Dark matter searches with the Cherenkov Telescope Array

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on behalf of the CTA Consortium

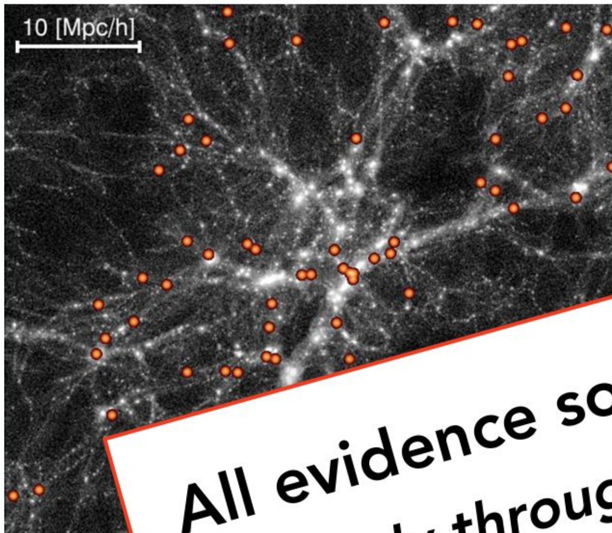
Outline

- Indirect dark matter searches with gamma rays
- Gamma-ray astronomy
- The Cherenkov Telescope Array
- Dark matter searches with CTA
- Conclusions

Dark matter

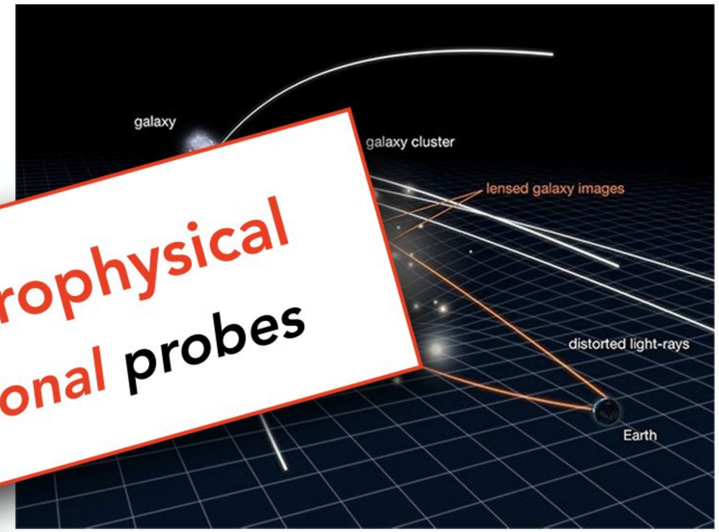
an essential building block of the Standard Model of Cosmology

large scale structures



100s Mpc

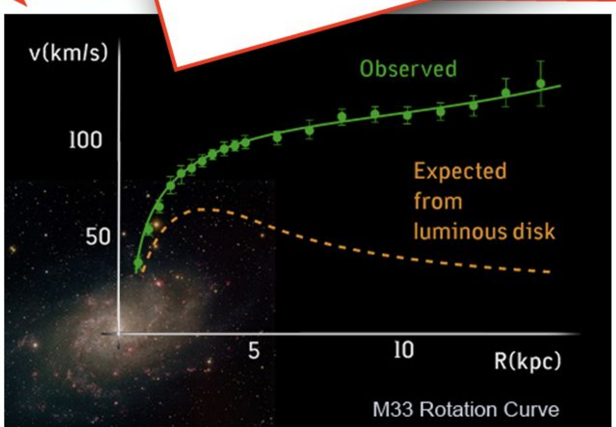
clusters of galaxies



Mpc

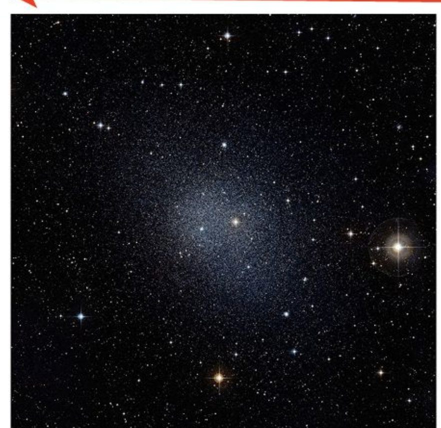
All evidence so far is astrophysical
And only through gravitational probes

Milky



100s kpc

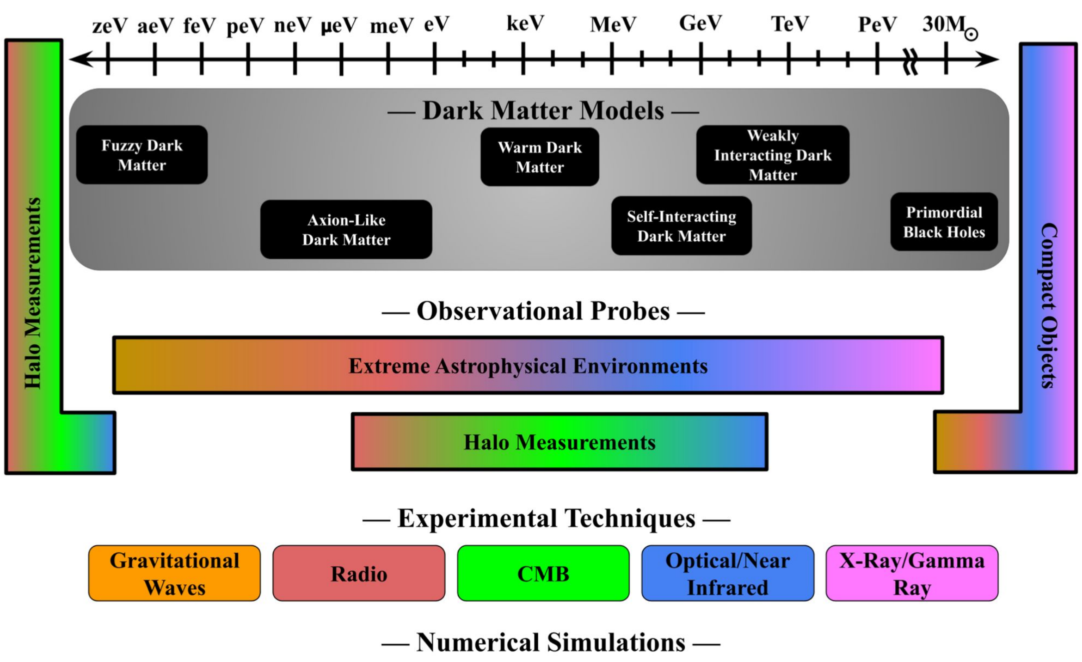
dwarf galaxies



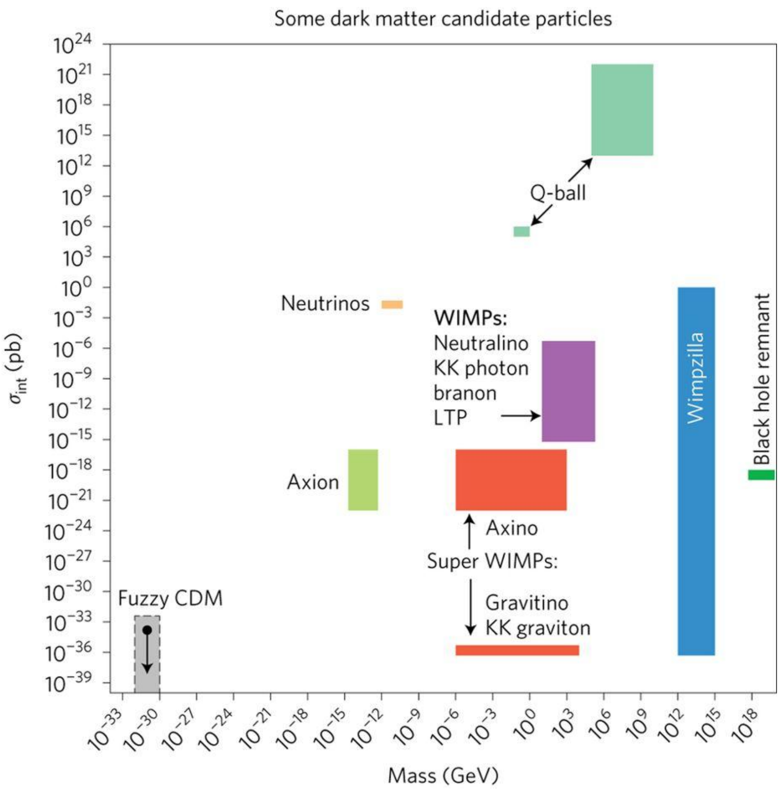
<~ kpc

Slide G. Zaharijas

Dark Matter Candidates



A. Drlica-Wagner et al SNOWMASS Cosmic Probes arxiv: 2209.08215

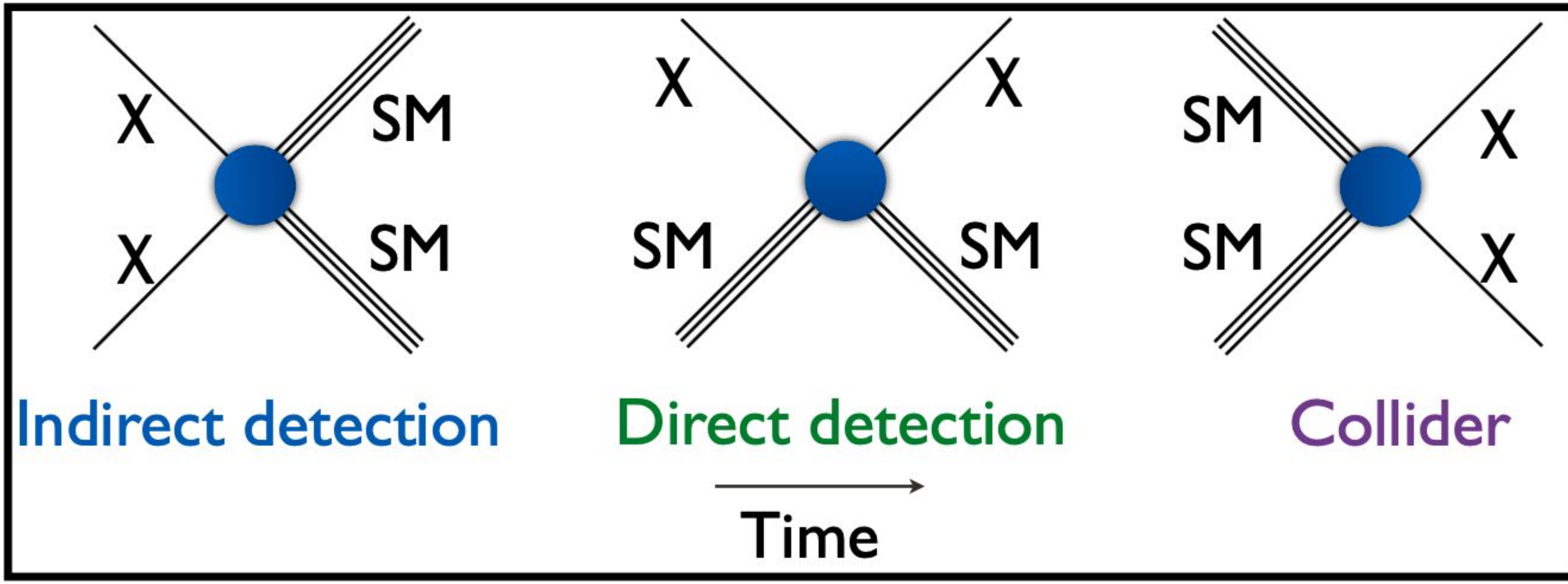


J. Conrad and O. Reimer Nature Physics 13, 224–231 (2017)

Today's focus: WIMPs

Dark matter particles: search strategies

Weakly interacting massive particles (WIMPs) were created in the early universe and predicted in extensions of the Standard Model (e. g. supersymmetric models).



- Indirect detection: look for Standard Model particles - electrons/positrons, photons, neutrinos, protons/antiprotons - produced when dark matter particles collide or decay. Today's focus
- Direct detection: look for atomic nuclei "jumping" when struck by dark matter particles, using sensitive underground detectors.
- Colliders: produce dark matter particles in high-energy collisions, look at visible particles produced in the same collisions, check for apparent violation of energy/momentum conservation.

Slide by Tracy Slatyer

Indirect WIMP searches

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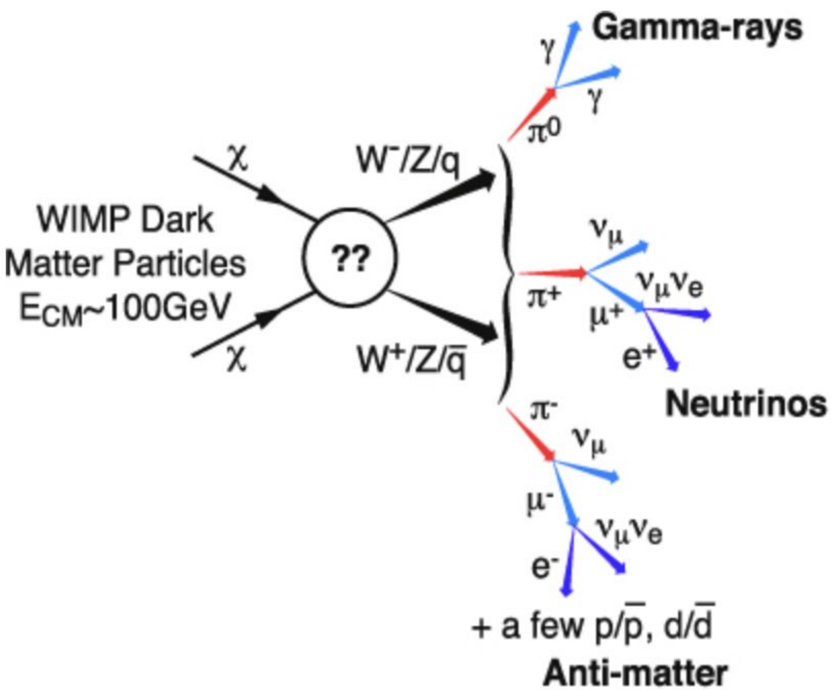
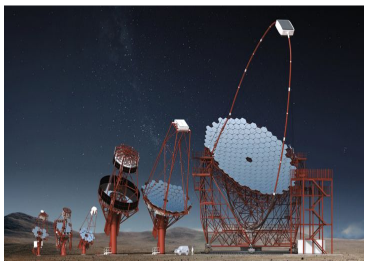
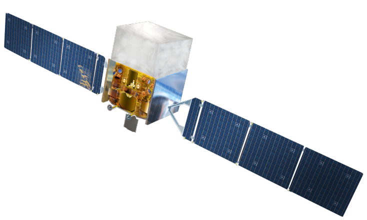


Adapted from E. A. Baltz et al, J. Cosmol. Astropart. Phys. JCAP07 (2008) 013

Indirect WIMP searches with gamma rays



$$\Phi_\gamma(E_{\max}, E_{\min}) = \int_{E_{\min}}^{E_{\max}} \frac{1}{2} \frac{\langle \sigma v \rangle}{4\pi m_\chi^2} \sum_f B_f \frac{dN_\gamma^f}{dE_\gamma} dE_\gamma \int_{\Delta\Omega(\alpha,\phi)} d\Omega \int_{\text{los}} ds\, \rho_{\text{DM}}^2(r(s, \alpha_{\text{int}}))$$



Indirect WIMP searches with gamma rays

$$\Phi_\gamma(E_{\rm max}, E_{\rm min}) = \int_{E_{\rm min}}^{E_{\rm max}} \frac{1}{2}\frac{\langle \sigma v \rangle}{4\pi m_\chi^2} \sum_f B_f \frac{dN_\gamma^f}{dE_\gamma} dE_\gamma \int_{\Delta\Omega(\alpha,\phi)} d\Omega \int_{\rm los} ds\, \rho_{\rm DM}^2(r(s, \alpha_{\rm int}))$$

Particle physics factor:

- Depends on the WIMP particle mass, the annihilation cross section, on the weight of different channels (branching ratios)
- Either continuum or monoenergetic line

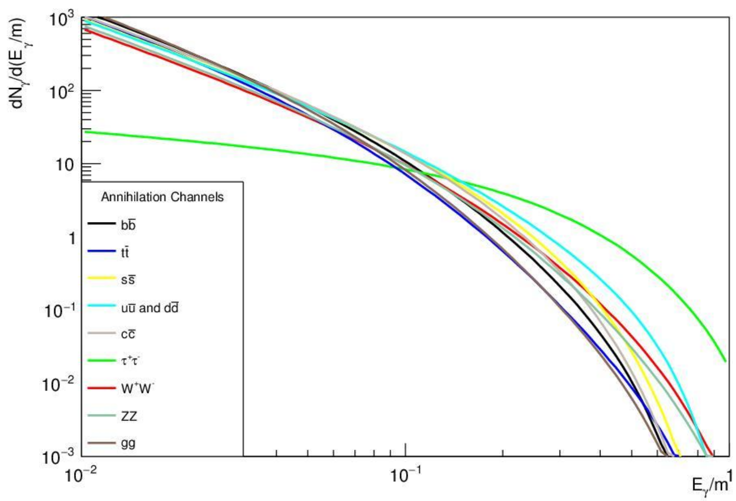


Image credit: K. Nakashima

Indirect WIMP searches with gamma rays

$$\Phi_\gamma(E_{\max}, E_{\min}) = \int_{E_{\min}}^{E_{\max}} \frac{1}{2}\frac{\langle\sigma v\rangle}{4\pi m_\chi^2} \sum_f B_f \frac{dN_\gamma^f}{dE_\gamma} dE_\gamma \int_{\Delta\Omega(\alpha,\phi)} d\Omega \int_{\mathrm{los}} ds\, \rho_{\mathrm{DM}}^2(r(s, \alpha_{\mathrm{int}}))$$

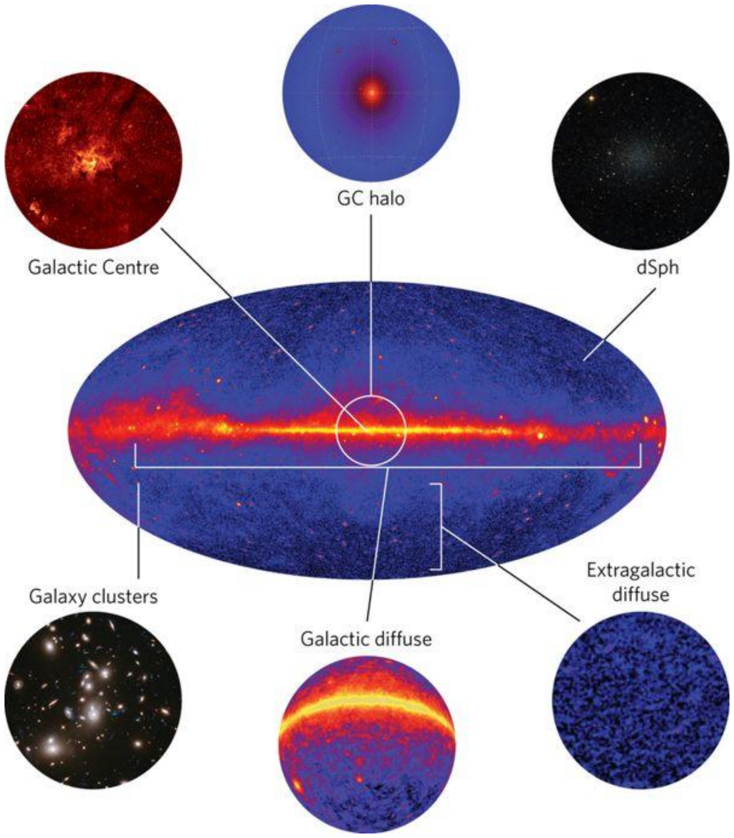
Astrophysical J factor:

- DM density profile to be assumed
- Find targets with high DM density

Astrophysical targets

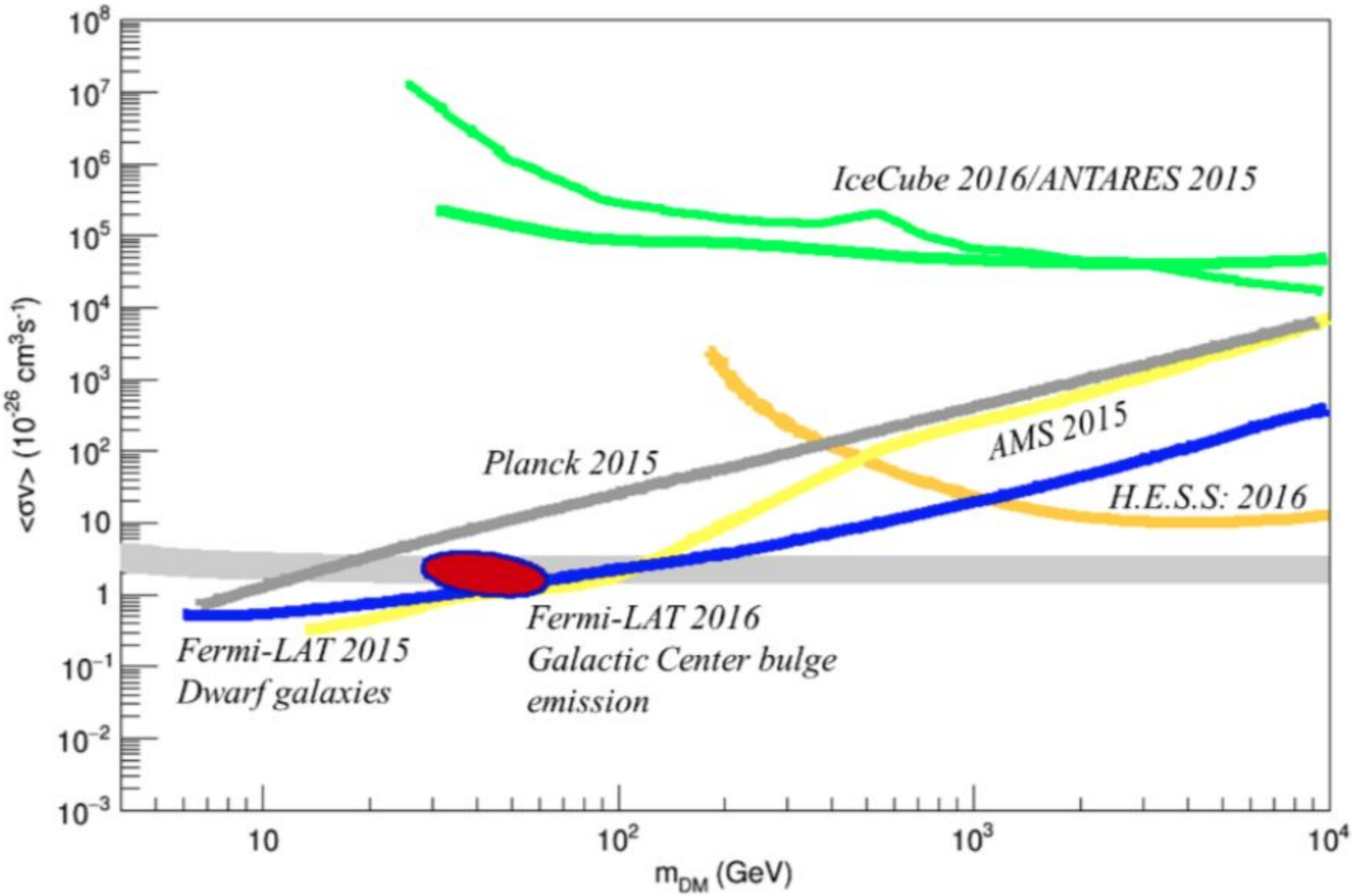
The following aspects has to be taken into account to choose a target:

- Distance
- Dark matter content
- Presence of astrophysical gamma-ray sources



J. Conrad and O. Reimer Nature Physics 13, 224–231 (2017)

Indirect WIMP searches: Current status



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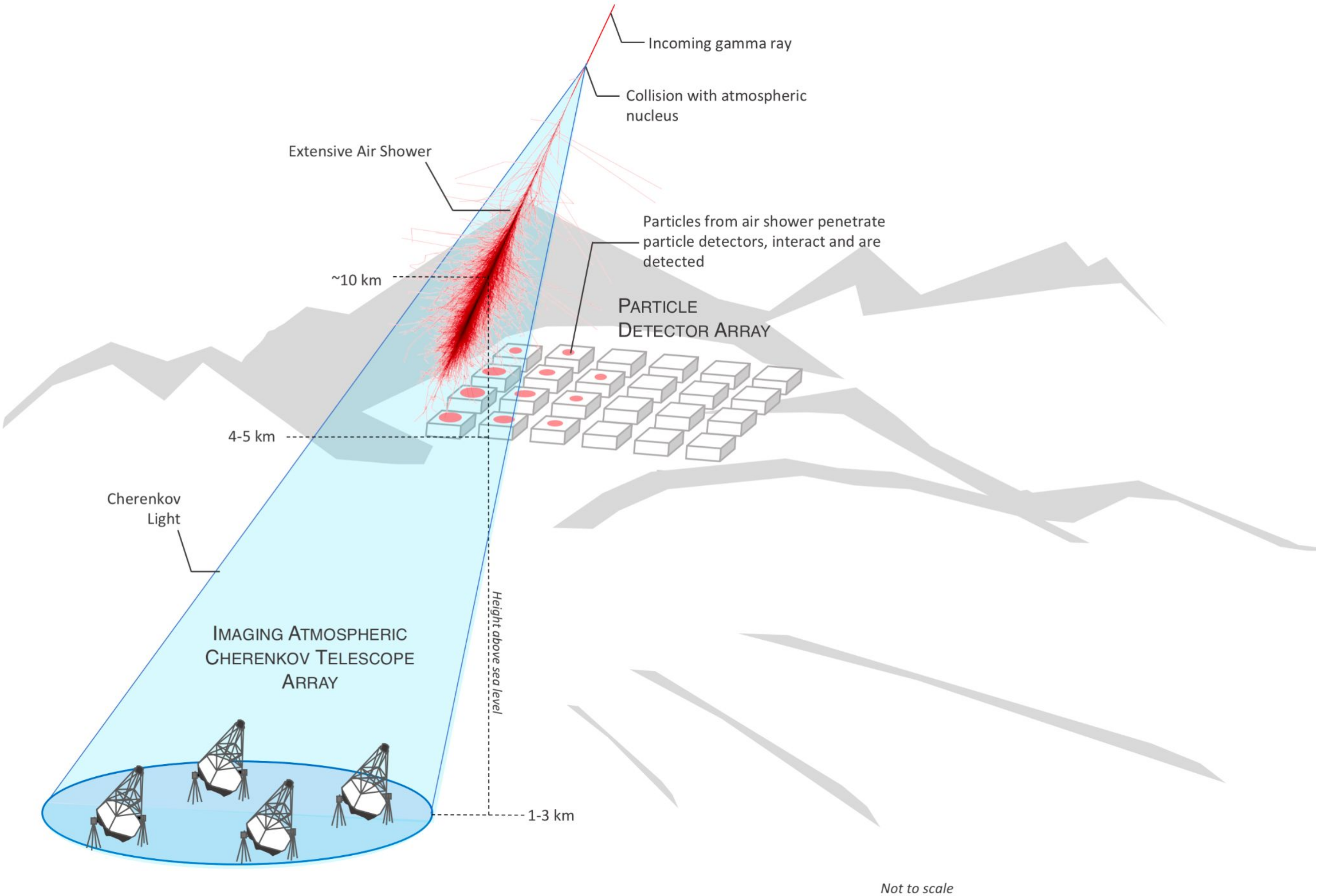
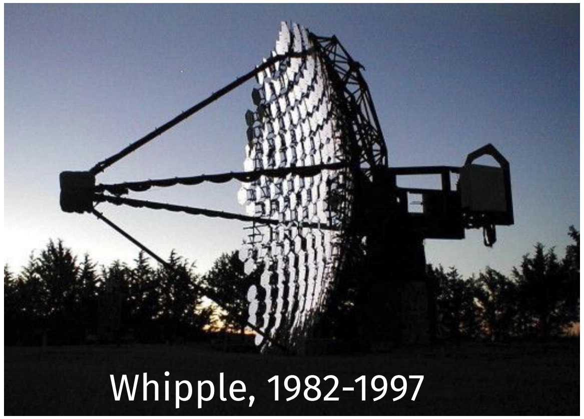
Ground-based gamma-ray detection



Credits: Richard White, MPIK

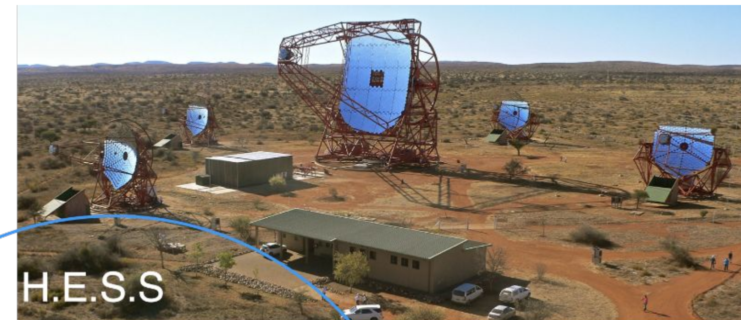
Gamma-ray astronomy



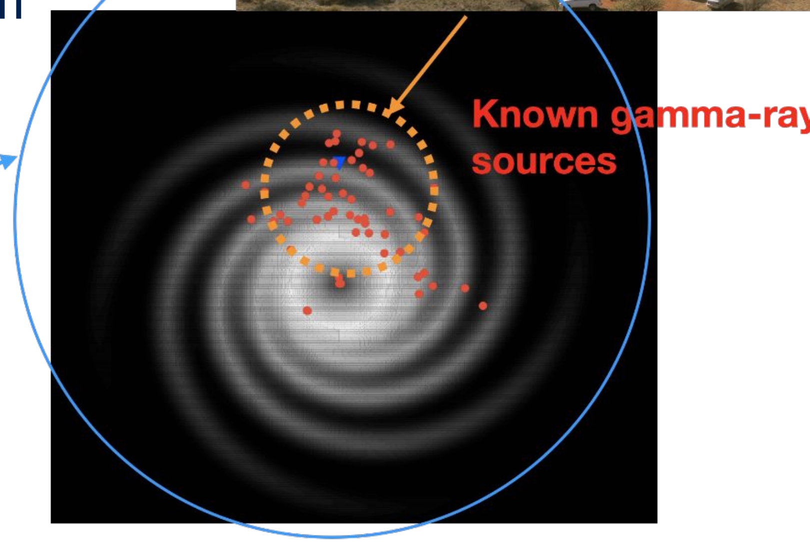
- Whipple was the first Imaging Atmospheric Cherenkov Telescope.
- 1989: Very first TeV observation of the Crab nebula by Whipple.
- Today: more than 250 TeV sources detected. Rapidly growing !

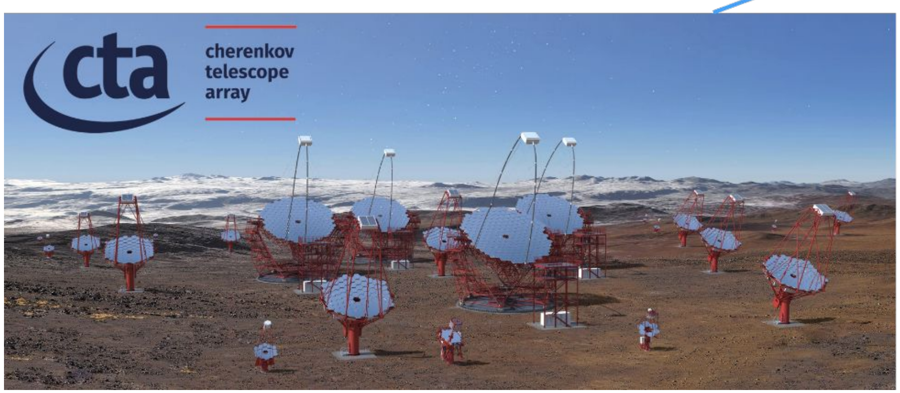
How can we make it even better ?

The Cherenkov Telescope Array (CTA) compared to current generation Imaging Air Cherenkov telescopes:



- 5-10 x more sensitive
- 5 x better angular resolution
- 2.5 x larger field of view





CTA technology

CTA will explore a broad range of energies (20 GeV -300 TeV) using three classes of telescopes

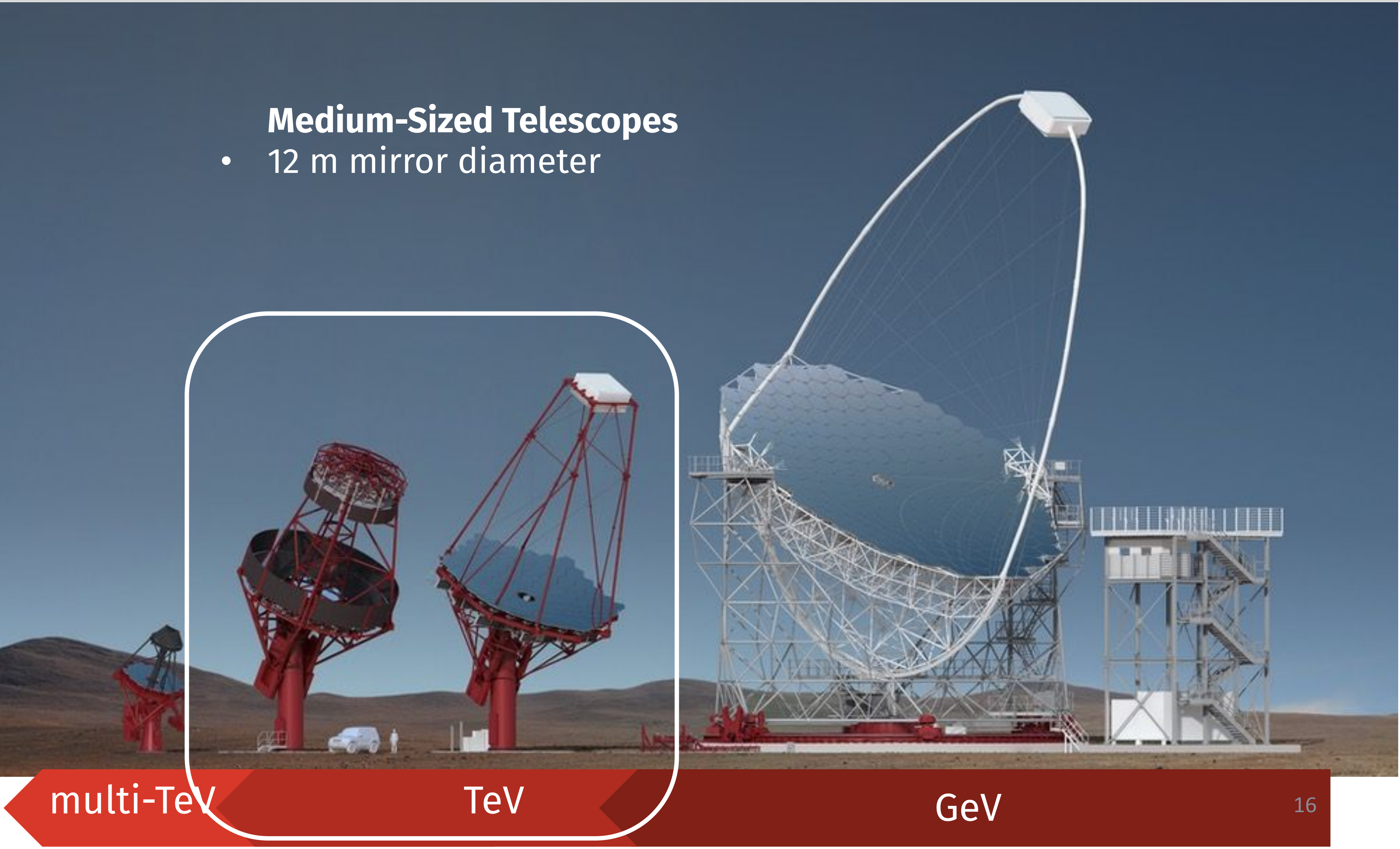
Small-Sized Telescopes

- 4 m mirror diameter

multi-TeV | TeV | GeV

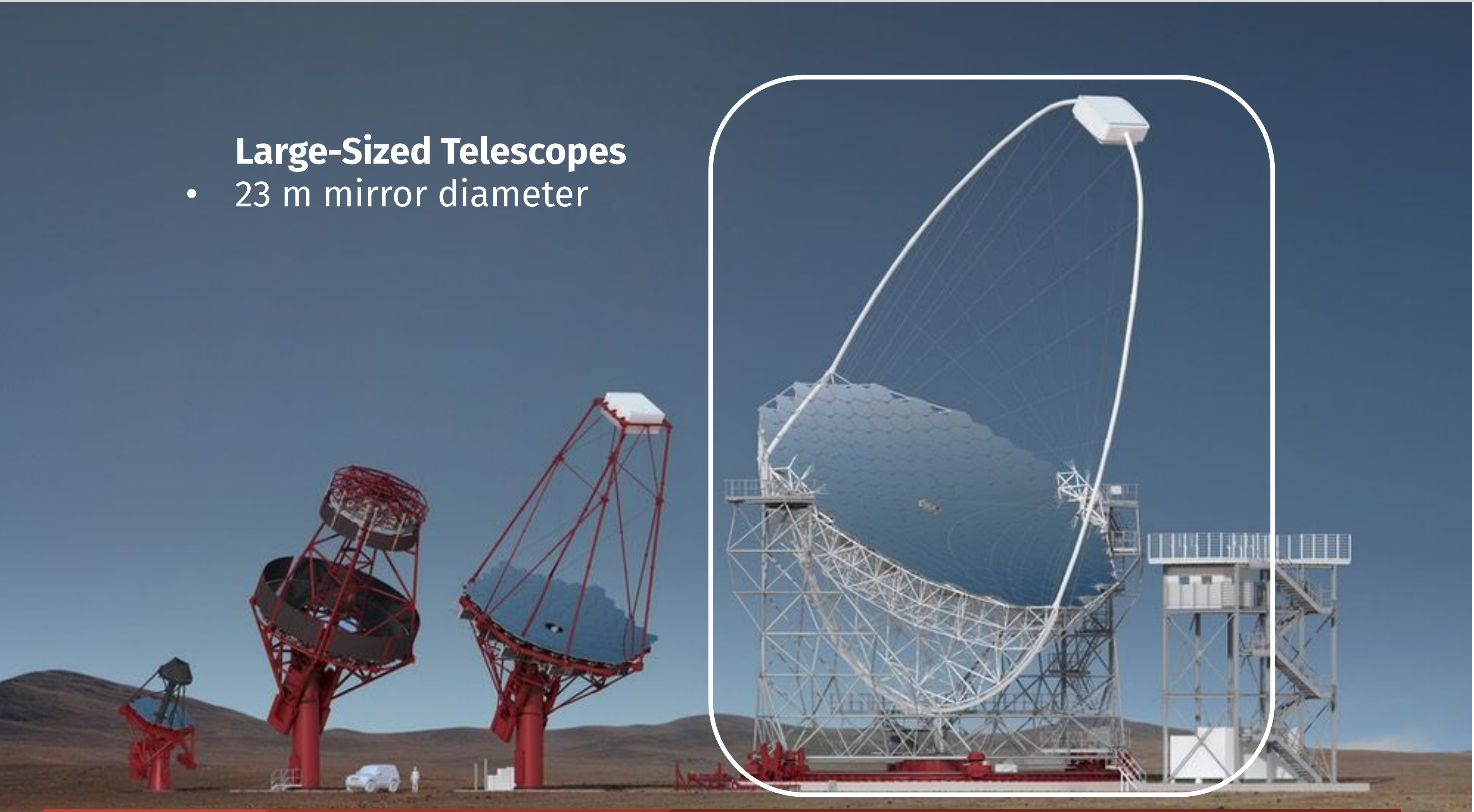
CTA technology

CTA will explore a broad range of energies (20 GeV -300 TeV) using three classes of telescopes



CTA technology

CTA will explore a broad range of energies (20 GeV -300 TeV) using three classes of telescopes



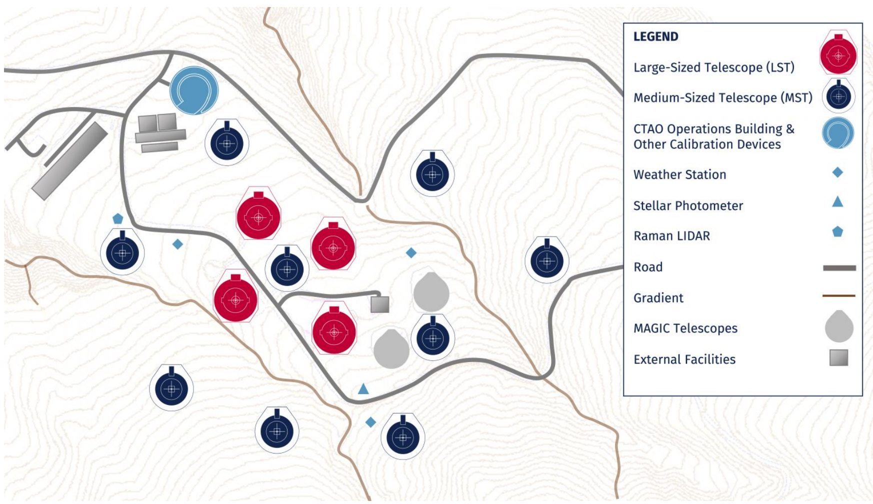
multi-TeV | TeV | GeV

The CTA array and operation sites

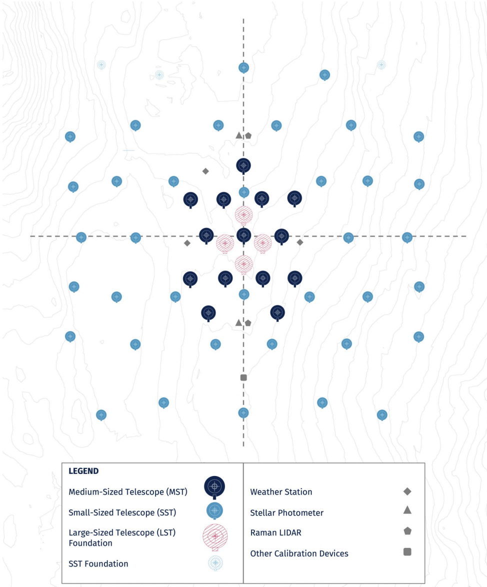
The project status

Construction phase (for 5 years after the ERIC* is in place):

- significant improvement wrt current running facilities
- significant increase of the discovery space and high-impact science



Northern Array: 4 LSTs and 9 MSTs



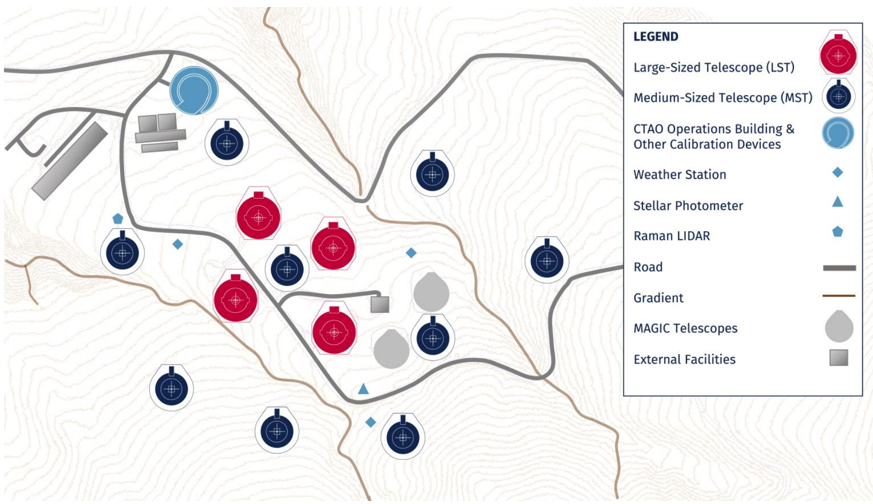
Southern Array: 14 MSTs and 37 SSTs+

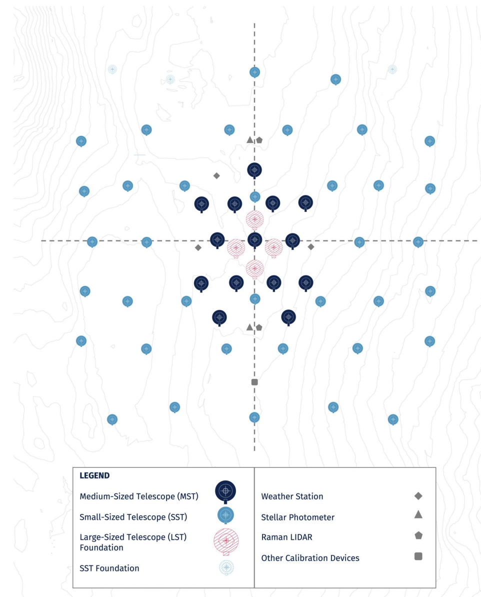
*ERIC: European Research Infrastructure Consortium

The project status

Construction phase (for 5 years after the ERIC is in place):

- significant improvement wrt current running facilities
- significant increase of the discovery space and high-impact science

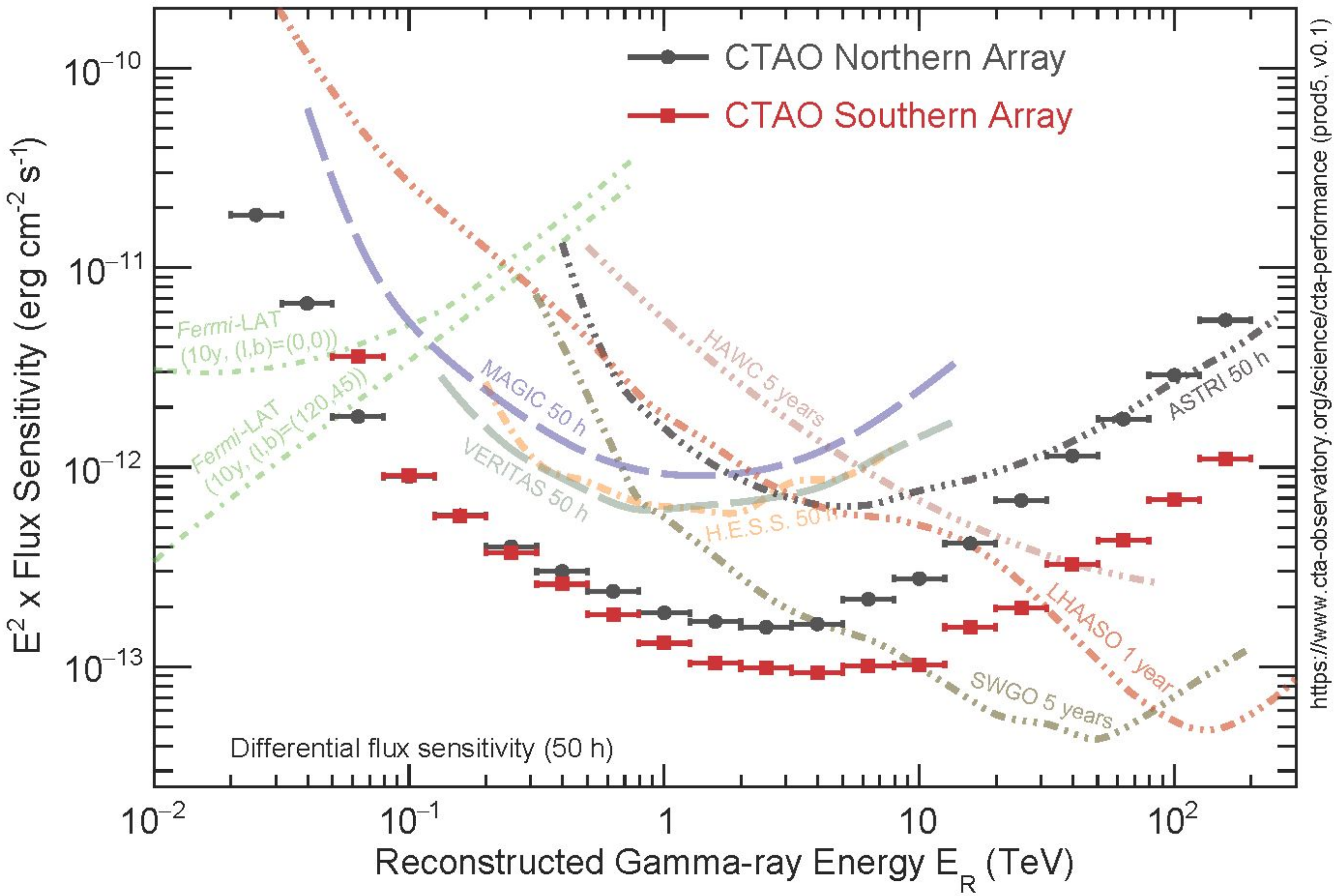




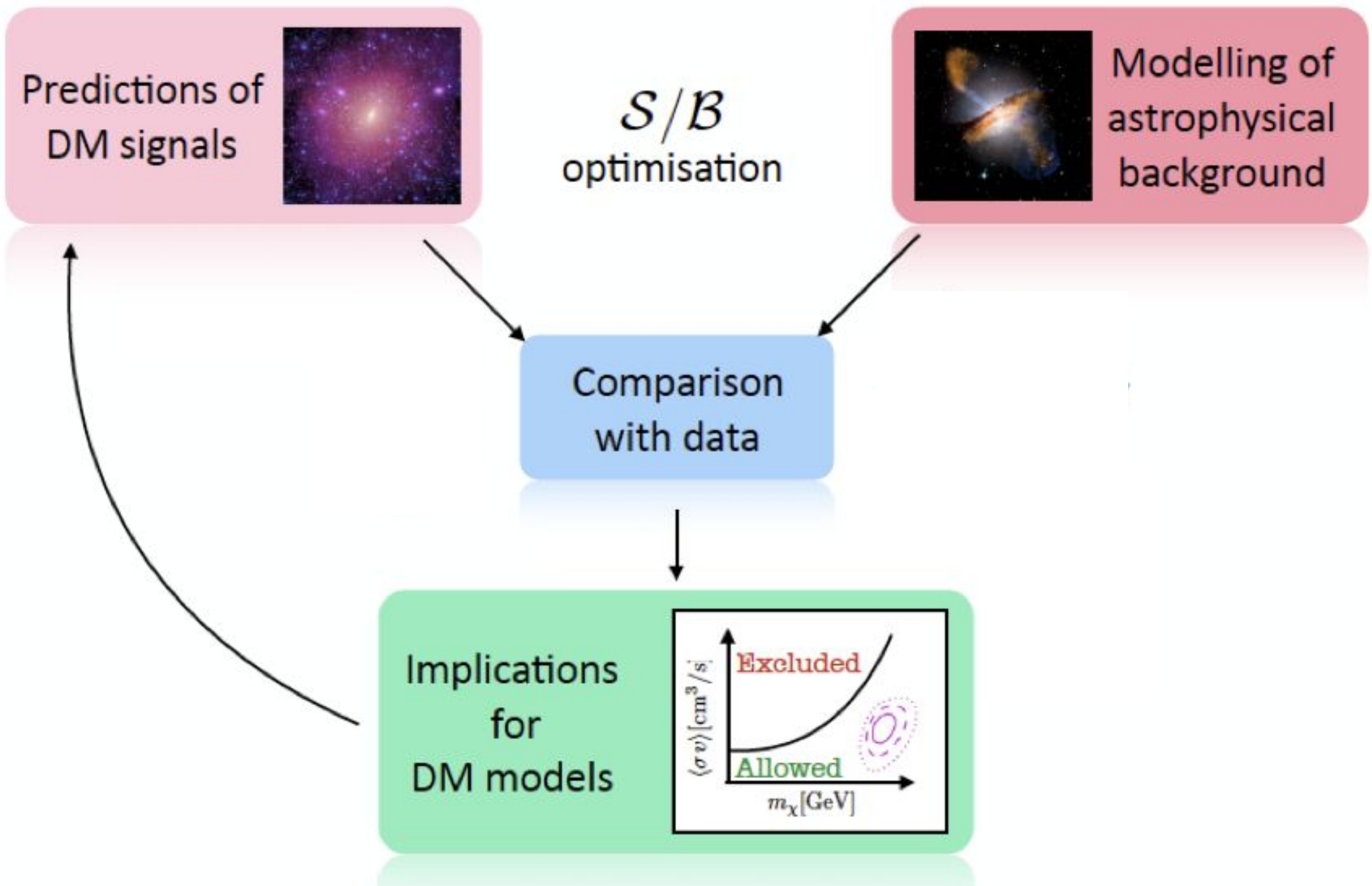
Operations and enhancement phase:

- operations of the observatory and construction towards the full scope configuration

Gamma-ray flux sensitivity



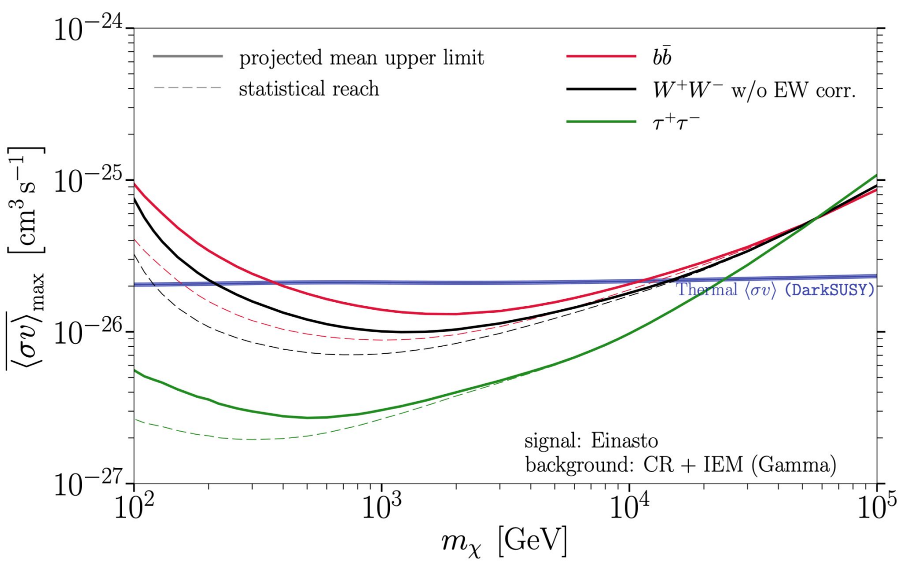
DM searches with CTA: Analysis strategy

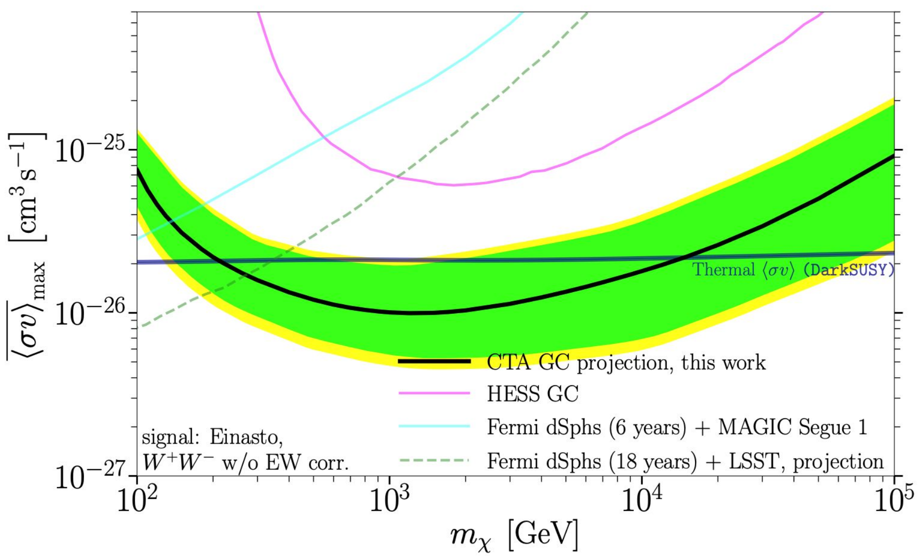


Slide F. Calore

DM searches in the Galactic Centre

- Distance: 8.5 kpc
- DM content: $\log_{10} J$ [$\mathrm{GeV^2 cm^{-5}}$]=22.85
- Observation time: 525 h
- Astrophysical gamma-ray sources:
  - Fermi bubbles
  - diffuse emission (CR interactions)
  - point-like sources (unresolved?)



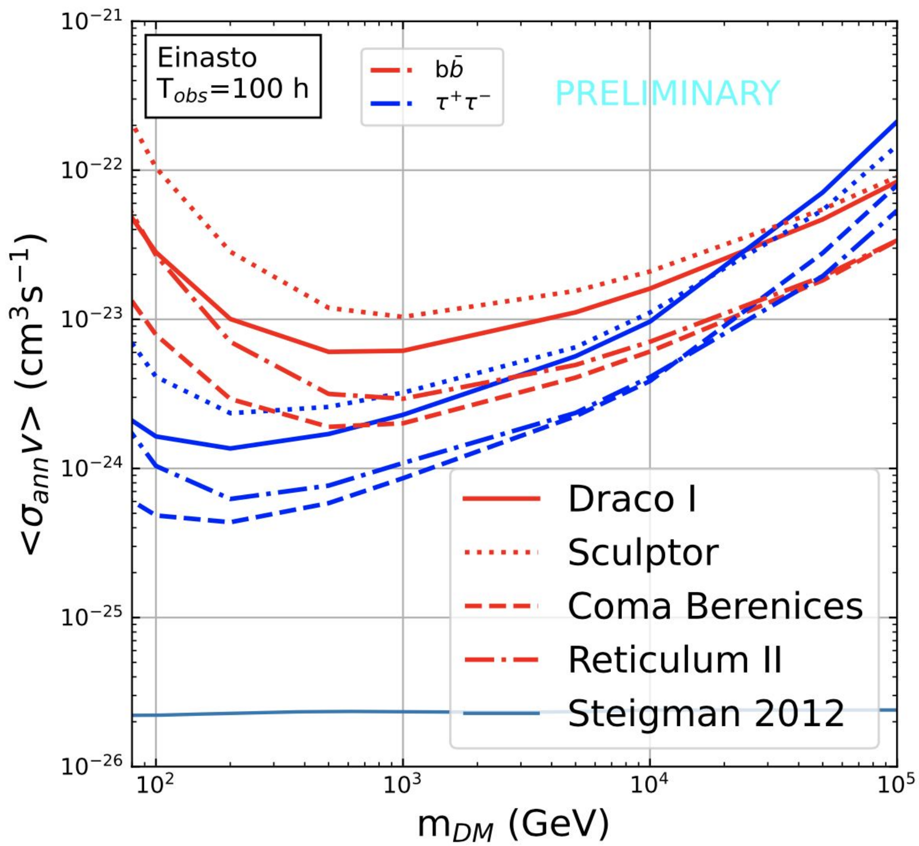


The CTA Consortium, JCAP 01 (2021) 057

Dwarf Spheroidal Galaxies

- 3 best targets per site identified
- DM content: the most DM dominated objects in the universe
- Observation time: 100 hours/source
- Astrophysical gamma-ray sources:
  - almost none

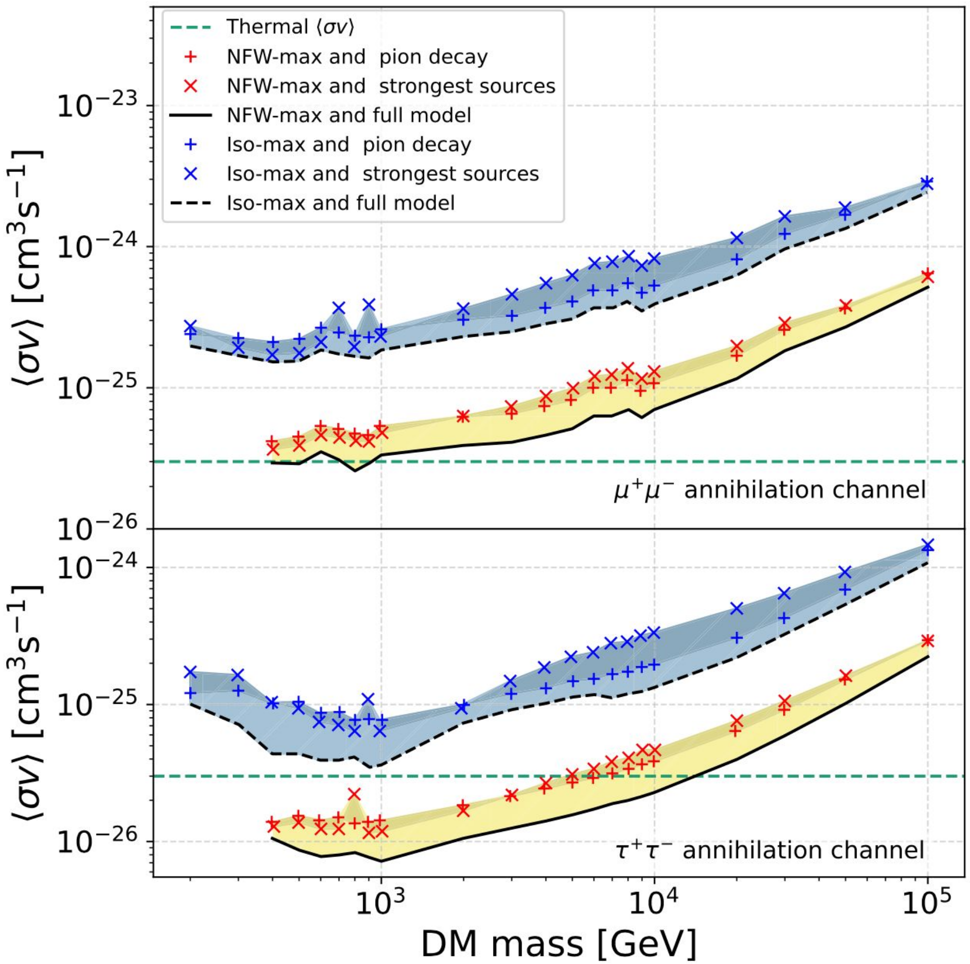
The CTA Consortium, in preparation



DM searches in the Large Magellanic Cloud

The CTA Consortium, Mon.Not.Roy.Astron.Soc. 523 (2023) 4, 5353-5387

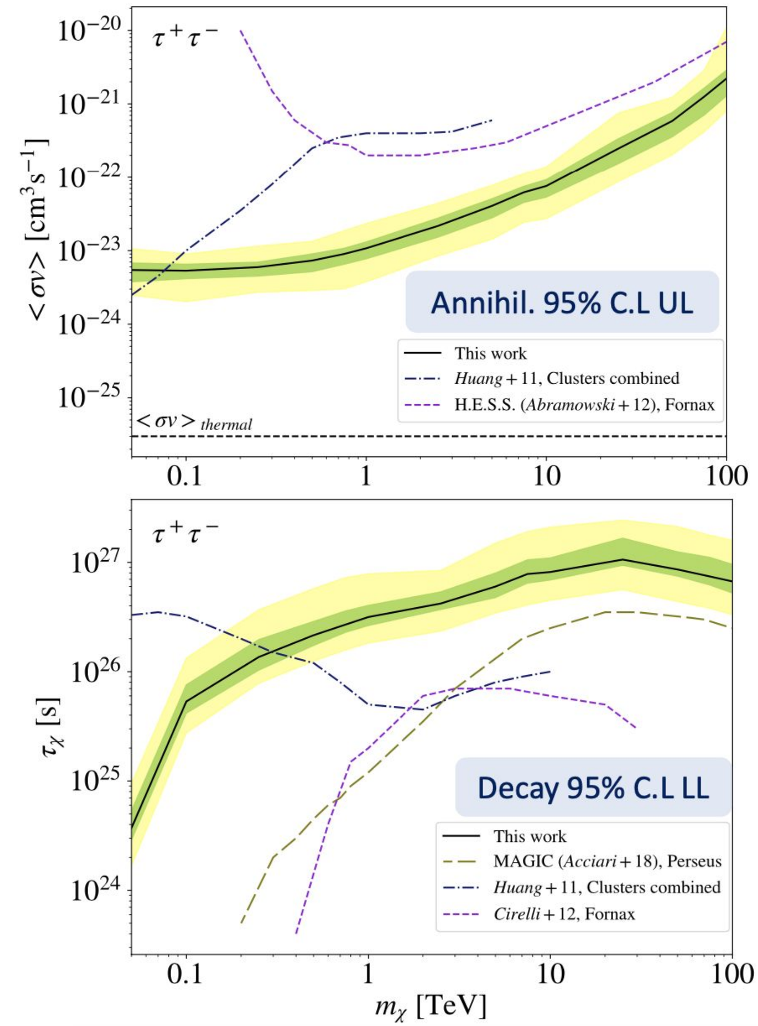
- Distance: 50.1 kpc
- DM content: $\log_{10}J$ [$GeV^2 cm^{-5}$]=21.14
- Observation time: 340 h
- Astrophysical gamma-ray sources:
    - 4 known sources: SNR, PWN
    - diffuse emission (CR interactions)



Perseus Cluster

- Distance: 75 Mpc
- DM content: $\log_{10}$J [GeV^{2}cm^{-5}]=18.43, $\log_{10}$D [GeV cm^{-2}]=19.20
- Observation time: 300 h
- Astrophysical gamma-ray sources:
  - Active Galactic Nuclei
  - diffuse emission (CR interactions)

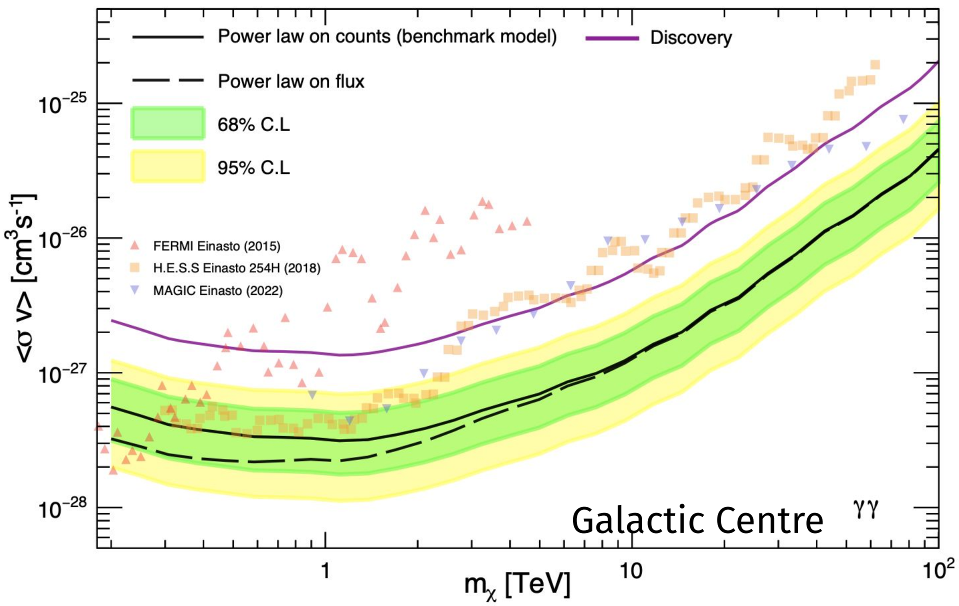
The CTA Consortium, in preparation

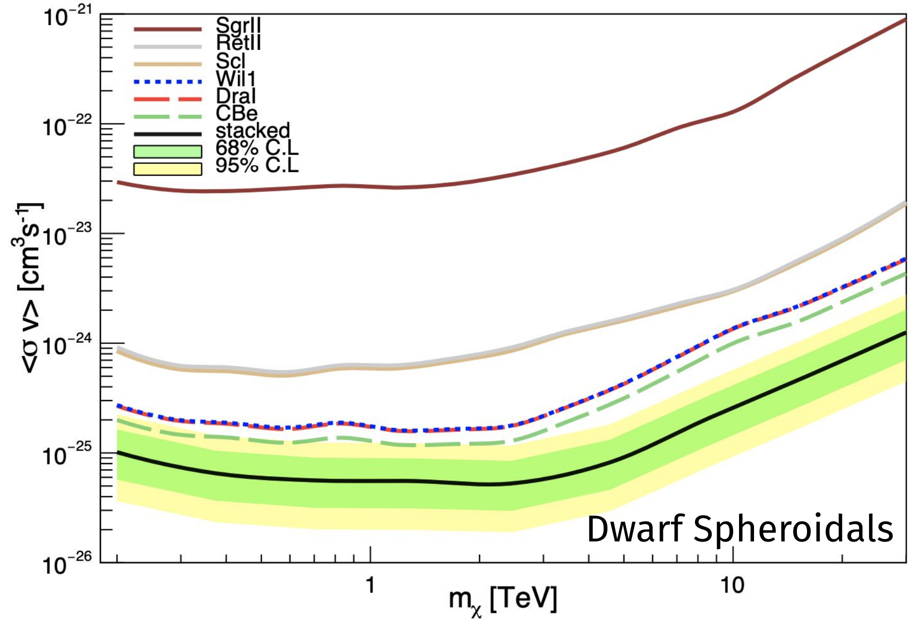


Dark matter line searches

Most sensitive TeV gamma-ray instrument to identity gamma-ray lines: due to its superior energy resolution compared to current generation IACTs.

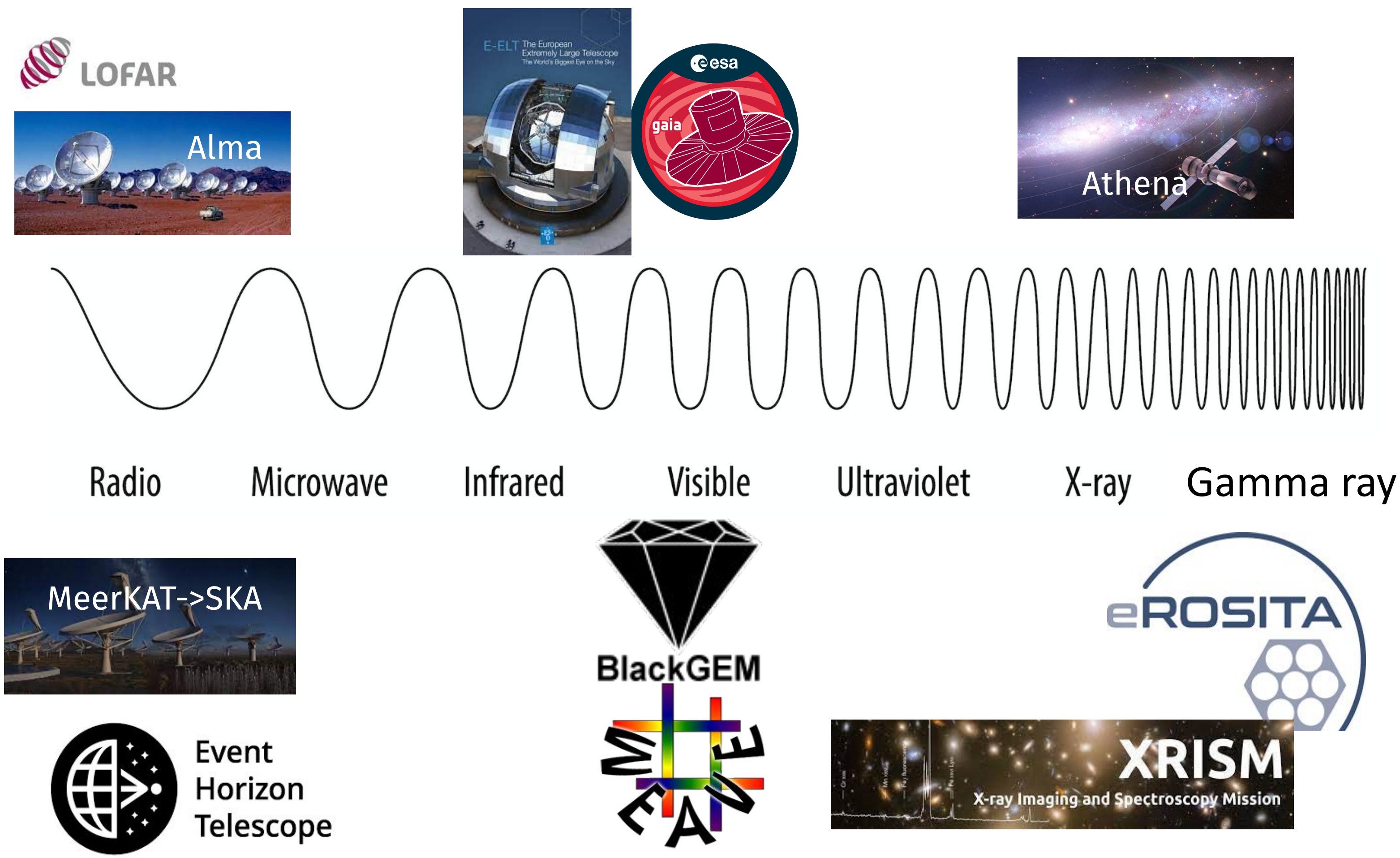
The CTA Consortium, in preparation





Synergies with the MWL community

NB: incomplete list



and multi-messenger observations too!

Conclusions

- The Cherenkov Telescope Array (CTA) is the future project for ground-based TeV gamma-ray astronomy with superior performance wrt current generation observatories.
- CTA has exceptional potential to explore thermally produced DM in the TeV range.
- Given its broad sky coverage CTA will search for DM at the galactic (GC) and extragalactic scale (Perseus cluster etc).
- The full exploitation of CTA science case, including DM searches, requires MWL/MM synergies.

Credit: Tiziana Abegg, CTAO.

backup

CTA performance