PROSPECTS FOR INDIRECT DARK MATTER SEARCHES WITH THE CHERENKOV TELESCOPE ARRAY

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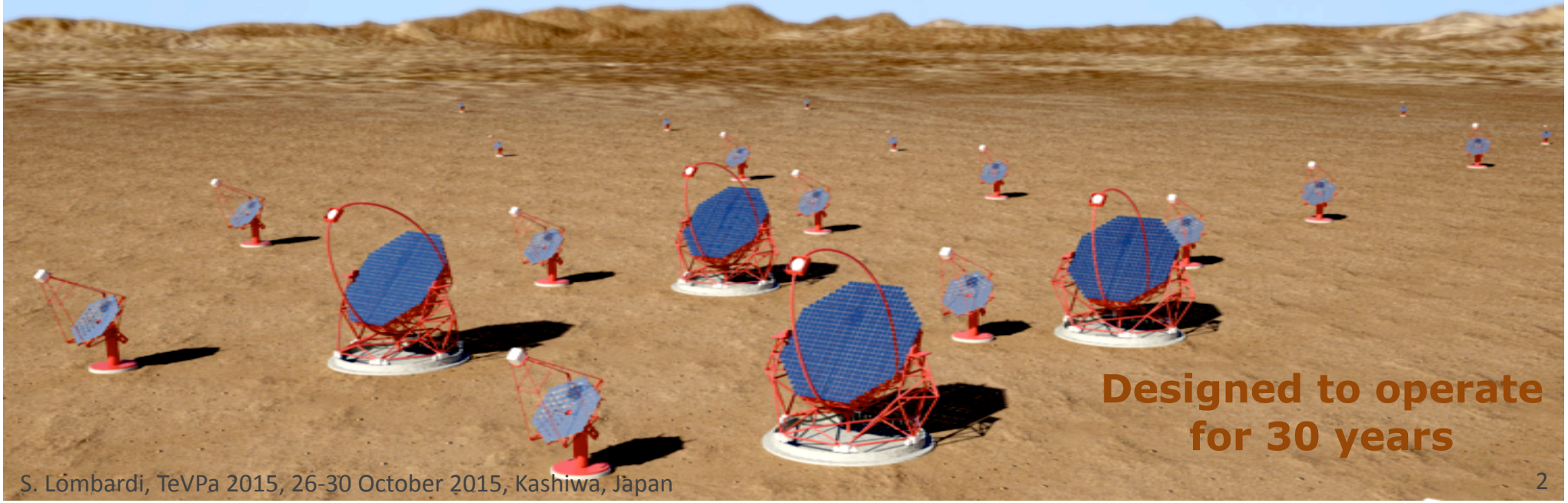
For the CTA Consortium

CTA PROJECT

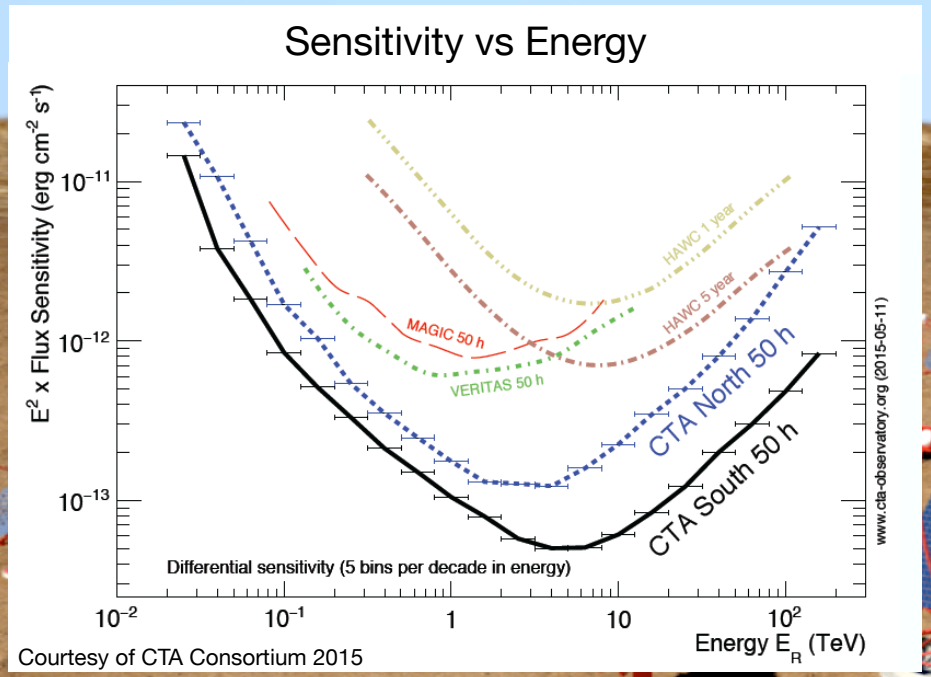
- Next generation ground based Gamma-ray Observatory
- Open observatory
- Two sites with total > 100 telescopes
  - Southern Site: Near Paranal in Chile
  - Northern Site: La Palma, Canary Islands
- 31 nations, ~300M€ project

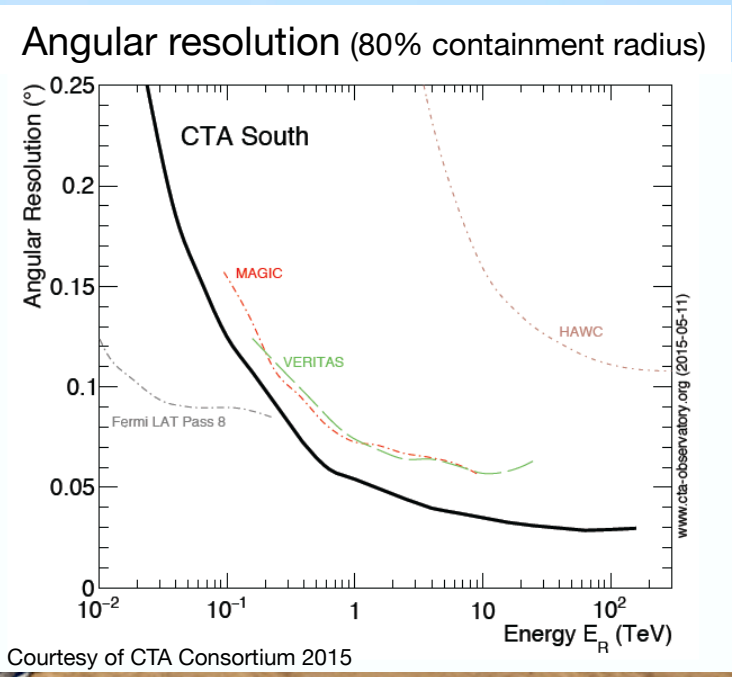


CTA ARRAY PERFORMANCE

Array configuration assumed for prospects shown here:

- Southern Site (~4km^2):
  - 4 Large-size telescopes (LSTs)
  - 24 Medium-size telescopes (MSTs)
  - 72 Small-size telescopes (SSTs)
- Northern Site (~0.4km^2):
  - 4 Large-size telescopes (LSTs)
  - 15 Medium-size telescopes (MSTs)





LIKELY SCENARIO: (WIMPY) PARTICLE DARK MATTER

- particle candidates in-line with observations: **weakly interacting massive particles (WIMPs)**
- **thermal production** in early Universe; freeze-out mechanism by **self-annihilation** or decay, leaving measured relic density

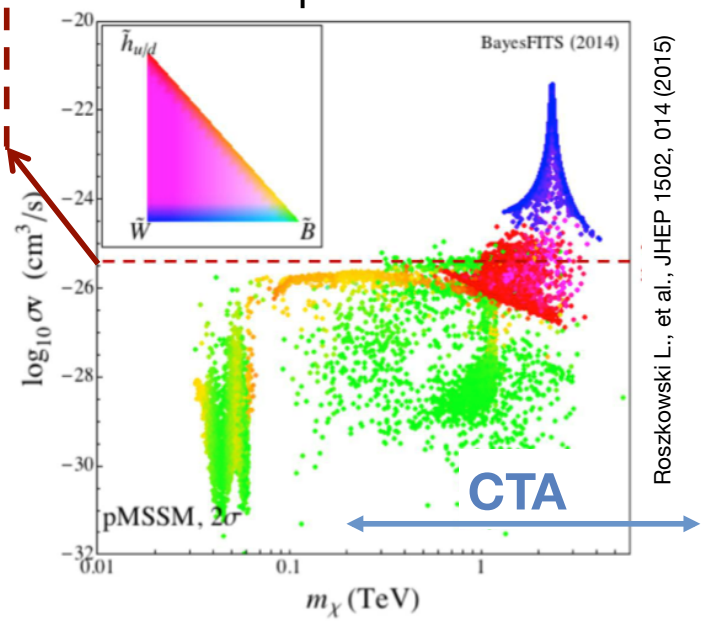
$$\chi\chi \rightarrow f\bar{f}$$

f : Standard Model particles

$$\Omega_\chi h^2 \approx 0.1 \left(\frac{\langle \sigma v \rangle|_{T_{cd}}}{3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}} \right)^{-1}$$

Canonical Relic Thermal Cross Section

recent pMSSM scan:

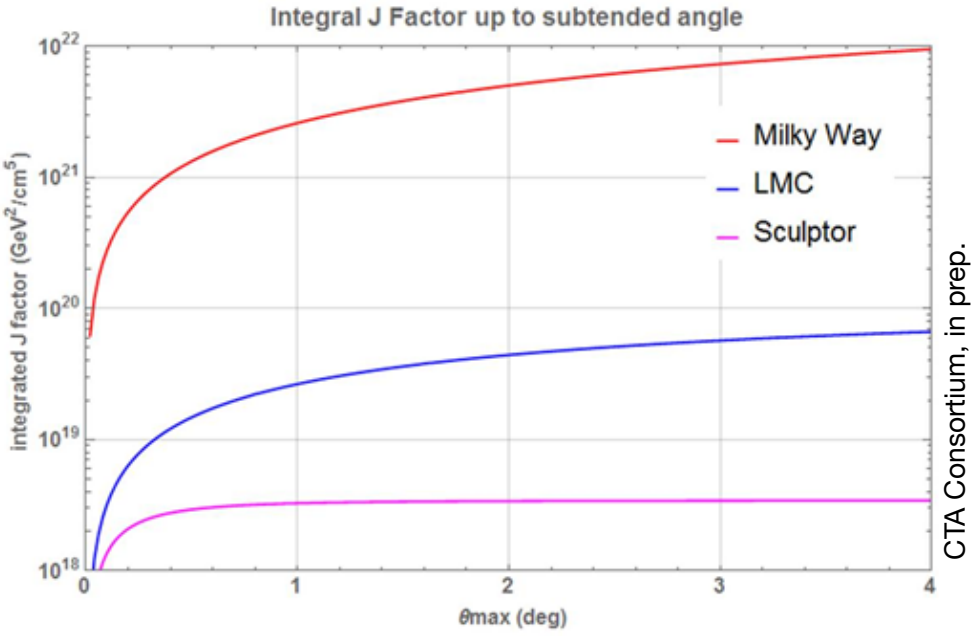


- candidates from a variety of BSM theories such as **Supersymmetry** (SUSY), Universal Extradimensions, etc.
- WIMPs mass range O(10 GeV) – O(100 TeV)

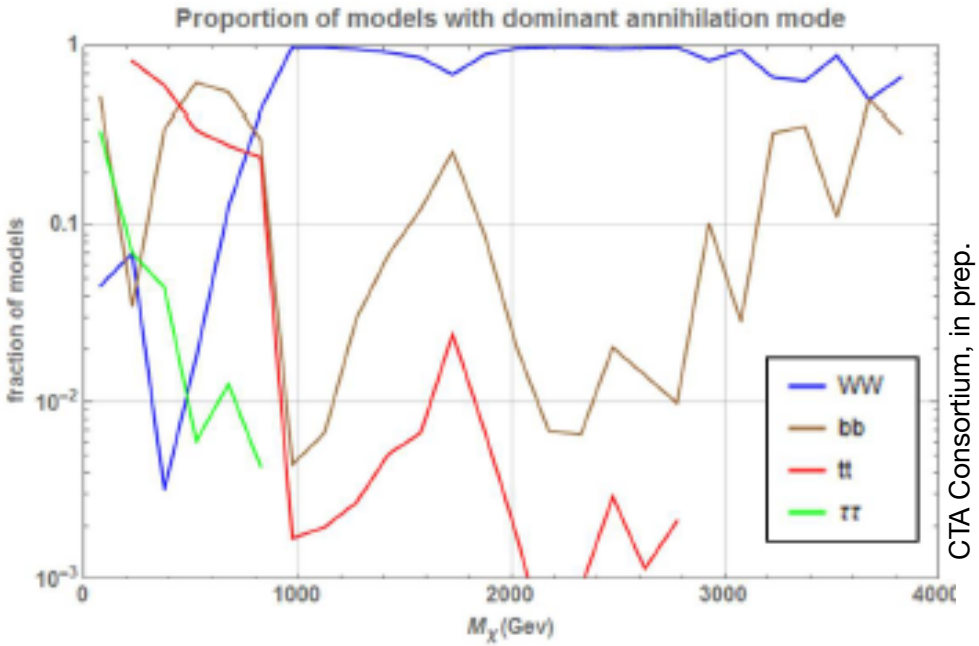
RATES FOR DM ANNIHILATION

Event rate: $$N_{DM} = \frac{t_{obs}\ \mathrm{J}(\Delta\Omega) < \sigma v >}{8\,\pi\, M_{\chi}{}^{2}} \int_{E_{min}}^{E_{max}} \frac{dN_{DM}}{dE}(E)\, A_{eff}(E)\, dE$$

J-factor: $$\mathrm{J}(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{line-of-sight} \rho^{2}[r(l)]dl$$



Milky Way galaxy largest J-Factor



$W^{+}W^{-}$ dominate mode in pMSSM at 1 TeV

GENERAL STRATEGY

Scientific objectives

A. DM detection

- measure signal strength
  [<σv>, mass, l.o.s.-density]
- study spectral signatures,
  [mass (cutoff),
  annihilation channels
  (spectral features)]
- spatial morphology
  [DM distribution]

➔ **identify DM particle and properties; measure DM abundance and distribution**

B. Non-detection

- constrain signal strength
- constrain spectral signatures
- constrain spatial morphology

➔ **provide long-term legacy limits**

PRIMARY DARK MATTER SEARCH TARGETS FOR CTA

The Milky Way Galactic Halo

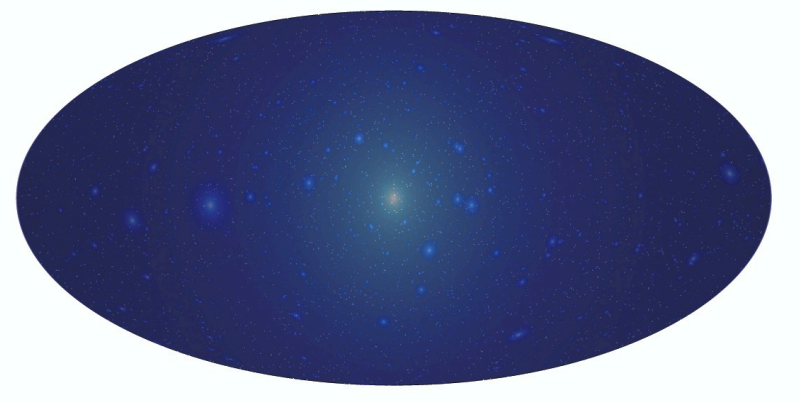


Image credit: JG 2008

Milky Way Satellites

Draco. Image credit: J. Moore et al. 2012

The Large Magellanic Cloud

Image credit: NASA

OBSERVATIONAL PROGRAM

CTA Dark Matter Program

- 10 years of observation in total
- first 3 years:
  - focus on Galactic Center halo (GH),
    optimizing brightness and robustness at the same time
  - crosscheck with ultra-faint/best dSphs;
    cleaner environment (low background) but fainter signal than GH

- in the case of a GC/GH detection:
  - keep checking with the best dSphs if <σv> is large,
    otherwise deep GC/GH pointing only

- in the case of no detection:
  - produce legacy limits:
    choose best target known at that time

PROPOSED SCHEDULING

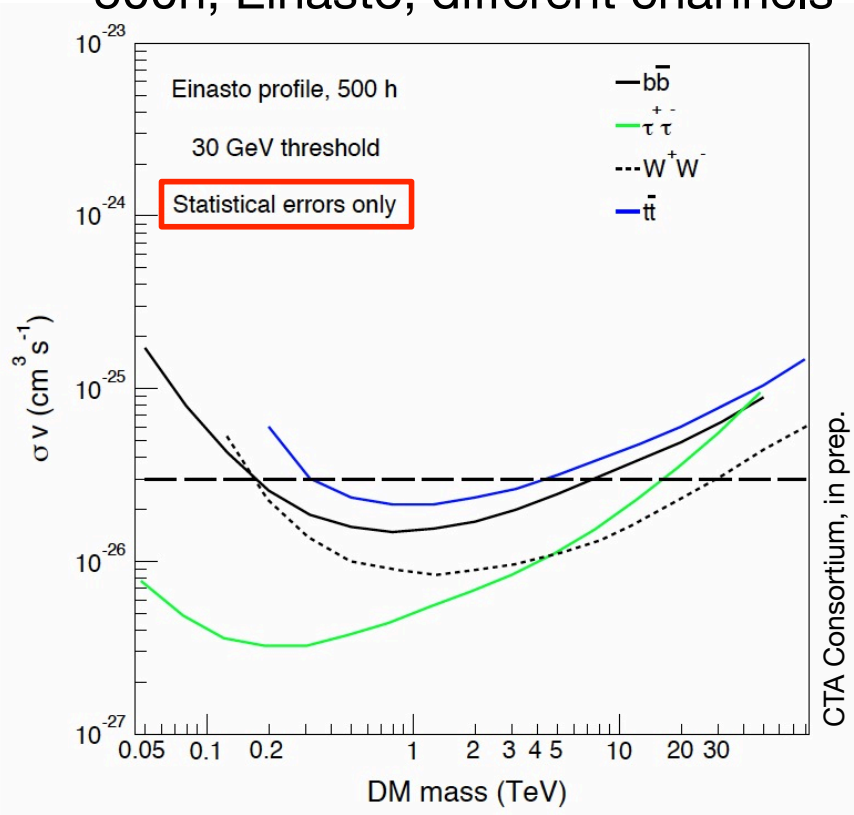
Table 4.1 – Strategy for dark matter observations over ten years with CTA. The first three years are devoted to the deep observation of the Galactic Centre (GC) together with the observation of the best ultra-faint dwarf galaxy. In case of non-detection of the GC, observations starting in the fourth 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

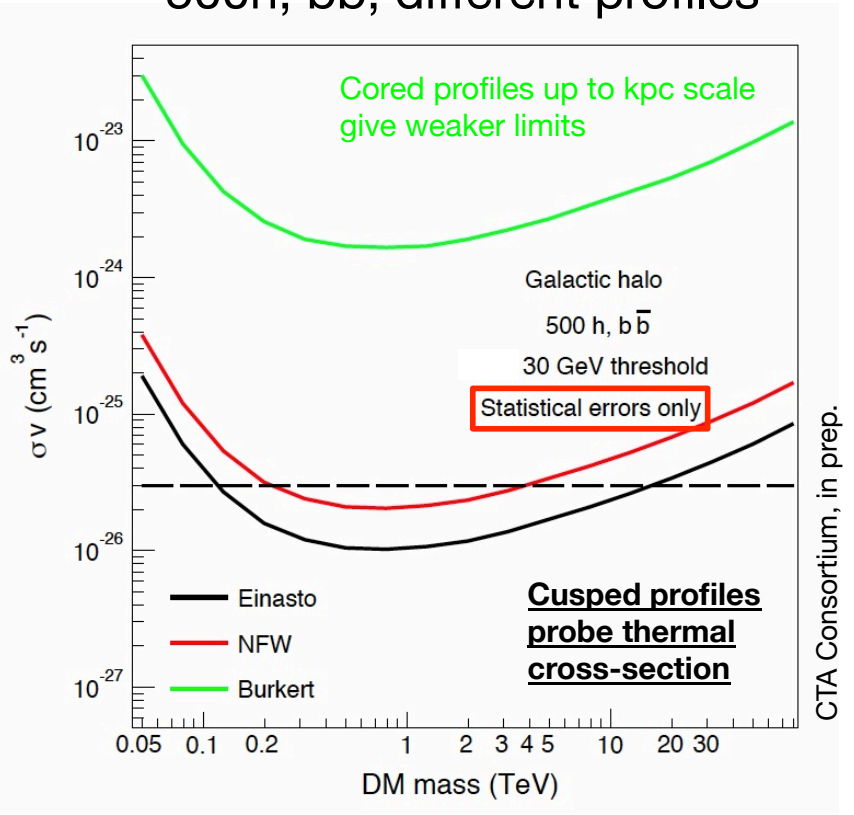
CTA Consortium, in prep.

GALACTIC HALO SENSITIVITY

500h, Einasto, different channels



500h, $b\bar{b}$, different profiles



- **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)

DWARF GALAXIES

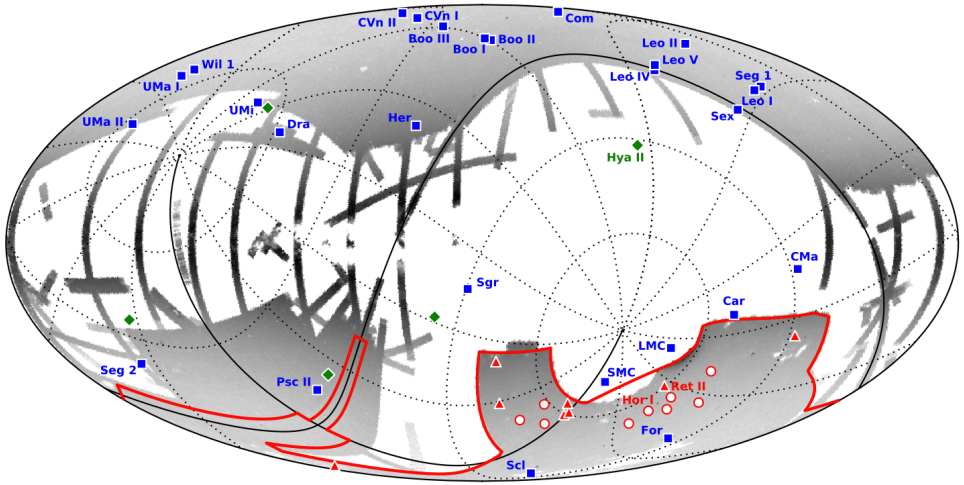
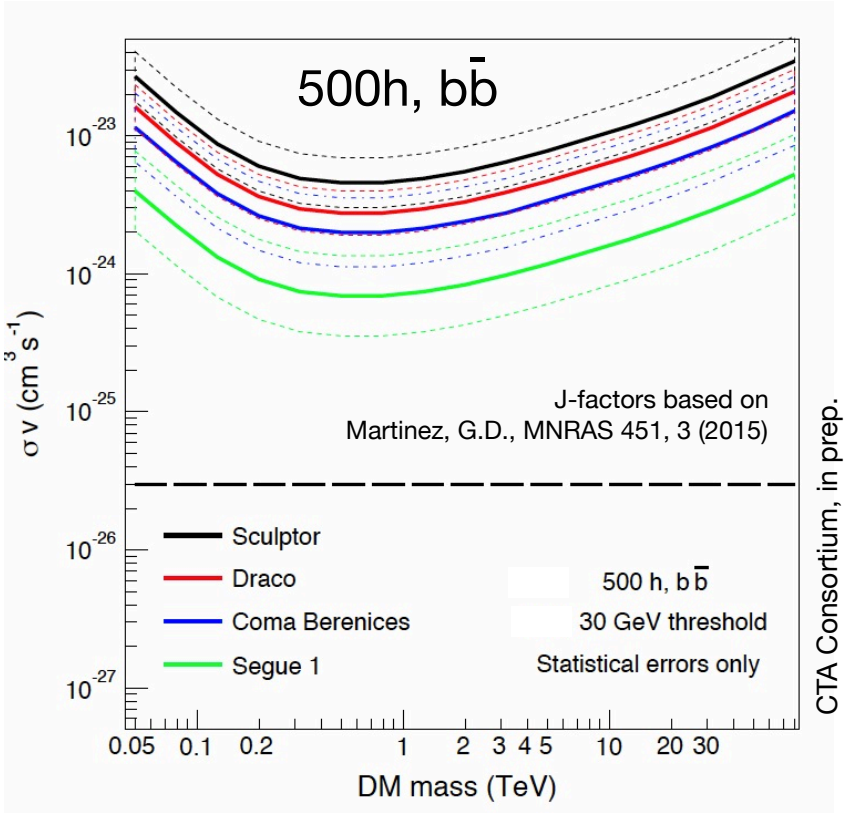


Image credit: A. Drlica-Wagner et al. (DES Coll.), arXiv:1508.03622

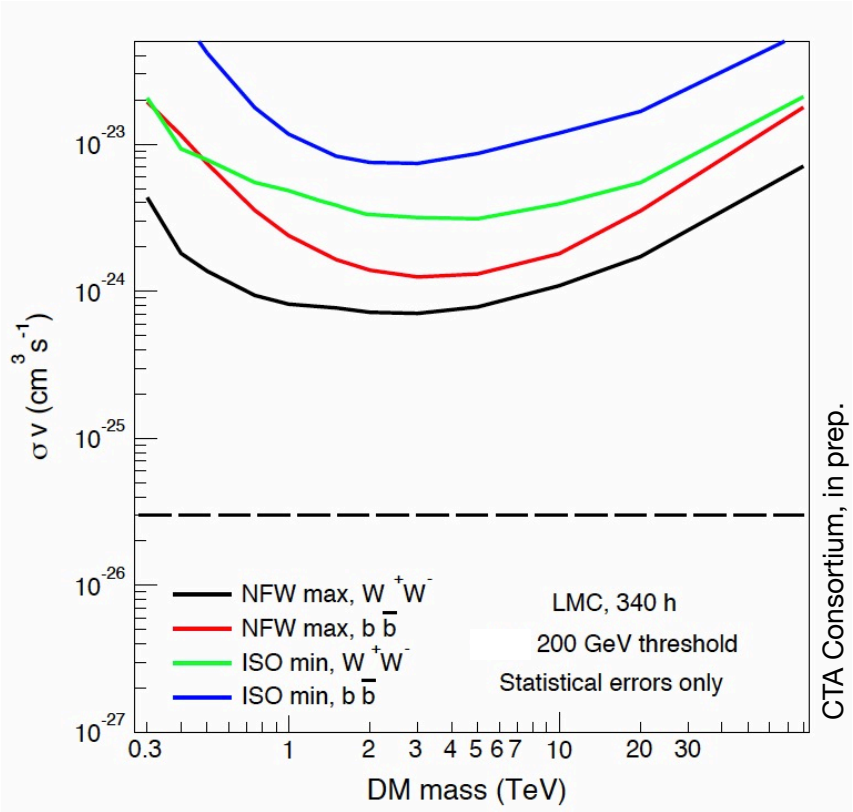
- MW satellite galaxies, D= 15 — 250 kpc
- luminosities $\gtrsim 1000\ L_\odot$
- large M/L up to $1000\ M_\odot/L_\odot$
- no astrophysical background
  (no gas content, no gamma-ray emitters)
- new ultra-faint dSphs to be discovered with next-generation sky surveys *(DES, LSST, SkyMapper, Pan-STARRS)*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

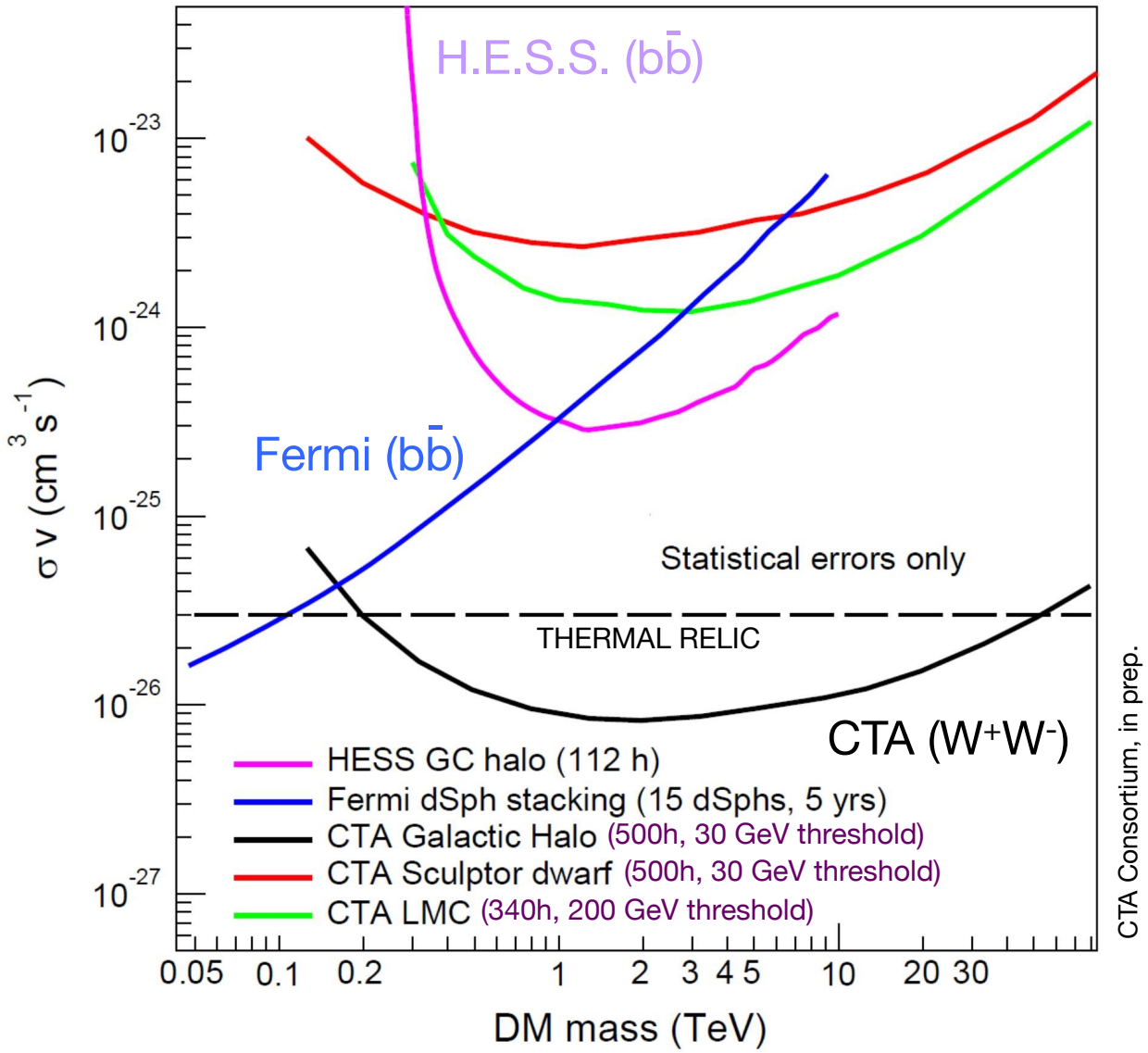
LARGE MAGELLANIC CLOUD

340h, 200 GeV threshold,
different profiles and channels



- *non-DM proposal for 340h*
- hosts many interesting astrophysical sources
- extended source to CTA
- may have a high J-factor
- similar systematics issues as Milky Way Galaxy Halo

SENSITIVITY OF MAIN TARGETS



- **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

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

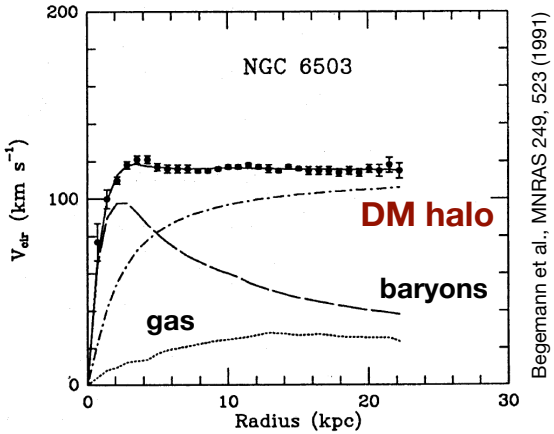
- **Complementary observations (with different uncertainties) of MW Dwarfs and LMC will be conducted to extend the search:**
  - Crosschecks for GC observations results
  - Robust legacy constraints in the case of non-detection

- **Results will be complementary to direct detection and colliders, and the synergy with Fermi-LAT will be able to probe thermal WIMPs from a few GeV up to tens of TeV**

BACKUP SLIDES

EVIDENCE FOR DARK MATTER

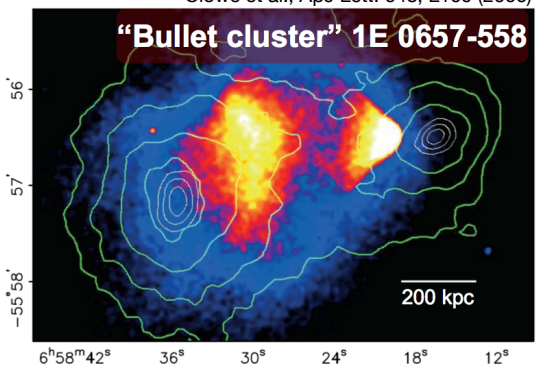
compelling evidence for an invisible matter component on all observable distance scales

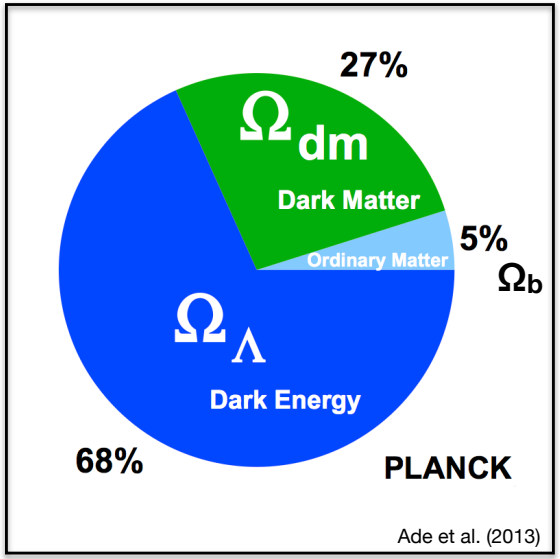


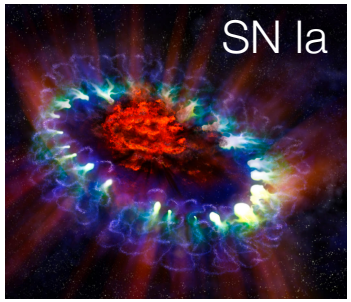
dynamical constraints

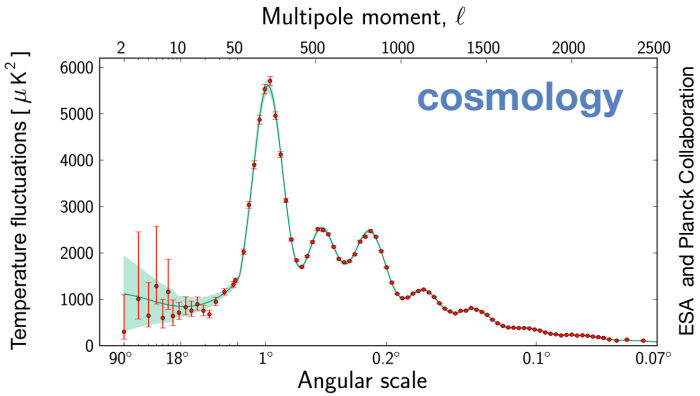
gravitational lensing

Clowe et al., ApJ Lett. 648, L109 (2006)

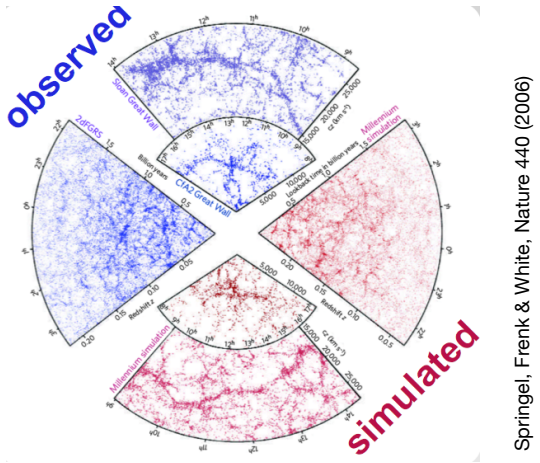








large-scale structure



e.g., Jungman et al. (1996), Bertone et al. (2005)

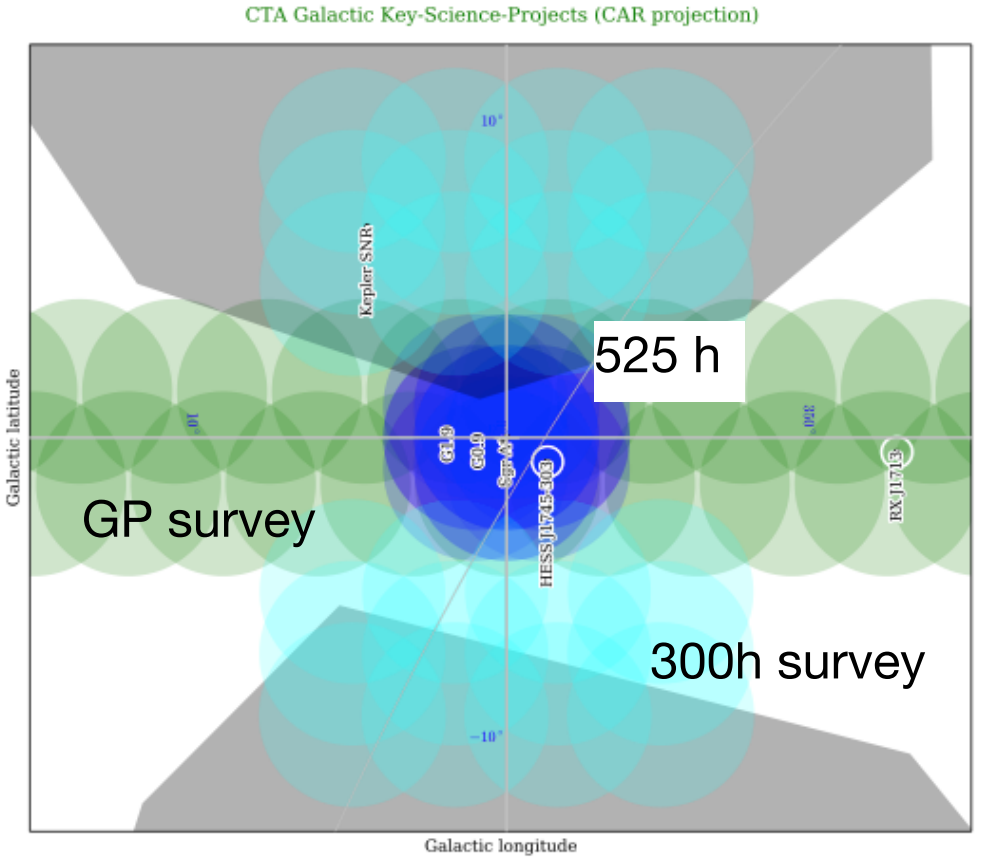
GALACTIC CENTER OBSERVATIONS

- except DM, multiple science topics covered, e.g.
  Galactic Center source, diffuse emission, SNRs, PWNe, central radio lobes, Galactic bulge, Fermi Bubbles, Kepler SNR

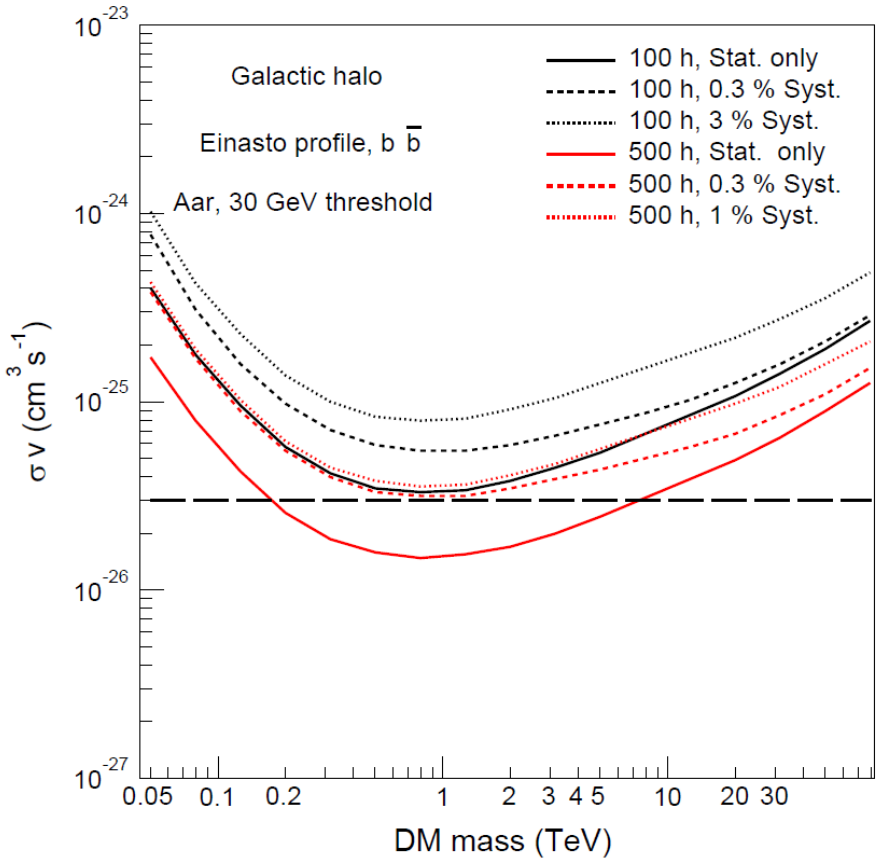
- 525 h deep exposure to uniformly cover the central 5 deg
  (wobble)

- + 300 h extended survey,
  ~10 deg x 10 deg
  (improves sensitivity on cored profiles)

- + Galactic Plane survey



SYSTEMATIC ERRORS



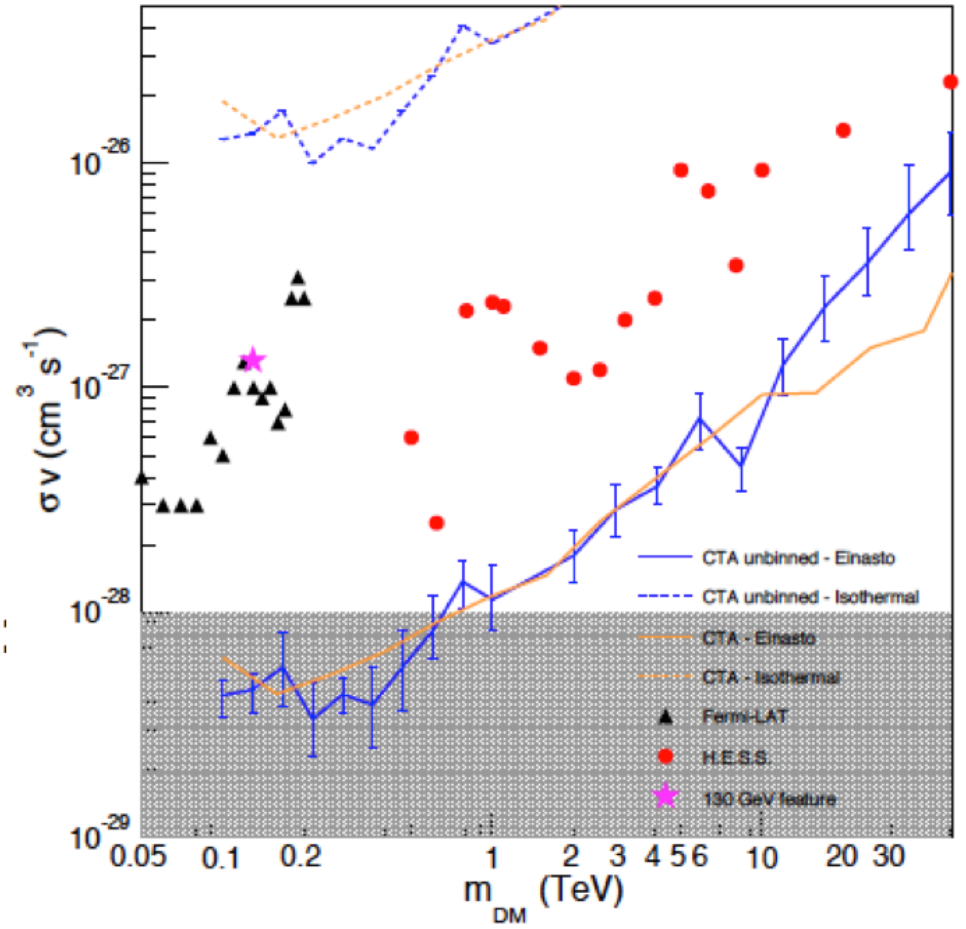
Treatment of *uncorrelated* systematic errors following method of Silverwood et al, JCAP 03:05, 5 (2014).

However, real instrumental and background systematics are *correlated.*

Extensive work in progress to evaluate and plan actions to control systematics.

GALACTIC CENTER: LINE SEARCH

- data within a circle of 1 deg radius around the center
- standard astrophysical emission taken into account as background
- systematics expected to be small for line searches
- **sensitivity improvement by a factor of ~10 expected**

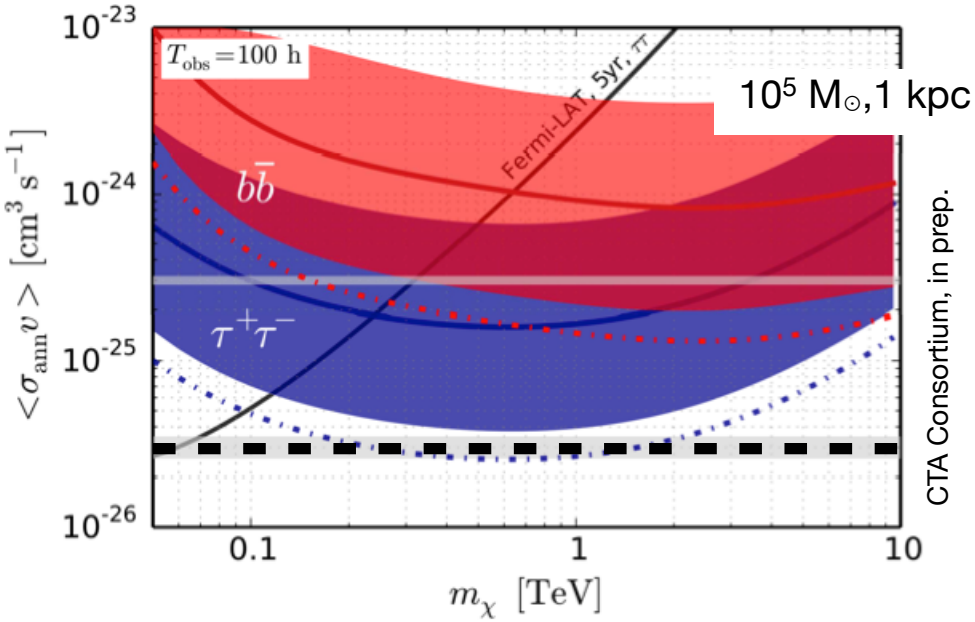


CTA Consortium, in prep.

DARK CLUMPS

- dark matter subhalos
  - small-scale DM subhalos may have accumulated too few baryons to be detected as dSph: —> dark clumps
  - massive (> 10^4 $M_\odot$), nearby (< 5 kpc) subhalos may be detectable

  - **large uncertainties, but discovery potential**



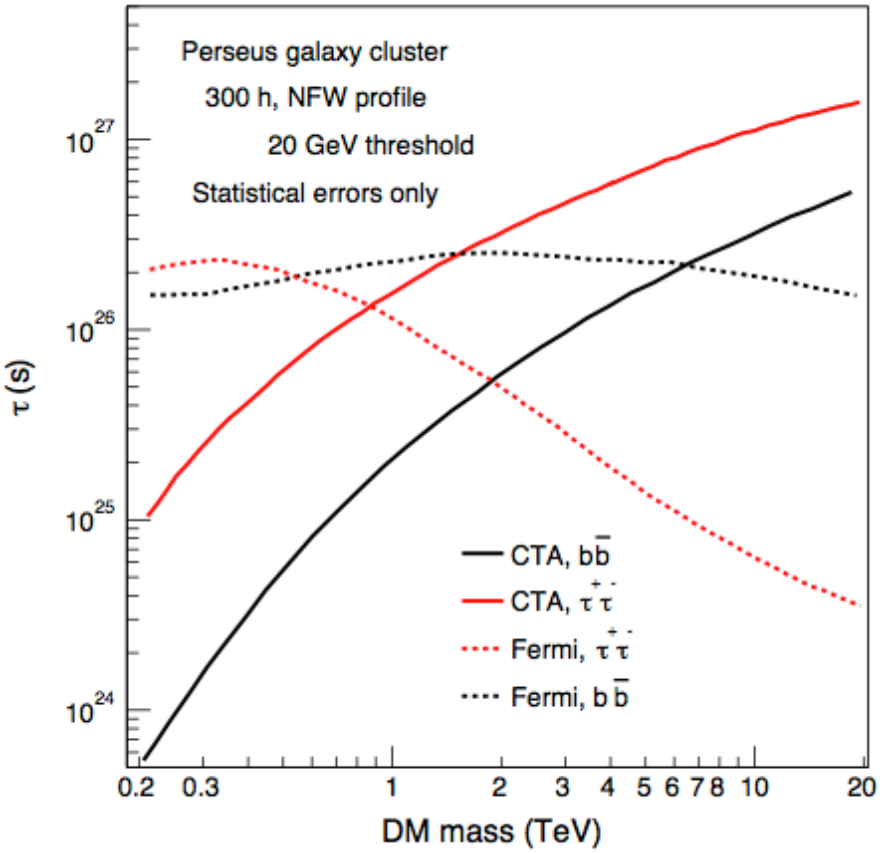
GALAXY CLUSTERS (DECAYING DM)

- Galaxy clusters among the largest and most massive gravitationally bound systems in the Universe (10^{14} - 10^{15} $M_{\odot}$)

- high DM content, ~80%
- may benefit from substructure boost

- separate proposal for Perseus observations, 300 h; DM analysis may profit

- **large uncertainties, but promising for decaying DM**



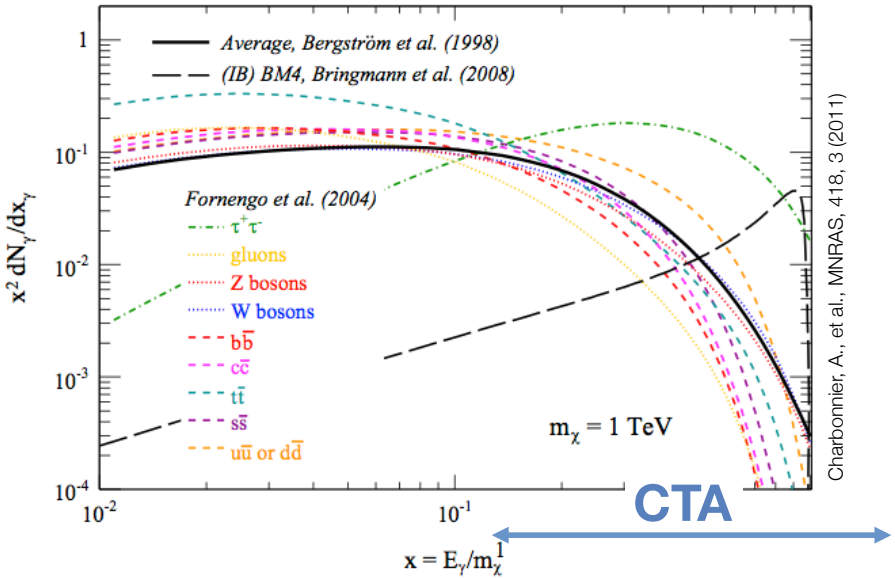
CTA Consortium, in prep.

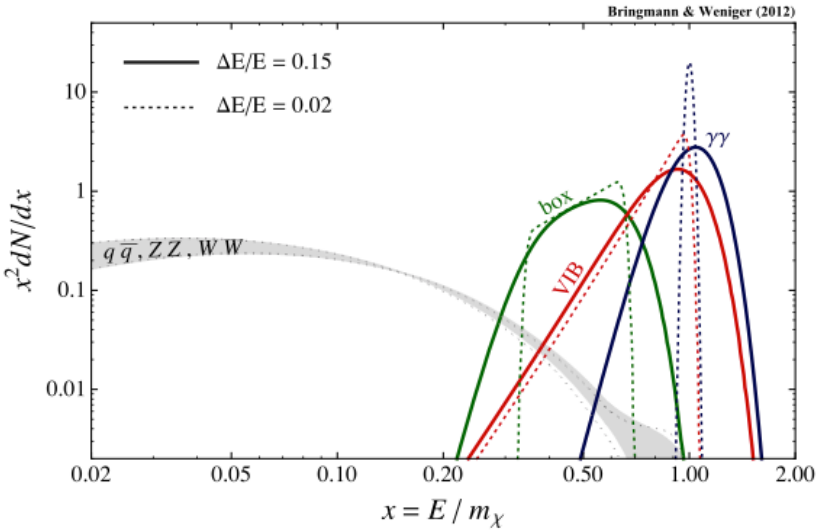
GAMMA-RAY SPECTRAL SIGNATURES

(i) hadronization and decay of SM states:
continuous spectrum with distinct cutoff to the WIMP mass

(ii) virtual internal Bremsstrahlung, final state radiation:
sharp spectral signatures

(iii) gamma-ray lines
(loop suppressed, ~10^{-3})





Gamma-ray flux

$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\frac{dN_\gamma}{dE_\gamma}\int d\Omega \int_{los} ds \rho^2(s(r))$$

DM density profile

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: $\rho(r) = \rho_s \frac{1}{(1+r/r_s)(1+(r/r_s)^2}$