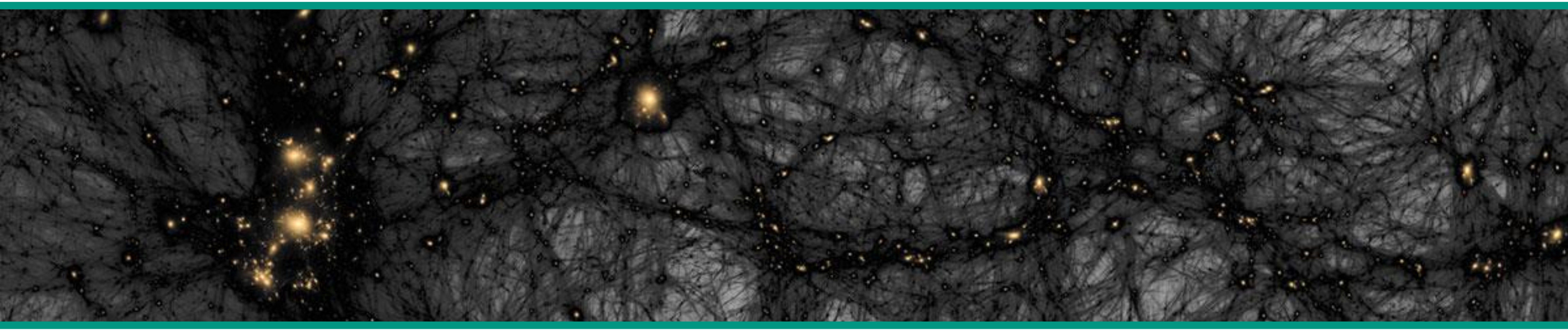
Astroparticle physics *I* – Dark Matter

Winter term 23/24 Lecture 14 Dec. 21, 2023



Recap of Lecture 13

- **Dark Matter:** $\boldsymbol{SUSY}$ & **how to build a successful** $\boldsymbol{CDM -}$ **candidate**

  - we can order $\boldsymbol{DM}$ candidates along their mass $\boldsymbol{m}$ & cross section $\boldsymbol{\sigma_{tot}}$

  - $\boldsymbol{WIMPs}$: $\boldsymbol{SUSY}$ connects **fermions** ⇔ **bosons**, important $\boldsymbol{R}$ – parity $\boldsymbol{R_P = +1, -1}$

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

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

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

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

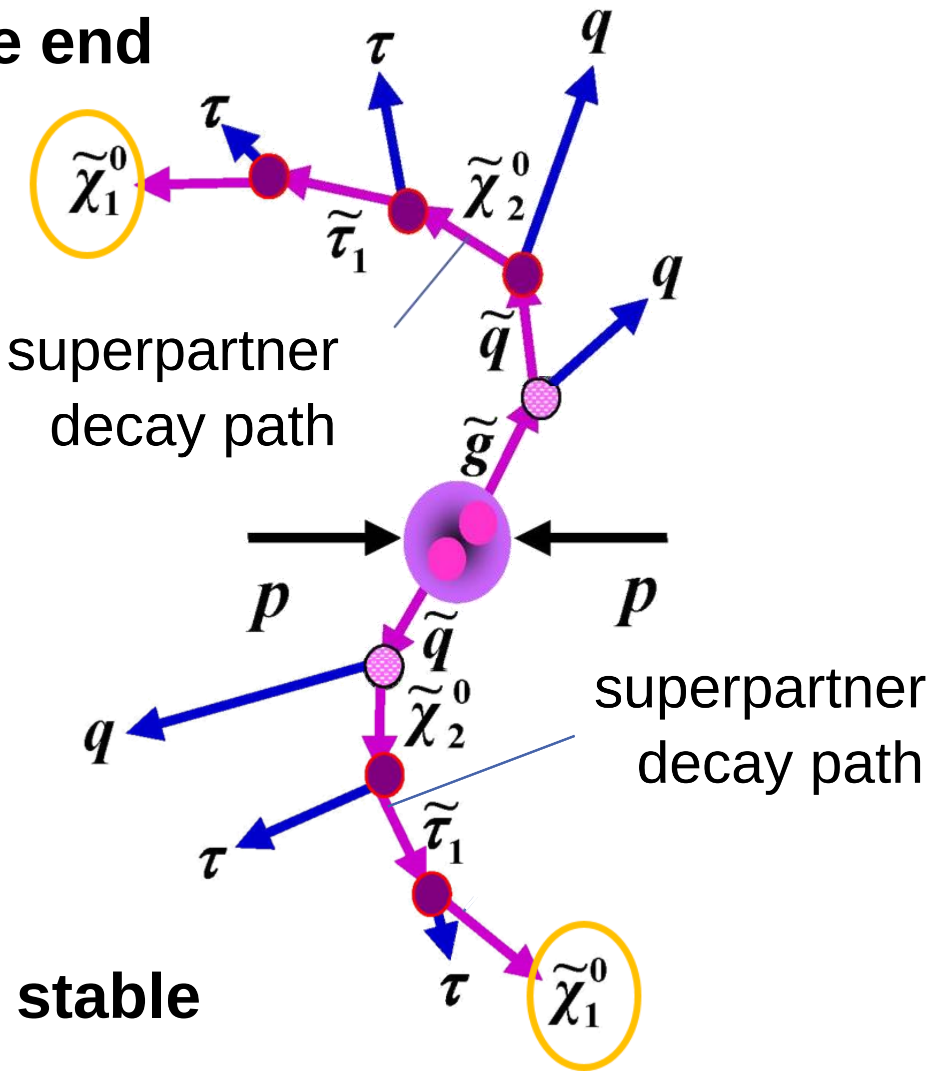
$SUSY$ – signatures at the LHC experiments

- $\boldsymbol{neutralinos}$ **escape the detector region at the end of a superpartner decay chain**

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

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

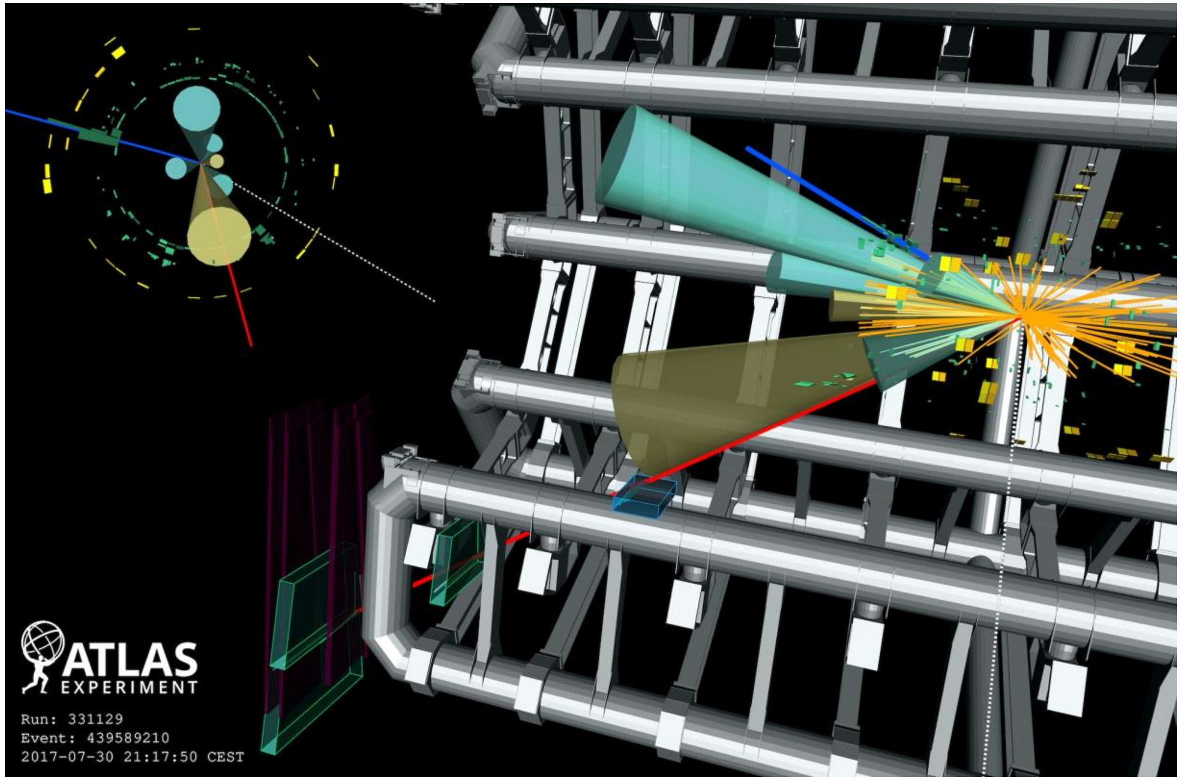
  - missing energy / momentum carried away:
    lightest $\boldsymbol{SUSY}$ – particle ($\boldsymbol{LSP} = \boldsymbol{neutralino}$) is **stable**

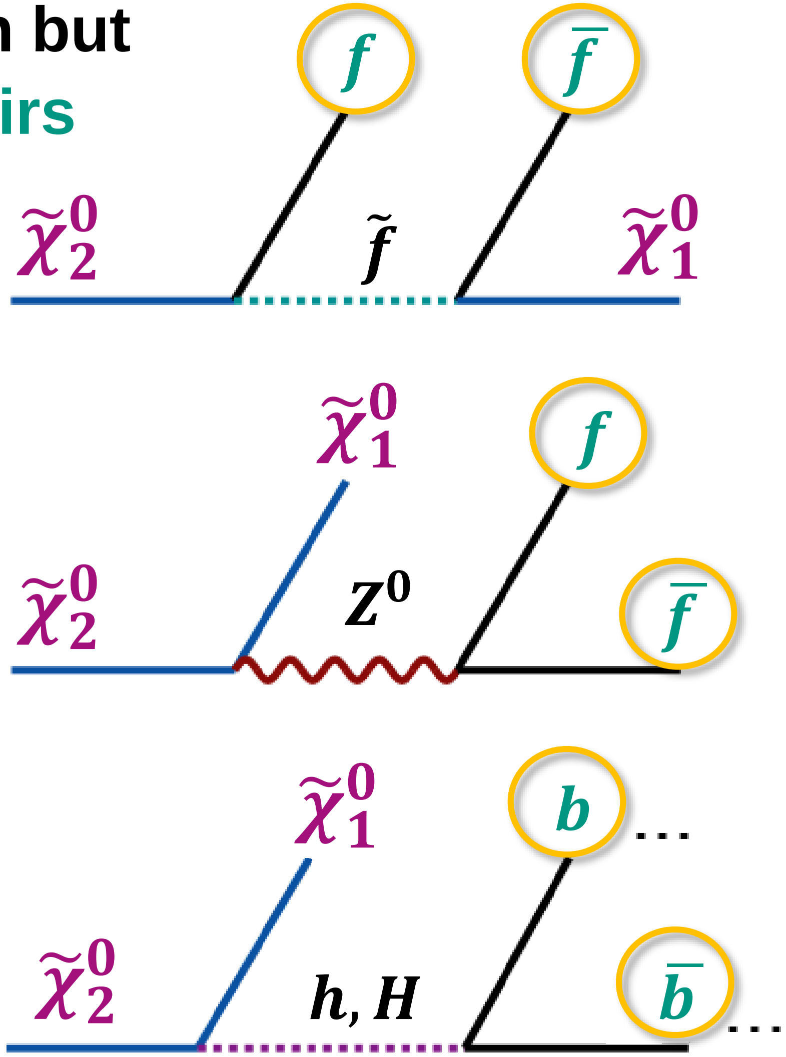


$SUSY$ – signatures at the LHC experiments

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

  - signature: lepton pairs, hadrons,…



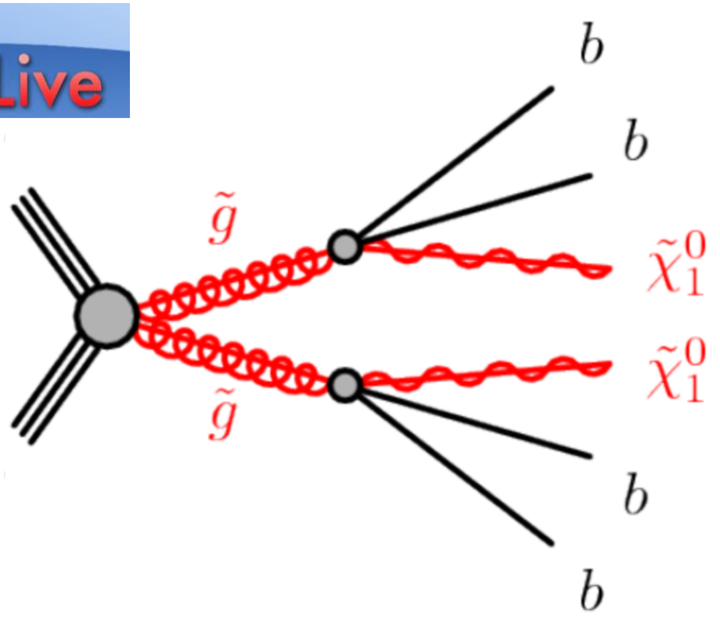


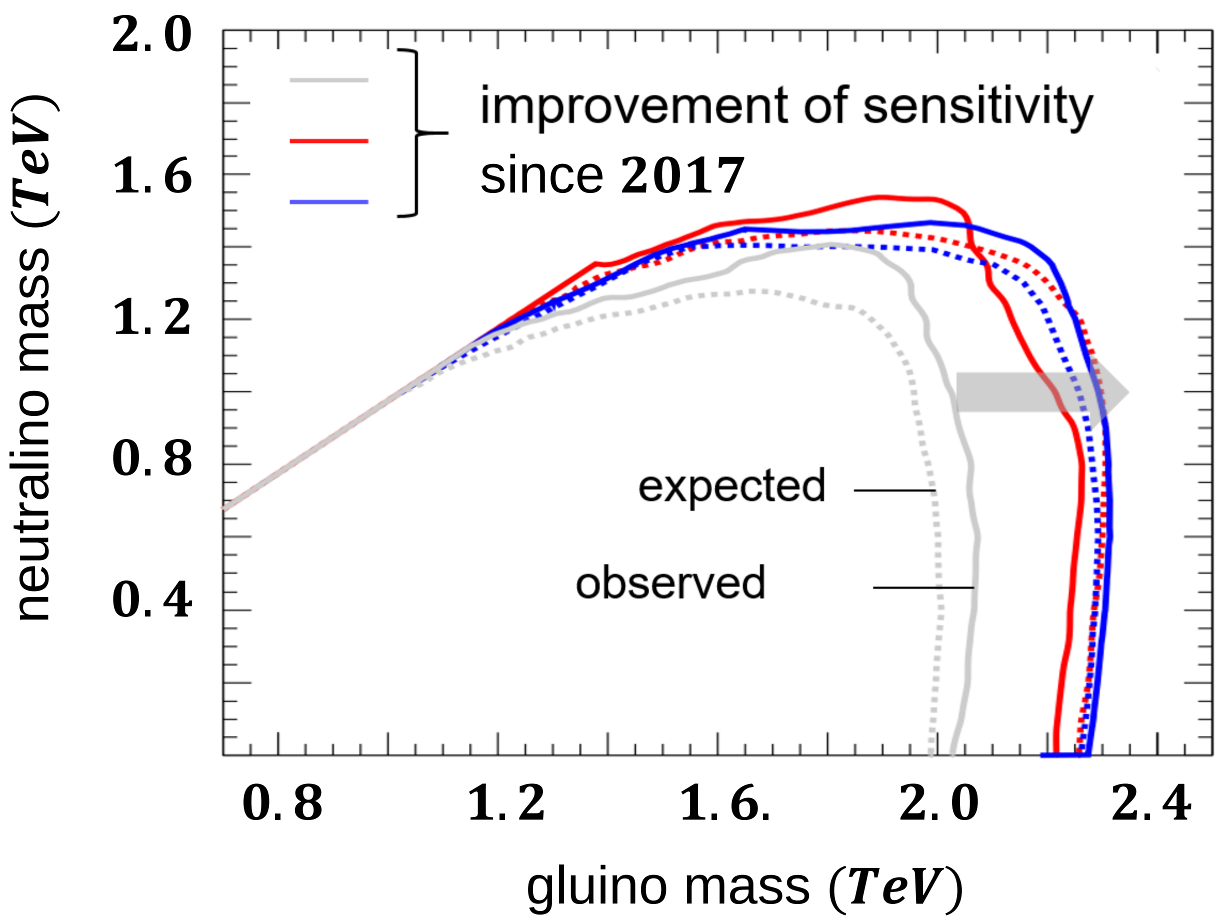
$SUSY$ – searches at CMS and $ATLAS$: no signal

- **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

- $\boldsymbol{PDG}$ $\mathbf{2022}$: $\boldsymbol{neutralino}$ mass $> \mathbf{1}\ \boldsymbol{TeV}$





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

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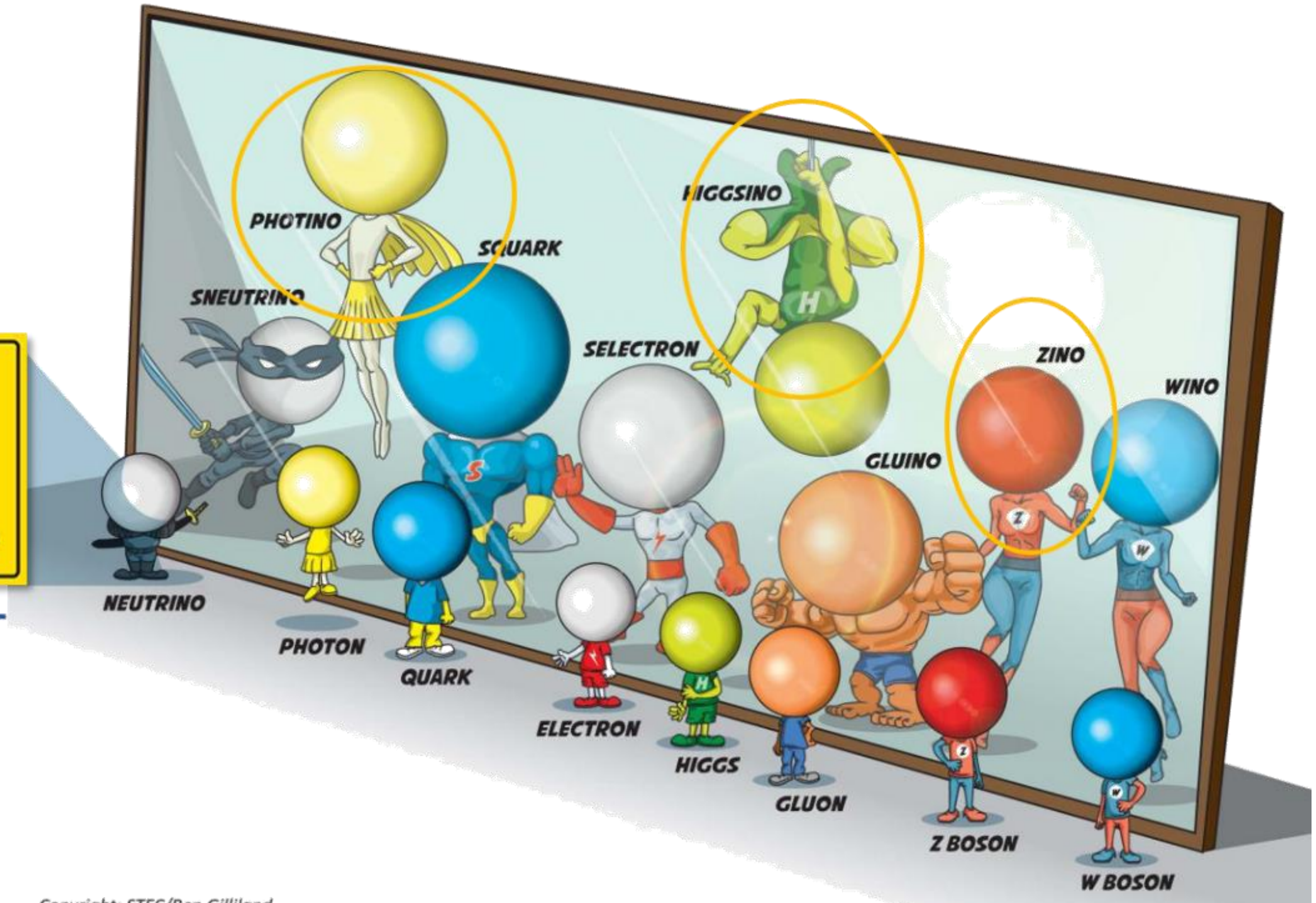
- **Recent limits on the masses of $SUSY$ – particles**

NO SIGNAL

CERN



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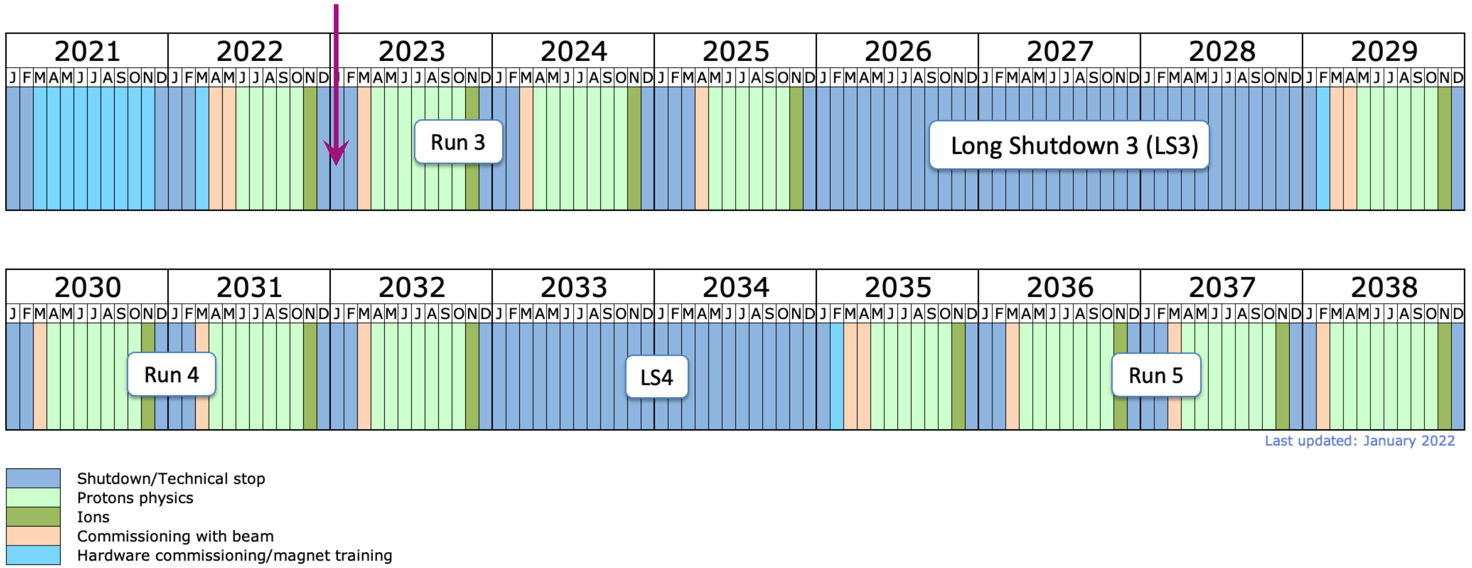
*somehow this mirror does not work!

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

- **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 & data flow



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

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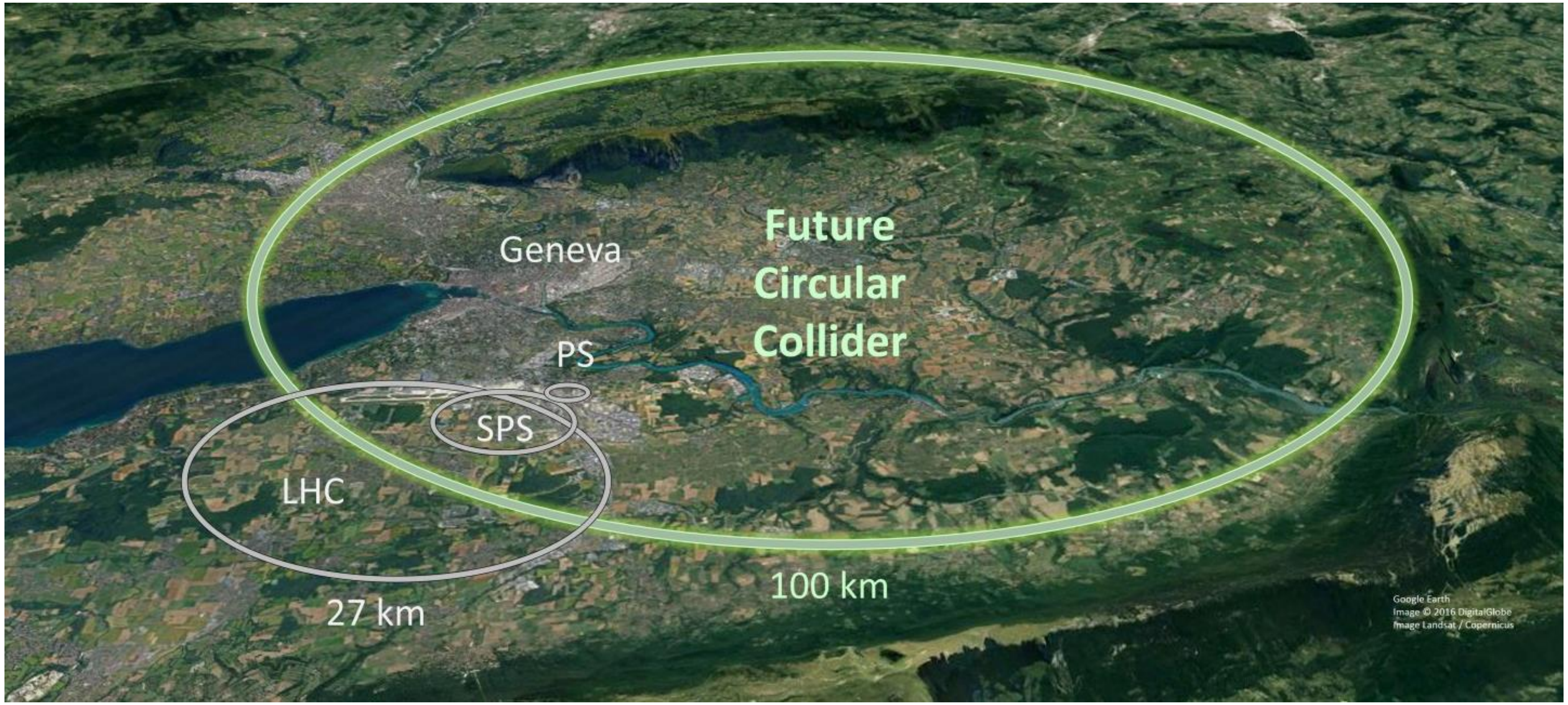
- On the drawing board of $CERN$: the **F**uture **C**ircular **C**ollider FCC

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

- $FCC - pp$:
  pp – collisions for $SUSY$ & $WIMP$ – searches

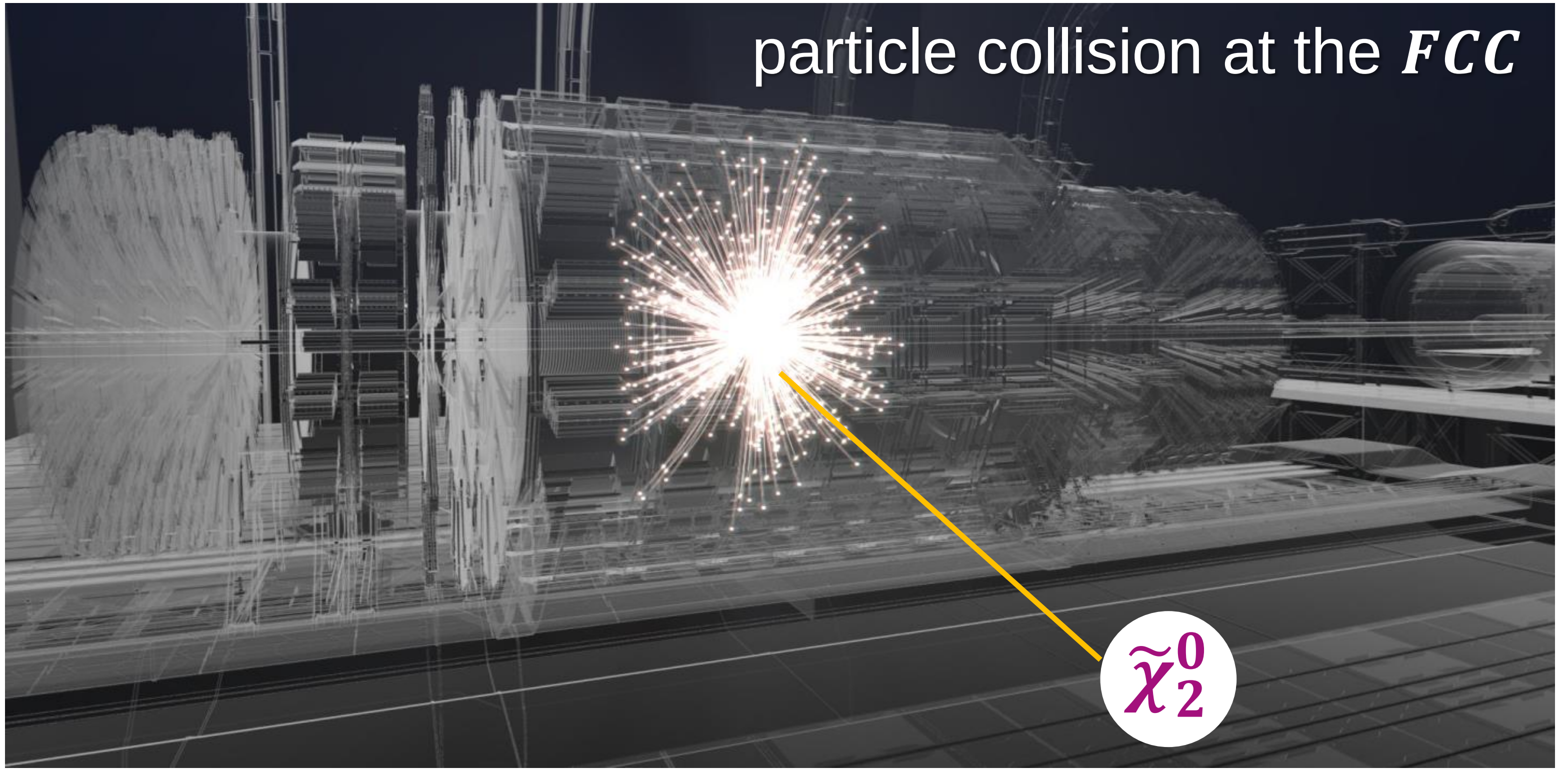
- $FCC - ee$:
  e^+e^- – collisions to study $h\ W^\pm\ Z^0$ at $\sqrt{s} = 90 - 350\ GeV$



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

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

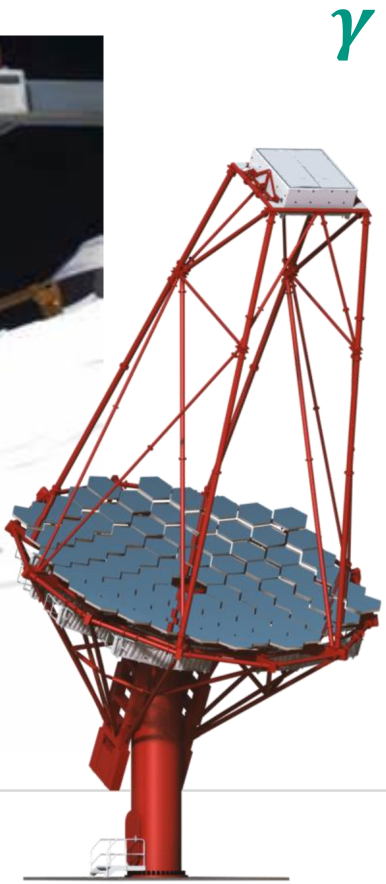
- planned future pp – collider with $\mathbf{2\pi r = 100\ km}$ for cms $\sqrt{s} = 100\ TeV$



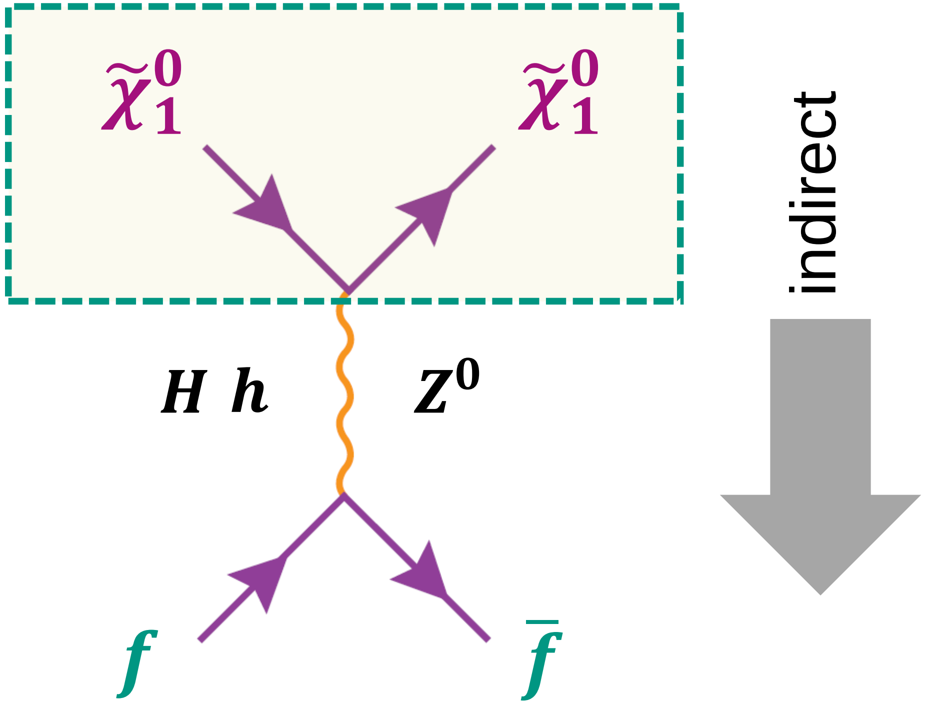
4.3 Indirect $WIMP$ detection methods

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

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



annihilation process

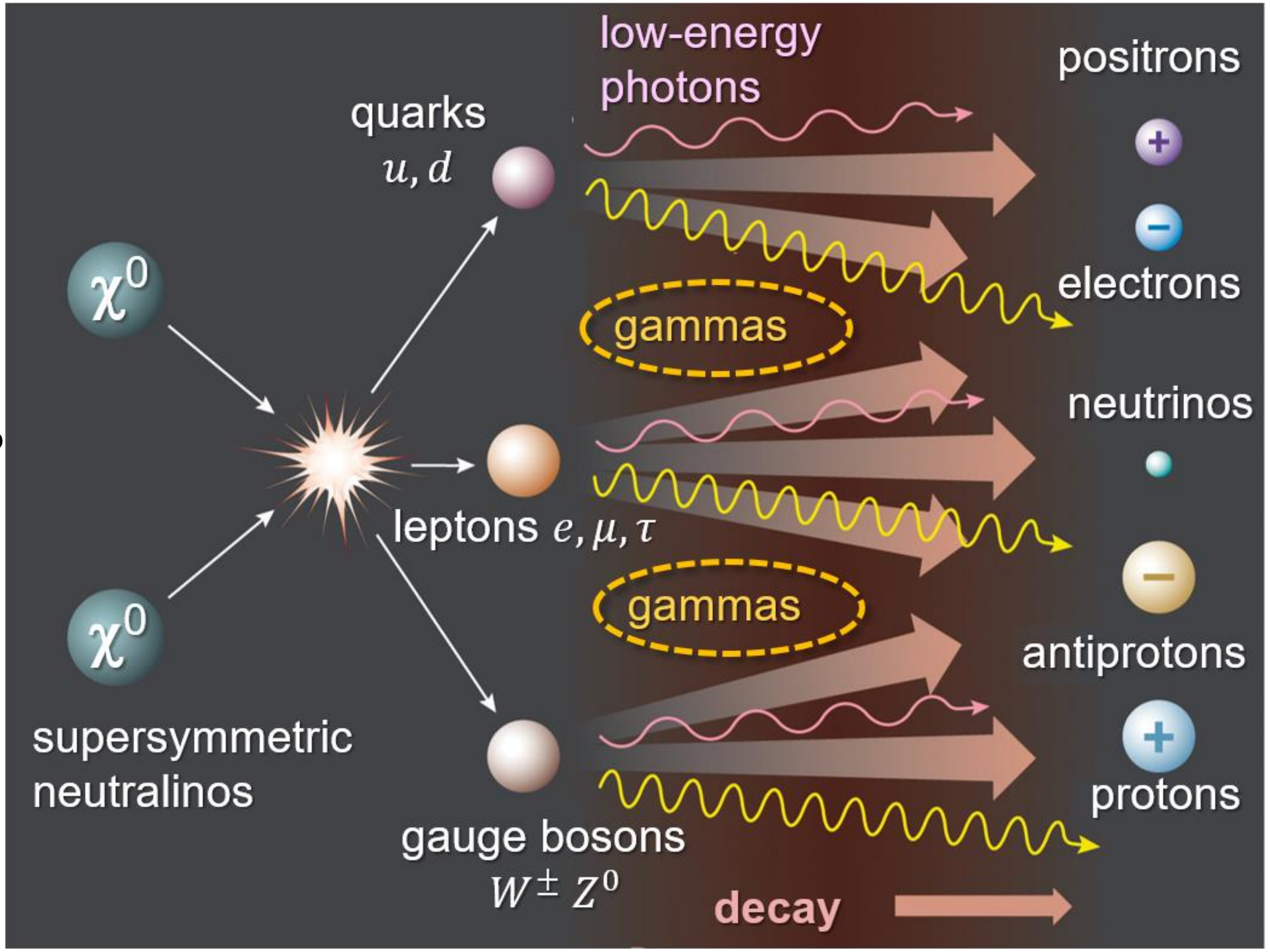


messenger particles

Annihilation processes of galactic $neutralinos$

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

where?
how?



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

neutrinos:
- hadronic/leptonic decays

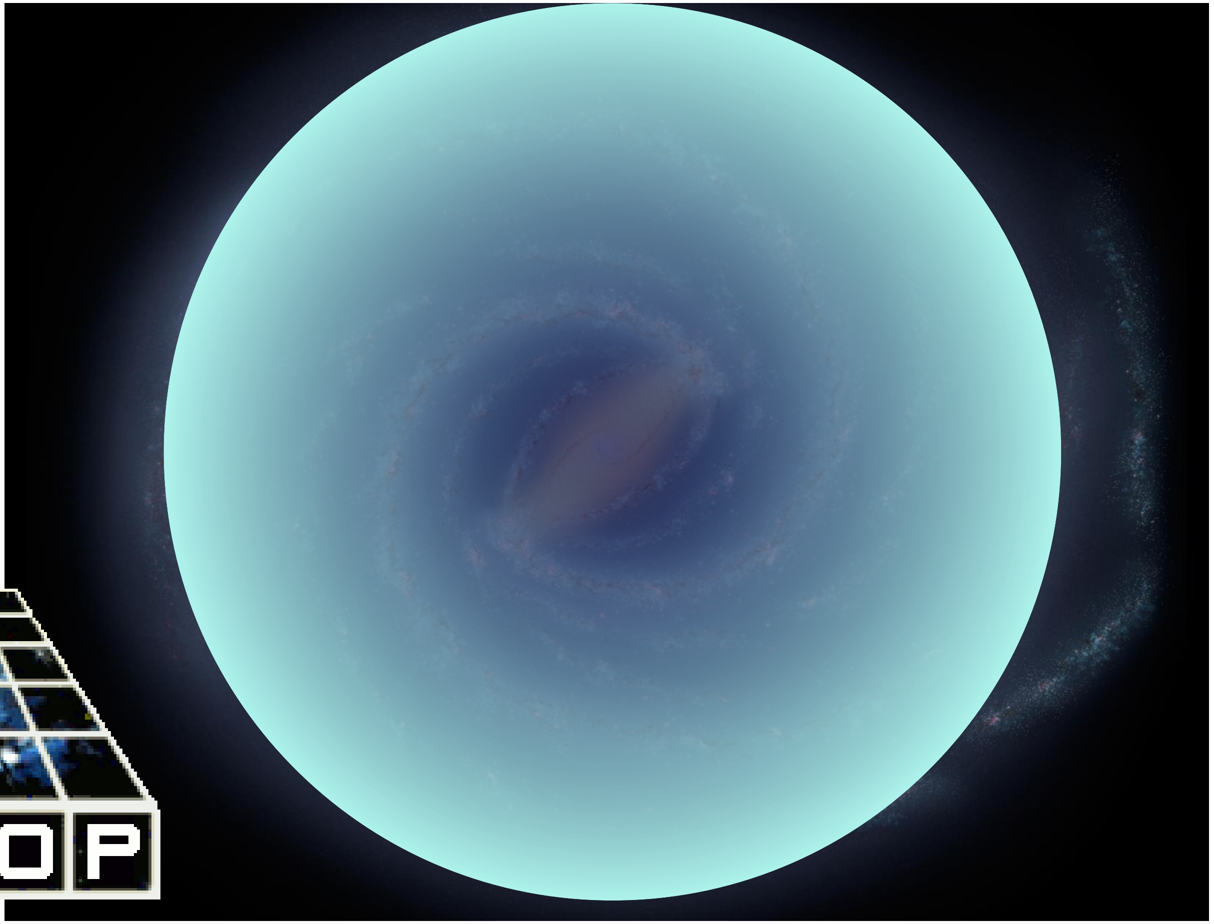
gammas:
- hadronic decays
- bremsstrahlung

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

Modelling of annihilation processes

- **Particle physics** ($\boldsymbol{DarkSUSY}$**: annihilation of** $\boldsymbol{\chi^0}$) **meets astrophysics (**$\boldsymbol{DM}$ **halo model** & $\boldsymbol{GALPROP}$**)**

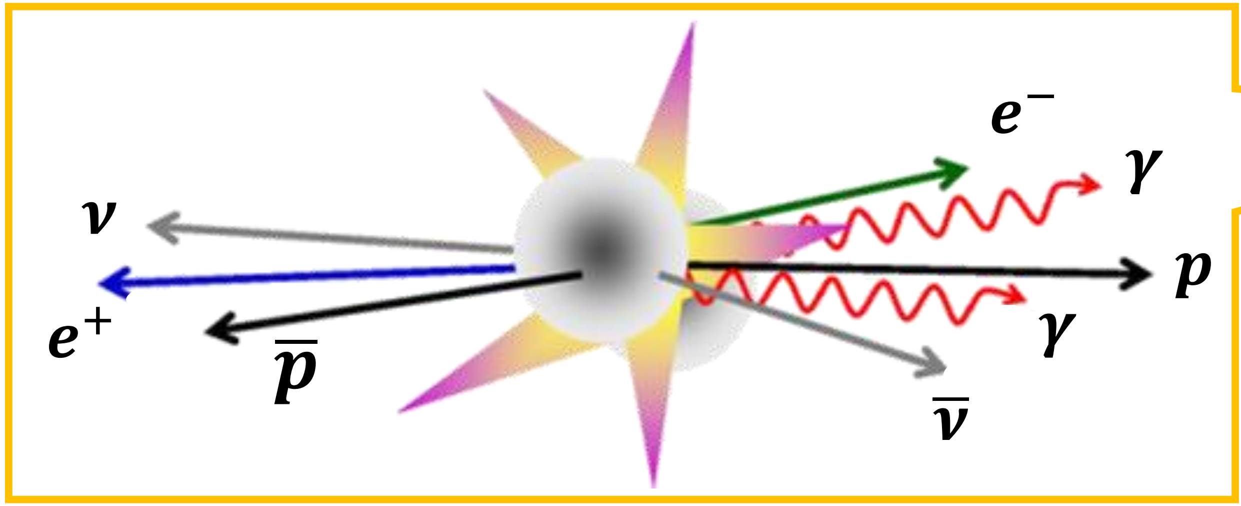
  - search for $\boldsymbol{WIMP}$ annihilations in the $\boldsymbol{DM}$ – halo of our galaxy is ***strongly*** model–dependent

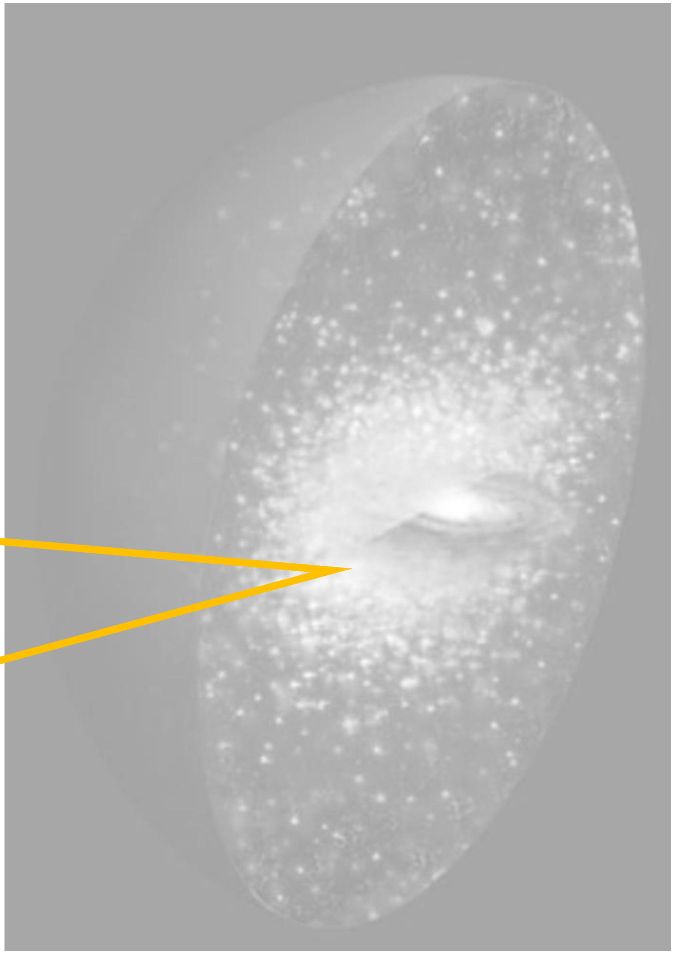


Modelling of annihilation processes

- 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

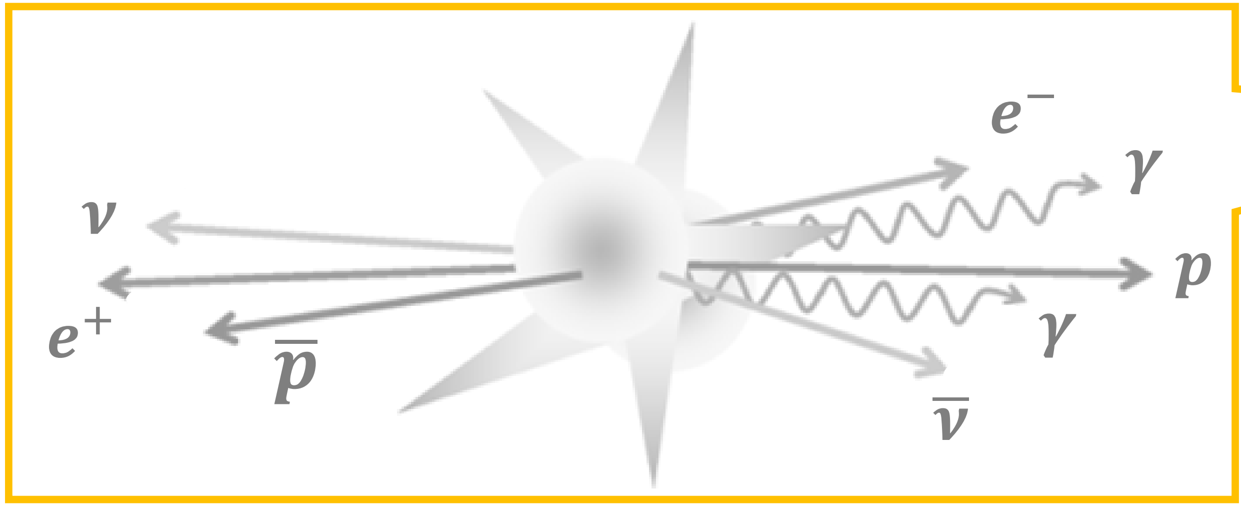


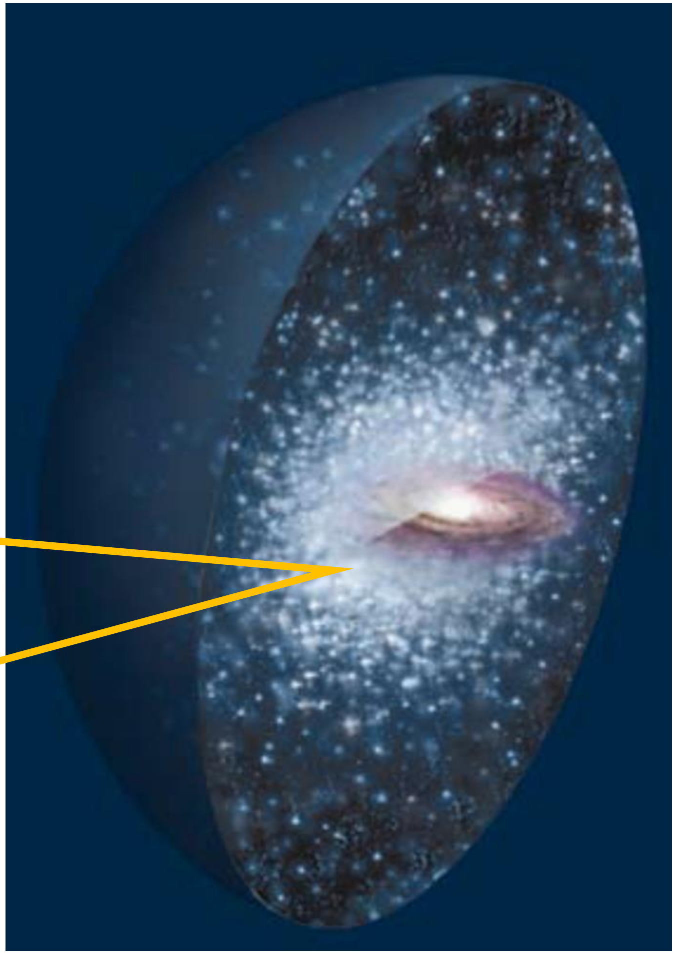


Modelling of annihilation processes

- 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*



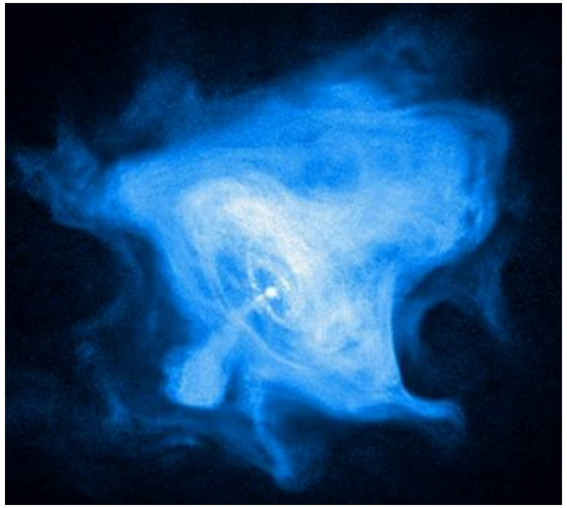


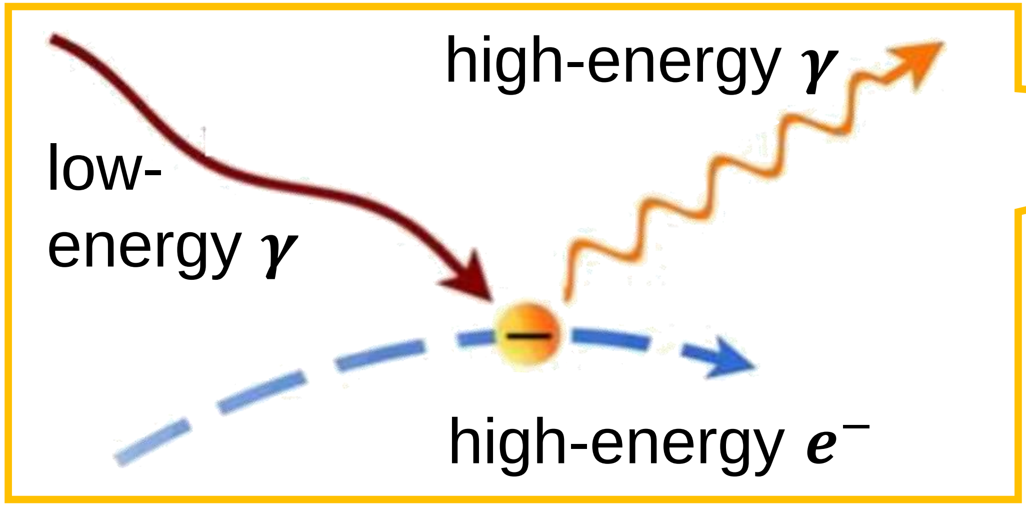
*see chapter 2.1

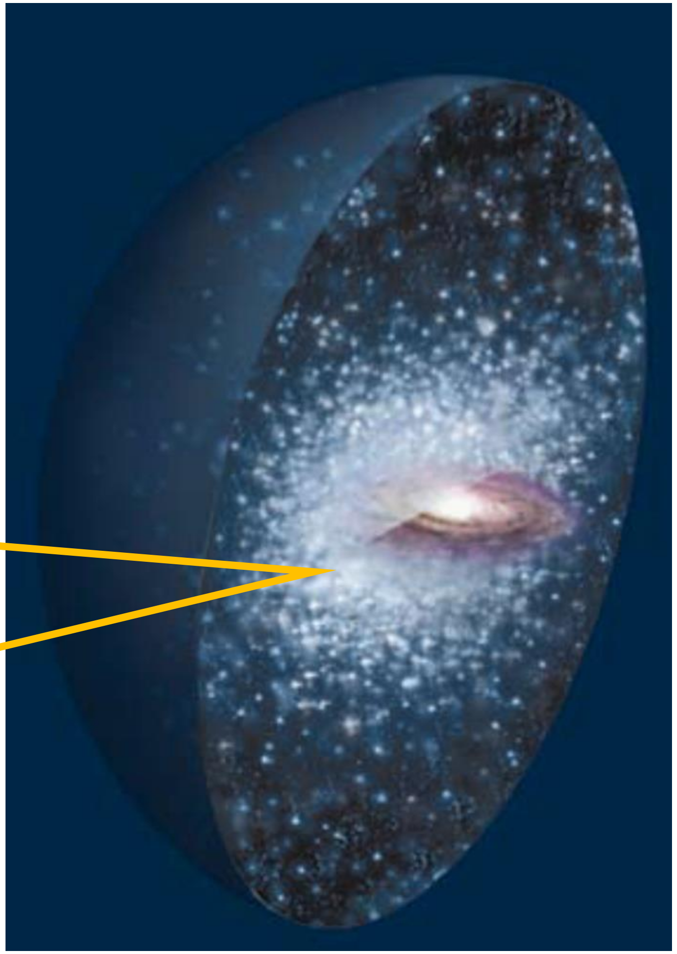
Modelling of background processes

- 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)



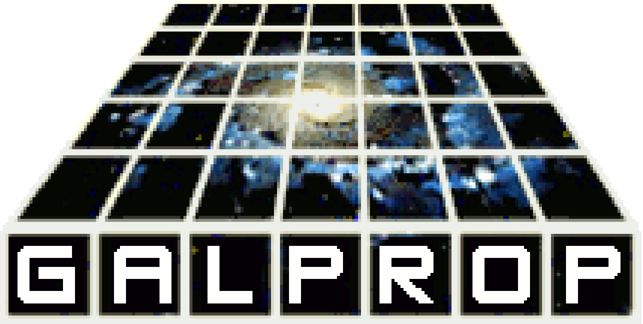


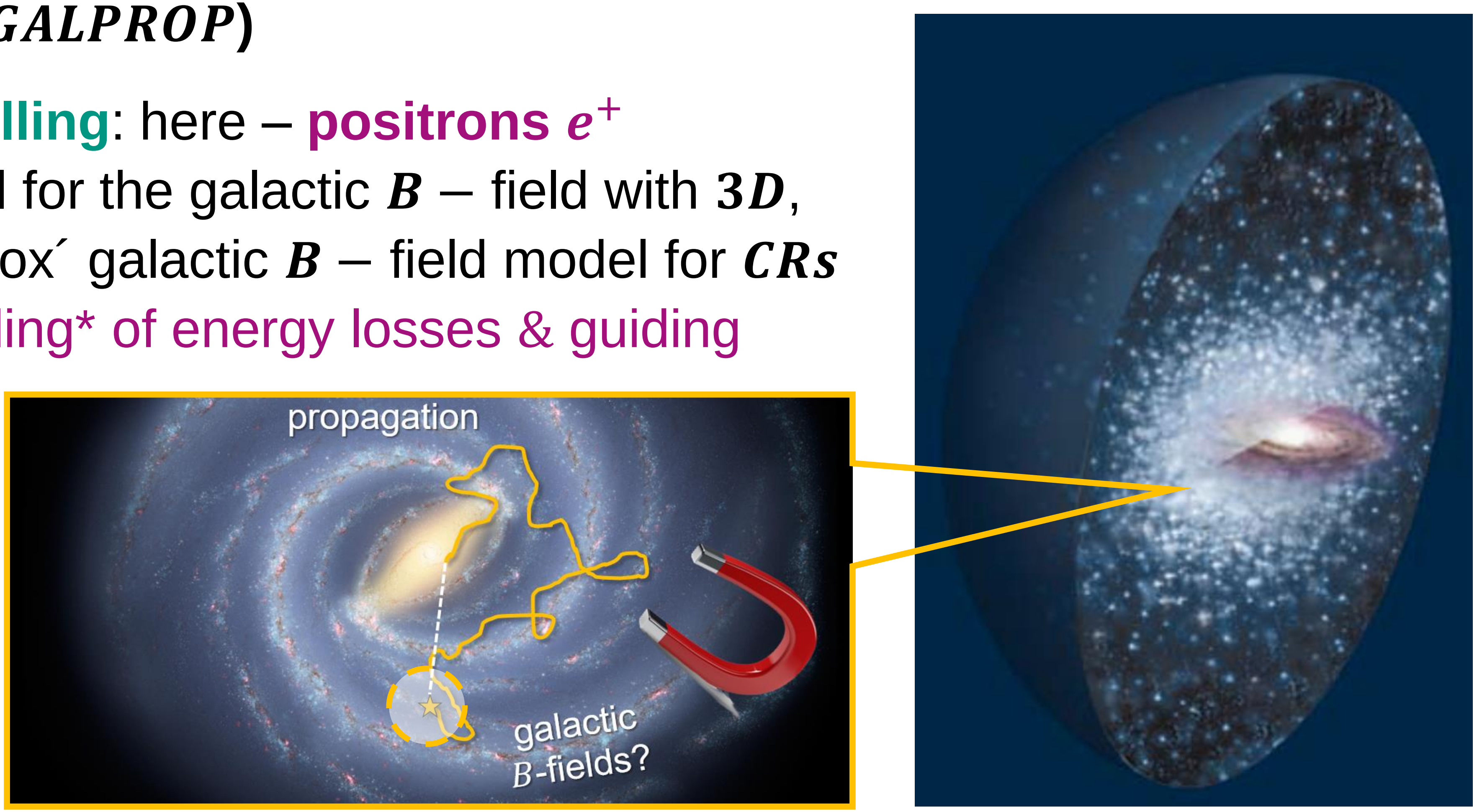


Modelling of messenger propagation

- 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

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

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

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

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

PARTICLE PHYSICS

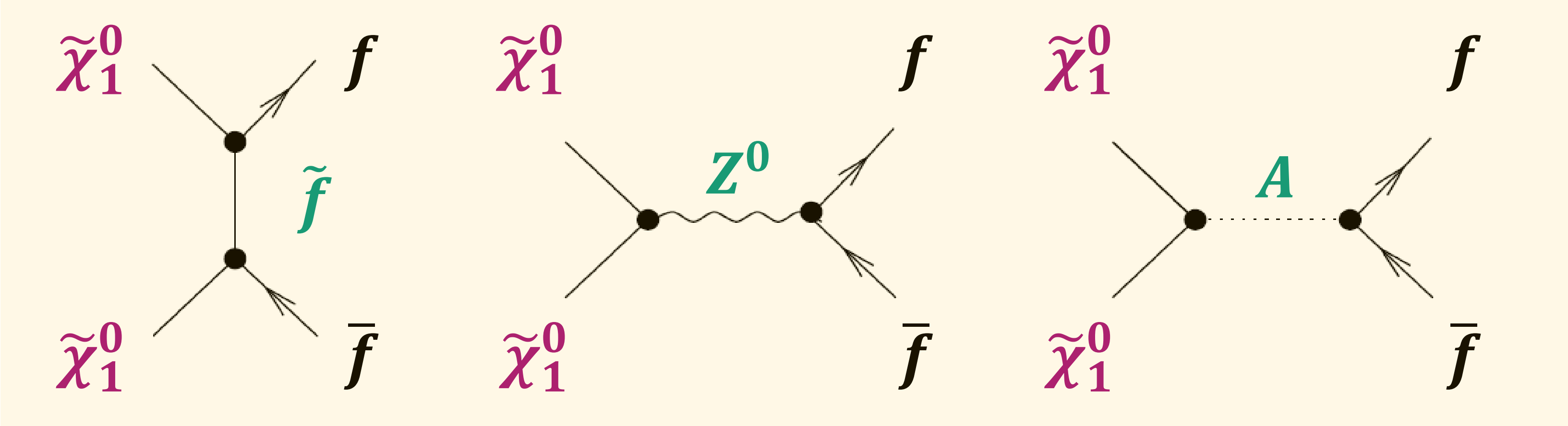
ρ_{CDM}	density profile of DM – halo
v	$WIMP$ velocity profile

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 $(\tilde{f})$

s – **channel** (annihilation):
Z^0 – boson
pseudo–scalar A

σ_{Ann} $xsec$ from theory estimates

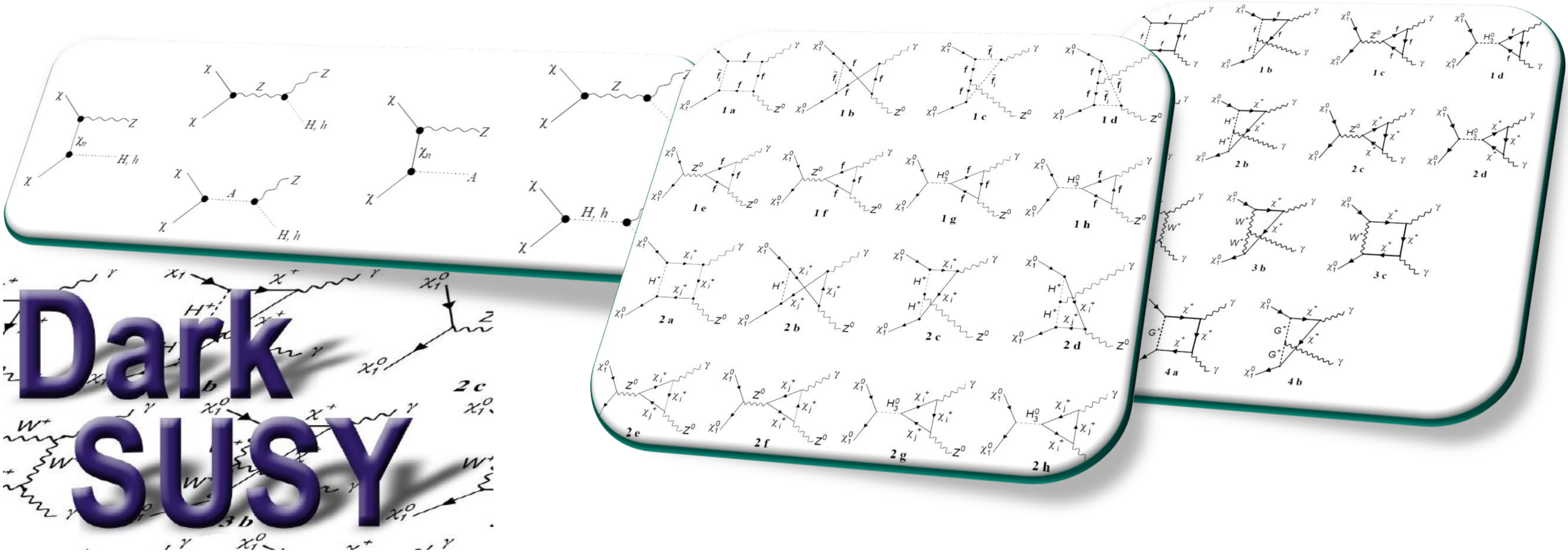
PARTICLE PHYSICS

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

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

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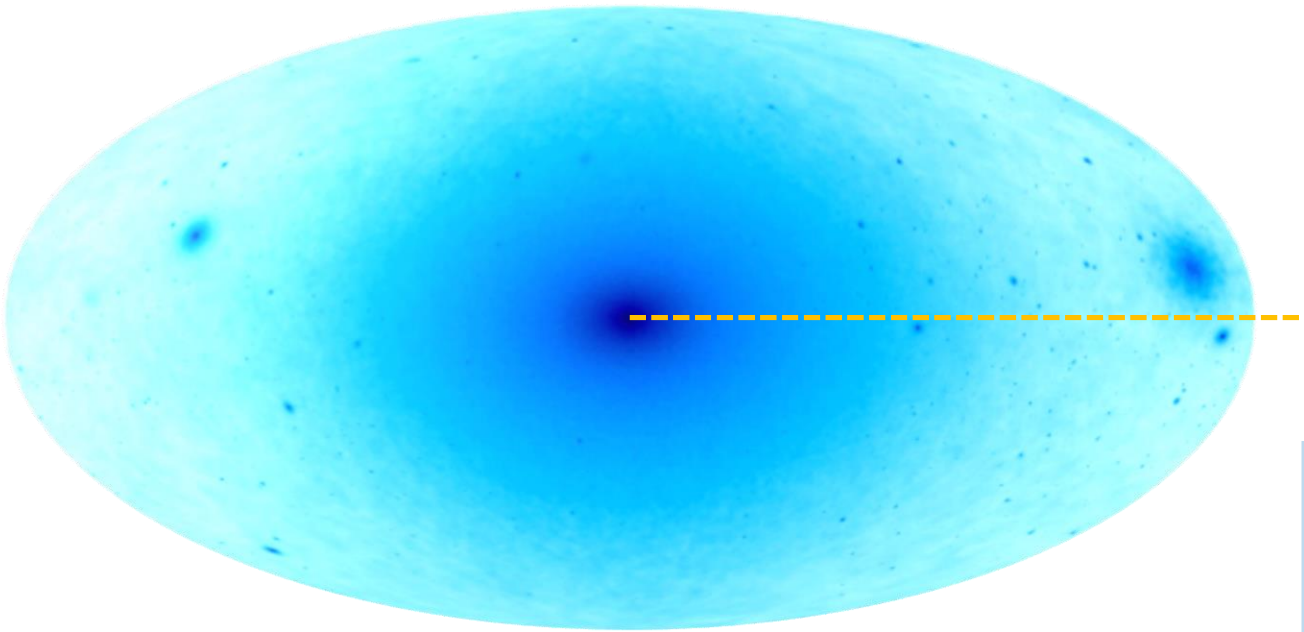
- **Modelling of DM halos: finding the correct density profile $\rho(r)$**

  - DM density values very important for annihilation studies



expected DM – annihilations
in Mollweide projection

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

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

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

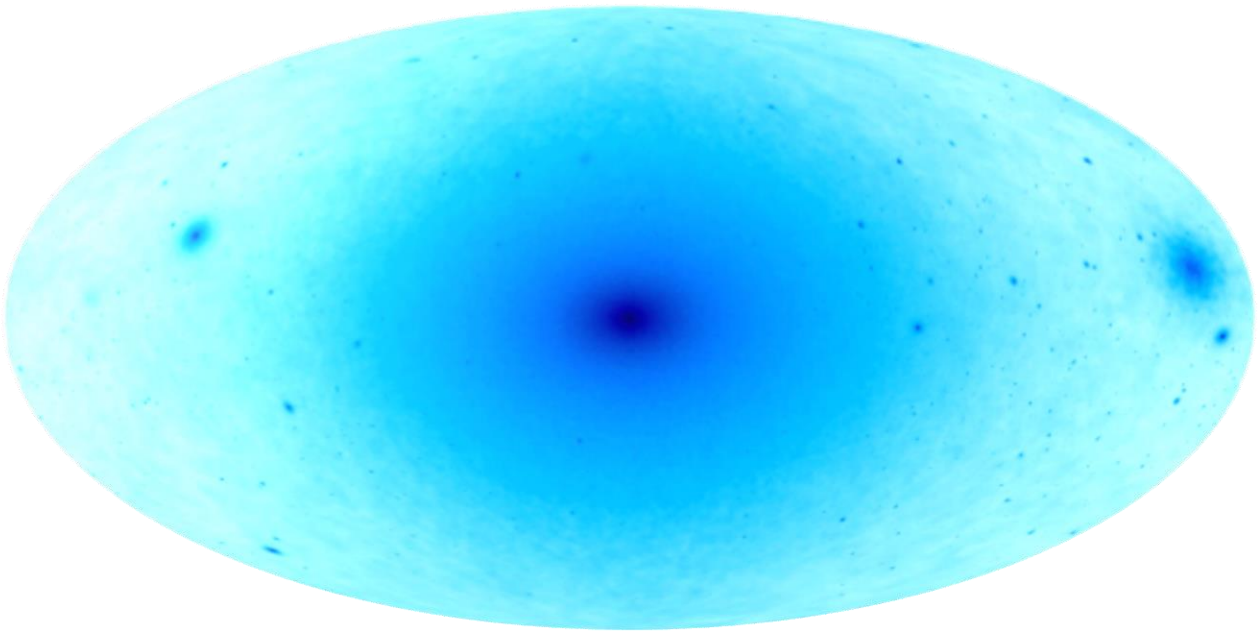
ASTRO PHYSICS

Annihilation processes: a closer look at dark halos

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

  - Navarro–Frenk–White (NFW) propose a detailed profile, simplified here to

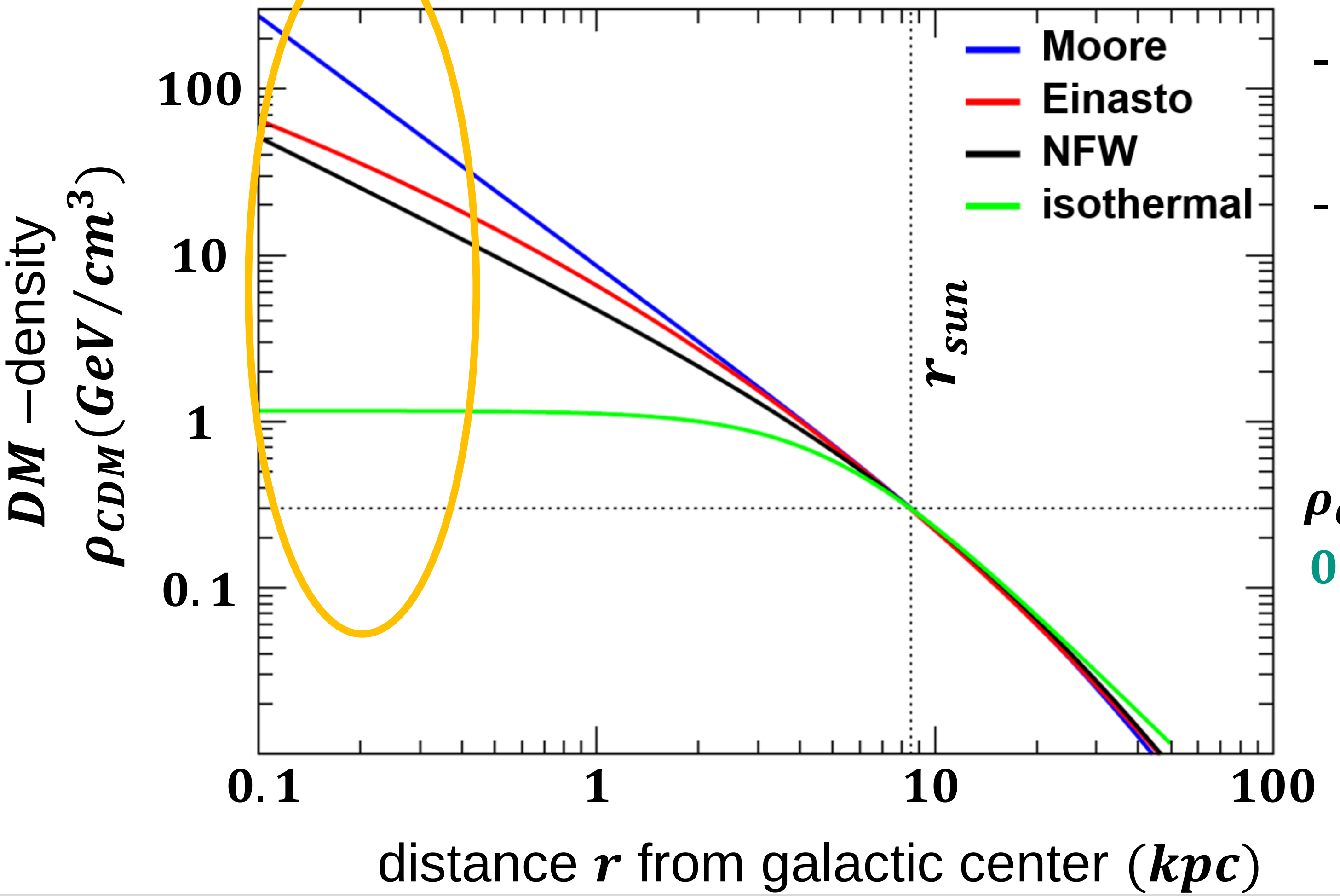
$$\boxed{\rho_{CDM}(r) \sim {}^{1}/_{r^2}}$$



expected DM – annihilations
in Mollweide projection

Annihilation processes: a closer look at dark halos

- **Modelling of DM halos: comparison of different published halo profiles**



- halo–core: up to $300\ GeV/cm^3$

- **inner halo modelling** yields vastly different values:

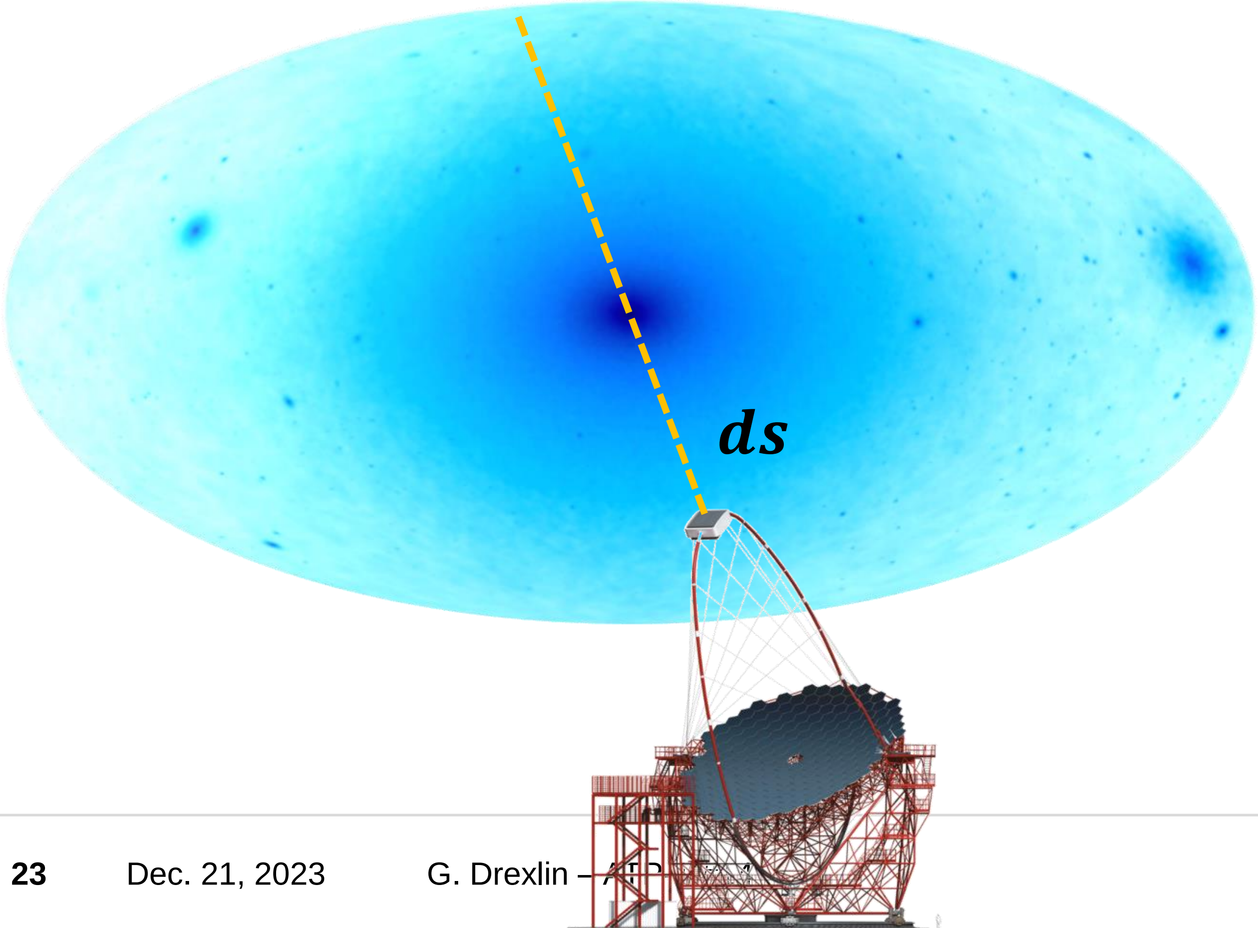
$\rho_{CDM}(r_{sun}) =$ $0.3\ GeV/cm^3$

compare $Moore$ $\Leftrightarrow NFW$ $\Leftrightarrow isothermal$

Annihilation processes: along the line–of–sight

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

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



γ – flux

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

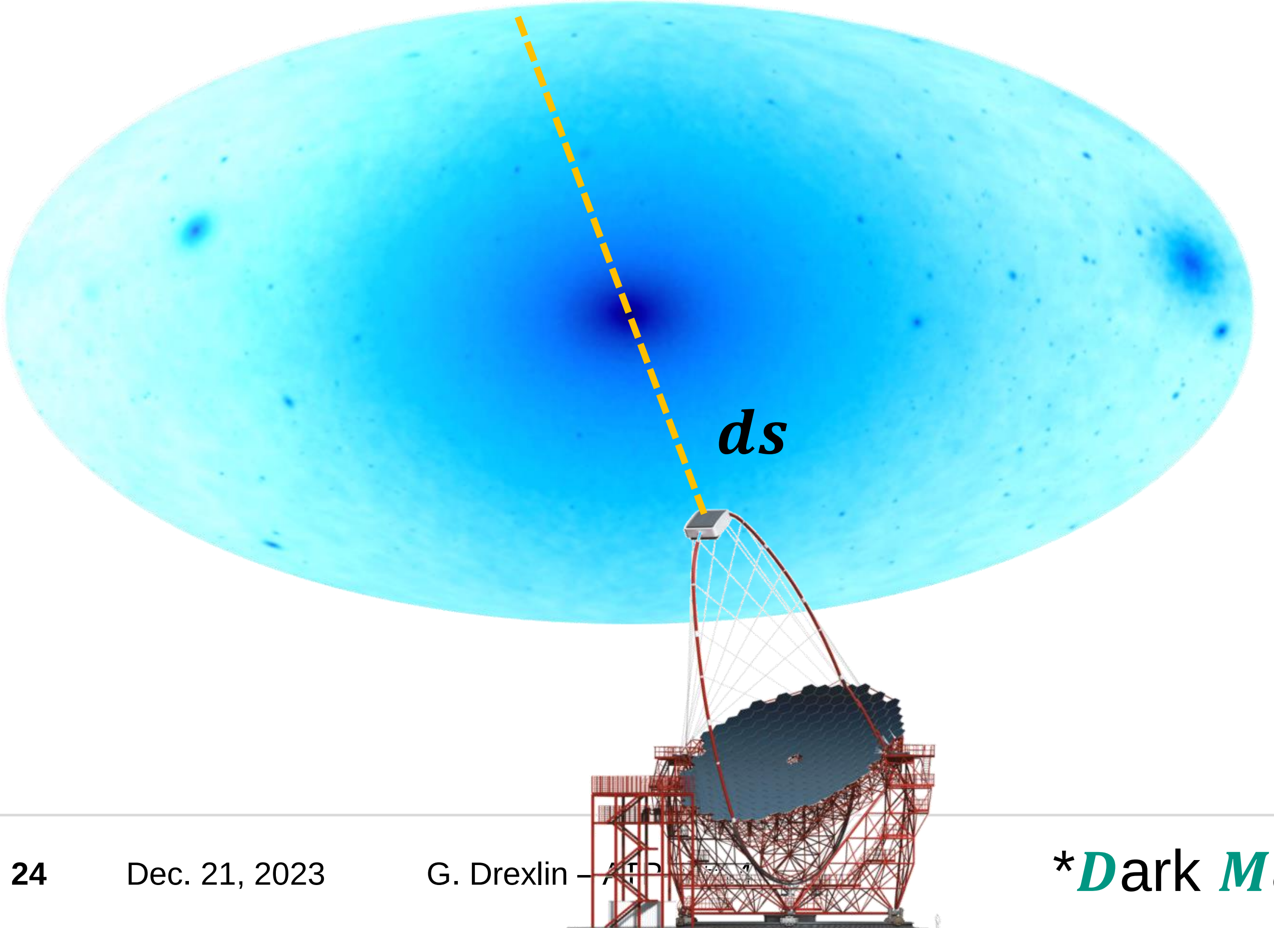
annihilation cross section averaged over $WIMP$ velocity

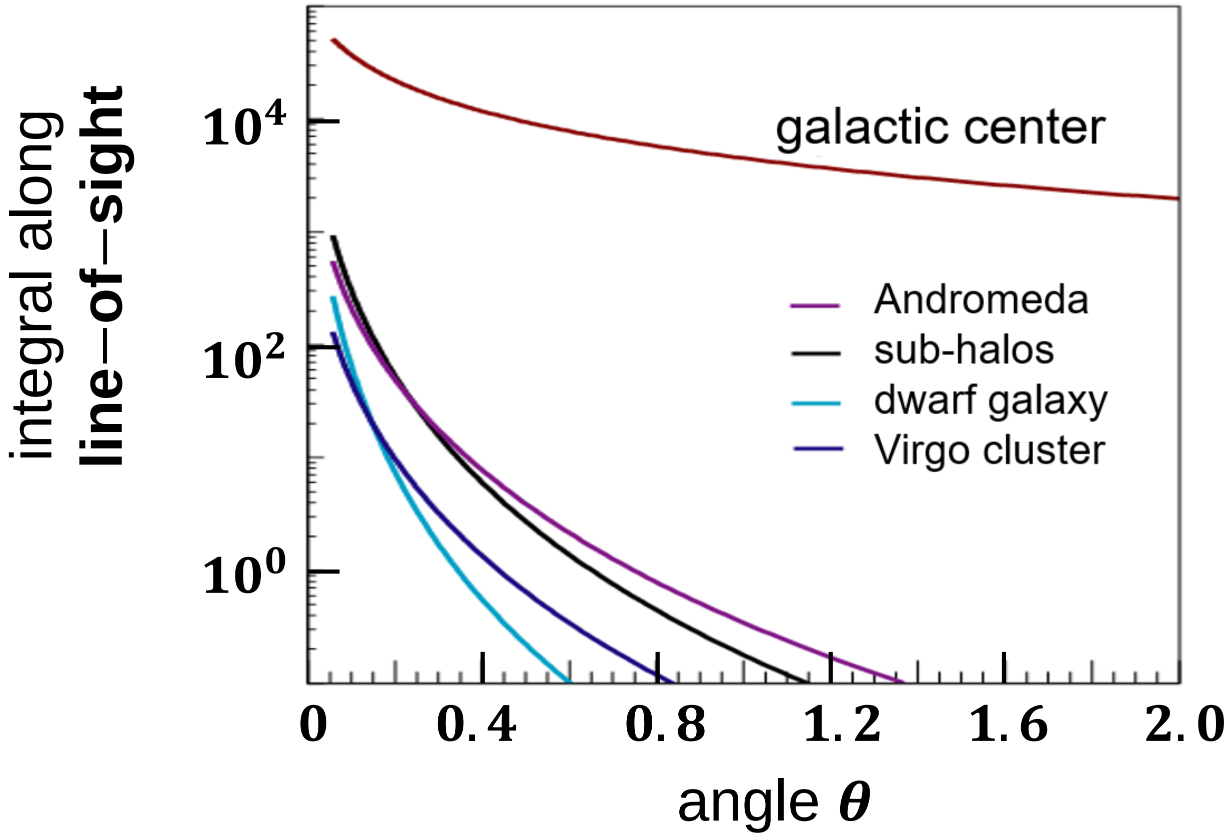
$WIMP$ mass

Annihilations from DM: where to look

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

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

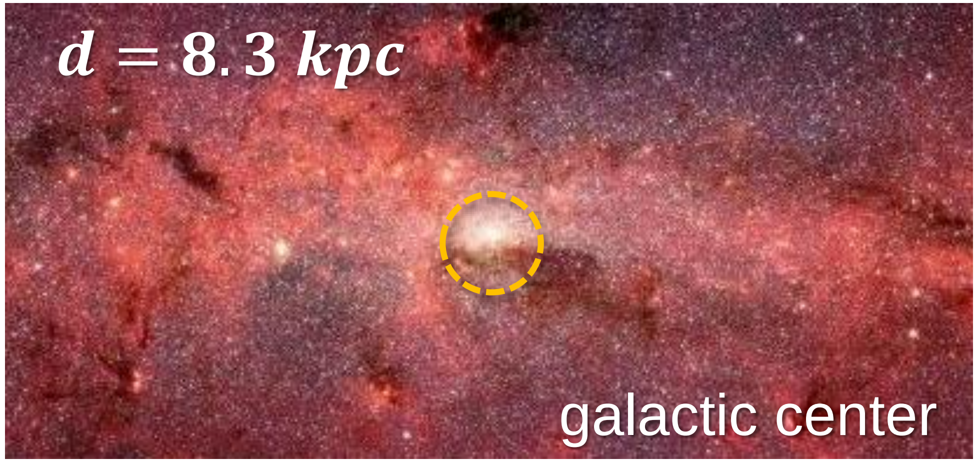


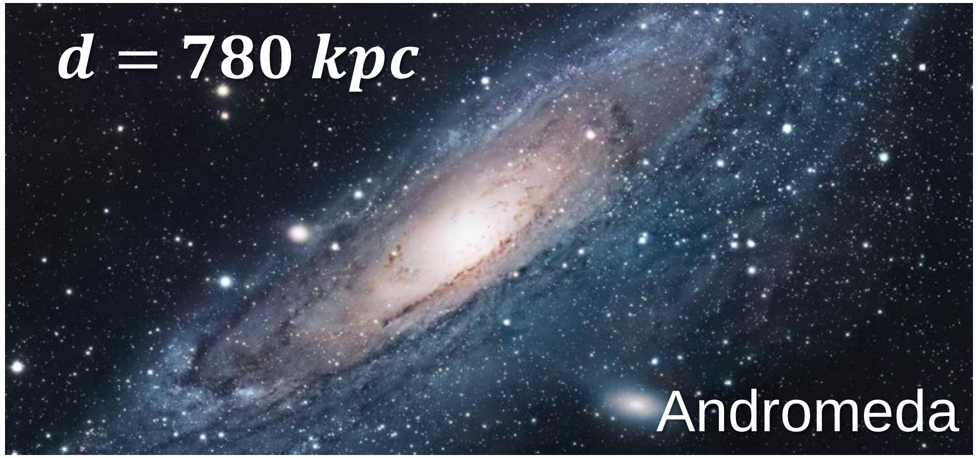


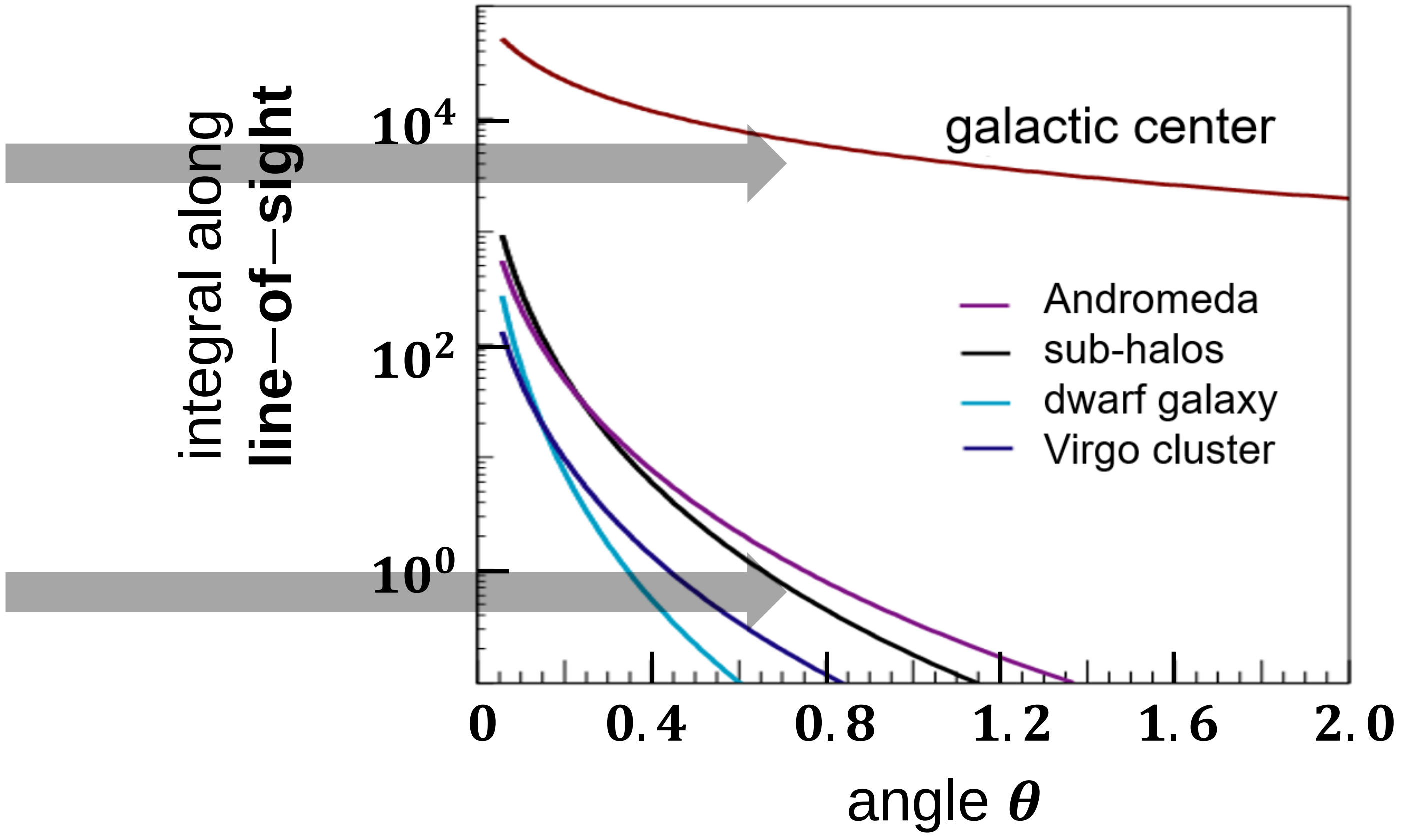
*Dark Matter Annihilation

Annihilations from DM: where to look

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

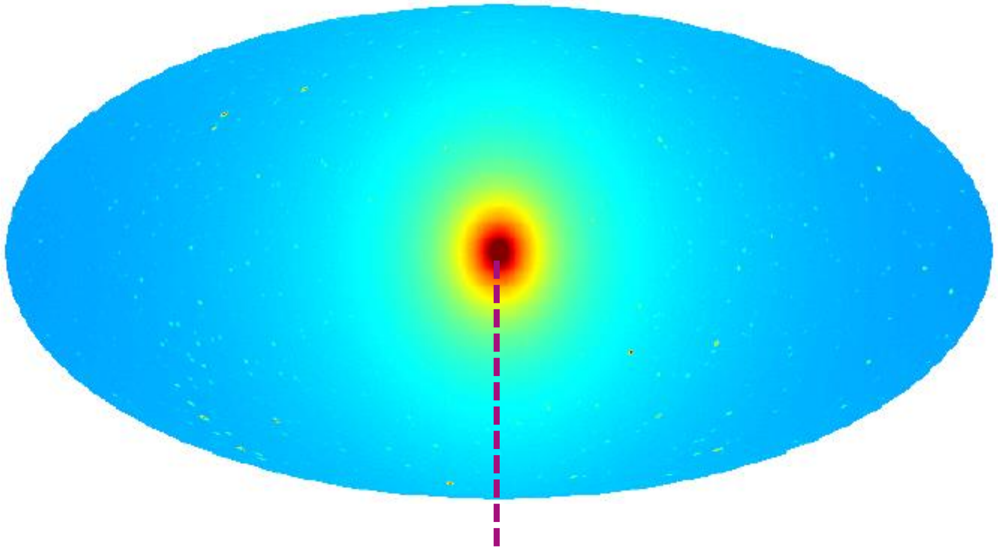






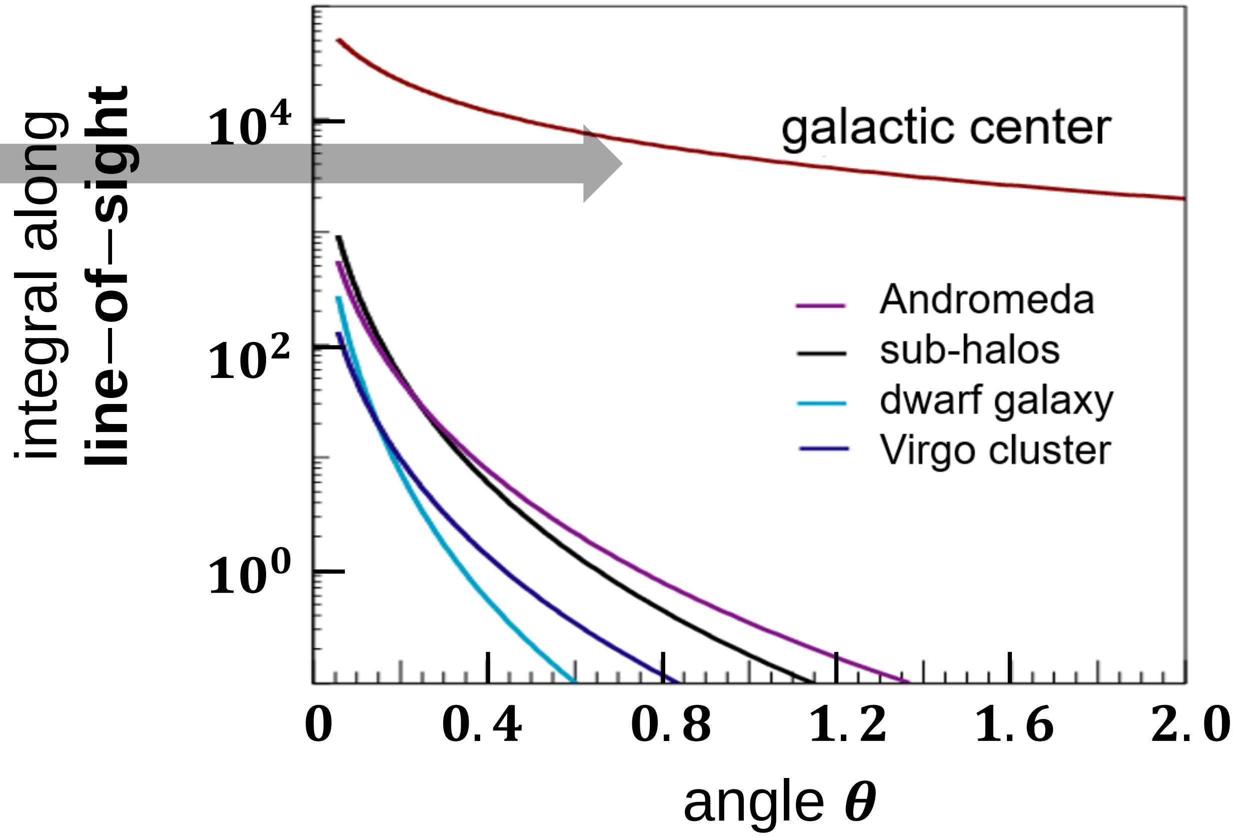
Annihilations from DM: where to look

- Simulated DMA signals: the galactic center ´overwhelms´ all other sources



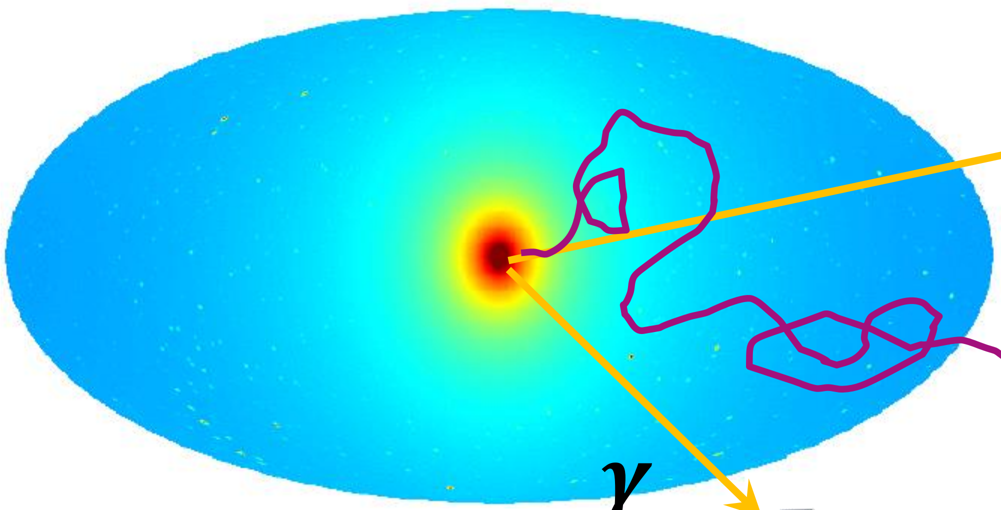
- expected $\boldsymbol{DMA}$ flux (for $\boldsymbol{m = 1\,TeV}$ & $\boldsymbol{\sigma_{Ann} = 1\,pb}$) is **VERY** small:

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

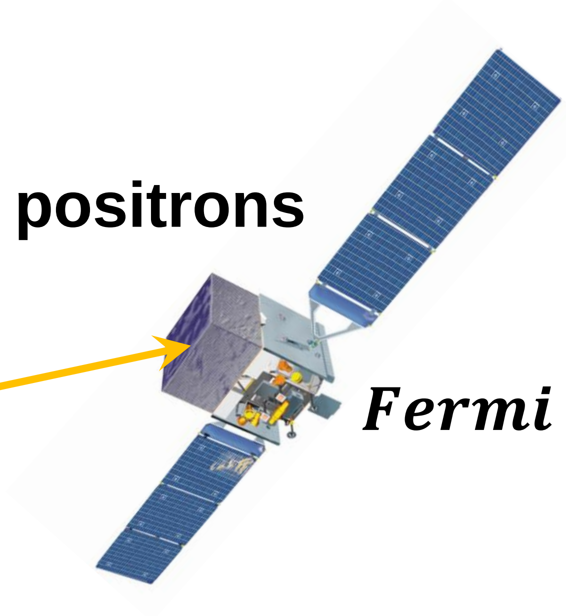


$4.4.1$ Gammas and positrons

- Searching for DMA signals with gammas and positrons



γ

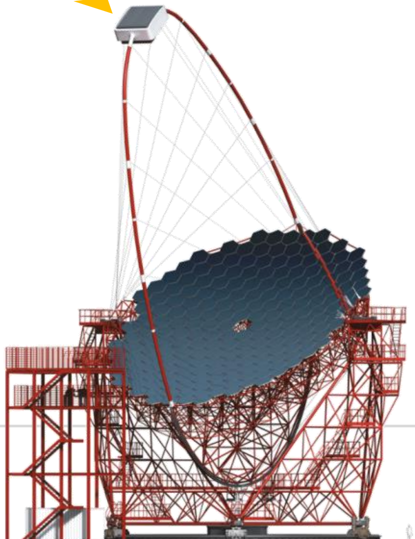


GeV:
$\boldsymbol{Fermi}$ observatory

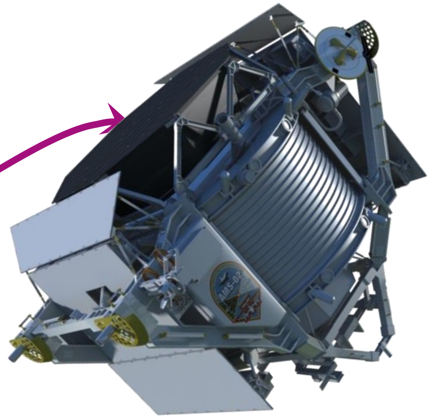
γ

e^+

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



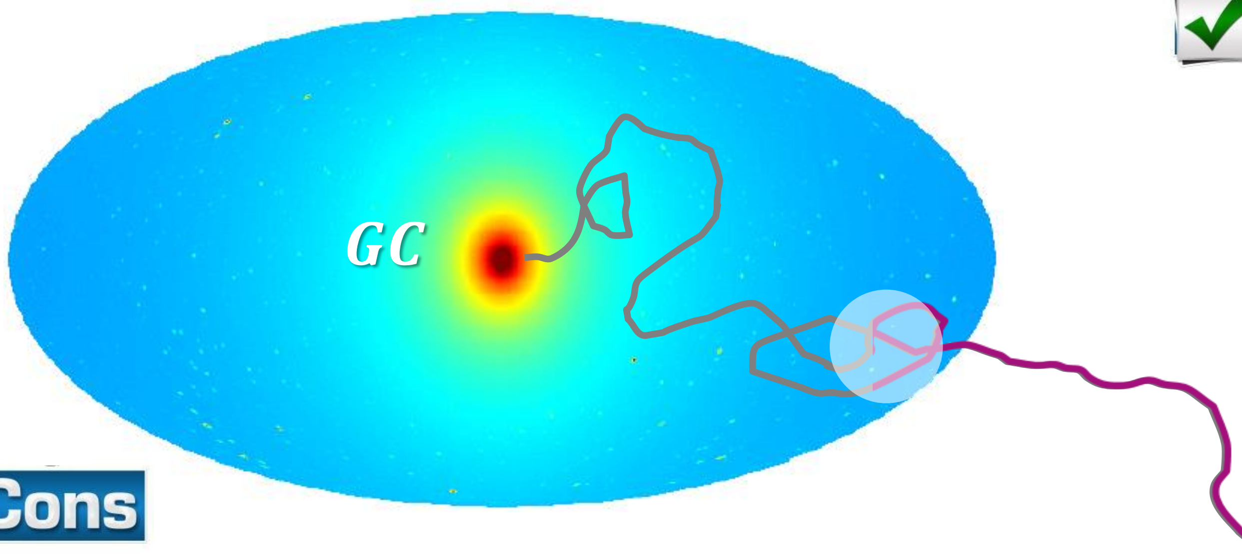
$GeV \ldots TeV$:
$IACT$

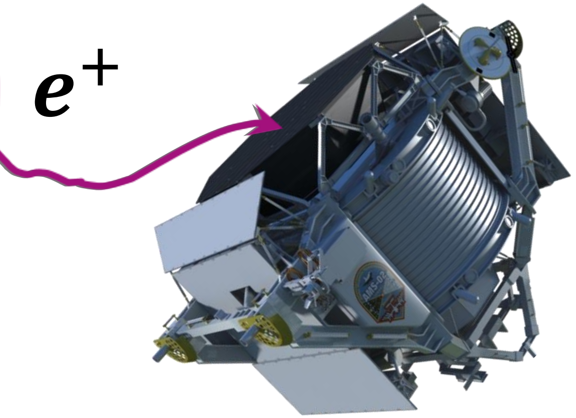


$GeV \ldots TeV$:
$AMS - 02$ experiment

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

$GeV \ldots TeV$:
$AMS - 02$ experiment

Cons

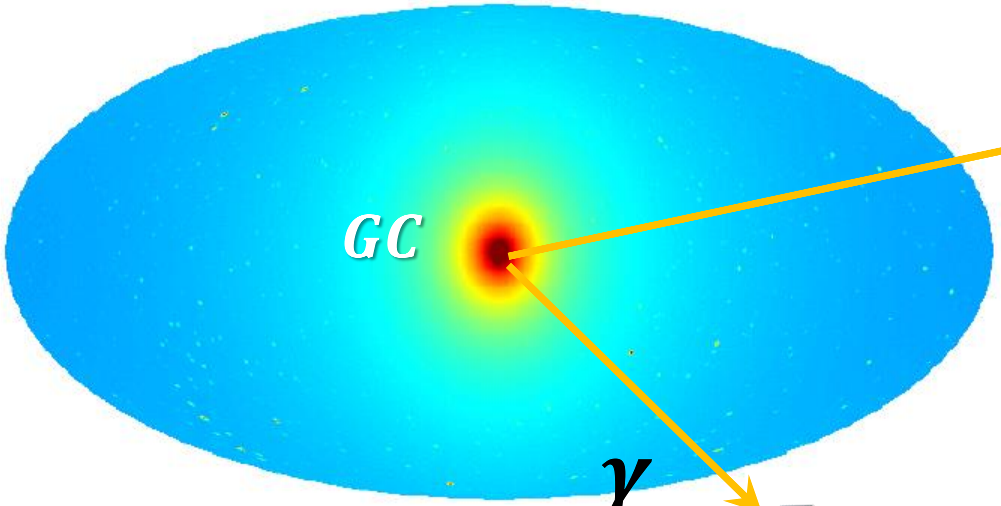
strong **deflection** in galactic B – fields

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

*Galactic Center

Gammas as DMA messengers from the galaxy

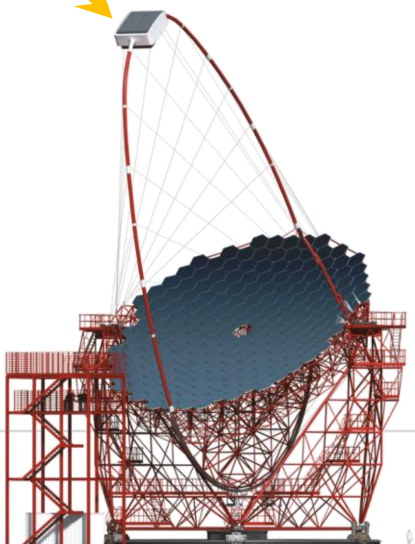
- **Advantages of gamma experiments**



γ

GeV:
$\boldsymbol{Fermi}$ observatory

γ

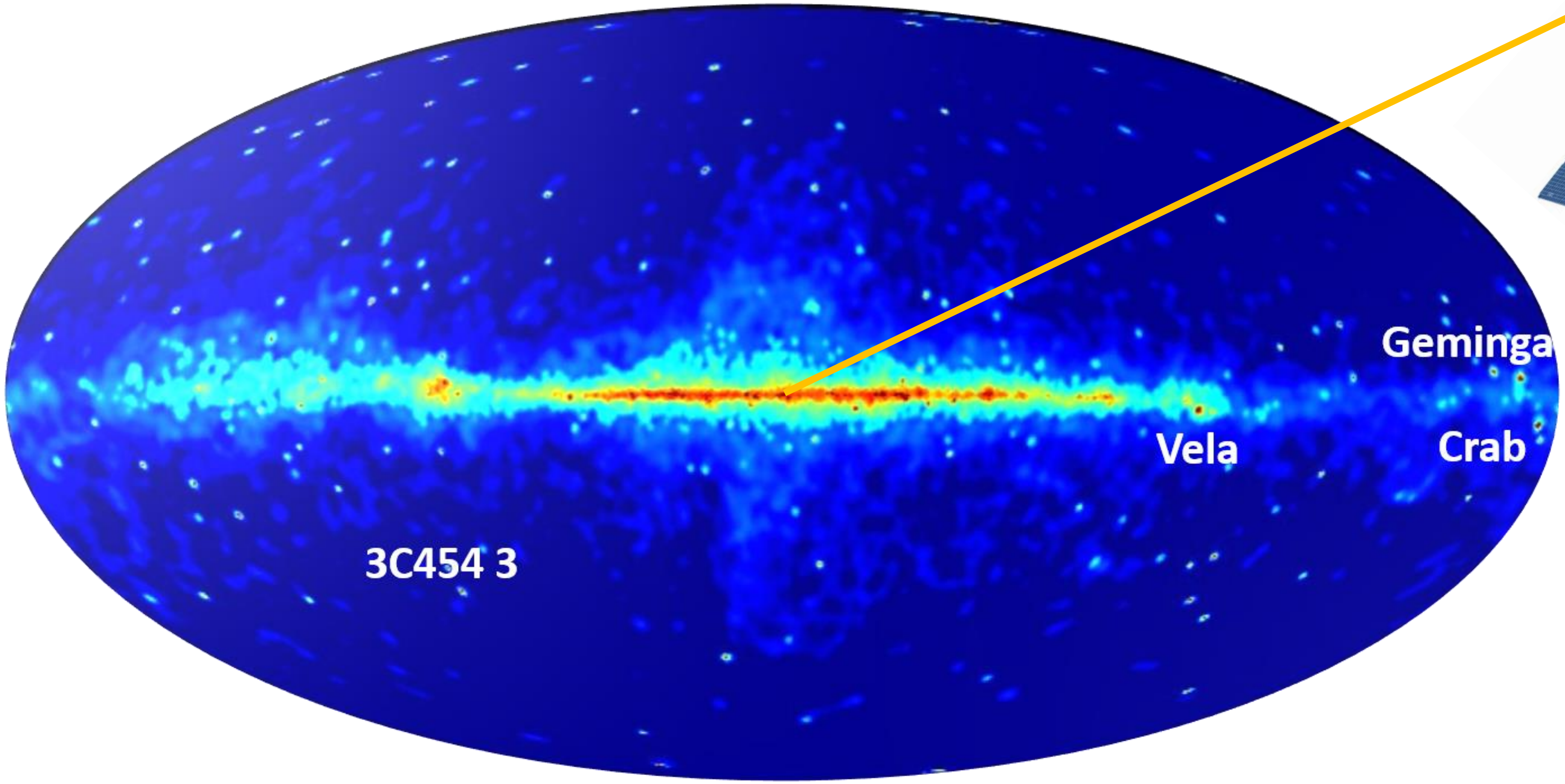


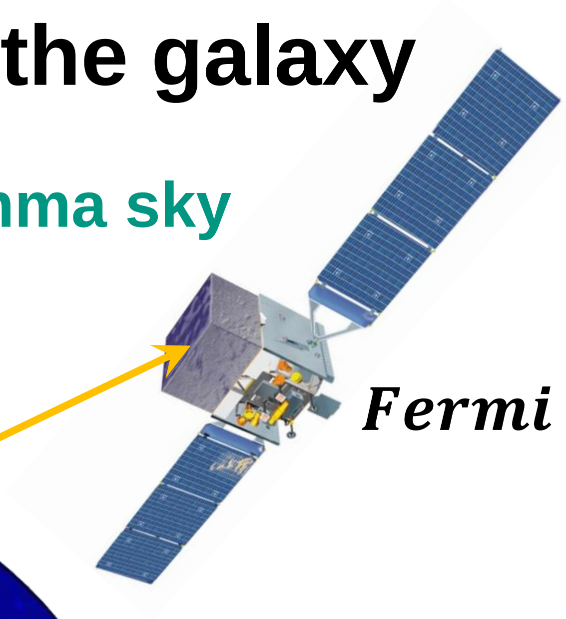
$GeV \ldots TeV$:
Imaging Atmospheric Cherenkov Telescope

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

Gammas as DMA messengers from the galaxy

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





GeV:
$\boldsymbol{Fermi}$ observatory

- many astrophysical gamma sources*: $\boldsymbol{SNRs}$, **pulsars**, $\boldsymbol{ISM}$,...

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

*see chapter $\mathbf{2.1.3}$ Gamma Telescopes

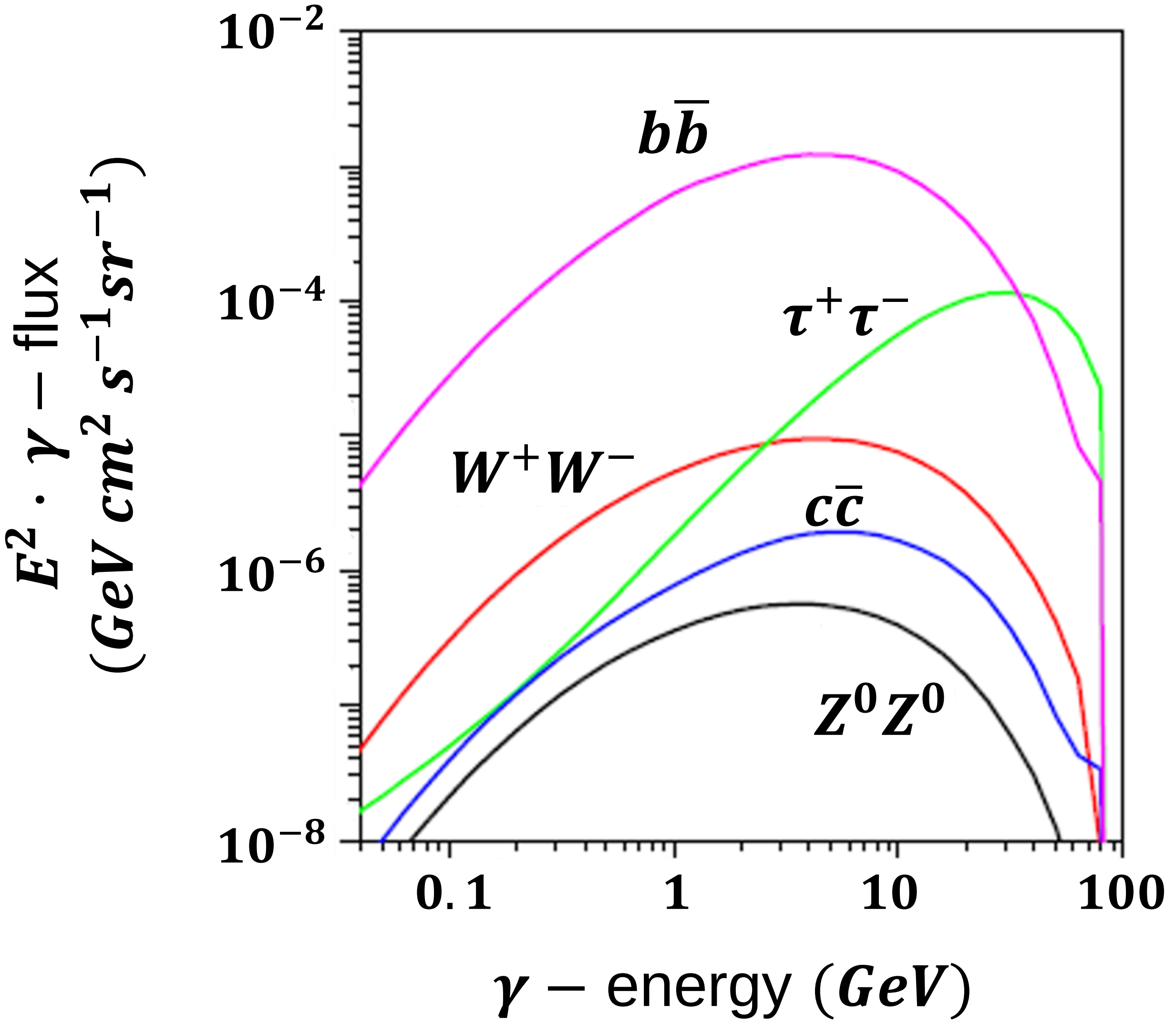
Gammas as DMA messengers: expected energies

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

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

- maximum $\boldsymbol{\gamma}$ – energy extends up to $\boldsymbol{WIMP}$ **mass** (here: $\boldsymbol{m = 80\ GeV}$)

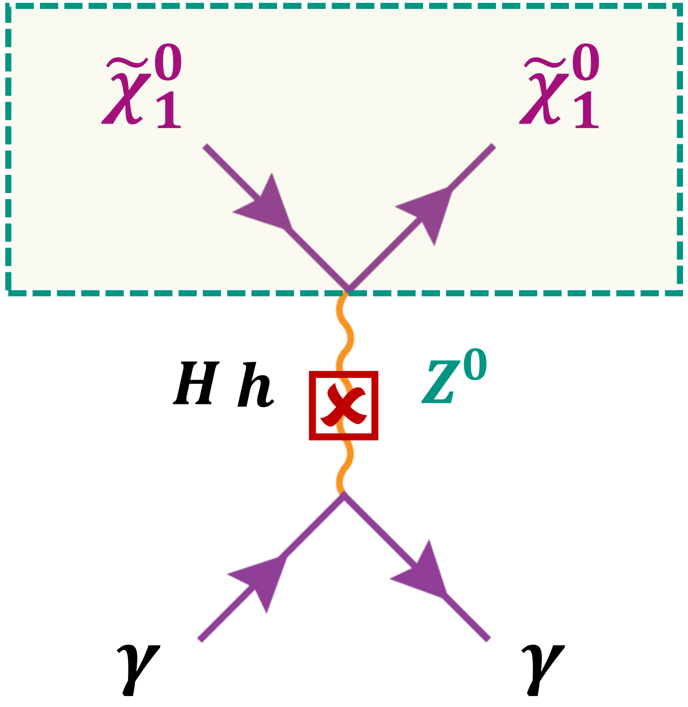
- $\boldsymbol{\gamma}$ – energy distribution depends on the (unknown) **dominant** annihilation channel ($\rightarrow \boldsymbol{b\bar{b}}, \ldots$)



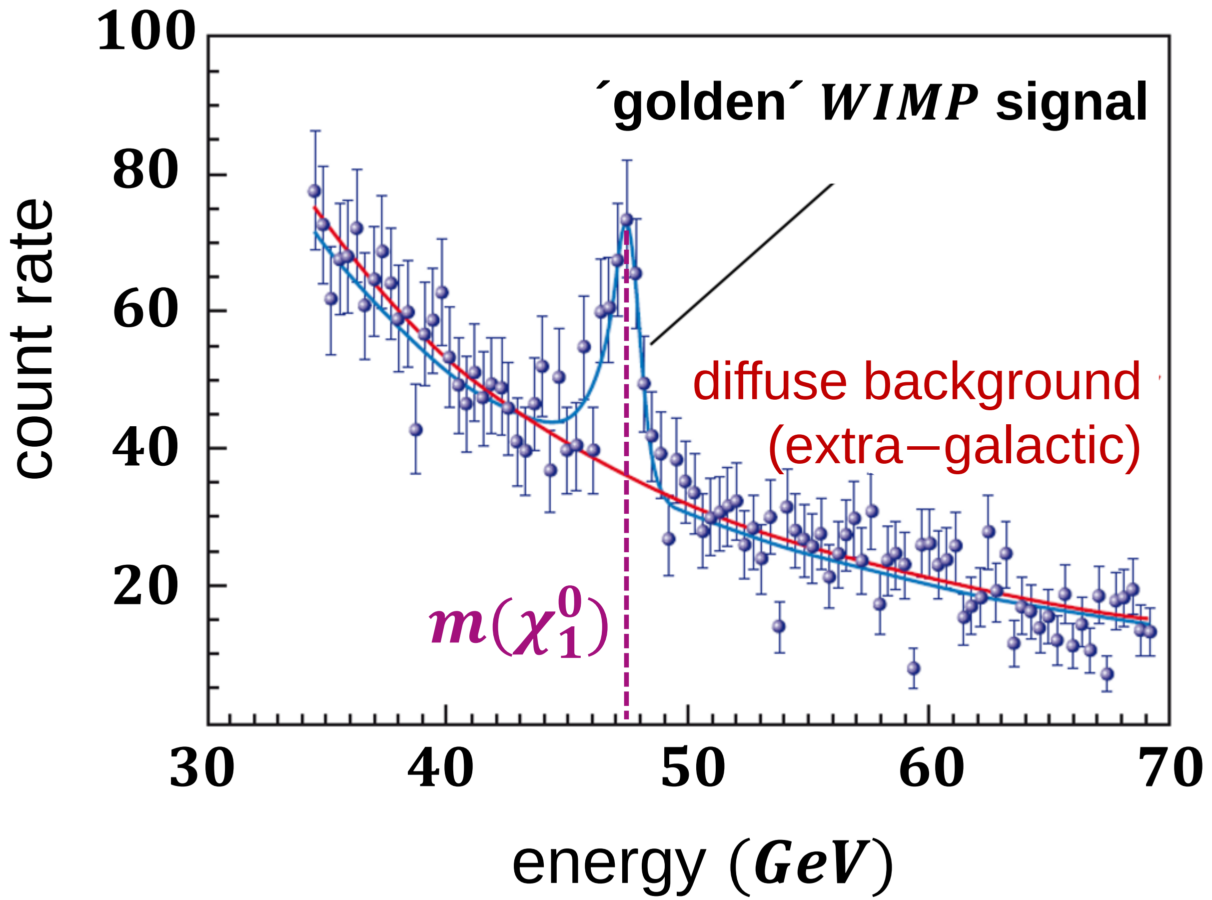
Gammas as DMA messengers: ´golden´ signal

- **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**



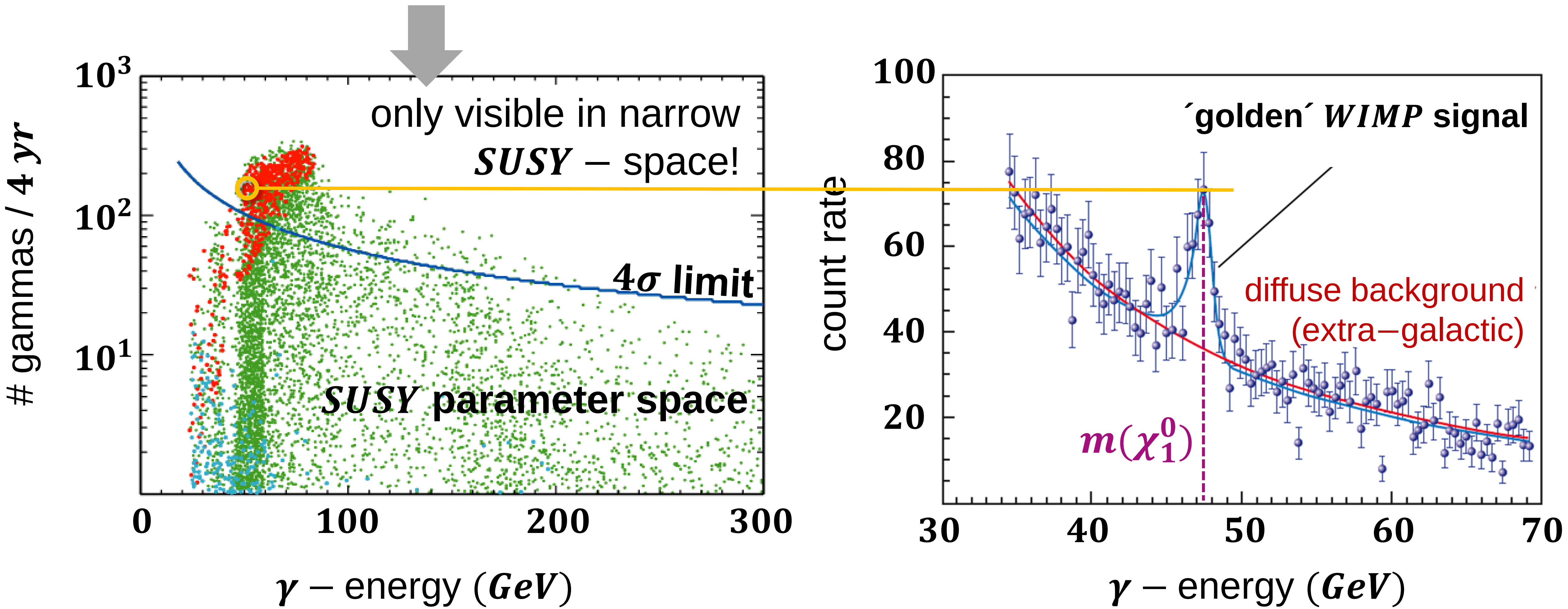
„smoking gun“



Gammas as DMA messengers: golden signal

Karlsruhe Institute of Technology

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



Gammas as DMA messengers: $FERMI$

Karlsruhe Institute of Technology

■ **Fermi Gamma−Ray Telescope: most sensitive GeV − gamma observatory**

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

- key instrument: Large Area Telescope (LAT)
  ⇨ detect gammas via **pair conversion**

Fermi satellite mission	
Data taking	since mid−2008
orbit	$560\ km$
dimensions	$2.8\ m\ (h) \times 2.5\ m\ (\emptyset)$
mass	$4.3\ t$
γ-energies	$20\ MeV\ \ldots\ 300\ GeV$
effective area	$1\ m^2$
angular resolution	~ 1´

Fermi Gamma-ray Space Telescope

Fermi: the *L*arge *A*rea *T*elescope *LAT*

LAT

Karlsruhe Institute of Technology

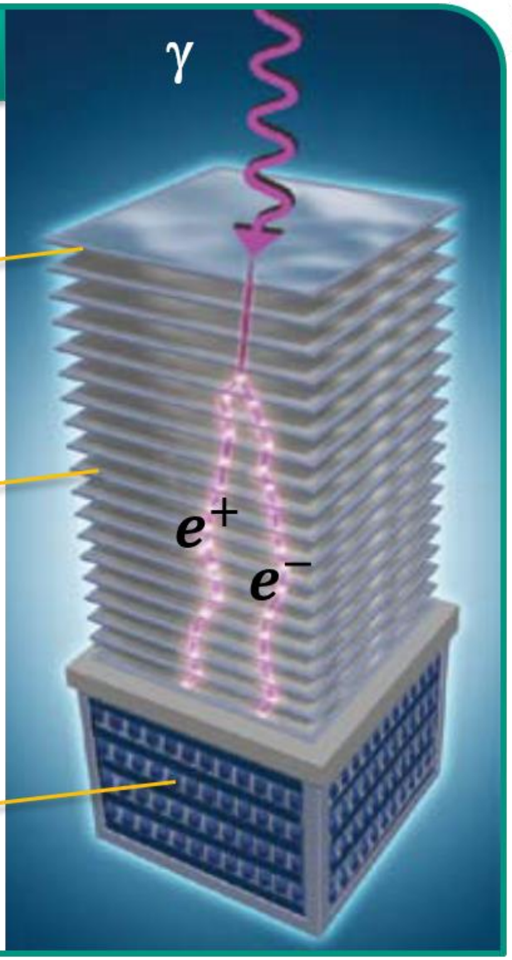
- **Pair conversion of gammas with 16 towers**

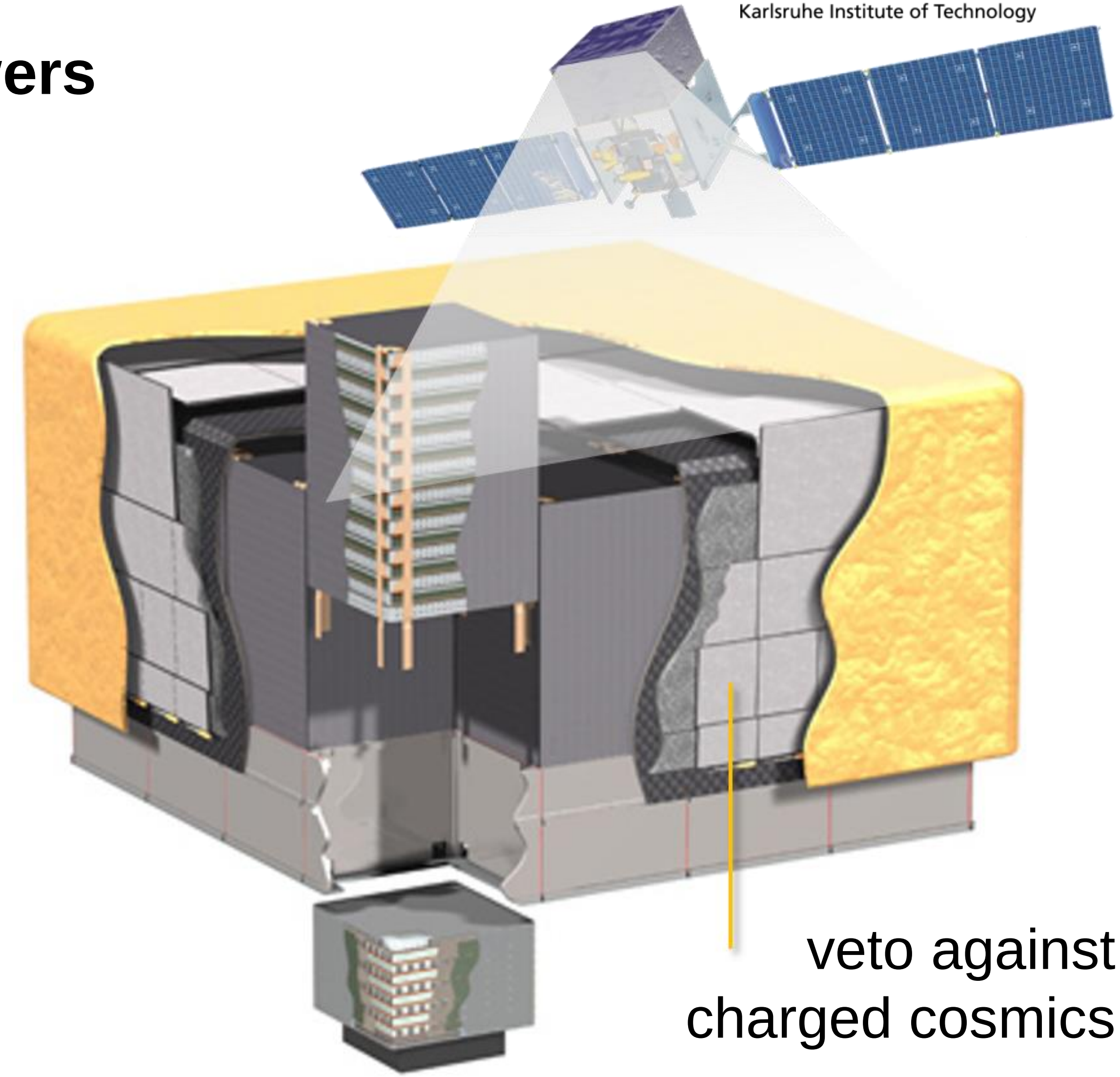
single LAT tower

γ – conversion
($16\ W$ – foils)

Si – strips
(track detection)
⇨ **γ – direction**

$ECAL\ (= 8.6\ \Lambda_0)$
CsJ – scint.
⇨ **γ – energy**





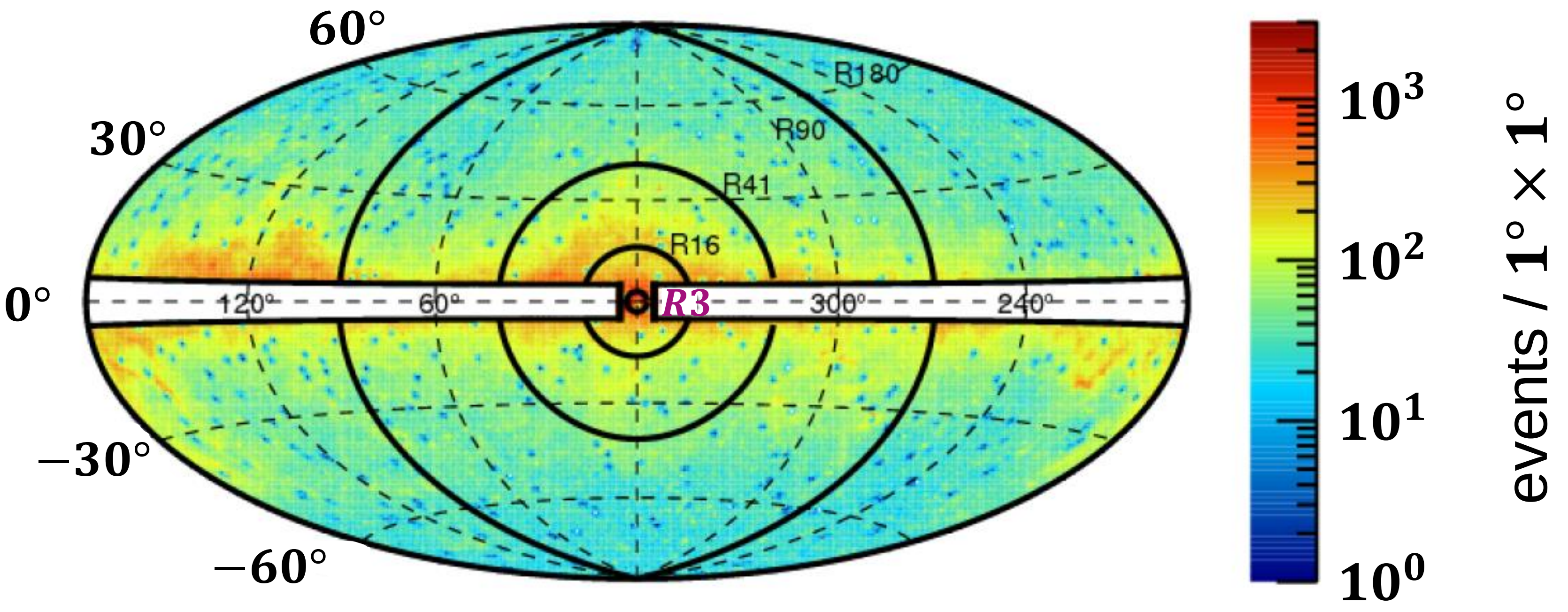
How do you look for a DMA signal in the sky?

Karlsruhe Institute of Technology

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

- define a series of ROIs (Regions$-O$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

Karlsruhe Institute of Technology

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

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

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

- (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: **highly** controversial discussions about this interpretation of the γ – excess

- (likely) astrophysics 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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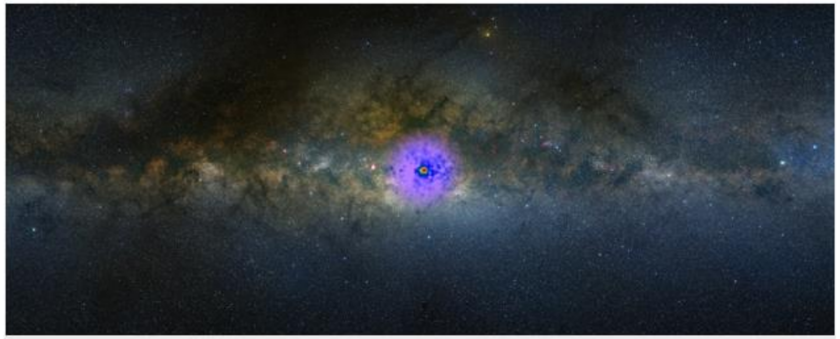
nature.com



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

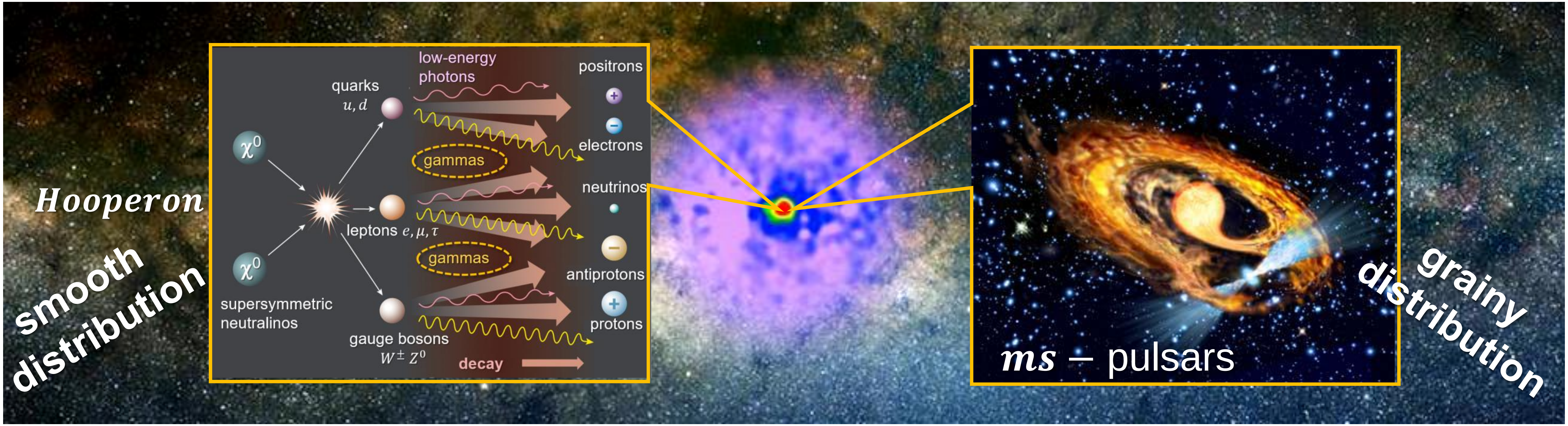
*this is a pun name for χ_1^0, coined after the first author

Fermi observes an excess at the galactic center

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

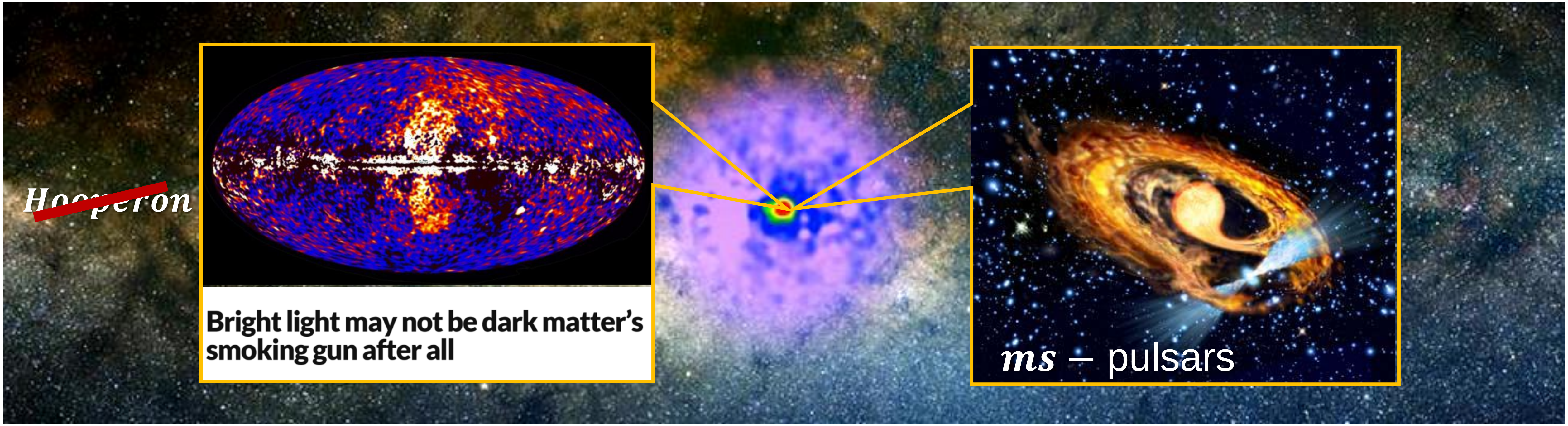
  - *DMA* interpretation: annihilation of ´***Hooperons***´ into ***GeV*** – scale gammas

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



Fermi observes an excess at the galactic center

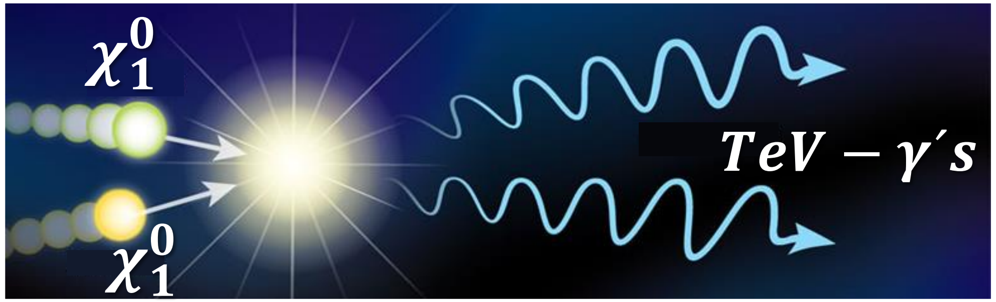
- **2023: this is not a signal of *DMA* (*aka* the ´*Hooperon*´) but ´new pulsars´**
  - update: **no evidence** for a ***Hooperon*** in ***DMA*** search focused on dwarf galaxies
  - astrophysics interpretation: a new class of ***ms* – pulsars** at the galactic center ☑



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



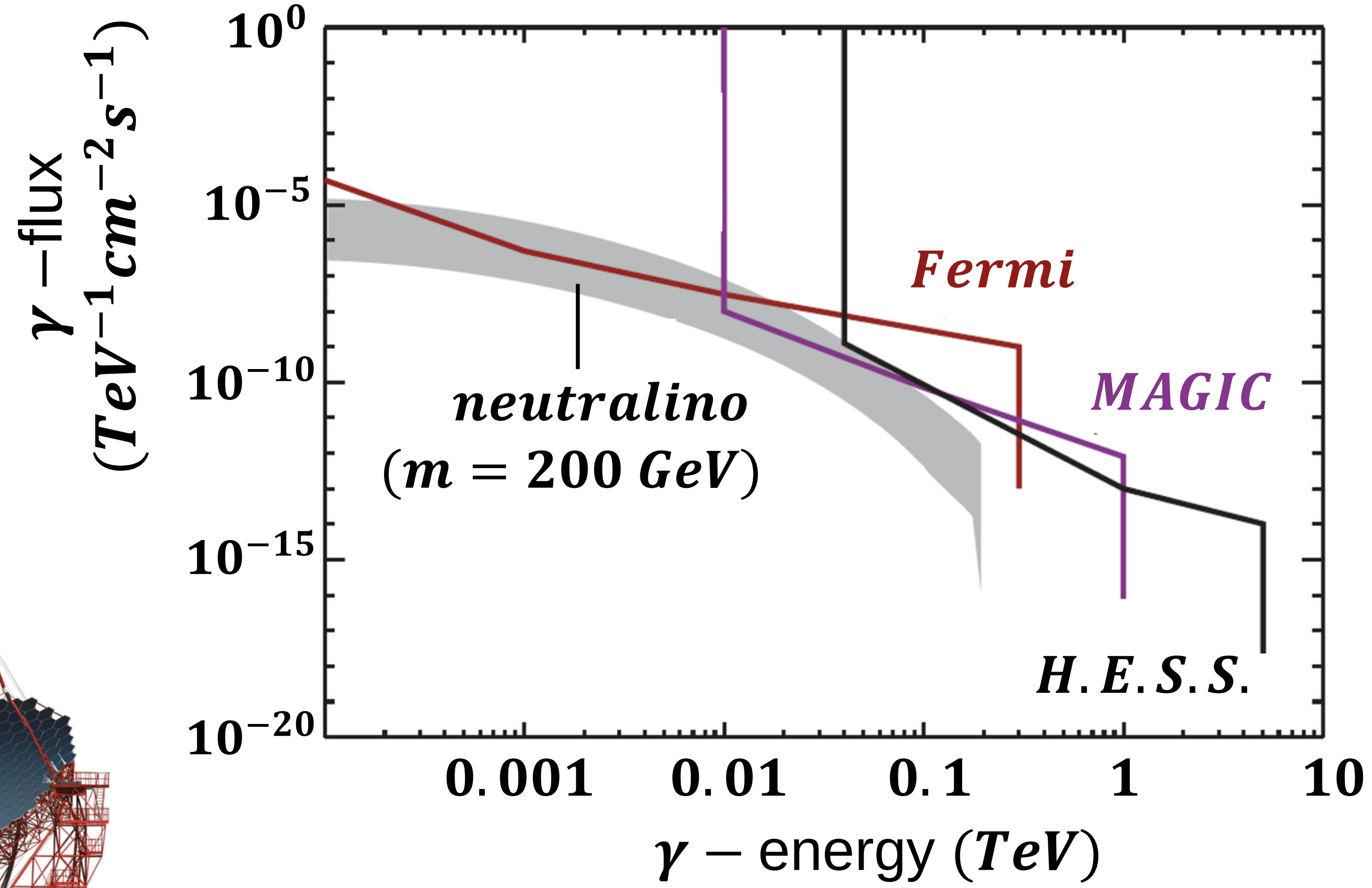
Comparing the DMA sensitivites

- **A clear advantage of $IACTs$: we extend DMA searches to higher $\gamma-$ energies**

- $\boldsymbol{IACTs}$: extended energy range, excellent angular resolution, but rather narrow field–of–view

- $\boldsymbol{IACTs}$: long exposures required due to small $\boldsymbol{DMA}\ \boldsymbol{\gamma}-$ fluxes from $\boldsymbol{TeV}-$ scale (very heavy) neutralinos

$$\boxed{\boldsymbol{\Phi_{Ann}} \sim \frac{\mathbf{1}}{\boldsymbol{m^2_{CDM}}}}$$

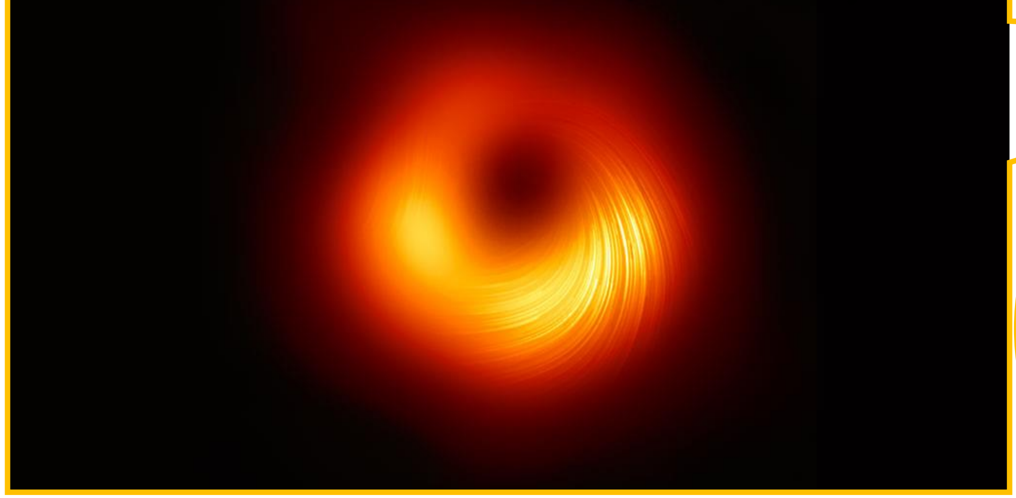


Let´s point our $IACT$ to the galactic center

- **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!

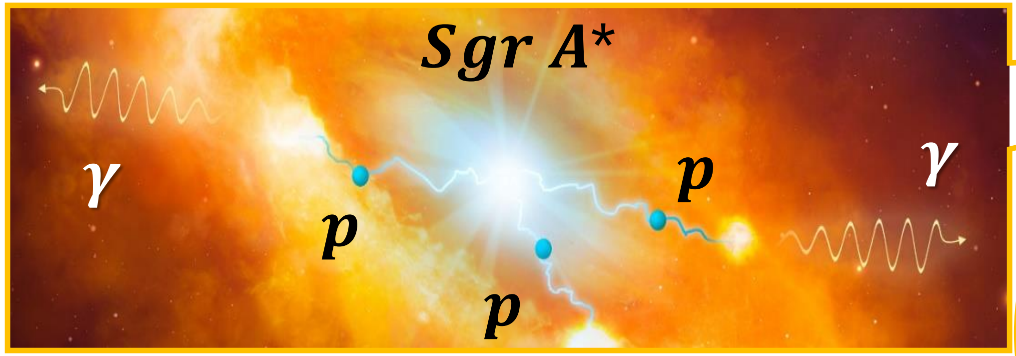
Event Horizon Telescope (EHT)



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!

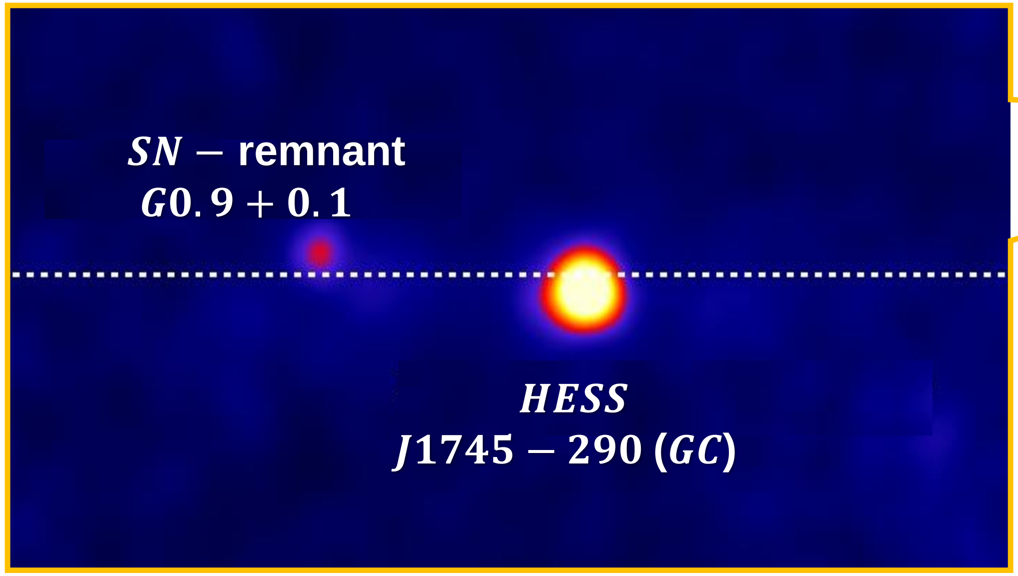


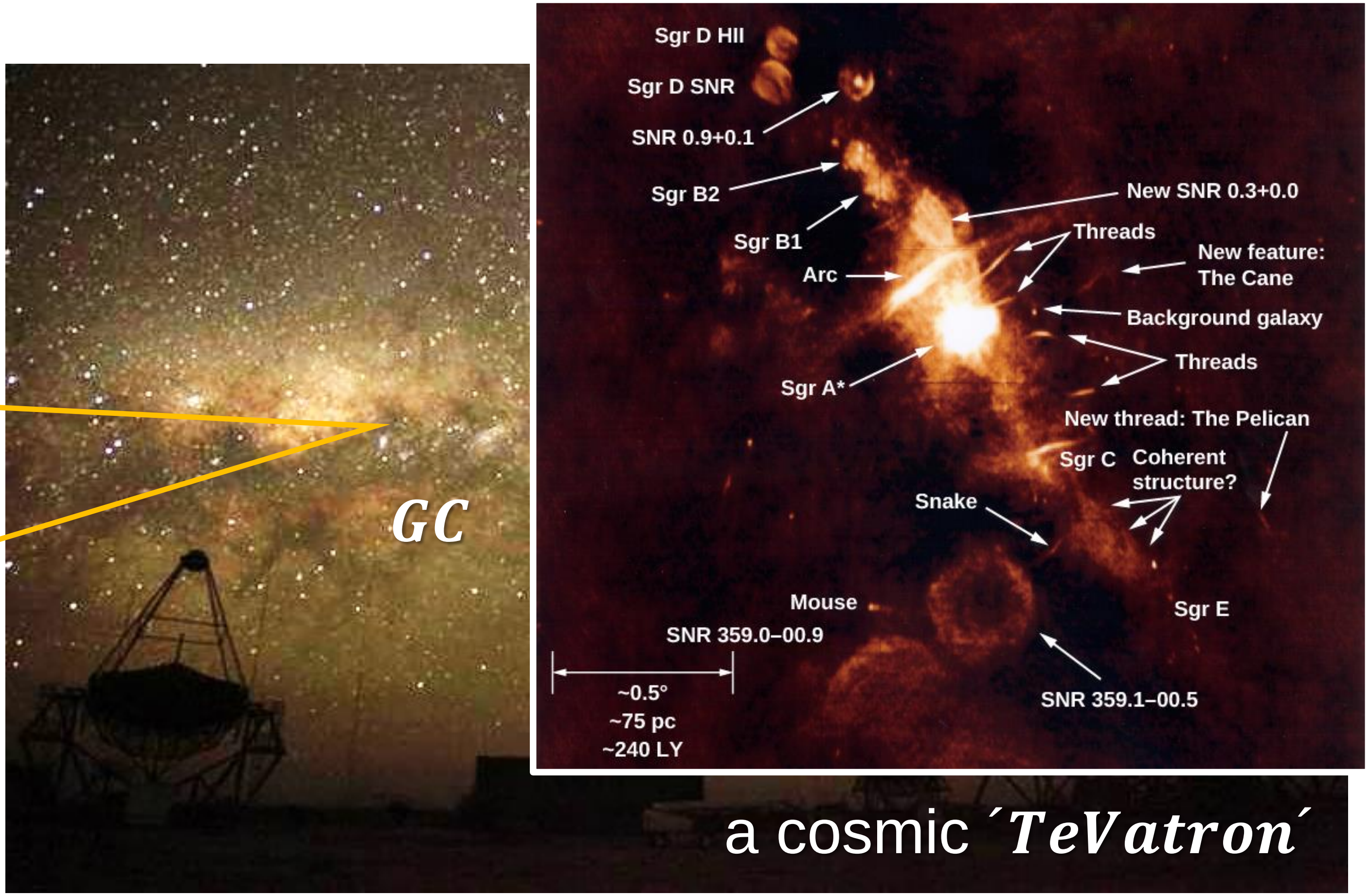
will we be able to see a DMA signal there?

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??



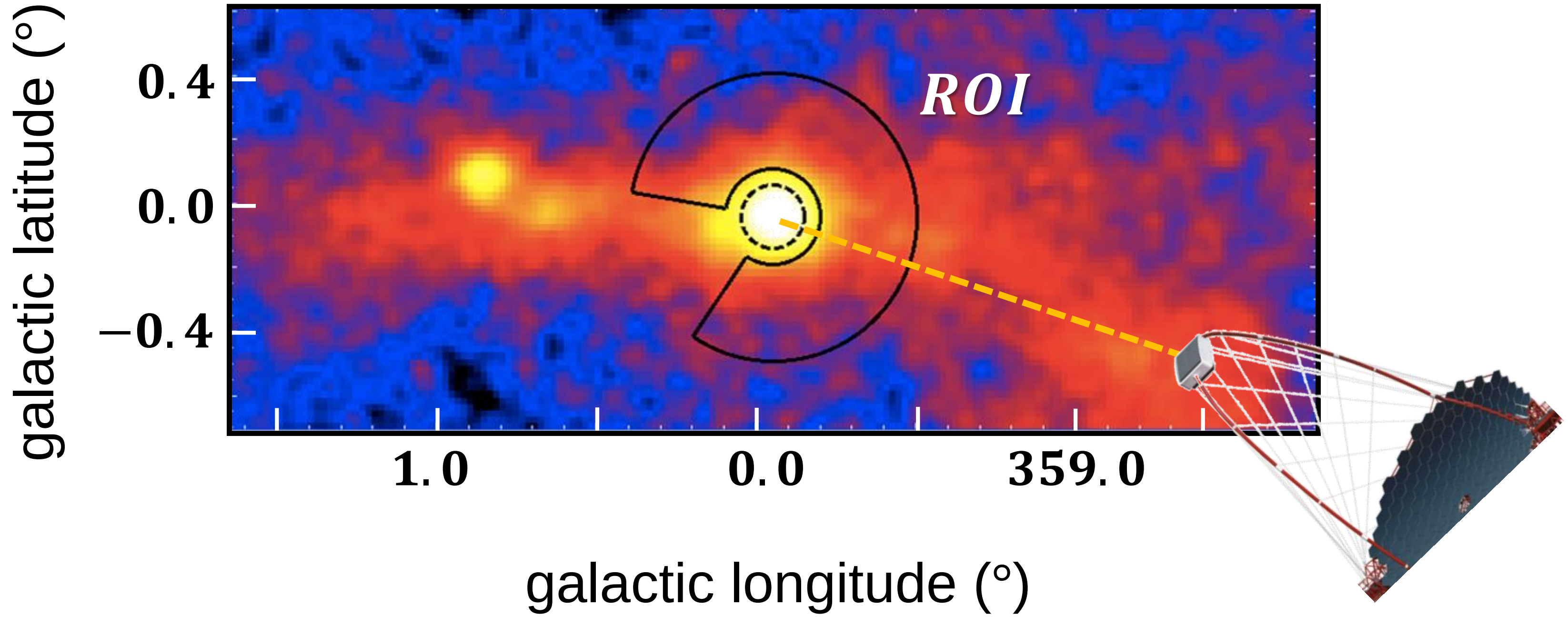


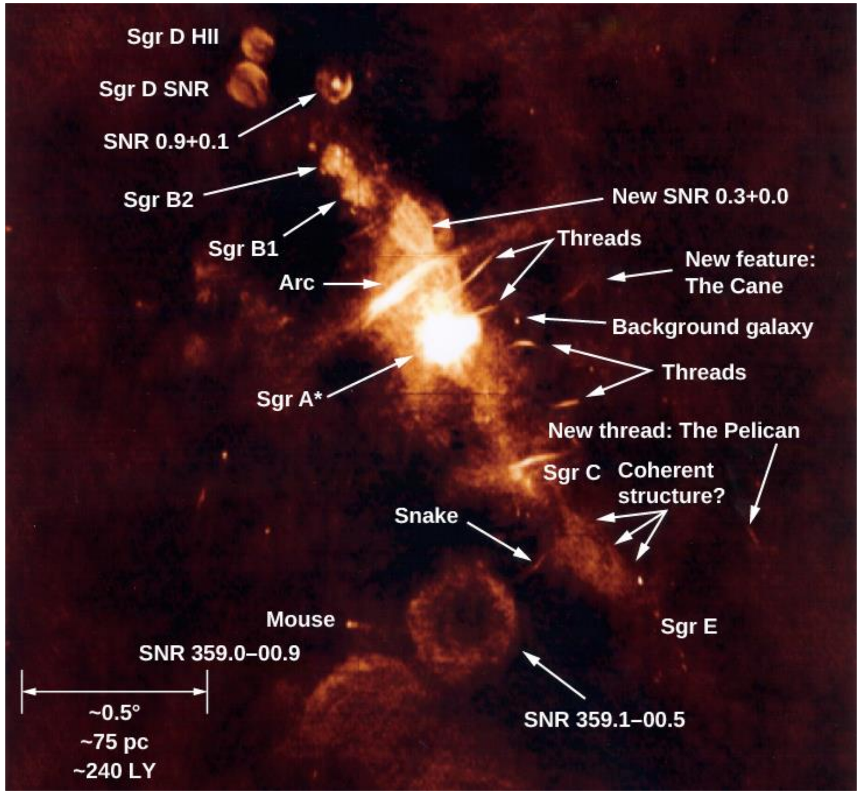
a cosmic ´$TeVatron$´

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

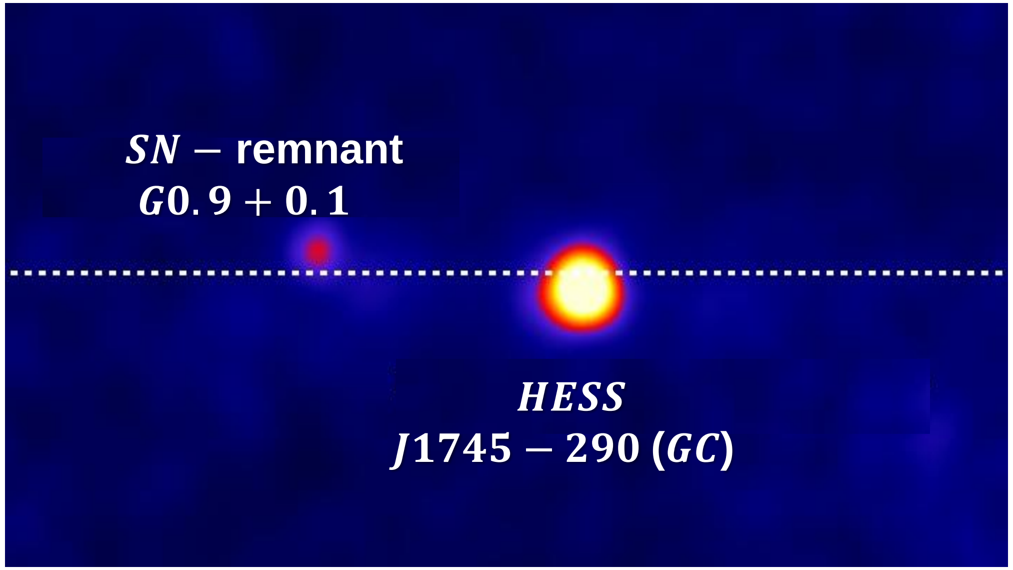
- we compare different $\boldsymbol{R}$egions–$\boldsymbol{O}$f–$\boldsymbol{I}$nterest ($\boldsymbol{ROI}$), similar to the $\boldsymbol{Fermi}$ analysis at lower energies

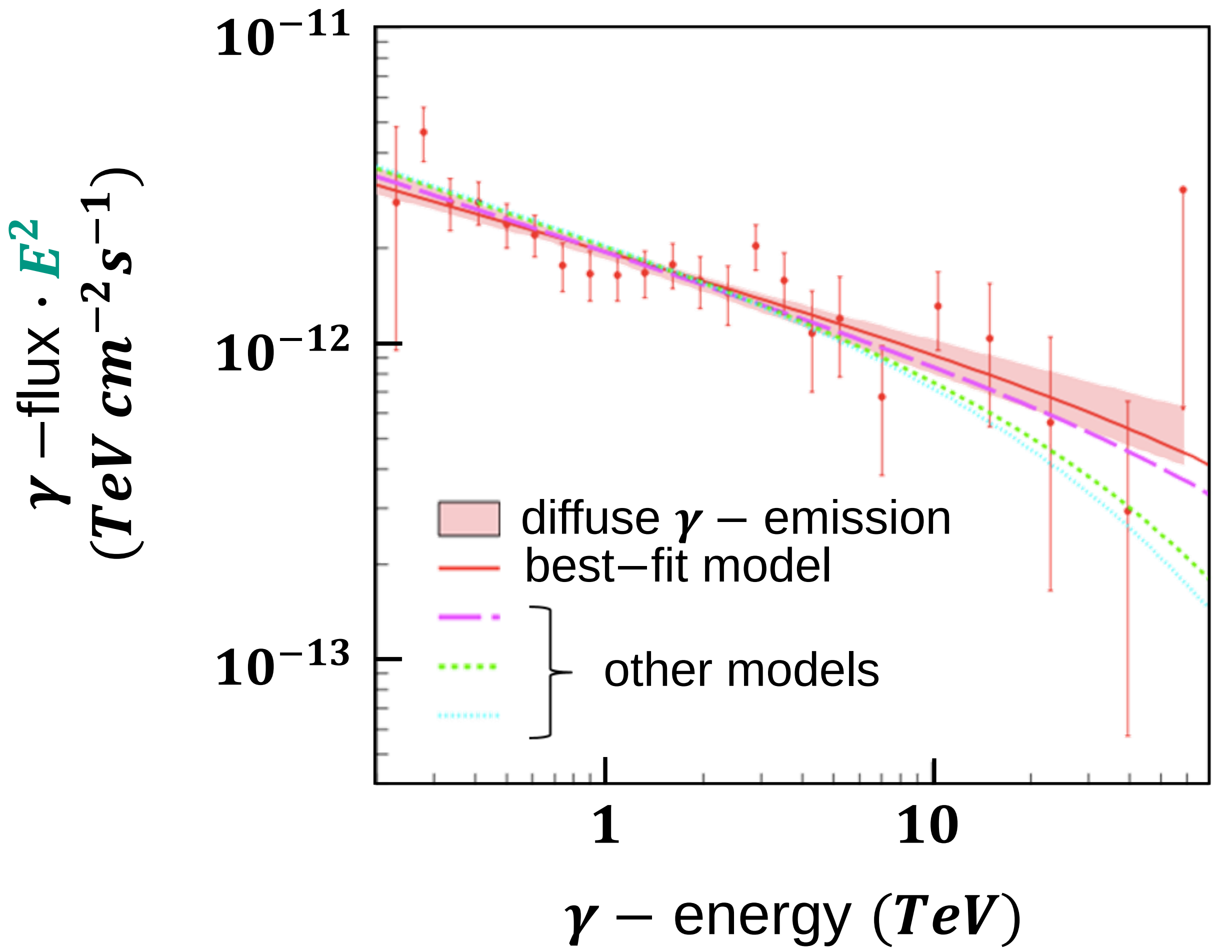




$IACT$ results from the galactic center

- the GC: a **featureless power–law spectrum**, a clear indication of astrophysics
  - inner–most ROI: gammas from acceleration of charged particles & subsequent γ – production

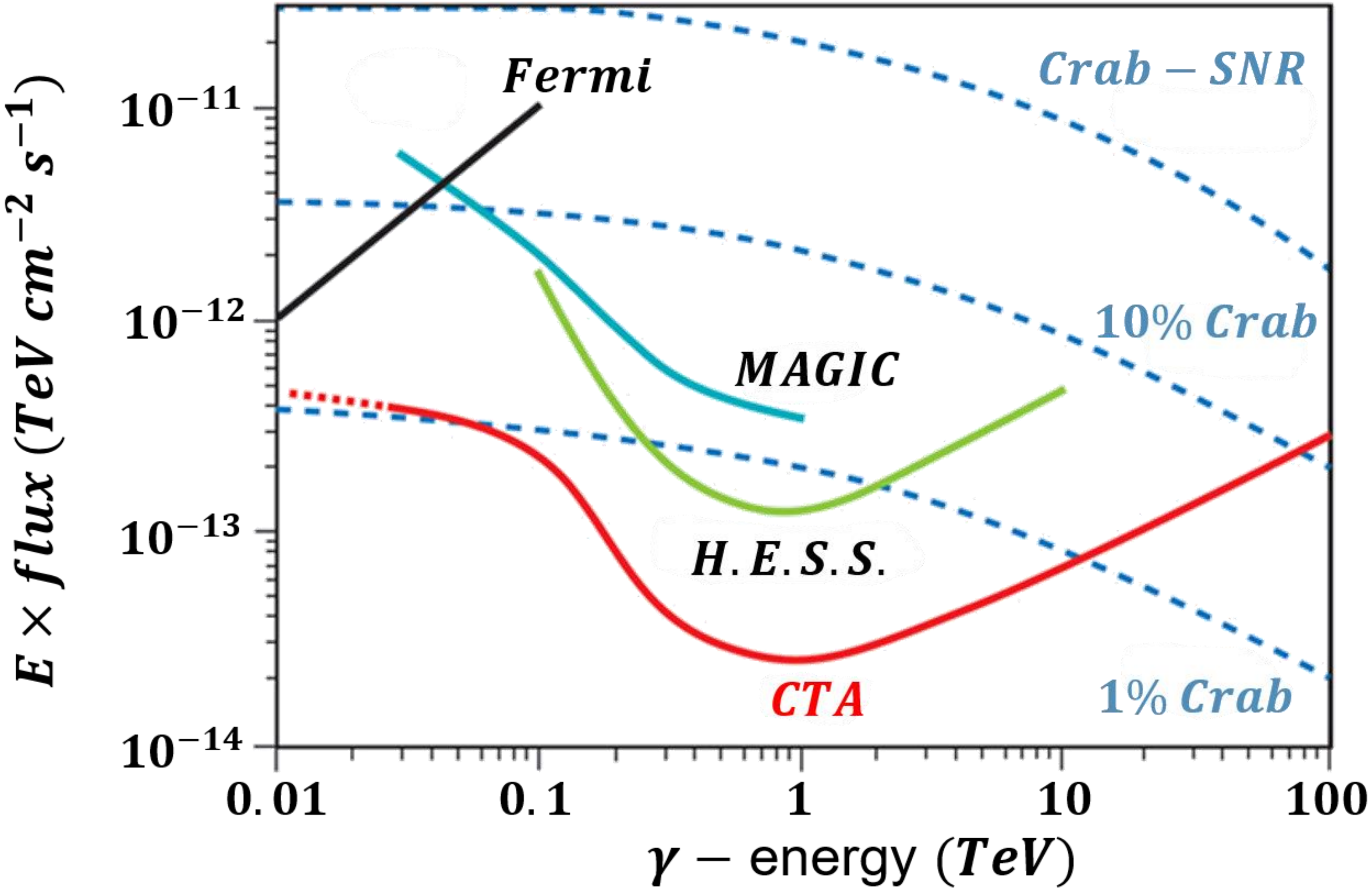




$IACT$ results in the future: expected CTA limits

- **The future *C*herenkov *T*elescope *A*rray* will search for DMA signals**

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



*see lect. $9, p. 9 - 15$

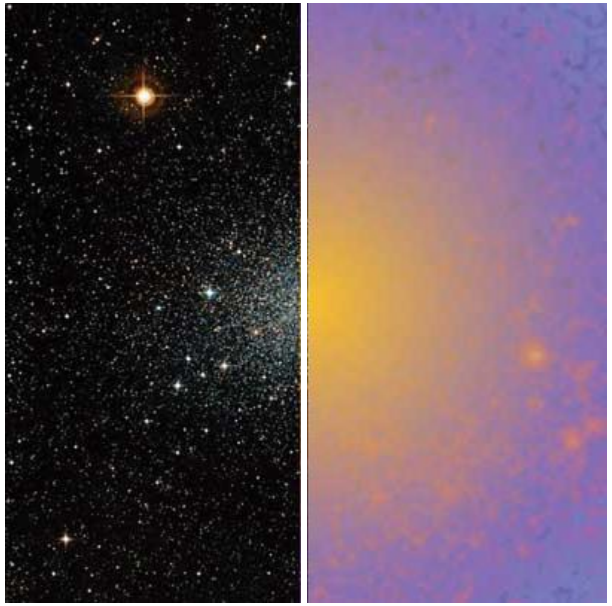
$IACT$ results in the future: expected CTA limits

- The future *C*herenkov *T*elescope *A*rray will search for DMA signals

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

⇨ ideal, composed of 99% DM!

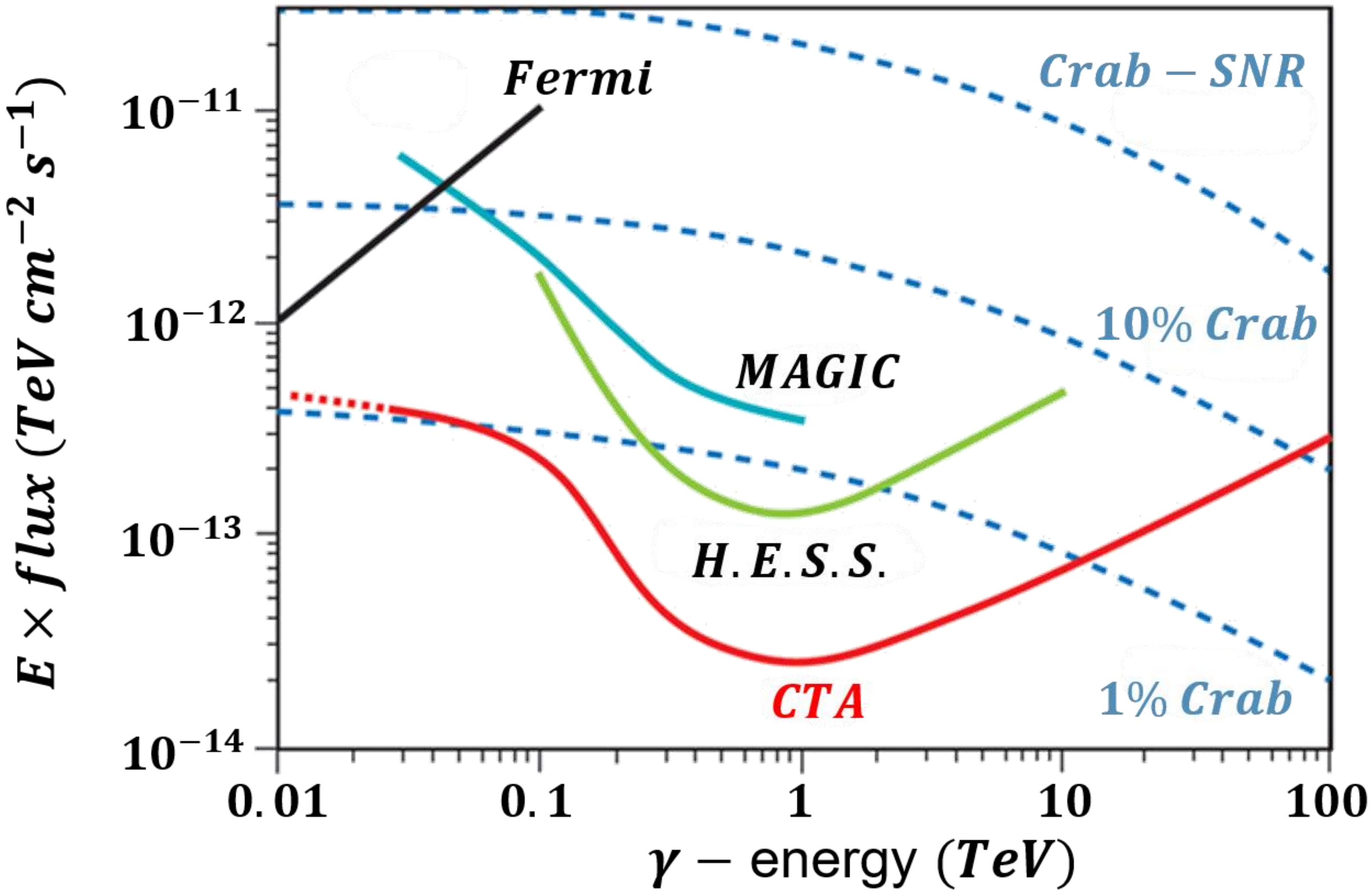
optical **(photo)**



γ´s (MC)

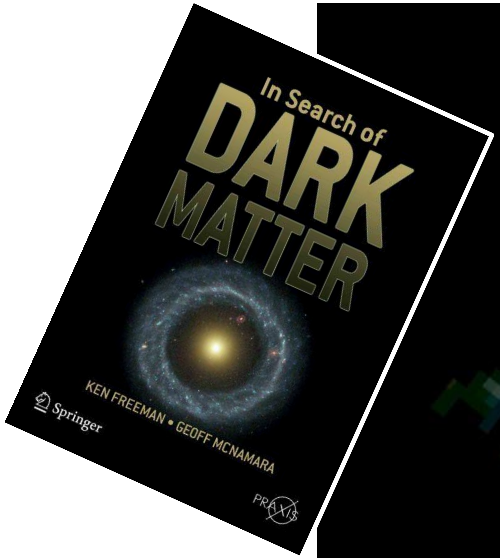
stars

DMA



A Christmas tree made from CR tracks

- **Seasons Greetings & a happy New Year 2024**



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