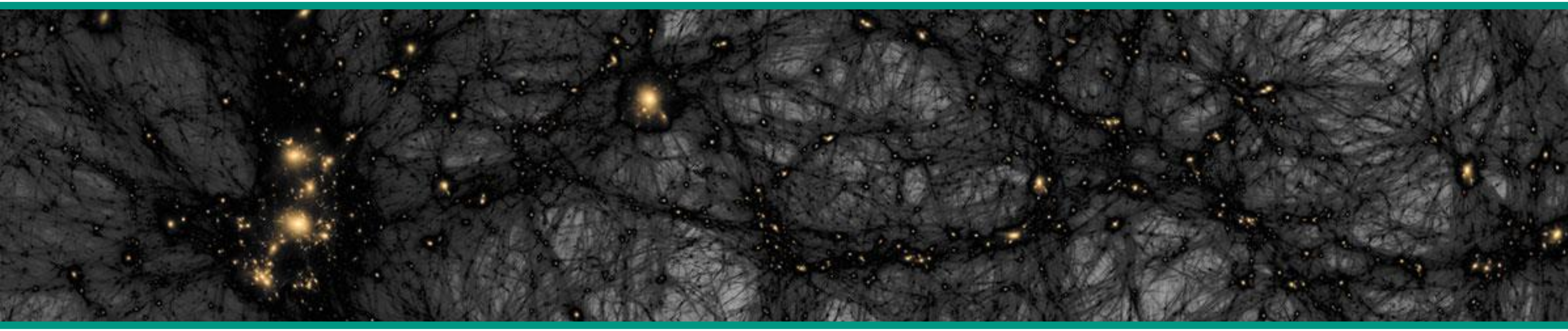
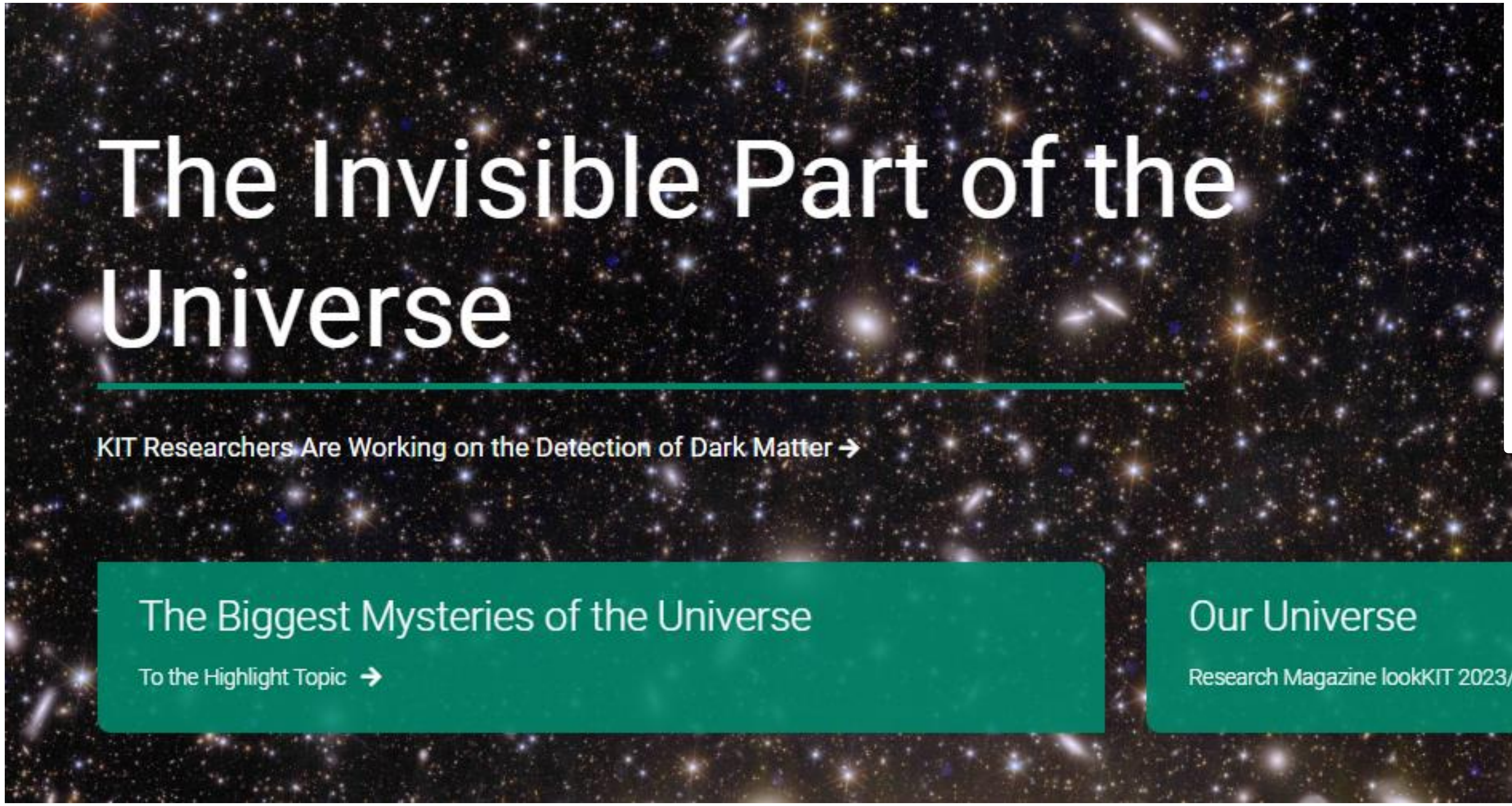
Astroparticle physics *I* – Dark Matter

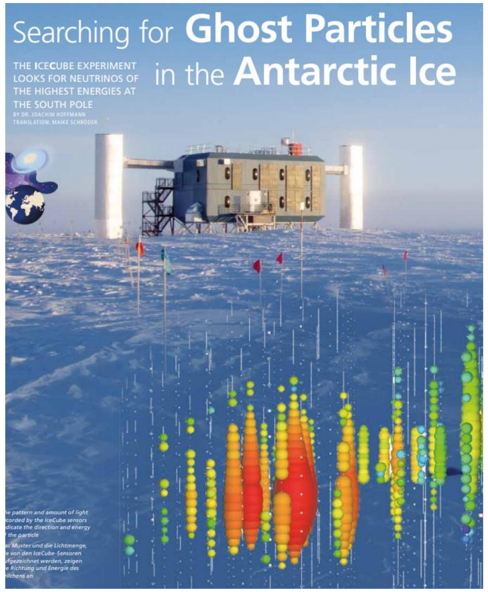
Winter term 23/24 Lecture 15 Jan. 11, 2024



A Happy & successful New Year 2024

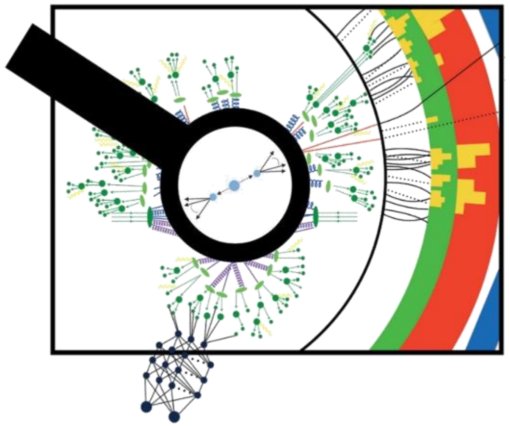
- ***Dark Matter*** **welcomes you at the site** ***kit.edu***





Recap of Lecture 14

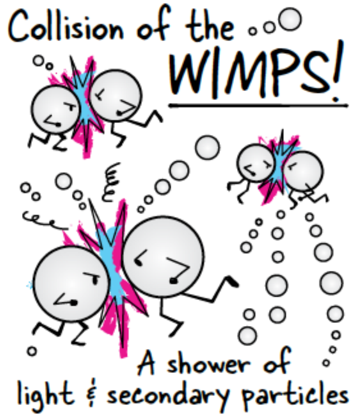
- **Dark Matter Searches:** $\boldsymbol{LHC}$ **searches** & $\tilde{\chi}^0$ – **annihilation in** $\boldsymbol{\gamma' s}$ **in the halo**



- $\boldsymbol{LHC}$ searches for $\boldsymbol{SUSY}$ – **decay cascades** from $\boldsymbol{gluinos}$ to $\boldsymbol{neutralinos}$: lepton/hadron pairs, **missing** $\boldsymbol{E_T, p_T}$

- **no** signal in $\boldsymbol{pp}$ – collisions, $\boldsymbol{Run2}$: limit $\boldsymbol{M(\tilde{\chi}^0) \geq 1\ TeV}$, $\boldsymbol{Run3}$ since mid–$\boldsymbol{2022}$, $\boldsymbol{HL-LHC}$: $\boldsymbol{2029 \ldots 38}$, then: $\boldsymbol{FCC}$ (?)

- $\boldsymbol{DM}$ – **annihilation in the halo**: **particle–** (decay channels) & **astro– physics** ($\boldsymbol{NFW}$ profile) to calculate **messenger spectrum**: $\boldsymbol{\gamma, \nu, e^+, \bar{p}}, \ldots$

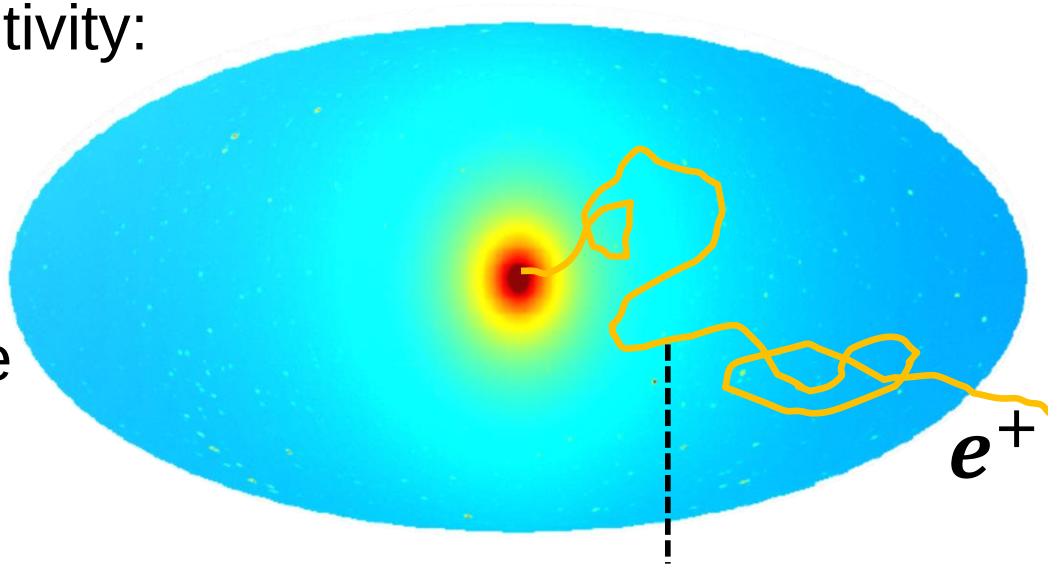


- results of $\boldsymbol{DMA}$ searches based on **gammas**
  $\boldsymbol{GeV}$ – scale: $\boldsymbol{FERMI}$ excess – $\boldsymbol{Hooperon}$ or $\boldsymbol{ms}$ – pulsars?
  $\boldsymbol{TeV}$ – scale: $\boldsymbol{IACTs}$ to the $\boldsymbol{GC}$ – many astrophysical sources

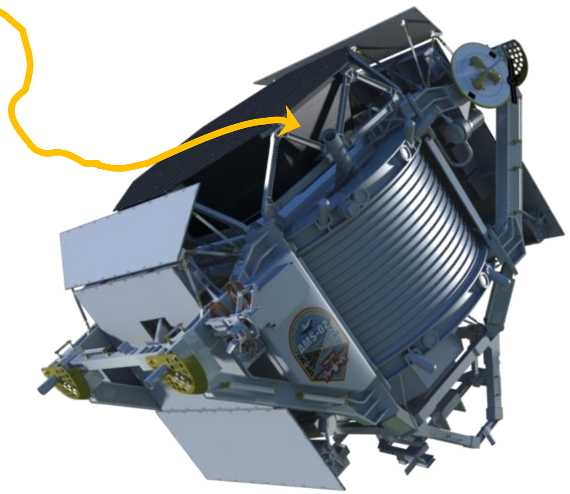
Positrons as DMA messengers

- **Positron signal is challenging due to e^+ transport characteristics in galaxy**

- key to high $\boldsymbol{DM}$ – sensitivity: careful study of all transport phenomena of $\boldsymbol{e}^+$ in galactic $\boldsymbol{B}$ – **fields** (but: local source at distance $\boldsymbol{d} = \boldsymbol{kpc}$) !



$\boldsymbol{GeV \dots TeV}$ – scale:
$\boldsymbol{AMS}$ – **02** experiment



strong deflection in galactic $\boldsymbol{B}$ – **field**

⇨ **huge energy losses** during propagation:
$\boldsymbol{e}^+$ only from local $\boldsymbol{DM}$ – halo

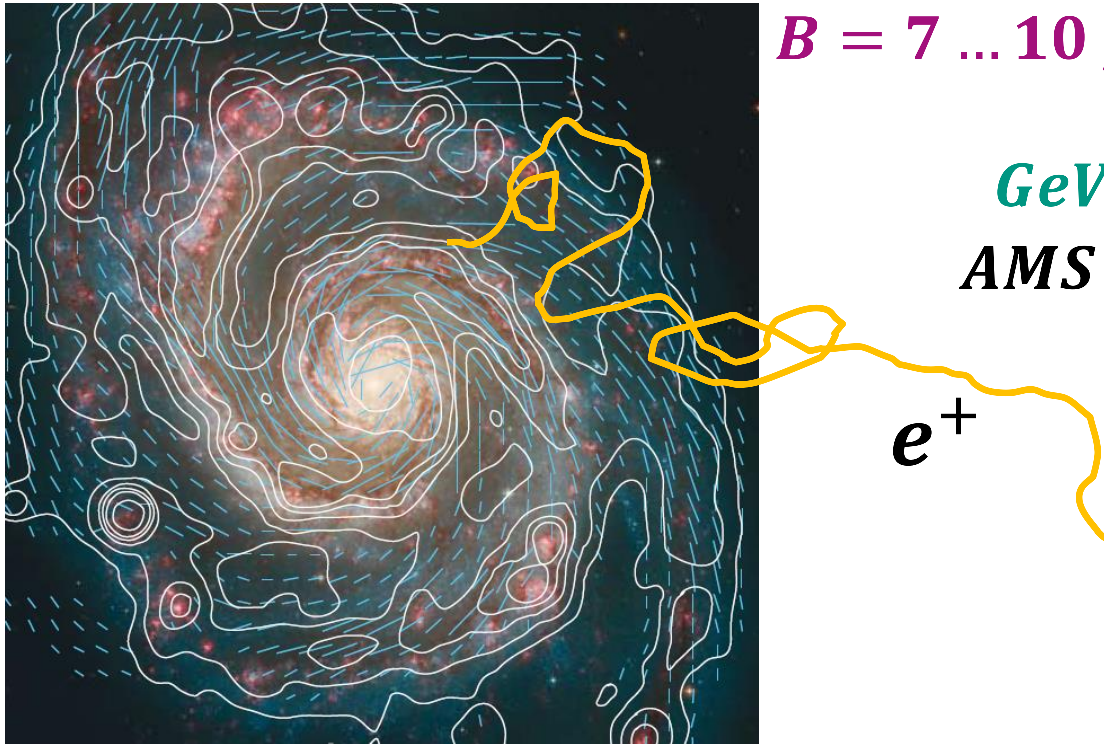
GALPROP

Positrons as DMA messengers

- A closer look at transport phenomena of e^+ from DMA in the galactic halo

- key systematics:

  - diffusion, convection
  - **energy losses ΔE**: absolute values & as function of $E(e^+)$
  - alignment of B – fields
  - also: radiation fields
  - ´normal´ CR – sources



alignment of B – fields in a typical spiral galaxy

$B = 7 \ldots 10\ \mu G$

e^+

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

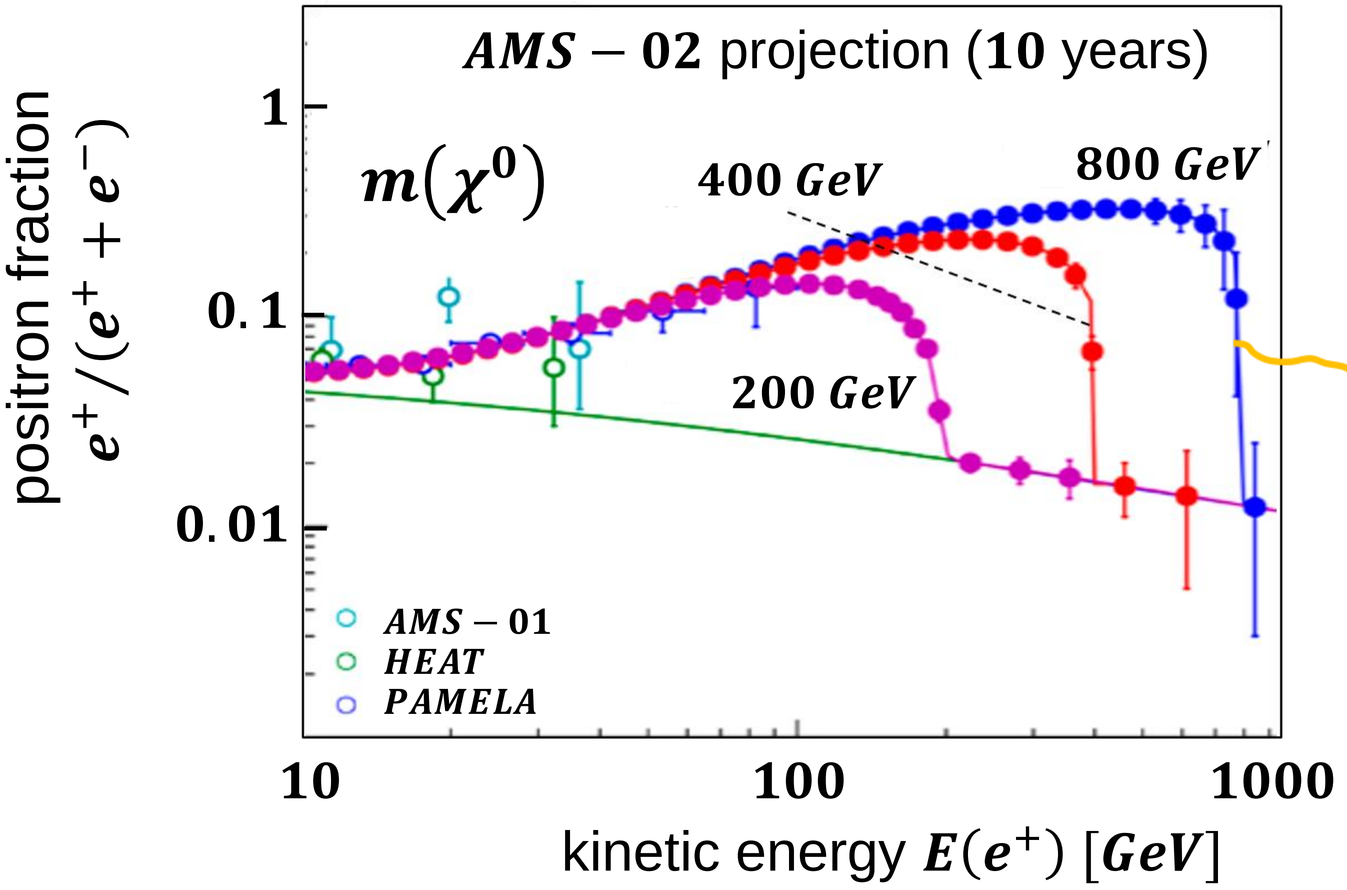
Positrons as DMA messengers

- A closer look at a **possible e^+ signal from DMA** (for different masses of χ^0)

- **DMA signal**:

  increase in the **fraction of e^+** as function of lepton kinetic energy

- **cut–off** at $E(e^+) = m(\chi^0)$



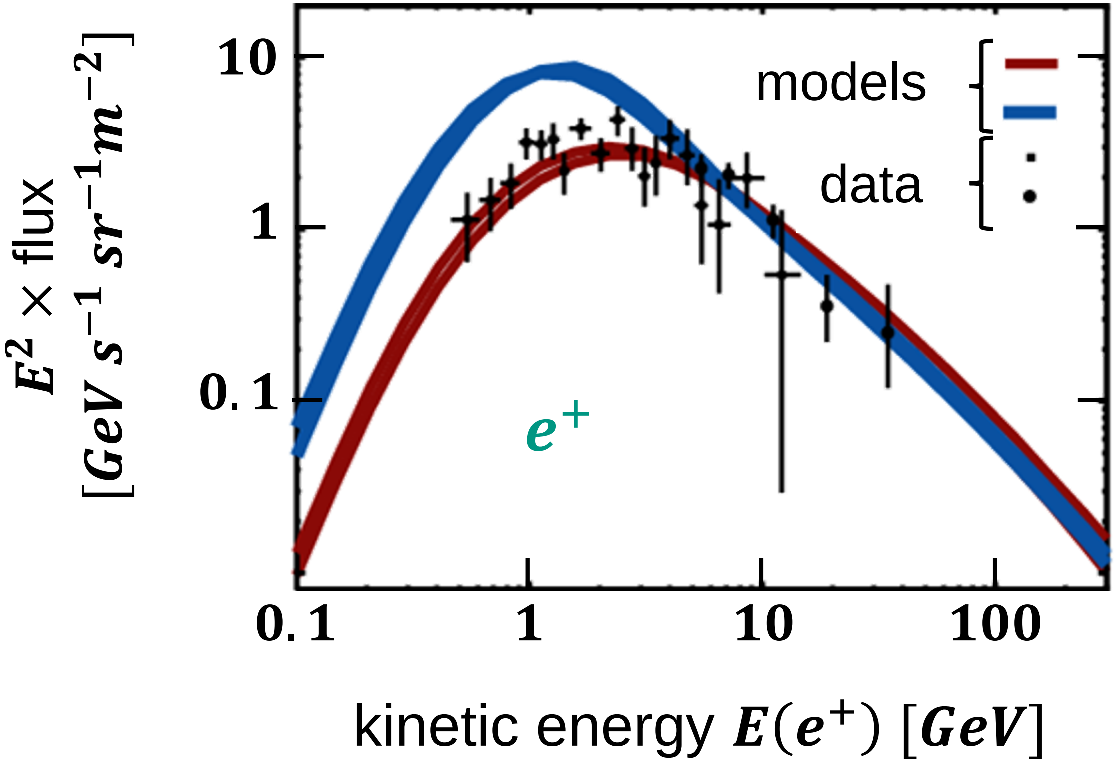
focus on high energies!

Background to DMA searches: astrophysical e^+

- **Early measurements of astrophysical e^+ from diffuse sources**

  - **origin of astrophysical positrons** has previously been studied in detail:

    interactions of **cosmic radiation** with the *I*nter–*S*tellar *M*edium (*ISM*): dust, gas (hot, intermediate, cold)

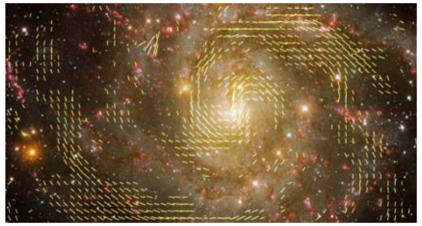


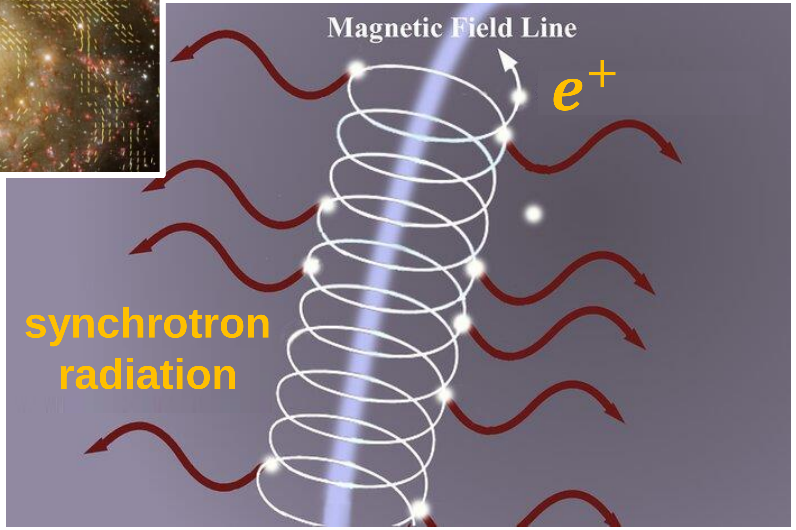
Background to DMA searches: astrophysical e^+

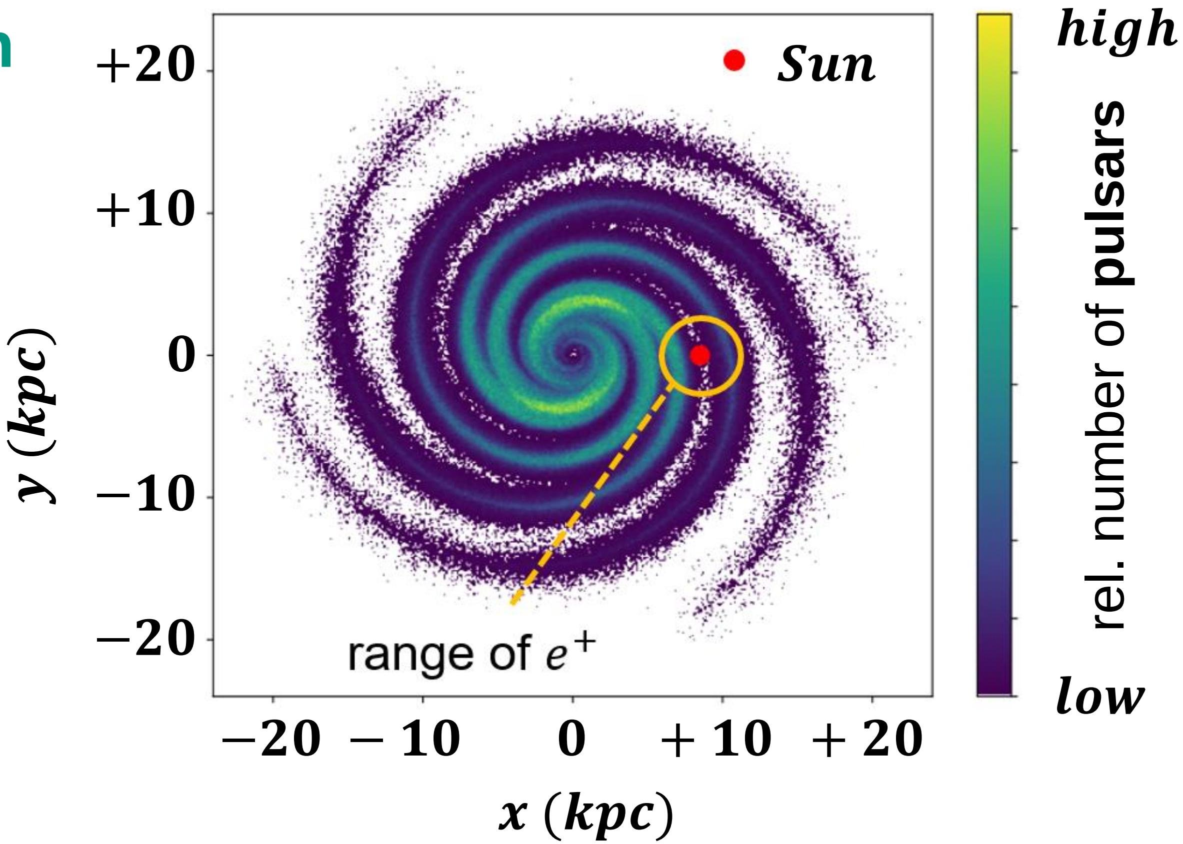
- **Very limited range of e^+ from astrophysical sources or DMA**

  - **energy losses** during **long−distance** (kpc) propagation of astrophysical e^+:

    major losses via: **synchrotron radiation** & **inverse Compton** effect (off star light & Cosmic Microwave Background CMB)







Searching for DMA with e^+: $AMS-02$

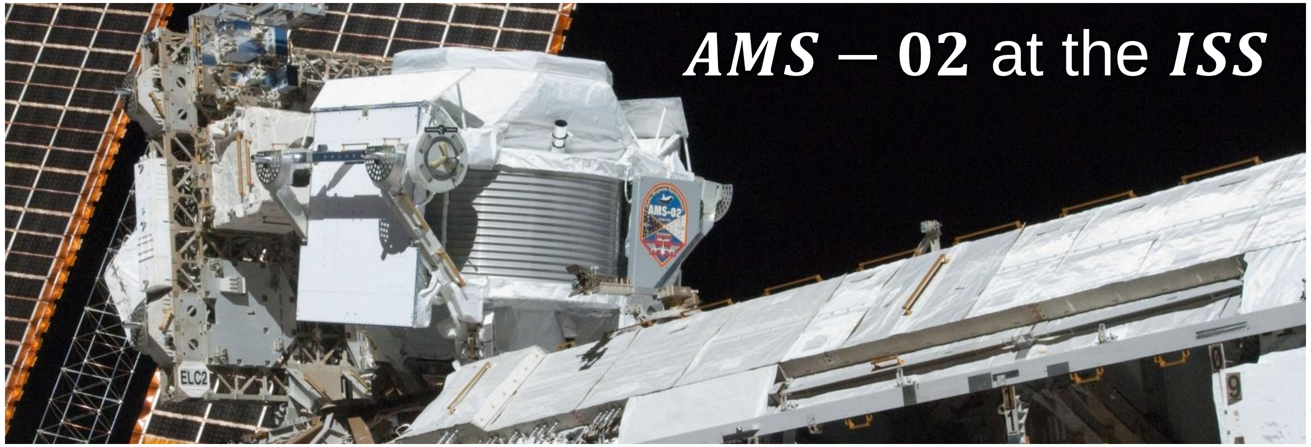
- **Alpha Magnetic Spectrometer (AMS): a particle detector onboard the ISS**

- search for **DM annihilation** ($e^+, \bar{p}$, ...)

- search for **antimatter** ($\overline{He}$, ...)

- investigations of cosmic radiation: flux, energies, composition

start: May $16, 2011$ with $STS-134$



$AMS-02$ at the ISS

Searching for DMA with e^+: $AMS-02$

- Alpha Magnetic Spectrometer (AMS): a particle detector onboard the ISS

  - ETP was participating in $AMS-02$ from $2002 \ldots 2020$ (contributions to the TRD)

[AMS-02 | The Alpha Magnetic Spectrometer Experiment (ams02.space)](ams02.space)

Searching for DMA with e^+: $AMS-02$ setup

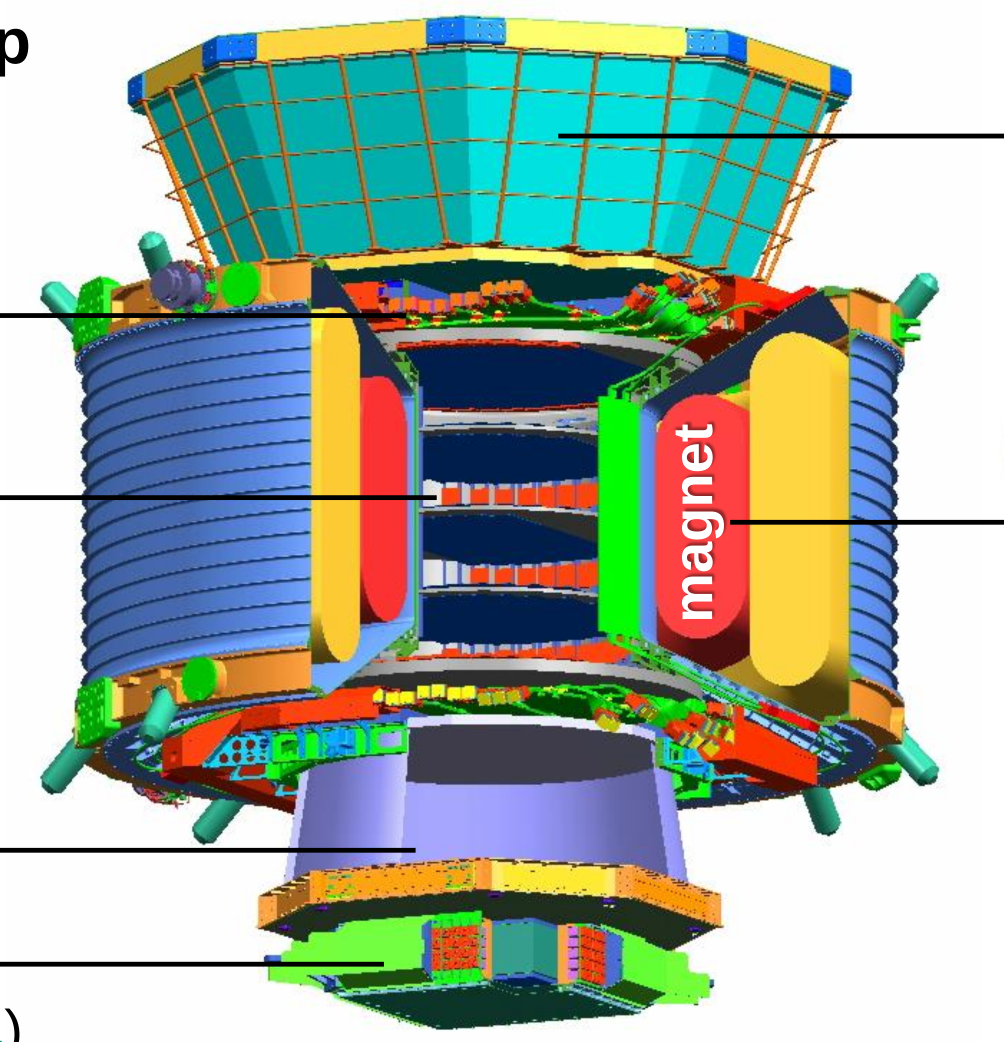
- Experimental setup

ToF
Time–of–Flight detector (β)

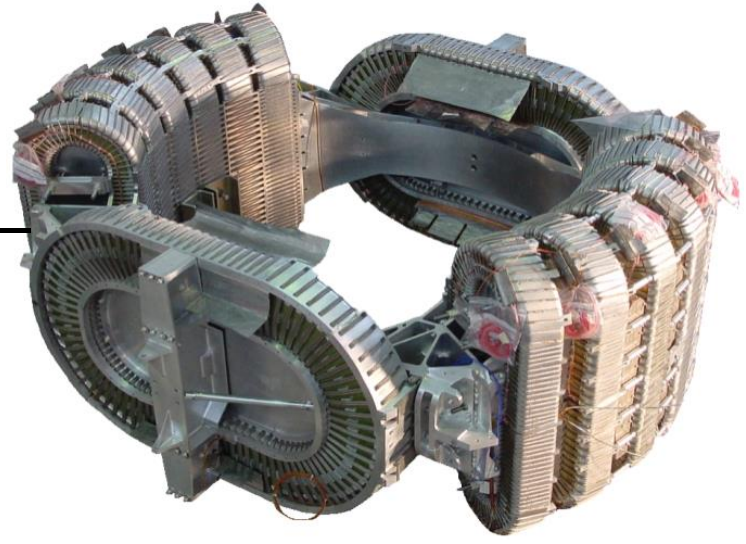
tracker & magnet
particle track (p)

$RICH$
Ring Imaging Cherenkov detector ($v < c$)

$ECAL$
Elmagn. CALorimeter (E_{tot})



TRD Transition Radiation Detector ($v \sim c$): light / heavy particles



$B = 0.12\ T$

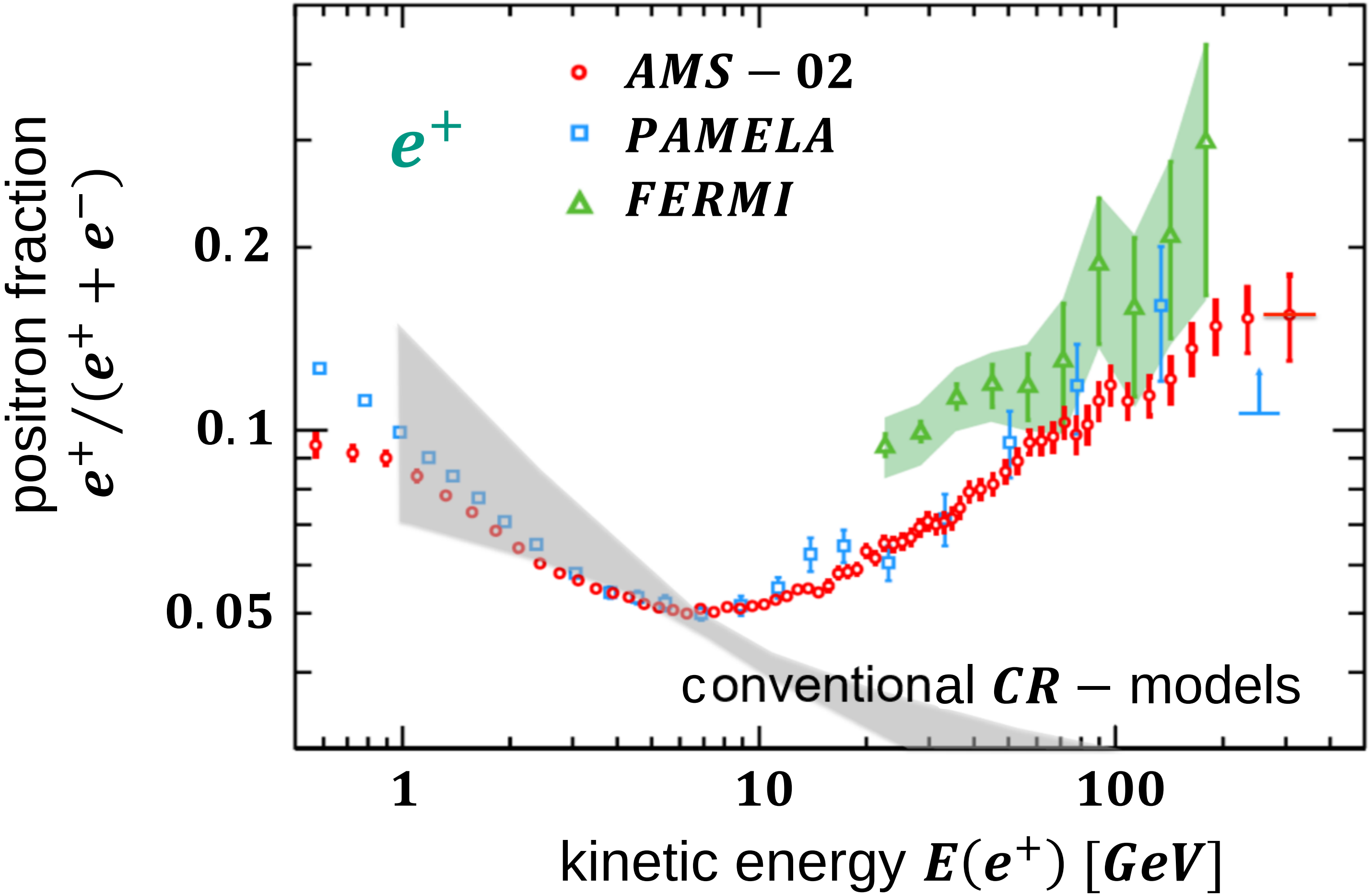
$AMS-02$ results: a high−energy excess of e^+

- $AMS-02$ confirms long−standing earlier observations: excess of positrons!

- the fraction of **cosmic e^+** does indeed increase for high energies, but we do not (yet??) see a cut−off at neutralino mass $m(\chi^0)$

- is this the ´**smoking gun**´ of DMA & evidence for DM?

- we need to check for other astrophysics scenarios first...



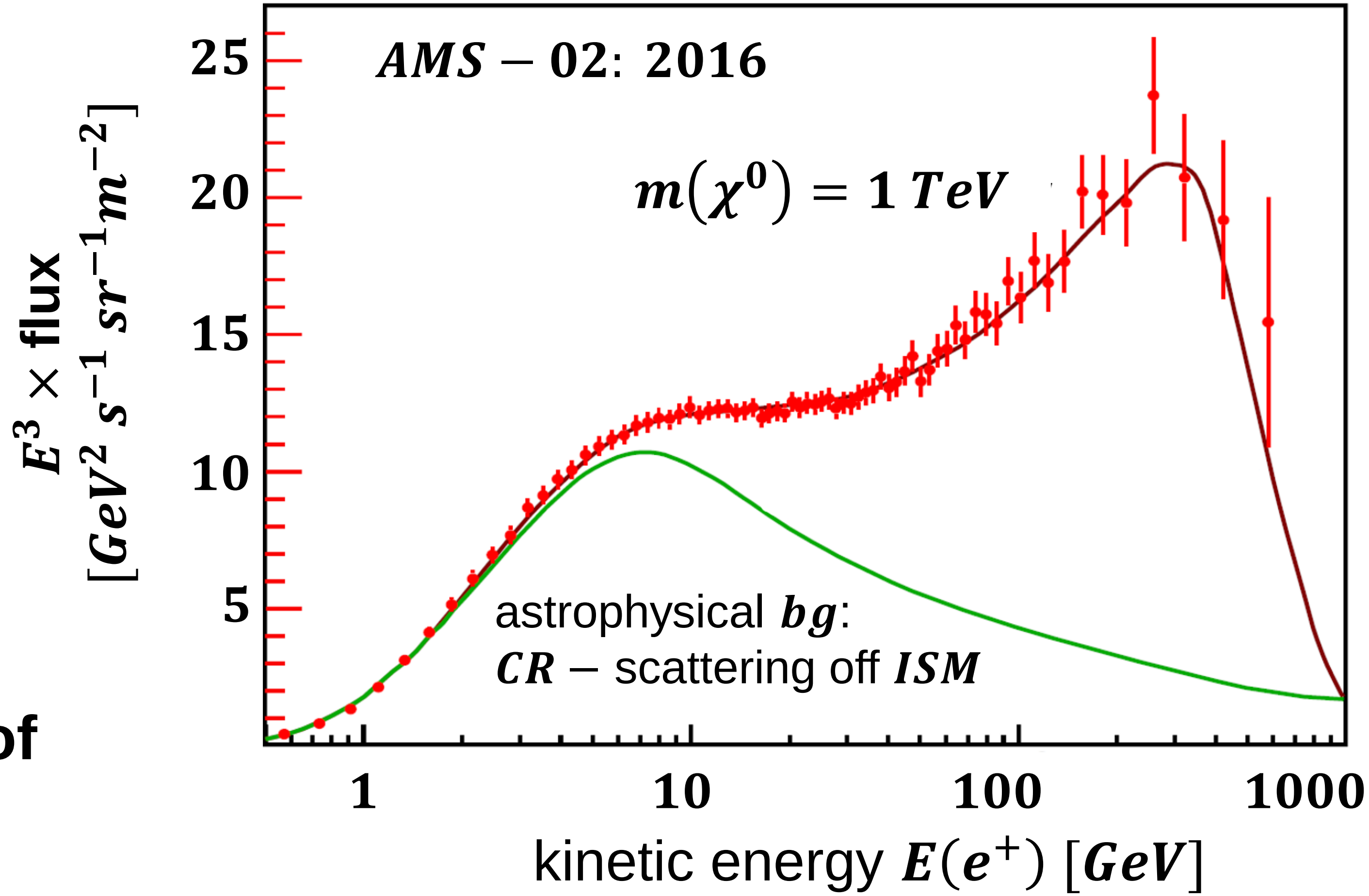
$AMS-02$ goals: observe high−energy e^+

- **$AMS-02$ observes energetic positrons almost up to the TeV − energy scale!**

- **the ´golden´ road to finding DM via e^+ − spectroscopy...**

  a) **astrophysical background** from ISM is diffuse & falls off rather steeply for all high−energy positrons

  b) **DMA signal** if the neutralino mass $m(\chi^0)$ is on TeV − scale: clear **excess of high−energy positrons**

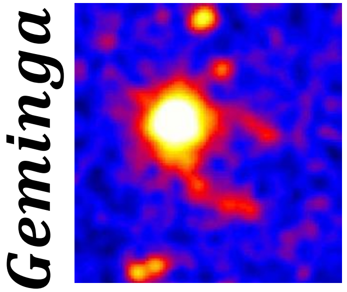


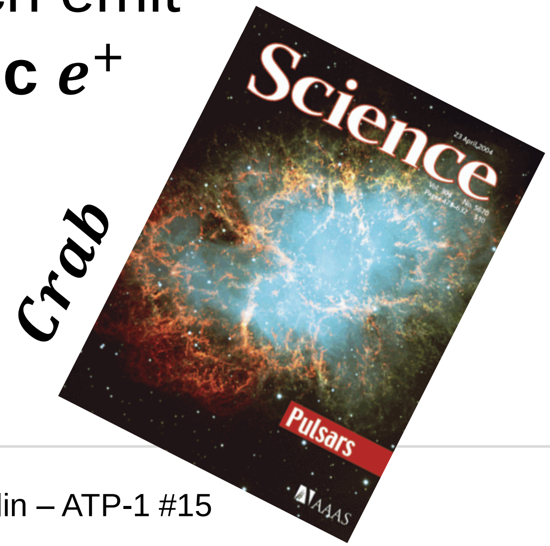
$AMS-02$ results: a high–energy excess of e^+

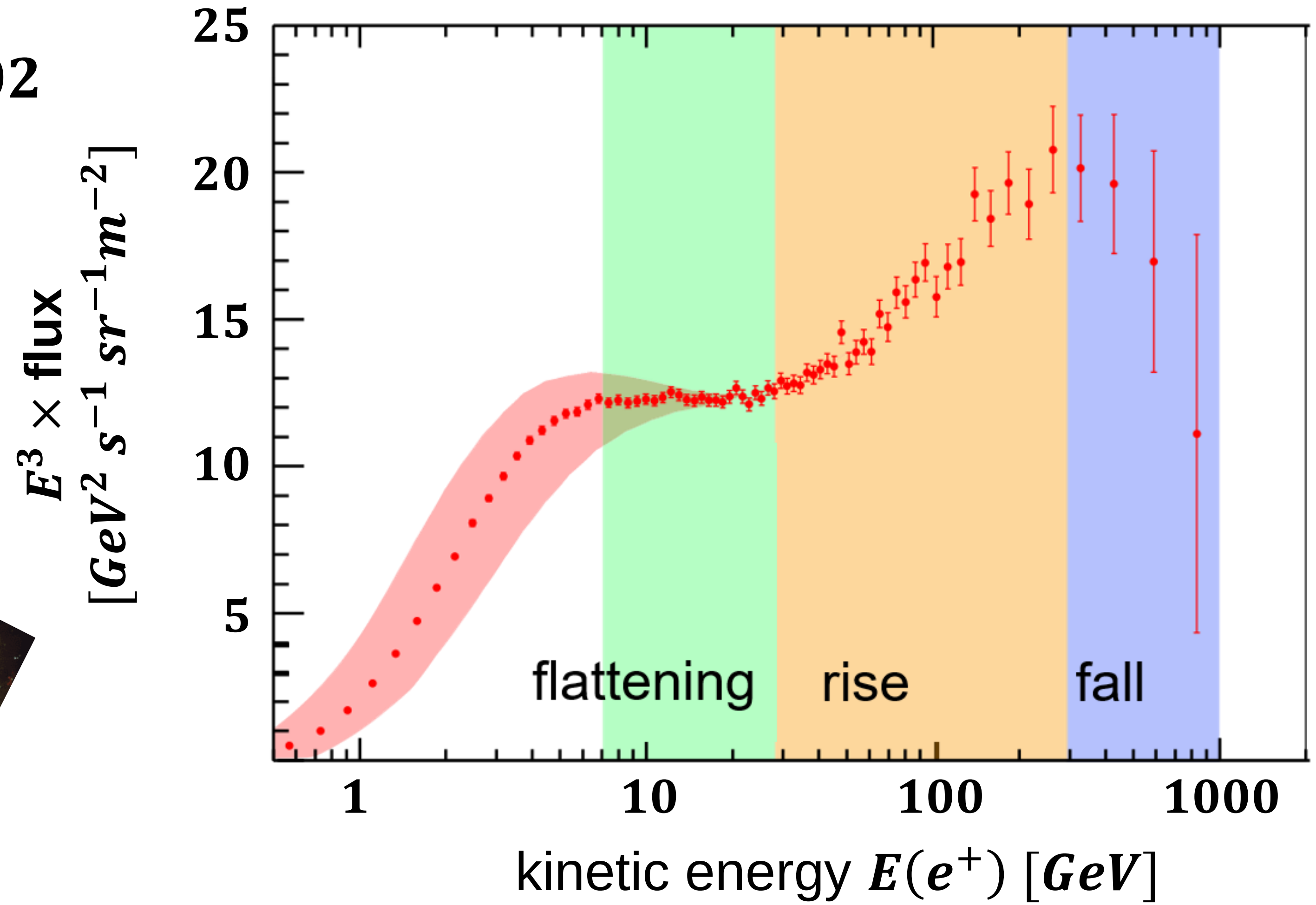
- What is its origin – DMA signal or astrophysical e^+ from nearby pulsars?

- difficult interpretation of $AMS-02$ data & e^+- spectroscopy…

  $a)$ astrophysical background
  young pulsars (pulsar wind nebulae) at $d = 0.3 \ldots 3\ kpc$ (nearby!) which emit **very energetic e^+**





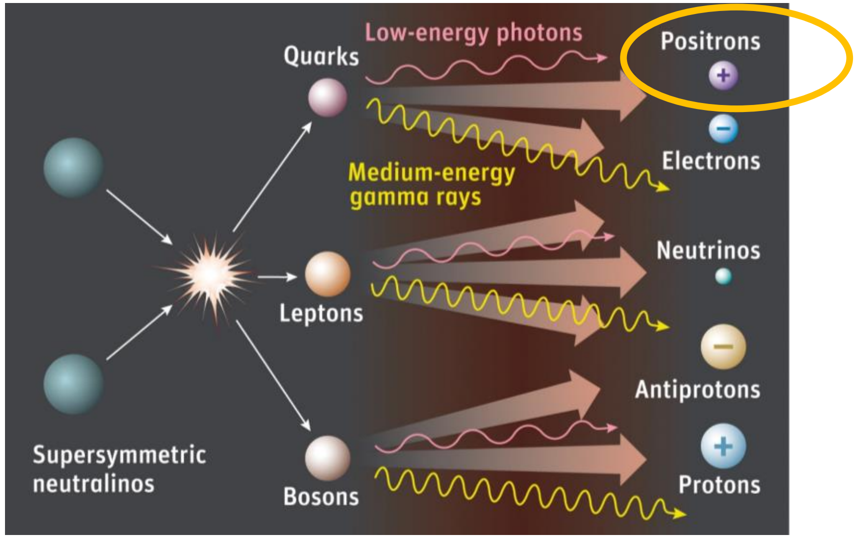


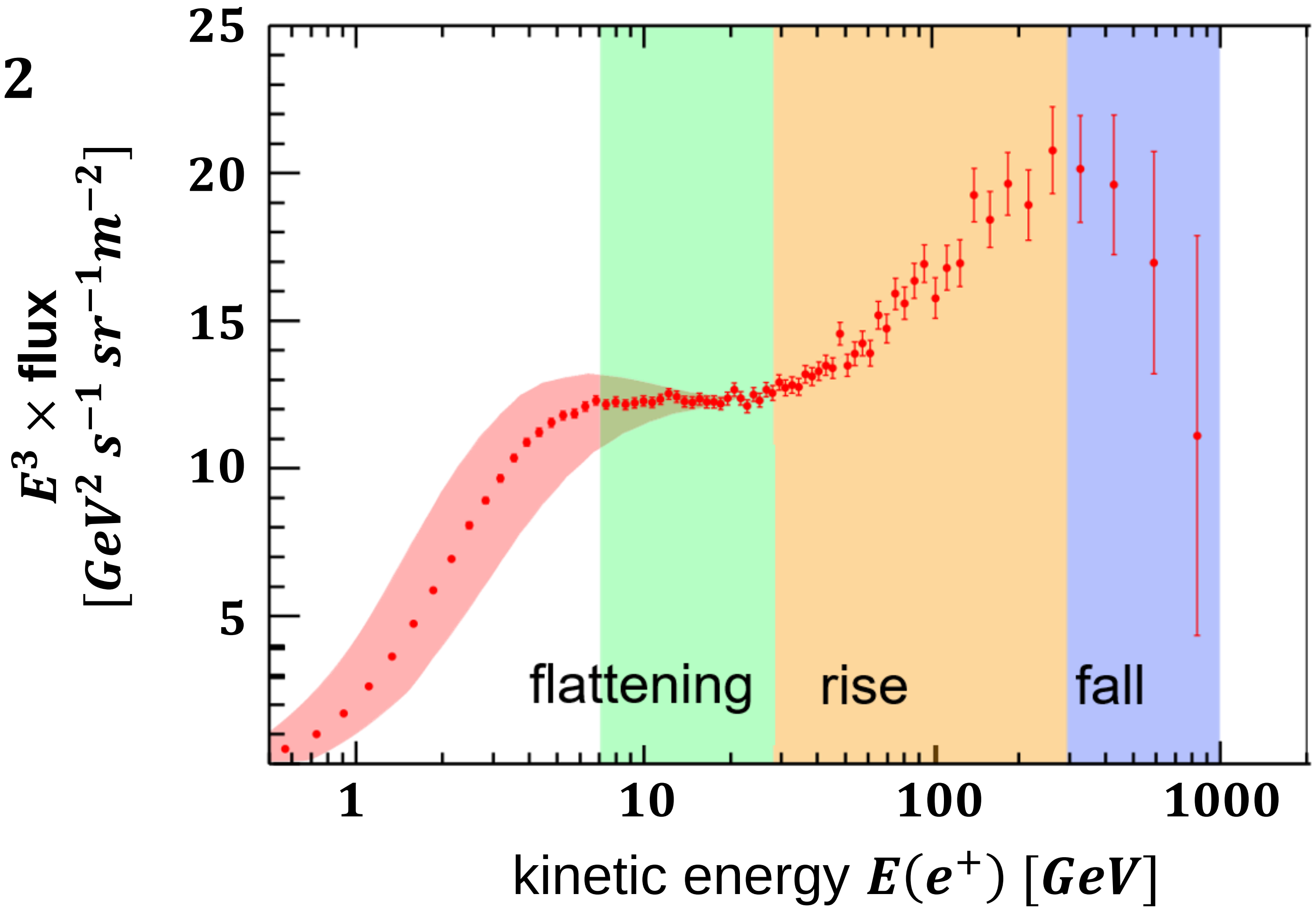
$AMS-02$ results: a high–energy excess of e^+

- What is its origin – ***DMA* signal** or astrophysical e^+ from nearby pulsars?

- difficult interpretation of $AMS-02$ data & e^+ – **spectroscopy**…

  $b)$ **signal** from ***DMA*** at ***GeV … TeV*** scale



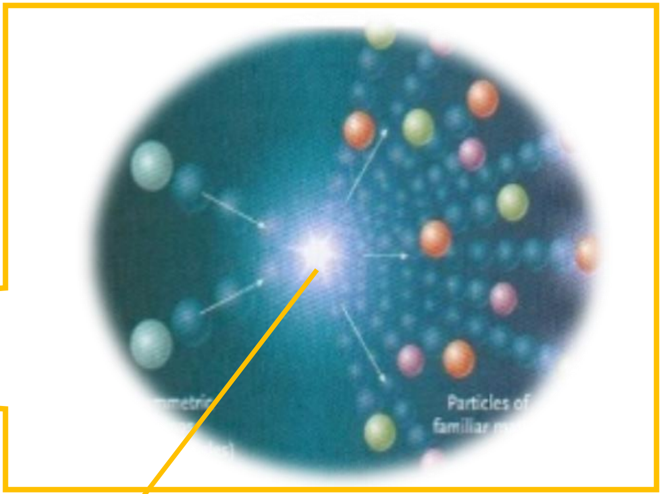


$AMS-02$ experiment: the future

- The search for DMA with messenger particles $e^+, \bar{p}$ will continue ...

4.4.2 Neutrinos

- **Searching for DMA in the center of the galaxy*** & **the sun with neutrinos**



*see Ch. $2.1.2$ – $IceCube$ results (Lect. #7, #8)

Neutrinos as DMA messengers from the solar core

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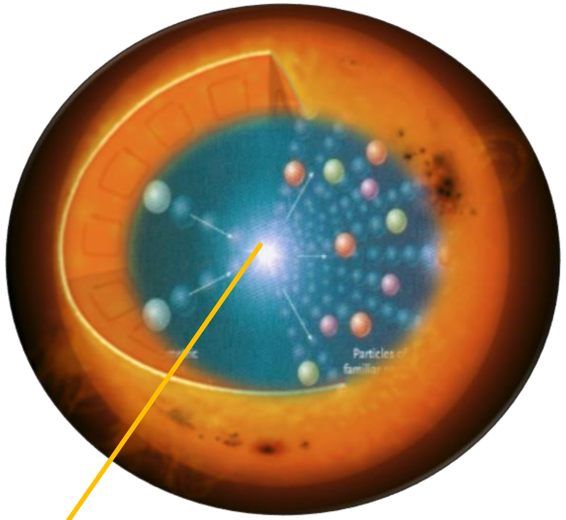
- **Interesting scenario: $WIMPs$ get trapped by the Sun**

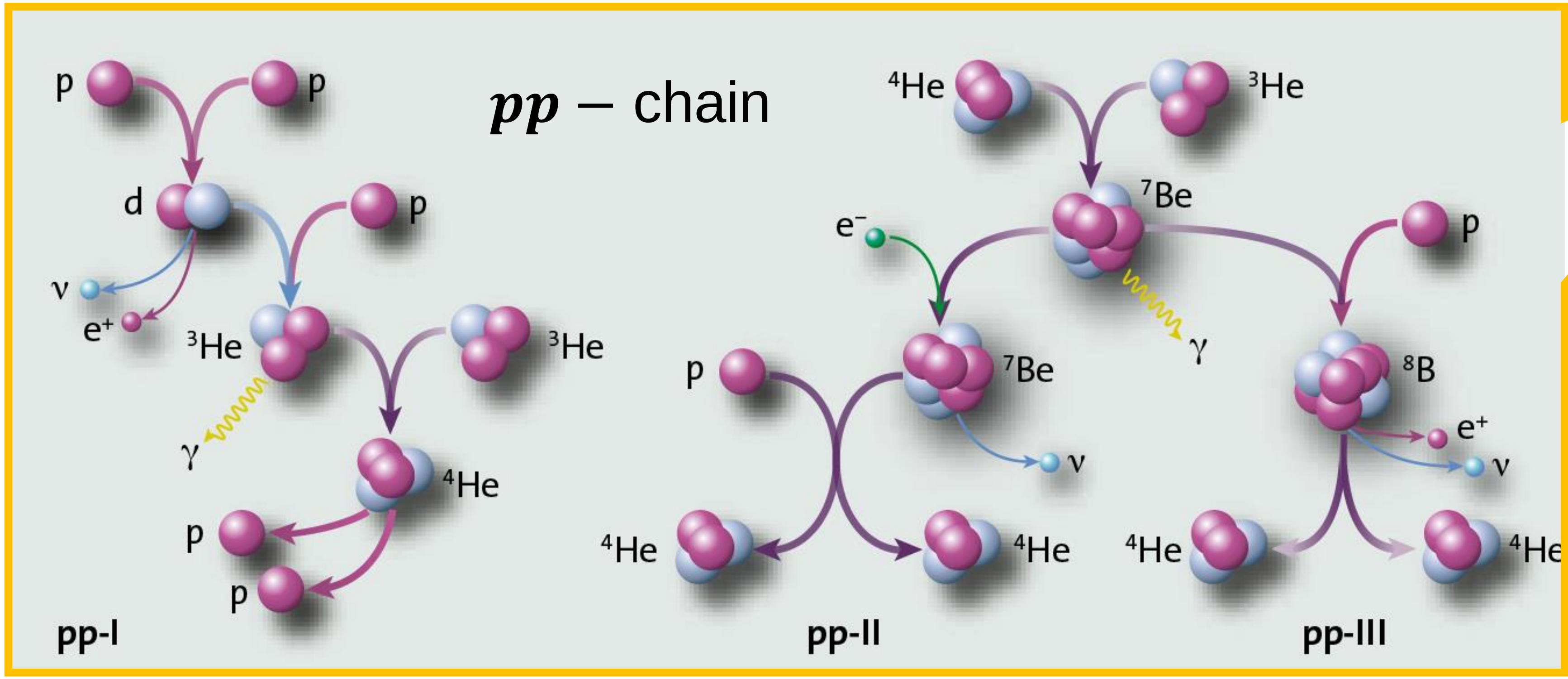


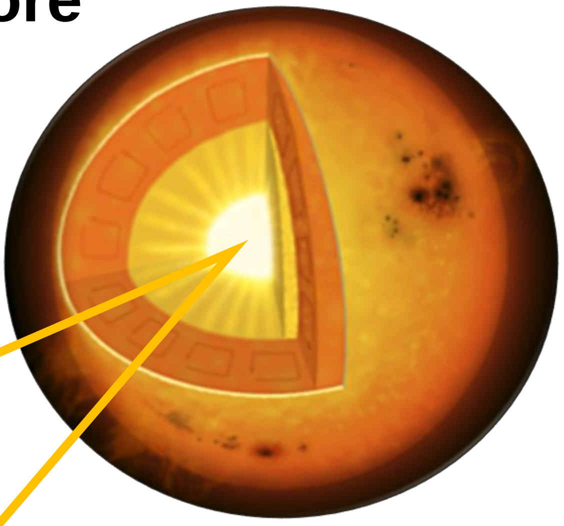
  - $WIMPs$ can scatter off solar matter & thereby lose energy ⇨ they get captured & **sink to the core**
  - there will be an **equilibrium** of the DM **capture rate R_C** & the DM **annihilation rate R_{DMA}** ⇨ do we see DMA? & how can we discriminate against **solar neutrinos**?

DMA in the core of the sun?

- **Standard scenario: MeV – neutrinos from the solar core**

  - pp – fusion reactions in the core of the sun*





*see $ATP – II$ (summer term 2024)

DMA in the core of the sun?

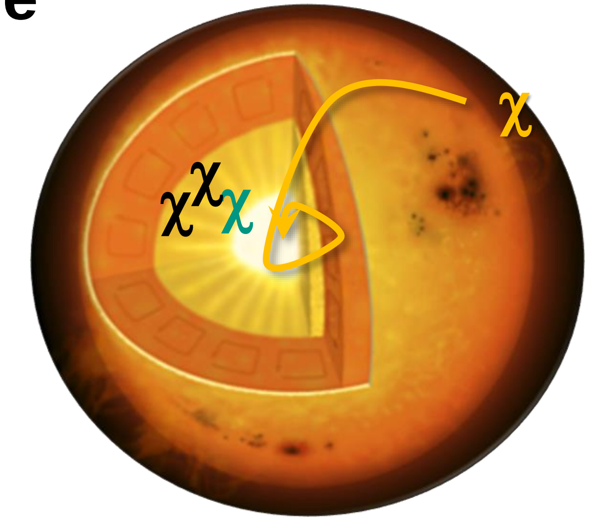
Karlsruhe Institute of Technology

- $SUSY$ – **scenario:** GeV – neutrinos **from the solar core**

  - spin–dependent interaction* of DM – halo $WIMPs$ with **solar matter** via exchange of a Z^0 – **boson**

  - NC – **scattering** off H – atoms results in an energy loss of $WIMP$ – neutralinos: subsequent **capture in the sun**

  - **calculation of capture rate** R_C depends on $WIMP$ **parameters**:



GeV

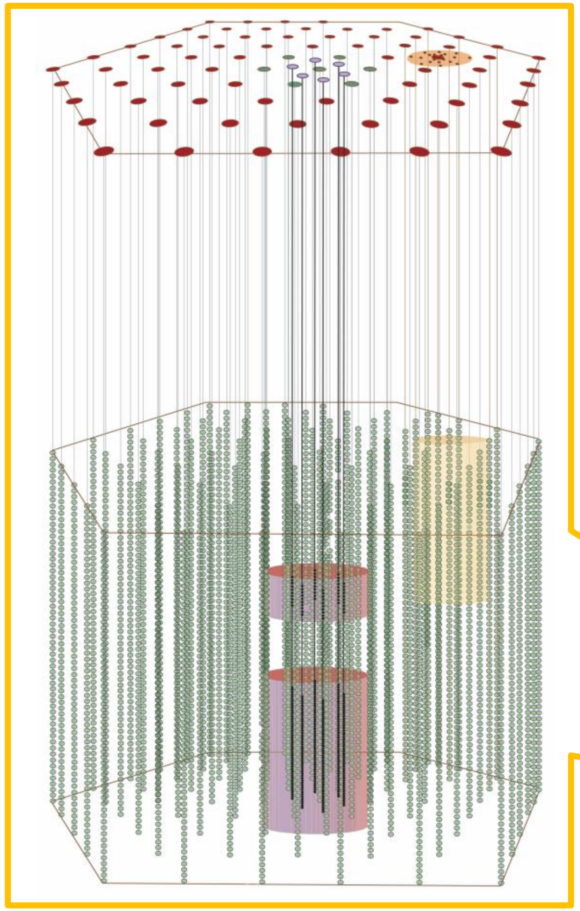
density → velocity → $xsec$ → mass

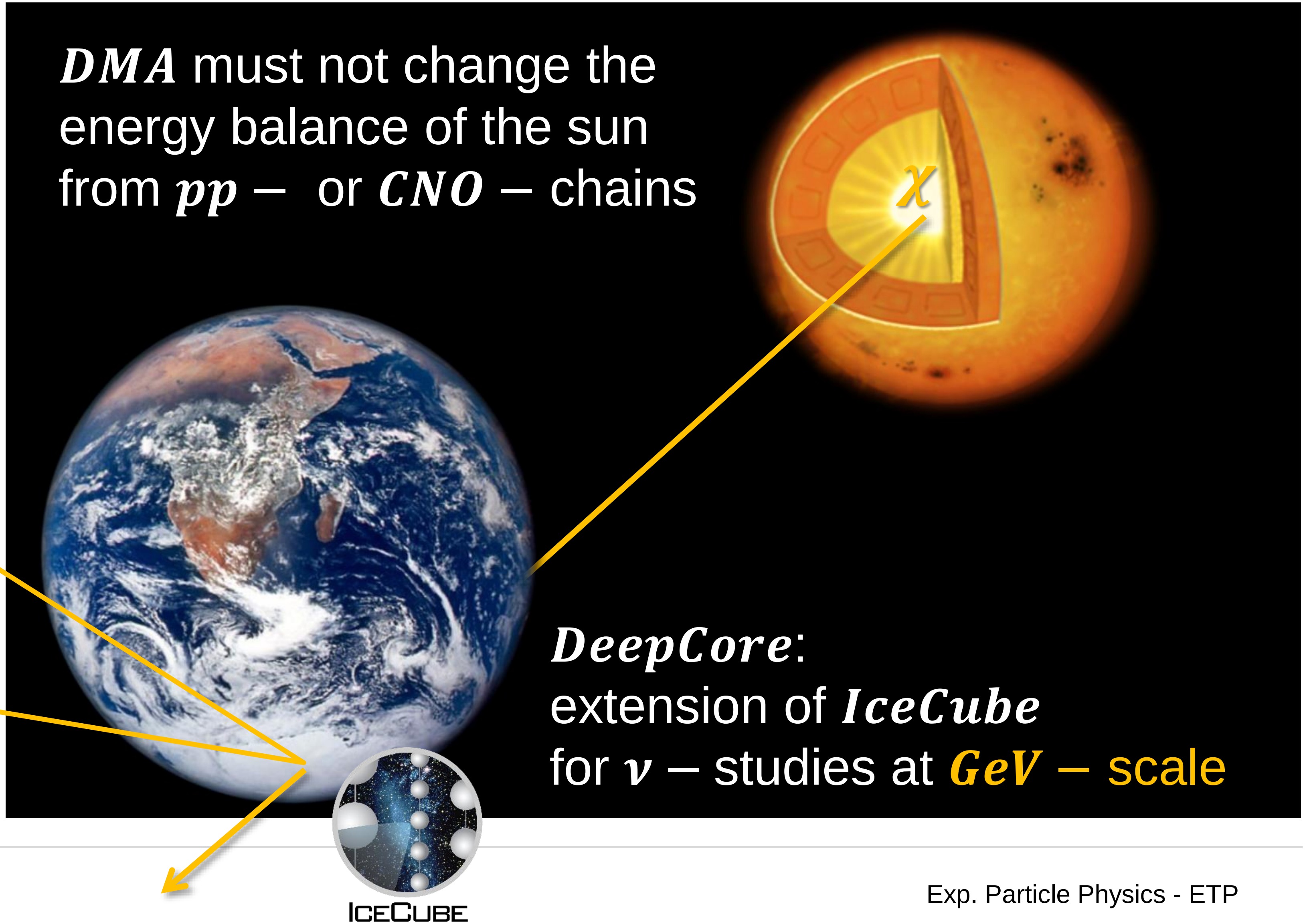
$$R_C \cong 3.35 \cdot 10^{20} s^{-1} \cdot \left(\frac{\rho_{DM,local}}{0.3\ GeV/m^3}\right) \cdot \left(\frac{270\ km/s}{v_{local}}\right)^3 \cdot \left(\frac{\sigma_{Spin}}{10^{-6}\ pb}\right) \cdot \left(\frac{100\ GeV}{m(\chi^0)}\right)^2$$

*because Z^0 – vector boson has a spin $S = 1$

Hunting GeV – scale neutrinos from DMA

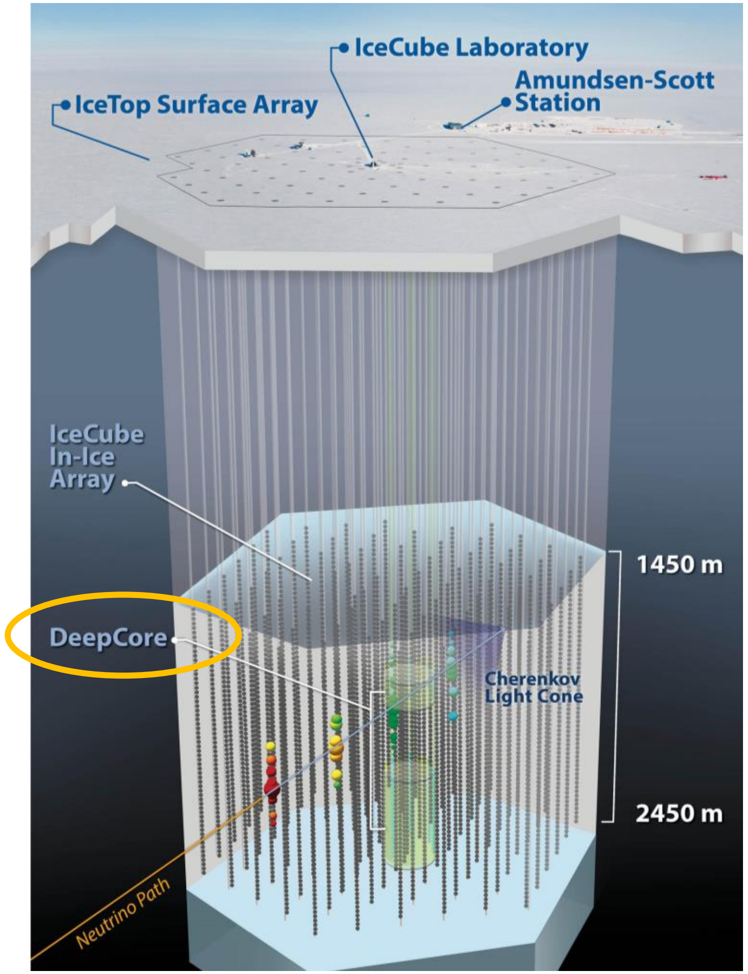
- $GeV - \nu\text{´}s$ from the sun

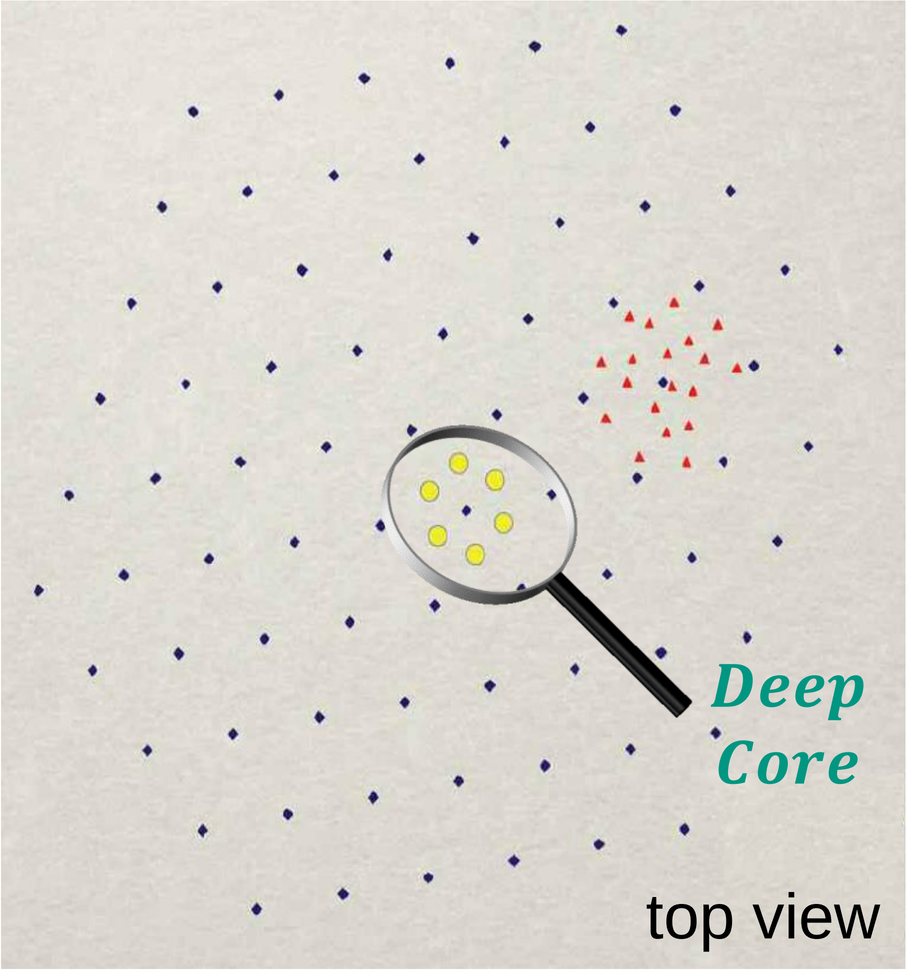




Hunting GeV – scale neutrinos from DMA

- $GeV - \nu's$ from the sun with $6\ DeepCore$ strings embedded in $IceCube$





- 6 new PMT – strings, each with $40\ PMTs$

⇨ improved sensitivity to detect $\nu's$ from DMA **in the solar core**

- DMA – search with ν_μ:
$E(\nu_\mu) = 10\ GeV \ldots 1\ TeV$

NO SIGNAL

Finally: could there be $WIMP$ burning stars?

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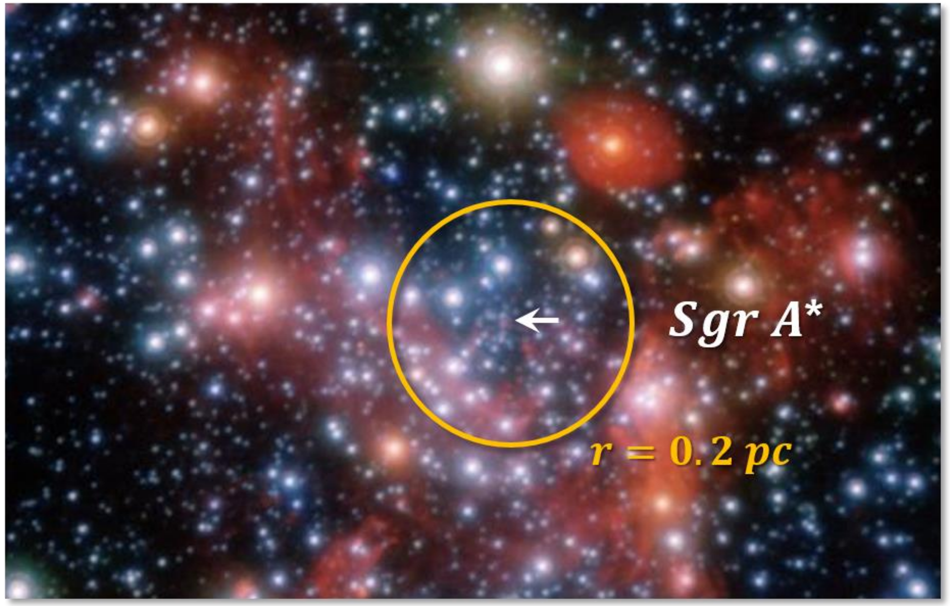
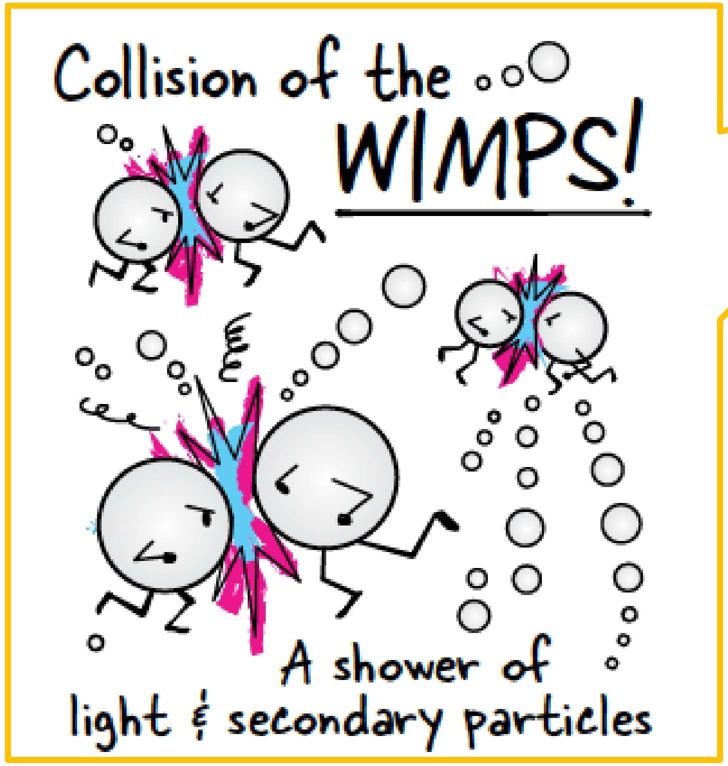
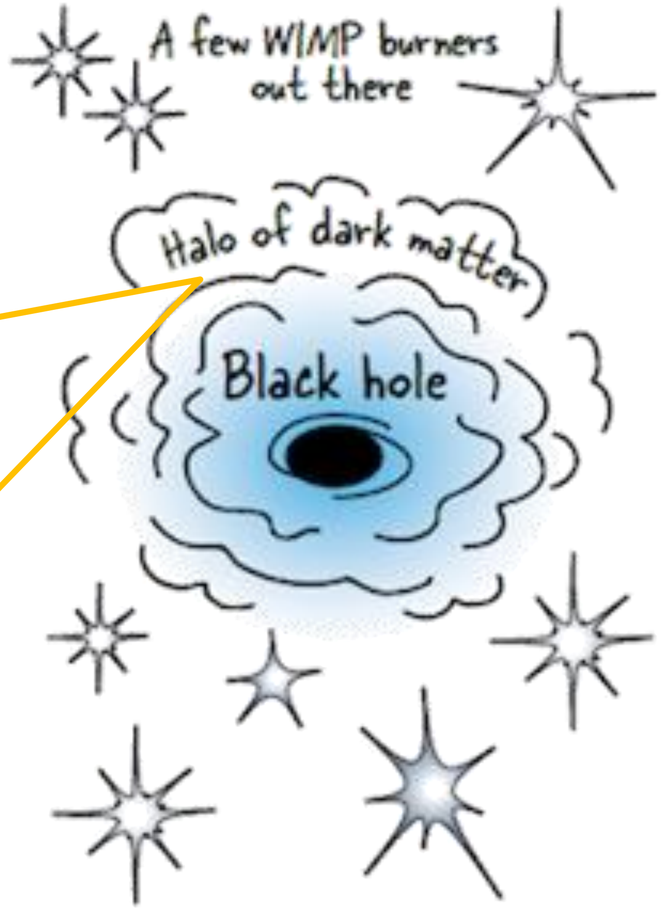
- **Why not settle for a new energy source: burn $WIMPs$ instead of hydrogen !**

  - an additional stellar energy source: **$WIMP$ annihilation**
  - stars located very close ($r < 1\ lyr$) to $SMBH$* ($Sgr\ A$*) are embedded in a ´**spike**´ of the galactic DM – halo core





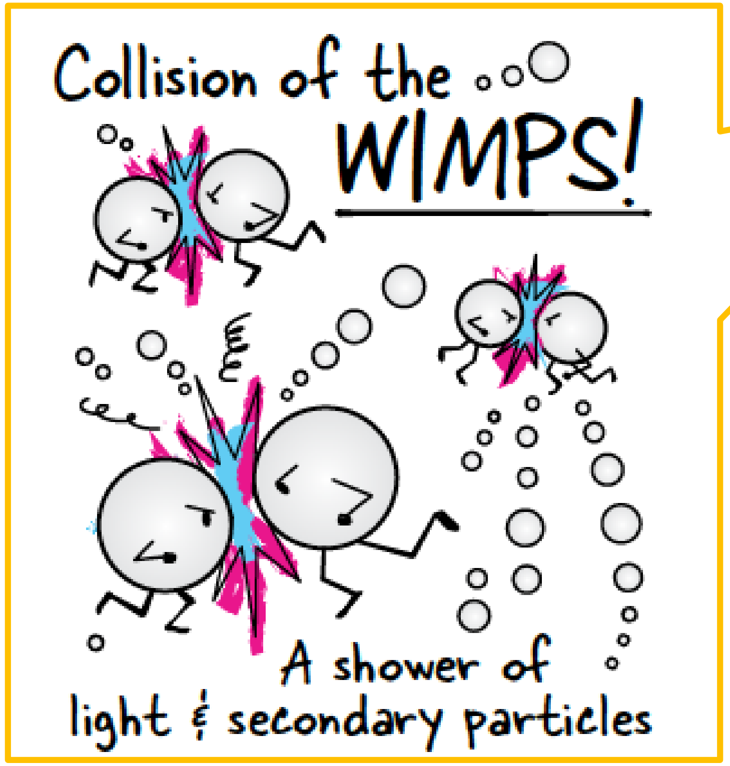


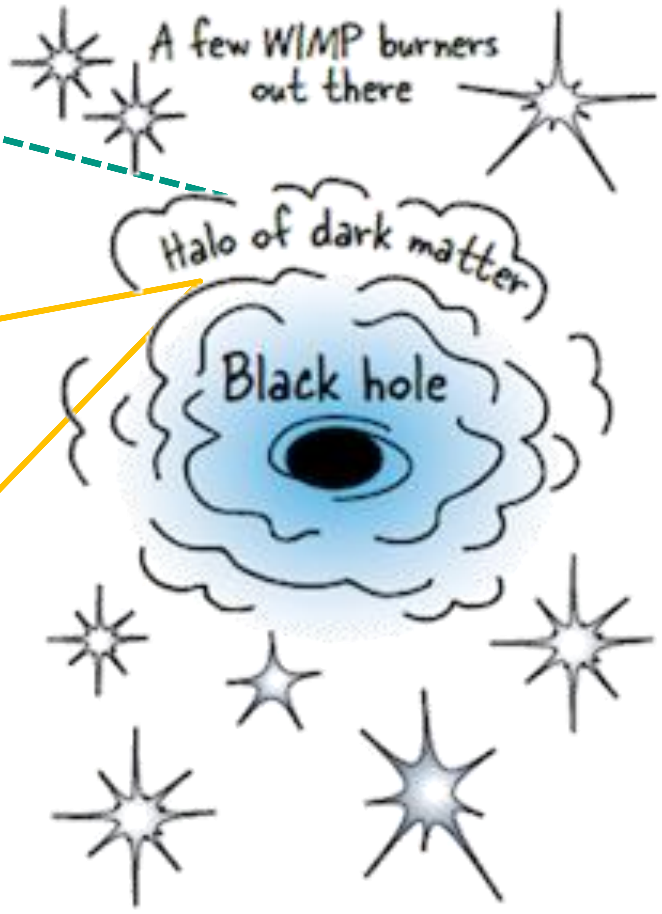
*Super–Massive Black Hole

Signature of $WIMP$ burning stars

- **Why not settle for a new energy source: burn $WIMPs$ instead of hydrogen!**

  - local DM – density $\rho_{DM}\ (r < 1\ lyr) > 10^9\ g/cm^3$
  - stars will capture a huge number of $WIMPs$ which will annihilate in the stellar cores





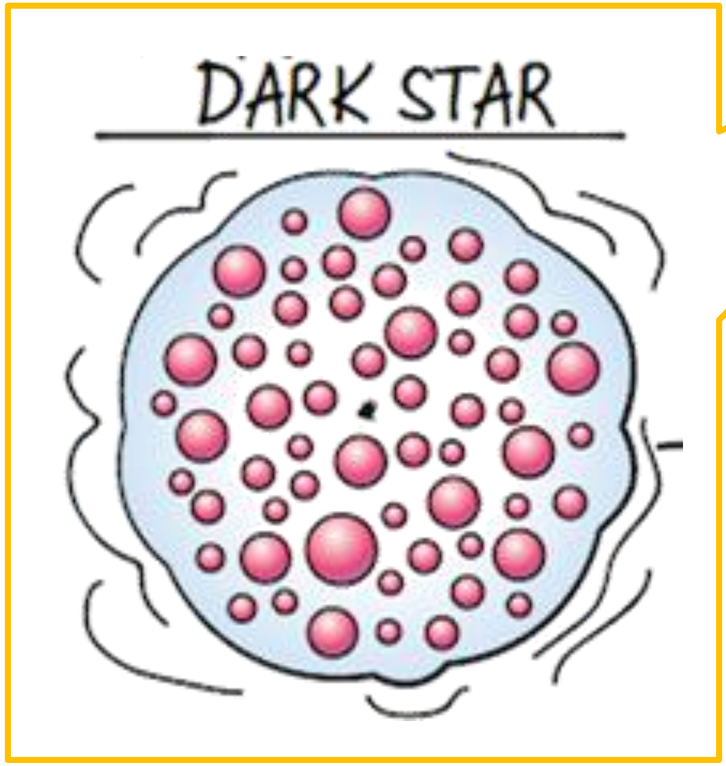
  - signature of ´$WIMP$ **burners**´: **modified stellar parameters**
    ⇨ completely convective stars

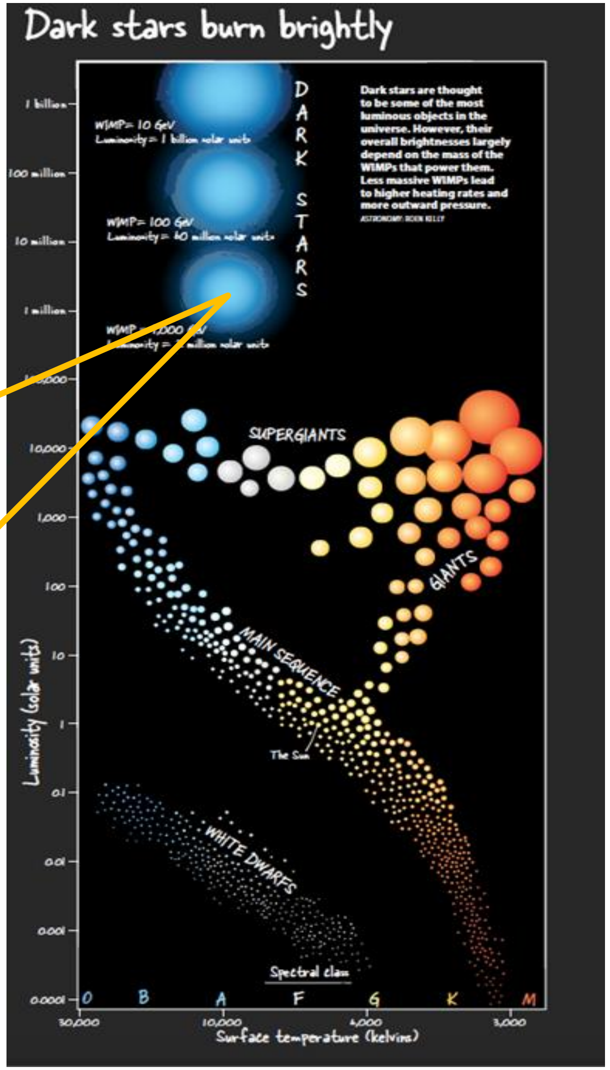
Search for $WIMP$ burning stars – the $JWST$

- **Why not settle for a new energy source:** burn $WIMPs$

  - **dark stars** in very early universe
  - early stars will capture a huge number of $WIMPs$:
    ⇨ filled with hydrogen &
    $1/1000$ dark matter

  - signature could be revealed*
    by the $JWST$



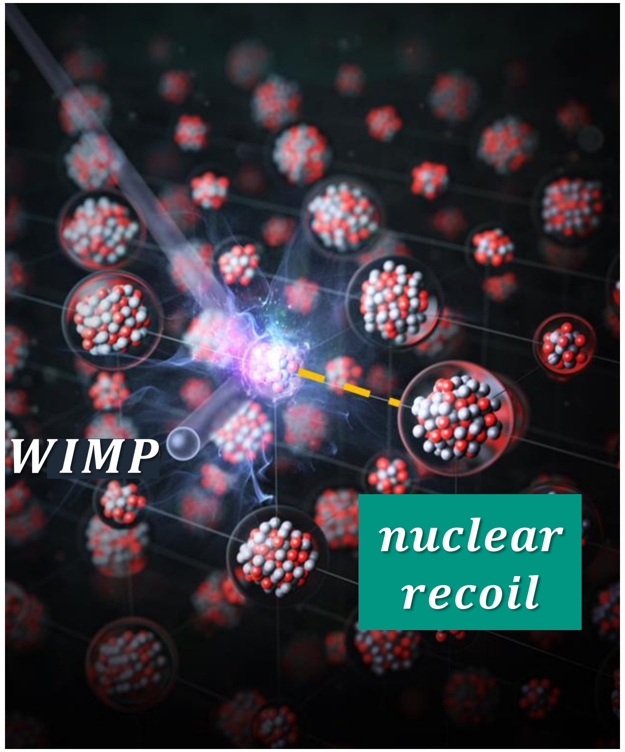


*2023: first 2 ... 3 candidates found !

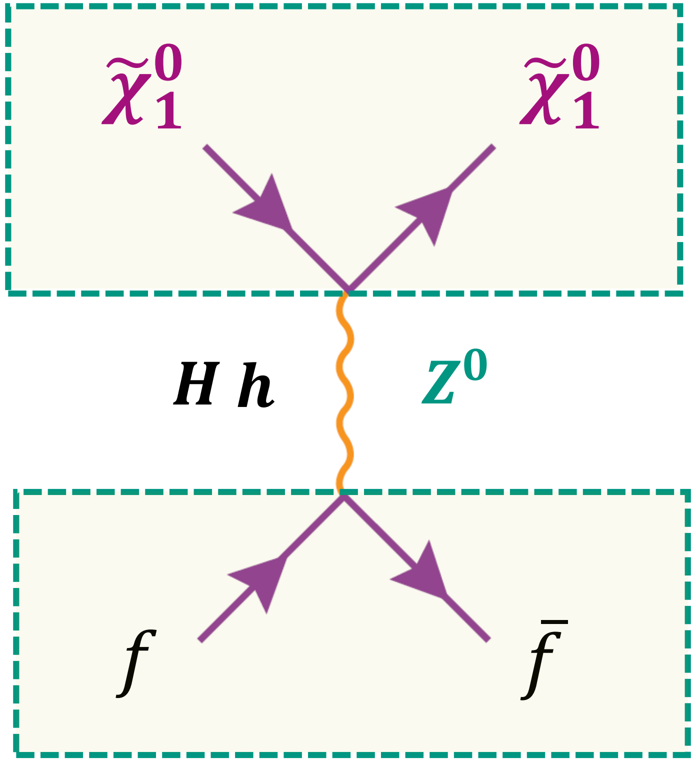
4.5 Direct detection methods for $WIMPs$

- We want to **directly detect** $WIMPs$ from the galactic $DM-$ halo: but how?

- $WIMP-$ **interactions** with the material of of our detector: **elastic scattering** processes **off a nucleus**!



neutralinos



galactic halo

f = target nucleus

collision kinematics

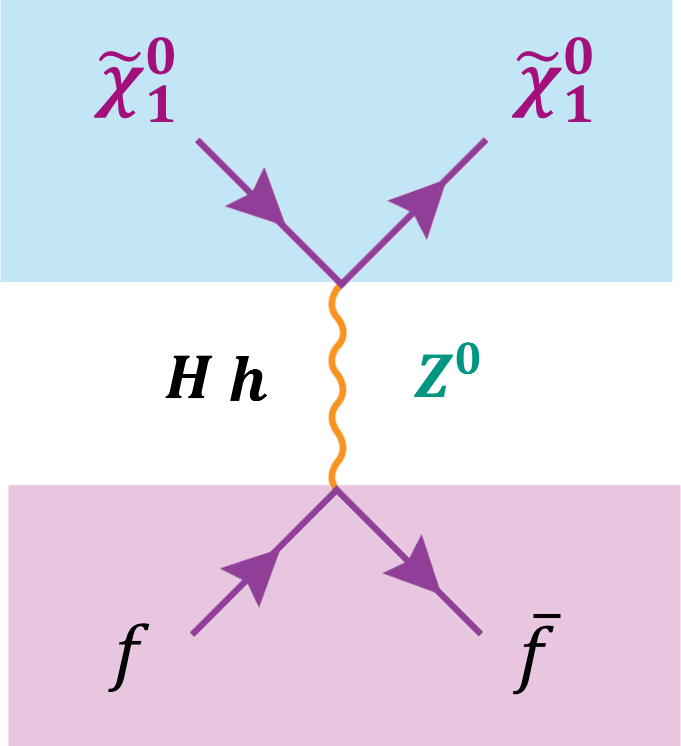
How to directly detect a $WIMP$ – the basics

- **Number of our DM – events: we need astro– & particle – physics**

- direct detection is also **model–dependent**

ρ_{CDM}	DM – density in solar system
v	$WIMP$ – velocity profile in halo
$\sigma_{scatter}$	$xsec$. from theory calculations
m_{CDM}	$neutralino$ mass (GeV … TeV)

$neutralinos$



ASTRO–PHYSICS

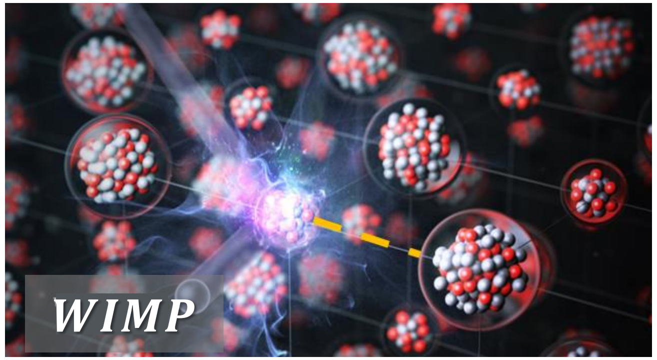
PARTICLE PHYSICS

collision kinematics

How to directly detect a $WIMP$ – the basics

- **To estimate the number of our DM – events we consider detector physics**

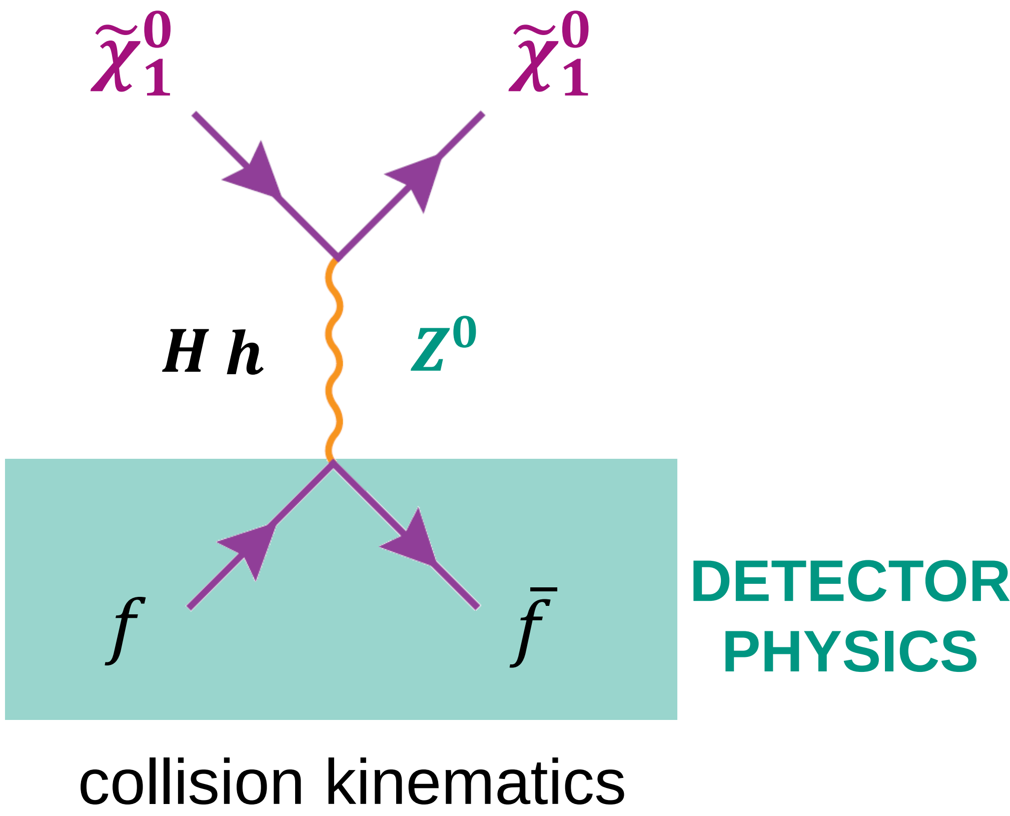
- what is the answer of our **solid–state detector** to an elastic nuclear recoil?



E_R detection of recoil enery of the target nucleus in the **solid state**

⇨ good knowledge of **detector properties**

$neutralinos$



How to directly detect a $WIMP$ – the basics

- To estimate the number R of our DM – events we bring all factors together

$$R = N_{target} \cdot \langle \Phi \rangle \cdot \langle \sigma_{SI/SD} \rangle$$

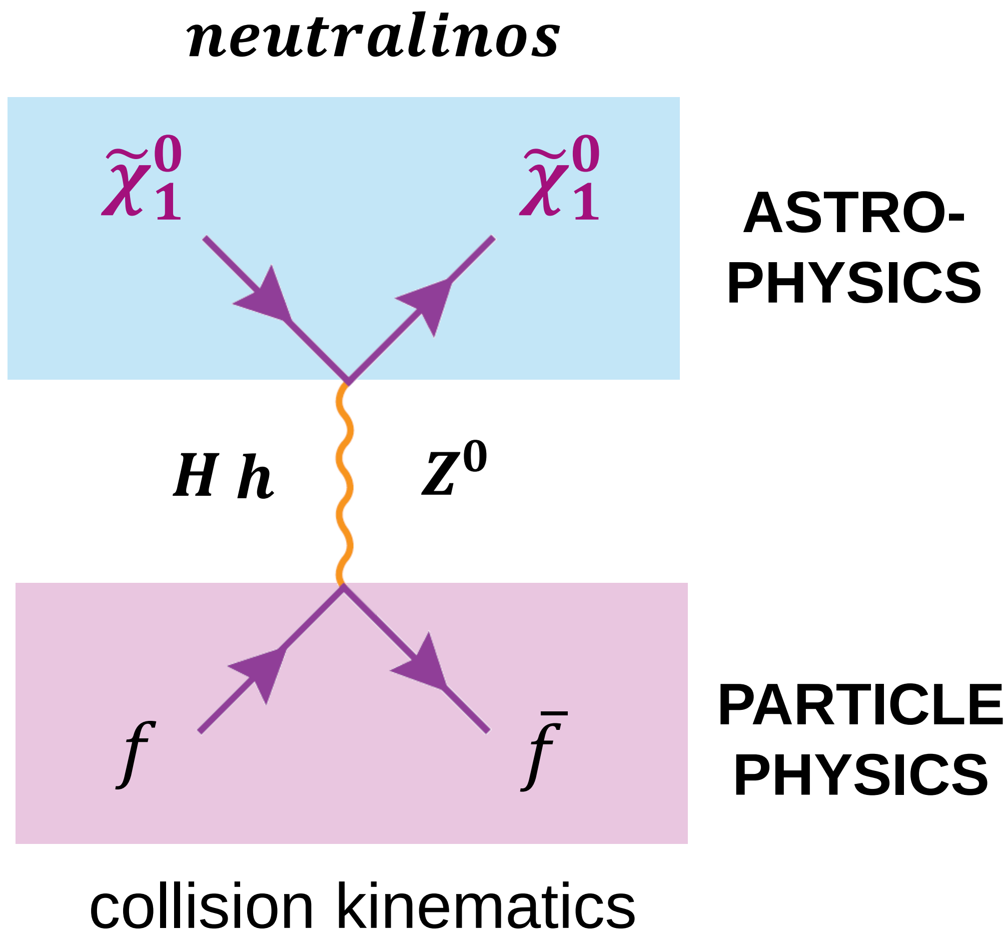
target **nuclei**

- $WIMP$ **flux** at solar system

- $WIMP$ flux–averaged **cross section**:

  σ_{SI}: Spin–Independent cross section (h, H)

  σ_{SD}: Spin–Dependent cross section (Z^0)



Estimating the $WIMP$ flux

- To estimate the number R of our DM – events we consider the $WIMP$ flux

$$R = N_{target} \cdot \langle \Phi \rangle \cdot \langle \sigma_{SI/SD} \rangle$$

$$m_{CDM} = 100\ GeV$$

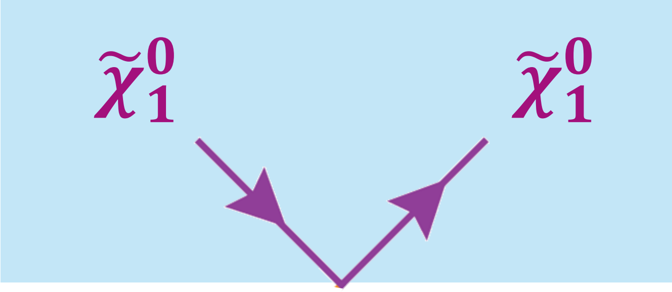
$$\rho_{CDM} = 0.3\ GeV cm^{-3}$$

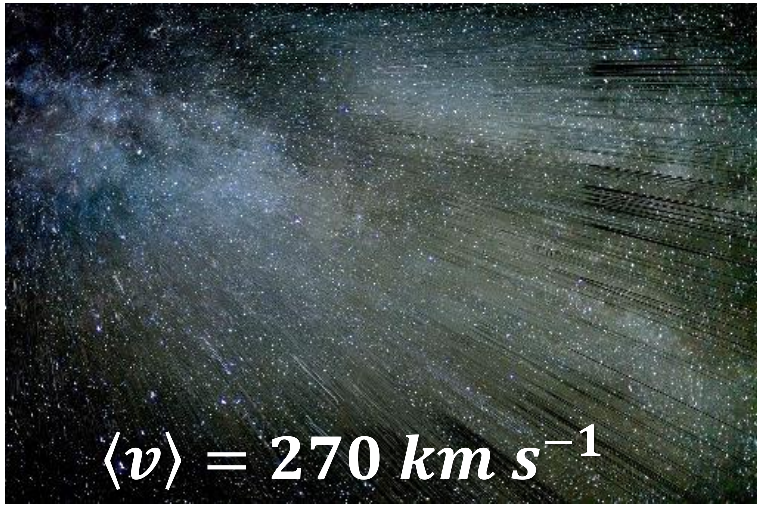
$$\langle \Phi \rangle = (\rho_{CDM} / m_{CDM}) \cdot \langle v \rangle$$

$$= (0.3/100)\ cm^{-3} \cdot 270 \times 10^5\ cm\ s^{-1}$$

$$\approx 80\,000\ cm^{-2}\ s^{-1}$$

neutralinos





POLL: do you prefer DM – coffee cups / squirrels?

- **How do YOU best remember (visualize) our local DM density?**

$A)$

$\mathbf{1}\ WIMP$

per coffee cup

$$\rho_{CDM} = 0.3\ GeV\ cm^{-3}$$

$B)$

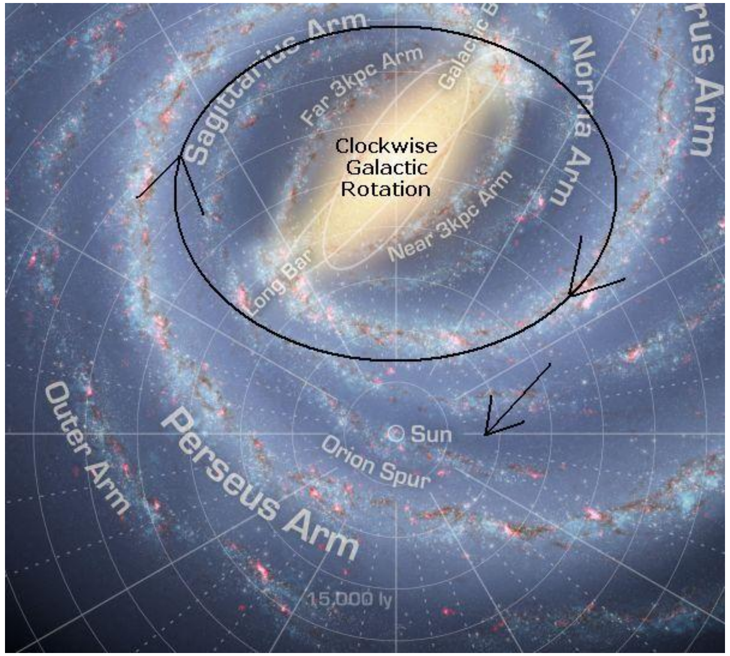
2 squirrels ($777\ g$)

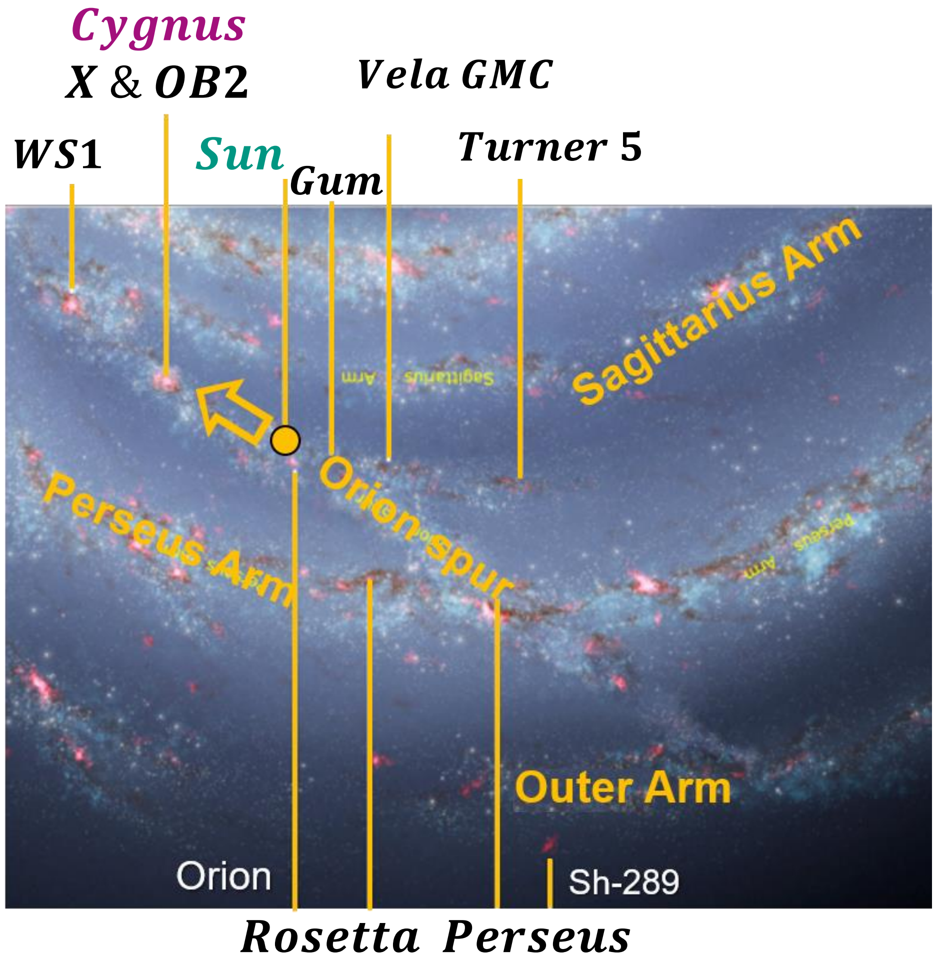
over Earth volume

Properties of the $WIMP$ flux: motion of the Sun

- **We expect that a $WIMP$ ´wind´ blows with a preferred direction**

  - motion of the Sun around the ***G*alactic *C*enter** (***GC***) induces a **preferred $WIMP$** direction: the **$WIMP$ wind**

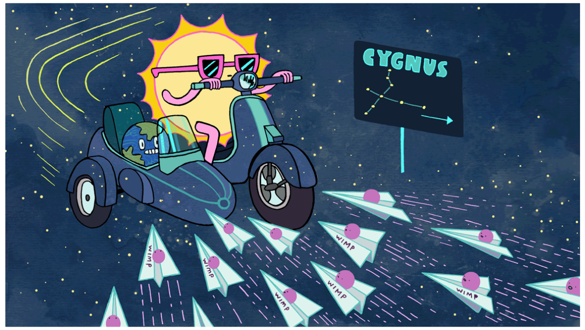


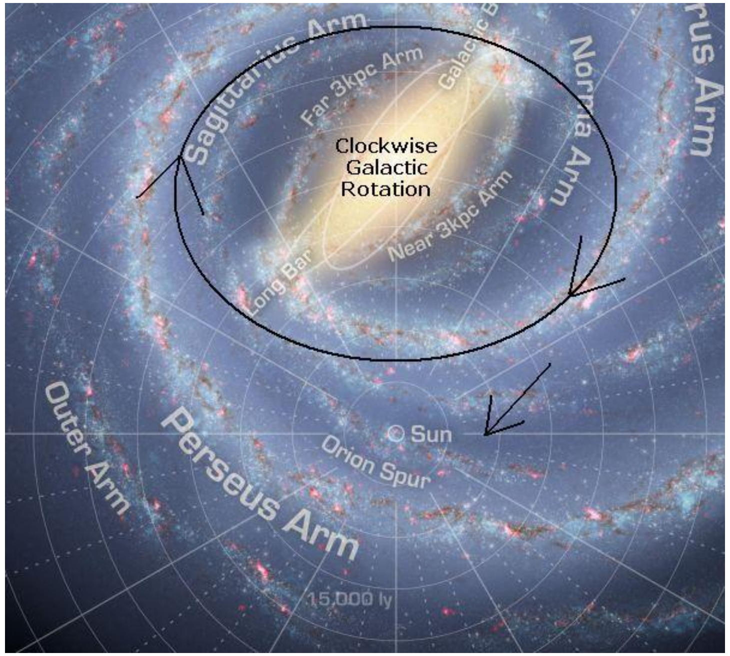


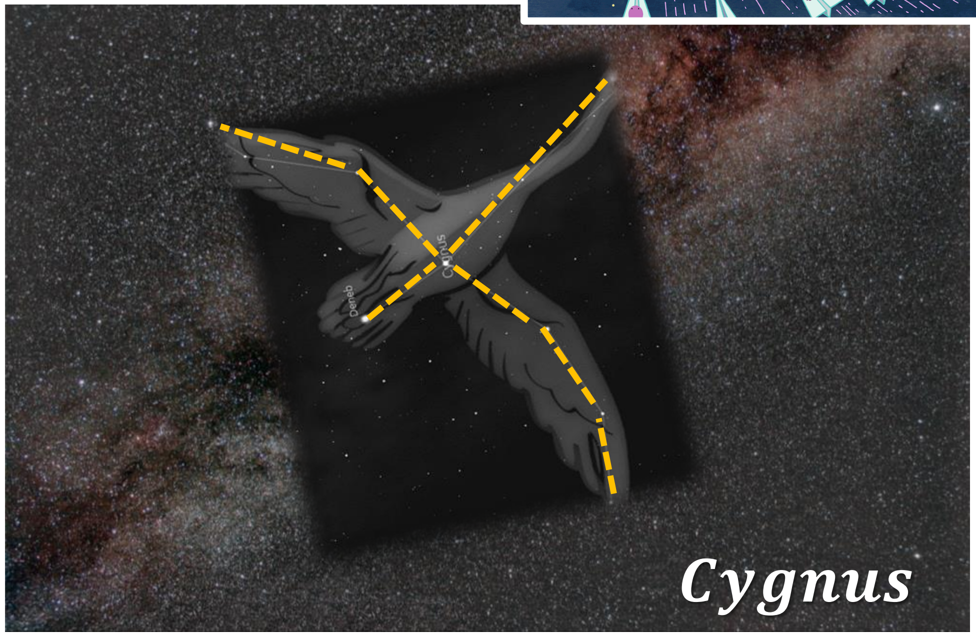
Properties of the $WIMP$ flux: $Cygnus$ region

- **We expect that a $WIMP$ ´wind´ blows with a preferred direction**

  - motion of the Sun around the G**alactic** C**enter** (GC) induces a **preferred $WIMP$** direction: the **$WIMP$ wind blows from $Cygnus$**



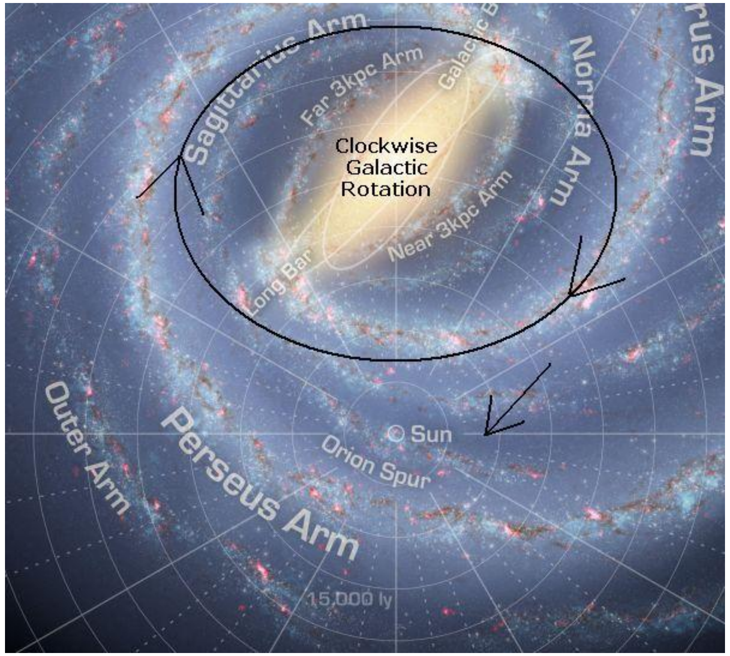


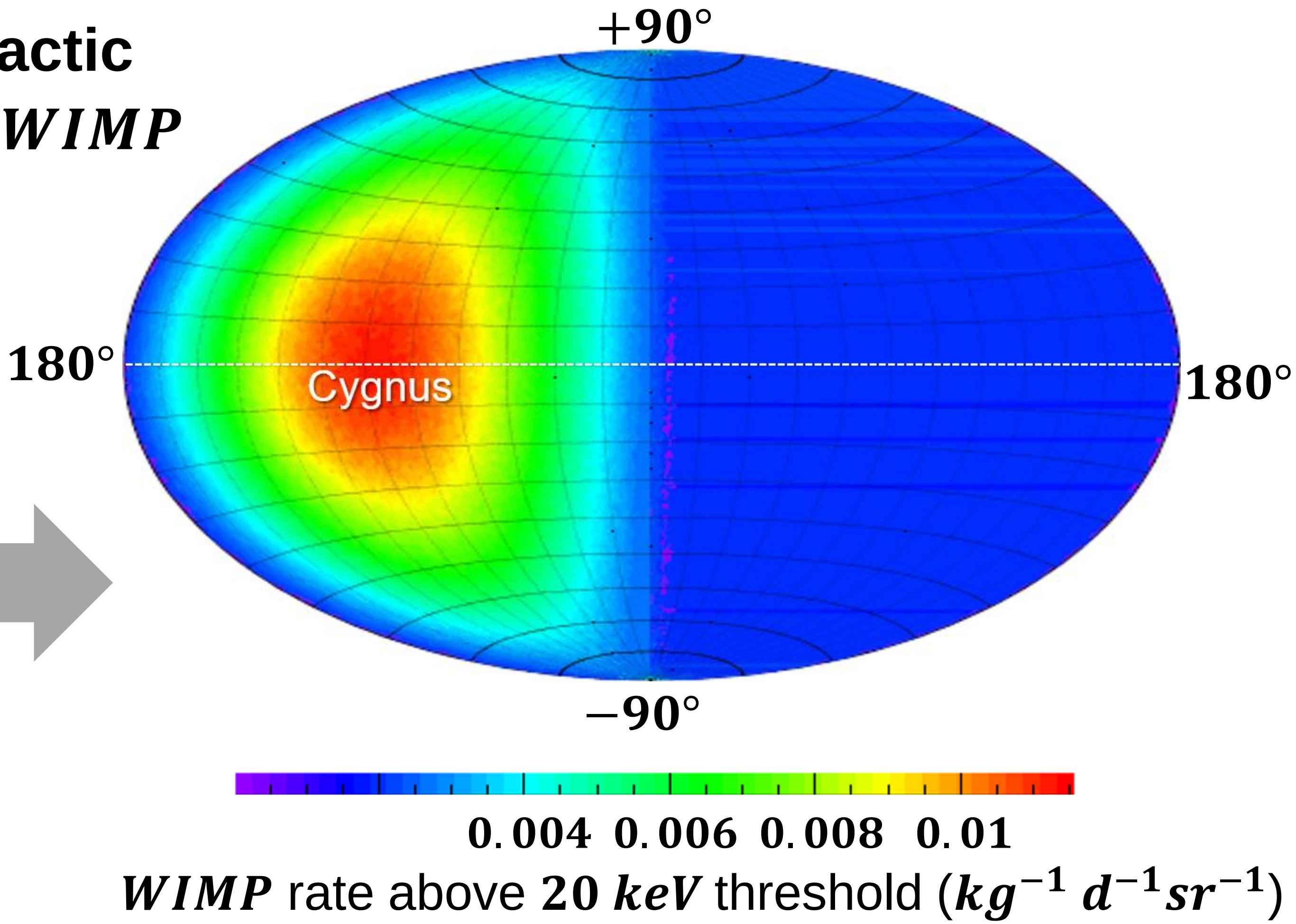


Properties of the $WIMP$ flux: $Cygnus$ region

- **We expect that a $WIMP$ ´wind´ blows with a preferred direction**

  - motion of the Sun around the **Galactic Center** (GC) induces a **preferred $WIMP$** direction: the **$WIMP$ wind**





Properties of the galactic $WIMP$ halo

- **The galactic DM – halo: what is its shape & its $WIMP$ velocity profile?**

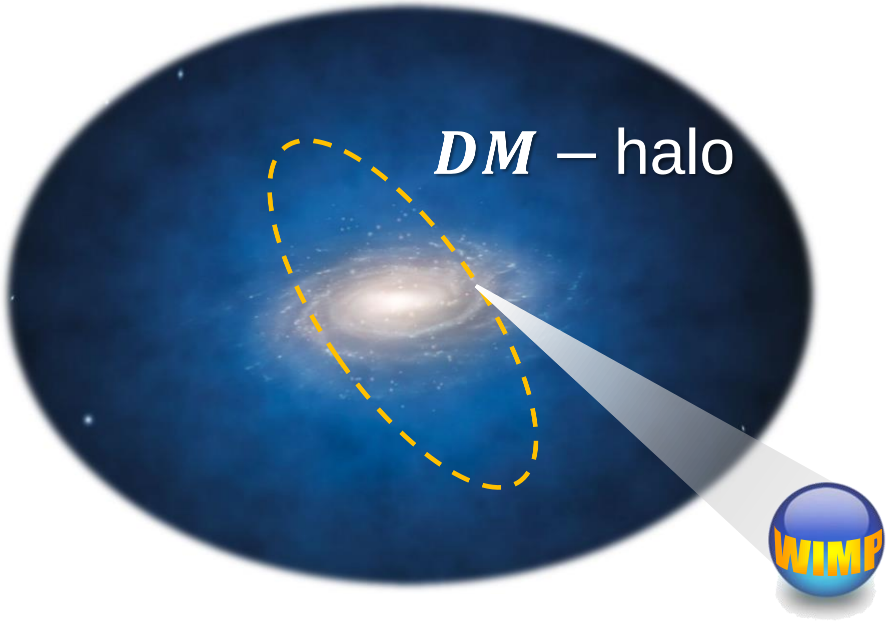
  - no large–scale rotation of entire $\boldsymbol{DM}$ – halo around the center of the galaxy

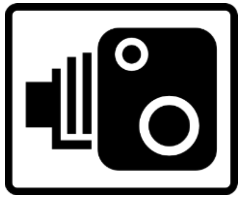
  - each $\boldsymbol{WIMP}$ follows individual Kepler orbit around the galactic center

  - from this a specific $\boldsymbol{WIMP}$ velocity profile $\boldsymbol{f(v)}$ follows, which can be calculated for varius **halo radii $\boldsymbol{r}$**

  - **shape:** we expect a tri–axial ellipsoid

  - $\boldsymbol{DM}$ – halo properties can be traced by stellar **velocity profile***



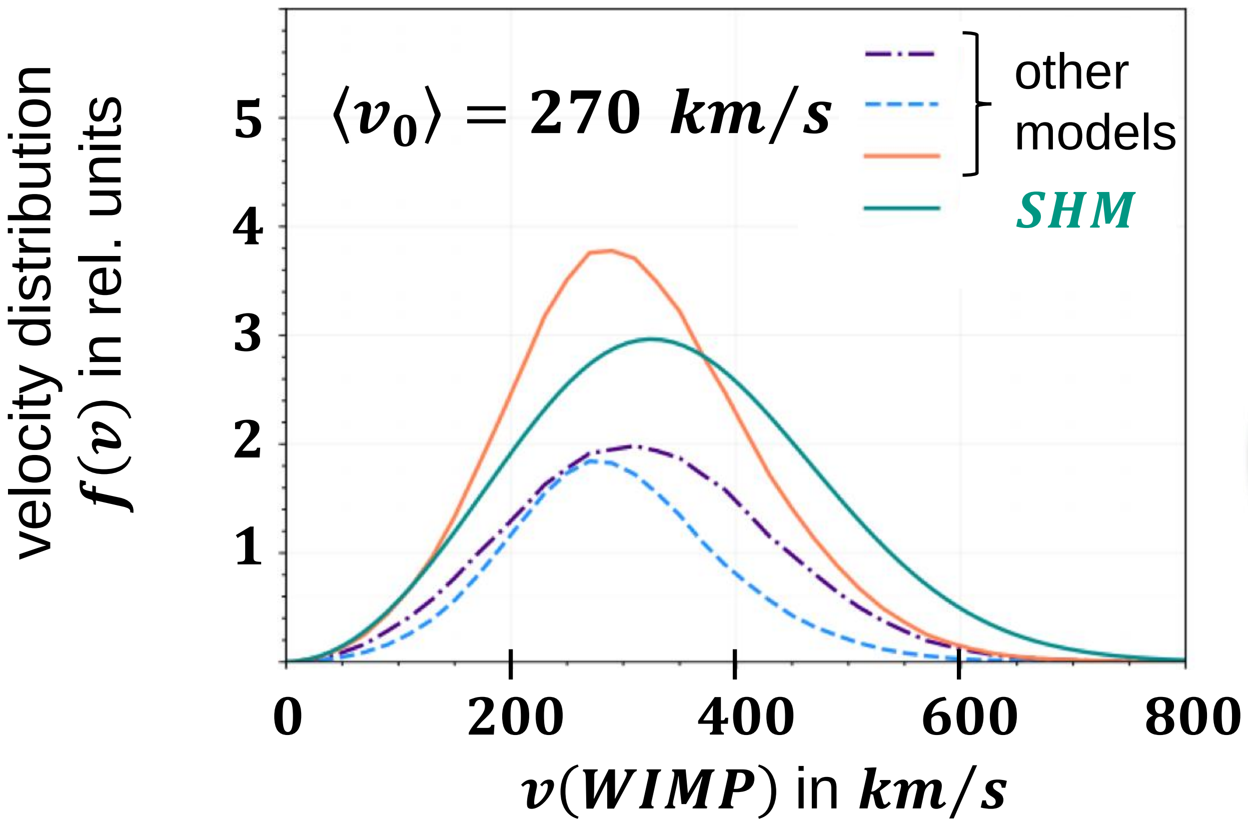


*see lecture #12

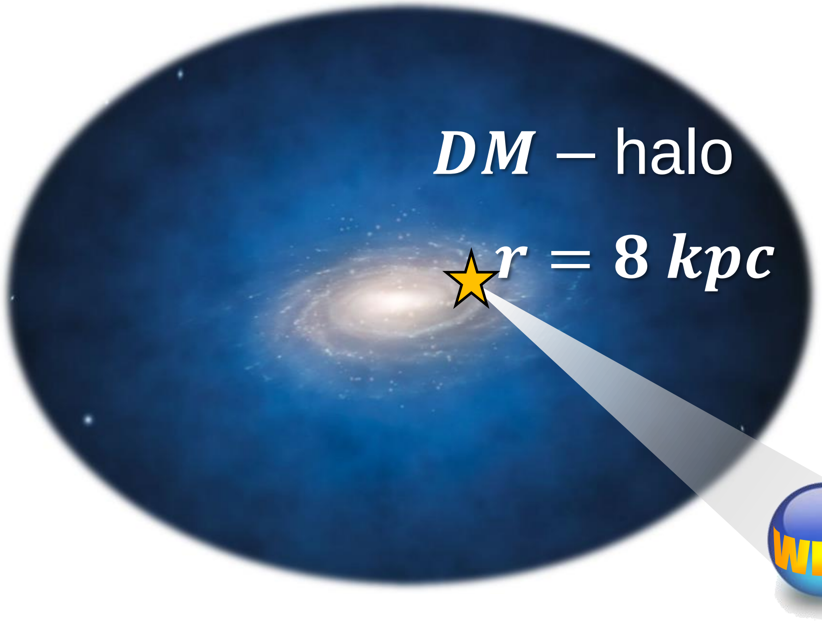
galactic $WIMP$ halo: velocity profile

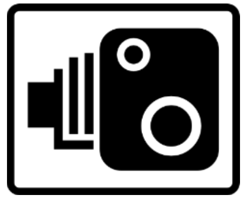
- **We are interested in the $WIMP$ velocity profile at our distance $r = 8\ kpc$**

  - Standard Halo Model (SHM) compared to other theoretical calculations



small differences remain

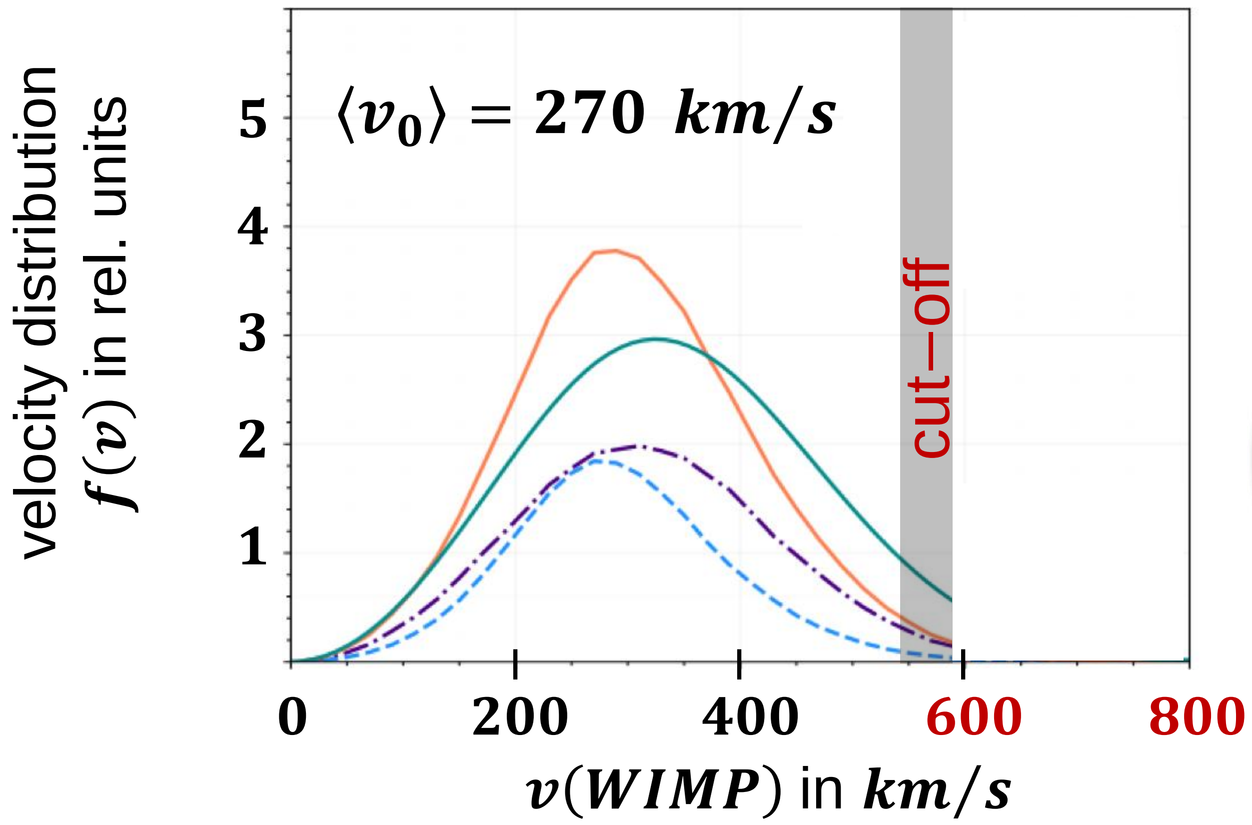


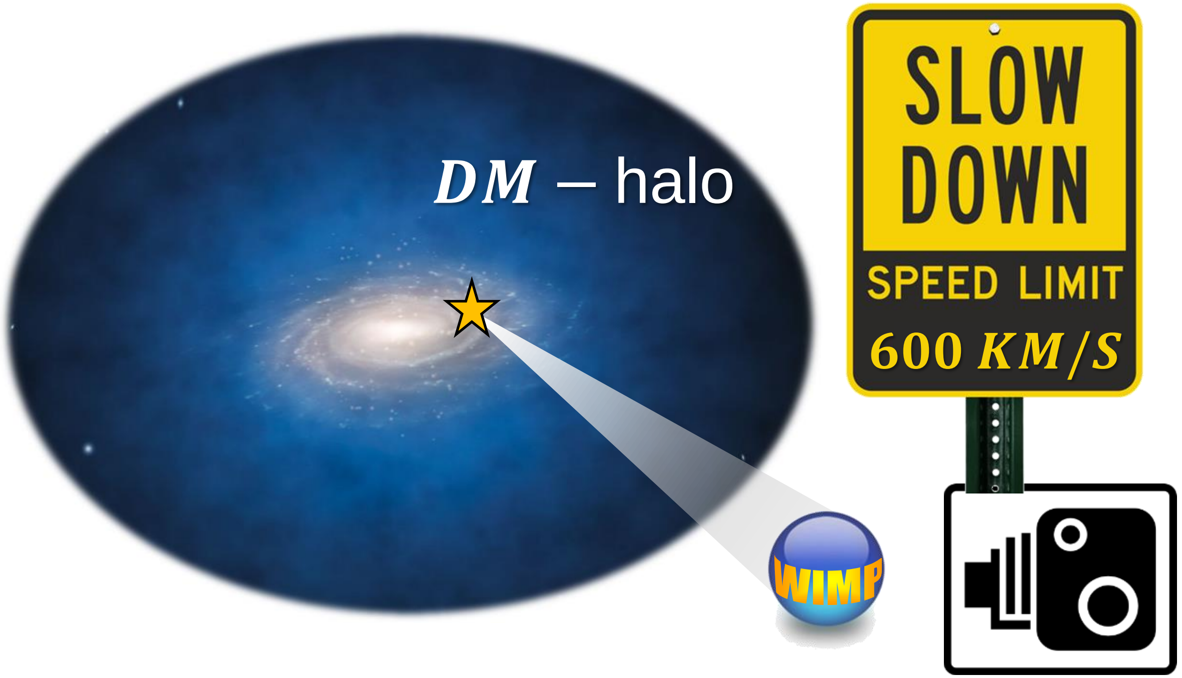


Properties of the galactic $WIMP$ halo

- $WIMP$ velocity profile at distance $r = 8\ kpc$: **cut−off parameter for $f(v)$**

  - for speeds of $v \geq 500 \dots 600\ \ km/s$: $WIMPs$ will escape galactic DM −halo

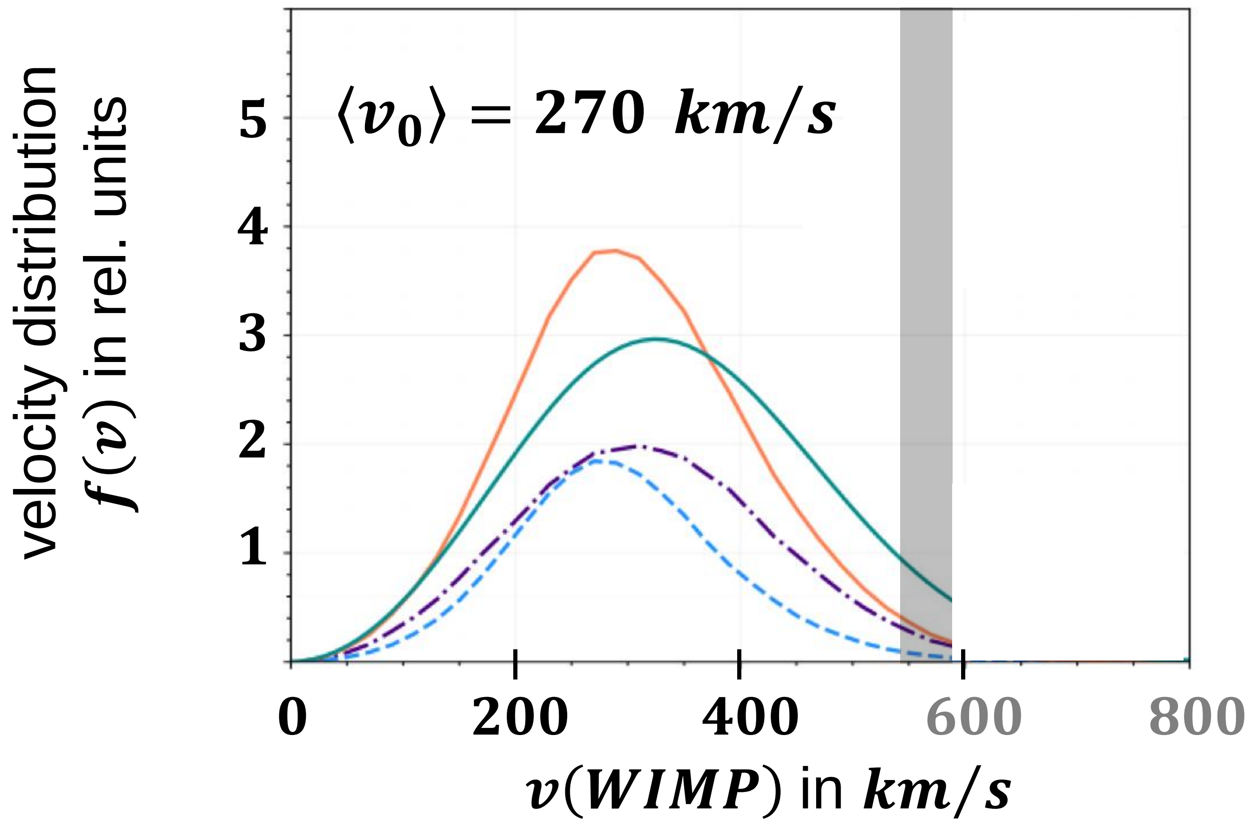




Properties of the galactic $WIMP$ halo: implications

- **There are fundamental implications of $f(v)$ for direct DM searches**

  - $WIMPs$ in galactic DM halo move **non–relativistically** with $\beta \approx 10^{-3}$

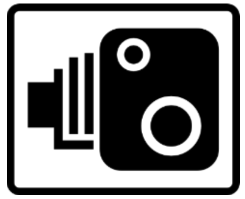


  - **kinetic energy E_{kin} of $WIMPs$**:

$$E_{kin} = \frac{1}{2} \cdot M(\chi^0) \cdot \beta^2$$

$M(\chi^0)$: $100\ GeV$ $\quad$ β^2: 10^{-6}

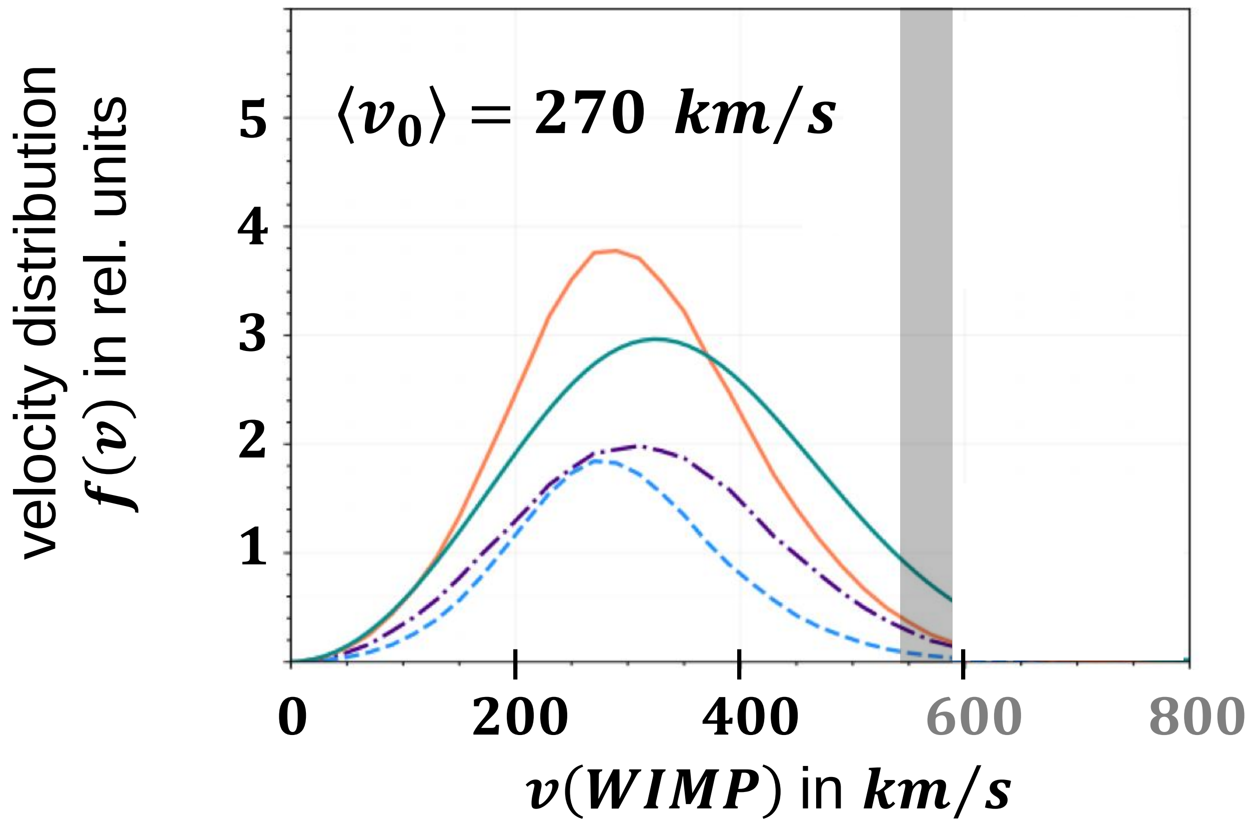
$$E_{kin} \approx 100\ keV$$

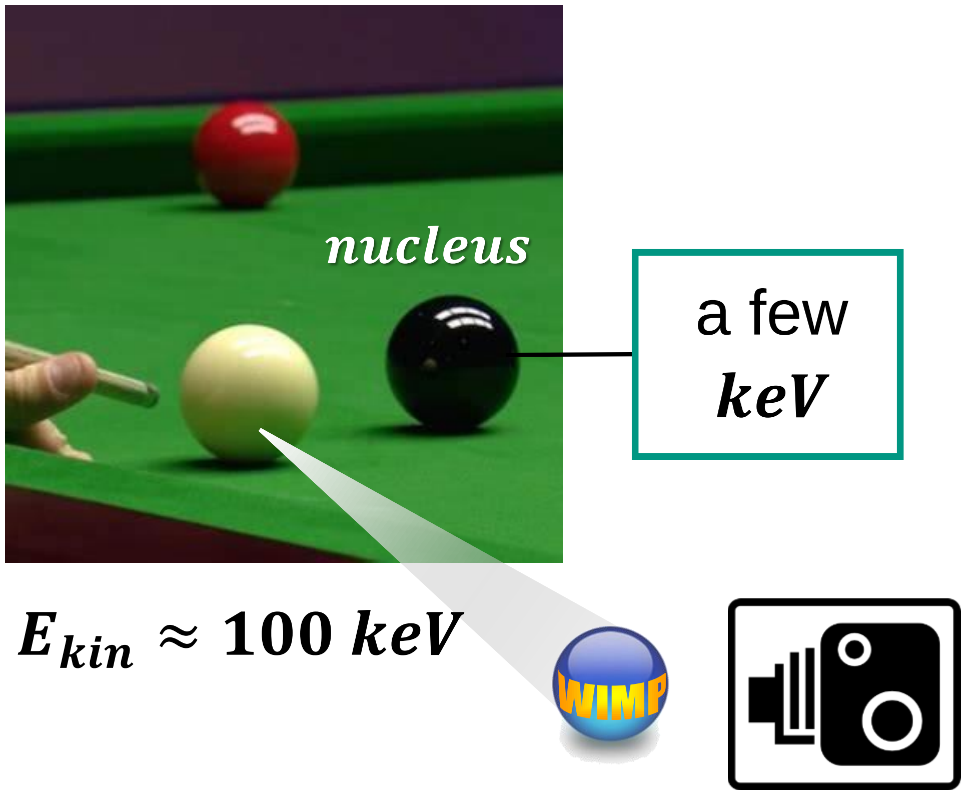


Properties of the galactic $WIMP$ halo: implication

- **There are fundamental implications of $f(v)$ for direct DM searches**

  - a nucleus will receive a **low–energy recoil of a few tens of keV** (at most)





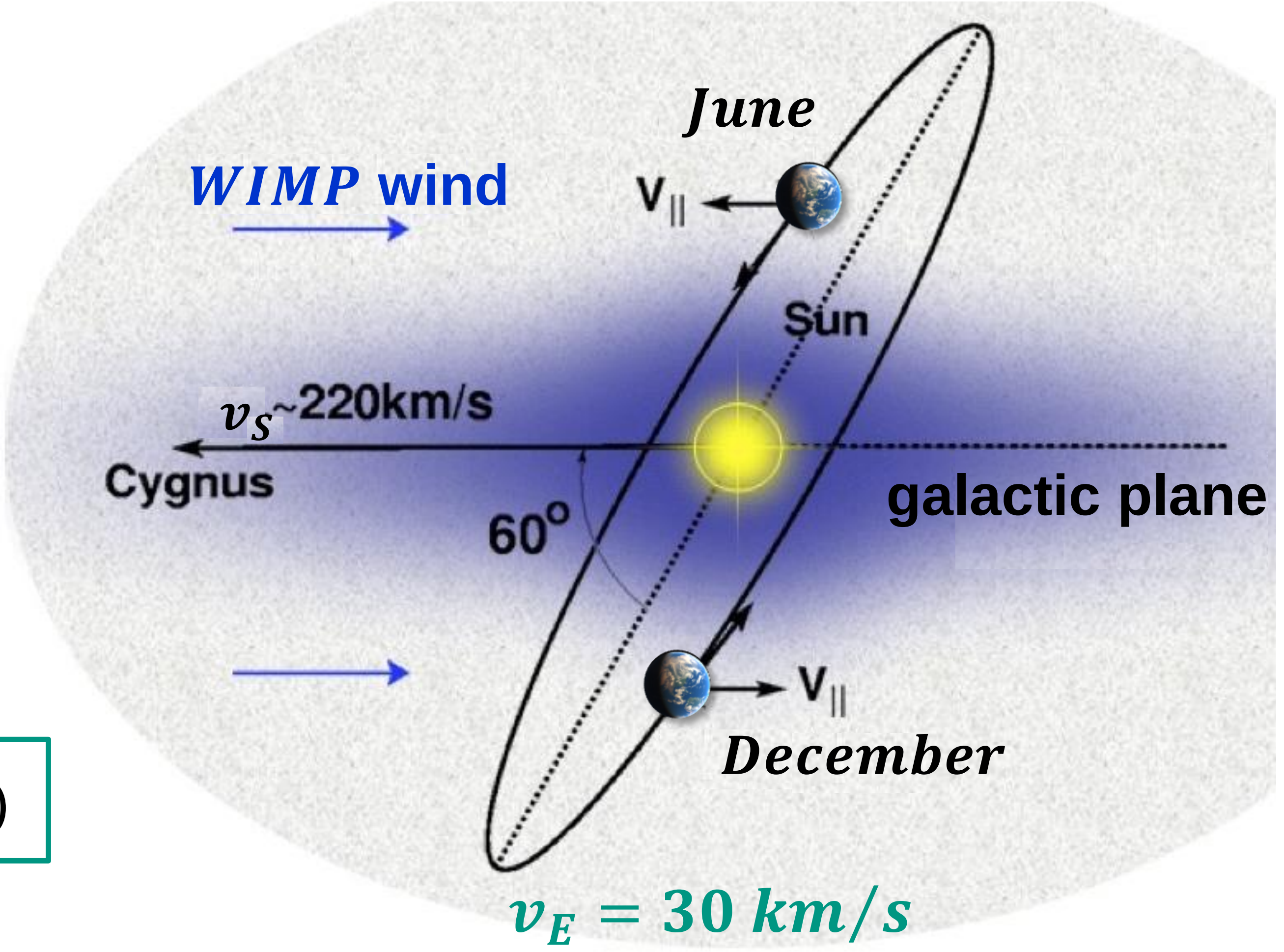
Direct detection of $WIMPs$: modulation of flux

- **Earth´s rotation around Sun causes a (smaller) variation of the $WIMP$ flux**

- velocity vectors of the **Sun** $\vec{v}_S$ & the **Earth** $\vec{v}_E$ add:
  ⇨ **seasonal variation** of the $WIMP$ **velocity distribution** $f(v)$

- this results (in the local coordinate system of our DM – detector) in a well–defined **time dependence**:

$$v(t) = v_S + v_E \cdot \cos(60°) \cdot \cos\omega(t - t_0)$$

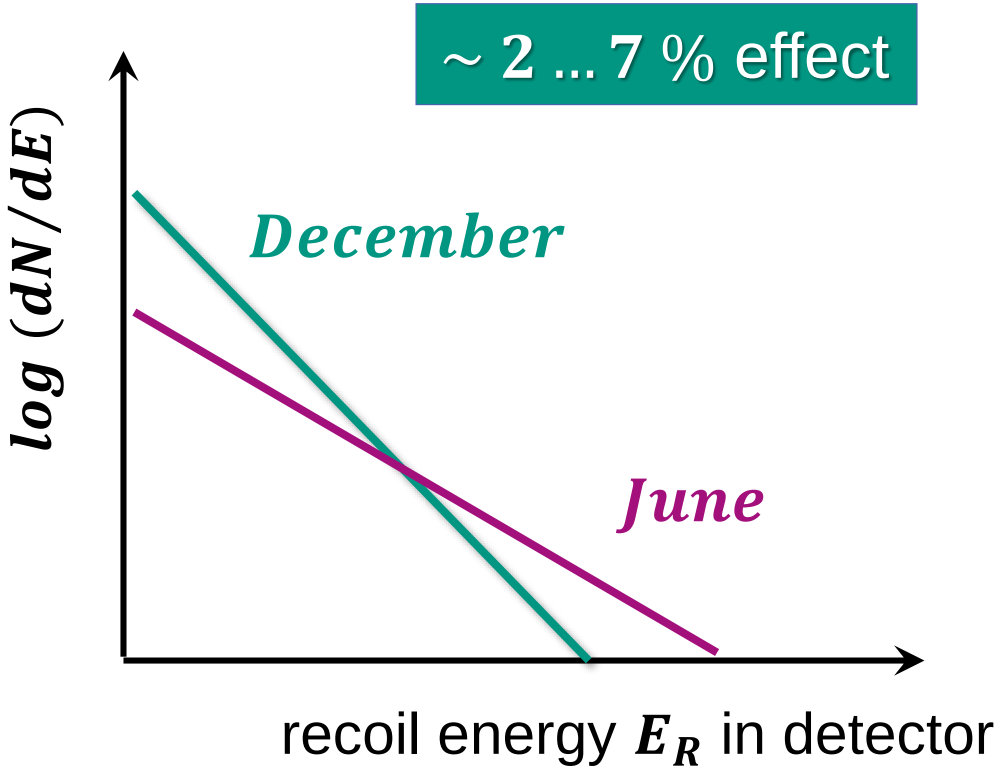


Direct detection of $WIMPs$: variation of E_R

- **Earth´s rotation around Sun causes a variation of the spectrum of E_R**

- phase: t_0 = **June, 2**
- length of period: $T = 1\ yr$

$$v(t) = v_S + v_E \cdot \cos(60°) \cdot \cos\omega(t - t_0)$$



Direct detection of $WIMPs$: interactions

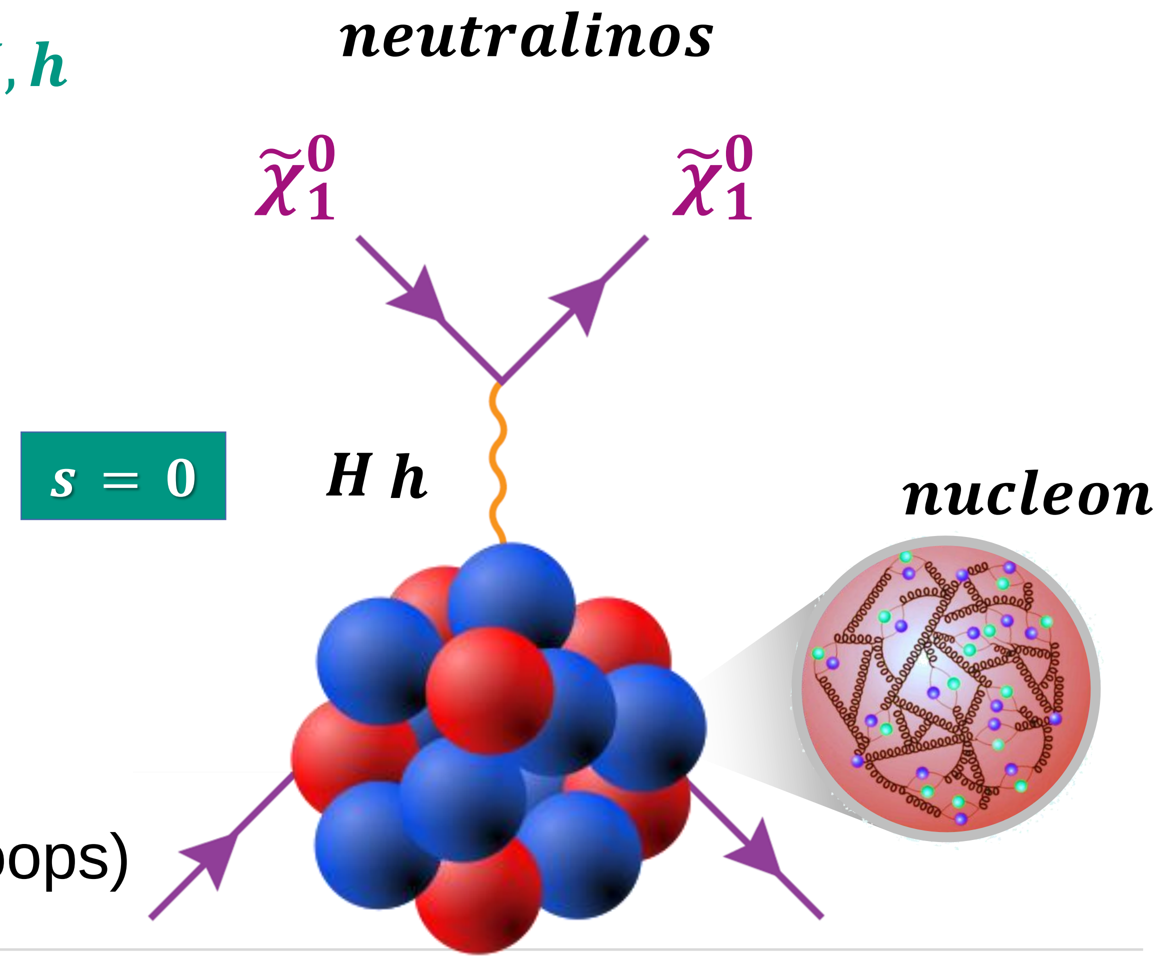
- $Neutralinos$ **can interact via two exchange interactions: scalar / vector**

- **scalar** interaction via light, heavy $Higgs$ H, h

σ_{SI}: Spin Independent

- $Higgs$ couples to the **mass distribution** of the target nucleus

- coupling **inside a** $nucleon$:
  not only to **valence quarks** but also to
  sea quarks & to **massless gluons** (via loops)



Direct detection of $WIMPs$: interactions

- $\boldsymbol{Neutralinos}$: scalar, spin–independent interaction cross section $d\sigma_{SI}/dq^2$

$$\frac{d\sigma_{SI}}{dq^2} \sim \frac{1}{v^2} \cdot \left[f_p \cdot Z + f_n \cdot (A - Z)\right]^2 \cdot F(q^2)$$

q^2: momentum transfer

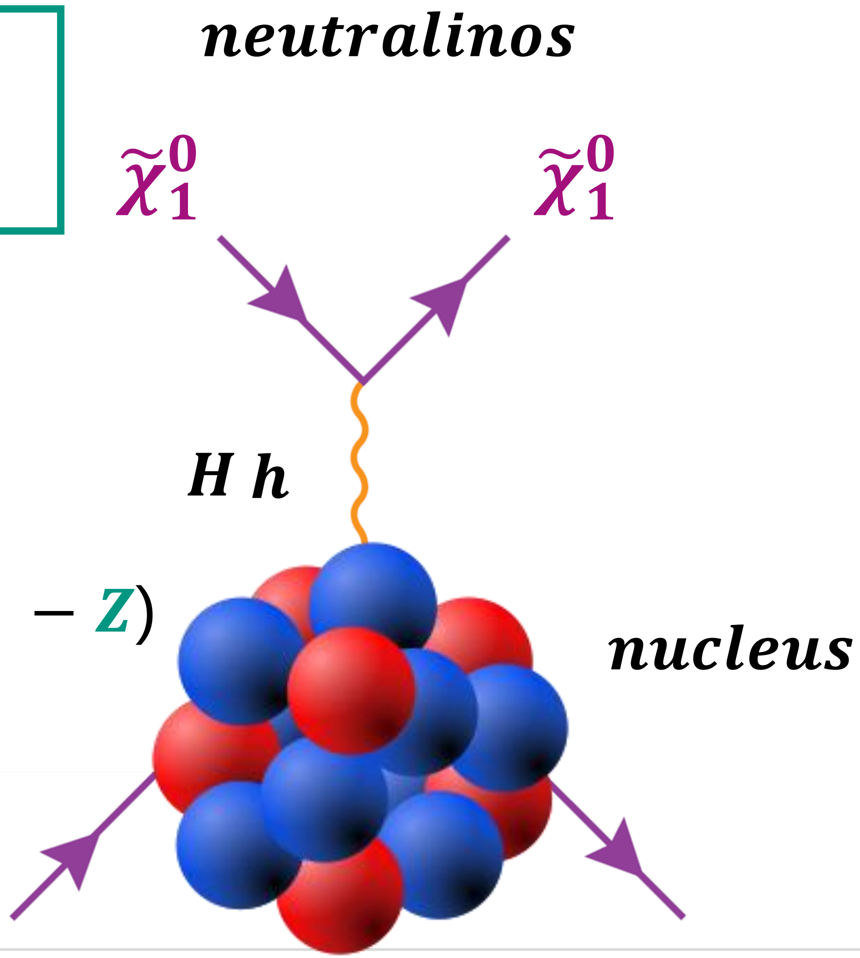
v: $WIMP$ velocity

A , Z : $\boldsymbol{nucleon}$ number A

$\boldsymbol{proton}$ number Z $\boldsymbol{neutron}$ number $(A - Z)$

f_p , f_n: spin–independent $WIMP$ – couplings to $\boldsymbol{protons}$, $\boldsymbol{neutrons}$ ($SUSY$ model)

as $m_p \approx m_n$ we excpect $f_p = f_n$



Direct detection of $WIMPs$: heavy nucleus

- $\boldsymbol{Neutralinos}$: **scalar, spin–independent interaction cross section** $d\sigma_{SI}/dq^2$

$$\frac{d\sigma_{SI}}{dq^2} \sim A^2 \cdot F(q^2)$$

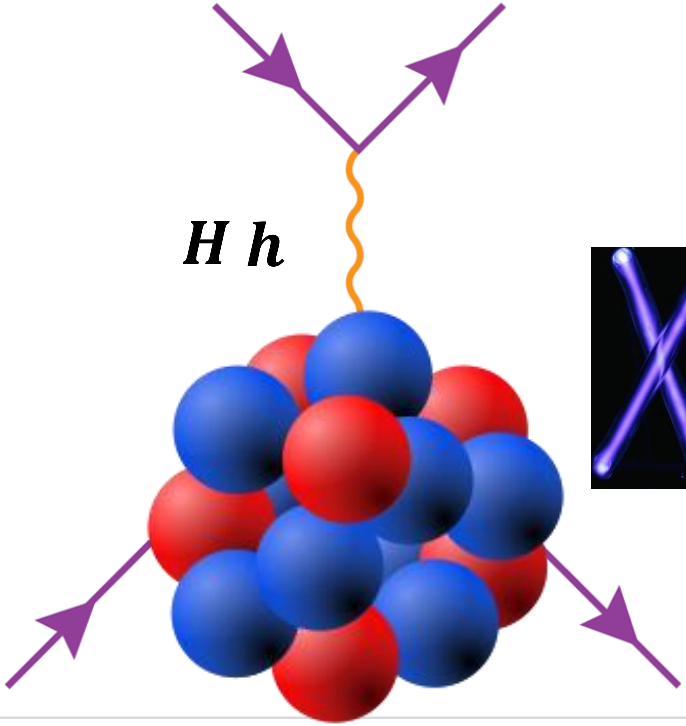
→ a large $\boldsymbol{nucleus}$ with $A > 100$ is very helpful

for $f_p = f_n$

scattering amplitudes off all $\boldsymbol{nucleons}$ **add** $\boldsymbol{coherently}$

L. Hofstadter

Xenon is best:
$A \approx 130$



Direct detection of $WIMPs$: the form factor $F(q^2)$

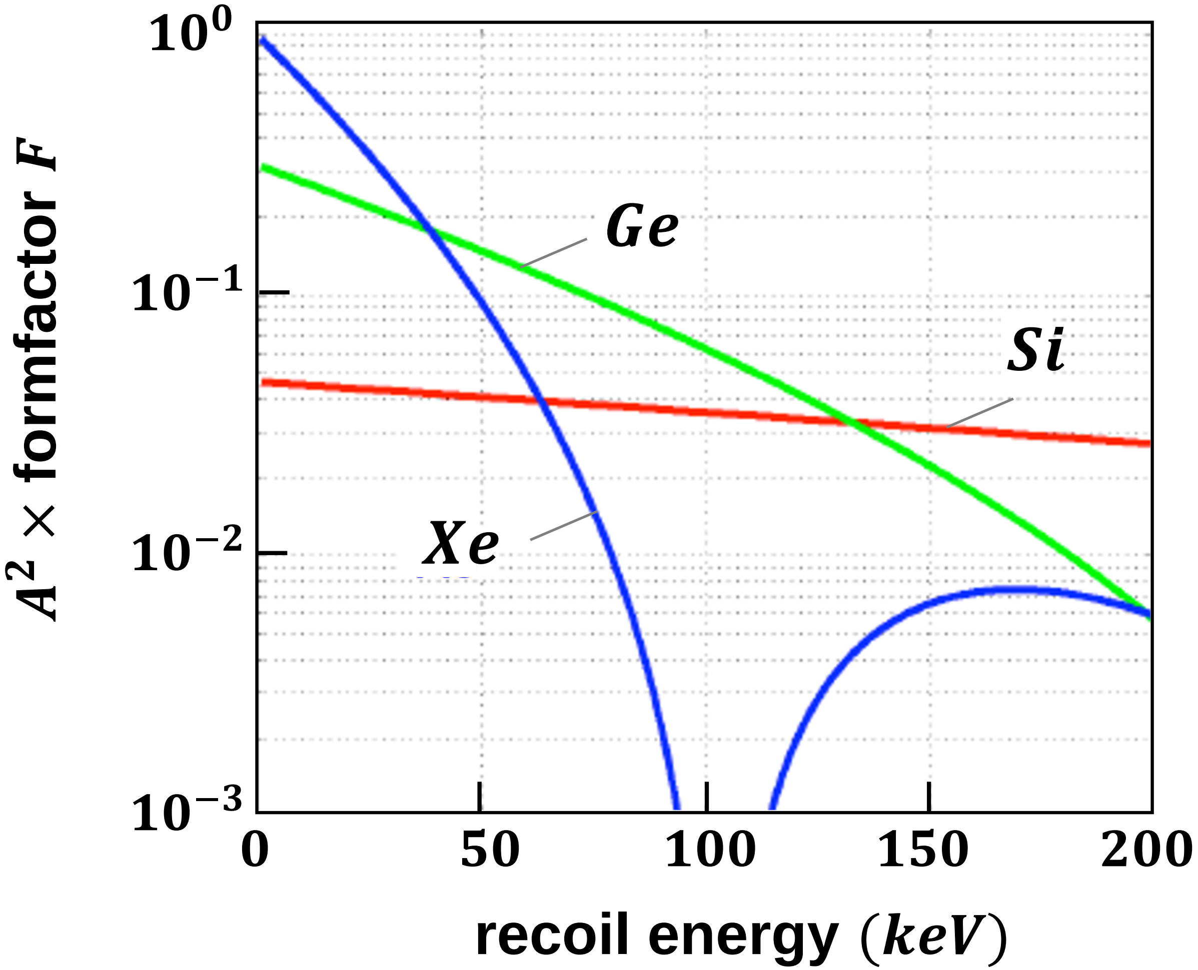
- $Neutralino$ **interactions: the important** $nuclear$ **form factor** $F(q^2)$

$$\frac{d\sigma_{SI}}{dq^2} \sim A^2 \cdot F(q^2)$$

- analogue to **electron scattering** off a $nucleus$ at high momentum transfer (see Mod. Ex. Phys. III)

R. Hofstadter

F is important

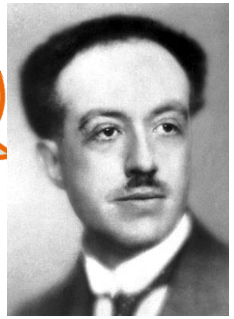


Direct detection of $WIMPs$: the form factor $F(q^2)$

- $\boldsymbol{Neutralino}$ **interactions: the importance of its** $\boldsymbol{de\ Broglie\ wavelength}$

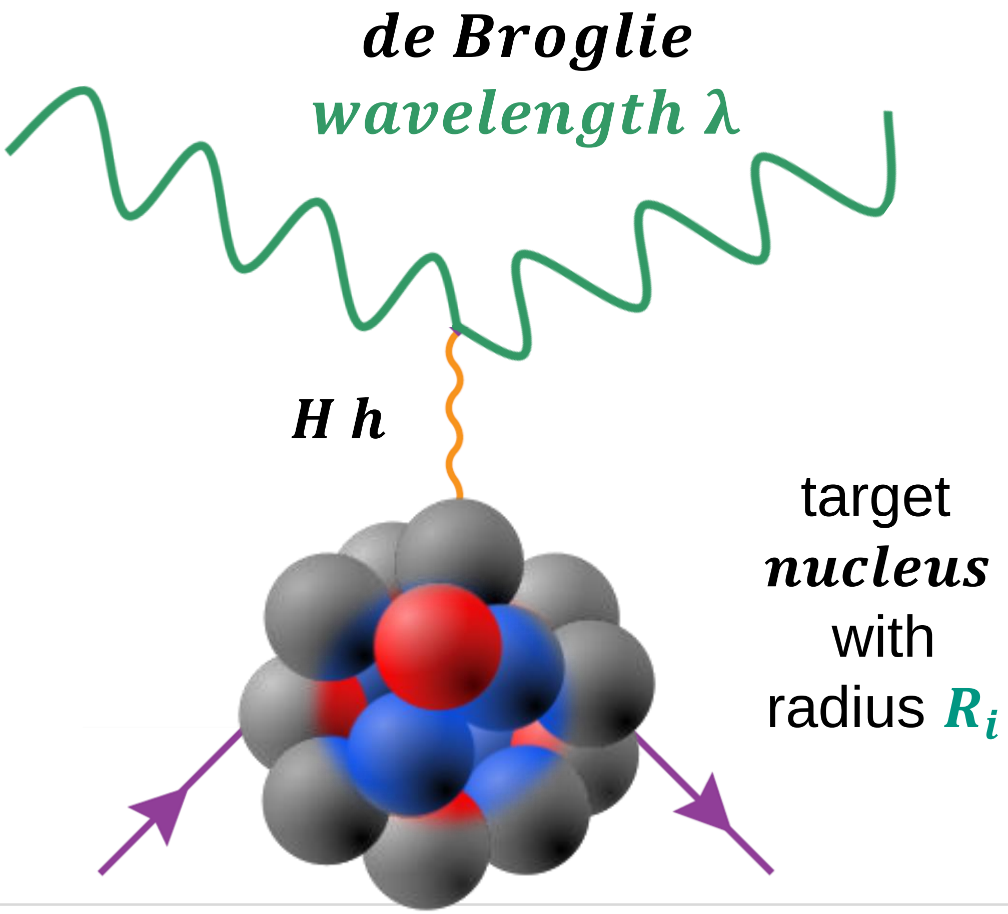
$$\frac{d\sigma_{SI}}{dq^2} \sim A^2 \cdot F(q^2)$$

- scattering amplitudes only add $\boldsymbol{coherently}$, in case that the $\boldsymbol{WIMP - de\ Broglie\ wavelength\ \lambda}$ is rather $\boldsymbol{long}$



L. De Broglie

λ is important



Direct detection of $WIMPs$: the form factor $F(q^2)$

- $Neutralino$ **interactions: the important condition for** $coherent\ scattering$

$$\frac{d\sigma_{SI}}{dq^2} \sim A^2 \cdot F(q^2)$$

- scattering amplitudes only add $coherently$,
in case the **following condition** is fulfilled:

$$q \cdot R_i \ll 1$$

(typcially only for $A < 50$)

momentum transfer $q \sim A \cdot 10^{-3}\ GeV$

$nuclear$ radius $R_i \sim A^{1/3} \cdot 7\ GeV^{-1}$