CEA – Saclay

cherenkov telescope array

# DARK MATTER AND FUNDAMENTAL PHYSICS WITH THE CHERENKOV TELESCOPE ARRAY

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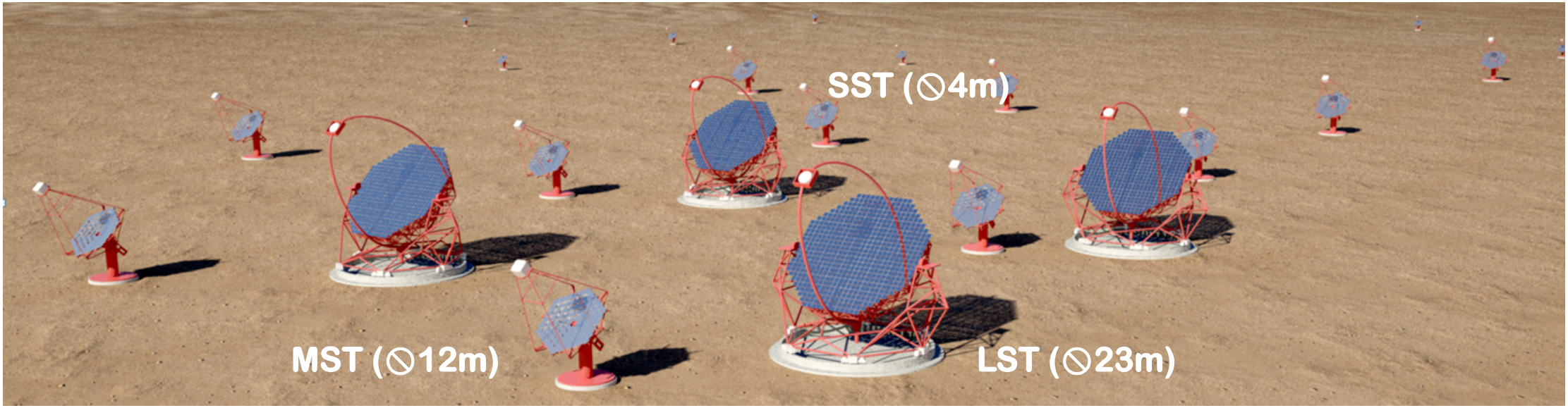
FOR THE CTA CONSORTIUM

28TH TEXAS SYMPOSIUM ON RELATIVISTIC ASTROPHYSICS
GENEVA, DECEMBER 13-18, 2015

# THE CTA PROJECT

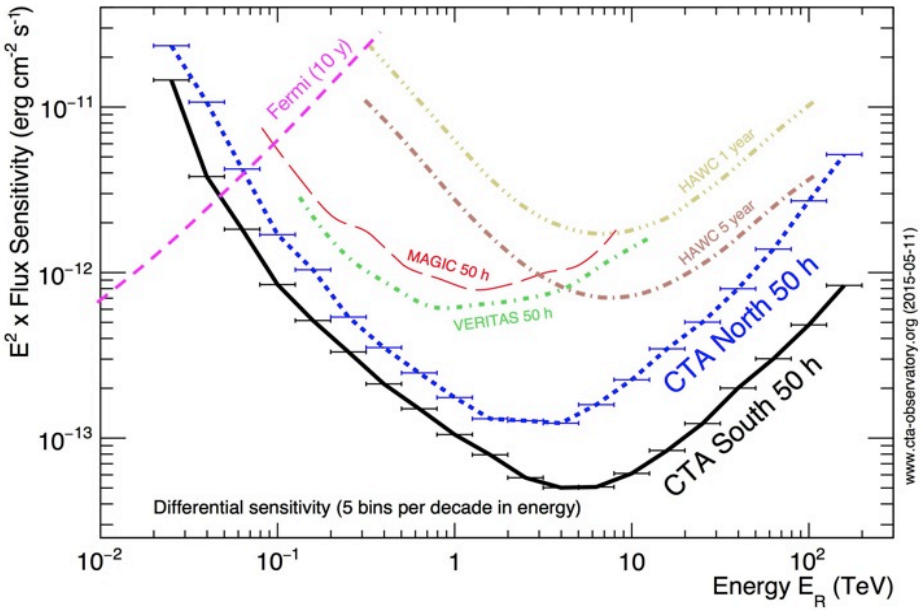



**+ SCT (⦸10m)**
**as a possible MST**

- Next generation ground-based gamma-ray observatory
- Open observatory
- Initial operation of 10 years
- Designed to function for 30 years
- Two sites with total > 100 telescopes
  - Southern Site: Near Paranal in Chile
  - Northern Site: La Palma, Canary Islands
- 31 nations, ~ €300M project (construction cost)

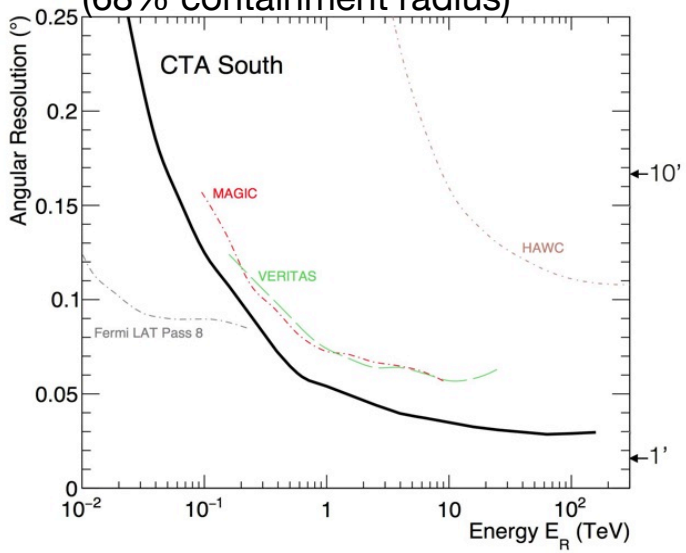
# EXPECTED PERFORMANCE

## Flux sensitivity



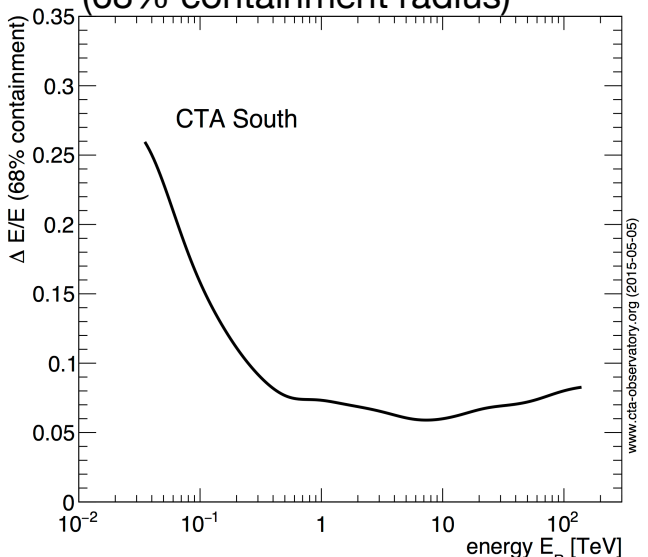

## Angular resolution

(68% containment radius)



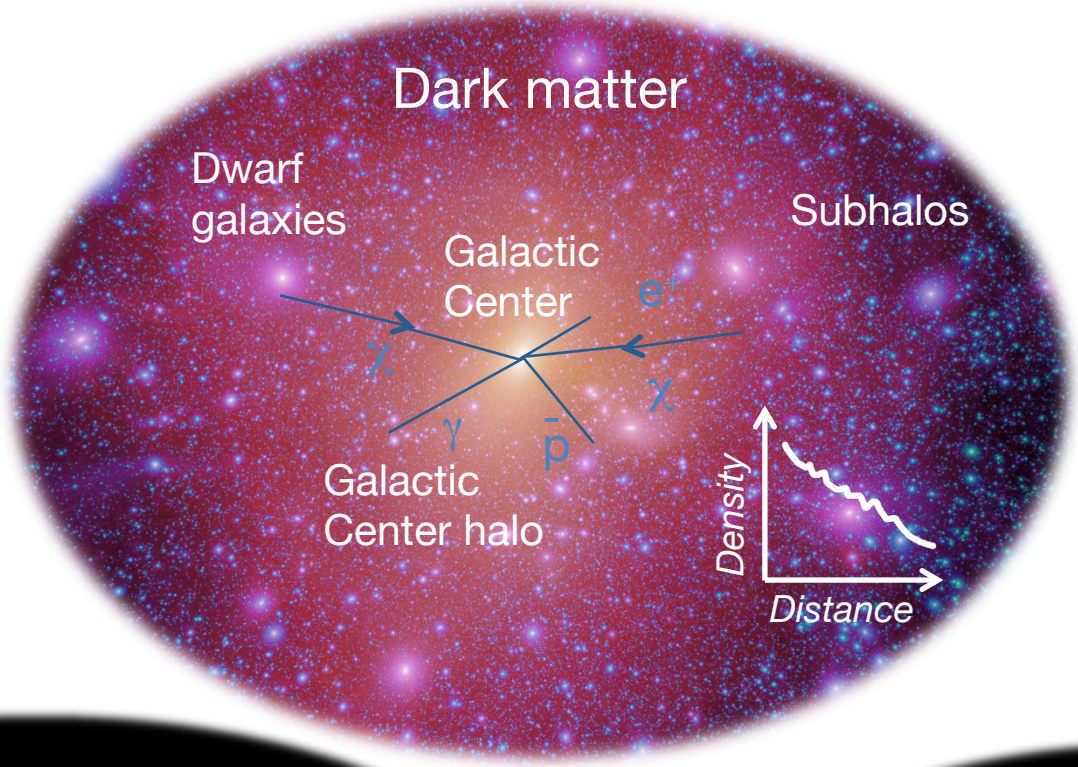

## Energy resolution

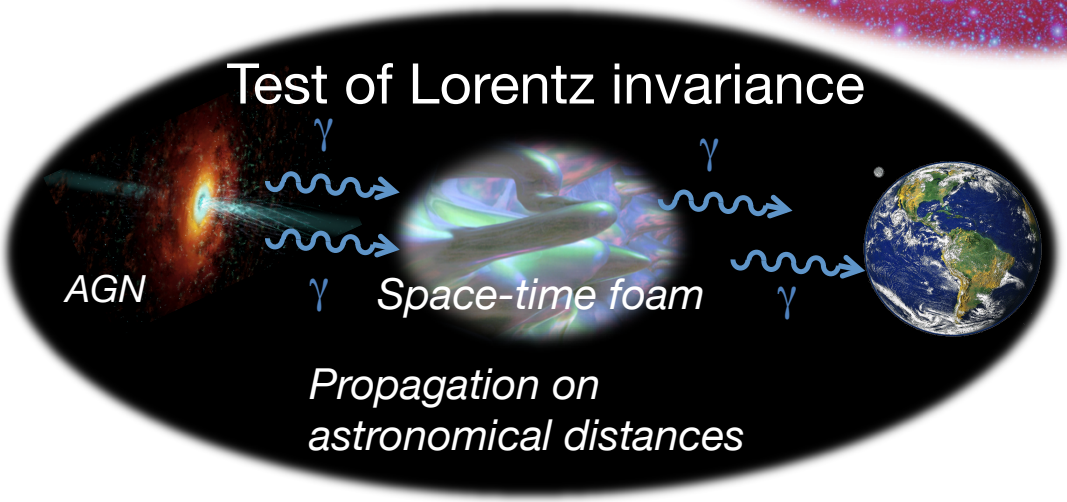
(68% containment radius)

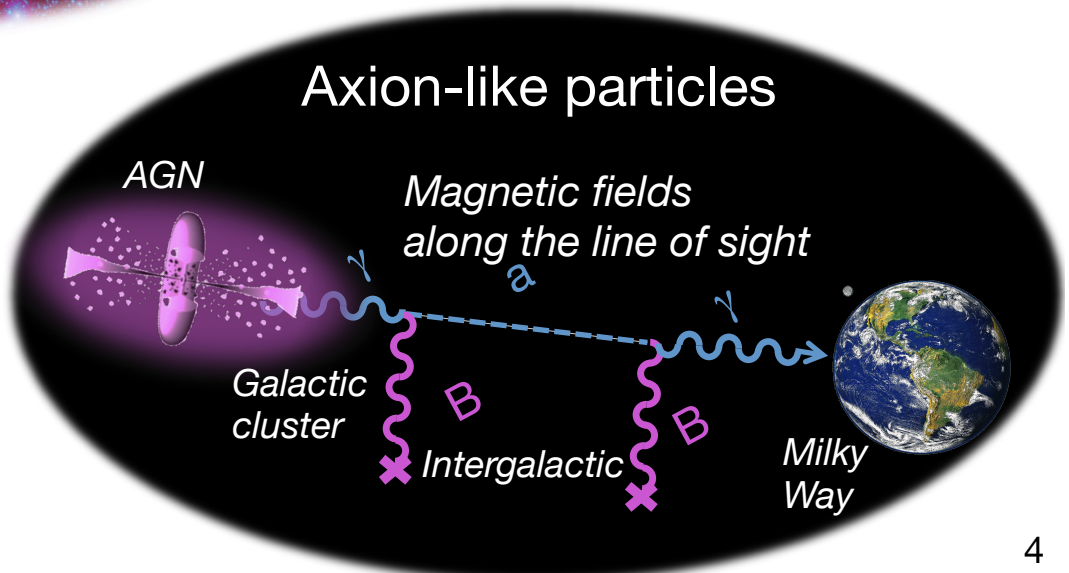



- Wide field of view > 8°
  - Measure diffuse emissions
  - Efficient survey of large fields
- Arcmin angular resolution
  - Resolve extended emission
- Energy resolution
  - Spectral features and discrimination against standard sources

# DARK MATTER AND FUND. PHYSICS



# WIMP DARK MATTER

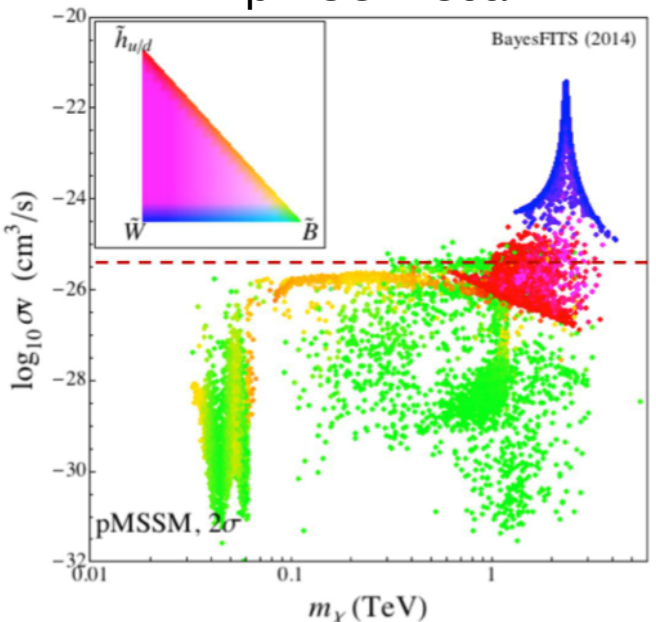
- Weakly Interacting Massive Particles (WIMPs)
  - The weak interaction mass scale and ordinary gauge couplings give right relic DM density without fine-tuning

$$\Omega_{\rm DM}h^2 = \frac{3\times10^{-27}\ {\rm cm^3 s^{-1}}}{\langle\sigma v\rangle} \qquad \langle\sigma v\rangle_{\rm W} \sim \frac{\alpha^2}{m^2_{\rm WIMP}} \sim 3\times10^{-26}{\rm cm^3 s^{-1}}$$

  - Mass scale O(GeV)-O(TeV), makes them cold dark matter
  - Provides benchmark for indirect detection: thermally-produced WIMPs

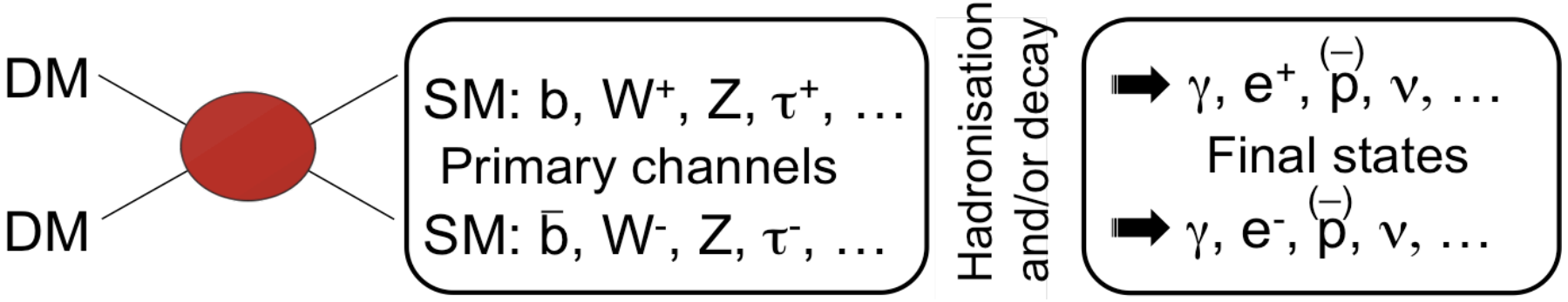
- WIMP candidates from a variety of BSM theories : SUSY, Extra-dimensions, …

pMSSM scan




Roszkowski et al., arXiv:1405.4289

# GAMMA-RAYS FROM DM ANNIHILATION




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

Particle Physics :

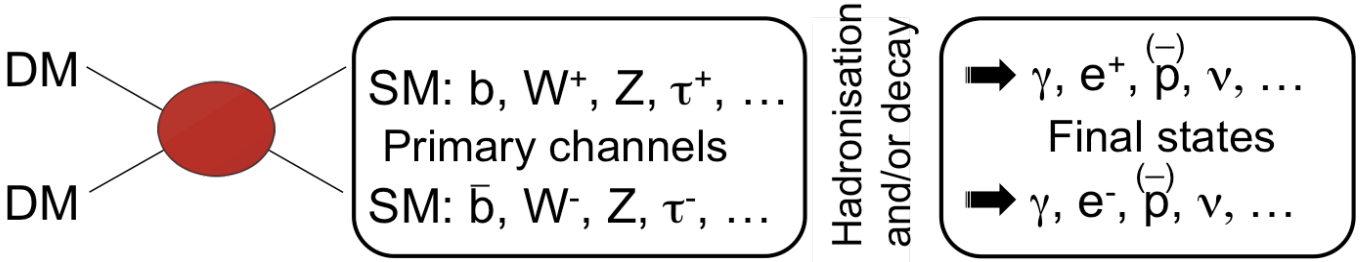
- Cross sections
- Differential photon yield
- DM particle mass

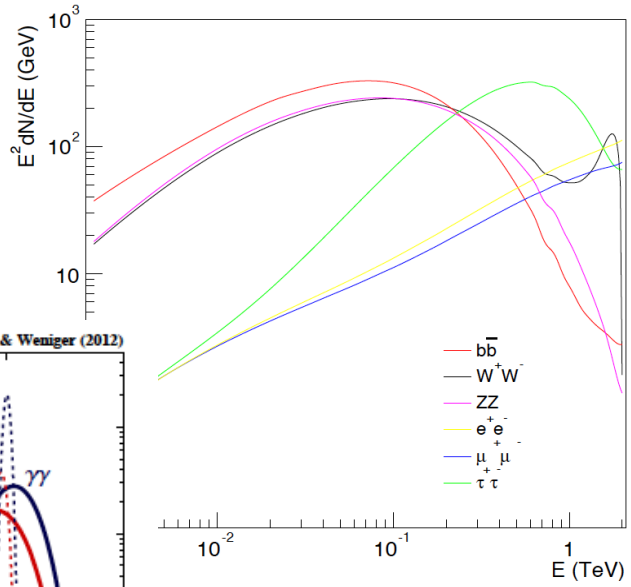
Astrophysics

→ modelling required for the DM distribution in the object

- Can reveal the abundance and distribution of DM
- Do not suffer from propagation effects at Galactic scale
- Characteristic features may be present in the spectrum in the 20 GeV -300 TeV energy range

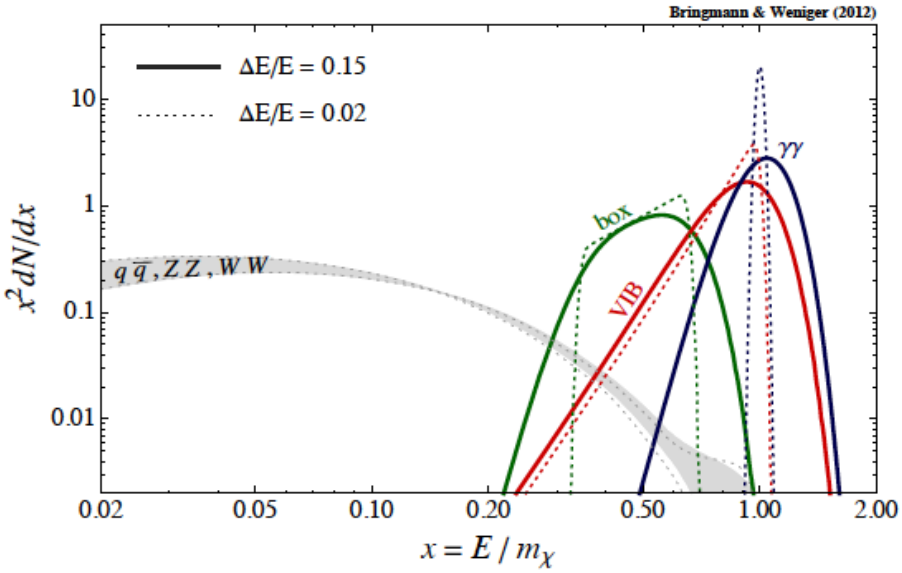
# GAMMA-RAY SIGNATURE




***Continuum emission***
("Secondary photons")
→ from fragmentation of quarks/massive gauge bosons (via $\pi_0$ decay)

***Gamma-ray lines***
→ from two-body annihilation into photons
→ forbidden at tree-level, generically suppressed by $O(\alpha^2)$



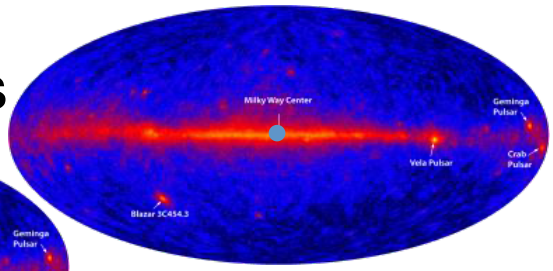

***Virtual Internal Bremsstrahlung (VIB)***
→ radiative correction to processes with charged final states
→ generically suppressed by $O(\alpha)$

Identification of DM is possible :
→ DM gamma-ray spectrum tells the DM mass and reaction process

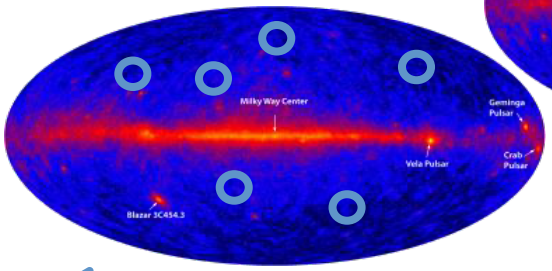
# TARGETS AND CHALLENGES

Likelihood of Strong signal

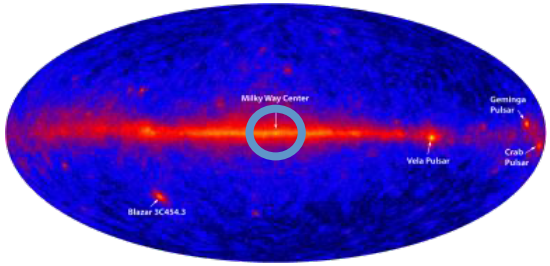
Galactic Centre




Galaxy clusters



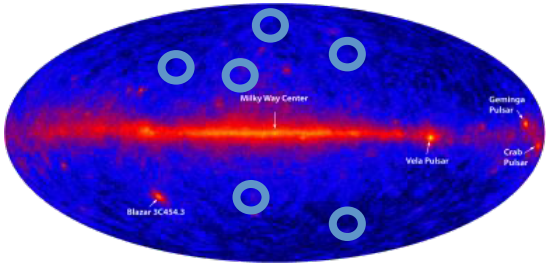

Galactic Center halo




Large Uncertainties

Robust Constraints

Dwarf Galaxies




- DM density matters …
- Astrophysical background matters as well

# CTA DARK MATTER STRATEGY

- 10 years of observations
- First 3 years:
  - the Galactic Centre halo
    *Fair balance between brightness and robustness*
  - Cross-check with an ultra-faint dwarf galaxy
    *Cleaner environment but weaker signal*

→ *500 hours in the first three years on GC halo*

→ *300 hours on the best dSph*

# CTA DARK MATTER STRATEGY

- 10 years of observations
- First 3 years:
  - the Galactic Centre halo
    *Fair balance between brightness and robustness*
  - Cross-check with an ultra-faint dwarf galaxy
    *Cleaner environment but weaker signal*

- Follow-up observations:
  - In case of detection at GC halo:
    - $\sigma v$ high enough : check DM signal towards best dSph with otherwise deep observations of GC region
  - If no detection :
    - focus observations on the best target at that time and produce legacy limits

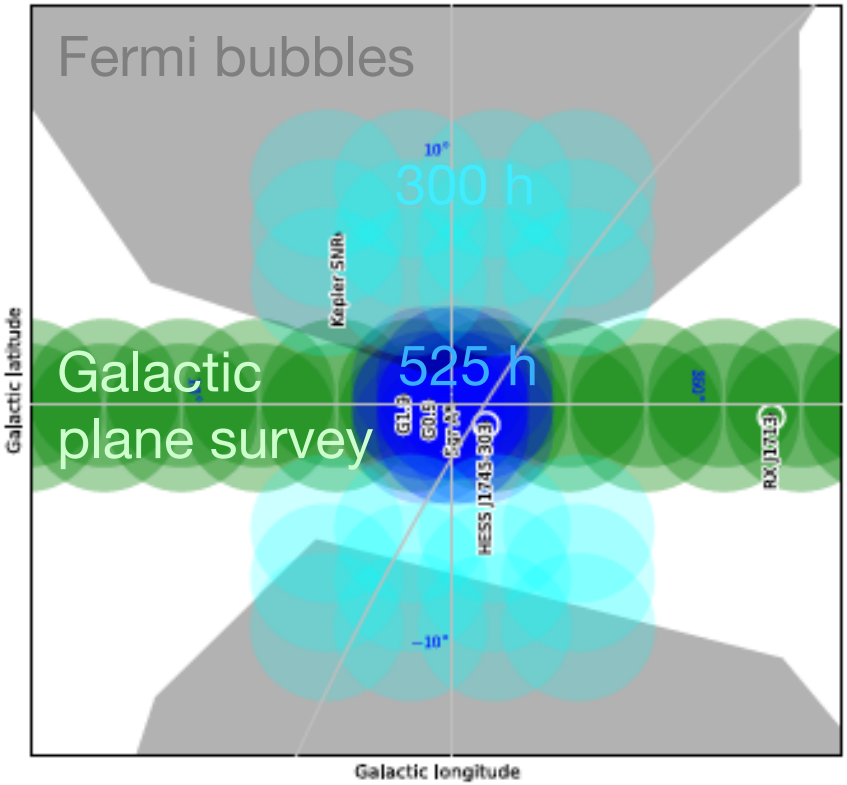
# DEEP OBSERVATIONS OF GC

- A variety of science topics covered :
  - Centre of DM halo
  - all of the known diffuse emission + nearby VHE sources
  - multiple SNRs (e.g. G 0.9, G 1.9,…)
  - multiple PWNe (e.g. Mouse)
  - Central Radio lobes (central ±1°) and arc features

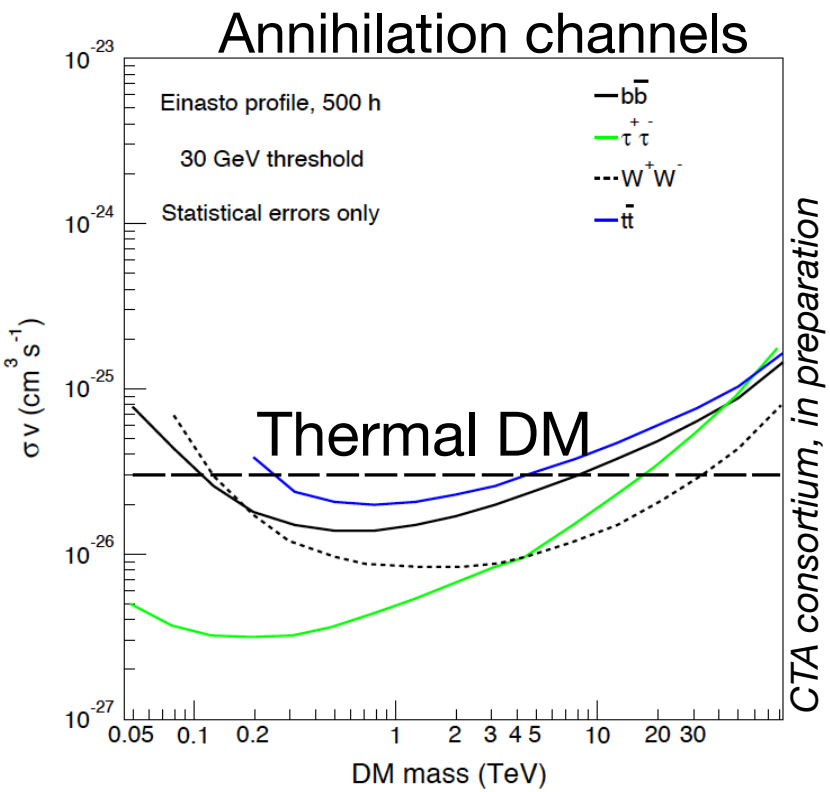
- Deep exposure in the inner 5° around Sgr A*: 525 h

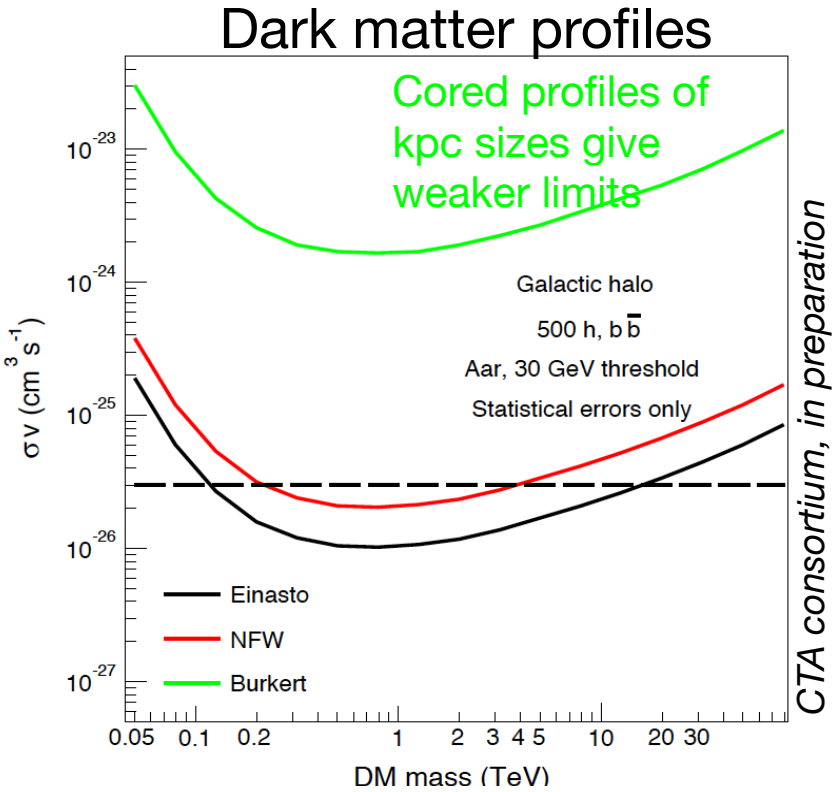
- Extended survey: 300 h 10°x10°
  - improves sensititivity to core profiles

- Legacy dataset



# GALACTIC CENTRE: SENSITIVITY

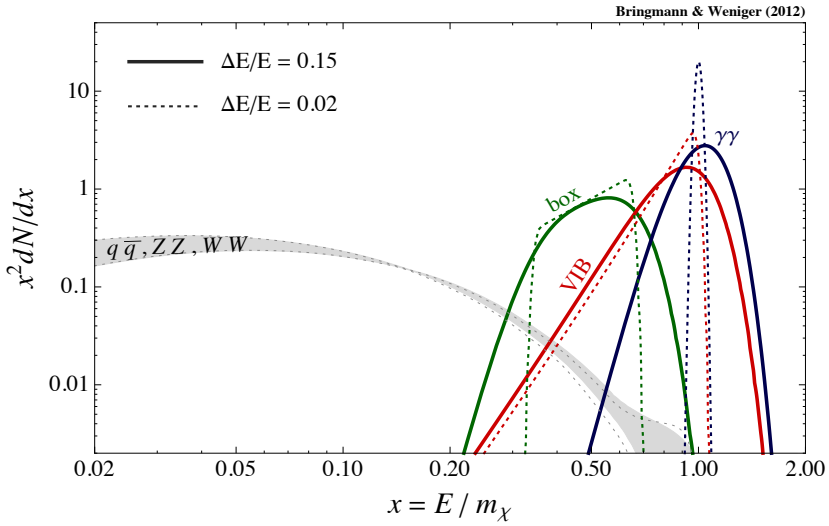



- Natural scale is within the reach of CTA for cuspy profiles:
  - for the first time in indirect detection with IACTs, CTA has the sensitivity to probe the expected parameter region for WIMPs
- Impact of the Galactic diffuse emission and systematics
- Work in progress to evaluate and control of systematics

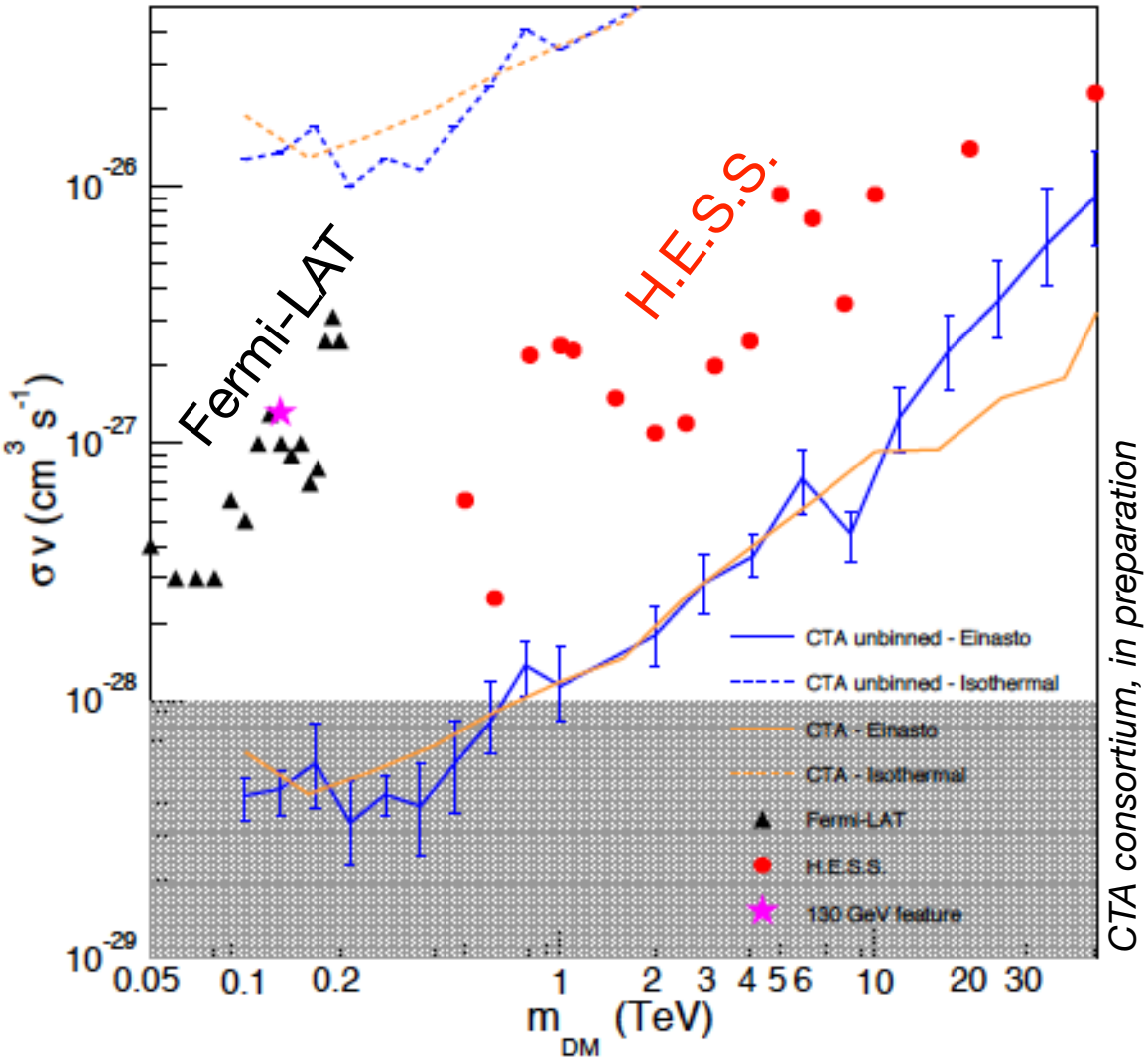
Silverwood, et al., JCAP 03, 055 (2015)
Lefranc, et al., PRD 91, 12 (2015)

# GALACTIC CENTRE: LINE SIGNAL

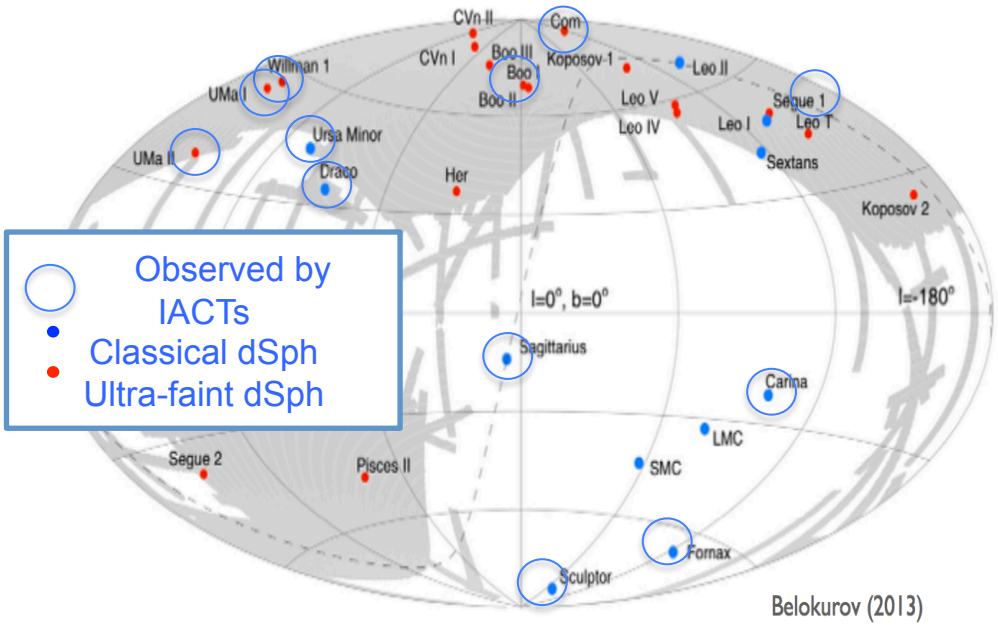



- CTA is also ideally suited to search for line signatures
  → smoking-gun for WIMPs

- Galactic Center region is the optimal place



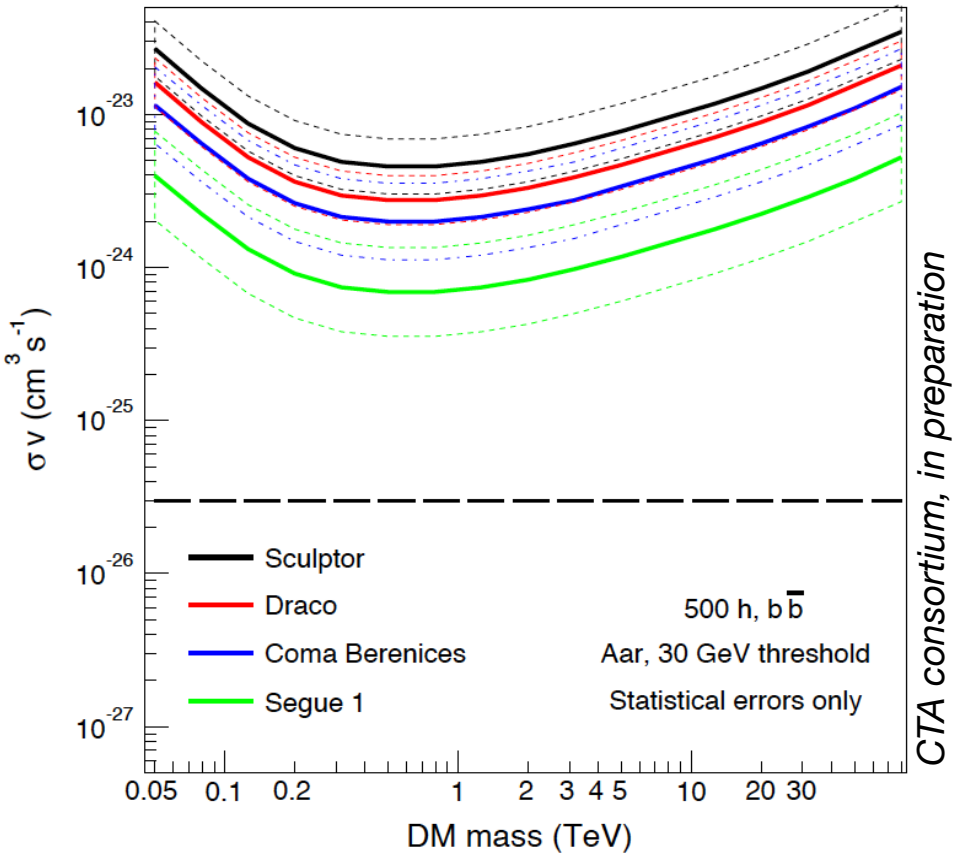
# DARK TARGETS


- A large number of DM subhalos are predicted to populate the Milky Way DM halo
  - Dwarf spheroidal galaxies
  - DM clumps (no gas, no stars)

- Dwarf galaxies : about 20 known
  - Most DM-dominated systems in the Universe
  - Environments with favorably low standard gamma-ray backgrounds
  - No standard VHE signal detected so far

# DWARF GALAXIES




| Target | Dec. [deg.] | Distance [kpc] | $\log_{10}$ (J/GeV$^2$cm$^{-5}$) |
|---|---|---|---|
| Sculptor | -83.2 | 79 | 18.47 ± 0.18 |
| Draco | +34.7 | 82 | 18.69 ± 0.16 |
| Coma Berenices | +23.4 | 44 | 18.83 ± 0.25 |
| Segue 1 | +16.1 | 23 | 19.31 ± 0.29 |

- N.B. recent doubts on Segue 1 J-factor due to interlopers in stellar-kinematic samples.

  Bonnivard et al., arXiv:1506.08209
- Work needed to quantify the systematics on the J-factors for ultra-faint dSphs

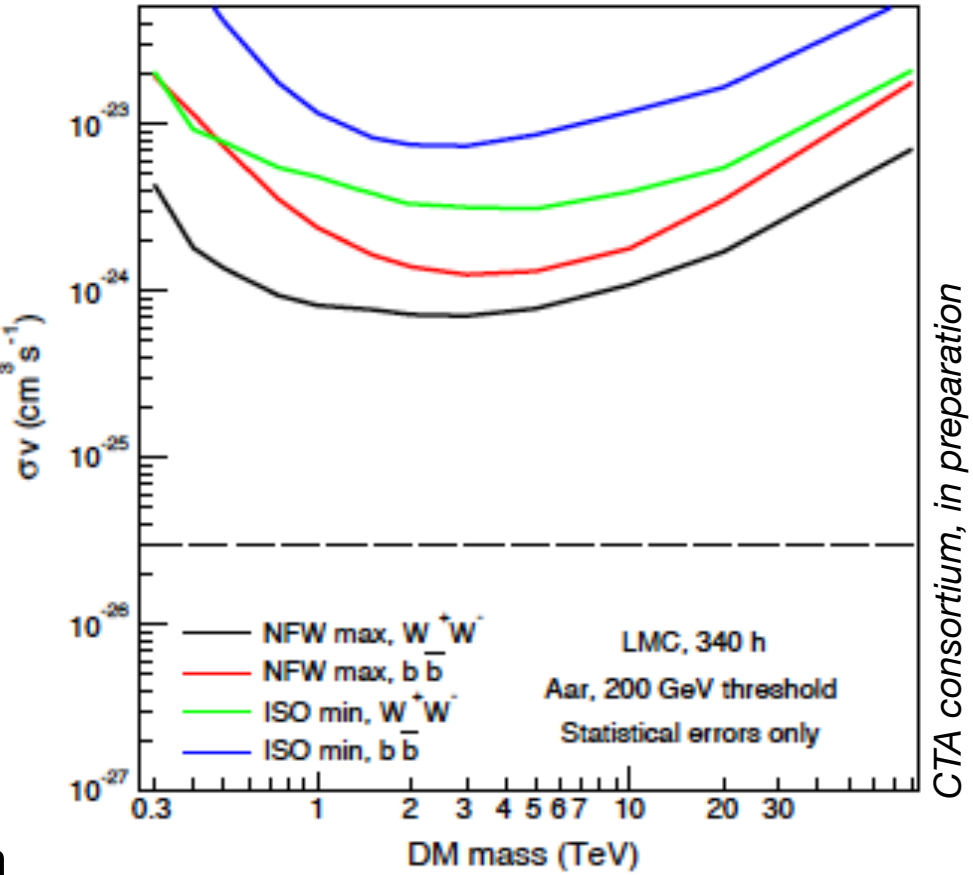
- New dwarf galaxy candidates discovered from the DES survey in the Southern hemisphere, e.g. Reticulum II
- More targets discovery expected in the future (Pan-STARRS, LSST, …)
- Will choose the most promising target with latest knowledge

# LARGE MAGELLANIC CLOUD

- A nearby satellite galaxy of the MW at 50 kpc
- Large DM content: ~$10^{10}$ Msun

- Astrophysical background:
  - diffuse gamma-ray background
  - TeV sources as recently detected by H.E.S.S. Science 347, 405 (2015)

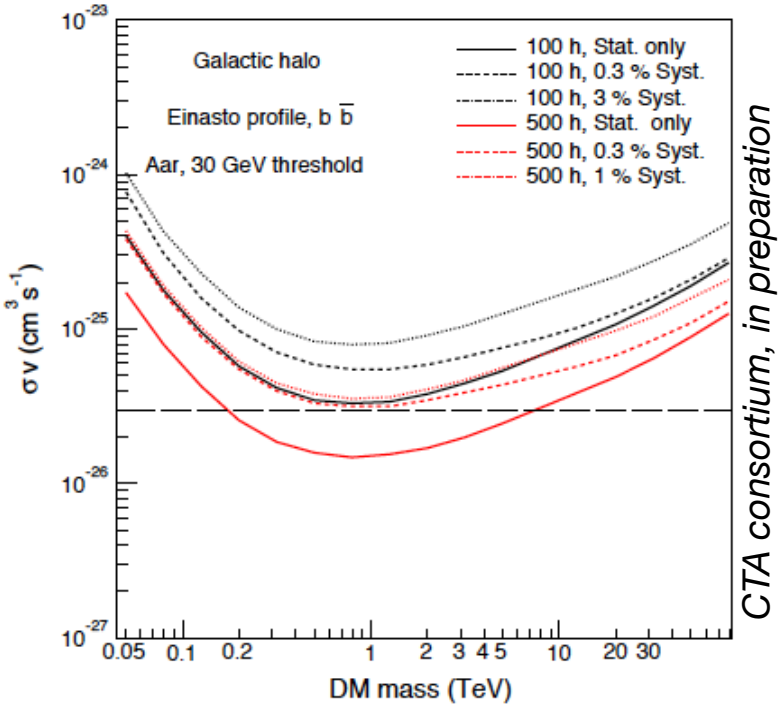
- Similar issues as the inner Milky Way halo

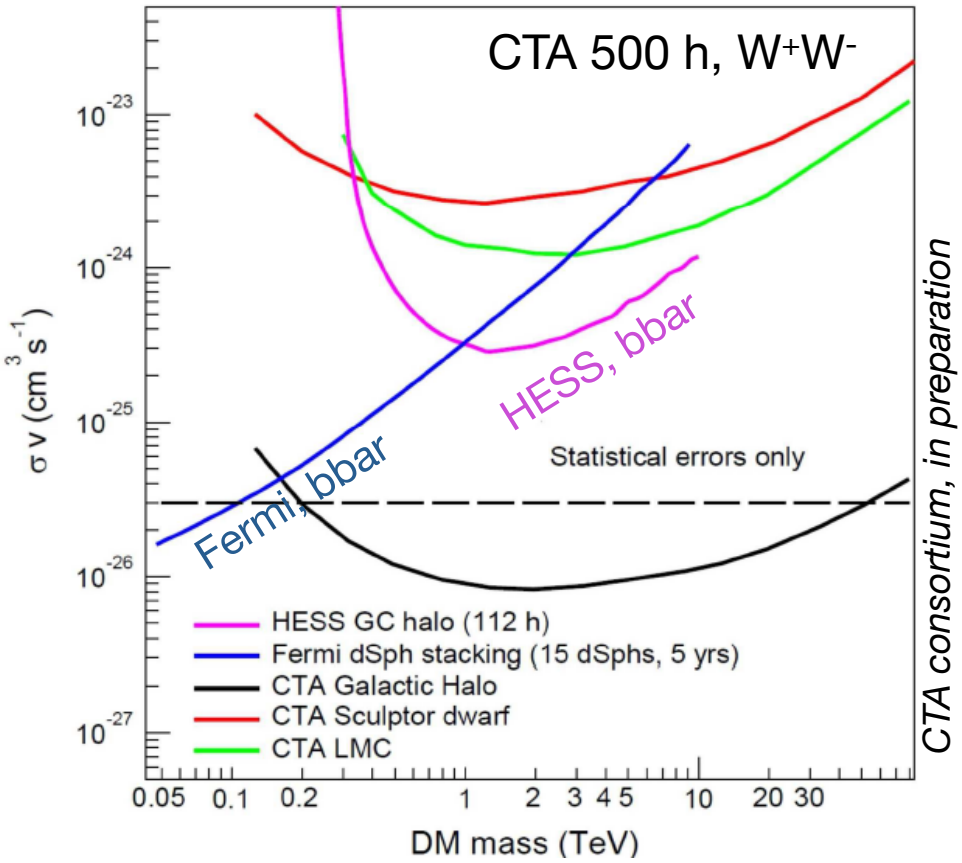



- Large zenith angle observation from Southern hemisphere → large energy threshold: ~200 GeV

# SENSITIVITY OF MAIN TARGETS

- For Galactic halo with cuspy profile, CTA can probe the thermal cross section
- Systematics must be controlled to reach the statistically possible sensitivity

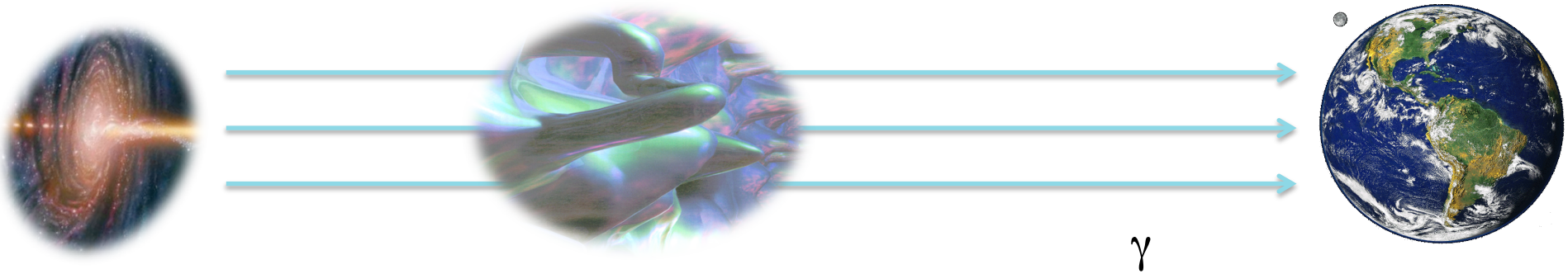


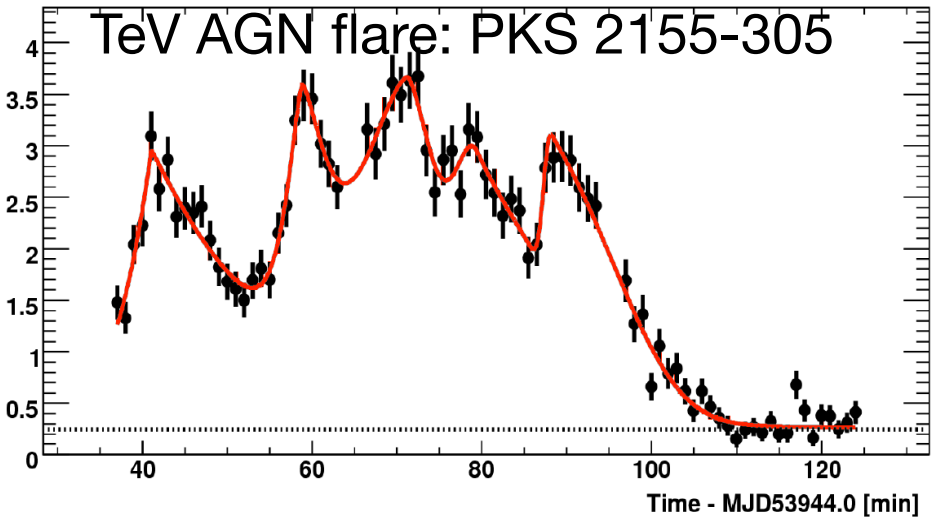

- Impact of correlated systematics
- Real instrumental and background systematics are correlated
- Extensive work in progress

# TEST OF LORENTZ INVARIANCE

- VHE photon propagation over cosmic distances

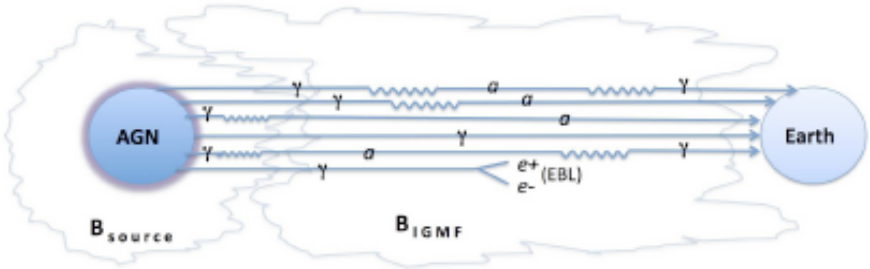



- Energy dependence of the dispersion relation of photons
  → search for photon energy dependent time lag
- The Planck scale for the linear term could be probed from detection of :
  - prompt emission of short and bright GRBs (such as GRB090510) ;
  - TeV photons from AGN flares
- Gamma-ray horizon measurements with hard spectrum distant AGNs



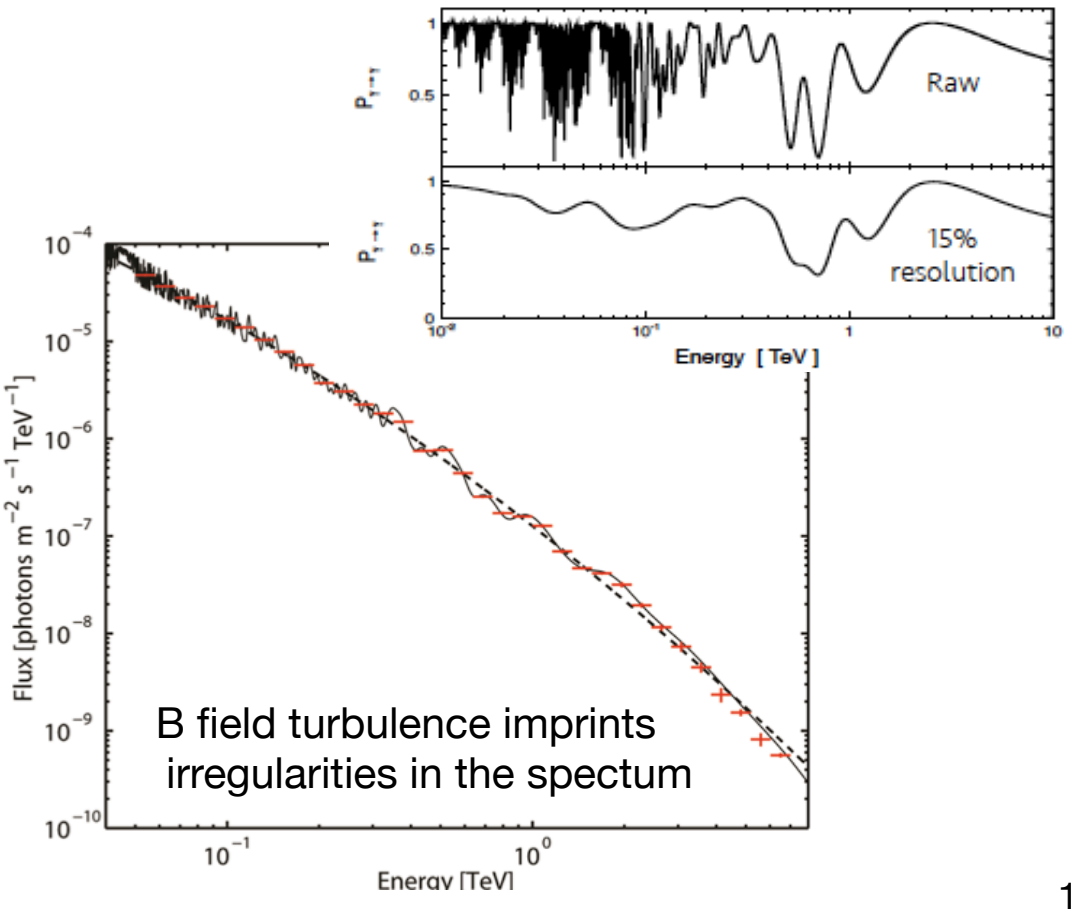
# AXION-LIKE PARTICLE SEARCHES

- Conversion of gamma-rays to/from axion-like particles (ALPs) can create
  - distinctive features in the spectra of gamma-ray sources ;
  - increased transparency of the universe by reducing the EBL absorption




- Ideal sources

  - Intrinsically bright at GeV-TeV energies (e.g. flaring AGN)
  - Large magnetic field strength integrated along the line of sight



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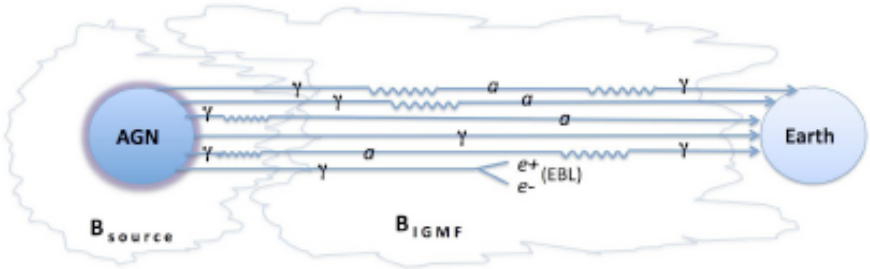
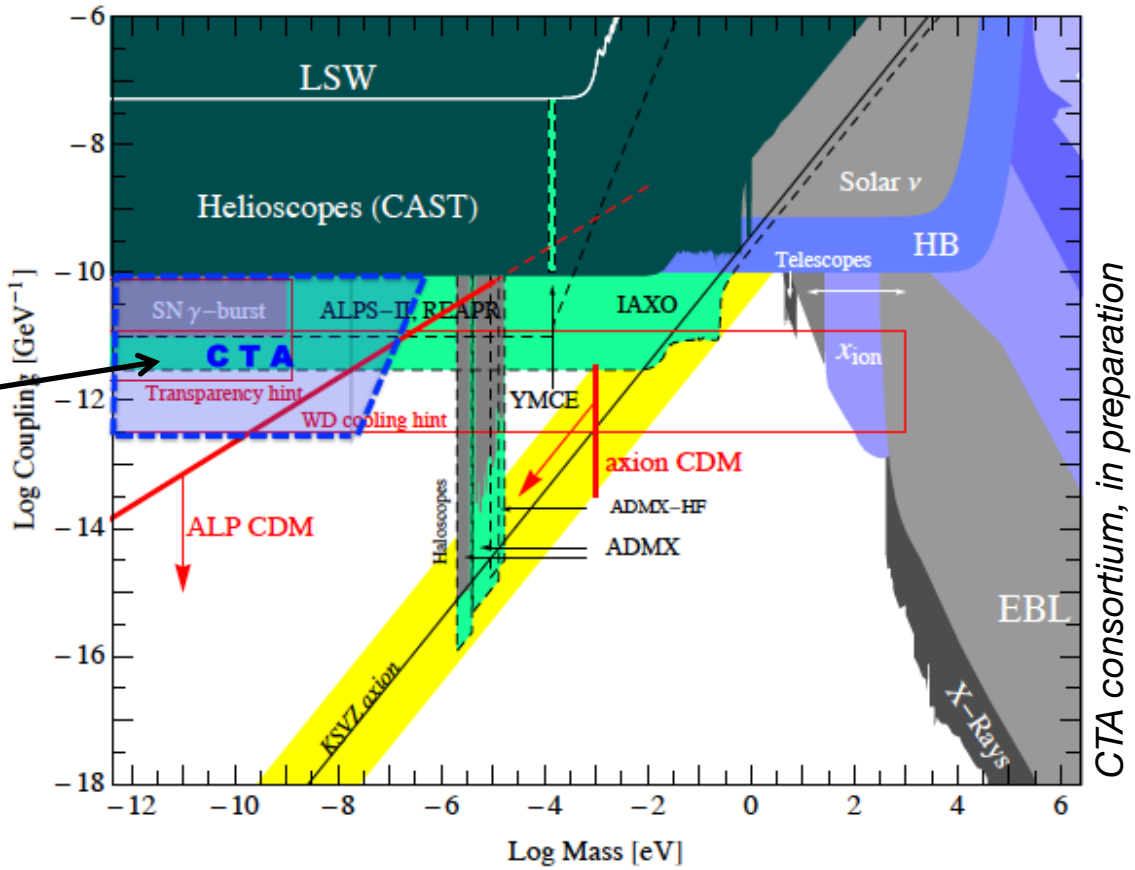


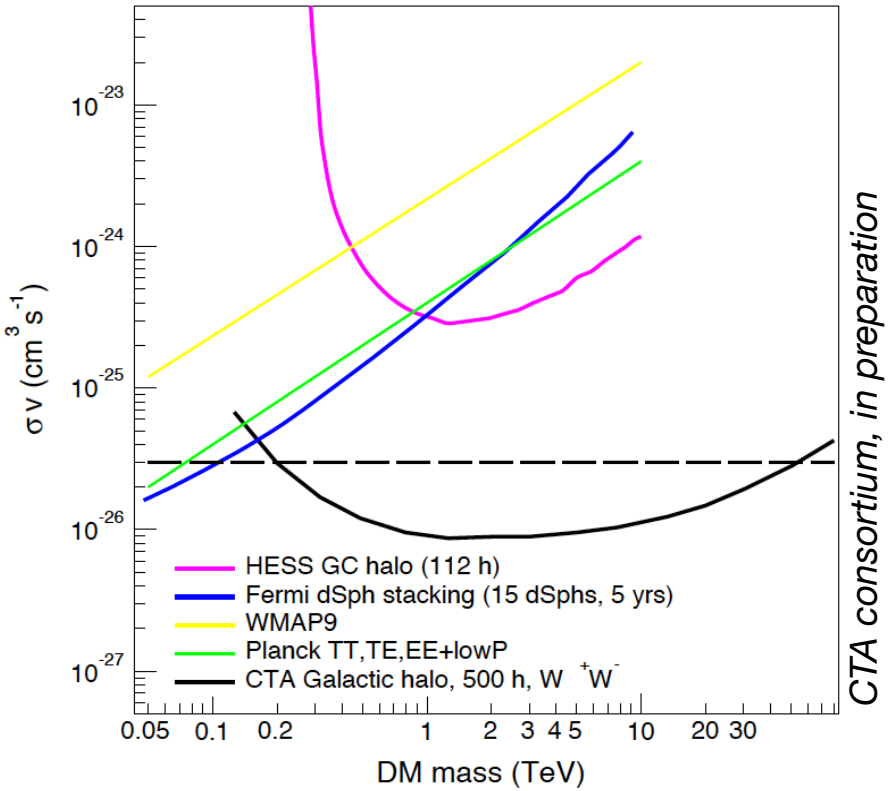

- Parameter space probed by CTA
  - Some ALP CDM models can be tested at neV mass scale




*CTA consortium, in preparation*

# SUMMARY

- Great possibility to discovery dark matter with Galactic Centre observations
  - CTA is the unique player in some regions of the parameter space
- CTA has good prospects for reaching WIMP models with thermal relic cross section for masses > 200 GeV
  - First time ever that natural scale for the cross section can be probed




- CTA also is sensitive to Axion-Like Particles in part of phase space relevant for Dark Matter
- Fermi/CTA will be able to probe thermal WIMPs from a few GeV up to a few tens of TeV
- CTA will be complementary to LHC/direct searches/astrophysical probes