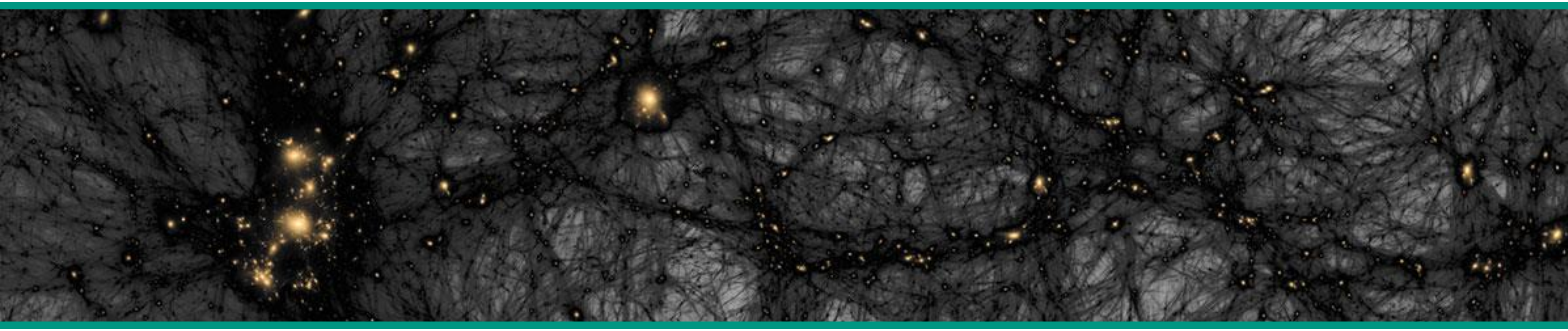
Karlsruhe Institute of Technology

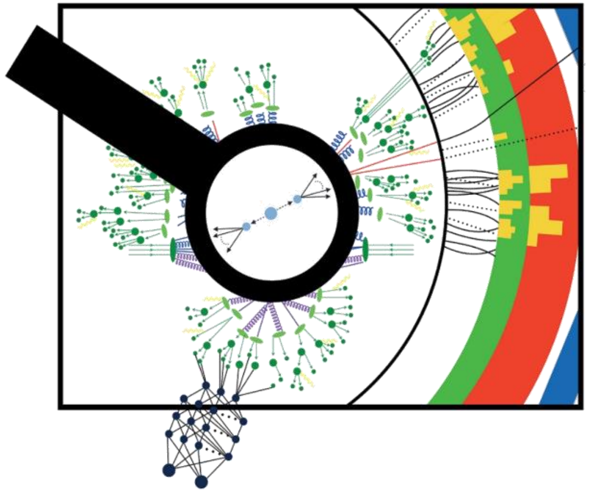
Astroparticle physics I – Dark Matter

WS22/23 Lecture 15 Jan. 18, 2023



Recap of Lecture 14

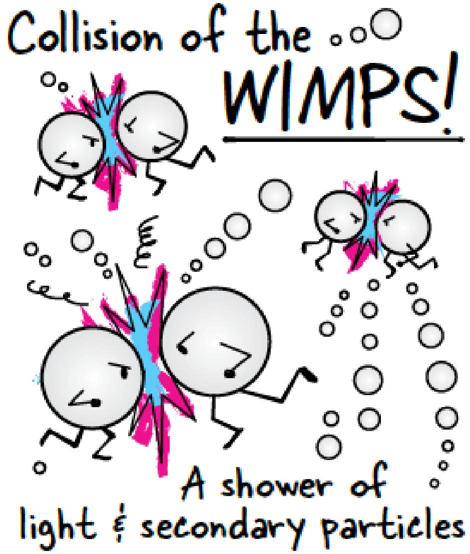
- **Dark Matter Searches: LHC & DM-Annihilation in gammas**



- **LHC**: search for $SUSY$ –decay cascades from gluinos to neutralinos – lepton/hadron pairs, missing E_T, p_T

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

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

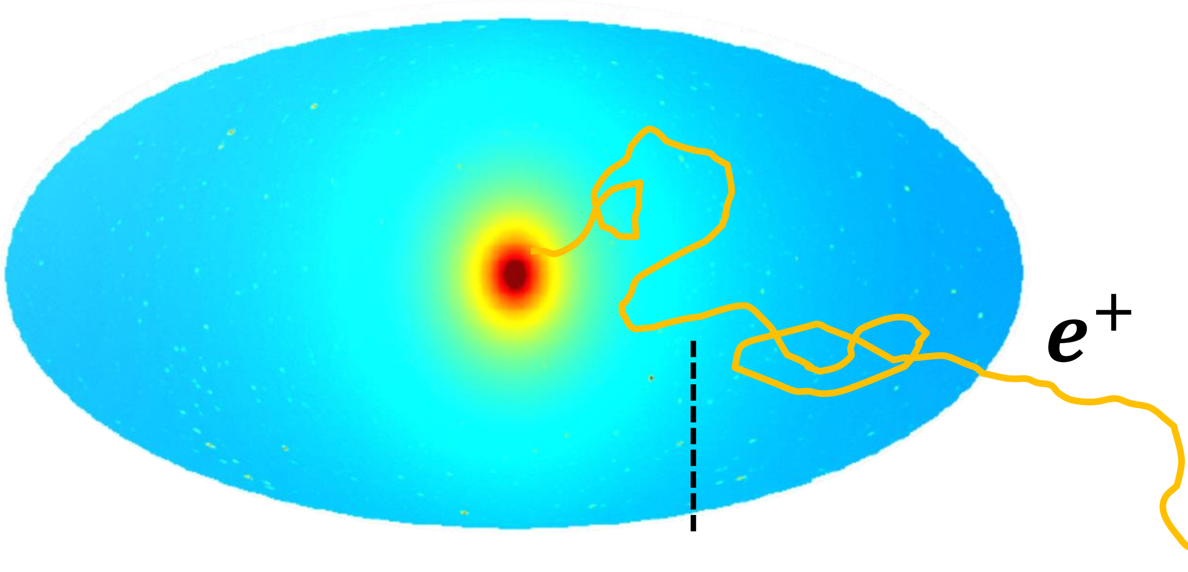


- DMA into gammas
  GeV – scale: FERMI excess – Hooperon or ms – pulsars?
  TeV – scale: IACTs to GC – many astrophysical sources

Positrons as DMA messengers

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

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



$\boldsymbol{GeV \ldots TeV}$ - scale:
AMS-02 experiment

GALPROP

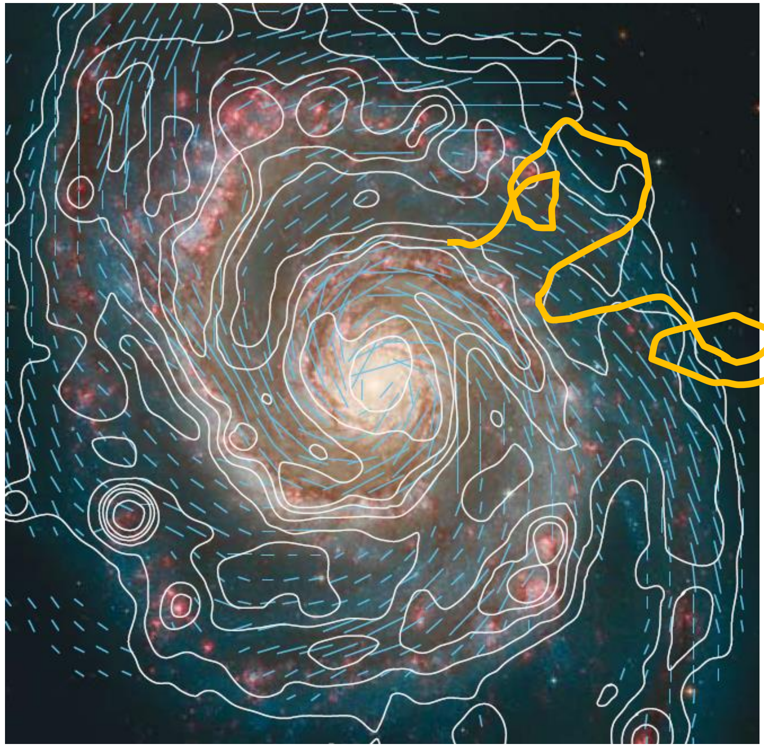
deflection in galactic B – field

⇨ huge energy losses during propagation:
e^+ only from local DM-halo

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
  - 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

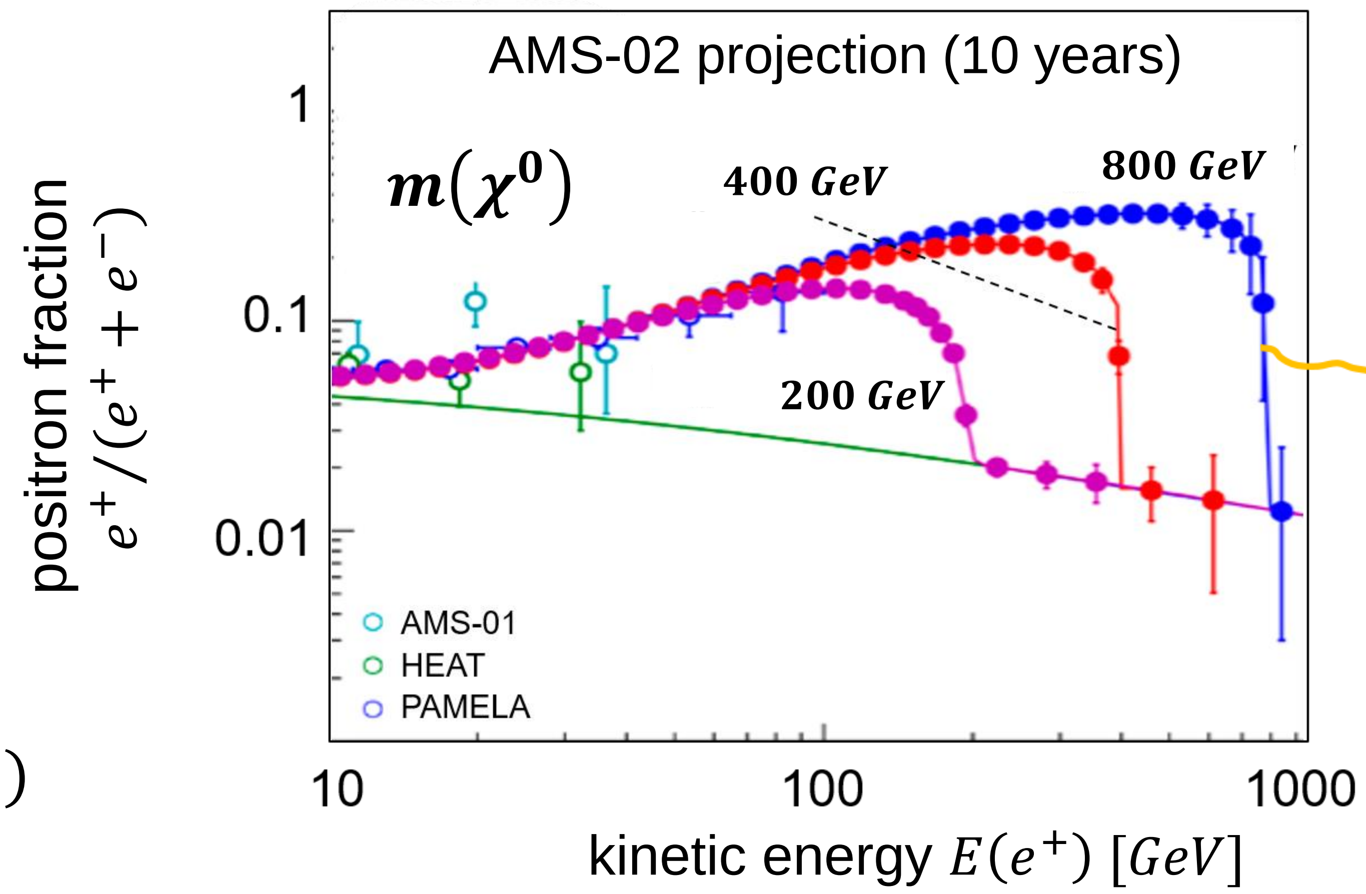
Positrons as DMA messengers

- 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 kinet. energy

- **cut-off** at $E(e^+) = m(\chi^0)$



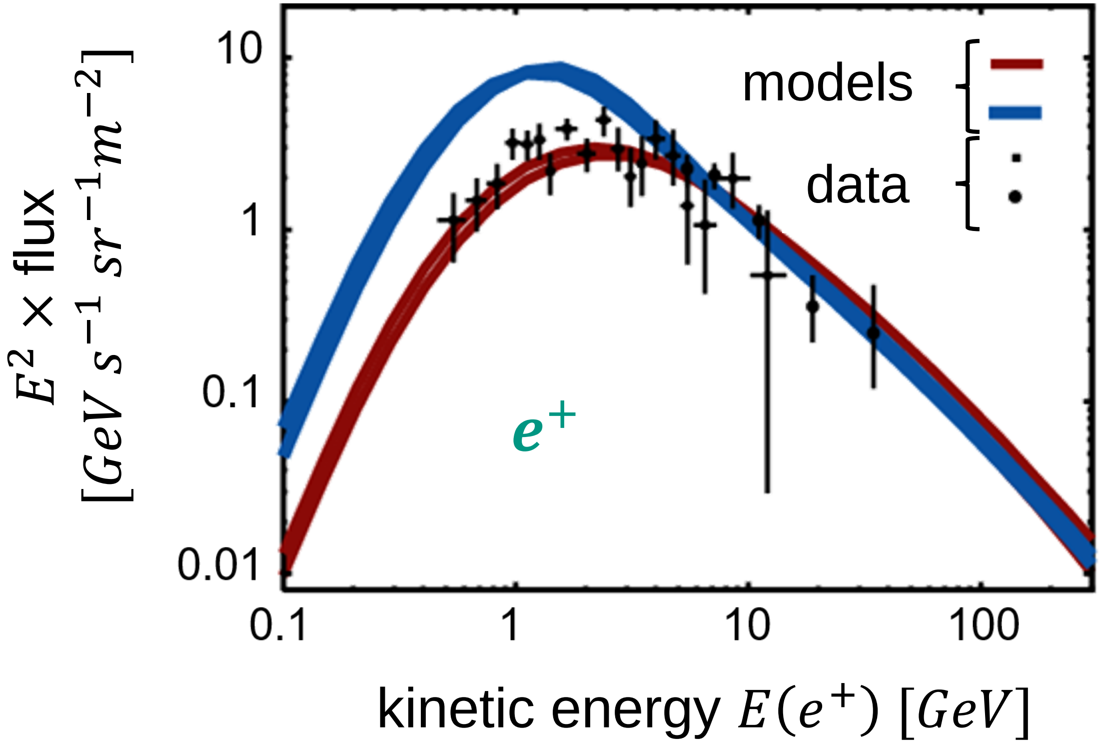
focus on high energies!

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 interstellar medium (ISM): dust, gas (hot, intermediate, cold)

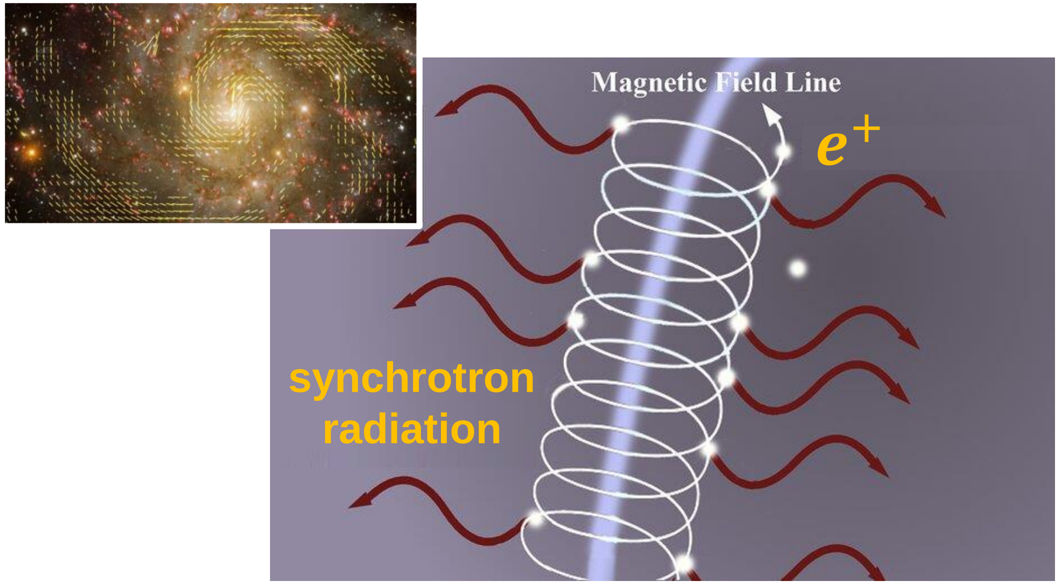


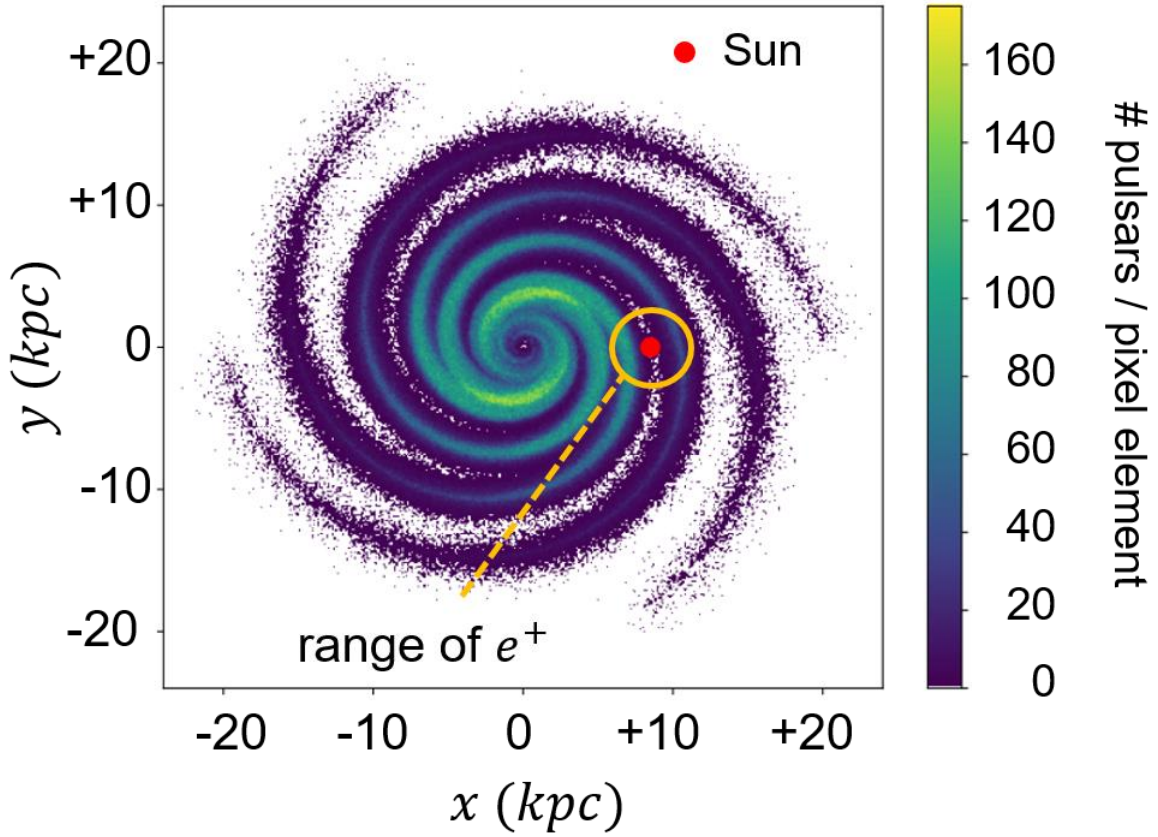
Background to DMA searches: astrophysical e^+

- **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

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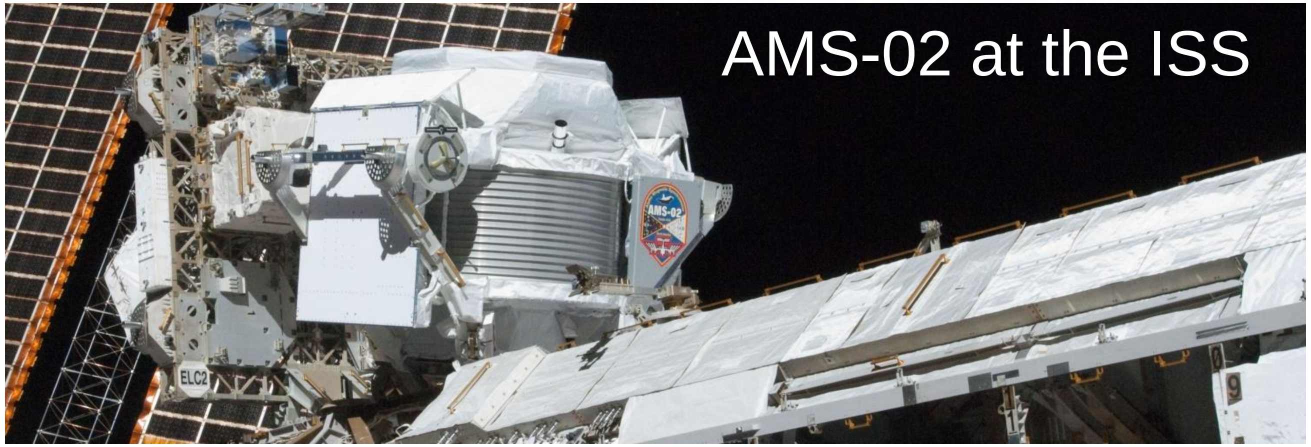
- **Alpha Magnetic Spectrometer (AMS): a particle detector onboard the ISS**

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

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

- investigations of cosmic radiation:
  flux, energies, composition

start: May 16, 2011 with STS134

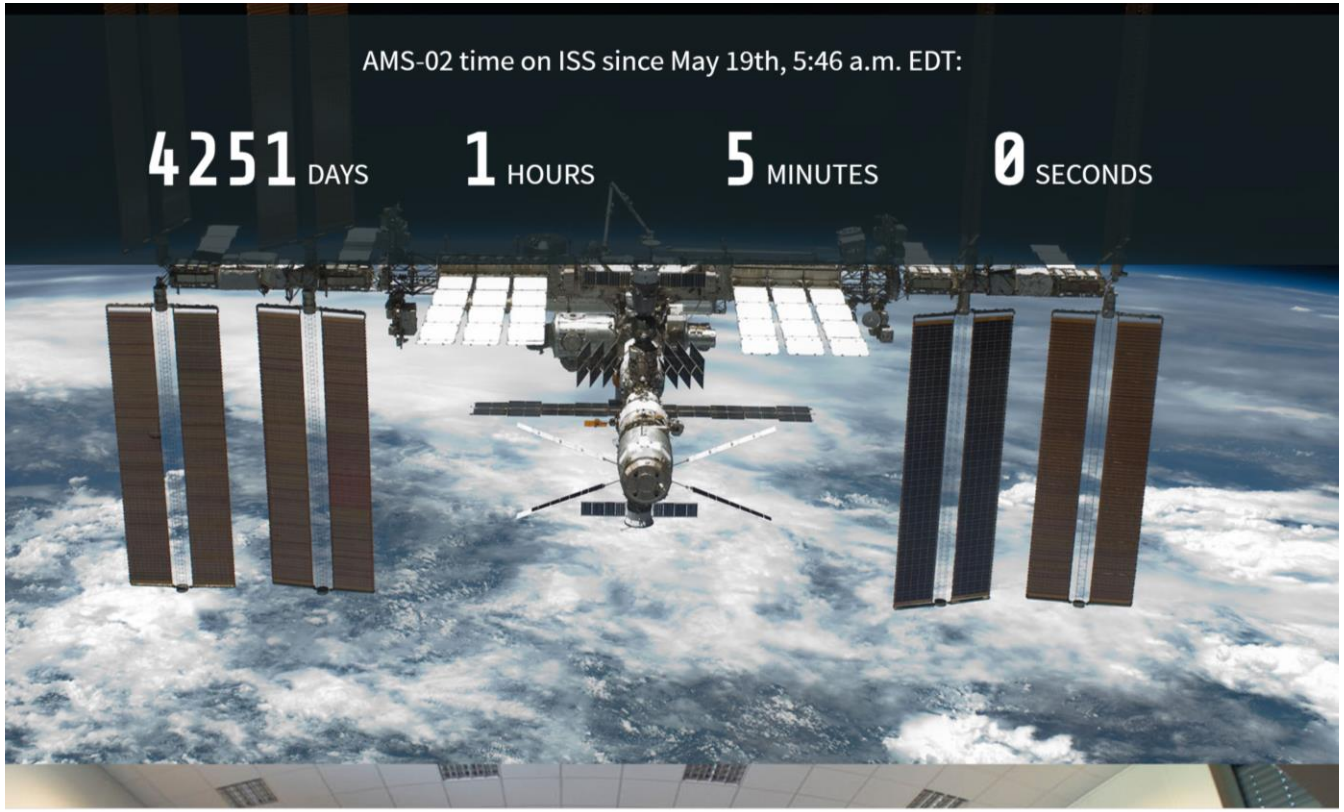


AMS-02 at the ISS

Searching for DMA with e^+: AMS-02

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

  - ETP has participated in AMS-02 from 2002…2020 (contributions to the TRD)



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

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

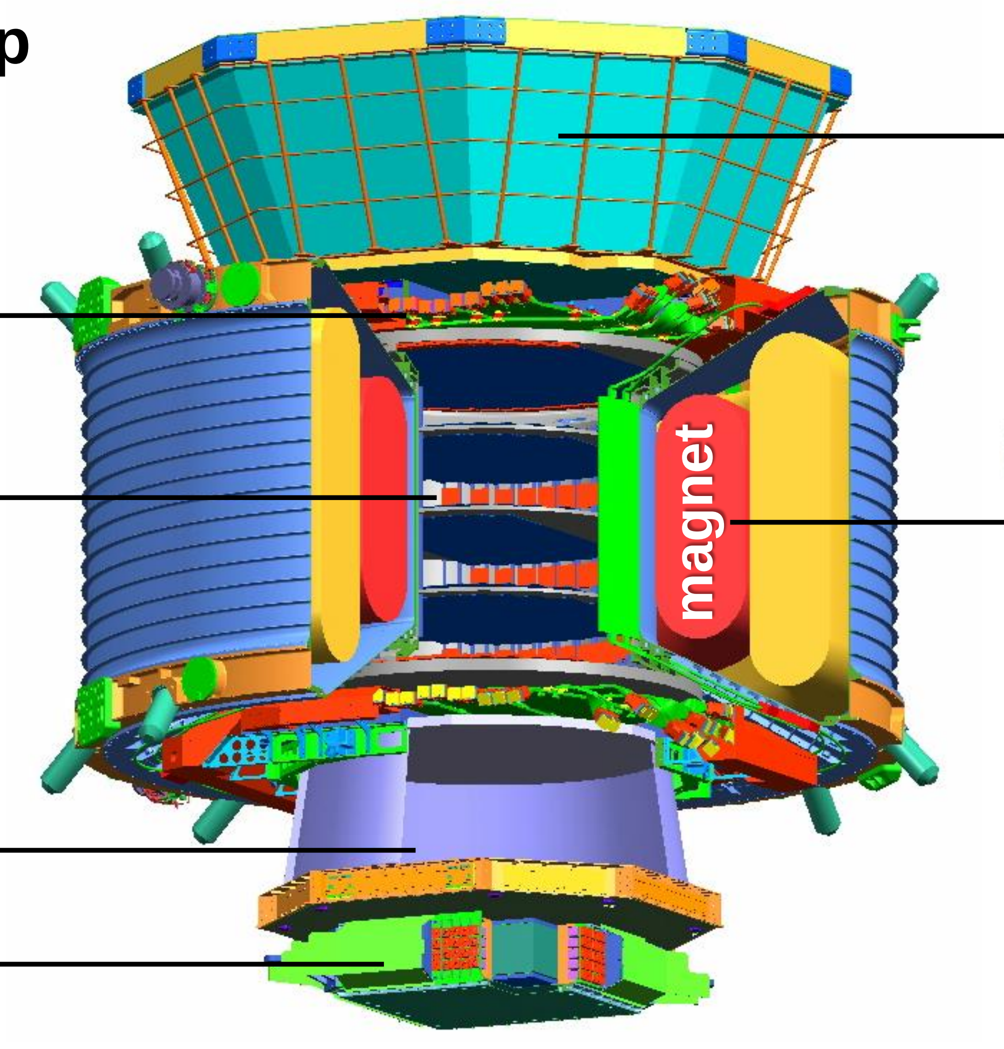
- **Experimental setup**

ToF -
Time-**o**f-**F**light
detector (β)

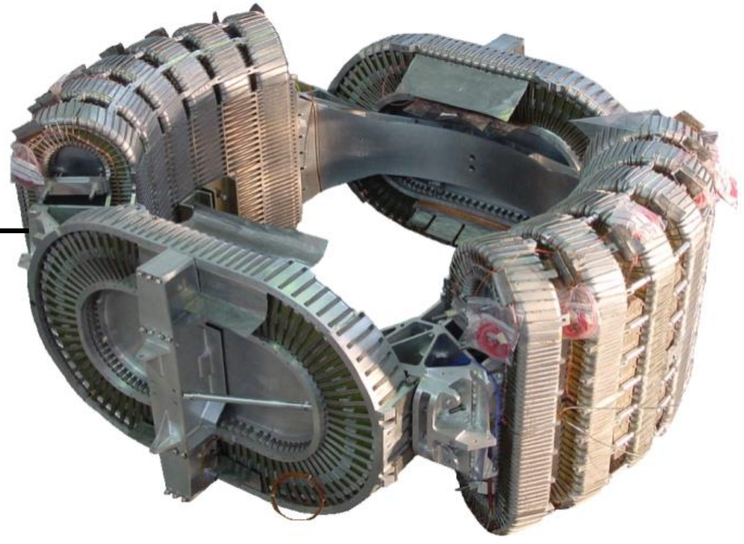
tracker & **magnet** -
particle track (p)

RICH -
Ring **I**maging
Cherenkov detector
($v < c$)

ECAL -
elmagn. calorimeter (E_{tot})



TRD - **T**ransition **R**adiation **D**etector ($v \sim c$): light/heavy particles



$$B = 0.12\ T$$

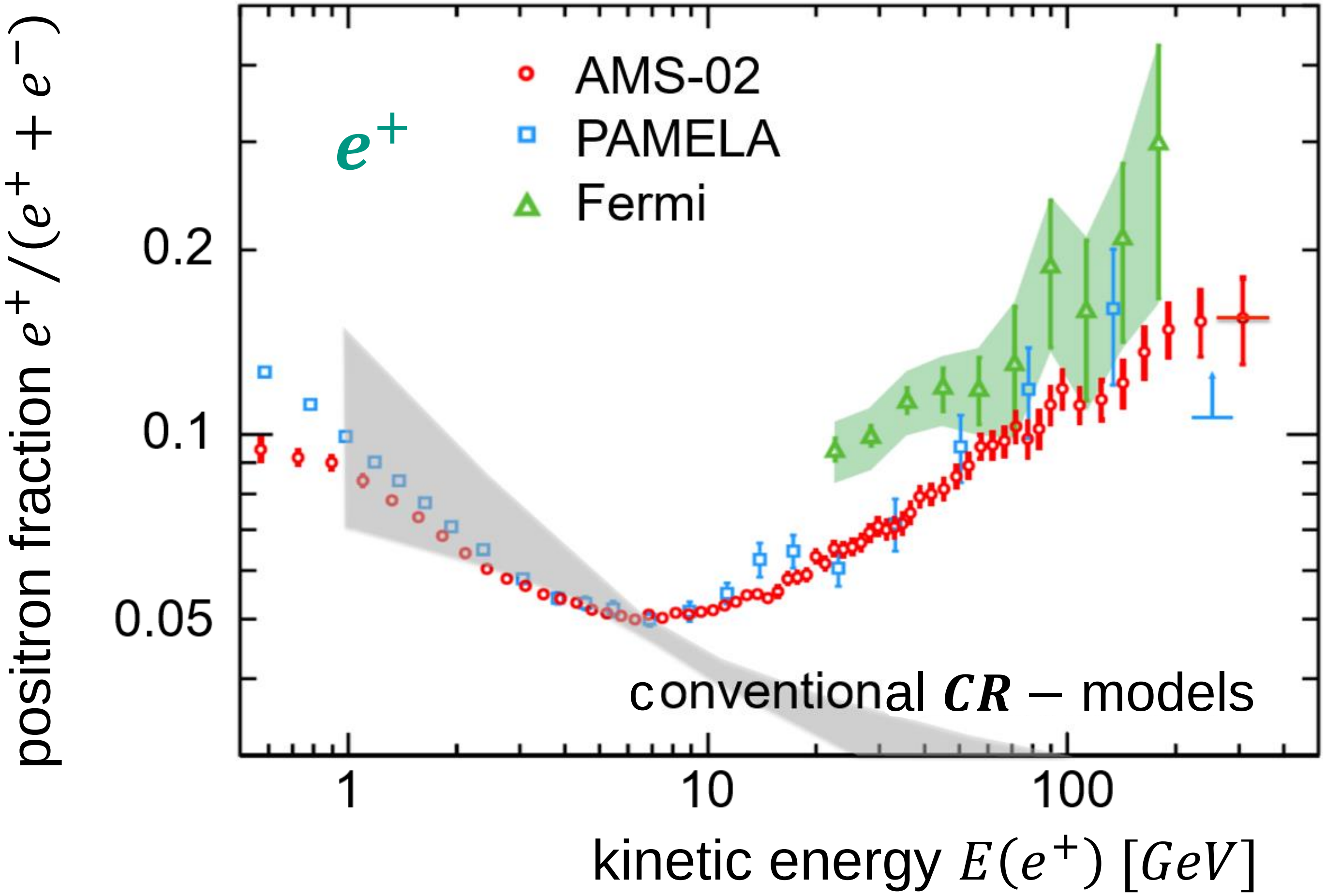
AMS-02 results: a high-energy excess of e^+

- 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 $\boldsymbol{m}(\boldsymbol{\chi}^0)$

- 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^+

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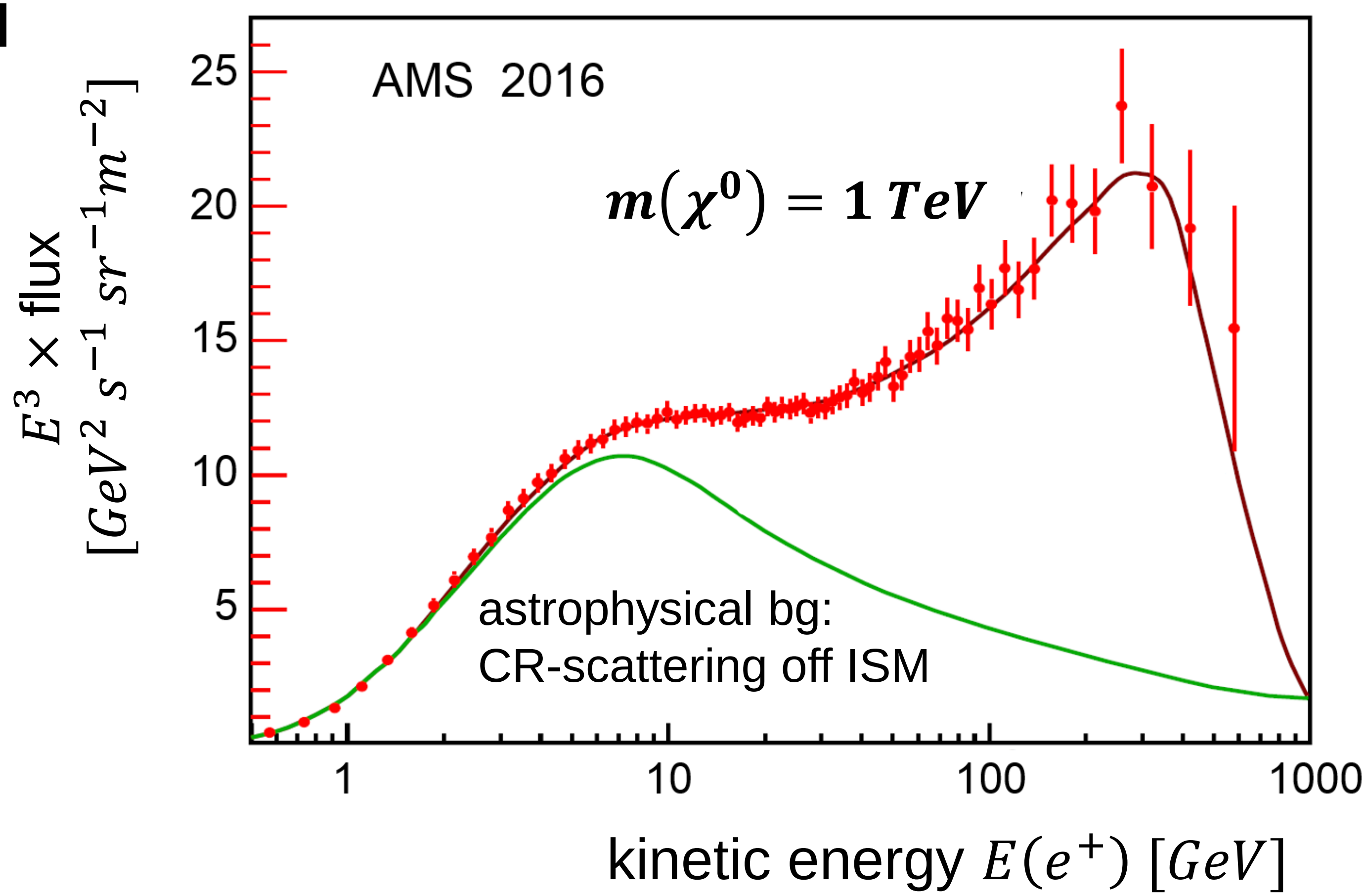
- **AMS-02 sees energetic positrons almost up to the TeV-energy scale!**

- 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 is on TeV-scale: clear **excess of high-energy positrons**



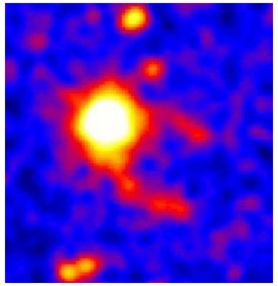
AMS-02 results: a high-energy excess of e^+

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

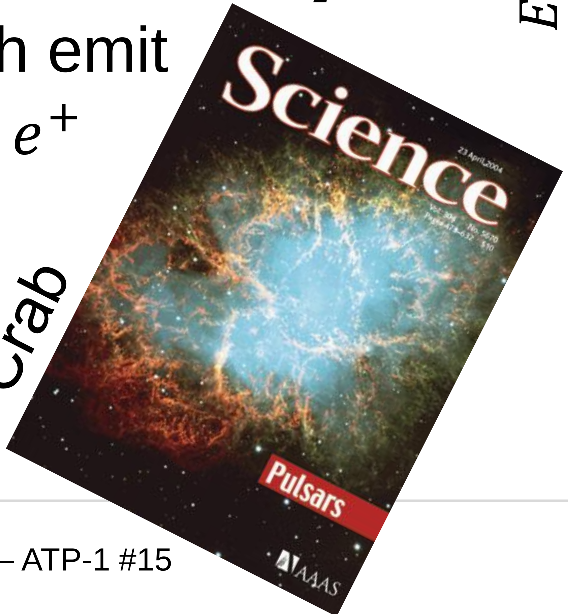
  - **difficult interpretation of AMS-02 data & e^+ – spectroscopy…**

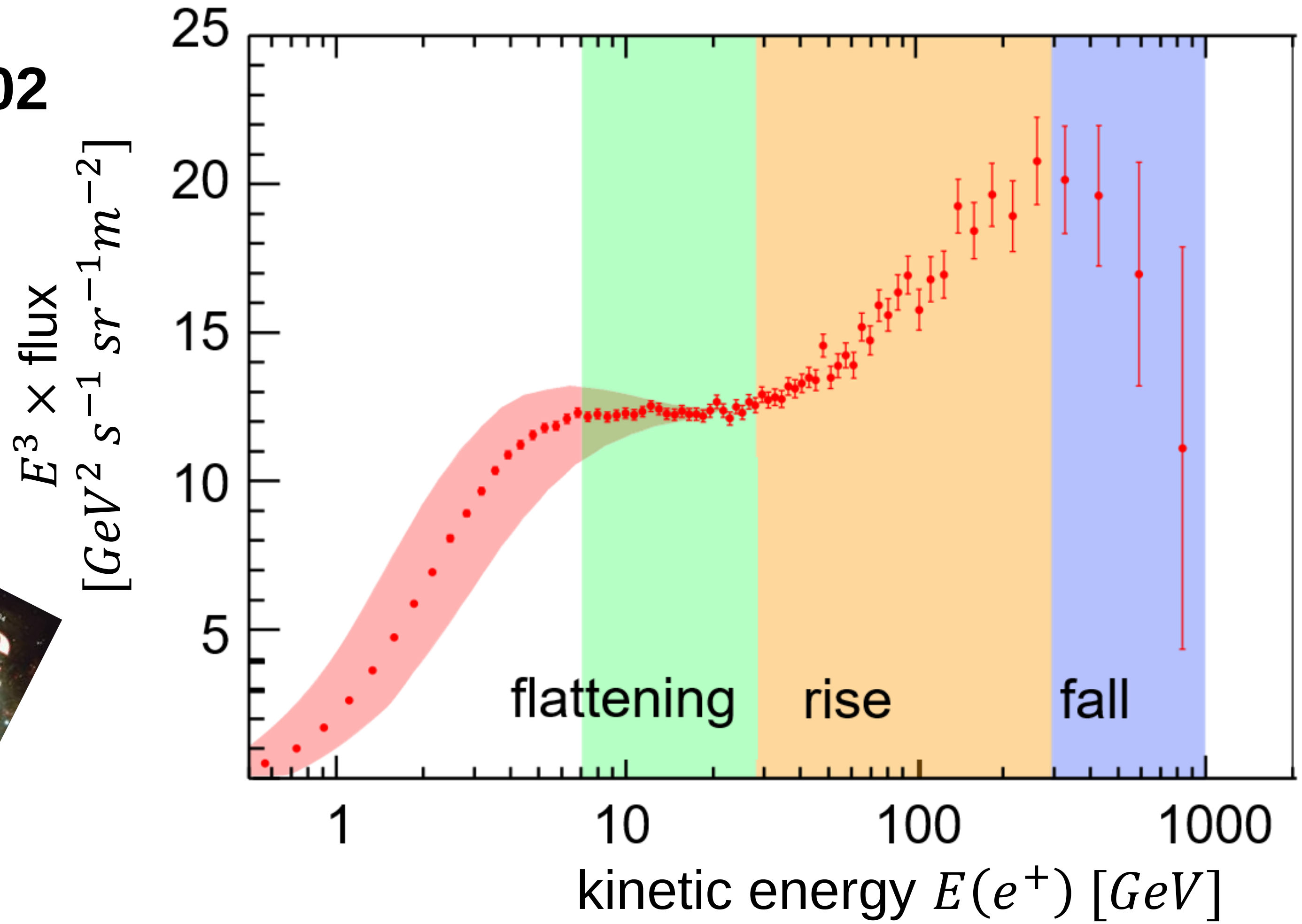
  a) astrophysical background
  young pulsars (pulsar wind nebulae) in $\boldsymbol{d = 0.3 \ldots 3\ kpc}$ (nearby!) which emit very energetic e^+

Geminga



Crab





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

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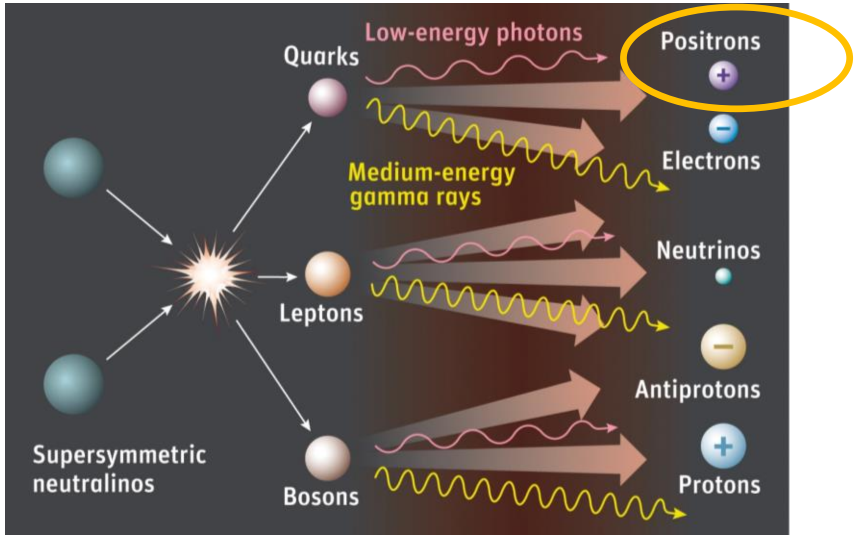
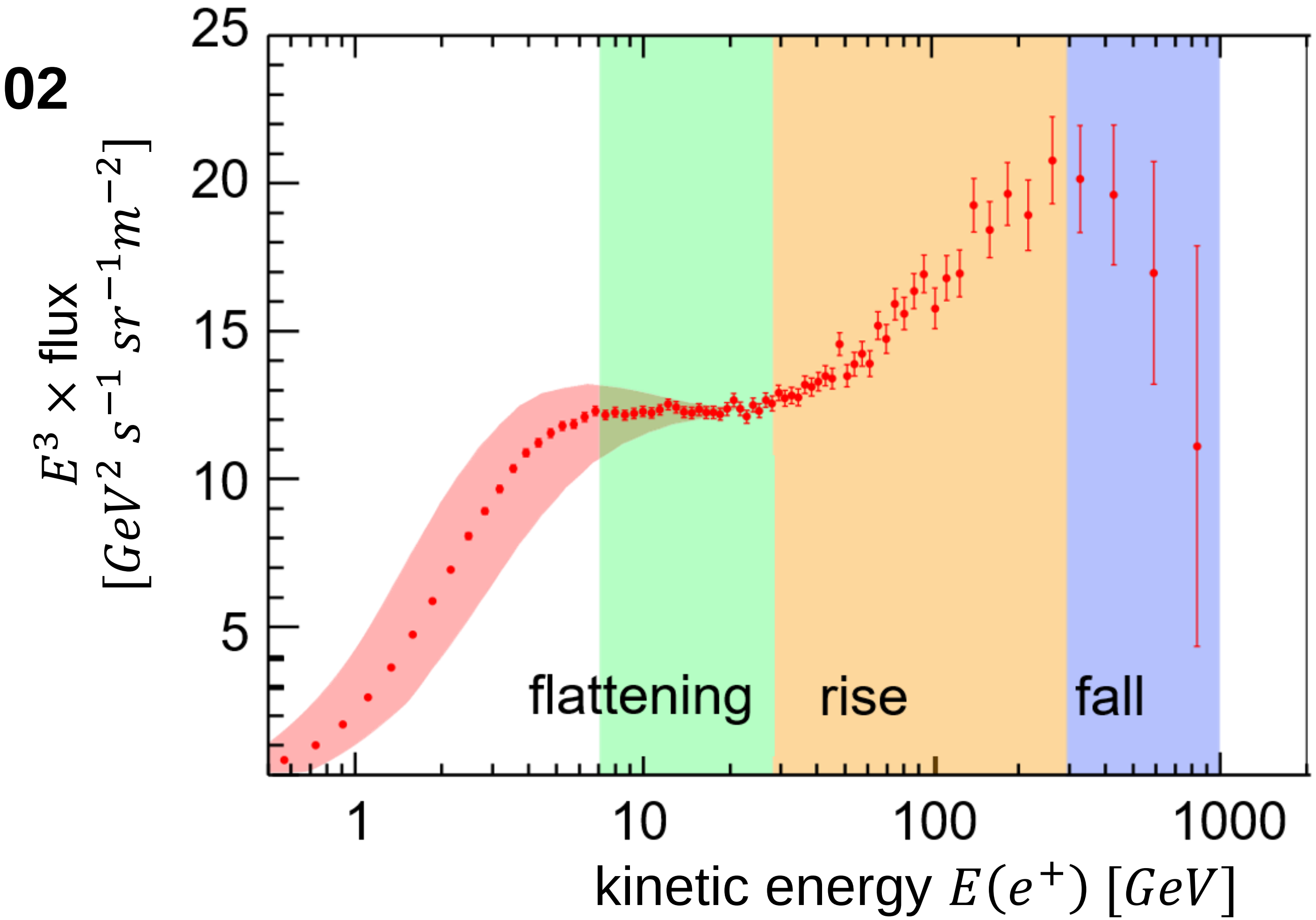
- **What is its origin – DMA signal or astrophysical e^+ from nearby pulsars?**

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

  b) signal from DMA at $GeV \ldots TeV$ scale



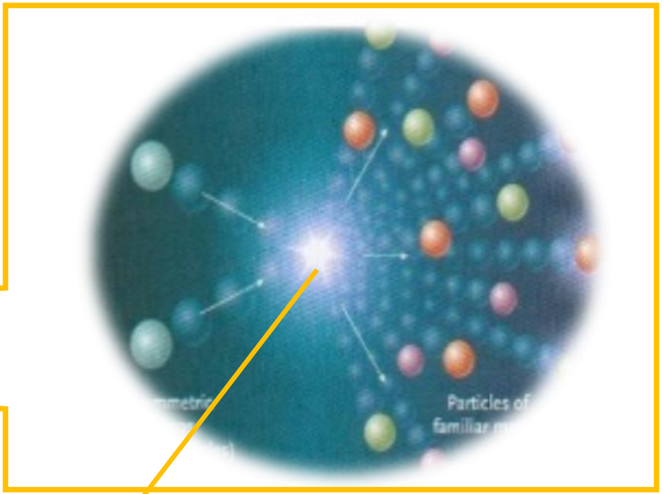


AMS-02 experiment: the future

- **The search for DMA with messenger particles $e^+, \overline{p}$ will continue…**

4.4.2 Neutrinos

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



*see chapt. 2.1.2 - IceCube results (Lect. #7, #8)

Neutrinos as DMA messengers from the solar core

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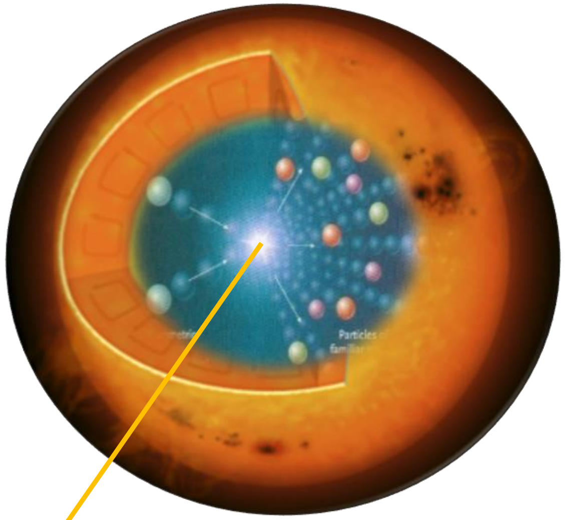
- **Interesting scenario: WIMPs get trapped by the Sun**

  - WIMPs can scatter off solar matter & thereby lose energy ⇨ they get captured & sink to the core

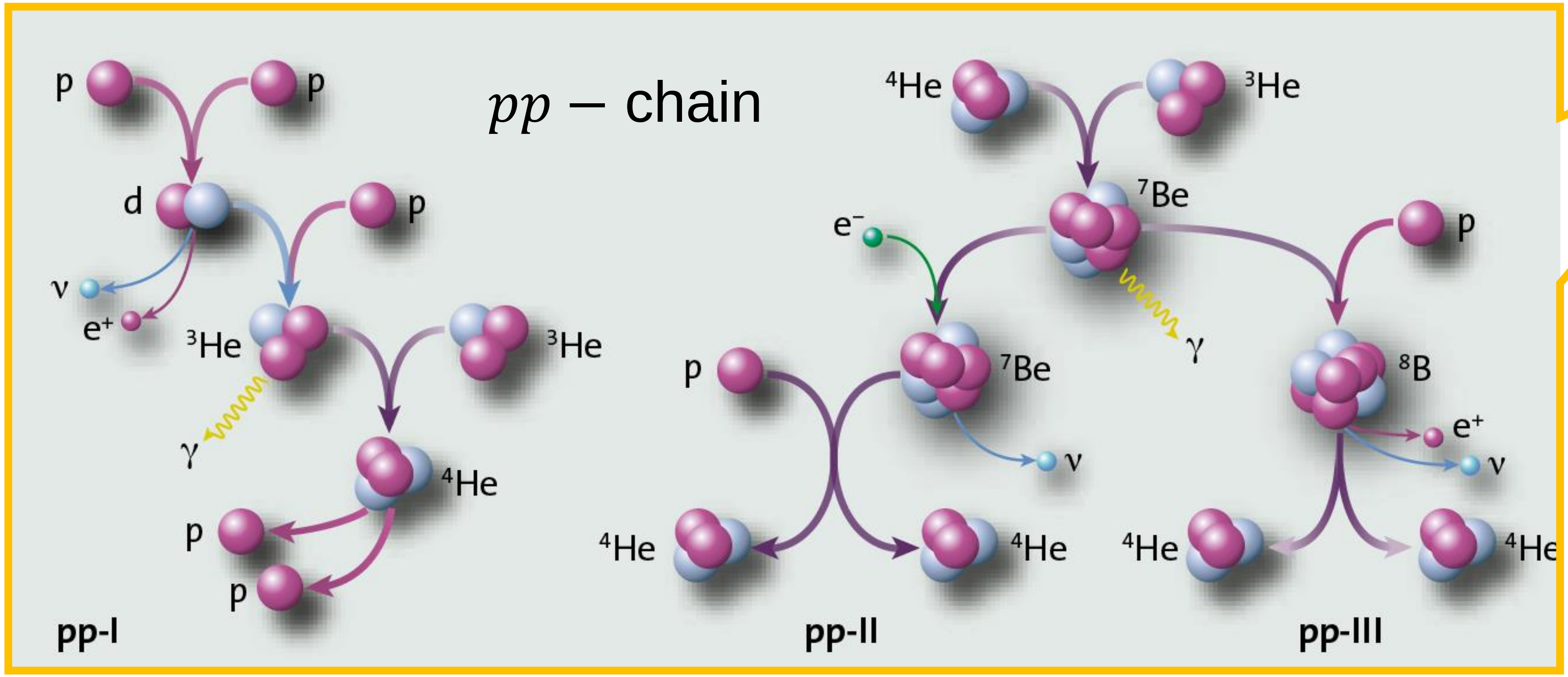
  - there will be an **equilibrium** of the DM capture rate R_C & the DM annihilation rate R_{DMA} ⇨ do we see DMA? & how can we discriminate against solar neutrinos?

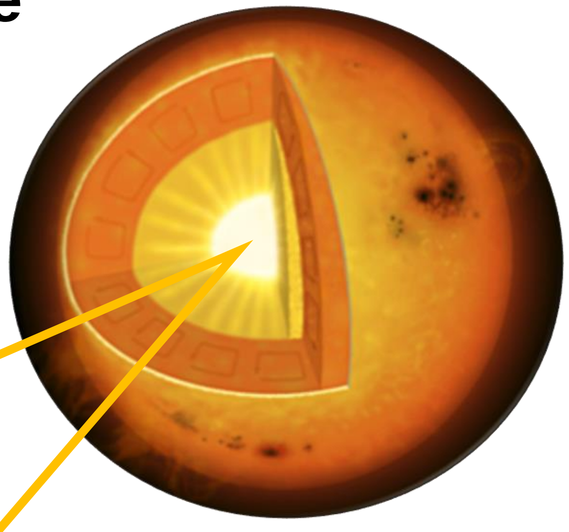


DMA in the core of the sun?

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

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



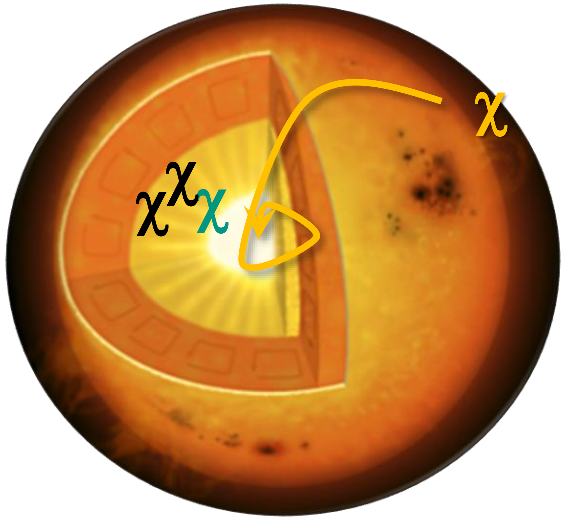


MeV

*see ATP-II (summer term 2023)

DMA in the core of the sun?

- **$SUSY$ – scenario: GeV-neutrinos from the solar core**
  - spin-dependent interaction* of 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

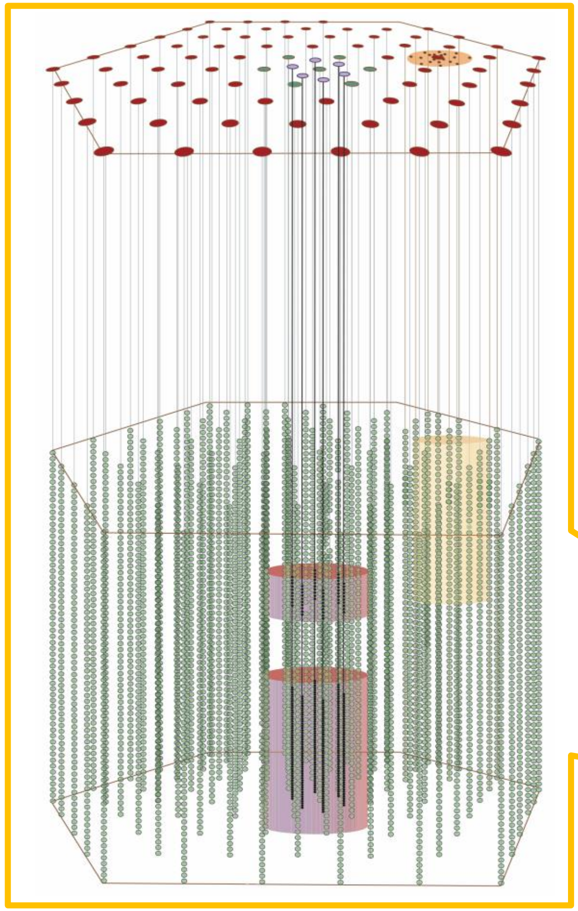
density → velocity → xsec → mass

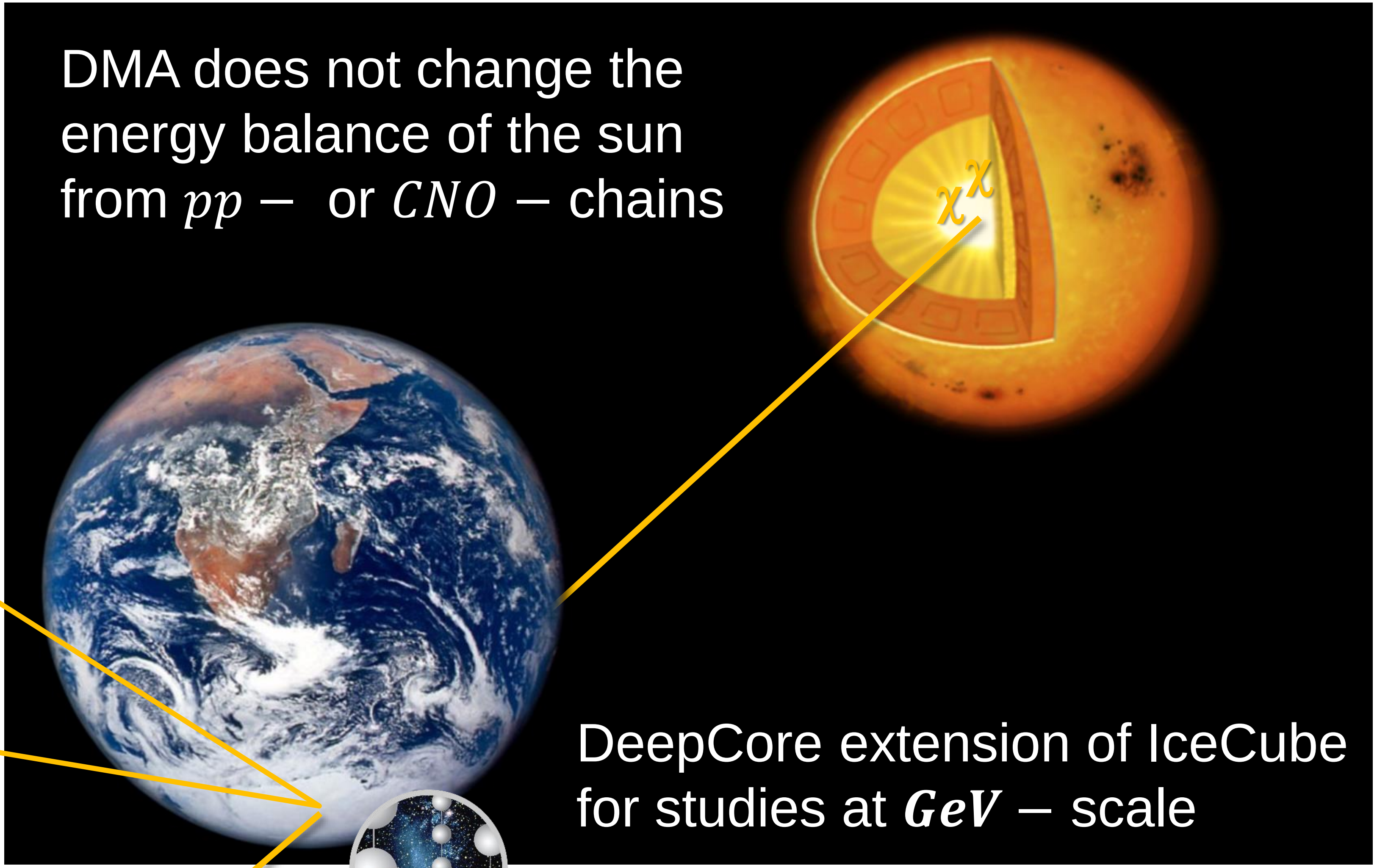
$$R_C \cong 3.35\times10^{20}\,s^{-1}\cdot\left(\frac{\rho_{lokal}}{0.3\,GeV/cm^3}\right)\cdot\left(\frac{270\,km/s}{v_{lokal}}\right)^3\cdot\left(\frac{\sigma_{Spin}}{10^{-6}\,pb}\right)\cdot\left(\frac{100\,GeV}{m\chi}\right)^2$$

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

Hunting GeV –scale neutrinos from DMA

- $GeV - \nu´s$ from the sun

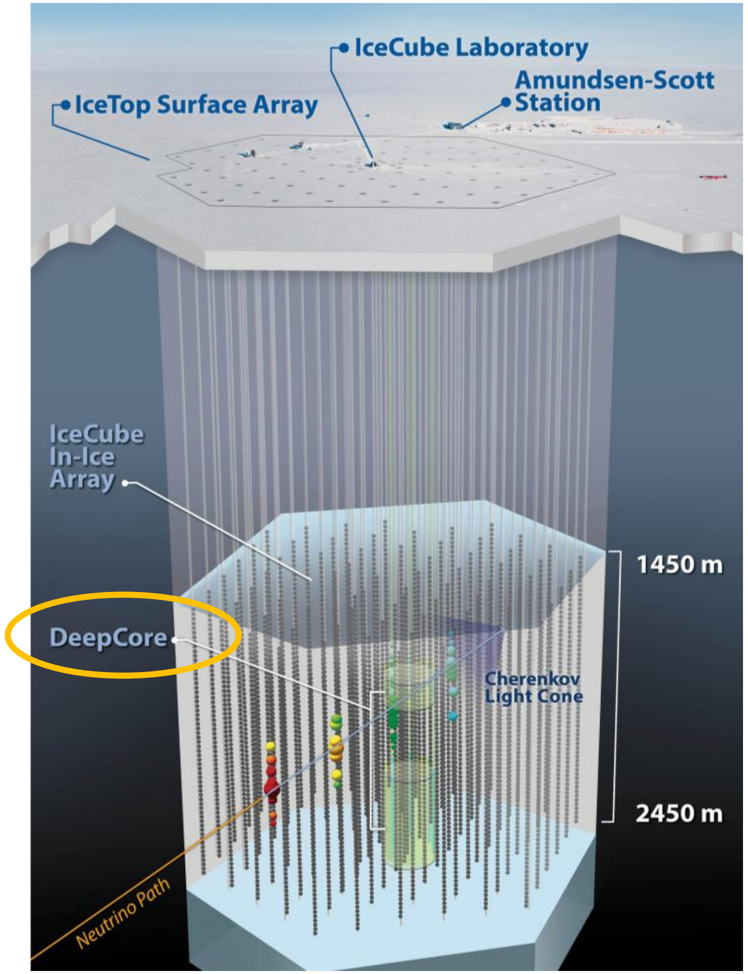


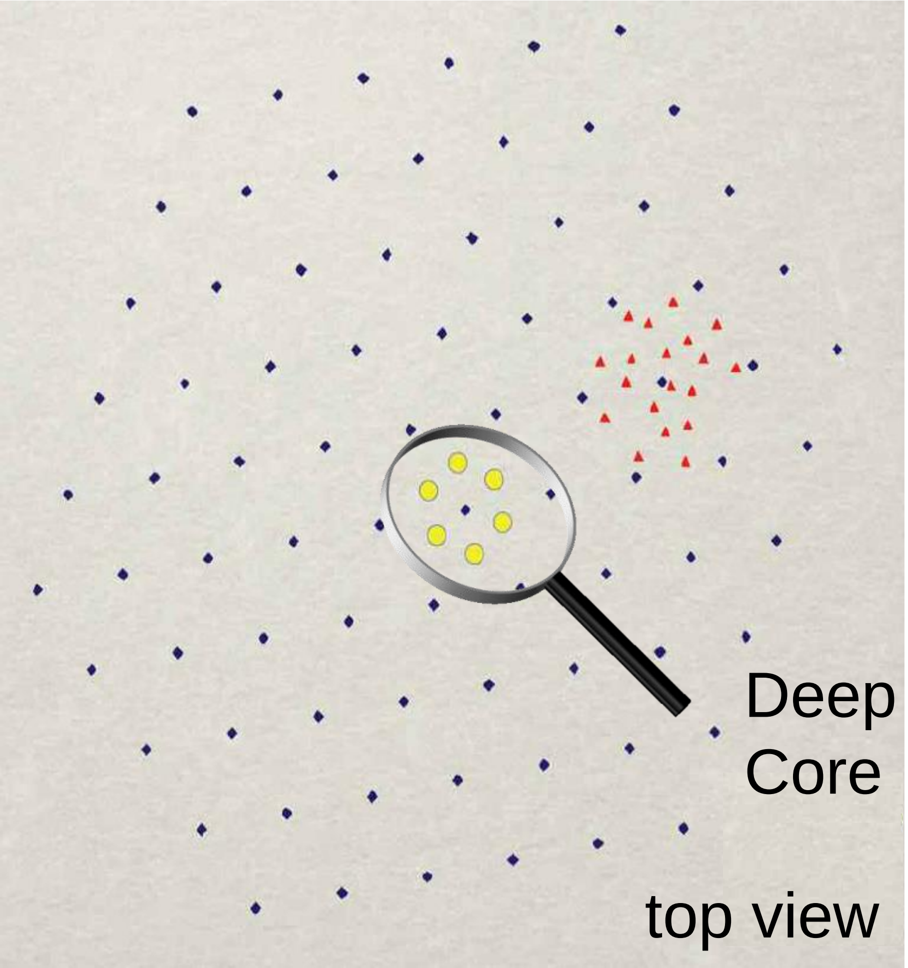


ICECUBE

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 $40\ PMTs$

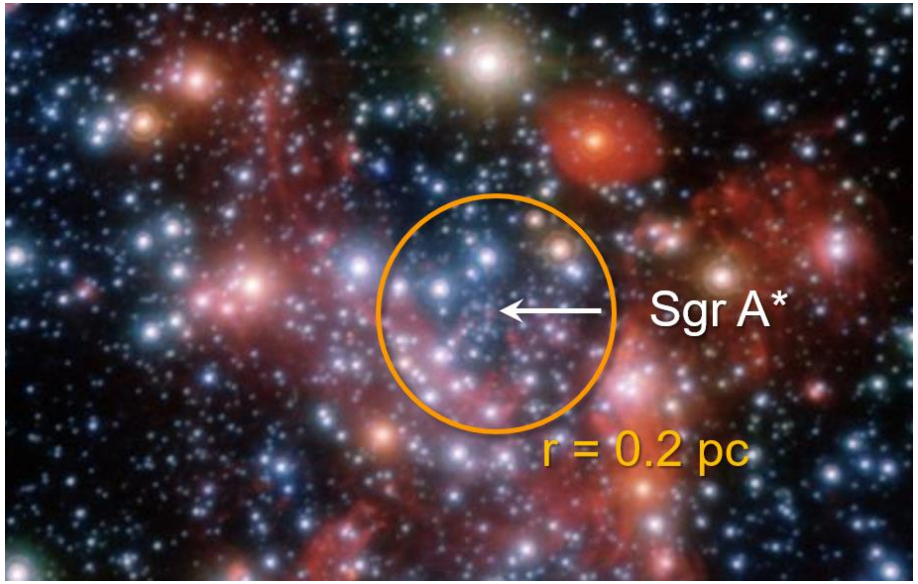
  ⇨ improved sensitivity to detect ν´s from **DMA in the solar core**

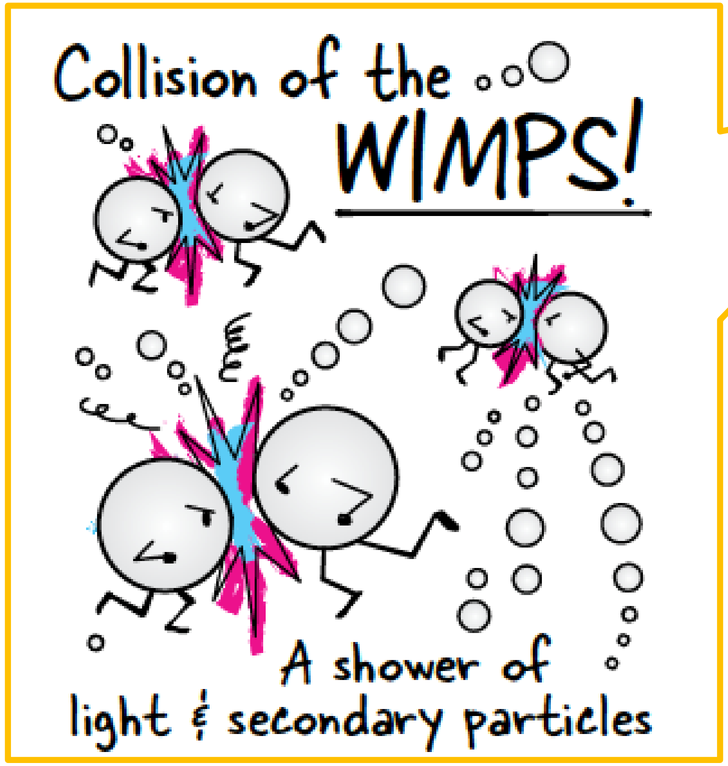
- DMA-search with $\boldsymbol{\nu_\mu}$ with $E(\nu_\mu) = 10\ GeV \ldots 1\ TeV$

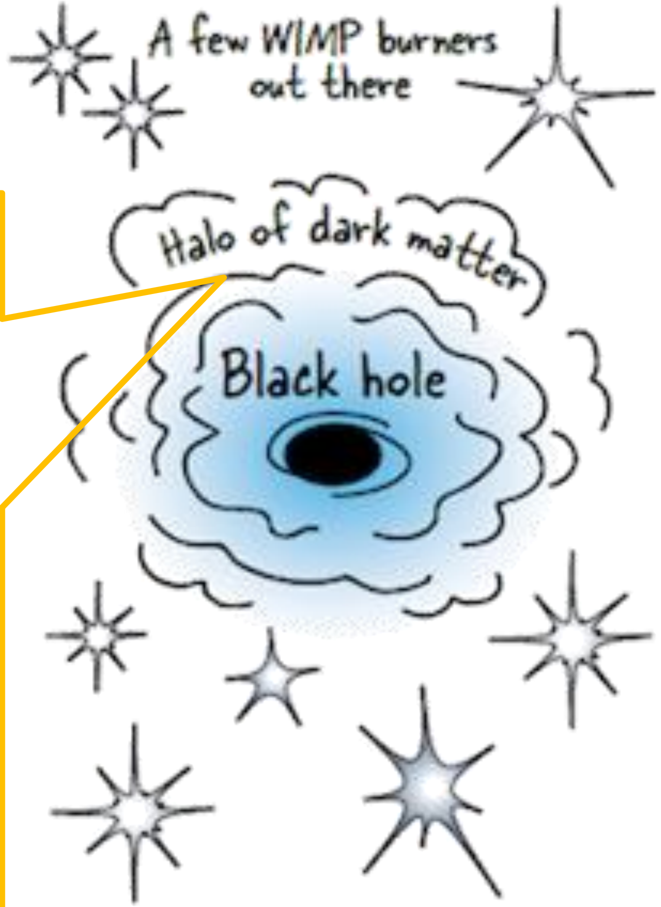
NO SIGNAL

INSERTION: could there be WIMP burning stars?

- **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





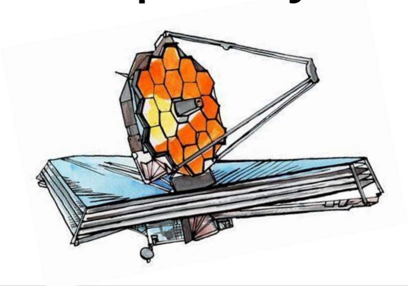


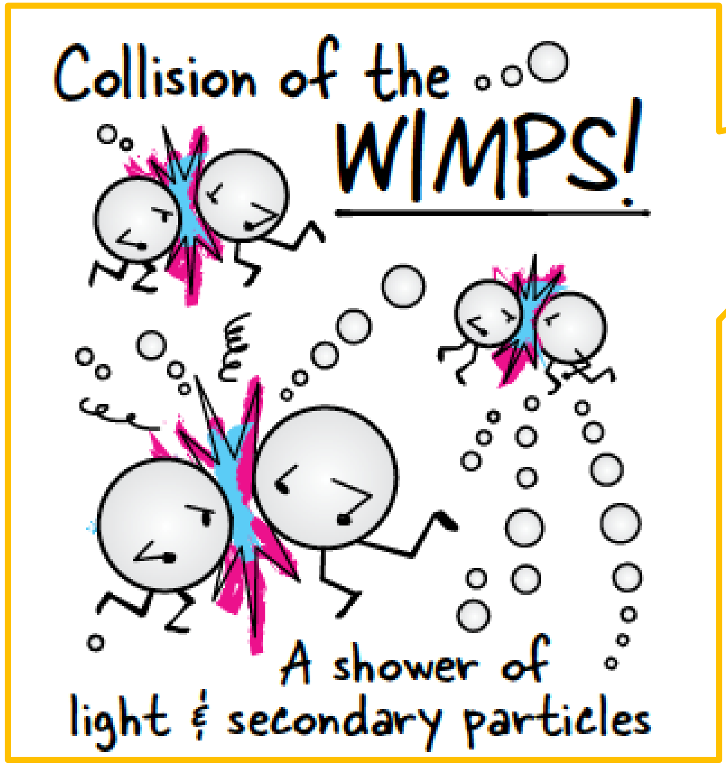
 *Super-Massive Black Hole

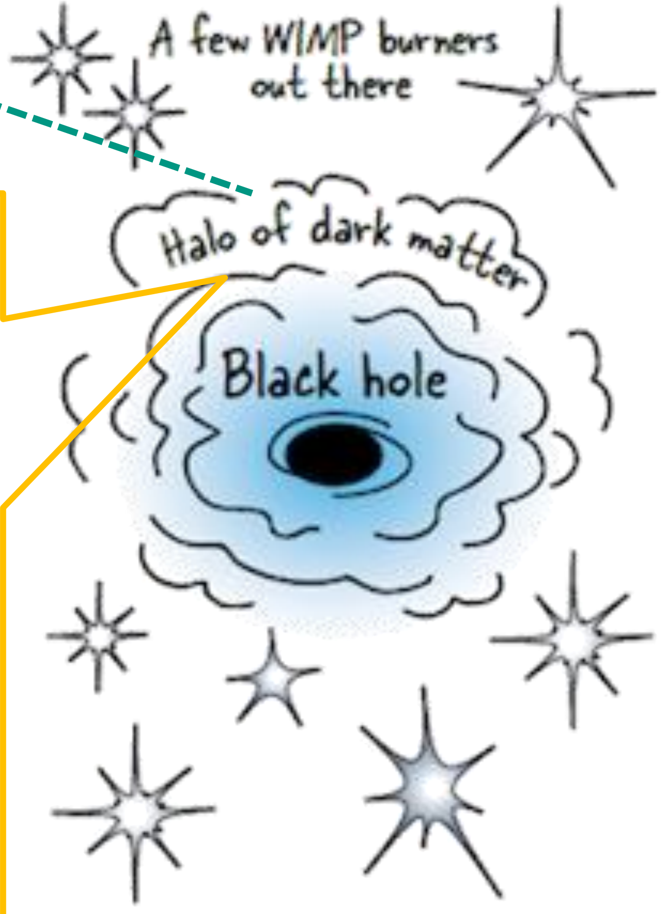
INSERTION: could there be WIMP burning stars?

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

  - local DM-density $\rho_{DM}\,(r < 1\,lyr) > \mathbf{10^9}\ \boldsymbol{g/cm^3}$
  - 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







INSERTION: could there be WIMP burning stars?

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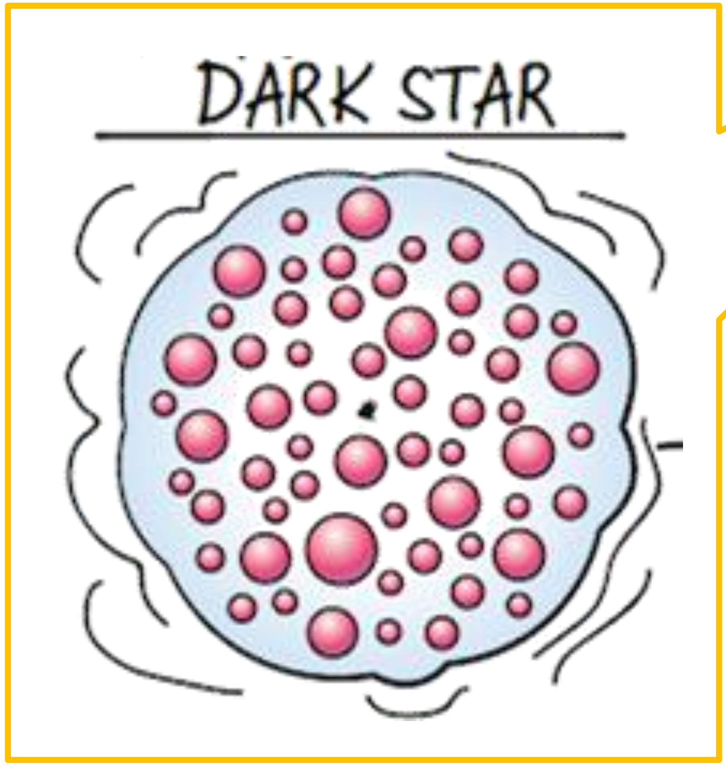
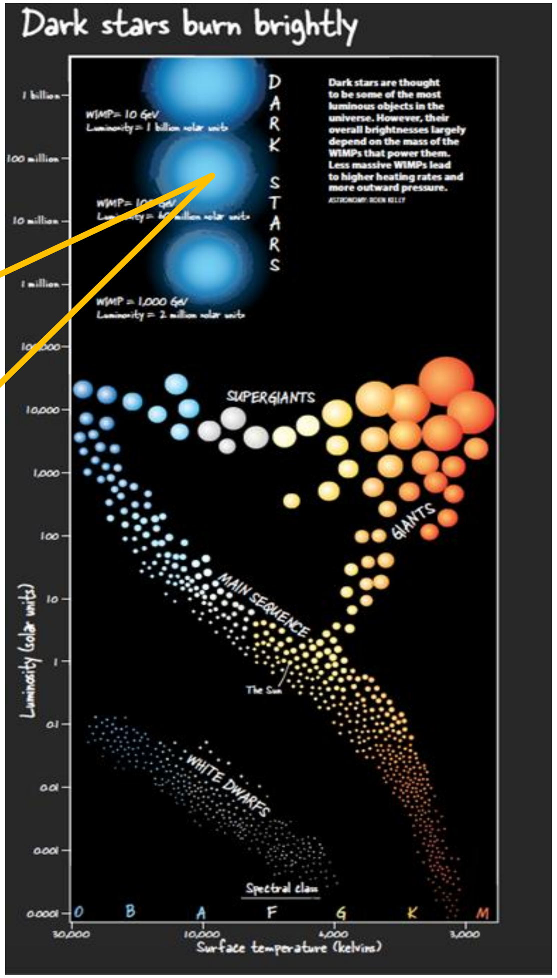
- **Why not settle for a new energy source: burn WIMPs instead of hydrogen!**

  - **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

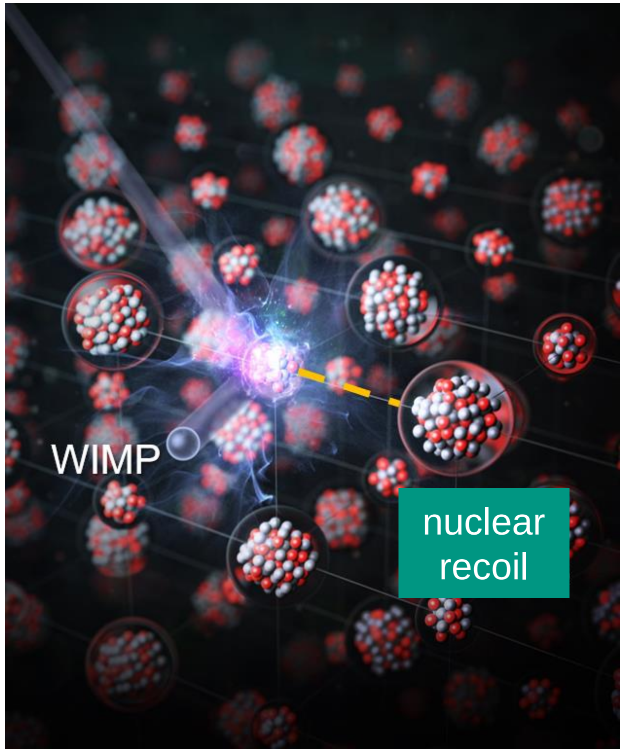




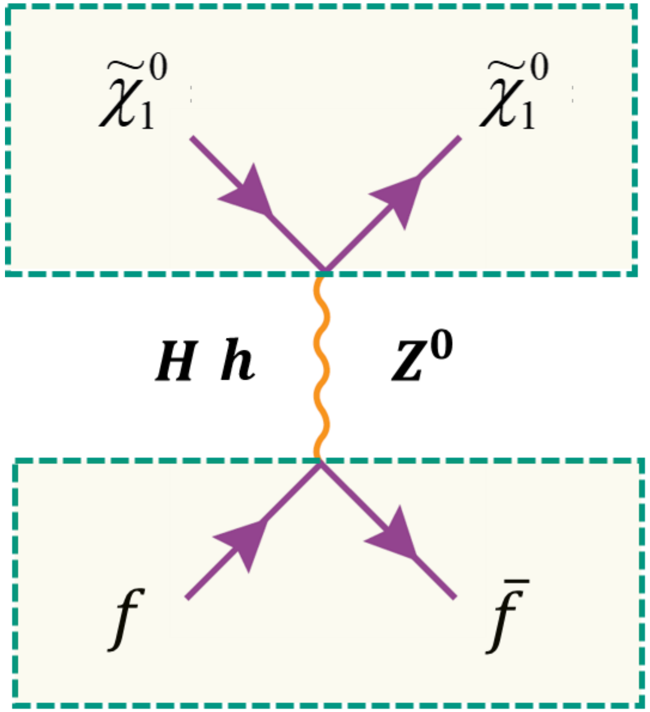
4.5 Direct detection methods for WIMPs

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

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



neutralinos



collision kinematics

galactic halo

f = target nucleus

How to directly detect a WIMP – the basics

- **To estimate the number of our DM-events we need astro- & particle physics:**

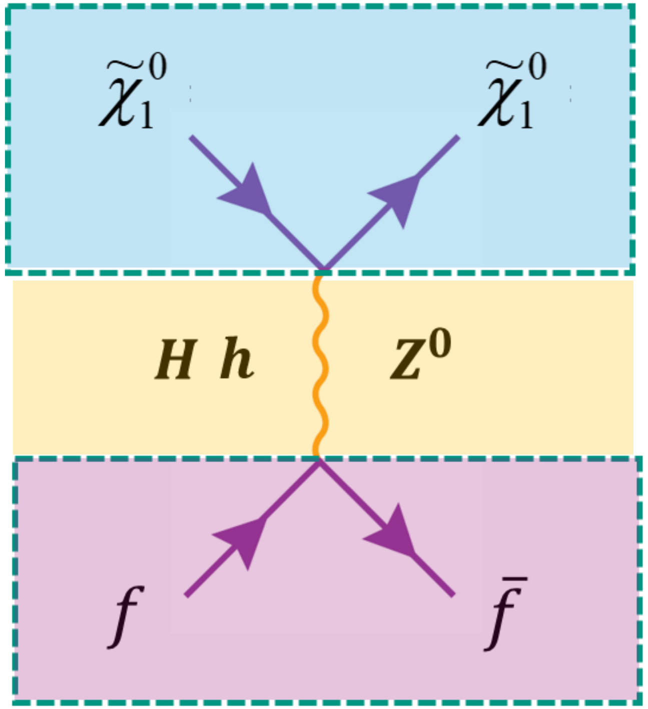
- direct detection is also model-dependent

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

ASTRO-PHYSICS

PARTICLE PHYSICS

neutralinos



collision kinematics

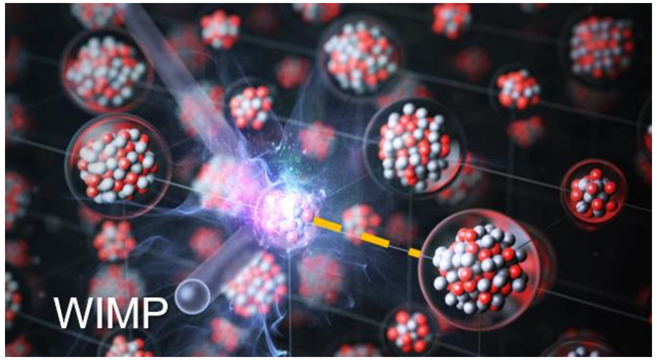
galactic halo

f = target nucleus

How to directly detect a WIMP – the basics

- **To estimate the number of our DM-events we need detector physics:**

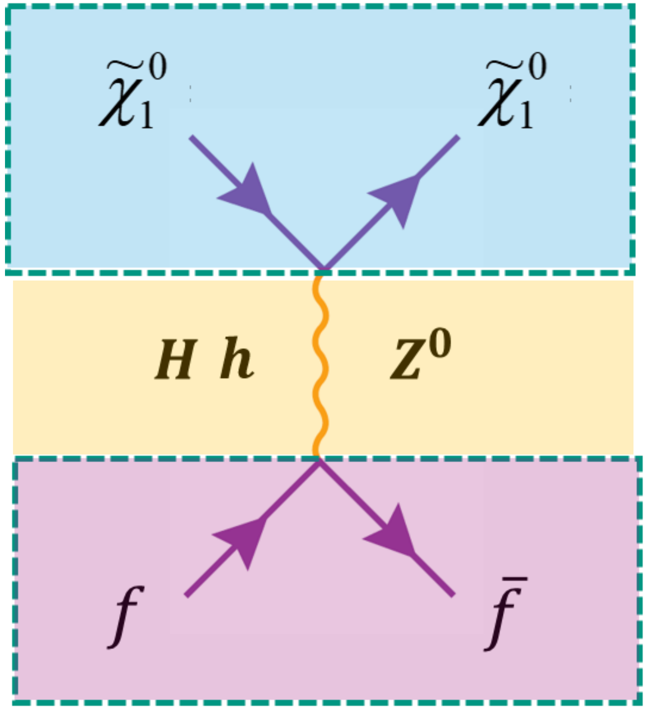
- what is the answer of our solid-state detector to an elastic nuclear recoil?



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

⇨ good knowledge of **detector properties**

neutralinos



galactic halo

DETCTOR PHYSICS

f = target nucleus

collision kinematics

How to directly detect a WIMP – the basics

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

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

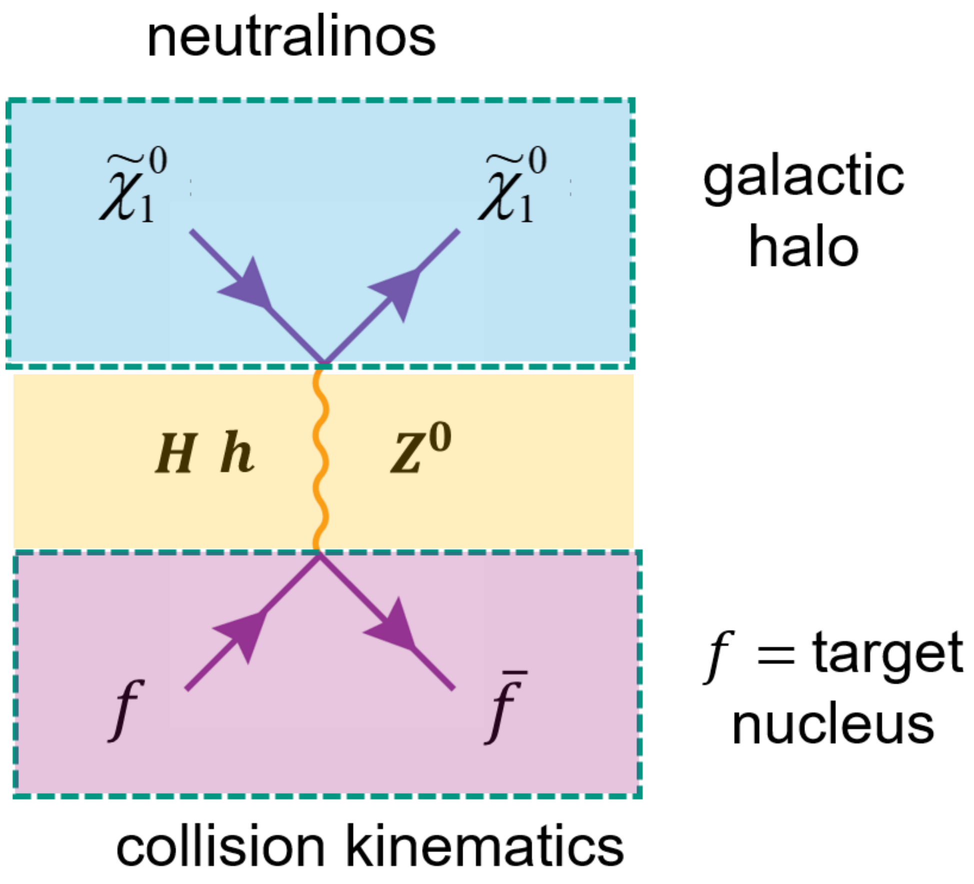
target nuclei

- 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

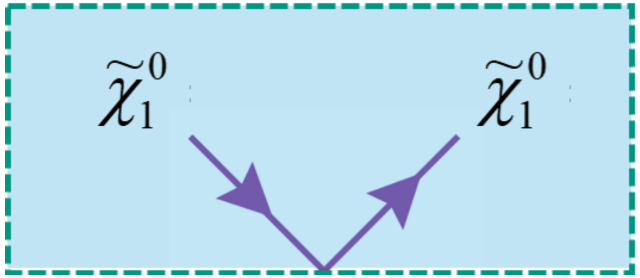
- To estimate the **number R** of our **DM-events** we bring all factors together:

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

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

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

neutralinos



galactic halo

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

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

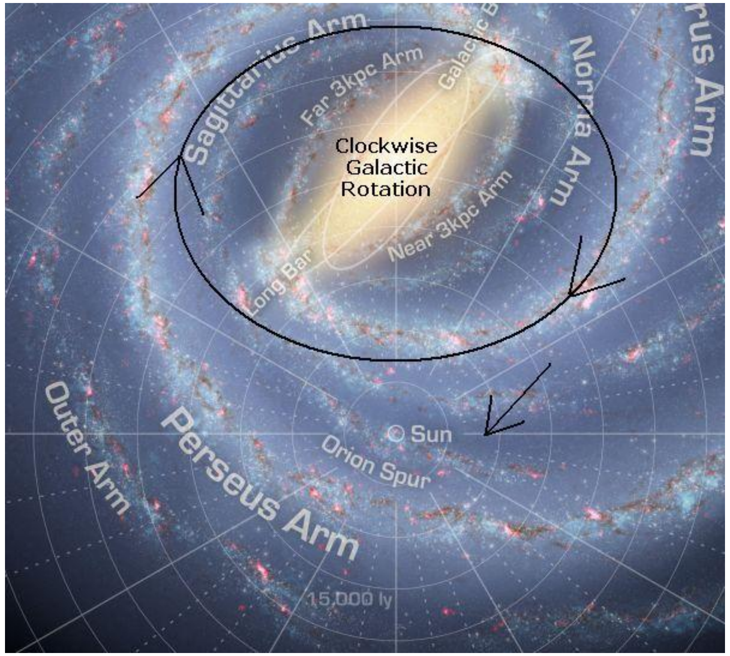
$$\approx 80\,000\ cm^{-2} s^{-1}$$

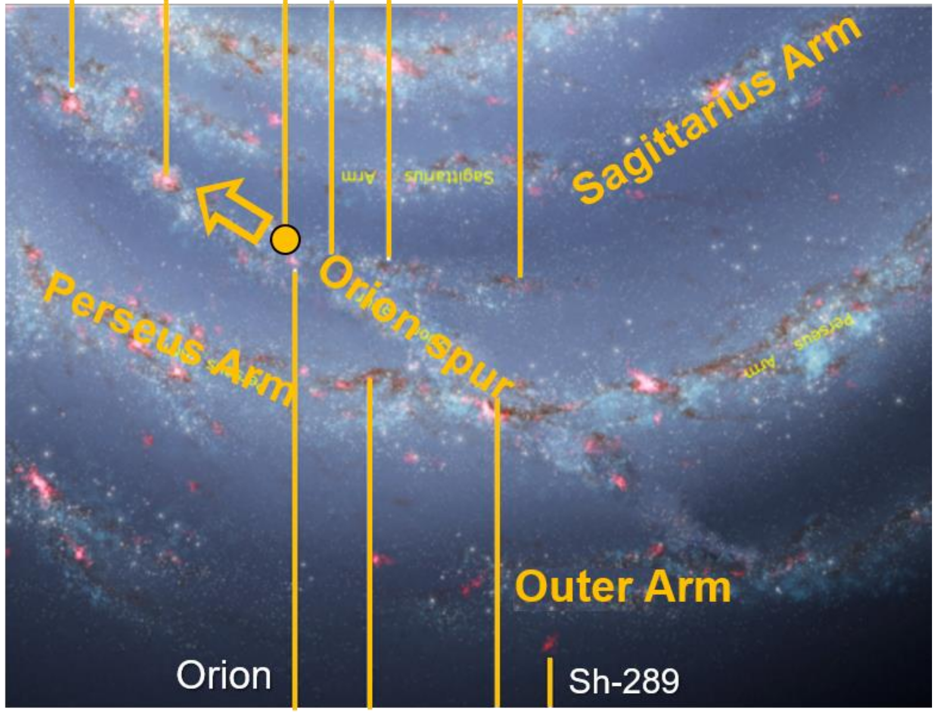
$$\langle v \rangle = 270\ km\ s^{-1}$$

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 Galactic Center (GC) induces a preferred WIMP direction: the **WIMP wind**

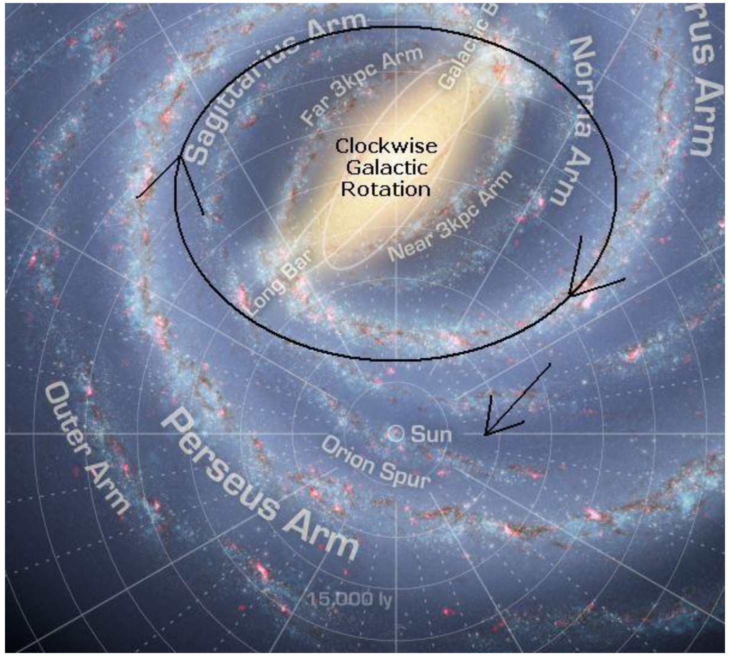


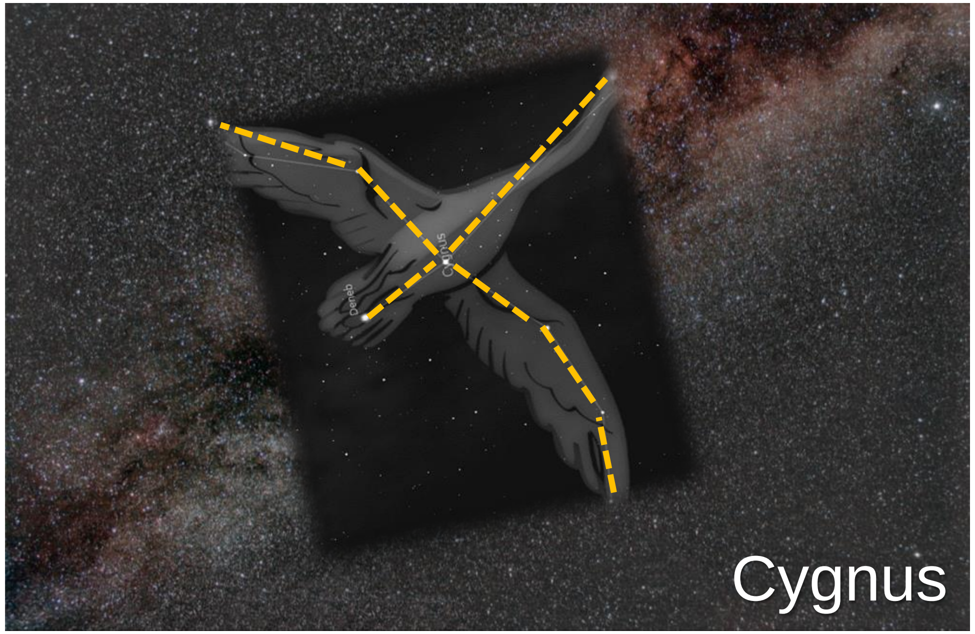


Properties of the WIMP flux: Cygnus region

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

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

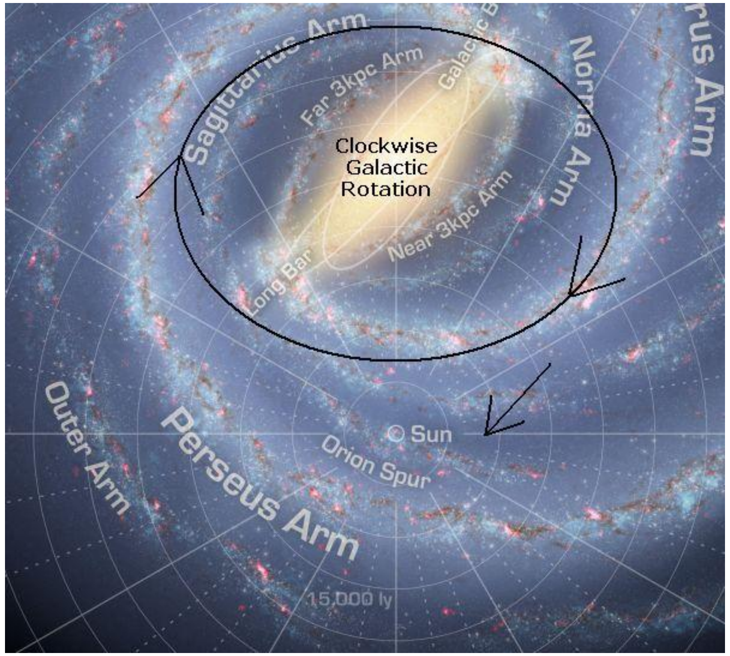


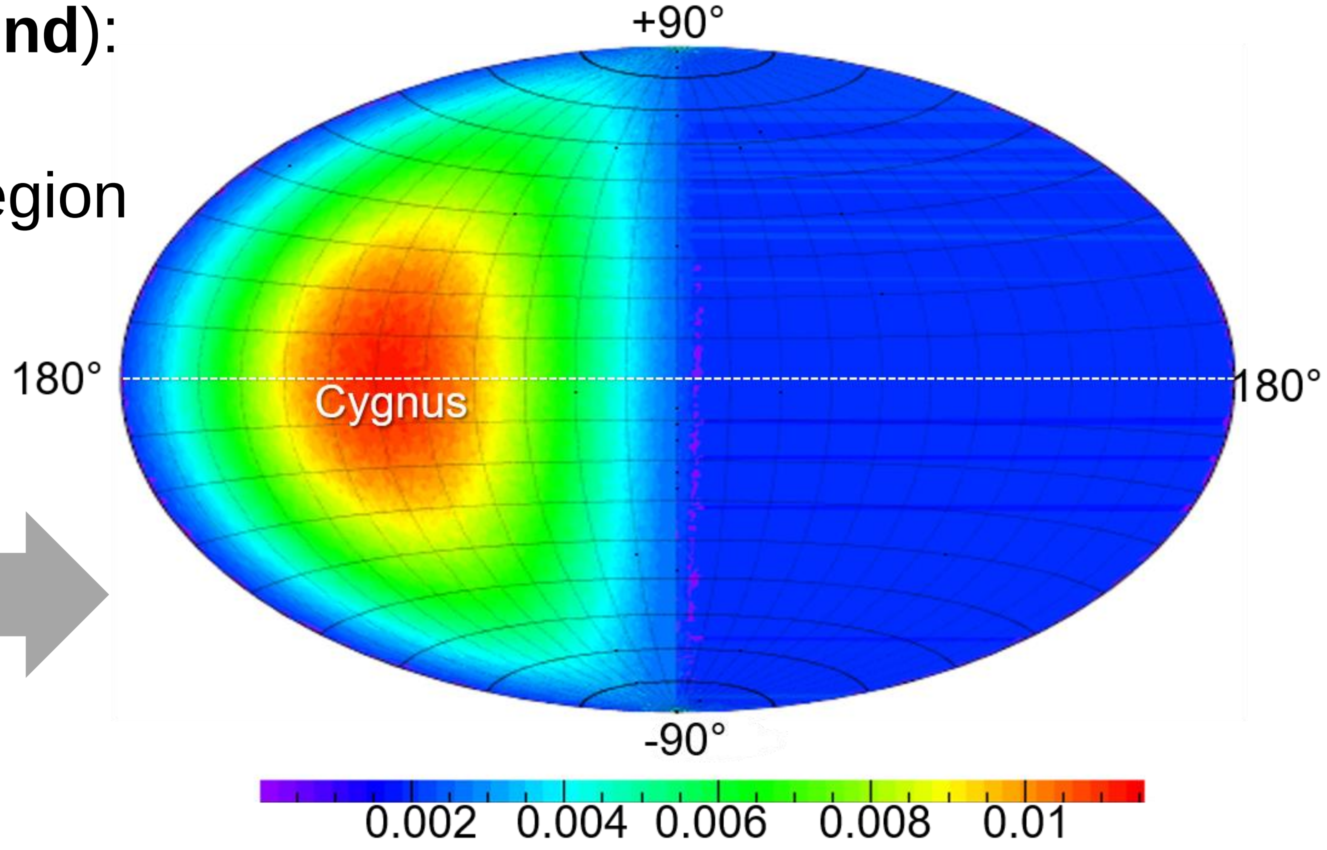


Properties of the WIMP flux: Cygnus region

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

  - preferred WIMP direction (**WIMP wind**): energetic nuclear recoils (here: threshold $= 20\ keV$) from Cygnus region





WIMP rate above 20 keV threshold ($kg^{-1}\ d^{-1} sr^{-1}$)

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

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

A)
1 WIMP
per coffee cup

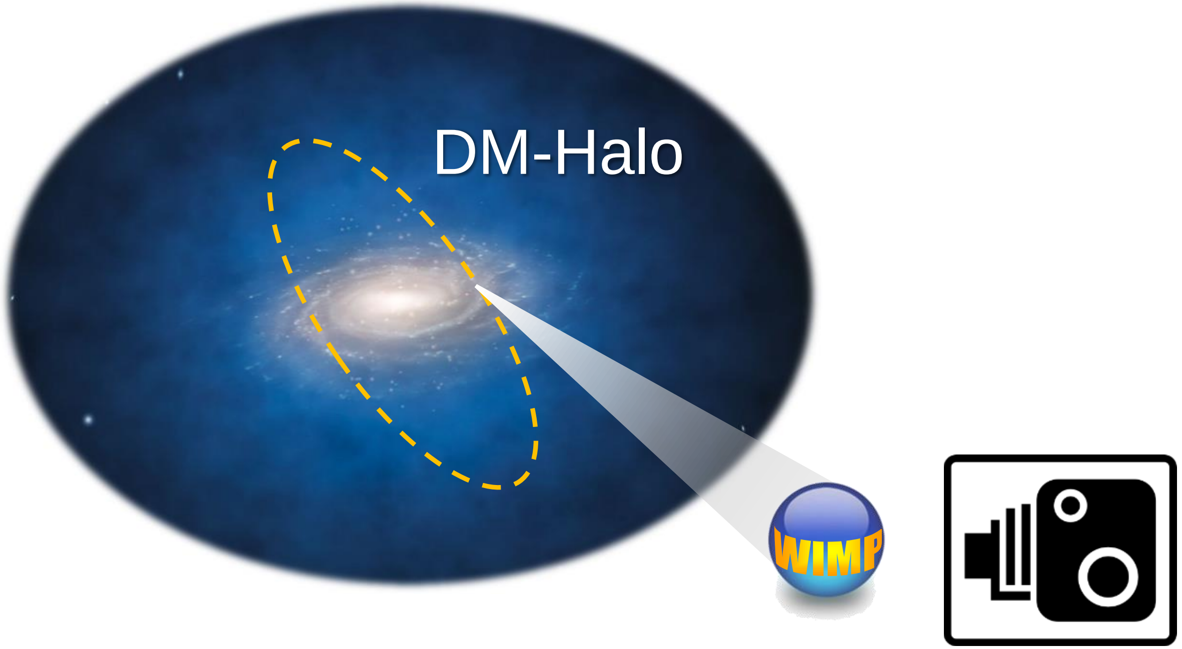
$$\rho_{CDM} = 0.3\ GeV\ cm^{-3}$$

B)
2 squirrels (777 g)
over Earth volume

Properties of the galactic WIMP halo

- **The galactic DM-halo: what is its shape, what is the WIMP velocity profile?**

  - no large-scale rotation of entire halo around the center of the galaxy
  - each WIMP follows individual Kepler orbit around the galactic center
  - from this a specific WIMP velocity profile $f(v)$ for varius **halo radii** $\boldsymbol{r}$ can be calculated
  - **shape:** we expect a tri-axial ellipsoid
  - DM-halo properties can be traced by stellar velocity profile*

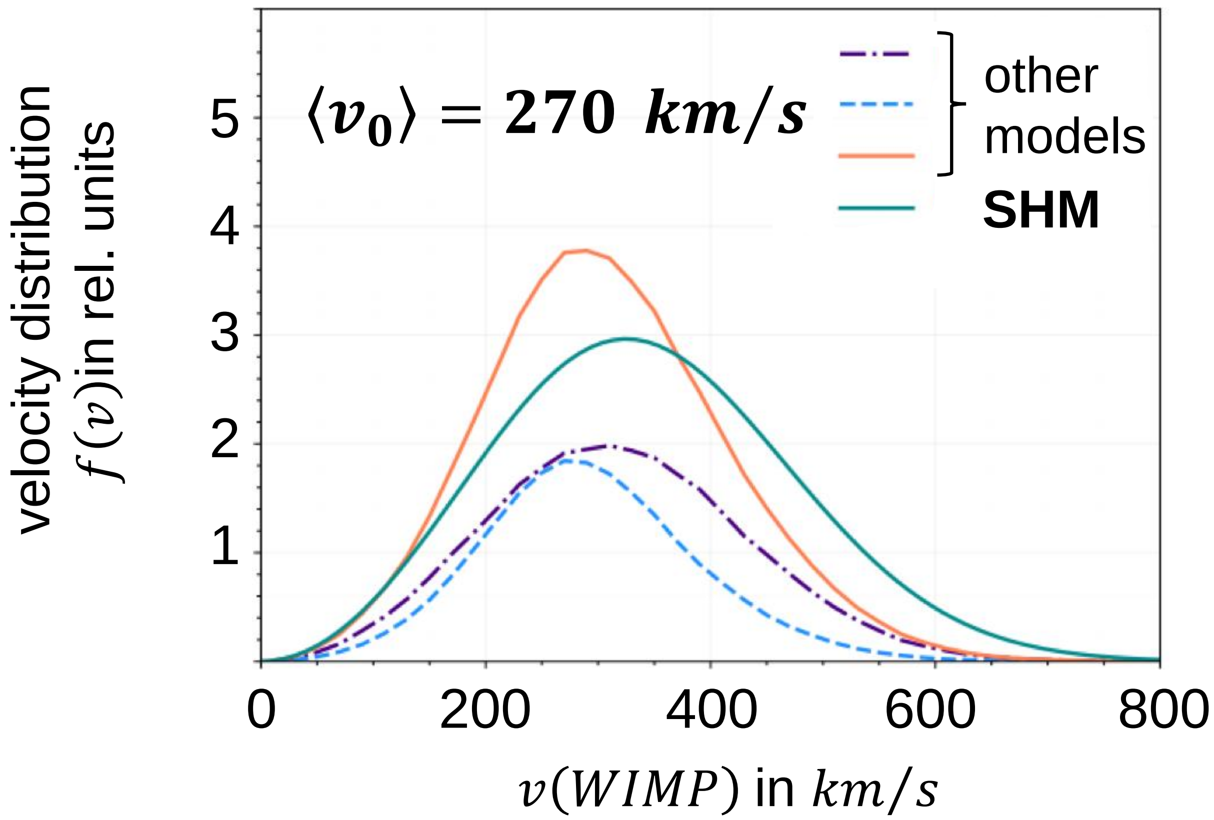


*see lecture #12 p. 42

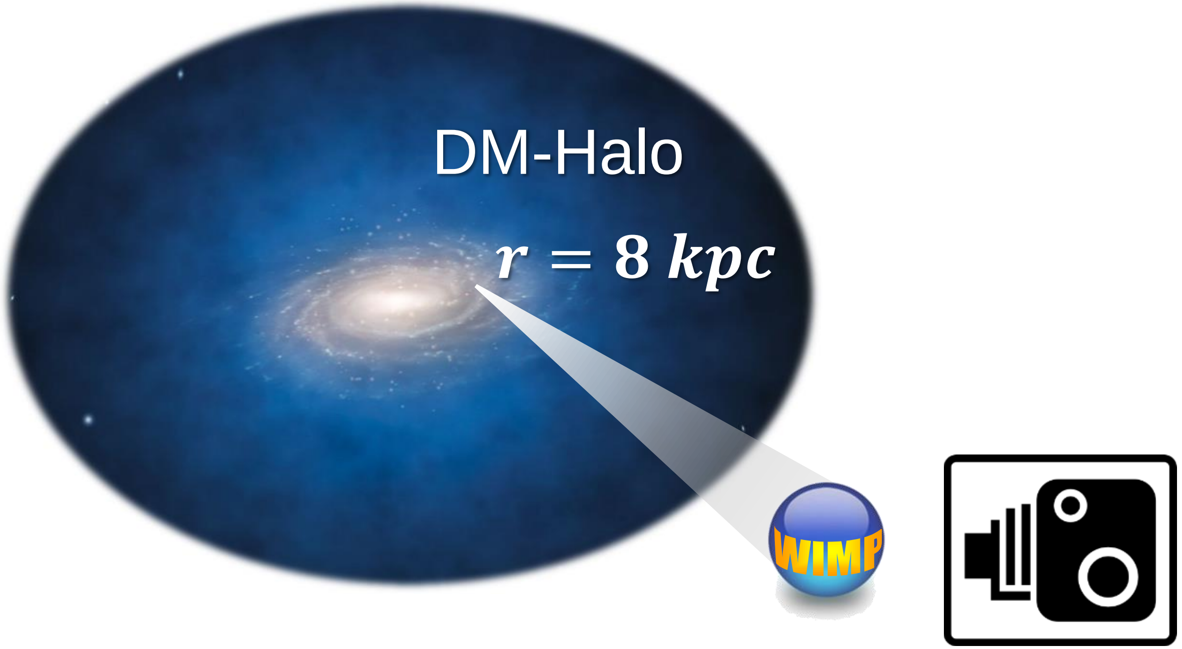
galactic WIMP halo: velocity profile

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

- **S**tandard **H**alo **M**odel (**SHM**) compared to other theoretical calculations:



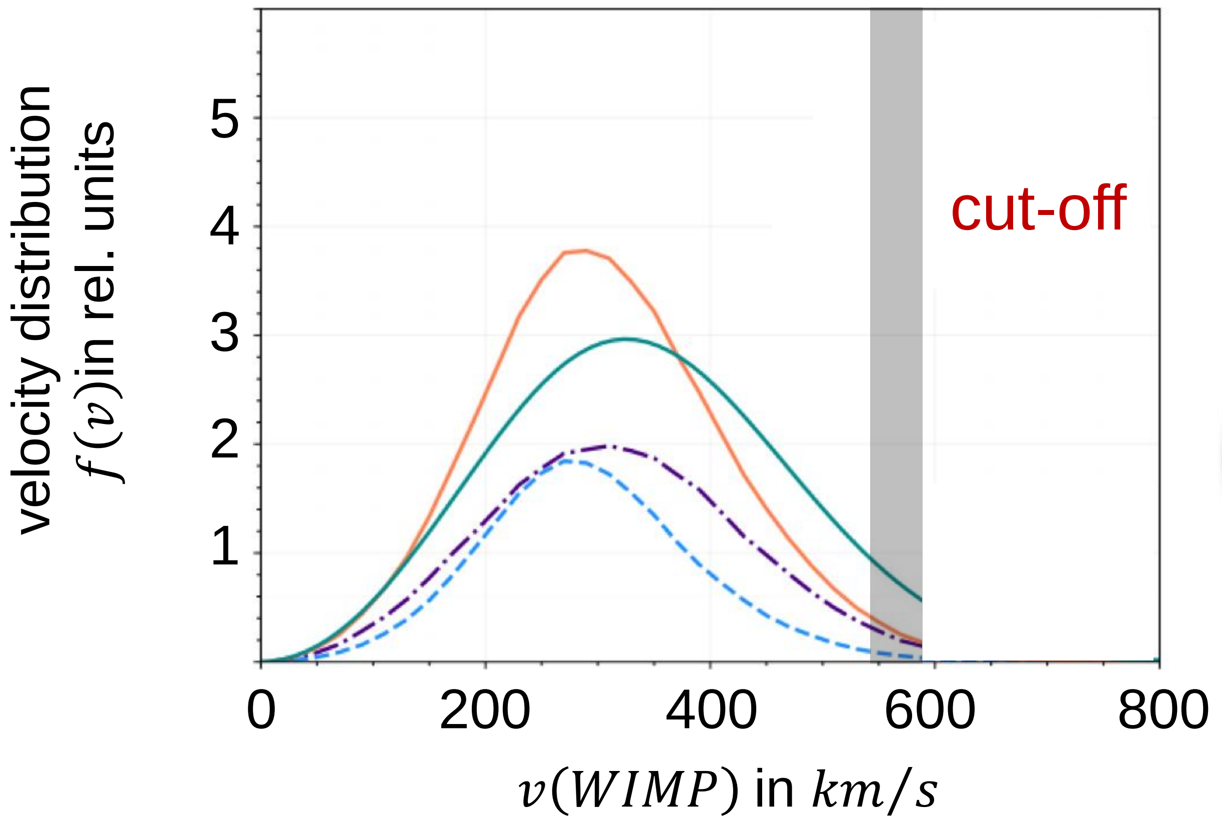
small differences remain

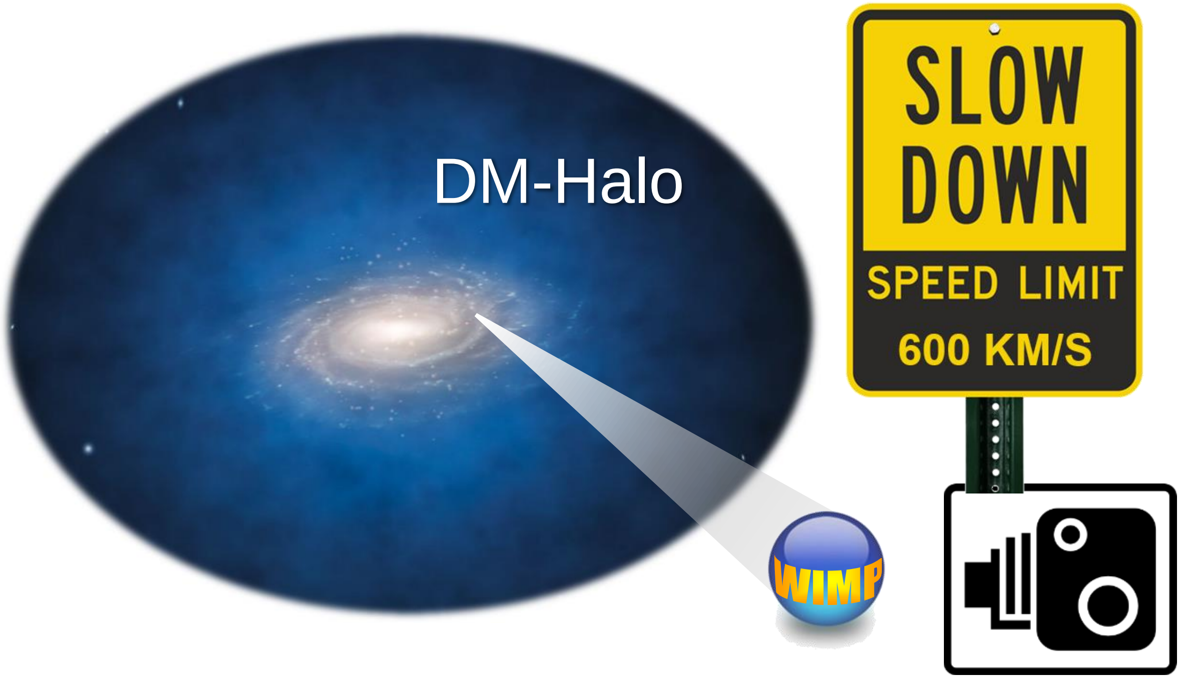


Properties of the galactic WIMP halo

- **the WIMP velocity profile at our 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



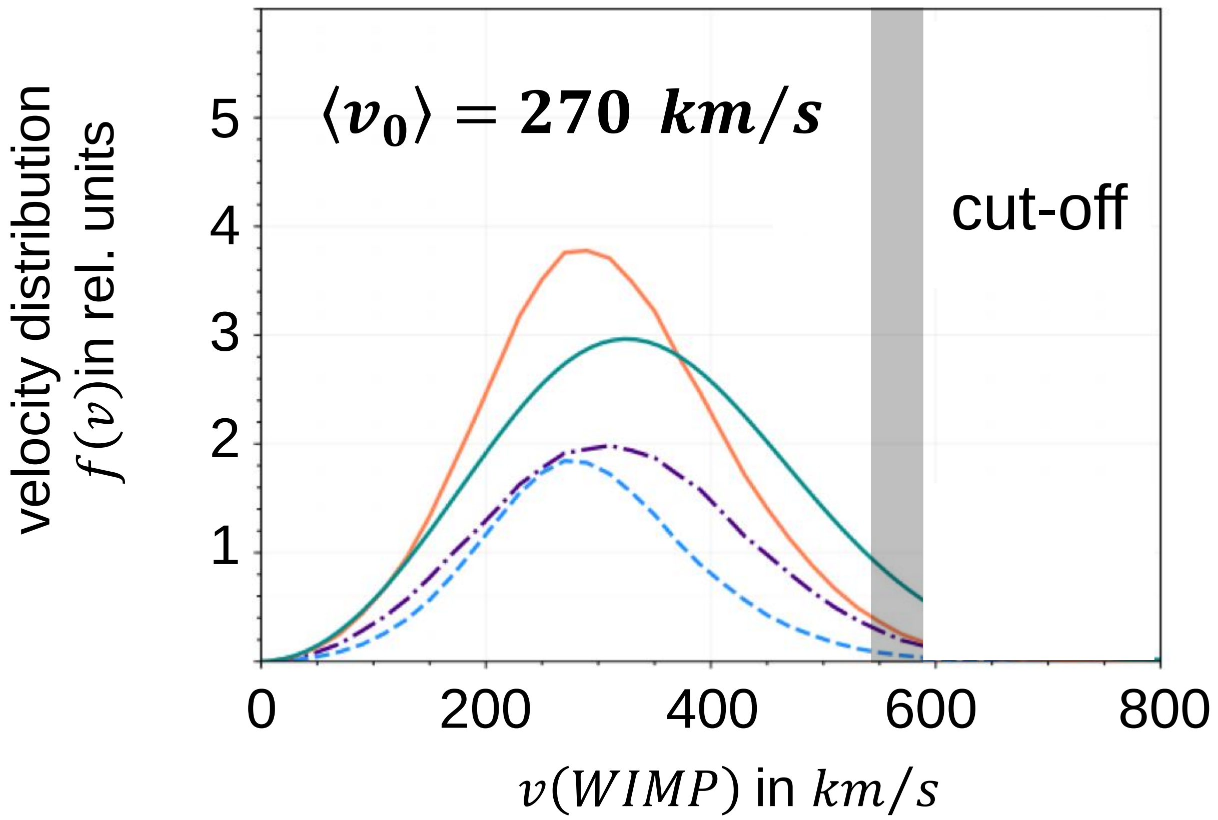


Properties of the galactic WIMP halo: implications

Karlsruhe Institute of Technology

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

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

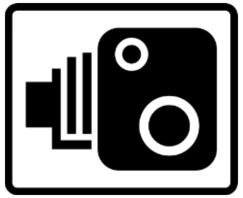


- **kinetic energy E_{kin} of WIMPs**:

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

$100\ GeV$ $\quad$ $\mathbf{10^{-6}}$

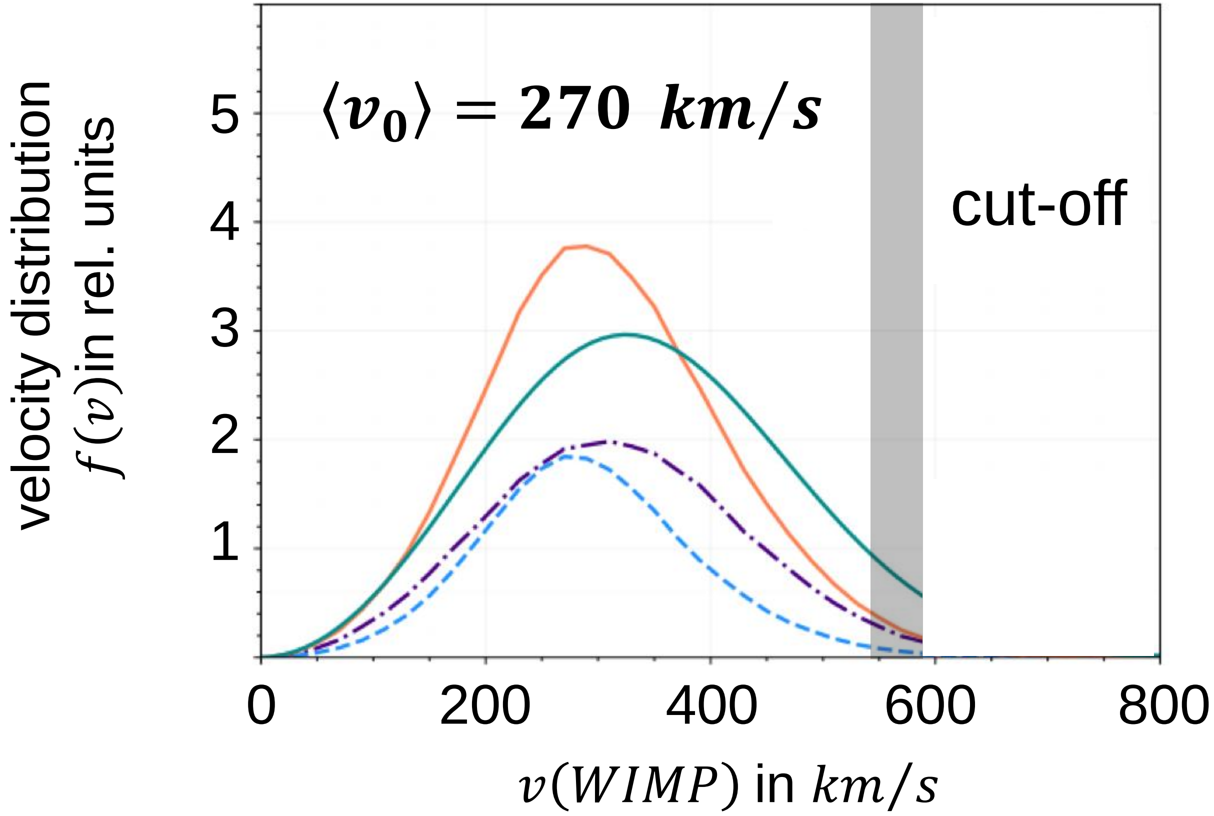
$$\boxed{E_{kin} \approx 100\ keV}$$

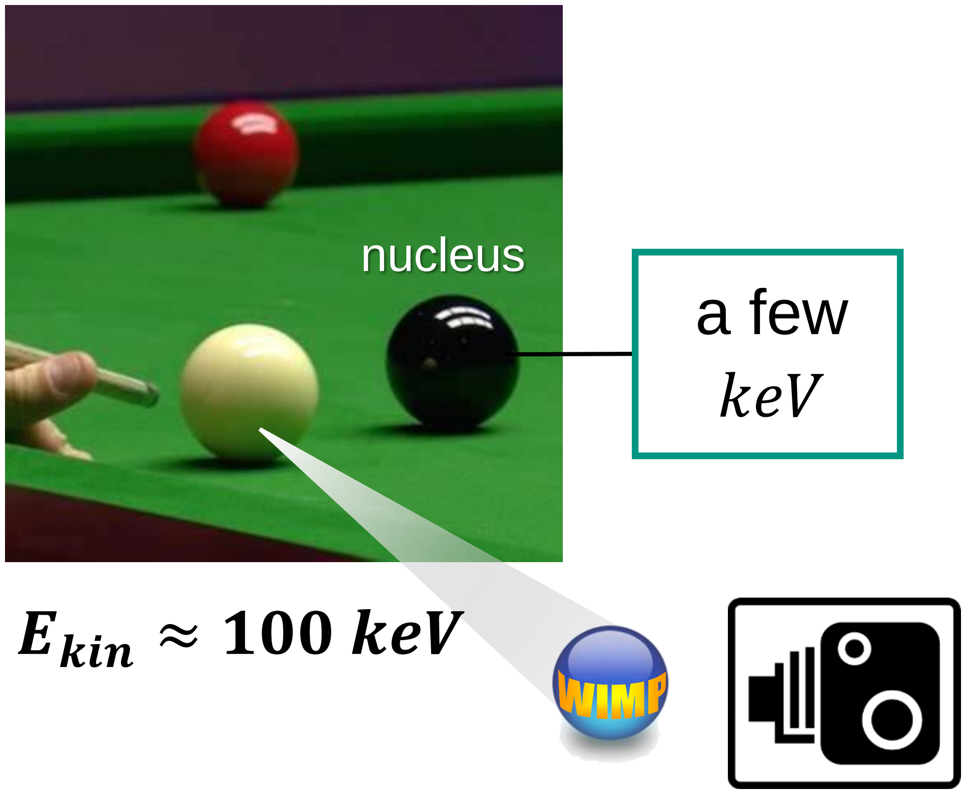


Properties of the galactic WIMP halo: implications

- **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)





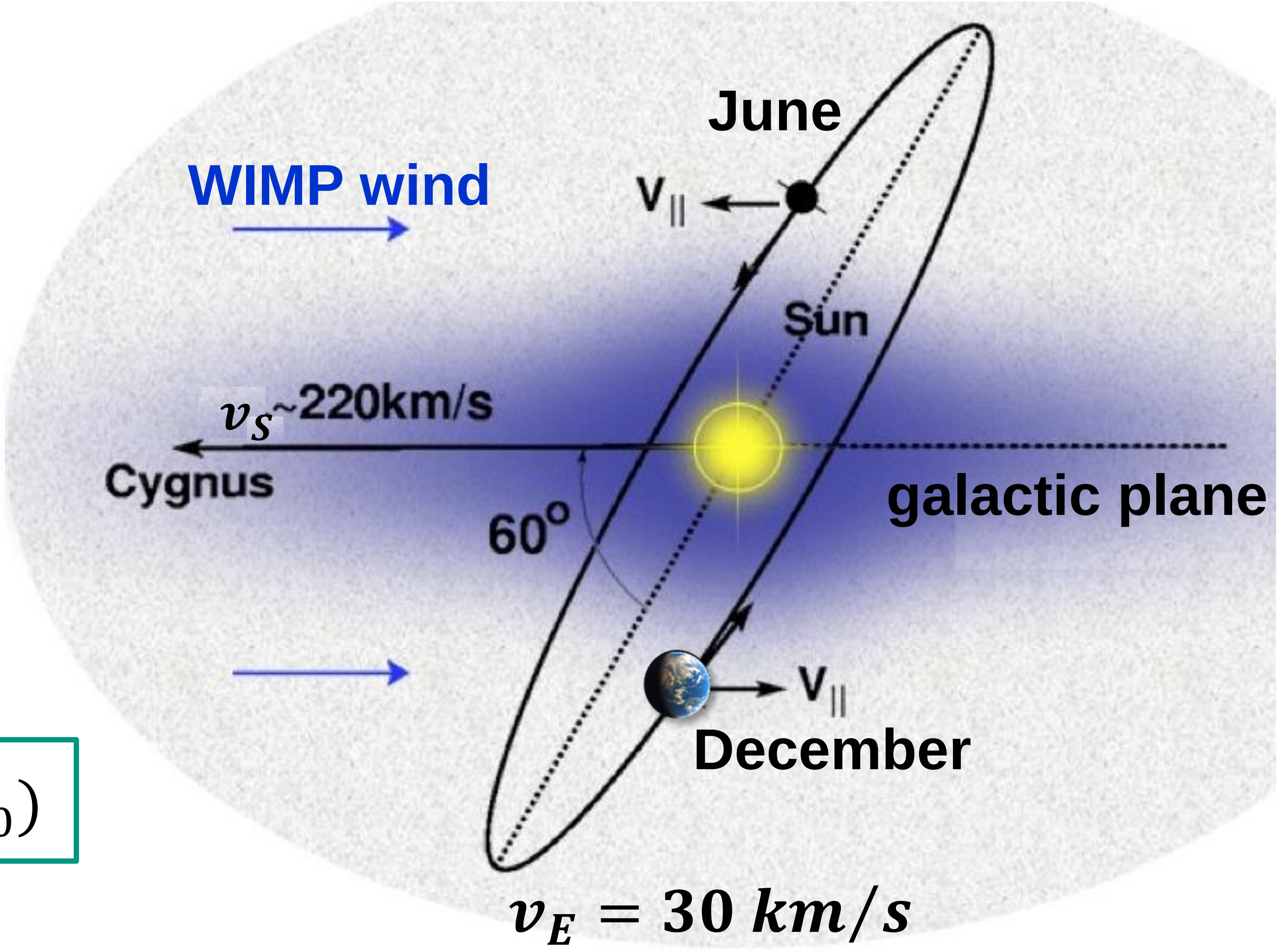
Direct detection of WIMPs: modulation of flux

- **Earth´s rotation around Sun casues 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 (for the local coordinate system of the DM-detector) in the following time dependence:

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



Direct detection of WIMPs: modulation of flux

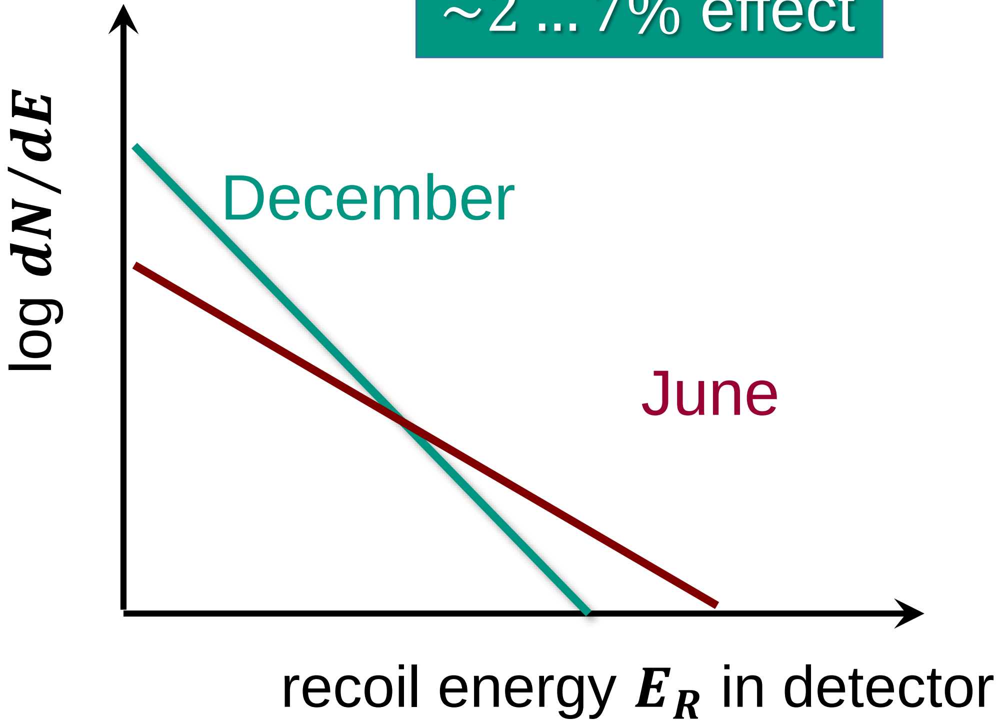
- Earth´s rotation around Sun casues a (smaller) variation of the WIMP flux

- phase: $t_0 =$ June, 2

- length of period: $\boldsymbol{T = 1\ yr}$

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

~2 ... 7% effect



Direct detection of WIMPs: interactions

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

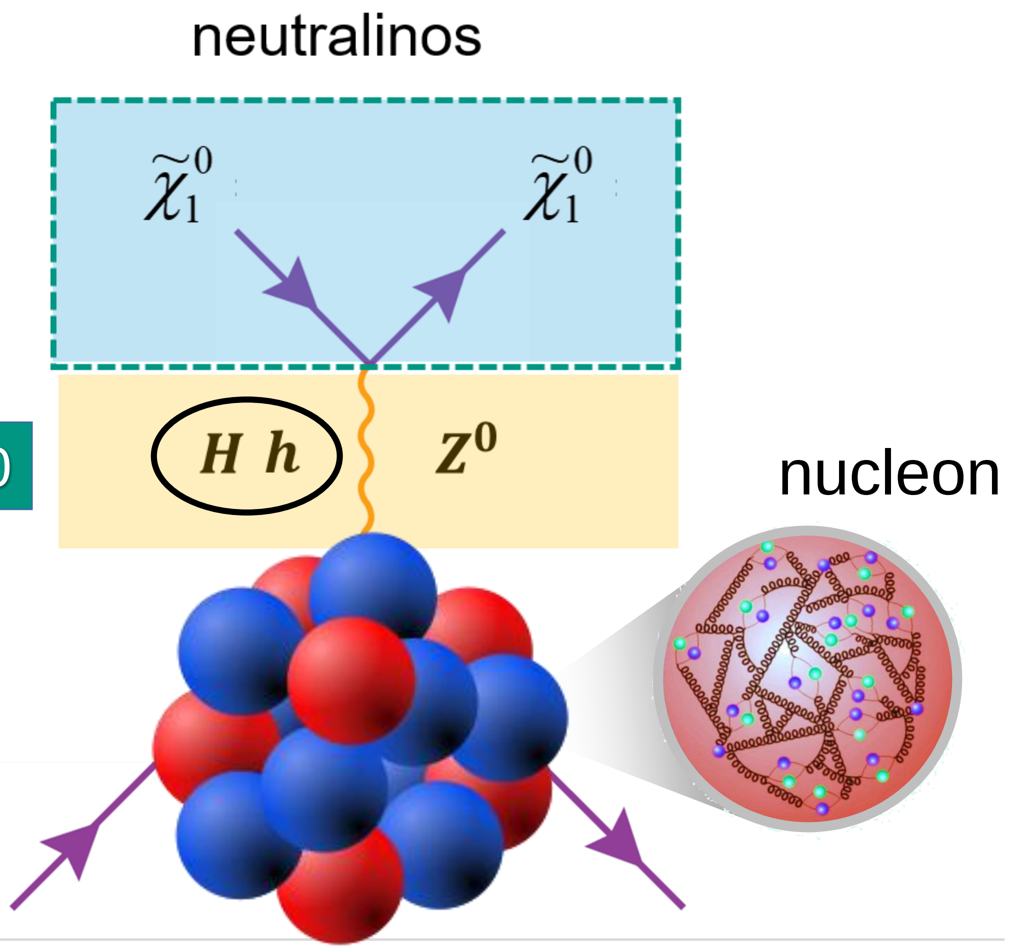
  - **scalar** interaction via light, heavy Higgs $\boldsymbol{H, h}$

  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, and to massless gluons (via loops)

s = 0



Direct detection of WIMPs: interactions

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

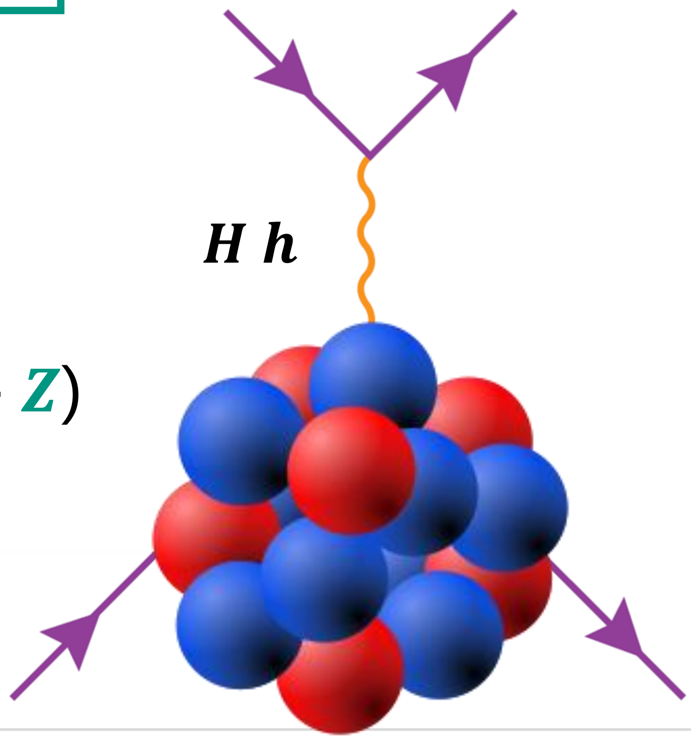
$$\boxed{\frac{d\sigma_{SI}}{dq^2} \sim \frac{1}{\pi \cdot \mathrm{v}^2} \cdot \left[f_p \cdot Z + f_n \cdot (A - Z) \right]^2 \cdot F(q^2)}$$

q^2: momentum transfer

v: WIMP velocity

A , Z : nucleon number A
proton number Z neutron number (A - Z)

f_p , f_n: spin-independent WIMP-couplings
to protons, neutrons ($SUSY$ model)
as $m_p \approx m_n$ we excpect $f_p = f_n$



Direct detection of WIMPs: interactions

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

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

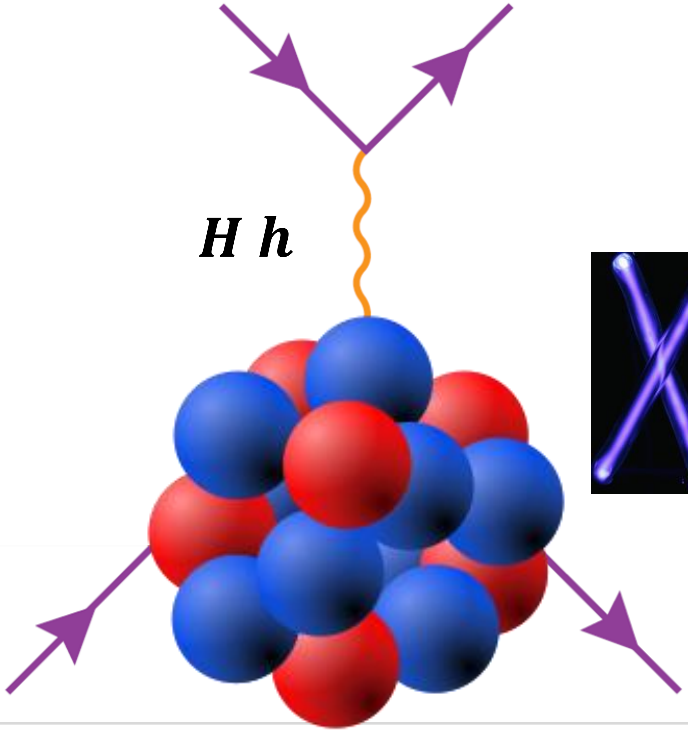
a large nucleus with $\boldsymbol{A > 100}$ is very helpful

for $f_p = f_n$

scattering amplitudes off all nucleons add coherently

L. Hofstadter

Xenon is best:
$A \approx 130$



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

Karlsruhe Institute of Technology

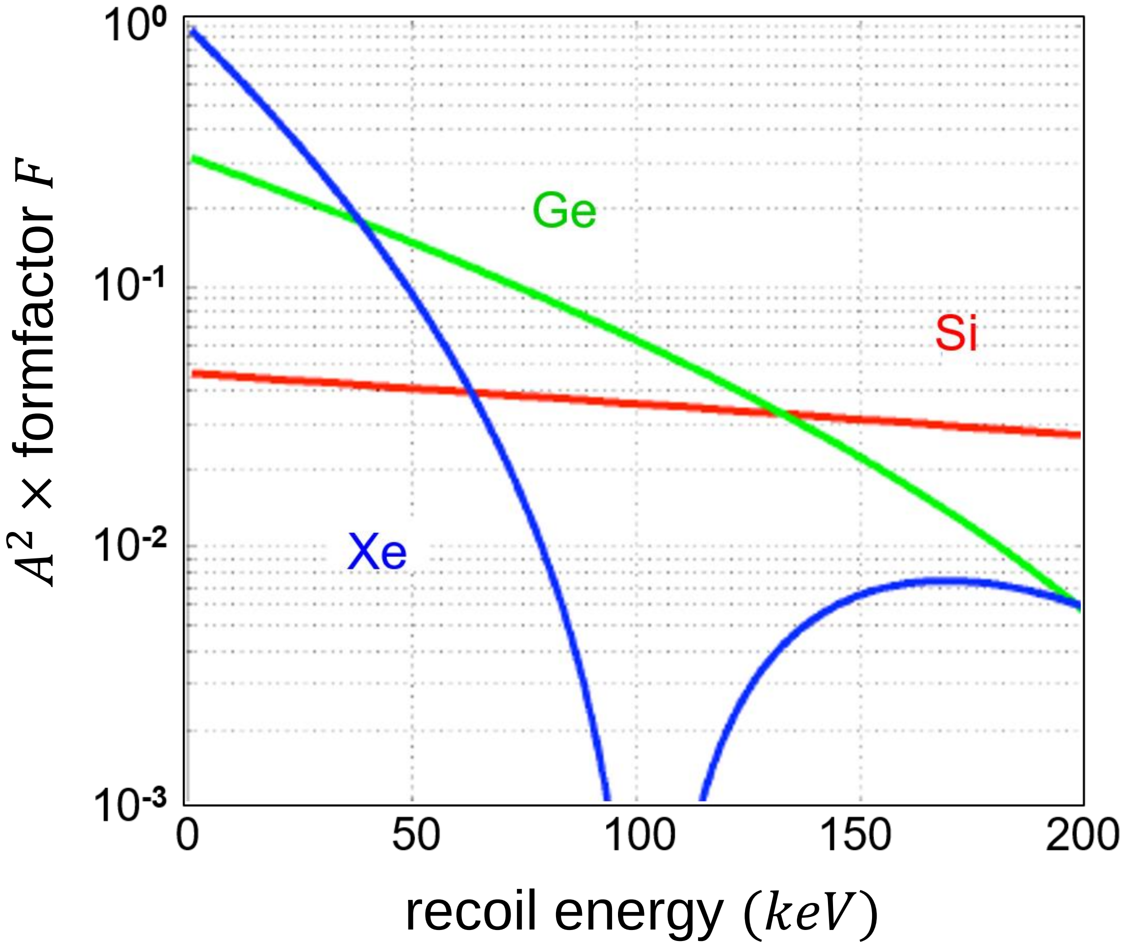
- **Neutralino interactions: the important nuclear form factor $F(q^2)$**

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

- 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 $F(q^2)$

Karlsruhe Institute of Technology

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

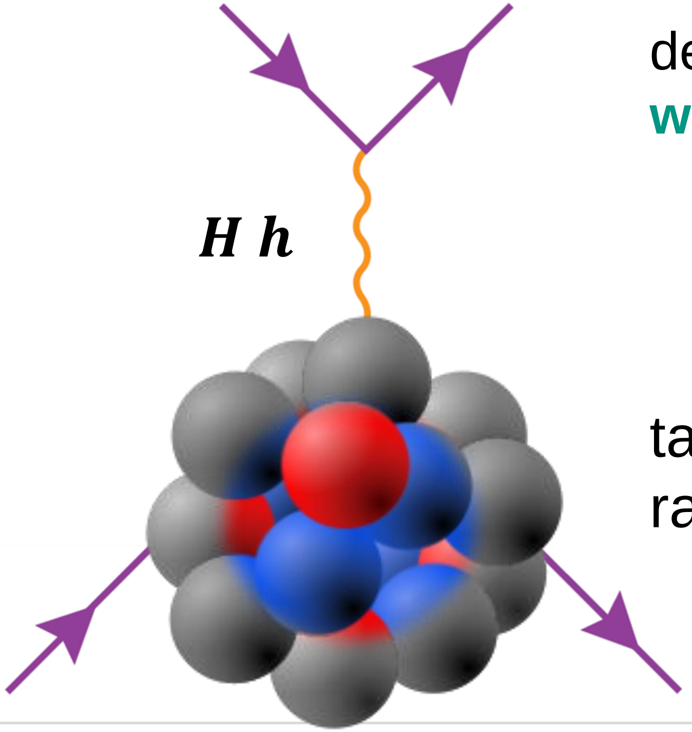
$$\boxed{\frac{d\sigma_{SI}}{dq^2} \sim A^2 \cdot F(q^2)}$$

Louis de Broglie

de Broglie
wavelength λ

- scattering amplitudes only add ***coherently***,
if the following condition is fulfilled:

$$\boxed{q \cdot R_i \ll 1}$$ (typcially only for $A < 50$)



target with
radius R_i

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

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