DARK MATTER AND FUNDAMENTAL PHYSICS WITH CTA

H.-S. Zechlin[1],

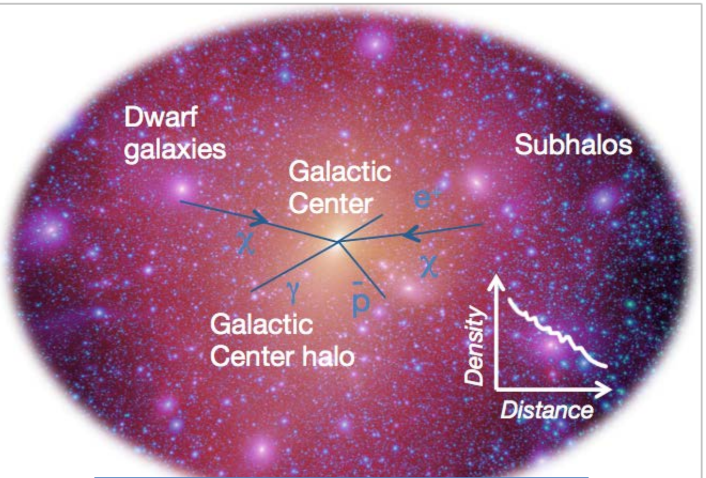
C. Balazs, T. Bringmann, T. Buanes, J. Carr, M. K. Daniel, M. Doro, C. Farnier, M. Fornasa, J. Gaskins, G. A. Gomez-Vargas, M. Hayashida, K. Kohri, V. Lefranc, A. Morselli, E. Moulin, N. Mirabal, J. Rico, T. Saito, M.A. Sánchez-Conde, M. Wilkinson, M. Wood, G. Zaharijas

For the CTA Consortium

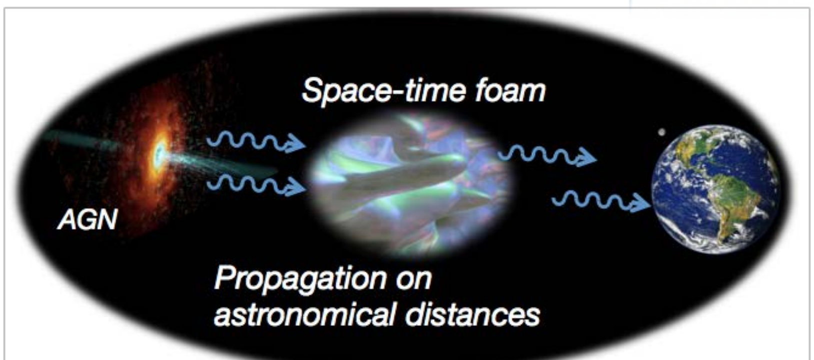
[1] University of Torino, Italy,
zechlin@to.infn.it

The Future of Research on Cosmic Gamma Rays
28 August 2015 - La Palma - Canary Islands

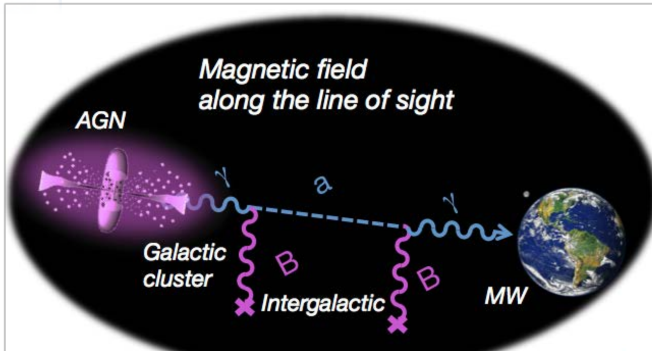
FUNDAMENTAL PHYSICS TOPICS



Particle Dark Matter

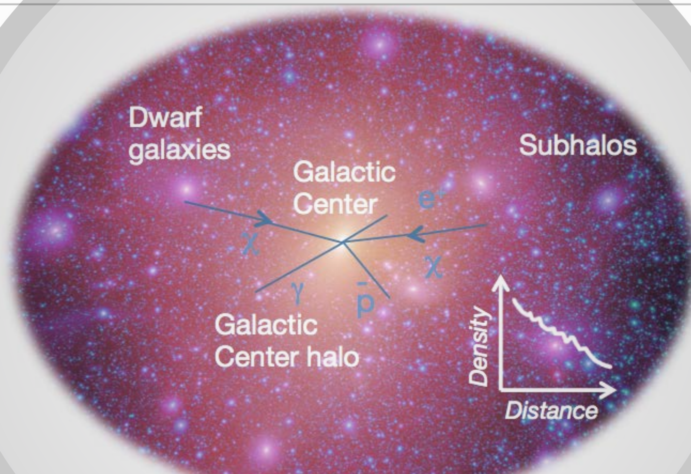


Lorentz Invariance

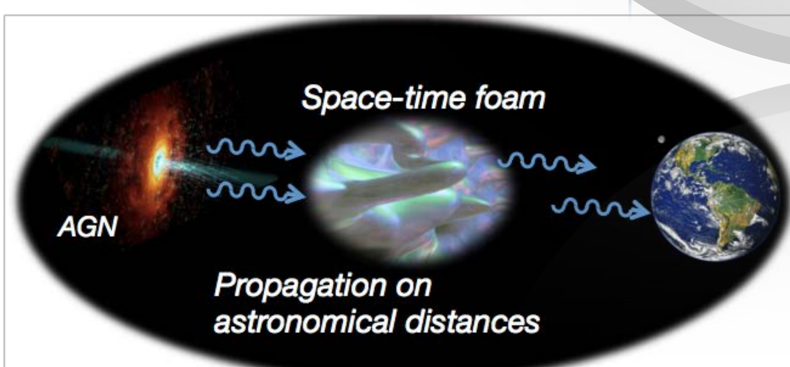


Axions

FUNDAMENTAL PHYSICS TOPICS



Particle Dark Matter



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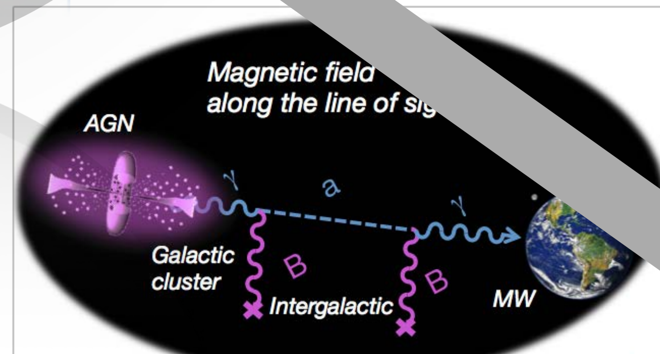
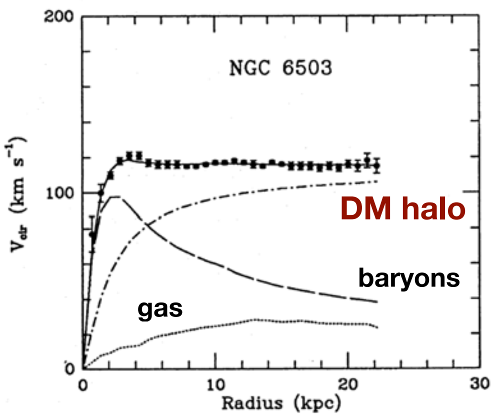


Axions

EVIDENCE FOR DARK MATTER

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

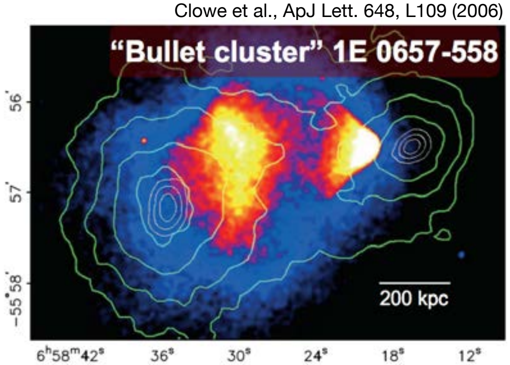


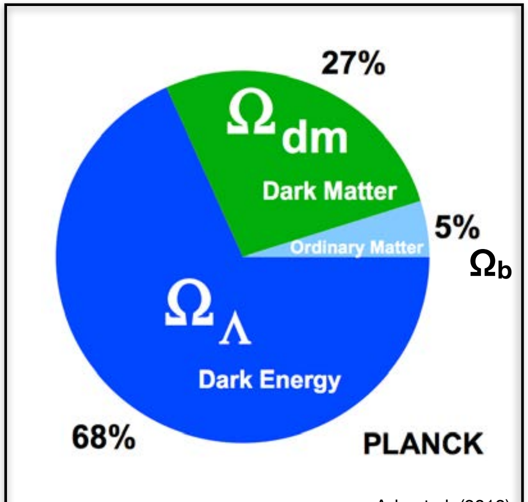
Begemann et al., MNRAS 249, 523 (1991)

dynamical constraints

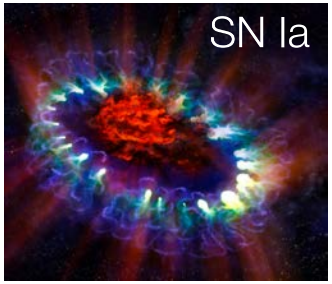
gravitational lensing

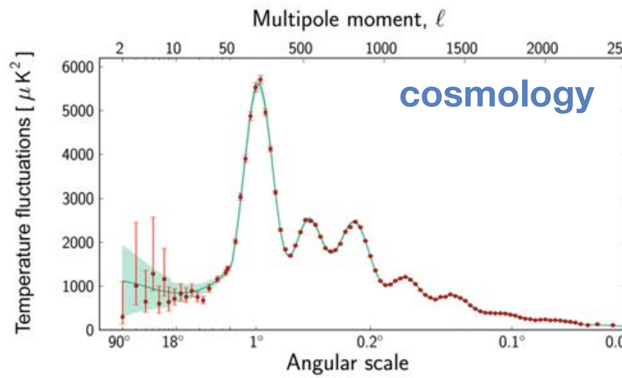
Clowe et al., ApJ Lett. 648, L109 (2006)





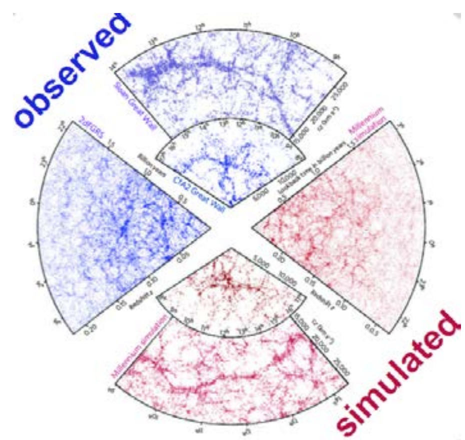
Ade et al. (2013)





ESA and Planck Collaboration

large-scale structure



Springel, Frenk & White, Nature 440 (2006)

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

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

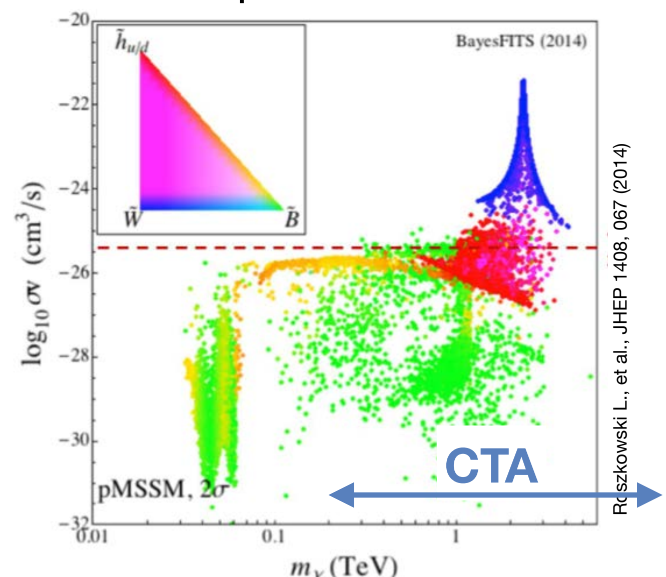
$$\Omega_\chi h^2 \approx 0.1 \left(\frac{\langle \sigma v \rangle |_{T_{\rm cd}}}{3 \times 10^{-26}\,{\rm cm}^3/{\rm s}} \right)^{-1}$$

$$\chi\chi \to f\bar{f}$$

f : Standard Model particles

- candidates from a variety of BSM theories such as **Supersymmetry** (SUSY), Universal Extradimensions, etc.

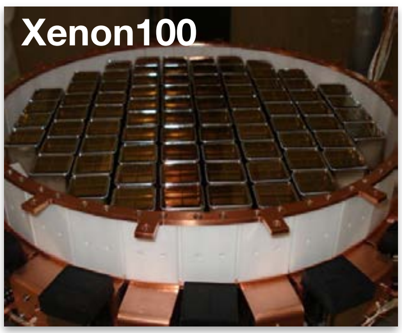
recent pMSSM scan:

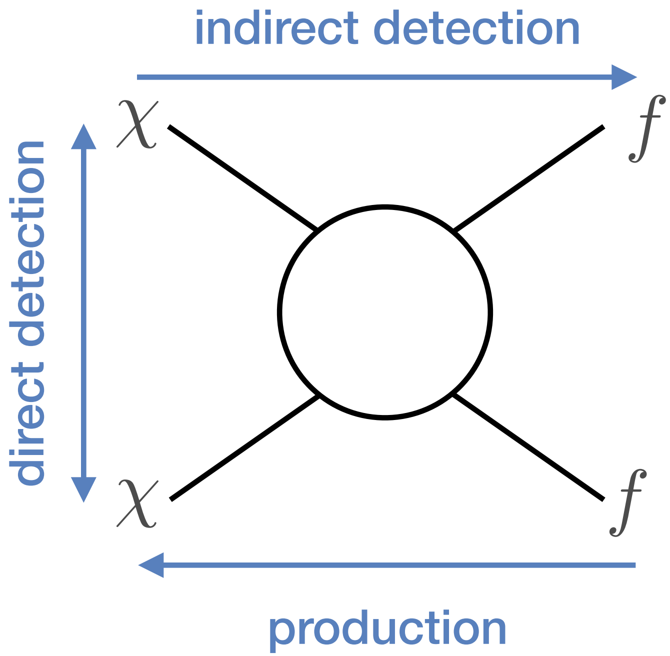


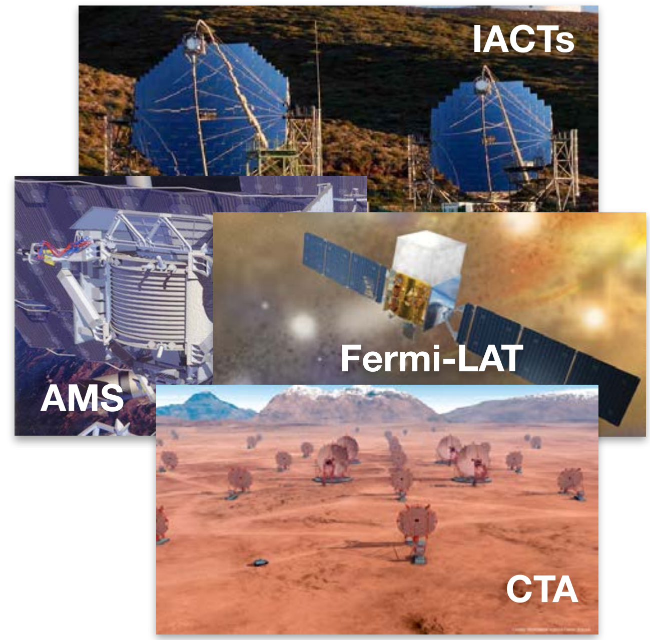
Roszkowski L., et al., JHEP 1408, 067 (2014)

WIMP DETECTION TECHNIQUES

3 complementary approaches:



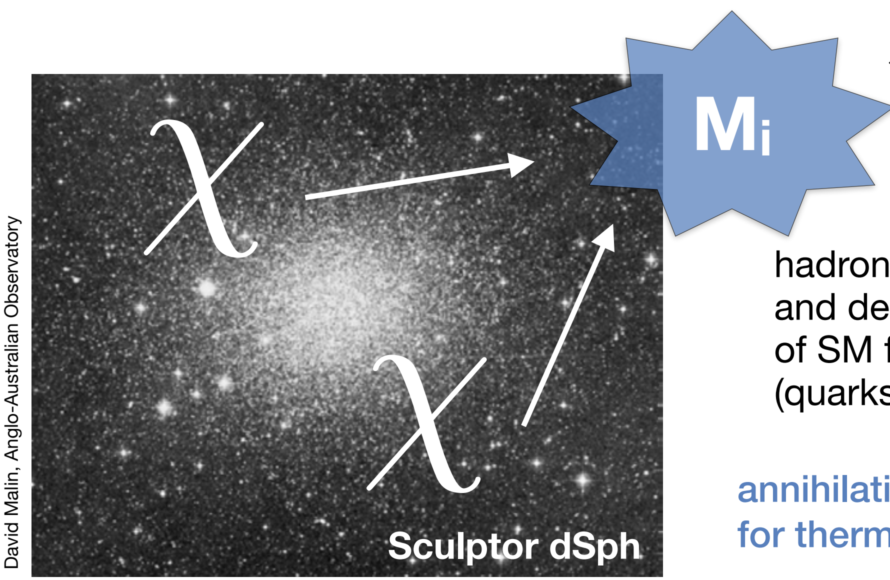


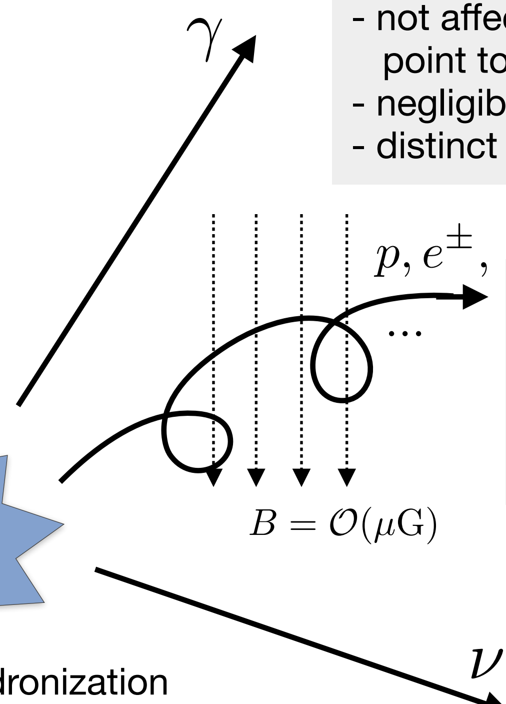


WIMP ANNIHILATION - INDIRECT DETECTION

SM final states:

$$\chi\chi \to q\bar{q}, l\bar{l}, \gamma\gamma, ZZ, W^+W^-, H$$





gamma rays
- not affected by B-fields; directly point to their origin
- negligible absorption in Galaxy
- distinct spectral shape

charged cosmic rays
- deflected by B-fields
- sizable energy losses
- however, low background for some (anti-deuterium)

neutrinos
- direct propagation
- no absorption
- however, not easy to detect

hadronization and decay of SM final states (quarks q, leptons l)

annihilation cross section for thermal production:

$$\langle\sigma v\rangle \approx 3\times10^{-26}\,\mathrm{cm^3\,s^{-1}}$$

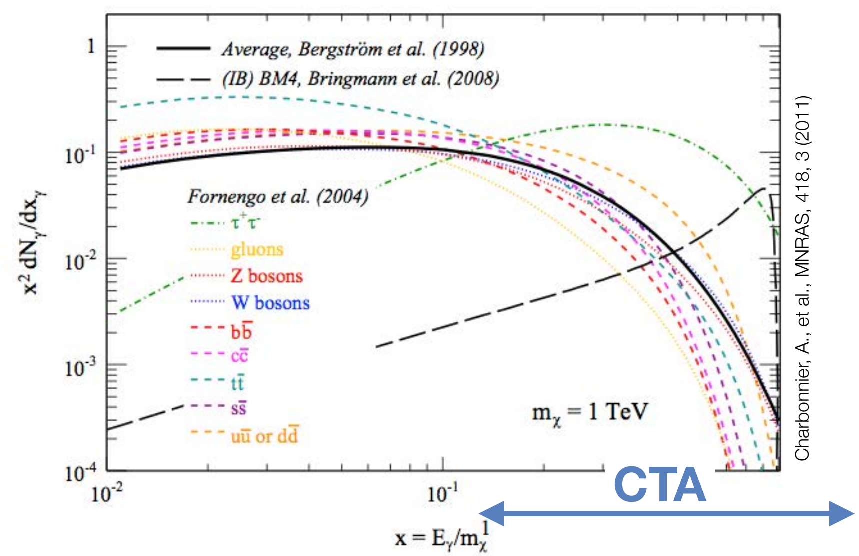
GAMMA-RAY SPECTRAL SIGNATURES

cherenkov telescope array

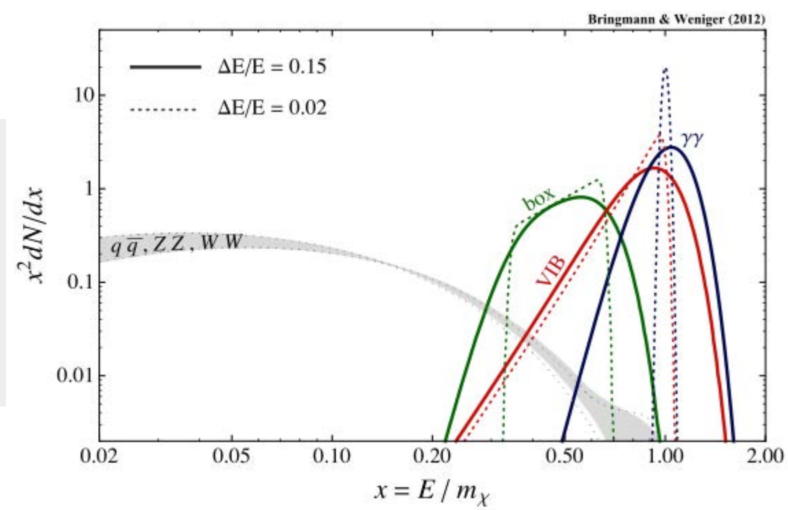
(i) hadronization and decay of SM states:
continuous spectrum with distinct cutoff to the WIMP mass

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

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



Charbonnier, A., et al., MNRAS, 418, 3 (2011)



Gamma-ray flux

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

DM density profile

GAMMA-RAY INSTRUMENTS
(SELECTION)

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]

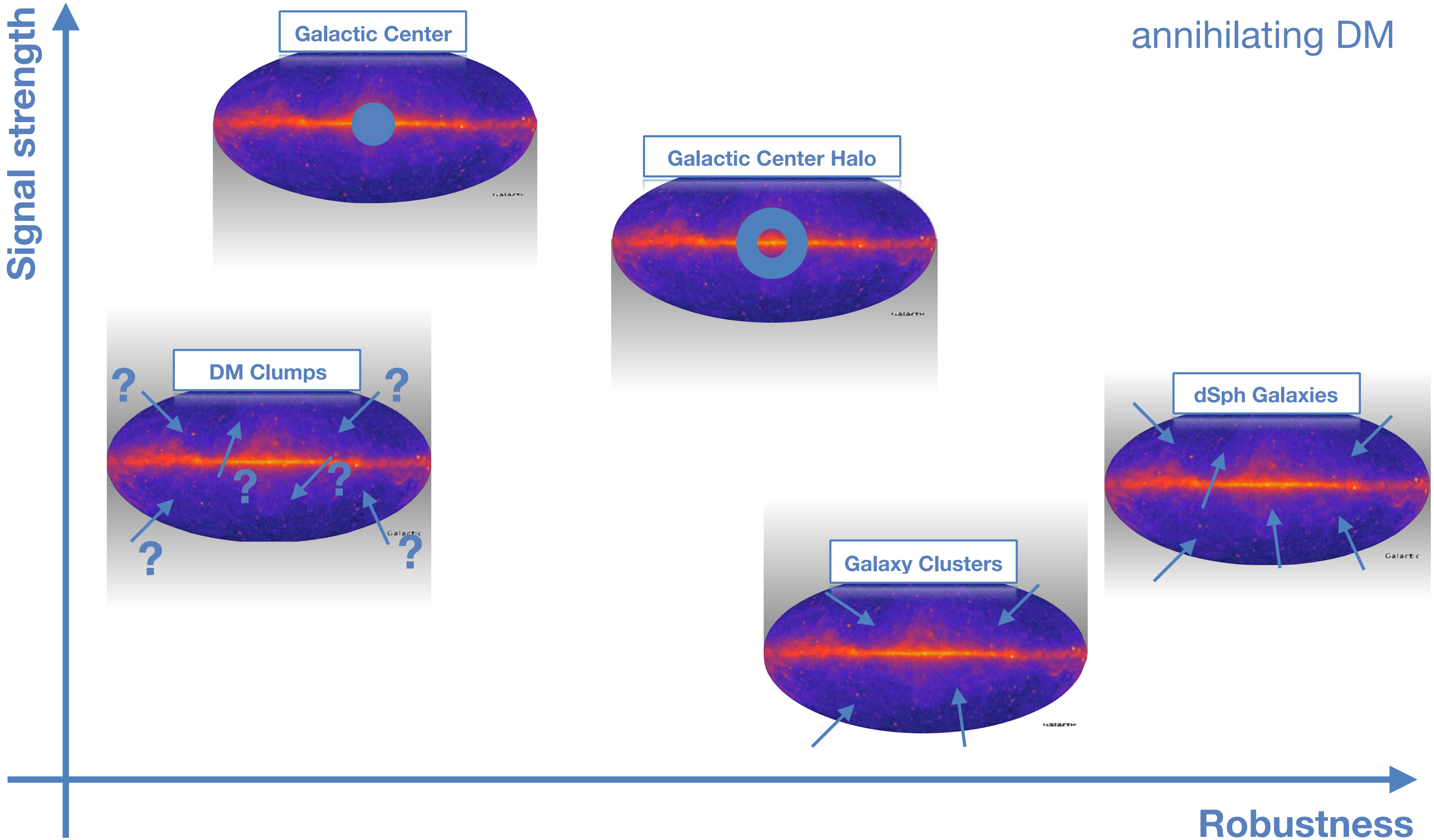
—> identify DM particle and properties; measure DM abundance and distribution

B. Non-detection

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

—> provide long-term legacy limits

TARGET SELECTION



GENERAL STRATEGY

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
  - x-check with ultra-faint/best dSph galaxy;
    cleaner environment (low background) but bright

- in the case of a GC/GH detection:
  - keep checking with the best dSph 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

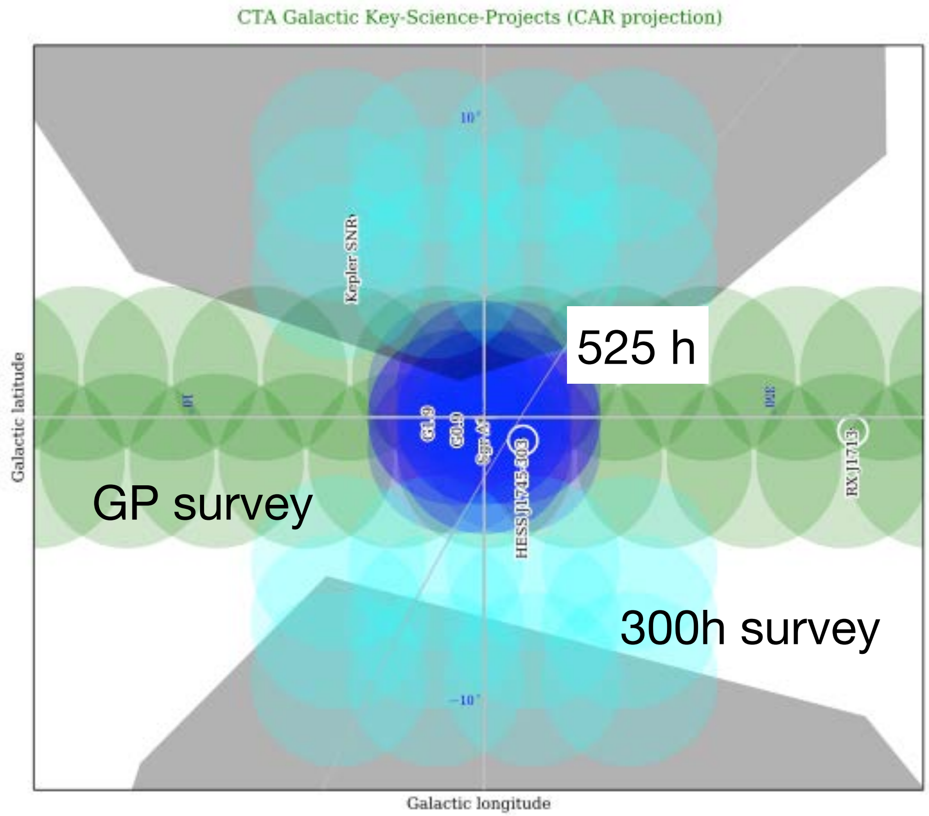
Table 4.1 – Strategy for dark matter observations over ten years with CTA. The first three years are devoted to the deep observation of the Galactic Centre (GC) together with the observation of the best ultra-faint dwarf galaxy. In case of non-detection of the GC, observations starting in the fourth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

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



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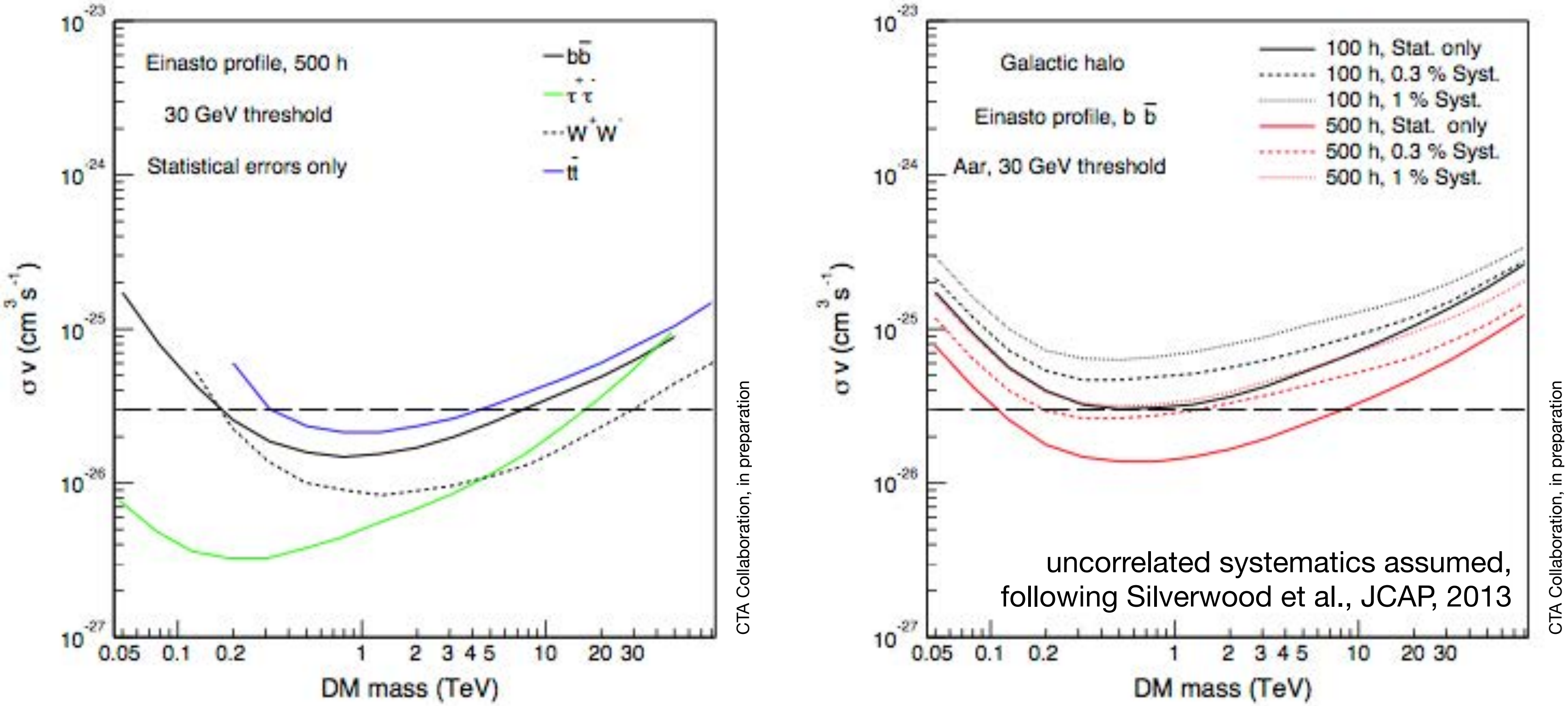
GALACTIC CENTER SENSITIVITY

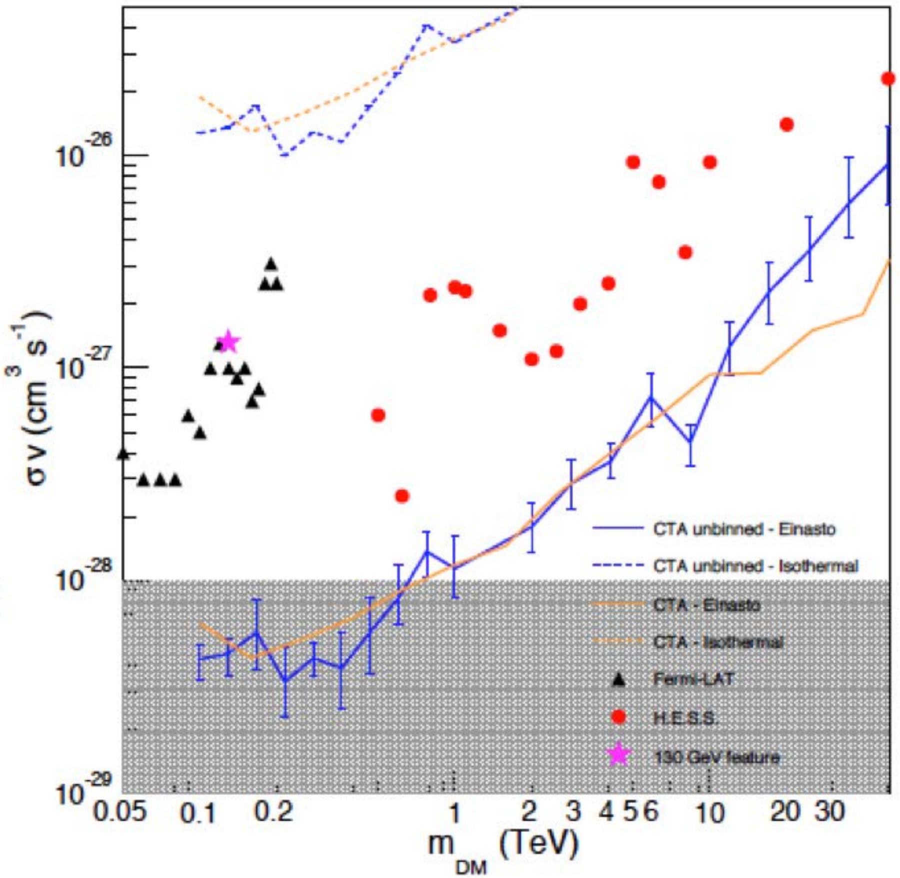


- **natural cross-section will be within the sensitivity reach of CTA!**
- on-source region has to be optimized carefully
- impact of Galactic diffuse foreground emission
- careful treatment and control of systematics mandatory; work in progress

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

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**



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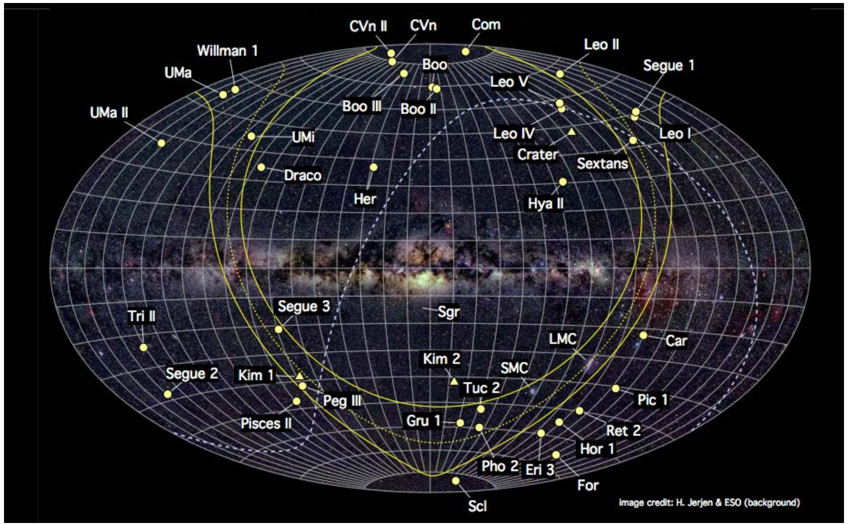
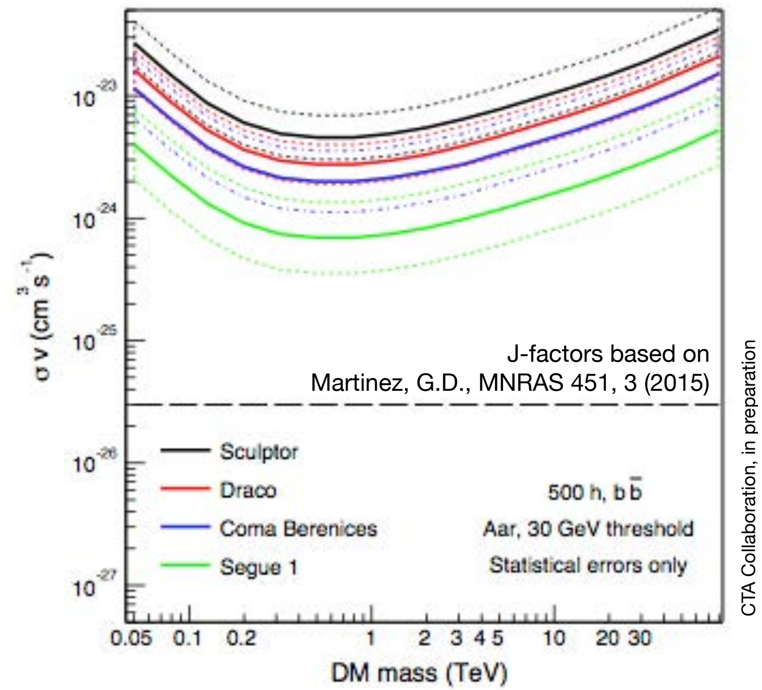
DWARF SPHEROIDAL GALAXIES AND DARK CLUMPS





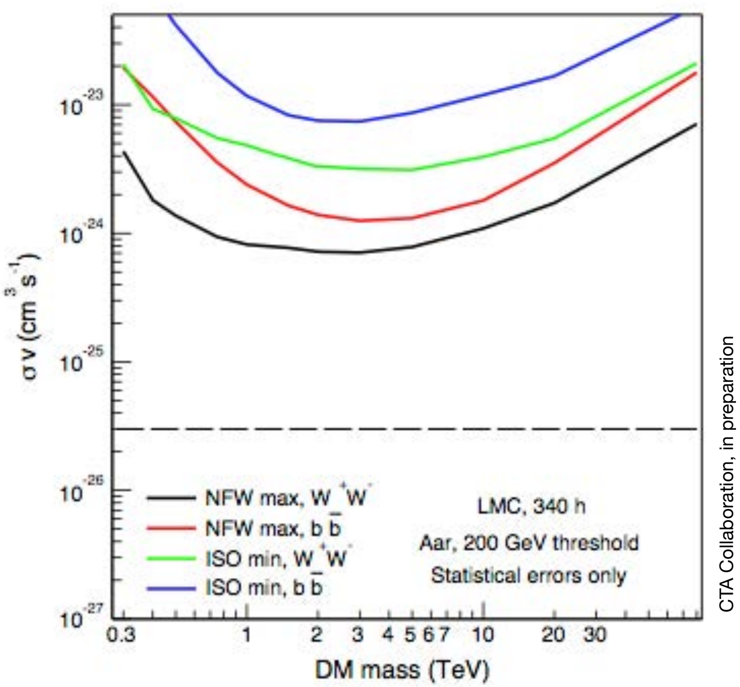
- MW satellite galaxies, D= 15 — 250 kpc
- luminosities ≳ 1000 L⊙
- large M/L up to 1000 M⊙/L⊙
- no astrophysical background
  (no gas content, no gamma-ray emitters)
- new ultra-faint dSphs to be discovered with next-generation sky surveys
  (DES, LSST, SkyMapper, Pan-STARRS)

- Sculptor, Draco, Segue I
  will be replaced with
  the best constrained/most promising dSphs known at the time of observation

- **robust constraints, but a factor of ~30 away from DM expectation**

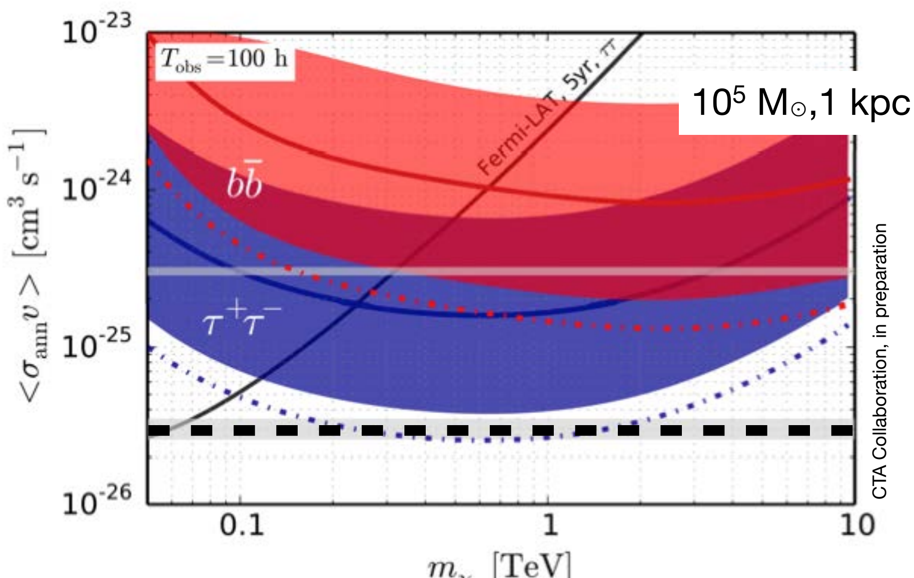
LMC, DARK CLUMPS

- special target:
  Large Magellanic Cloud (LMC)
  - *hosts many interesting astrophysical sources*
  - *non-DM proposal for 340 h*
  - *may have a high J-factor; extended source to CTA*



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

  - **large uncertainties, but discovery potential**



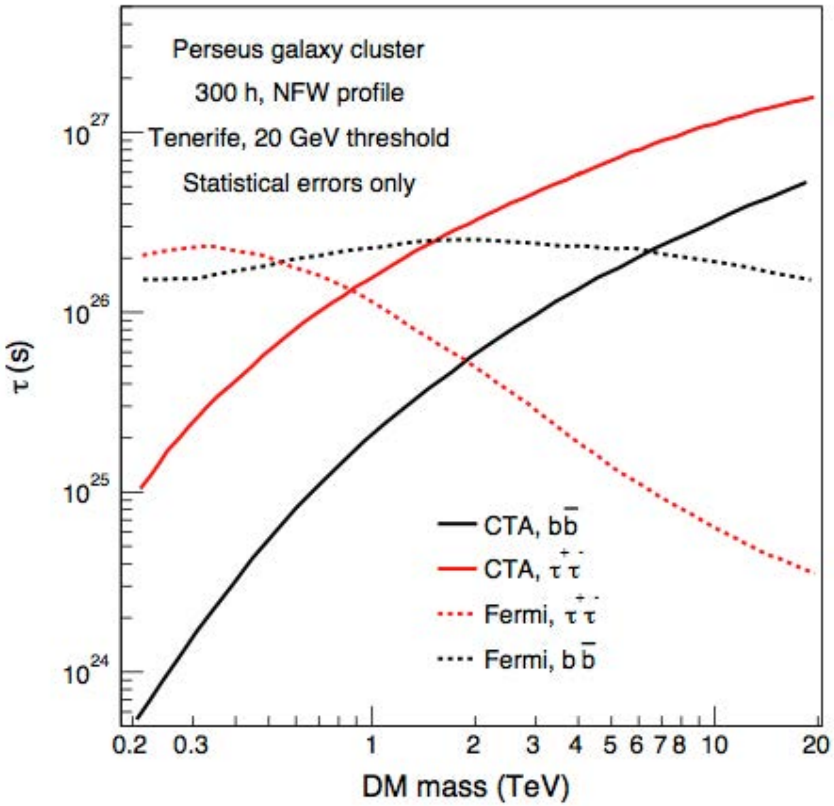
GALAXY CLUSTERS
(DECAYING DM)

- 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**

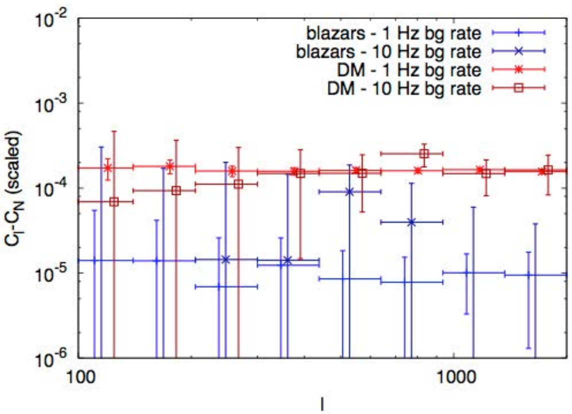


CTA Collaboration, in preparation

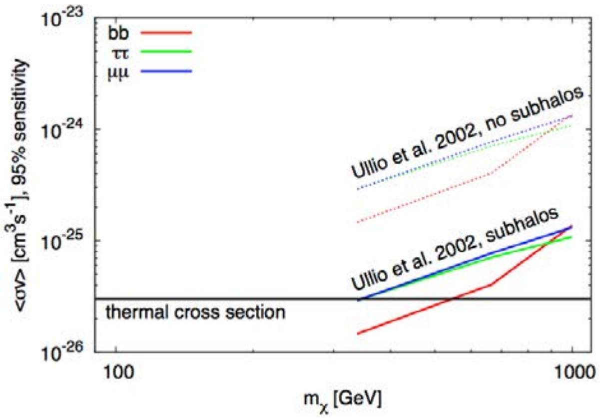
OTHER PROPOSALS

Ripken, J., Cuoco, A., Zechlin, H., et al., JCAP 01, 049 (2014)

- many other ideas under consideration in recent literature
- e.g., new physics may imprint in diffuse gamma-ray backgrounds
- isotropic diffuse gamma-ray background (IGRB) can be tackled with higher precision
- use small-scale spatial anisotropies to discriminate different components
- **CTA will provide good sensitivity; model-dependent**



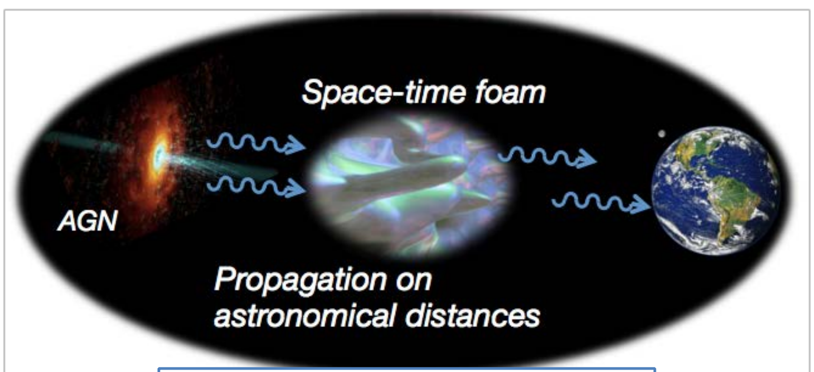
(d) Multiple fov, $10 \times 100\,\mathrm{h}$, $E_{\mathrm{thr}} = 300\,\mathrm{GeV}$



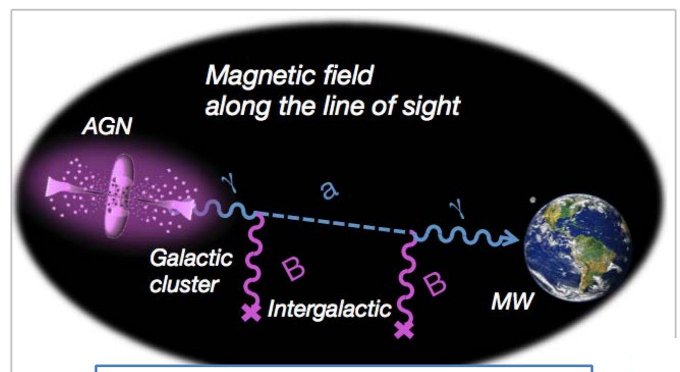
FUNDAMENTAL PHYSICS TOPICS

Photon Propagation Effects

—> synergistic with the AGN/EGAL observations, i.e., essentially no additional time will be required

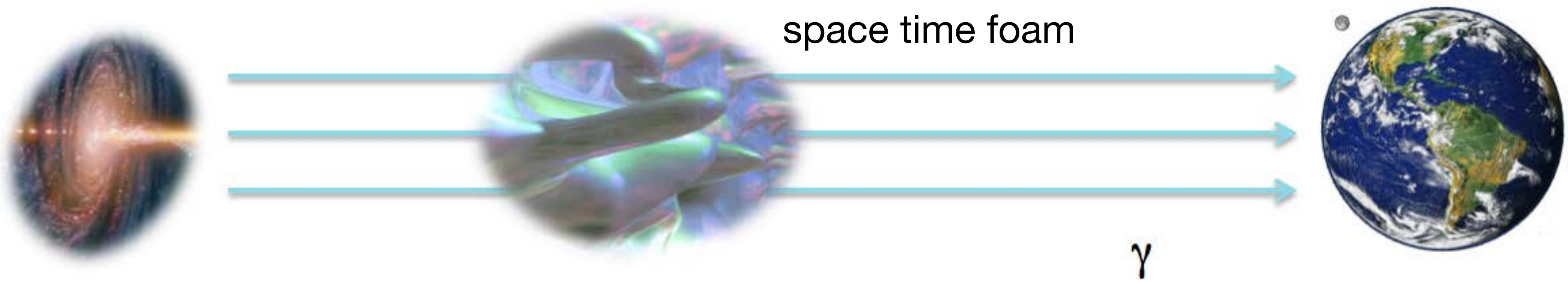


Lorentz Invariance



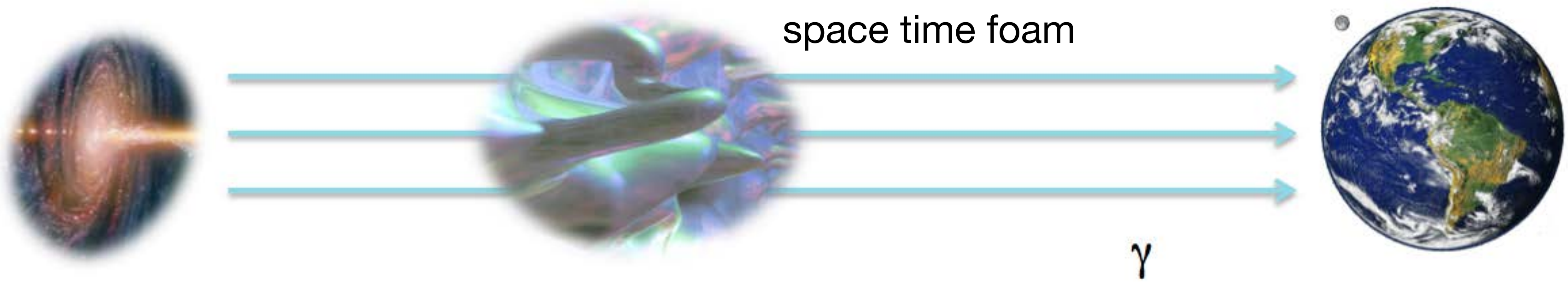
Axions

LORENTZ INVARIANZ VIOLATION



- photon dispersion relation may depend on energy;
  important at very high energies, approaching Planck scale
- observational signatures:
  - lag in arrival time of photons at different energy scales
  - gamma-ray horizon, i.e., the pair-annihilation cross section
- targets for CTA:
  - distant (!) and bright AGN with heavy flaring activity
  - short and bright GRBs
  - pulsars
- CTA will provide source-model independent limits
  (large variety of intrinsically different targets)
- intrinsic and propagation induced effects can be disentangled with CTA
  (large number of observed sources at different redshifts)

LORENTZ INVARIANZ VIOLATION



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sensitivity to linear and quadratic terms of photon dispersion relation; Planck scale can be probed with CTA

- CTA will provide source-model independent limits
  (large variety of intrinsically different targets)
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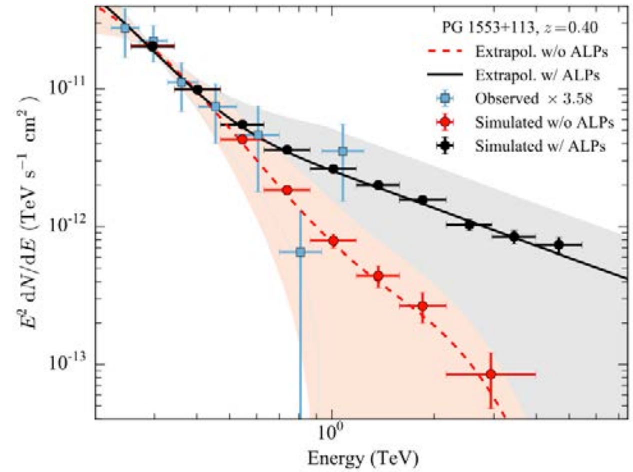
  (large number of observed sources at different redshifts)

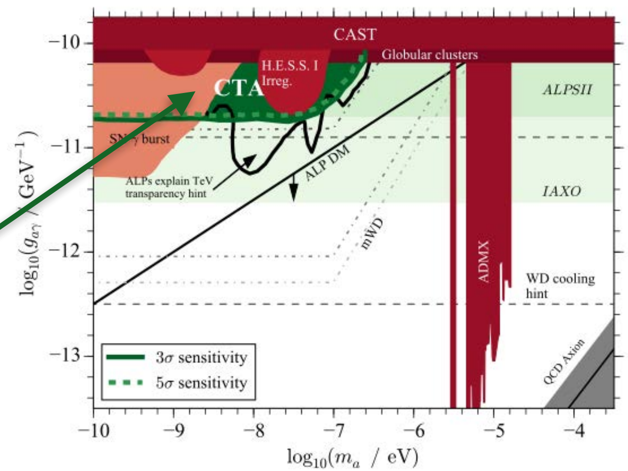
AXIONS/ALPS SEARCHES

- existence of axions motivated by strong CP problem; extended setup: axion-like particles (ALPs)
- photon-ALP conversion in ambient B-fields would
  - change observed gamma-ray spectra
  - increase transparency of the Universe by reducing EBL absorption
- B-fields can be source-intrinsic, galactic, or cosmic

- **CTA can constrain parts of ALPs parameter space; sensitivity to EBL transparency hint**



Meyer, M., Conrad, J., JCAP 12, 016 (2014)



Meyer, M., Conrad, J., JCAP 12, 016 (2014)

SUMMARY

- **CTA will have a unique discovery potential for particle dark matter in the mass range above 200 GeV**
- the energy overlap with Fermi-LAT will significantly help in constraining/ discovering dark matter in the GeV/TeV range
- results will be complementary to direct detection and colliders
- in the case of non-detection, long-standing legacy limits will significantly constrain the parameter space left for BSM scenarios such as SUSY