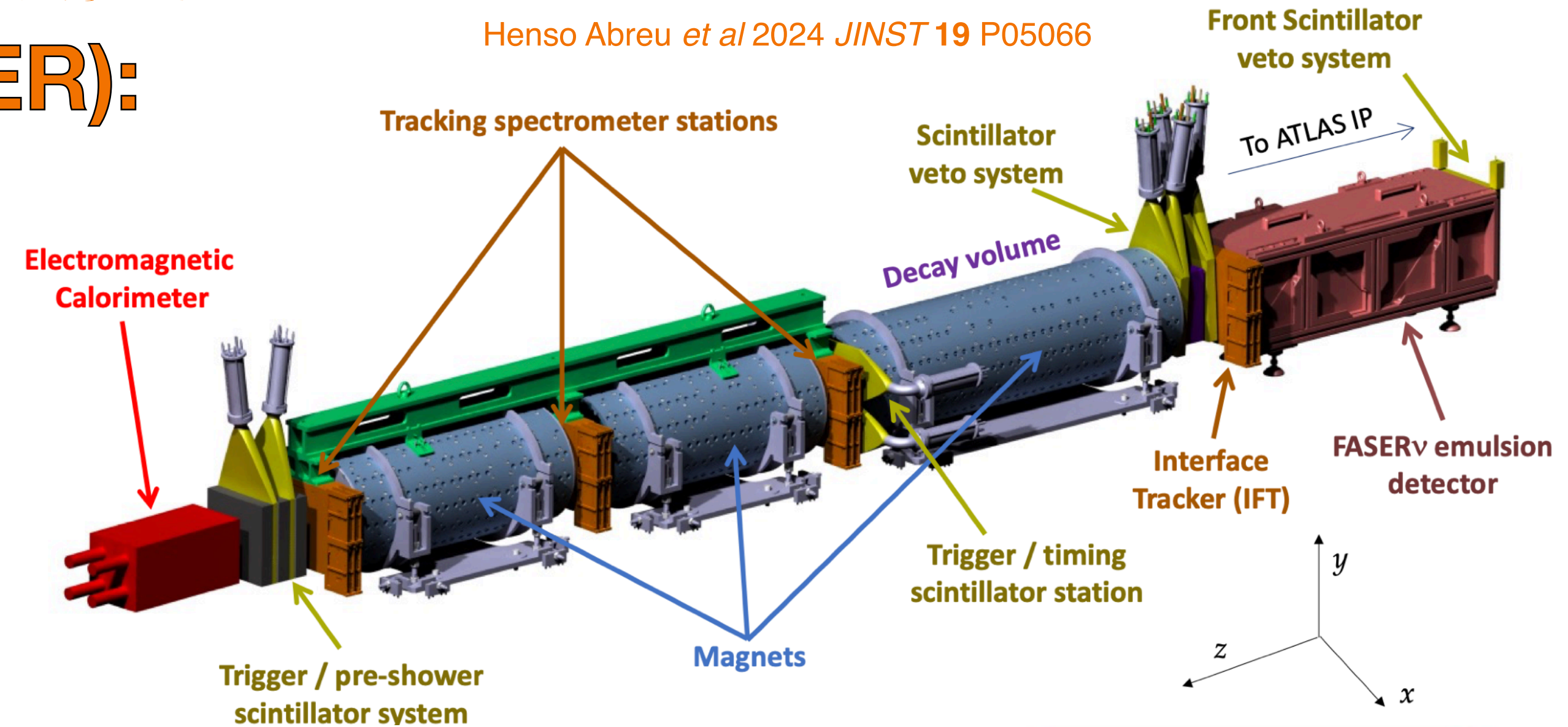
Detector characteristics	
Width:	44m
Diameter:	22m
Weight:	7000t

CERN AC - ATLAS V1997

ATLAS

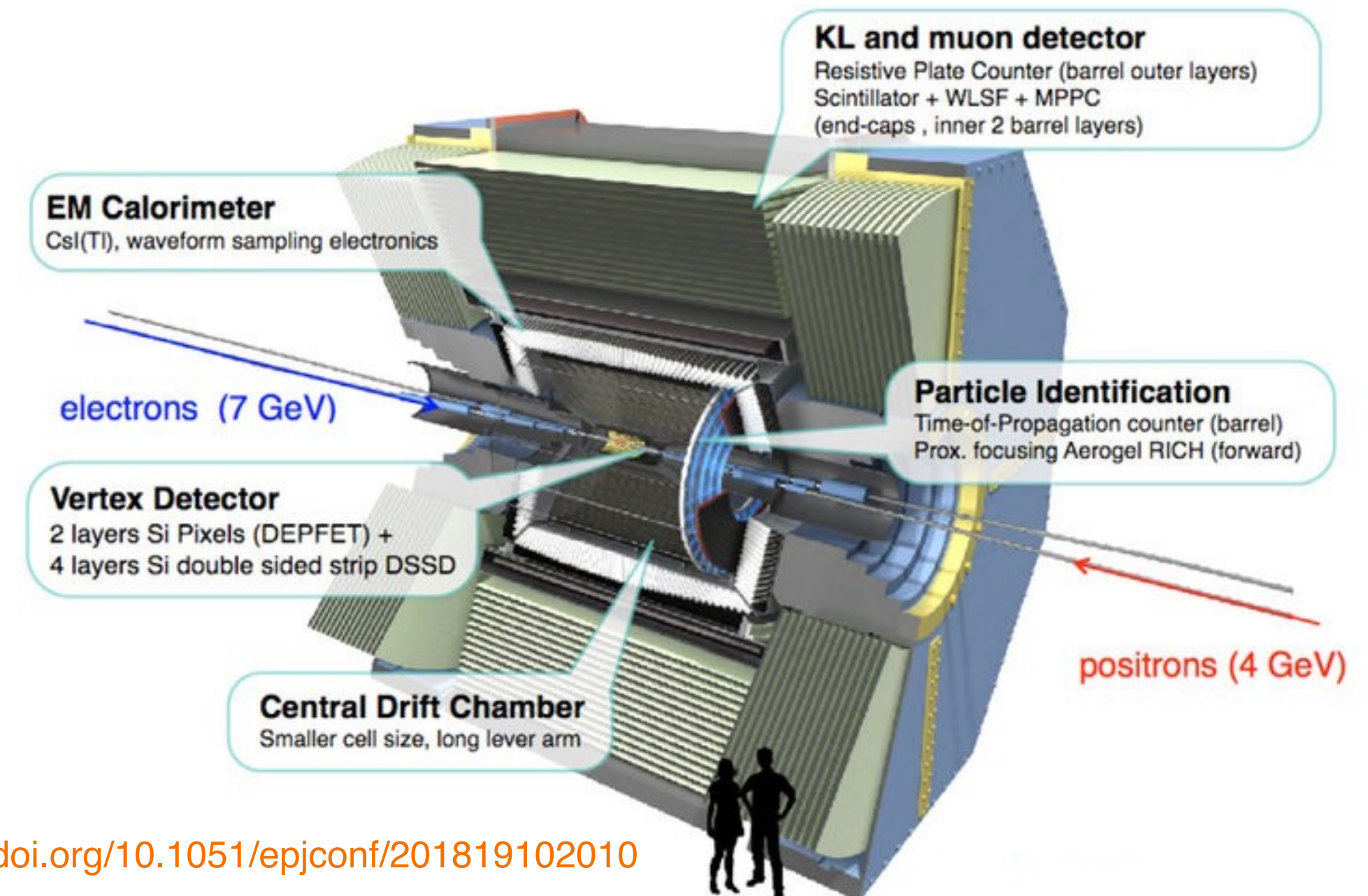
ForwArd Search ExpeRiment (FASER):

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



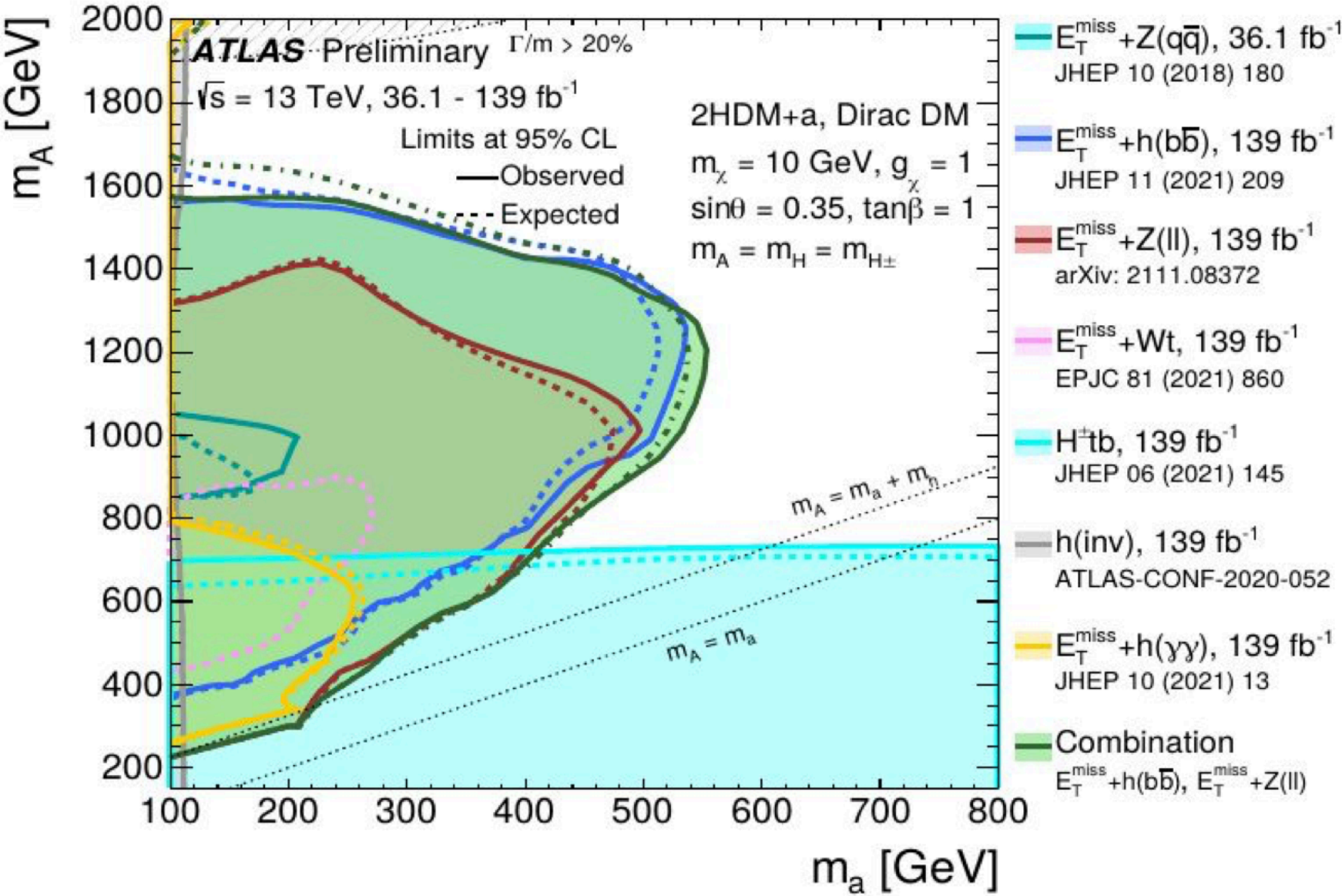
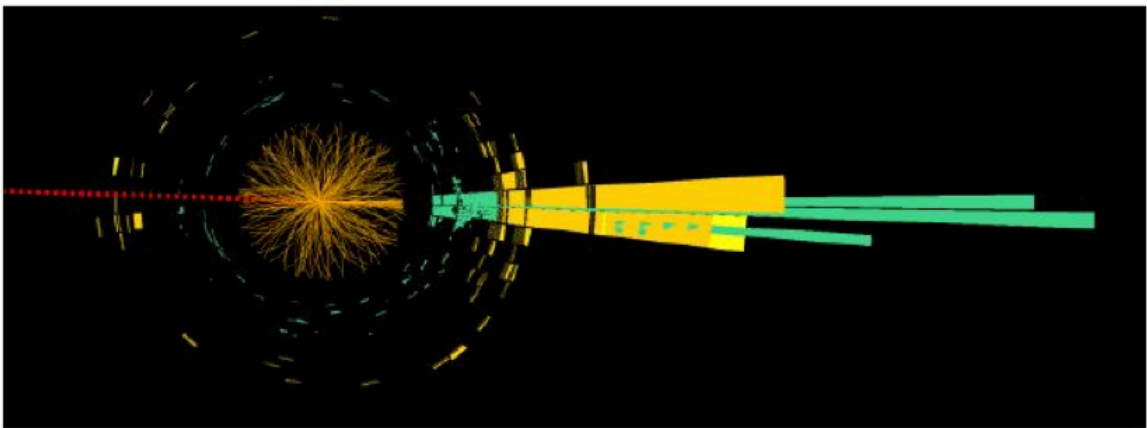
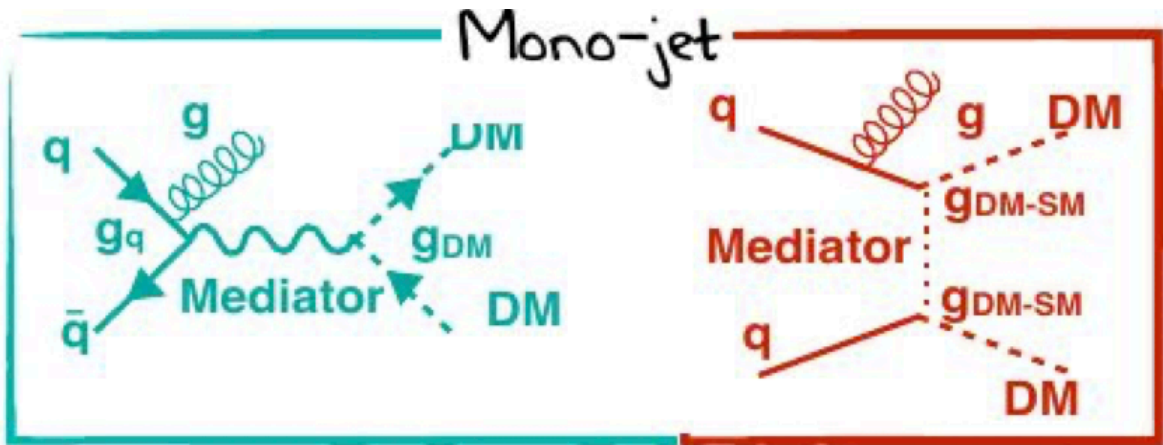
BELLE-2:

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



Model-Dependent Results:

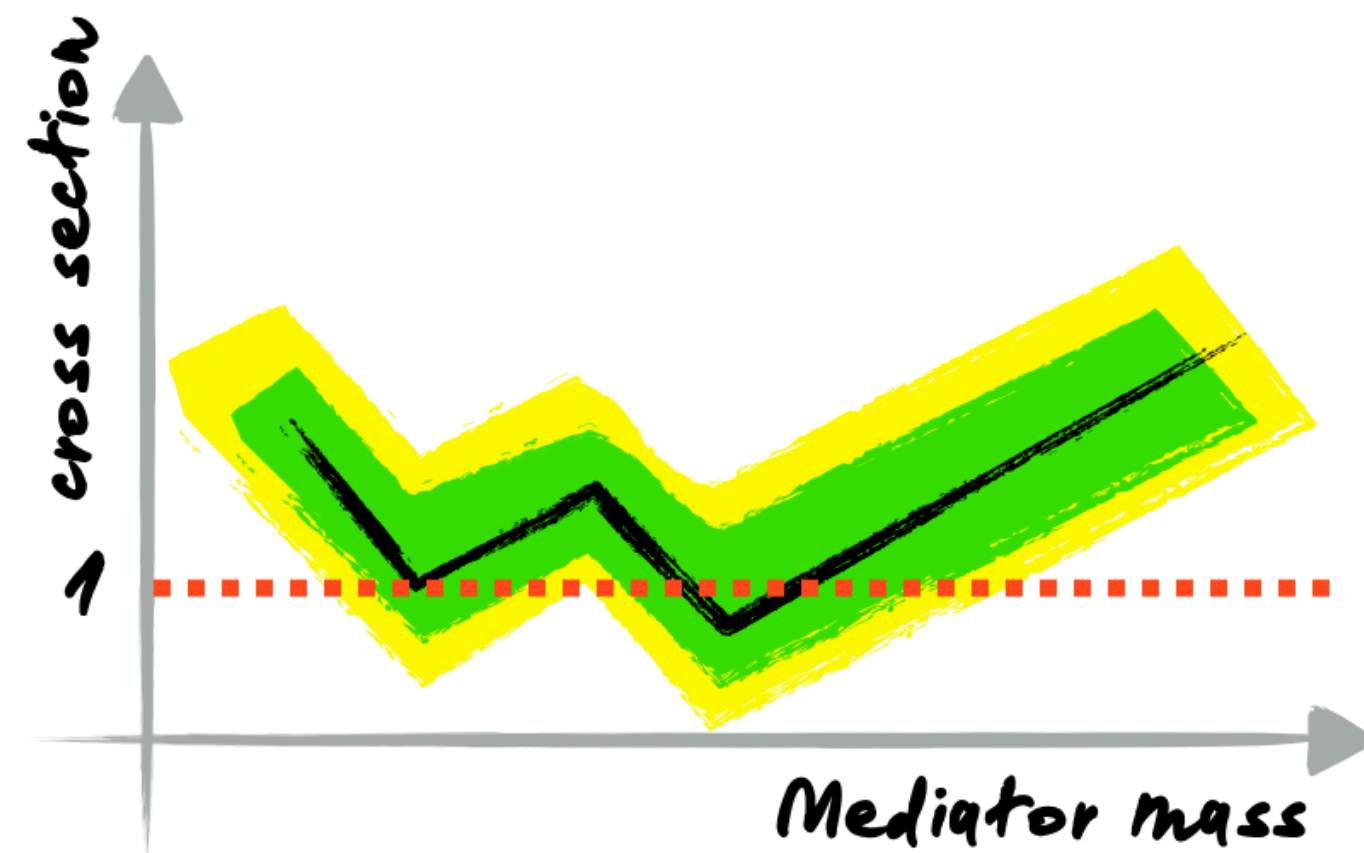
Example :
monojet with
 P_T missing



Comparison with Direct Detection Results 30

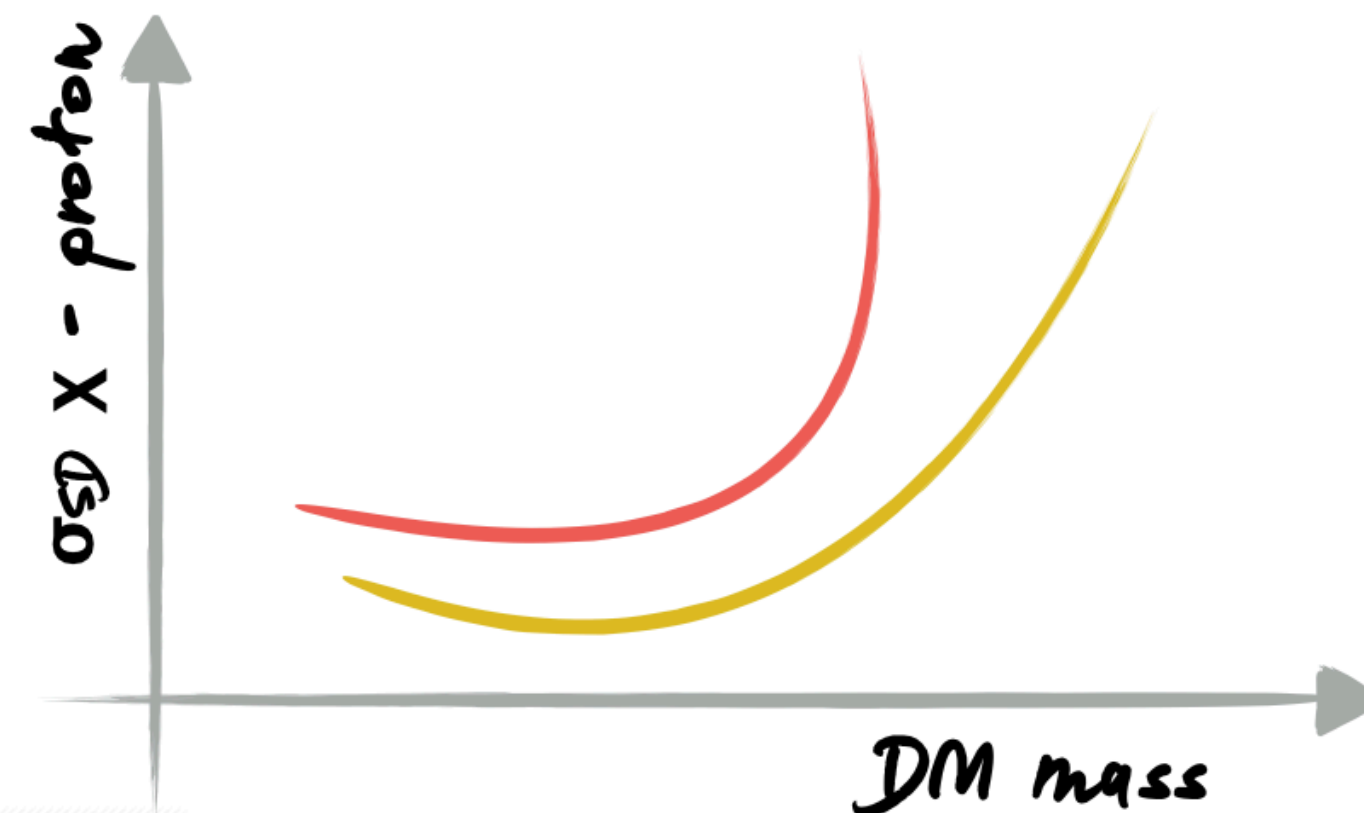
Credit Slide: Luca Scotto Lavina

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. Ciotto, Dark matter searches with the ATLAS detector