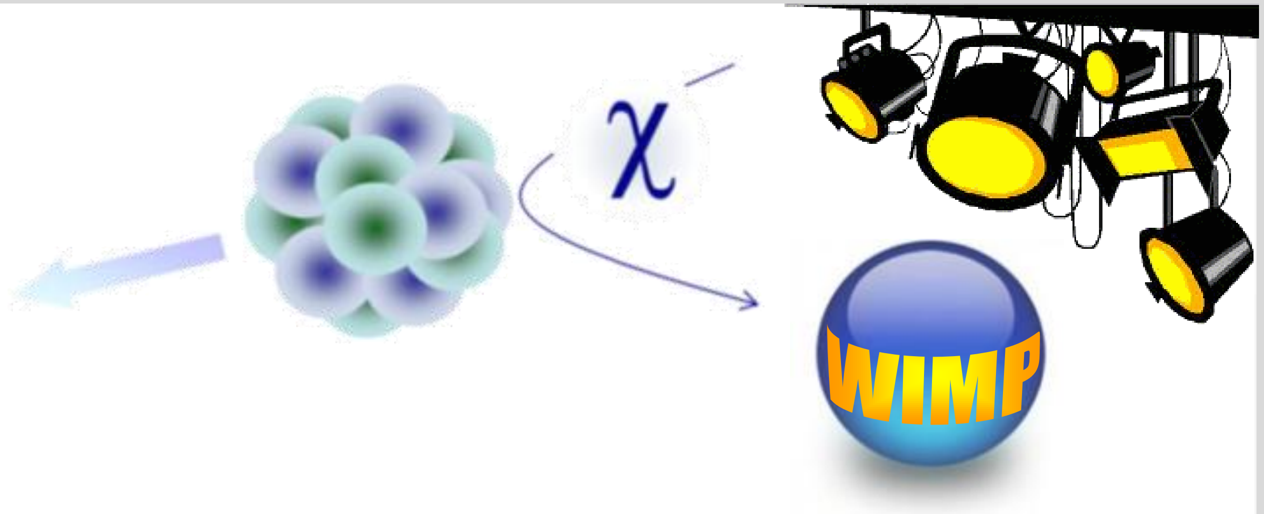


Dark Matter - II

GRK 1694: Elementarteilchenphysik bei höchster Energie und höchster Präzision

Workshop Freudenstadt 2015

September 30, 2015

Guido Drexlin, Institut für Experimentelle Kernphysik

WIMP candidates

weak interaction

σ_{EW} < 1 pb (= 10^{-36} cm²)
energy-dependent

Standard Model particles:

<u>neutrino cross section:</u>

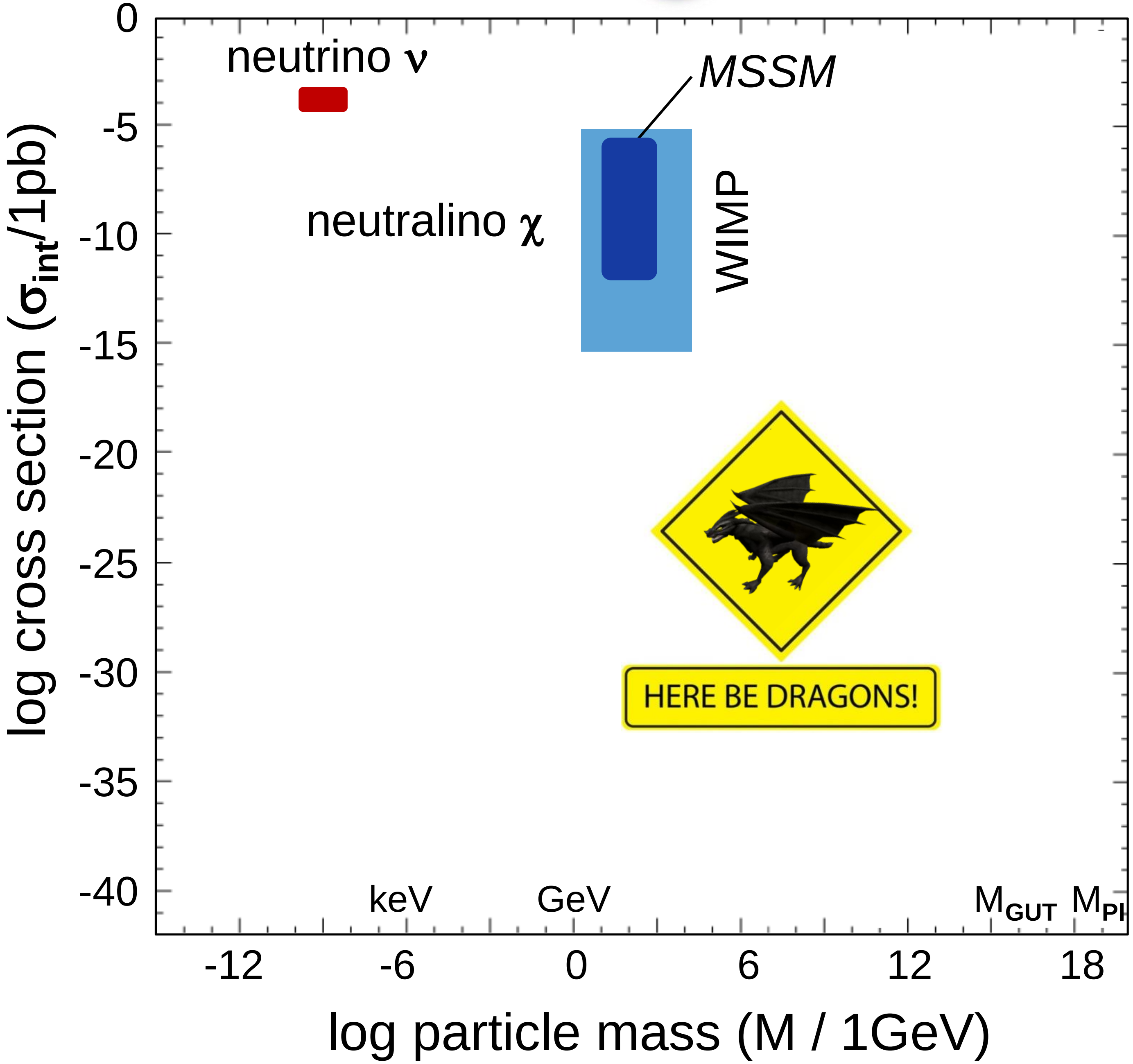
$\sigma_{\nu,EW}$ = 10^{-44} … 10^{-40} cm²
= 10^{-8} … 10^{-4} pb

supersymmetric particles:

<u>neutralino cross section:</u>

σ_{χ} = 10^{-48} … 10^{-42} cm²
= 10^{-12} …10^{-6} pb
~ 10^{-2} $\sigma_{\nu,EW}$

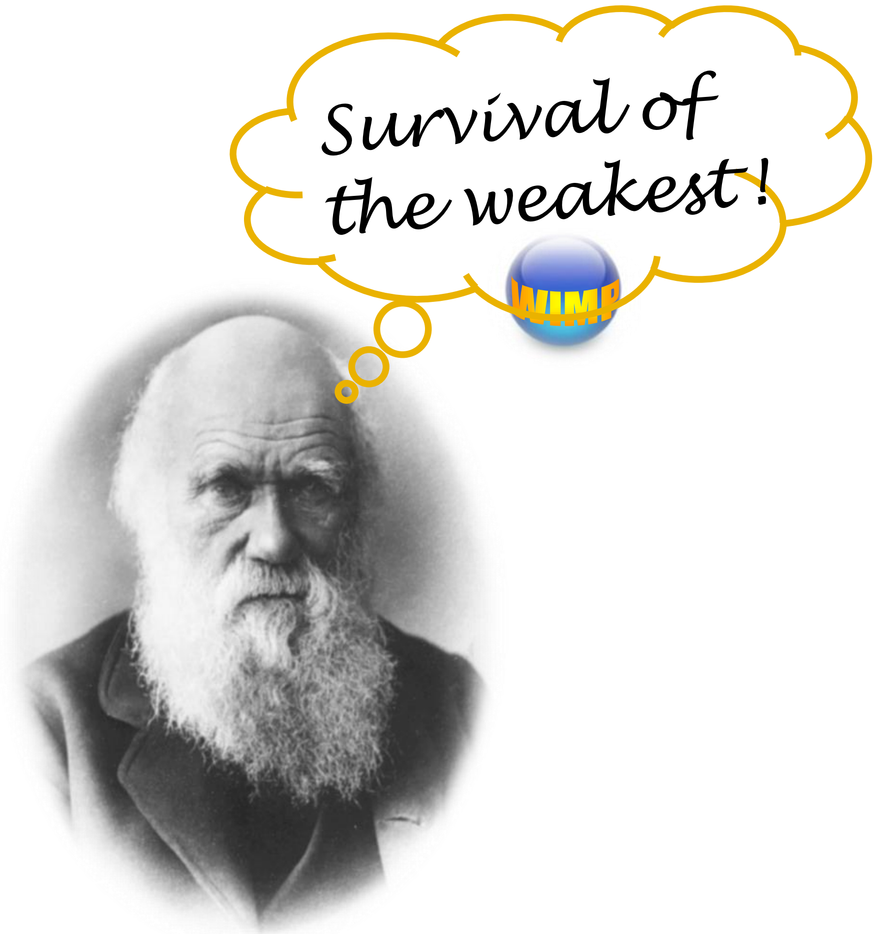
suppressed relative to $\sigma_{\nu,EW}$
due to mixing effects

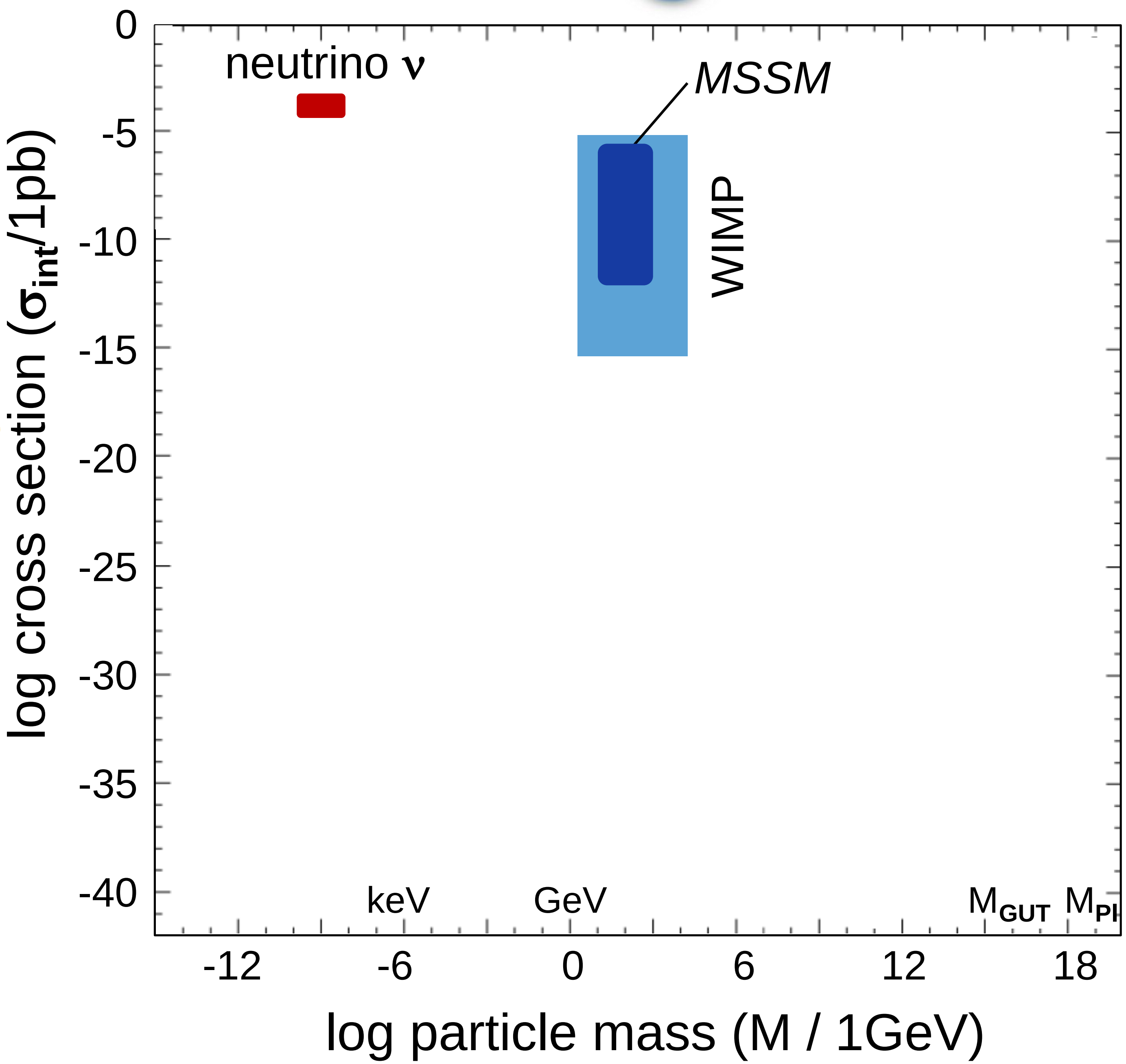


WIMP candidates

weak interaction

σ_{EW} < 1 pb (= 10^{-36} cm²)
energy-dependent





WIMP candidates

axion

light (10^{-6}…10^{-3} eV) WIMP, produced by non-thermal processes, solves the strong CP-problem (Peccei-Quinn)

axino

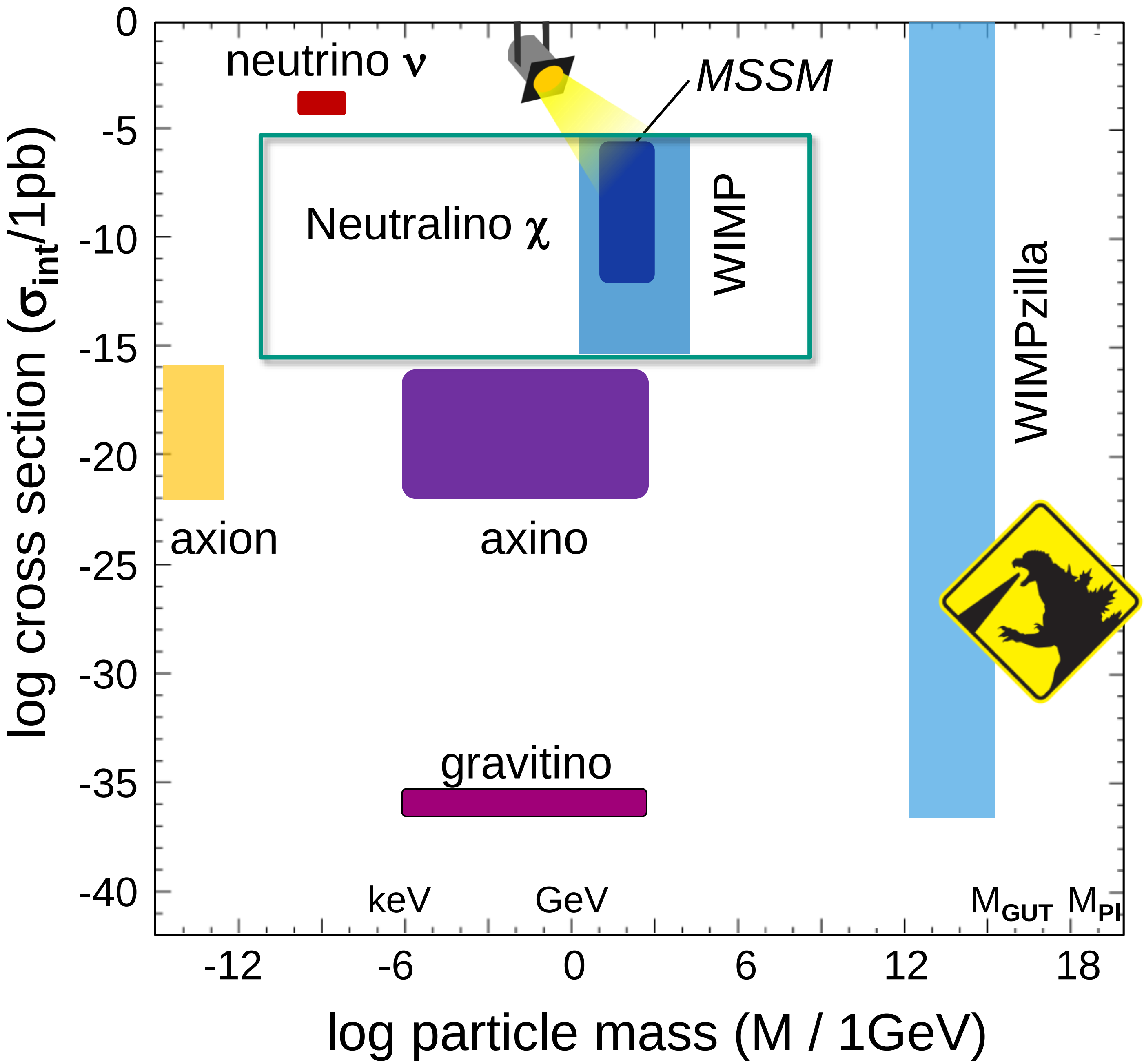
SUSY partner of axion, from decays of SUSY particles

gravitino

SUSY partner of graviton, only gravitational interaction

WIMPzilla

extremly massive, non-thermal relics (curvature effects)



outline of today´s lecture

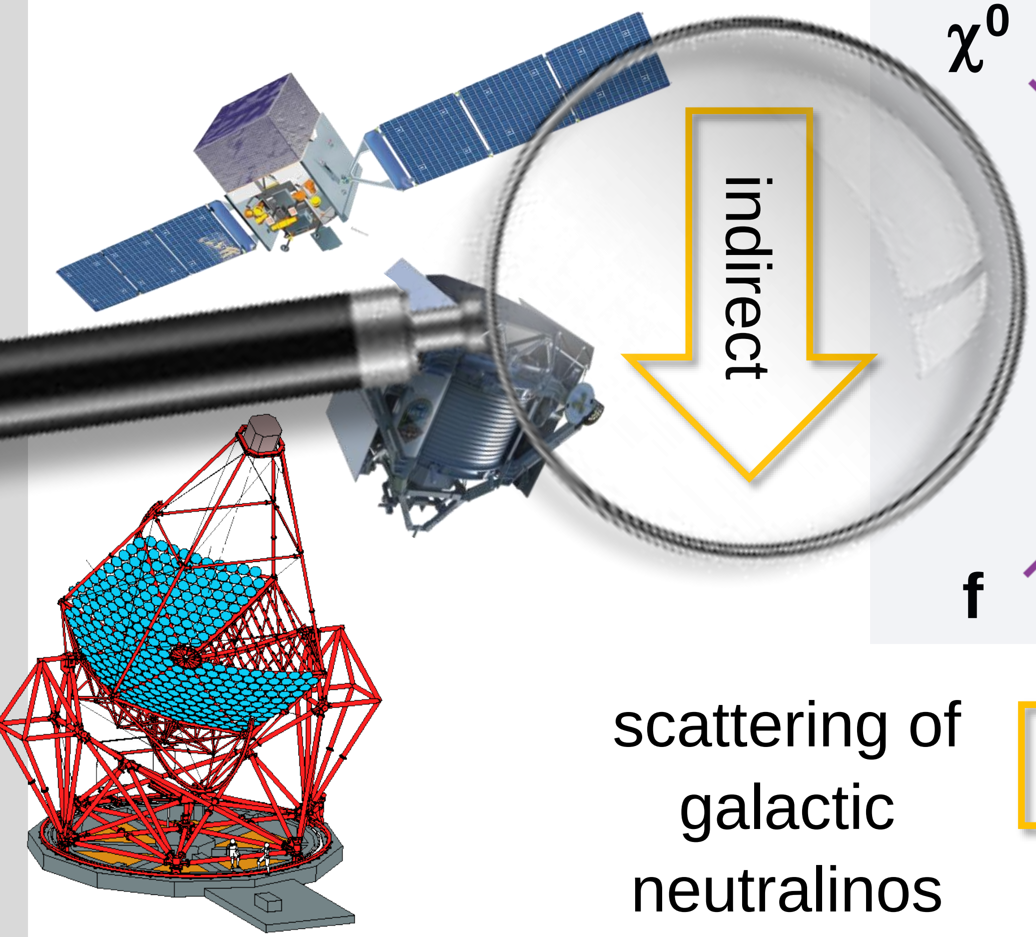
Dark Matter – 2: indirect searches for dark matter

- modelling of physics (signal)
- modelling of astrophysics (halo, background)
- messenger particles: gammas, positrons, anti-protons, neutrinos
- FERMI gamma-ray observatory
- GeV-excess @ GC: a model case for signal & background
- gammas at the TeV-scale: Atmospheric Cherenkov Telescopes
- charged messengers & neutrinos

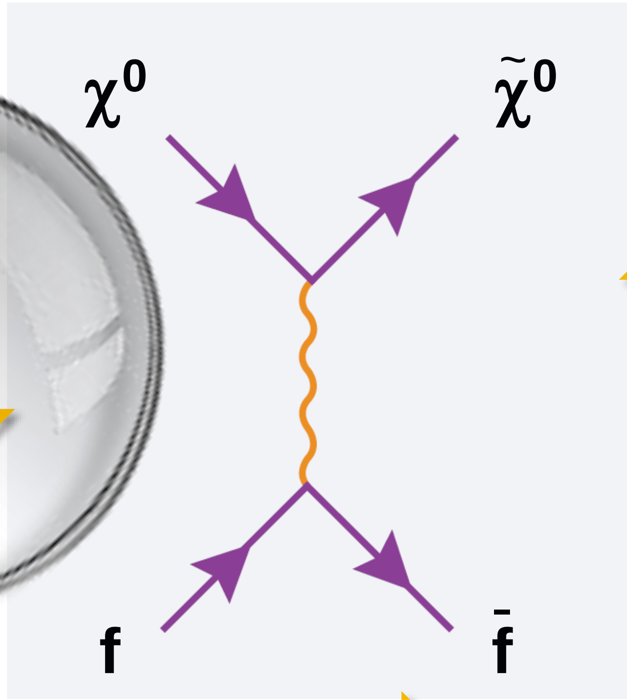
experimental WIMP searches

Karlsruhe Institute of Technology

annihilation of neutralinos in CDM halos

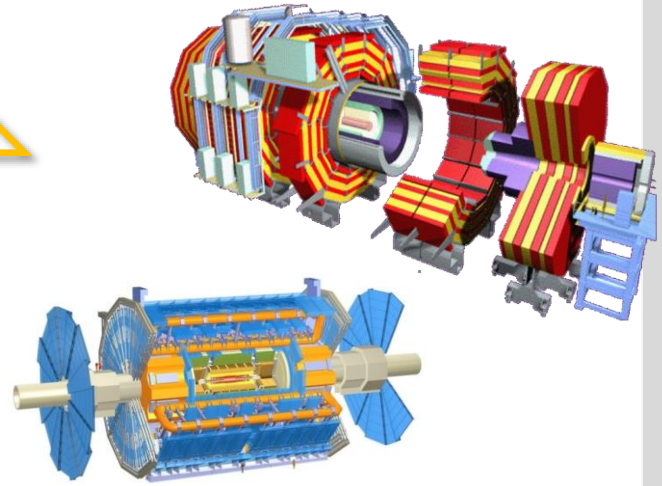


indirect



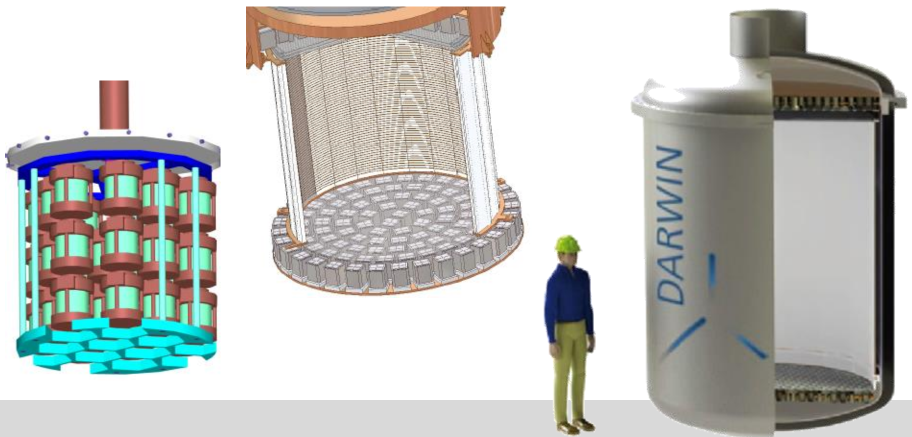
LHC

generation of neutralinos at LHC



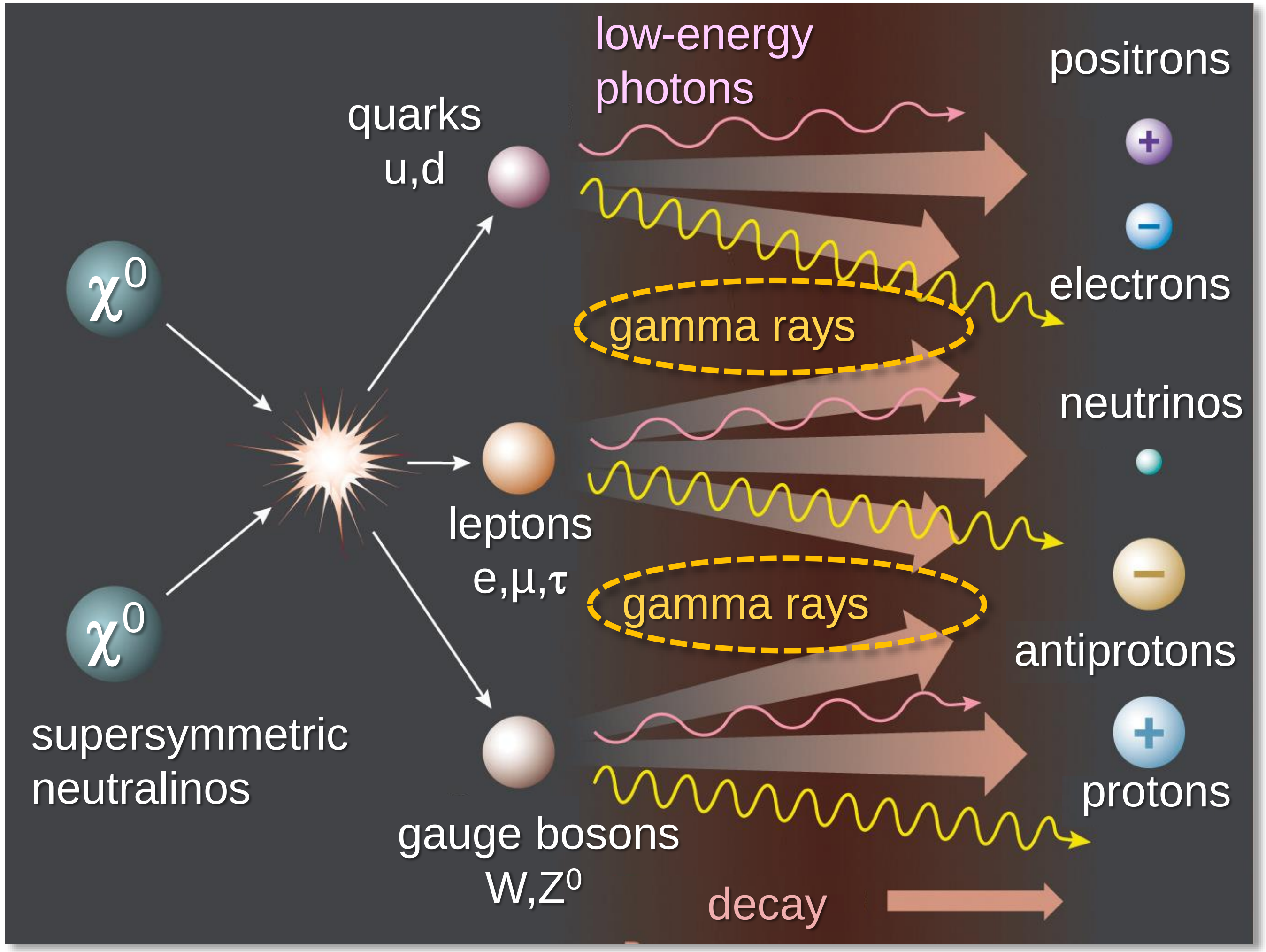
scattering of galactic neutralinos in detector

direct



indirect detection methods

- **Indirect detection of CDM:** observation of secondary particles from **WIMP annihilation processes** in the local group of galaxies
  - gammas (γ), neutrinos (ν), antiprotons ($\bar{p}$) & positrons (e^+)



electrons/positrons from:
- hadronic decays
- pair production
- direct production

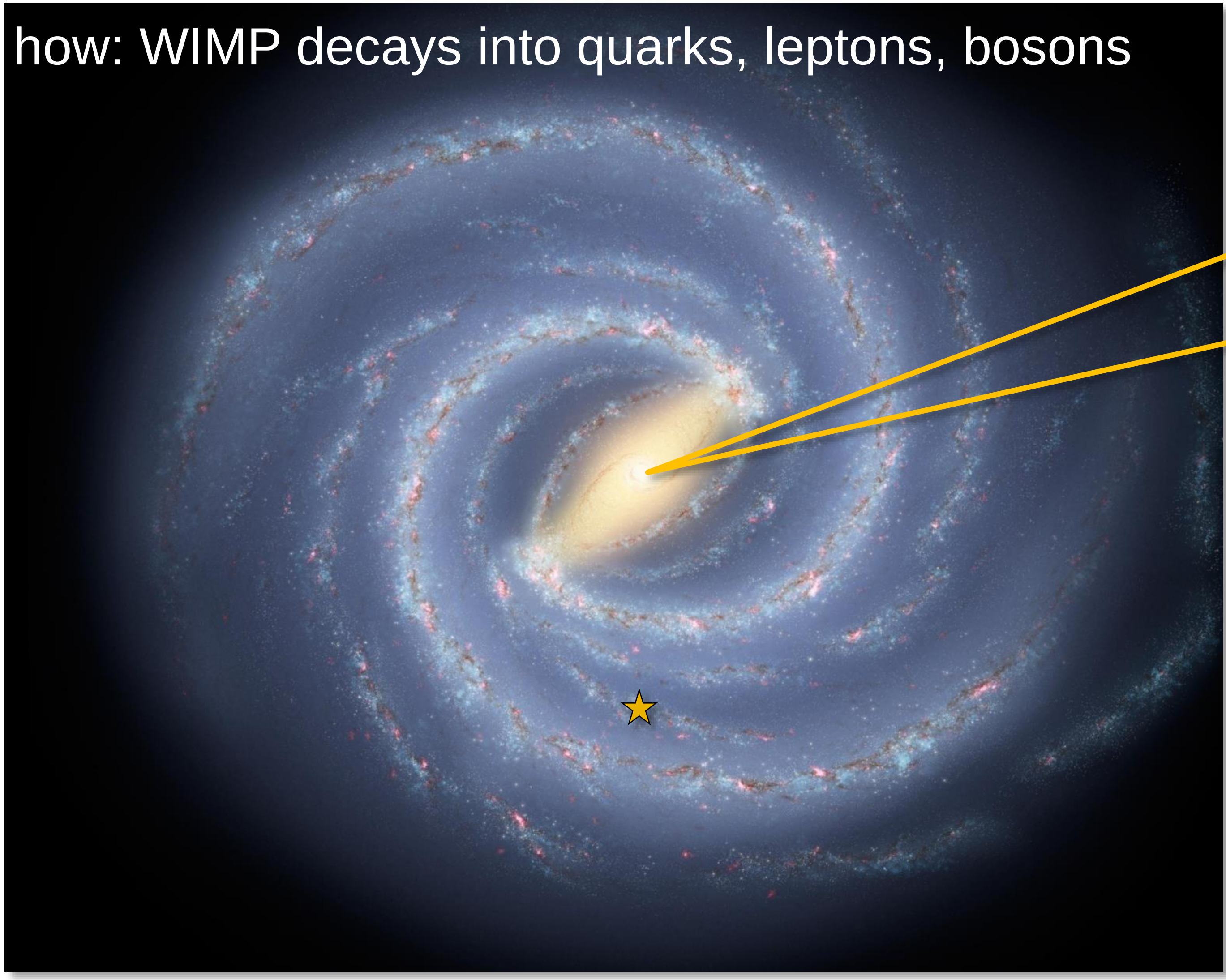
neutrinos from:
- hadronic/leptonic decays

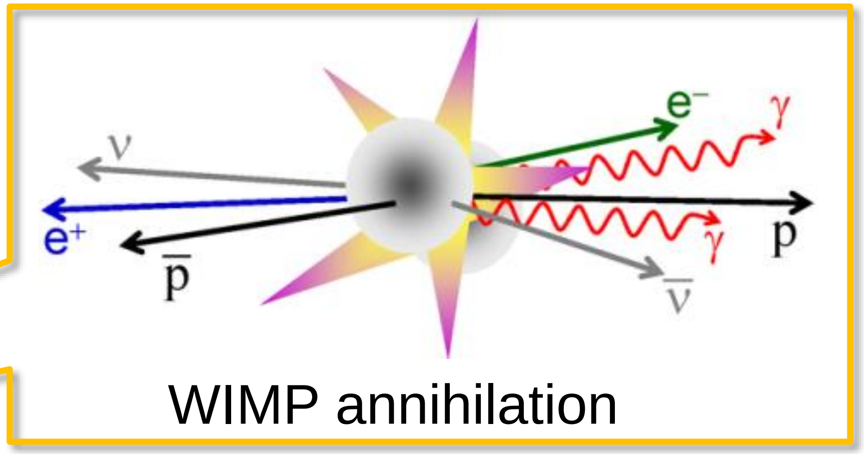
gammas from:
- hadronic decays
- bremsstrahlung

protons/antiprotons from:
- hadronisation & jets
- decays of gauge boson

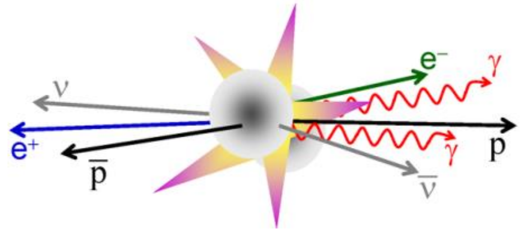
WIMP annihilation – modelling of signal

- **detection of WIMP annihilation** requires precise modelling of
  a) χ^0-signal: particle physics (decay modes)

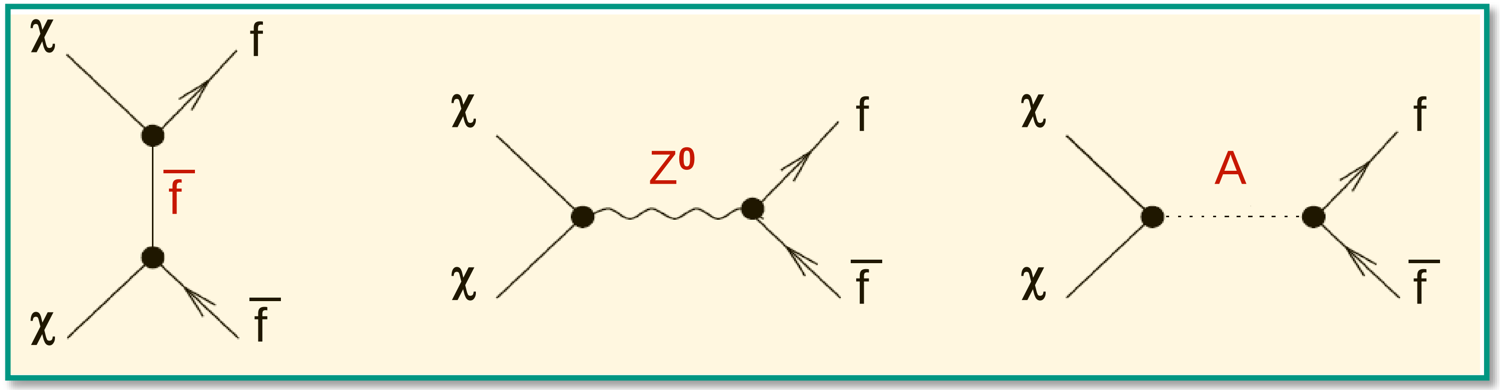




Neutralino annihilation processes



annihilation into fermion pairs (quarks, Leptons)



t-channel

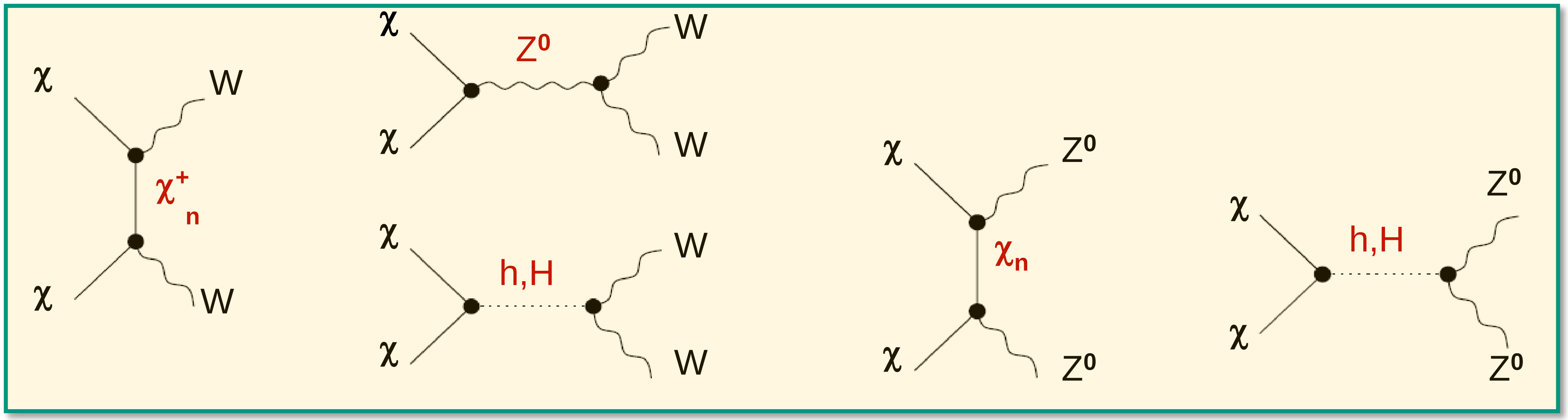
s-channel

s-channel
- Z^0 boson
- pseudoscalar Higgs A

t-channel
- sfermions

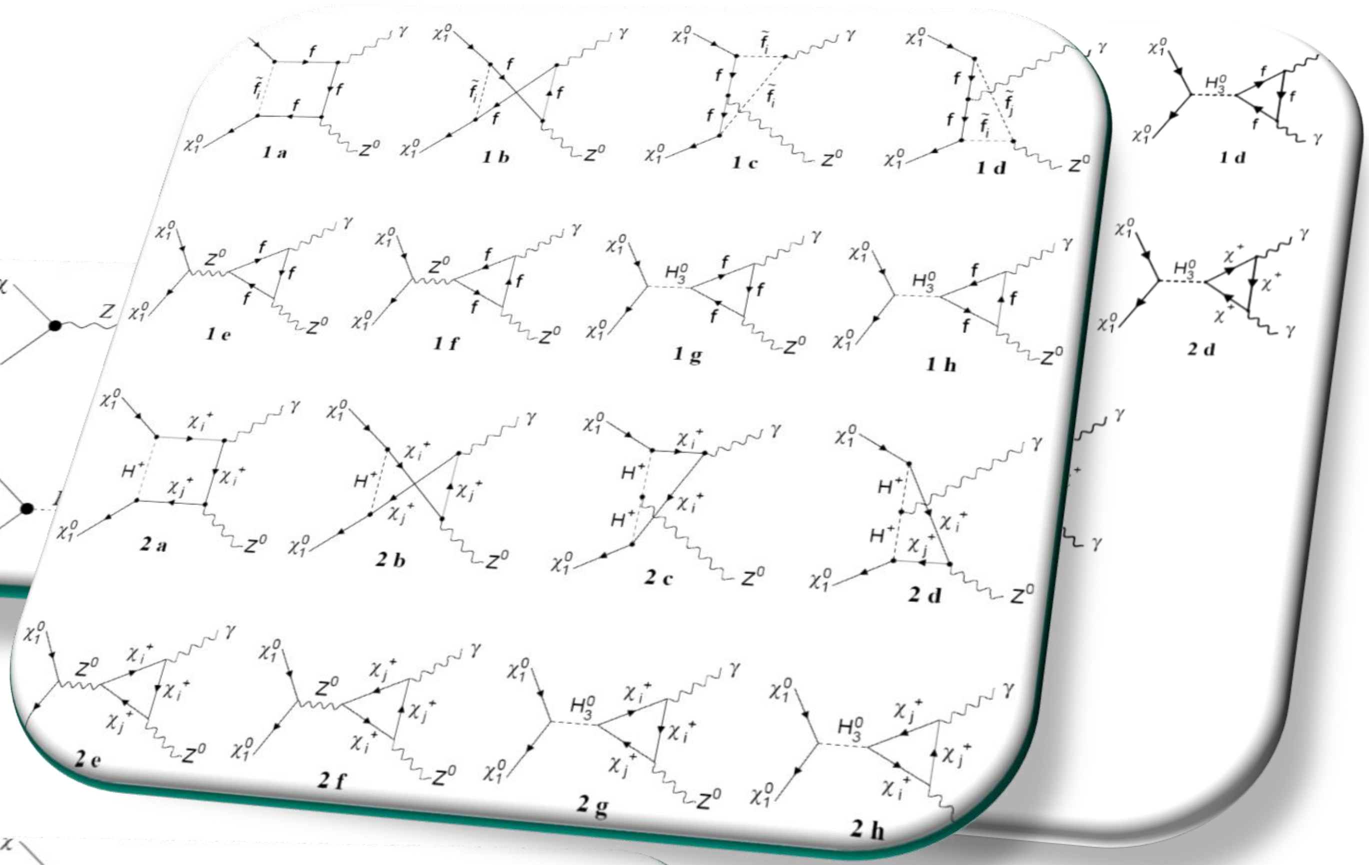
annihilation into gauge boson pairs $W^{\pm}$ Z^0

t-channel: charginos, neutralinos

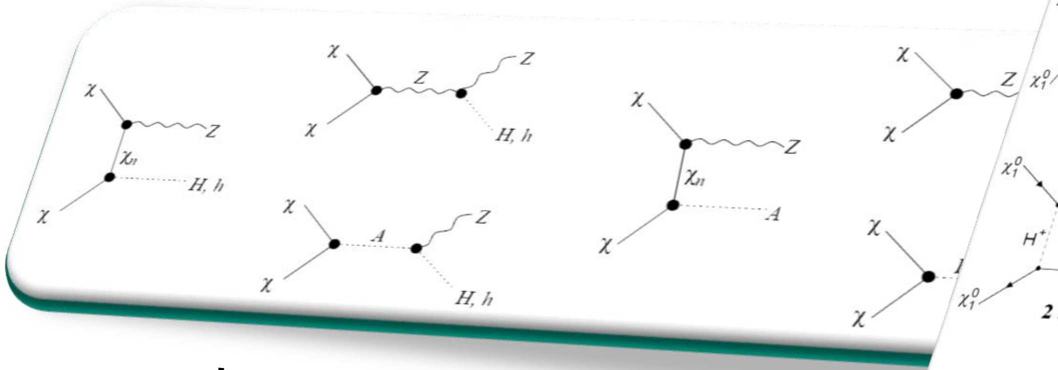


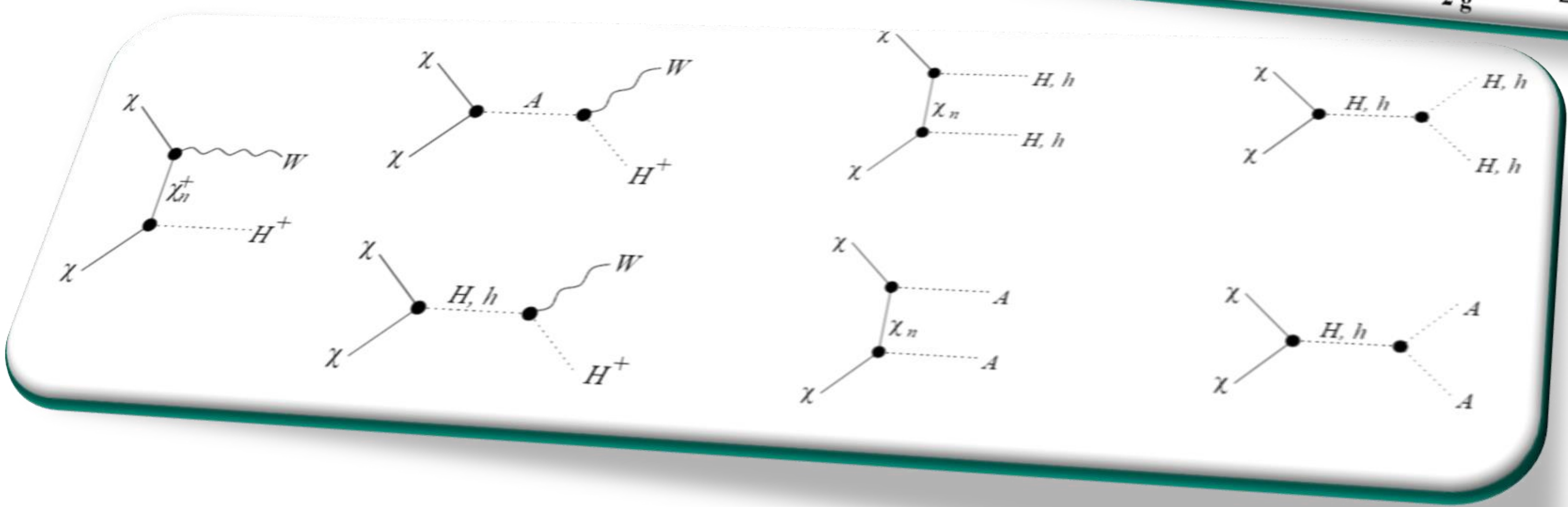
Neutralino annihilation processes

…an extract of further annihilation channels…



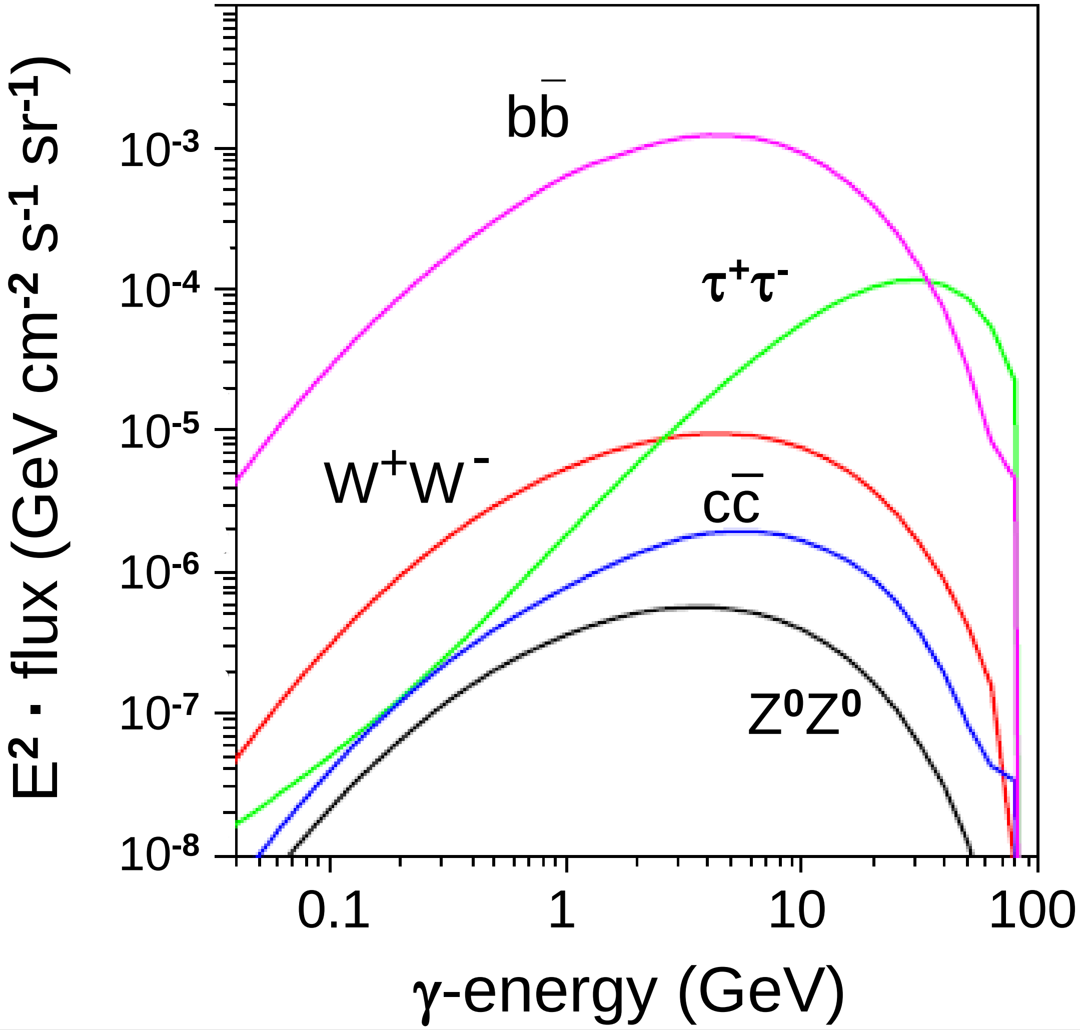
…into higgs bosons & gauge bosons…

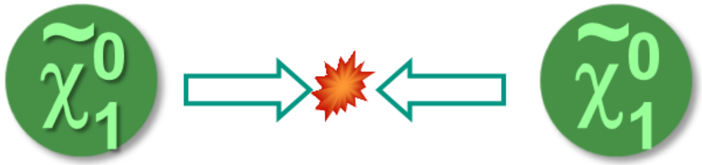




Gammas from WIMP annihilations

- **Neutralino annihilation** $\tilde{\chi}^0\tilde{\chi}^0 \rightarrow q\bar{q}$: fragmentation of quarks leads to **~30-40 gammas** (GeV-energies)
  gamma spectrum depends on annihilation channel ($\rightarrow$ bb, ZZ)





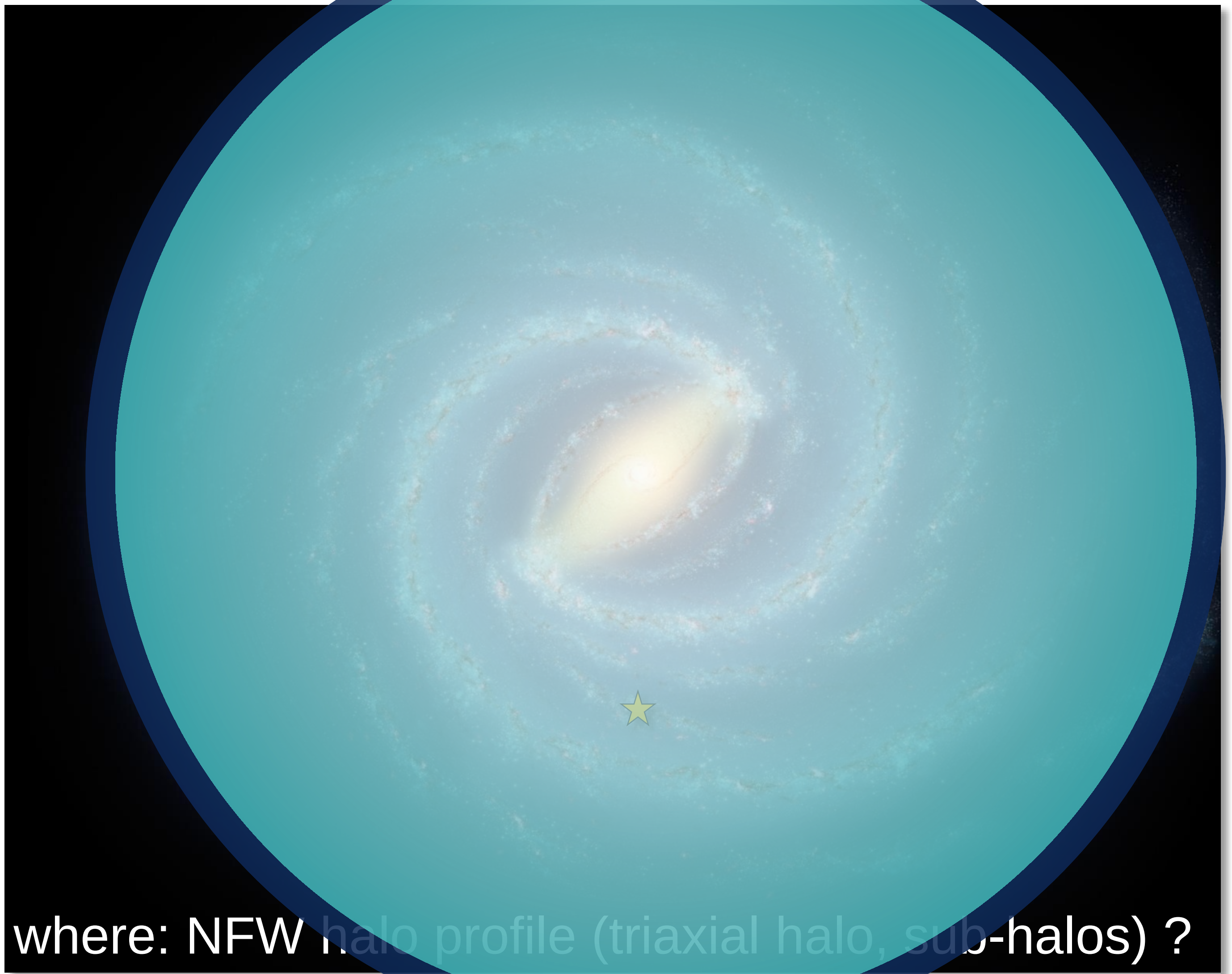
M = 100 GeV

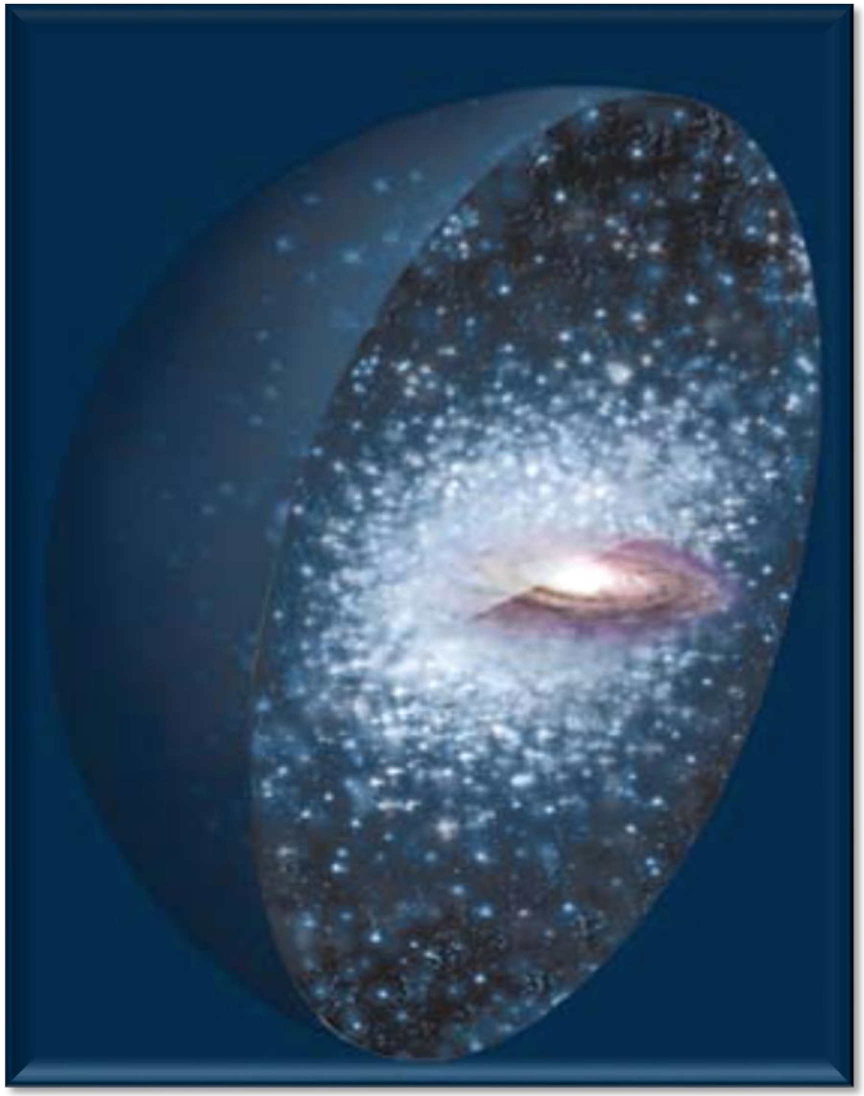
- decay channels depend on:
  a) WIMP mass M(χ^0)
  b) WIMP flavour composition
  (bino, wino, higgsino)

- χ^0-decays to light quarks u,d,… (and massless γ´s) are helicity suppressed

WIMP annihilation – modelling of signal

- **detection of WIMP annihilation** requires precise modelling of
  a) χ^0-signal: particle physics (decay modes) & astrophysics (halo model)





DMA-sources & halo profile

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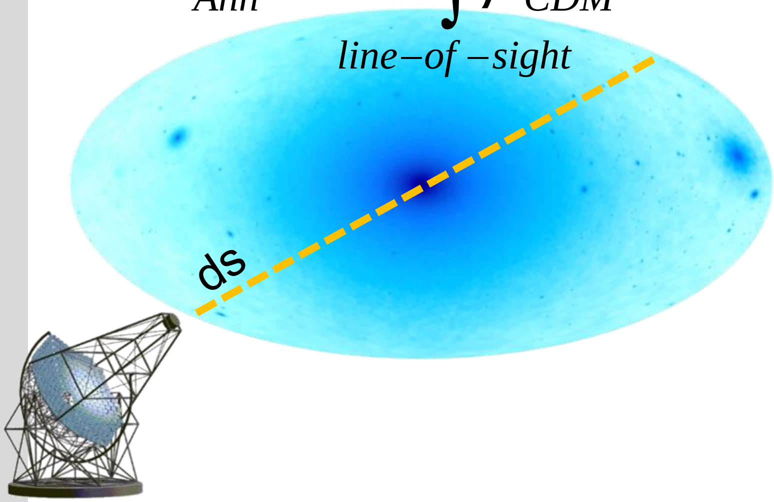
$$N_{Ann} \sim \int_{line-of-sight} \rho^2_{CDM} \cdot ds$$



- number N_{Ann} of WIMP annihilations in DM-halo (per unit time/volume):

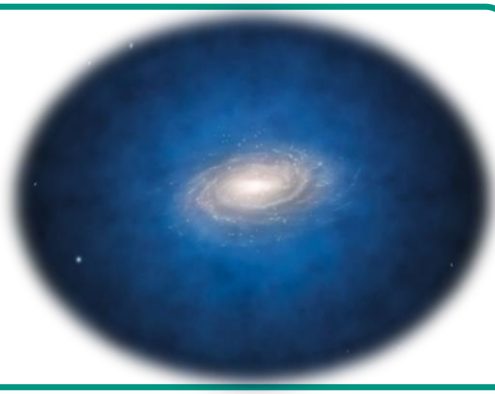
$$N_{Ann} \sim \langle \sigma_{Ann} \cdot \mathrm{v} \rangle \cdot n^2_{CDM}$$
$$\sim \langle \sigma_{Ann} \cdot \mathrm{v} \rangle \cdot \frac{\rho^2_{CDM}}{m^2_{CDM}}$$

ρ_{CMD}	from NFW profile of the CDM halo
v	WIMP velocity profile in the halo
σ_{Ann}	cross section from theoretical calculations

- WIMP annihilation rate in DM halos: $\Gamma_{Ann} \sim \rho^2_{CDM}$

  searching in **areas with DM overdensities**

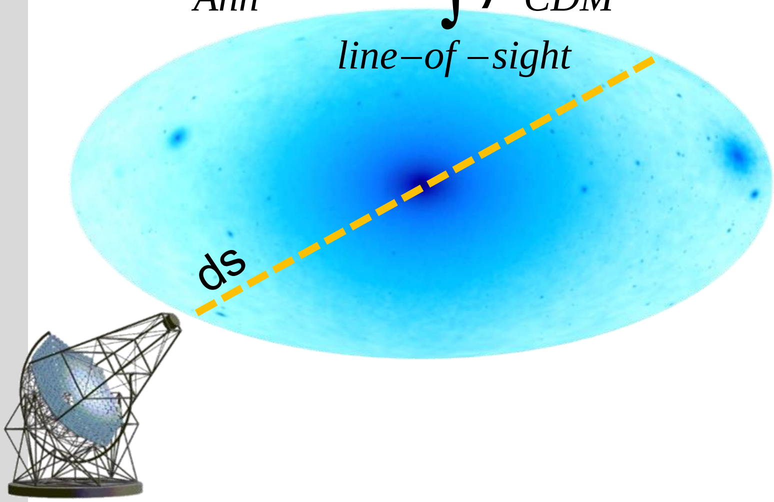
  - galactic centre
  - sub-halo centres: dwarf galaxies, …



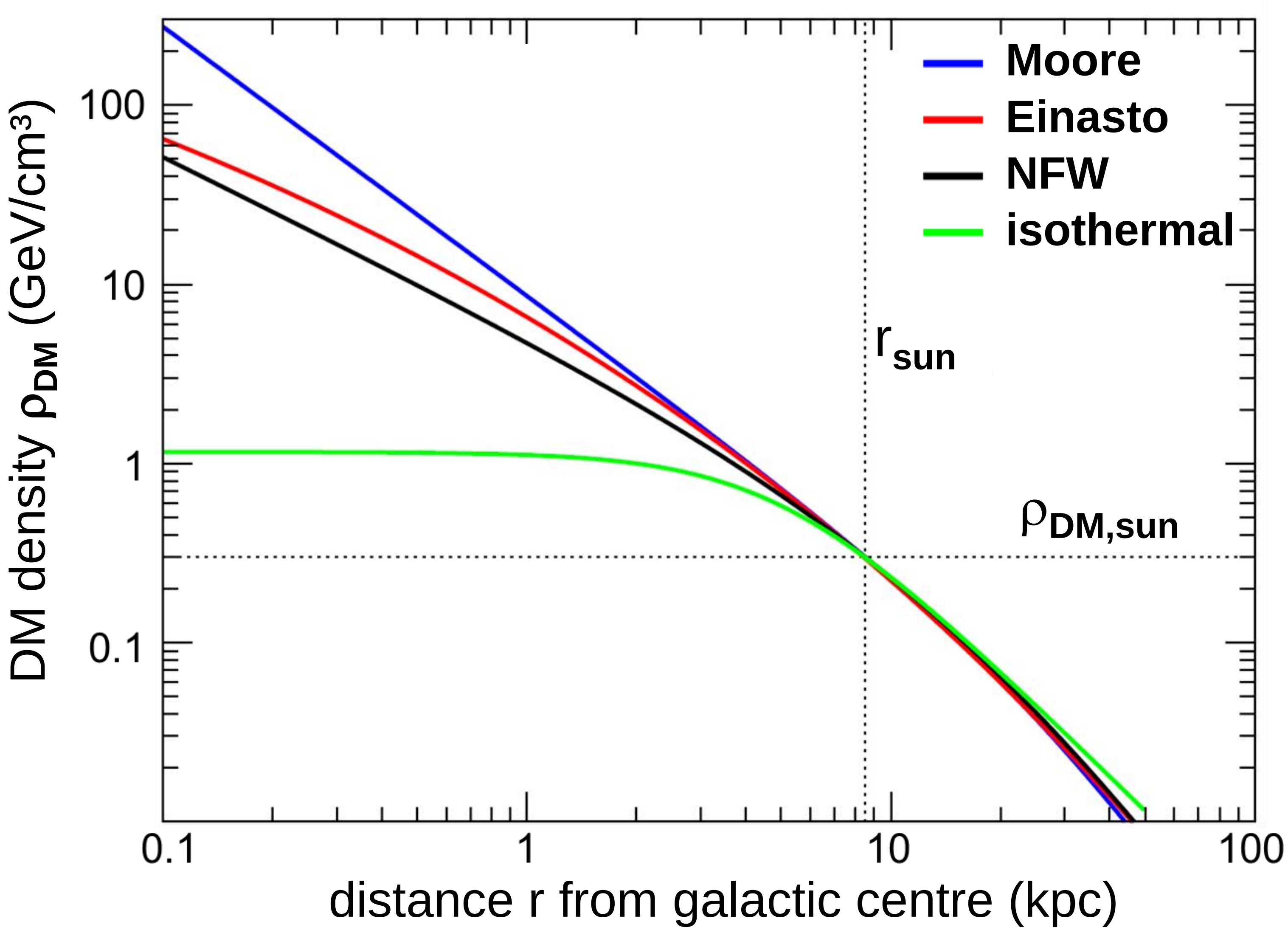
DMA-sources & halo profile

- **WIMP-density profile** in inner DM-halo strongly model-dependent!

$$N_{Ann} \sim \int_{line-of-sight} \rho_{CDM}^2 \cdot ds$$



- **DMA-signal rates are model-dependent**: different parameterisations of the radial WIMP halo profile



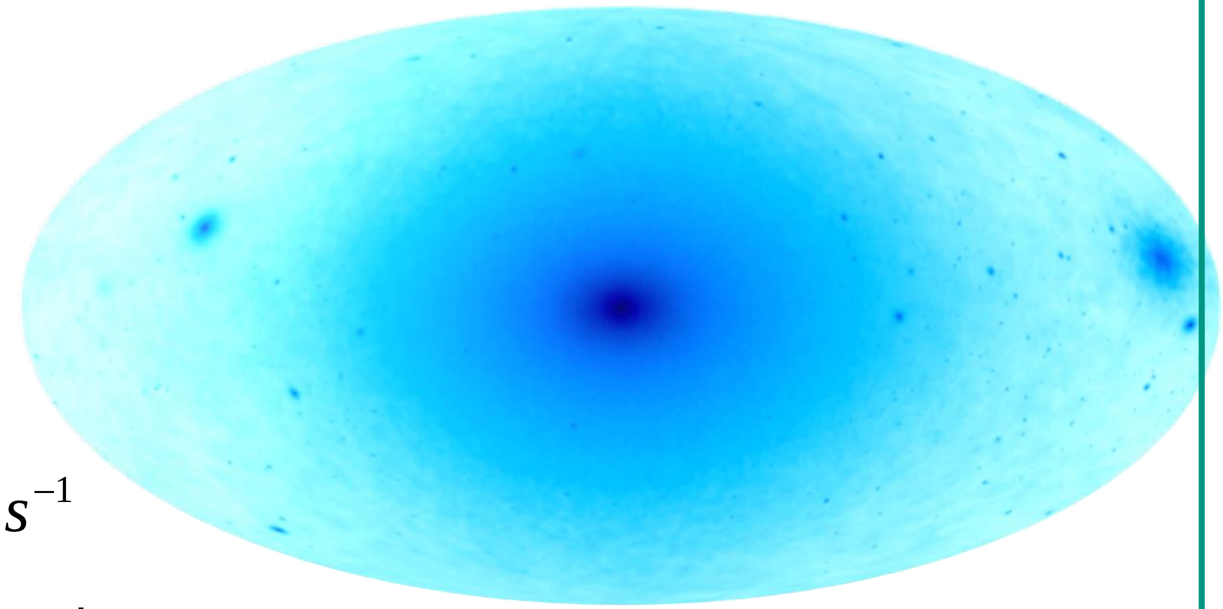
WIMP annihilation: line-of-sight

- energy-dependent flux $\Phi_{AP,i}$ of WIMP annihilation products (γ, ν) is given by the integration along the line-of-sight:

$$\Phi_{AP,i}(E) \sim \langle \sigma_{Ann} \cdot \text{v} \rangle \cdot \frac{1}{4\pi\, m_{CDM}^2} \cdot \frac{dN_i}{dE} \cdot \int\limits_{line-of-sight} \rho^2 ds$$

dN/dE: energy spectrum

1 pb   1 TeV



$$\Phi_{AP,i}(E, \Delta\Omega) \approx 5.6 \times 10^{-12} \cdot \Delta\Omega \quad cm^{-2} s^{-1}$$

ΔΩ: solid angle

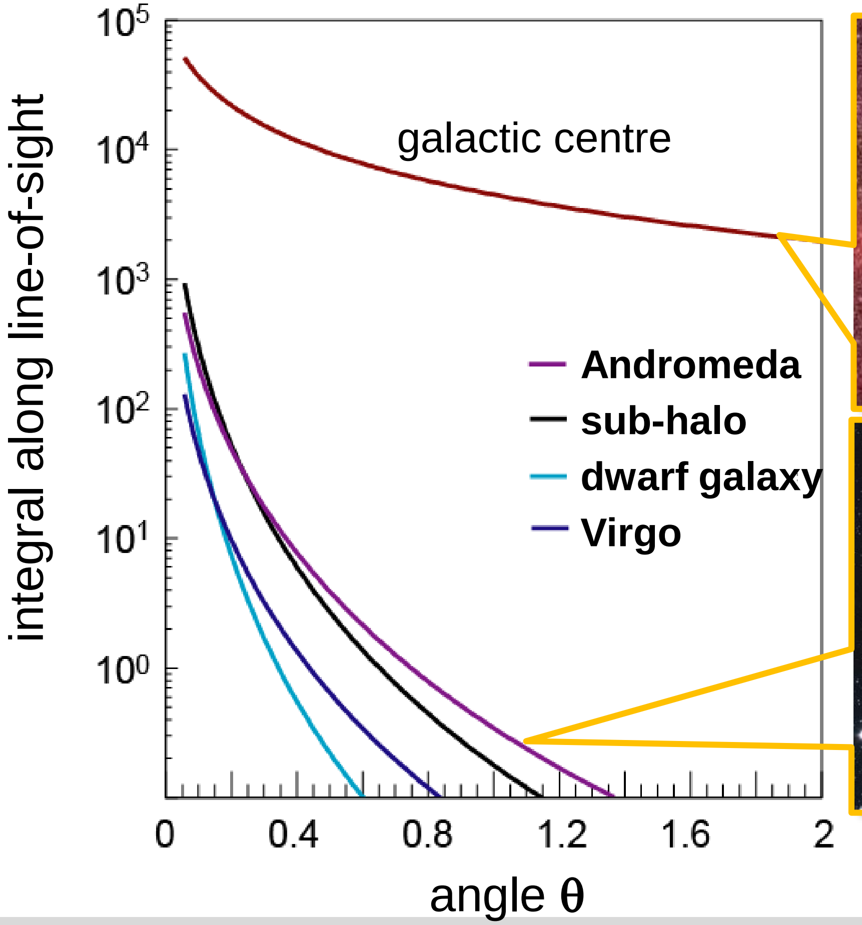
small flux of particles from DMA

WIMP annihilation: line-of-sight

- energy-dependent flux $\Phi_{AP,i}$ of WIMP annihilation products (γ, ν) is given by the integration along the line-of-sight:

$$\Phi_{AP,i}(E) \sim \langle \sigma_{Ann} \cdot v \rangle \cdot \frac{1}{4\pi\, m_{CDM}^2} \cdot \frac{dN_i}{dE} \cdot \int_{line-of-sight} \rho^2 ds$$

dN/dE: energy spectrum



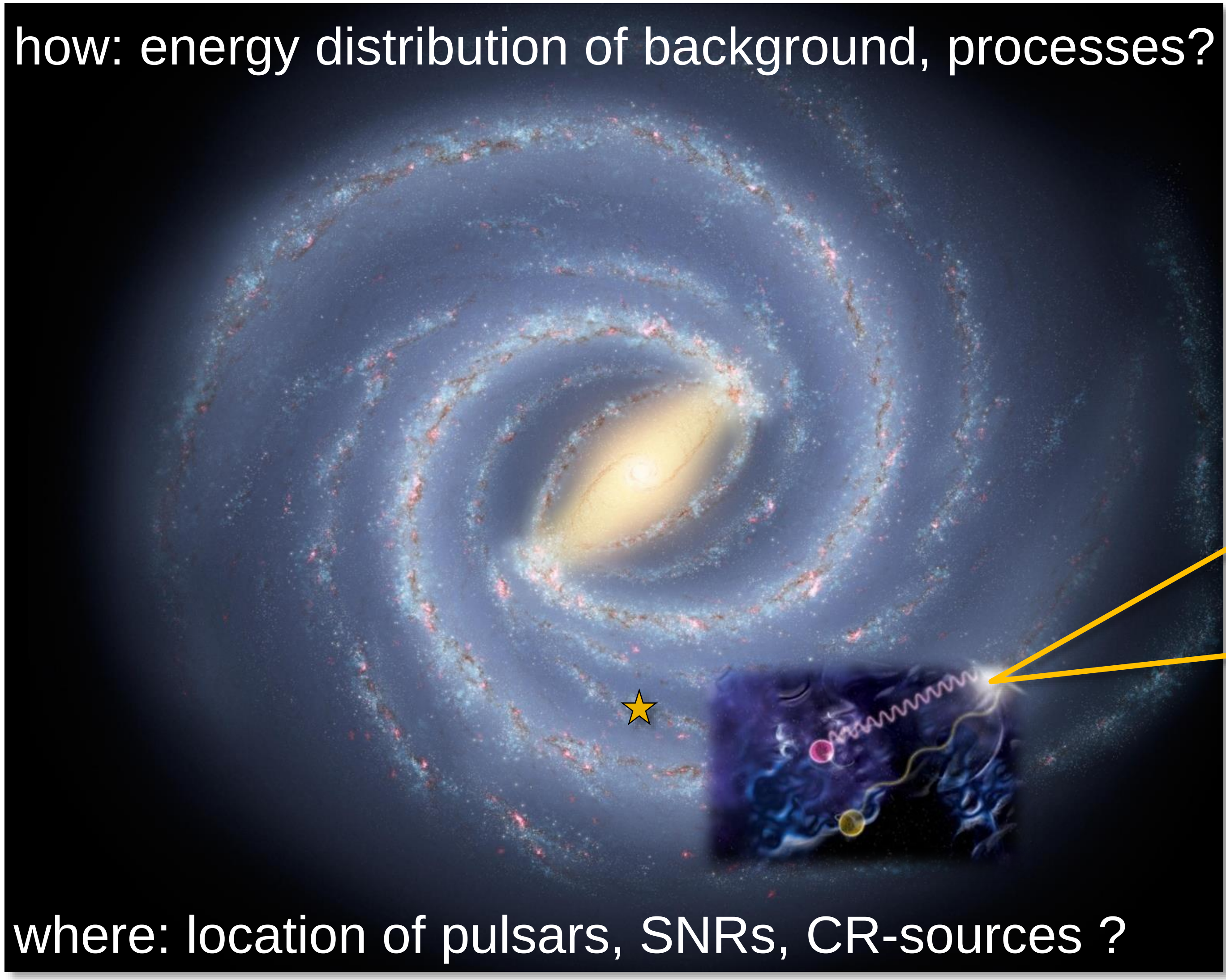
dominant source

d = 7.6 kpc

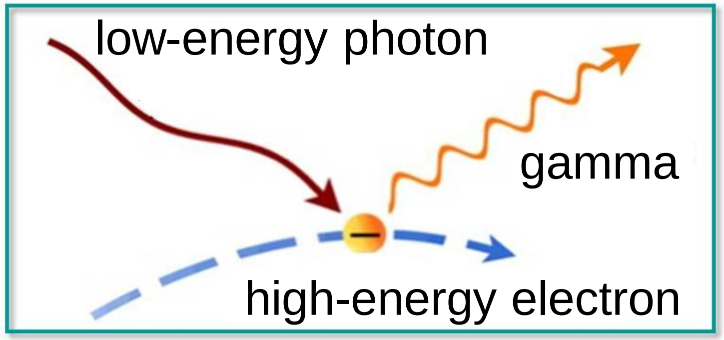
d = 780 kpc

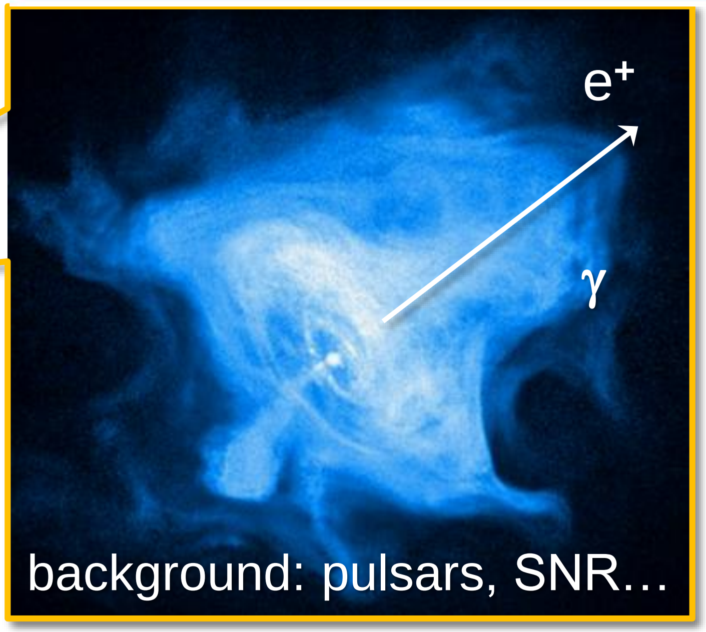
WIMP annihilation – modelling of background

- **detection of WIMP annihilation** requires precise modelling of
  b) astrophysical background (sources, background mechanism)



inverse Compton effect





WIMP annihilation: gamma background

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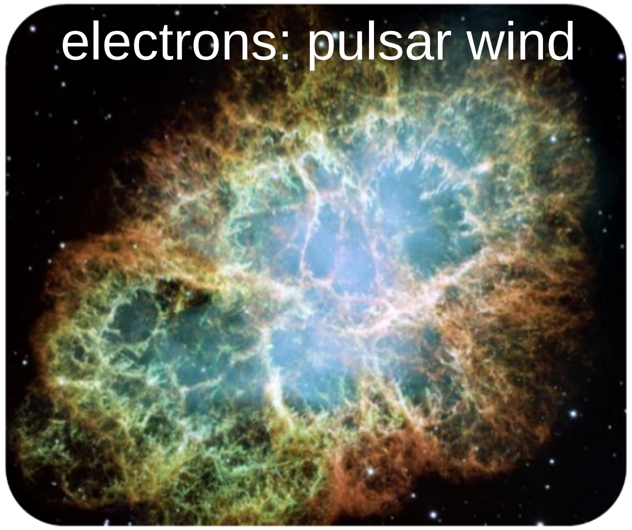
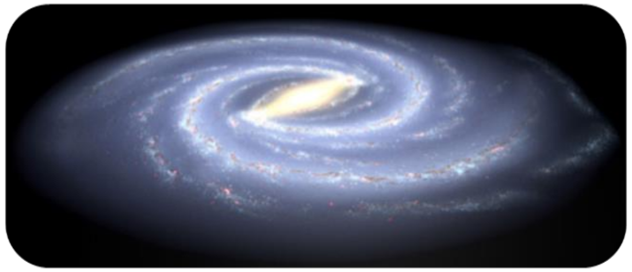
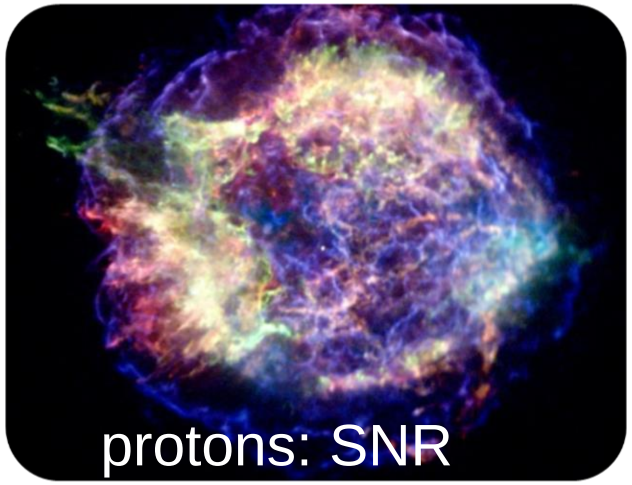
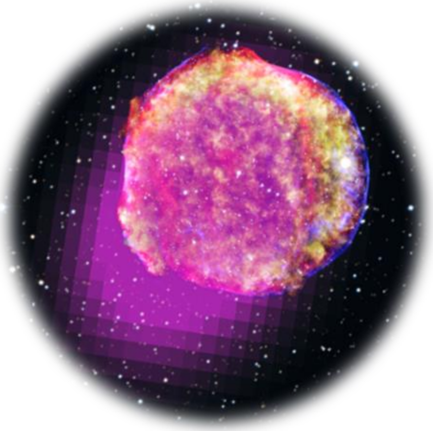
■ **astrophysical background processes for γ´s**

- are generated by the production and reactions of the (non-thermal) cosmic radiation
- various galactic sources:
  - a) SN-shock waves in SNRs (SuperNova Remnant)
  - b) pulsar winds, ms-pulsars
  - c) processes in the interstellar medium (ISM),
- extragalactic
  - a) active galactic nuclei

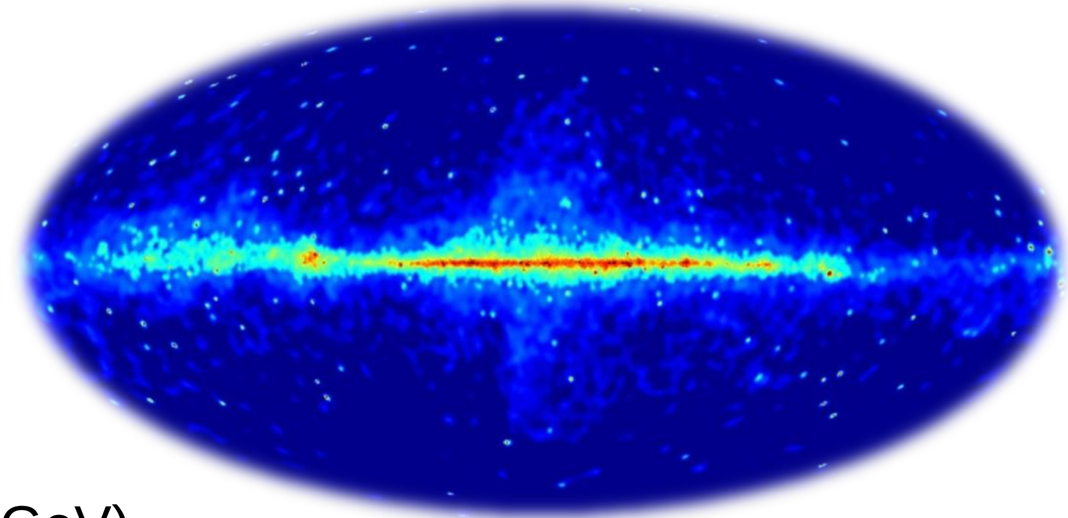






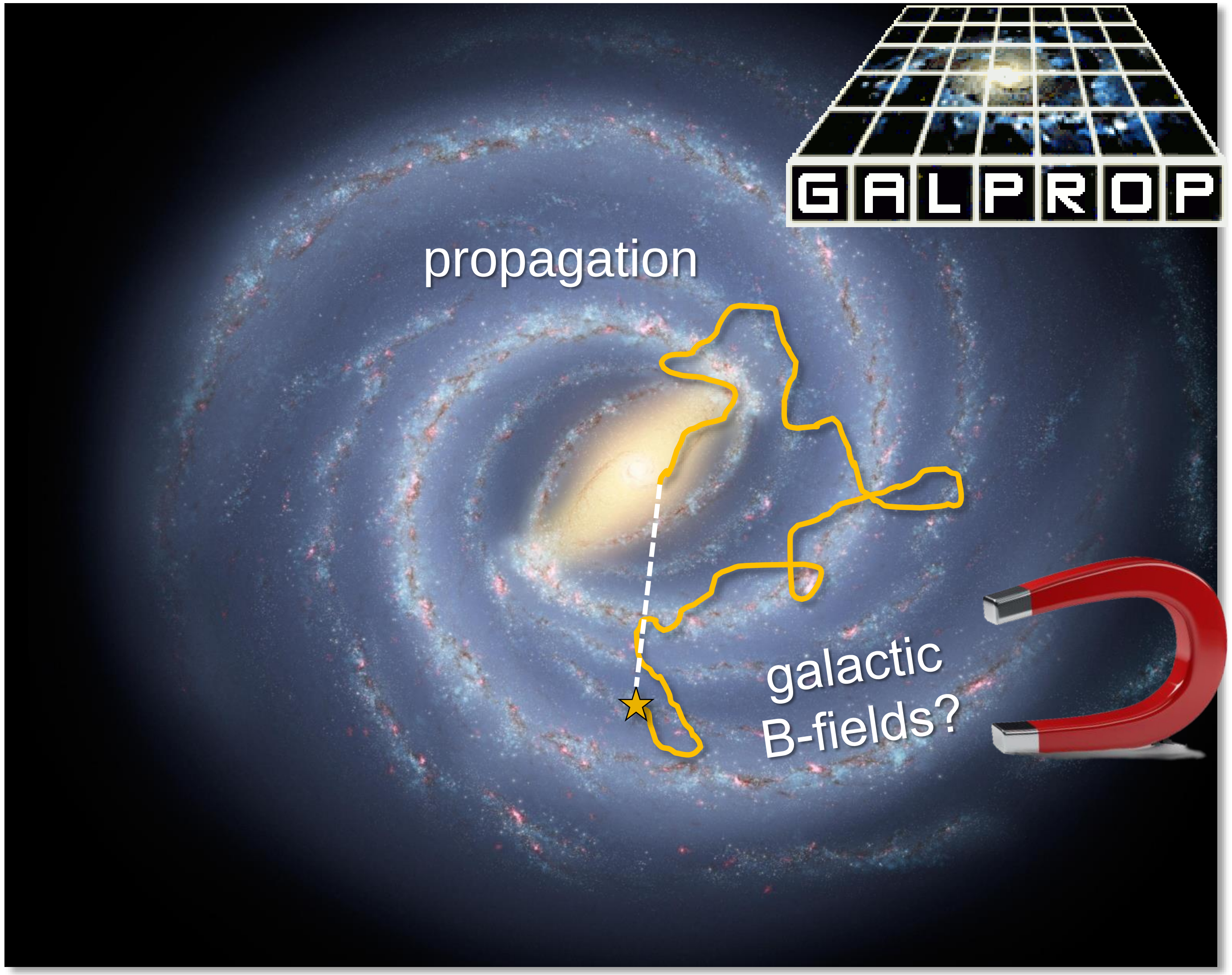


SN1006 in γ-rays (GeV)

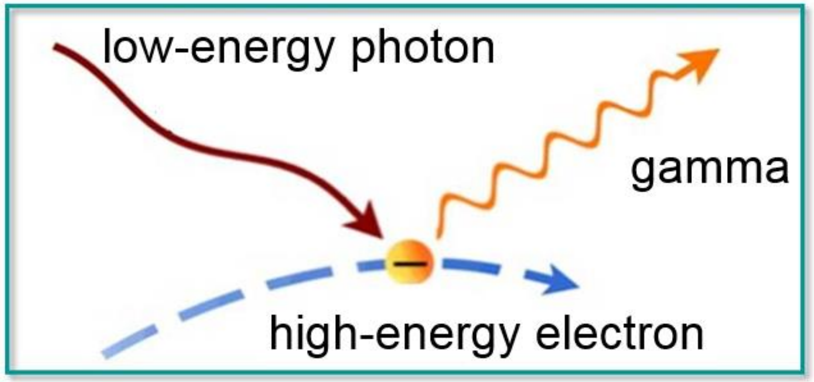


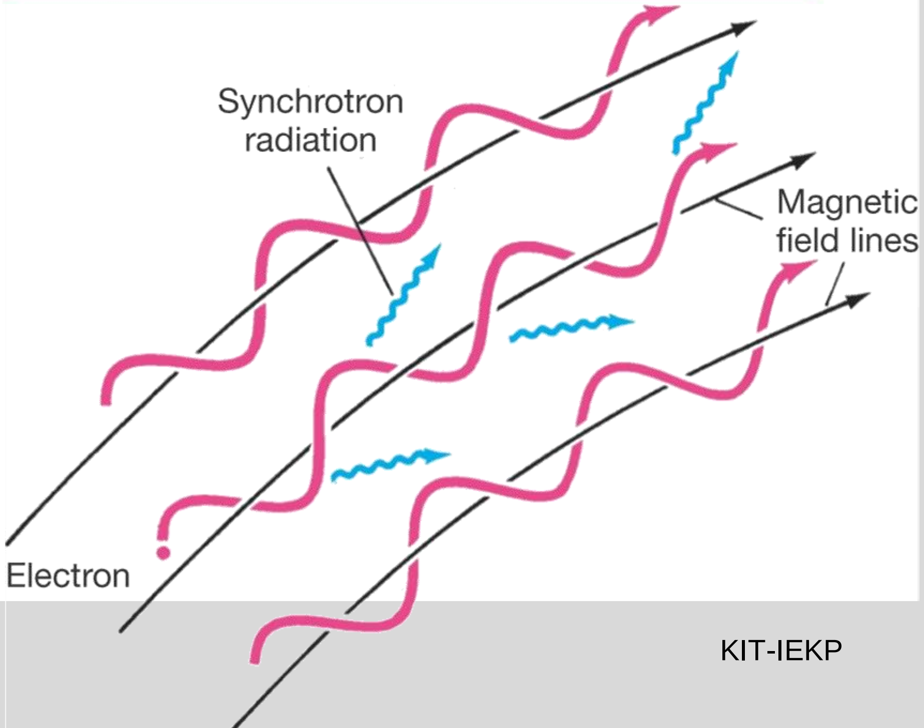
WIMP annihilation – modelling of transport

- **detection of WIMP annihilation** requires precise modelling of
  c) propagation of (anti-)protons & electron/positrons in galactic B-fields



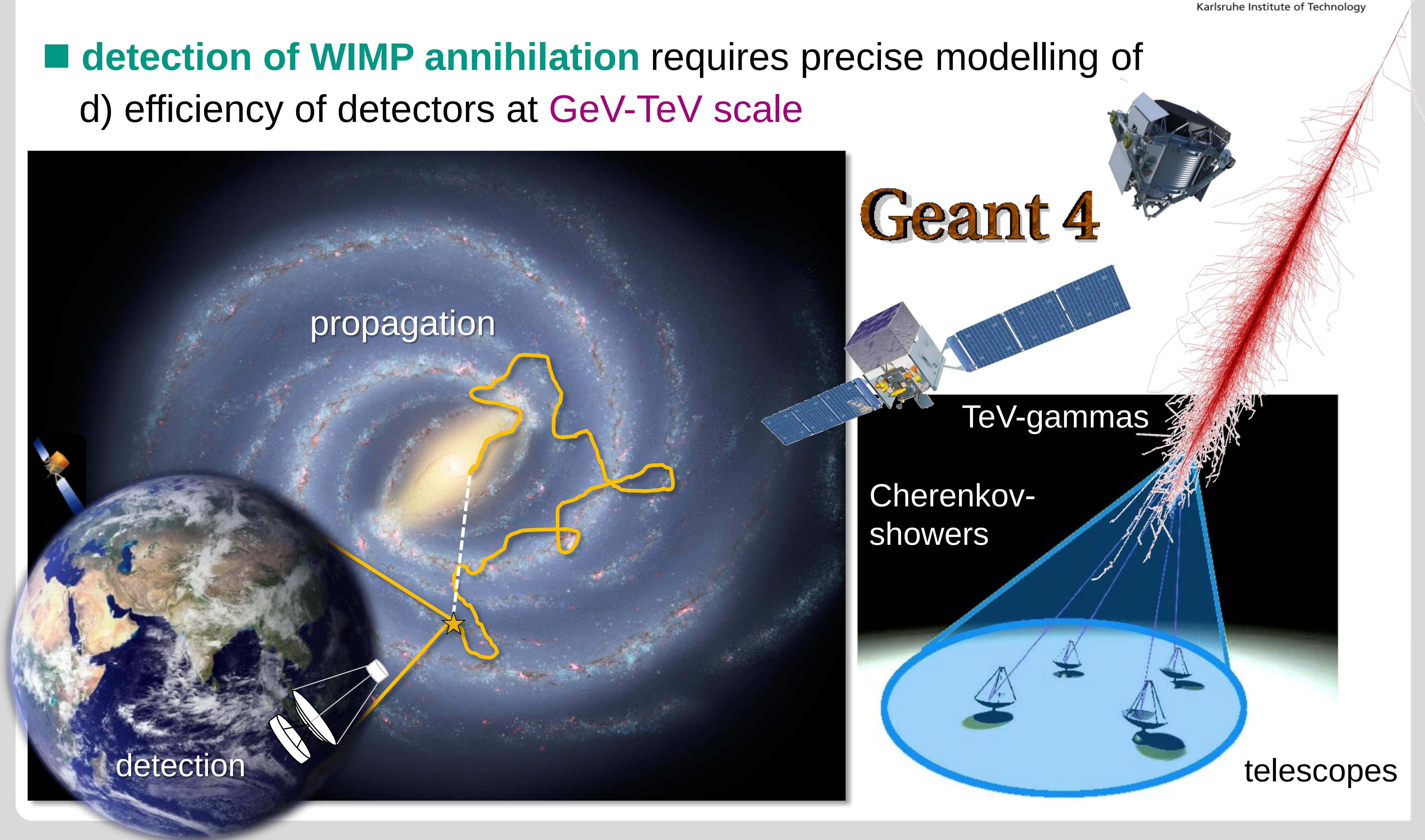
inverse Compton effect





WIMP annihilation – modelling of detection

- **detection of WIMP annihilation** requires precise modelling of
  d) efficiency of detectors at GeV-TeV scale



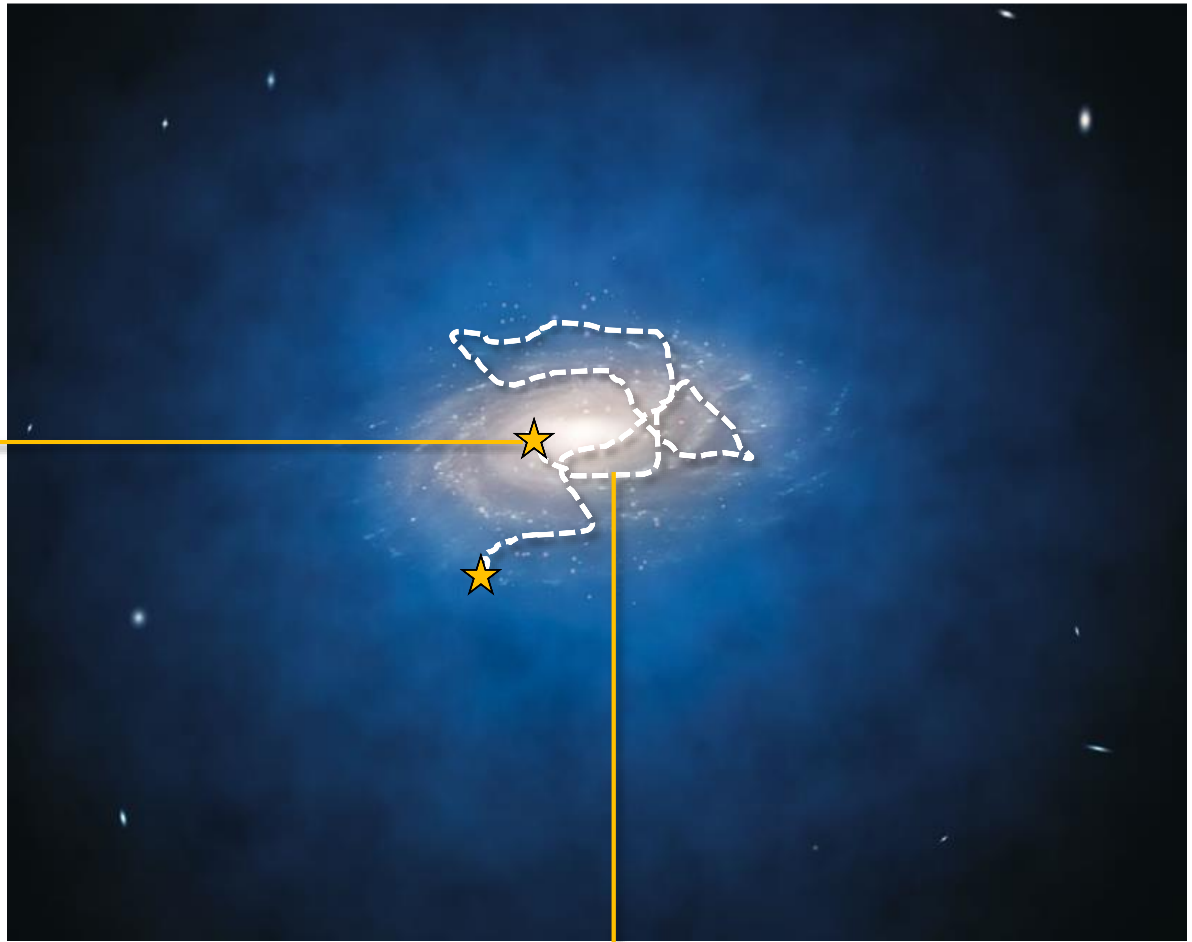
DMA – detection: uncertainties

- systematic effects from astrophysics & particle physics in detecting DMA:

ASTRO

DM halo profile
(sub-Halos?)

- background sources (pulsars, SNR,…)



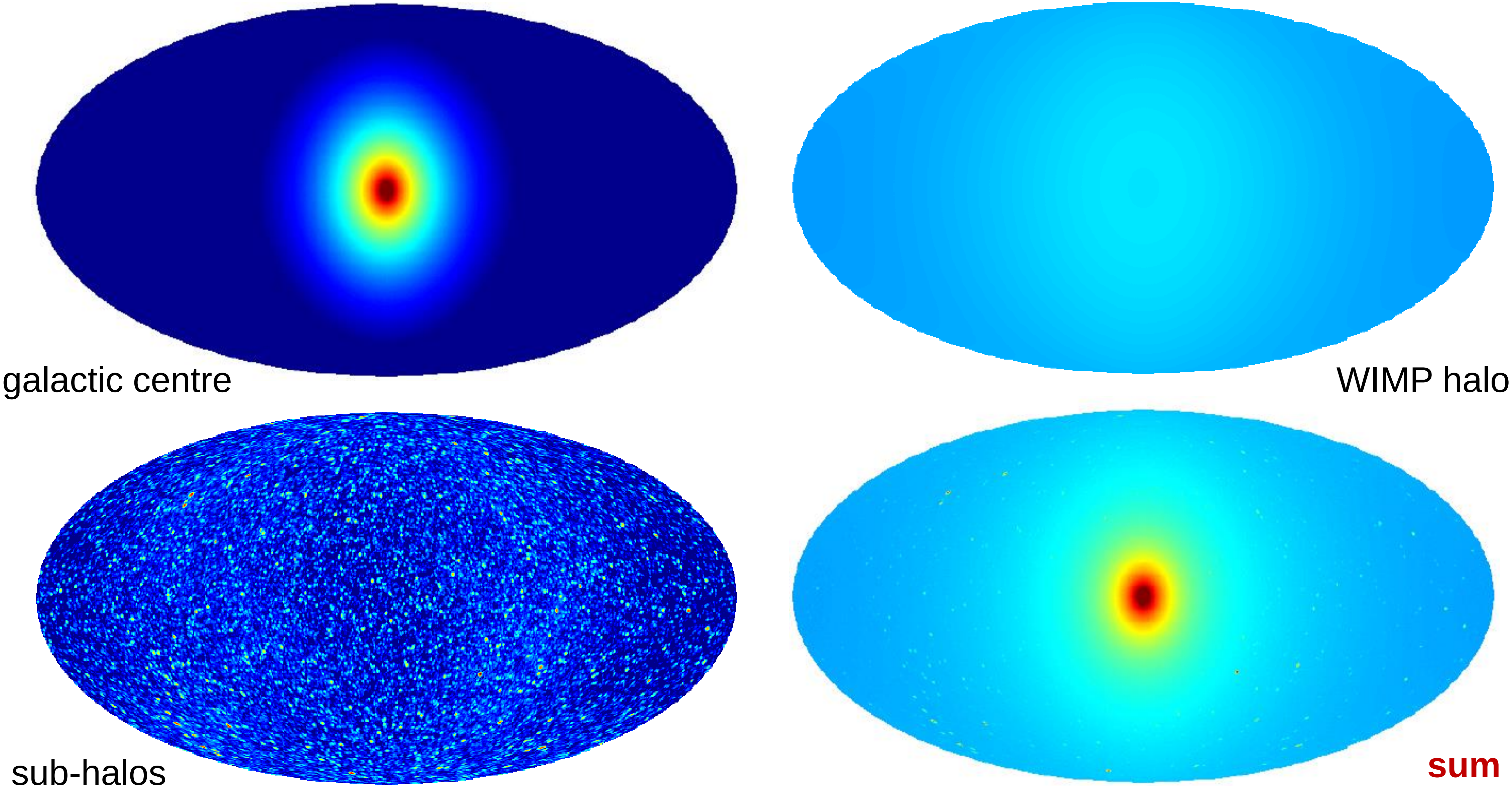
DM propagation
(energy losses, B-fields)

SUSY

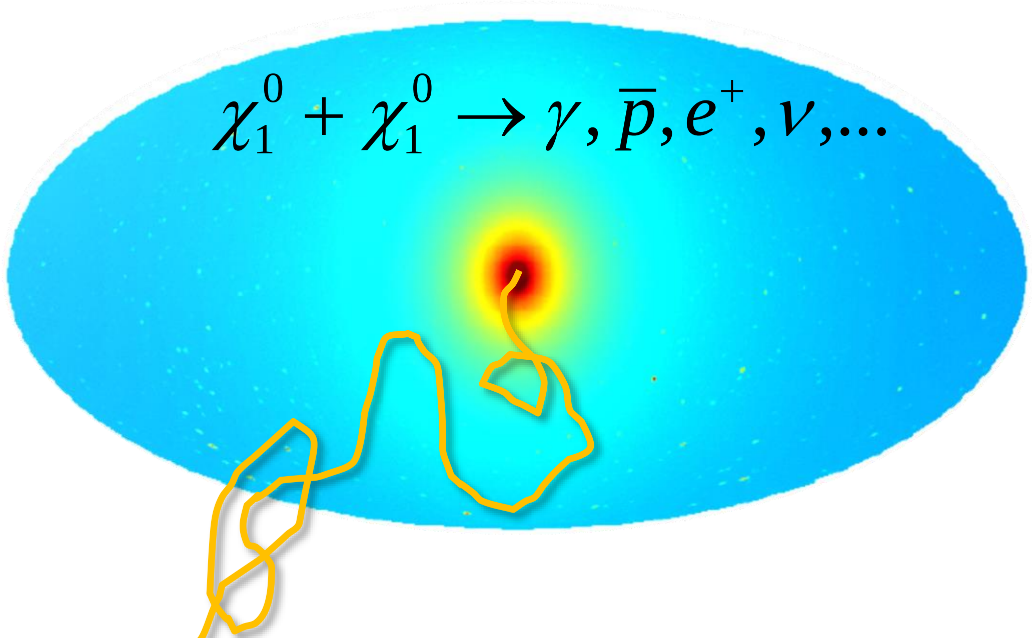
WIMP-properties:
- mass
- flavour ($\tilde{B}^0$, $\tilde{W}^0$)
- $\sigma_{Ann} \cdot v$
- decay channels

WIMP annihilation: modelling of signal

- modelling of different contributions to DMA signal

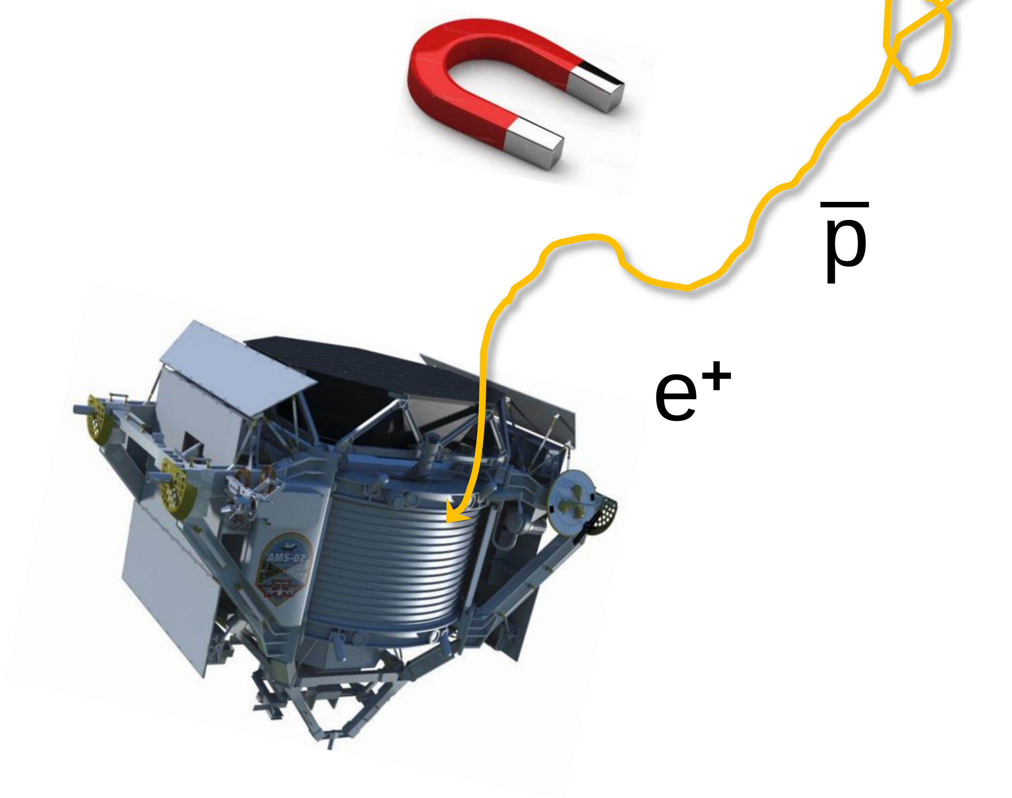


DMA: antiprotons, positrons



$$\chi_1^0 + \chi_1^0 \rightarrow \gamma, \bar{p}, e^+, \nu, \ldots$$

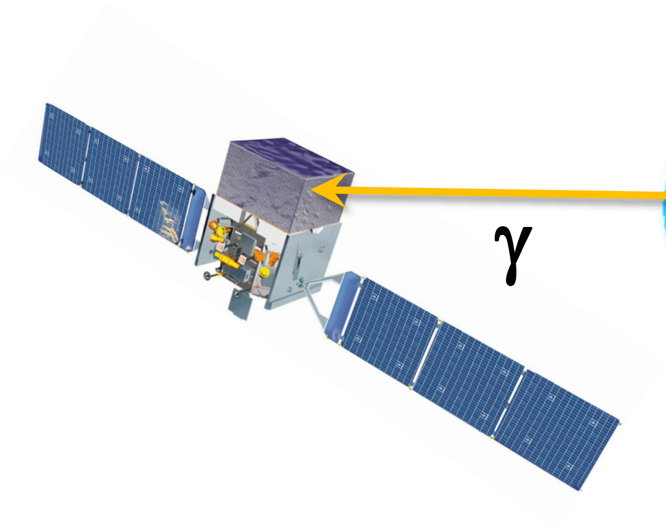
DM annihilation
in galactic centre,
in CDM sub-halos

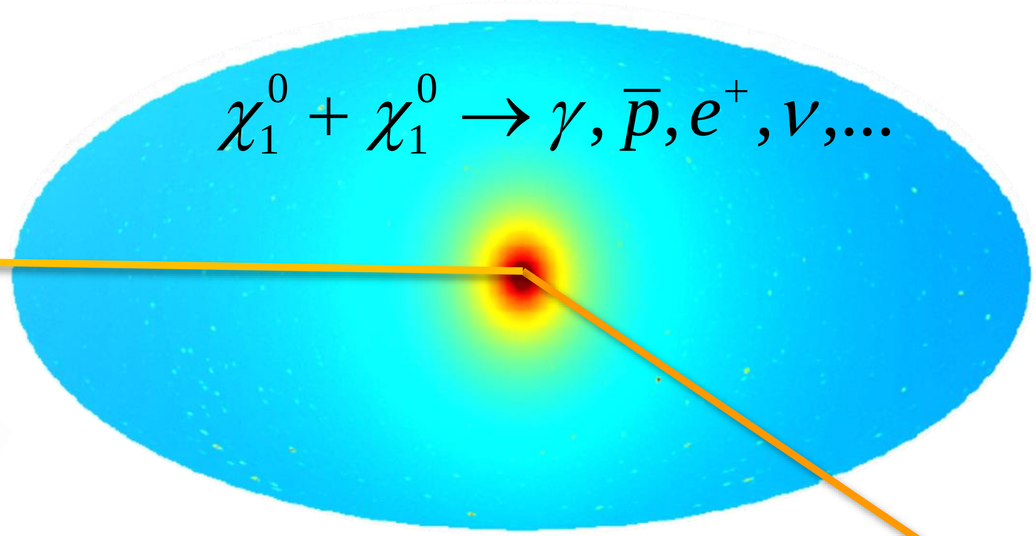


antiprotons, positrons:

- deflection in galactic B-field
- energy losses (e^+: local origin only)
- rather small backgroud (antiprotons) & well-defined (e/m) signal
- atmosphere shields p and e^+ : satellites with strong B-field (GeV)

DMA: Gammas

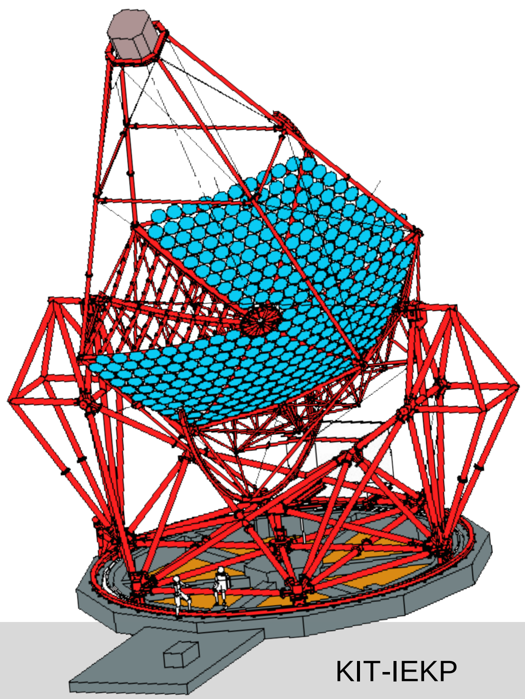




DM annihilation
in galactic centre,
in CDM sub-halos

γ

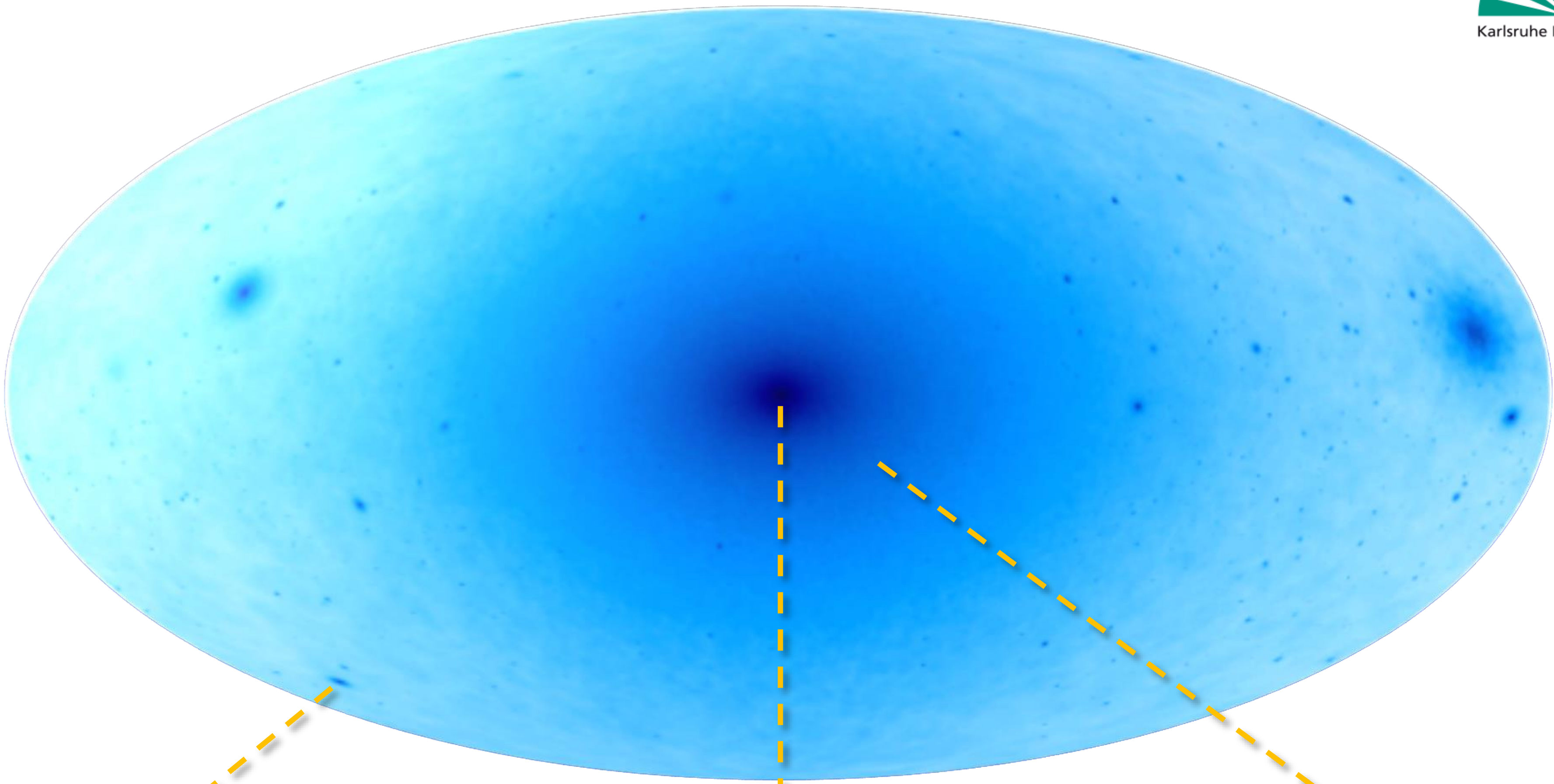
upper
atmosphere



Gamma-rays:

- point back to their region of origin (source)
- no energy losses (no inelastic scattering)
- no deflection in galactic B-fields
- gamma energies extend up to m(χ)
- but: atmosphere shields GeV-TeV γ´s:
  satellites (GeV) & Cherenkov-telescopes (TeV)

DMA: Gammas



extra-galactic:
good statistics 😐
diffuse background ☹

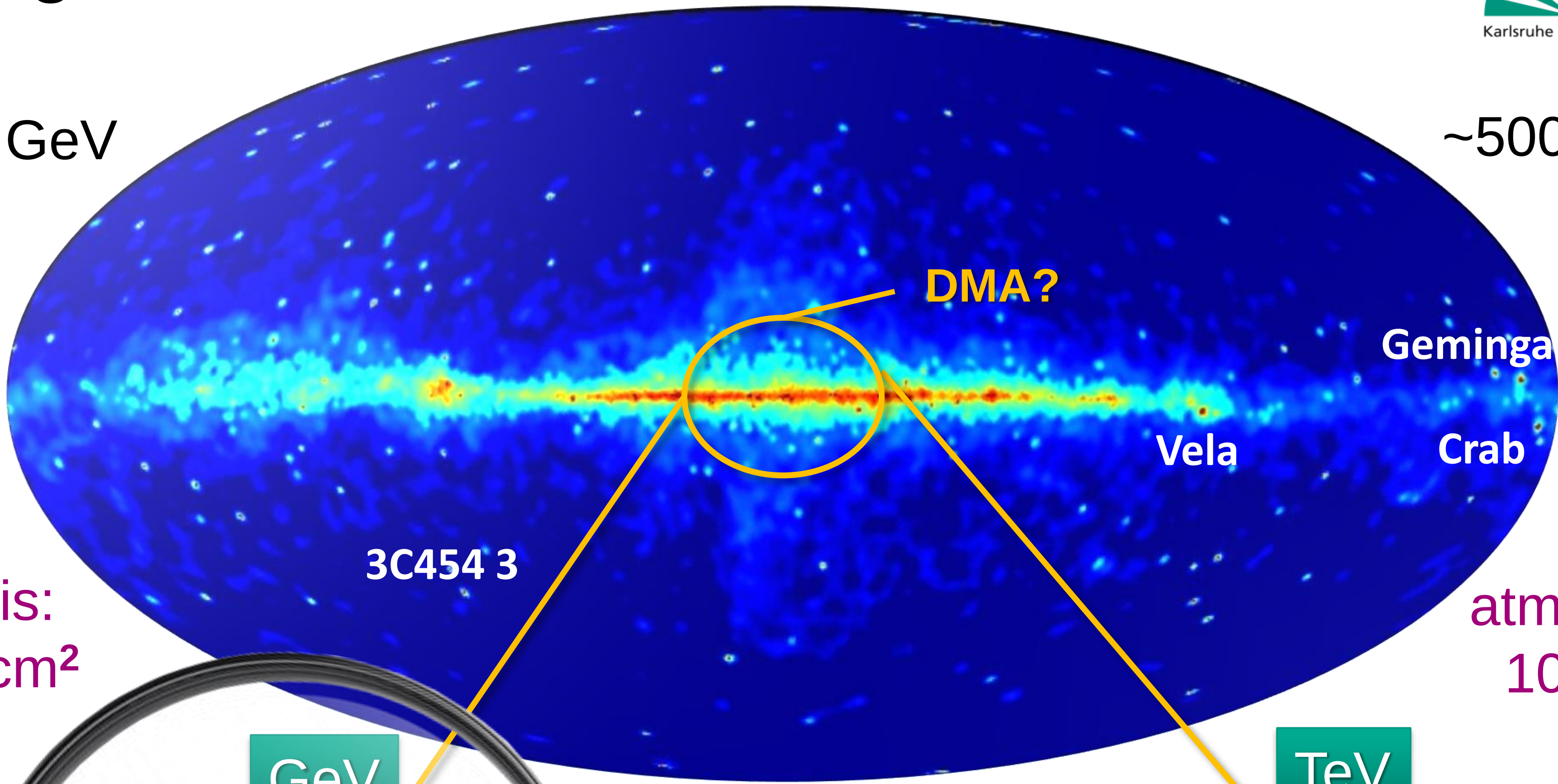
galactic centre:
very good statistics ☺
many bright sources ☹

galactic halo:
good statistics 😐
diffuse background ☹

DMA: gammas

E > 10 GeV

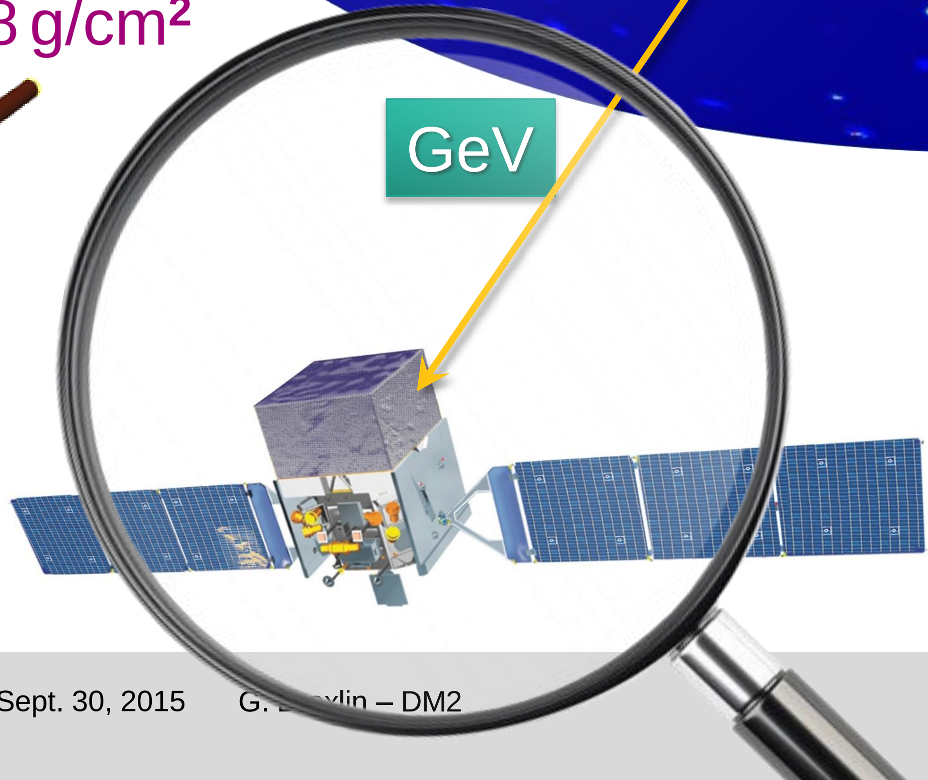
~500 sources



galaxis:
38 g/cm²

atmosphere:
1000 g/cm²

GeV

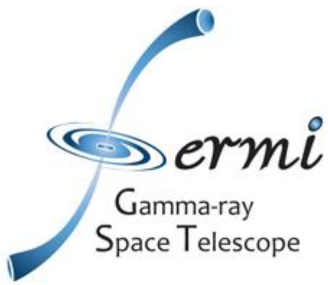


TeV

Fermi-Gamma-Observatory

- **Fermi-γ-Observatory**
  - principle: **pair conversion**
  - successor of Compton-GRO
    with major improvements:
    - larger effective area
    - better angular resolution
    - higher γ–energies

Fermi key parameters	
data taking	since mid-2008
altitude	560 km
dimensions	2.8 m(h) × 2.5 m(Ø)
weight	4.3 t
γ-energy interval	**20 MeV – 300 GeV**
effective area	1 m^2
angular resolution	**~ 1´**



Fermi – Large Area Telescope LAT

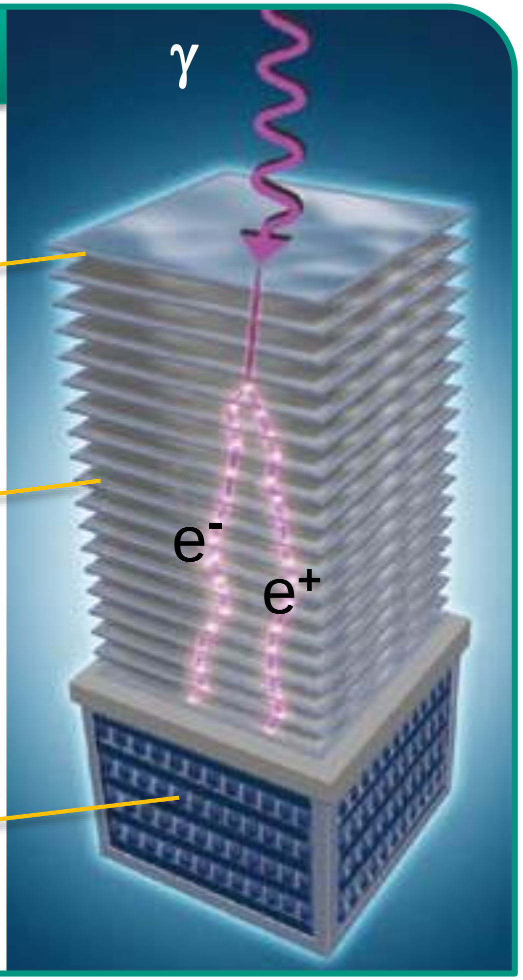
- **LAT**: large area ⇨ covered solid angle dΩ ~ 20% (at any time)
  - 4π coverage every 3 hours
  - 16 single towers

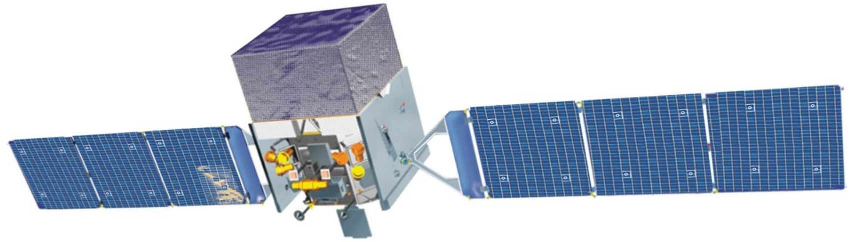
single tower

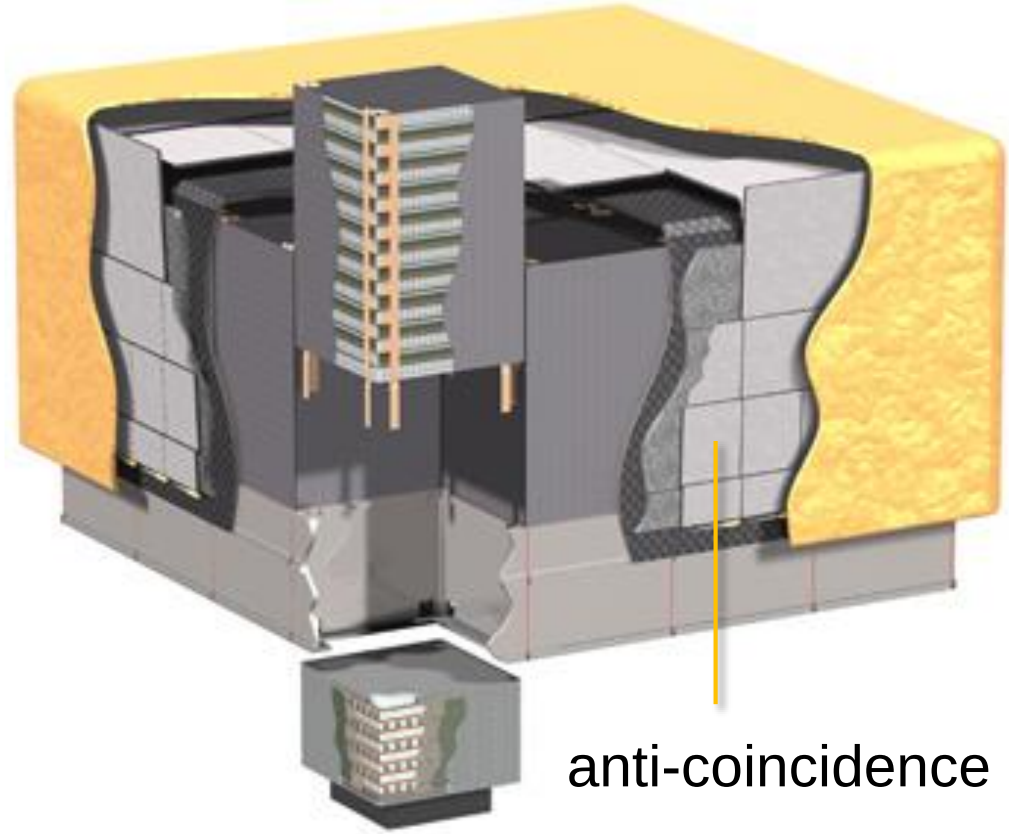
γ-conversion
(16 W-foils)

Si-strips
(tracker)
gamma-direction

calorimeter (8.6 Λ_0)
CsJ-crystals
Gamma energy



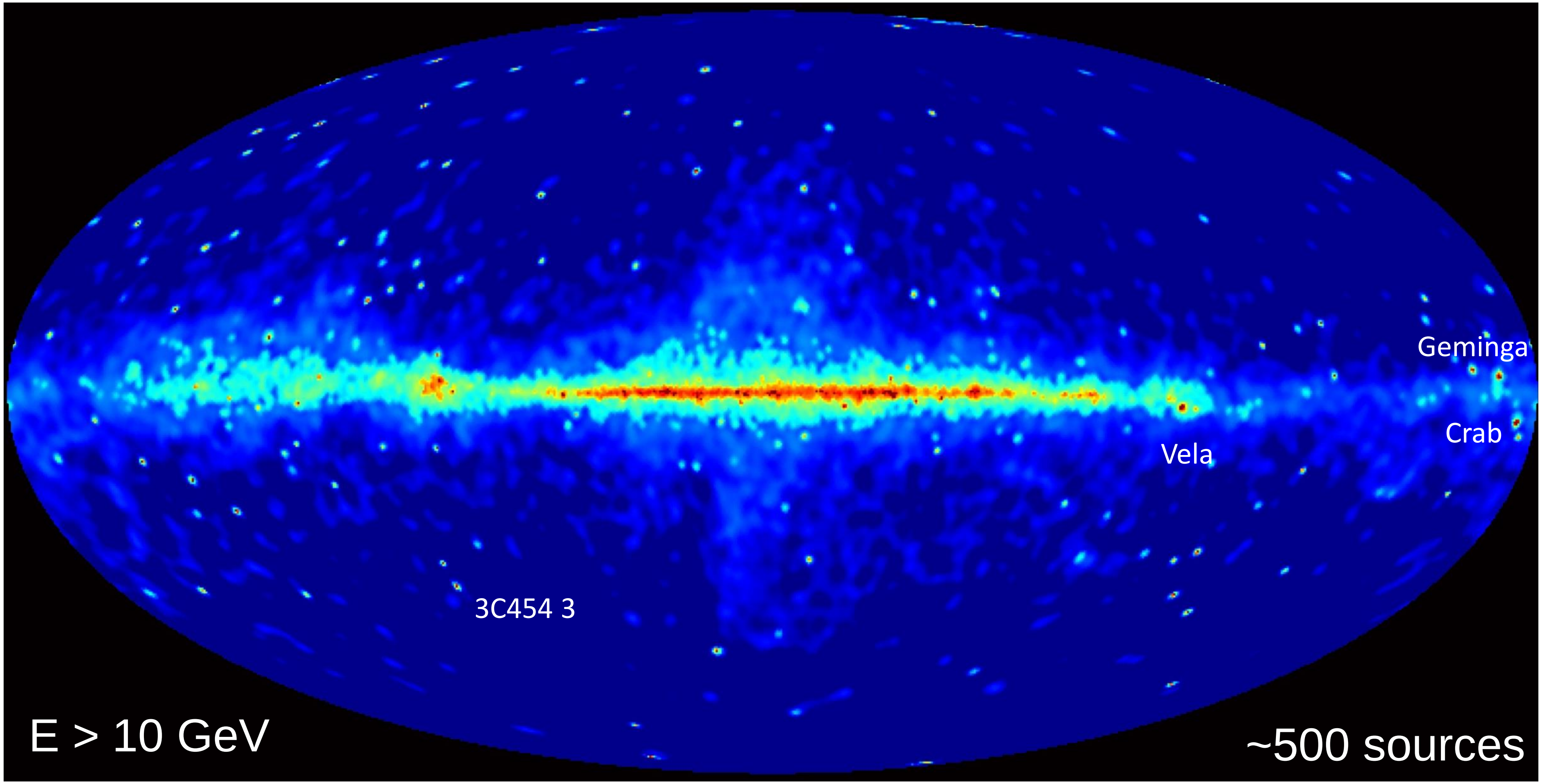




FERMI – results after 3 years

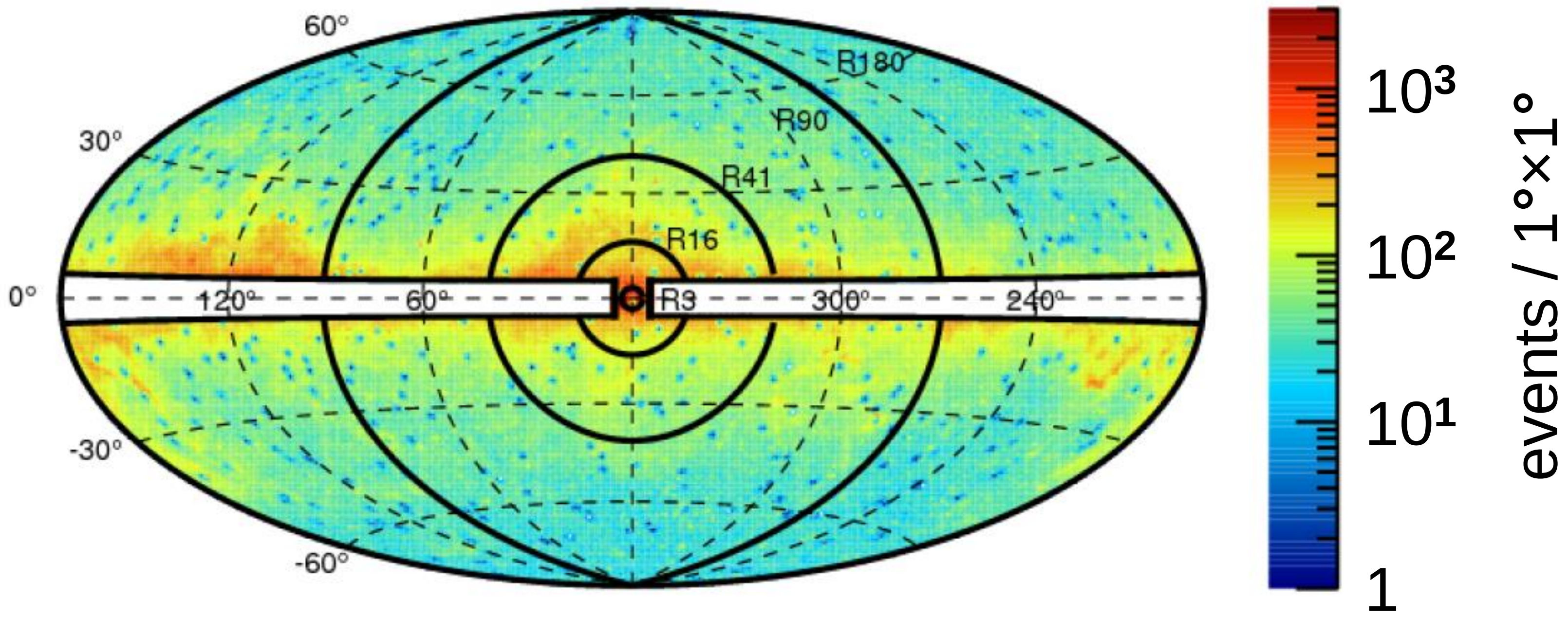
Karlsruhe Institute of Technology

- 3-year data taking with FERMI – galactic chart in multi-GeV gammas
  energy spectrum shows no clear hints for DM annihilation



Fermi – results after 3.7 years

- Data taking from 8/2008 – 4/2012: gamma map from 2.6 – 541 GeV
  - more than 500 point sources eliminated from dat

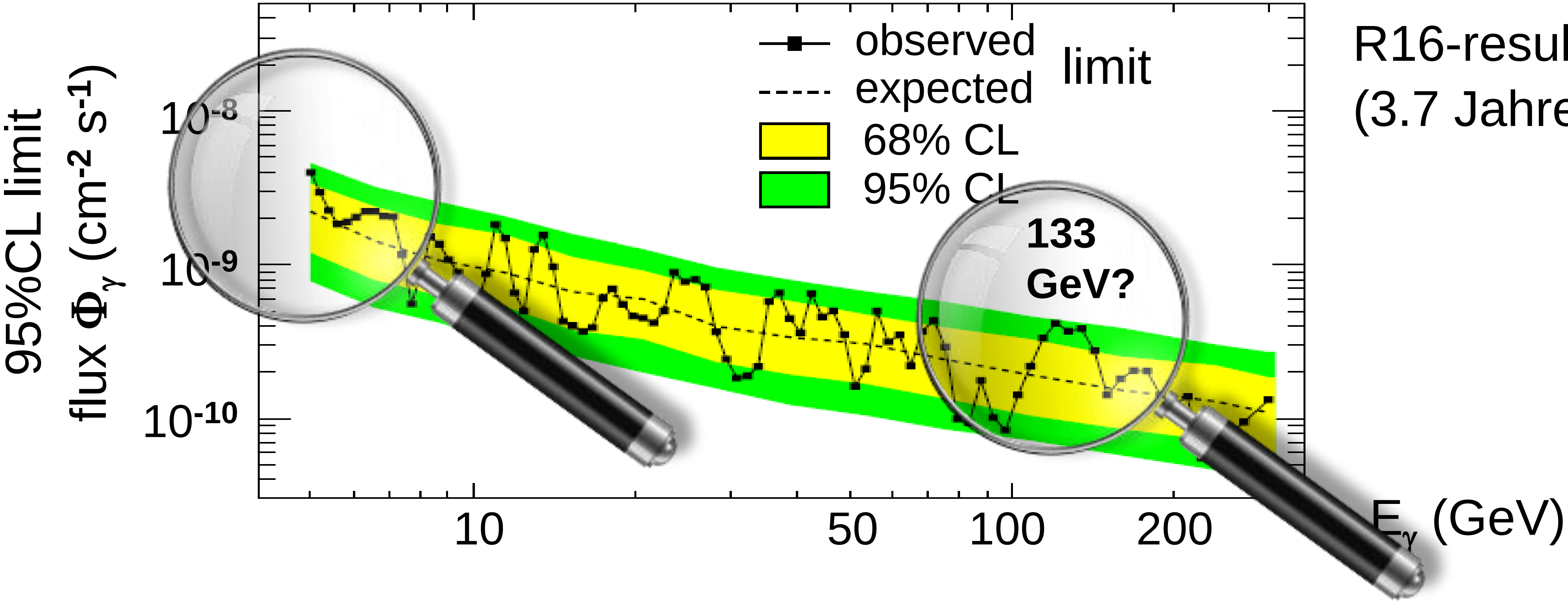


- definition of ROIs around galactic centre
  R3 - 3° / R16 - 6° / R41 - 41°
- Likelihood analyses to search for line sources

Fermi – results after 3.7 years

- Data taking from 8/2008 – 4/2012: gamma map from 2.6 – 541 GeV

  - **no significant γ-line** in overall dat-set ☹

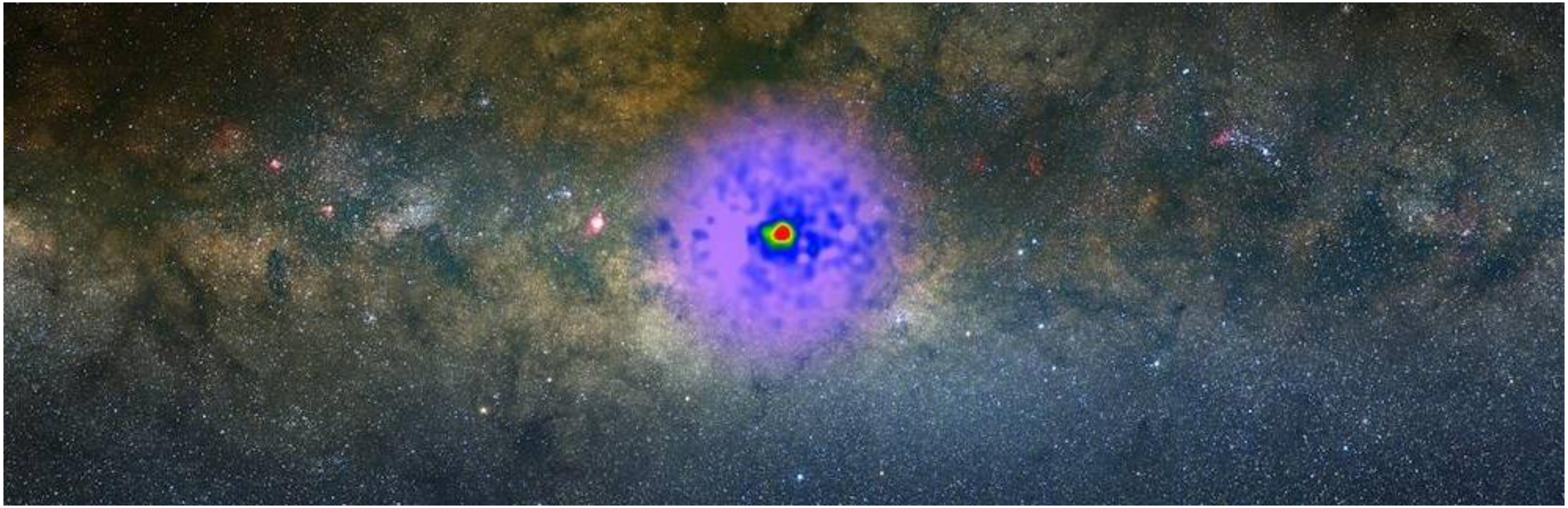


R16-results
(3.7 Jahre)

- weak hints for γ-line at **E_γ = 133 GeV** (most prominent in R3) ☺
- signal also observed (but weaker) in direction of earth horizon! ☹
- actual significance 1.5 – 3.2 σ (depends on interval & model) 😐

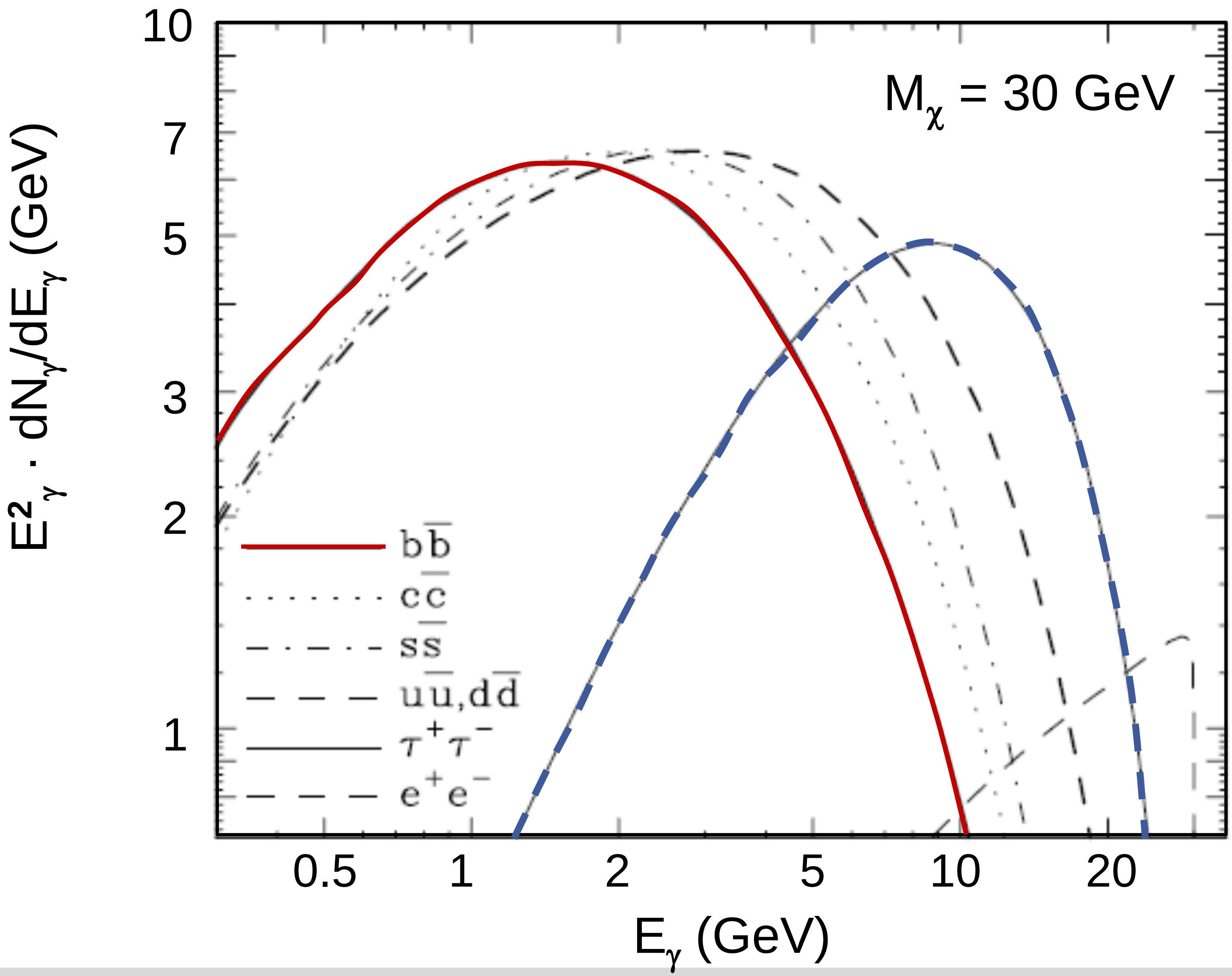
Fermi – 2014 update on results

- **excess of γ-events** in energy range 1-3 GeV, extending up to 1.5 kpc from GC
  - interpreted as decay of WIMP with M = 31-40 GeV → bb quarks
  (the „hooperon“: lead author Dan Hooper, Fermilab)



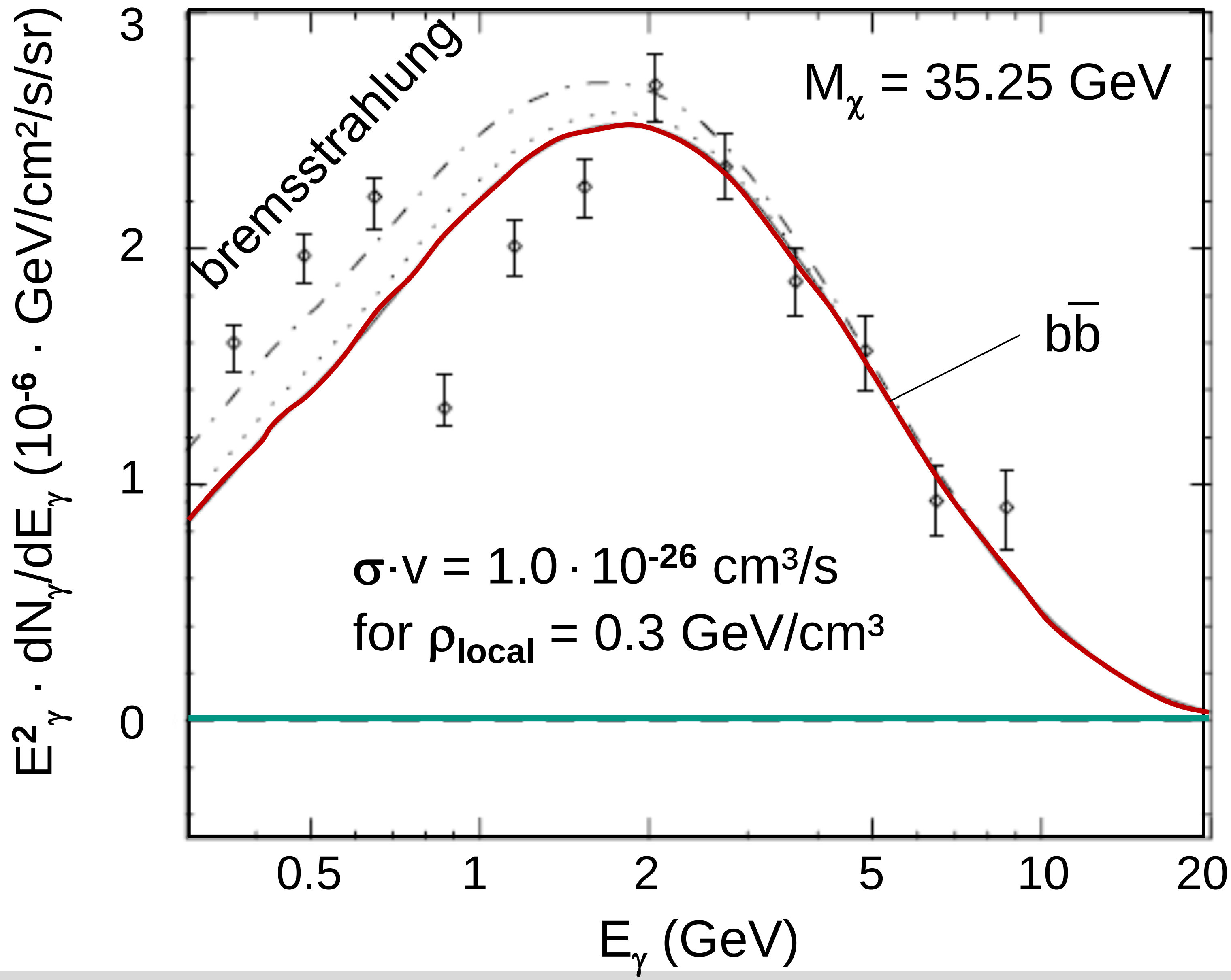
Fermi – 2014 update on results

- modelling of gamma spectra from 30 GeV WIMP-decays: $b\bar{b}$-channel?



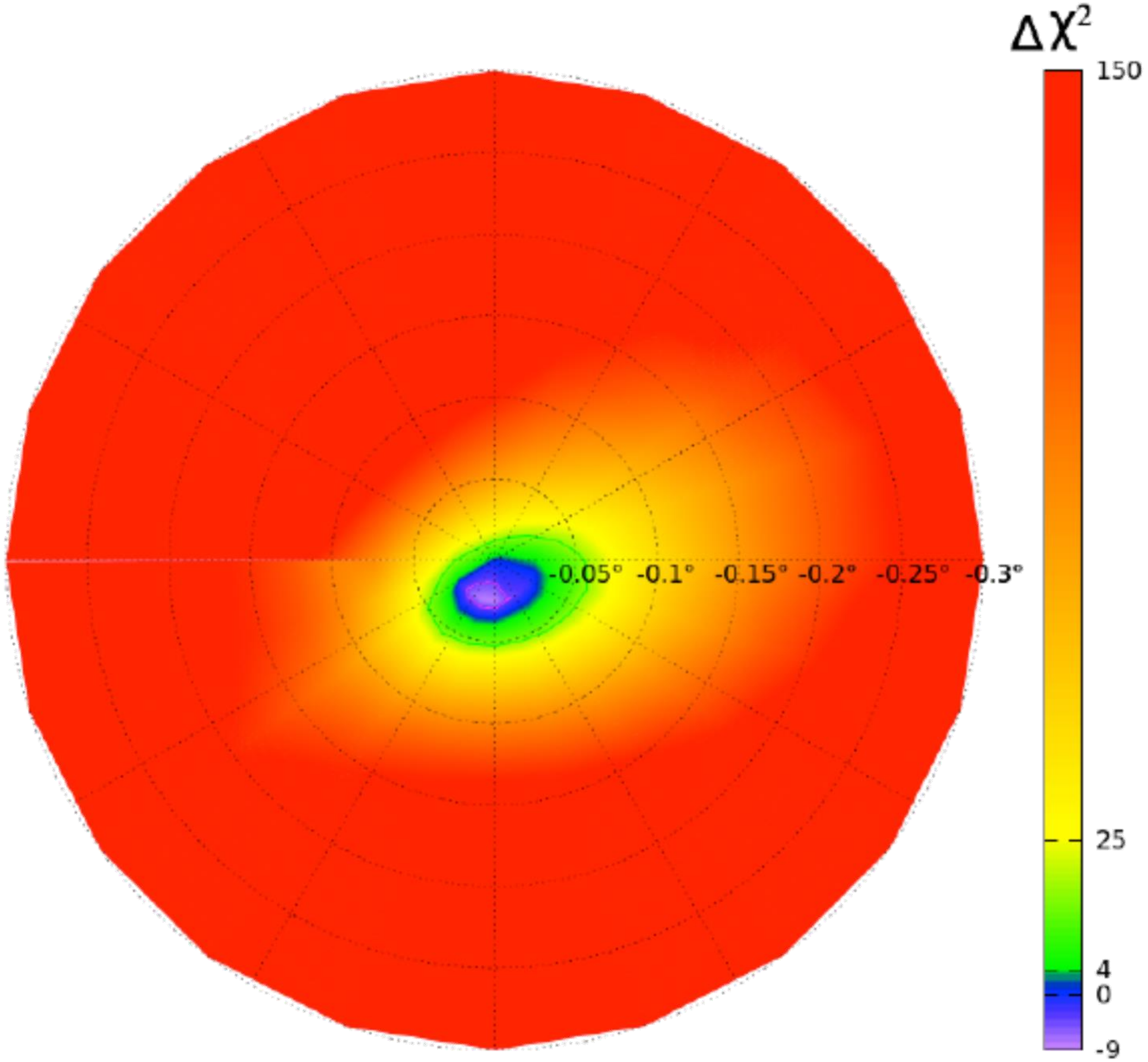
Fermi – 2014 update on results

- Fit to FERMI data by Hooper et al. for galactic NFW profile: **a hooperon?**



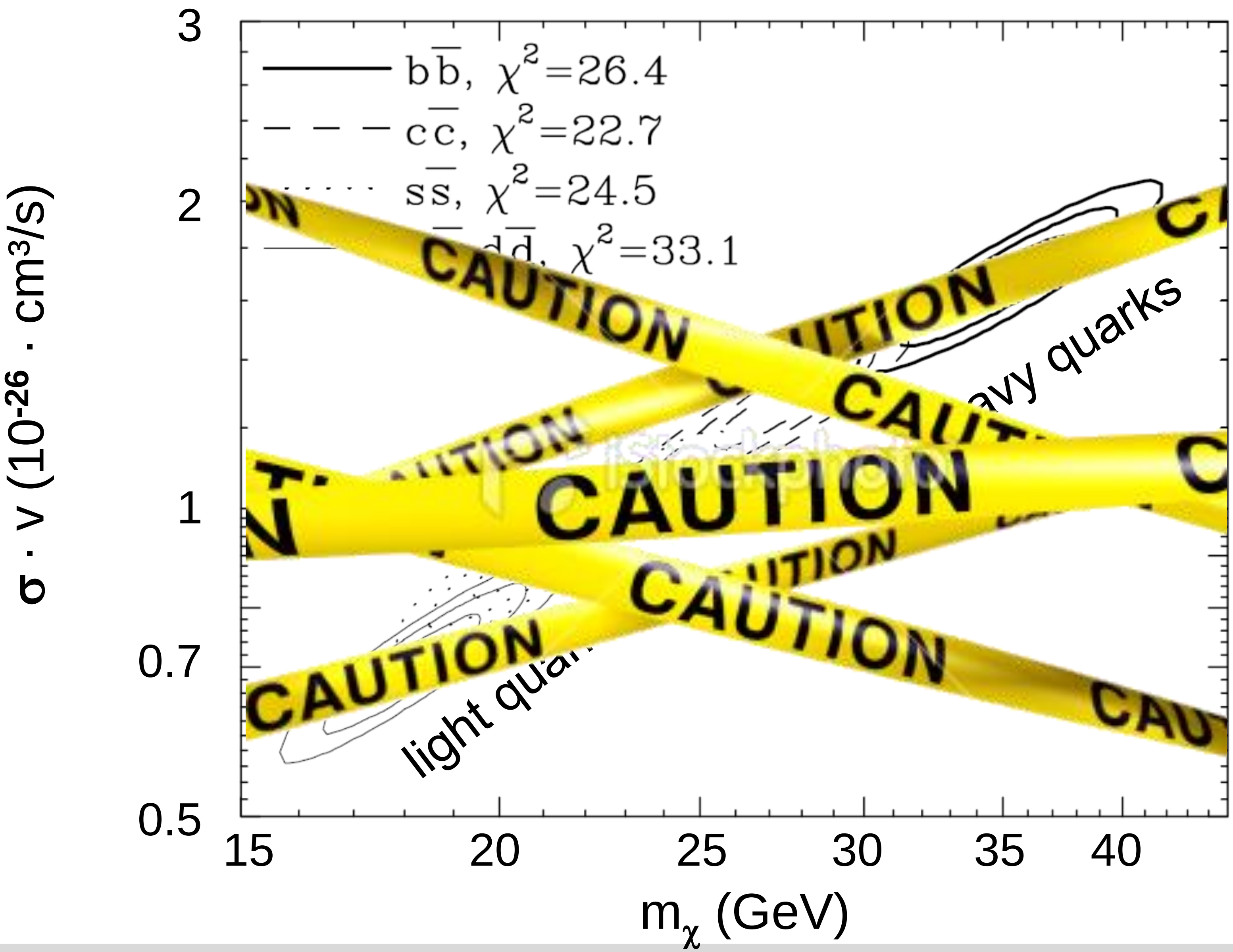
Fermi – 2014 update on results

- Fit to FERMI data by Hooper et al. for galactic NFW profile: centered on GC



Fermi – 2014 update on results

- Fit to FERMI data by Hooper et al. for galactic NFW profile: the parameters



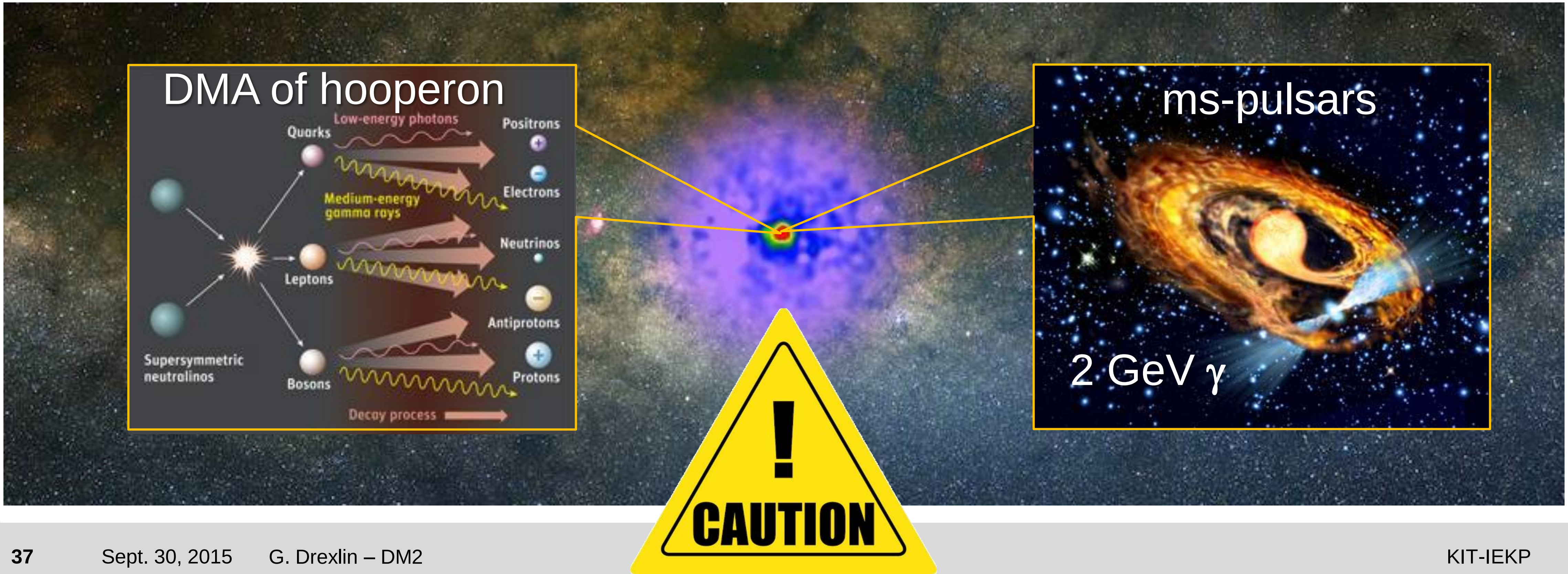
Fermi – 2014/15 update on results

Karlsruhe Institute of Technology

- **excess of γ-events** in energy range 1-3 GeV, extending up to 1.5 kpc from GC
  - could also stem from much more massive (200 GeV) neutralinos in MSSM
  - annihilation cross section $\sigma v = (1.4 – 2.0) \cdot 10^{-26}\ cm^3\ s^{-1}$
  - **conventional scenario** based on unresolved population of **ms-pulsars**

    (Weniger et al, arxiv:1506.05104)

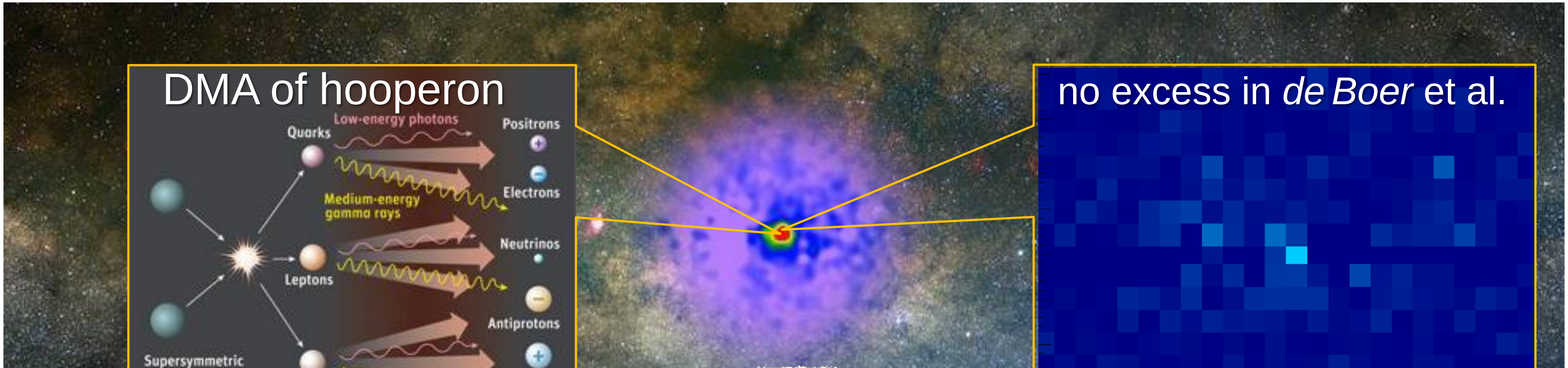
    ms-pulsars emit γ´s with E_γ ~ 2 GeV, distinct sources give a better fit

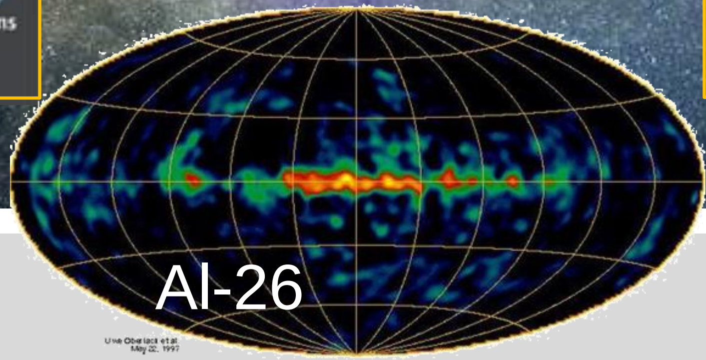


Fermi – 2015 results from KIT

BREAKING NEWS

- **excess of γ-events** in energy range 1-3 GeV disappears by proper modelling
  - γ-excess in galactic plane correlates with regions of Al-26 production (SNR)
  - scenario: **excess due to „old CRs“ in dense environment of GMCs**
  - hard component with $E^{-2.1}$ slope from „fresh CRs“ shows same morphology
  - conclusion by de Boer / Gebauer: „excess at GC disappears when GMC with high column density are correctly described“ arXiV:1509.0531 (17.9.15)

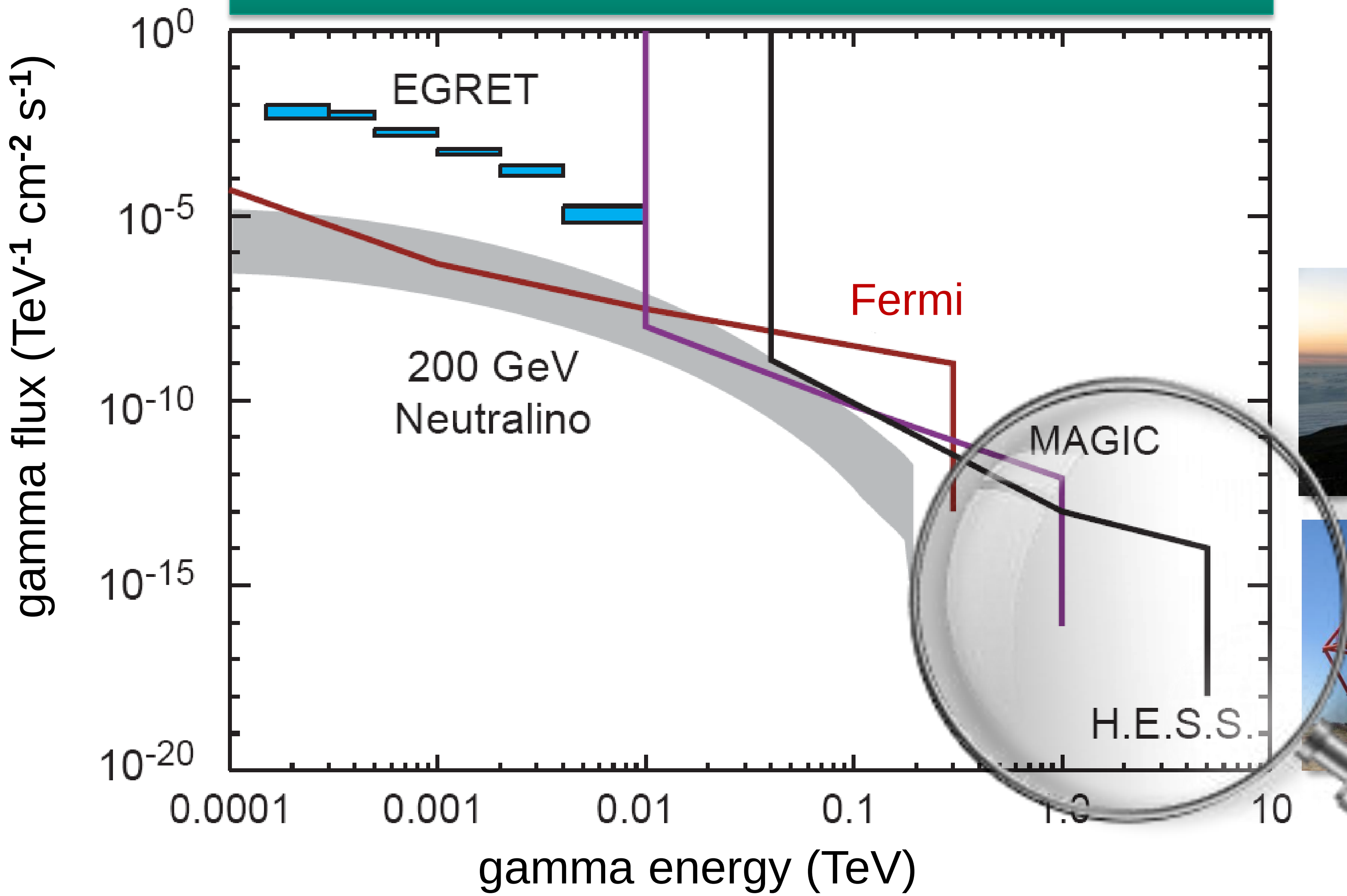




WIMP annihilation: IACTs & satellites

- IACT sensitivity is ideal for high γ-energies in the multi-TeV-region

MeV/GeV: satellites ⇔ TeV: IACTs



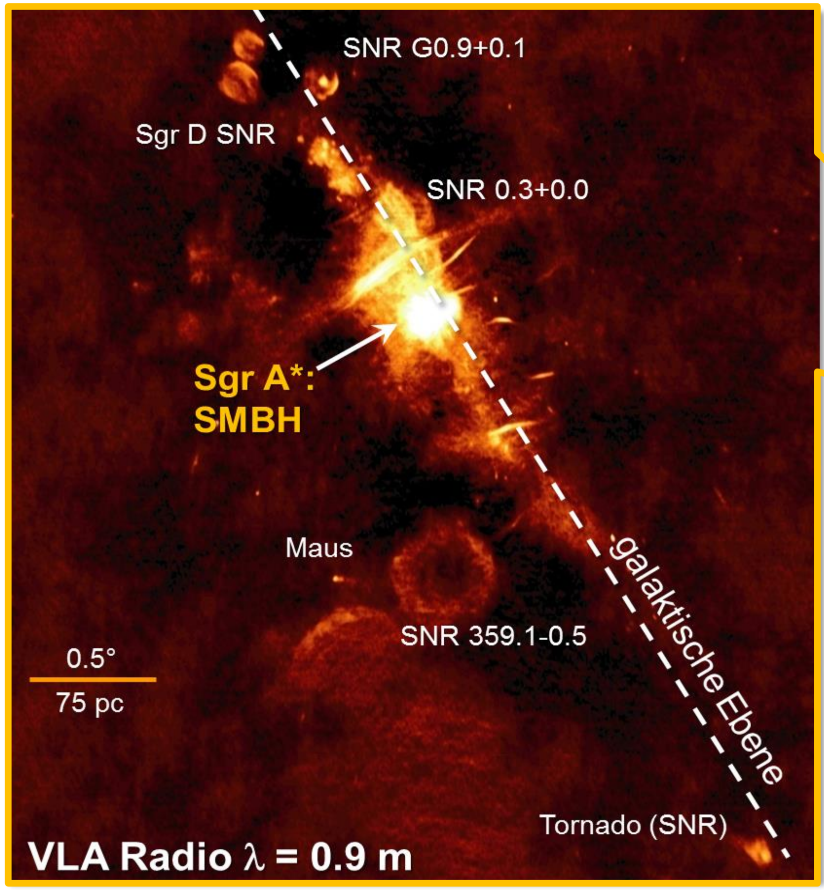
atmospheric Cherenkov telescopes

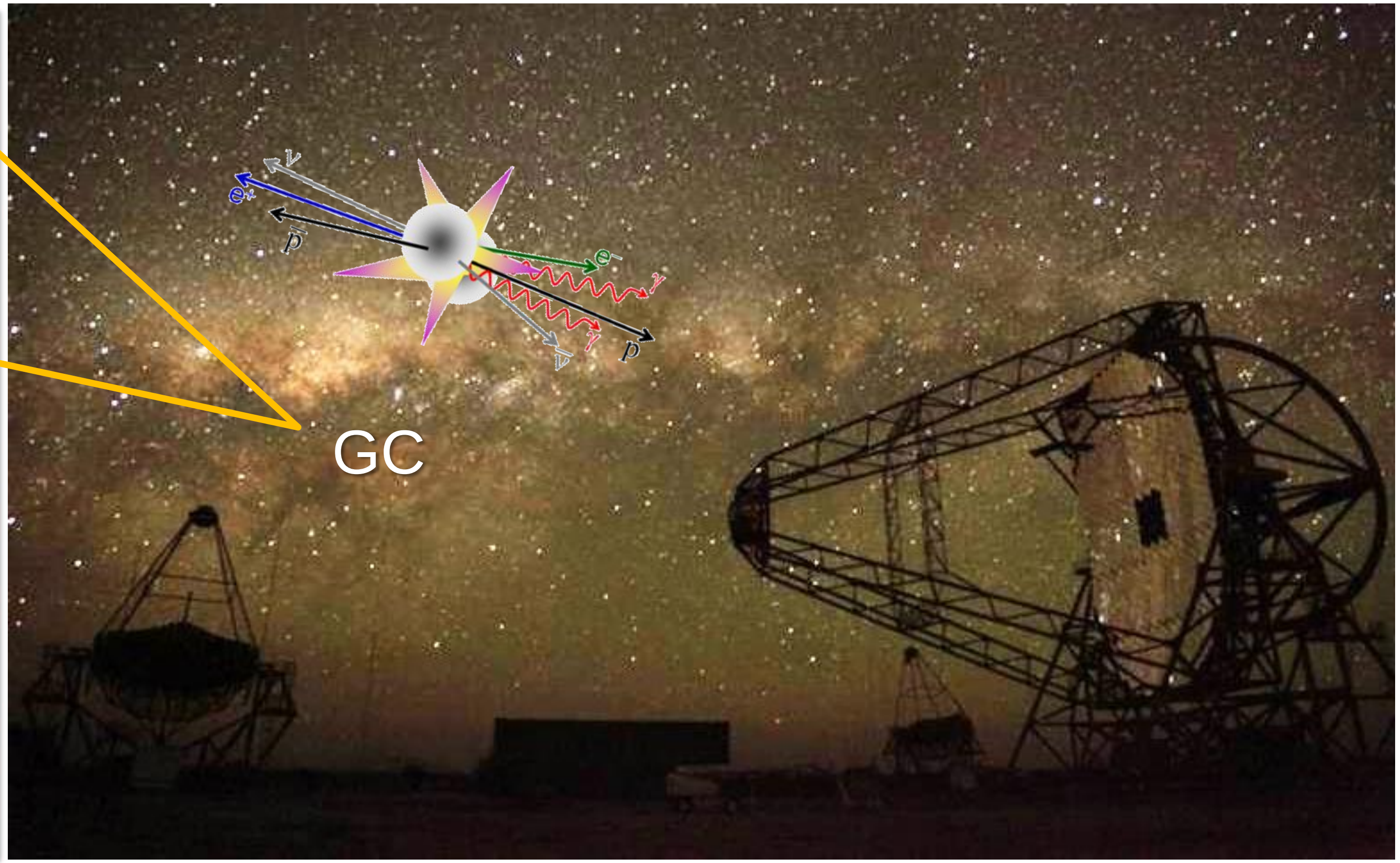
- **ground-based gamma astronomy at TeV-scale with IACTs:**

  Imaging Atmospheric Cherenkov Telescope

  search for TeV-gammas from DMA at galactic centre (GC)

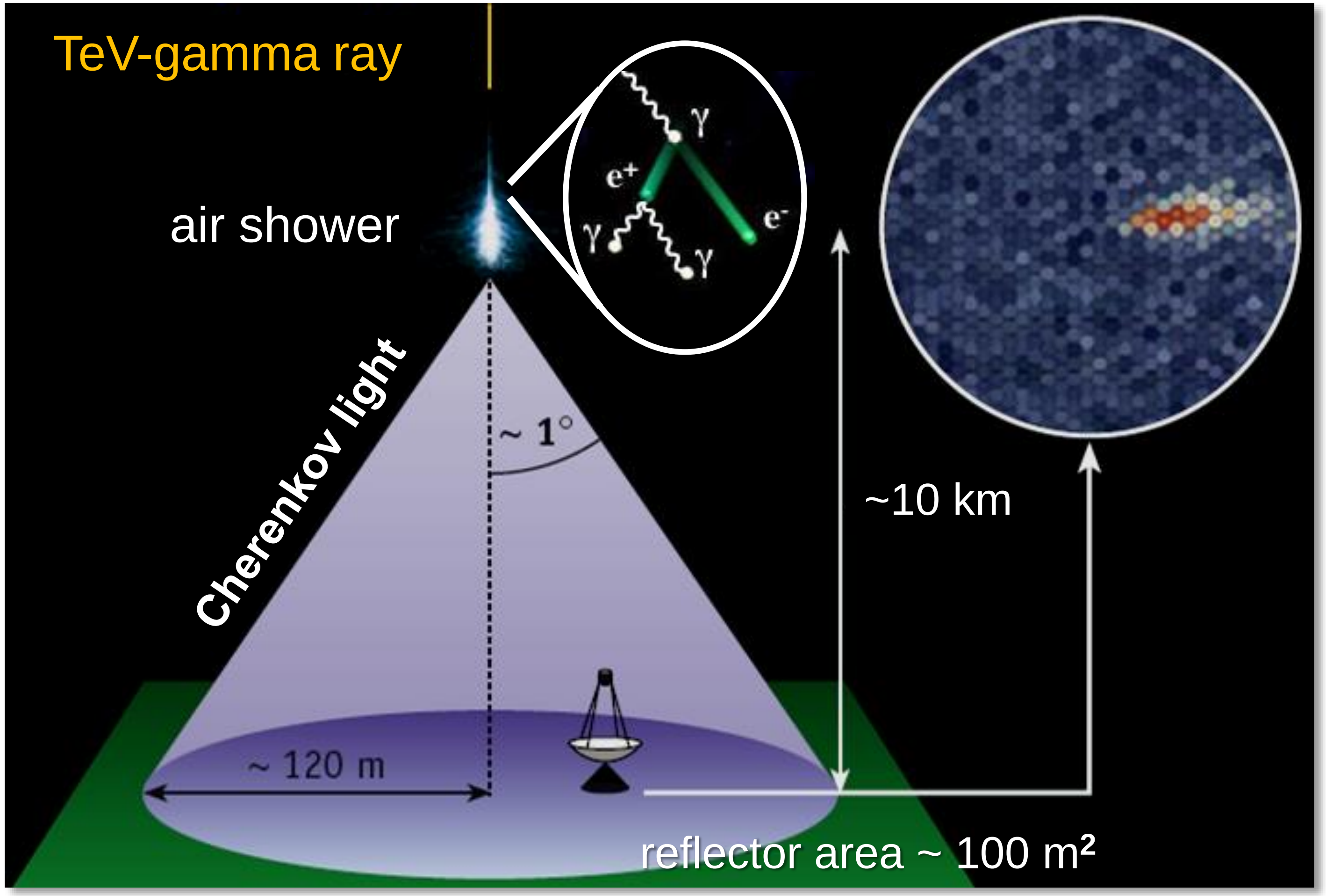
  - range of TeV-γ´s: ~ 100 Mpc - 1Gpc (o.k. for χ^0-annihilation)
  - telescope operation: only in clear moonless nights (~ 1000 h / year)

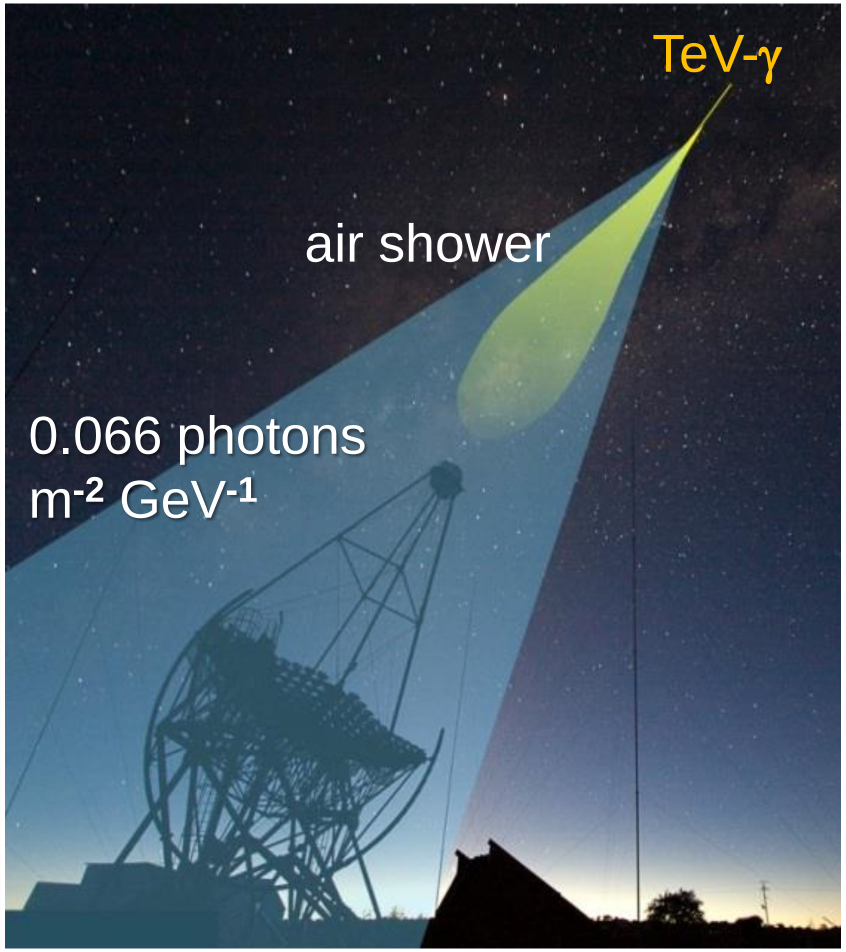




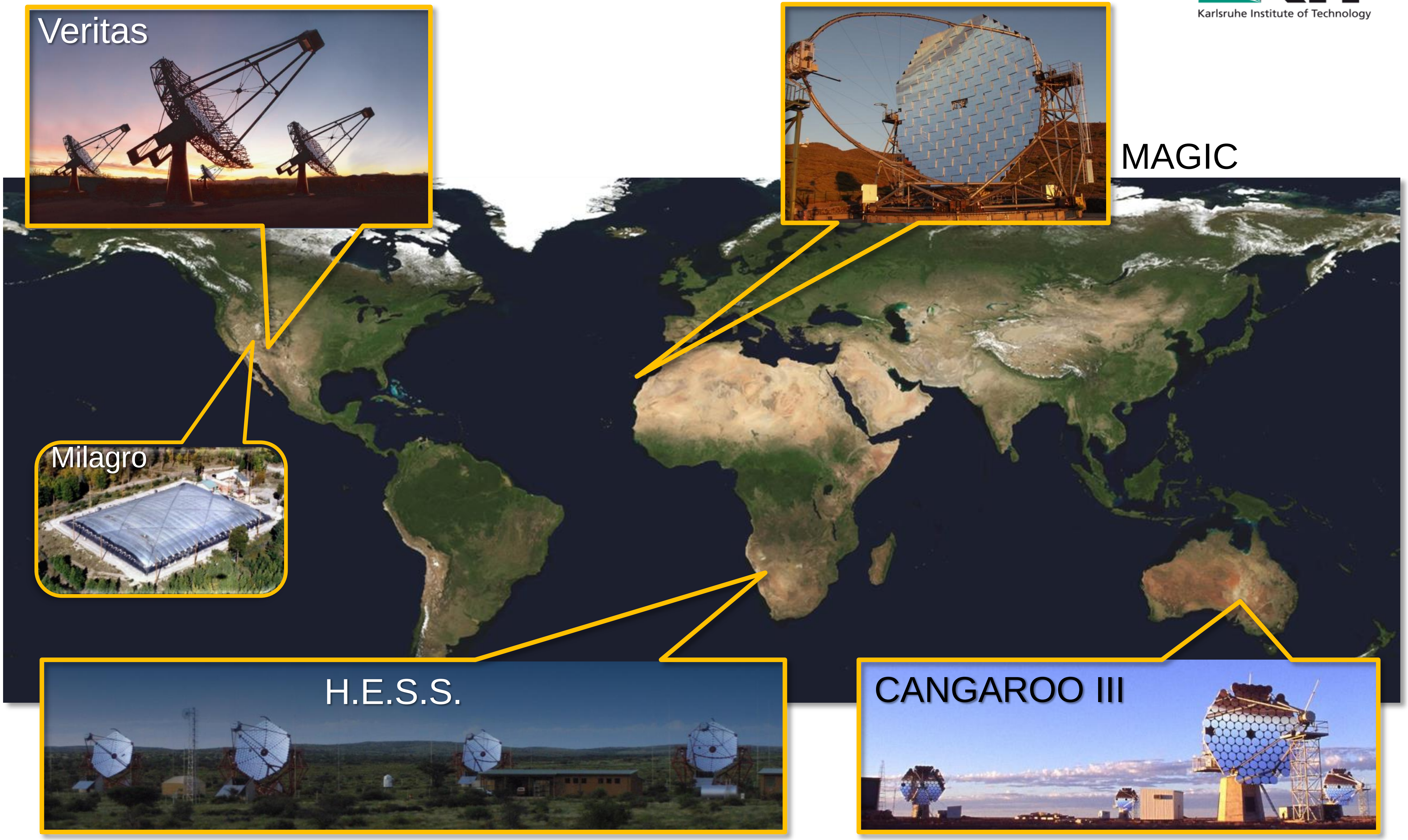
atmospheric Cherenkov telescopes

- **Ground-based gamma astronomy at TeV-scale with IACTs:**
  - TeV gammas initiate airshower cascades & generate charged particles
  - **cascade process**: $\gamma \rightarrow e^+e^-$ (pair production) $\rightarrow \gamma$ (bremsstrahlung) $\rightarrow$ …
  - relativistic e^+e^- emit Cherenkov-photons into a narrow cone (~1°)

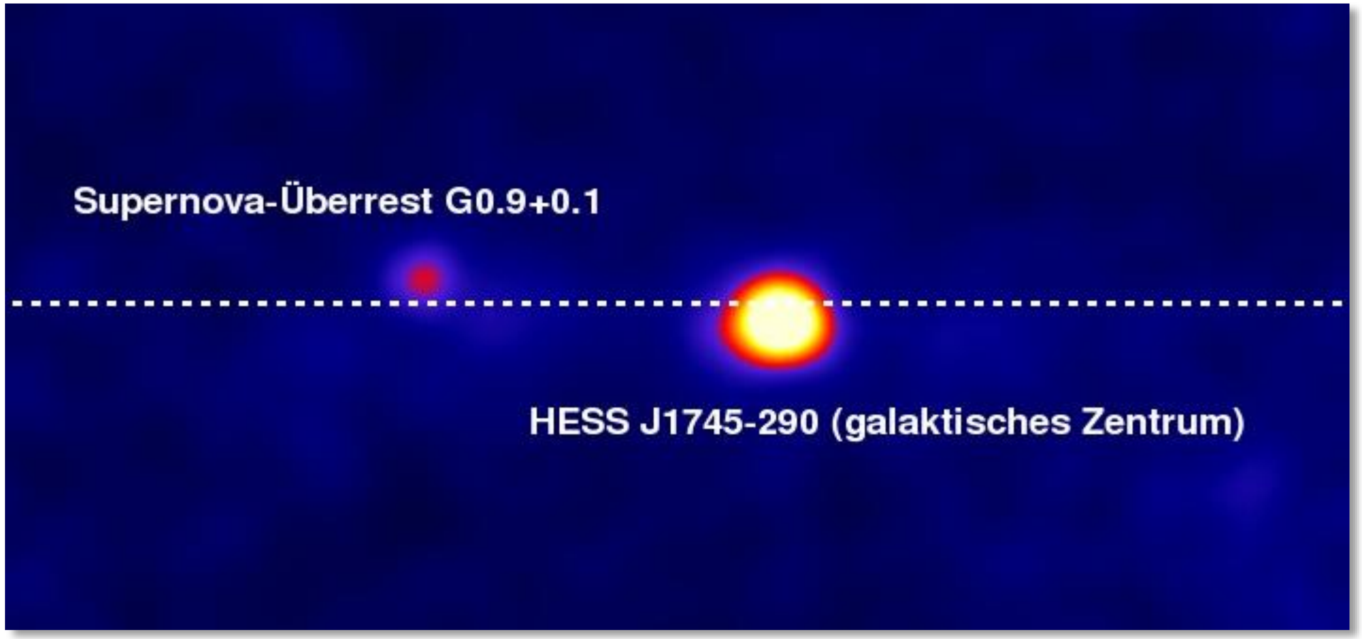


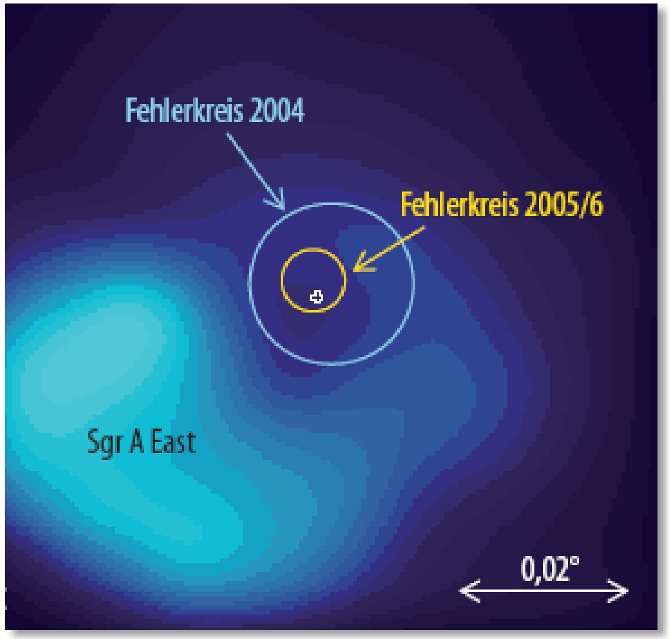


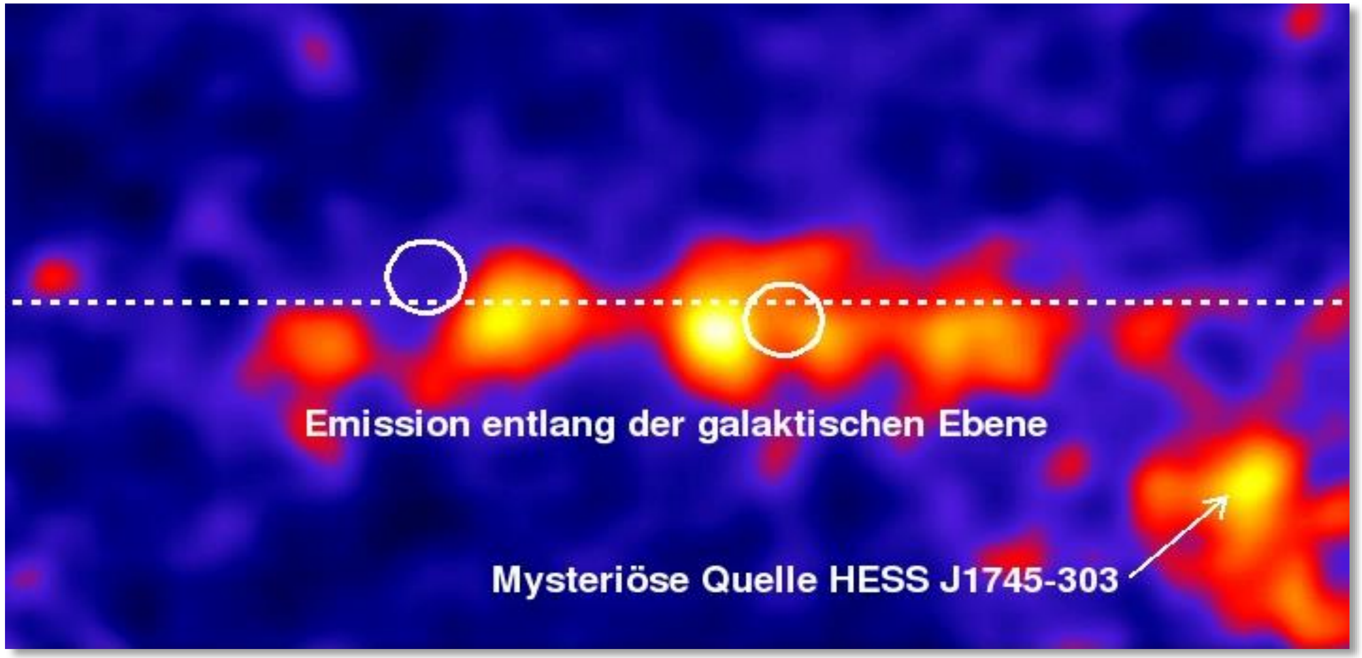
TeV – Gamma-observatories



H.E.S.S. – galactic centre in TeV gammas







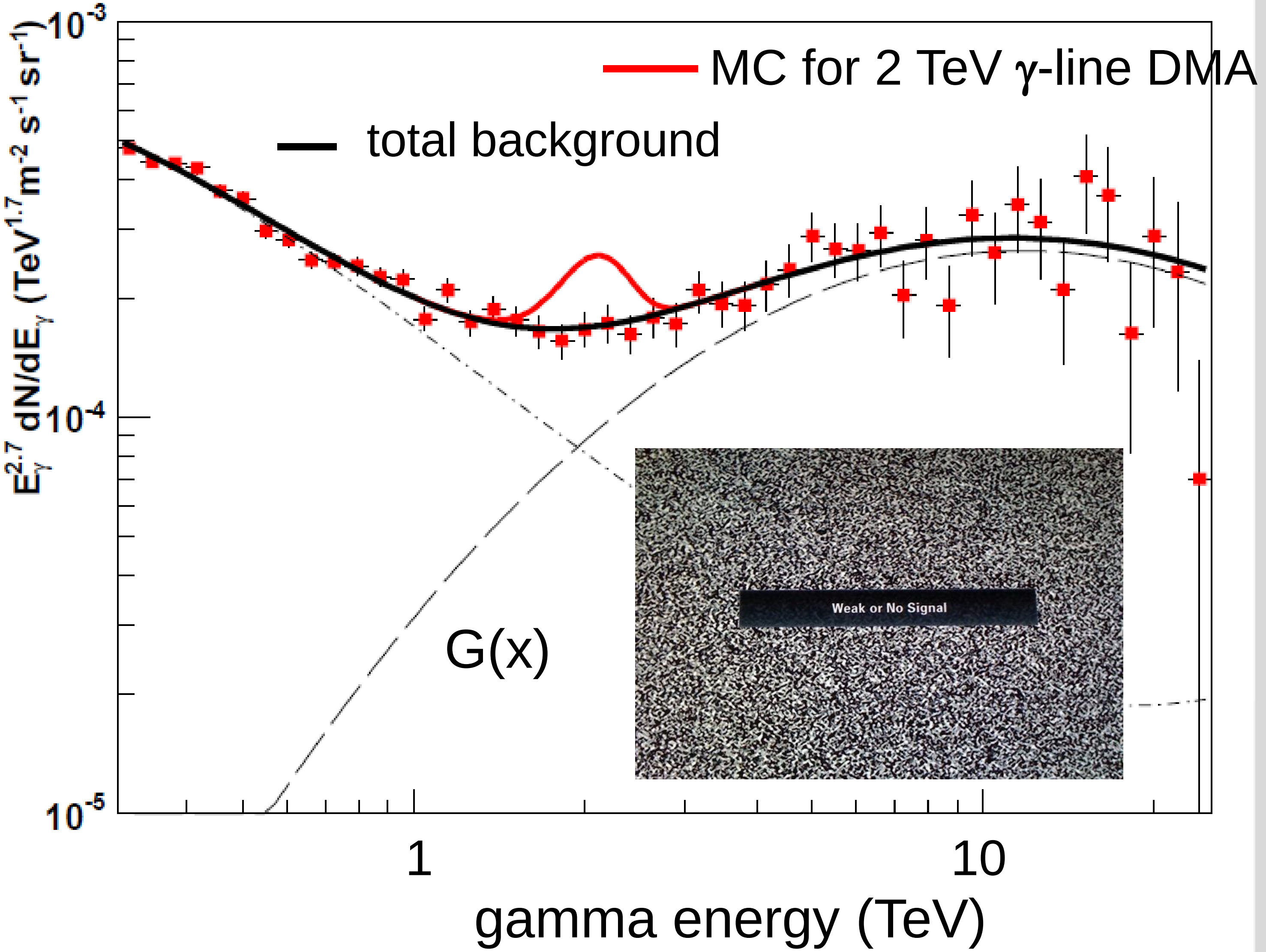
- HESS observes a clear **TeV γ–signal** from the galactic centre Sgr A*
- after subtraction of this source extended regions of TeV-γ-emission are visible: interactions of CR protons with giant molecular clouds

H.E.S.S. – galactic centre in TeV light

- search for mono-energetic DMA-line from 0.5 – 25 TeV in central 1° around galactic centre (avoiding galactic plane) over t = 112 h

- in inner regions @GC increased γ-rate due to HE cosmic rays
  ↳ supernova explosions
  ↳ activity of central SMBH

- phenomenological description G(x), P(x) of γ-energy spectrum
  ↳ **no signal**

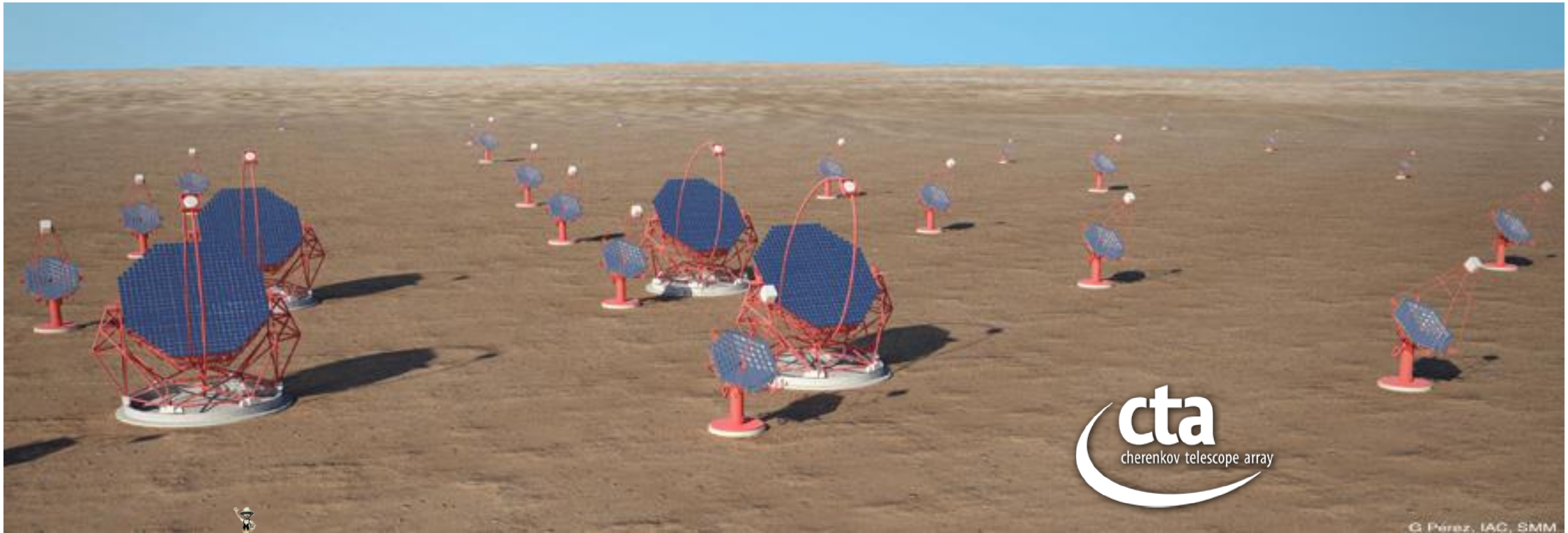


CTA observatory

CTA : world-wide flagship project of TeV gamma astronomy

Cherenkov Telescope Array CTA: (10 GeV – 100 TeV)

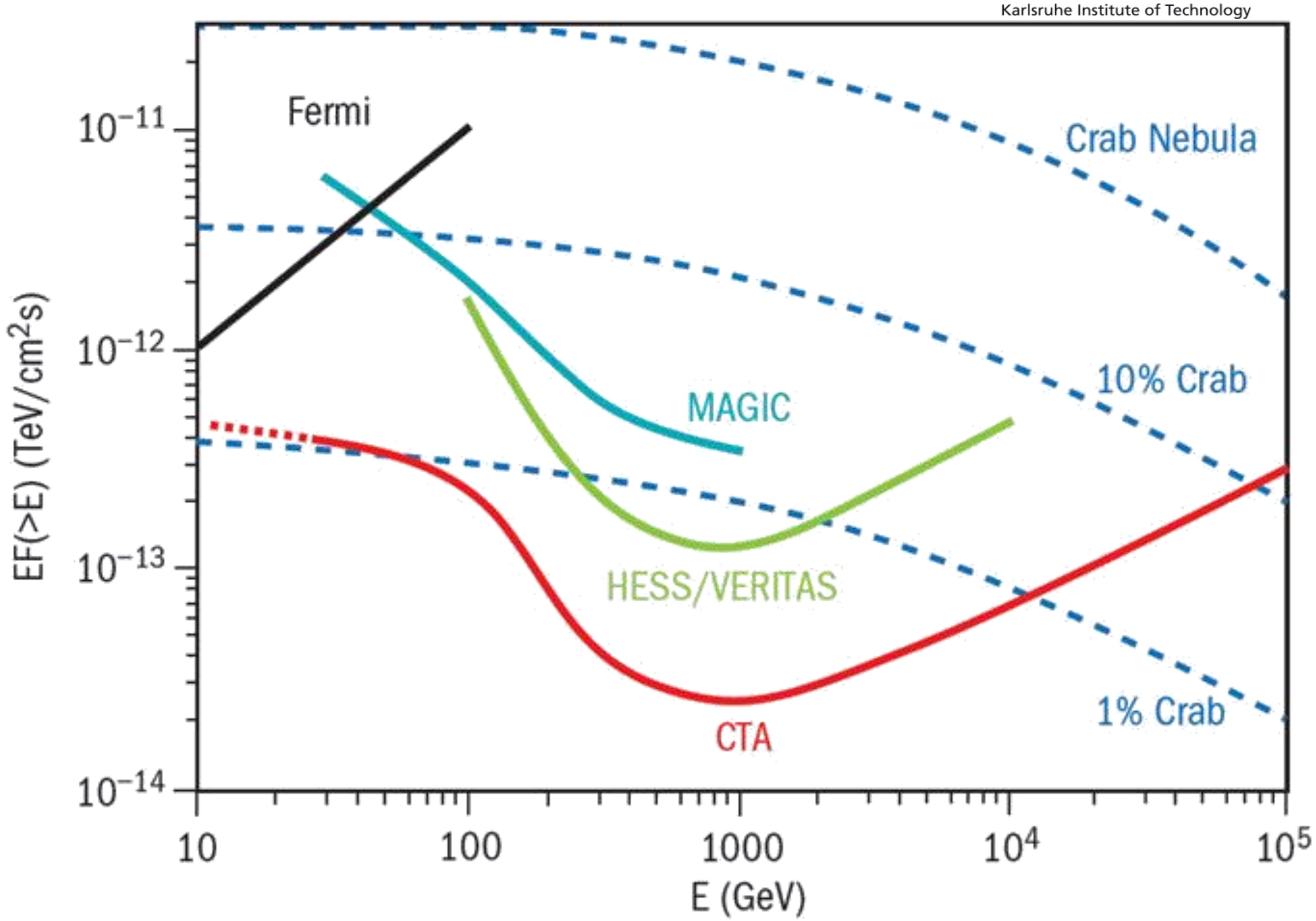
- new observatory: 1 × southern, 1 × northern hemisphere
- more than 100 Cherenkov telescopes of different size
- commissioning and first data-taking ~ 2020, will look for DMA

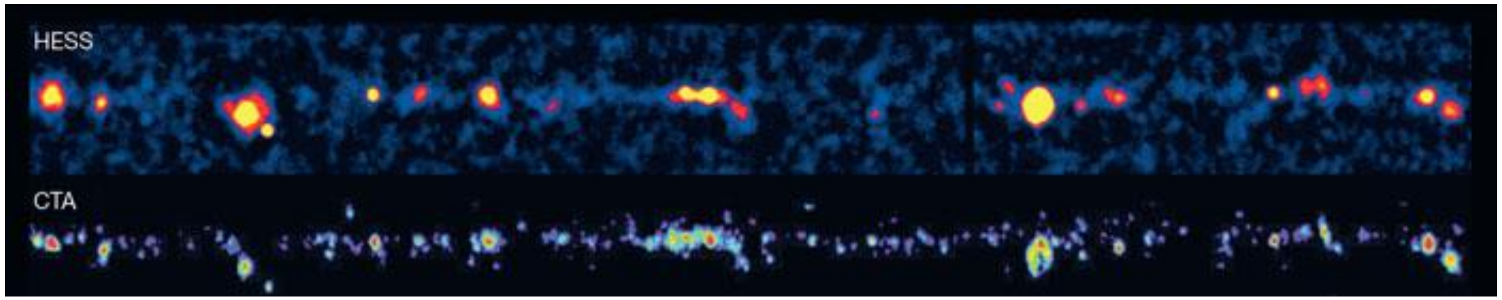


CTA observatory

- search for DMA in specific target regions:
  - galactic centre
  - galactic halo
  - **dwarf spheroidal galaxies**
  - diffuse emission

  focus on high energies ~ 1-10 TeV





CTA observatory

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