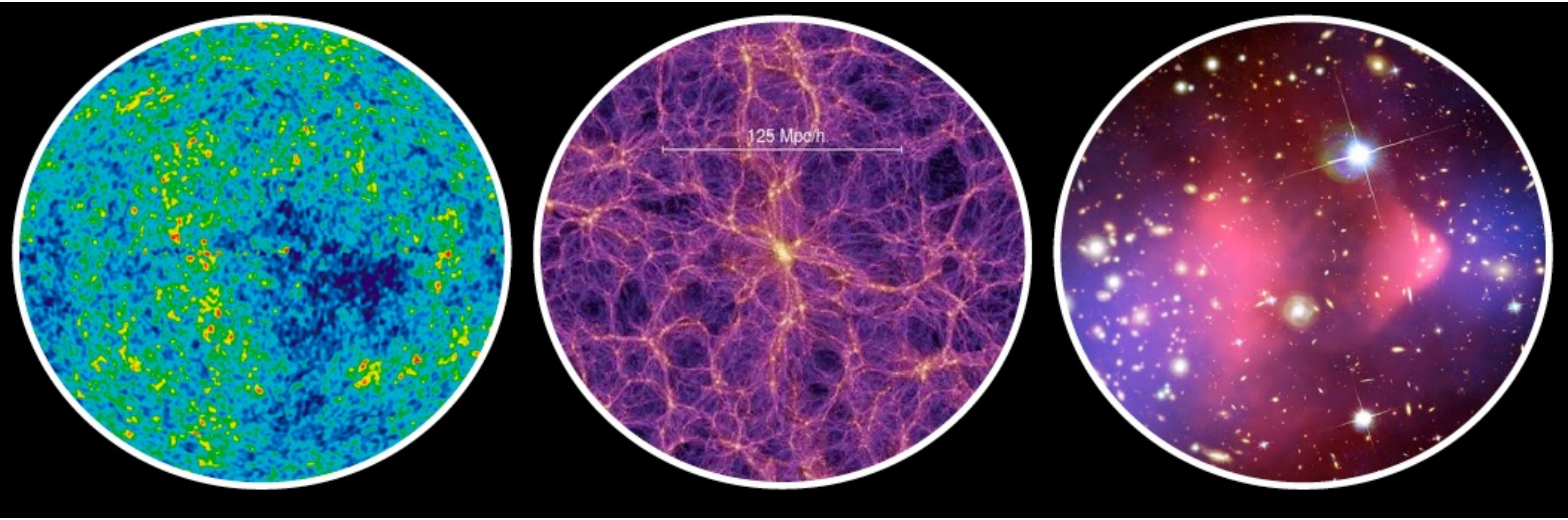
Gamma light from Dark Matter: status and near-future prospects

October 16-18. 2022, H.E.S.S. 20th Anniversary

Emmanuel Moulin,
CEA Saclay, Irfu, Paris-Saclay University

Dark matter : what do we know



- makes ~ 26% of total content
- 82% of total matter

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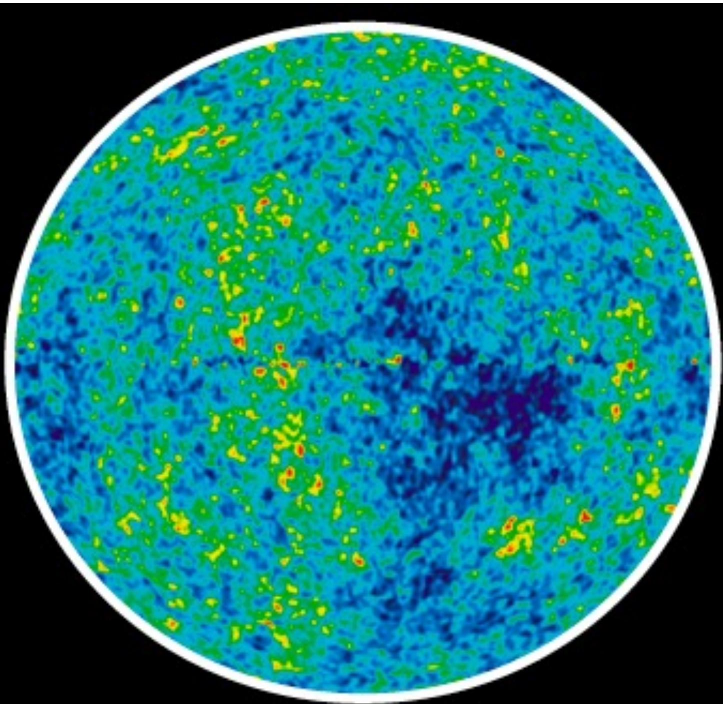
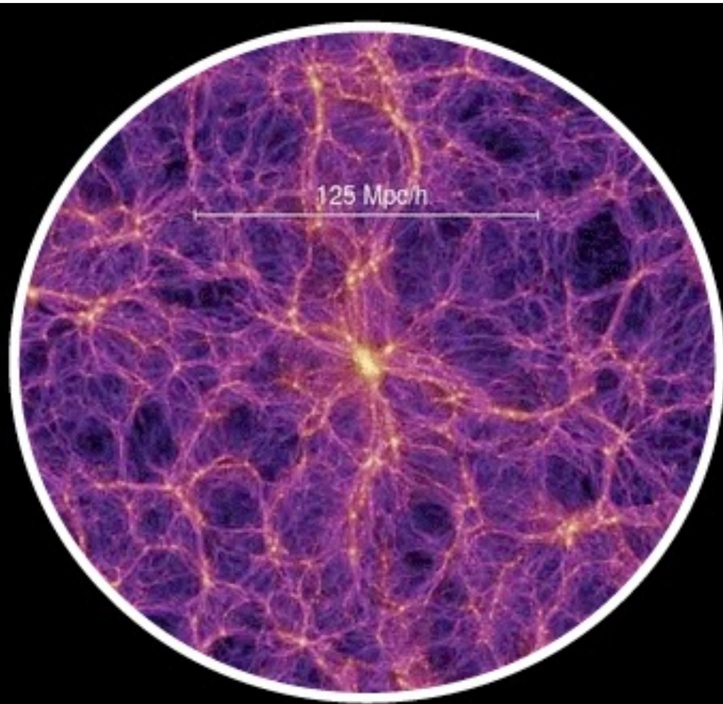


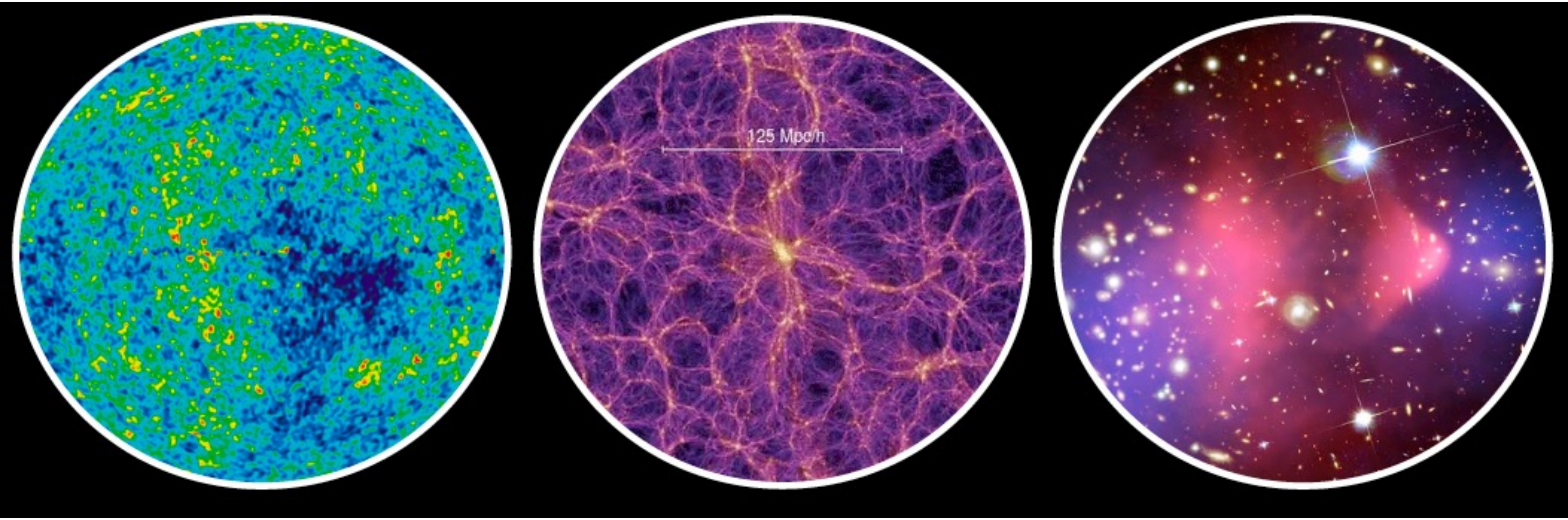


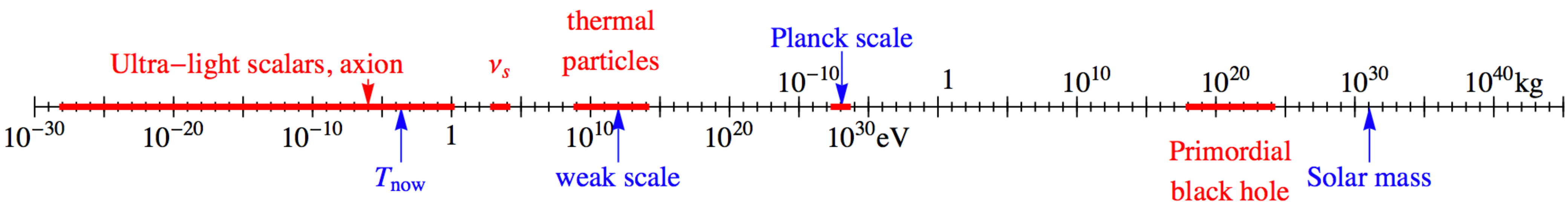
- makes ~ 26% of total content
- 82% of total matter

- neutral particle
- cold or not too warm
- very feebly interacting
- stable or very long lived
- possibly a relic from the early universe

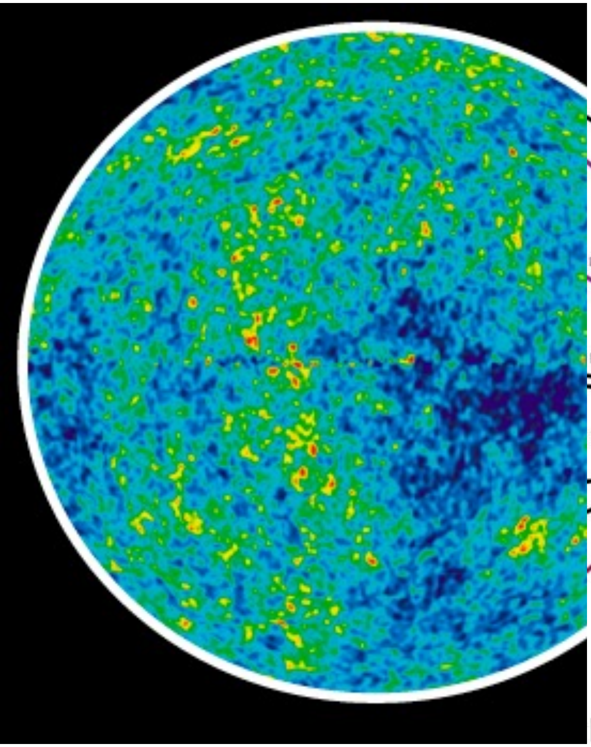
In the standard model of cosmology

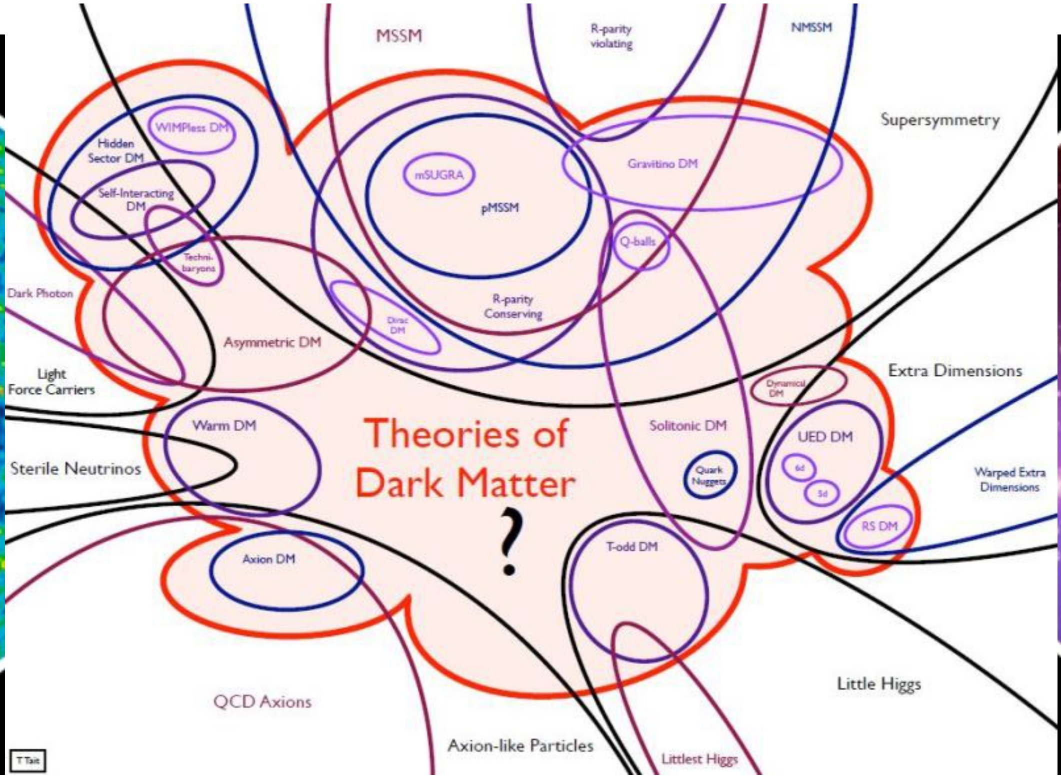
Dark matter : what we don't know

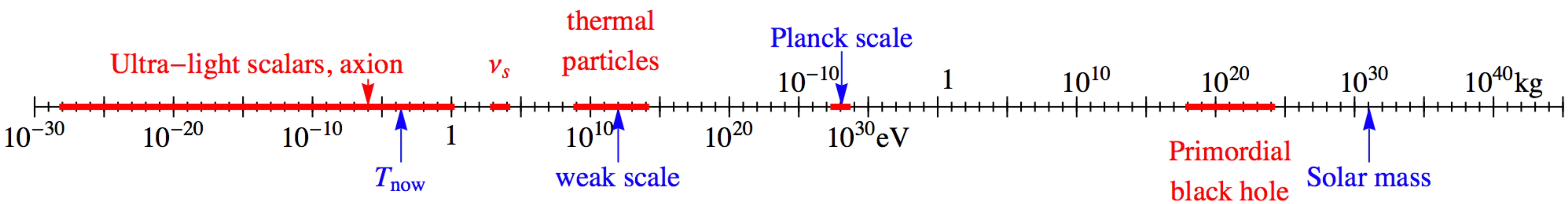




Dark matter : what we don't know







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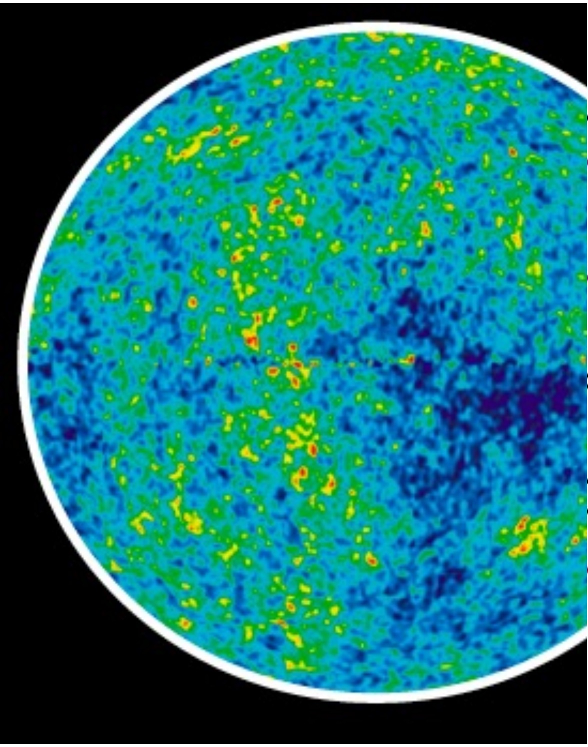
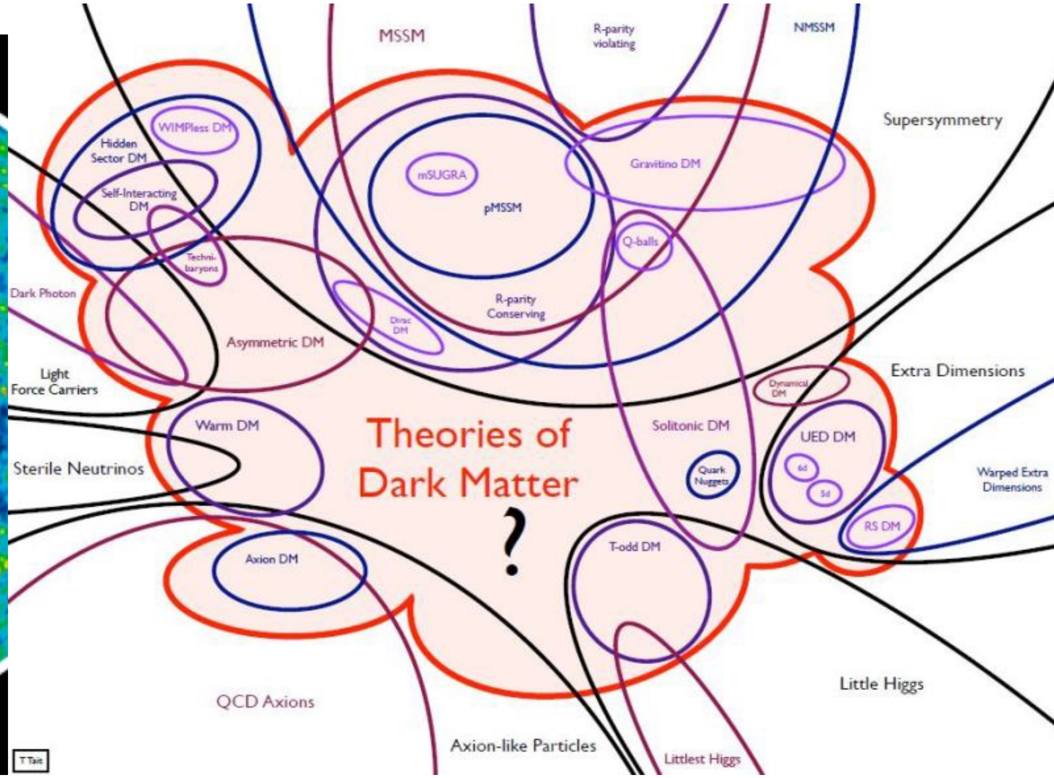
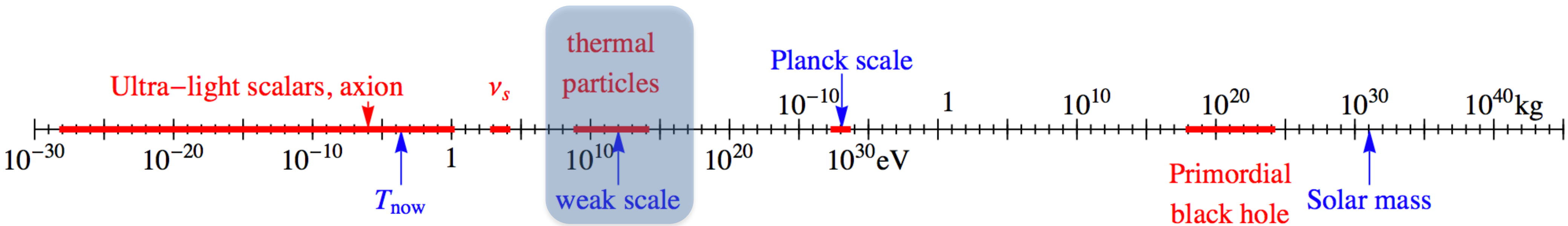




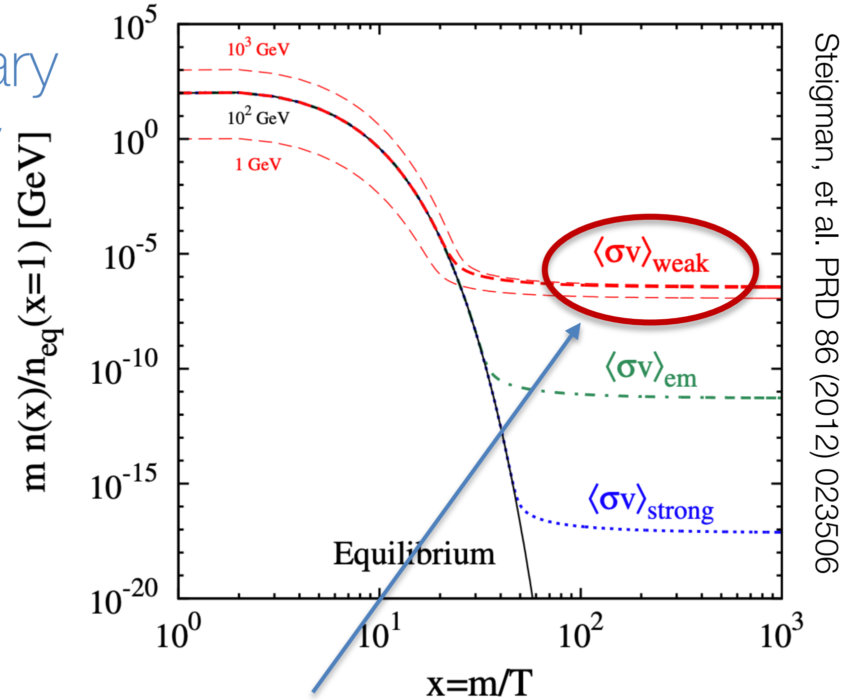


Dark Matter - thermal WIMPs

- The weak interaction mass scale and ordinary gauge couplings give right relic DM density

$$\langle \sigma v \rangle_{\mathrm{W}} \sim \frac{\alpha^2}{m^2_{\mathrm{WIMP}}} \sim 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

$$\Omega_{\mathrm{DM}} h^2 = \frac{3 \times 10^{-27}\ \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle}$$



Works in the ~10 MeV - 100 TeV mass range

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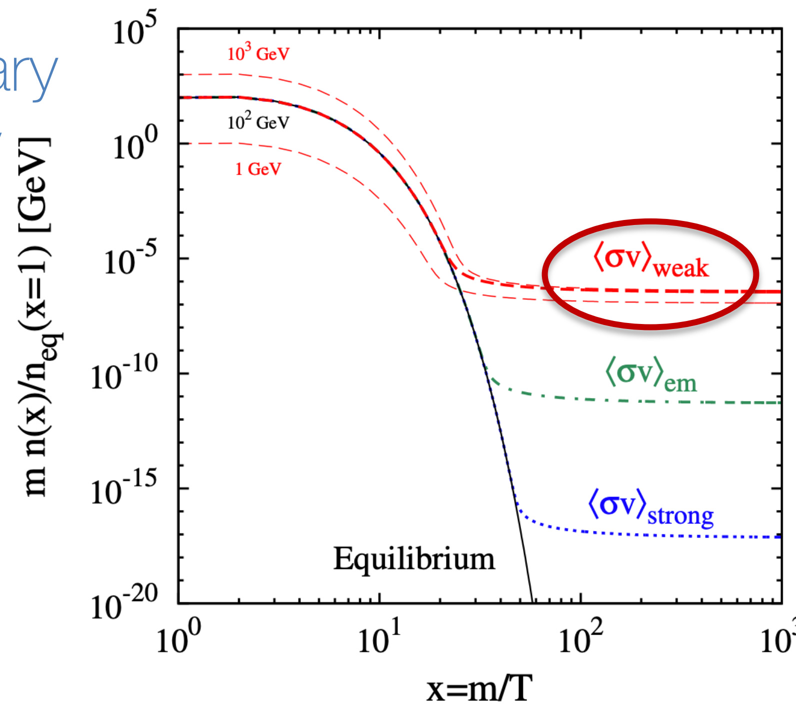
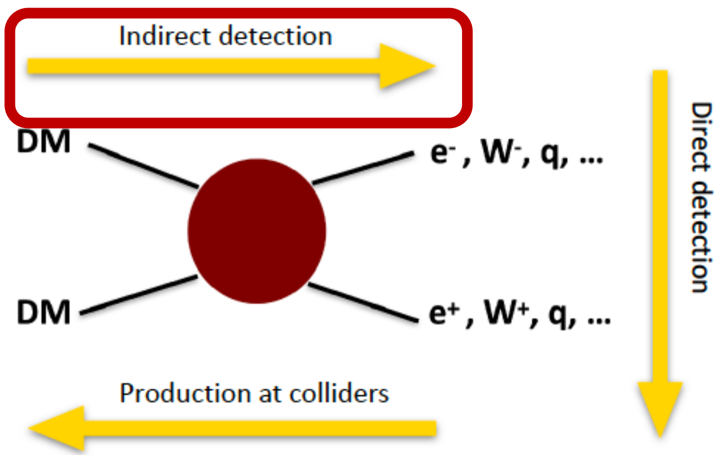
  - GeV-TeV mass scale makes them Cold DM



Steigman, et al. PRD 86 (2012) 023506

- Provides benchmark for indirect detection: thermally-produced WIMPs

Look for Standard Model particles - electrons/positrons, photons, neutrinos, protons/antiprotons - produced when DM particles collide or decay.



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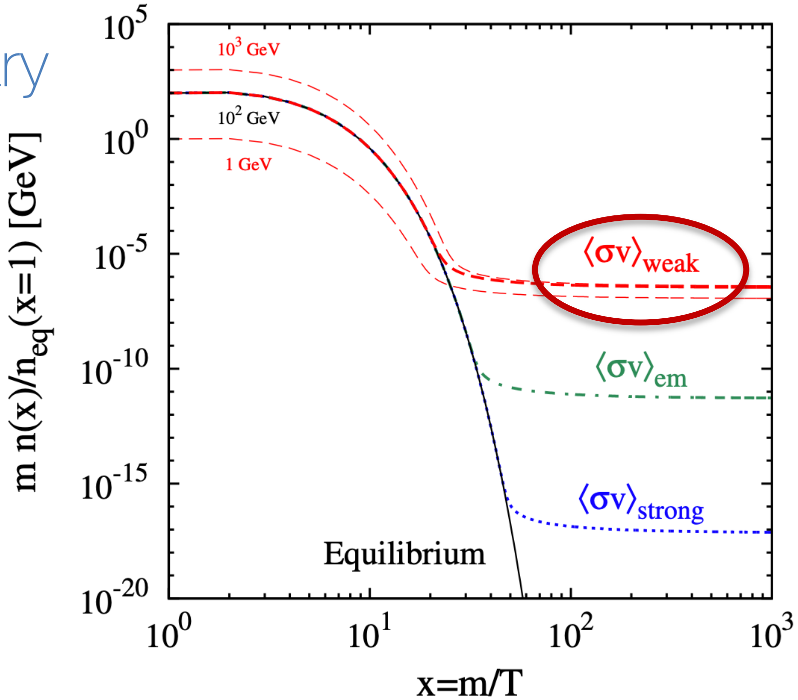

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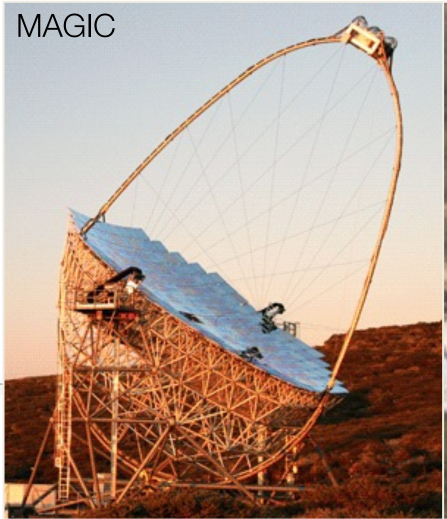

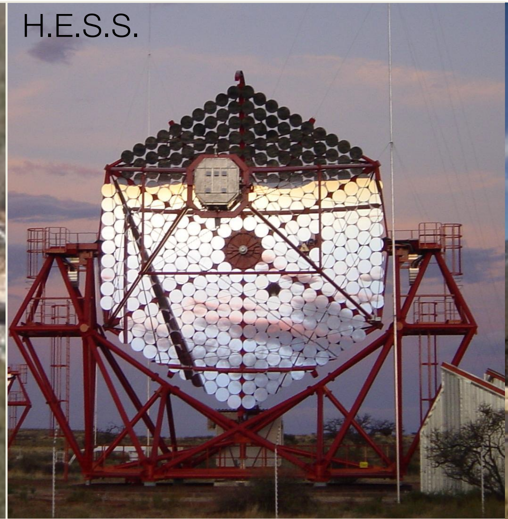

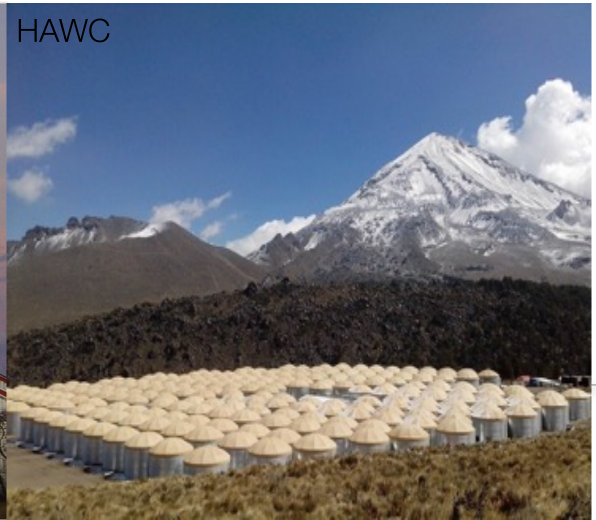

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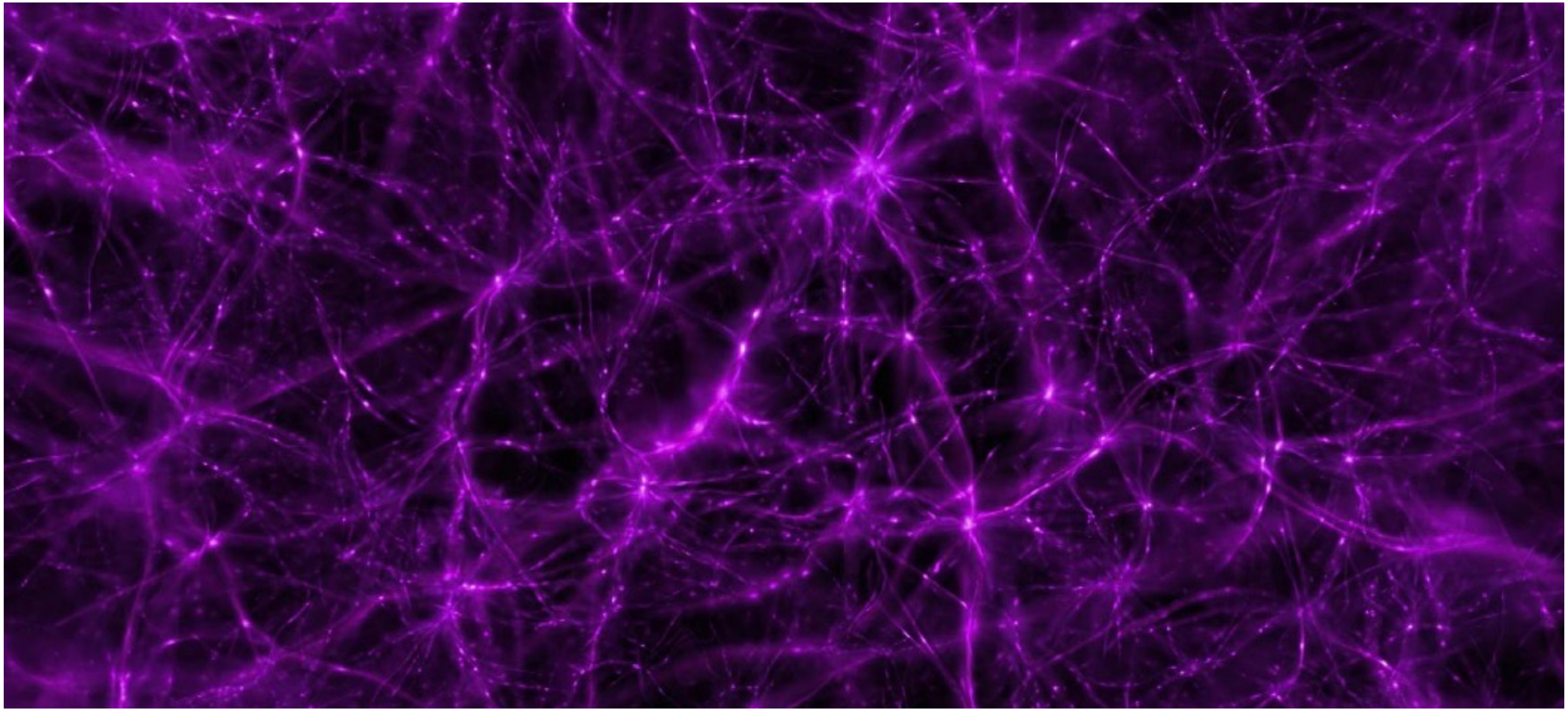

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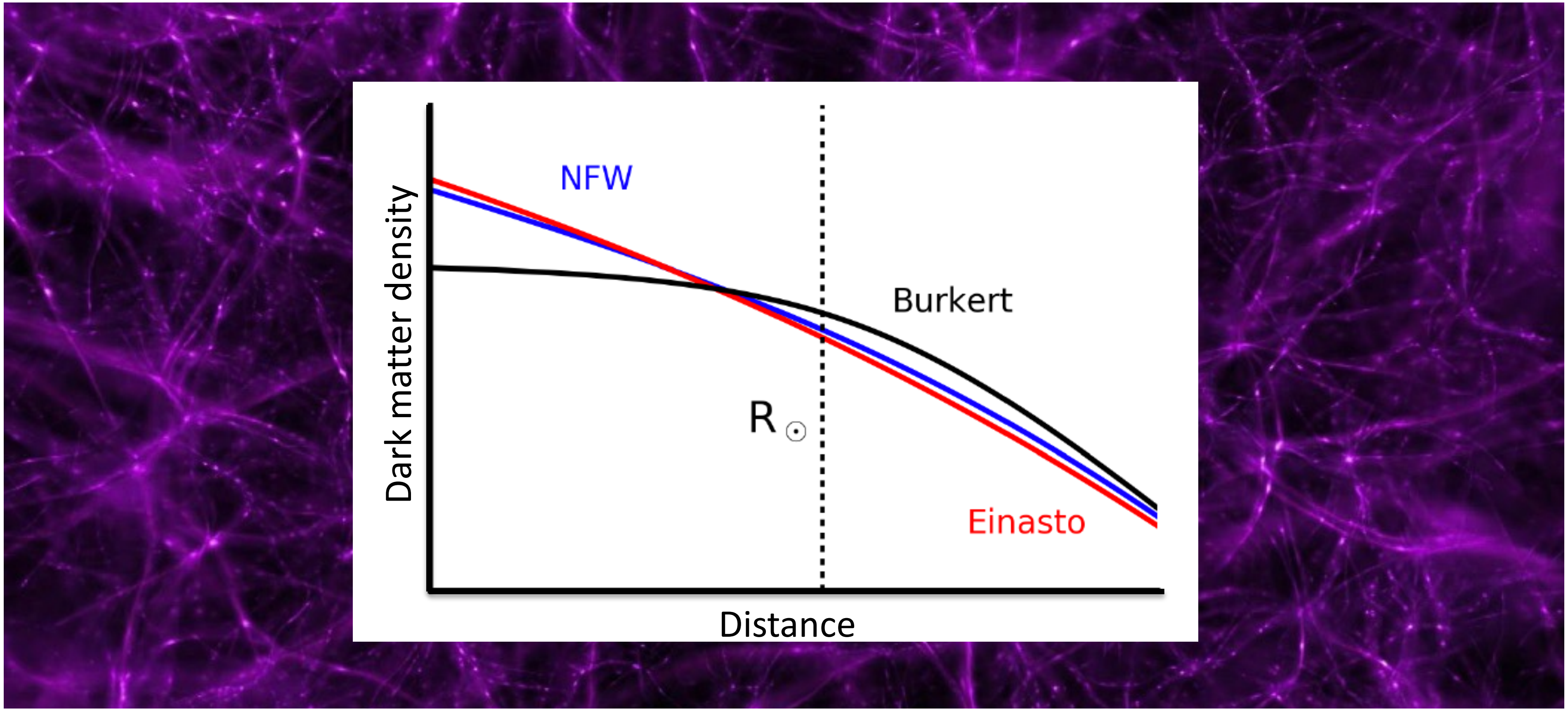

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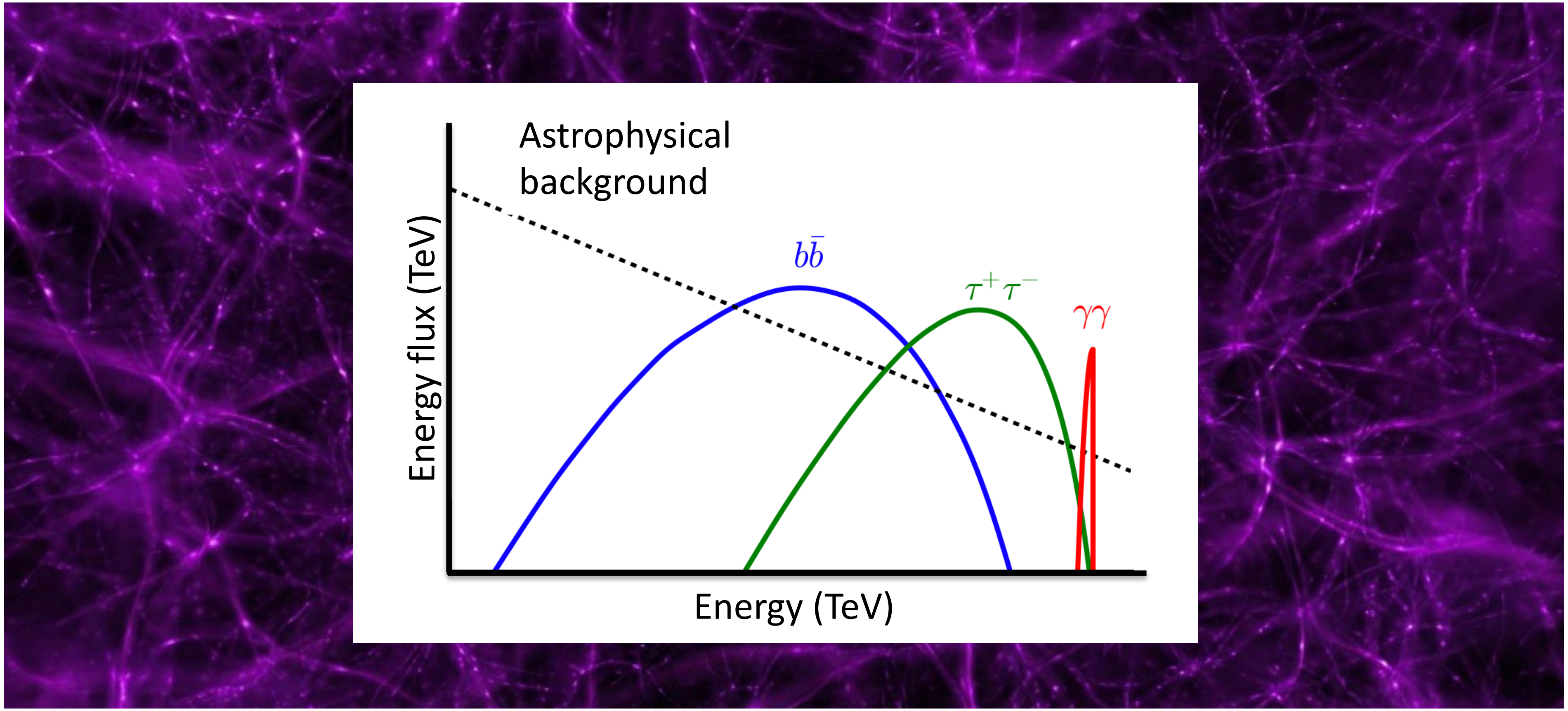
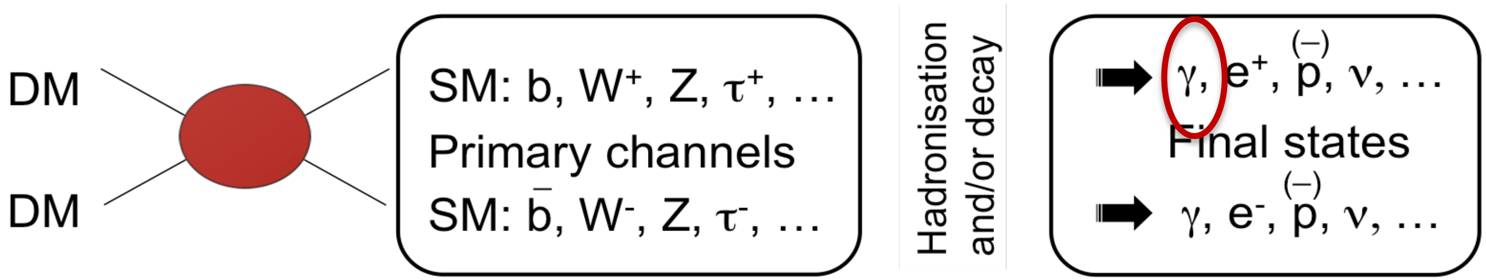


Why VHE gamma rays ?



$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \frac{1}{4\pi}\frac{\langle \sigma v\rangle}{2m^2_{DM}}\frac{dN_\gamma}{dE_\gamma} \times \int_{\Delta\Omega} d\Omega \int_{l.o.s} \rho^2(r[s])ds$$

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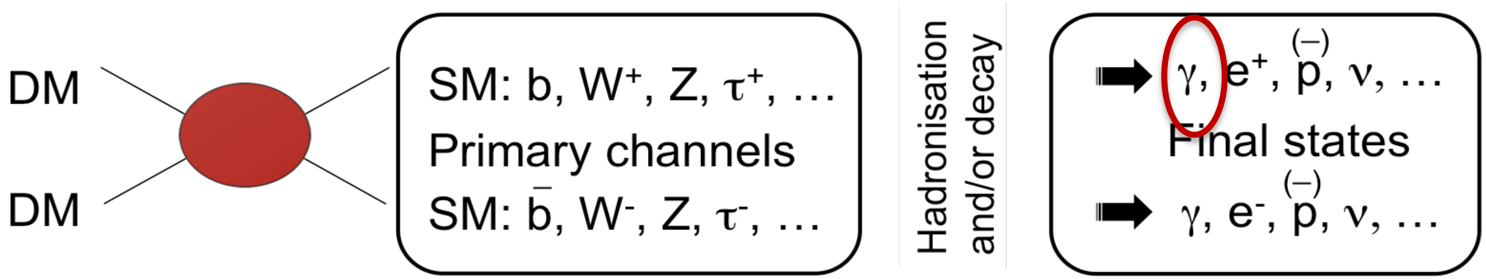

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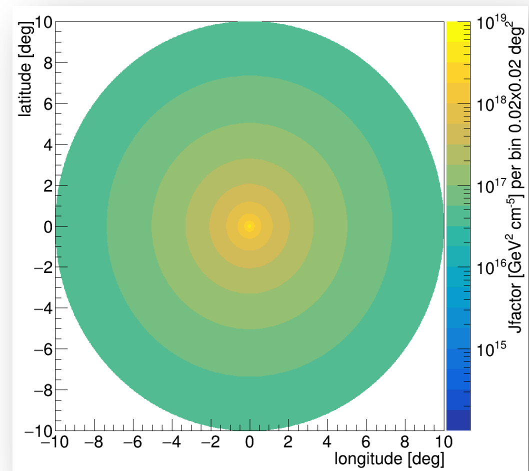
« J-factor »

- VHE (E> 100 GeV) gamma rays do not suffer from propagation effects at Galactic scale : they point back to the source
  - Can reveal the abundance and distribution of DM



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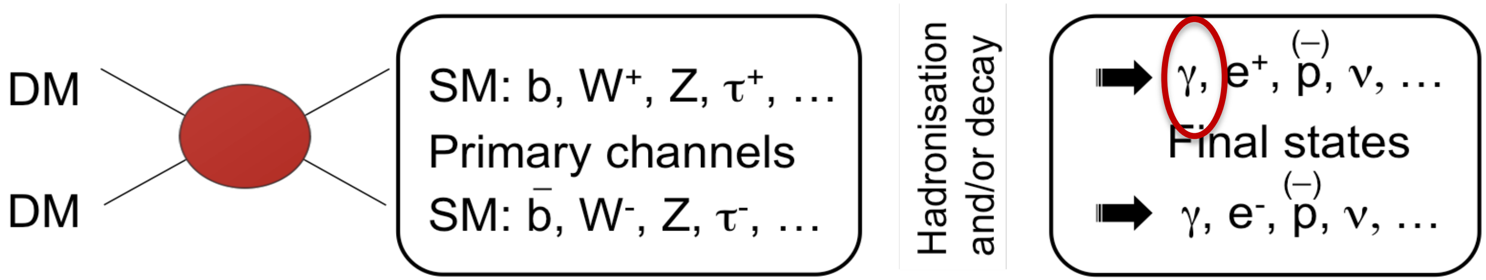

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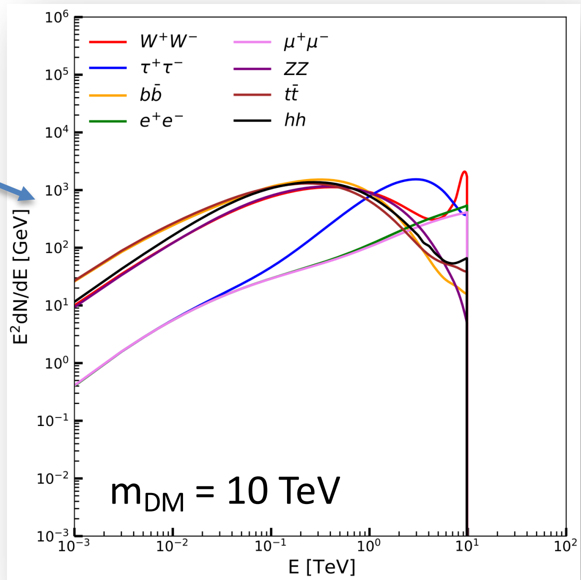
- Characteristic spectral features may be present in the spectrum at these energies
  - Good discrimination against background



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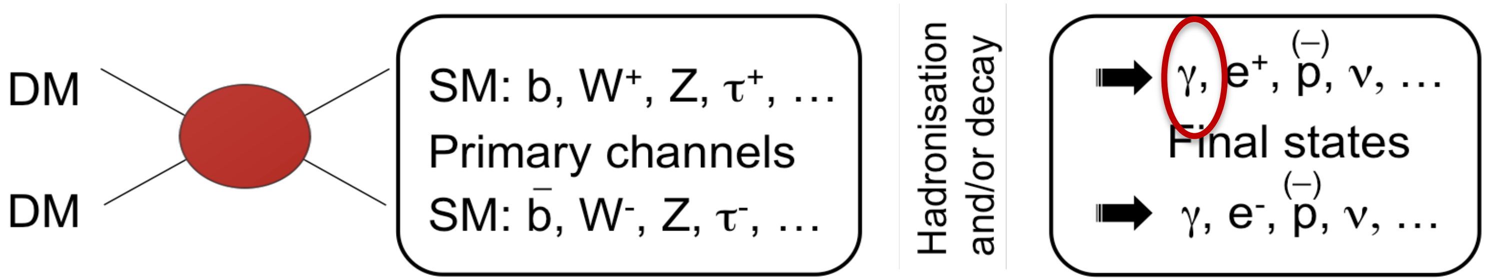

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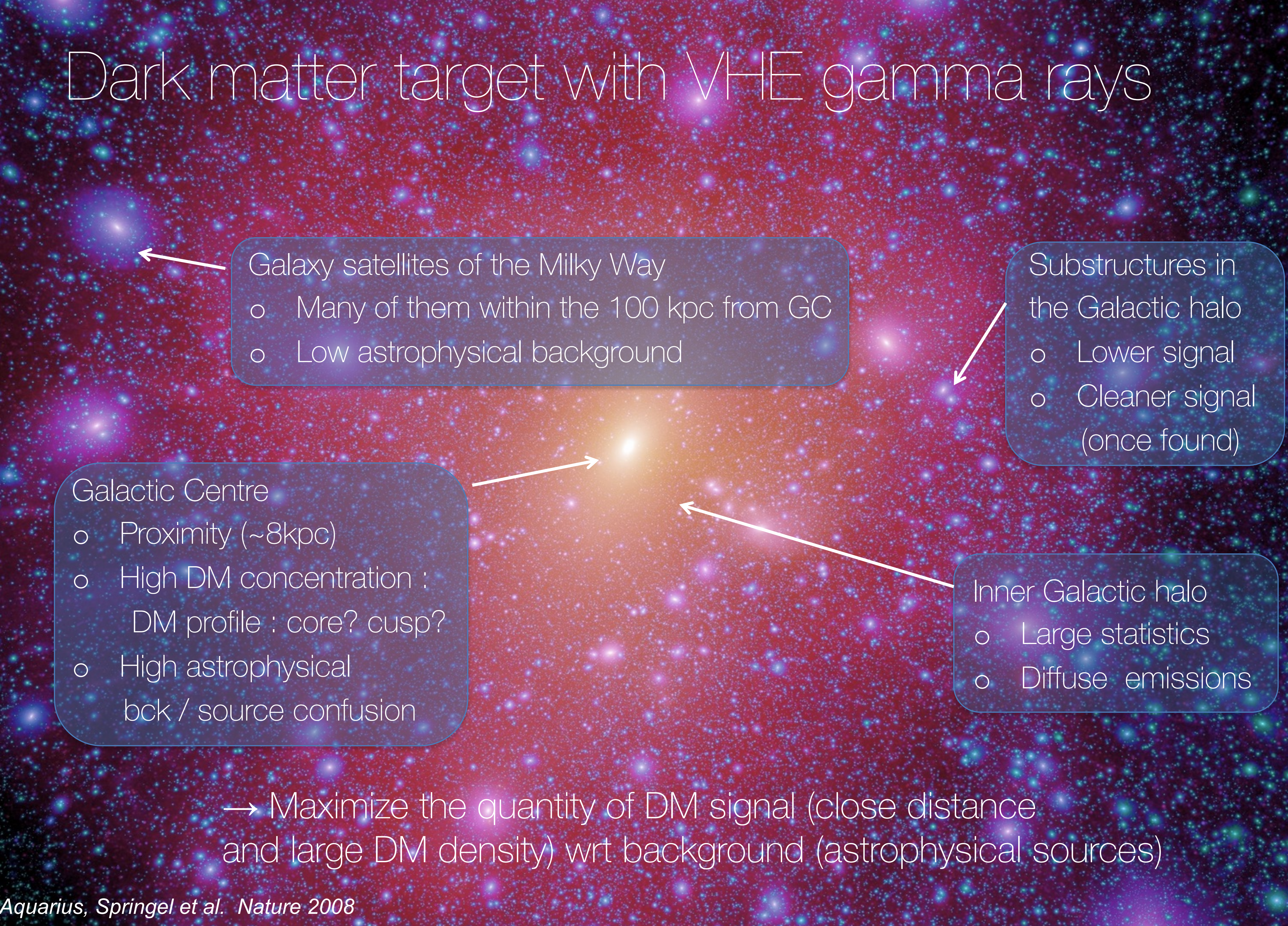
Identification of DM is possible

- the gamma-ray distribution in the sky can tell us the DM density distribution
- the gamma-ray spectrum can tells us the reaction process and DM mass


Dark matter target with VHE gamma rays
Galaxy satellites of the Milky Way
o Many of them within the 100 kpc from GC
o Low astrophysical background
Substructures in the Galactic halo
o Lower signal
o Cleaner signal (once found)
Galactic Centre
o Proximity (~8kpc)
o High DM concentration : DM profile : core? cusp?
o High astrophysical bck / source confusion
Inner Galactic halo
o Large statistics
o Diffuse emissions
→ Maximize the quantity of DM signal (close distance and large DM density) wrt background (astrophysical sources)
Aquarius, Springel et al. Nature 2008

Dark matter target with VHE gamma rays

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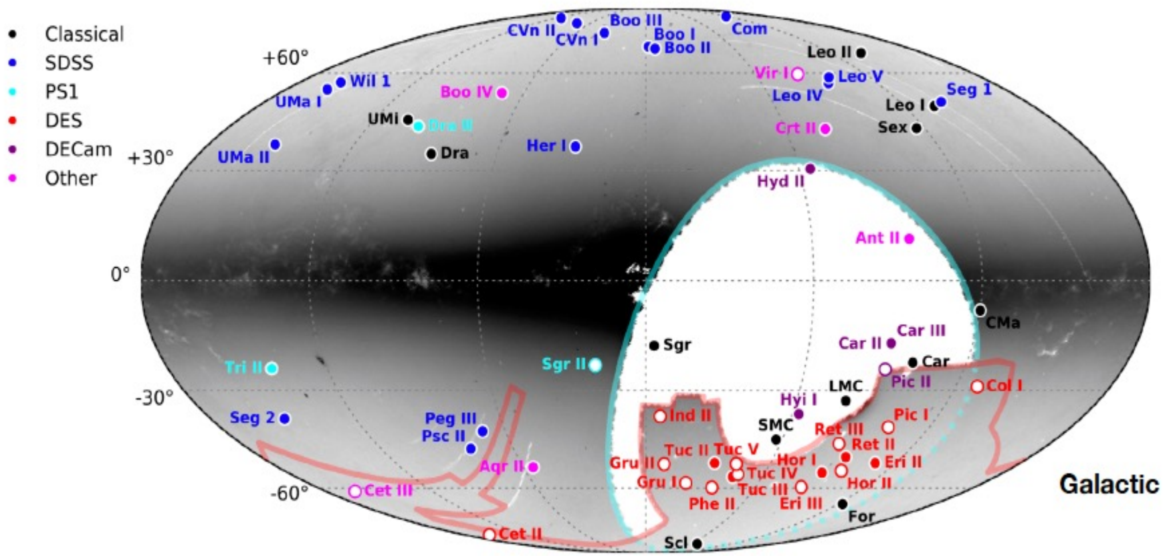
IACT observation strategy

- Deep observation of the central region of the Milky Way
- Observation of the most promising dwarf galaxies

Aquarius, Springel et al. Nature 2008

Nearby dwarf galaxy satellites of the MW

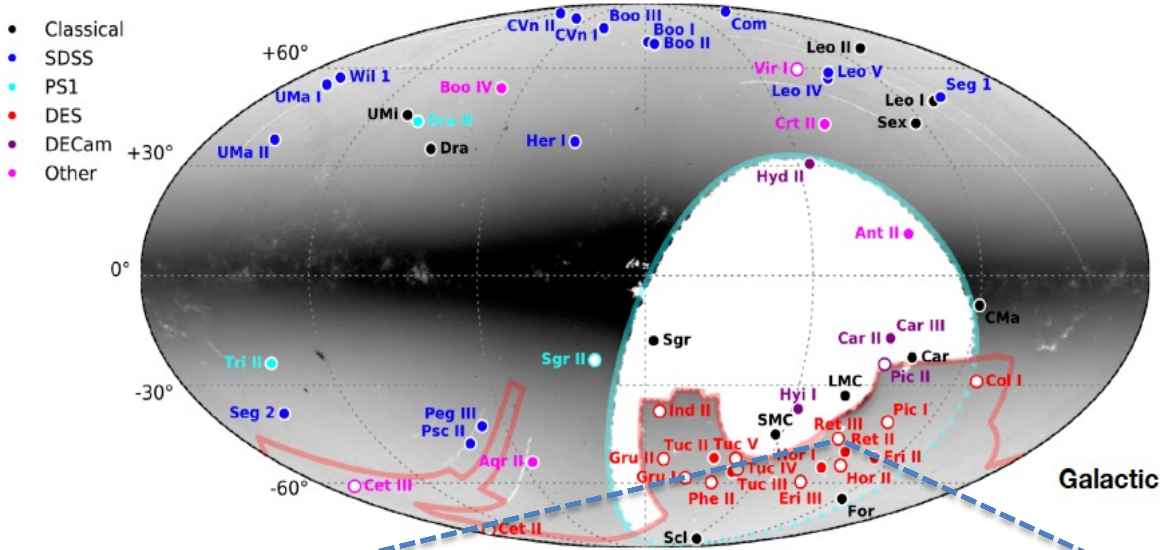


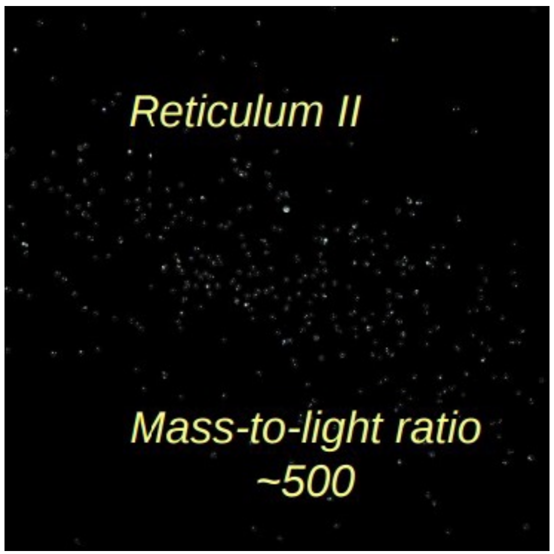
- No recent star formation
- Very low gas amount
- "Clean" target in VHE gamma rays

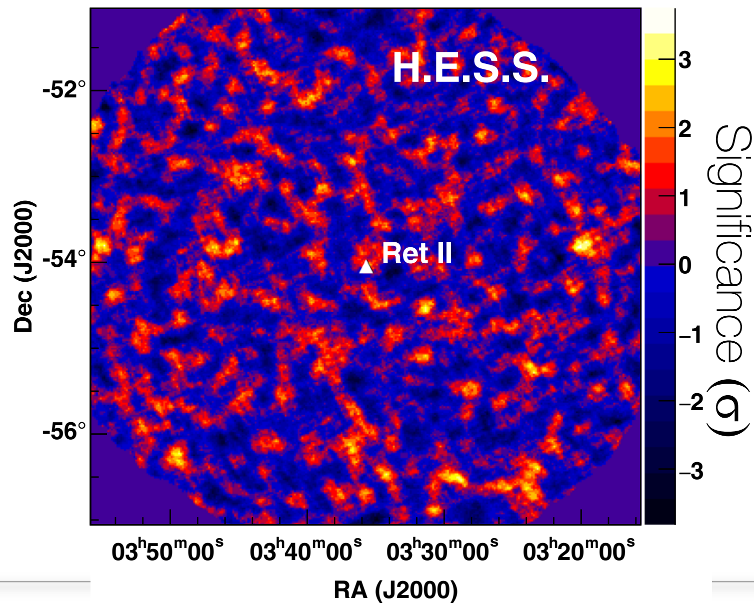
→ they could give unambiguous detection

- Sample of known Milky Way satellites has grown from ~25 to ~60 since 2015 with deep optical imaging surveys
- Current IACTs performed extensive observation program (>a few hundred hours) towards the most promising dSphs

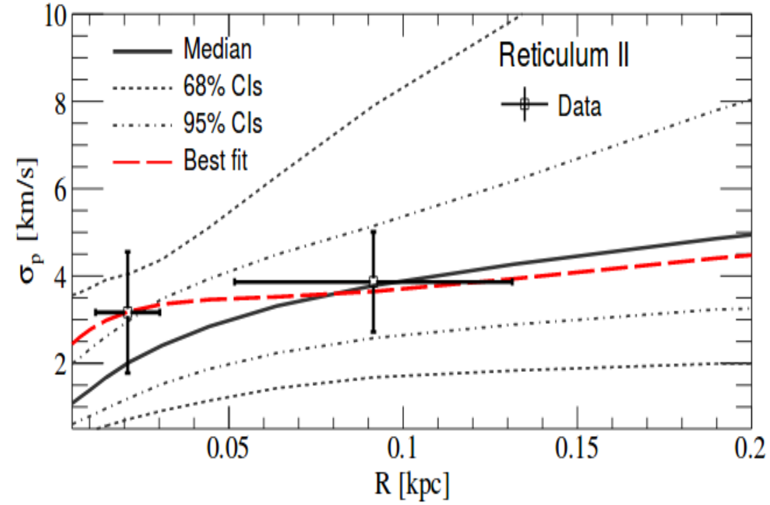
Nearby dwarf galaxy satellites of the MW



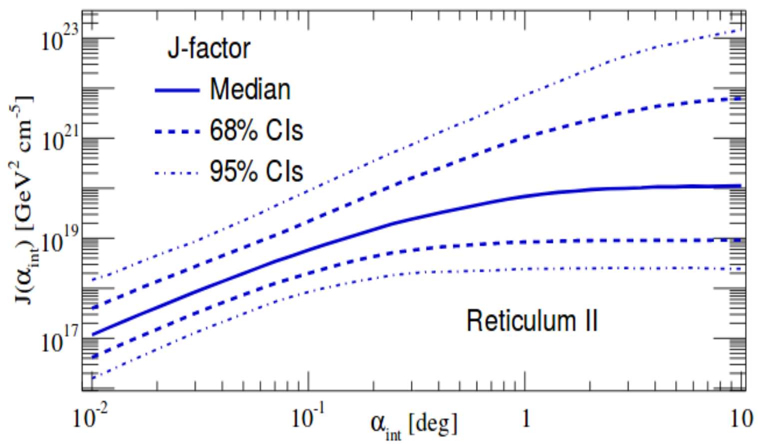




From stellar dispersion measurements



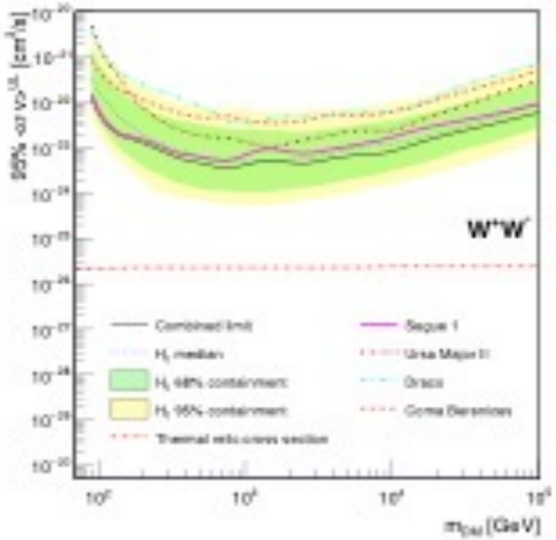
to J-factors



Nearby dwarf galaxy satellites of the MW

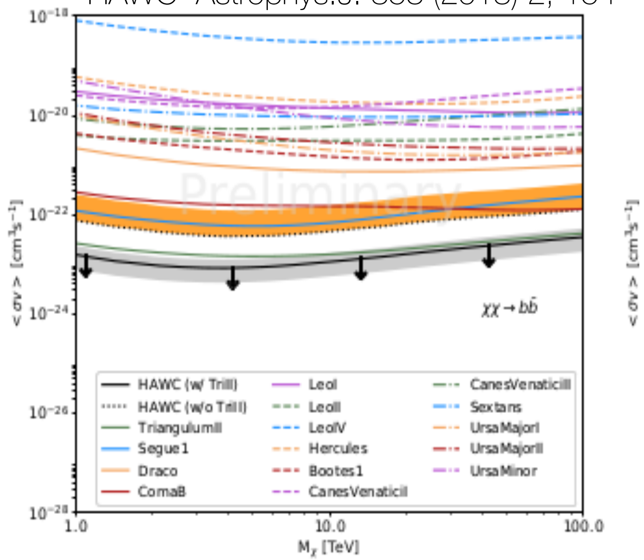
MAGIC observations of 4 dSphs:
Segue 1, Ursa Major II, Draco, Coma Berenices
- A combined analysis of 4 dSph datasets for a total of 354.3 h

MAGIC, Phys. of Dark Universe, 35 (2022) 100912

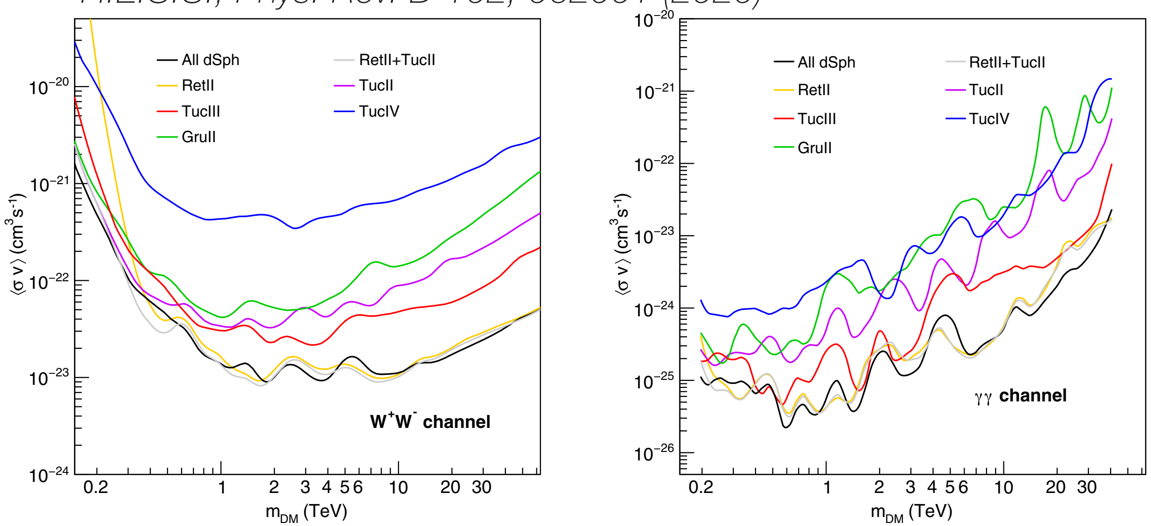


HAWC observations of 15 dSphs
- Combination in a joint likelihood analysis, 507 days of observations

HAWC Astrophys.J. 853 (2018) 2, 154

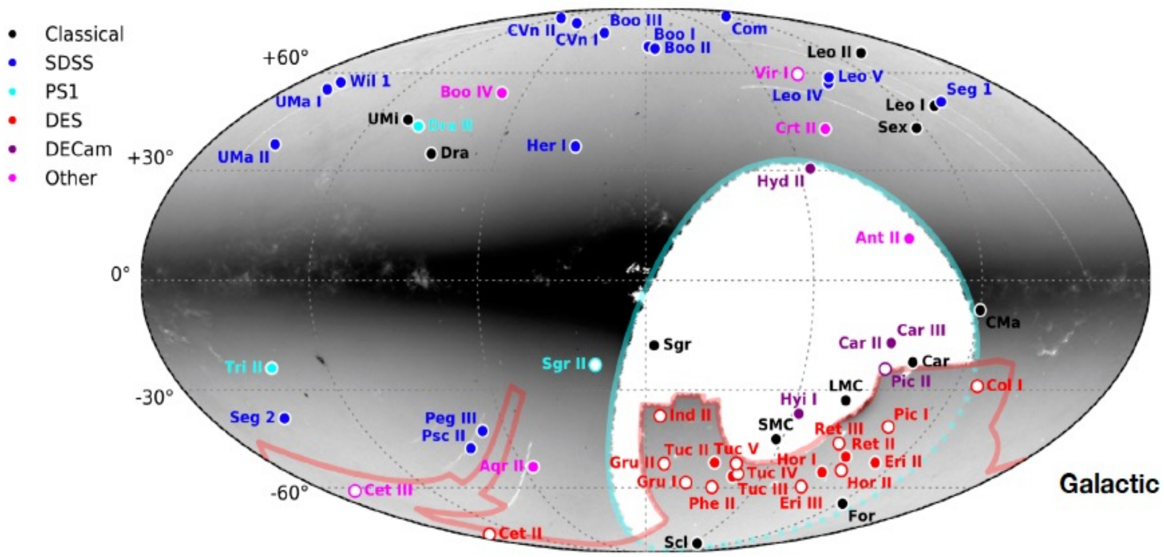


H.E.S.S., Phys. Rev. D 102, 062001 (2020)



H.E.S.S. observations – 80 hours
- A selection of Milky Way ultra-faint satellites by the Dark Energy Survey (DES)
- Some without spectroscopic J-values

Nearby dwarf galaxy satellites of the MW



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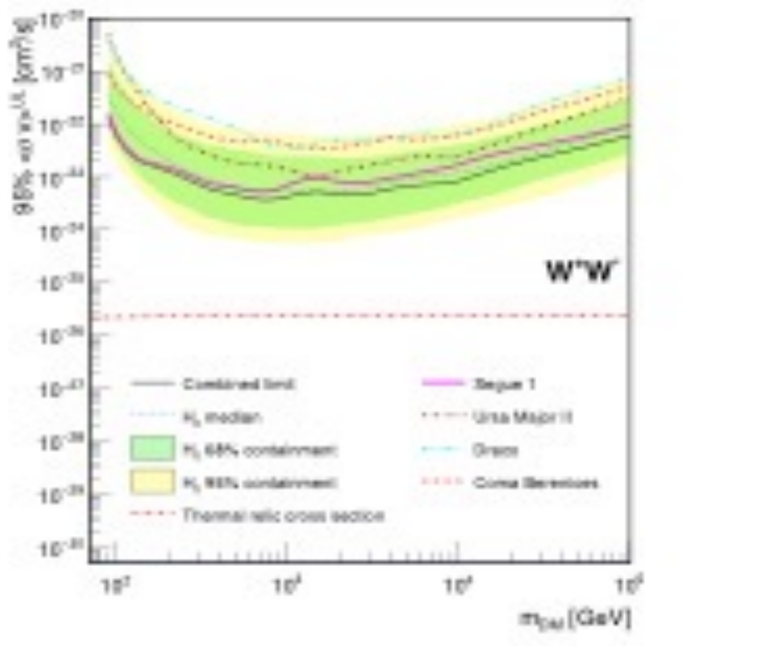
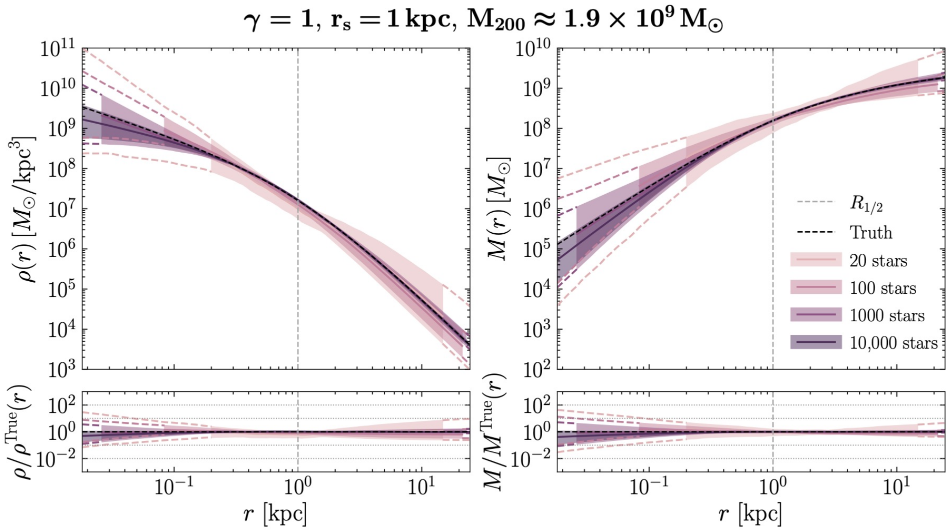


- Core vs. Cusp. DM profiles:



Chang&Necib 2021

Even for classical dSph galaxies like Fornax (about thousand stars detected) we may be lacking of data to disentangle between core and cusp profiles

Combining all dwarf galaxy observations

- Combination of the observation results towards 20 dwarf spheroidal galaxies (dSphs)
  - Significant increase of the statistics -> Increase the sensitivity to potential dark matter signals
  - Cover the widest energy range ever investigated : 20 MeV – 80 TeV

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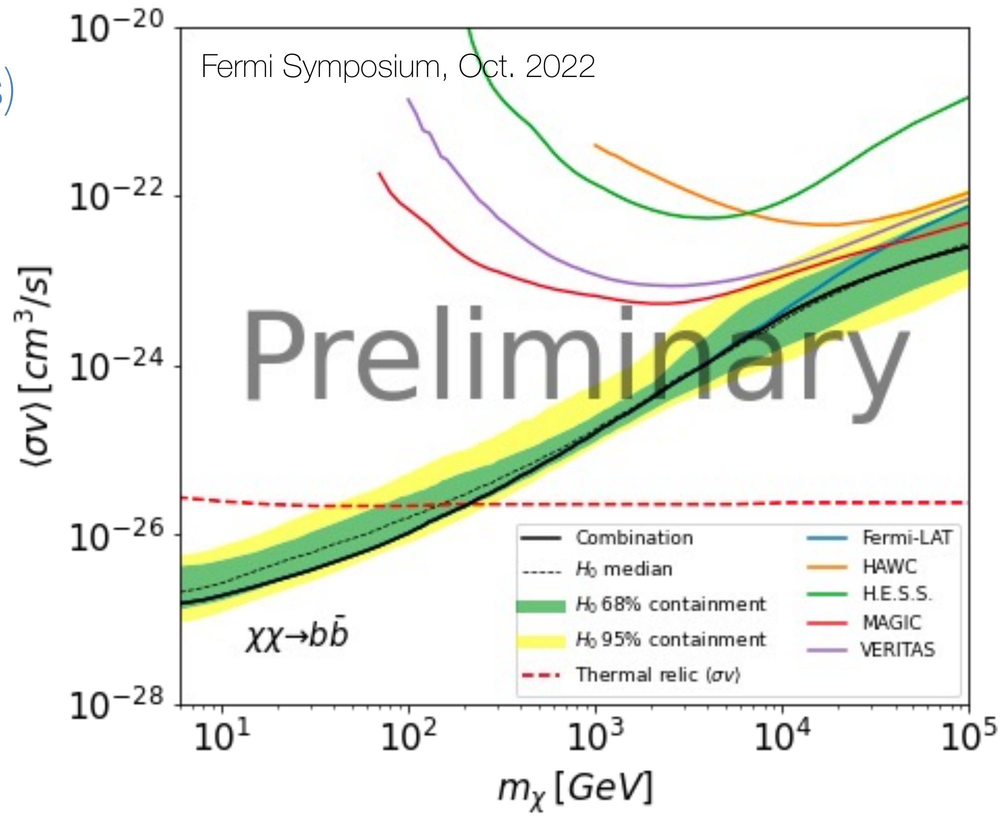
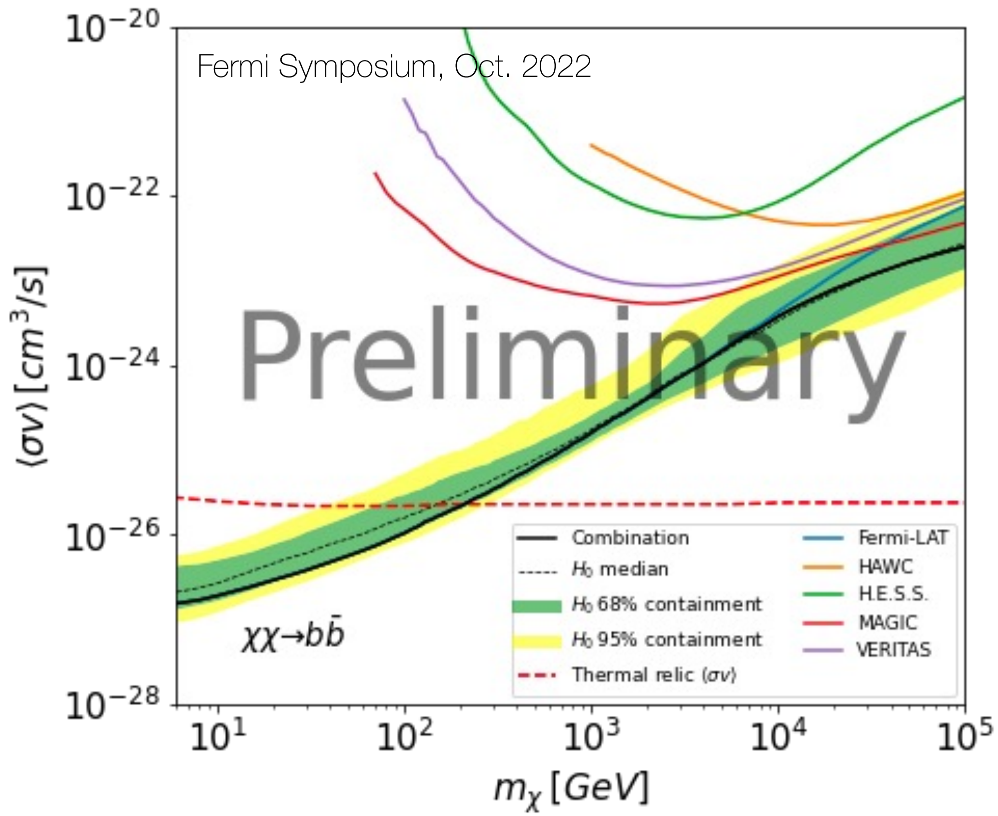
  - Significant increase of the statistics -> Increase the sensitivity to potential dark matter signals
  - Cover the widest energy range ever investigated : 20 MeV – 80 TeV
- Common elements :
  - Agreed model parameters
  - Sharable likelihood table formats
  - Joint likelihood test statistic



Combining all dwarf galaxy observations

- This analysis framework allows us to perform multi-instrument and multi-target analysis
- No significant DM signal was observed
- Combined limits range from 5 GeV to 100 TeV and improve individual limits up to a factor 2 to 3



An alternative: selected Unidentified Fermi-LAT Objects as Dark matter subhalos

Dark Matter subhalos in the Galactic halo

- Lower signal than the GC region
- No astrophyiscal background
- Location not known …

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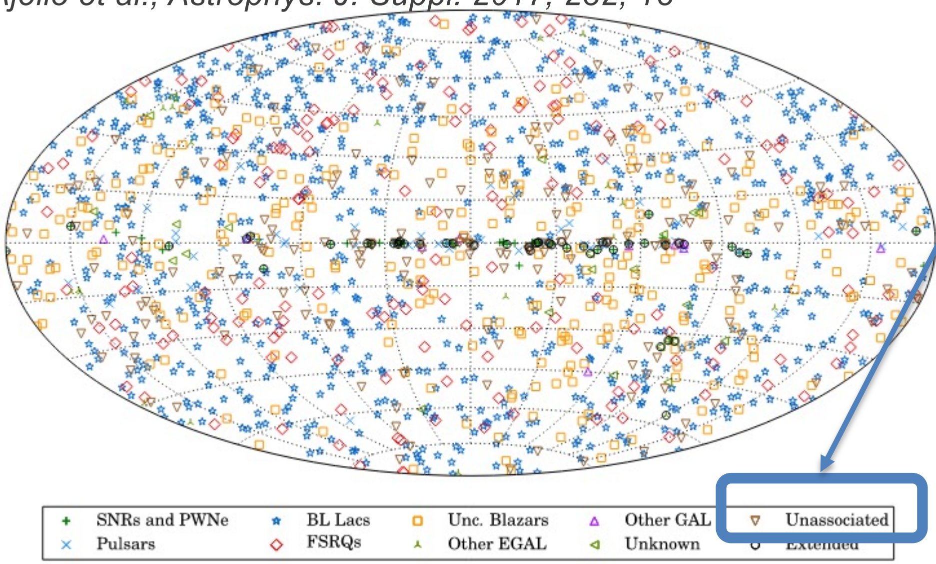
Ajello et al., Astrophys. J. Suppl. 2017, 232, 18



200 unassociated over 1556 sources in the catalogue;

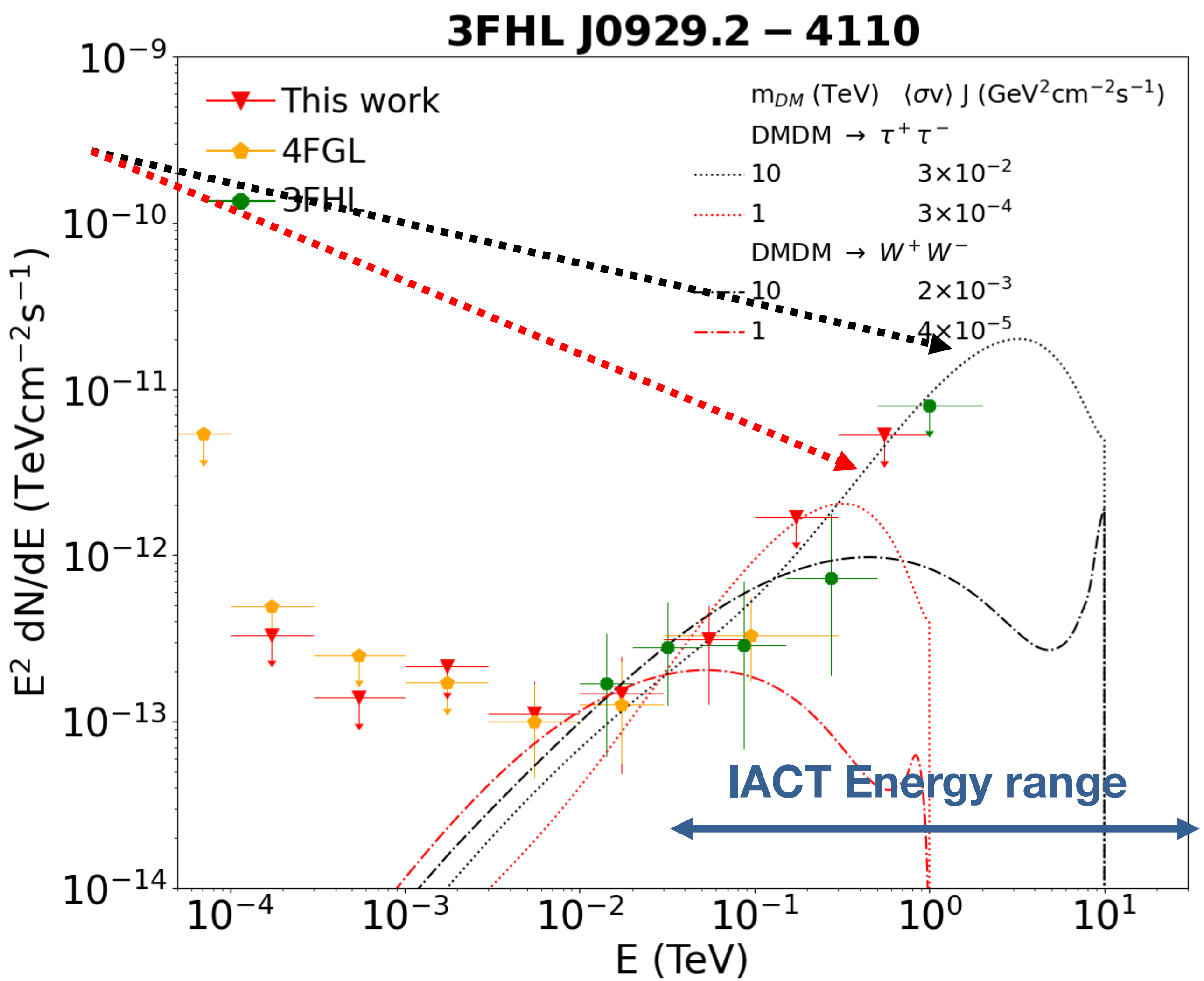
→ Selection through the Third catalog of Hard *Fermi*-LAT sources (3FHL) to obtain the most promising UFOs for the IACT observations.

An alternative: selected Unidentified Fermi-LAT Objects as Dark matter subhalos

- DM-induced emission models are viable according to Fermi-LAT measurements

- Need massive DM because no energy cut-off is seen from the Fermi-LAT

→ Observations at VHE with IACTs needed



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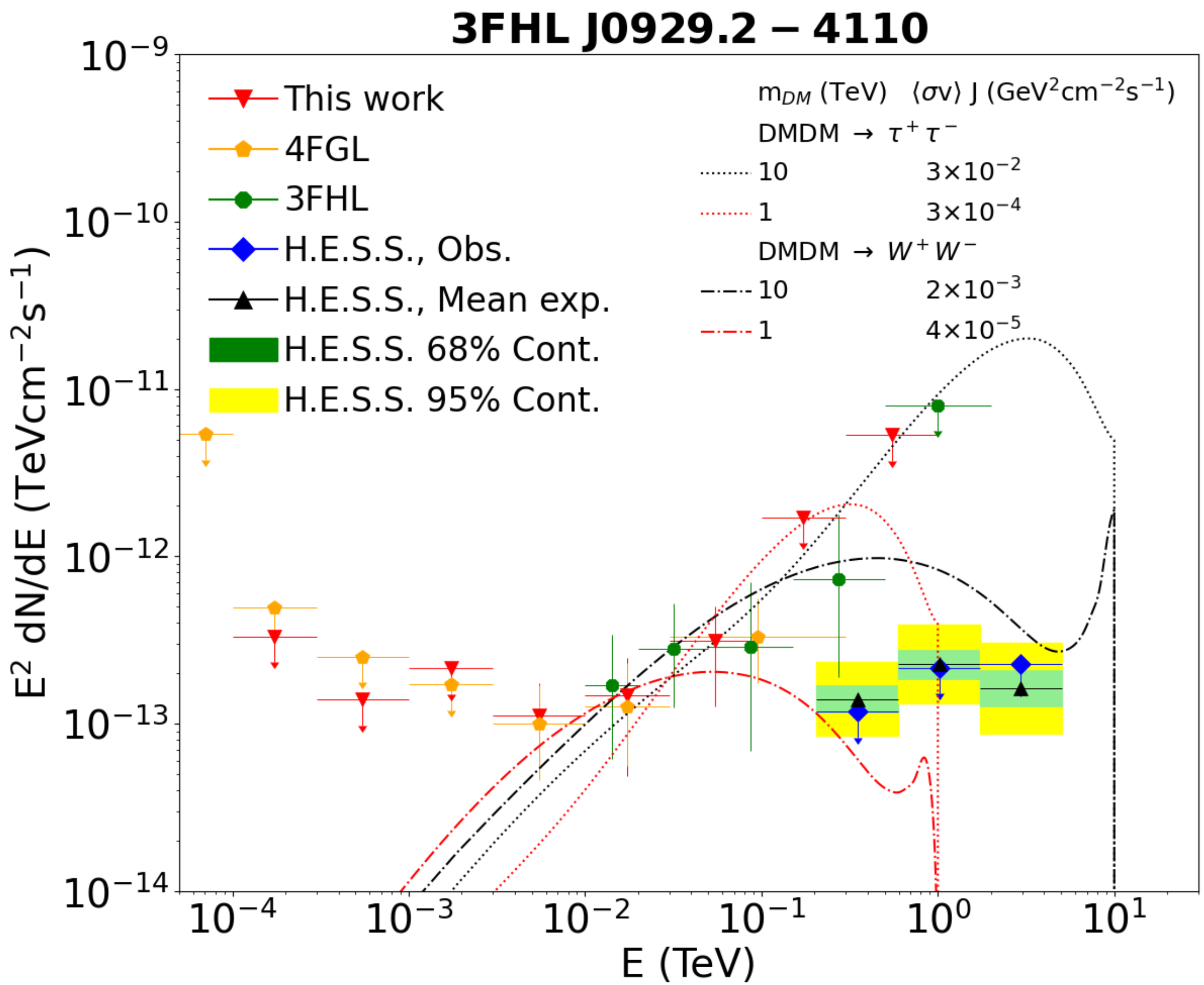
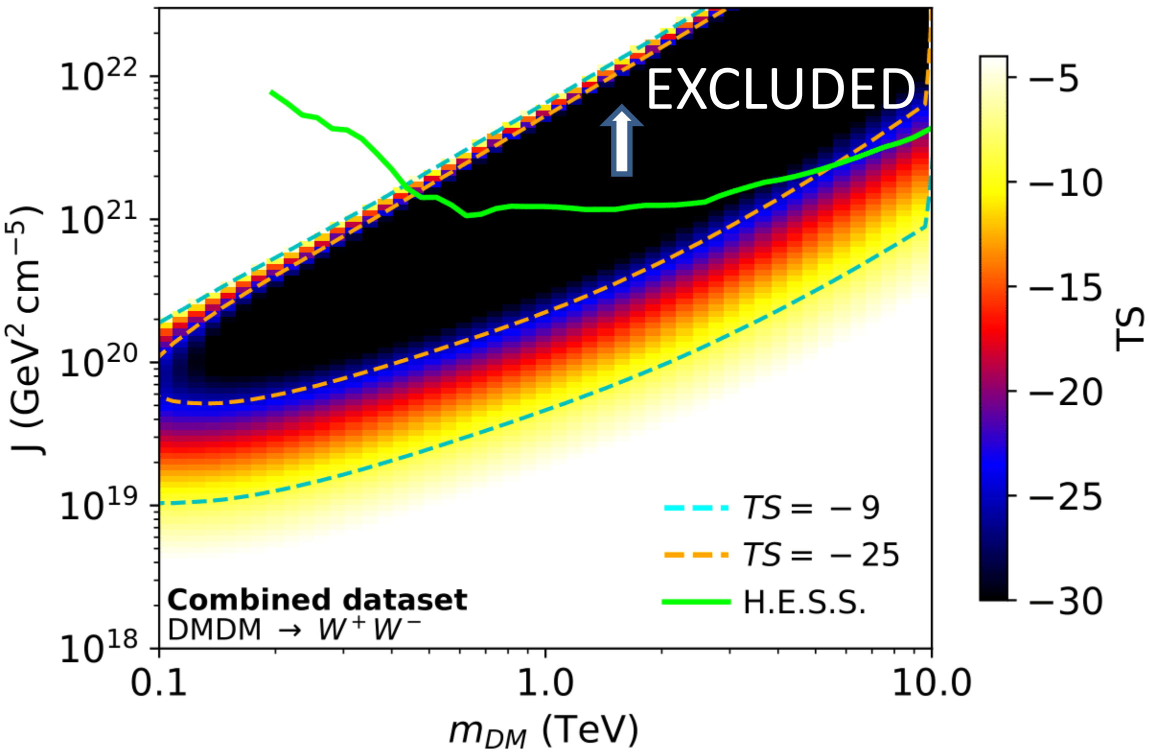
→ Strong constraints from IACTs



An alternative: selected Unidentified Fermi-LAT Objects as Dark matter subhalos

- Combination of the Fermi-LAT and H.E.S.S. datasets
- Assume thermally-produced WIMPs

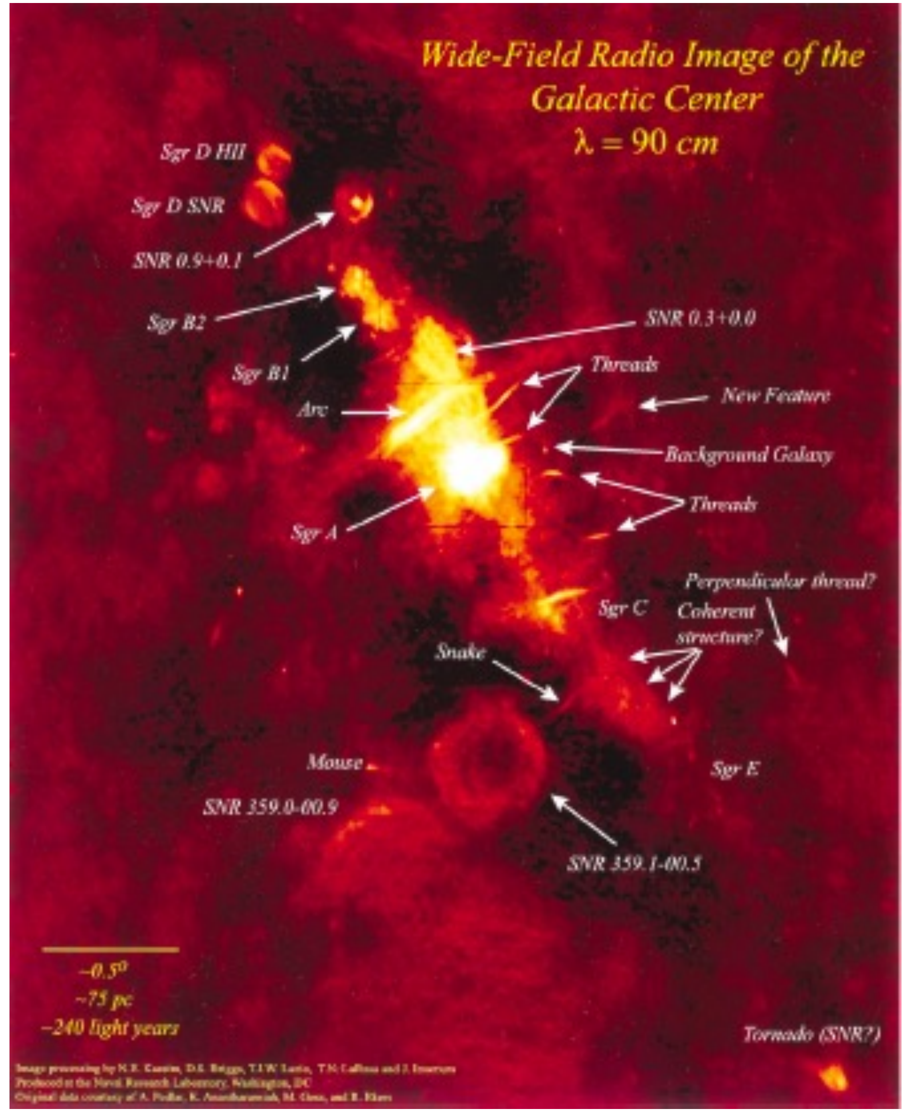
→ UFOs excluded as DM subhalos down to ~300 GeV with H.E.S.S. limits



High J-factors for subhalos from N-body cosmological simulations suffer from large uncertainties
→ therefore IACT model-independent constraints needed

Central region of the Milky Way

- A prime target to detect dark matter in VHE gamma rays
  - Proximity and expected high DM content
- A complex astrophysical region
- H.E.S.S. particularly well located to obverse the central region of the Milky Way under very favorable conditions
  - Long-term observation programme carried out by H.E.S.S. in the GC region

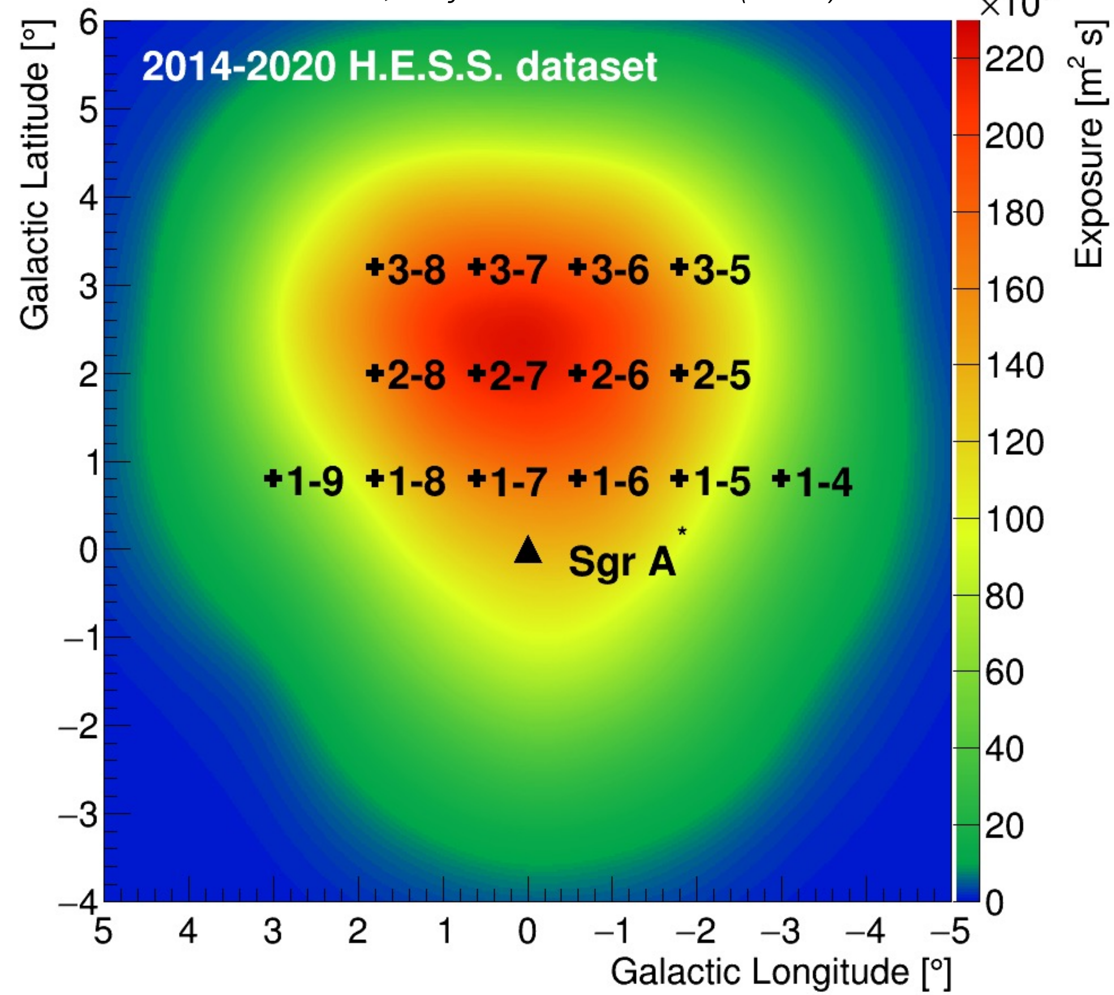


Central region of the Milky Way

- H.E.S.S. is performing a survey of the inner few degrees of the Galactic Centre region since 2015
  → provide unprecedented sensitivity to diffuse emissions
    - search for Dark matter signals
    - search for TeV outflows from the Galactic Centre

- The first ever conducted VHE gamma-ray survey of the Galactic Center (GC) region.

H.E.S.S. coll., Phys. Rev. Lett. 129 (2022) 111101



Central region of the Milky Way

- H.E.S.S. is performing a survey of the inner few degrees of the Galactic Centre region since 2015, i.e., Inner Galaxy Survey
  → provide unprecedented sensitivity to to dark matter
  → study in greater details the central diffuse emission
  → search for TeV outflows from the Galactic Centre

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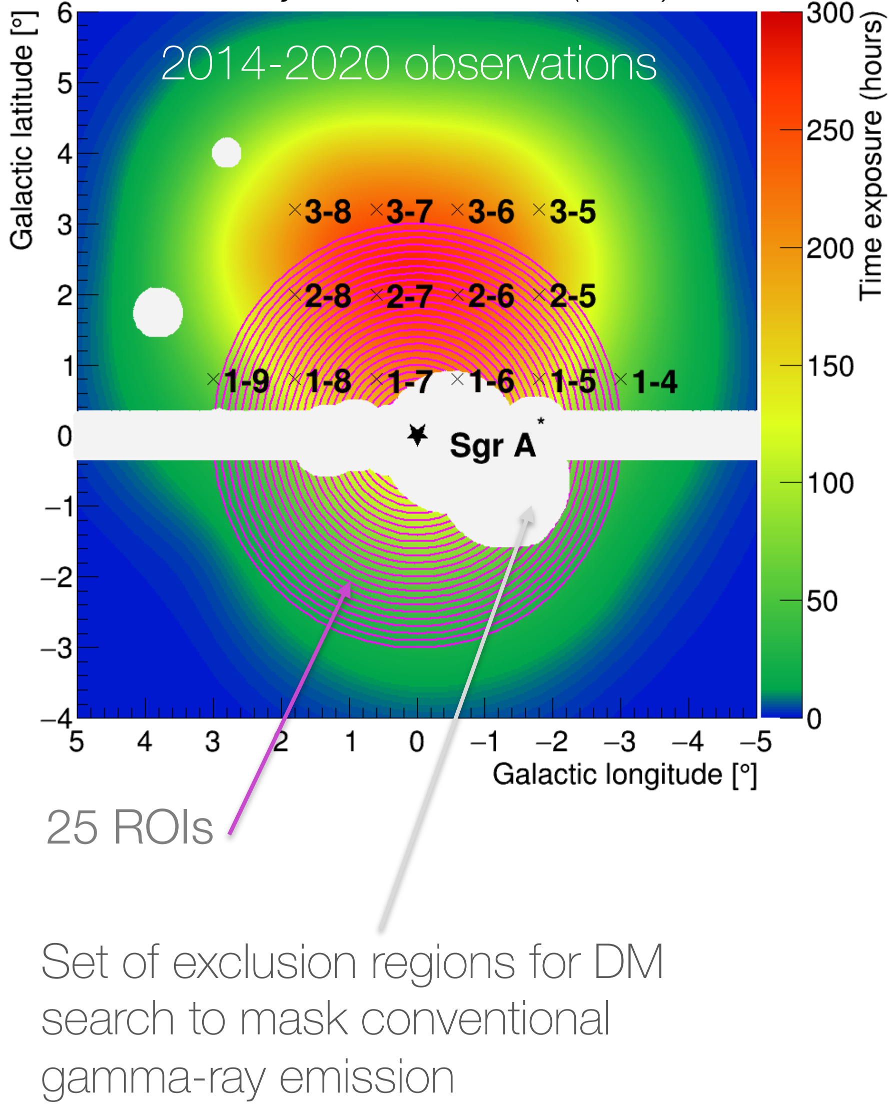
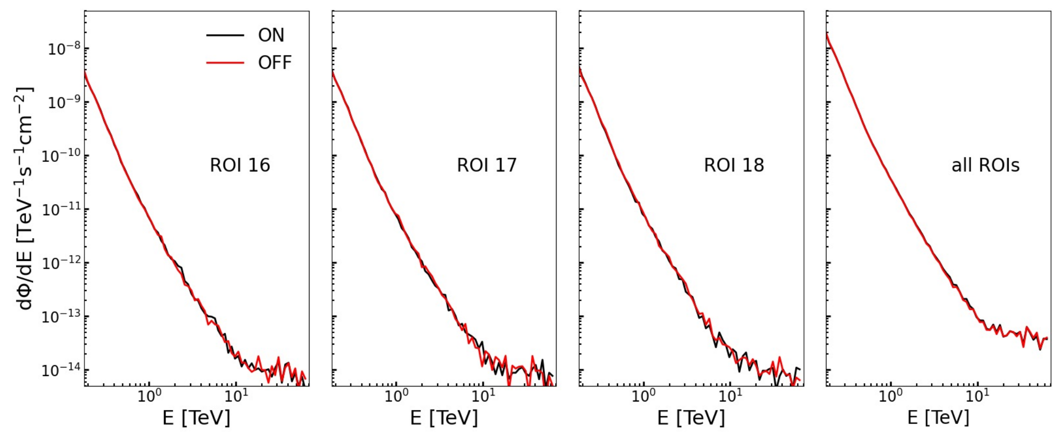


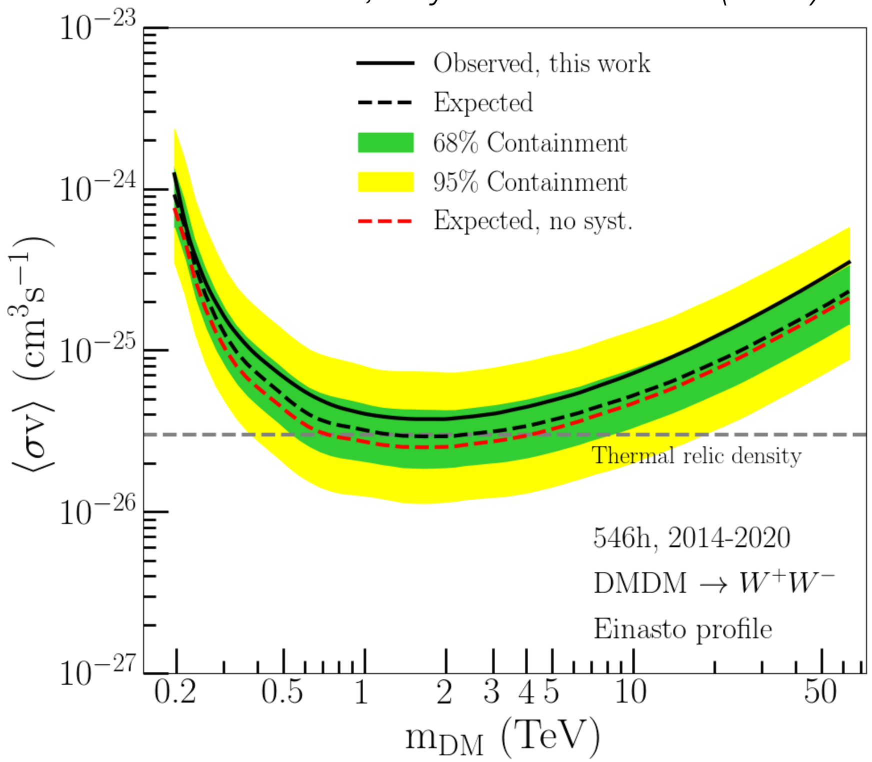
Dark matter search with the Inner Galaxy Survey

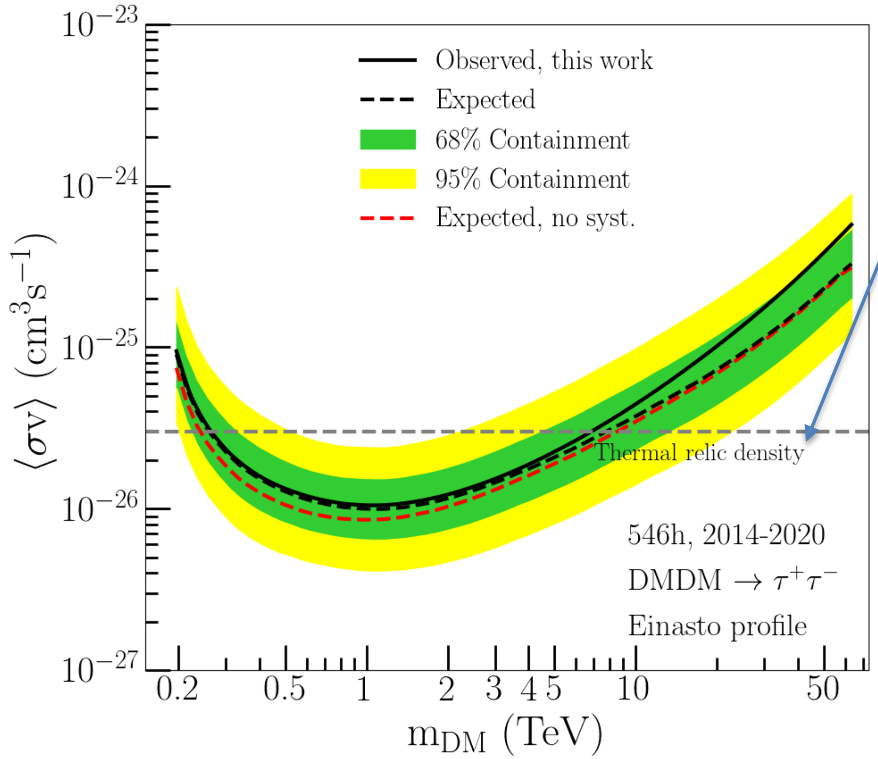
- No excess compatible with searched DM signal is found in any ROI for the whole energy range

→ 95% C.L. upper limits on <σv>



H.E.S.S. coll., Phys. Rev. Lett. 129 (2022) 111101





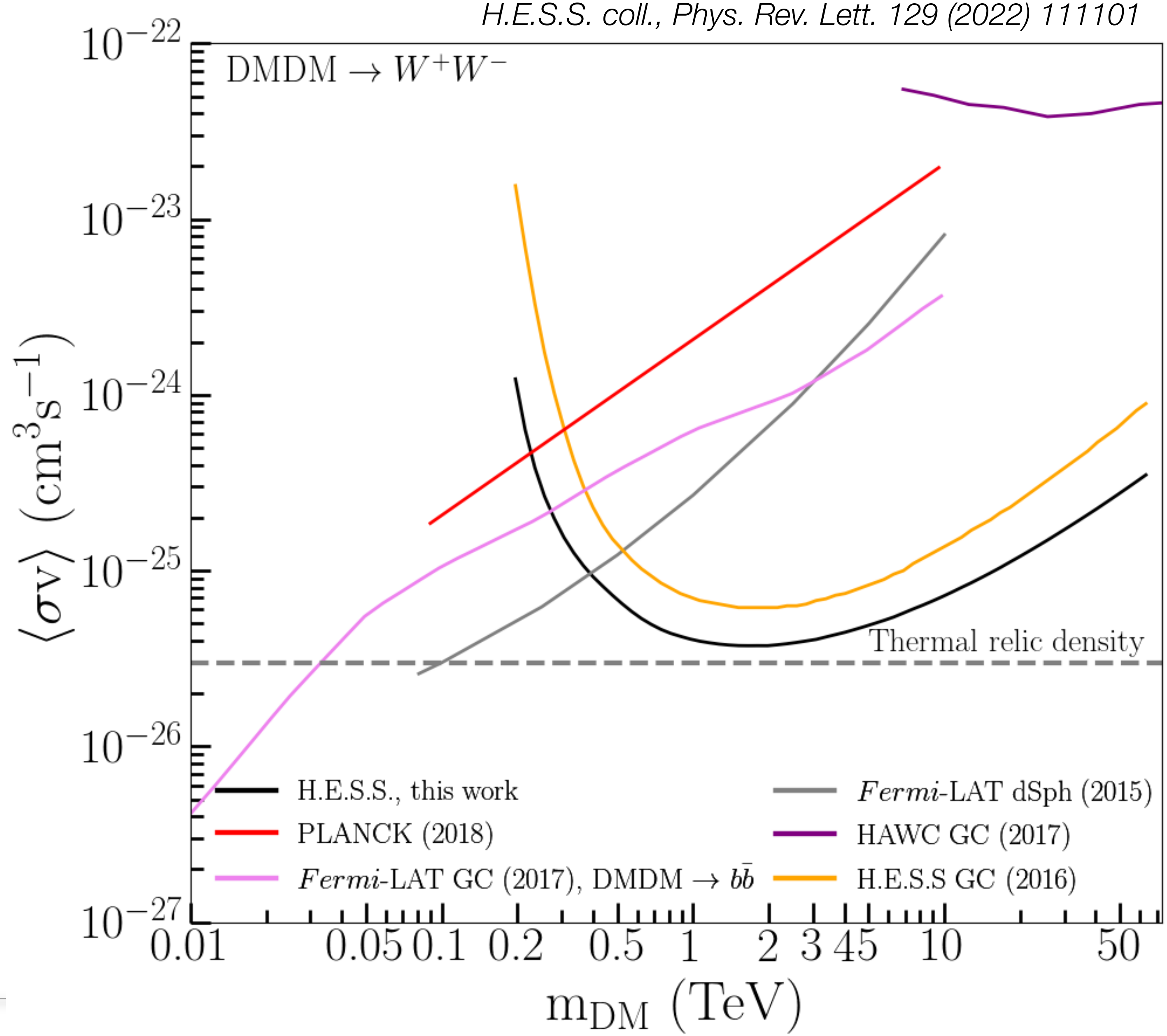
Thermal cross-section expected for annihilating WIMPs that account for 100% of DM

Dark matter search with the Inner Galaxy Survey

- Comparison with Fermi-LAT dSph and GC, HAWC dSph and GC, MAGIC Segue 1, PLANCK CMB, H.E.S.S. GC (2016).

  → Most constraining limits in the TeV-mass range

H.E.S.S. coll., Phys. Rev. Lett. 129 (2022) 111101



Dark matter : thermal WIMPs

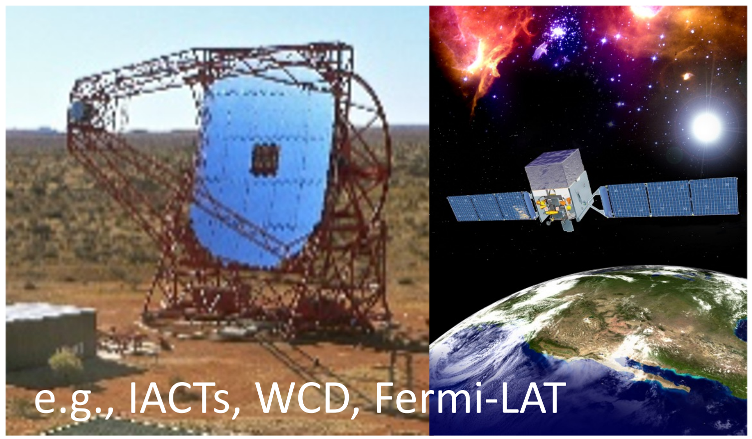
- The identification of DM is a multi-faceted problem which requires the synergy of complementary approaches

Dark matter : thermal WIMPs

- The identification of DM is a multi-faceted problem which requires the synergy of complementary approaches

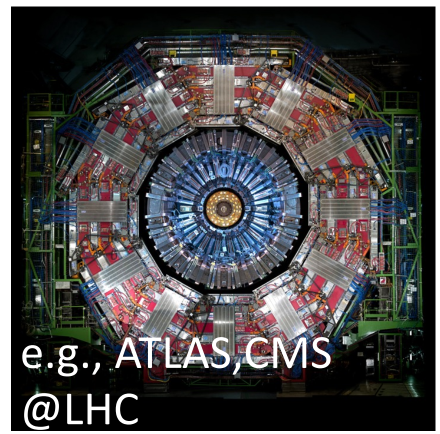
Underground experiments:

nuclear recoils



Ground-based telescopes and satellites

standard particles from annihilation or decay



Colliders

production of DM

Dark matter : thermal WIMPs

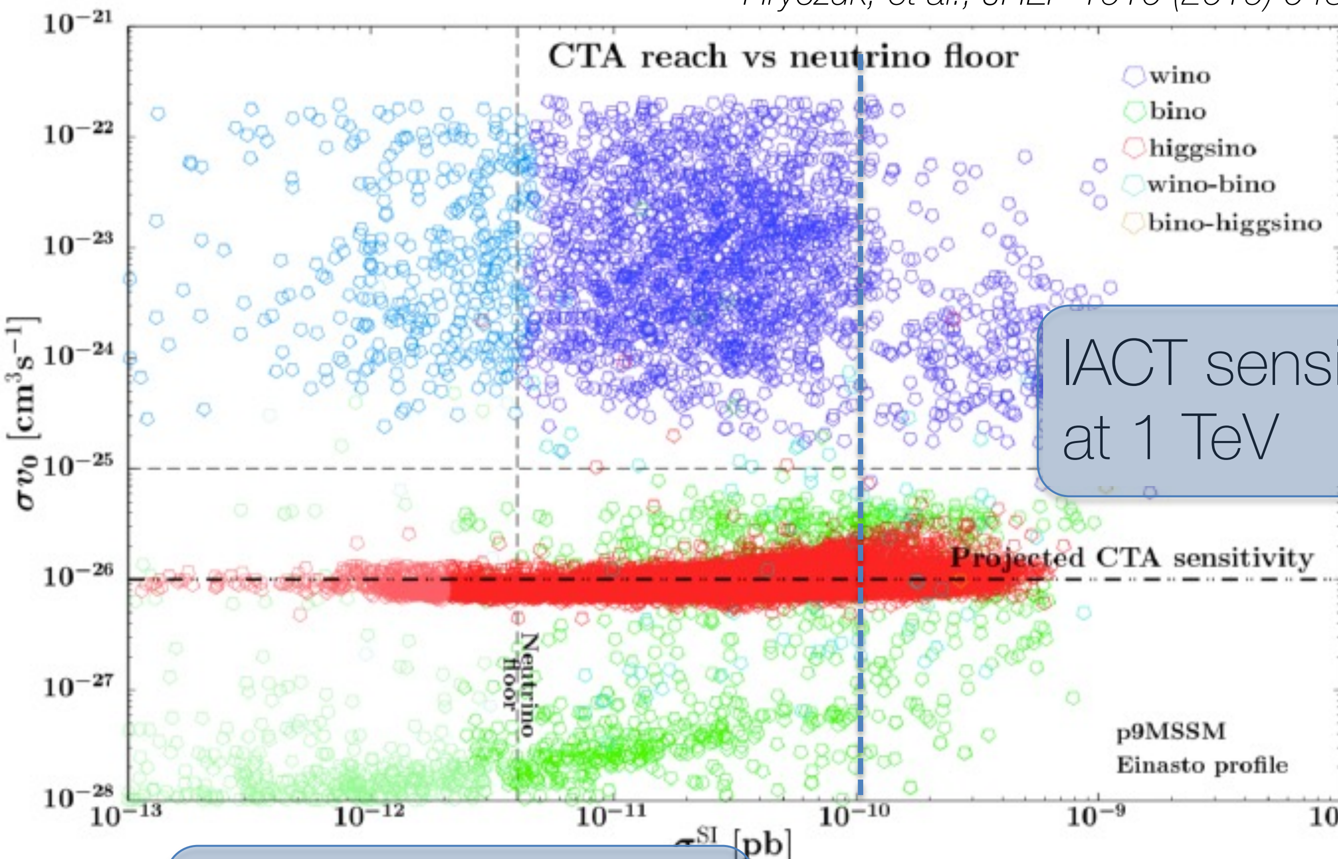
- The identification of DM requires the synergy of complementary approaches

- Some of the simplest classic WIMP models remain unconstrained - DM could still interact through the W and Z bosons!
- WIMP candidates provided in simple extension of the Standard Model of particle physics remain out of reach of direct detection experiments and/or collider searches
  - LHC searches have ruled out Wino masses below ~500 GeV
  - Higgsino : even ~400 GeV is a highly optimistic goal for the full LHC dataset
  - thermal masses are out of reach for the LHC for both candidates, and potentially difficult to discover even at future 100 TeV colliders, e.g., FCC

Dark matter : prototype TeV DM models

- Thermal Wino out of reach of direct detection
- Wino within the reach of current IACT sensitivity
- Higgisino is very challenging to probe

Hryczuk, et al., JHEP 1910 (2019) 043



IACT sensitivity at 1 TeV

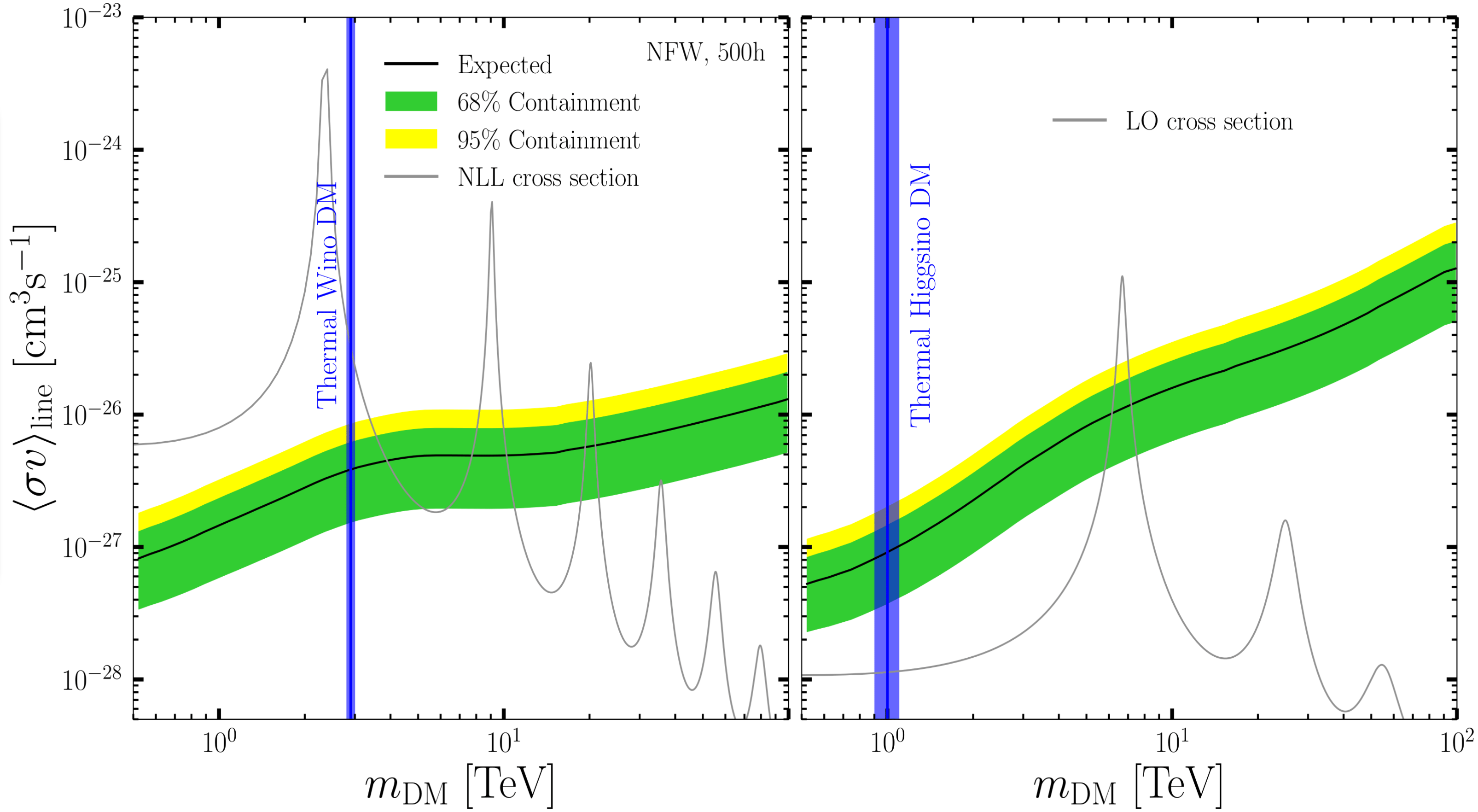
Neutrino floor for direct detection

LUX-ZEPLIN (LZ) sensitivity at 1 TeV

Dark matter : prototype TeV DM models

Montanari, Moulin, Rodd, submitted to Phys. ReV. D

- Thermal Winos are excluded
- Thermal Higgsinos are not, by a factor of a few



→ Wino DM masses are excluded to up about 10 TeV

→ Higgsino DM masses are excluded at about 6.5 TeV

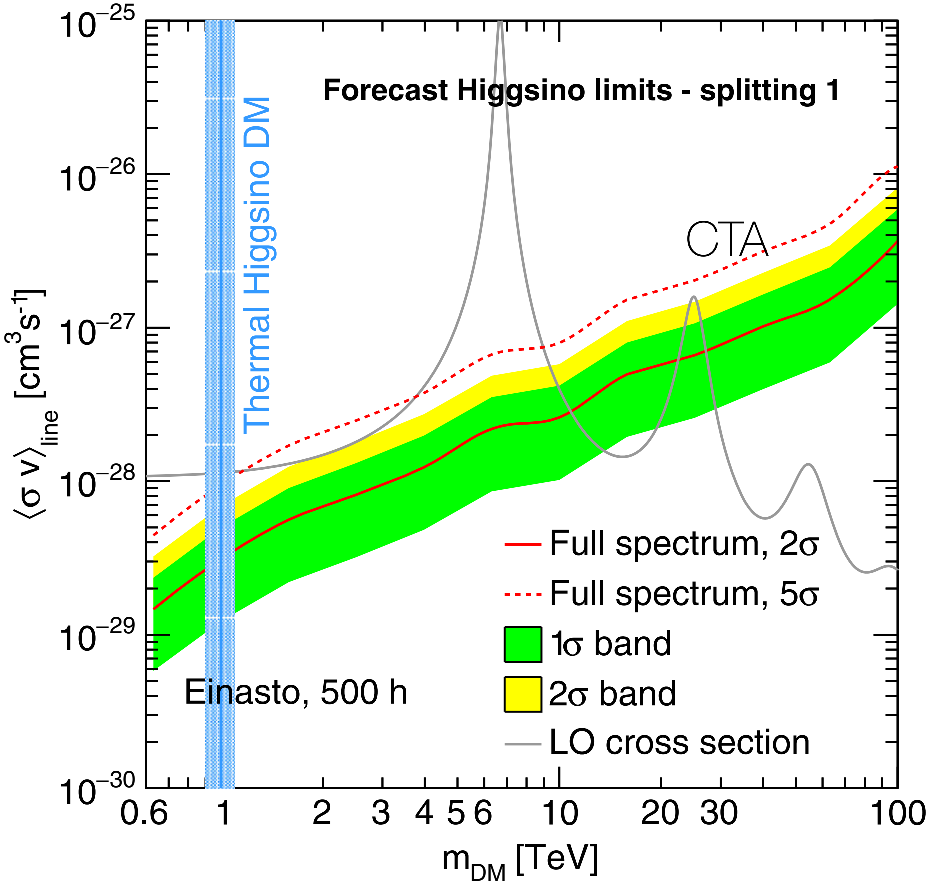
Prospects for annihilating Dark Matter

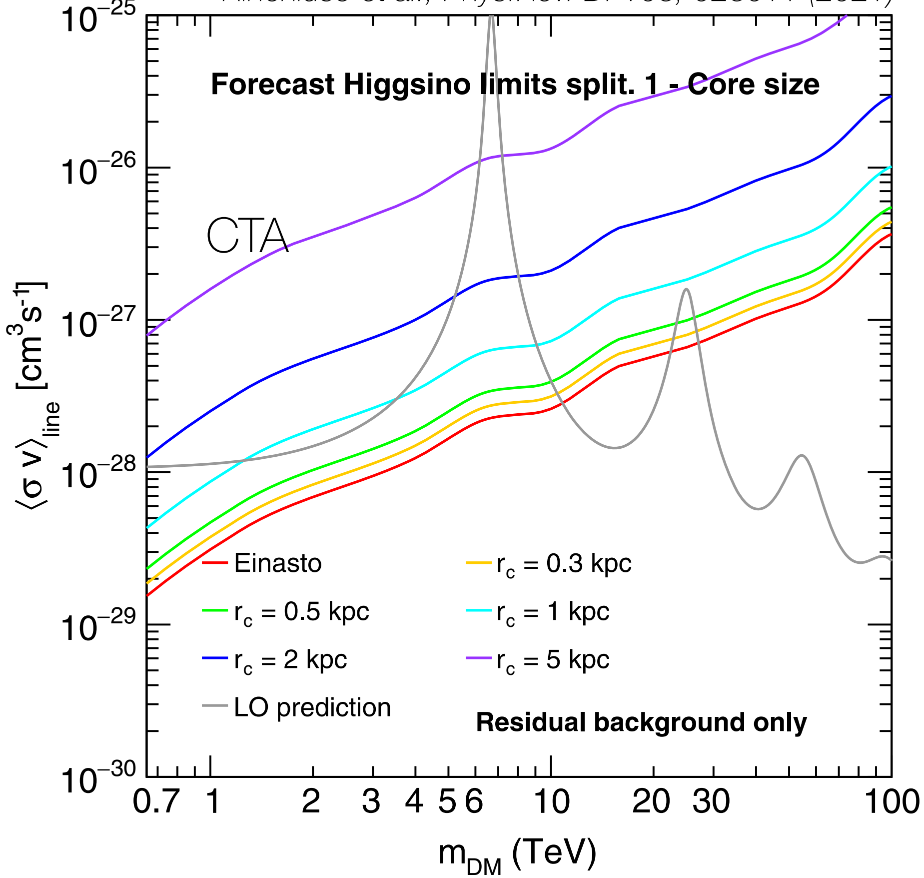
- 2 sites: La Palma/ Chile
- A factor ~10 increase in flux sensitivity
- Energy coverage 30 GeV – 300 TeV
- Arcminute angular resolution
- Energy resolution up to 5% in the TeVs

CEA - Saclay

Prospects for annihilating Dark Matter

Rinchiuso et al., Phys.Rev. D. 103, 023011 (2021)





- The thermal Higgsino is within the reach of CTA
  - even for 1 kpc core DM profile can be probed

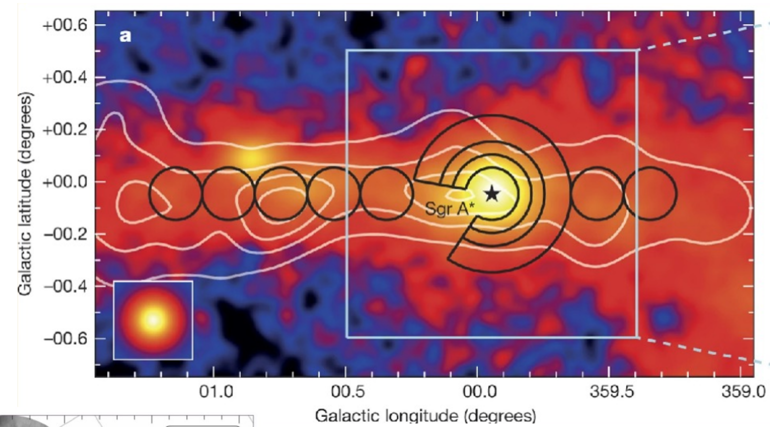
CEA - Saclay

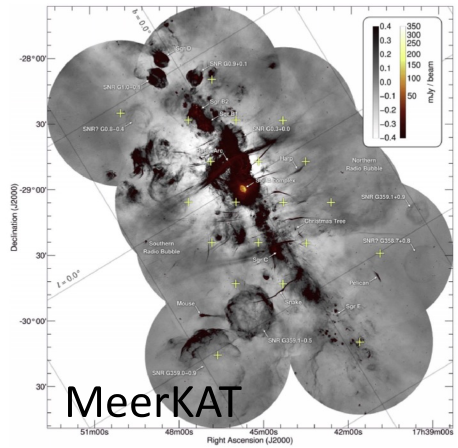
Sensitivity reach with current IACTs in the Inner Galactic halo

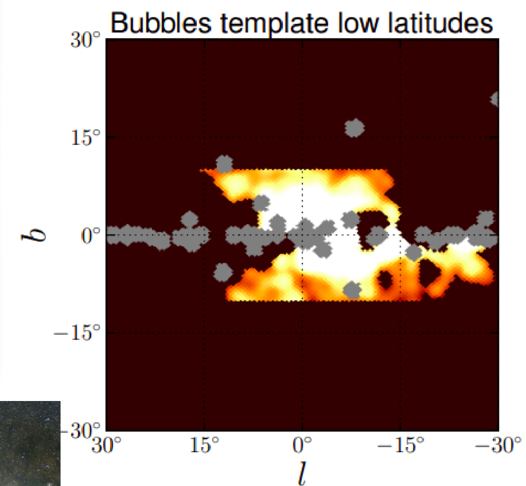
- The GC region is a very large data set for H.E.S.S (+800 hours), obtained over many years with changing camera/telescope configurations

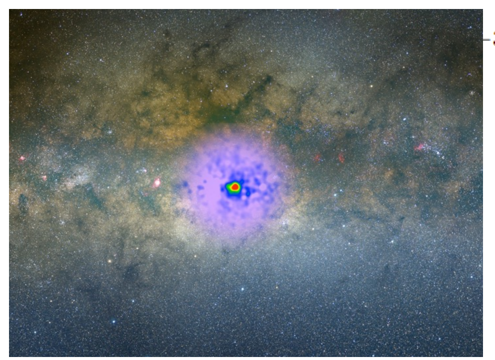
- This is a crowded region : Fermi Bubbles, an hypothetical population of millisecond pulsars, …
  with extended structures beyond single fov and/or source confusion

- Challenges in treating systematics in a large dataset, background estimation and – rejection as well as separation of sources







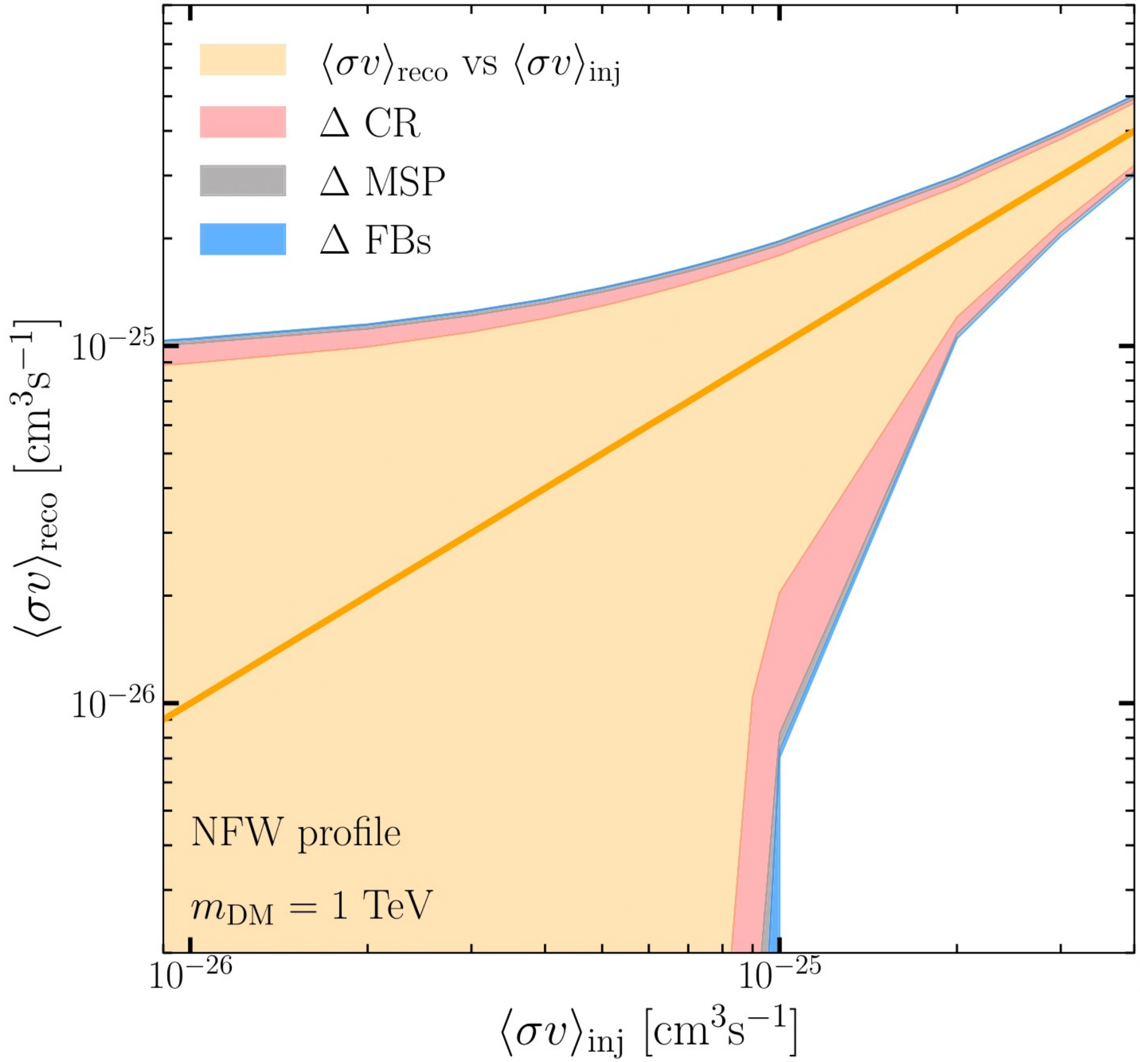


The Galactic Centre Excess seen by Fermi-LAT

Sensitivity reach with current IACTs in the Inner Galactic halo

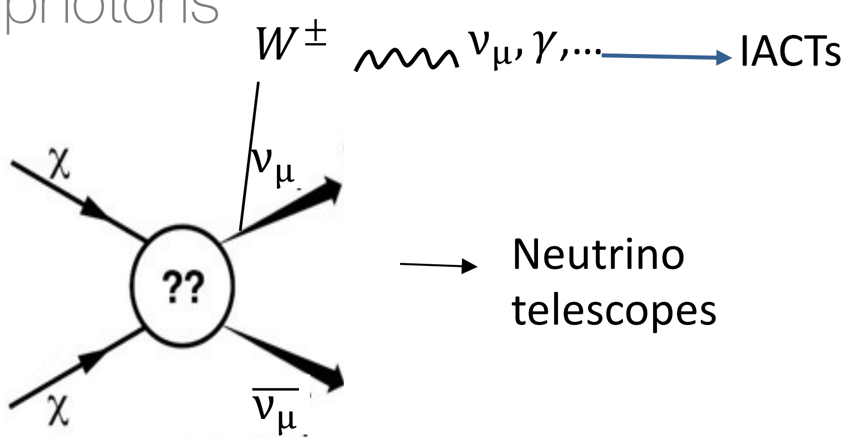
- The GC region is a very large data sets for H.E.S.S (+800 hours), obtained over many years with changing camera/telescope configurations
- Sensitivity is statistics dominated
  → continued data collection with existing IACTs remains important with the highest control of systematics

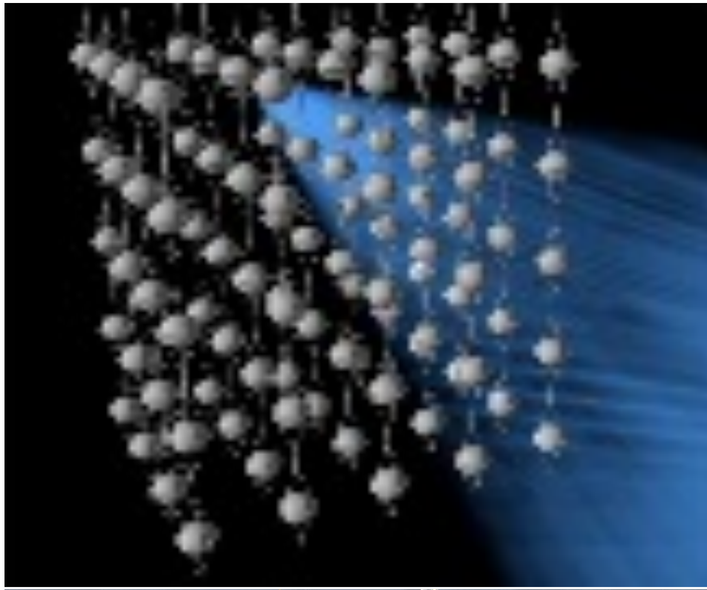
Montanari, Moulin, Rodd, submitted to Phys. ReV. D

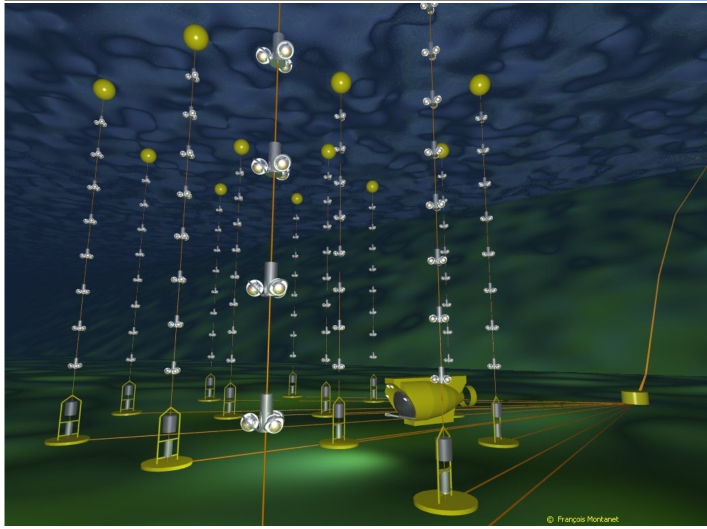


Multi-messenger dark matter searches

- Multi-TeV DM models searches for heavier DM is inherently multimessenger
- IACTs can probe final states that are traditionally the focus of neutrino telescopes like IceCube and ANTARES
  - Even two-body neutrino final states do not simply produce a neutrino line, but can further produce a considerable flux of photons

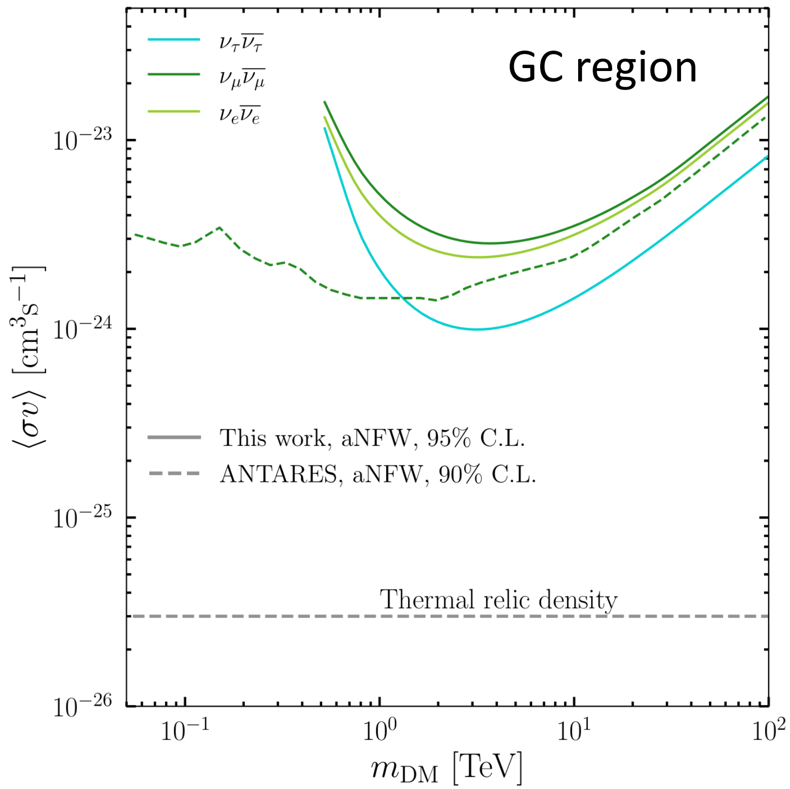


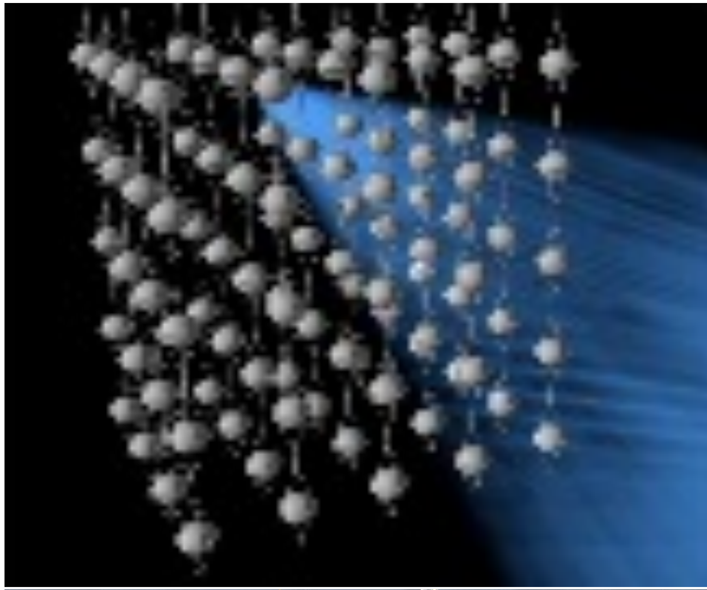


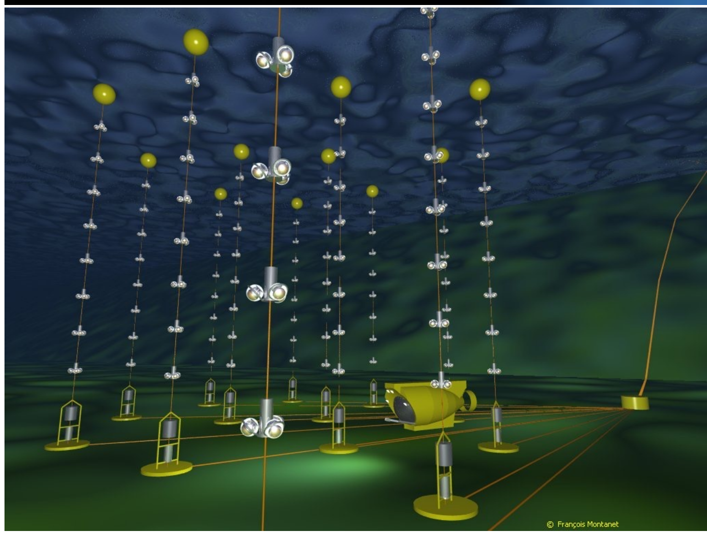


Multi-messenger dark matter searches

- Multi-TeV DM models searches for heavier DM is inherently multimessenger







- IACT searches are competitive to search for these channels

Summary

- IACTs bring stringent constraints on a variety of targets for TeV dark matter
- The Galactic Centre region is a prime target for TeV dark matter detection
- Dwarf galaxies could be used to cross-check a potential DM signal in the GC
- H.E.S.S. is probing thermal-relic TeV dark matter
- Some of the simplest thermal TeV DM models remain still out of reach
- CTA should bring decisive information to the thermal-WIMP paradigm

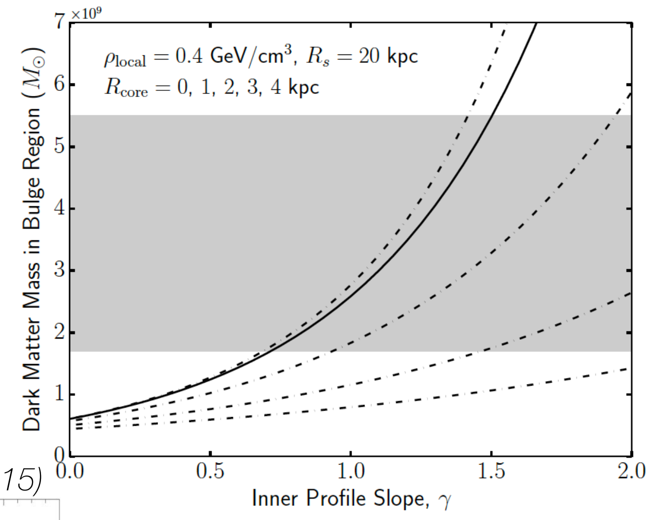
Thanks for your attention

Central region of the Milky Way

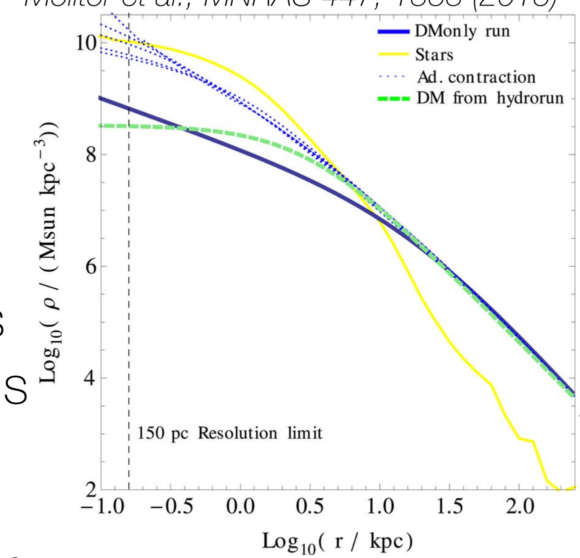
Modelling of the DM distribution in the GC region:

- Mass modelling using kinematic tracers (stars, gas, …) :
  - careful modeling of the baryonic component and has associated large systematic uncertainties,
- Hydrodynamical N-body simulations:
  - Physics of baryons plays a crucial role at small scales
  - Baryonic feedback on the DM halo → large uncertainties
  - the resolution limit of simulations becomes relevant

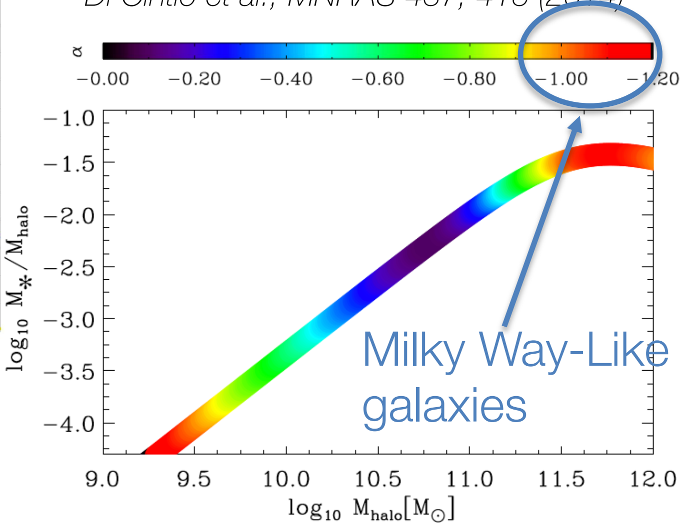
Portail et al. MNRAS 448, 713 (2015)



Molitor et al., MNRAS 447, 1353 (2015)



Di Cintio et al., MNRAS 437, 415 (2014)



- DM distribution not firmly predicted from simulations nor constrained by observations