Karlsruhe Institute of Technology

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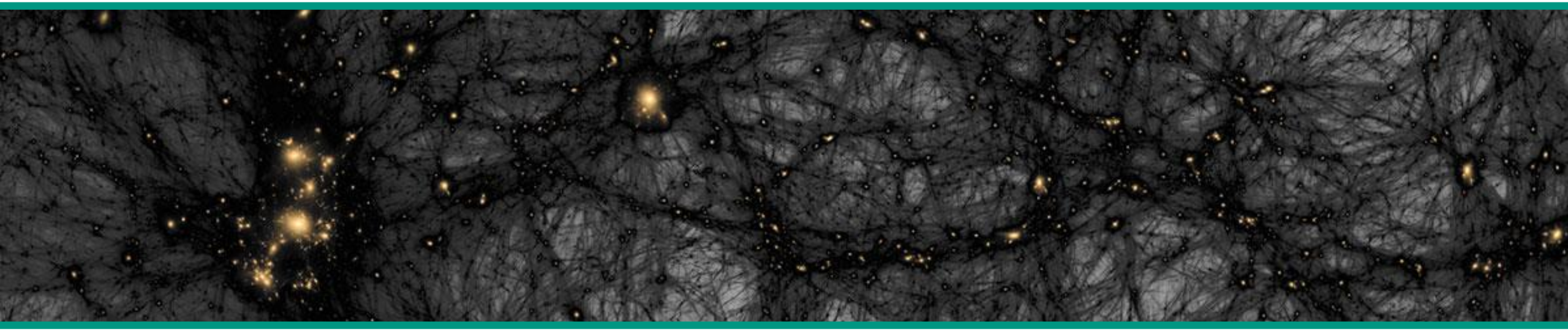
Astroparticle physics I – Dark Matter

WS22/23 Lecture 14 Jan. 12, 2023



A (left-over) Christmas tree made from CR tracks

- **A happy New Year 2023**

from overlapping tracks of cosmics & α –decay chain events recorded with standard iphone6 sensors

Recap of Lecture 13

- **Dark Matter: supersymmetry & how to build a successful CDM candidate**

  - we can order DM candidates along their mass m & cross section σ_{tot}

  - $SUSY$: connects **fermions** ⇔ **bosons**, important: R-parity $R_P = +1, -1$

  - LSP of $SUSY$ is stable over cosmological times, expect TeV –scale mass

  - neutralino = mass eigenstate, a superposition of flavour states $\tilde{\gamma}^0$ $\tilde{Z}^0$ $\tilde{H}_u^0$ $\tilde{H}_d^0$

  - Feyman diagrams for neutralinos: – production – annihilation – scattering

  - searches for $SUSY$ & neutralinos at LHC with $\sqrt{s} = 13.6\,TeV$

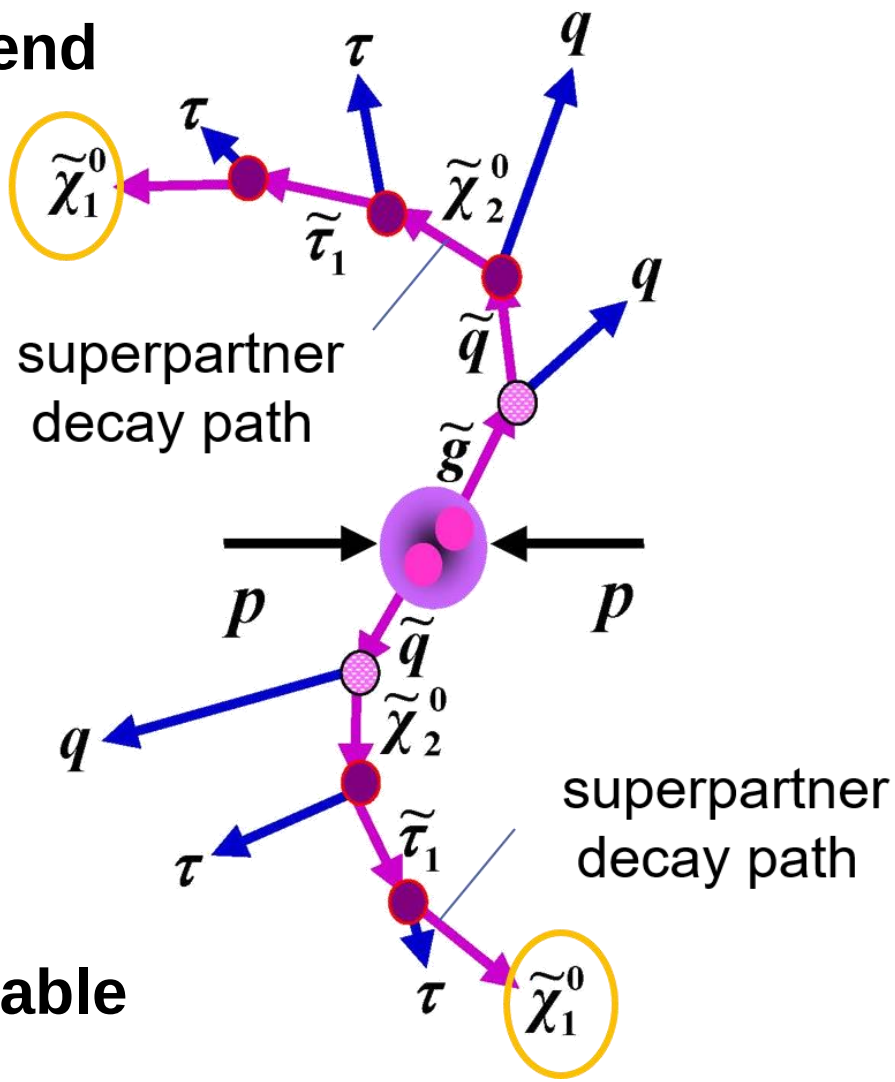
$SUSY$ –signatures at the LHC collider

- **neutralinos escape the detector region at the end of a superpartner decay chain**

  - production:
    pp –collision results in a **pair** of $SUSY$ – particles (due to **multiplicative** R-parity R_P)

  - decay cascade:
    very **massive** $SUSY$ – particles (such as gluinos produced in strong interactions) **decay**
    ⇨ emission of SM – particles also $(e^+, e^-, q, \ldots)$

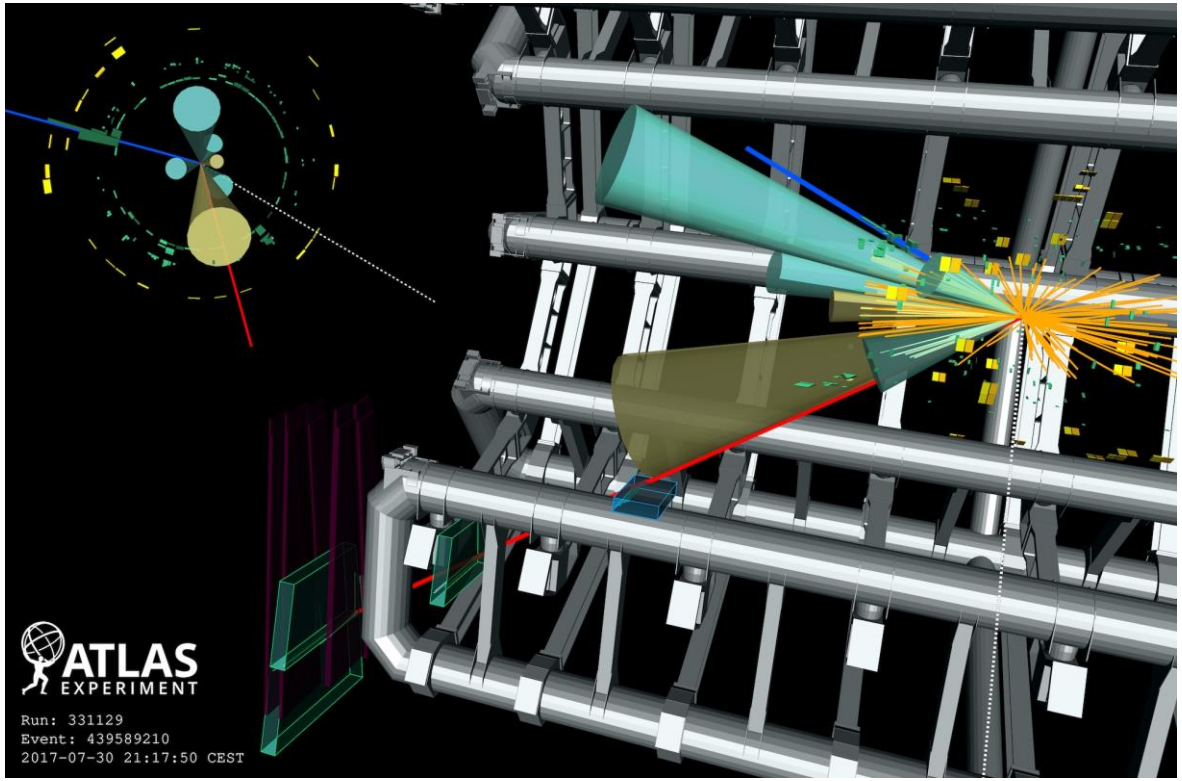
  - missing energy / momentum carried away:
    lightest $SUSY$ – particle (LSP = neutralino) is **stable**

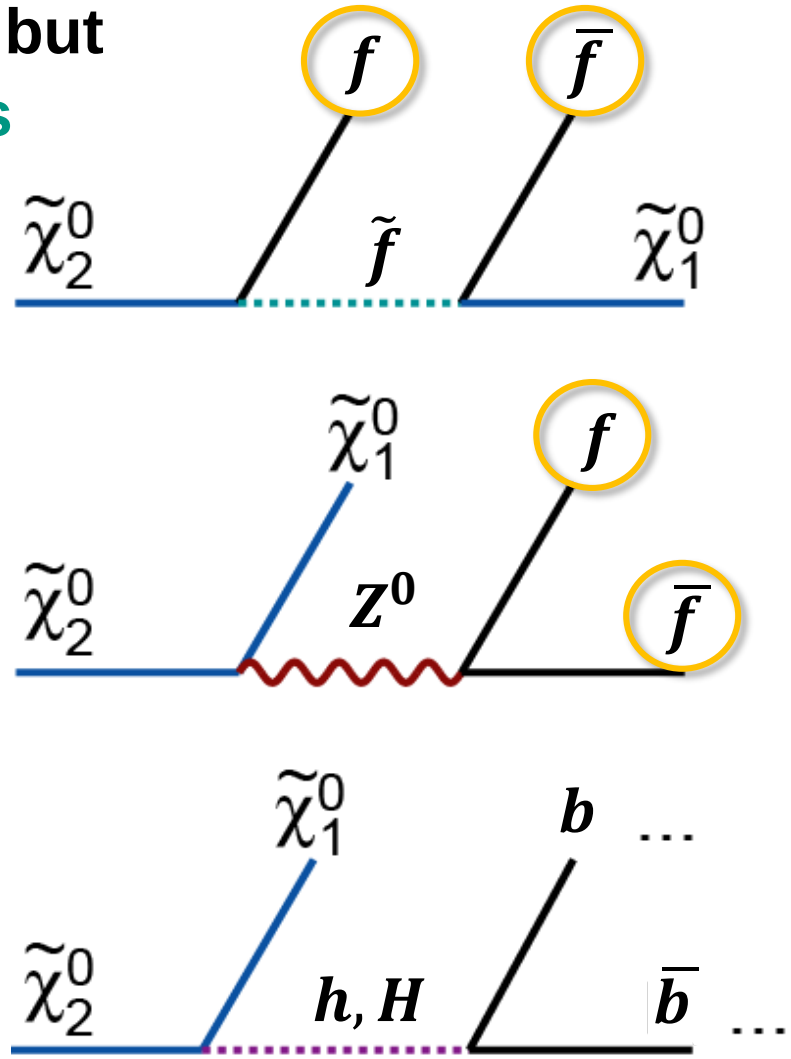


$SUSY$ –signatures at the LHC collider

- **Unstable neutralinos escape the vertex region but this is accompanied by emission of SM – pairs**

  - signature: lepton pairs, hadrons,…



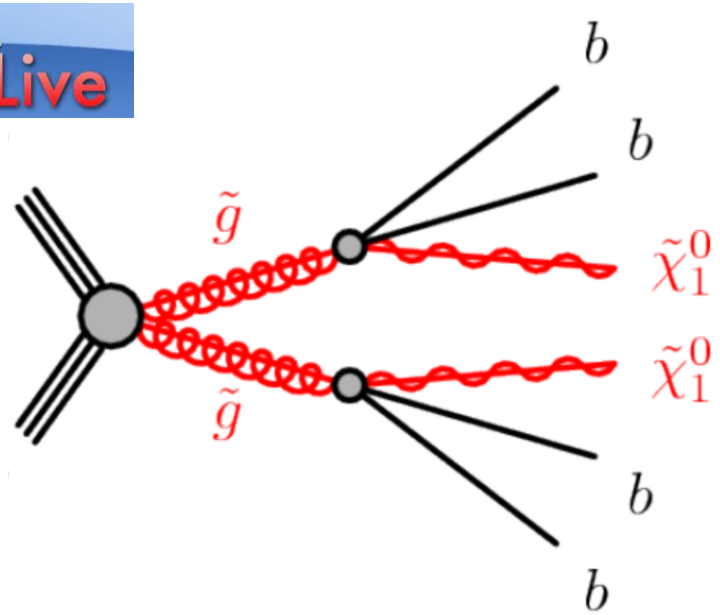


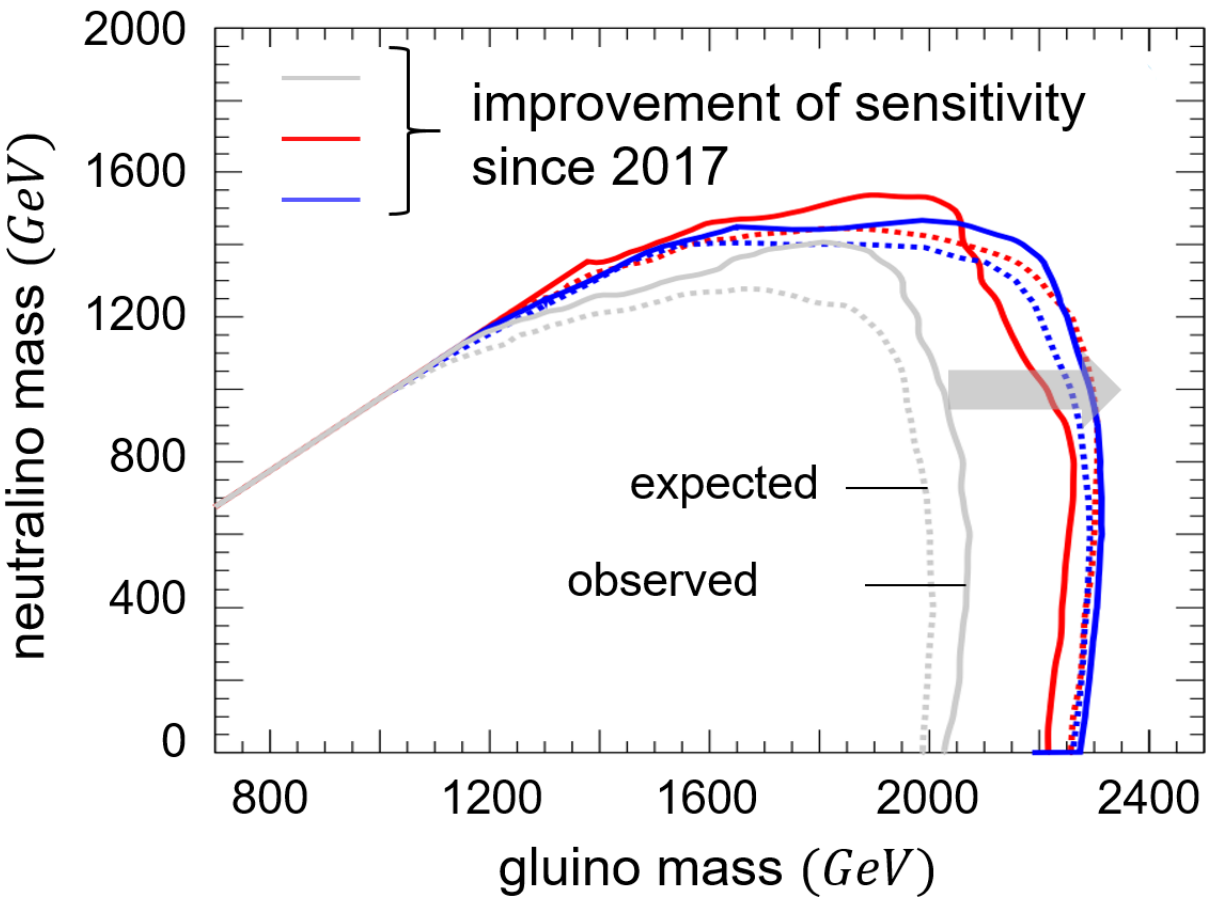
$SUSY$ –searches at CMS and ATLAS: no signal

- **Recent limits on the masses of $SUSY$ – particles: here $\tilde{g}$ vs. neutralino χ_1^0**

- no signal (yet), Run 3 data are currently being analysed

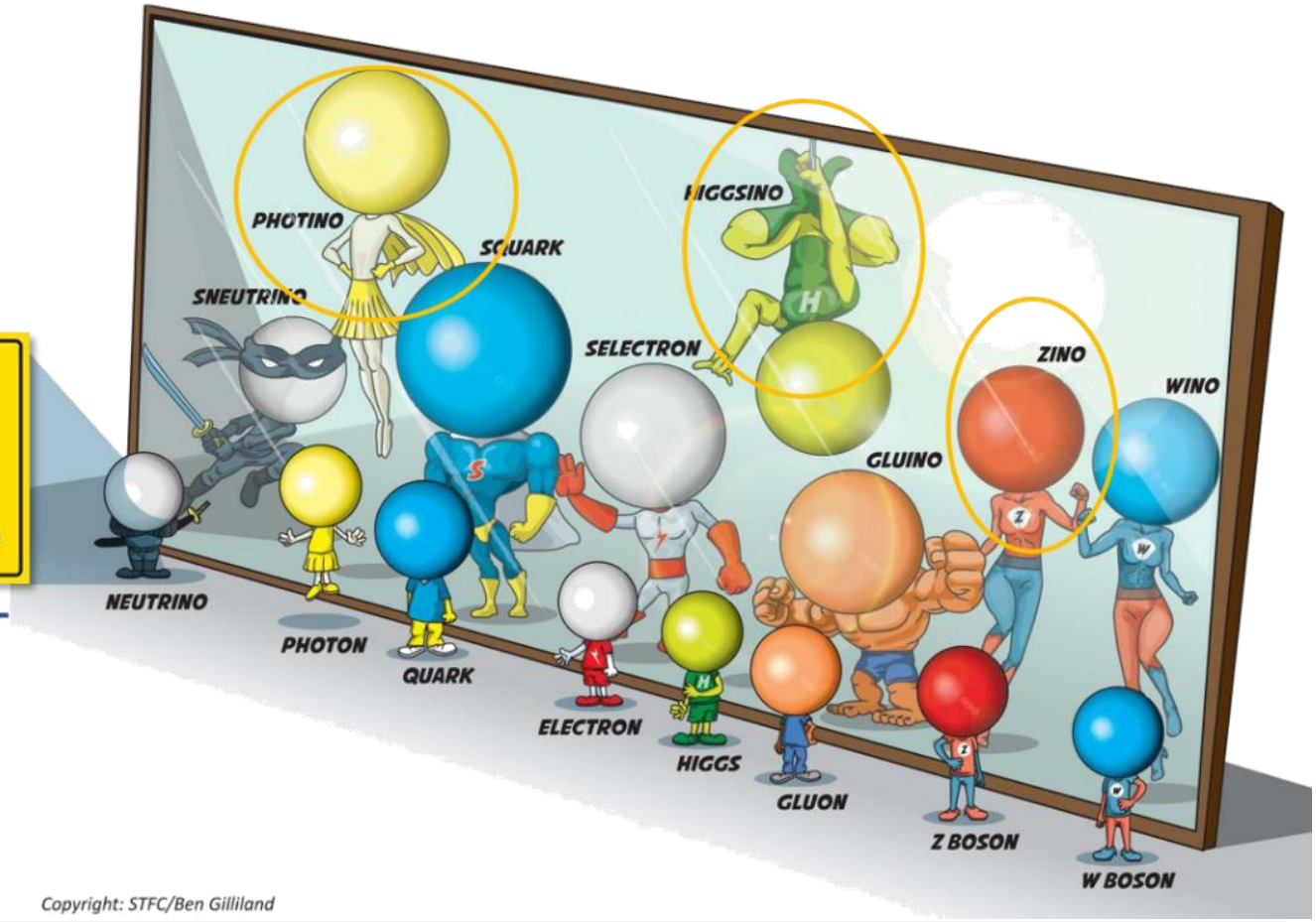
- PDG 2022: neutralino mass $> 1\ TeV$





$SUSY$ –searches at CMS and ATLAS: no signal

- **Recent limits on the masses of $SUSY$ – particles**



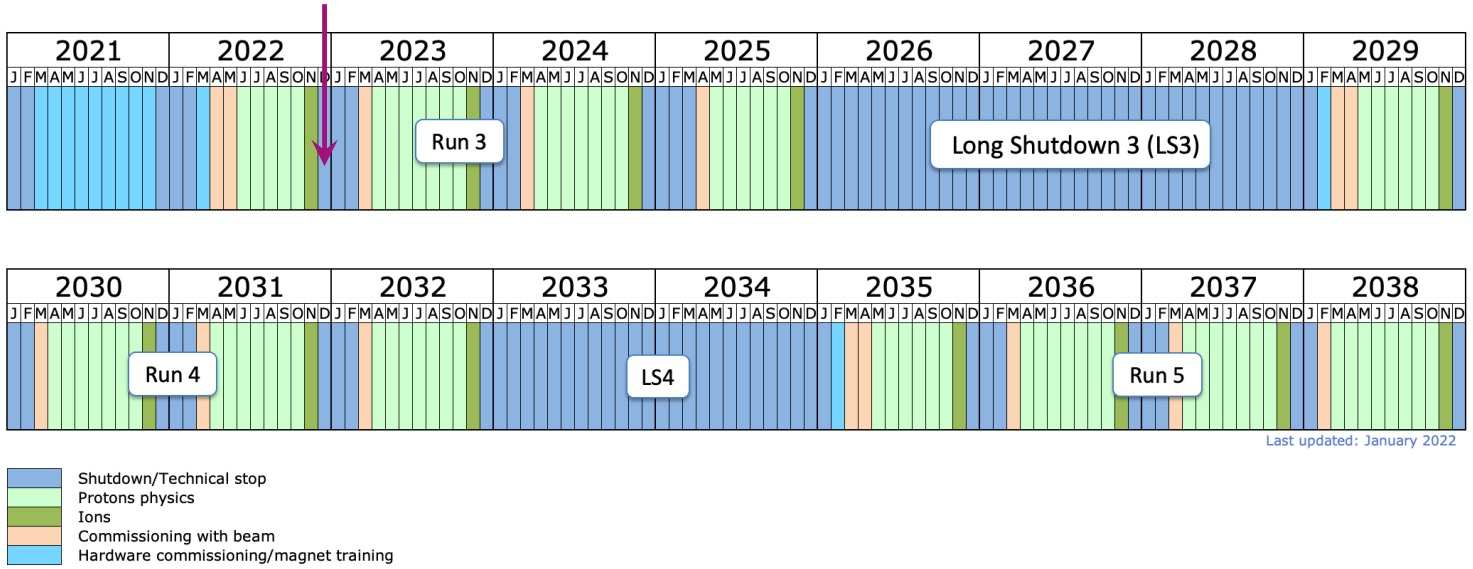
*somehow this mirror does not work!

$SUSY$ –searches at the HL-LHC (2029 … 2038)

- **From the current Run 3 to the LS3 and then: enter the HL-LHC**

  - LS3: major upgrade of LHC ($B = 11\,T$) towards luminosity $L = 5 \ldots 7.5 \times 10^{34}\, cm^{-2} s^{-1}$

  - LS3: major upgrade of experiments ATLAS and CMS to handle luminosity



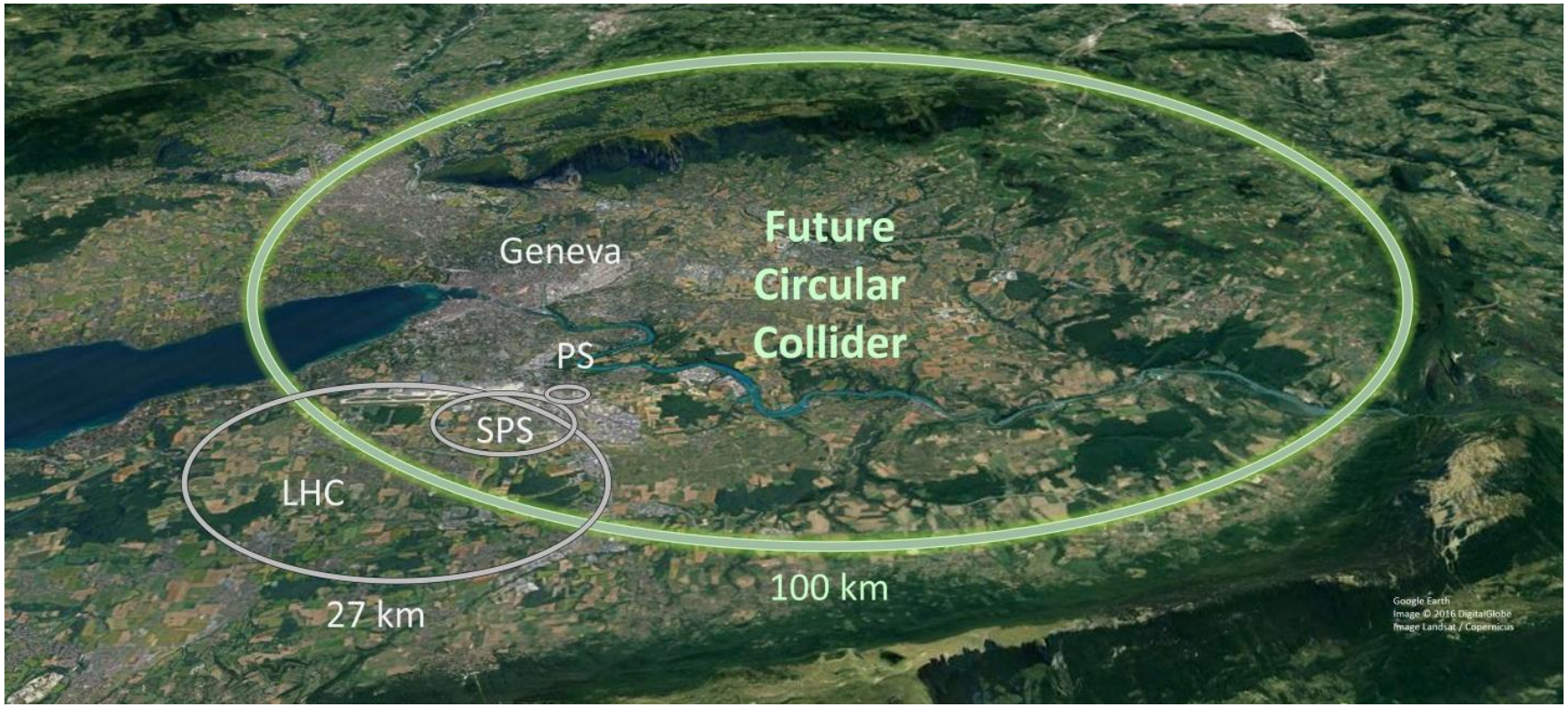
$SUSY$ –searches in the (far?) future

- **On the drawing board of CERN: the Future Circular Collider FCC**

- planned future pp – collider with $2\pi r = 100\ km$ for energy $\sqrt{s} = \mathbf{100\ TeV}$

- $\boldsymbol{FCC - pp}$:
  pp – collisions for
  $\boldsymbol{SUSY}$/**WIMP-search**

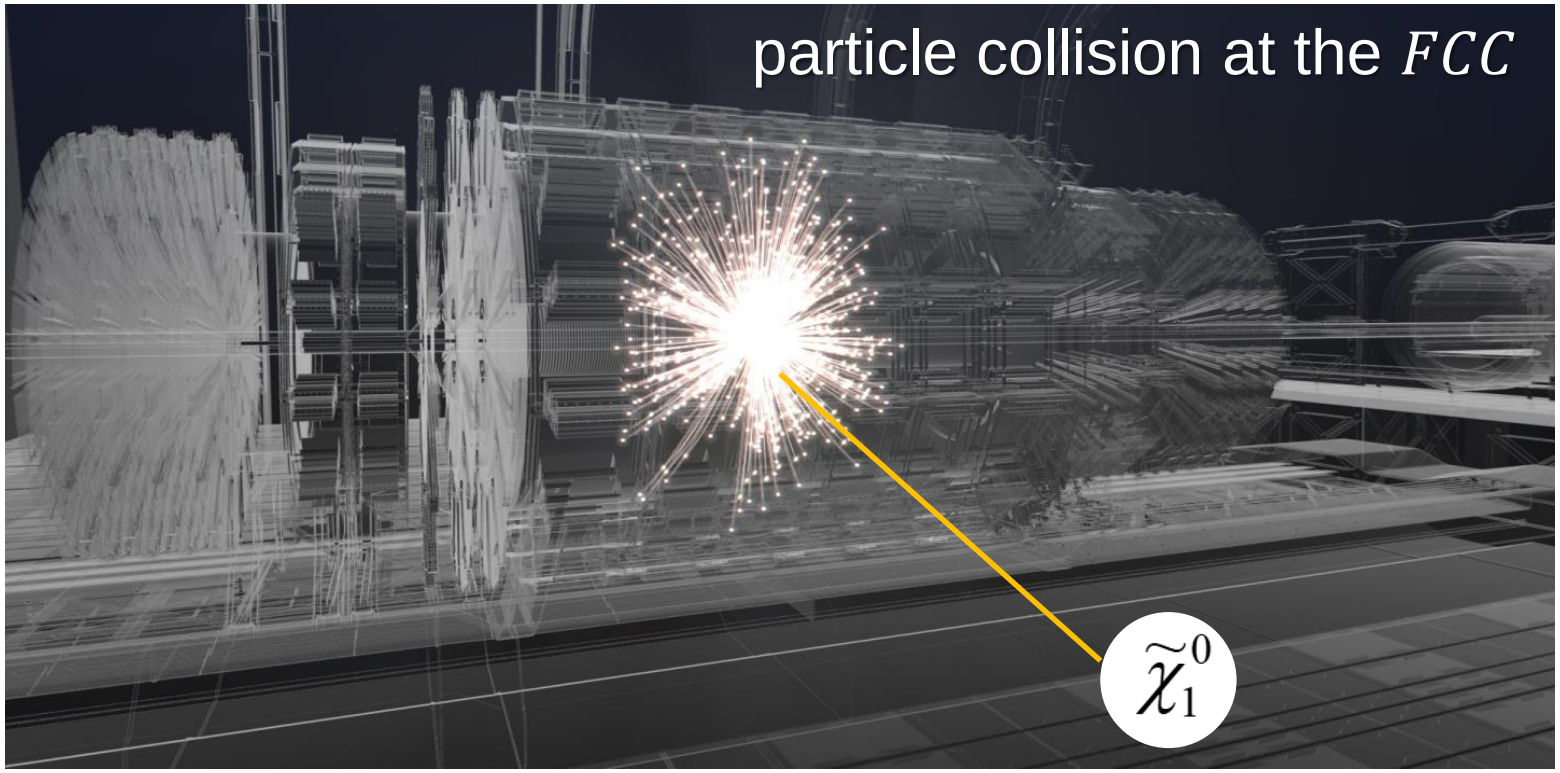
- $\boldsymbol{FCC - ee}$:
  e^+e^- –collisions for study of h $W^{\pm}$ Z^0 at $\sqrt{s} = 90 - 350\ GeV$



$SUSY$ –searches in the (far?) future: $2050s\ ff.$

- **On the drawing board of CERN: the Future Circular Collider FCC**

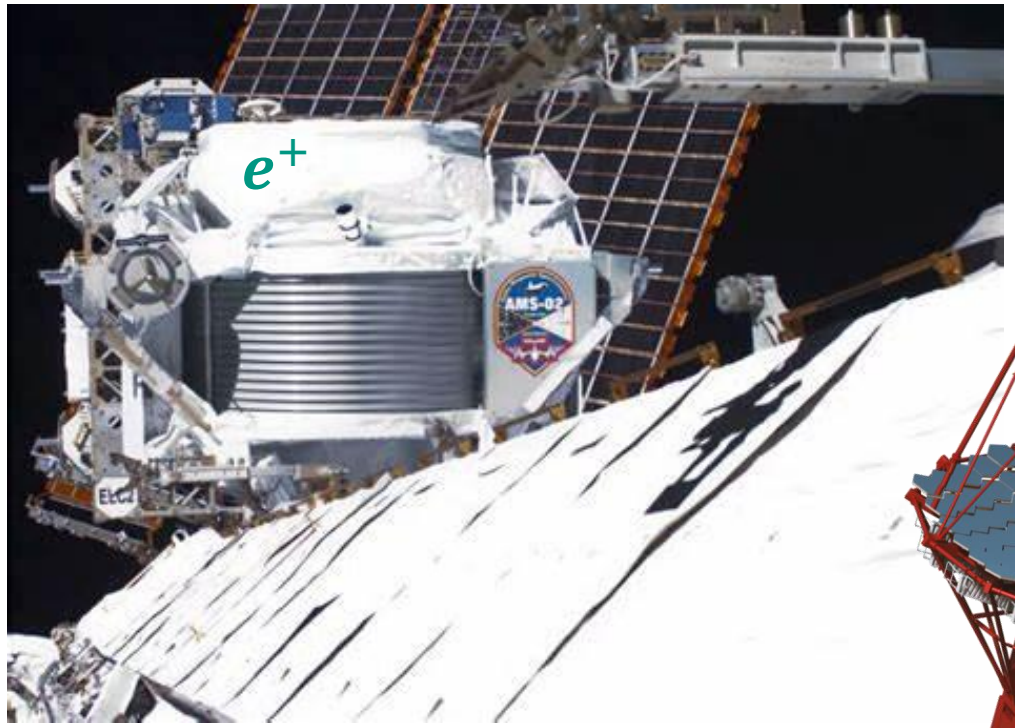
- planned future pp – collider with $2\pi r = 100\ km$ for energy $\sqrt{s} = \mathbf{100\ TeV}$

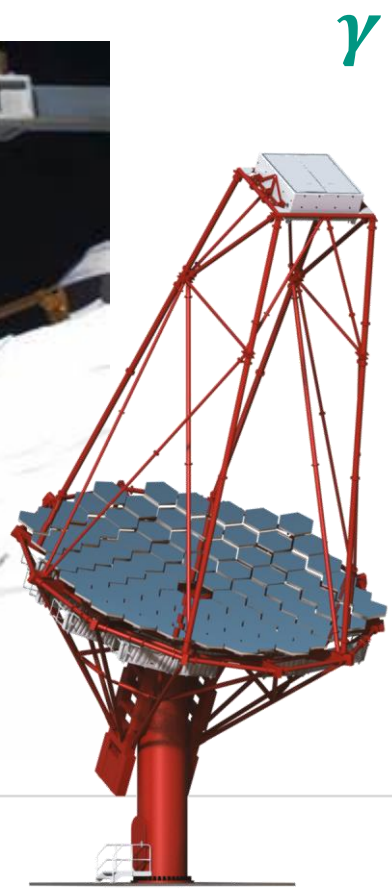


4.3 Indirect WIMP detection methods

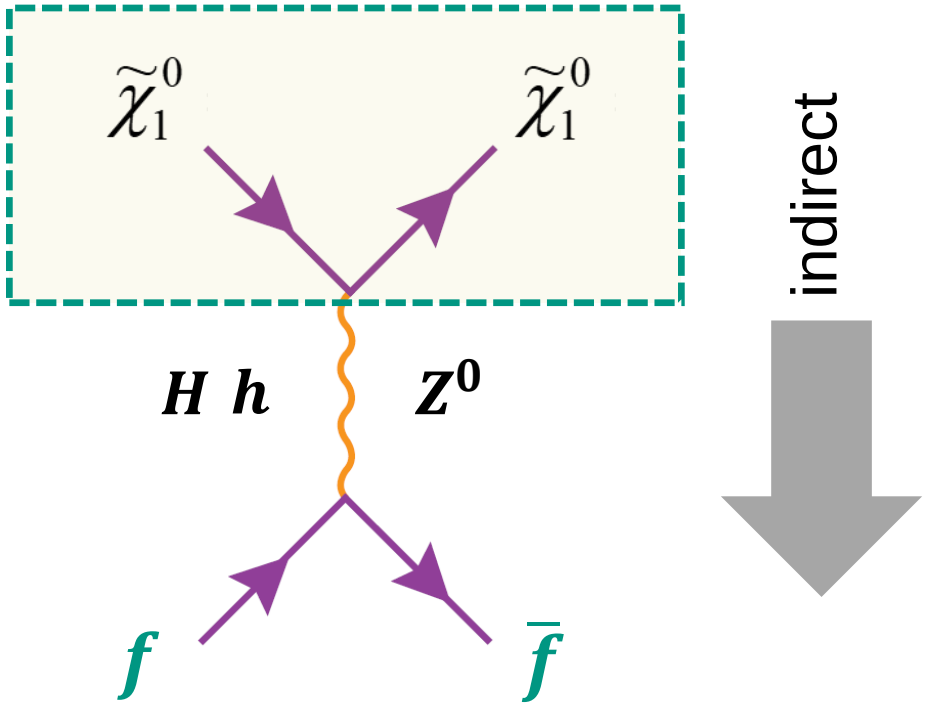
- **Searching for annihilation processes of WIMPs in the galactic DM-halo**

  - messenger particles with energies on the $GeV \ldots TeV$ – scale



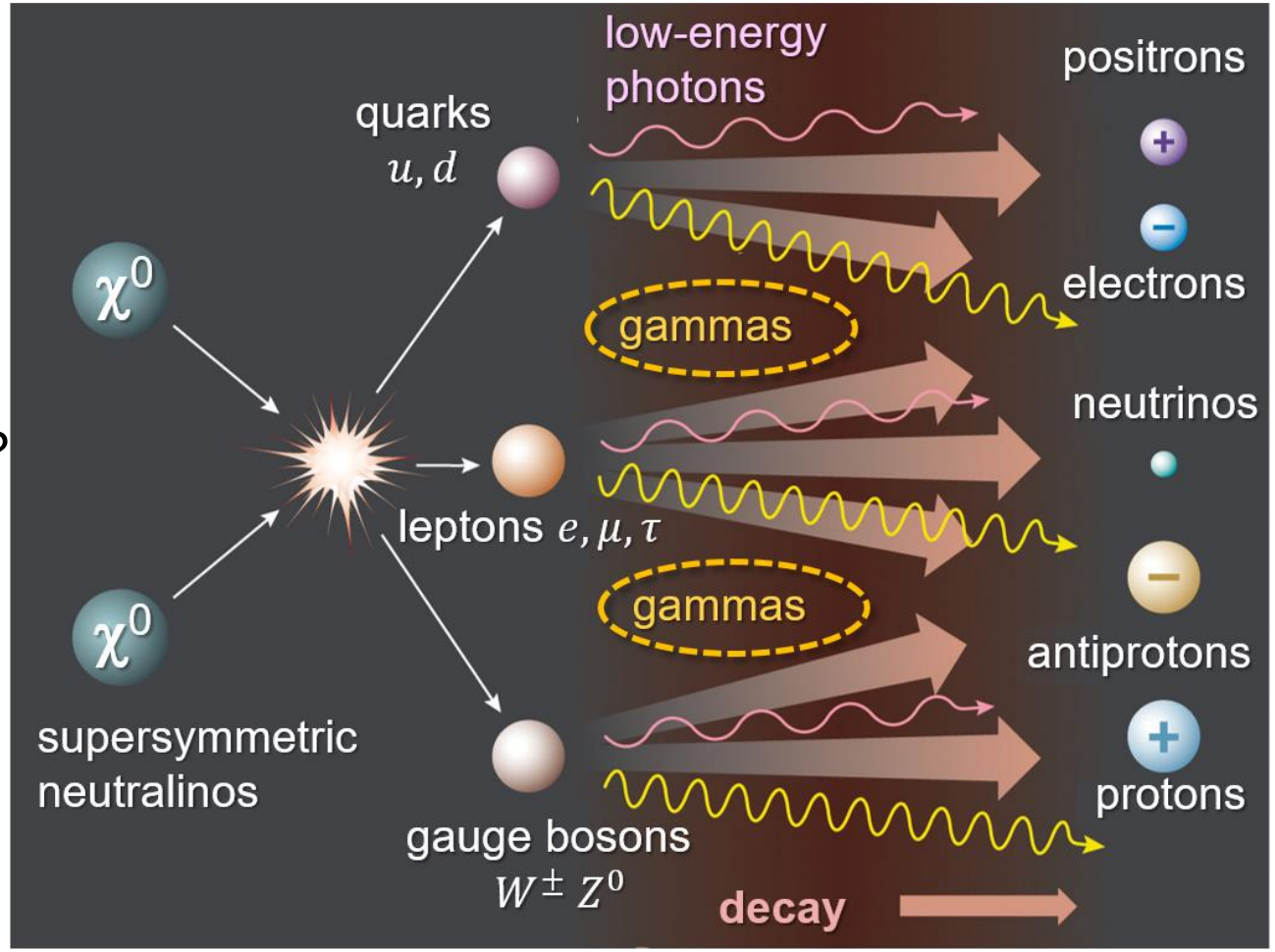


annihilation process



Annihilation processes of galactic neutralinos

- **A variety of DM-messenger particles from inner DM-halo: $\gamma's$, e^+, $\bar{p}$, ...**



electrons/positrons:
- decays of hadrons
- pair production
- direct production

neutrinos:
- hadronic/leptonic decays

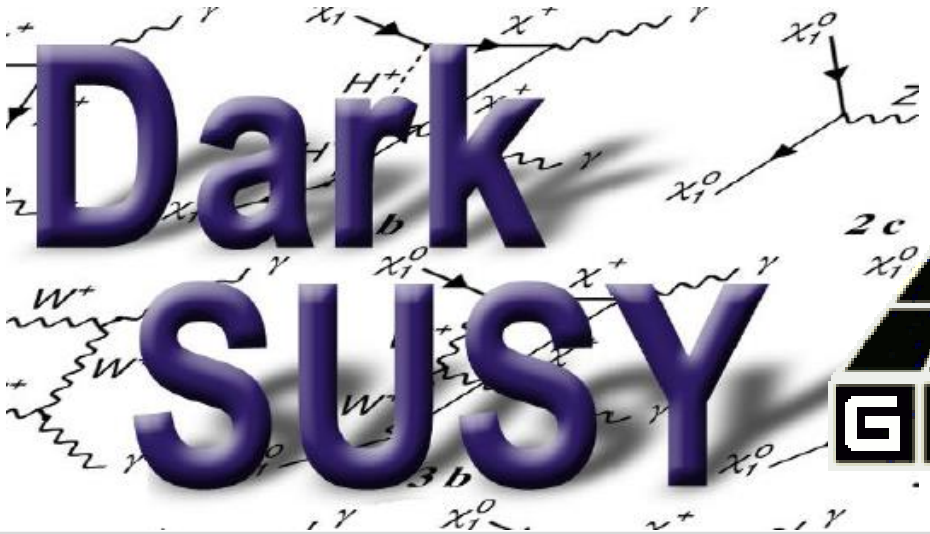
gammas:
- hadronic decays
- bremsstrahlung

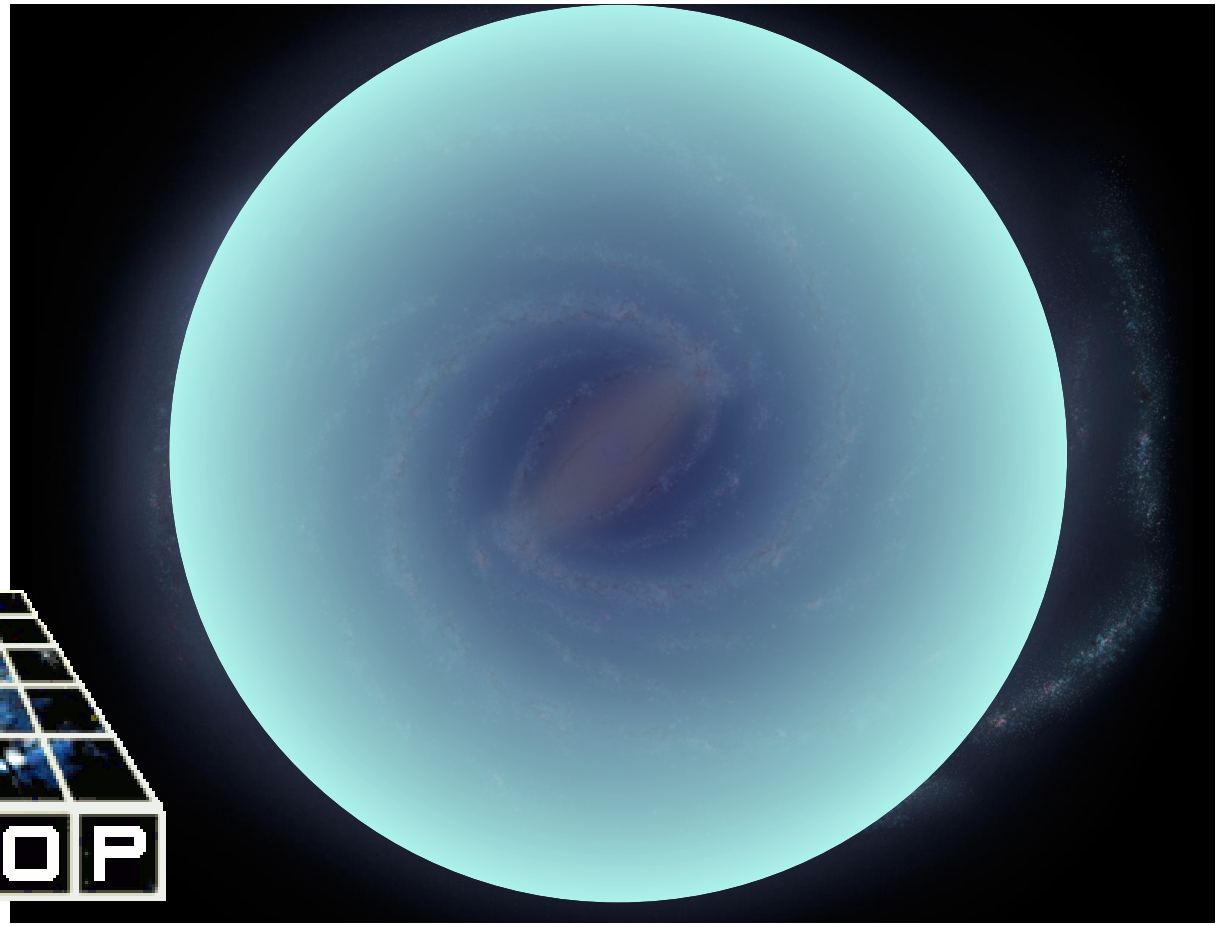
protons/anti-protons:
- hadronisation & jets
- decays of gauge bosons

Modelling of annihilation processes

- **Particle physics** (**DarkSUSY: annihilation of χ^0**) **meets** **astrophysics** **(DM halo model & GALPROP)**

  - search for WIMP annihilations in the DM-halo of our galaxy is ***strongly*** model-dependent

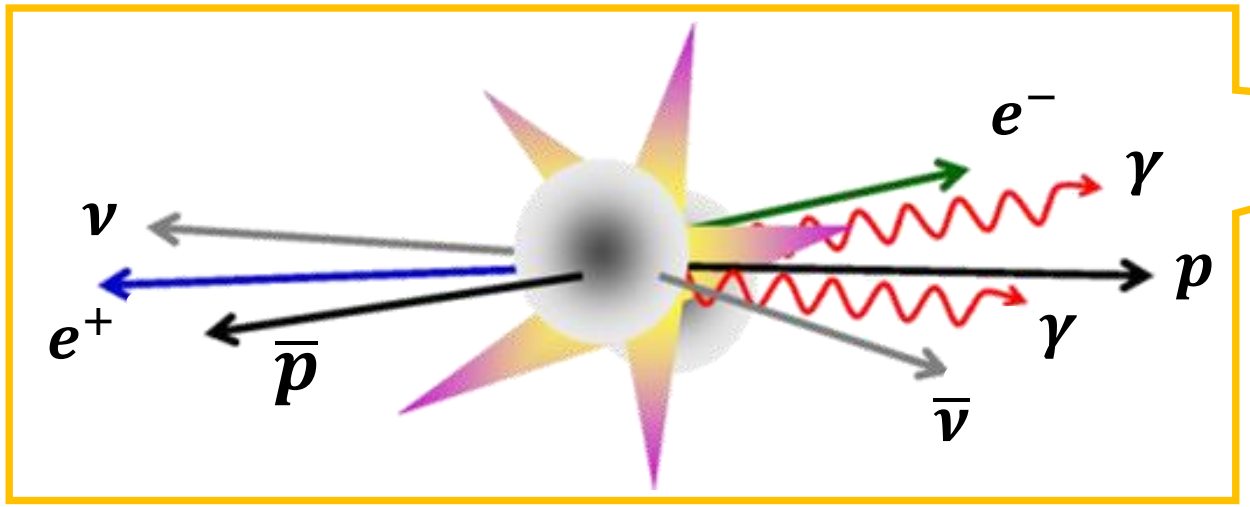


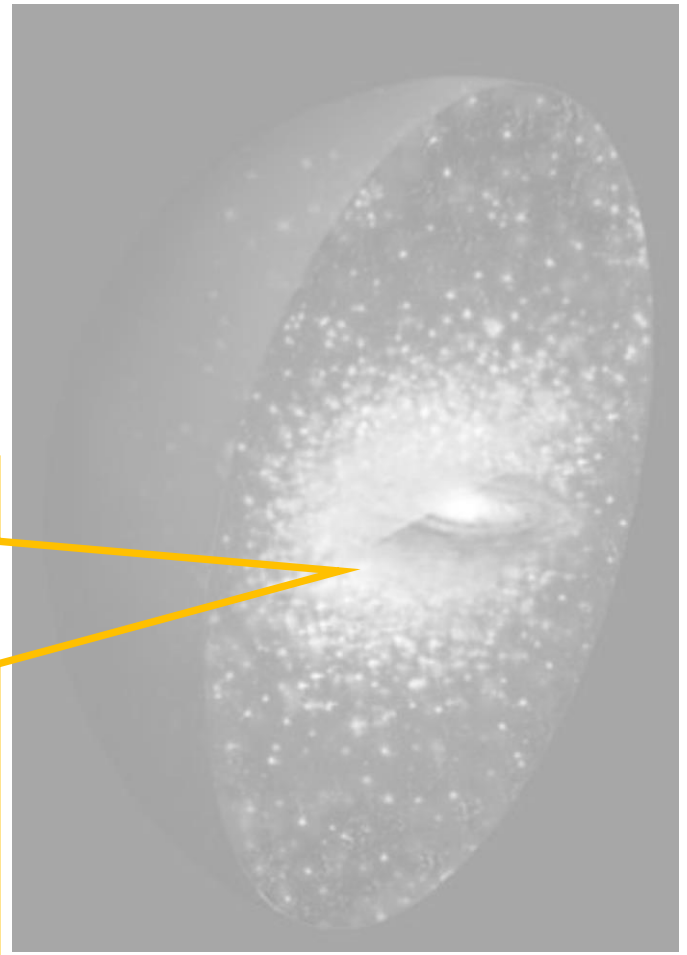


Modelling of annihilation processes

- **Particle physics** (**DarkSUSY: annihilation of χ^0**) **meets** **astrophysics** **(DM halo model & GALPROP)**

  - **particle theory**:
    selection of a $SUSY$ **– model** with specific neutralino properties: mass, flavour ratios, annihilation modes,
    ⇨ **energy spectrum** of resulting messenger particles

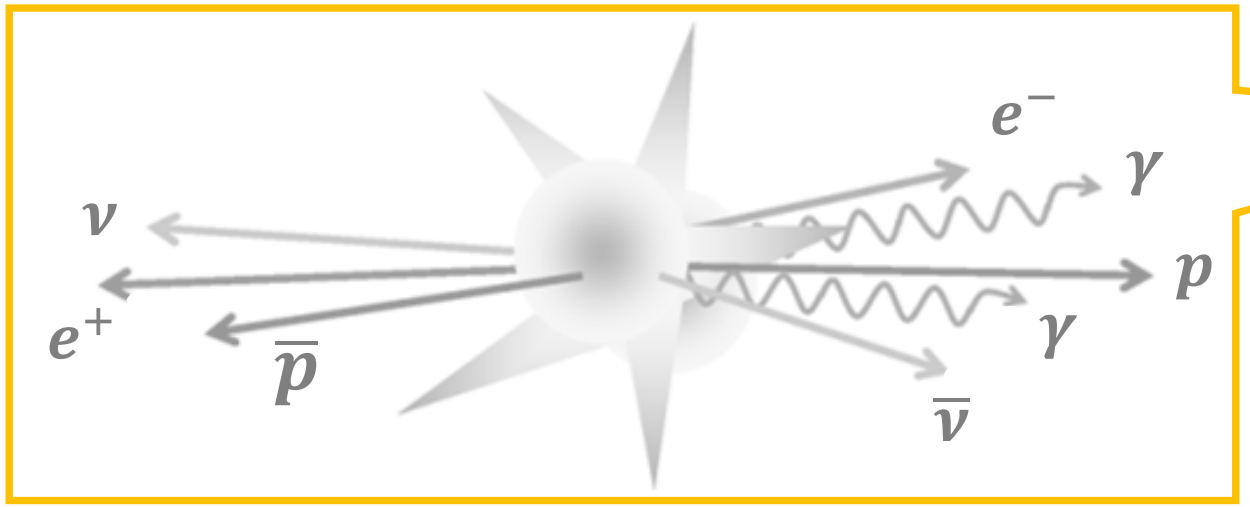


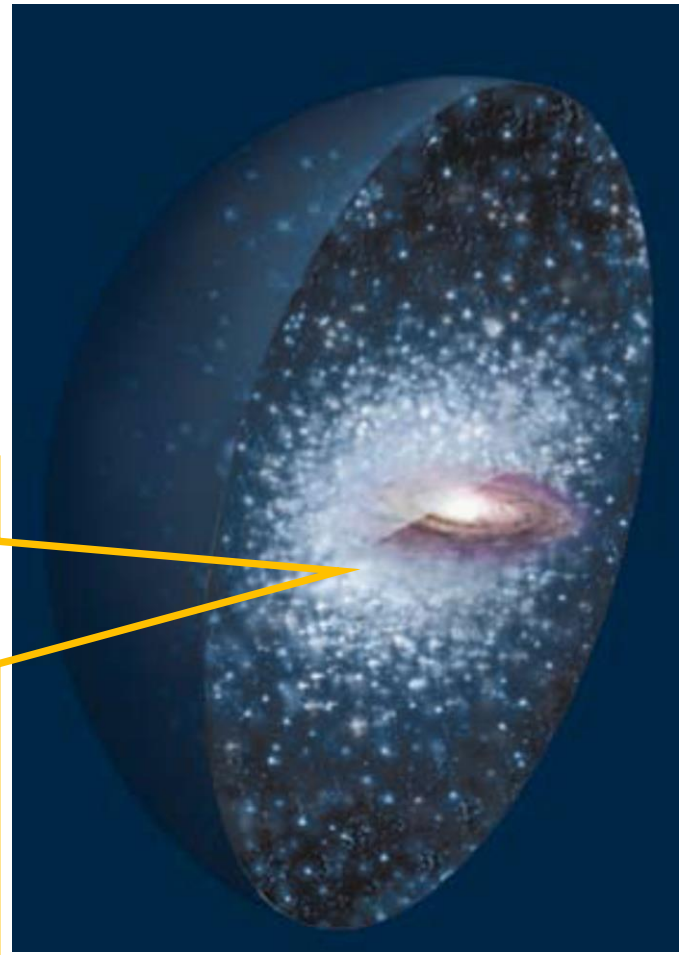


Modelling of annihilation processes

- **Particle physics** (**DarkSUSY: annihilation of χ^0**) **meets** **astrophysics** **(DM halo model & GALPROP)**

  - **astrophysics theory**:
    selection of a **DM-halo model** with specific density profile (especially in central part), WIMP velocities
    ⇨ also important: modelling of background spectrum

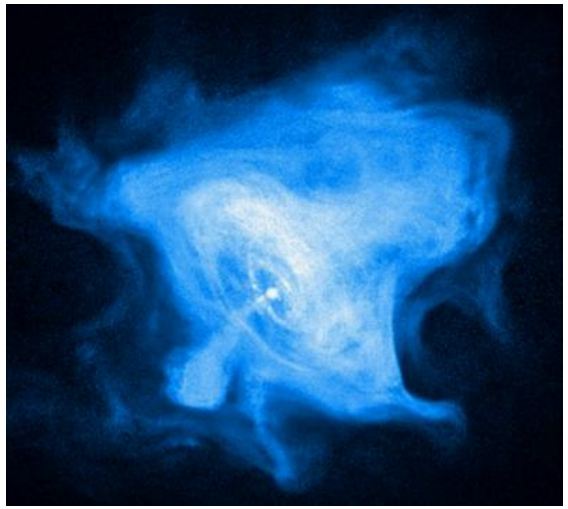


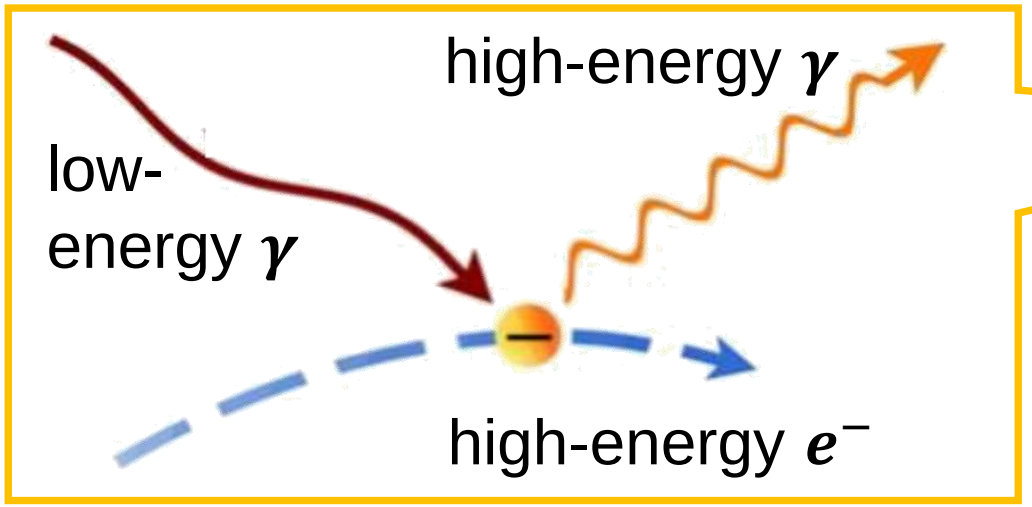


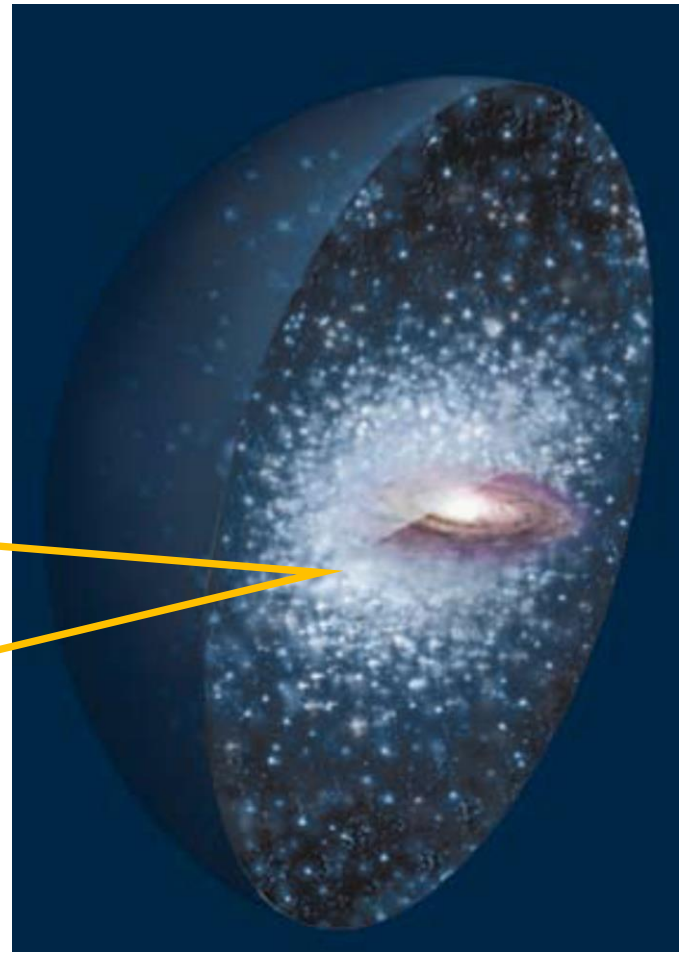
Modelling of annihilation processes

- **Particle physics** (**DarkSUSY: annihilation of χ^0**) **meets** **astrophysics** **(DM halo model & GALPROP)**

  - **background modelling**: here - inverse Compton effect
    - ⇨ selection of a source: pulsar (normal or ms –), SNR, micro-quasar, diffuse background, galactic center
    - ⇨ important: modelling based on realistic scenario (B, ρ)



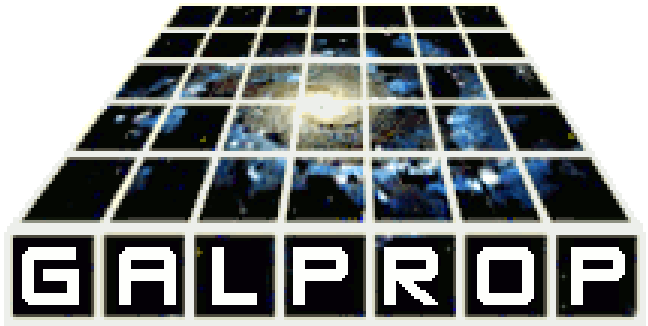


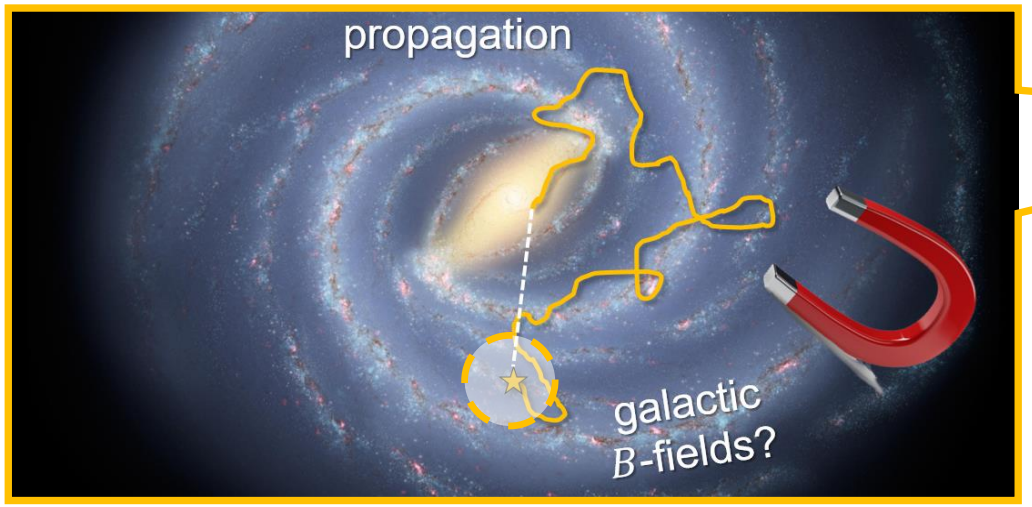


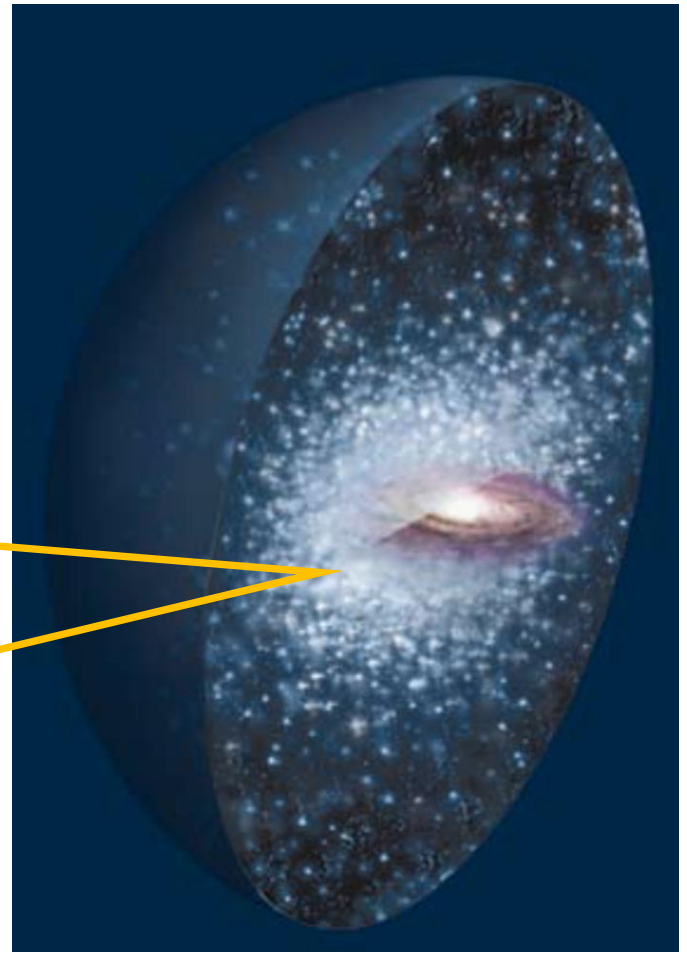
Modelling of annihilation processes

- **Particle physics** (**DarkSUSY: annihilation of χ^0**) **meets** **astrophysics** **(DM halo model & GALPROP)**

  - **propagation modelling**: here – positrons e^+
    selection of a model for the galactic B – field with 3D,
    often used: ´leaky box´ galactic B – field model for CRs
    ⇨ important: modelling* of energy losses & guiding







* GALPROP: Home (stanford.edu)

Modelling of annihilation processes

- **Combining parameters from particle physics & astrophysics**

  - number N_{Ann} of annihilations of a WIMP with mass m_{CDM} in our galactic DM-Halo per unit time t / volume V

$$N_{Ann} \sim \langle \sigma_{Ann} \cdot \mathrm{v} \rangle \cdot n_{CDM}^2$$

$$\sim \boxed{\langle \sigma_{Ann} \cdot \mathrm{v} \rangle \cdot \frac{\rho_{CDM}^2}{m_{CDM}^2}}$$

$$\rho_{CDM} = n_{CDM} \cdot \frac{m_{CDM}}{V}$$

σ_{Ann}	xsec from theory estimates
m_{CDM}	neutralino mass $(GeV \ldots TeV)$

PARTICLE PHYSICS

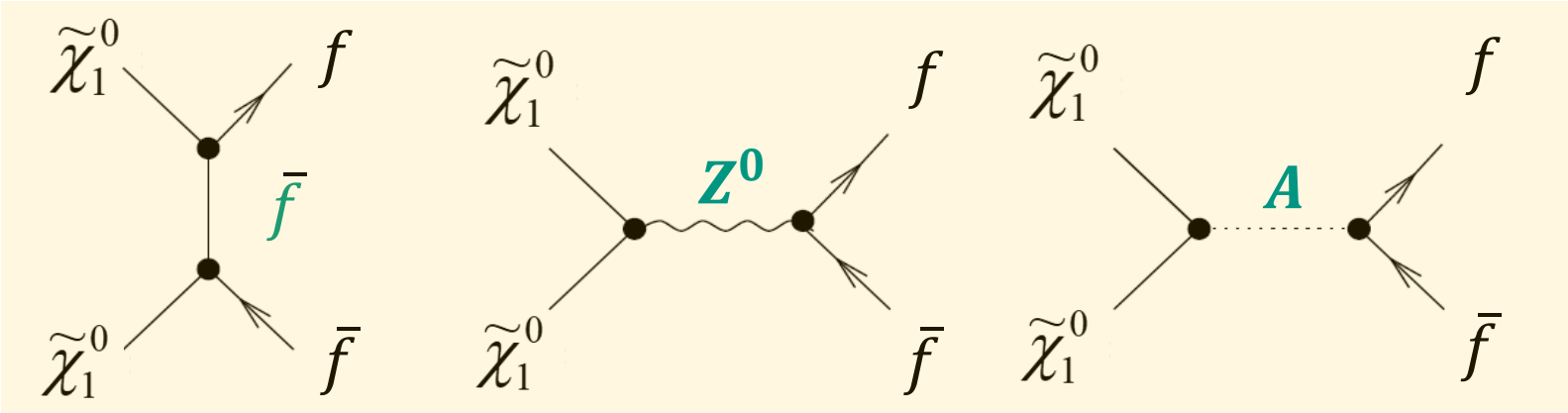
ρ_{CDM}	density profile of DM-halo
v	WIMP velocity profile

ASTRO PHYSICS

Annihilation processes: a closer look at theory

- **Relevant Feynman diagrams at the tree level**

  - we need to consider all Feynman graphs, not only tree level….



t – channel (transformation):
- sfermions ($\tilde{\nu}$)

s – channel (annihilation):
- Z^0 – boson
- pseudoscalar A

σ_{Ann} xsec from theory estimates

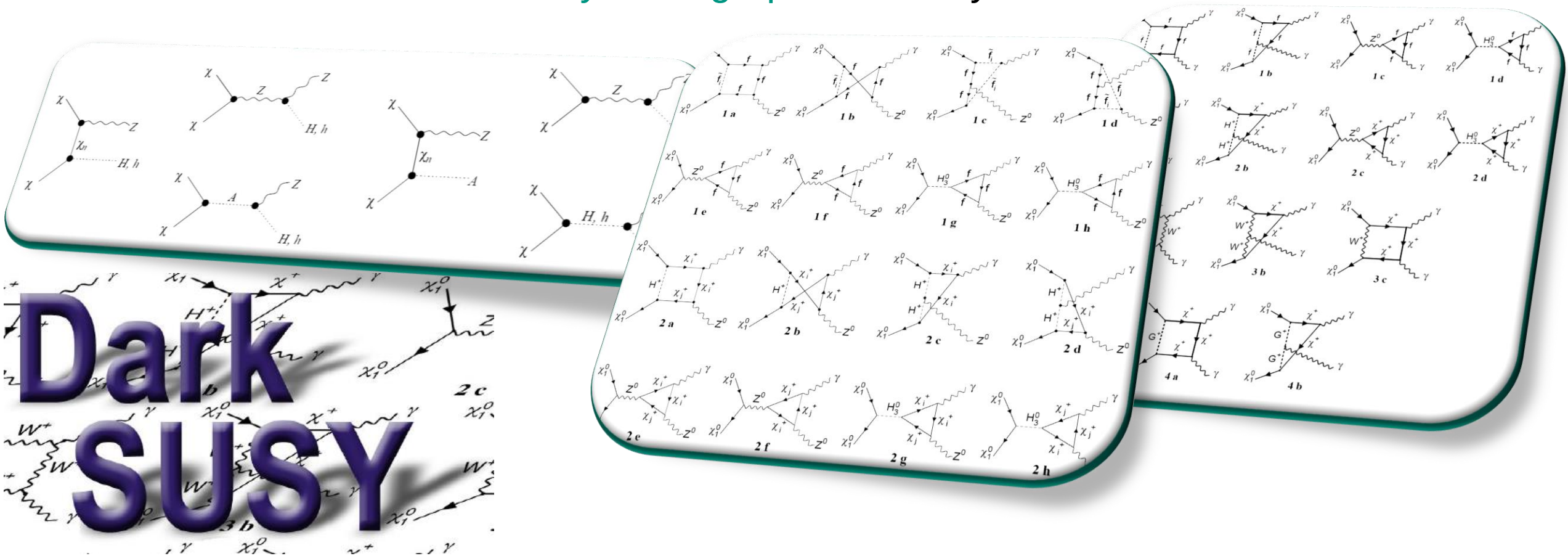
- further annihilation channels into pairs of gauge bosons $W^{\pm}\, Z^0$ in both t – and s – channel

PARTICLE PHYSICS

Annihilation processes: a closer look at theory

- **Relevant Feynman diagrams at higher orders: a small sample of channels**

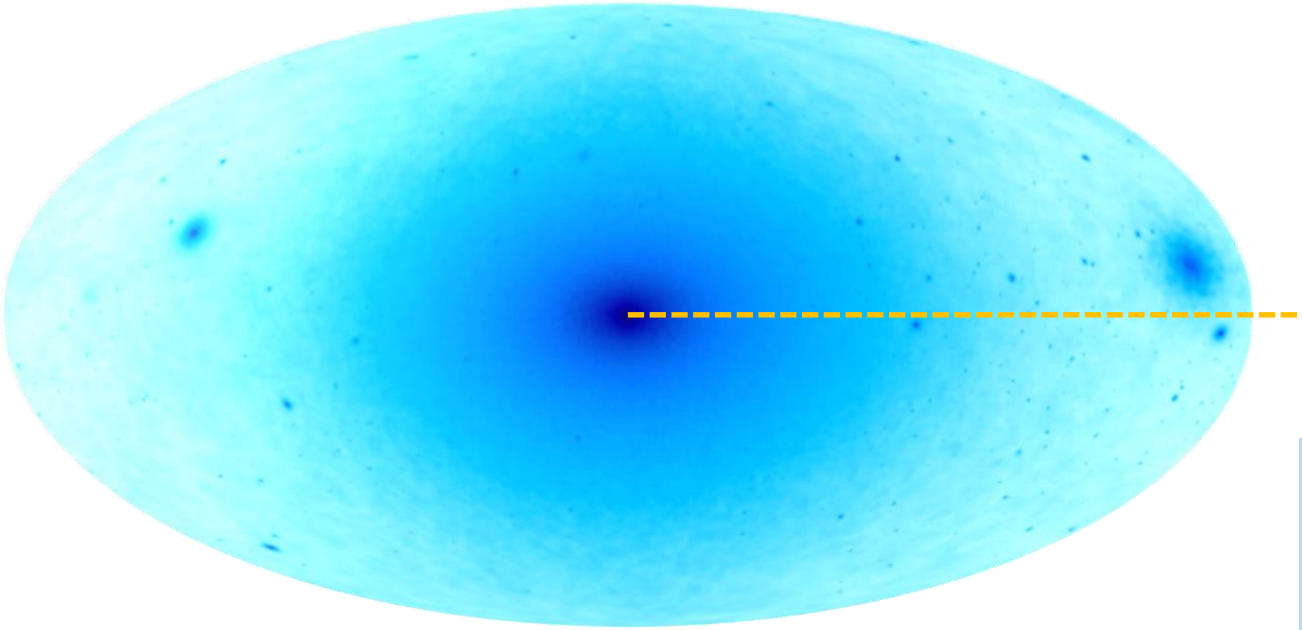
  - we need to consider all Feynman graphs, not only tree level….



Annihilation processes: a closer look at dark halos

- **Modelling of DM halos: finding the correct density profile**

  - DM density values very important for annihilation studies



expected DM-annihilations
in a Mollweide projection

$$N_{Ann} \sim \rho_{CDM}^2$$

galactic center:
DM-profile ρ_{CDM} peaks (´DM-spike´)

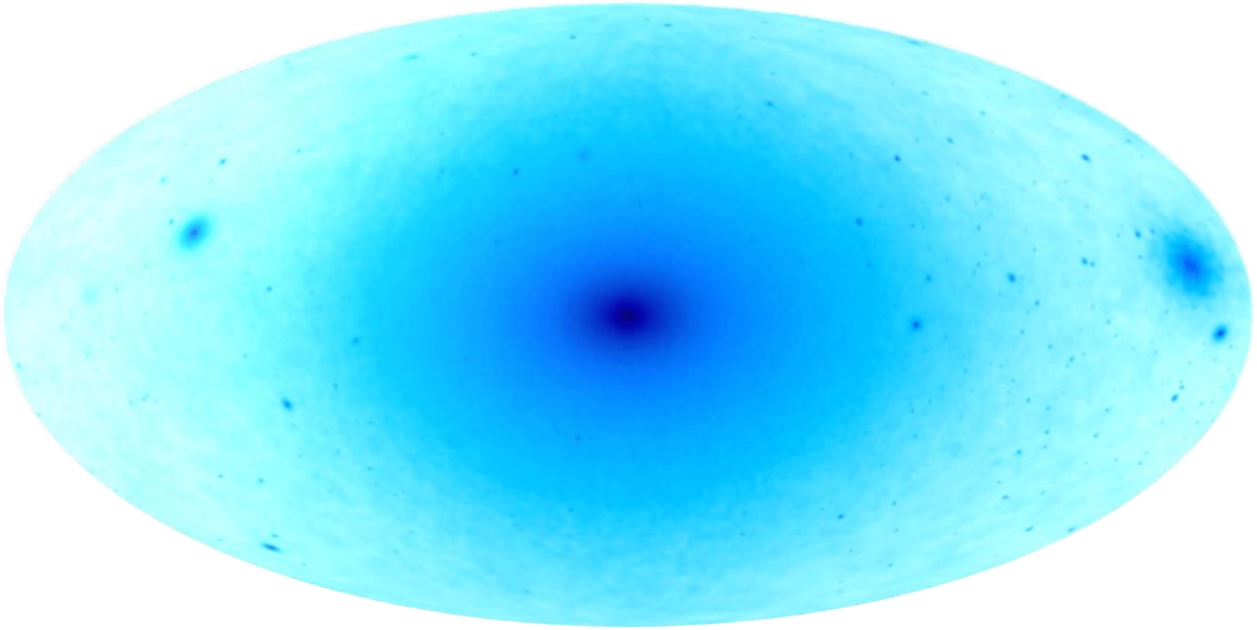
ρ_{CDM}	density profile of DM-halo
v	WIMP velocity profile

ASTRO PHYSICS

Annihilation processes: a closer look at dark halos

- **Modelling of DM halos: a ´de facto´ standard is the NFW profile**

  - **N**avarro-**F**renk-**W**hite (**NFW**) propose the ´NFW profile´, simplified here to

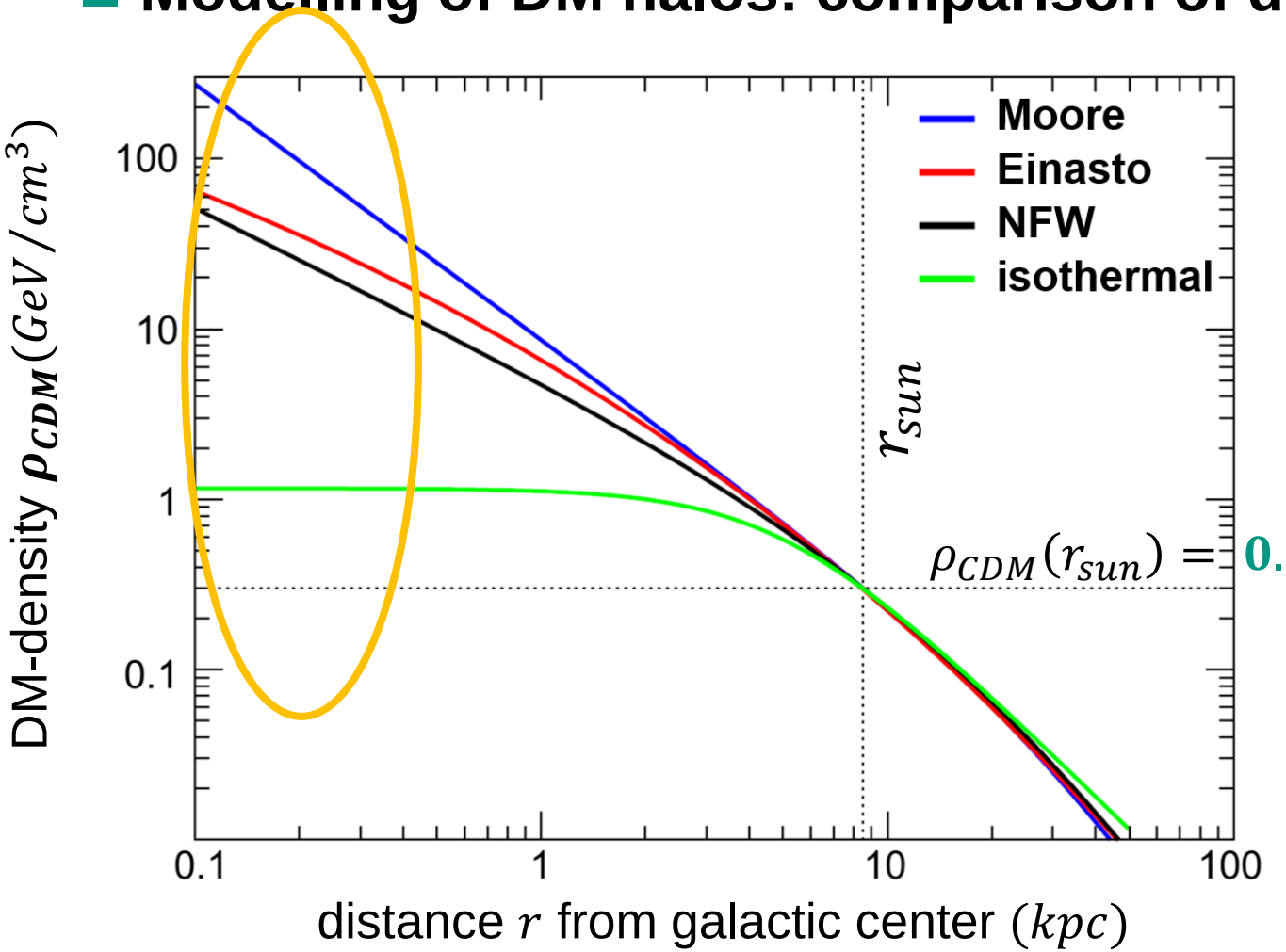


expected DM-annihilation rate
in a Mollweide projection

$$\rho_{CDM}(r) \sim {}^{1}/_{r^2}$$

Annihilation processes: a closer look at dark halos

- **Modelling of DM halos: comparison of different halo profiles being proposed**

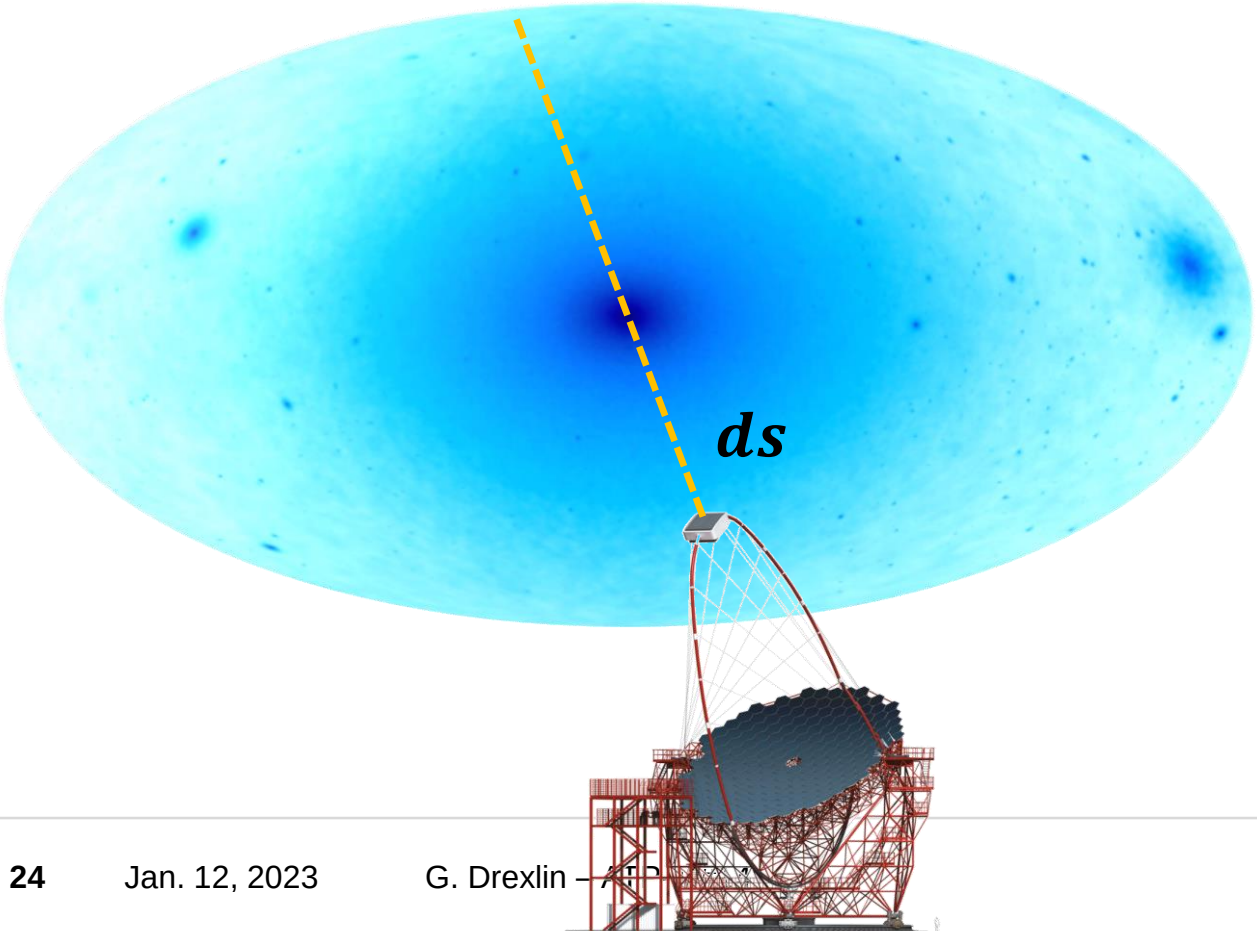


- **inner halo modelling** gives vastly different values (compare Moore ⇔ NFW ⇔ isothermal)
- halo-core: up to $\mathbf{300\ GeV/cm^3}$

Annihilation processes viewed along line-of-sight

- **Gammas as messenger particles: integration of signal along line ds**

- Cherenkov telescopes, pointed at the galactic center, observe an integrated signal



$$\Phi_{Ann} \sim \langle \sigma_{Ann} \cdot v \rangle \cdot \frac{1}{m_{CDM}^2} \cdot \int_{line-of-sight} \rho_{CDM}^2 \cdot ds$$

γ –flux

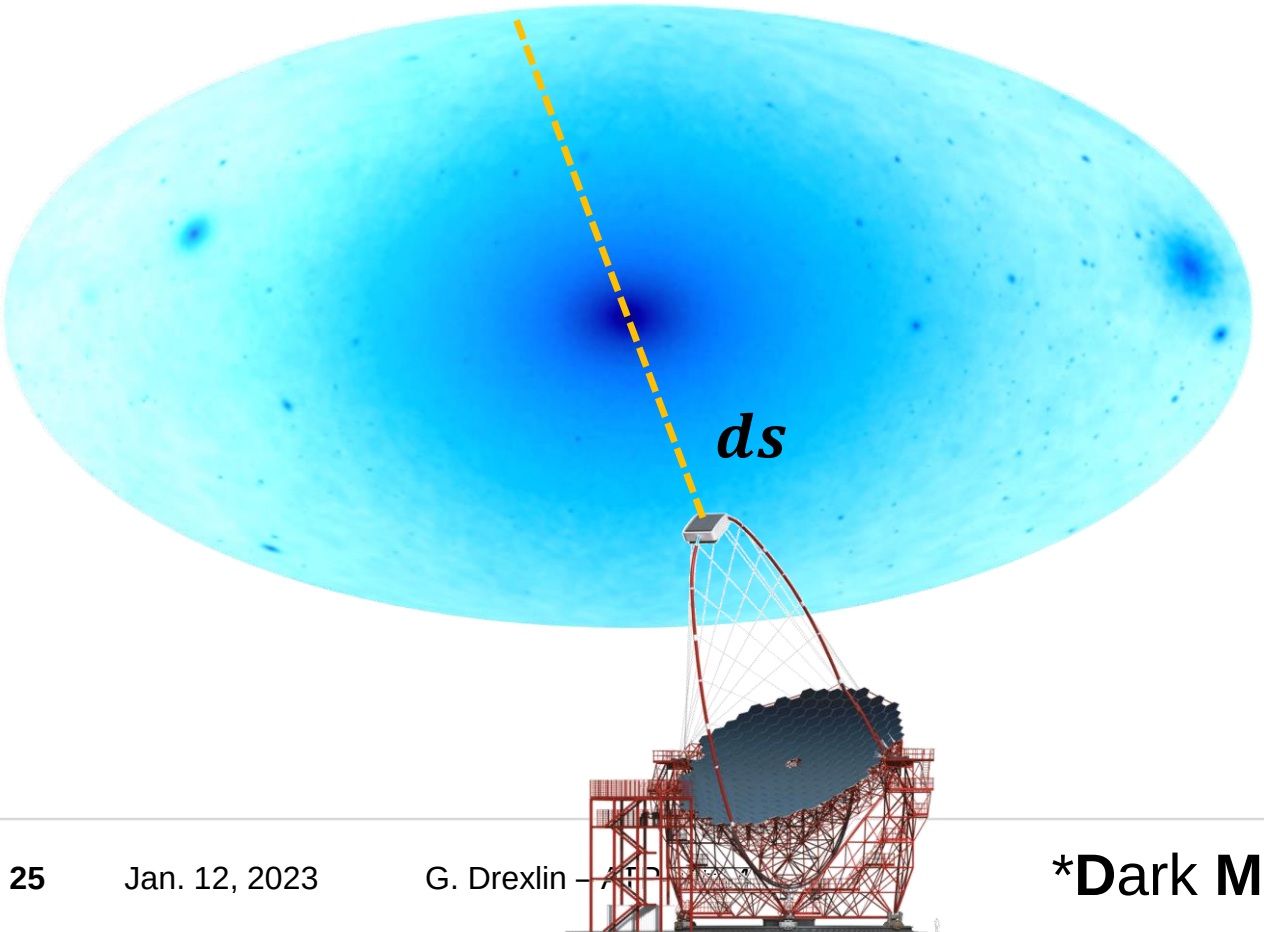
annihilation cross section averaged over WIMP velocity

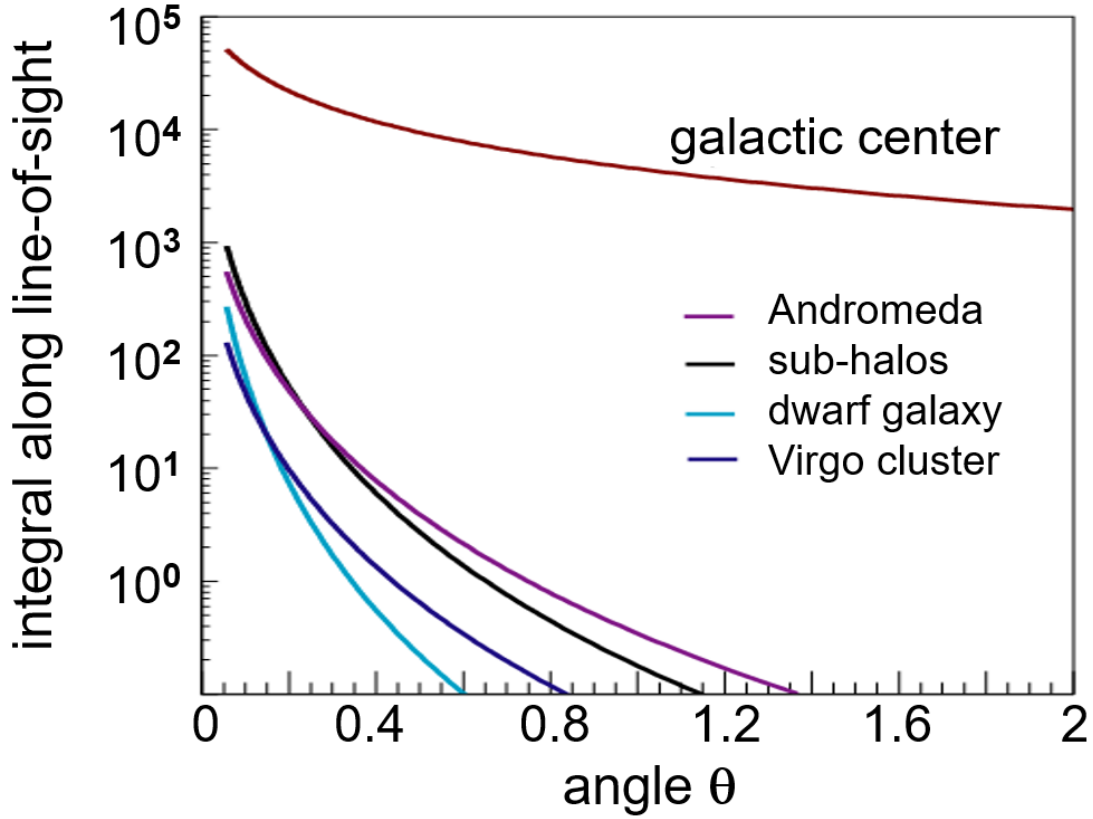
WIMP mass

Annihilations from DM: where to look

- **Gammas as messengers: we focus our telescope on the galactic center!**

  - it is best to look at the center of our galaxy: much larger DMA*-Signal

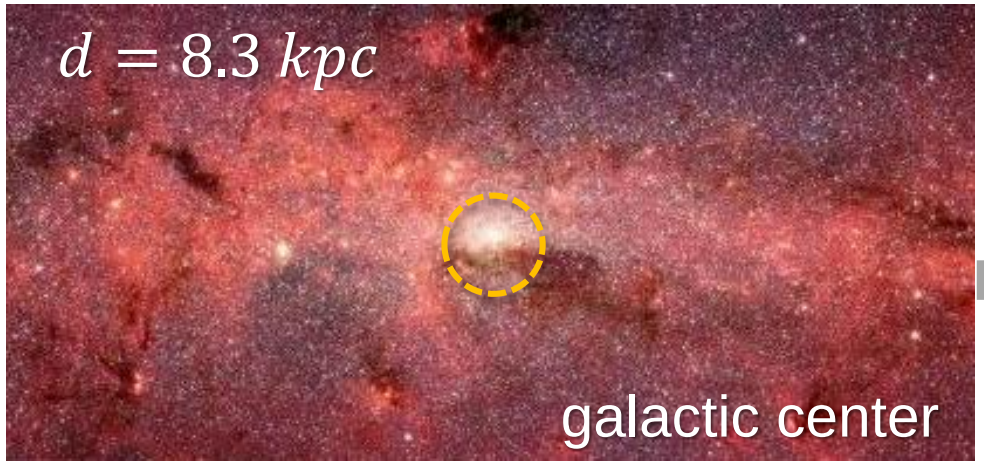


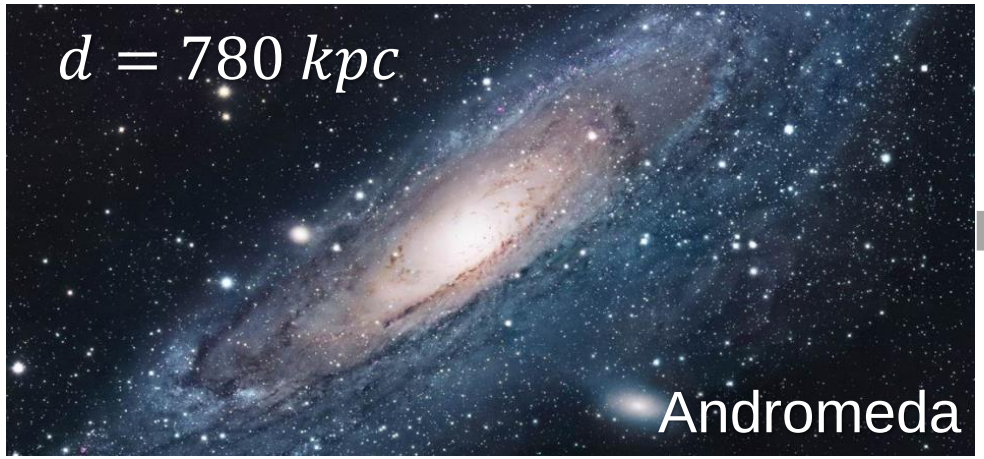


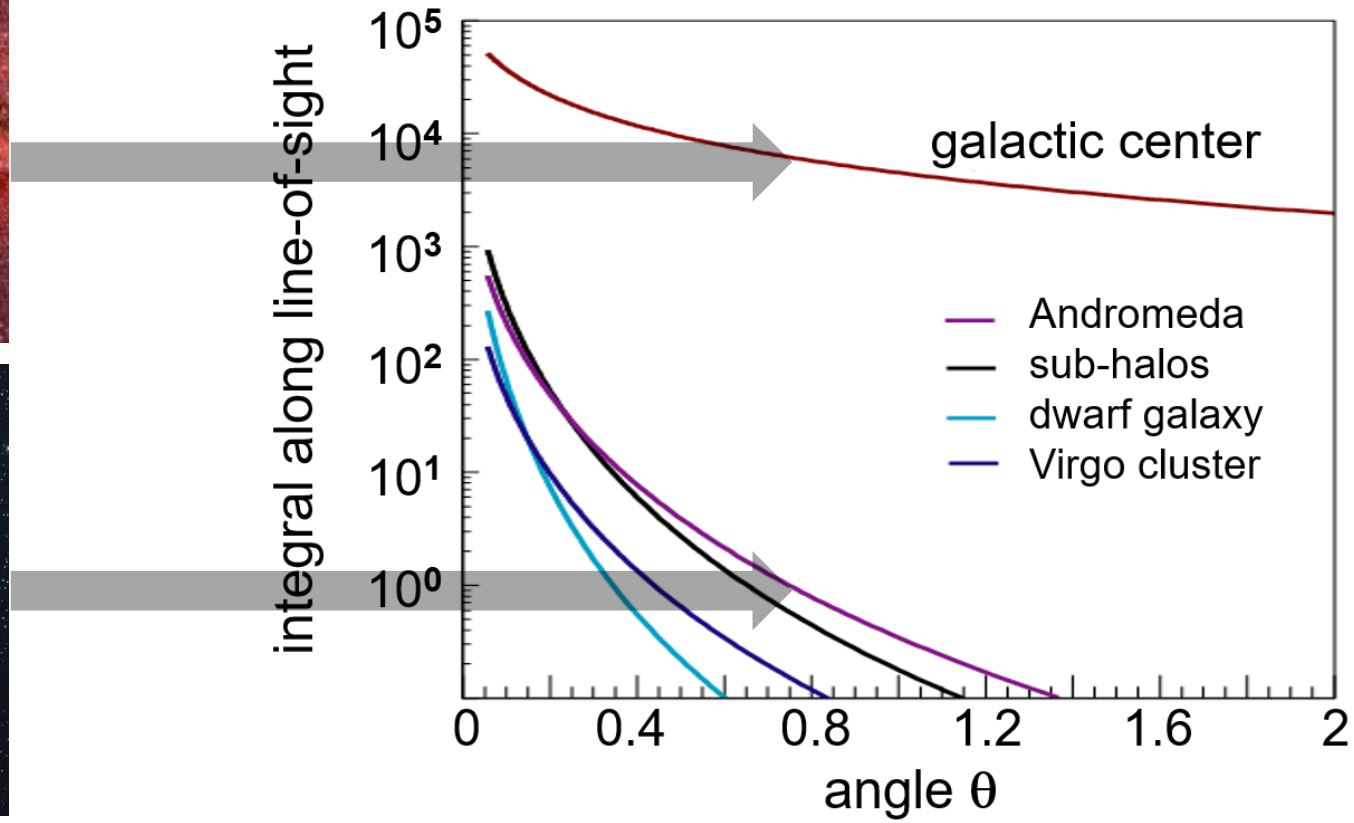
*Dark Matter Annihilation

Annihilations from DM: where to look

- **Gammas as messengers: we will focus our IACT on the galactic center!**

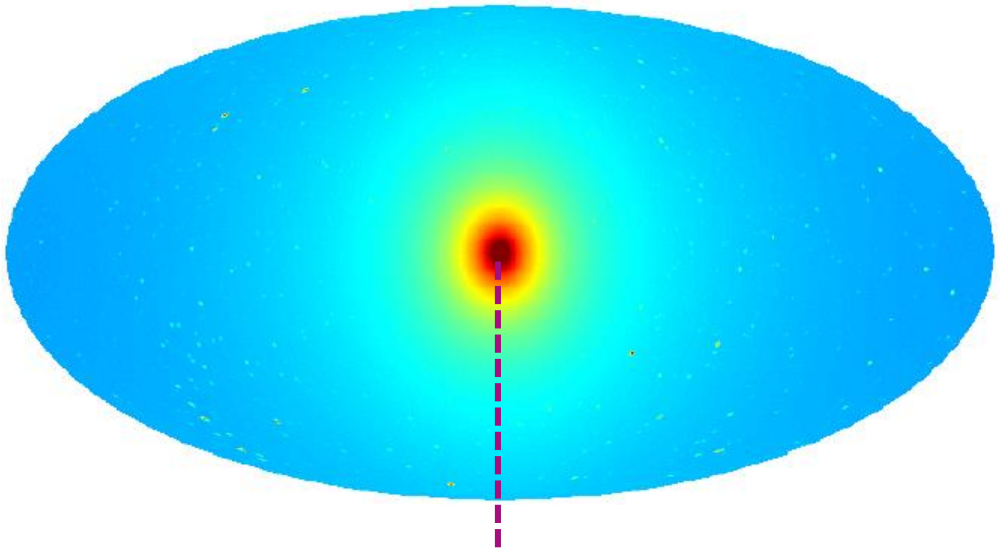


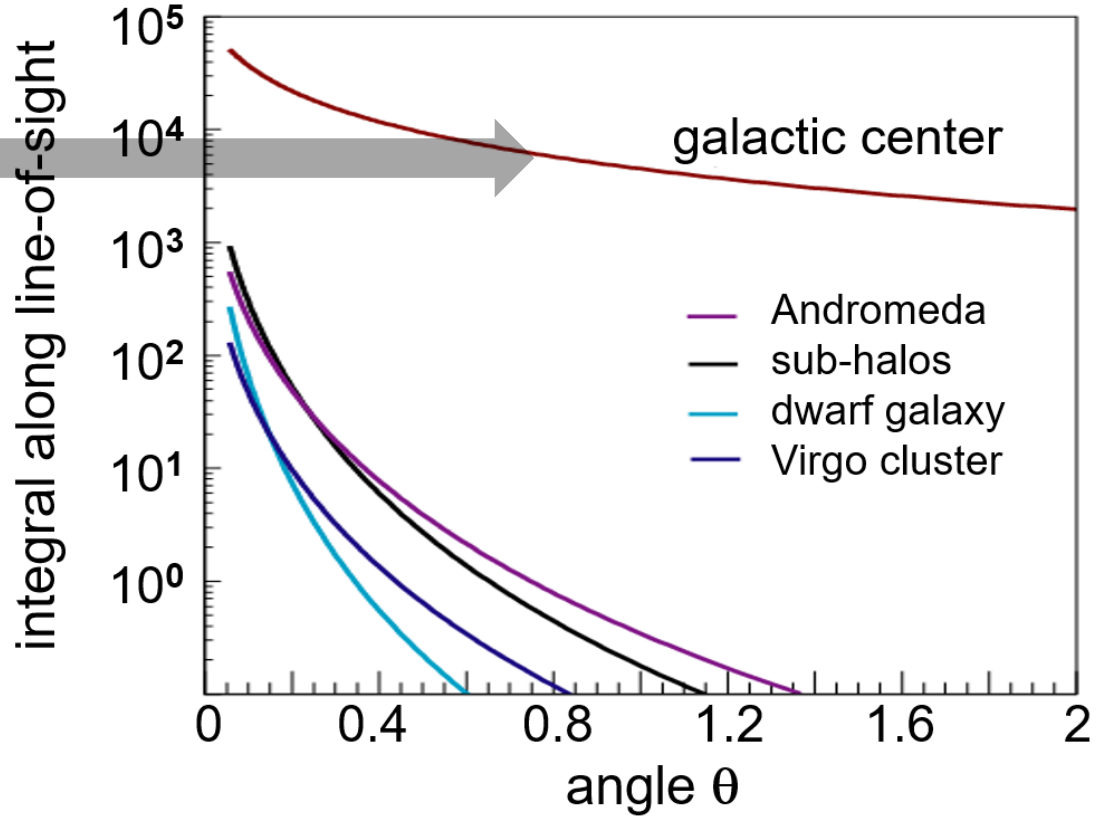




Annihilations from DM: where to look

- **Simulated DMA signals - the galactic center ´overwhelms´ other sources**





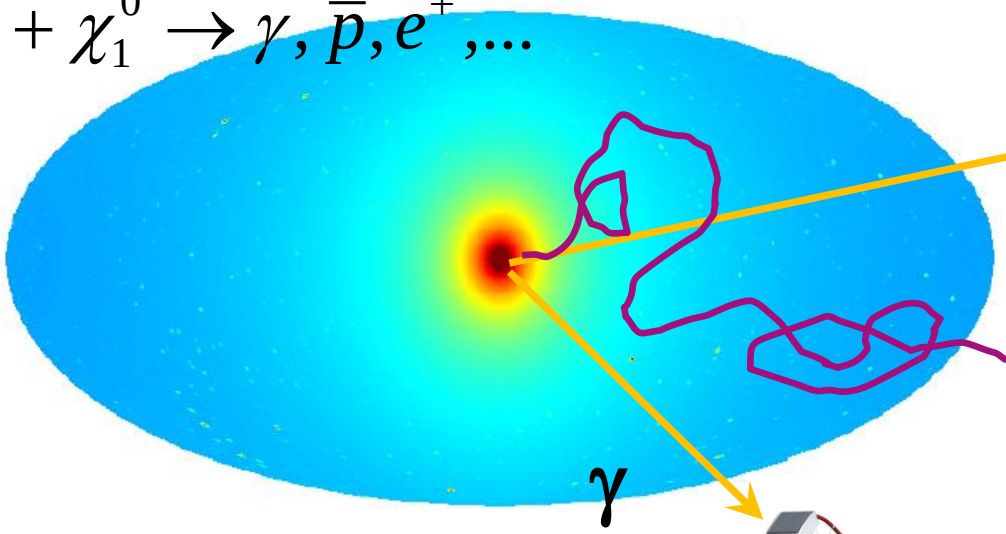
- expected DMA flux (for $m = 1\,TeV$ & $\sigma_{Ann} = 1\,pb$) is VERY small:

$$\Phi_{Ann} \sim \mathbf{5 \cdot 10^{-12}}\ \gamma´s\ cm^{-2}\ s^{-1} sr^{-1}$$

4.4.1 Gammas and positrons

- **Searching for DMA signals with gammas and positrons**

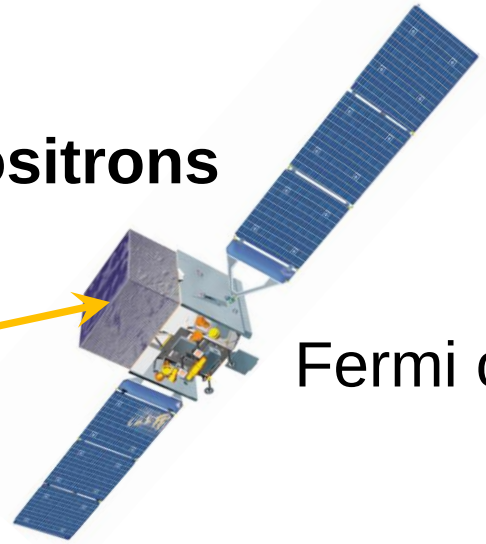
$\chi_1^0 + \chi_1^0 \rightarrow \gamma, \bar{p}, e^+, \ldots$



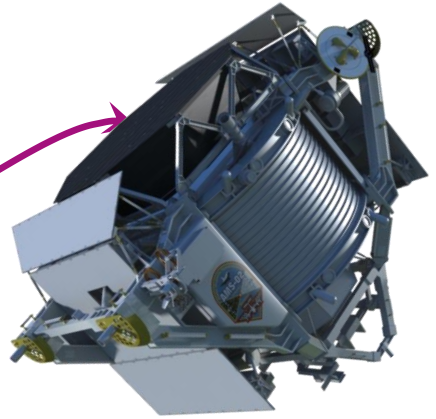
γ

γ

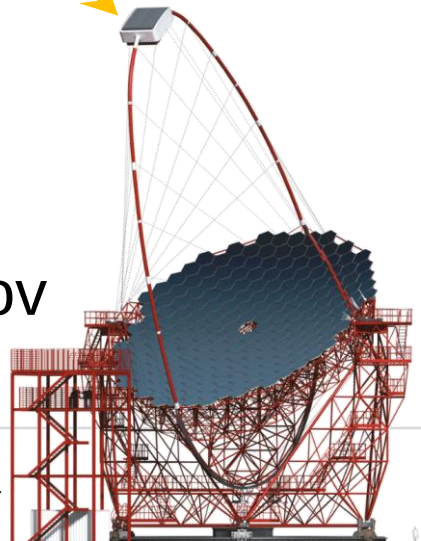
e^+



GeV:
Fermi observatory



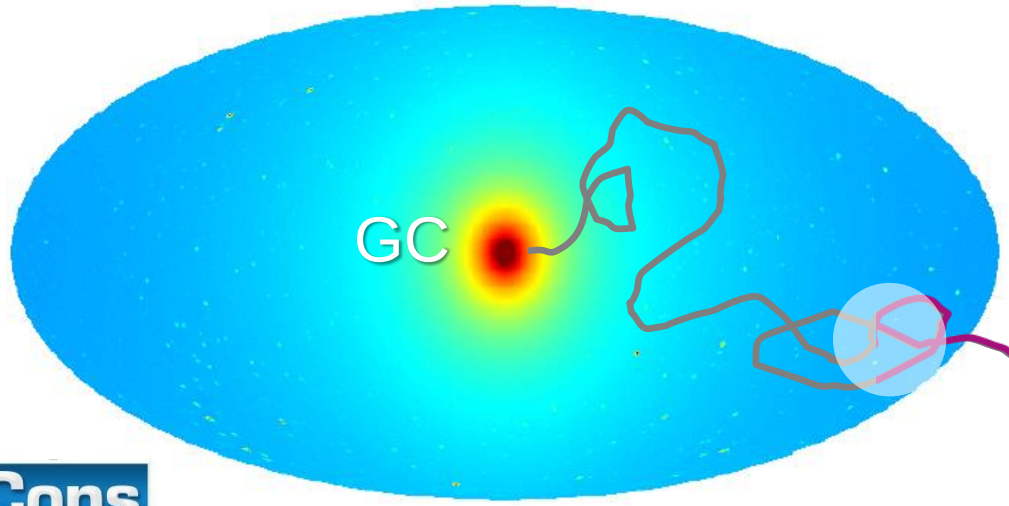
$GeV \ldots TeV$:
AMS-02 experiment



$GeV \ldots TeV$:
Imaging Cherenkov Telescope

Positrons as DMA messengers from the galaxy

- **Advantages / disadvantages of experiments using positrons**



Pros

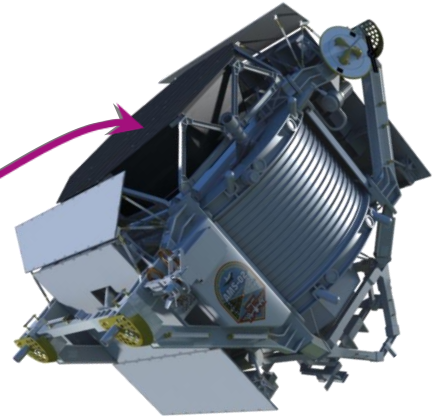
clear identification of e^+:
(e/m) **ratio** via on-board
B – field in satellite mission

Cons

strong deflection in galactic B –fields

⇨ energy losses during propagation from GC*
e^+ detection only from local DM halo

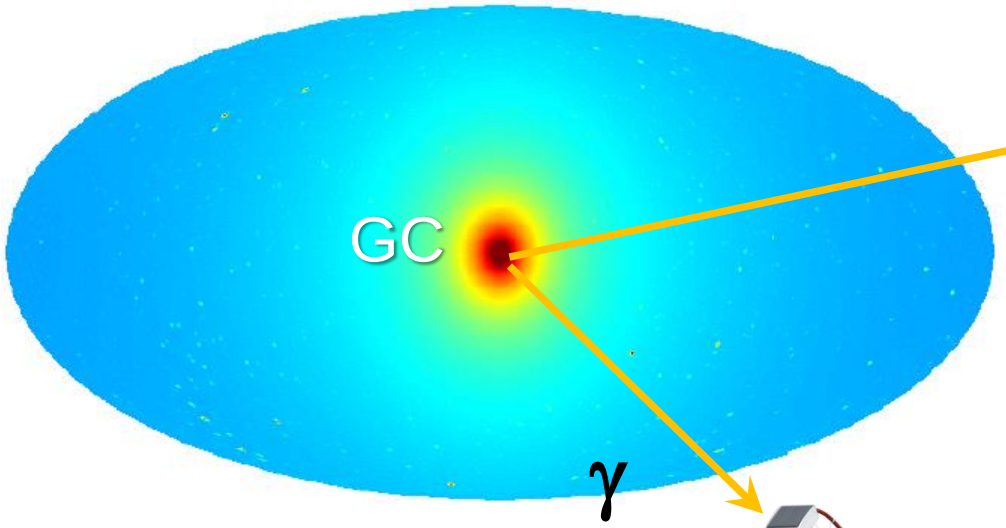
e^+



GeV ... TeV:
AMS-02 experiment

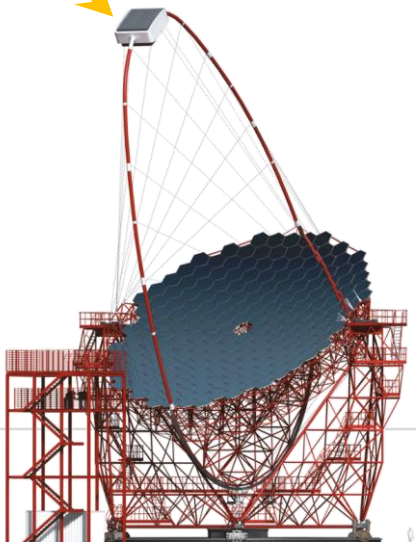
Gammas as DMA messengers from the galaxy

- **Advantages of gamma experiments**



GeV:
Fermi observatory

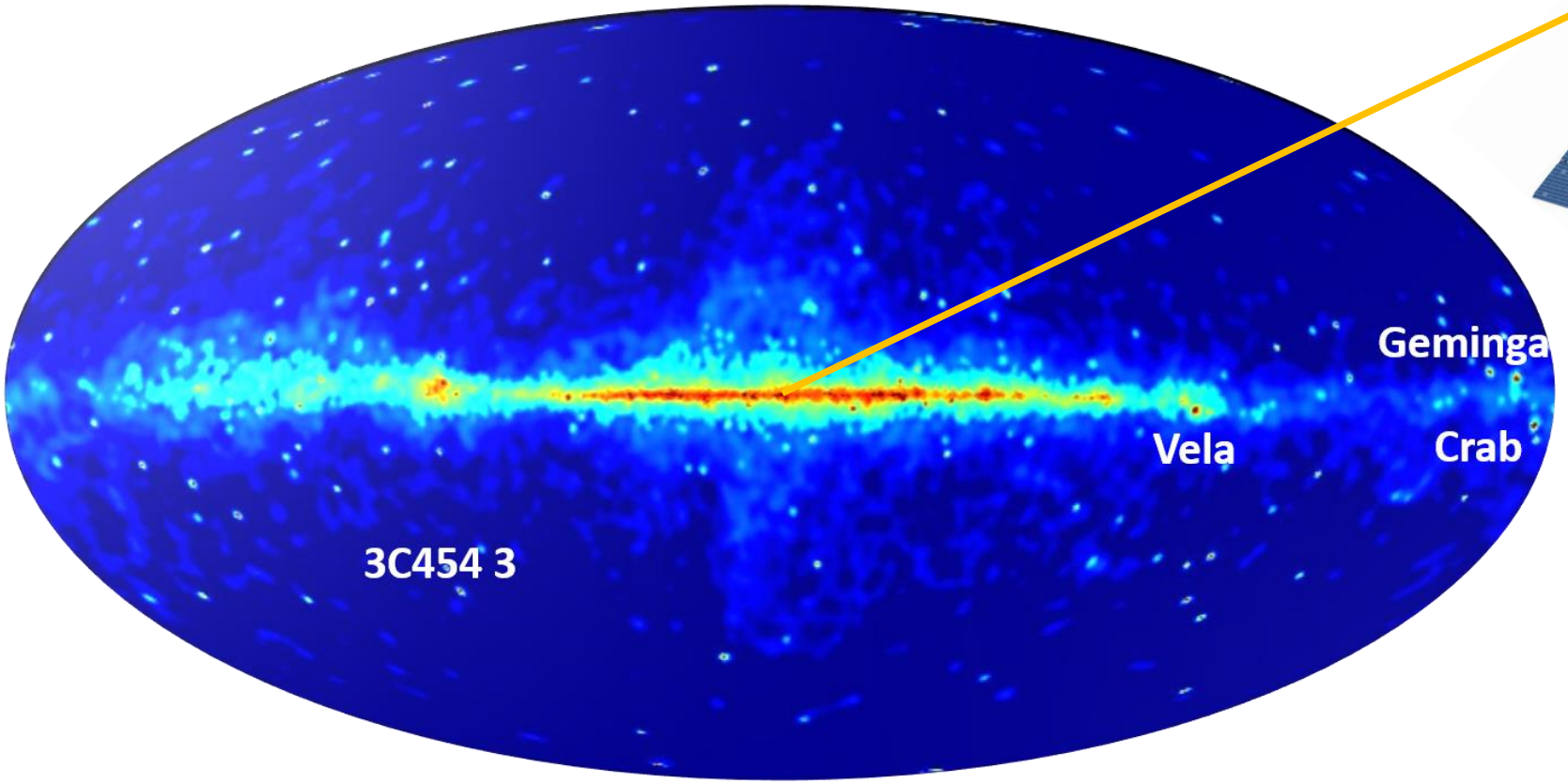
- $\gamma´s$ point back to their origin (the GC): no deflection in galactic B –fields
- $\gamma´s$ suffer no energy losses from the GC
- $\gamma´s$ can be detected by satellites or by IACTs



GeV ... TeV:
Imaging **A**tmospheric **C**herenkov **T**elescope

Gammas as DMA messengers from the galaxy

- **We have very detailed maps of the GeV – gamma sky**



GeV:
Fermi observatory

- many astrophysical gamma sources*: $SNRs$, pulsars, ISM,…

- column density of the entire galaxy
$\rho d = 38\ g/cm^2$

*see chapter 2.1.3 Gamma Telescopes

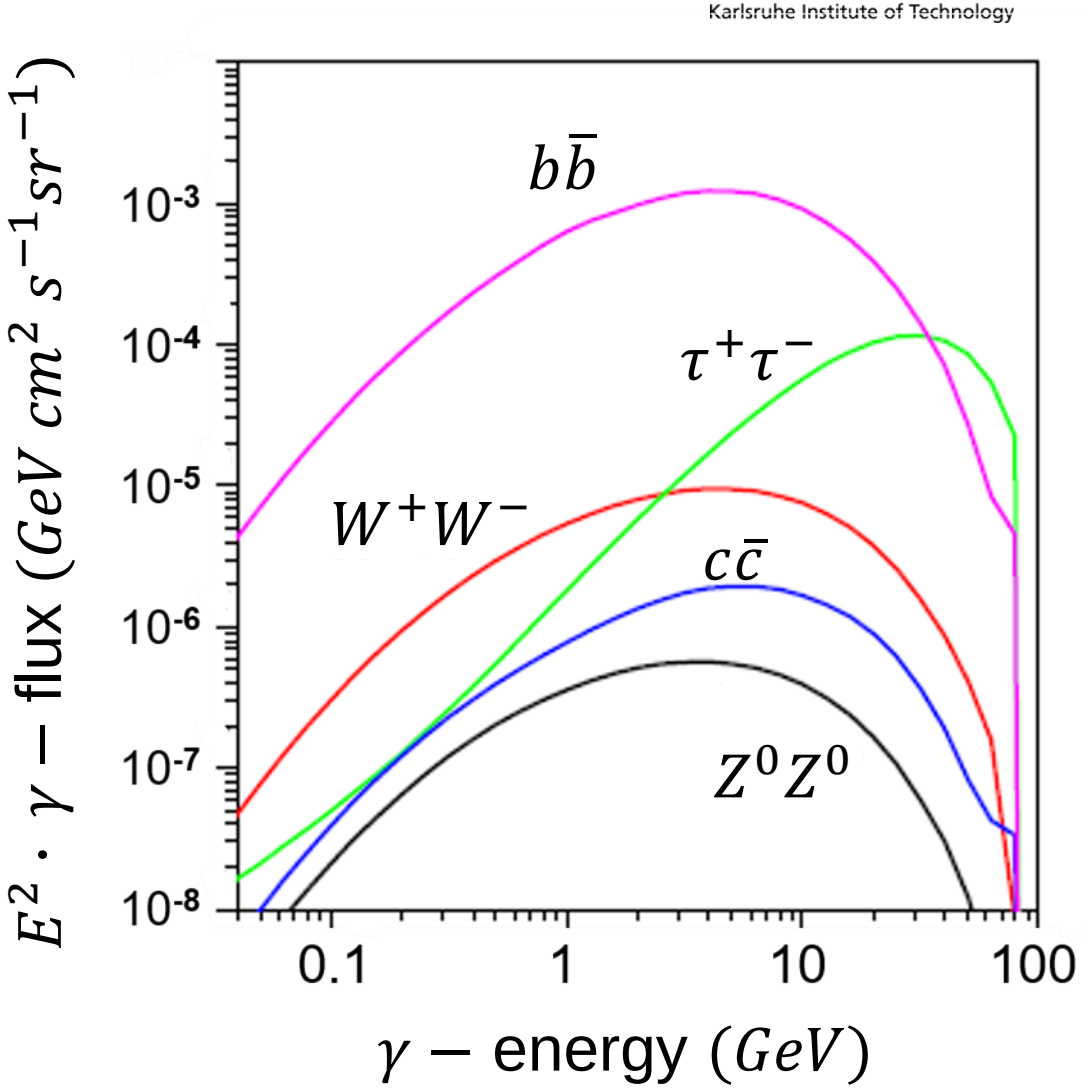
Gammas as DMA messengers: expected energies

- **Expected distributions strongly depend on annihilation channels**

  - we expect about $\mathbf{30 \ldots 40}\ \boldsymbol{\gamma' s}$ from quark fragmentation processes (GeV – scale)

  - maximum γ – energy extends up to **mass of WIMP** (here: $80\ GeV$)

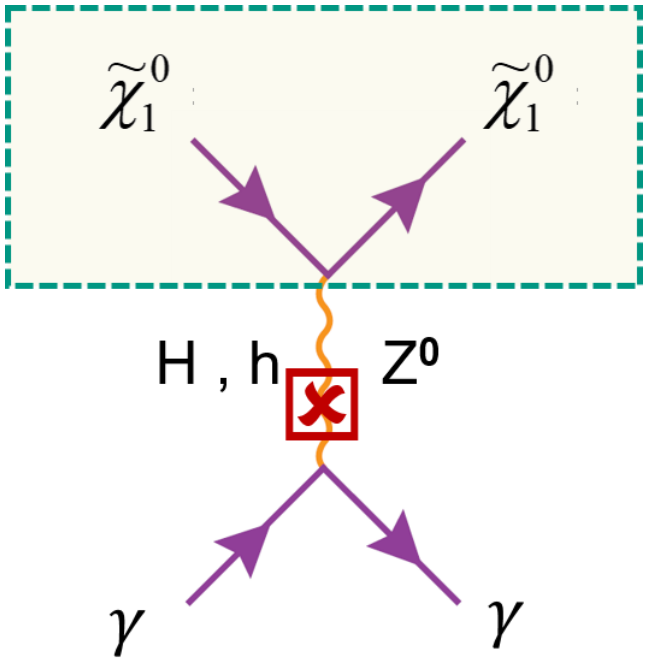
  - γ – energy distribution depends on the (unknown) dominant annihilation channel ($\rightarrow b\bar{b}, \ldots$)



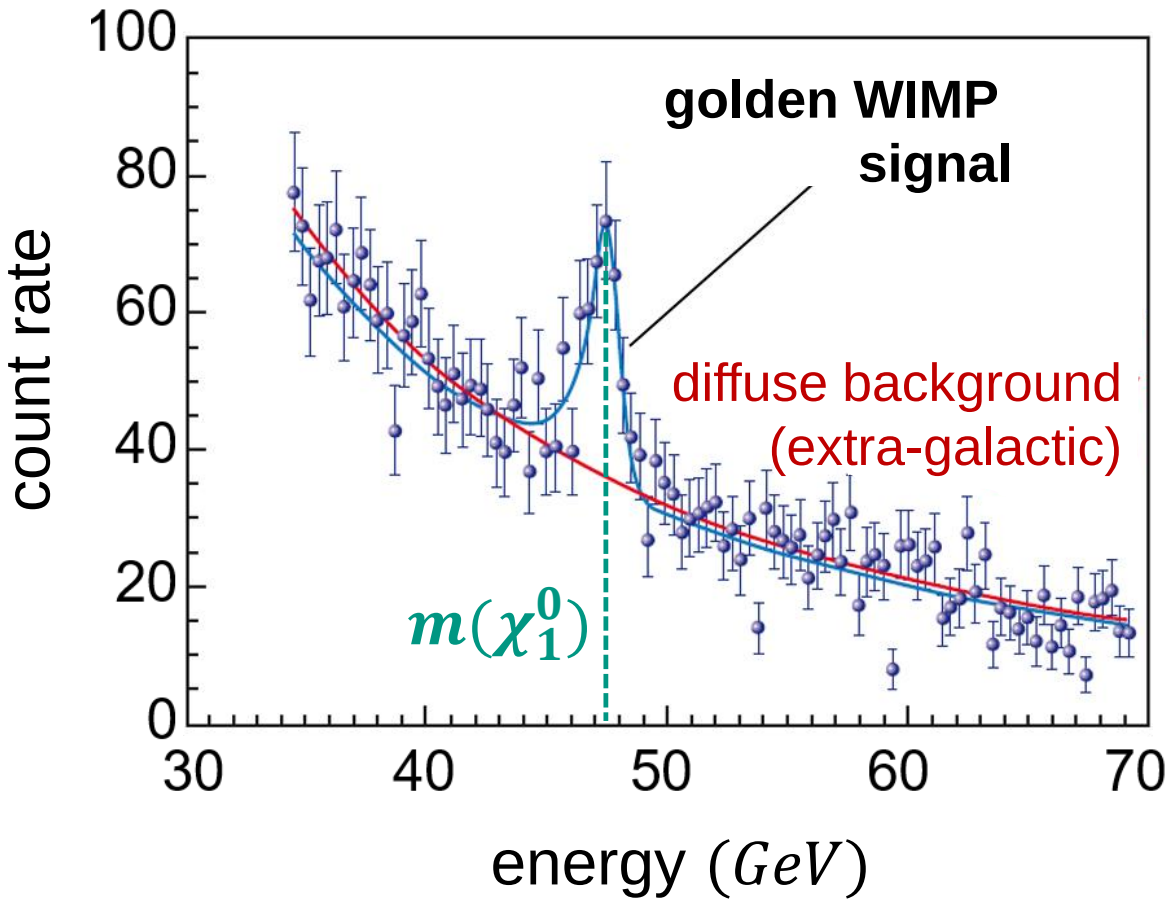
Gammas as DMA messengers: golden signal

- **Hopes of identifying a ´*smoking gun*´ of DMA via a (golden) γ –line at $m(\chi_1^0)$**

- line-signal from $\tilde{\chi}^0\tilde{\chi}^0 \rightarrow \gamma\gamma$ is suppressed,
  ⇨ no coupling on tree level, only via loops

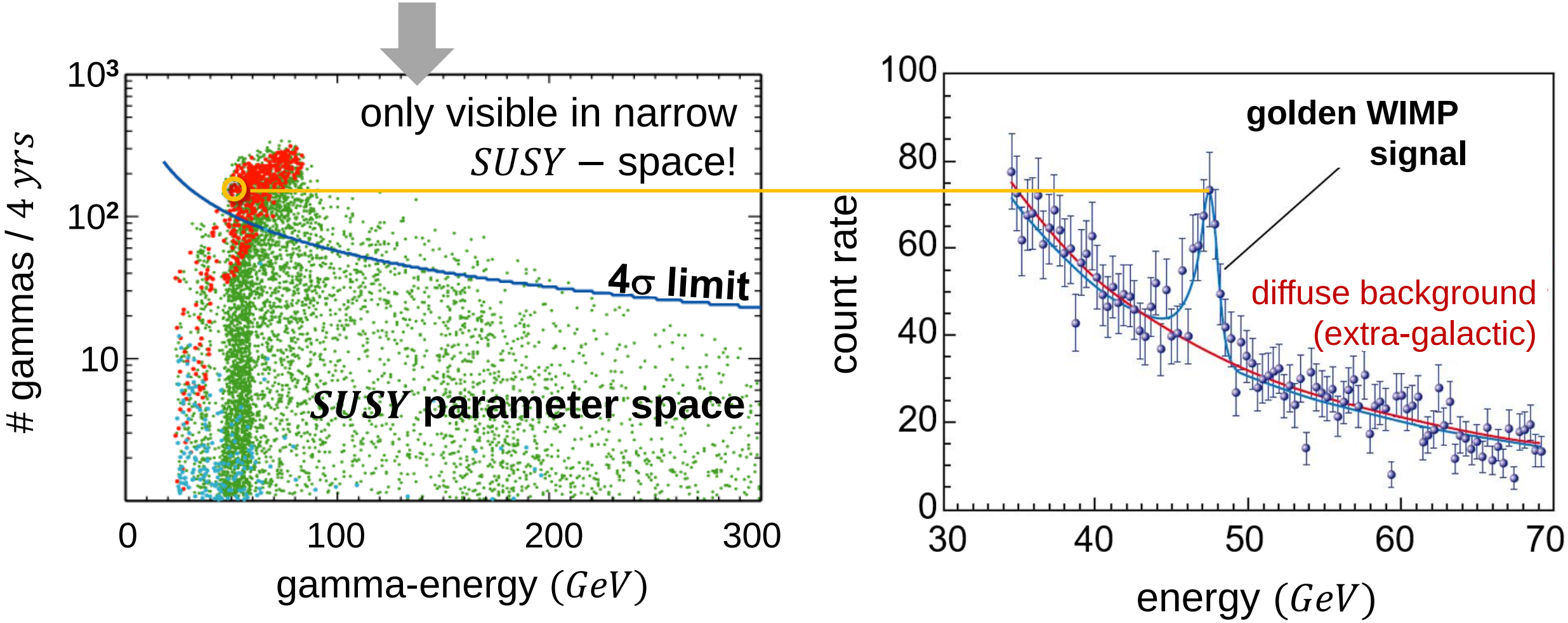


„smoking gun“



Gammas as DMA messengers: golden signal

- no ´*smoking gun*´ of DMA via γ –line at $m(\chi_1^0)$ observed in data of FERMI



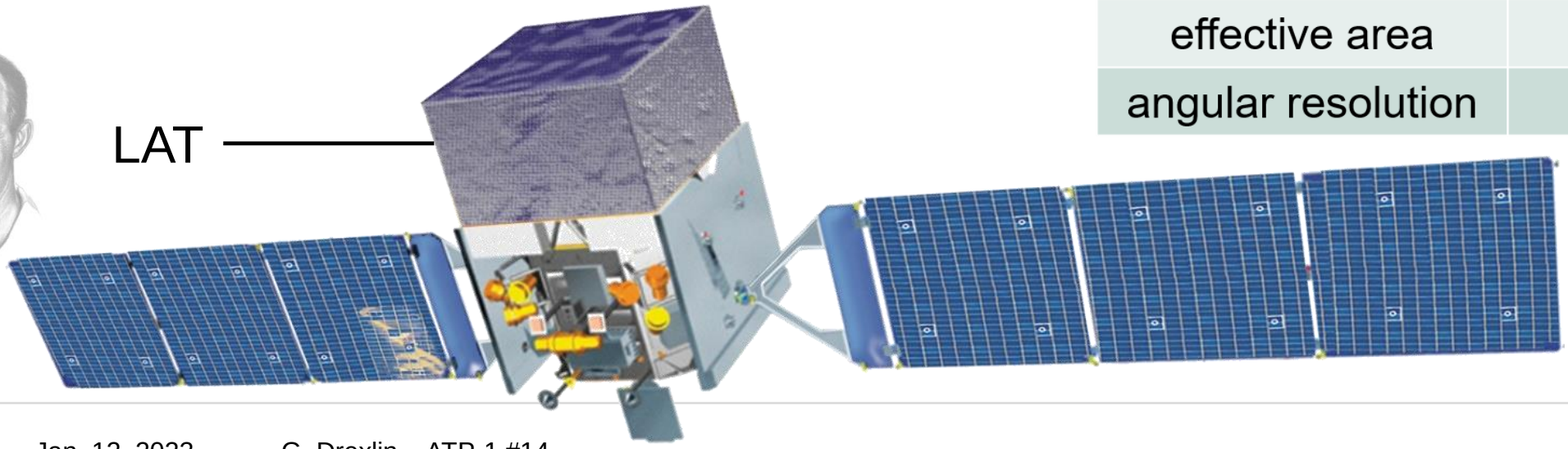
Gammas as DMA messengers: FERMI

- **Fermi Gamma Ray Telescope: the most sensitive GeV – gamma observatory**

- goal: long-term study of gamma ray sky
  large area, high angular resolution

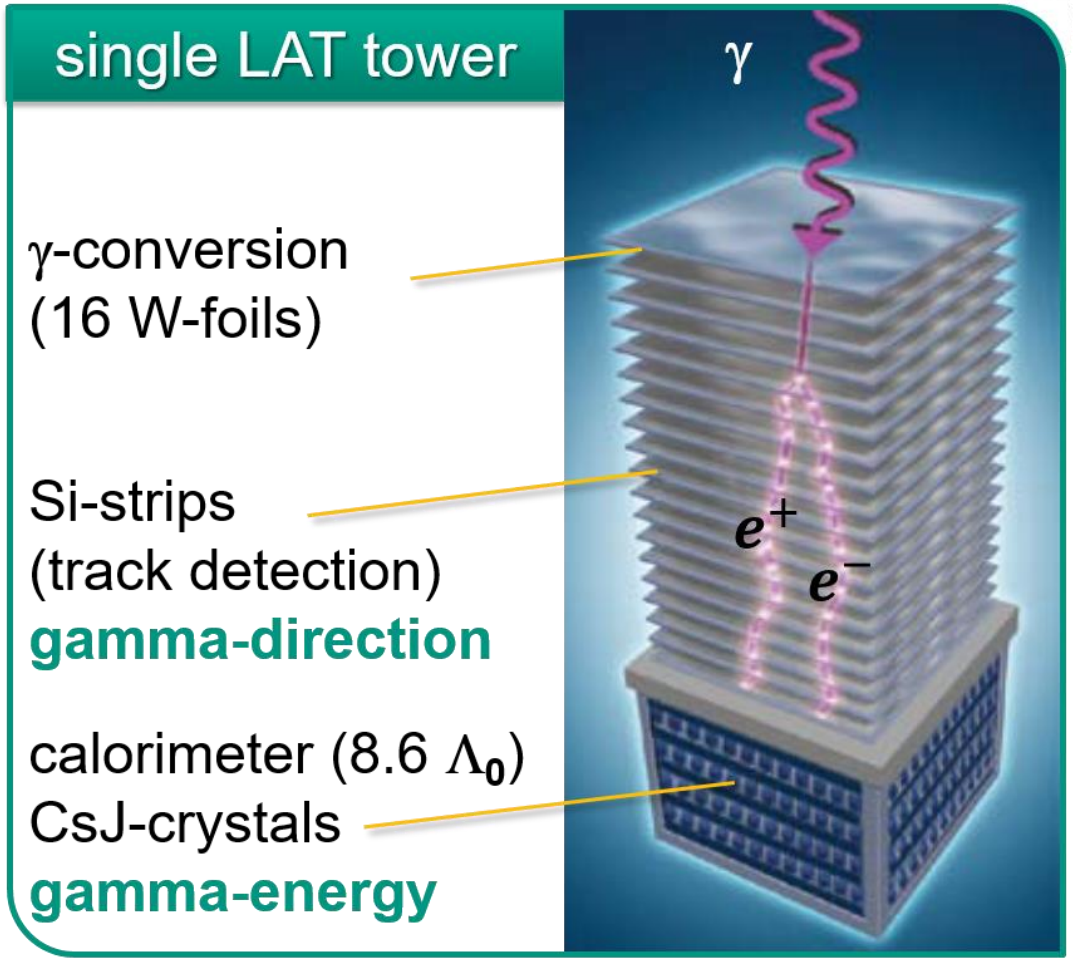
- key instrument: **L**arge **A**rea **T**elescope (**LAT**)
  ⇨ detect gammas via **pair conversion**

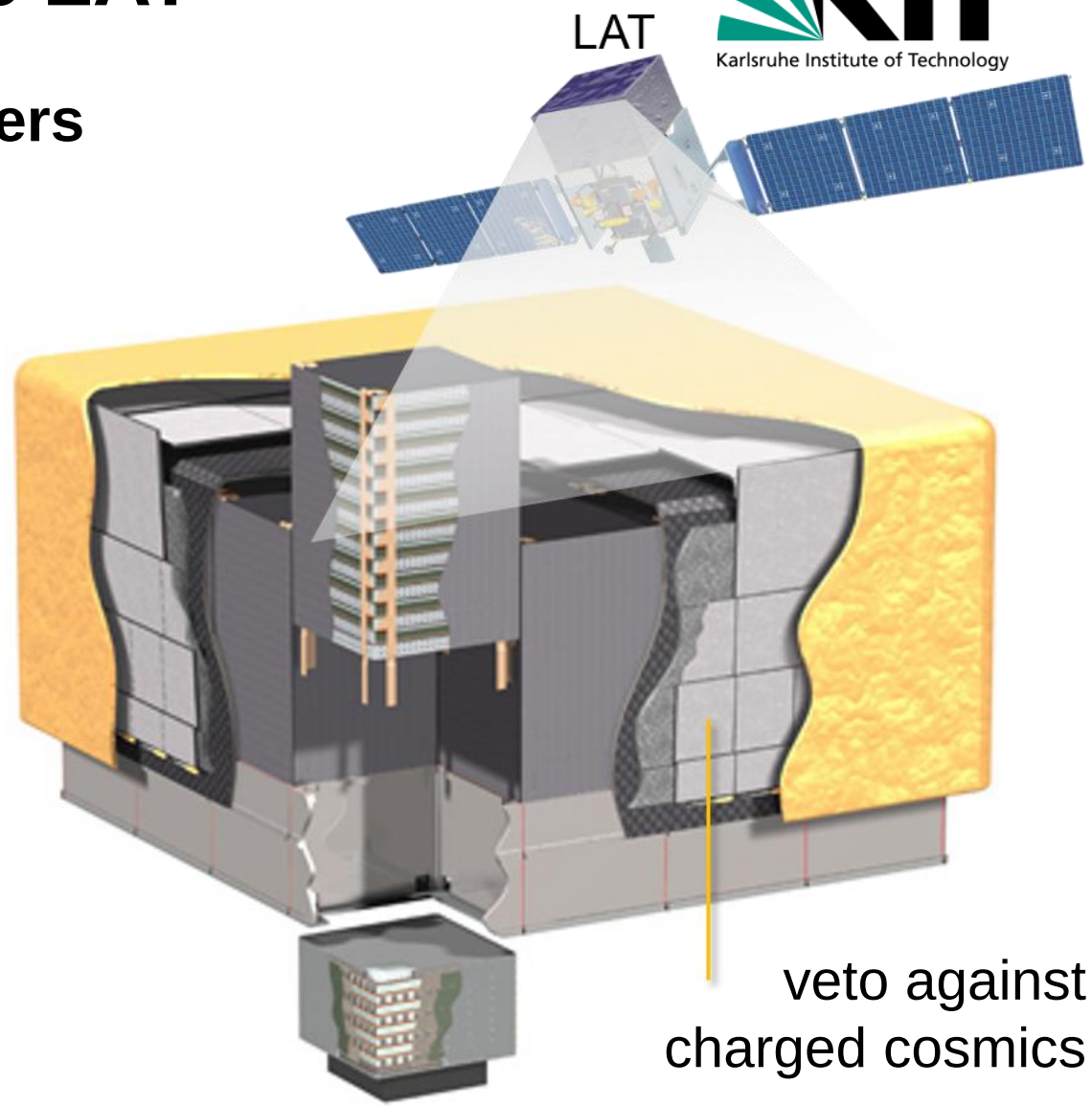
Fermi satellite mission	
Data taking	since mid-2008
orbit	560 km
dimensions	2.8 m(h) × 2.5 m(Ø)
mass	4.3 t
γ-energies	**20 MeV – 300 GeV**
effective area	1 m²
angular resolution	**~ 1´**



Fermi: the Large Area Telescope LAT

- **Pair conversion of gammas with 16 towers**



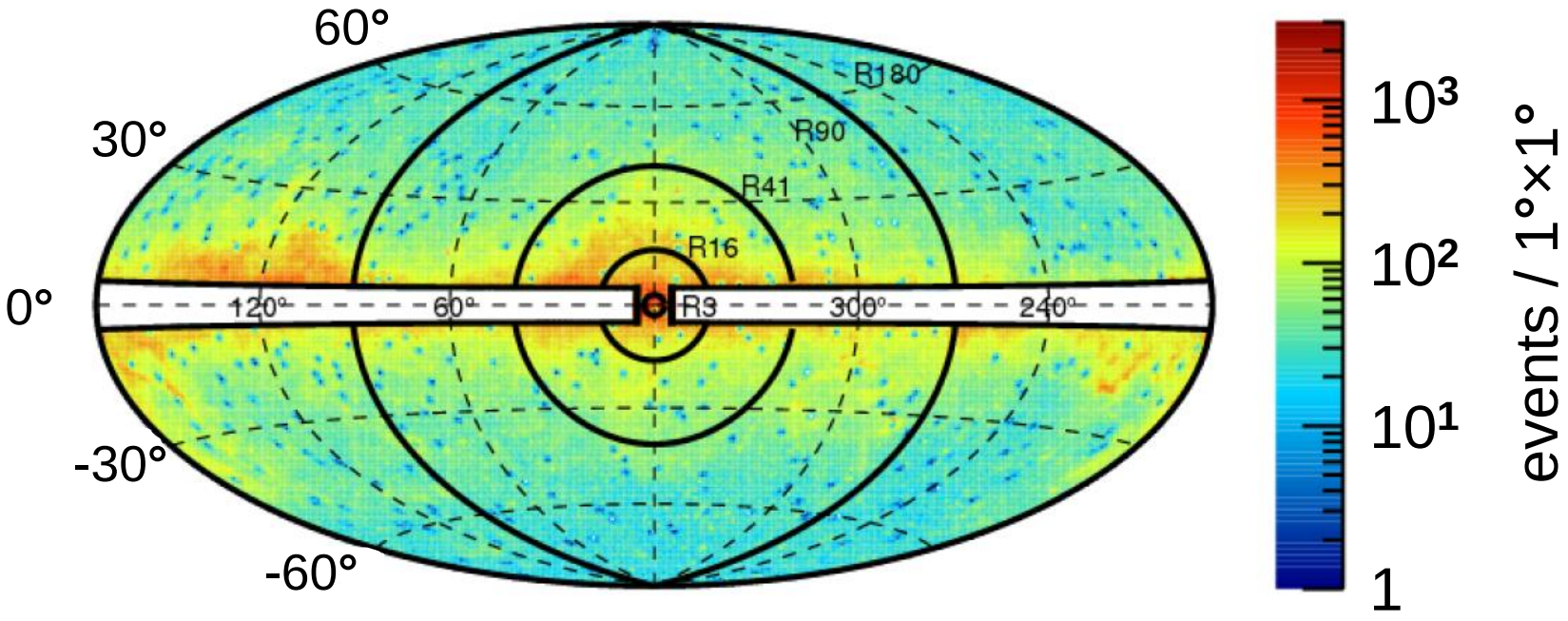


How do you look for a DMA signal in the sky?

- **Mollweide projection of Fermi-LAT data focused on galactic center (R3)**

  - we define a series of **ROI**s (**R**egions-**O**f-**I**nterest) R3 - 3° / R16 - 16° / R41 - 41°

  - we expect & search for a DMA-signal in the innermost region R3 - 3°



Fermi observes an excess at the galactic center

- **2014/15: is this a signal of DMA (*aka* the ´Hooperon*´) or ´just some pulsars´**

- from innermost galactic region $r < 1.5\ kpc$ ☑

- but: rather low γ –energies $E_\gamma = 1 \ldots 3\ GeV$ ☒

- (boldly!) interpreted as **WIMP-signature**

  fitted mass: $m(\chi_1^0) = 31 - 40\ GeV$

  DMA channel: $\chi_1^0 + \chi_1^0 \rightarrow b\bar{b}$

- since then: **very** controversial discussions about this interpretation of the γ – excess

- (likeky) astrophysical explanation: ms – pulsars

Mysterious galactic signal points LHC to dark matter

High-energy particles at centre of Milky Way now within scope of Large Hadron Collider.

Davide Castelvecchi

05 May 2015 | Corrected: 06 May 2015

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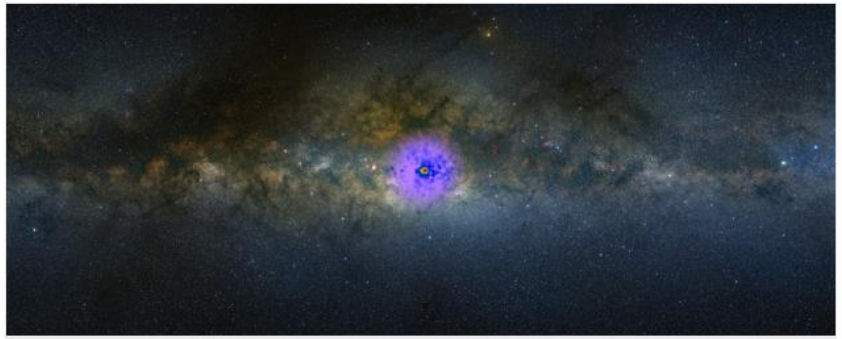
nature.com



A. Mellinger, CMU; T. Linden, Univ. of Chicago/NASA Goddard

γ-rays (shown in false colour) emitted from the Galactic Centre are giving the LHC a firm target in its hunt for dark matter.

It is one of the most disputed observations in physics. But an explanation may be in sight for a mysterious excess of high-energy photons at the centre of the Milky Way. The latest analysis[1] suggests that the signal could come from a dark-matter particle that has just the right mass to show up at the world's largest particle accelerator.

The Large Hadron Collider (LHC), housed at the CERN particle-physics laboratory near Geneva, Switzerland, is due to restart colliding protons this summer after a two-year hiatus (see 'LHC 2.0: A

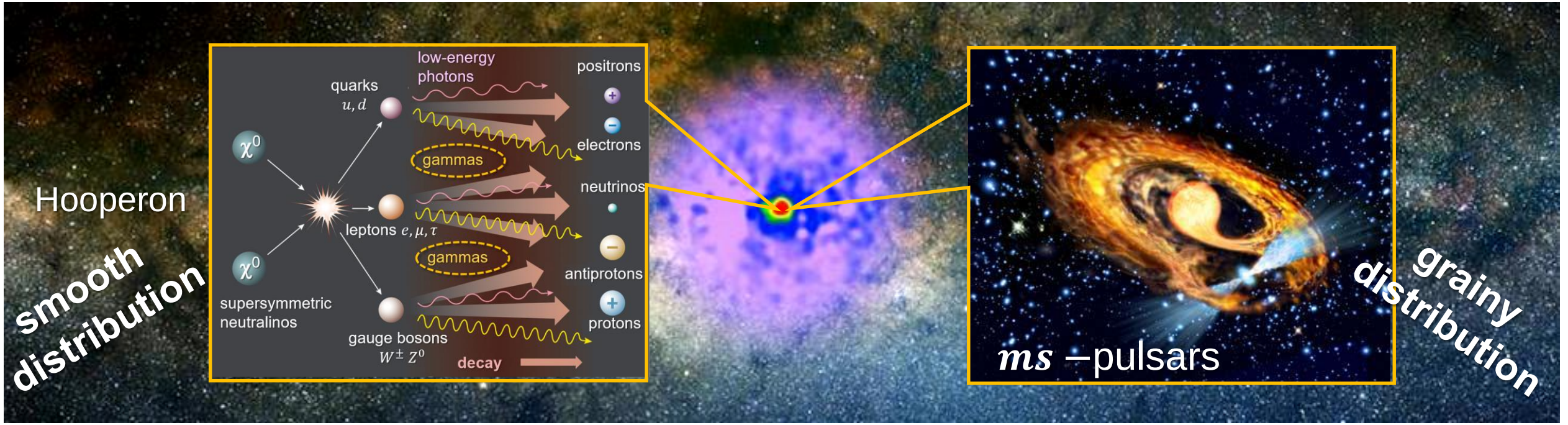
*this is a pun name for χ_1^0 , coined after the first author

Fermi observes an excess at the galactic center

- **2014/15: is this a signal of DMA (*aka* the ´Hooperon´) or ´just some pulsars´**

  - DMA interpretation: annihilation of ´**Hooperons**´ into GeV – scale gammas

  - astrophysics interpretation: a new class of $\boldsymbol{ms}$ **–pulsars** at the galactic center

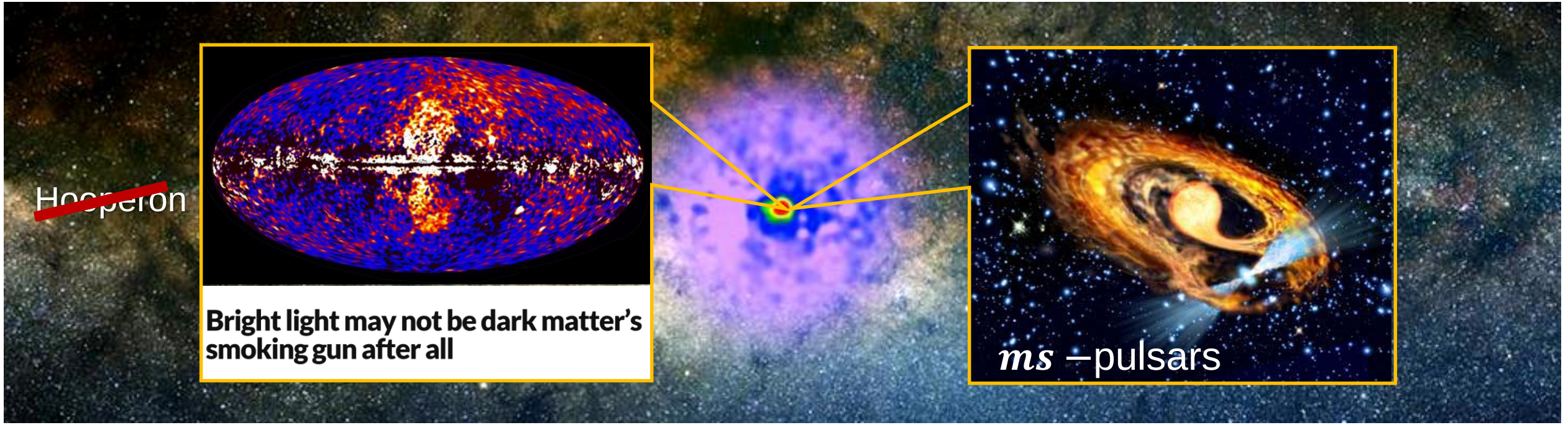


Fermi observes an excess at the galactic center

- **2014/15: is this a signal of DMA (*aka* the ´Hooperon´) or ´just some pulsars´**

  - update: **no evidence** for a Hooperon in DMA search focused on dwarf galaxies

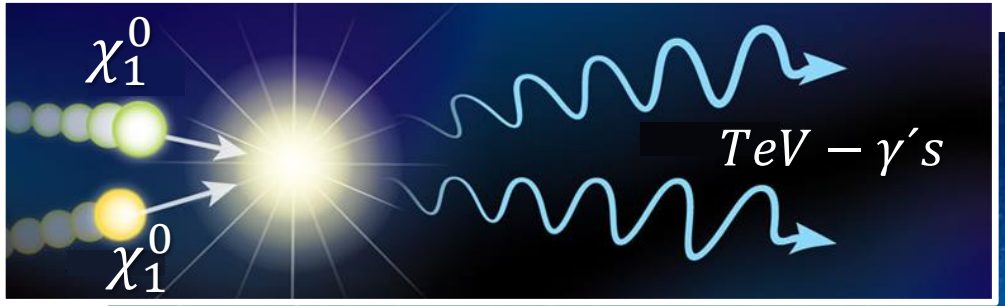
  - astrophysics interpretation: a new class of ms **–pulsars** at the galactic center ☑



Let´s search for a DMA signal in the $TeV\ \gamma-$ sky

- **Using Imaging Atmospheric Cherenkov Telecopes to hunt a DMA signal**

  - if neutralinos are very massive we expect a DMA-signal in the TeV – range



H.E.S.S.

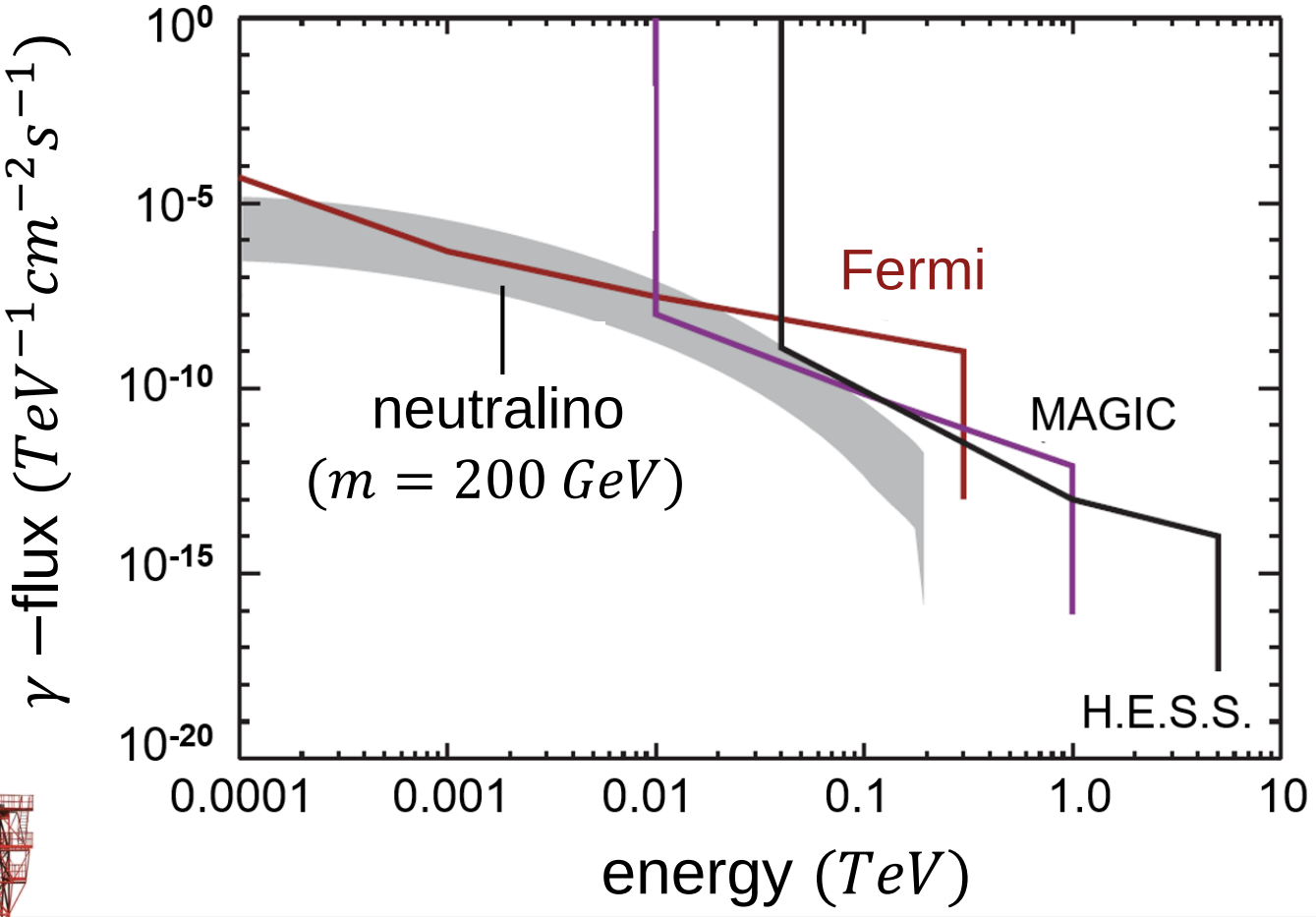
Comparing the DMA sensitivites

- **A clear advantage of IACTs: we extend DMA searches to higher γ –energies**

- IACTs: extended energy range, excellent angular resolution, but rather narrow field-of-view

- IACTs: long exposures required due to small DMA γ – fluxes from TeV – scale (very heavy) neutralinos

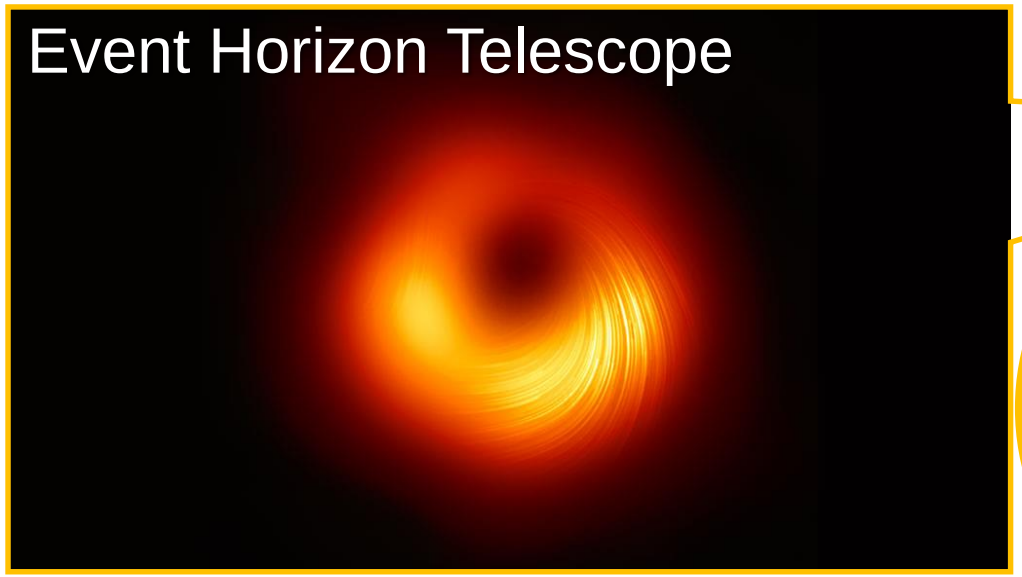
$$\Phi_{Ann} \sim \frac{1}{m_{CDM}^2}$$



Let´s point our IACT to the galactic center

- **Using Imaging Atmospheric Cherenkov Telecopes to hunt a DMA signal**

  - the galactic center is a very active place with a central supermassive black hole
    ⇨ many astrophysical sources!



Let´s point our IACT to the galactic center

- **Using Imaging Atmospheric Cherenkov Telecopes to hunt a DMA signal**

  - the galactic center is a very active place with a central supermassive black hole
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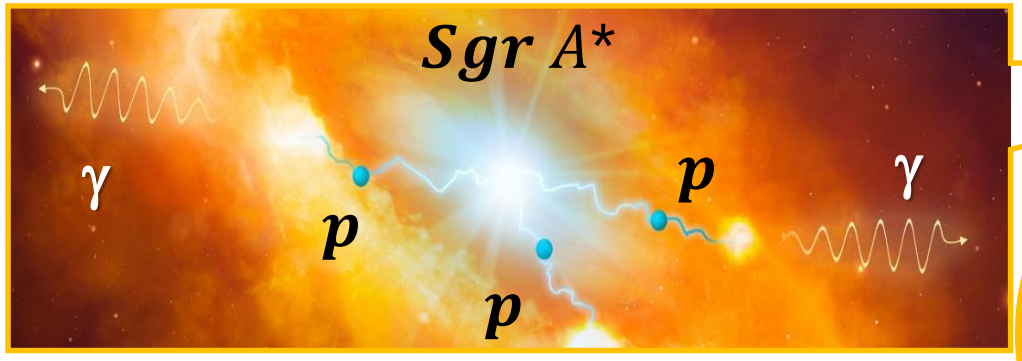
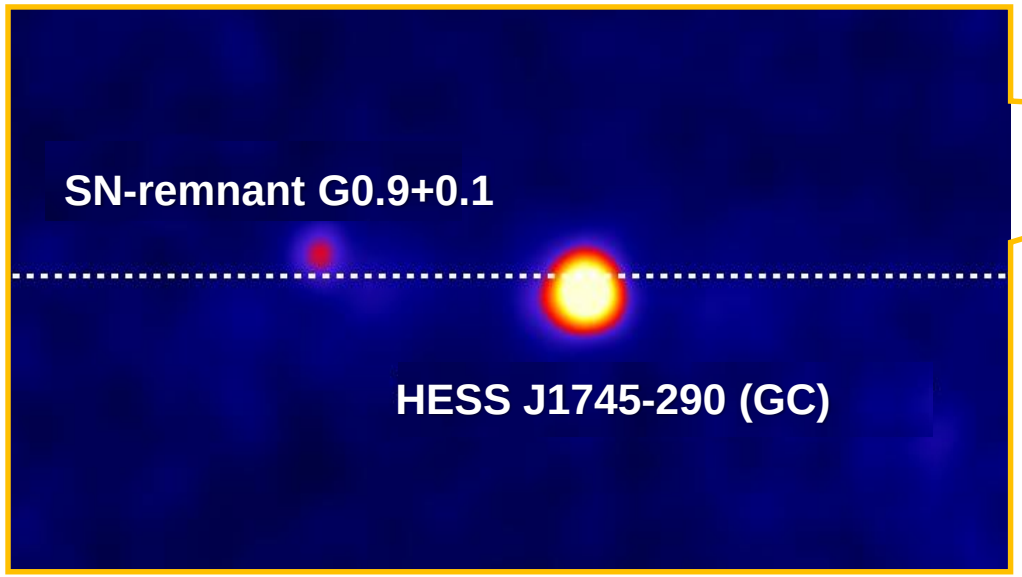


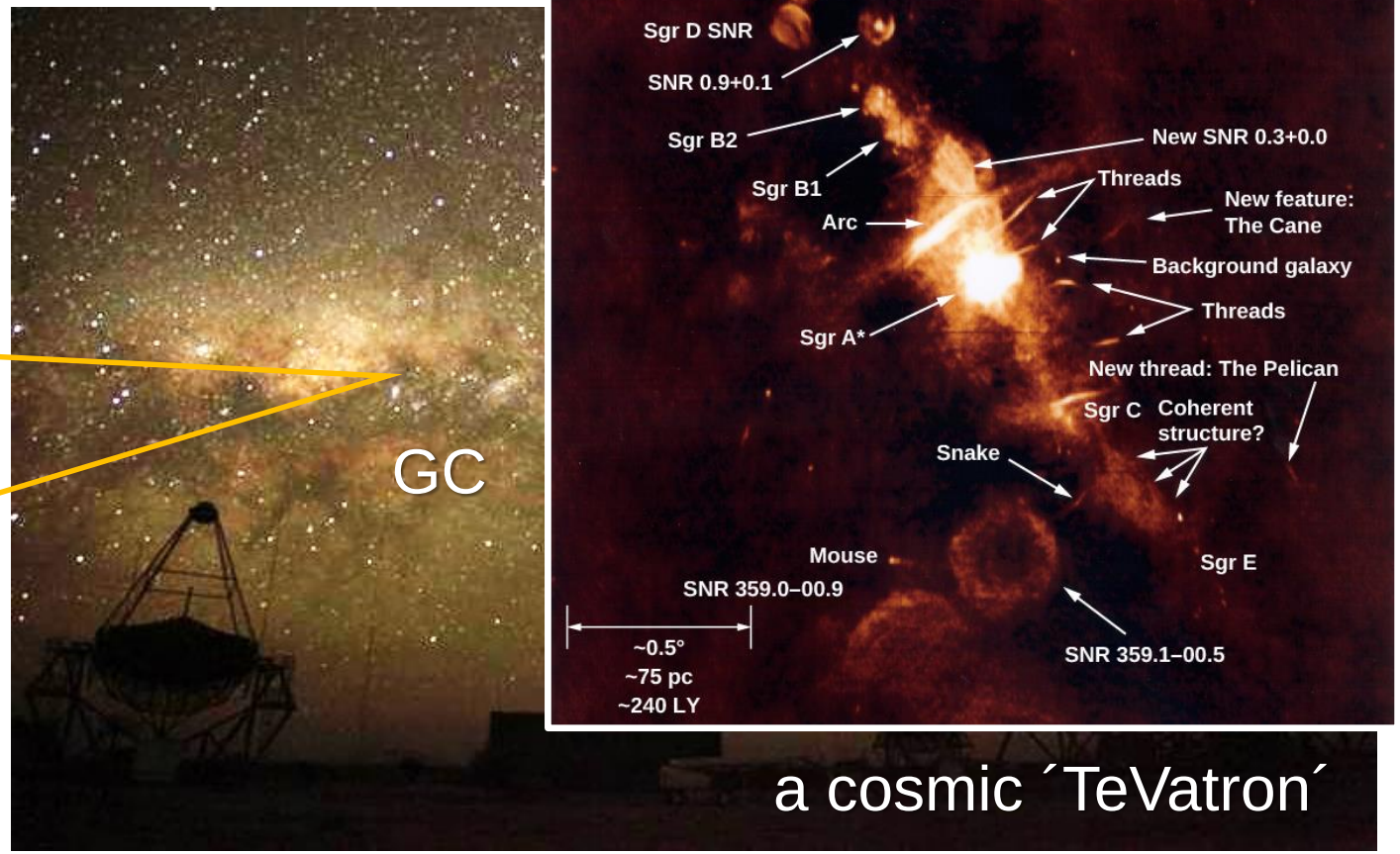
will we be able to see a DMA signal there?

Let´s point our IACT to the galactic center

- **the GC: a supermassive black hole & many SN remnants – all close together**

  - we see a clear signal at $TeV - \gamma$ –energies from the galactic center! Is this coming from DMA indeed??

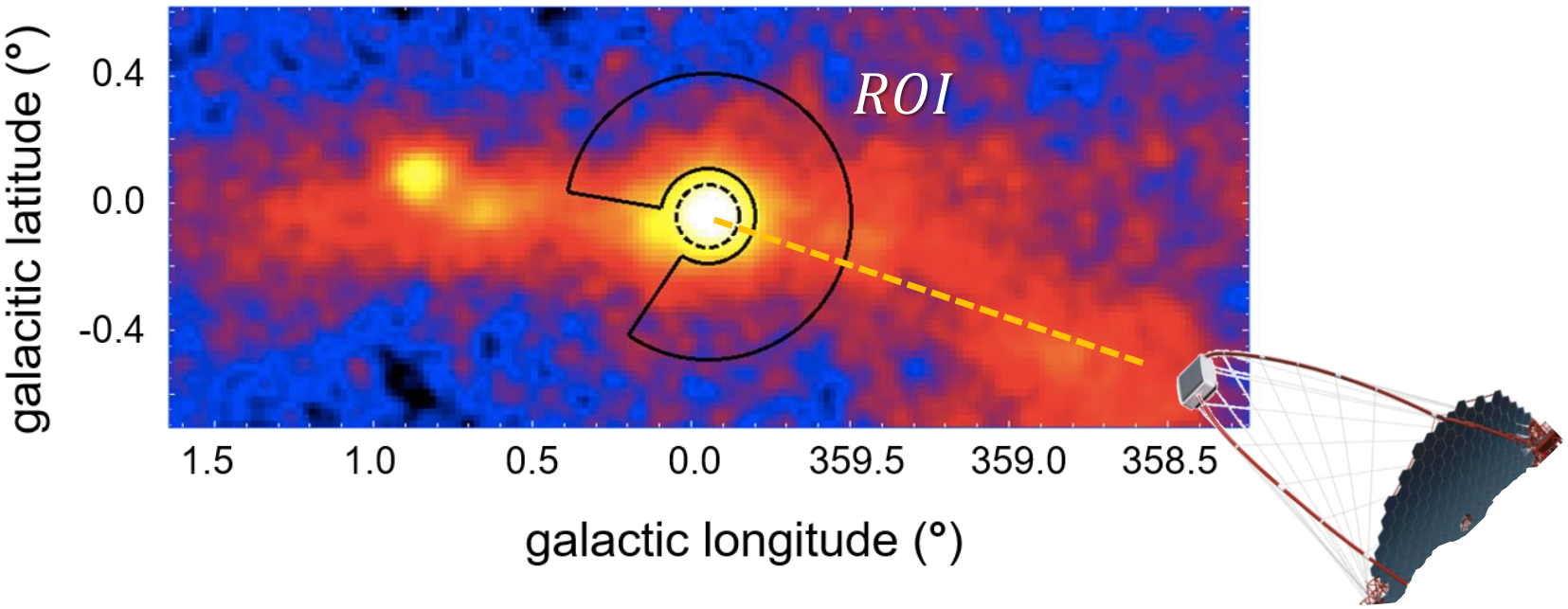


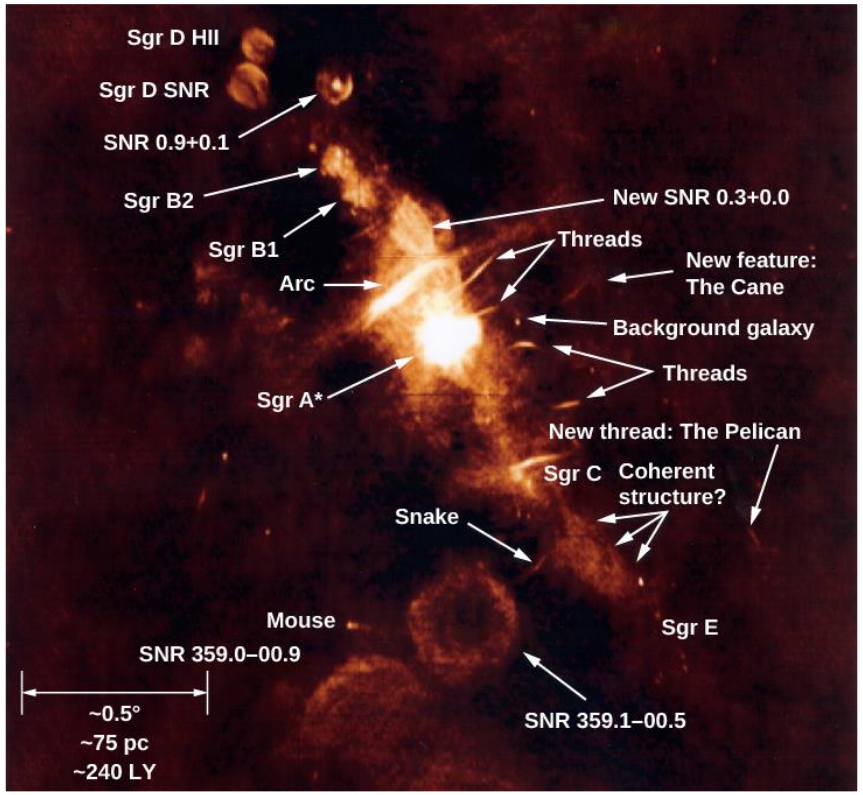


Let´s point our IACT to the galactic center

- **the GC: zoom in please – we want to focus on the very heart of our galaxy**

  - we compare different Regions-Of-Interest (ROI), similar to the Fermi analysis at lower energies

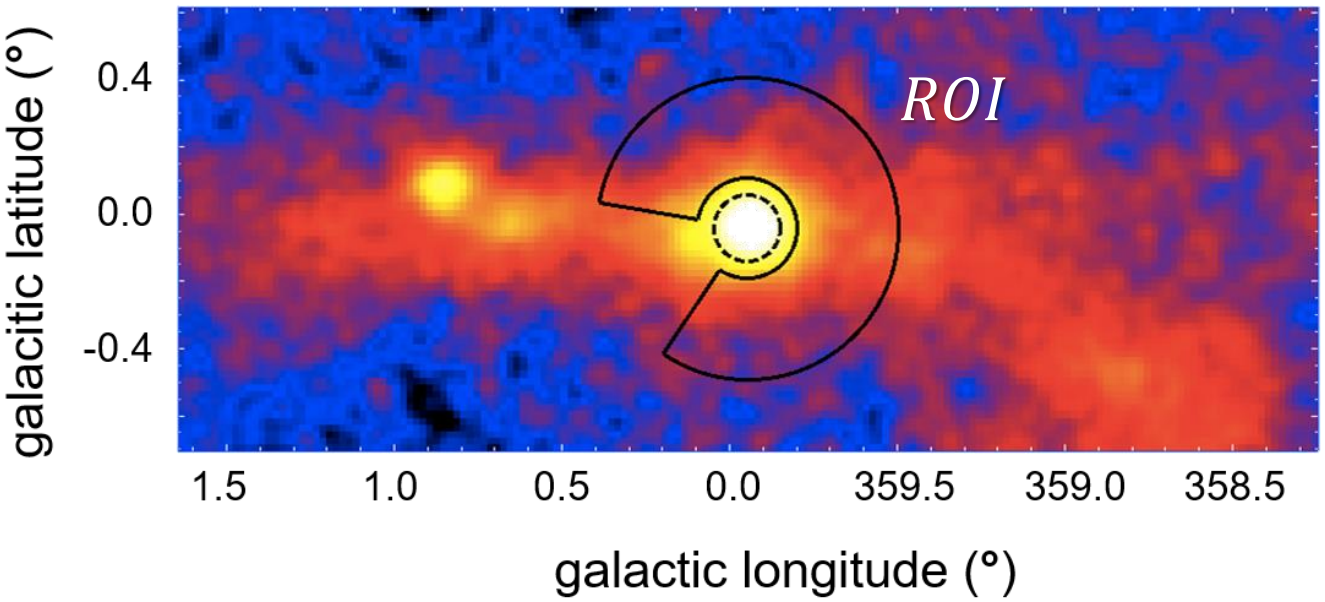


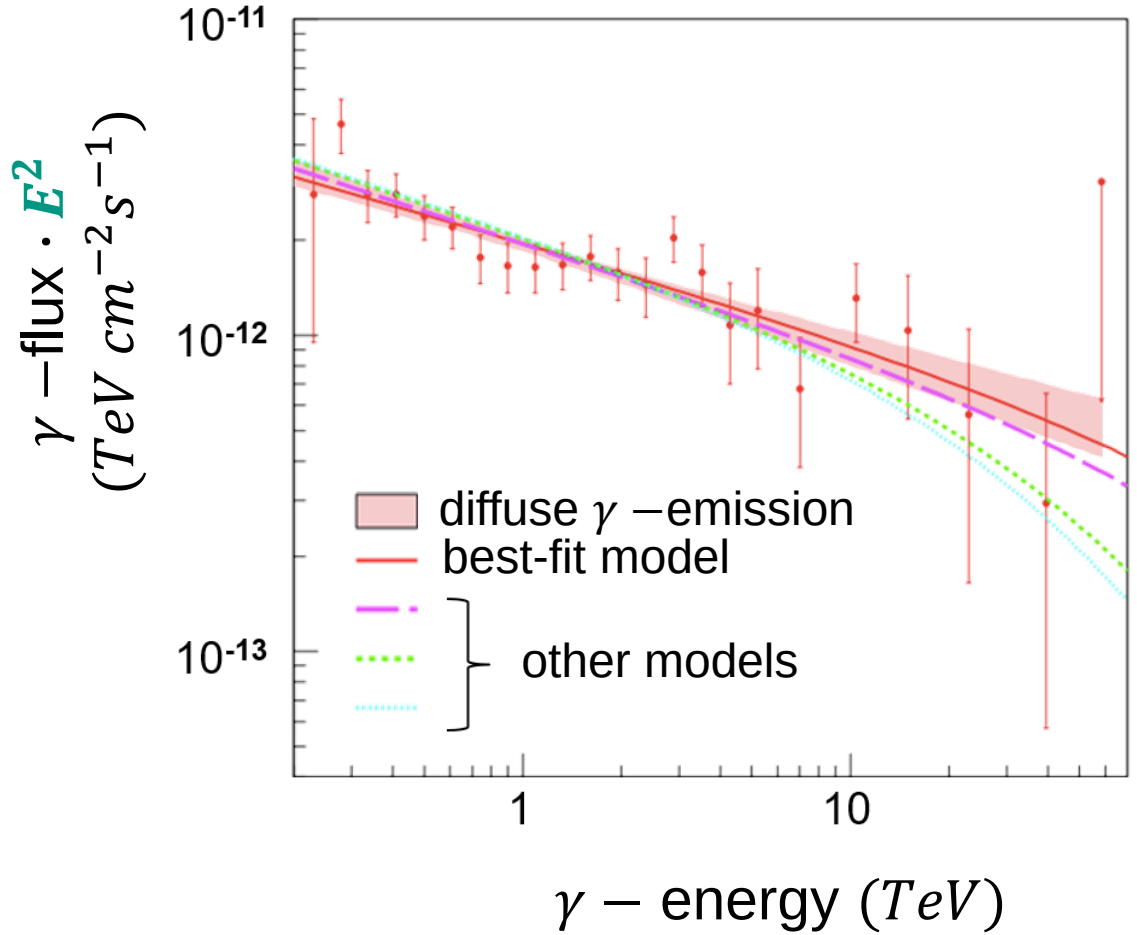


IACT results from the galactic center

- **the GC: a featureless power-law spectrum, a clear induction of astrophysics**

  - innermost ROI: gammas from acceleration of charged particles & subsequent γ – production

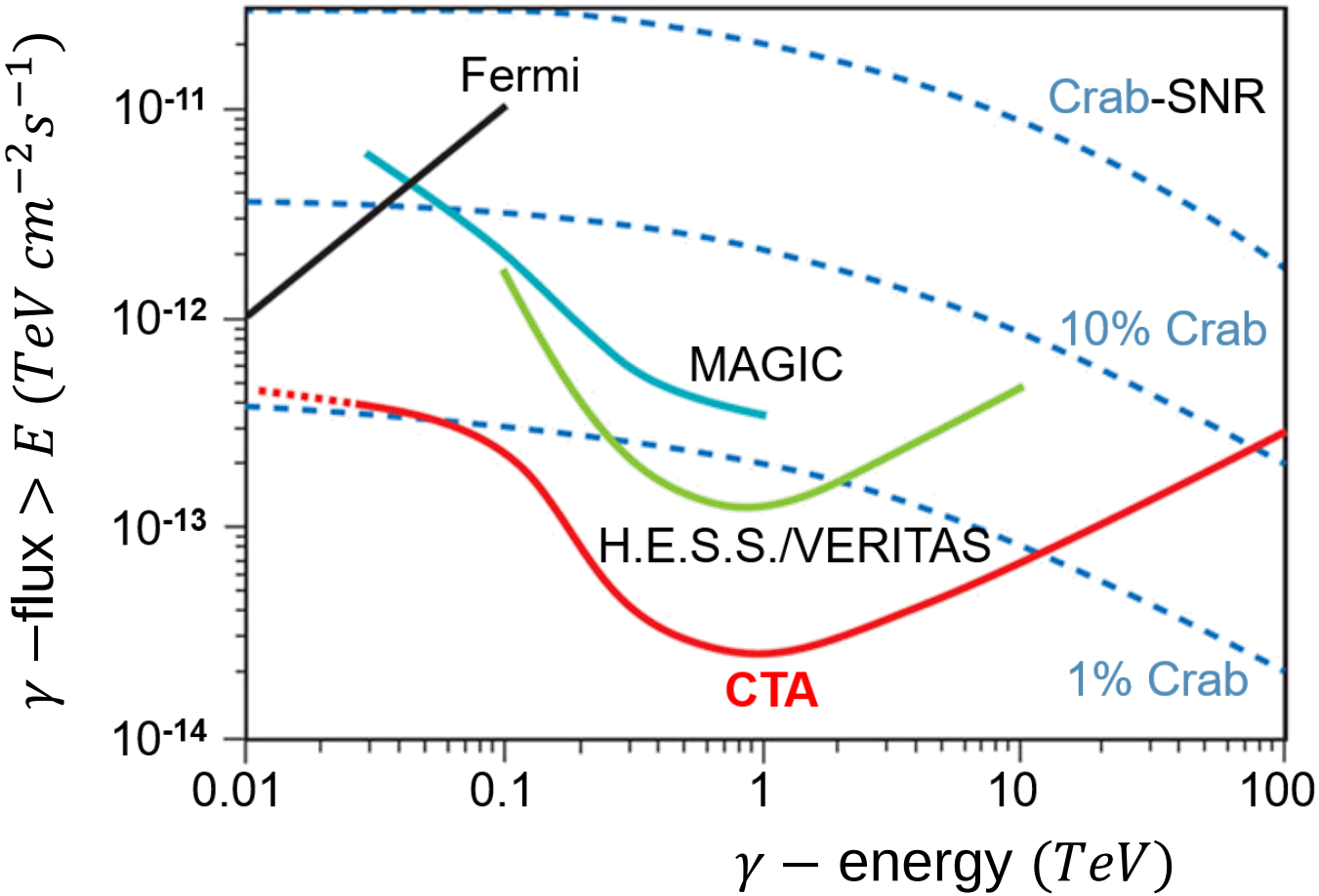




IACT results in the future: expected CTA limits

- **The future Cherenkov Telescope Array will search for DMA signals**

  - CTA will look for DMA at the
    - galactic center
    - galactic halo



IACT results in the future: expected CTA limits

- **The future Cherenkov Telescope Array will search for DMA signals**

  - CTA will look for DMA at
    - **dwarf spheroidals**

      ⇨ ideally suited as 99% DM!

optical (photo)

stars

γ´s (MC)

DMA