1st INAF MA4 Workshop, 6-7 June 2016, Bologna

Indirect Dark Matter searches in gamma-rays from space-based and ground-based instruments

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and
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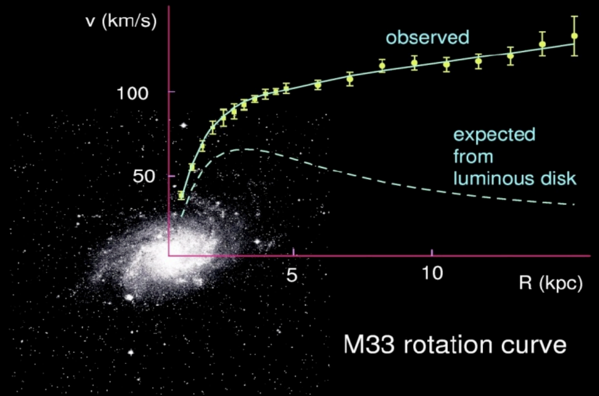
Outline

- ✧ Intro: Indirect Dark Matter searches and gamma-rays instruments
- ✧ Current achievements and prospects
- ✧ Summary and outlook

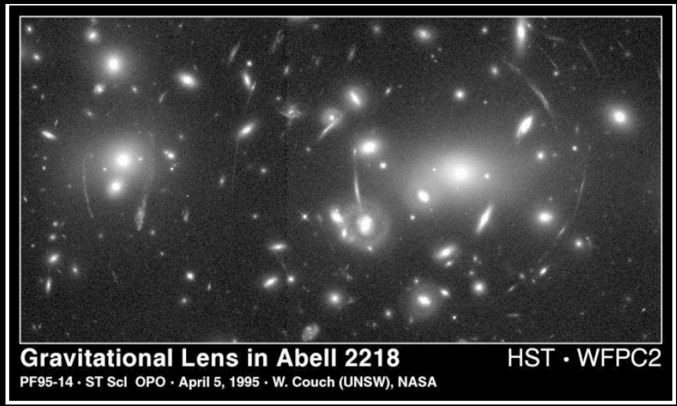
Dark Matter evidence

✧ Compelling evidences from a large (~85%) non-baryonic component of the matter density of the Universe at all astrophysical scales (kpc to Gpc)

Galaxy rotational curves

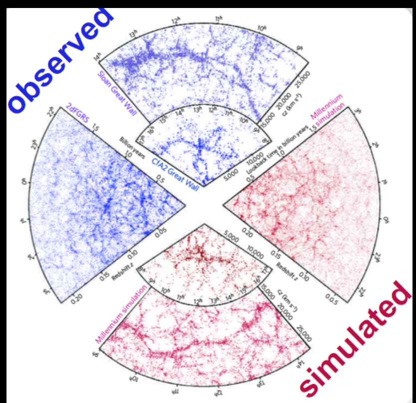


Gravitational lensing

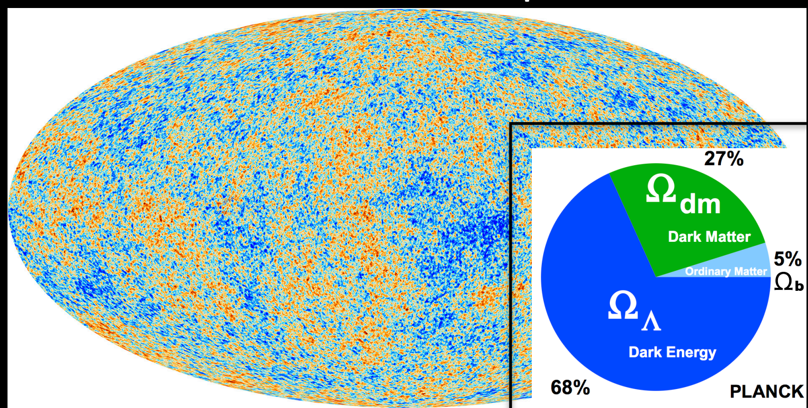


Colliding clusters

Large-scale structure



CMB anisotropies



ΛCDM model seems to fit all current cosmological data

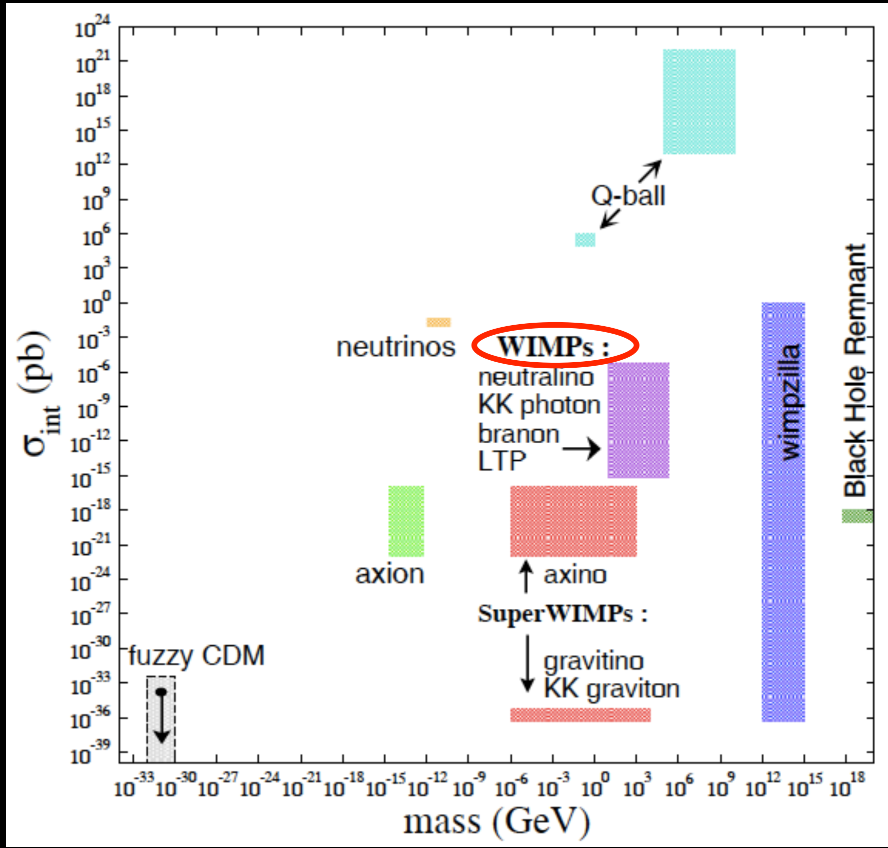
Planck Coll. 2015, *arXiv:1502.01589* (accepted by A&A)

Likely scenario: (WIMPy) Particle Dark Matter

✧ Standard Cosmological scenario:
Λ-Cold-Dark-Matter (ΛCDM), Ω_{DM}~0.27

✧ WIMPs are a class of particularly interesting CDM candidates:
- Neutral electric and color charges
- Interaction at weak scale
- Stable on cosmological scales
- Correct relic density
- Massive
- NON-BARYONIC origin
- May produce signals detectable by current or next-generation experiments

✧ Several SM extensions contain WIMP candidates: Supersymmetry (SUSY), minimal SM extensions, extra dimensions models, and others

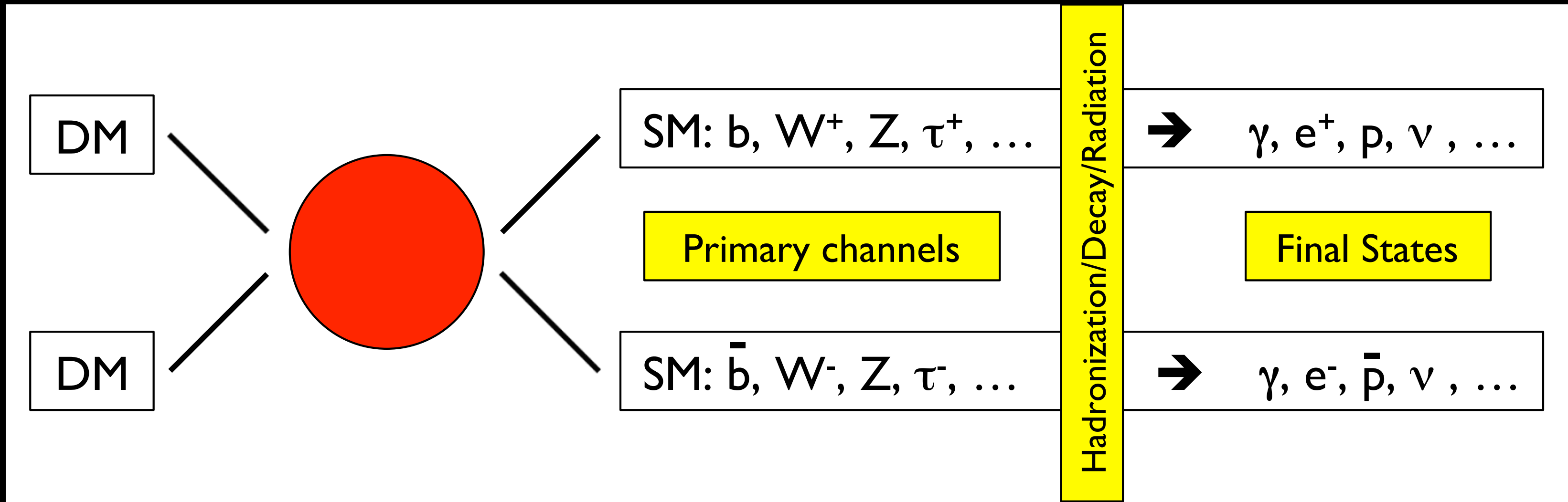


Present WIMPs mass range:
$m_{DM} \gtrsim$ 10 GeV up to tens of TeV
$<\sigma v_{DMDM}> \sim 3 \times 10^{-26}\ cm^3 \cdot s^{-1}$

Indirect Dark Matter searches

✧ DM searches: **Direct / Indirect / Direct Production / Astrophysical Probes**

✧ Indirect searches for detection of SM products (**including gamma-rays**) from annihilation or decay of Dark Matter particles:



✧ Gamma-rays as final states are of major interest because:

- **do not suffer from propagation effects**
- trace back to abundance / distribution of DM
- show peculiar spectral features (*smocking guns*)

➔ Identification of DM mass and reaction process

➔ Disentangle from astrophys. bkg

Indirect Dark Matter searches

✧ Expected **differential gamma-ray fluxes:**

$$\frac{d\Phi(\Delta\Omega)}{dE'} = \frac{d\Phi^{PP}}{dE'} \times J(\Delta\Omega)$$

	Particle Physics factor:	Astrophysical factor:
Annihilation:	$\frac{d\Phi^{PP}}{dE'} = \frac{1}{4\pi}\frac{\langle\sigma_{ann}v\rangle}{2m_\chi^2}\frac{dN}{dE'}$	$J_{ann}(\Delta\Omega) = \int_{\Delta\Omega}\int_{los}\rho^2(l,\Omega)dl\,d\Omega.$
Decay:	$\frac{d\Phi^{PP}}{dE'} = \frac{1}{4\pi\,\tau_\chi m_\chi}\frac{dN}{dE'}$	$J_{dec}(\Delta\Omega) = \int_{\Delta\Omega}\int_{los}\rho\,(l,\Omega)dl\,d\Omega.$
	Large uncertainties from Fund. Phys. No target dependences (straightforward stacking analysis)	Large uncertainties from DM profiles (robust limits from less uncertain targets)

Main targets

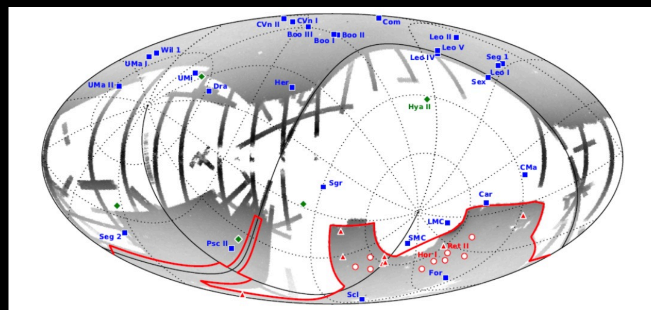
✧ *Galactic center?*
+ Highest *J-factor*
– Very high astroph. bkg
– Uncertainties on inner DM distribution
– Southern Hemisphere

✧ *Galactic halo?*
+ High *J-factor*
– Not fully-free from astroph. bkg
– Extended
– Southern Hemisphere

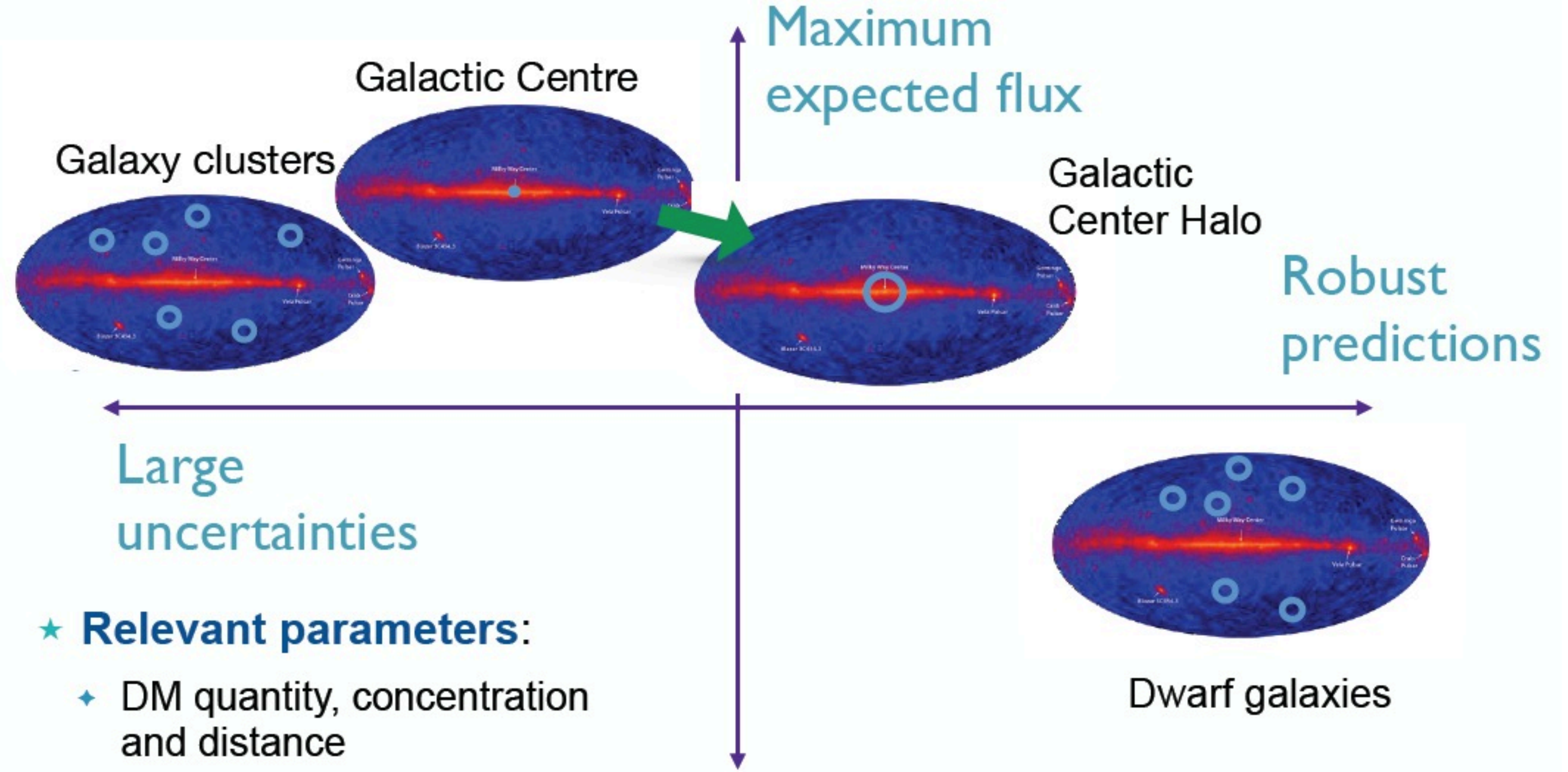
✧ *Galaxy Clusters?*
+ Huge amount of DM
– High astroph. bkg
– Extended
– High uncertainties on *J-factors*

✧ *DM Clumps?*
+ Free from astroph. bkg
+ Nearby and numerous
– To be found!
– Bright enough?

✧ *Dwarf Galaxies?*
+ DM dominated (high M/L ratios)
+ Free from astroph. bkg
+ Close (<~100 kpc)
+ Slightly extended at most
+ Less uncertainties on *J-factors*
– *J-factors* ~100 lower than for GC



Main targets



- **Relevant parameters**:
  - DM quantity, concentration and distance
  - Uncertainties
  - Astrophysical background

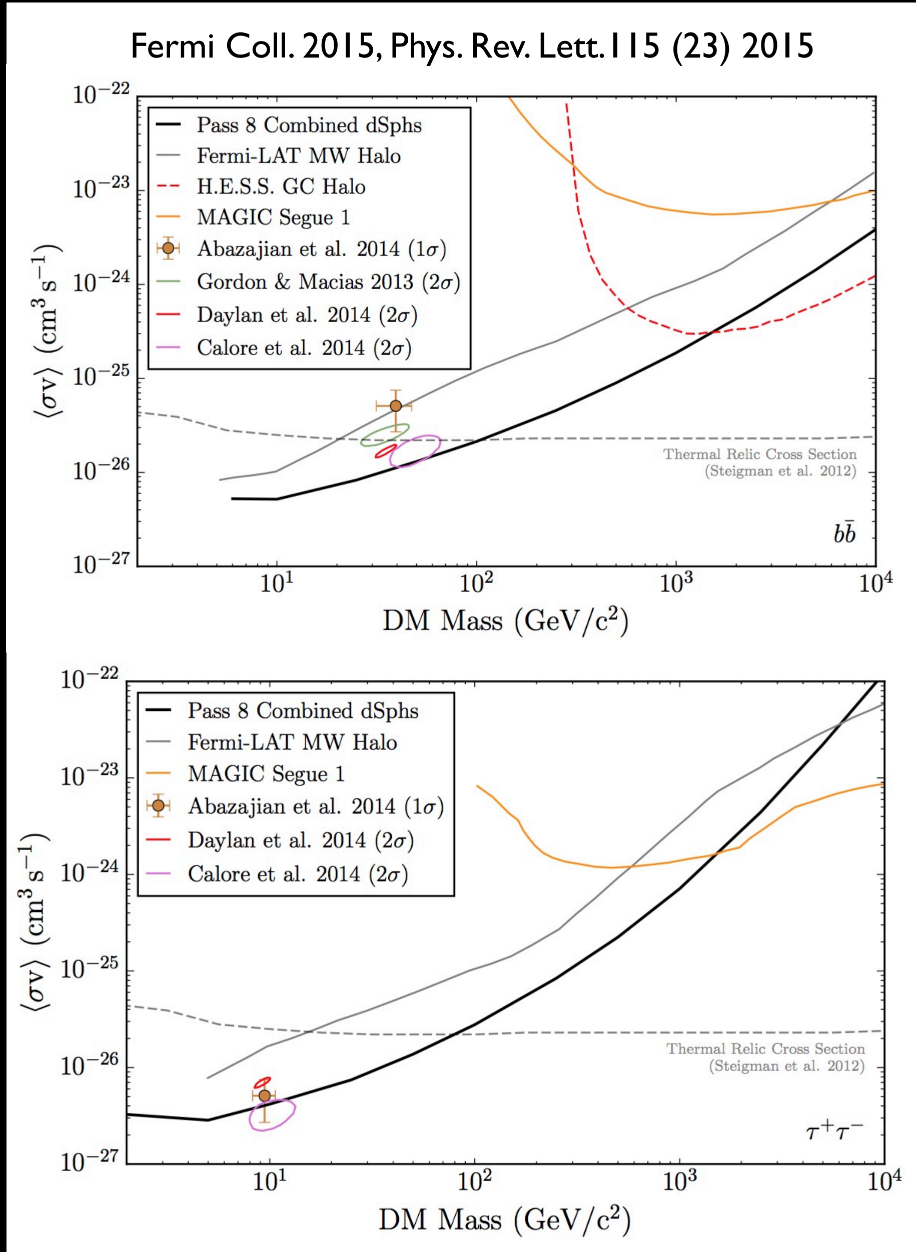
Gamma-ray instruments

See talks of Session E: "Satelliti e telescopi Gamma"

Current achievements

- Current most constraining results up to ~TeV mass value from 6-years combined dSphs from **Fermi-LAT** (limits for m_{χ}<~100GeV below thermal cross-section)
- **H.E.S.S.** galactic halo results are the strongest above ~1TeV (*but may be affected by rather high uncertainties from DM profile assumption*)
- **MAGIC** Segue1 limits are the strongest IACTs results from dSphs (most robust limits above ~TeV)

Fermi-LAT and ground-based instruments are complementary for indirect DM searches



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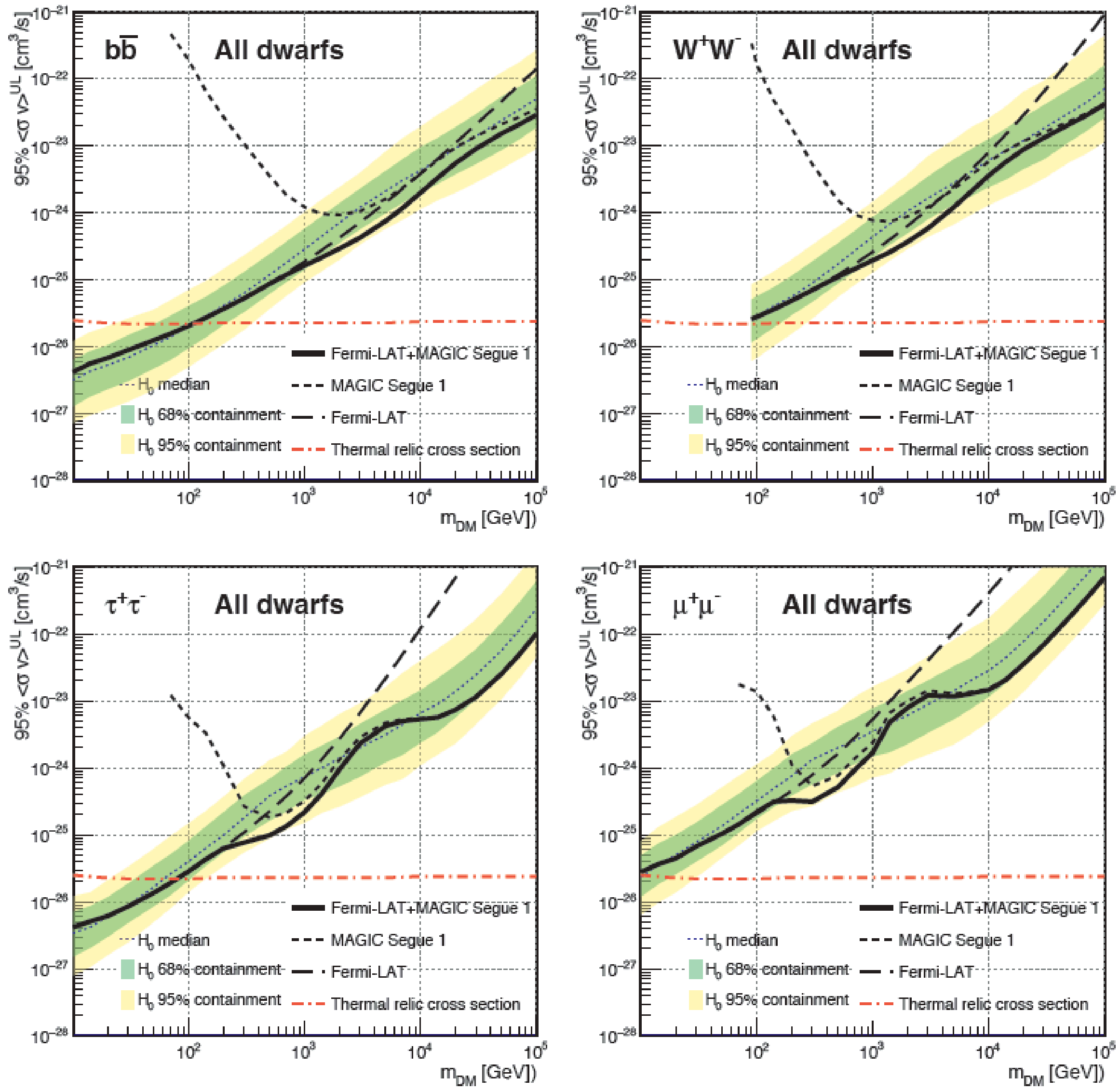
Current achievements

Combined Fermi-LAT and MAGIC limits on dSPhs through the “*Full Likelihood* analysis” by *J. Aleksić, J. Rico, M. Martinez JCAP 10 (2012) 032 (arXiv:1209.5589*

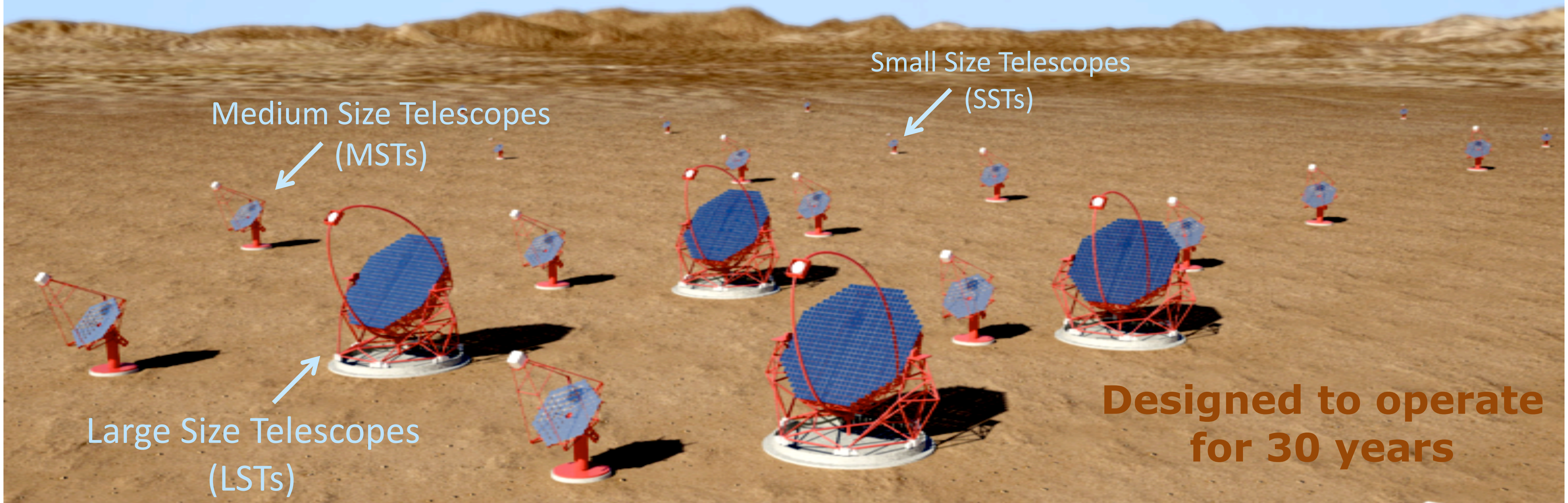
- coherent limits window from 10 GeV to 100 TeV (widest range explored so far)
- better global limits in the mass overlapping regions (up to a factor ~2)
- above ~TeV (depending on the considering channel) IACTs dominate for discovery capability and/or achievement of best limits

MAGIC Coll. + M.Wood et al., JCAP 02 (039) 2016



The Cherenkov Telescope Array (CTA) observatory

- Next generation ground based Gamma-ray Observatory
- Open observatory
- Two sites with total > 100 telescopes (LSTs+MSTs+SSTs)
  - Southern Site: Near Paranal in Chile (selected for negotiations)
  - Northern Site: La Palma, Canary Islands (selected for negotiations)
- 31 nations, ~300M€ project

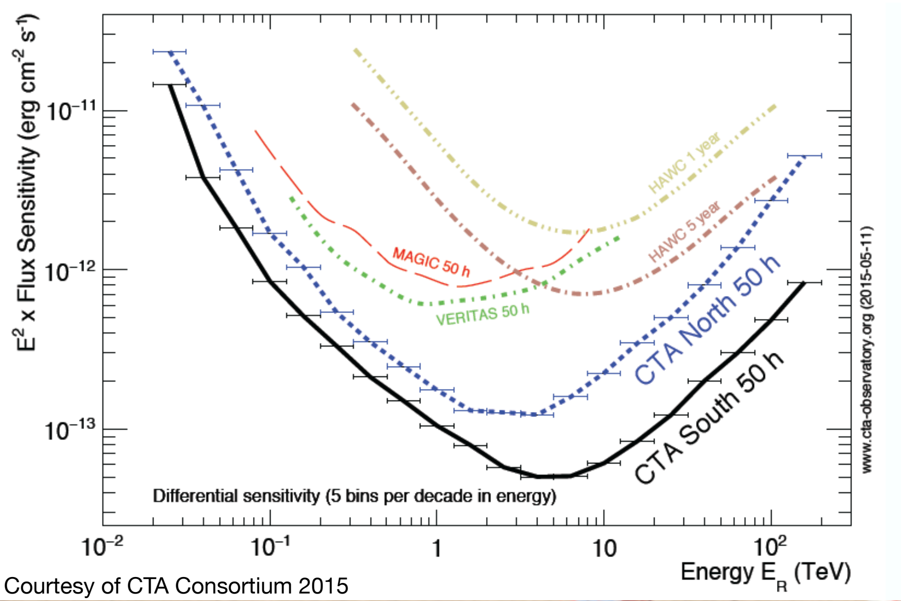


CTA ARRAY PERFORMANCE

Array configuration assumed for prospects shown here:

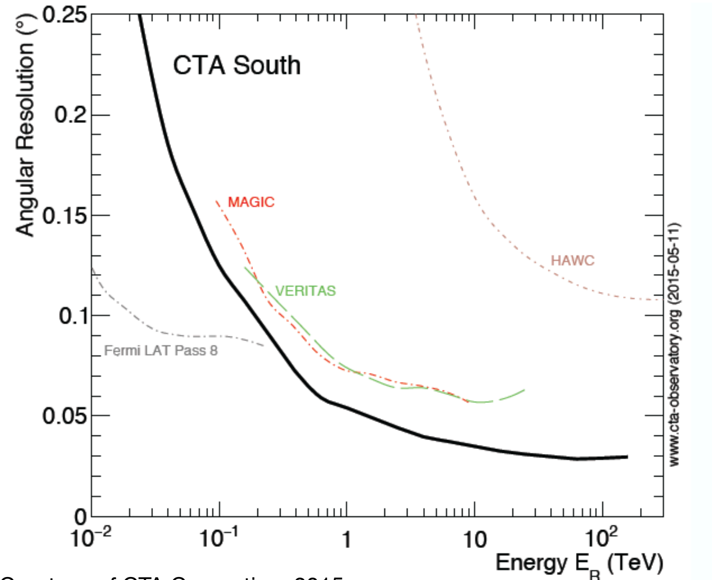
- Southern Site (~4km²):
  - 4 Large-size telescopes (LSTs)
  - 24 Medium-size telescopes (MSTs)
  - 72 Small-size telescopes (SSTs)
- Northern Site (~0.4km²):
  - 4 Large-size telescopes (LSTs)
  - 15 Medium-size telescopes (MSTs)

Sensitivity vs Energy



Courtesy of CTA Consortium 2015

Angular resolution (80% containment radius)



Courtesy of CTA Consortium 2015

CTA prospects

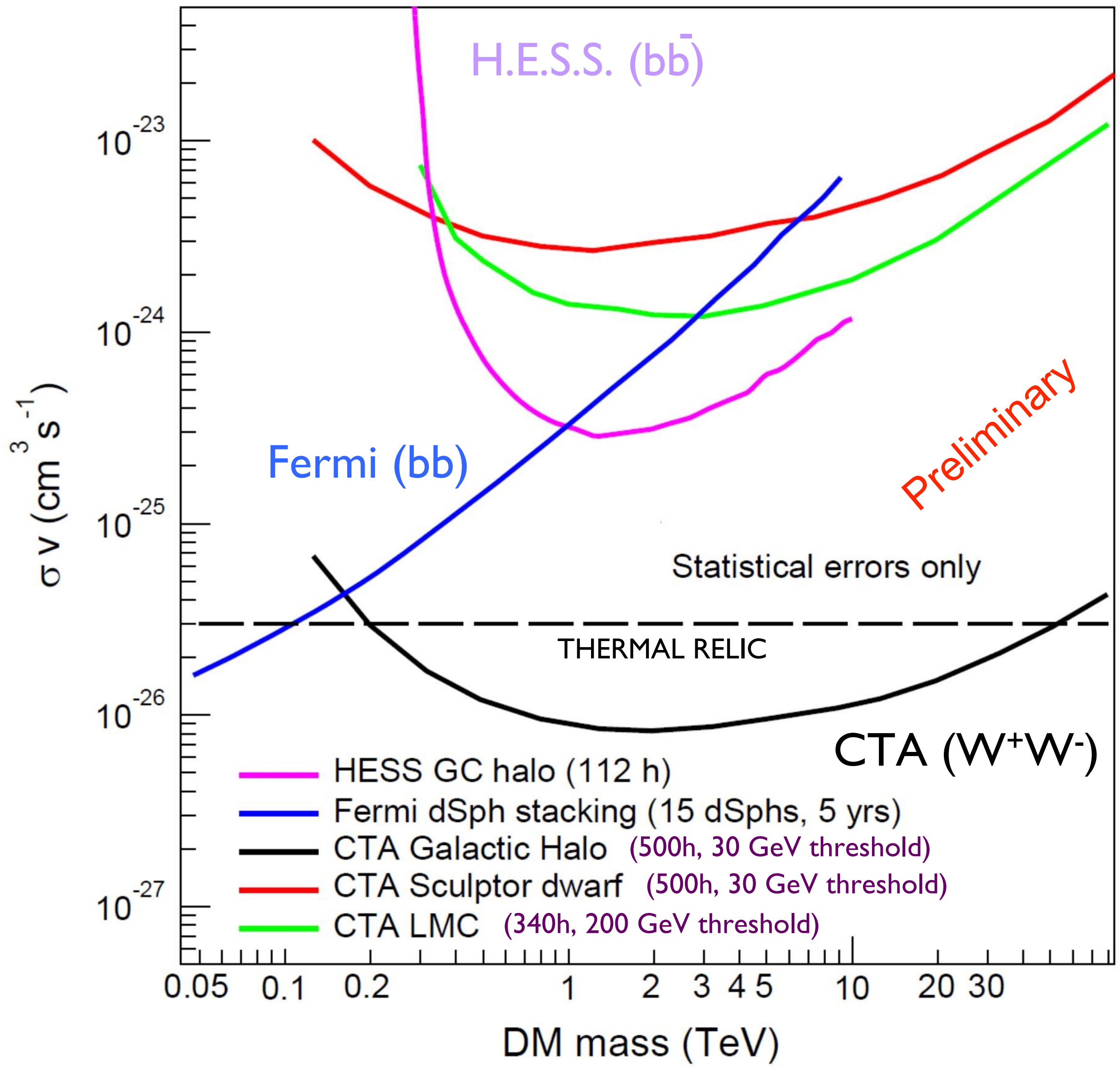
PROPOSED SCHEDULING

Table 4.1 – Strategy for dark matter observations over ten years with CTA. The first three years are devoted to the deep observation of the Galactic Centre (GC) together with the observation of the best ultra-faint dwarf galaxy. In case of non-detection of the GC, observations starting in the fourth year focus on the most promising target at that time to provide legacy constraints.

Year	1	2	3	4	5	6	7	8	9	10
Galactic halo	175 h	175 h	175 h							
Segue 1 (or best) dSph	100 h	100 h	100 h							
				in case of detection at GC, large σv						
Segue 1 (or best) dSph				150 h	150 h	150 h	150 h	150 h	150 h	150 h
Galactic halo				100 h	100 h	100 h	100 h	100 h	100 h	100 h
				in case of detection at GC, small σv						
Galactic halo				100 h	100 h	100 h	100 h	100 h	100 h	100 h
				in case of no detection at GC						
Best Target				100 h	100 h	100 h	100 h	100 h	100 h	100 h

CTA Consortium, in prep.

CTA prospects



- **For Galactic Halo with *cuspy* profile CTA can probe below thermal cross-section**
- Dwarfs observations for crosschecks in cleaner environments and robust long-term legacy limits
- Systematics must be controlled extremely well to achieve statistically-possible sensitivity

The ASTRI project

The **ASTRI Project** (led by INAF) has two main goals:

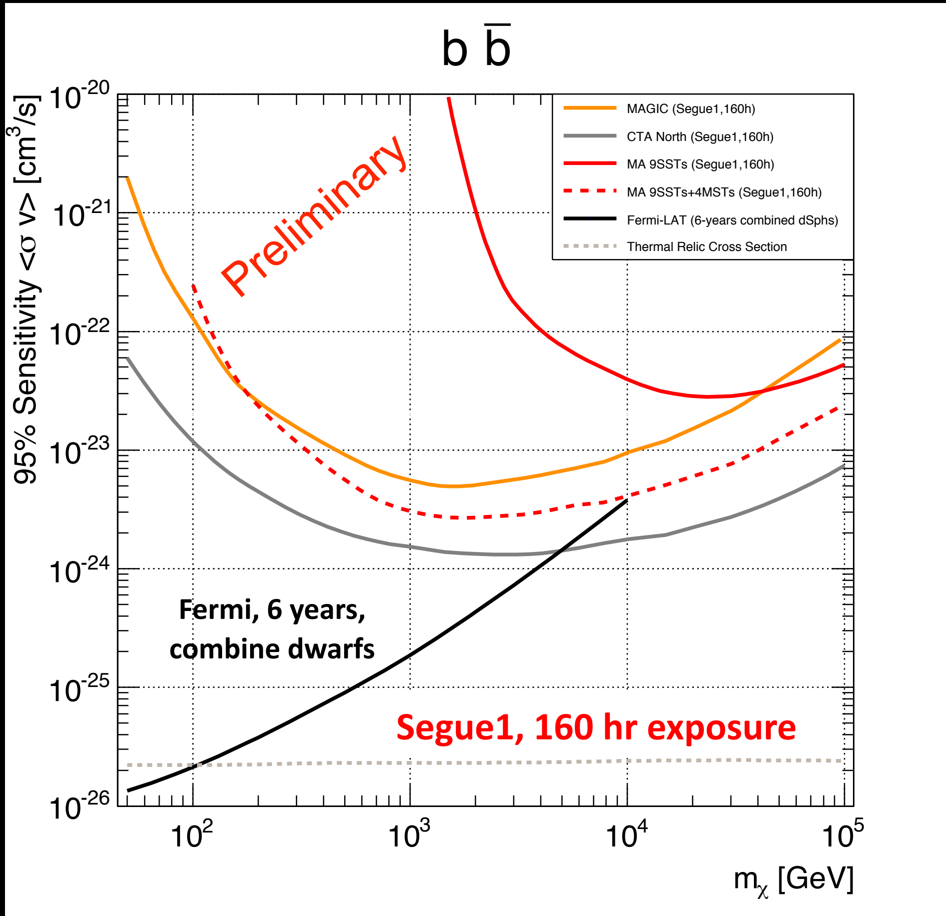
- an **end-to-end prototype** of the CTA small-size telescope in a dual mirror configuration (**ASTRI SST-2M**), inaugurated on 2014 Sept. 24th and currently under testing at the INAF observing station on Mt. Etna (Sicily)
- an **ASTRI mini-array** composed of **9 SST-2M telescopes** proposed to be installed at the chosen CTA Southern site in 2018

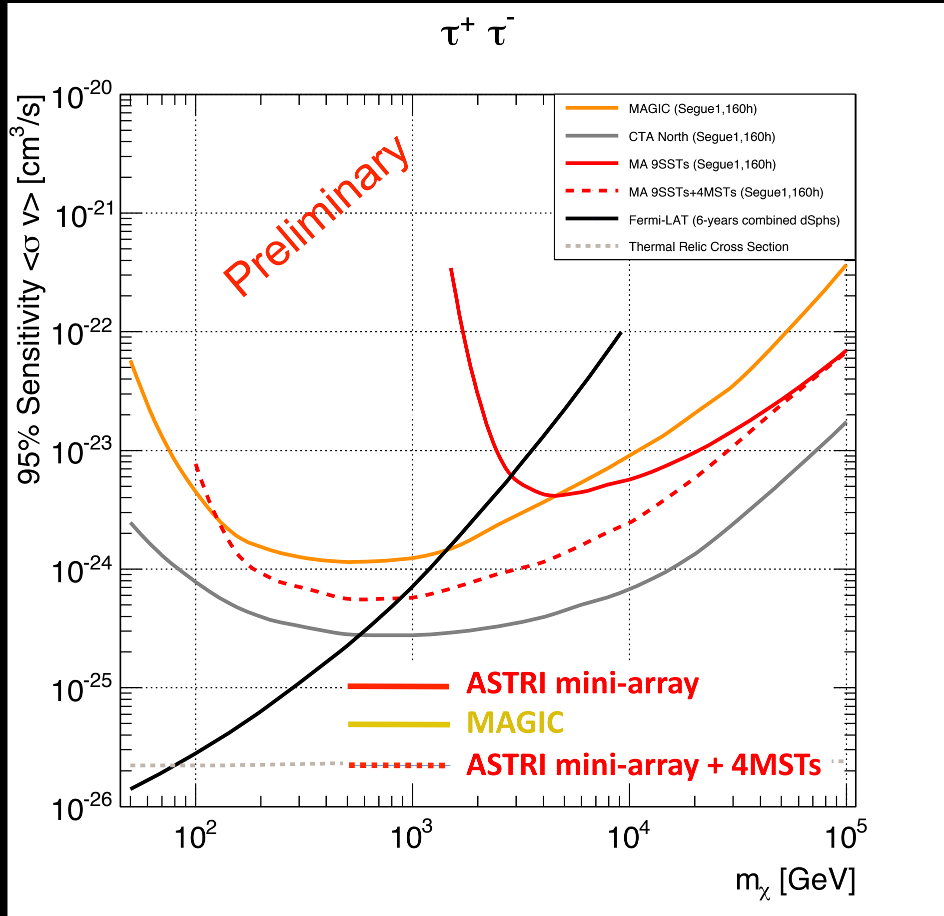

Inauguration @ Serra La Nave observing station (Mt. Etna, Sicily)
Credits: T. Abegg


Artistic view of the ASTRI mini-array @ CTA Southern site
Credits: A. Stamerra

ASTRI mini-array prospects

Giammaria, Lombardi et al., Proc. TAUP2015





MA(9SSTs): Limited prospects for m_χ > tens of TeV

MA(9SSTs+4MSTs): Promising prospects for m_χ > ~0.1TeV

MA(9SSTs): Interesting prospects for m_χ > few TeVs

MA(9SSTs+4MSTs): Promising prospects for m_χ > ~0.1TeV

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Summary

✧ Complementary between satellite and ground-based γ-ray instruments for indirect Dark Matter searches

- satellites dominate below ~TeV (some limits still below thermal cross-section)
- IACTs dominate above few hundreds of GeV

✧ Current best limits from Fermi-LAT dSphs stacked analysis, H.E.S.S Galactic Halo (*although high uncertainties in the DM profile*) and MAGIC dSphs (*robust but less constraining limits*)

✧ Current IACTs, like MAGIC, are actively carrying on indirect DM searches with different targets ➔ this enhances the chance of DM detection / limits can be combined with e.g. Fermi-LAT ones in order to improve overall limits and cover coherently a huge energy window

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Summary

✧ CTA will have a unique discovery potential for particle dark matter (in the > 200 GeV mass range) with Galactic Centre observations:

- For many annihilation channels CTA will test the canonical thermal relic annihilation cross section (in the case of a *cuspy* Galactic Halo density profile)
- Understanding and controlling systematics is of utmost importance

✧ Results will be complementary to direct detection and colliders, and the synergy with Fermi-LAT and new gamma-ray satellites (such as DAMPE and future Gamma-400) will be able to probe thermal WIMPs from a few GeV up to tens of TeV

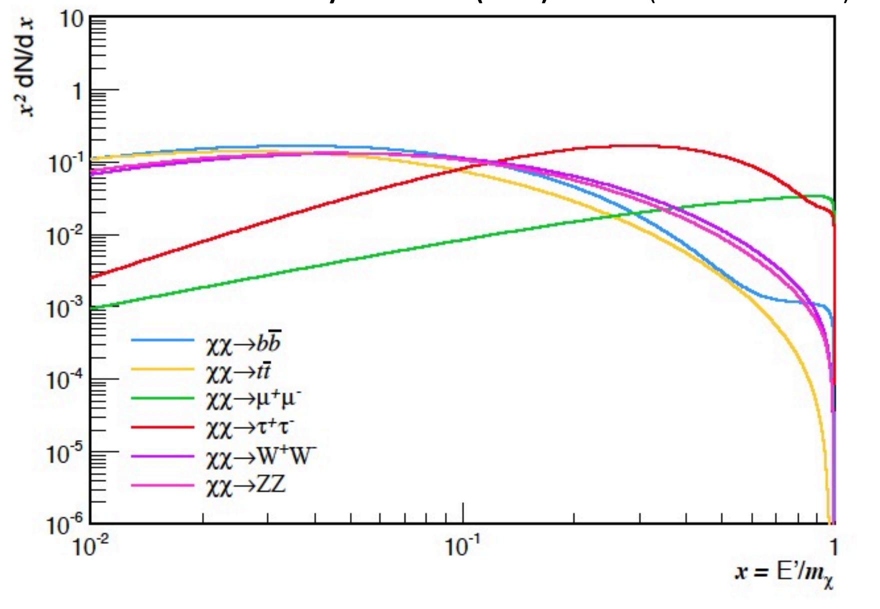
Backup

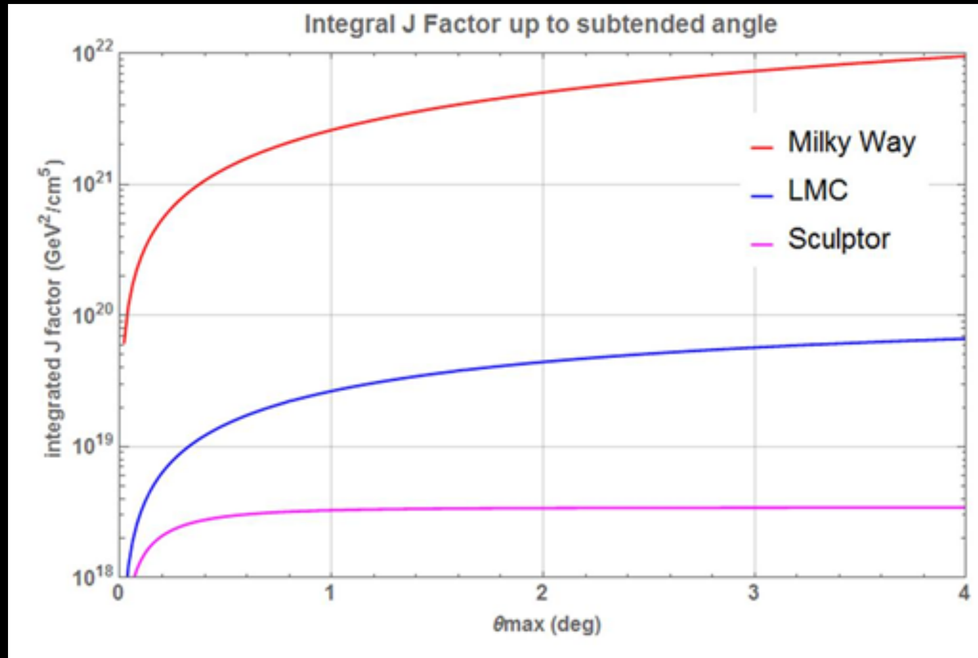
Indirect Dark Matter searches

- Expected **differential gamma-ray fluxes:**

$$\frac{d\Phi(\Delta\Omega)}{dE'} = \frac{d\Phi^{PP}}{dE'} \times J(\Delta\Omega)$$

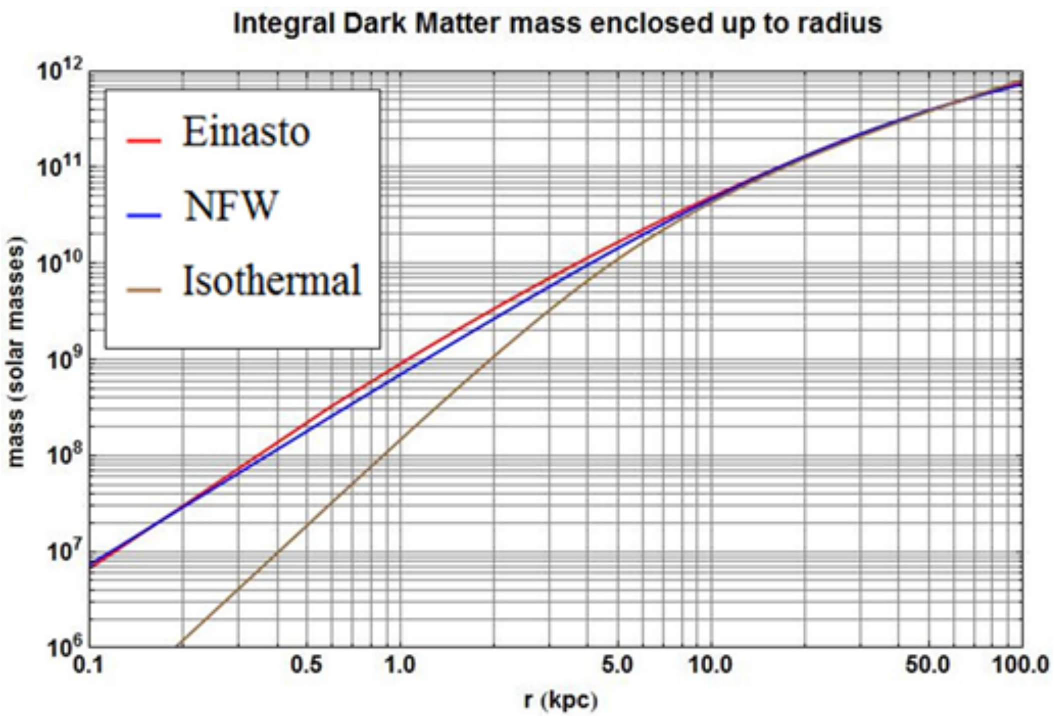
Cembranos et al. **Phys. Rev. D83 (2011) 083507** (arXiv:1009.4936)



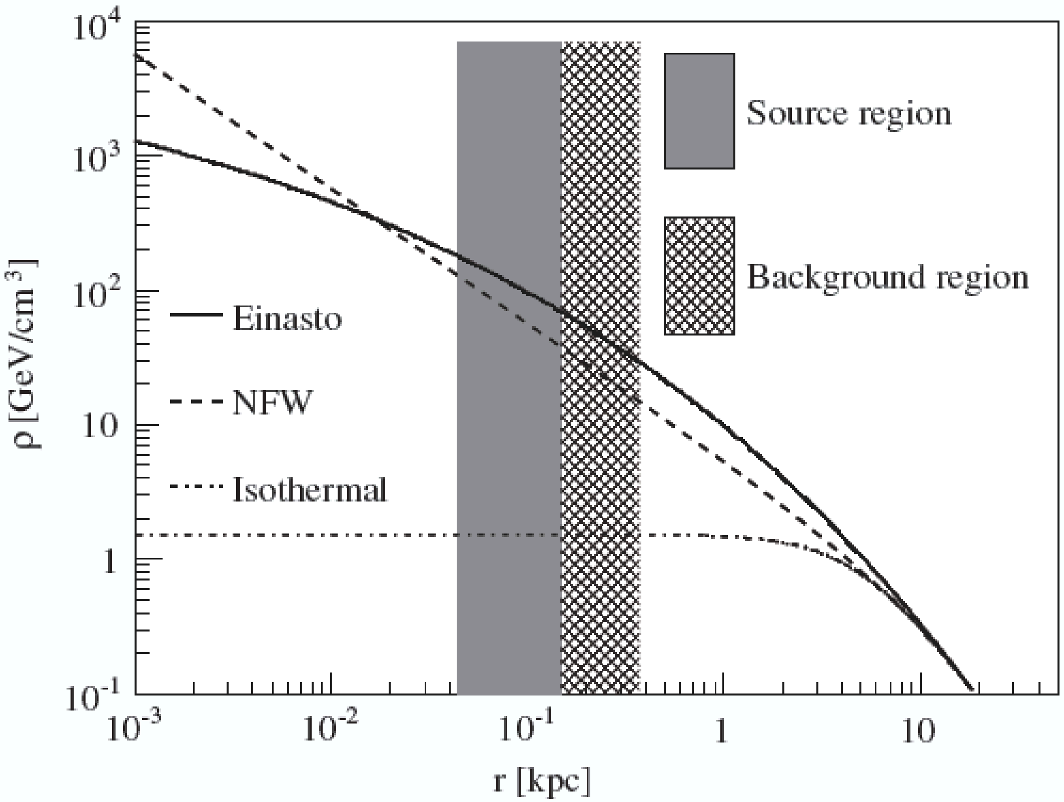


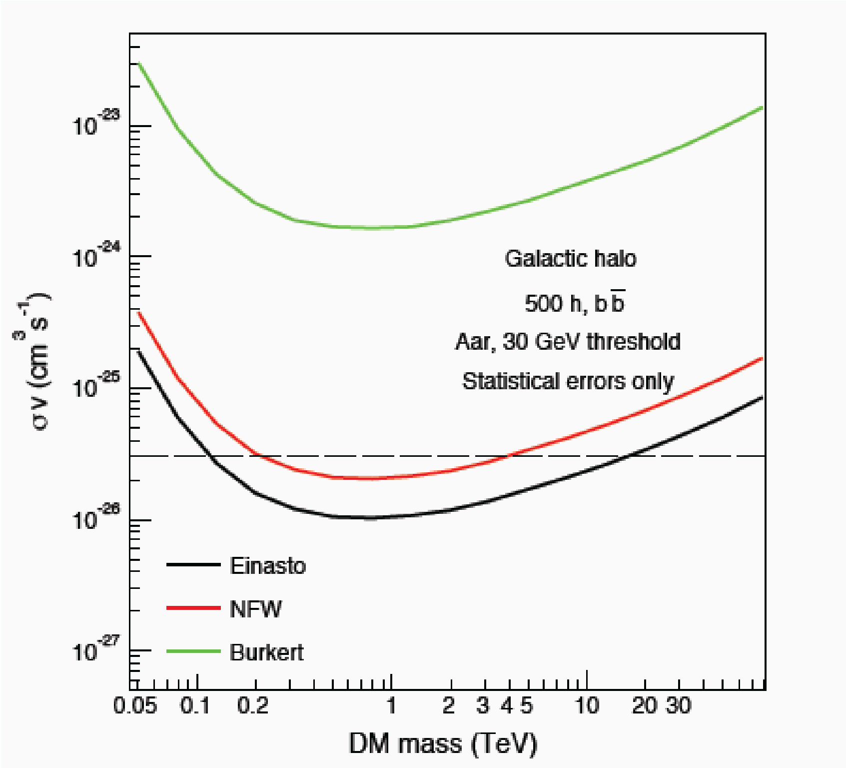
DARK MATTER DENSITY PROFILES

- NFW: $\rho(r) = \rho_s \frac{r_s}{r}\left(1 + \frac{r_s}{r}\right)^2$
- Einasto: $\rho(r) = \rho_s \, exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right\}$
- Isothermal: $\rho(r) = \rho_s \frac{1}{1+(r/r_s)^2}$
- Burkert: $\rho(r) = \rho_s \frac{1}{(1+ r/r_s)(1+(r/r_s)^2}$



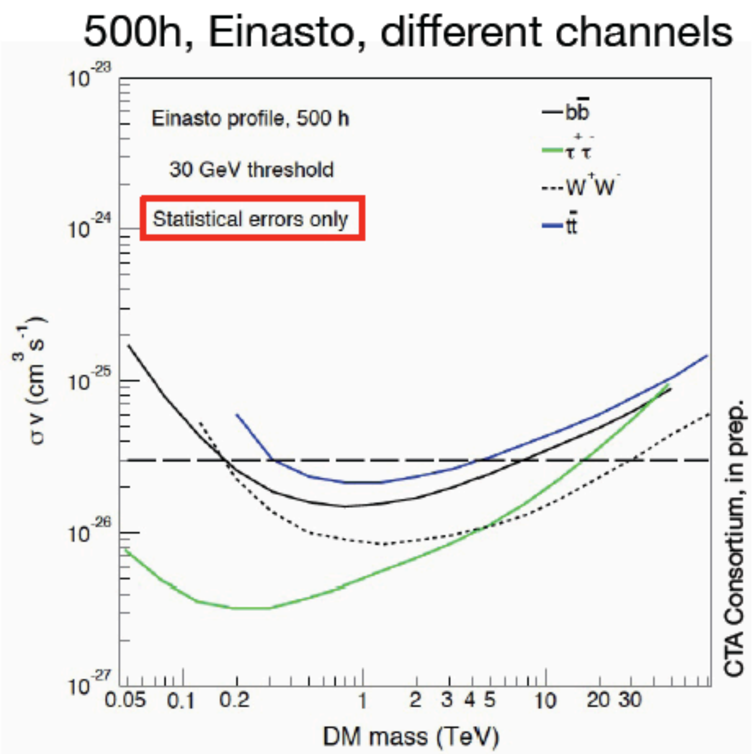
GALACTIC CENTER HALO: DM UNCERTAINTIES

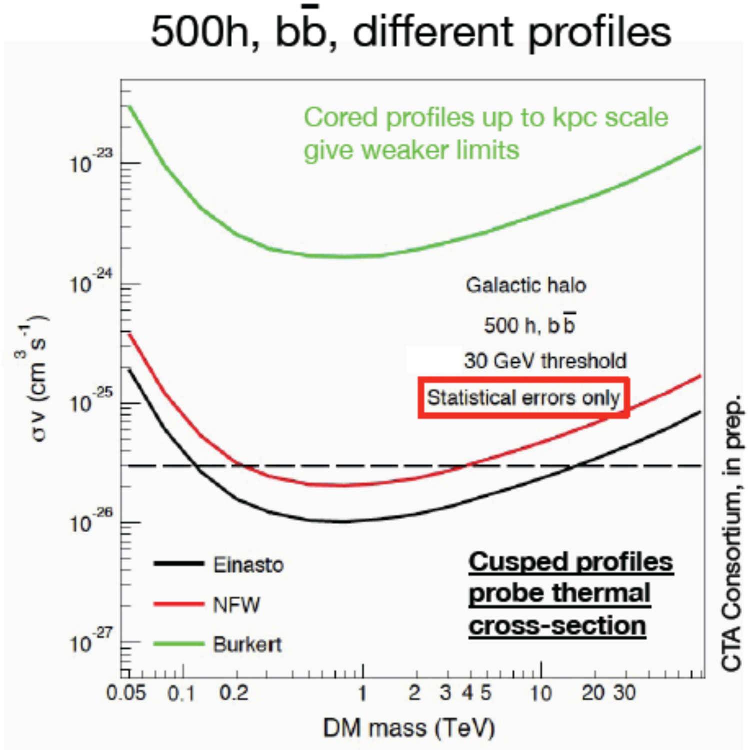




CTA DM prospects

GALACTIC HALO SENSITIVITY





- **natural cross-section will be within the sensitivity reach of CTA!**
- very complex environment, extended emission, astrophysical background
- **careful treatment and control of systematics mandatory; work in progress**

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

CTA DM prospects

cta cherenkov telescope array

DWARF GALAXIES

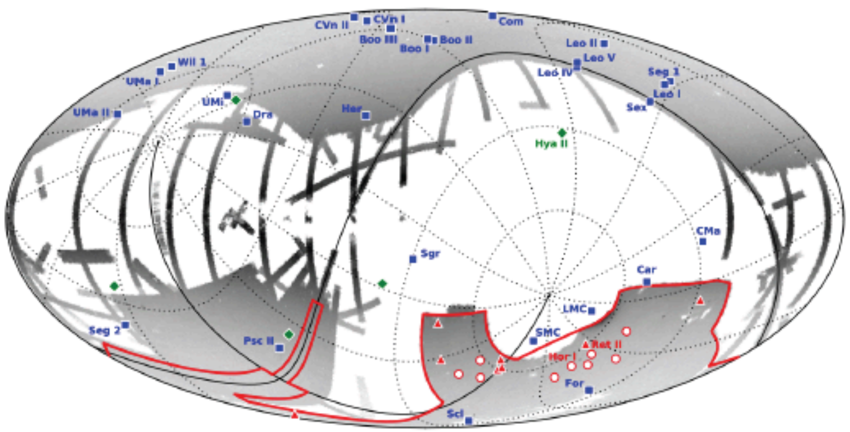
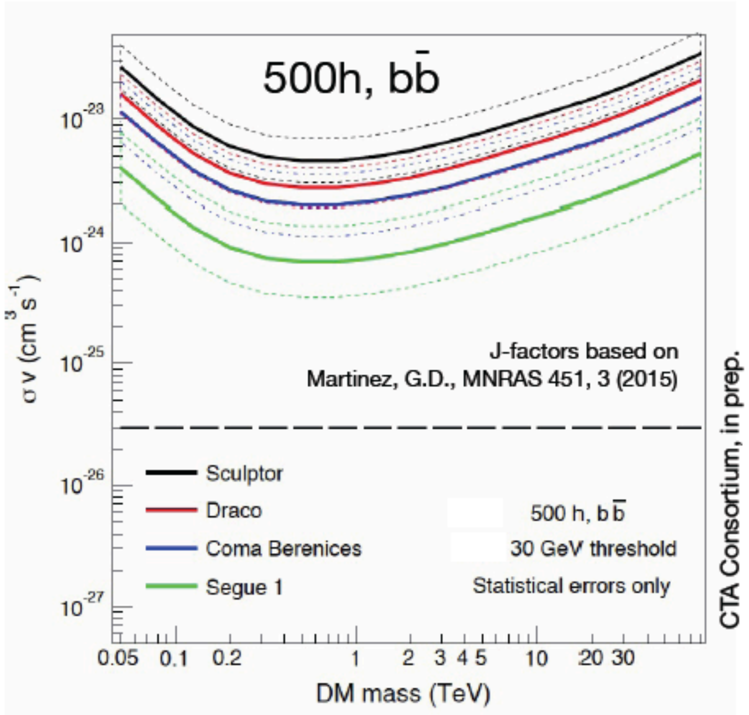


Image credit: A. Drlica-Wagner et al. (DES Coll.), arXiv:1508.03622

- MW satellite galaxies, D= 15 — 250 kpc
- luminosities ≳ 1000 $L_\odot$
- large M/L up to 1000 $M_\odot/L_\odot$
- no astrophysical background
  (no gas content, no gamma-ray emitters)
- new ultra-faint dSphs to be discovered with next-generation sky surveys *(DES, LSST, SkyMapper, Pan-STARRS)*
- ~20 new dSph candidates *already discovered* (of which several with spectroscopic confirmation)



- the best constrained/most promising dSphs known at the time of observation will be chosen
- robust constraints, but a factor of ~30 away from DM expectation

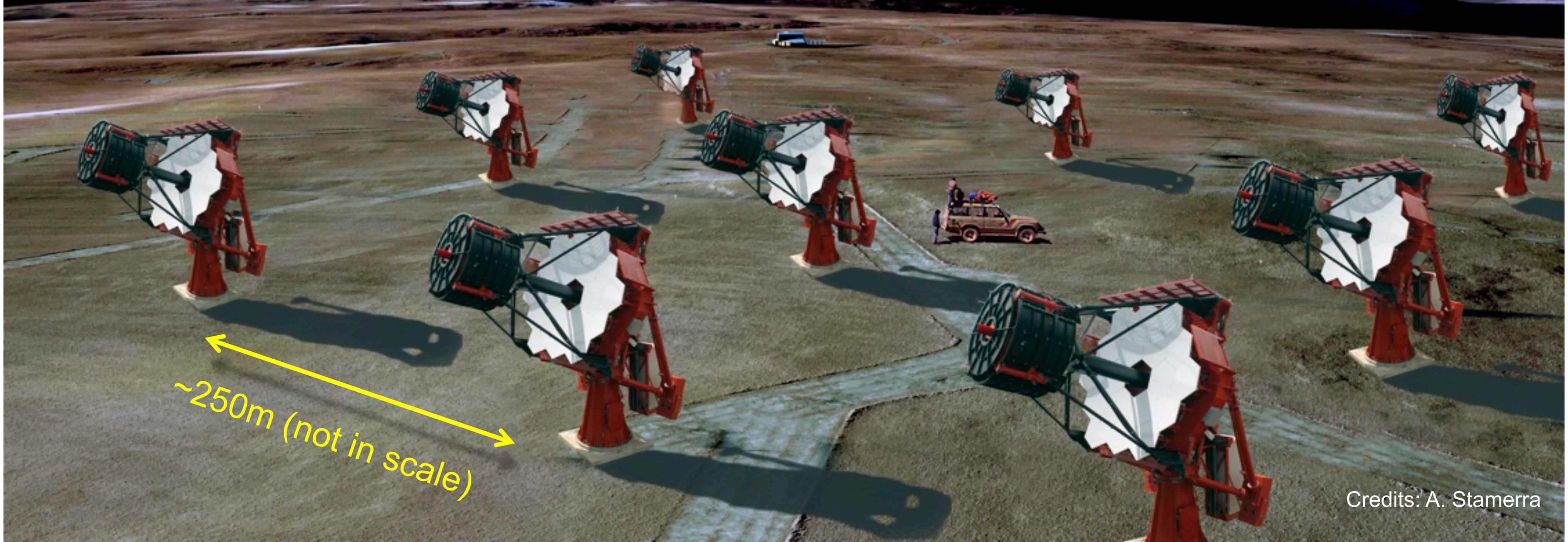
The ASTRI SST-2M mini-array

Led by the Italian National Institute for Astrophysics
in collaboration with:

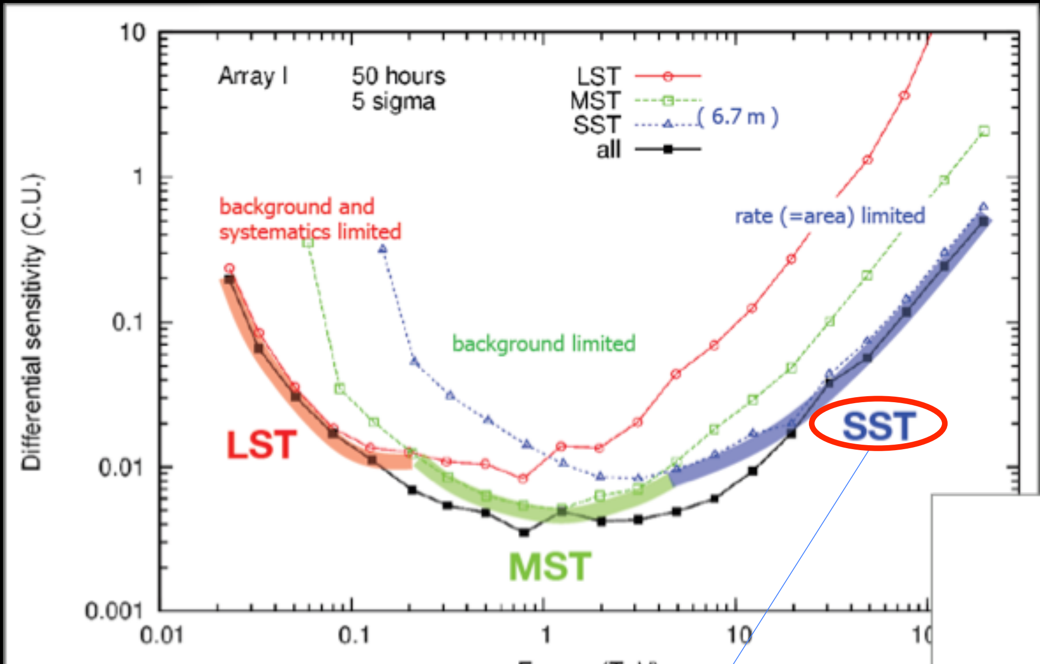
Universidade de São Paulo & FAPESP, Brazil

North-West University, South Africa

Proposed to be installed at the final southern CTA site as one of the CTA precursors (implementation in 2017)

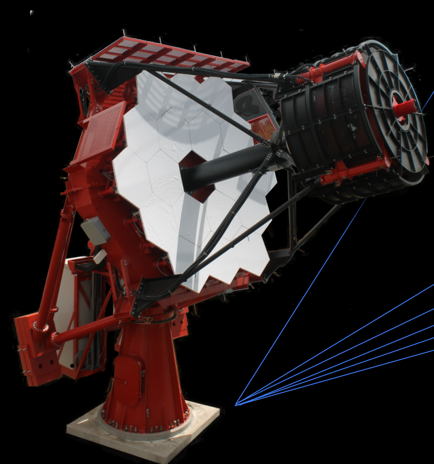


ASTRI in the framework of CTA

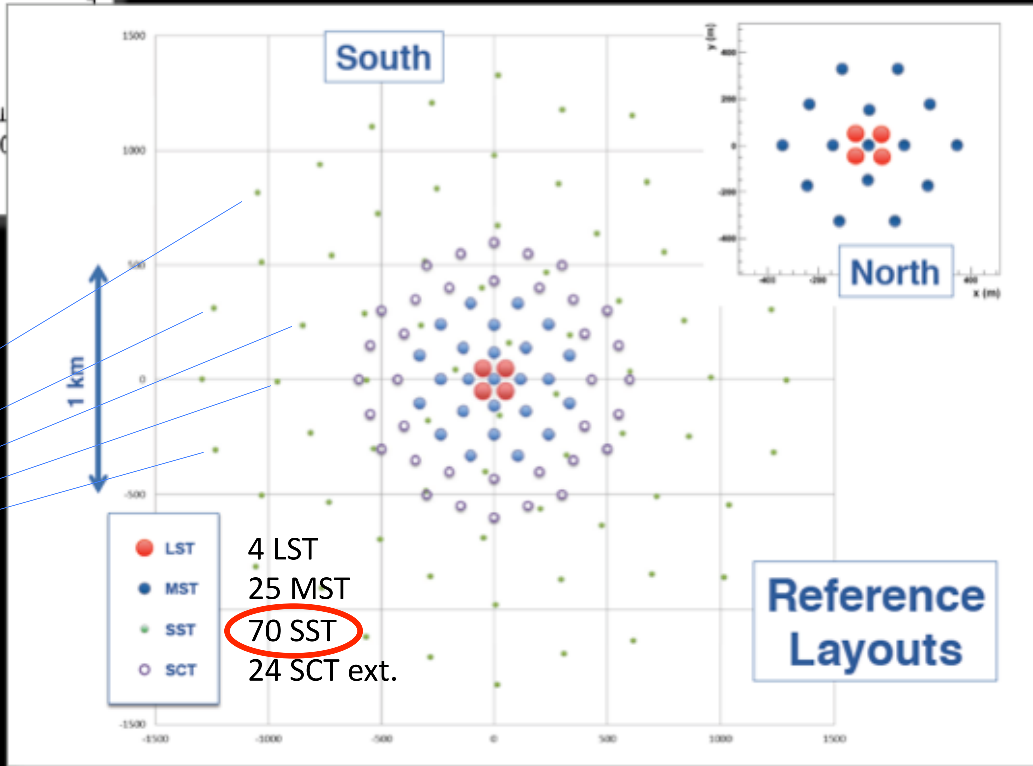


Credits: CTA Consortium

We aim at the production and deployment of about half (~35) of the CTA SST sub-array to explore the energy range above the TeV threshold



ASTRI SST-2M



ASTRI mini-array performance

- ✧ **Preliminary performance**

  based on MC-CTA Prod2

  and official CTA-MC pipelines

- ✧ **Sensitivity**

  slightly better than H.E.S.S.

  above ~10 TeV for an array

  composed of 9 telescopes

- ✧ **Angular resolution**

  a few (4–5) arcmin

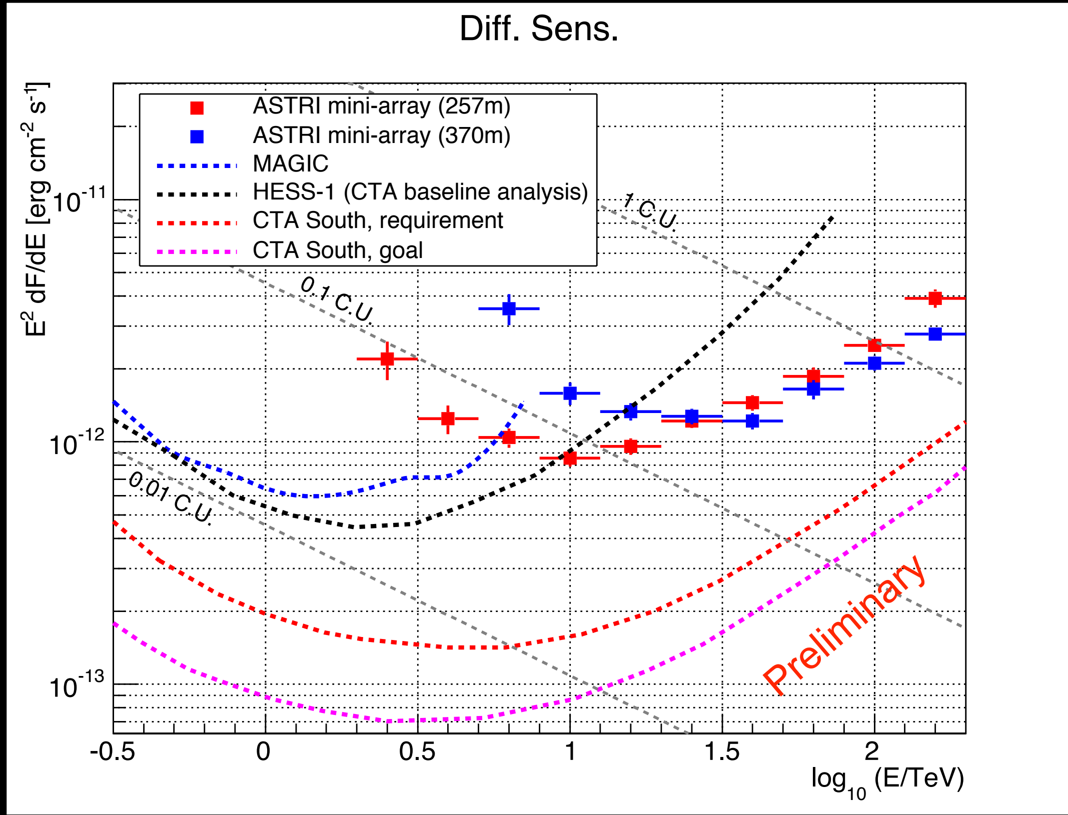
- ✧ **Energy resolution**

  of the order of 10-15%

- ✧ **Wide field of view**

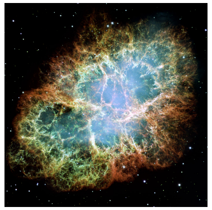
  ~10°

Di Pierro et al., proc. TAUP 2015, in press



ASTRI mini-array scientific aims

Supernova Remnants

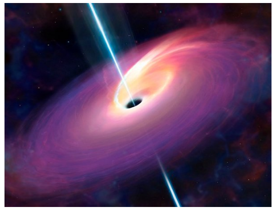


- SNRs
- Pevatrons
- SNRs interacting with molecular clouds

PWNe

Gamma-ray Binaries

Extreme BL Lacs



- Synchrotron peak > 1 keV
- Inverse Compton peak > 1 TeV

Less beamed AGNs

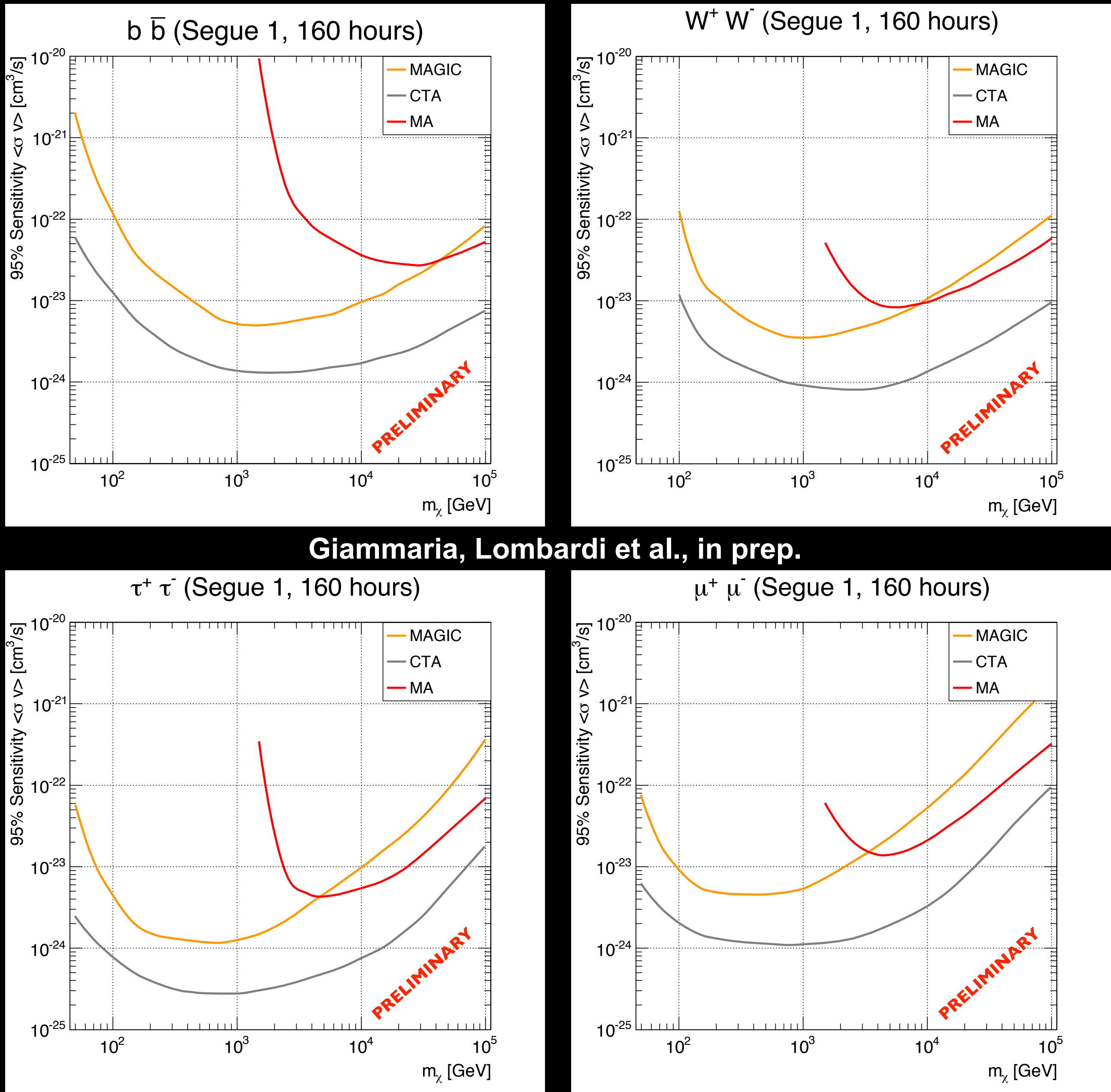
- Radio galaxies

Starburst Galaxies

Dark Matter and exotic physics

ASTRI mini-array prospects

MA = 9SSTs (Eth~1.5TeV)



Giammaria, Lombardi et al., in prep.

MA(9SSTs): Limited prospects for m_χ > tens of TeV

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