Searching for Dark Matter in the Galactic Dwarf Spheroidal Satellites

Foundations & outline of my PhD project

Moritz Hütten

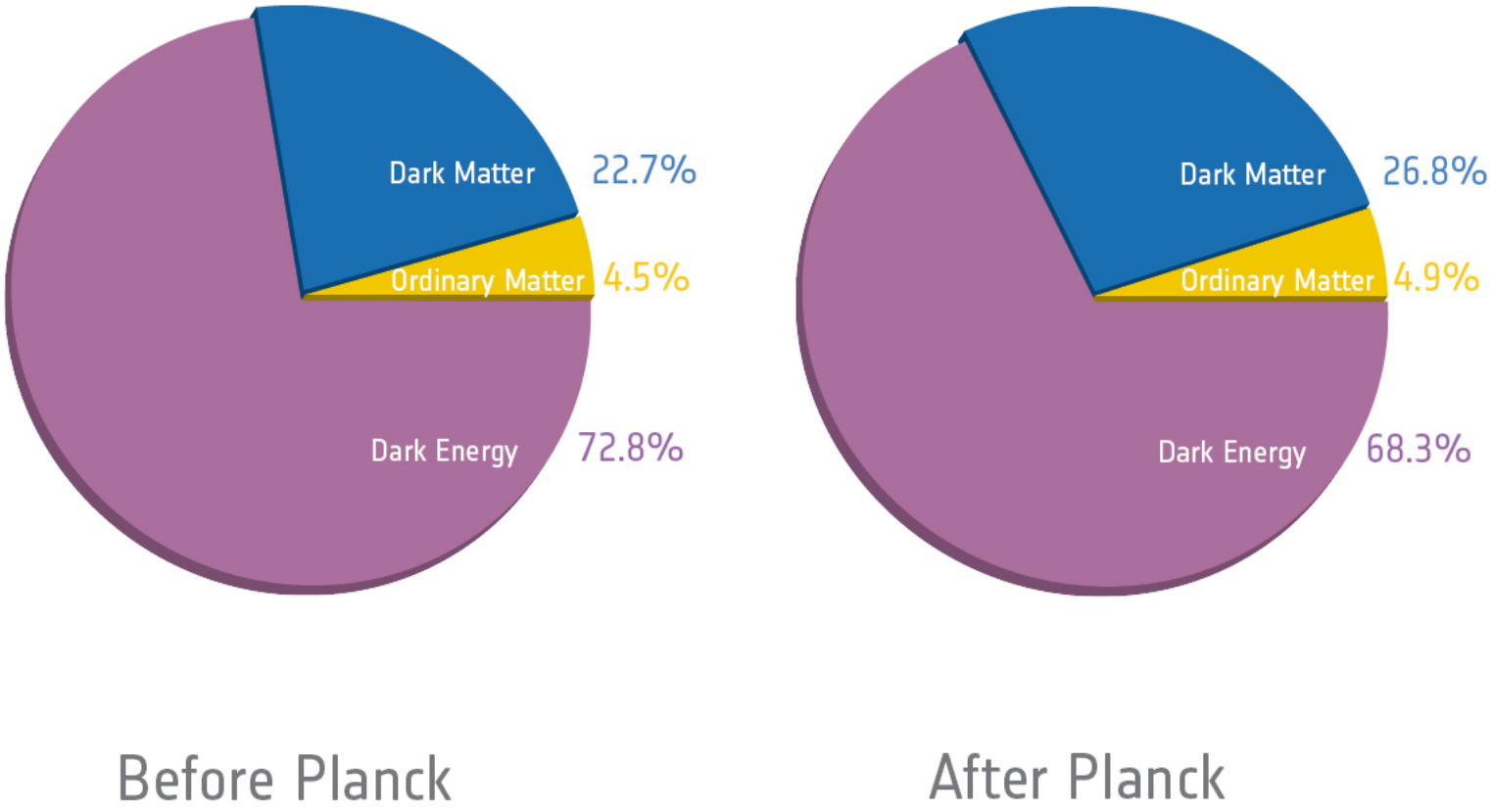
Graduate School "Mass Spectrum Symmetry"
DESY Zeuthen, supervisor: Gernot Maier

September 16, 2013

Outline:

1. **A glimpse of Dark Matter: what, where & why?**
2. **Dark Matter annihilation**
   - gamma ray flux equation
   - annihilation channels
   - Dark Matter density in dSph satellites
3. **Imaging Air Cherenkov Telescopes**
4. **Thesis topics**
   - spectral profiles
   - spatial profiles
   - upper limit for Dark Matter cross section $\langle \sigma v \rangle$

A glimpse of Dark Matter: what, where & why?



matter composition of the Universe after the Planck mission
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Evidences of Dark Matter

- motion of stars within galaxies:
  - stationary equilibrium of stars in elliptical galaxies
  - rotational speed of stars in spiral galaxies
  - spiral arm formation in spiral galaxies

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Constraints on DM particles explaining everything at one swoop:

- no electrical charge
- no color charge
- "cold": non-relativistic speed at structure formation
- very stable against decay (lifetime $\geq$ age of the Universe)
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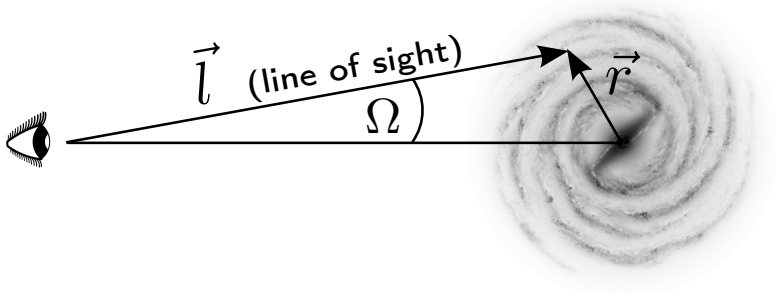
- such WIMP's supposed to annihilate/decay into e.m. interacting SM secondary particles (mostly photons)
- indirect detection of D.M. by detection of secondary photons

Dark Matter annihilation γ-flux



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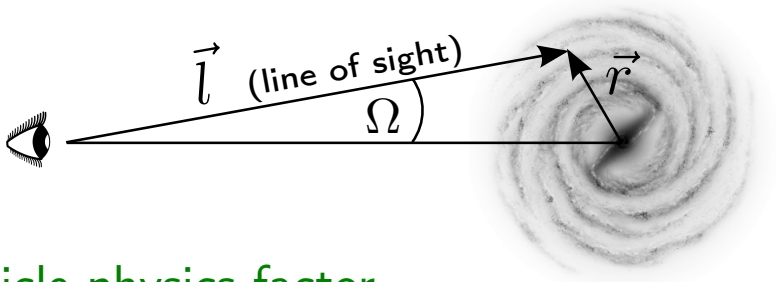
E_γ	Energy of photons hitting the earth
$\langle\sigma v\rangle$	velocity averaged annihilation cross section of D.M. particle
m_χ	mass of D.M. particle
$b_i \cdot dN_\gamma^i/dE_\gamma$	branching annihilation channels (b_i: branching ratio)
ρ_{DM}	Dark Matter density

Dark Matter annihilation γ-flux



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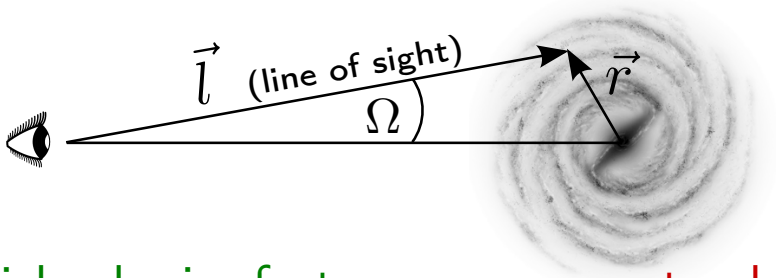

particle physics factor | astrophysical factor

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Annihilation (or decay) branches	dominant signals (final states)
$W^\pm$, Z, gluon, quarks (u, d, c, s, t, b)	p, $\bar{p}$, D, $\bar{D}$, $e^\pm$, ν, γ
e	$e^\pm$
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γ	γ
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standard model particles D.M. could annihilate or decay into
from Porter et al. (2011)

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note: $$\int_0^{E_\gamma = m_\chi}\sum_i^{\text{channels}} b_i \frac{dN_\gamma^i}{dE_\gamma}\,dE_\gamma < 1$$

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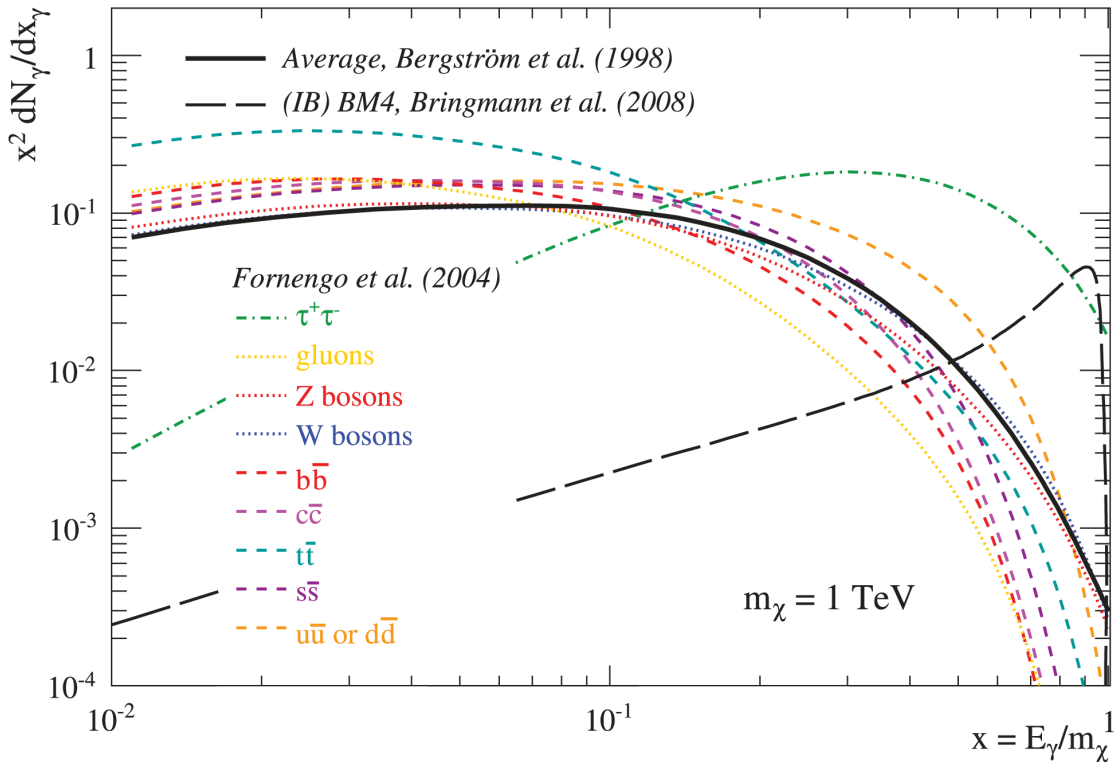

Simulated differential spectra of neutralino annihilation for a particular model taken from Charbonnier at al. (2011)

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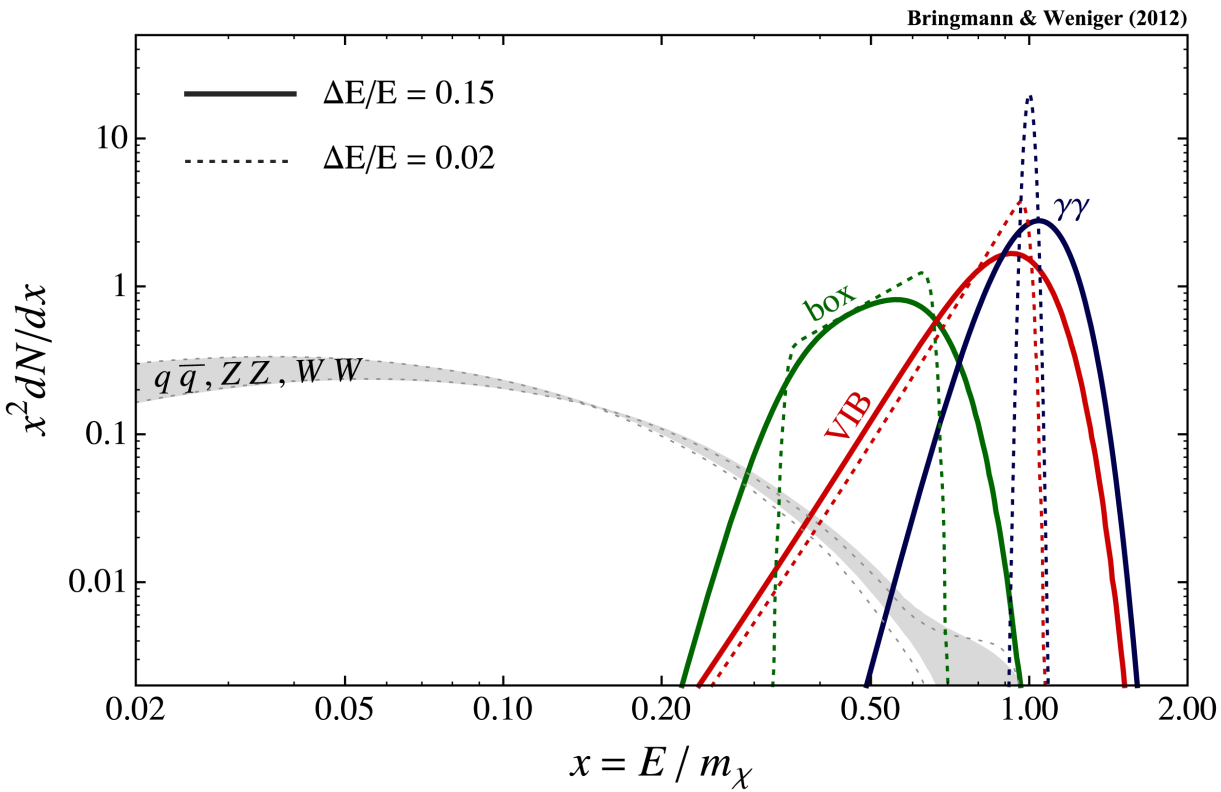

Simulated differential spectra of neutralino annihilation for a particular model taken from Bringmann & Weniger (2012)

2.) Astrophysical factor (D.M. density)

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Annihilation rate highly dependent of the dark matter density:

- cusp- vs. core profiles (high density in the galaxy's center)
- Scale-dependent enhancement (resonances or sub-clustering)
  $\rightarrow$ possible boost-factor for annihilation rate

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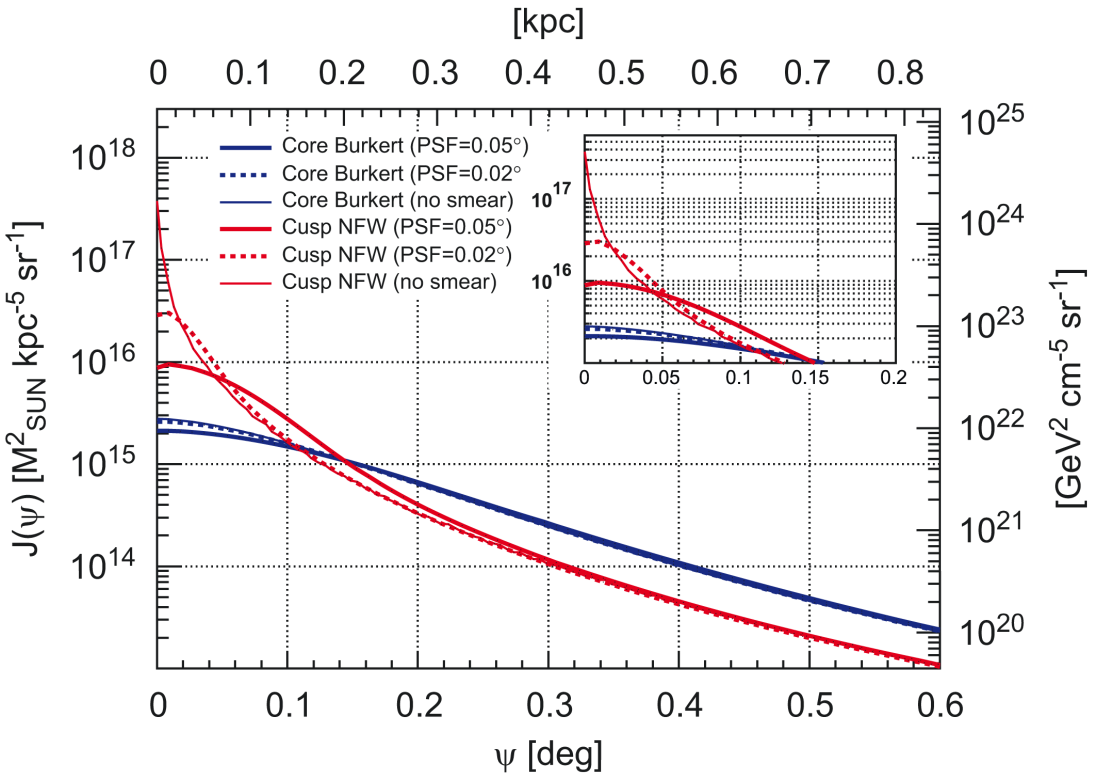

Assumed (from simulation) density profiles $J = \int_{l.o.s.}\rho_{\text{DM}}^2\,dl$ for Draco dSph galaxy taken from Fornasa (2011)

How to observe D.M. annihilation γ-rays?

To observe these potential γ-fluxes, we now need good astrophysical sources, which:

- presumably offer high Dark Matter densities
- are located close to us
- have – relatively – low background noise

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Milky Way's Galactic Center	vs.	Dwarf Spheroidal Satellites
⊕ high D.M. density		⊕⊕ very high D.M. density
⊕ very close: $8.3\,\mathrm{kpc}$		⊖ further away: $24 - 150\,\mathrm{kpc}$
⊖ high γ-ray background		⊕ low γ-ray background

How to observe D.M. annihilation γ-rays?

Additionally, we need a magic telescope which:

- is able to detect very energetic photons: $E_\gamma = \mathcal{O}(\mathrm{GeV})$ ... $\mathcal{O}(\mathrm{TeV})$
- is sensitive for very low fluxes: $\Phi_\gamma^{\text{ann.}} \lesssim 10^{-12}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (within the GRK funding time...)
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$$\Phi_\gamma^{\text{ann.}} = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}}_{\substack{\mathcal{O}(10^{22}\,\frac{\mathrm{cm}^3}{\mathrm{s}\cdot\mathrm{kg}^2}) \\ \text{for } m_\chi \approx 100\,\mathrm{GeV}}} \cdot \underbrace{\int_{\Delta E} \sum_i^{\text{channels}} b_i \frac{dN_\gamma^i}{dE_\gamma}\, dE_\gamma}_{\lesssim \mathcal{O}(1)} \cdot \underbrace{\int_{\Delta\Omega} \int_{l.o.s.} \rho_{\text{DM}}^2[r(l,\Omega)]\, dl\, d\Omega}_{\substack{\lesssim \mathcal{O}(10^{-30}\,\frac{\mathrm{kg}^2}{\mathrm{cm}^5}) \\ \text{for dSph; depending on density profile}}}$$

How to observe D.M. annihilation γ-rays?

Fermi LAT (since 2008)

Space-based telescopes

VERITAS telescope array, Arizona

Ground based telescopes: Imaging Air Cherenkov telescopes

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Fermi LAT (since 2008)

Space-based telescopes

⊕ high sensitivity below $100\,\mathrm{GeV}$
⊕ observation 24h/7 days

⊖ poor sensitivity above $100\,\mathrm{GeV}$
⊖ expensive!

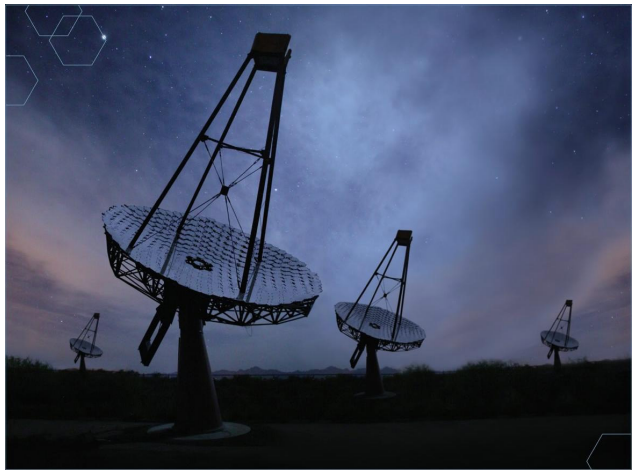
VERITAS telescope array, Arizona

Ground based telescopes: Imaging Air Cherenkov telescopes

⊕ good sensitivity above $100\,\mathrm{GeV}$

⊖ poor sensitivity below $100\,\mathrm{GeV}$
⊖ observation only by night, good weather and faint moon

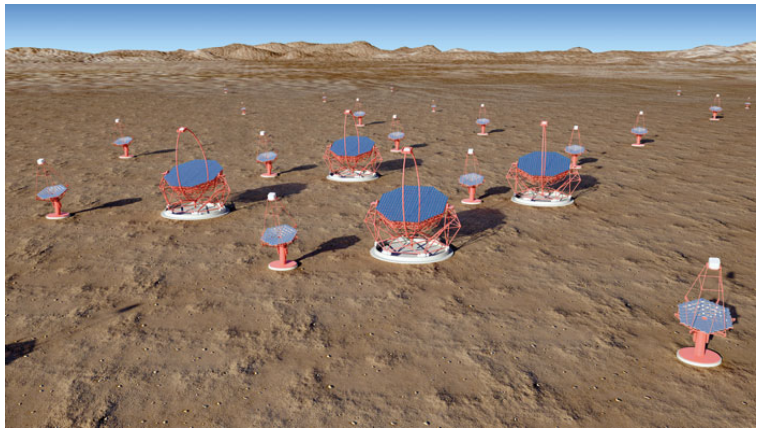
Imaging Air Cherenkov telescopes



VERITAS telescope array, Arizona

H.E.S.S. telescope array, Namibia

MAGIC telescope array, Canary Islands



CTA observatories: in the future

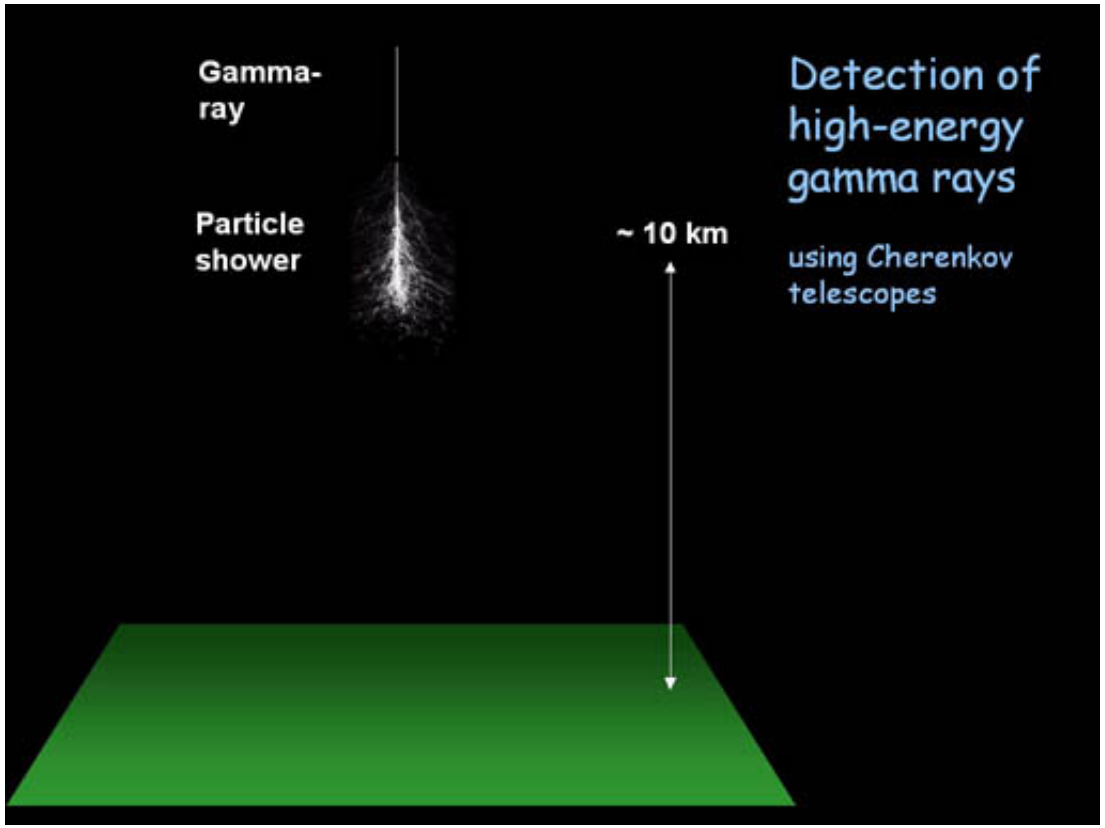
Imaging Air Cherenkov telescopes: how it works

- unfortunately (fortunately for us) the atmosphere is opaque for VHE photons: they are completely absorbed in the atmosphere and do not reach the ground.
- But we can turn this handicap into an advantage by the basic idea:

Use the whole earth's atmosphere as detector!

Imaging Air Cherenkov telescopes: how it works

1.) VHE photons deposit their energy in secondary particles, which are accelerated to speeds $v > c_{\text{atmosphere}}$:



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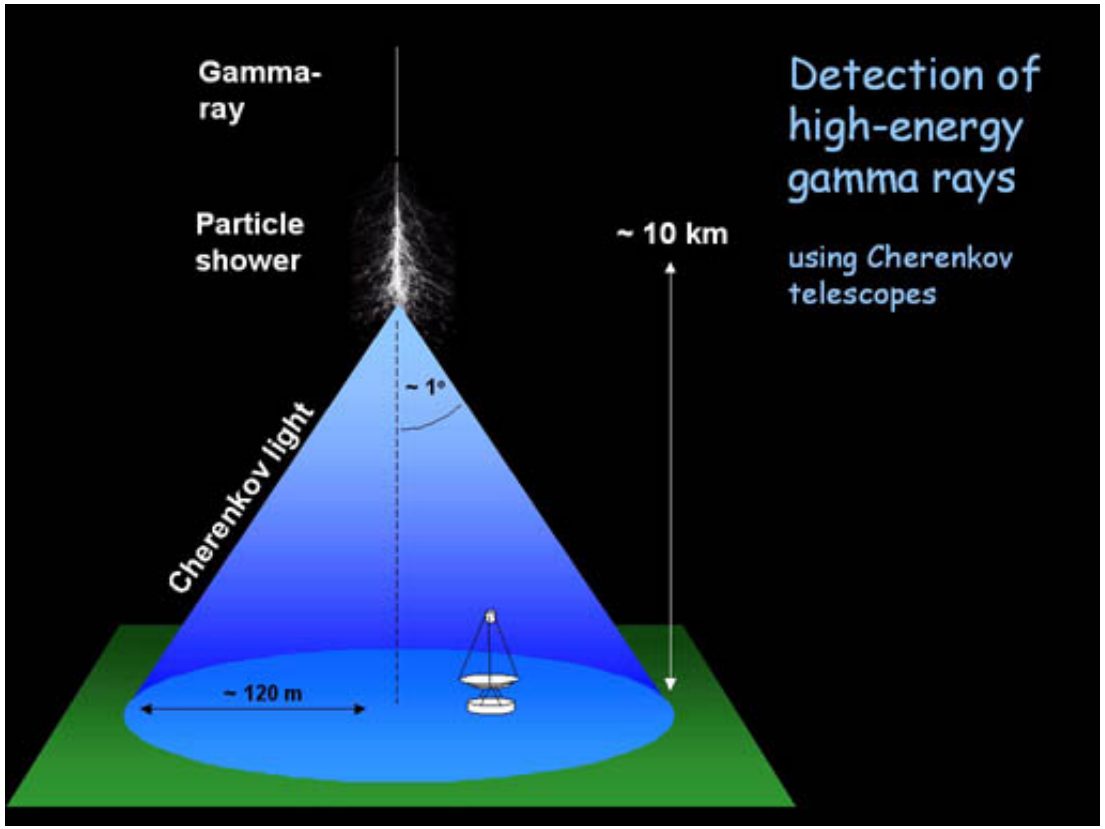
Imaging Air Cherenkov telescopes: how it works

2.) Consequently, the secondary particles emit Cherenkov light which we can finally detect :



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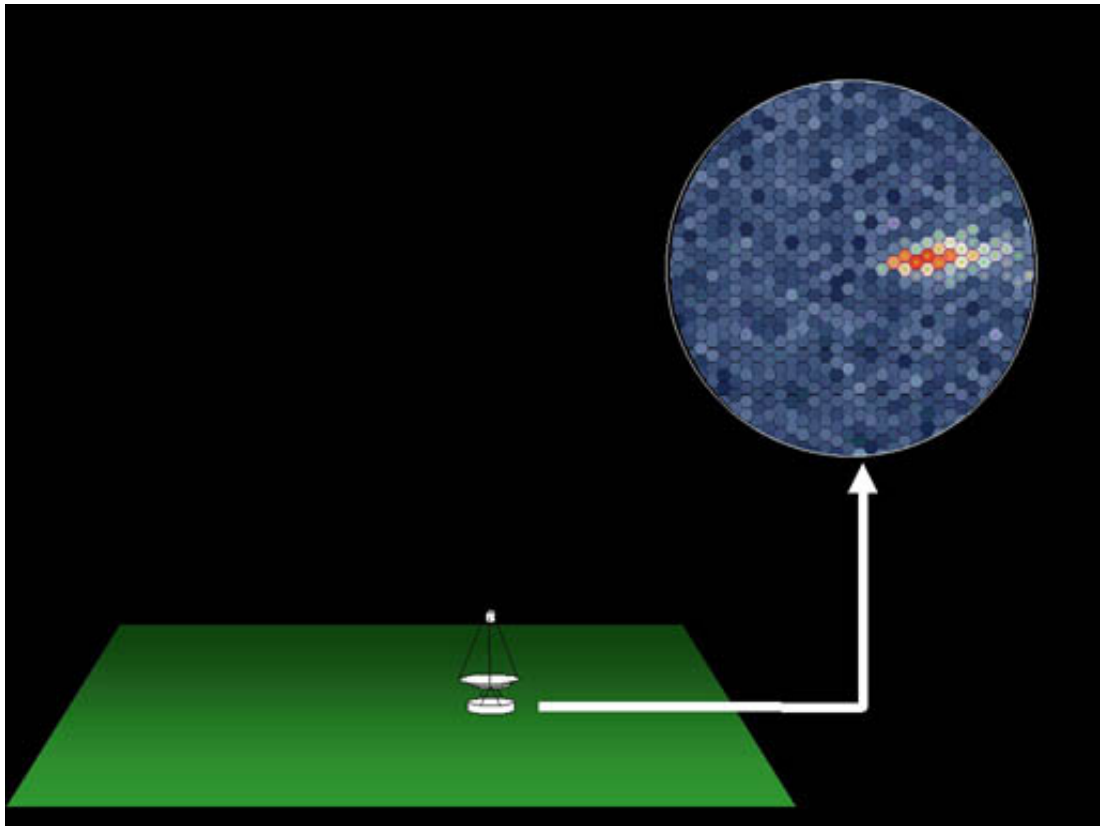
Imaging Air Cherenkov telescopes: how it works

3.) By the intensity of the light and the shape the signal
we can determine direction and energy of the VHE photon:



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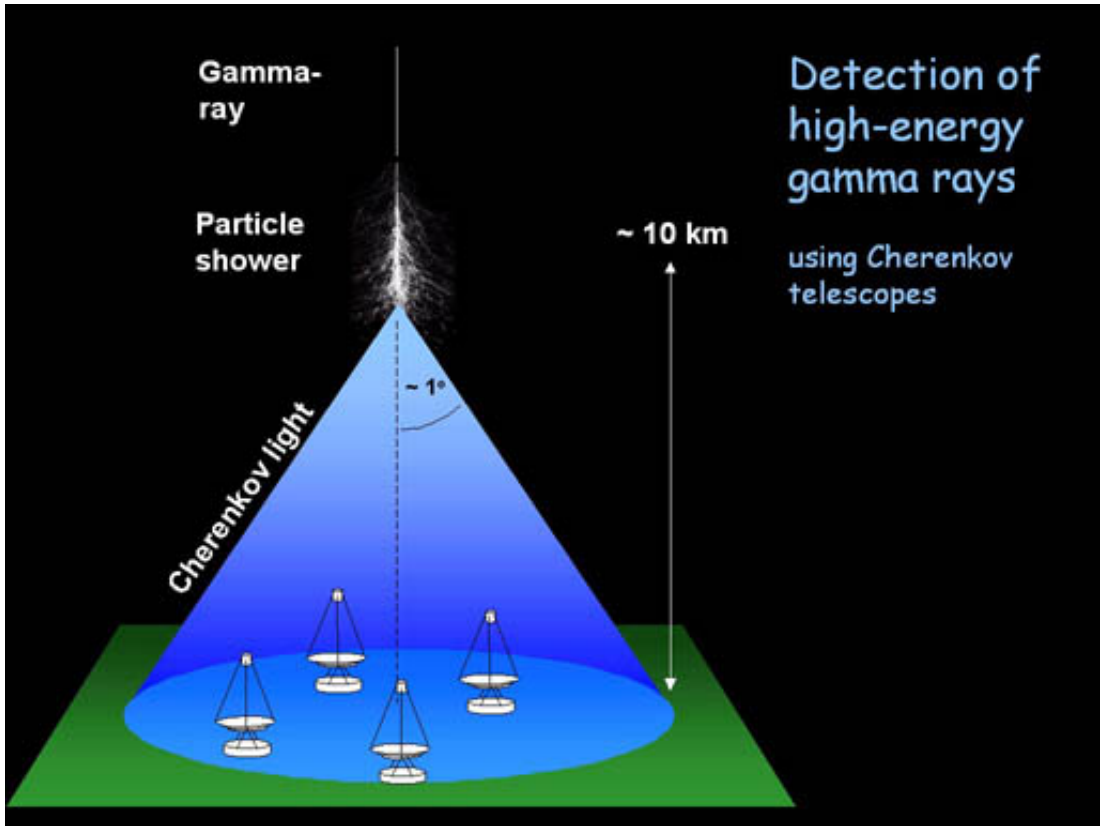
Imaging Air Cherenkov telescopes: how it works

4.) By an array of several telescopes within the light cone we can improve spatial and energy resolution:



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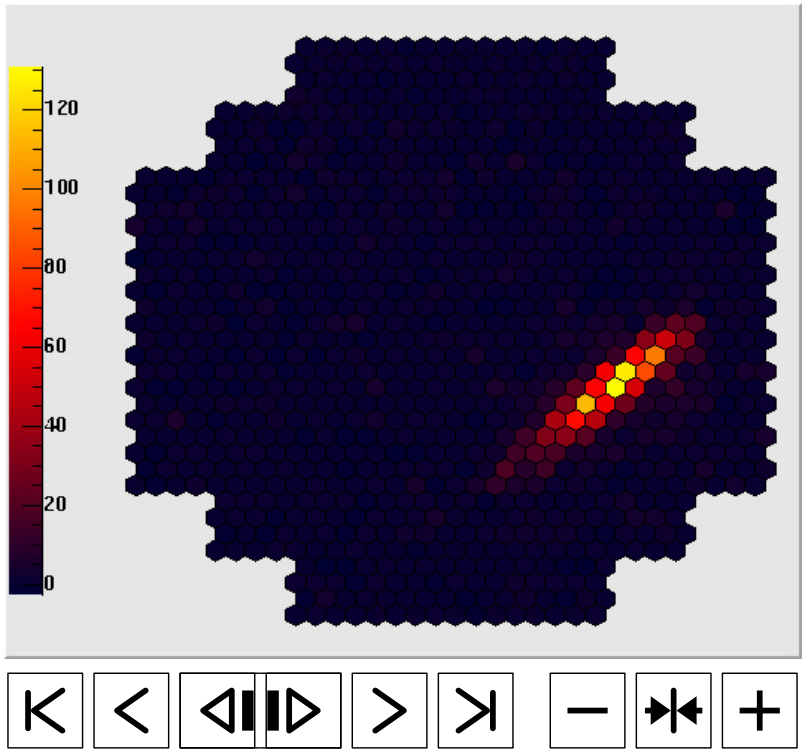
Imaging Air Cherenkov telescopes

5.) and how it looks watching through a Cherenkov telescope:



Cherenkov images recorded with the first H.E.S.S. telescope in 2002
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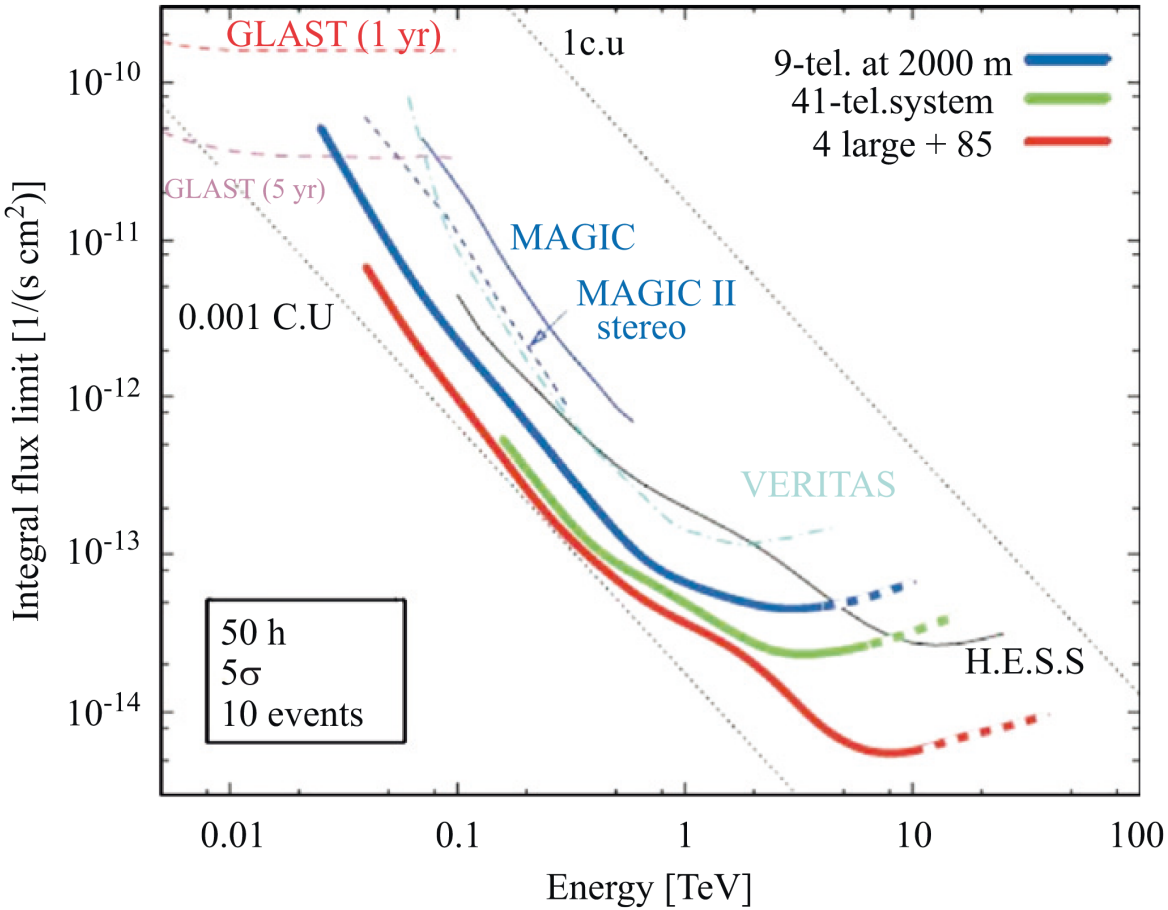
Thesis topics: where do we stand



Sensitivity of current and future IACTs
taken from Fornasa (2011)

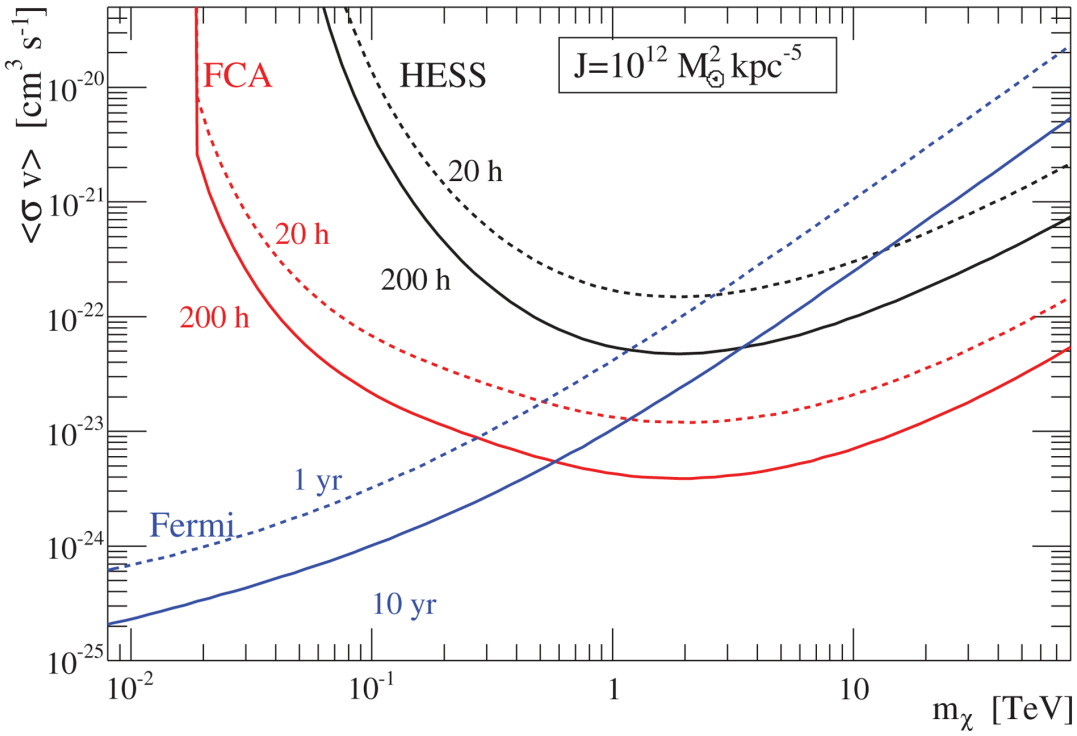
Thesis topics: principal aims

- constrain parameter space of possible WIMP properties
  - mass m_χ
  - velocity averaged cross section $\langle \sigma v \rangle$
  - annihilation channels (lines vs. continuous spectra)
- improve sophisticated analysis methods: discriminate D.M. spectrum from background

1.) Data stacking

Increase observation time artificially by

- combining Fermi and Veritas data (+ H.E.S.S., MAGIC,...)
- combining data of several similar dSph



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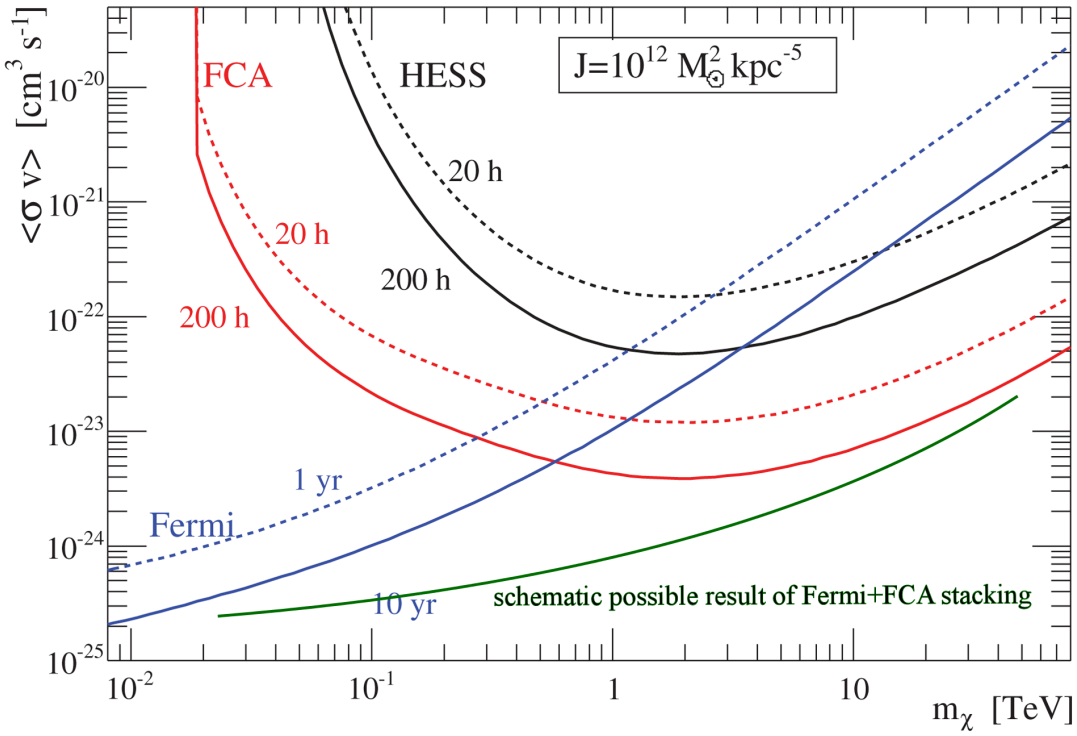


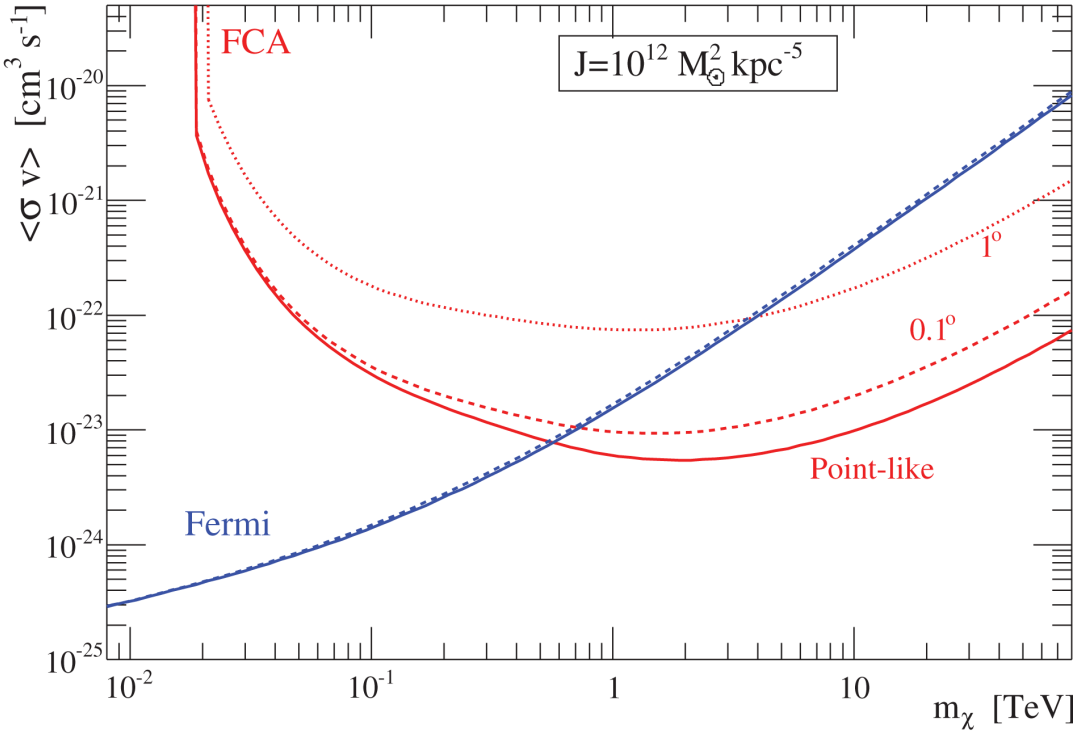
Possible shift of lower $\langle \sigma v \rangle$ limit by stacking (schematic)
taken from Charbonnier et al. (2012)

2.) Examine influences of spectral features

- significance of different spectral profiles
  - boost of flux in special energy ranges ΔE: energy interval with optimal signal-to-background ratio
  - sharp lines as "smoking gun"
- simulation of spectra with DarkSUSY

3.) Improve angular resolution of telescope data

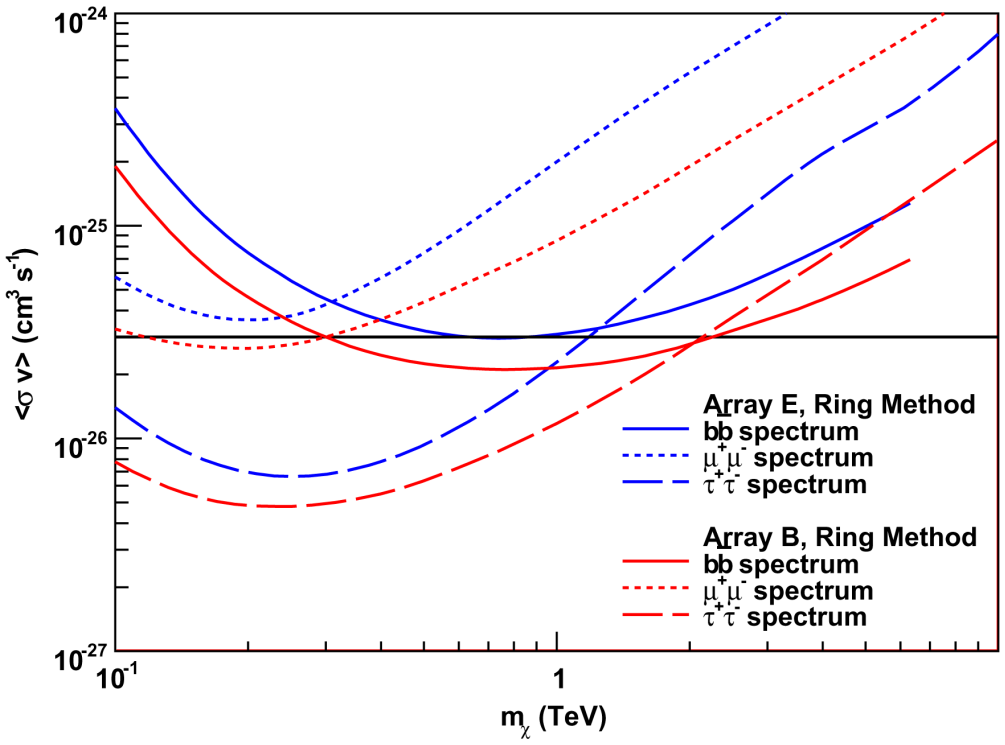
→ better signal-to-background ratio in case of highly concentrated source (cusp profile)!



Lower limit for $\langle \sigma v \rangle$ detectable with the future CTA for certain source elongations and corresponding resolution
taken from Charbonnier et al. (2012)

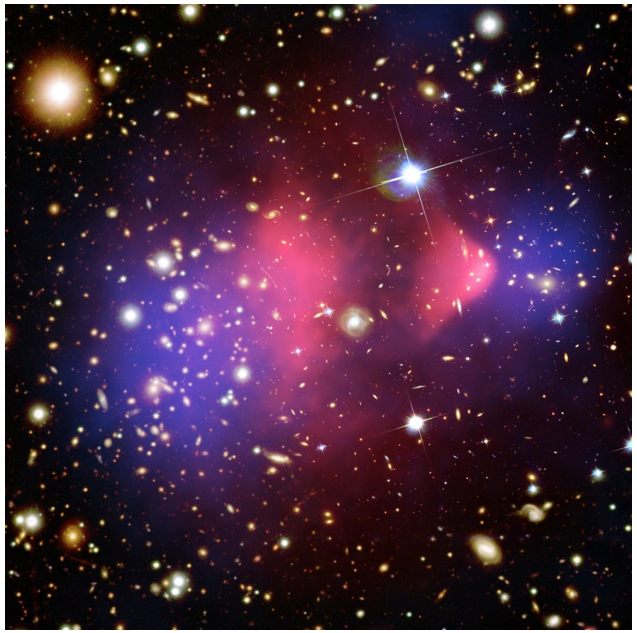
4.) Design properties of future CTA

determine most promising parameters for influencing the CTA design for Dark Matter detection purposes



CTA sensitivites for different telescope alignments and annihilation spectra taken from Doro et al. (2013)

And now to work!



Thank you for your attention