Dark matter searches with CTA

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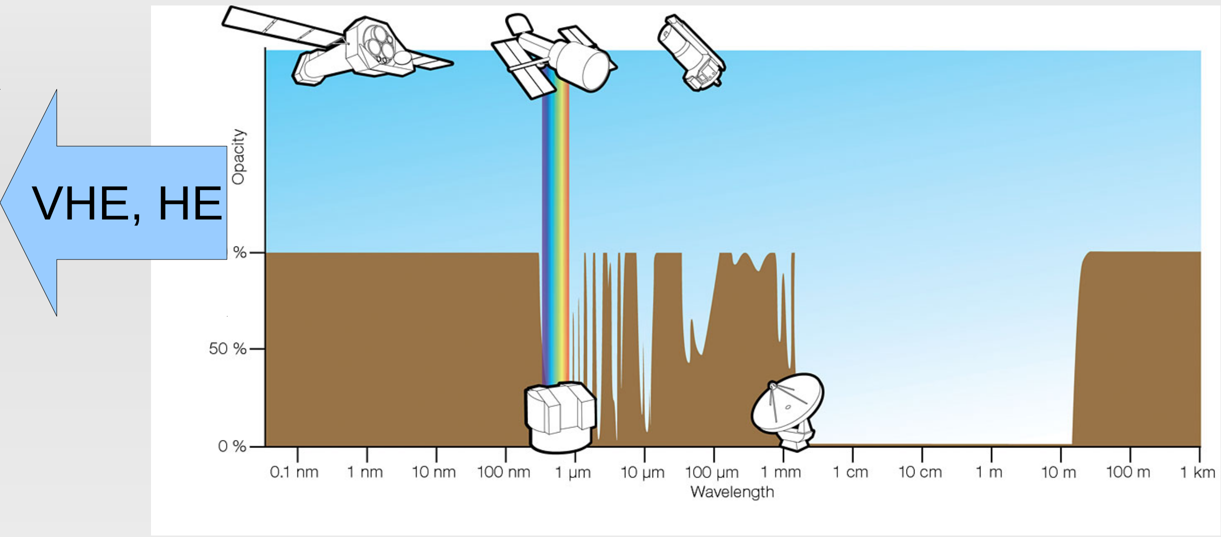
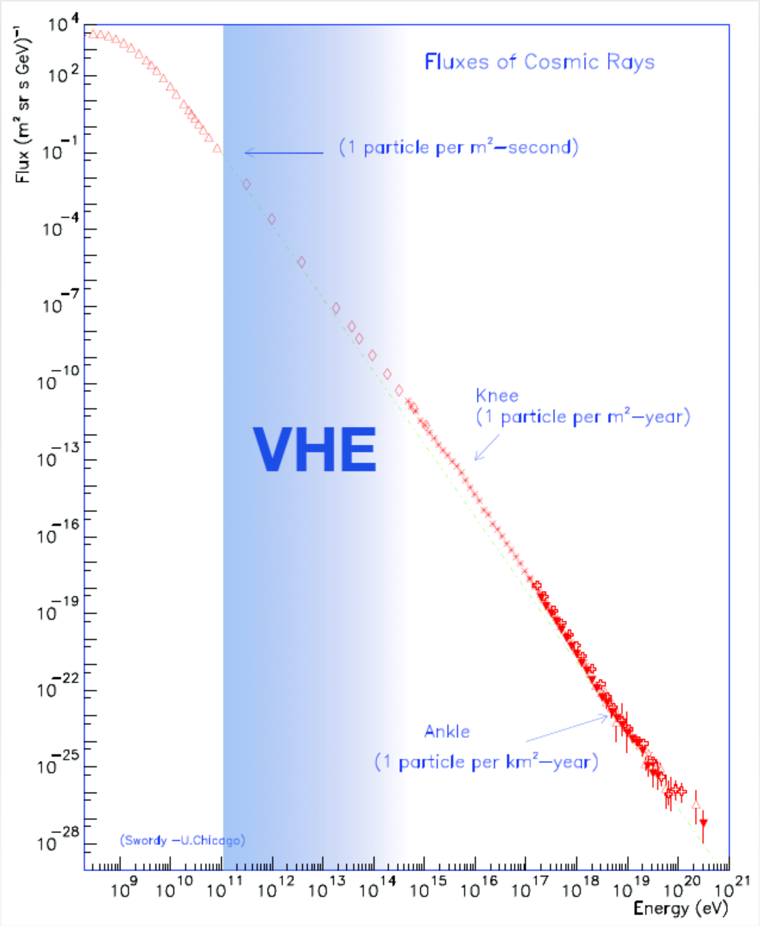
OUTLINE

- VHE astronomy
- The Cherenkov Telescope Array
- Dark matter searches
- Conclusion

Detecting γ-rays





- Convention

  HE : High Energy (E ≥ 100 MeV)

  VHE : Very High Energy (E ≥ 100 GeV)

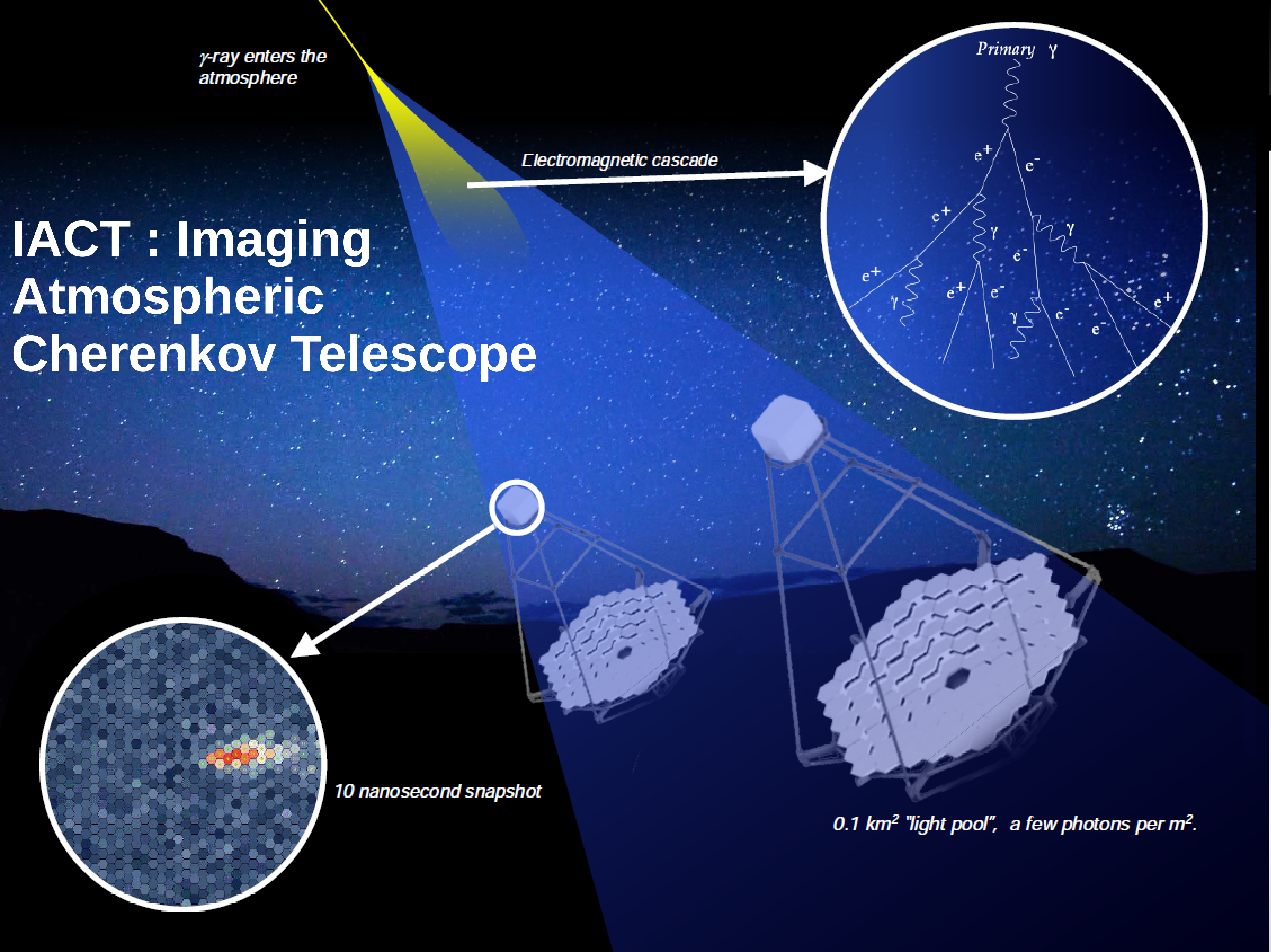
- γ-rays are not deflected by B

  → study of sources and production mecanisms

- Atmosphere is opaque to γ-rays

  Satellite exp. for HE

  IACTs for VHE (very low fluxes <1 ph/m^2/y)


IACT : Imaging Atmospheric Cherenkov Telescope
γ-ray enters the atmosphere
Electromagnetic cascade
Primary γ
e+
e-
γ
10 nanosecond snapshot
0.1 km² "light pool", a few photons per m².

CTA - Cherenkov Telescope Array

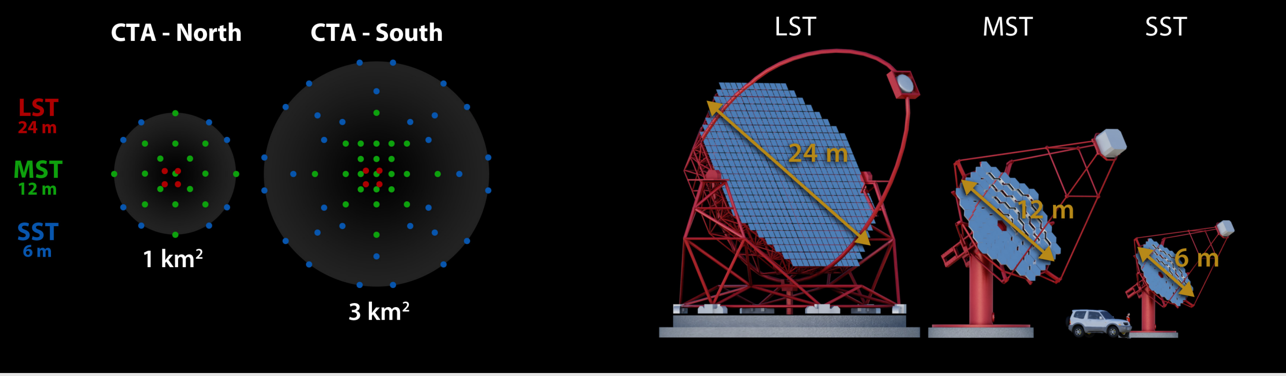
Currently in the preparatory phase

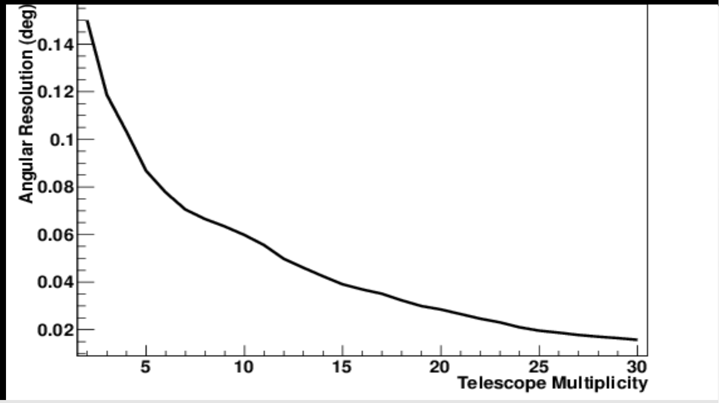
Construction phase : end of 2015

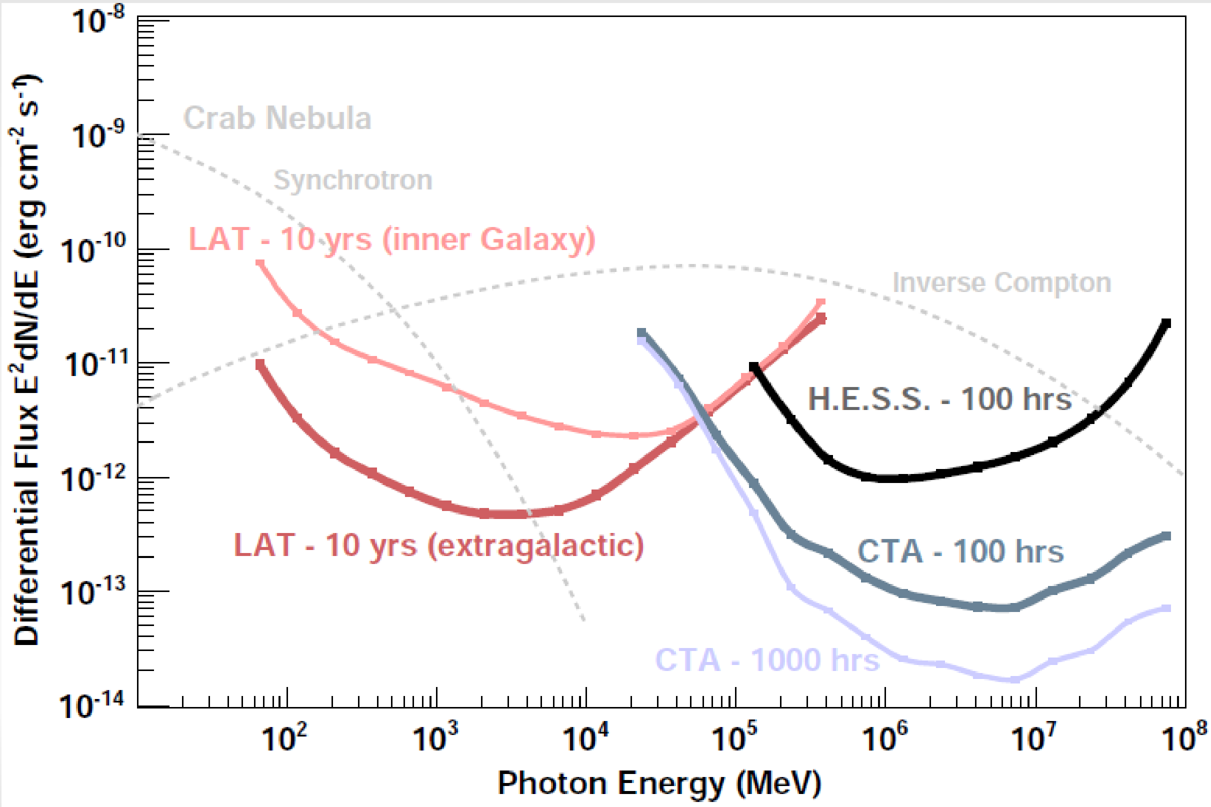
>1000 sources expected

~ 1000h obs/y

CTA - Cherenkov Telescope Array

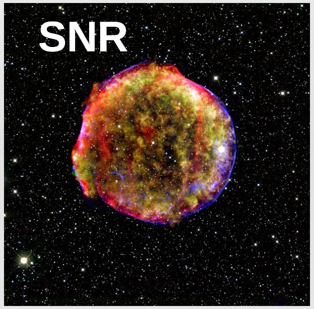


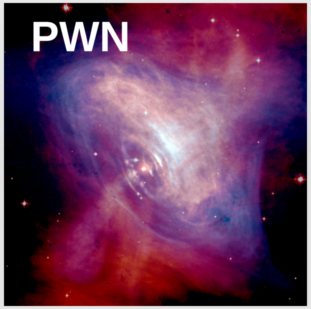


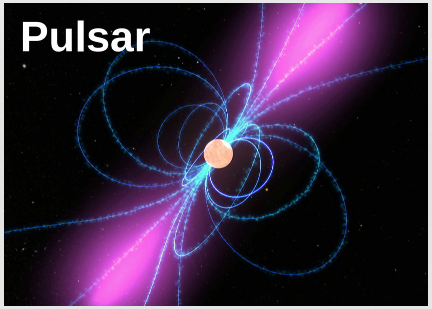


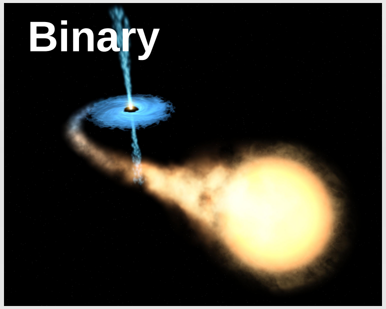
Science with CTA: probing the extreme Universe & beyond

Galactic sources







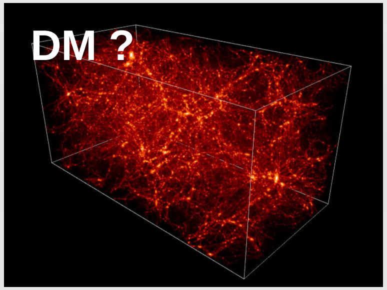


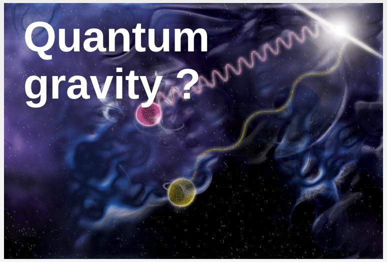
Extragalactic sources

Theme 1: Cosmic Particle Acceleration, Propagation and Impact
Theme 2: Probing Extreme Environments
Theme 3: Physics Frontiers

1. What is the nature of Dark Matter? How is it distributed?
2. Do axion-like particles exist?
3. Is the speed of light a constant for high-energy photons?

Physics Frontiers

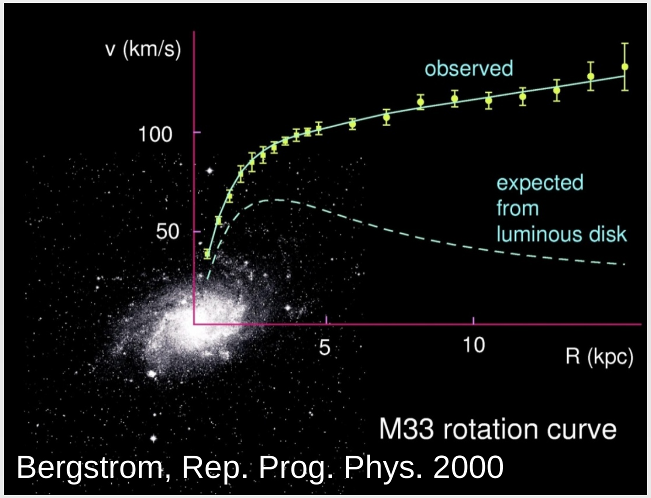




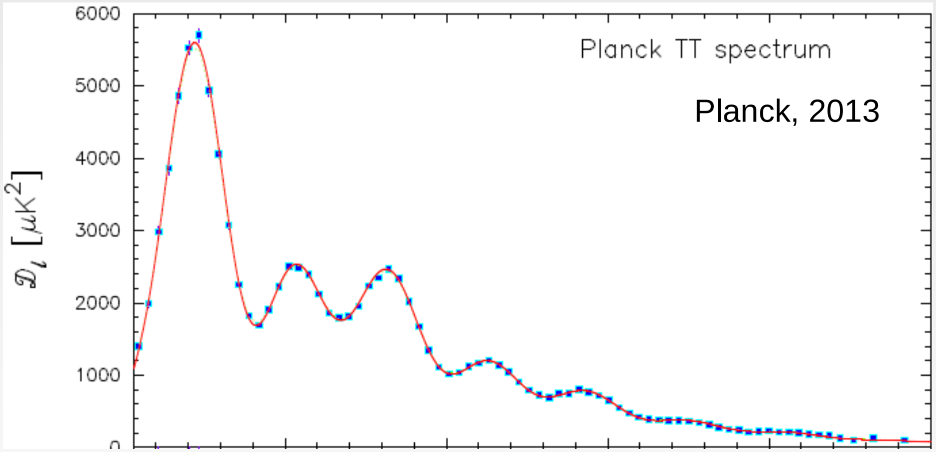
Theme 3-1
Dark matter in the Universe – really ?

Coma galaxy cluster

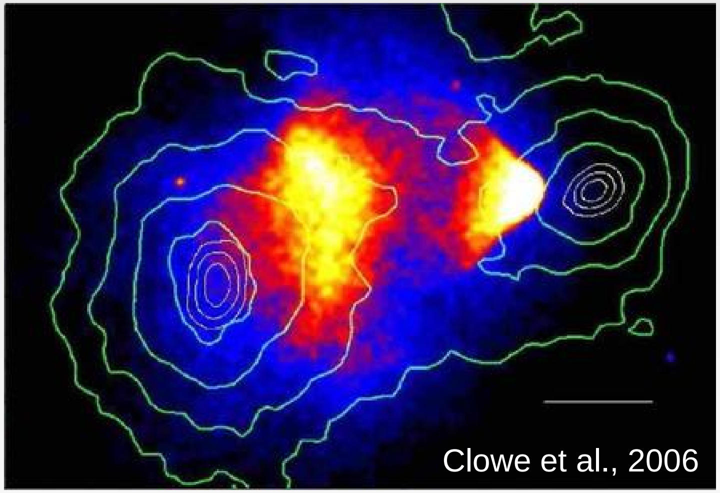
Fritz Zwicky, 1933: "If this over-density is confirmed we would arrive at the astonishing conclusion that dark matter is present with a much greater density than luminous matter."



M33 rotation curve
Bergstrom, Rep. Prog. Phys. 2000



Planck, 2013



Clowe et al., 2006

YES ! At all scale.

γ-ray flux from WIMP annihilations

$$\Phi^{\gamma}_{WIMP}(E,\Psi) = J(\Psi) \times \Phi^{PP}(E)$$

$$J(\Psi) = \int_{los} dl(\Psi)\, \rho^2(l)$$

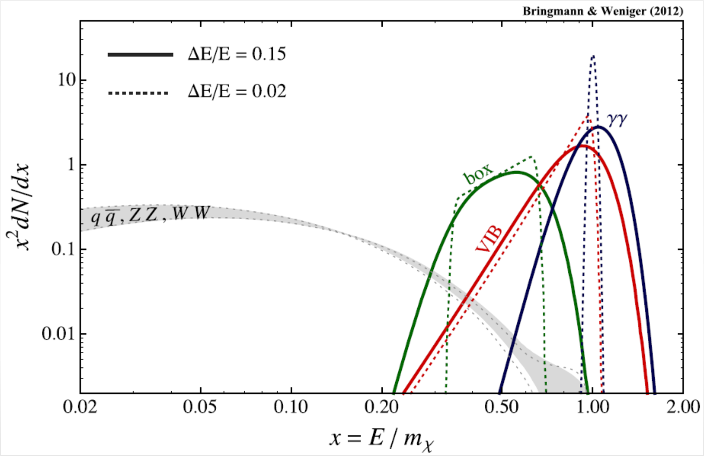
$$\Phi^{PP}(E) = \frac{1}{2}\frac{\langle\sigma v\rangle}{m^2_{DM}} \sum_f B_f \frac{dN^{\gamma}_f}{dE}$$

- **Astrophysic factor :**
  - nb of annihilations
    → intensity of gamma-rays

  Uncertainties :
  - density profile, diffusion, absorption,...

- **Particle physic factor :**
  - nb of γ-ray produced per annihilation
    → spectral shape

  Uncertainties :
  - cross section, mass, branching ratios,...

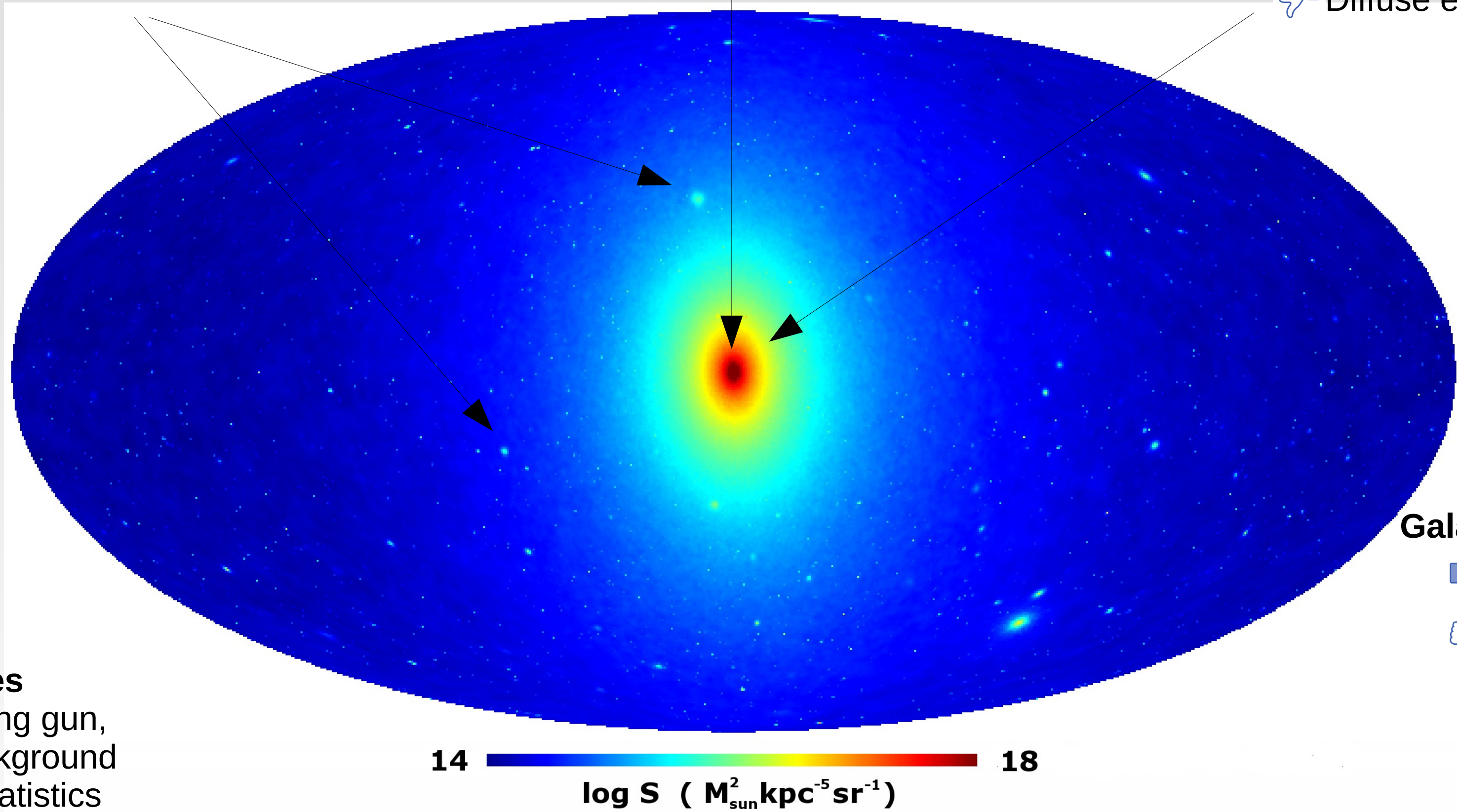


Targets

Dwarf galaxies
- 👍 Low background, small uncertainties
- 👎 Low statistics

Galactic centre
- 👍 Large statistic
- 👎 Source confusion, DM density uncertainties

Galactic halo
- 👍 Large statistic
- 👎 Diffuse emission

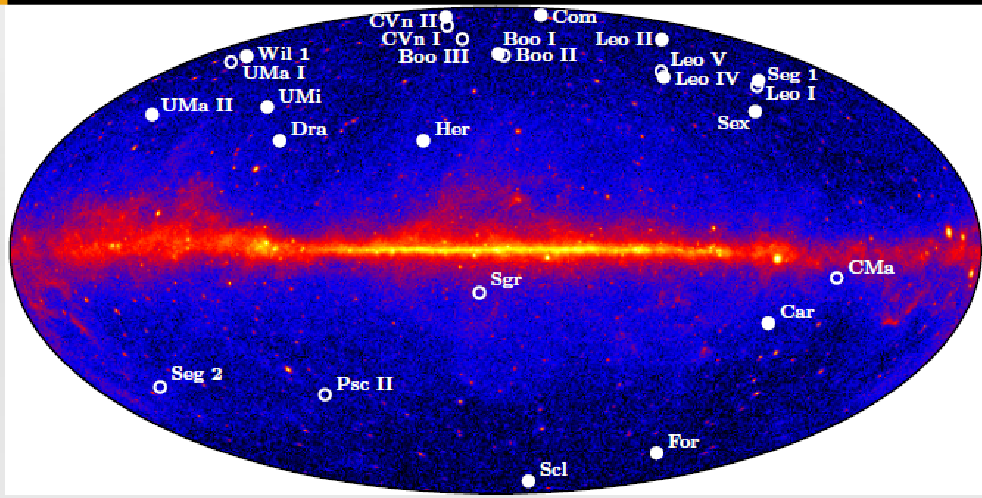


Galaxy clusters
- 👍 Large reservoir (decay)
- 👎 Low statistics, astrophysical bkg

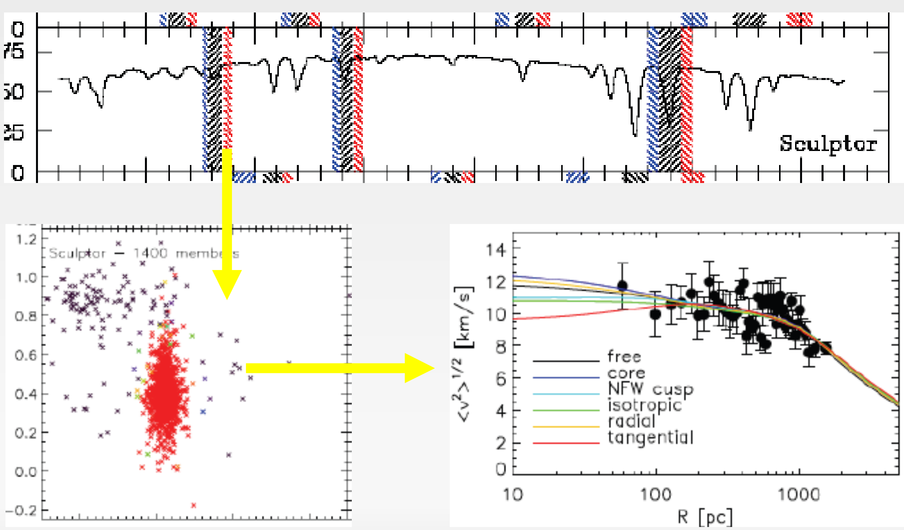
Spectral lines
- 👍 Smoking gun, no background
- 👎 Low statistics

Extragalactic
- 👍 Large statistics
- 👎 Astrophysical bkg

Dwarf spheroidal galaxies



- DM dominated (M/L ~ 10 – 100)
- Nearby (~100 kpc)
- Low background
- Stellar velocities can be used to estimate DM density (and uncertainties can be propagated to constraints)



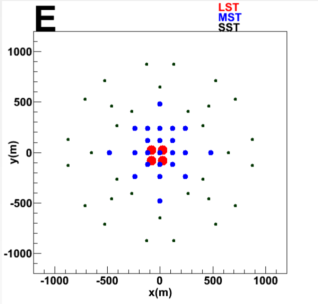
Name	l deg.	b deg.	d kpc	$\overline{\log_{10}(J)}$ $\log_{10}[\mathrm{GeV^2 cm^{-5}}]$	σ	ref.
Bootes I	358.08	69.62	60	17.7	0.34	[17]
Carina	260.11	−22.22	101	18.0	0.13	[18]
Coma Berenices	241.9	83.6	44	19.0	0.37	[19]
Draco	86.37	34.72	80	18.8	0.13	[18]
Fornax	237.1	−65.7	138	17.7	0.23	[18]
Sculptor	287.15	−83.16	80	18.4	0.13	[18]
Segue 1	220.48	50.42	23	19.6	0.53	[14]
Sextans	243.4	42.2	86	17.8	0.23	[18]
Ursa Major II	152.46	37.44	32	19.6	0.40	[19]
Ursa Minor	104.95	44.80	66	18.5	0.18	[18]

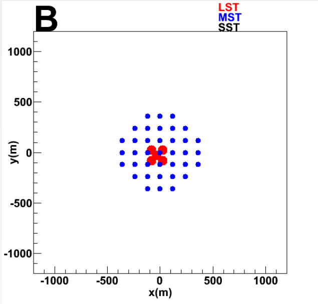
CTA view of dSph (I)

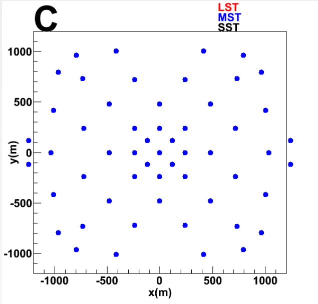
Sensitivity requirements

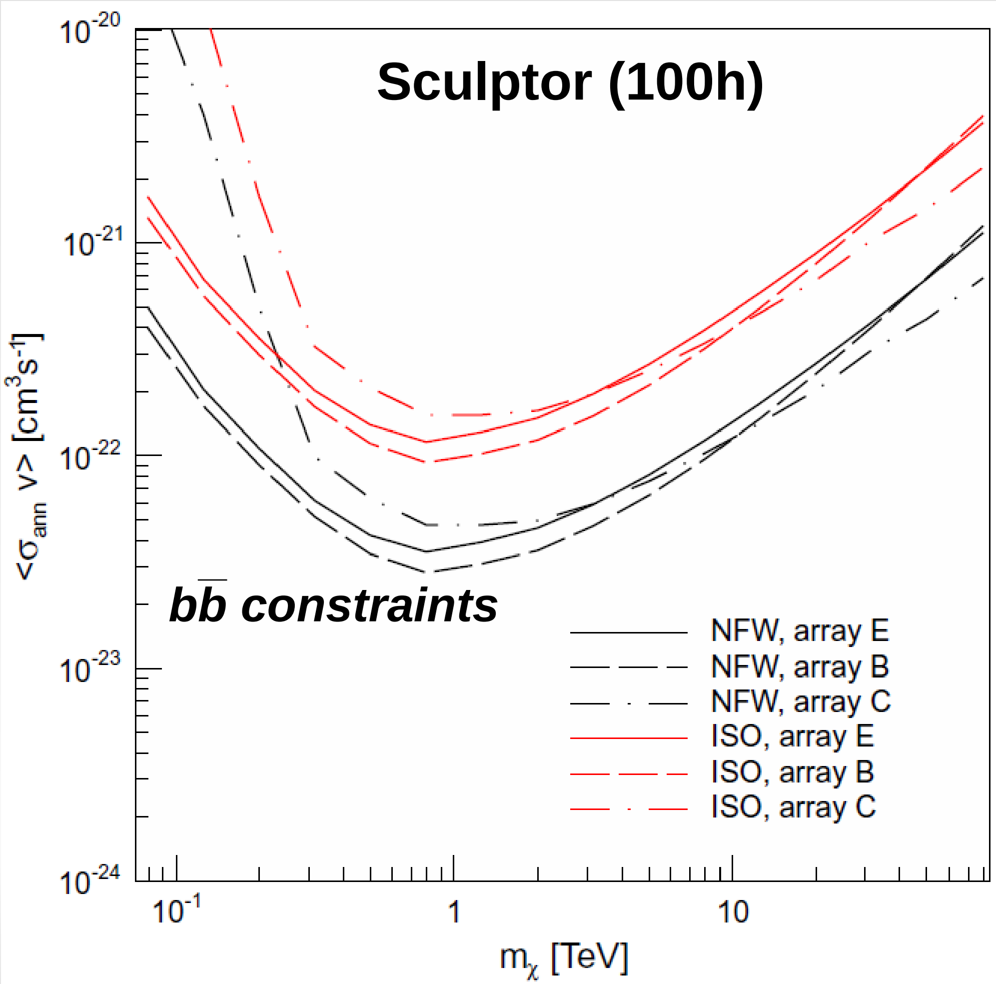
- Nγ > 10
- Nγ/Nbkg > 3 %
- Ncontrol regions = 5
- Nσ>5 (Li & Ma, 1983) or 95%CL UL

Sensitivity studies for different arrays







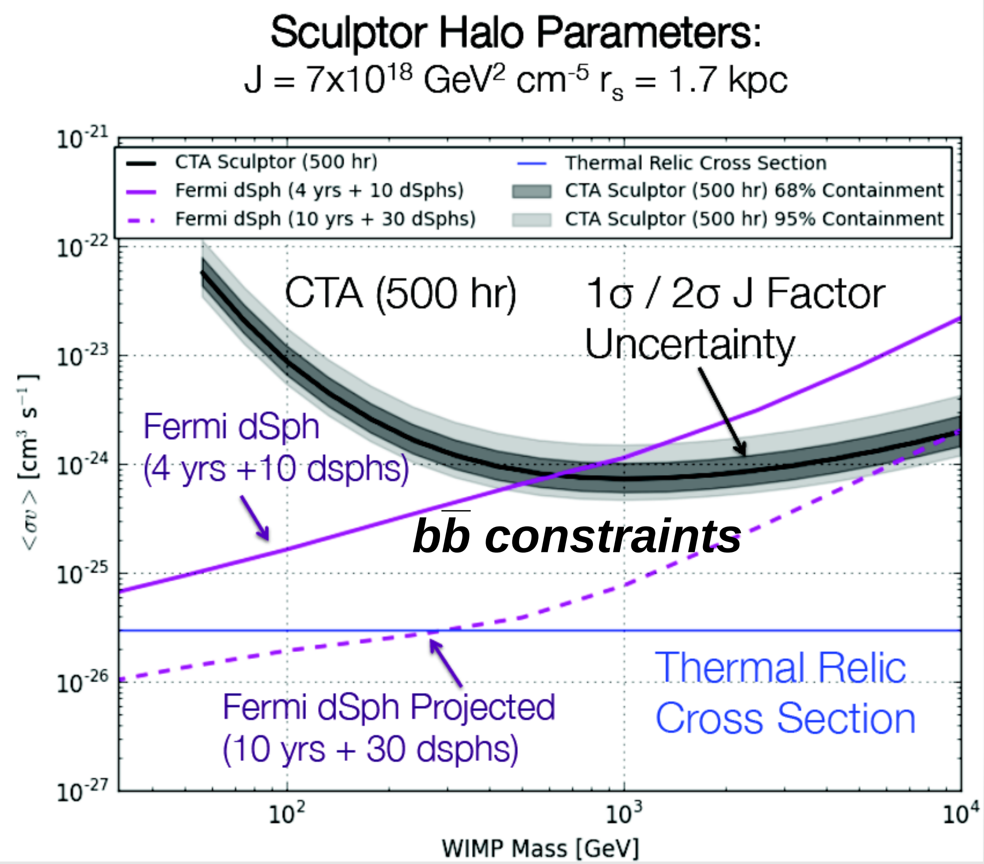


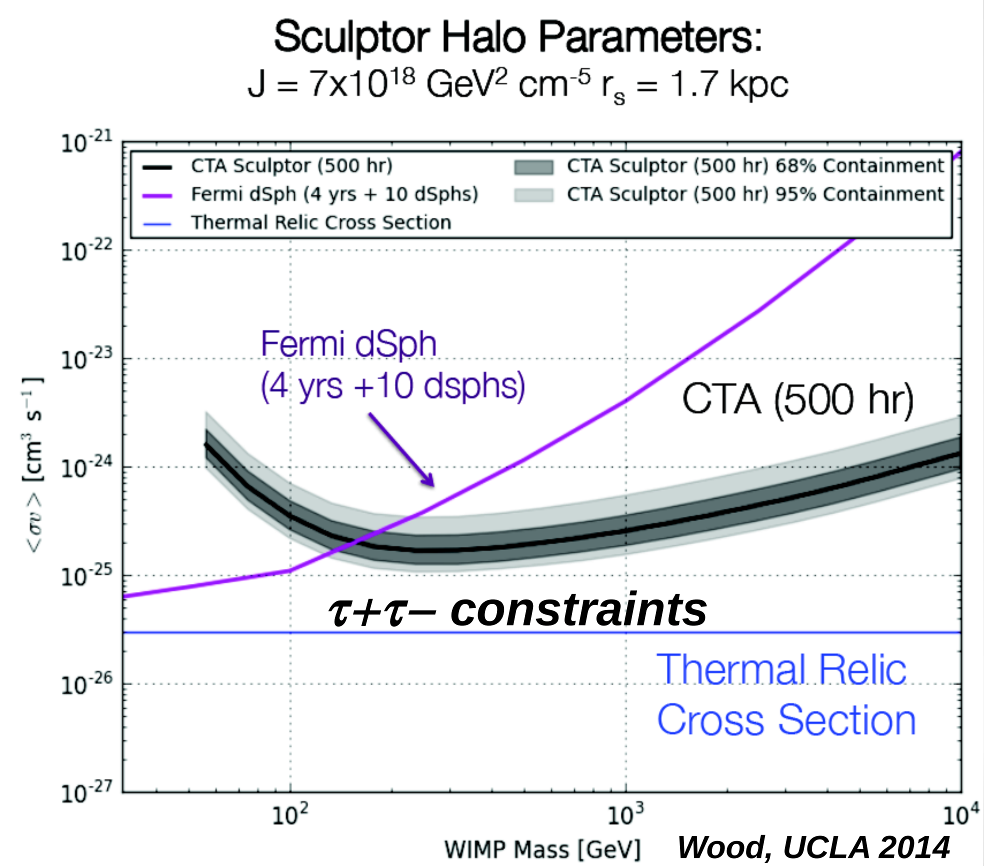
CTA view of dSph (II)

New analysis :
- template-based shower selection/discrimination + additional MSTs
- binned-likelihood analysis of final event list + J-factor uncertainty

→ significant increased of sensitivity

Expected sensitivity (Asimov data set)

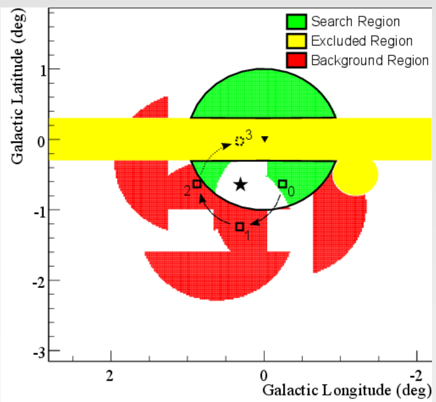


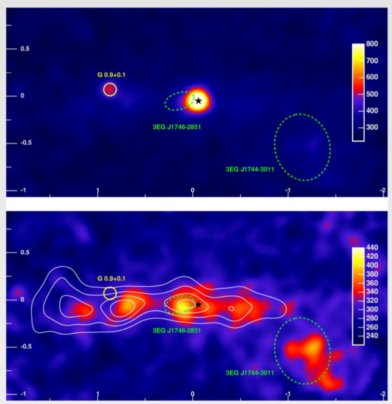


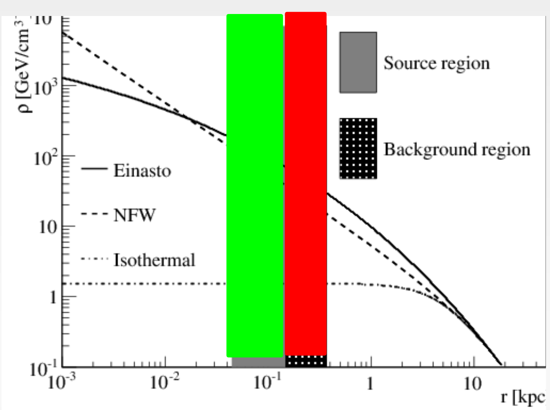
Wood, UCLA 2014

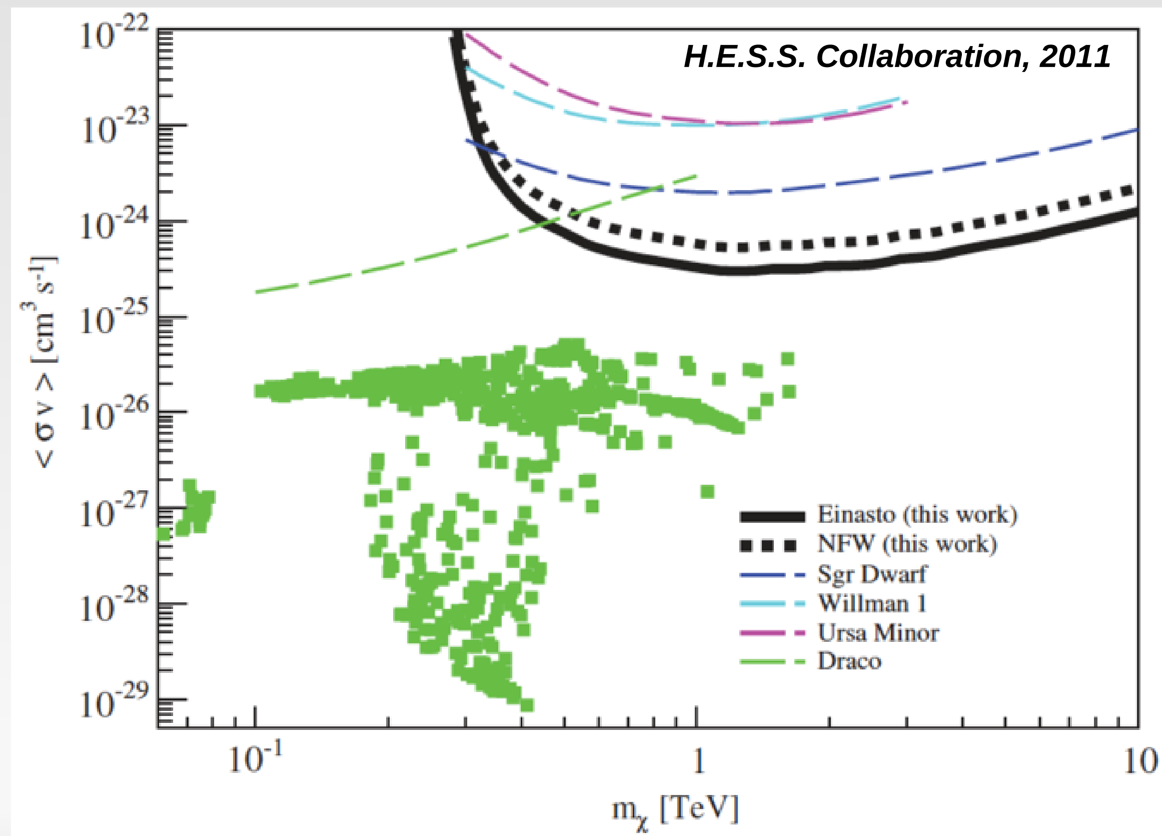
Galactic centre halo

- Close-by and strong signal expected
- Reduced uncertainties wrt centre itself
- Better control of background
- Best constraints so far (H.E.S.S.)

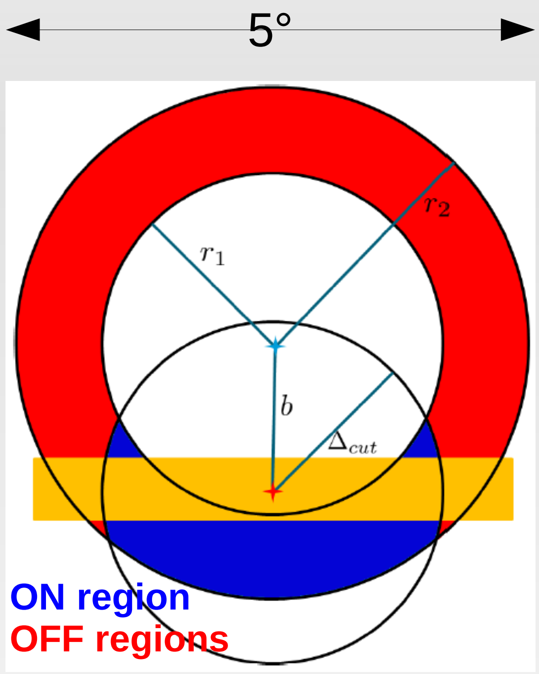


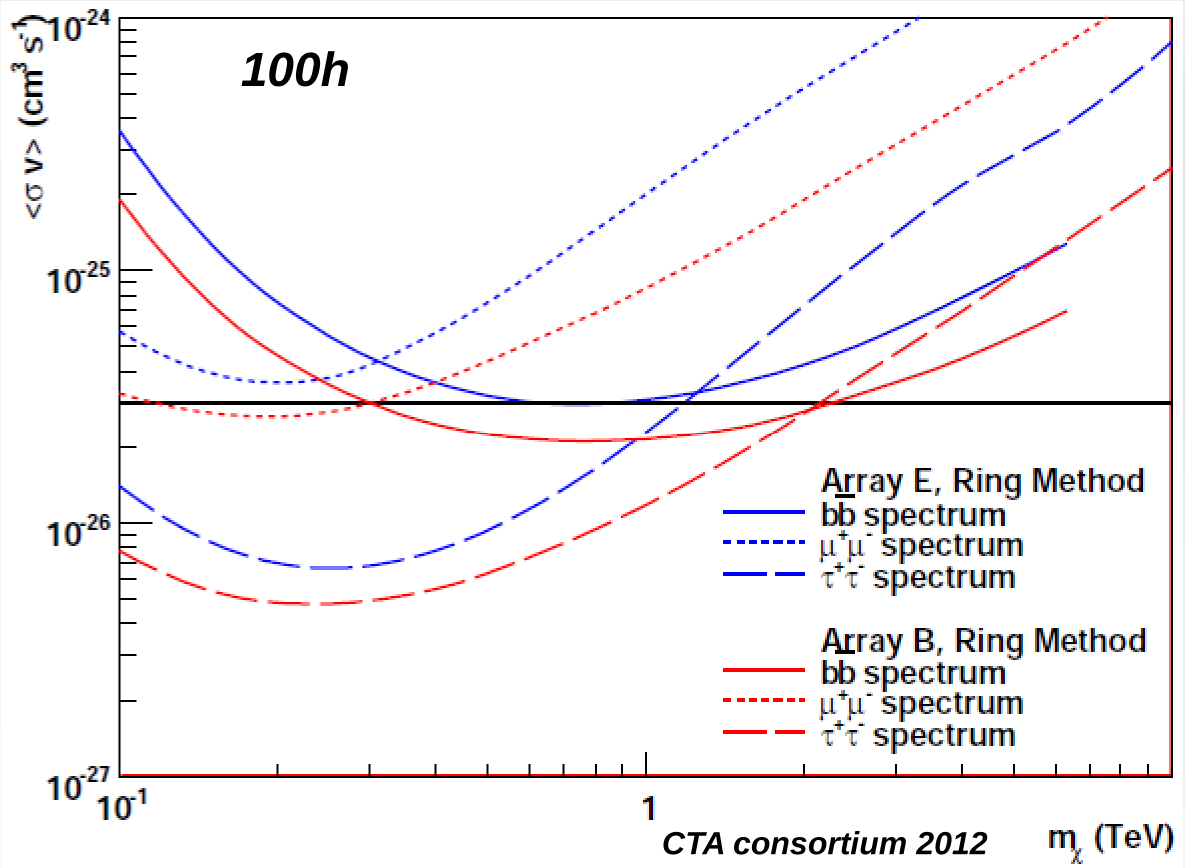






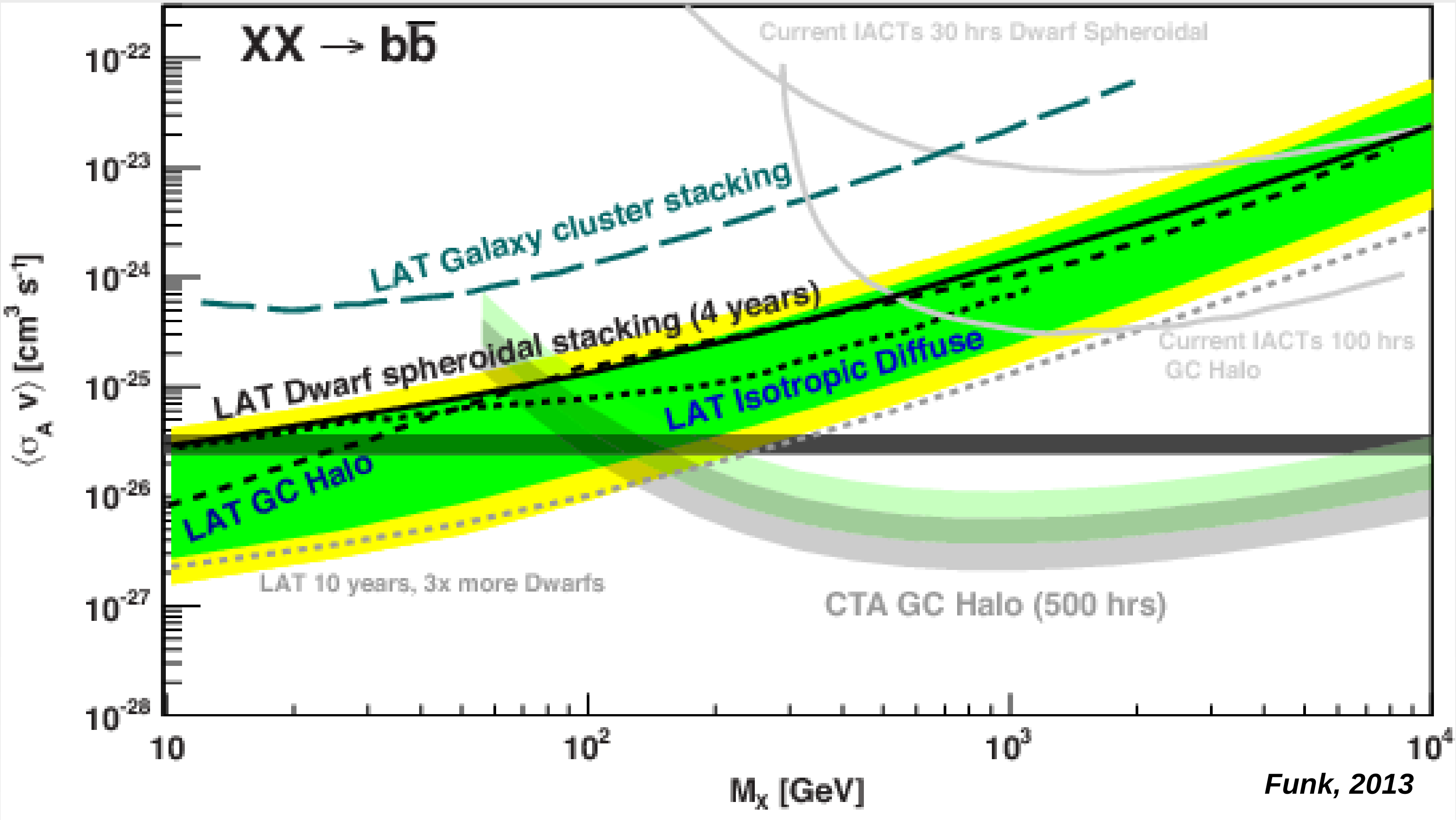
Galactic centre halo with CTA





⇒ CTA will have the best sensitivity for large WIMP masses
Test of SUSY models compatible with thermal relic density

Galactic centre halo with CTA

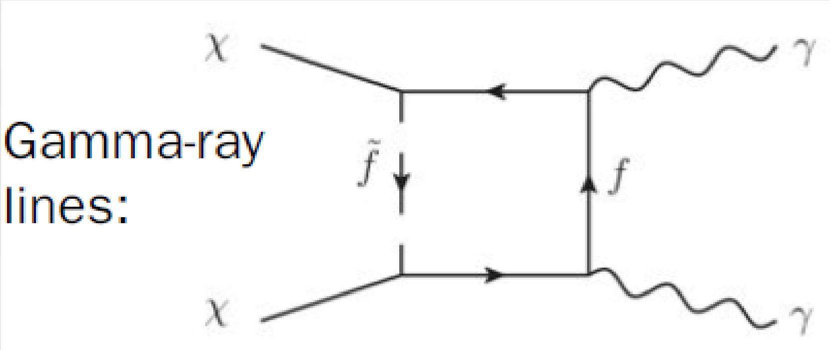


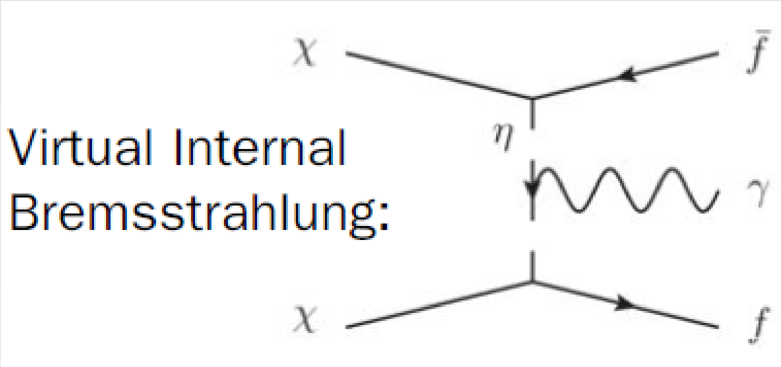
Funk, 2013

Sensitivity can be increased by use of new analysis and additional MST contribution by US
CTA will be the key player for WIMP searches > few 100th GeV

Line-like signal from DM annihilation

- **Smoking gun** of DM since no other astrophysical sources are foreseen to mimic such signal





- Line arising from $\chi\chi \rightarrow \gamma X$ [X = γ,Z,H]

$$E_\gamma = m_\chi \left(1 - \frac{m_X^2}{4 m_\chi^2}\right)$$

- Internal Bremsstrahlung :
  - Final state radiation
  - Virtual IB

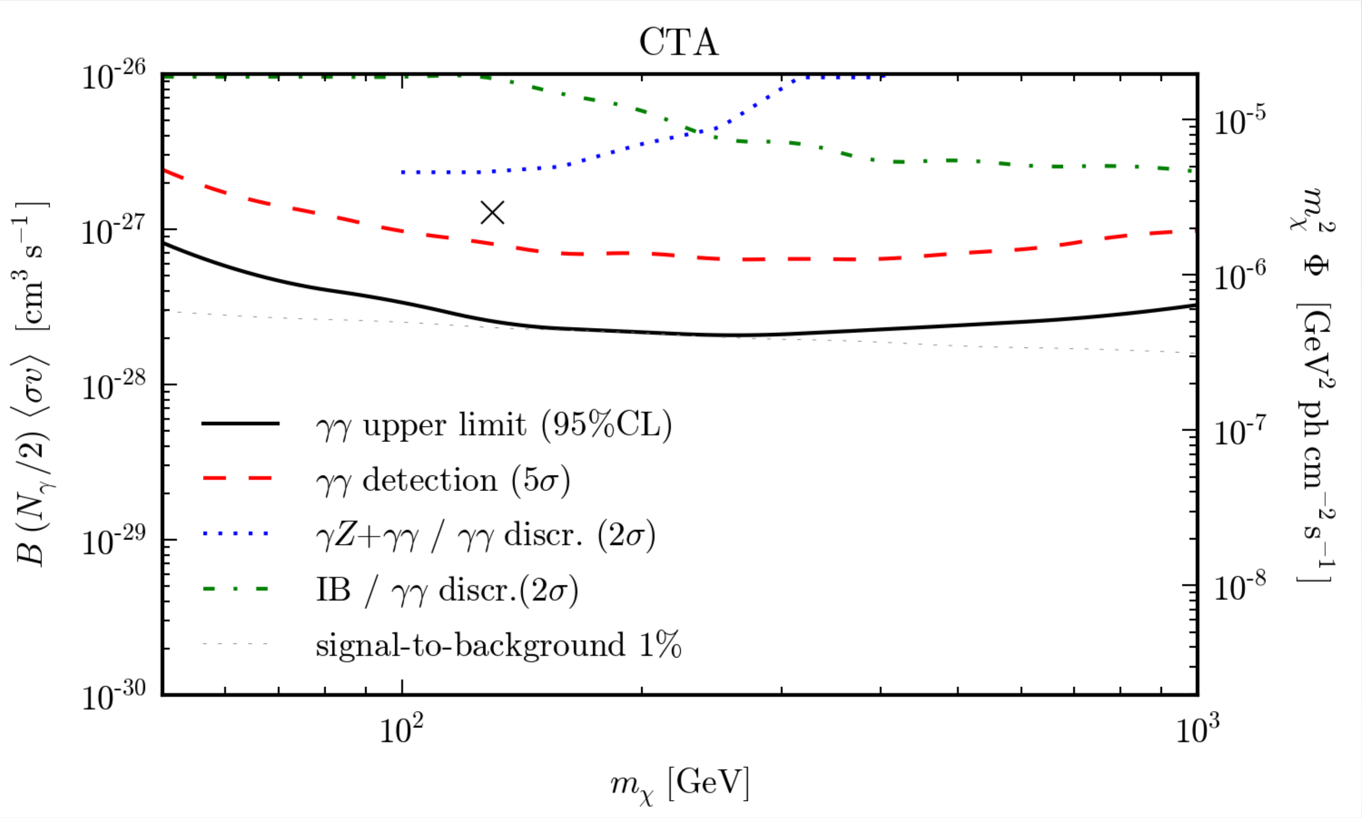
  is very model dependant, a broader feature

- Search for a bump, sharp excess over the distribution of background events

CTA expectations

CTA expectations

- Weniger (2012) signal >5σ in 5h [syst. uncertainties]
- 1 vs 2 lines distinction reachable with additional time and refined analysis



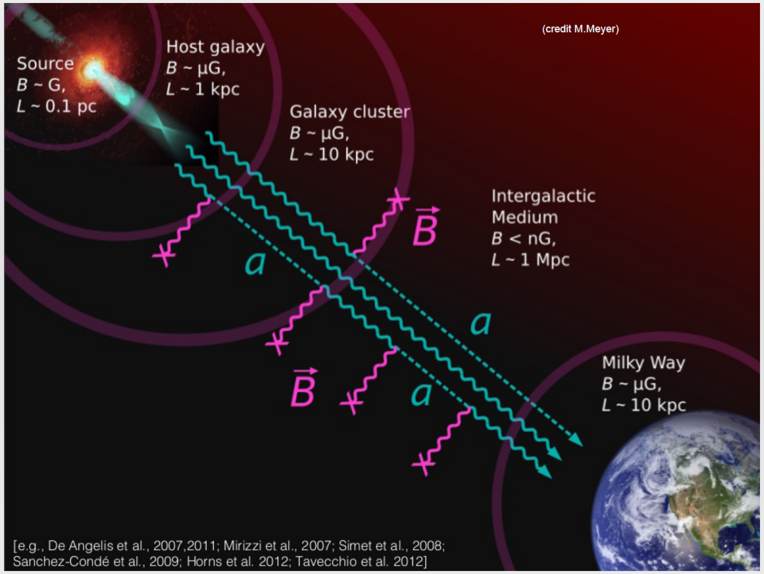
Bergström, Bertone, Conrad, CF, Weniger., 2012

Theme 3-2
Axion-like particles (ALPs)

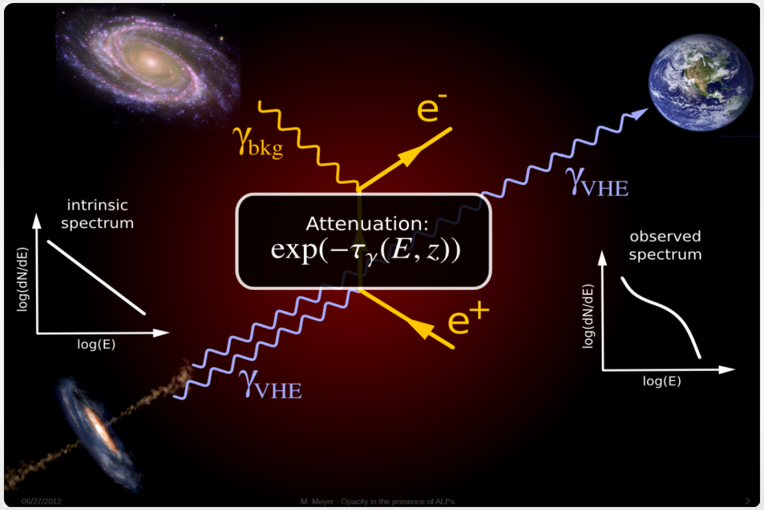
ALP similar to axions but mass m_a and coupling $g_{\gamma a}$ unrelated

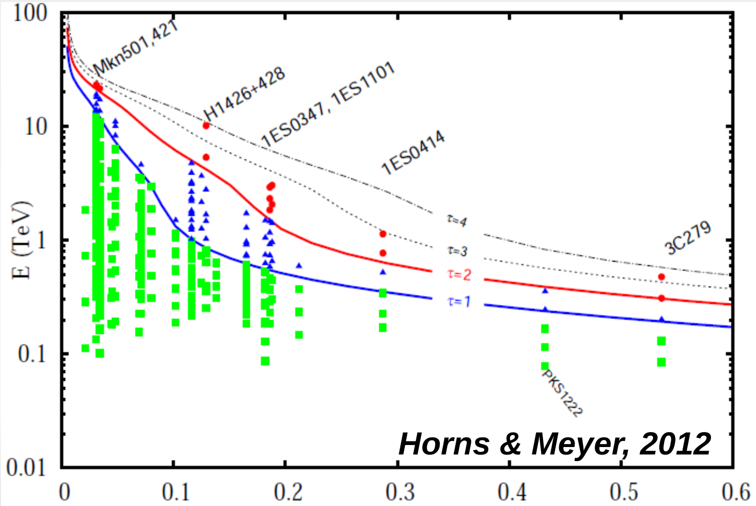
$$L_{a\gamma} = \frac{-1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma} \boldsymbol{E}.\boldsymbol{B}\, a$$

γ/ALP conversion in presence of B-field
⇒ modification of opacity



Hints of Universe transparency from observation of VHE AGNs located at large optical depth





Search for ALP with CTA (I)

Test statistic (w/ and wo/ALP) study based on energy bins located in optically thick regime ($\tau>2$)

(Meyer, Conrad, Montanino, subm.)

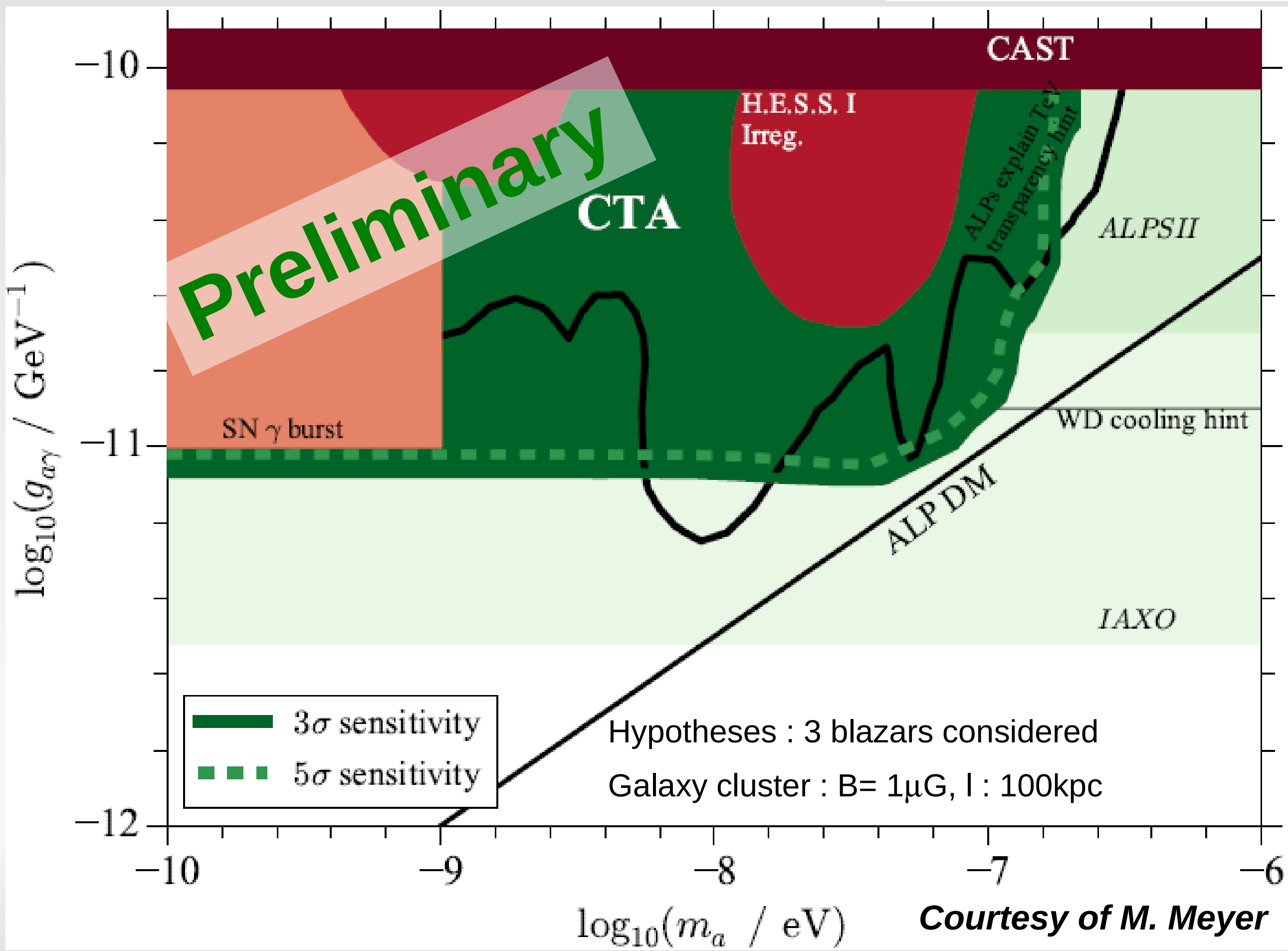
$$\mathcal{L}(\mu, \mathbf{b}; \alpha | N_{\mathrm{ON}}, N_{\mathrm{OFF}}) = \prod_{\substack{i \\ \tau(E_i, z)>2}} f(N_{i,\mathrm{ON}} | \mu_i + b_i) f(N_{i,\mathrm{OFF}} | b_i/\alpha).$$

f: Poissonian probability mass function

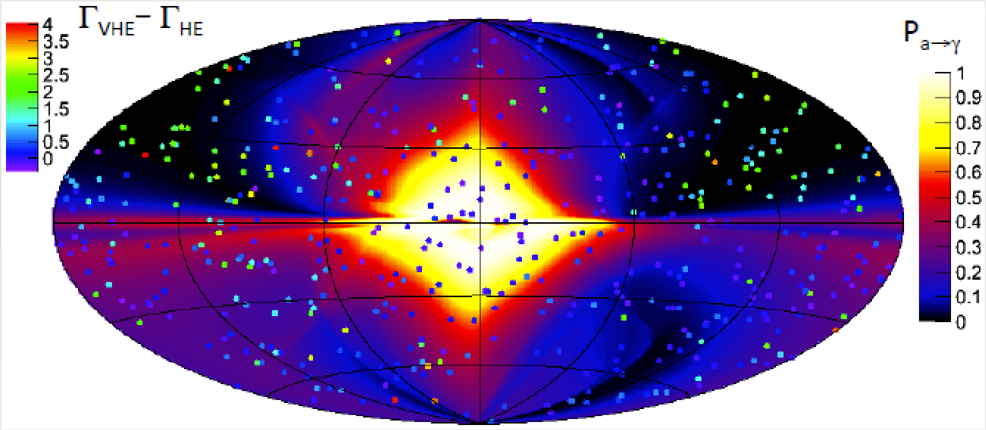
$$\lambda(\tilde{\mu}; \alpha | N_{\mathrm{ON}}, N_{\mathrm{OFF}}) = \frac{\mathcal{L}(\tilde{\mu}, \hat{\hat{\mathbf{b}}}(\tilde{\mu}); \alpha | N_{\mathrm{ON}}, N_{\mathrm{OFF}})}{\mathcal{L}(\hat{\mu}, \hat{\mathbf{b}}; \alpha | N_{\mathrm{ON}}, N_{\mathrm{OFF}})}$$

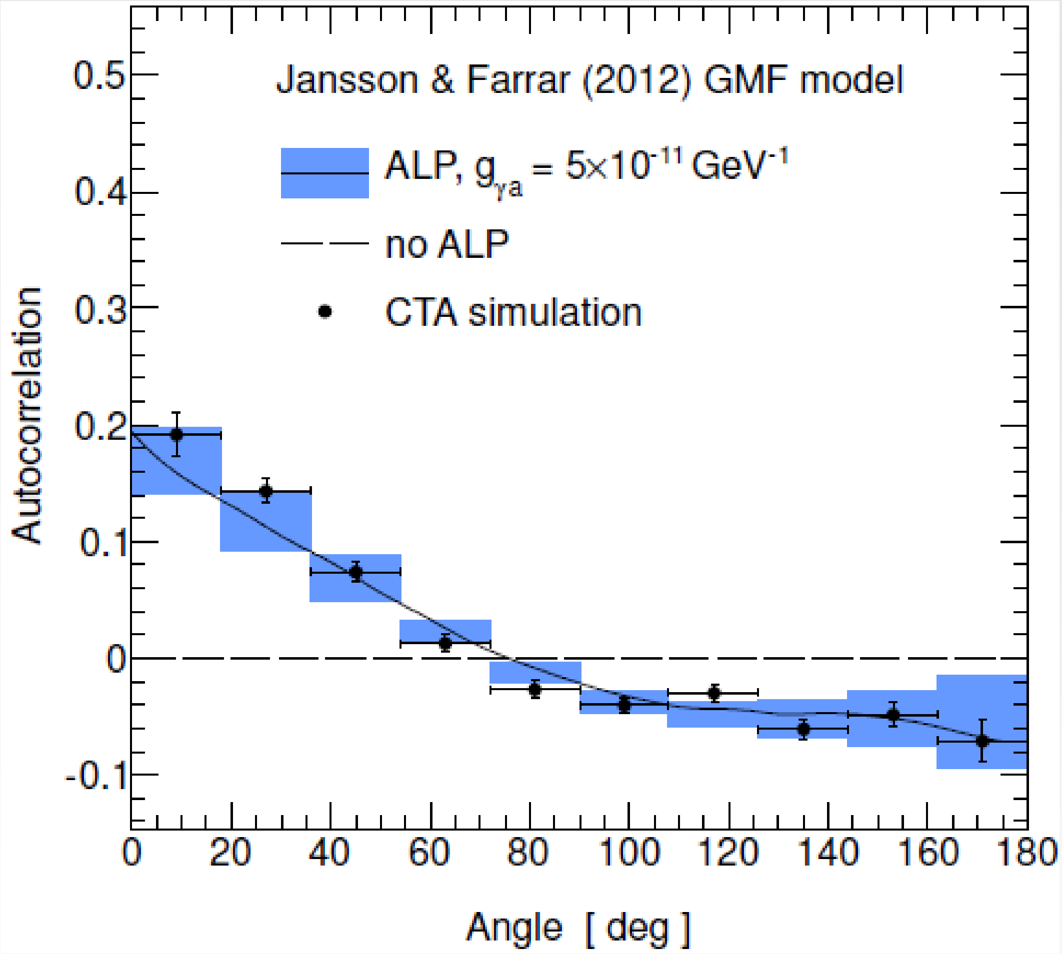
Expected counts w/o ALPs — Background counts that maximizes L for fixed μ

Expected counts w/ ALPs that maximizes L — Background counts that maximizes L



Search for ALP with CTA (II)





Wouters & Brun, 2014

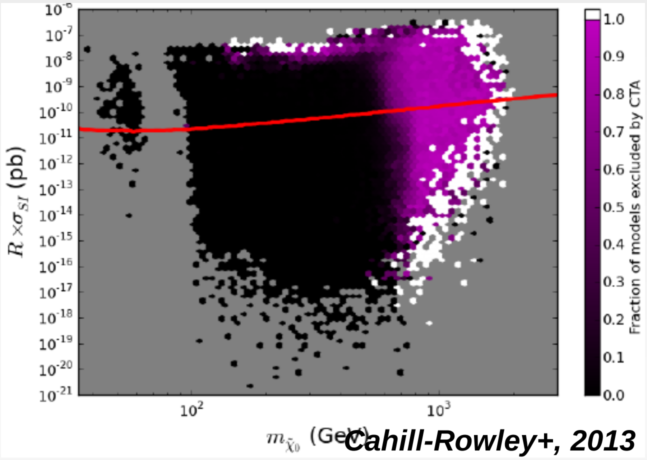
Auto-correlation of spectral changes between high and very-high E

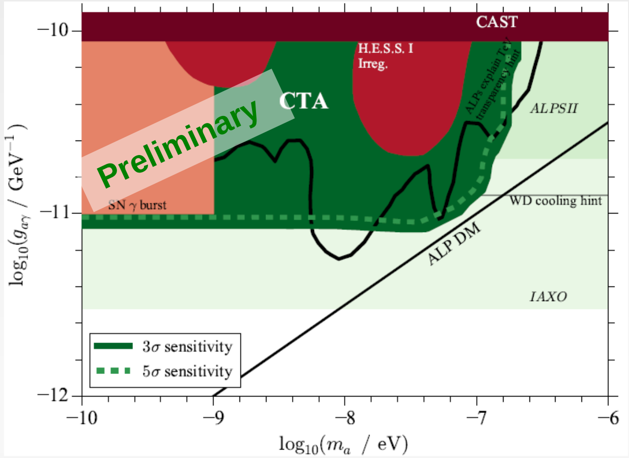
Requires

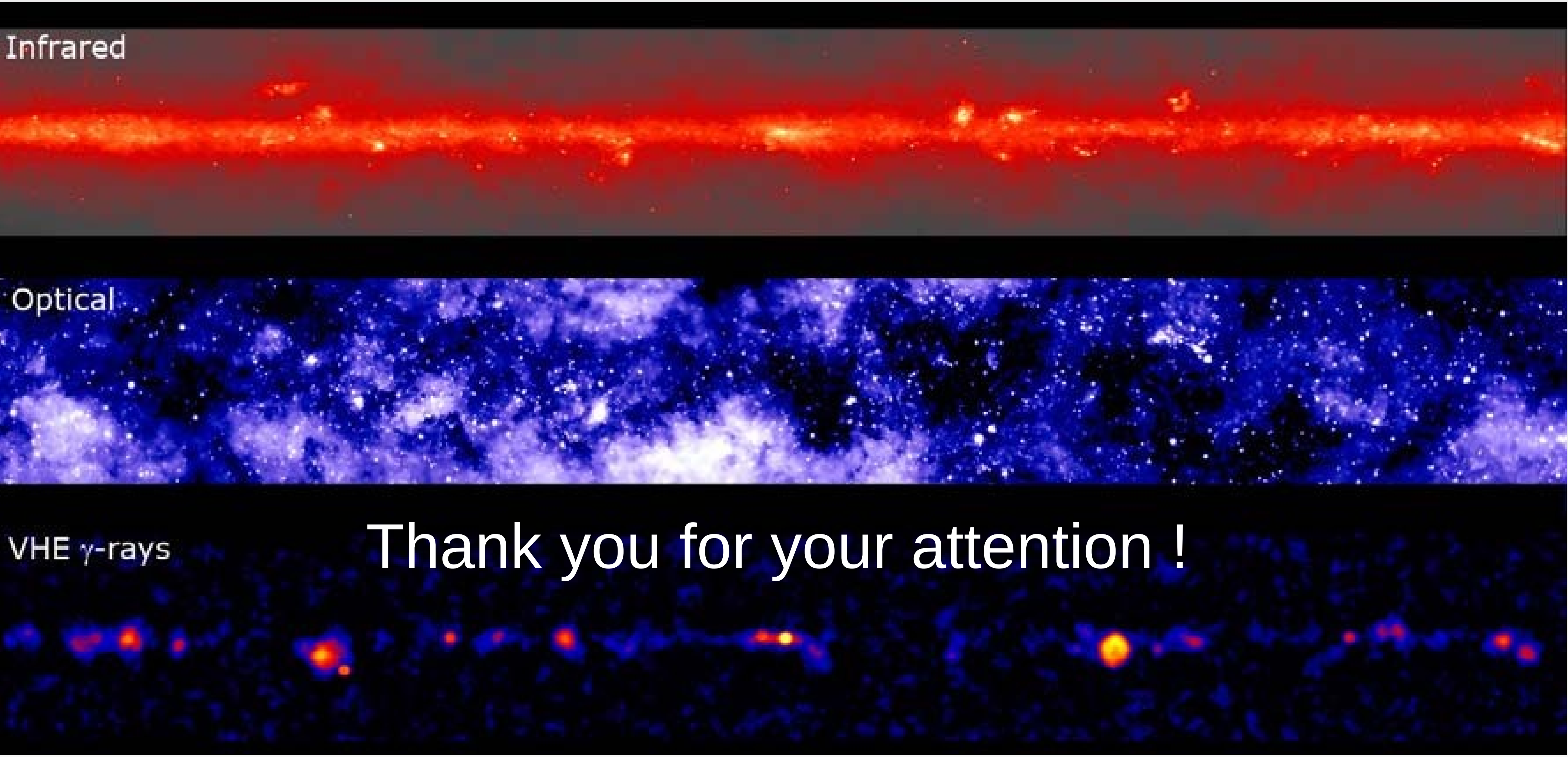
- Large statistics
- Good spectral measurements

Conclusions

- The CTA observatory will enlarge a new window of our Universe and discover 1000 sources
- CTA is a multi-purpose, multi-channel experiment (also for electrons/positrons and heavy nuclei studies)
- CTA offers unique capabilities to access large mass WIMPs
- CTA will probe the transparency hint and test the presence of ALPs







Thank you for your attention !