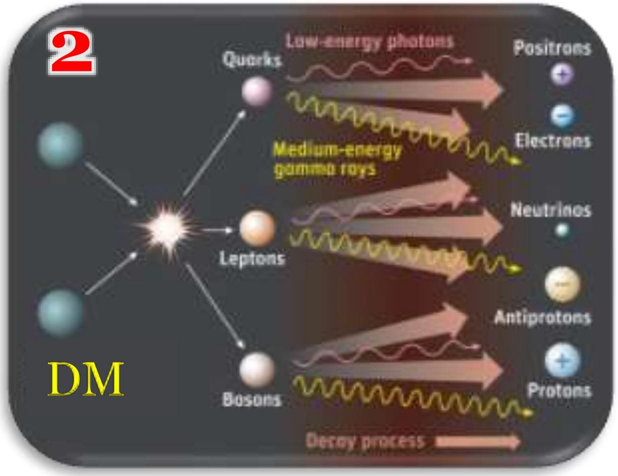
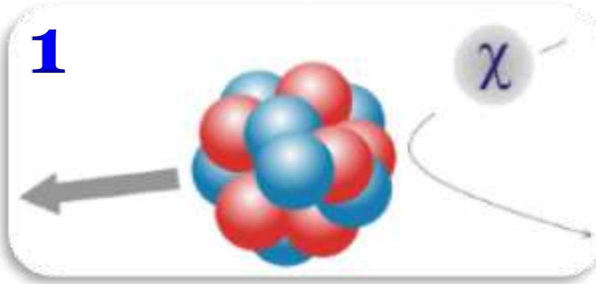
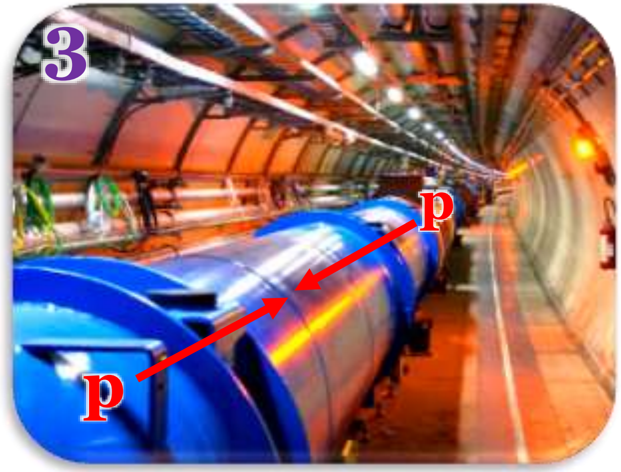
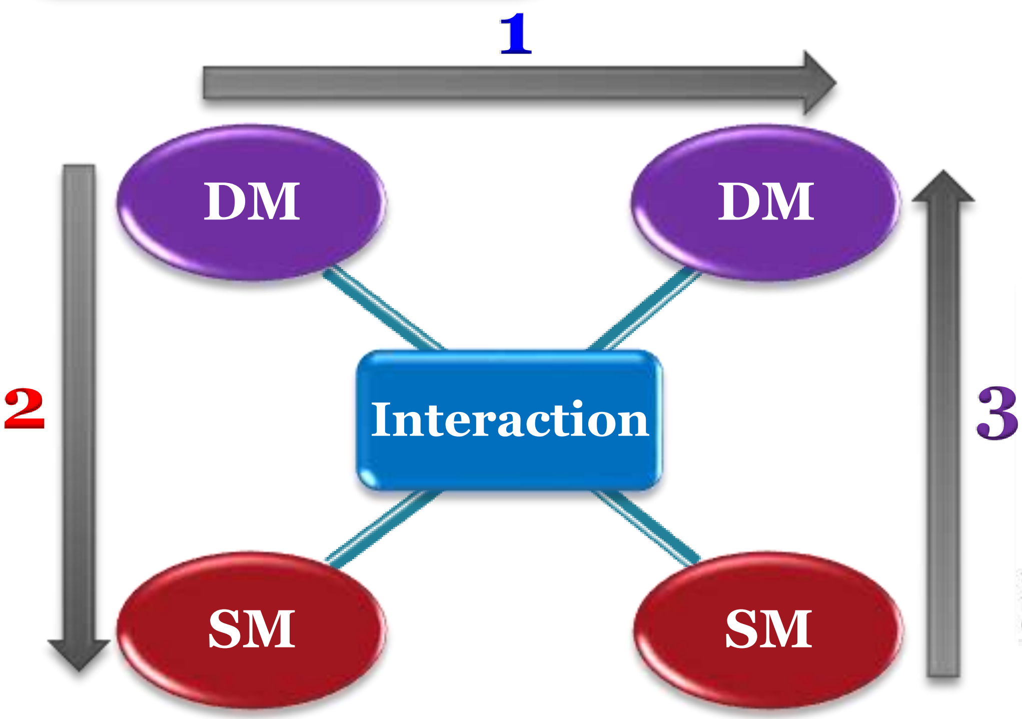
Conventional DM Search Strategies

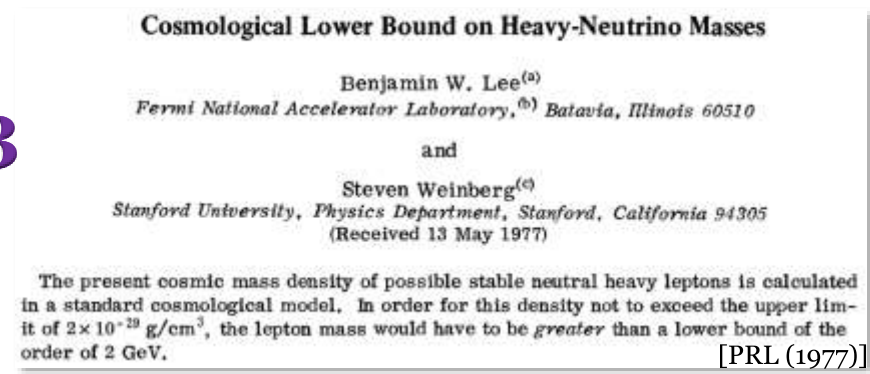








- ❖ Based on the WIMP paradigm.



Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[(a)]
Fermi National Accelerator Laboratory,[(b)] *Batavia, Illinois 60510*

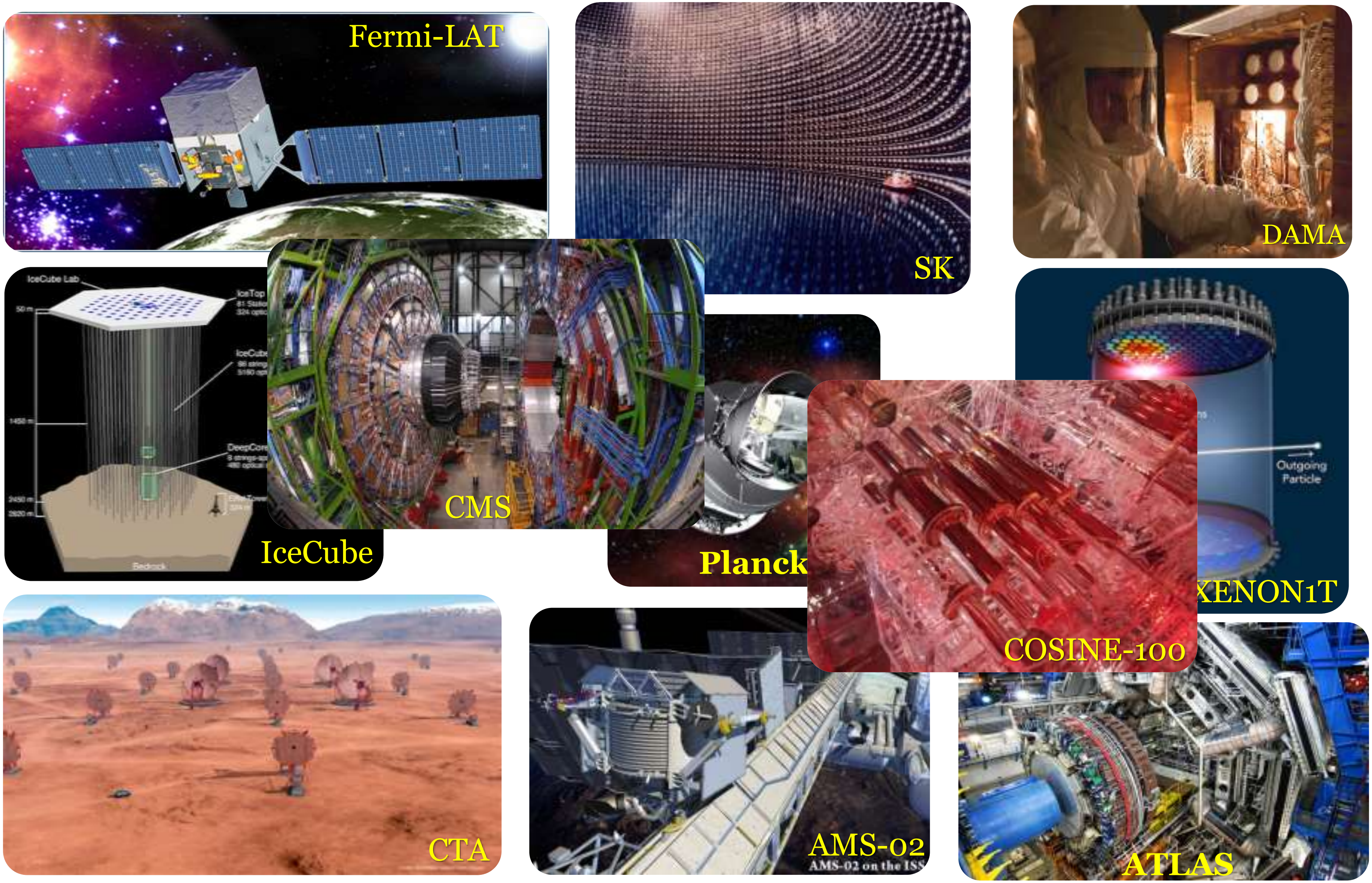
and

Steven Weinberg[(c)]
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

[PRL (1977)]

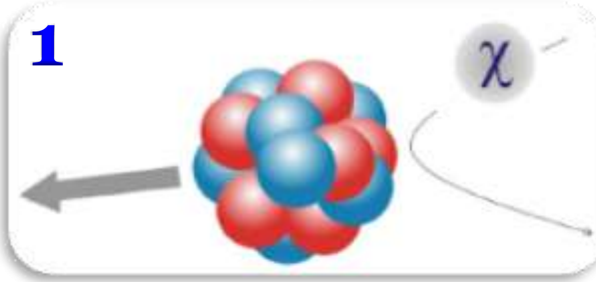
Diverging Efforts for DM Searches

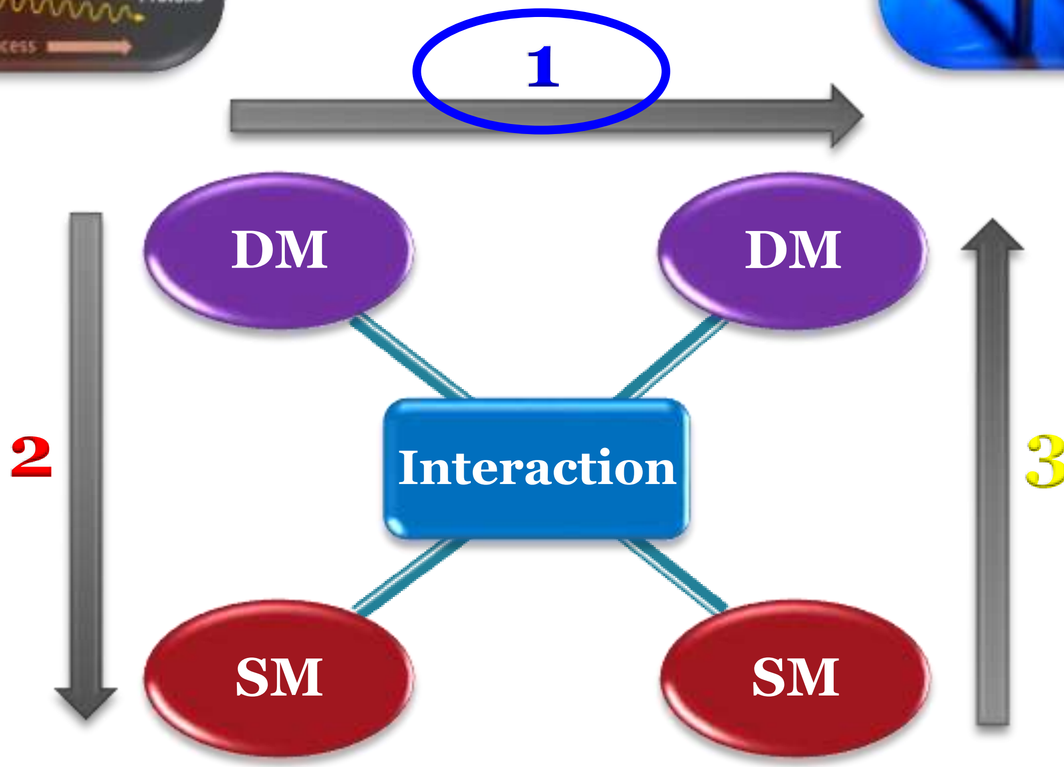


3. Direct Detection

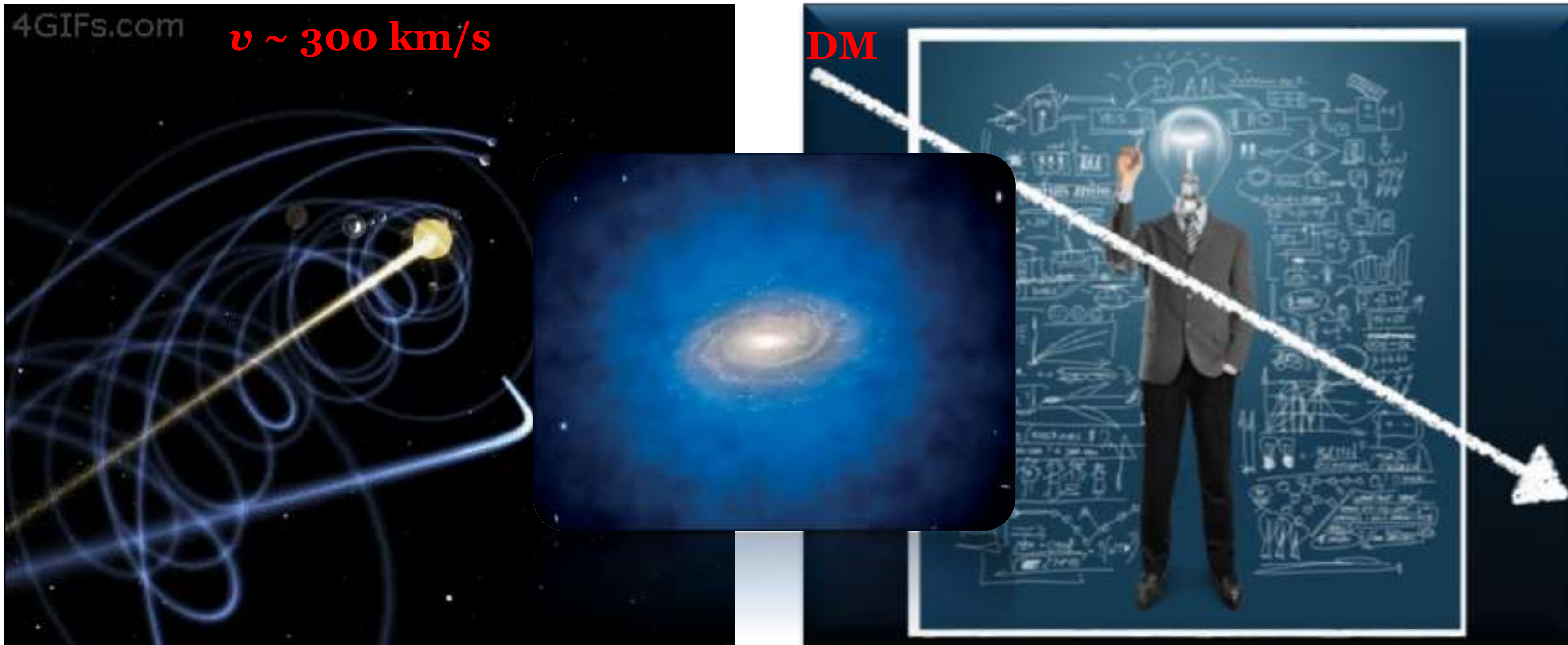
Target Particle Recoil

DM Direct Detection





Dark Matter vs Human



- When $m_{\rm DM} \sim m_{\rm p} \sim 0.94$ GeV: $\underbrace{300\ \mathrm{km/s} \times \frac{0.4\ \mathrm{GeV/cm^3}}{0.94\ \mathrm{GeV}}}_{\text{flux}} \times \underbrace{60\ \mathrm{cm} \times 170\ \mathrm{cm}}_{\text{area}}$

$$\approx\ 10^{11}/\mathrm{s}$$

✓ $\Phi_\chi = n_\chi v_{\rm rel}$ & $n_\chi = \rho_\chi / m_\chi$

- ~10^{11}/s DM's penetrate our body for $m_{\rm DM} \sim m_{\rm p}$!

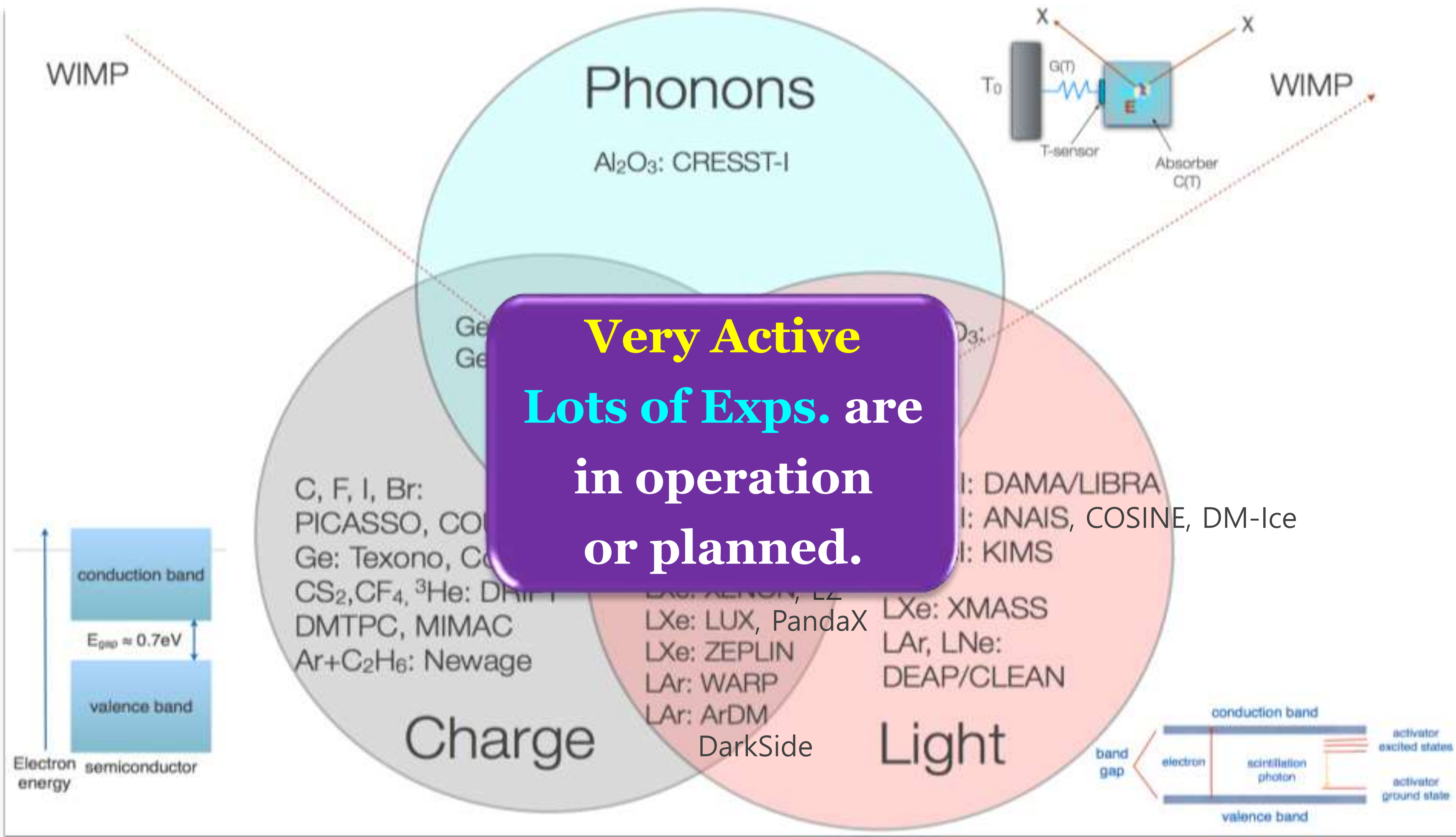
DM Direct Detection

❖ DM: all around us! → recoil of DM-nucleus scattering based on E & p conservation!

❖ What is measure: E of recoiling nucleus ~ 1-100 keV for m_{DM} ~ 1-100 GeV ($E_k \sim mv^2$ with $v/c \sim 10^{-3}$)

❖ Challenges: very small E, small event rate, large backgrounds

Detection Techniques



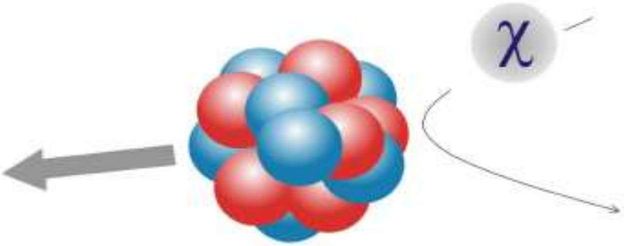
Very Active
Lots of Exps. are
in operation
or planned.

DM direct detection

local DM flux: $\phi_\chi \sim 10^5\,\text{cm}^{-2}\text{s}^{-1} \left(\frac{100\,\text{GeV}}{m_\chi}\right)\left(\frac{\rho_\chi}{0.4\,\text{GeV}\,\text{cm}^{-3}}\right)$

assuming DM has non-gravitational interactions ("WIMP")

look for recoil of DM-nucleus scattering M. Goodman, E. Witten, PRD 1985



cnts / keV recoil energy E_R:

$$\frac{dN}{dE_R}(t) \propto \frac{\rho_\chi}{m_\chi} \int_{v>v_{\min}} d^3v \frac{d\sigma}{dE_R} v f_\oplus(\vec{v}, t)$$

ρ_χ DM energy density, default: 0.3 GeV cm^{-3}

$v_{\min}$: minimal DM velocity required to produce recoil energy E_R

T. Schwetz, PPC11 CERN

Beginning of DM Direct Detection

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

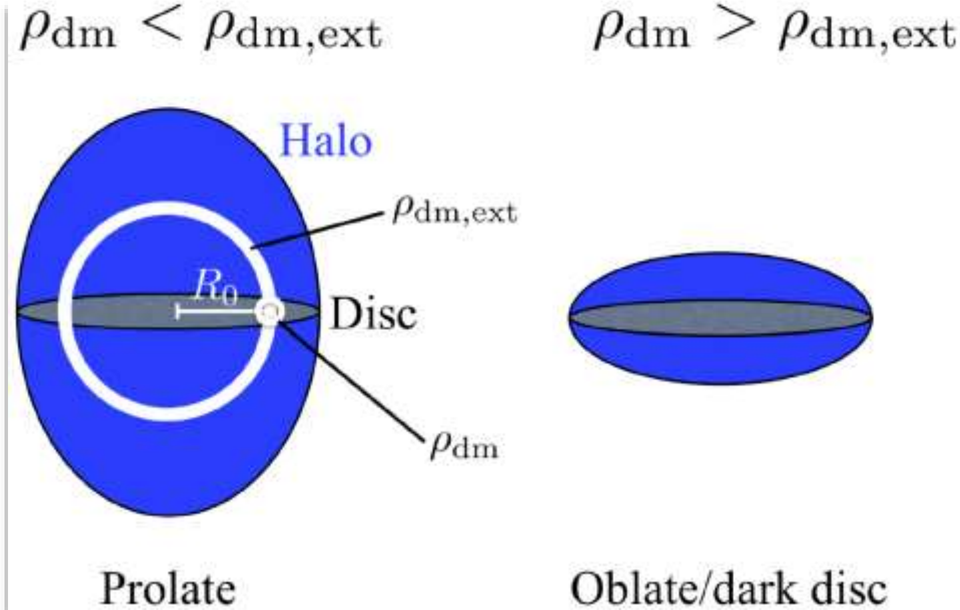
PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany
(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small ($10-10^3$ eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

DM Local Density



- Two main approaches to measuring ρ_{DM}
  - Local measures: the vertical kinematics of stars in the local Milky Way ➔ 'tracers'
  - Global measures: inter/extrapolating ρ_{DM} from the rotation curve
- Recently, there have been attempts to bridge two scales.

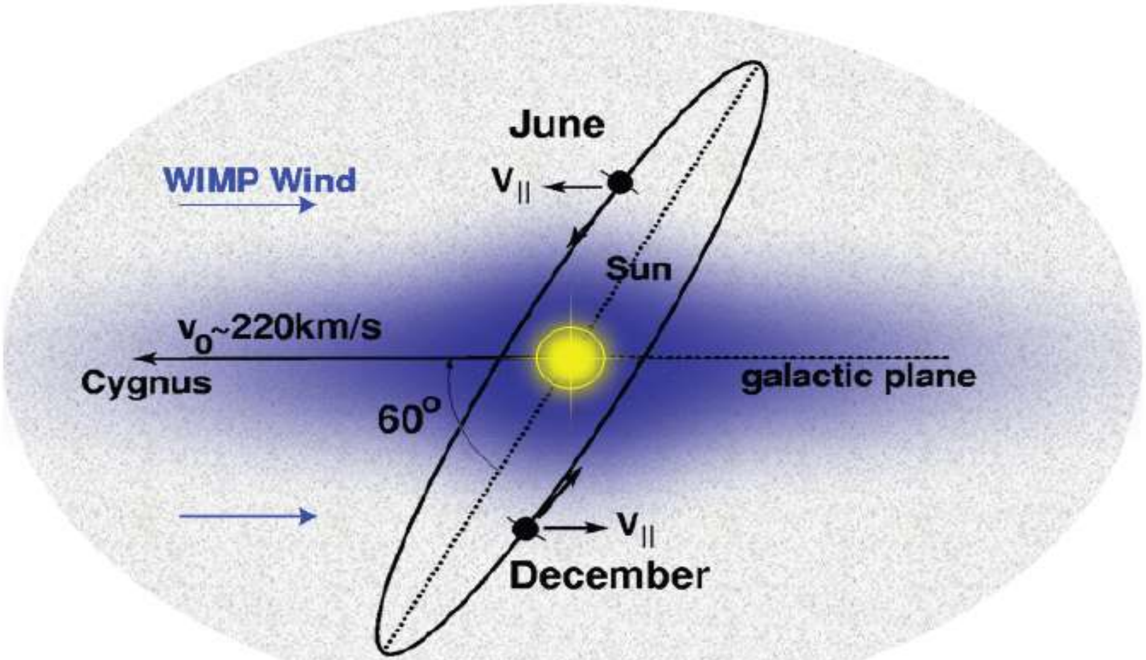
DM velocity distribution

$$f_\oplus(\vec{v}, t) = f_{\rm gal}(\vec{v} + \vec{v}_\odot + \vec{v}_\oplus(t)) \qquad f_{\rm gal}(\vec{v}) \approx \begin{cases} N \exp\left(-v^2/\bar{v}^2\right) & v < v_{\rm esc} \\ 0 & v > v_{\rm esc} \end{cases}$$

$\bar{v} \simeq 220\,\mathrm{km/s}$ $\quad v_{\rm esc} \simeq 550\,\mathrm{km/s}$

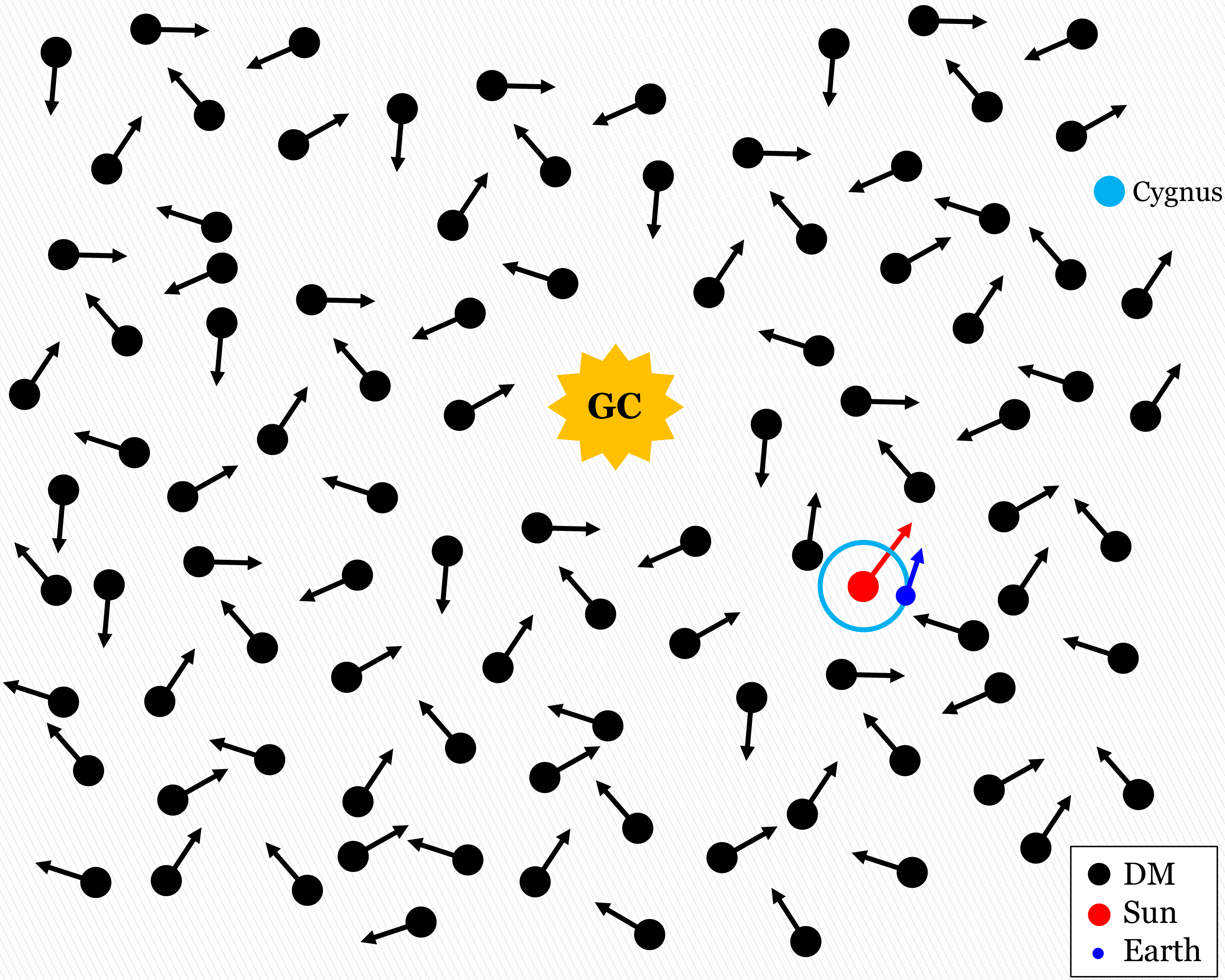
sun velocity: $\vec{v}_\odot = (0, 220, 0) + (10, 13, 7)\,\mathrm{km/s}$

earth velocity: $\vec{v}_\oplus(t)$ with $v_\oplus \approx 30\,\mathrm{km/s}$



MB distribution is used for describing particle speeds in idealized gases, where the particles move freely inside a stationary container without interacting with one another, except for very brief collisions in which they exchange E & p with each other or with their thermal environment.

T. Schwetz, PPC11 CERN

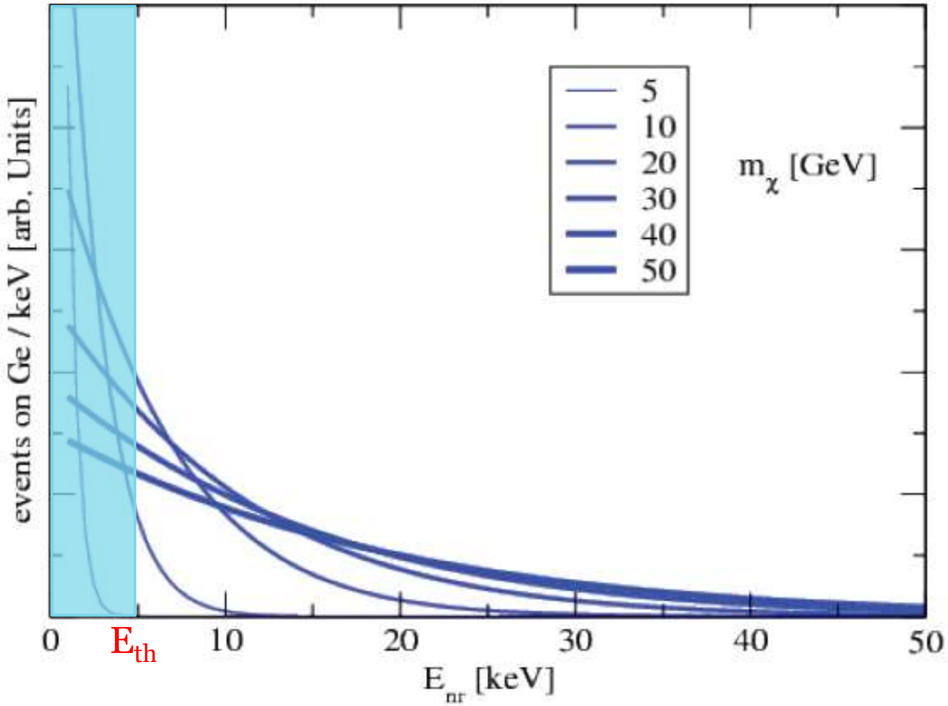


Cygnus
GC
DM
Sun
Earth

Event spectrum

$$\frac{dN}{dE_R}(t) = \frac{\rho_\chi}{m_\chi}\,\frac{\sigma_p |F(q)|^2 A^2}{2\mu_p^2}\int_{v>v_{\min}(E_R)} d^3v\,\frac{f_\oplus(\vec{v},t)}{v}$$

$v_{\min} = \frac{m_\chi + M}{m_\chi}\sqrt{\frac{E_R}{2M}}$: minimal DM velocity needed for recoil energy E_R



$m_\chi \ll M$:

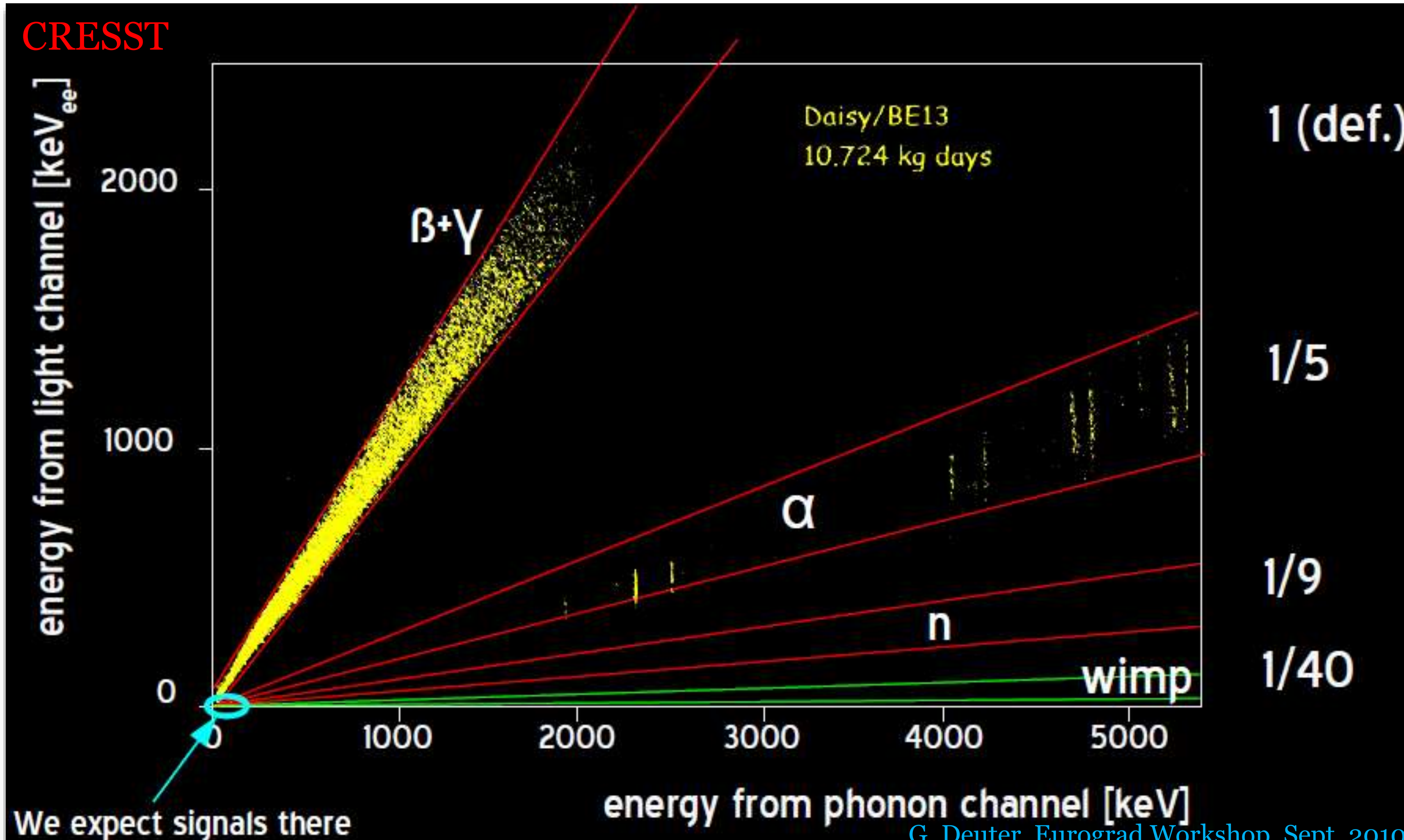
$$v_{\min} \approx \frac{\sqrt{ME_R/2}}{m_\chi}$$

spectrum gets shifted to low energies for low WIMP masses

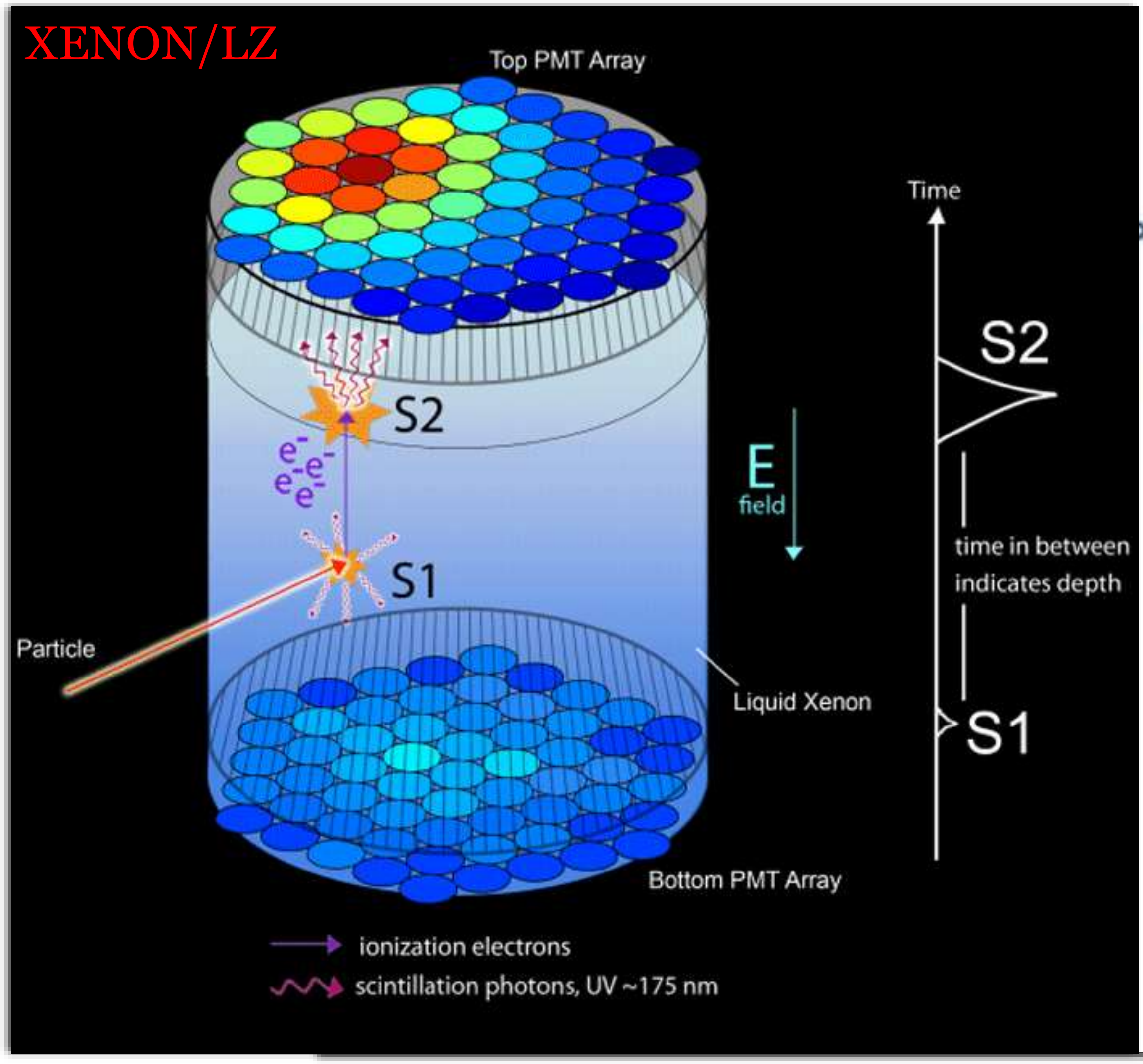
$\Rightarrow$ energy threshold is crucial

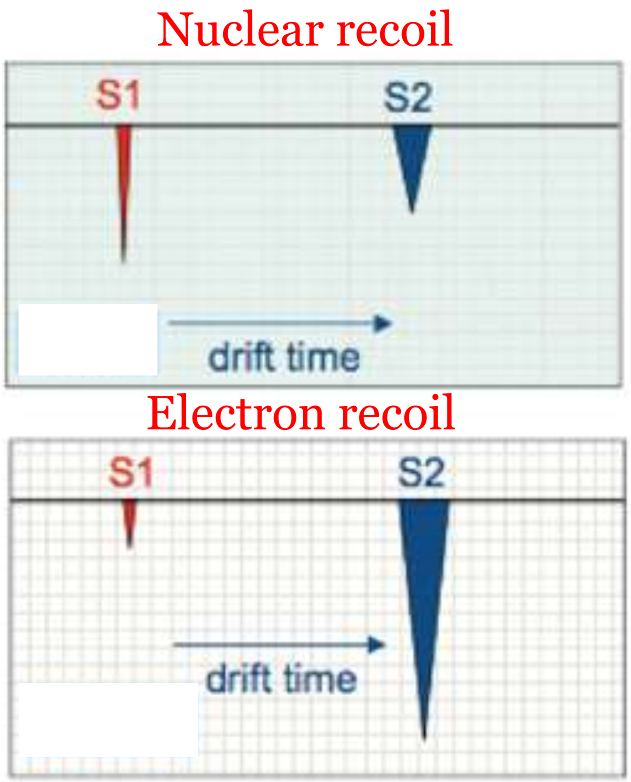
T. Schwetz, PPC11 CERN

Event Discrimination



Event Discrimination

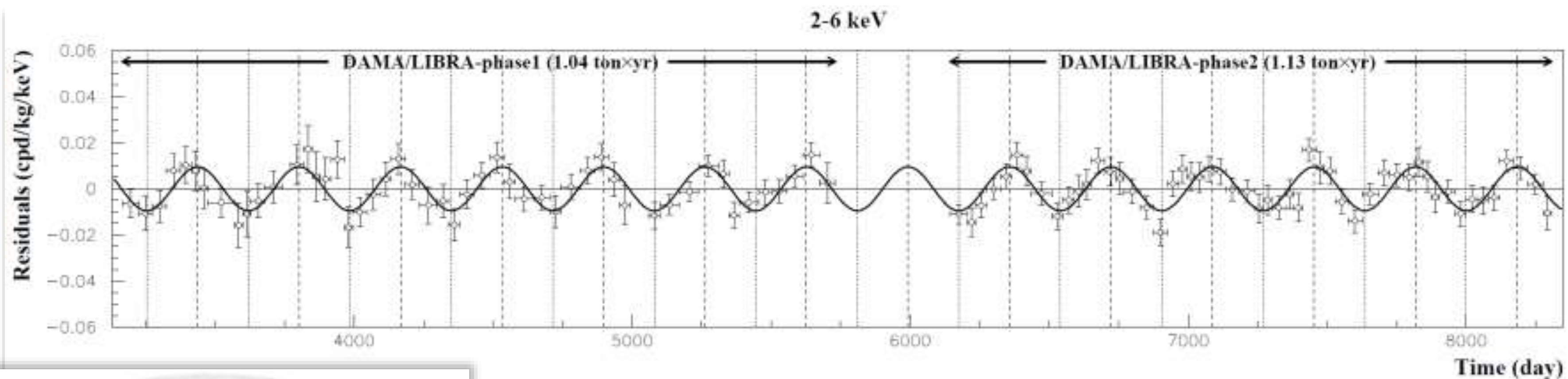


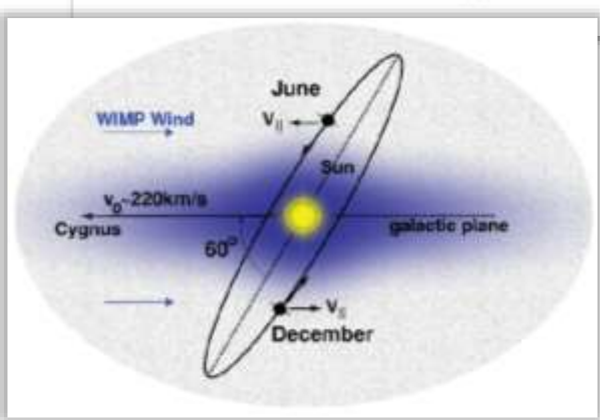


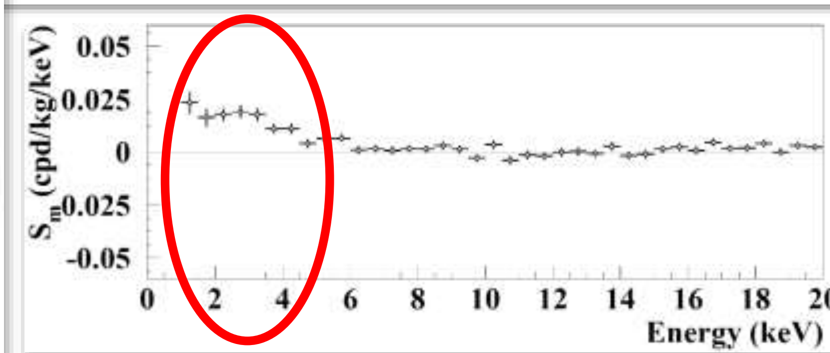
Annual Modulation

DAMA [arXiv: 1805.10486]

- As the Earth orbits the Sun, *v* of the detector relative to the DM halo varies.
- DAMA has detected an annual modulation in the event rate (12.9 σ significance).
- 14 annual cycles, modulation amplitude: 0.0103 ± 0.0008 in the (2-6) keV
- Phase: 145 ± 5 days (cf. June 2nd), Period: 0.999 ± 0.001 yr

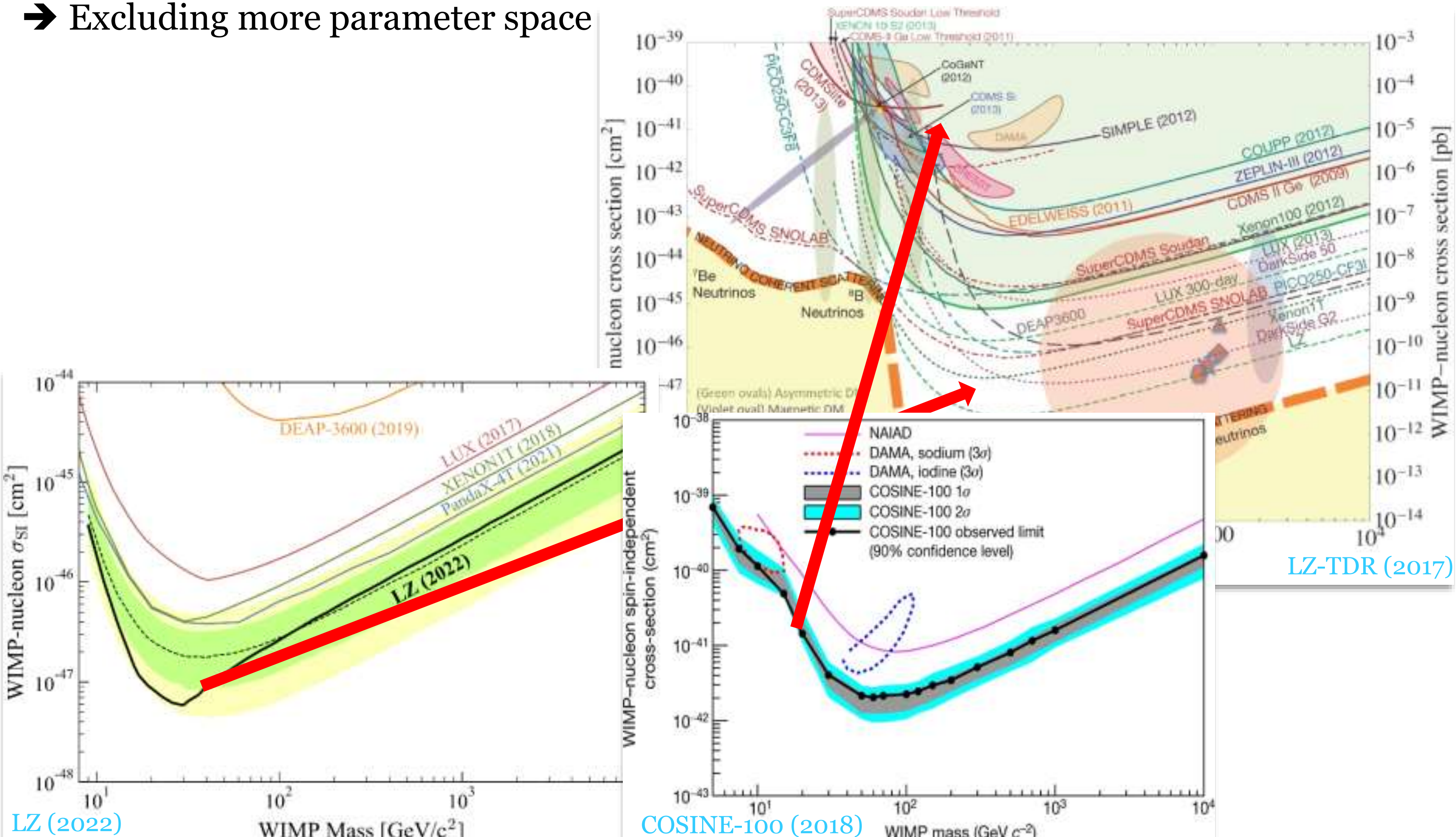






Current Status Direct DM Searches

- ❖ No (solid) observation of DM signatures w/ BG modeling
- ➔ Excluding more parameter space

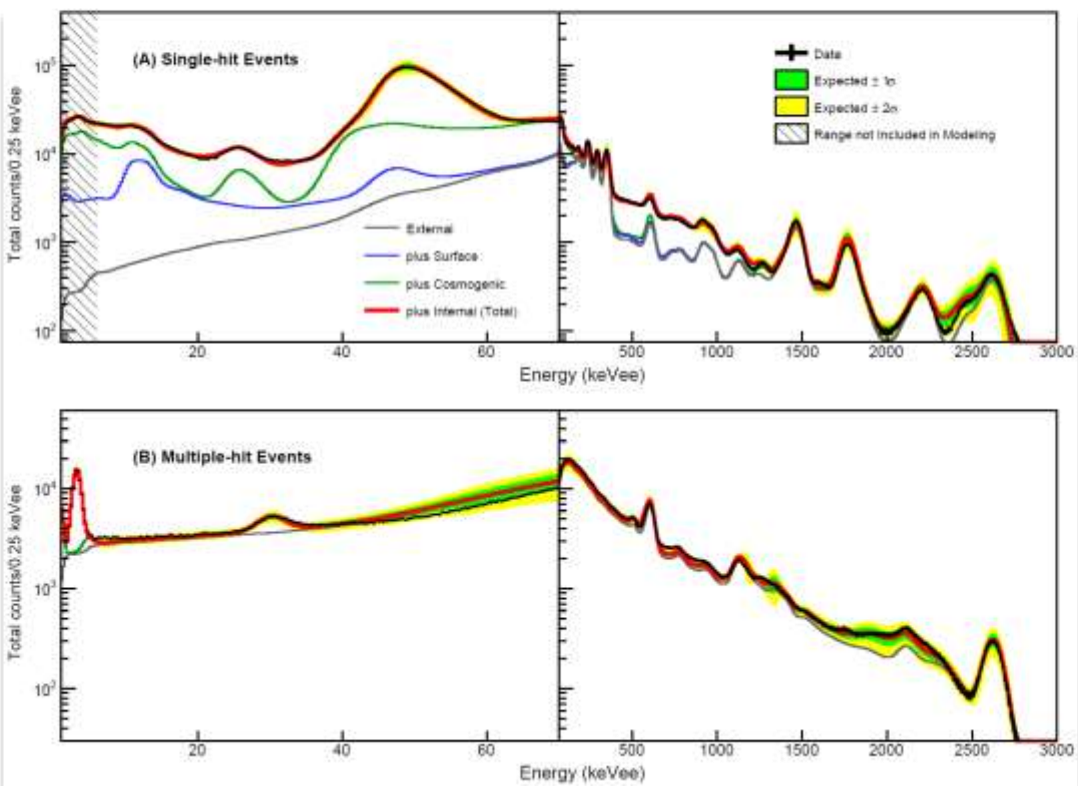


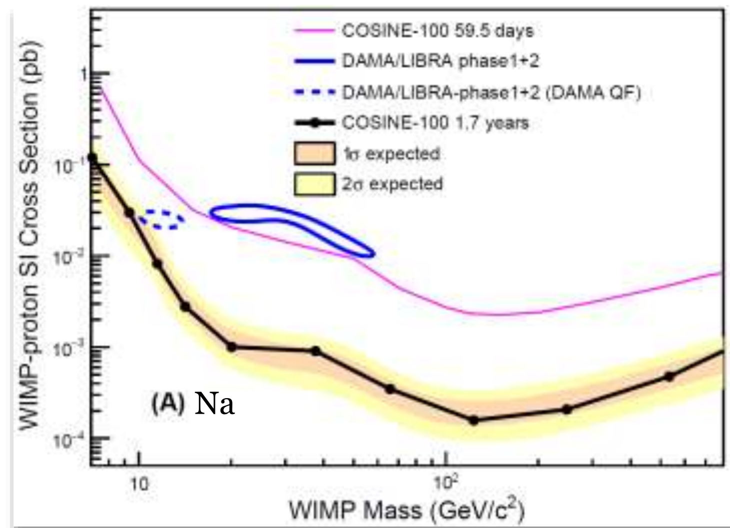
Current Status Direct DM Searches

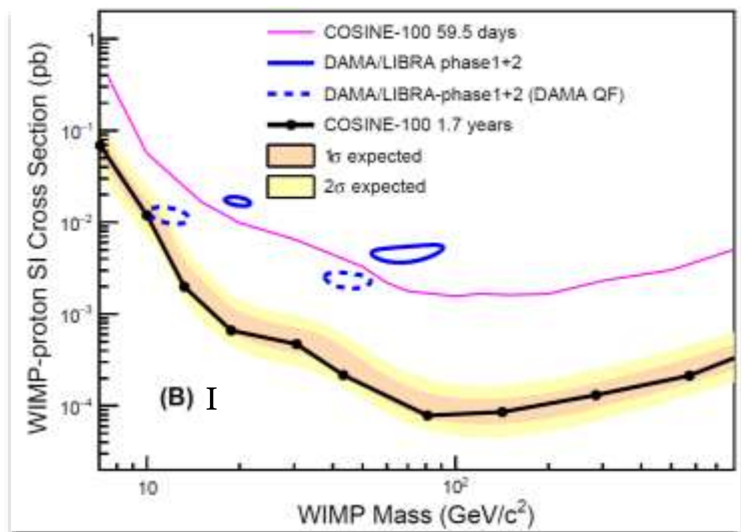
COSINE-100 [arXiv: 2104.03537]

❖ No (solid) observation of DM signatures w/ BG modeling

➔ Excluding more parameter space

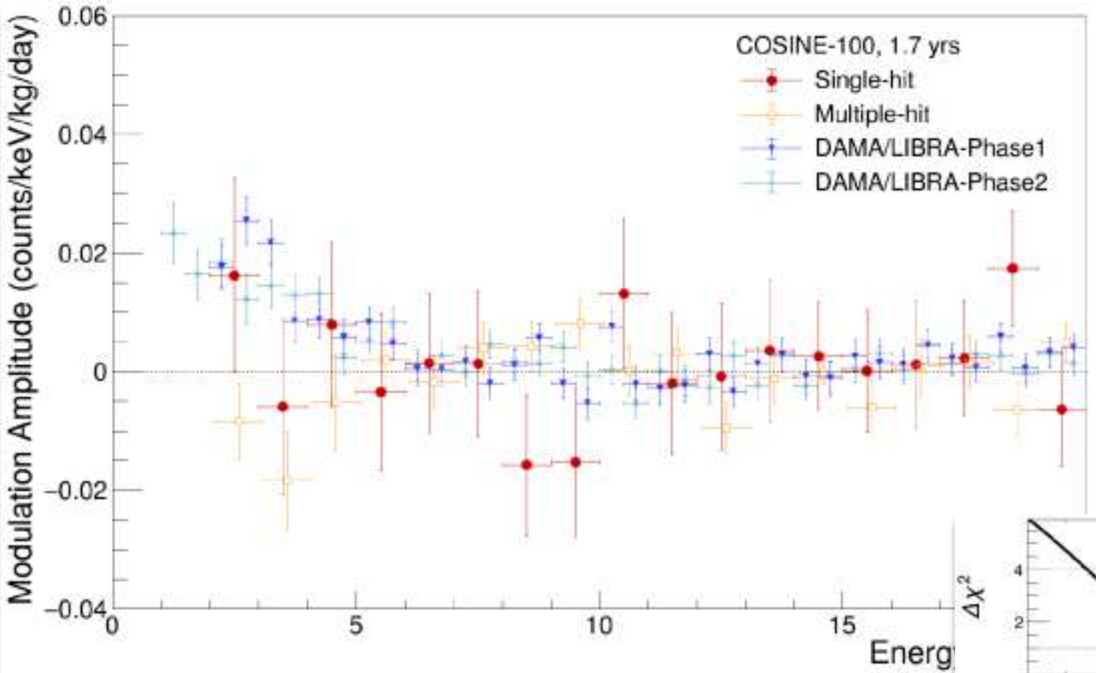




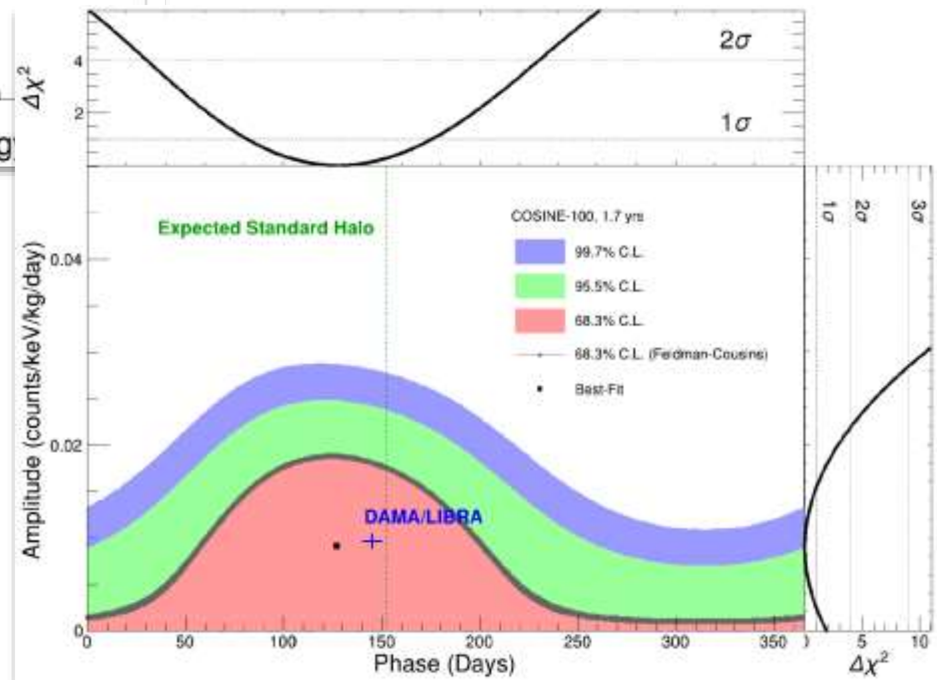


Current Status of Annual Modulation

COSINE-100 (2019)

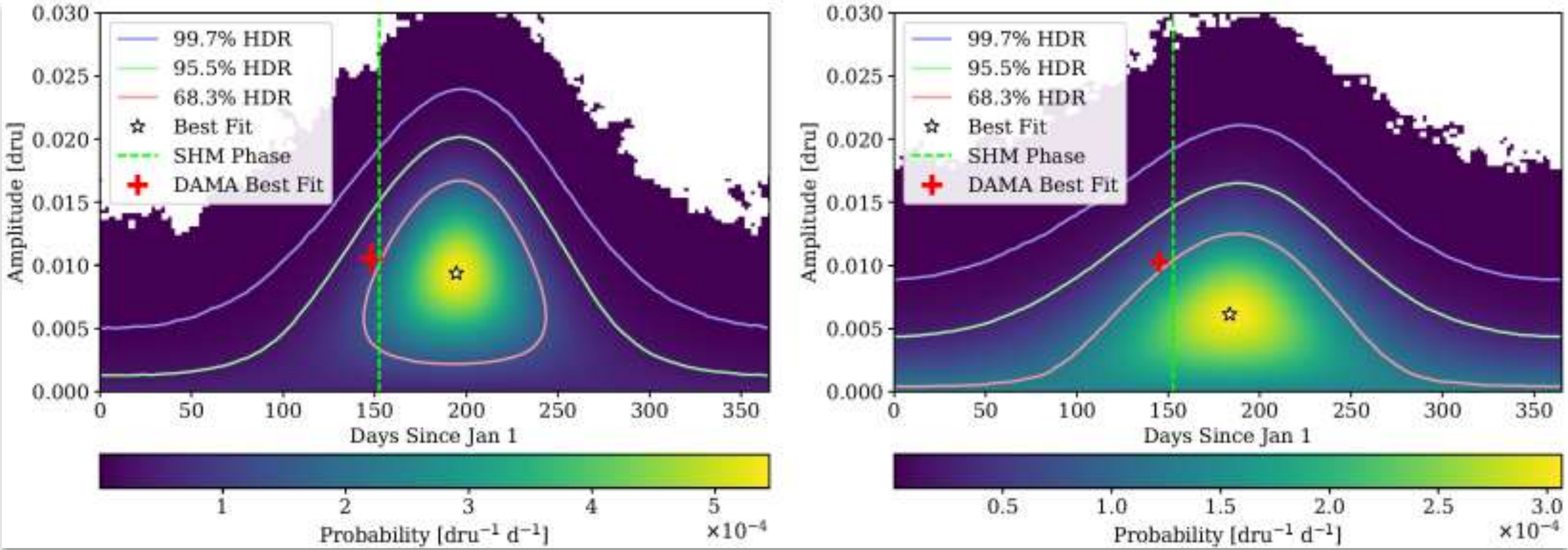


In summary, we report the results from the search for a dark matter–induced annual modulation signal in NaI(Tl) based on 1.7 years of COSINE-100 data. A fit to the 2–6 keV energy range returns a modulation amplitude of 0.0092±0.0067 cpd/kg/keV with a phase of 127.2±45.9 d. At 68.3% C.L., this result is consistent with both the null hypothesis and DAMA/LIBRA's 2–6 keV best fit value.

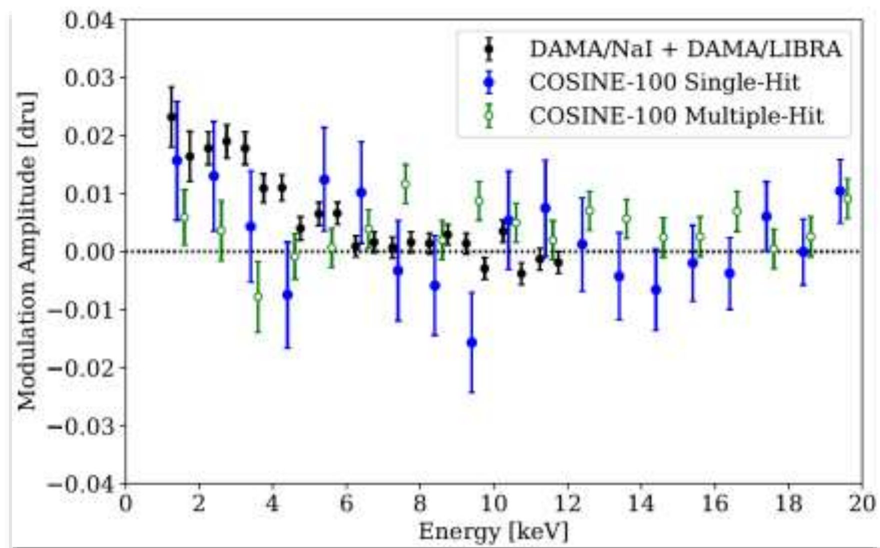


Current Status of Annual Modulation

COSINE-100 [arXiv: 2111.08863]



Configuration	Amplitude [dru]	Phase [days]
COSINE-100 1–6 keV (This result)	0.0067±0.0042	152.5 (fixed)
COSINE-100 2–6 keV (This result)	0.0050±0.0047	152.5 (fixed)
COSINE-100 2–6 keV (2019 result [14])	0.0083±0.0068	152.5 (fixed)
ANAIS 1–6 keV (2021 result [16])	-0.0034±0.0042	152.5 (fixed)
ANAIS 2–6 keV (2021 result [16])	0.0003±0.0037	152.5 (fixed)
DAMA/LIBRA 1–6 keV (phase2 [7])	0.0105±0.0011	152.5 (fixed)
DAMA/NaI+LIBRA 2–6 keV [7]	0.0102±0.0008	152.5 (fixed)
COSINE-100 1–6 keV (This result)	$0.0094^{+0.0073}_{-0.0072}$	$194.5^{+49.0}_{-50.5}$
COSINE-100 2–6 keV (This result)	$0.0061^{+0.0064}_{-0.0061}$	Unconstrained
COSINE-100 2–6 keV (2019 result [14])	0.0092±0.0067	127.2±45.9
DAMA/LIBRA 1–6 keV (phase2 [7])	0.0106±0.0011	148±6
DAMA/NaI+LIBRA 2–6 keV [7]	0.0103±0.0008	145±5



Current Status of Annual Modulation

COSINE-100 [arXiv: 2208.05158]

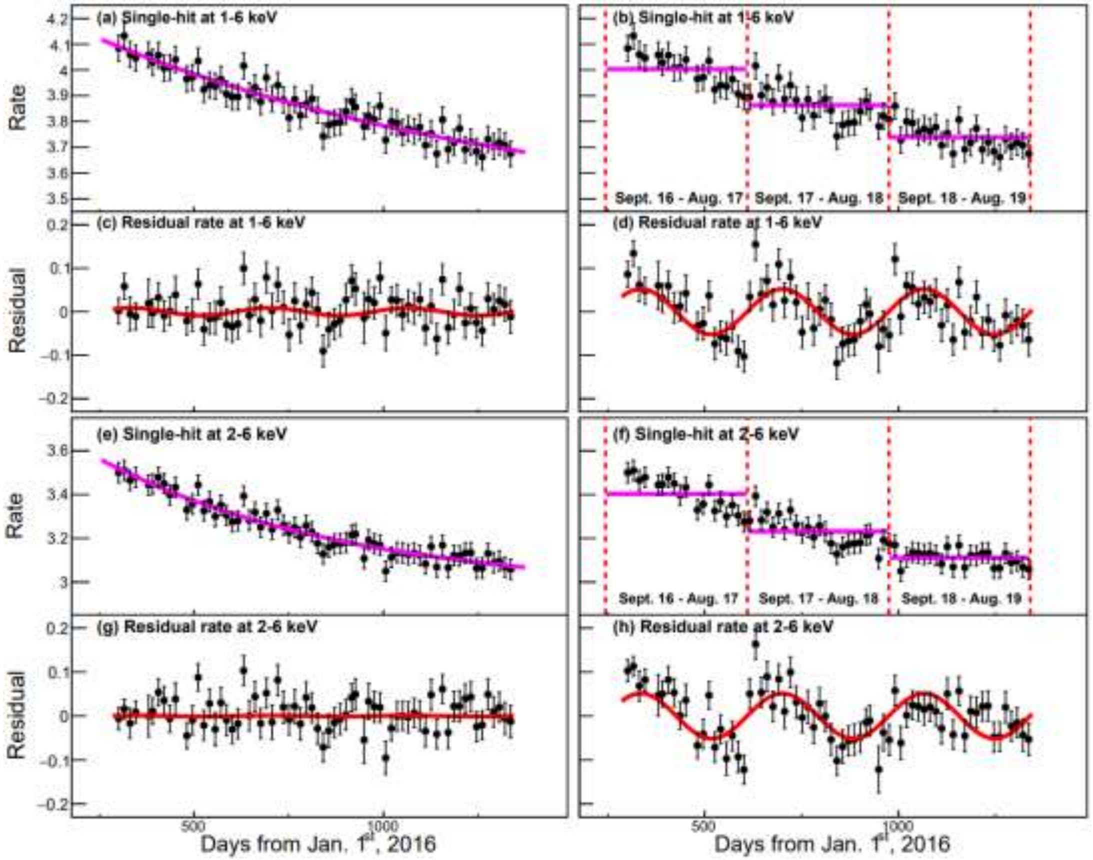
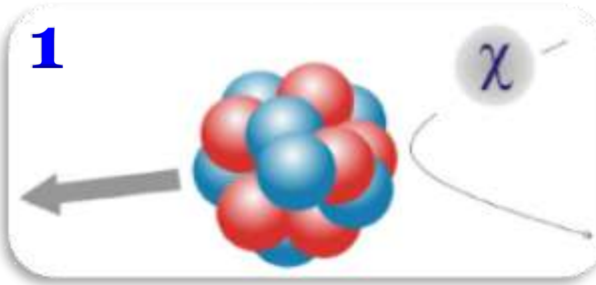


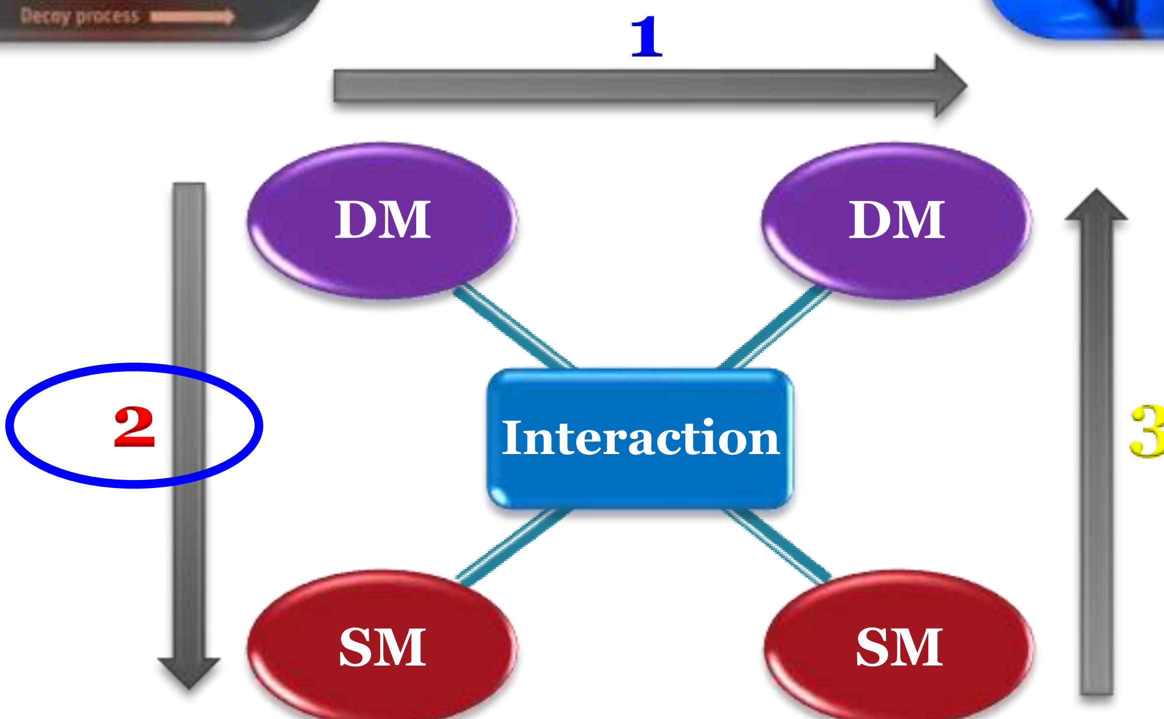
FIG. 4. **Single-hit event rates in the unit of counts/keV/kg/day as a function of time.** The top four panels present time-dependent event rates as well as the residual rates in the single-hit 1–6 keV regions with 15 days bin. Here, the event rates are averaged for the five crystals with weights from uncertainties in each 15 days bin size. Purple solid lines present background modeling with the single exponential (a) and the yearly averaged DAMA-like method (b). Residual spectra for the single exponential model (c) and the DAMA-like model (d) are fitted with the sinusoidal function (red solid lines). Same for 2–6 keV in the bottom four panels. Strong annual modulations are observed using the DAMA-like method while the result using the single-exponential models are consistent with no observed modulation.

4. Indirect Detection

Cosmic Rays

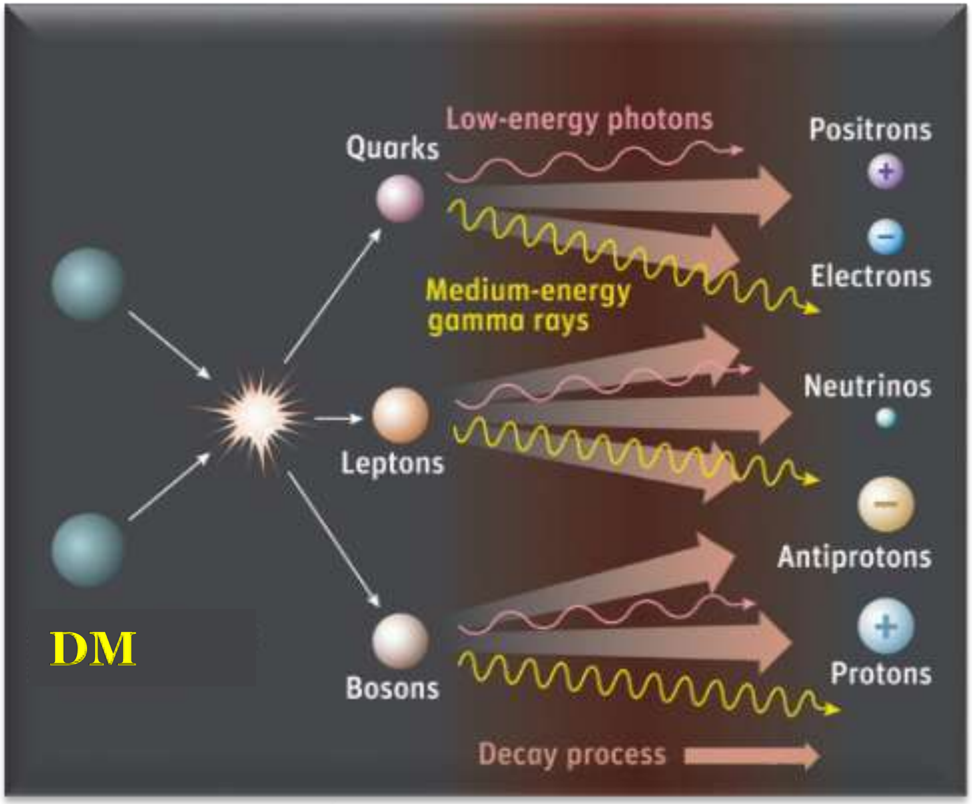
DM Indirect Detection





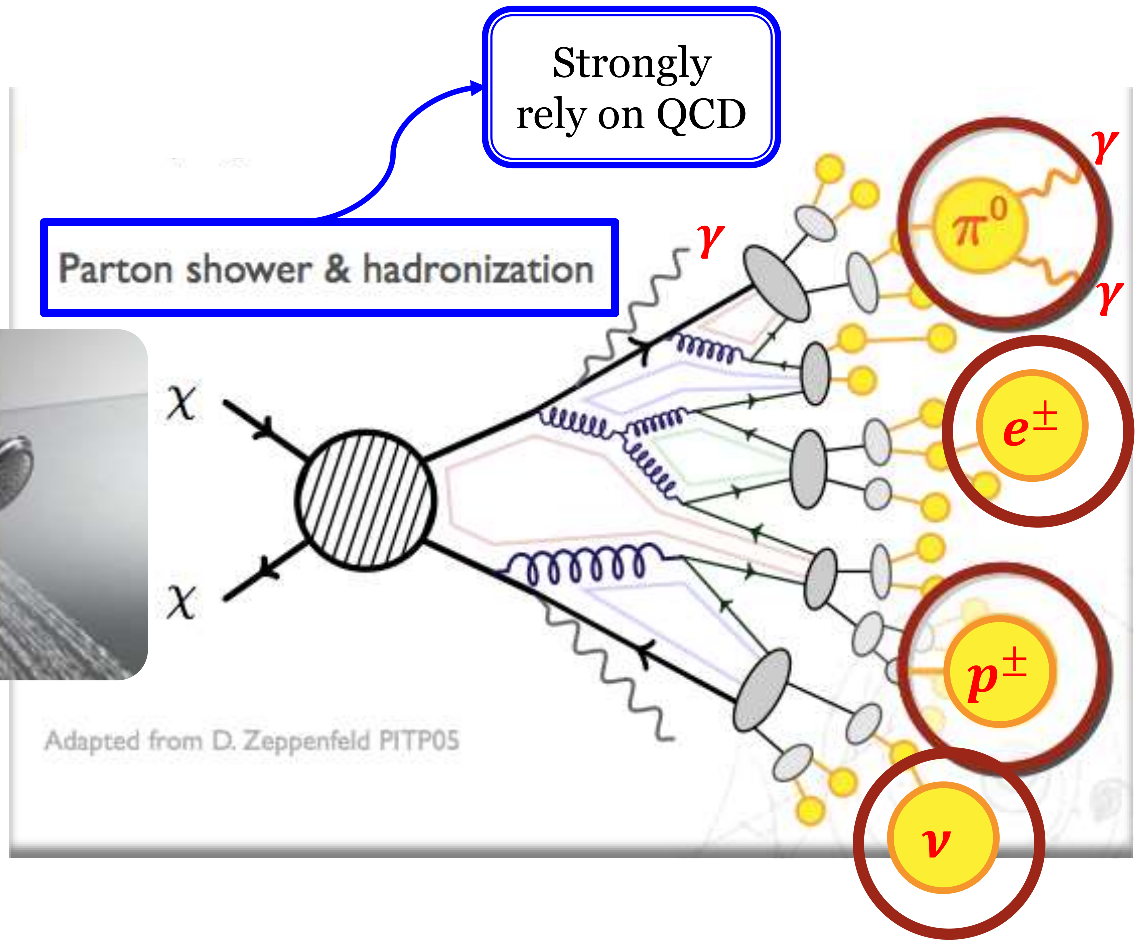
Cosmic Rays from DM

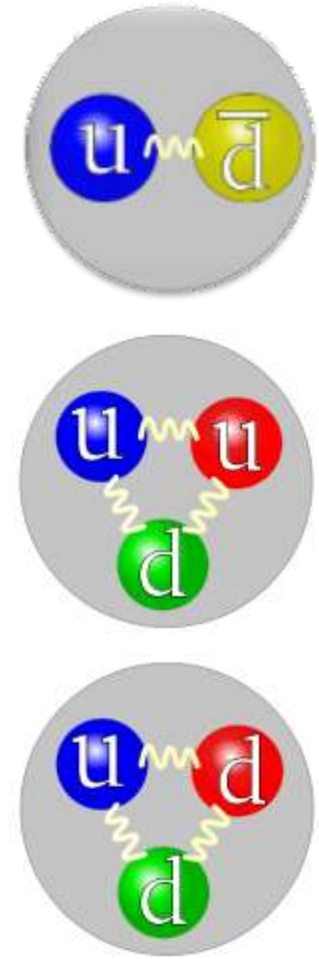
❖ Search for the products of DM annihilation and/or decay: γ, ν, $e^{\pm}$, p, ...



Cosmic Rays from DM: Showering

- ❖ Final states from DM annihilation and/or decay: γ, $e^{\pm}$, $p^{\pm}$, ν, ...





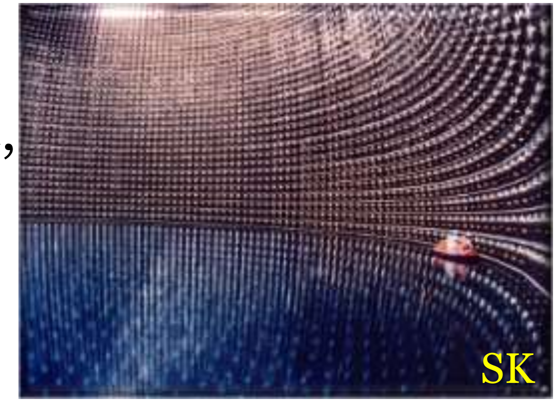
Cosmic Ray Experiments

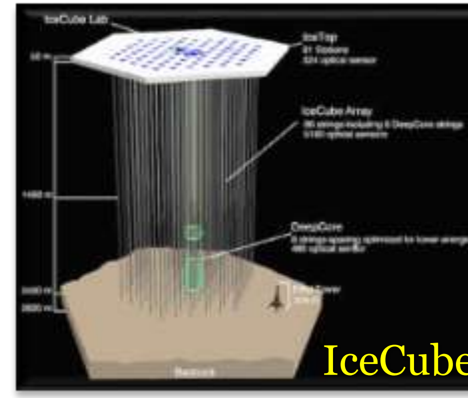
- ❖ Ground-based
  MAGIC, HESS, CTA, IceCube, Super-K, Hyper-K, DUNE, …

- ❖ Balloon-based:
  ATIC, PPB-BETS, …

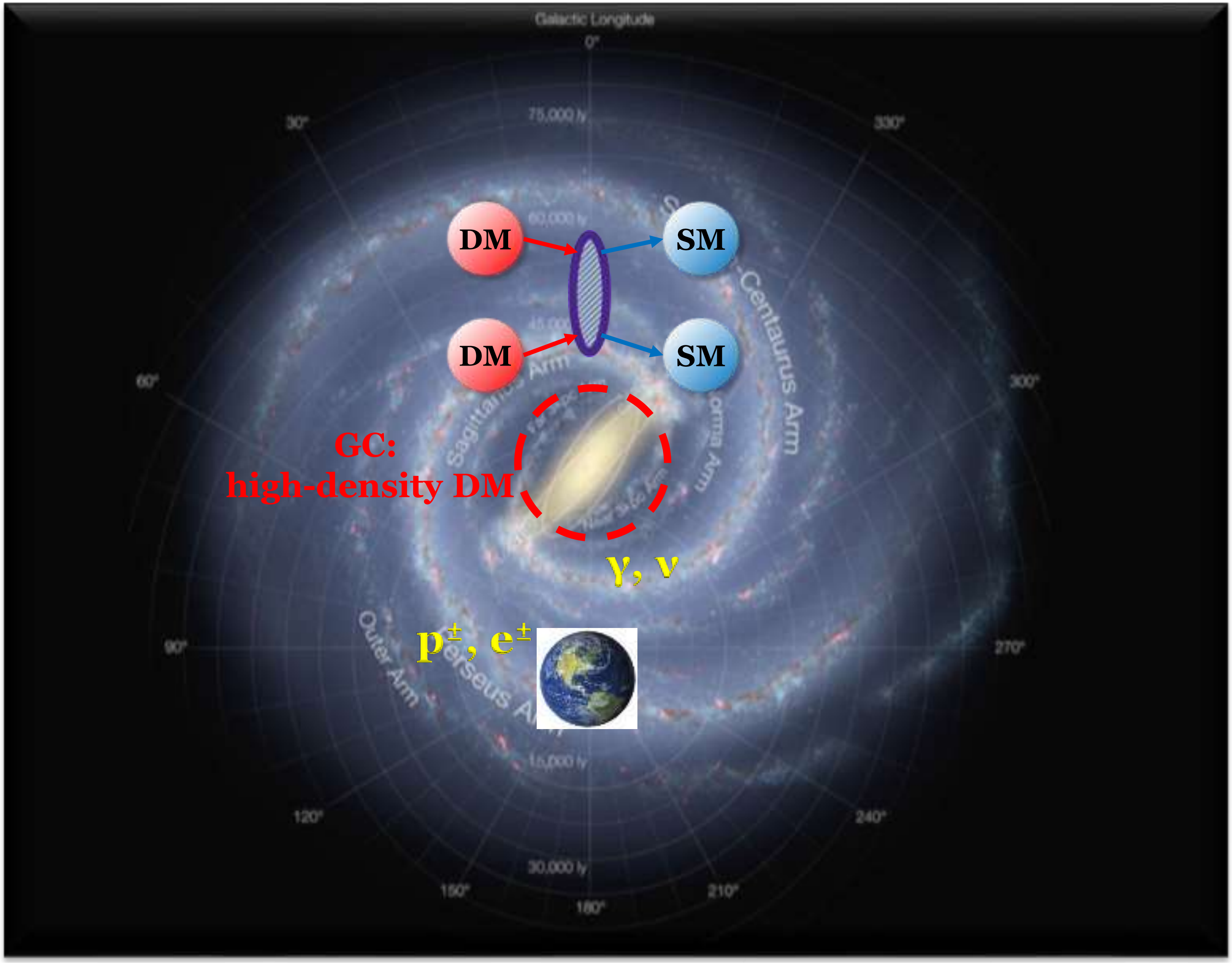
- ❖ Satellite-based:
  AMS, Chandra, Fermi-LAT, PAMELA, XMM-Newton, DAMPE, ASTROGAM, …

  - ✓ Great sensitivity to cosmic-ray signals
  - ✓ Better chance to have the information for extracting DM properties

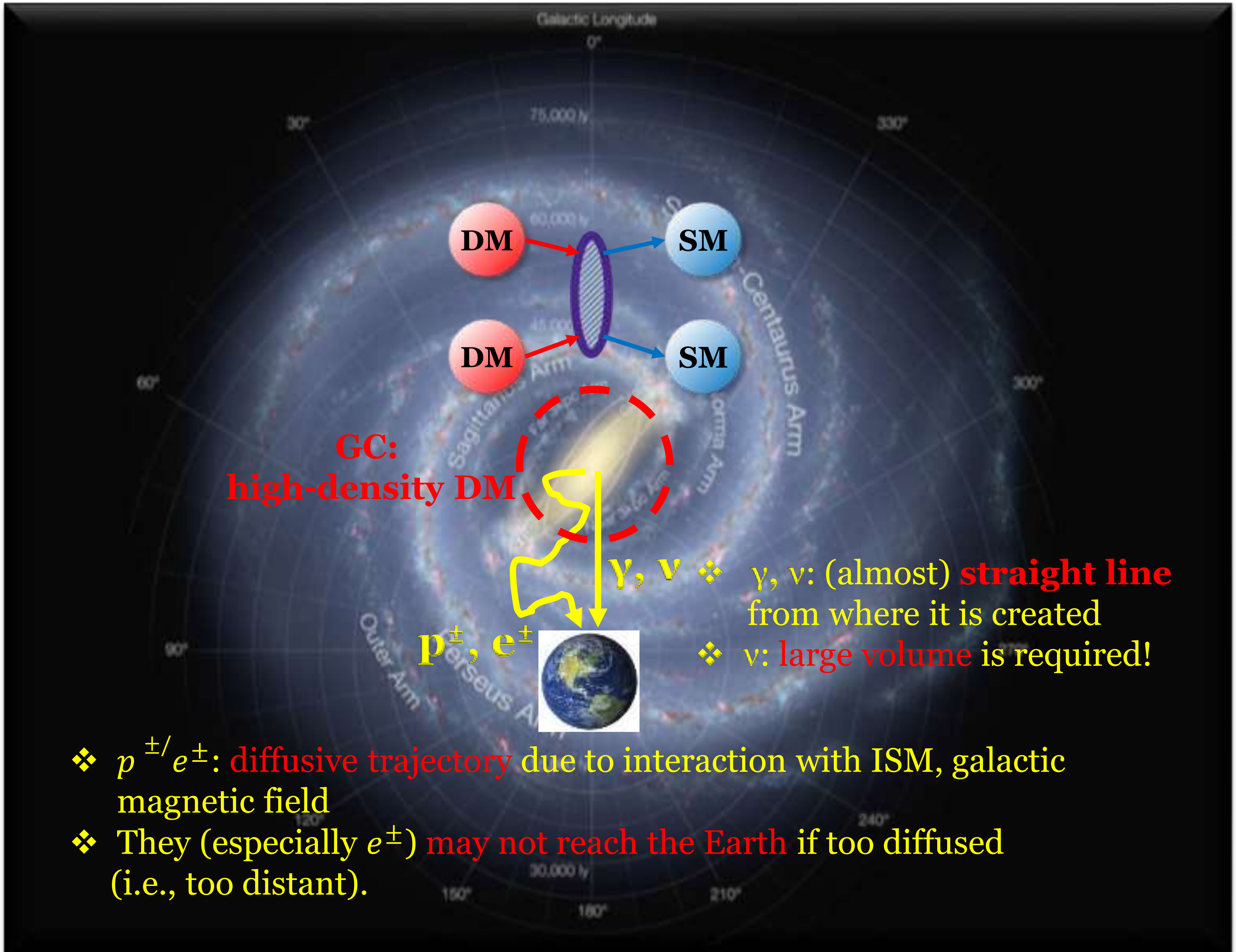




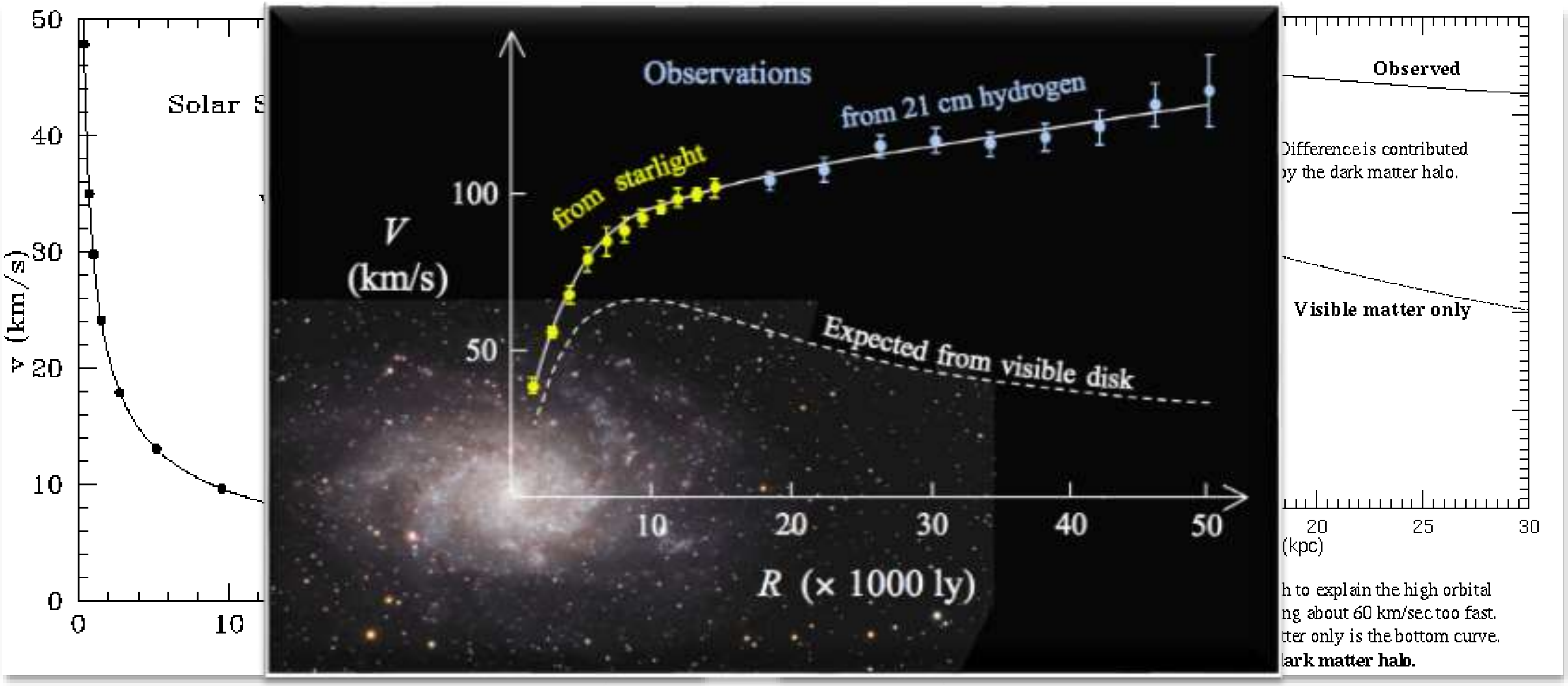
Indirect Detection: Cosmic Rays



Indirect Detection: Cosmic Rays



Galaxy Rotation Curve

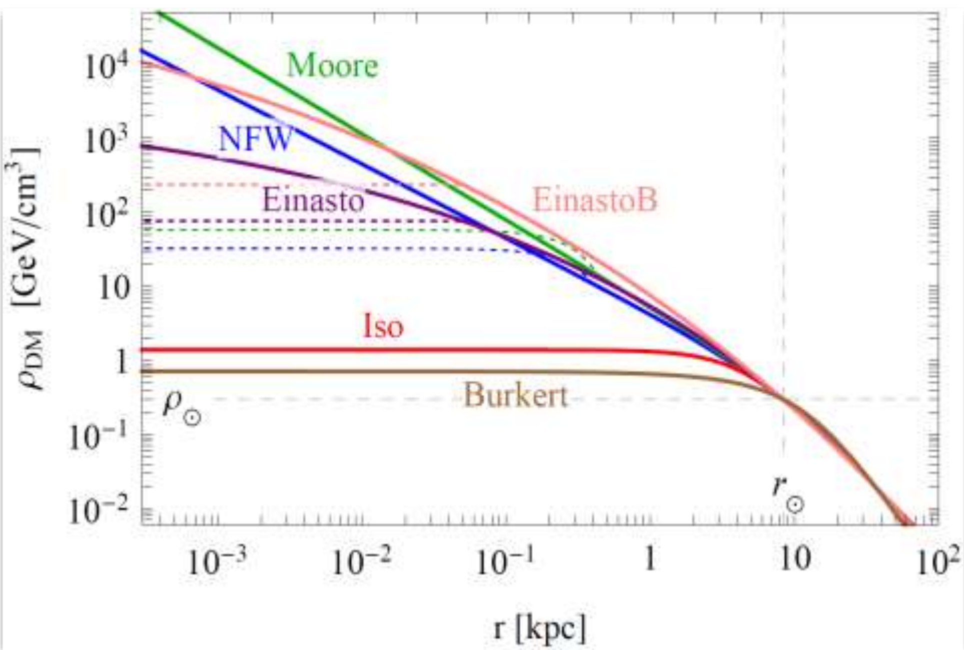


Vera Rubin

$$\frac{GMm}{r^2} = \frac{mv^2}{r} \rightarrow v \propto \sqrt{\frac{GM}{r}}$$

$$v \sim \text{constant} \rightarrow M(r) \propto r$$

DM Halo Profiles



$$\text{NFW}: \quad \rho_{\rm NFW}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

$$\text{Einasto}: \quad \rho_{\rm Ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

$$\text{Isothermal}: \quad \rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

$$\text{Burkert}: \quad \rho_{\rm Bur}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$

$$\text{Moore}: \quad \rho_{\rm Moo}(r) = \rho_s\left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84}$$

DM halo	α	r_s [kpc]	ρ_s [GeV/cm^3]
NFW	–	24.42	0.184
Einasto	0.17	28.44	0.033
EinastoB	0.11	35.24	0.021
Isothermal	–	4.38	1.387
Burkert	–	12.67	0.712
Moore	–	30.28	0.105

Fluxes at Production: Primary Channels

DM + DM $\Rightarrow$

$$e_L^+e_L^-,\ e_R^+e_R^-,\ \mu_L^+\mu_L^-,\ \mu_R^+\mu_R^-,\ \tau_L^+\tau_L^-,\ \tau_R^+\tau_R^-,$$
$$q\bar{q},\ c\bar{c},\ b\bar{b},\ t\bar{t},\ \gamma\gamma,\ gg,$$
$$W_L^+W_L^-,\ W_T^+W_T^-,\ Z_LZ_L,\ Z_TZ_T,$$
$$hh,$$
$$\nu_e\bar{\nu}_e,\ \nu_\mu\bar{\nu}_\mu,\ \nu_\tau\bar{\nu}_\tau,$$
$$VV\to 4e,\ VV\to 4\mu,\ VV\to 4\tau,$$

- Primary channels (including annihilation amplitudes, relative ratios → σv_i): determined by particle physics
- Flux of DM annihilation products: $\Phi \propto \sigma v\, n^2(r)$

  $n(r)$: the number density of a DM particle

Fluxes at Production: Secondary Channels

DM+DM → Primary channel → Secondary channel

Theoretical model
(+ CalcHEP/MadGraph)

Simulation:
HERWIG/PYTHIA

$e_L^+e_L^-$, $e_R^+e_R^-$, $\mu_L^+\mu_L^-$, $\mu_R^+\mu_R^-$, $\tau_L^+\tau_L^-$, $\tau_R^+\tau_R^-$

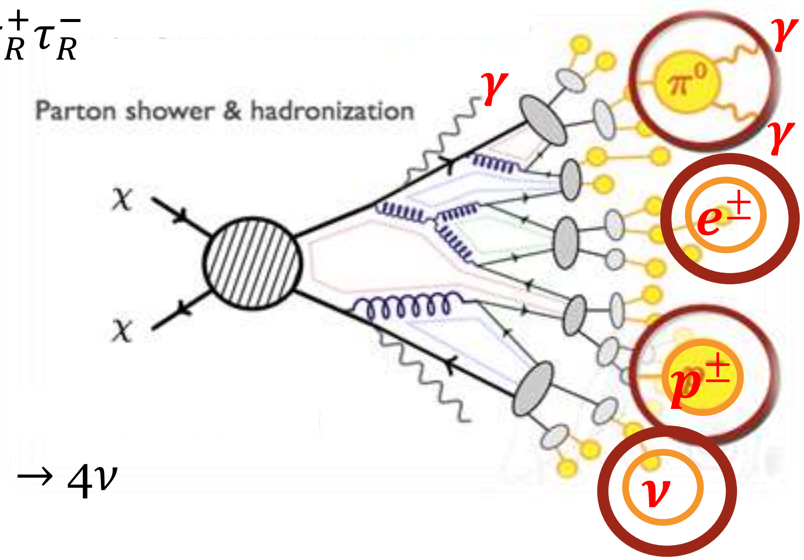
$q\bar{q}$, $c\bar{c}$, $b\bar{b}$, $t\bar{t}$, $\gamma\gamma$, gg,

Z_LZ_L, Z_TZ_T, $W_L^+W_L^-$, $W_T^+W_T^-$,

hh,

$\nu\bar{\nu}_e$, $\nu\bar{\nu}_\mu$, $\nu\bar{\nu}_\tau$,

$VV \to 4e$, $VV \to 4\mu$, $VV \to 4\tau$, $VV \to 4\nu$



Final Fluxes

❖ Cosmic rays from DM annihilation is described by

$$\Phi_i(\psi, E) = \sigma v \frac{\mathrm{d}N_i}{\mathrm{d}E} \frac{1}{8\pi m_{\mathrm{DM}}^2} \int_{\text{line of sight}} \mathrm{d}s\, \rho^2(r(s, \psi))$$

Final Fluxes

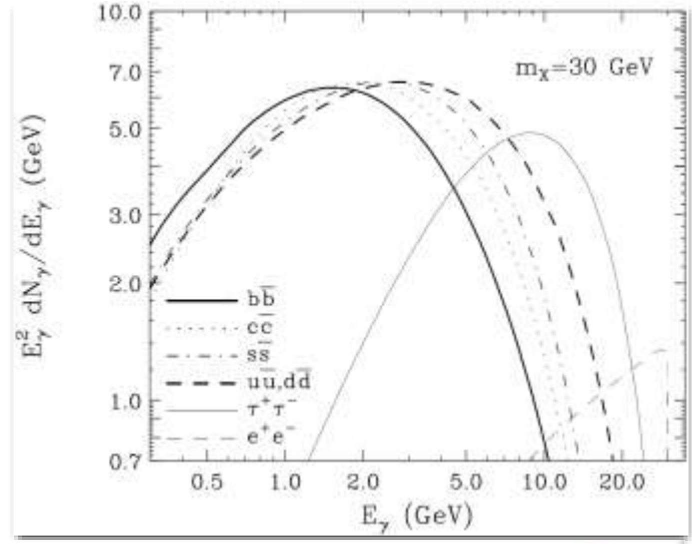
❖ Cosmic rays from DM annihilation is described by

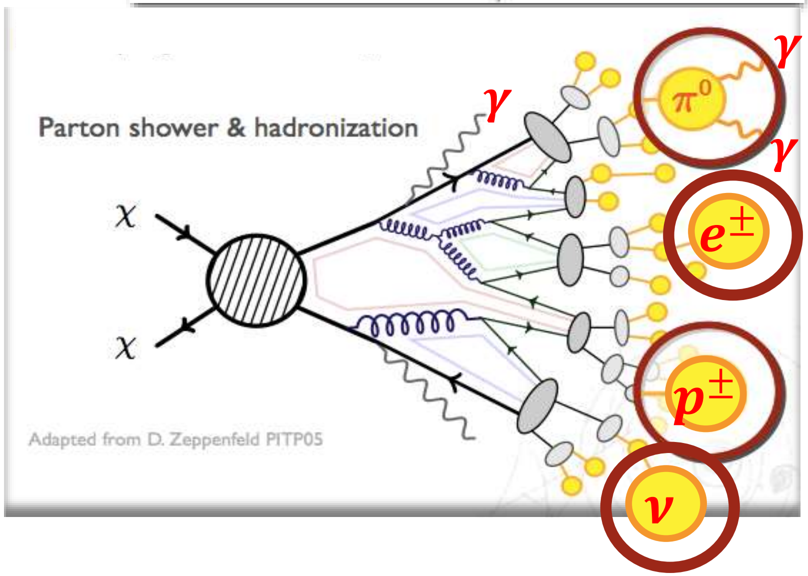
$$\Phi_i(\psi, E) = \sigma v \frac{dN_i}{dE} \frac{1}{8\pi m_{DM}^2} \int_{\text{line of sight}} ds\, \rho^2(r(s,\psi))$$

γ, ν, (e±, p±)

γ, ν, e±, p±

1) Shape of spectrum





Final Fluxes

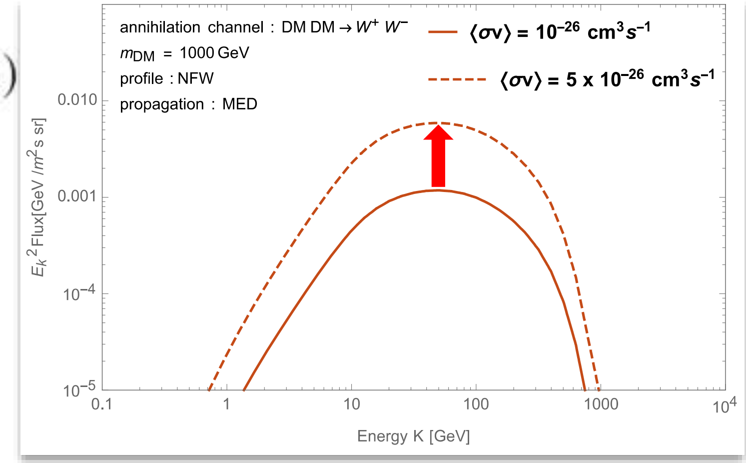
- Cosmic rays from DM annihilation is described by

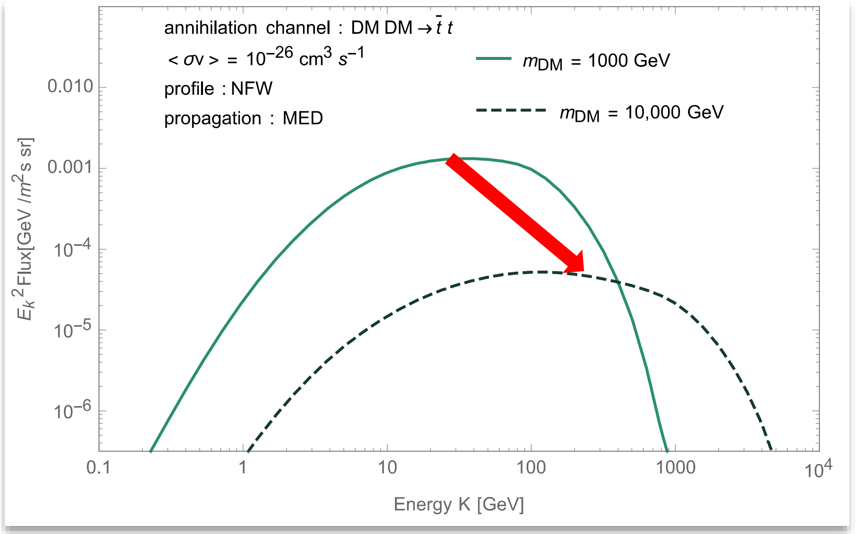
$$\Phi_i(\psi, E) = \sigma v \frac{dN_i}{dE} \frac{1}{8\pi m_{\rm DM}^2} \int_{\rm line\ of\ sight} ds \rho^2(r(s,\psi))$$

number density of DM
$n_{\rm DM}=\rho_{\rm DM}/m_{\rm DM}$

1) Shape of spectrum

2) Normalization of the signal





Final Fluxes: γ, ν

❖ Cosmic rays from DM annihilation is described by

$$\Phi_i(\psi, E) = \sigma v \frac{dN_i}{dE} \frac{1}{8\pi m_{DM}^2} \int_{\text{line of sight}} ds \rho^2(r(s,\psi))$$

number density of DM
$n_{DM}=\rho_{DM}/m_{DM}$

1) Shape of spectrum

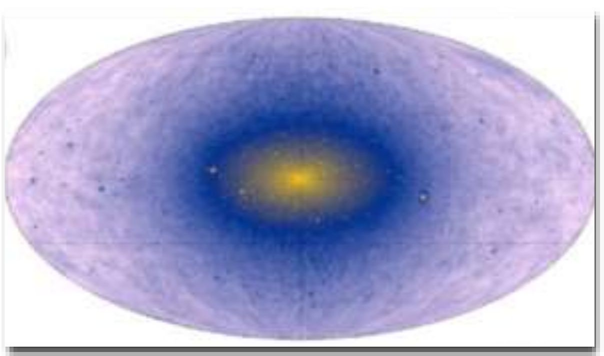
2) Normalization of the signal

γ, ν

3) γ, ν: Signal concentrated around the GC,

Spherical symmetry, Morphology

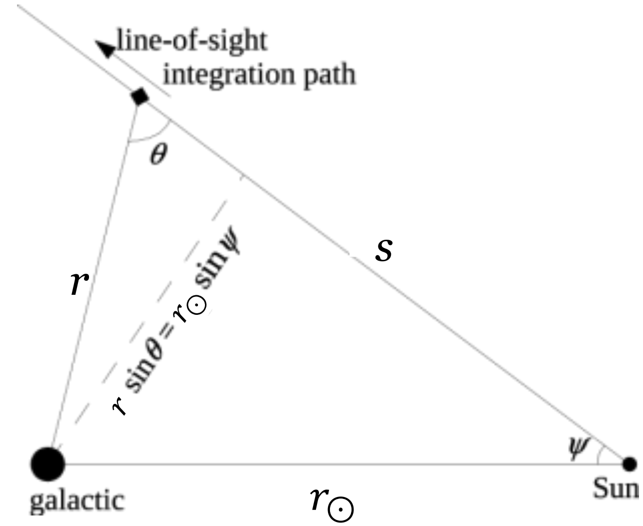
determined by the DM distribution



Final Fluxes: γ, ν

- Cosmic rays from DM annihilation is described by

$$\Phi_i(\psi, E) = \sigma v \frac{\mathrm{d}N_i}{\mathrm{d}E} \frac{1}{8\pi m_{\mathrm{DM}}^2} \int_{\text{line of sight}} \mathrm{d}s\, \rho^2(r(s,\psi))$$



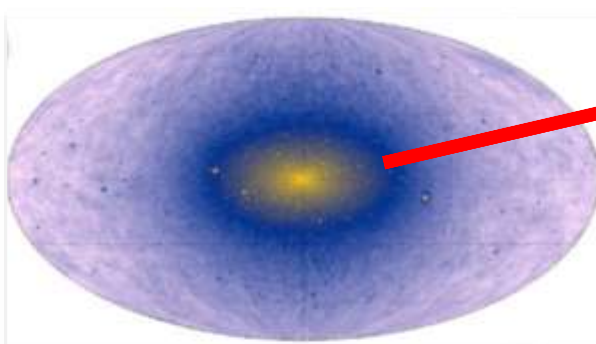
number density of DM
$n_{\mathrm{DM}} = \rho_{\mathrm{DM}}/m_{\mathrm{DM}}$

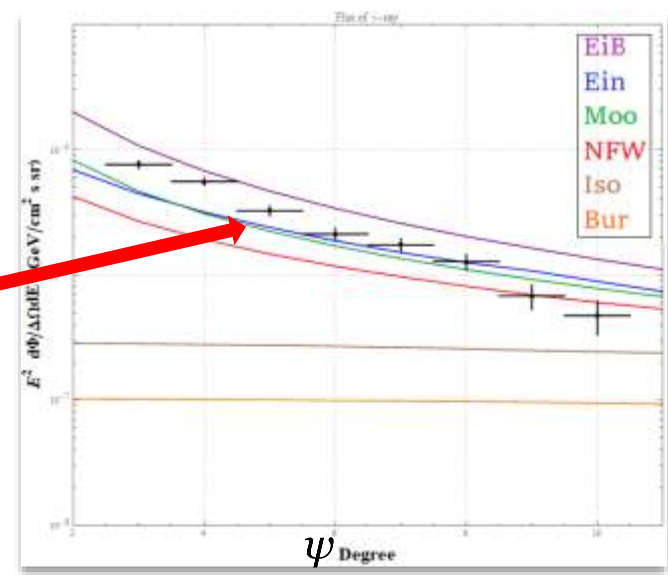
1) Shape of spectrum

2) Normalization of the signal

γ, ν

3) γ, ν: Signal concentrated around the GC, Spherical symmetry, Morphology determined by the DM distribution

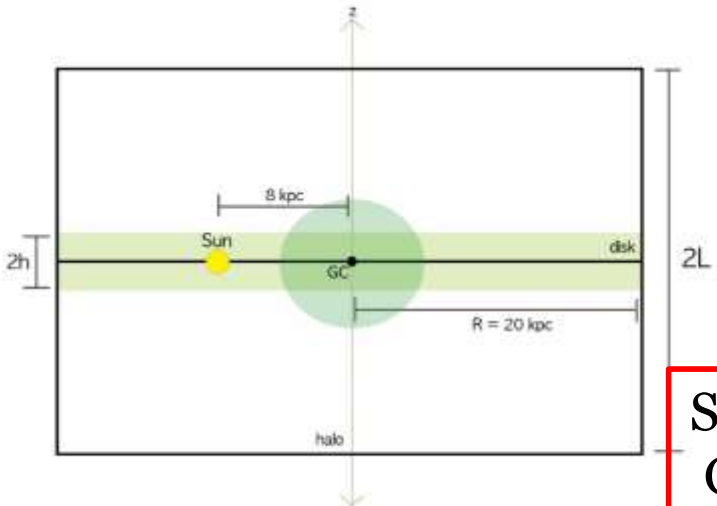




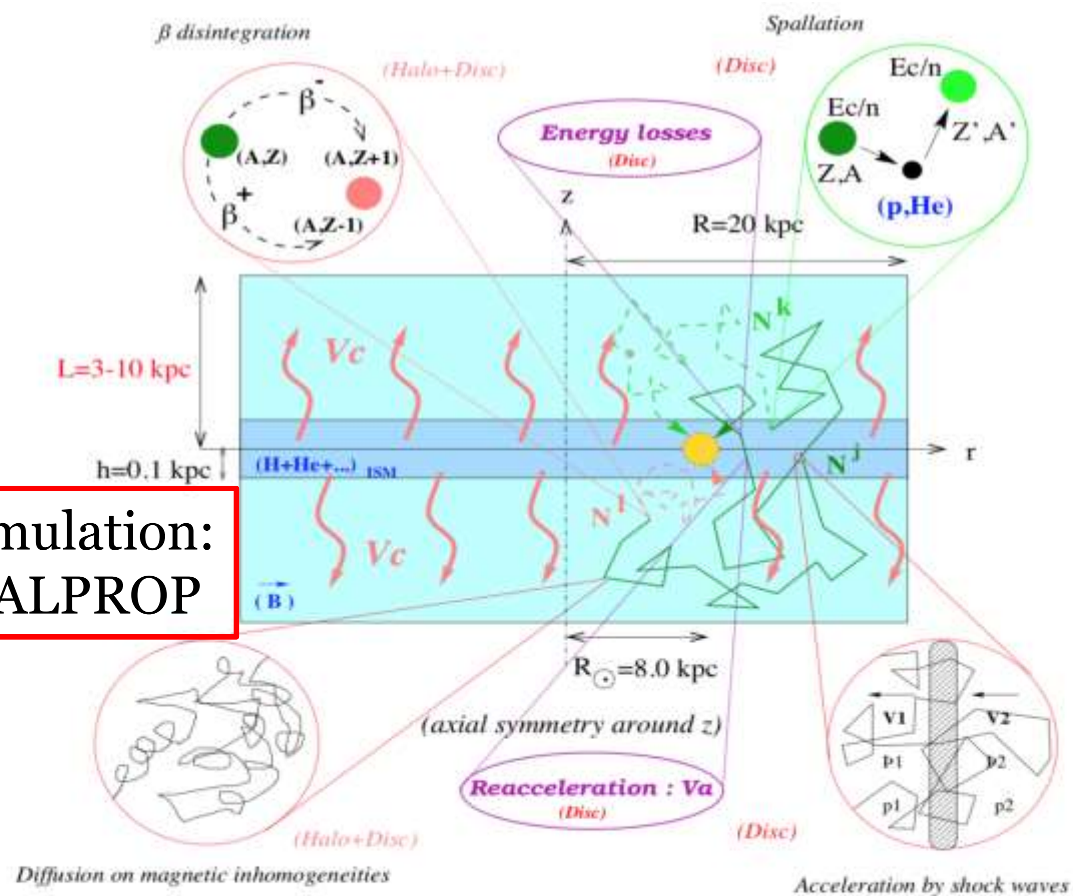

Life is not easy for
any for us.
Marie Curie

Propagation of Charged Particles

Diffusion zone



Simulation: GALPROP



Hints from Cosmic-Rays?

❖ DM signatures in cosmic-ray observations?

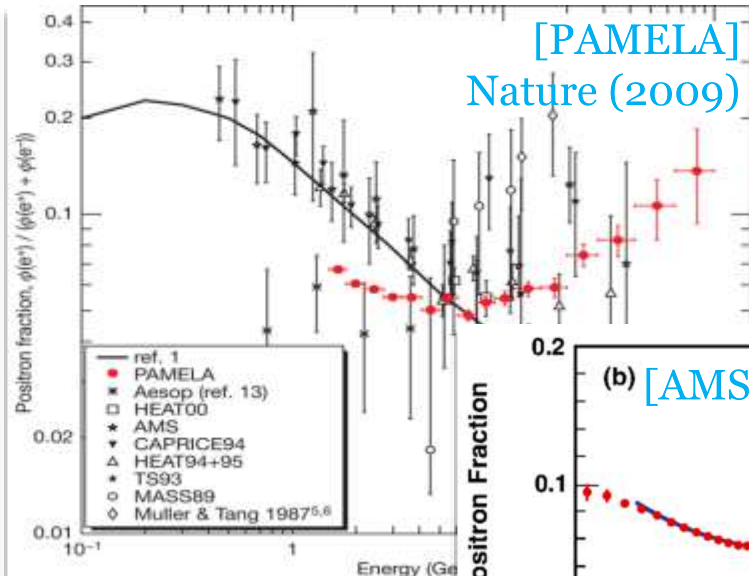
- SPI/INTEGRAL ($\gamma \rightarrow e^+$): 511 keV line
- PAMELA ($e^\pm$, $p^\pm$, …): e^+ excess
- ATIC (e^-+e^+): e^-e^+ excess
- Fermi-LAT (e^-+e^+, γ): e^-e^+ excess, 130 GeV line, GeV excess
- AMS-02 ($e^\pm$, $p^\pm$, …): e^+ ($\bar{p}$) excess
- XMM-Newton (X-ray): 3.5 keV line
- IceCube (ν): PeV events
- …

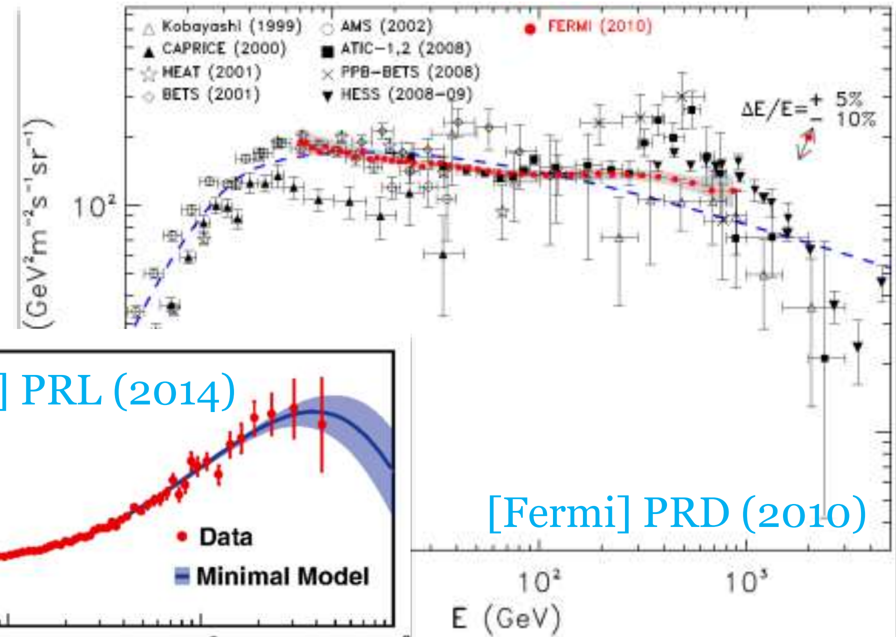
Hints from Cosmic-Rays?

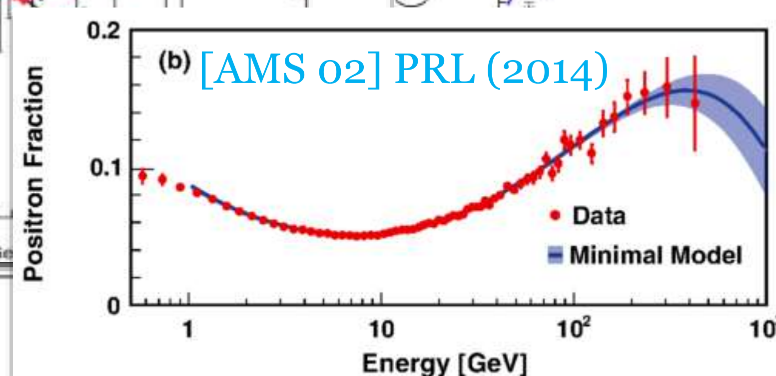
❖ DM signatures in cosmic-ray observations?

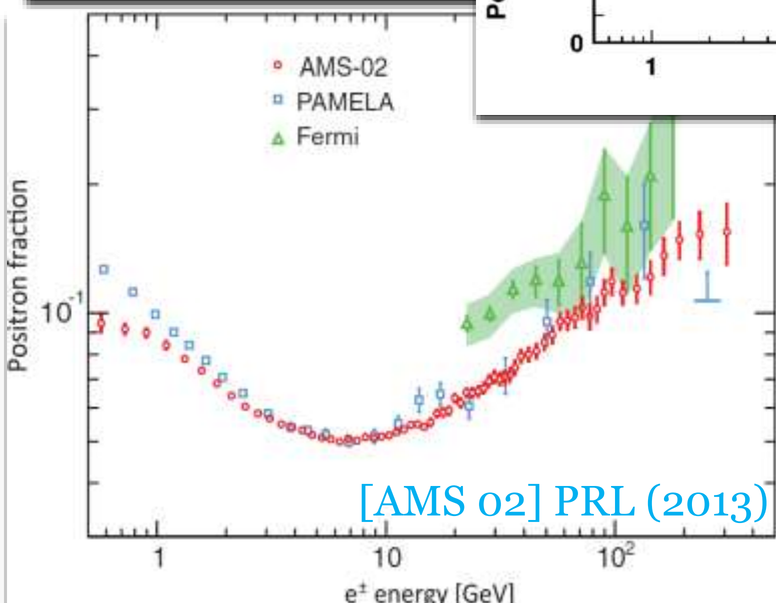
- SPI/INTEGRAL ($\gamma \rightarrow e^+$): 511 keV line
- PAMELA ($e^\pm$, $p^\pm$, …): e^+ excess
- ATIC (e^-+e^+): e^-e^+ excess
- Fermi-LAT (e^-+e^+, γ): e^-e^+ excess, 130 GeV line, GeV excess
- AMS-02 ($e^\pm$, $p^\pm$, …): e^+ ($\bar{p}$) excess
- XMM-Newton (X-ray): 3.5 keV line
- IceCube (ν): PeV events
- …

DM Indirectly Detected? ($e^{\pm}$)







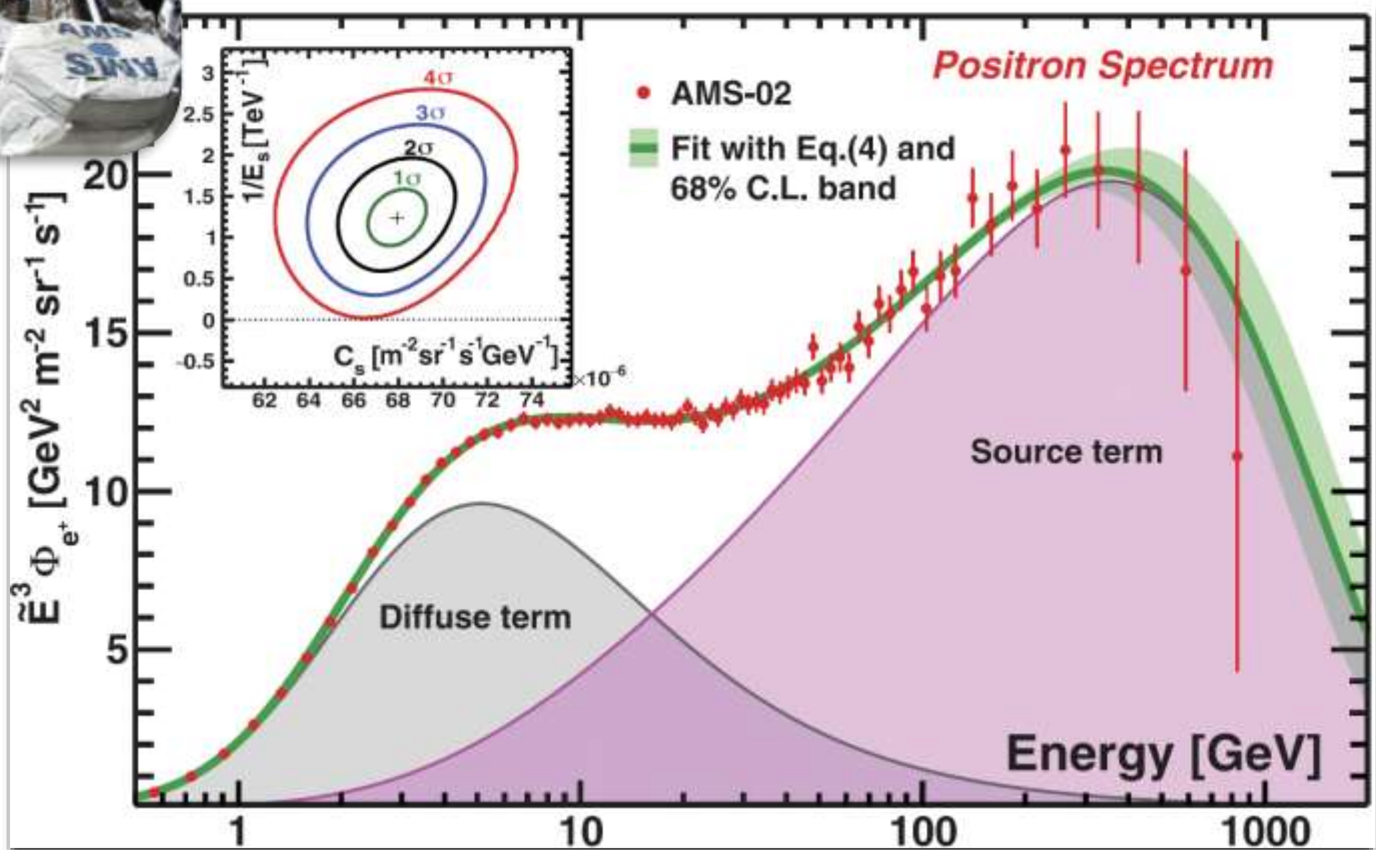


❖ PAMELA, Fermi-LAT, AMS-02:

➔ Excess in e^+/e^- fraction and $e^+ + e^-$ flux

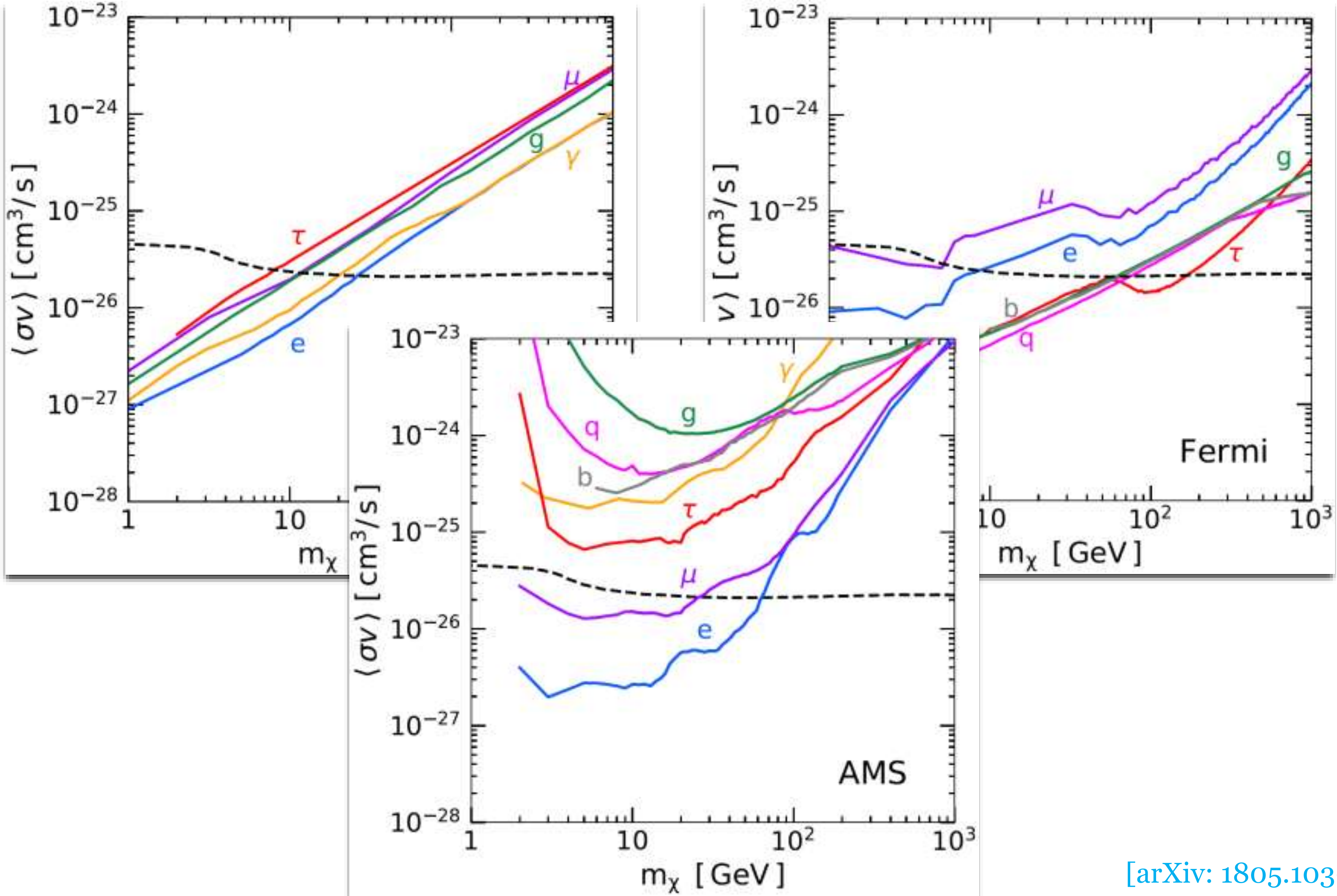
❖ Require new sources of e^+ & e^-

e^+ Excesses: AMS-02



[AMS 02] PRL (2019)

Status of Indirect Searches



[arXiv: 1805.10305]

Exercises

3. Nuclear recoil spectrum in DM direct detection:

(a) $v_{\min} = \sqrt{E_R m_N / 2\mu_{\chi N}^2} = \frac{m_\chi + m_N}{m_\chi} \sqrt{E_R / 2m_N}$

(b) Shape of nuclear recoil spectrum (dependence on m_χ)

4. Fluxes of DM annihilation products, e.g., $e^\pm, \bar{p}$:

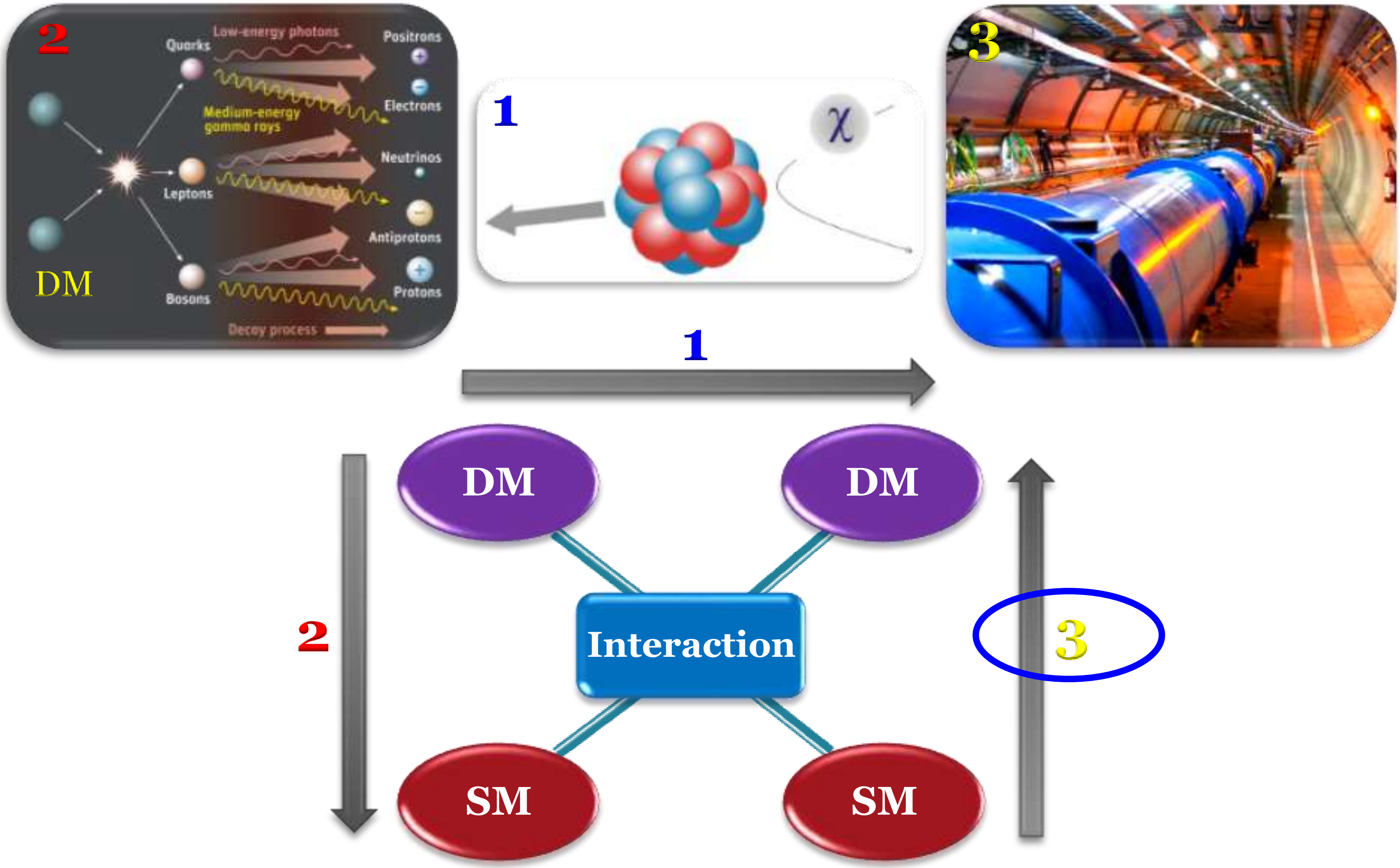
(a) Annihilation cross section dependence

(b) m_χ dependence

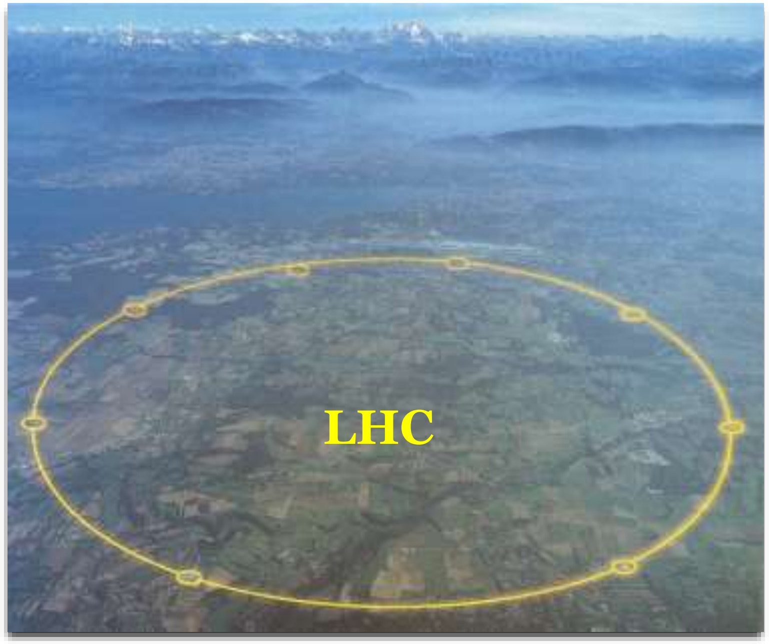
5. Collider

Direct Production

DM Production @ Colliders

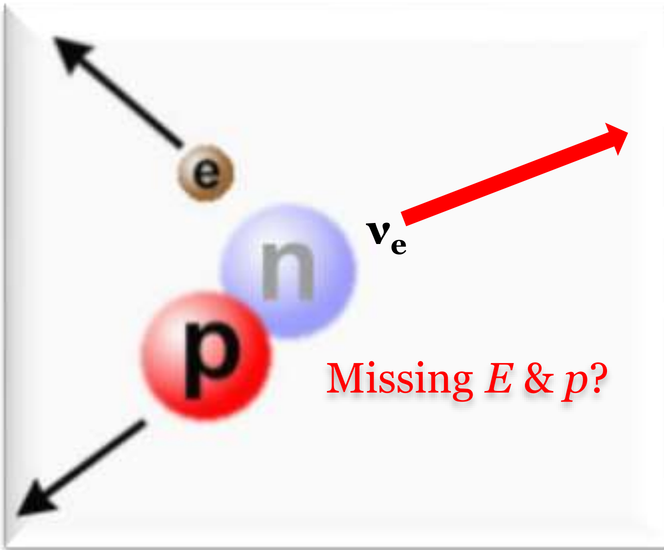


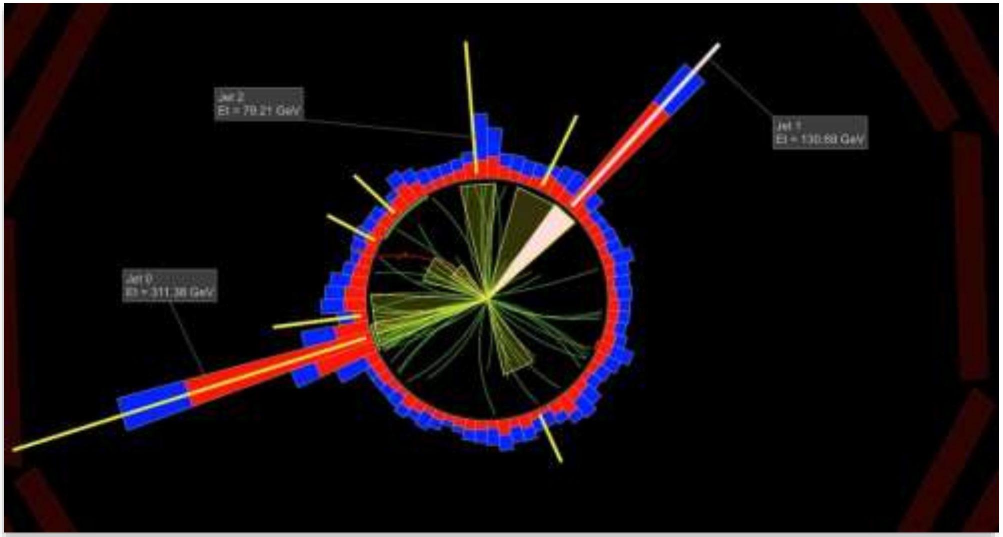
Collider Physics



- Production of heavy particles (e.g. super-partner, Z', t', B, ...) ← $E=mc^2$
- LHC Run I & II, Belle I: no conclusive evidence of DM yet
- LHC Run III (13.6 TeV), Belle II (high luminosity): have been upgraded & now running!

DM at Colliders

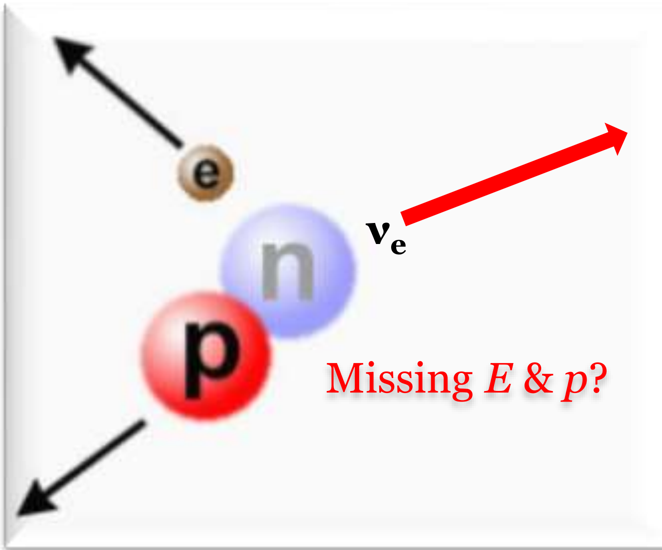


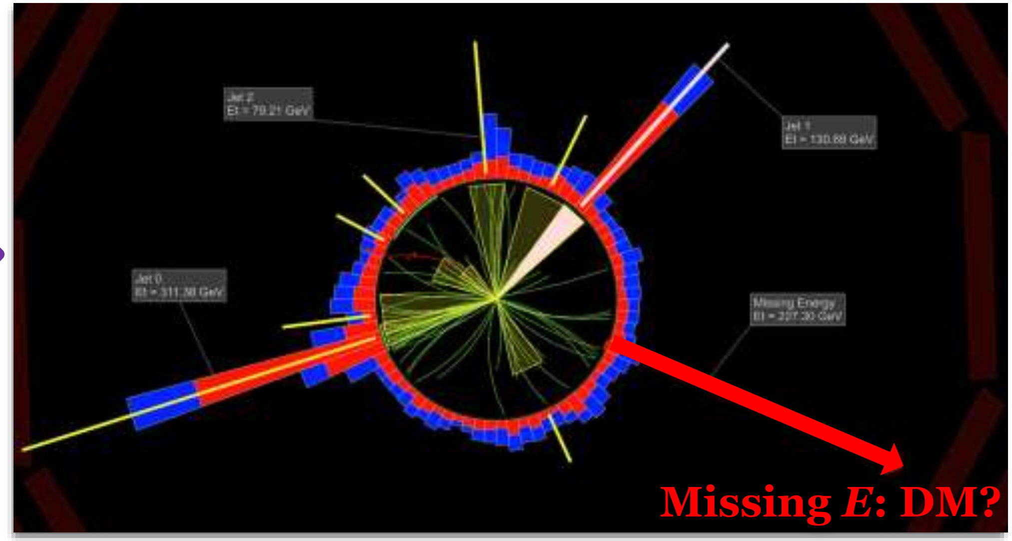


Pauli(1930) Fermi(1932)

- ν: to explain Missing *E*, *p*, *S* in the beta decay
- Nature(1934): “Too remote from reality!”

DM at Colliders





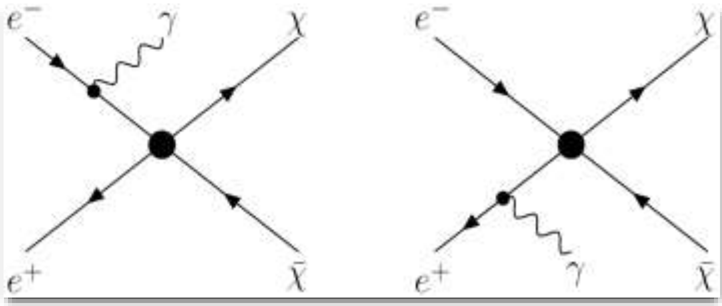

Pauli(1930)

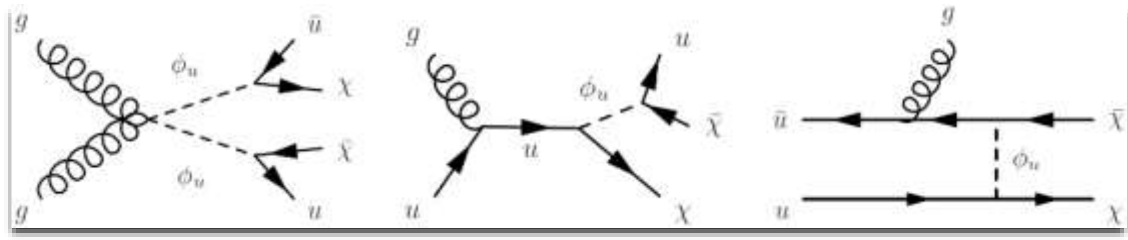

Fermi(1932)

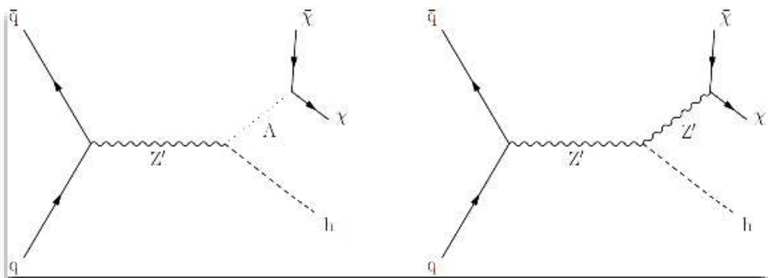
- ν: to explain Missing E, p, S in the beta decay
- Nature(1934): “Too remote from reality!”
- DM cannot be directly detected

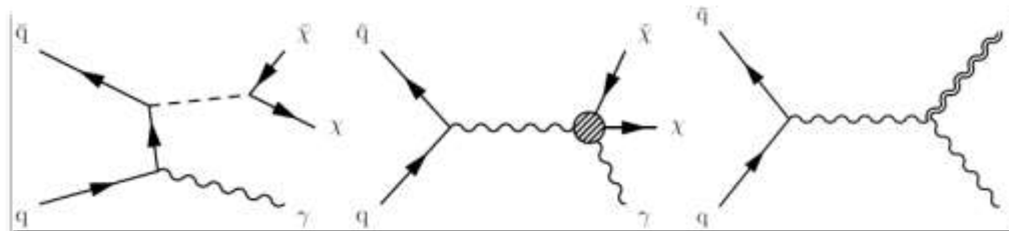
  → regarded as Missing E

Collider Searches







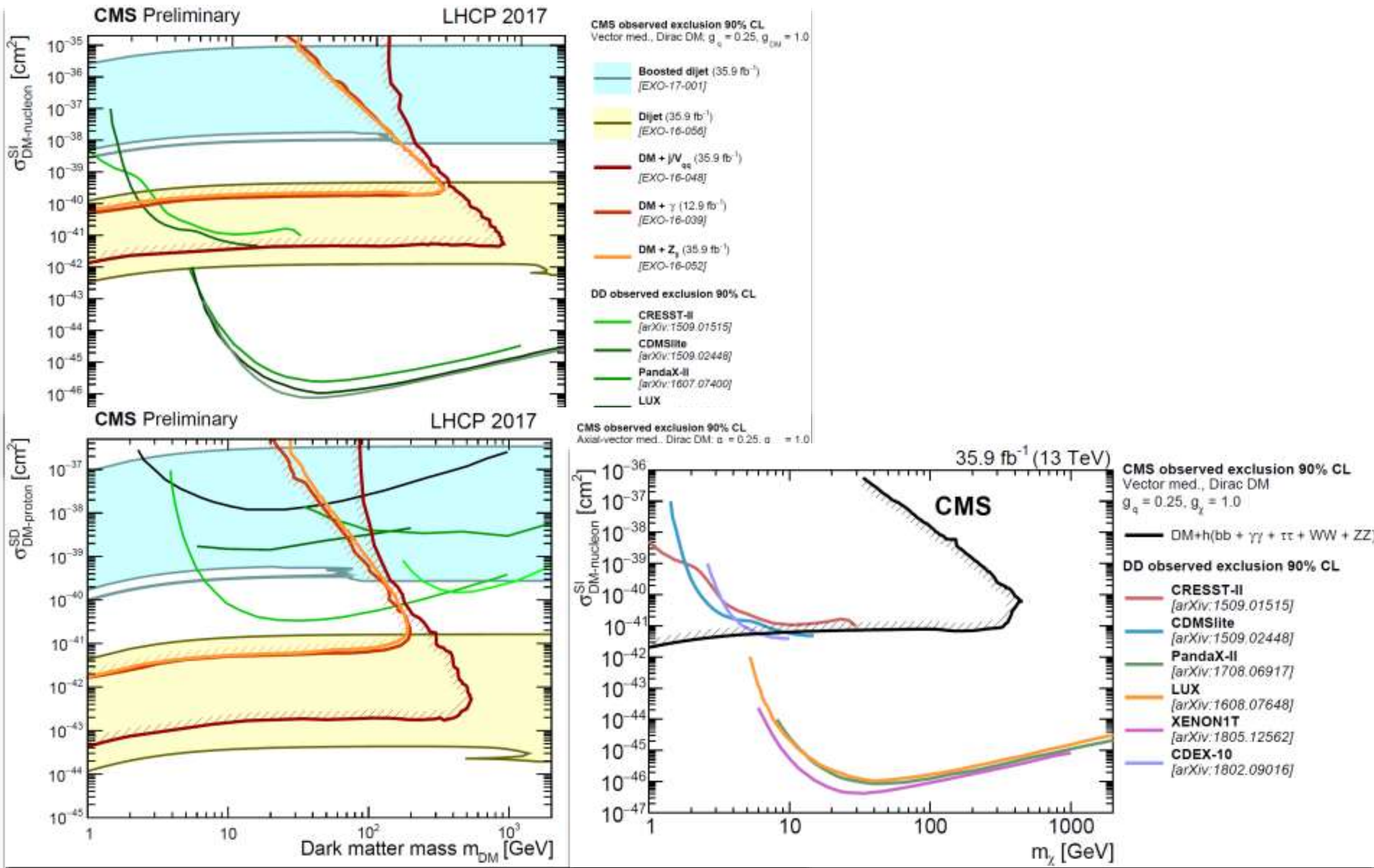


- LEP/ILC/Belle II/LHC/…: mono-X+E_T

  → limits on $\sigma_{\chi\text{-}e/N}$ & $\langle\sigma v\rangle_{\chi\chi\to ll,\, qq,\, \ldots}$

Constraints on DM models

Current Status of LHC Searches

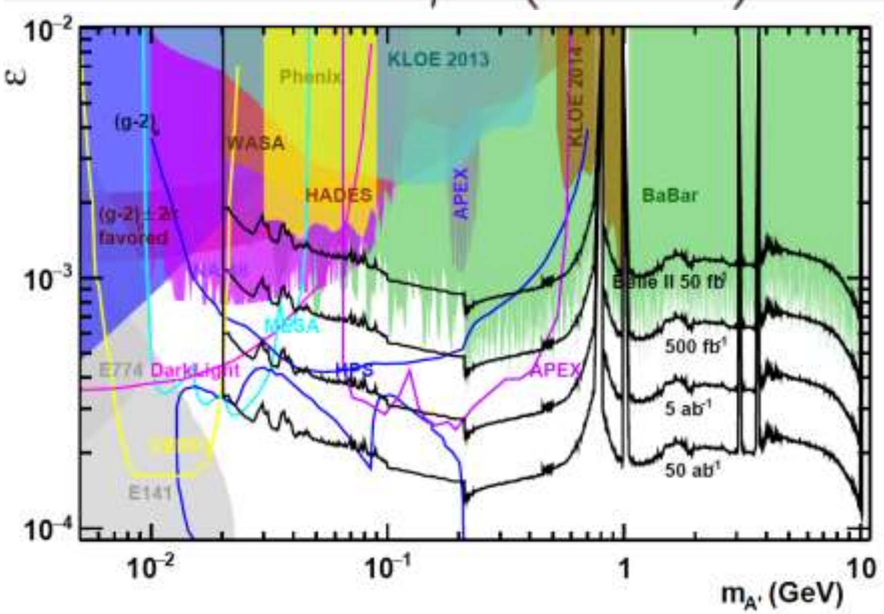


Dark Photon in Belle II

Prospects with Belle II

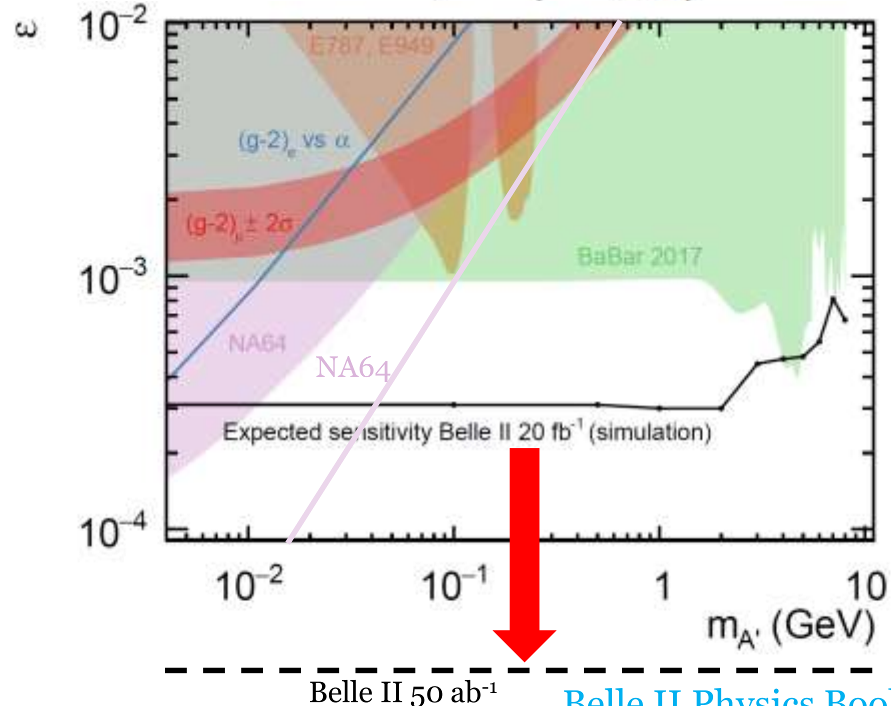
$m_X < 2m_{DM}$

$e^+e^- \to \gamma\, A'(\to \ell^+\ell^-)$



$m_X > 2m_{DM}$

$e^+e^- \to \gamma\, A'(\to \chi\bar{\chi})$



Belle II Physics Book
[arXiv: 1808.10567]

Something New?

DM Landscape: A Very Wide Mass Range

Ultra-light
(QCD) axion,
hidden photon,
scalar field,
fuzzy,
non-thermal

Super-light
sterile ν,
axino,
warm DM,
can be
thermal

Light
SIMP,
ELDER,
can be
thermal

WIMP
well-motivated,
extensively
studied,
thermal
No firm
signal yet!

Super-heavy
composite,
WIMPzilla,
Q-ball,
Fermi-ball,
dark-quark
nugget,
non-thermal

Astrophysical object
MACHO, PBH,
non-particle