Search for the Dark World

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Outline

- Introduction - history & evidence
- What is DM? - candidates
- How can we find?
  - ✓ Direct searches
  - ✓ Indirect searches - cosmic-ray
  - ✓ DM & Collider

References

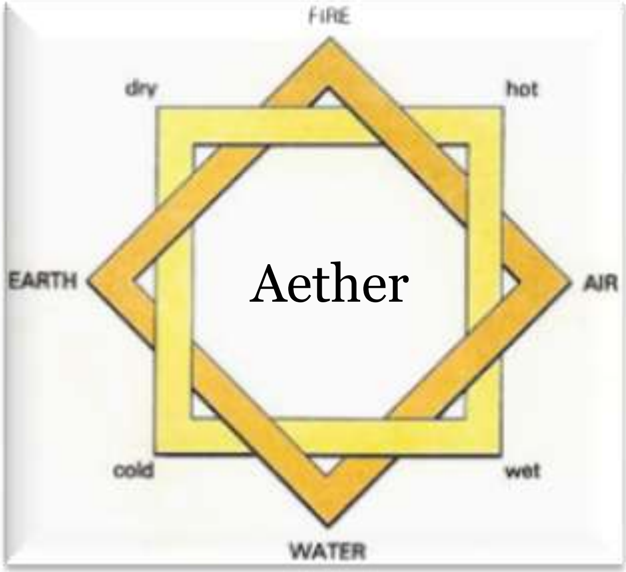
- The Early Universe (by Edward Kolb & Michael Turner)
- Supersymmetric DM (ph/9506380 by G. Jungman, M. Kamionkowski, K. Griest)
- Particle DM: Evidence, Candidates and Constraints (ph/0404175 by G. Bertone, D. Hooper, J. Silk)
- Yet Another Introduction to DM (1705.01987 by Tilman Plehn)
- Review of mathematics, numerical factors, and corrections for DM experiments based on elastic nuclear recoil (Astroparticle Physics Vol.6, Issue 1 (1996) 87-112 by J.D. Lewin & P.F. Smith)

1. Introduction

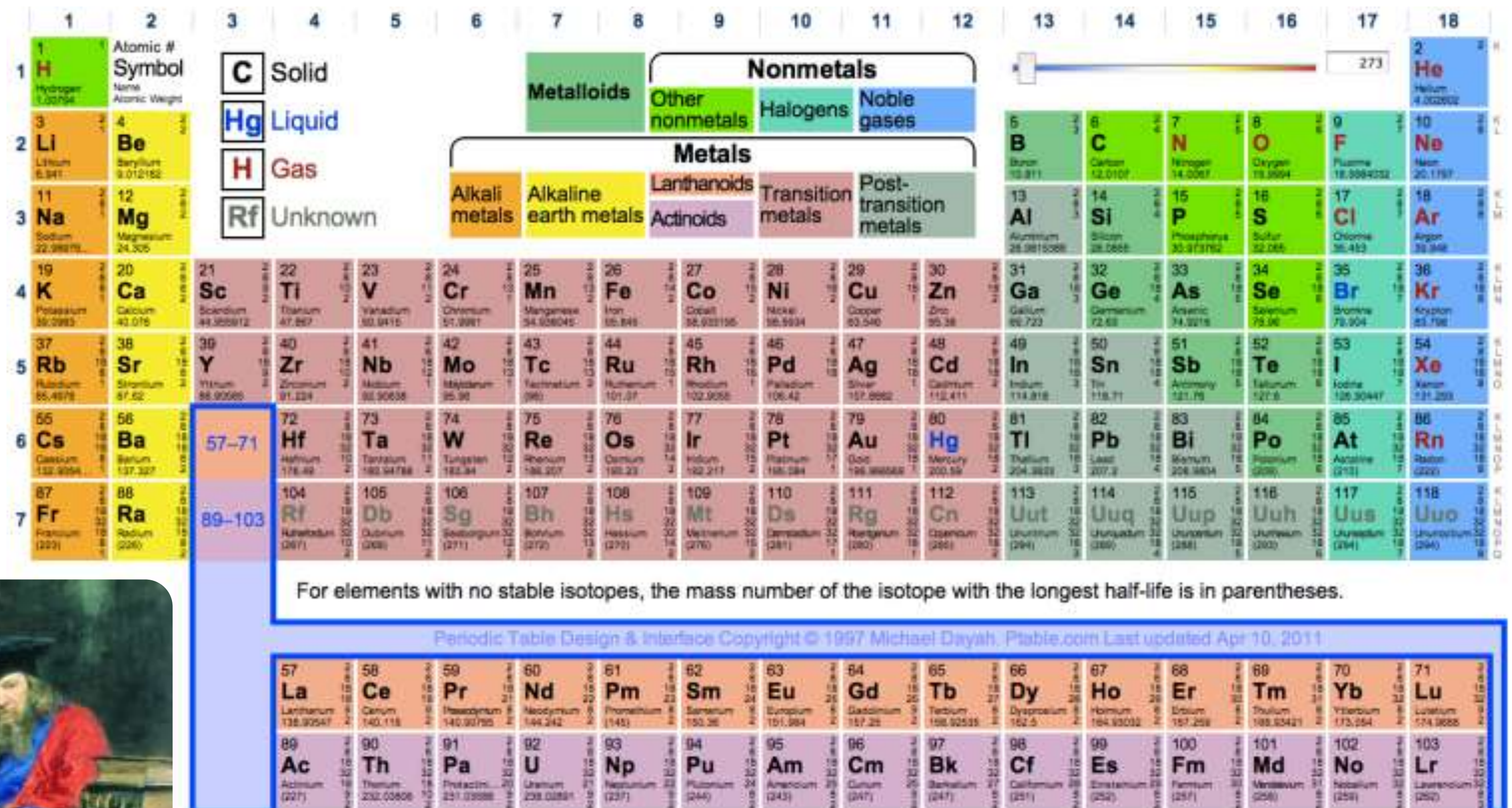
history & evidence

Eternal Questions

❖ Ancient Greek: 4 basic elements



19~20th c: Periodic Table



Dmitri Mendeleev
(1869)

Now: Standard Model (SM)

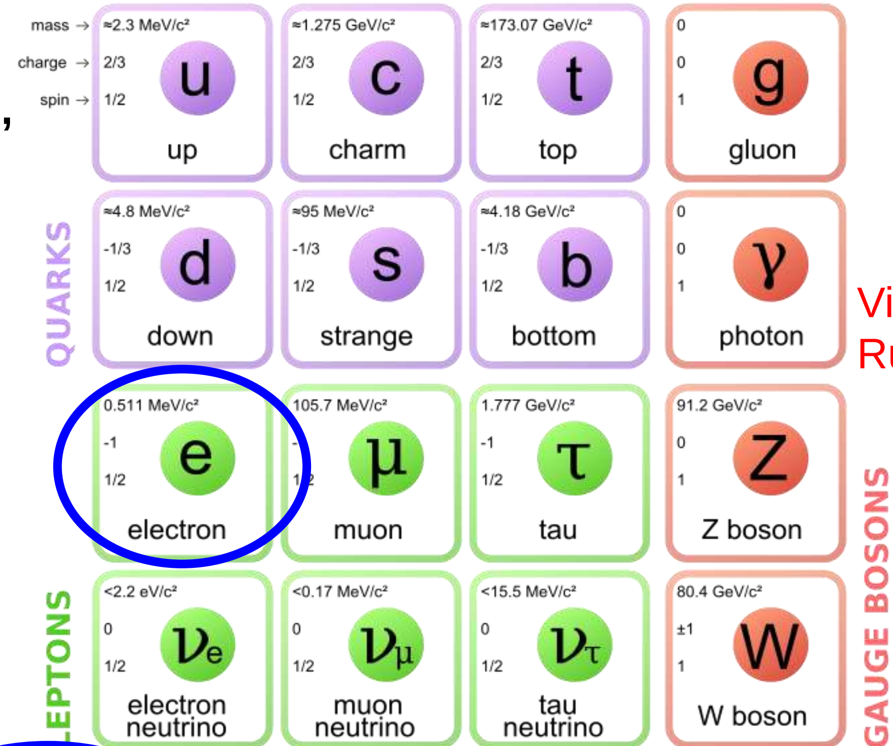
SLAC/BNL, 1974

CDF/D0, 1995

E288, 1977

Pluto, 1978
Jade/Pluto/Petra, 1979

1st evidence, SLAC, 1968



Villard, 1900
Rutherford, 1903

UA1/UA2, 1983

Thomson, 1897

Anderson 1936

SLAC-LBL , 1975

Cowan-Reines, 1956

BNL, 1962

DONUT, SLAC-LBL , 2000

GeV ~ m_p

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CDF/D0, 1995

E288, 1977

Pluto, 1978
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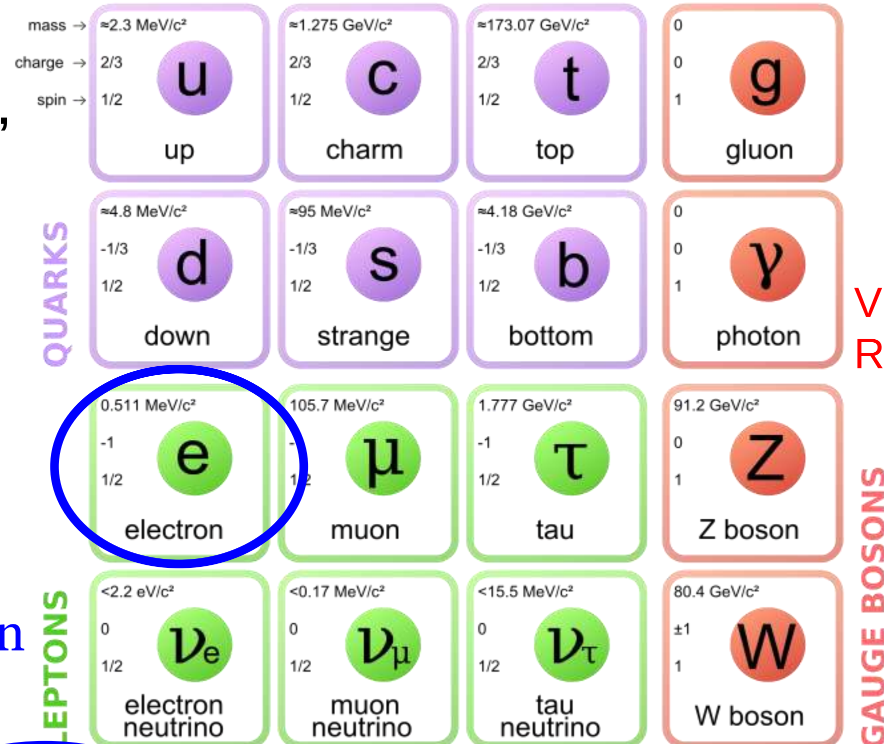
1st evidence, SLAC, 1968



Villard, 1900
Rutherford, 1903

UA1/UA2, 1983

➢ Pauli exclusion principle II

Thomson, 1897

Anderson 1936

SLAC-LBL , 1975

Cowan-Reines, 1956

BNL, 1962

DONUT, SLAC-LBL , 2000

GeV ~ m_p

Higgs (1964)!

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

Chicago (USA)

Geneva (Europe)

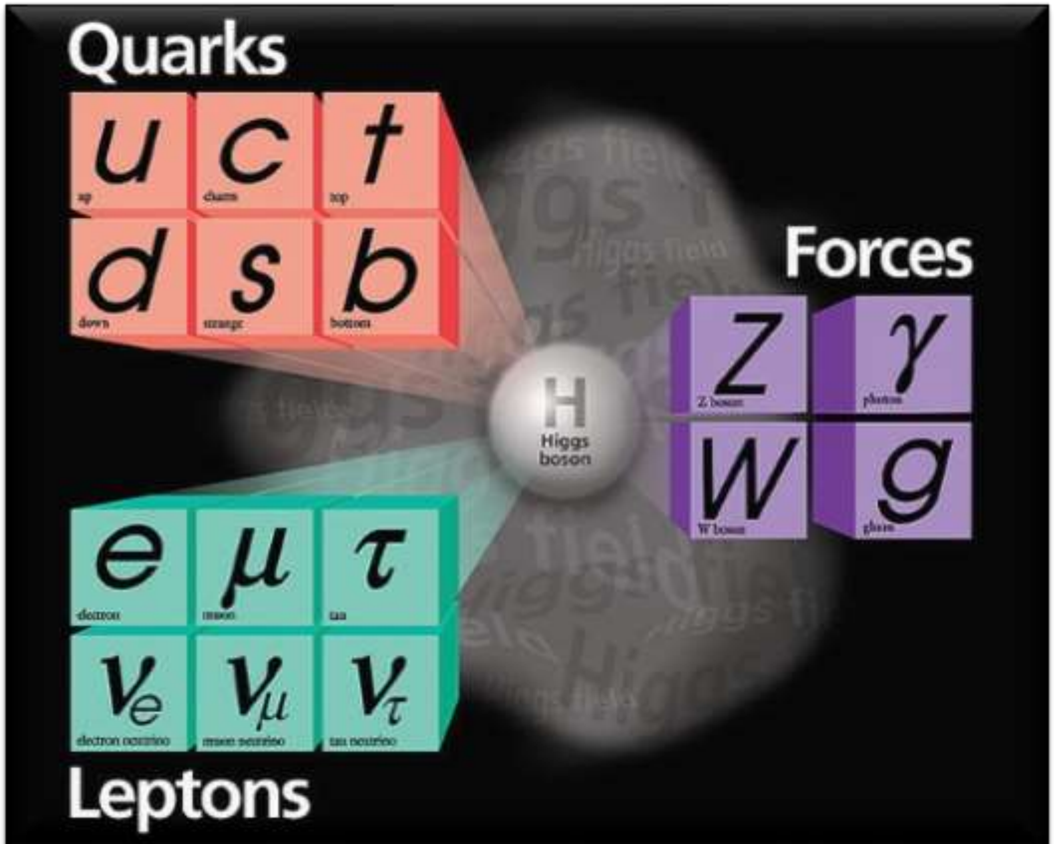
Higgs in Europe ?

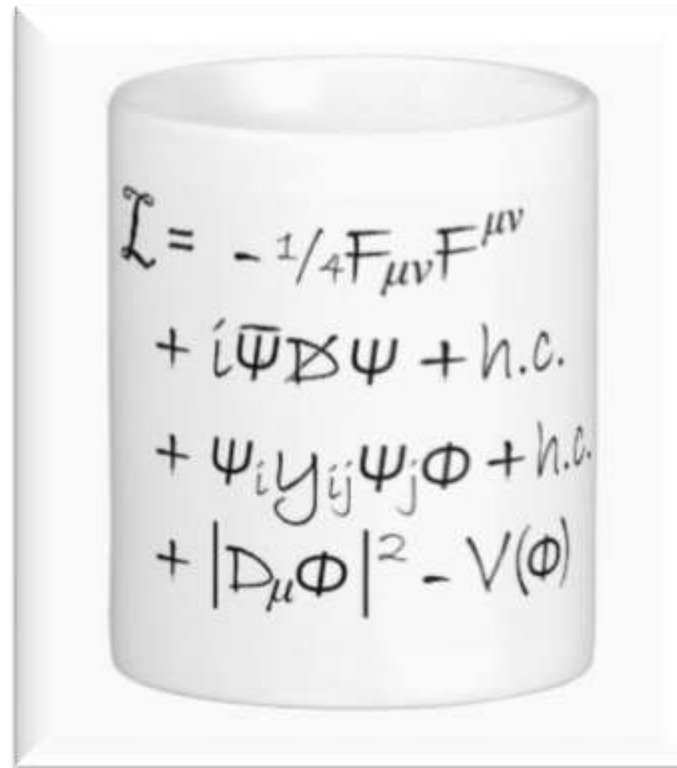
- Pauli exclusion principle II

Higgs (2012)!

Higgs is discovered!

Standard Model (SM)

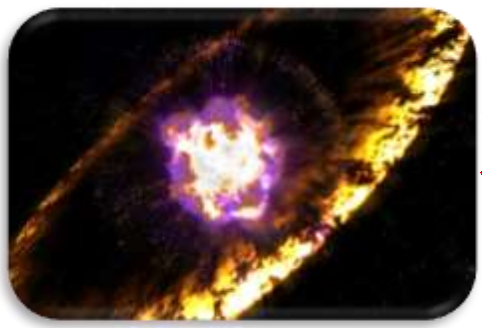




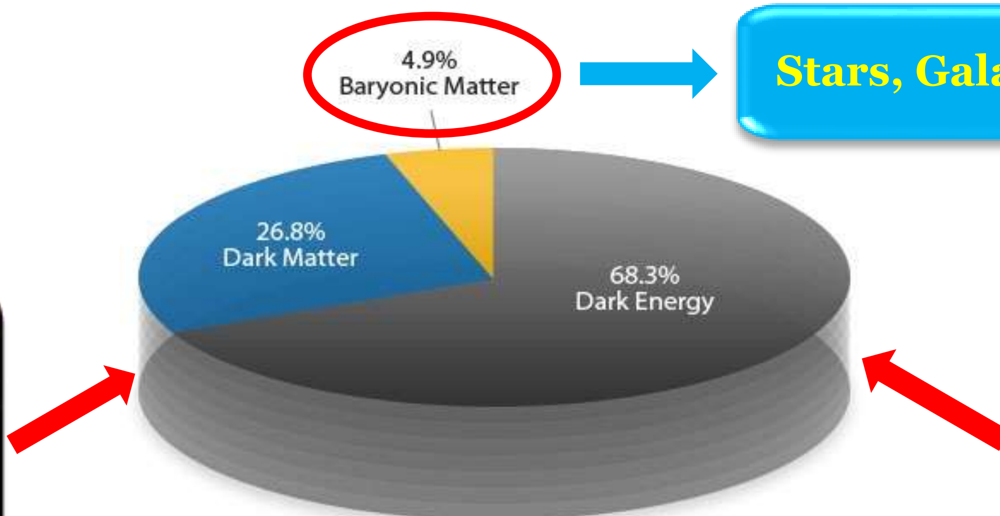

NEED

Message from Cosmology

❖ Modern cosmology → Cosmic pie



Supernova



Stars, Galaxies, H, …

Planck → CMB

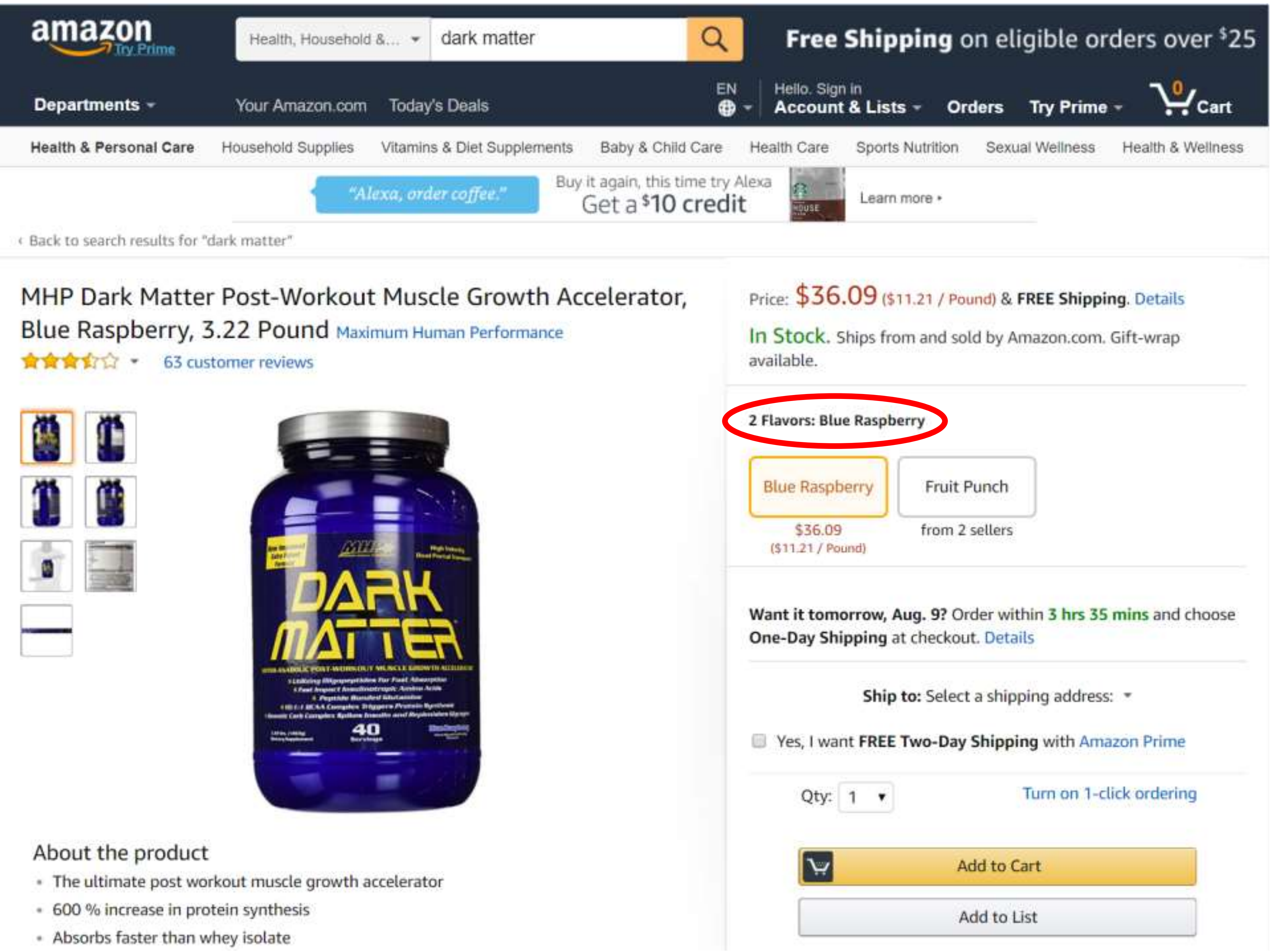
❖ The standard model explains only ~5% of the M-E of the Universe.

Question in the New Century!

What's
the matter?

↓

What's
Dark Matter?


amazon Try Prime
Health, Household &...
dark matter
Free Shipping on eligible orders over $25
Departments
Your Amazon.com
Today's Deals
EN
Hello. Sign in
Account & Lists
Orders
Try Prime
0
Cart
Health & Personal Care
Household Supplies
Vitamins & Diet Supplements
Baby & Child Care
Health Care
Sports Nutrition
Sexual Wellness
Health & Wellness
"Alexa, order coffee."
Buy it again, this time try Alexa
Get a $10 credit
Learn more
‹ Back to search results for "dark matter"
MHP Dark Matter Post-Workout Muscle Growth Accelerator, Blue Raspberry, 3.22 Pound
Maximum Human Performance
63 customer reviews
DARK MATTER
40
About the product
The ultimate post workout muscle growth accelerator
600 % increase in protein synthesis
Absorbs faster than whey isolate
Price: $36.09 ($11.21 / Pound) & FREE Shipping. Details
In Stock. Ships from and sold by Amazon.com. Gift-wrap available.
2 Flavors: Blue Raspberry
Blue Raspberry
$36.09
($11.21 / Pound)
Fruit Punch
from 2 sellers
Want it tomorrow, Aug. 9? Order within 3 hrs 35 mins and choose One-Day Shipping at checkout. Details
Ship to: Select a shipping address:
Yes, I want FREE Two-Day Shipping with Amazon Prime
Qty: 1
Turn on 1-click ordering
Add to Cart
Add to List

Dark Matter (DM)

❖ Postulated by Fritz Zwicky in early 1930's

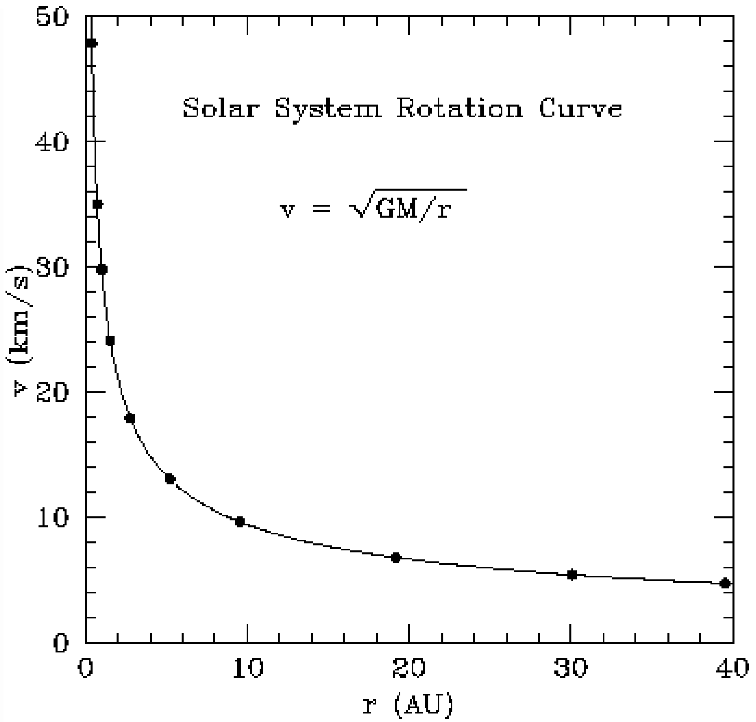
❖ Rediscovered by Vera Rubin in 1970

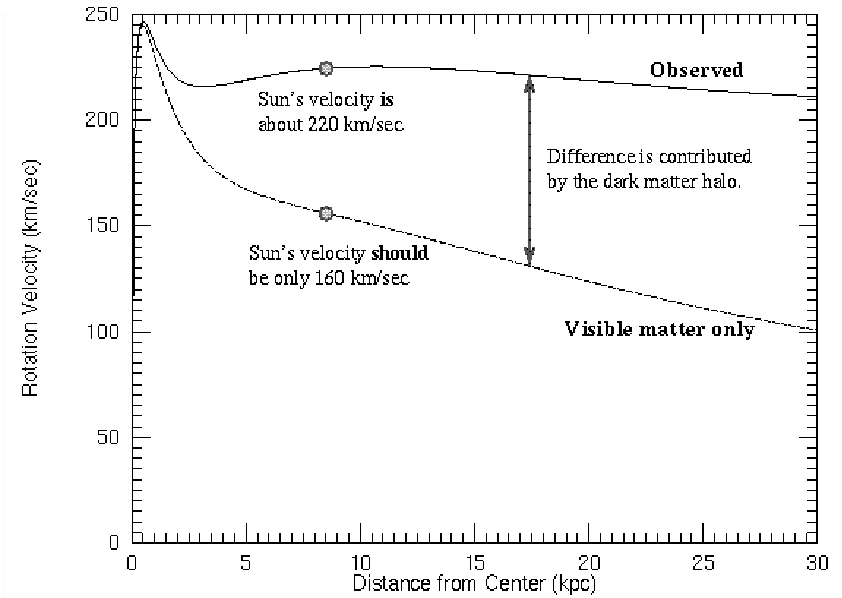
❖ **Compelling paradigm**:

- ✓ massive, non-luminous, non-relativistic (→ cold), stable particles
- ✓ ~ 1/4 of the Universe

Observational Evidence of Dark Matter

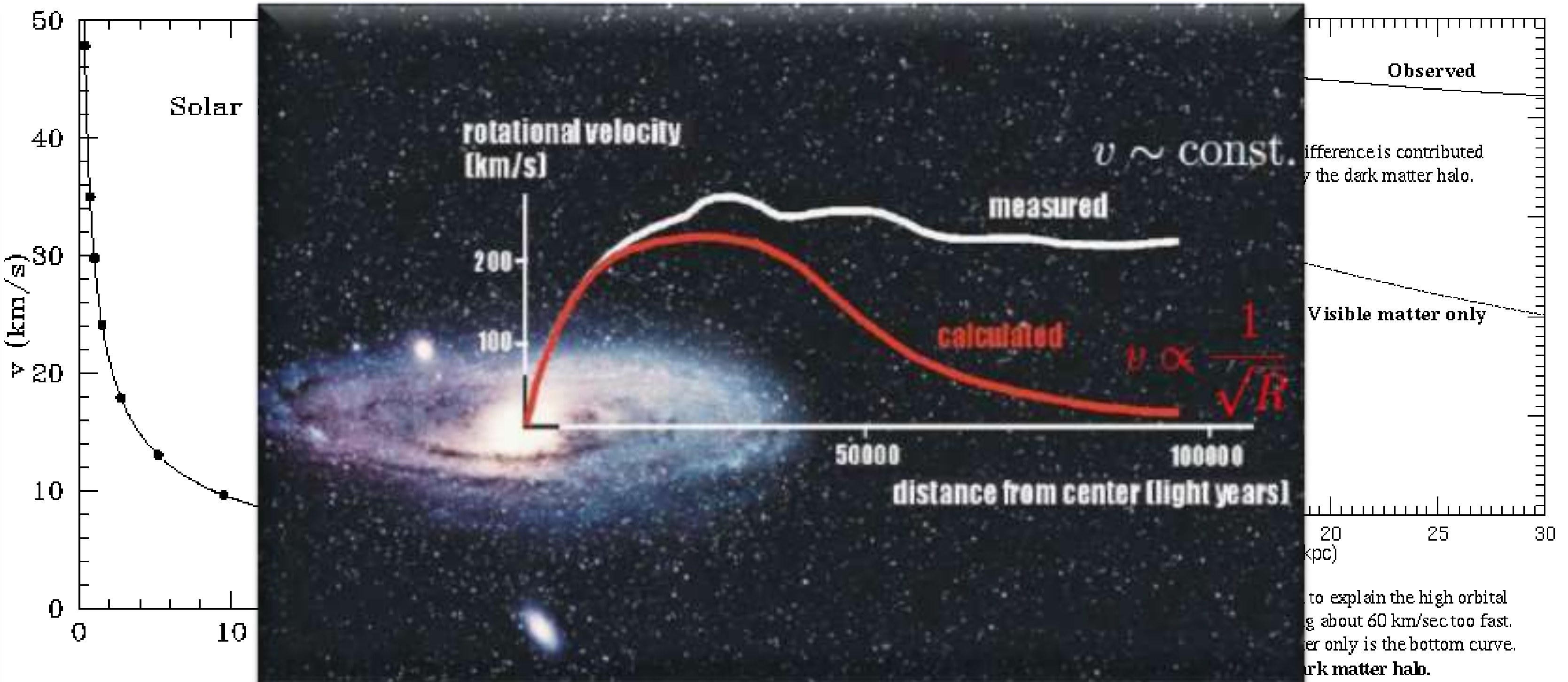
Galaxy Rotation Curve





The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two curves is evidence for a **dark matter halo.**

Galaxy Rotation Curve

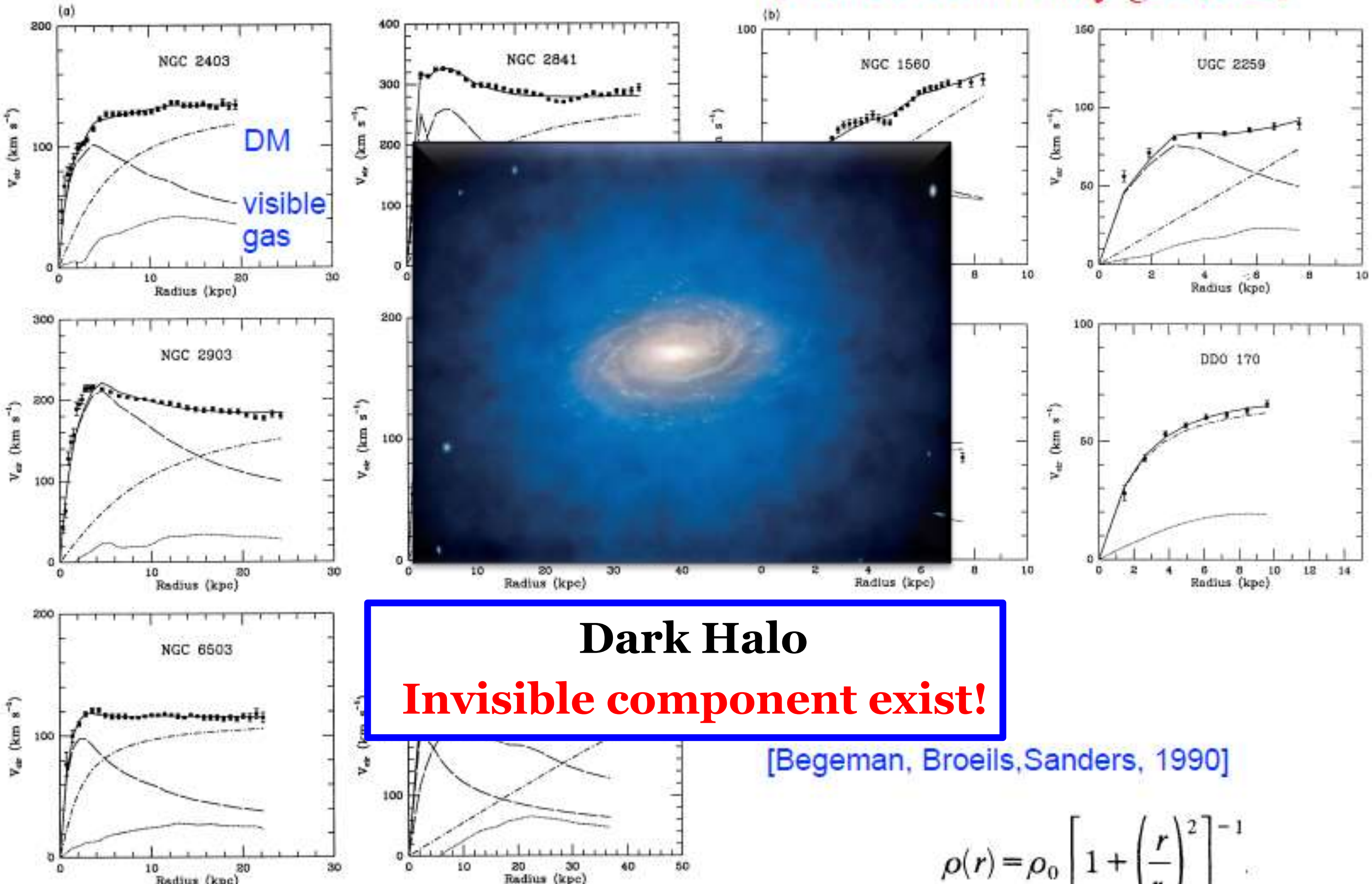


$$\frac{GMm}{r^2} = \frac{mv^2}{r} \rightarrow v \propto \sqrt{\frac{GM}{r}}$$

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

❖ Much more galaxies

(Lower luminosity galaxies)



Dark Halo

Invisible component exist!

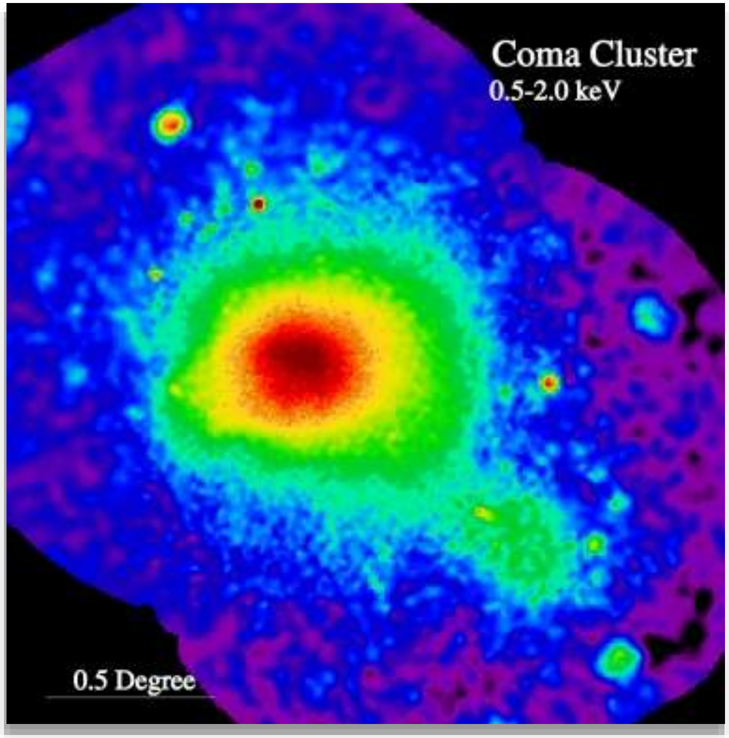
[Begeman, Broeils,Sanders, 1990]

$$\rho(r) = \rho_0 \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-1}$$

Figure 1. Three-parameter dark-halo fits (solid curves) to the rotation curves of sample galaxies. The rotation curves of the individual components are also shown: the dashed curves are for the visible components, the dotted curves for the gas, and the dash-dot curves for the dark halo. The fitting parameters are the mass-to-light ratio of the disc (M/L), the halo core radius (r_c), and the halo asymptotic circular velocity (V_h). The galaxies from the sample of Begeman are shown in (a) and the lower luminosity galaxies in (b). Best-fit values for the free parameters are given in columns 2, 3 and 4 of Table 2.

Coma Cluster

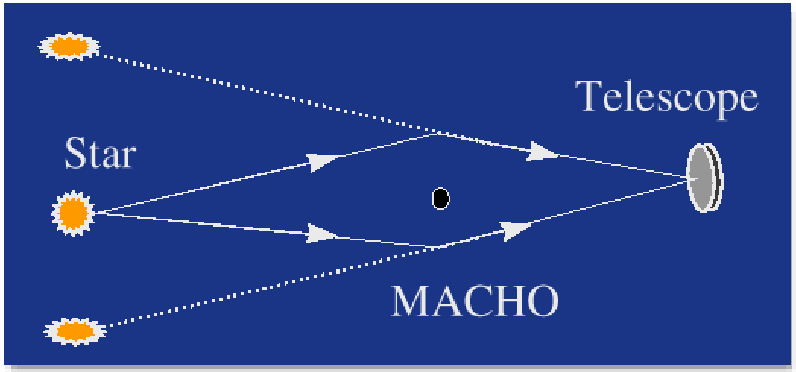
❖ The gravity of the cluster: too weak to contain the hot gas.
→ It would evaporate!: $T \propto v^2 \Leftrightarrow v^2 \propto GM/r$

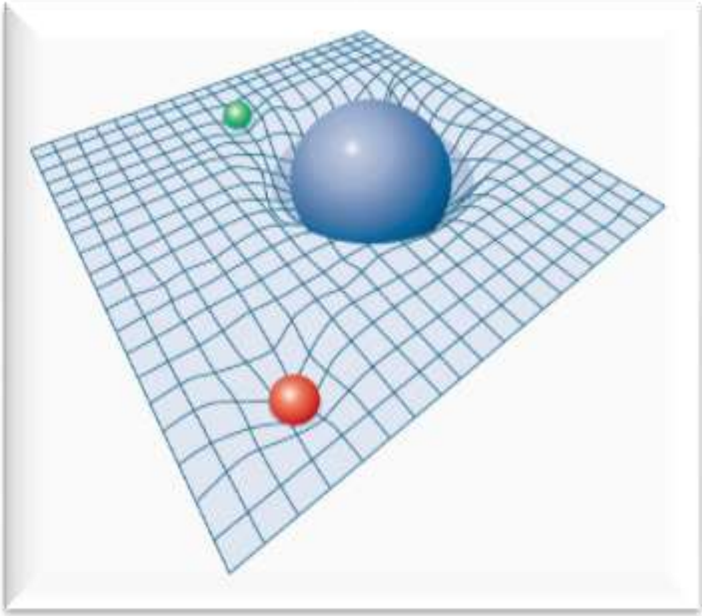


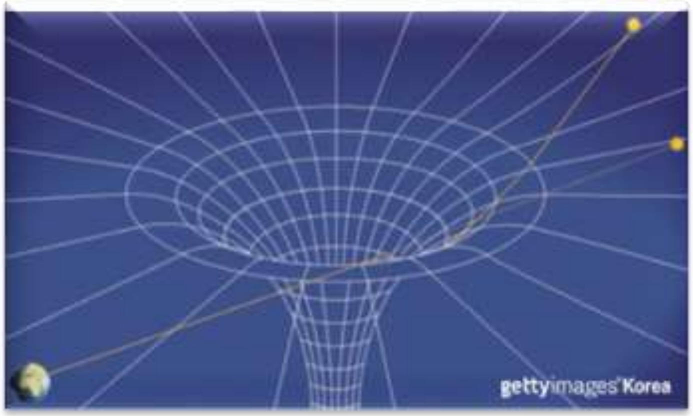
x-ray image from the ROSAT satellite

Gravitational Lensing

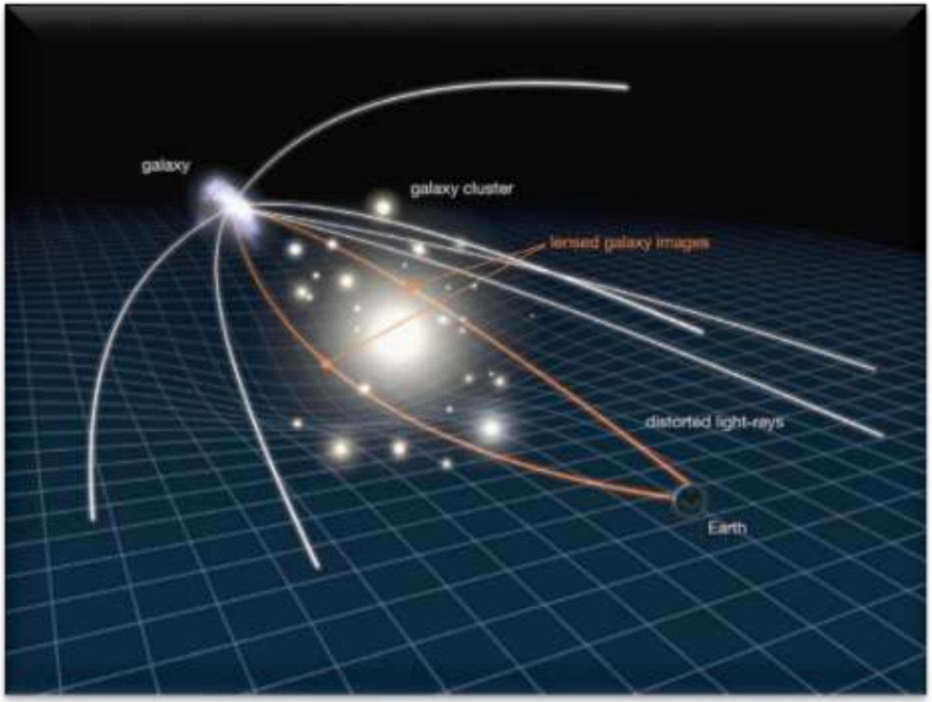
- General relativity: M distorts space-time
  ➔ When light passes around a massive object, it is bent!

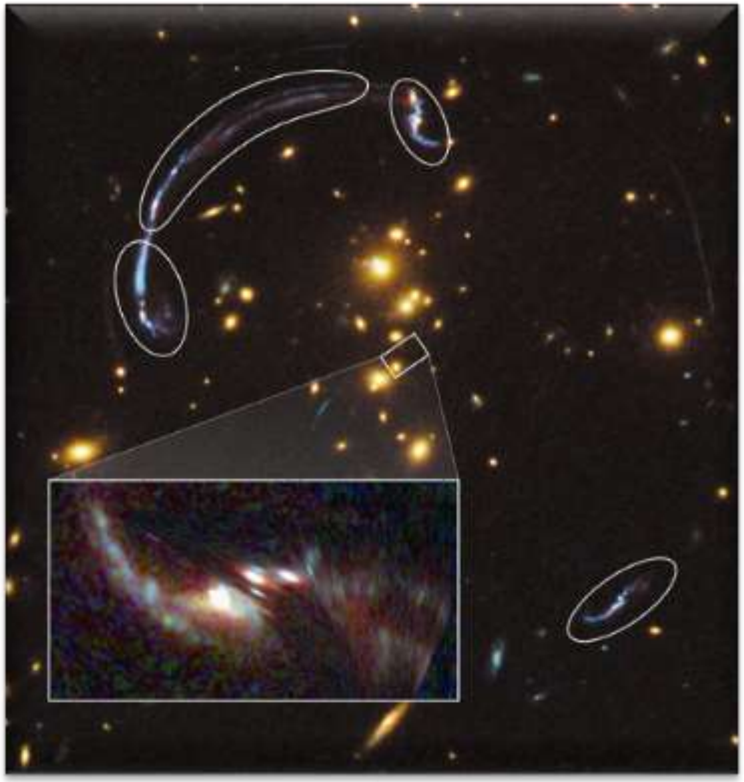






Gravitational Lensing





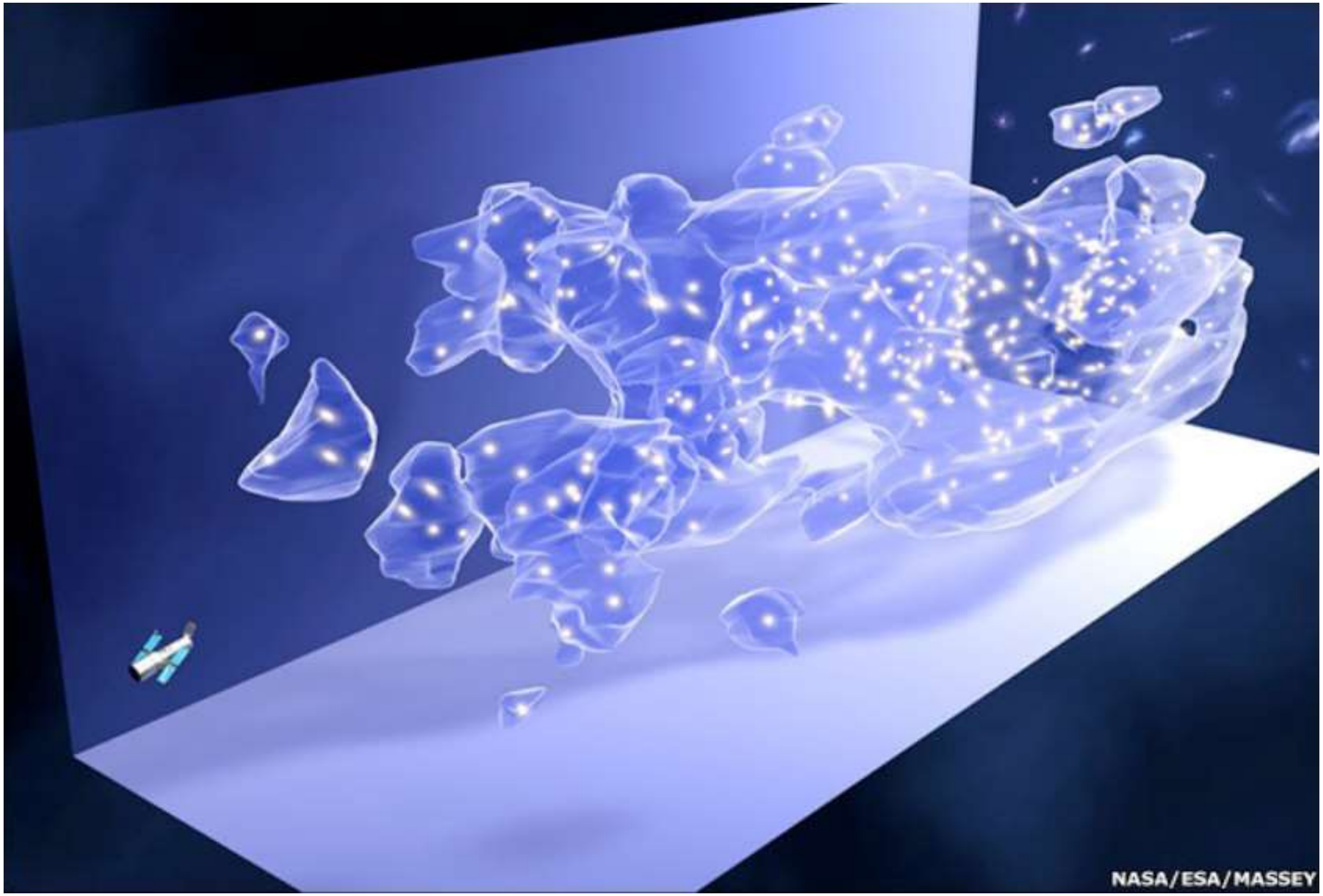
- Stars and hot gas:

  too small to bend the light from the background galaxies so much

  → **Great concentration of DM !**

Gravitational Lensing

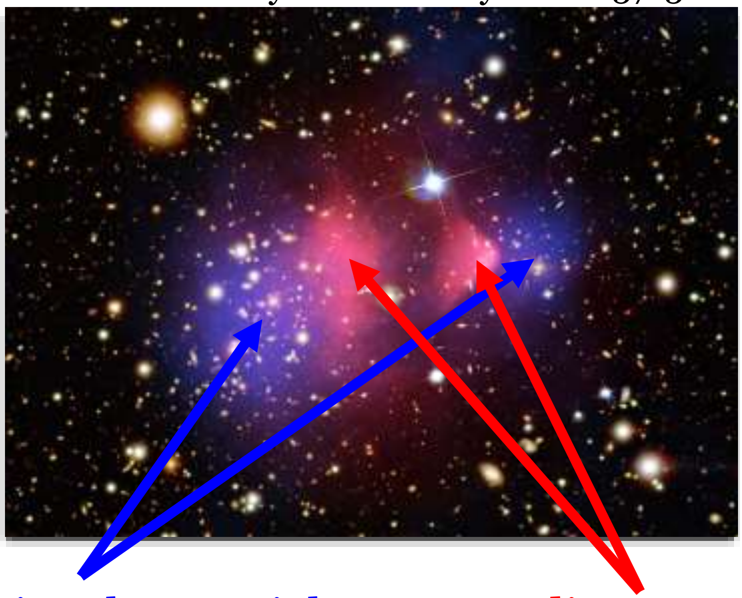
❖ Gravitational attraction of DM acts a template, pulling normal matter.
→ Large-scale structures!



Bullet Cluster

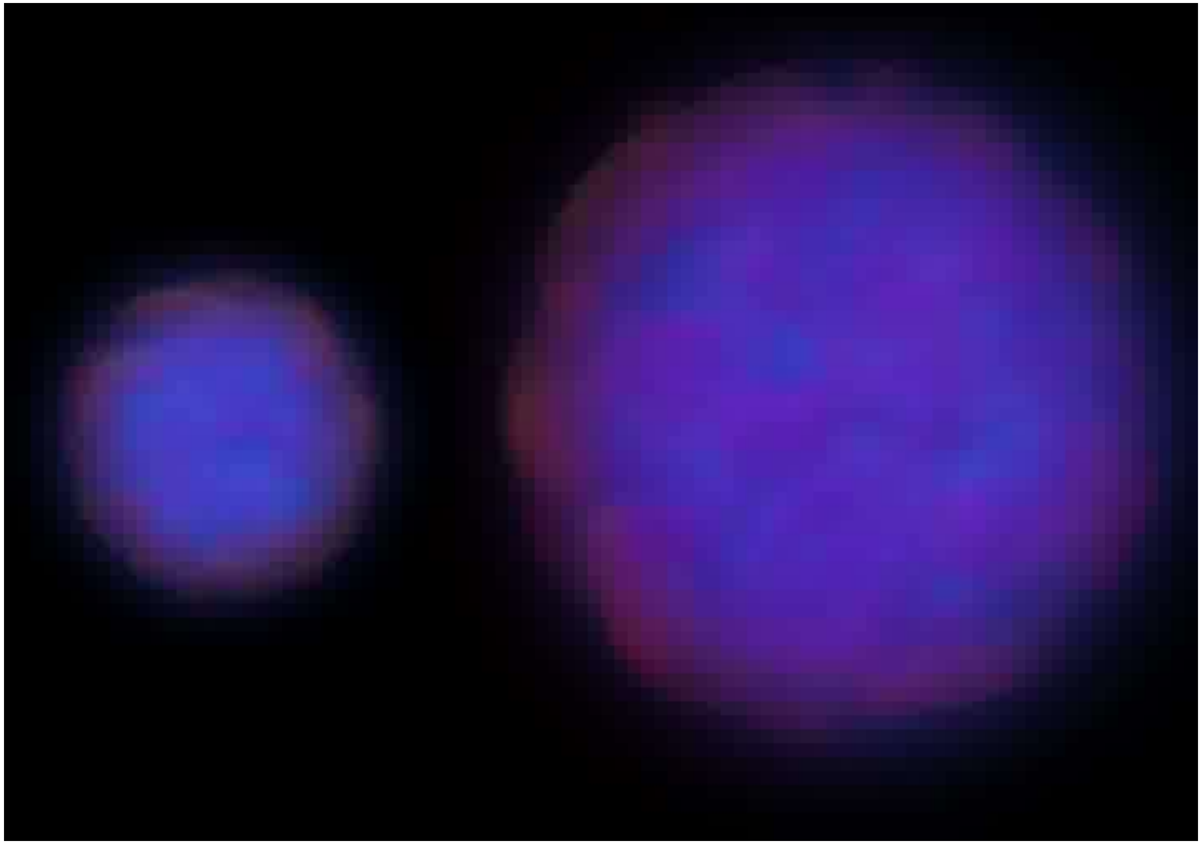
- Two colliding galaxy clusters
  → significant displacement between their center of visible matter & gravitational potential

Chandra X-Ray Observatory: 1E 0657-56



Bullet Cluster

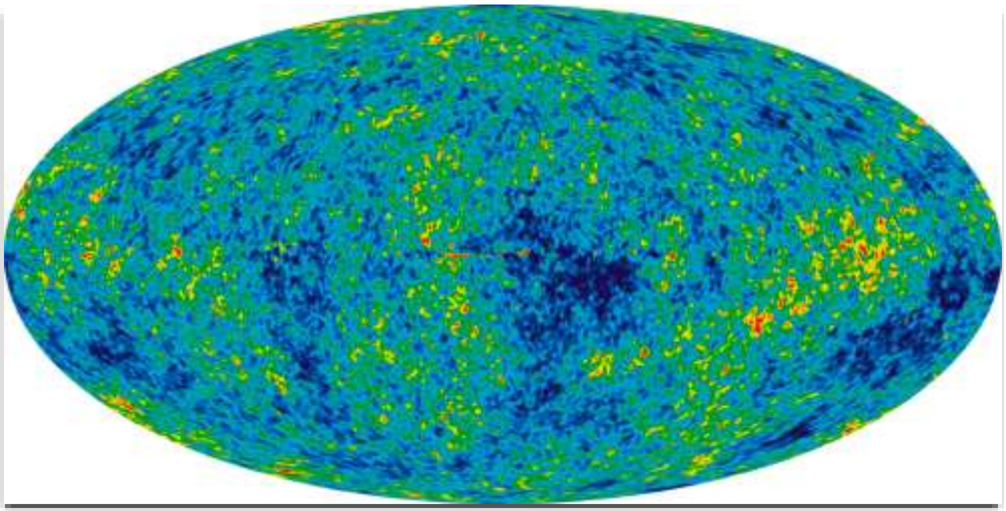
- Simulation of two colliding galaxy clusters



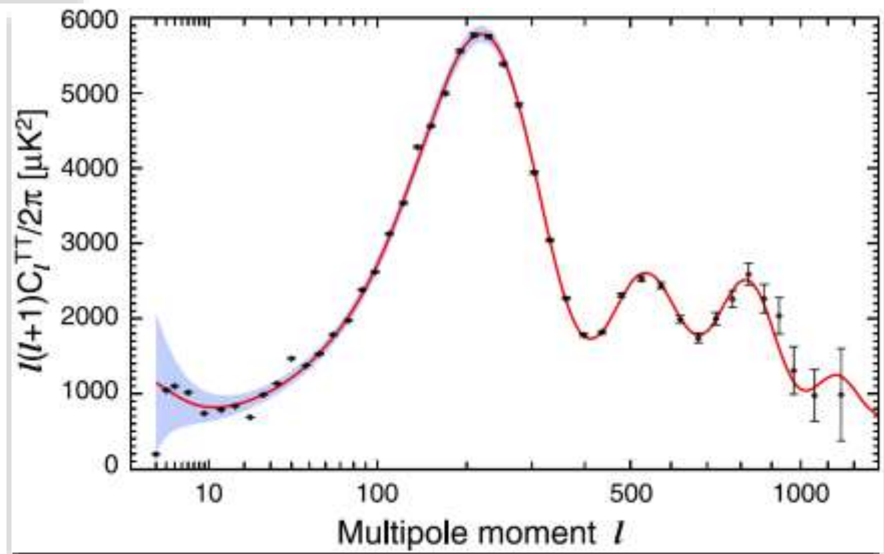
http://chandra.harvard.edu/photo/2006/1e0657/1e0657_bullett_anim_lg.mpg

CMB/CMBR

자세한 내용: 최기영 교수님의 강연 참고~!!



$T_0 \sim 2.725$ K
$\delta T/T \sim 10^{-5}$



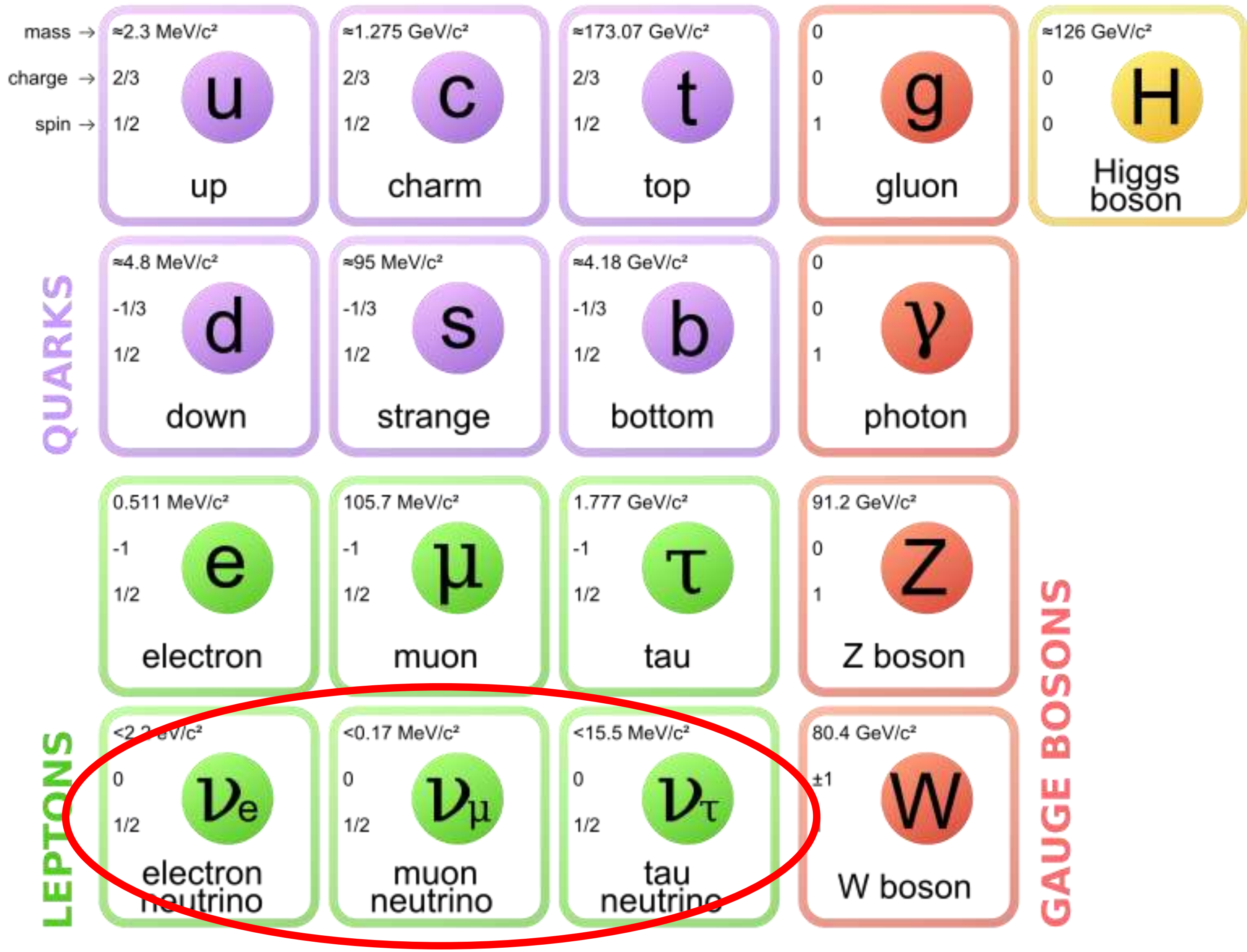
Much More Evidence

- ✓ Structure formation
- ✓ Cosmic microwave background radiation (CMBR)
- ✓ Sky surveys
- ✓ Type Ia supervovae
- ✓ Baryonic acoustic oscillation (BAO)
- ✓ …

2. DM candidates

잠시만요~~~
DM Candidates in SM ?

Standard Model



Neutrinos

(아마도) 최기영 교수님의
연에서 관련 내용이...

❖ The only EM neutral & stable particles

❖ Decoupled when still relativisti… MeV):

$$\Omega_\nu h^2 \ldots$$

❖ Observational …s: $\sum m_\nu < 1$ eV → too small.

❖ Too hot …ort free streaming length.

Not good candidate!!

Cold DM

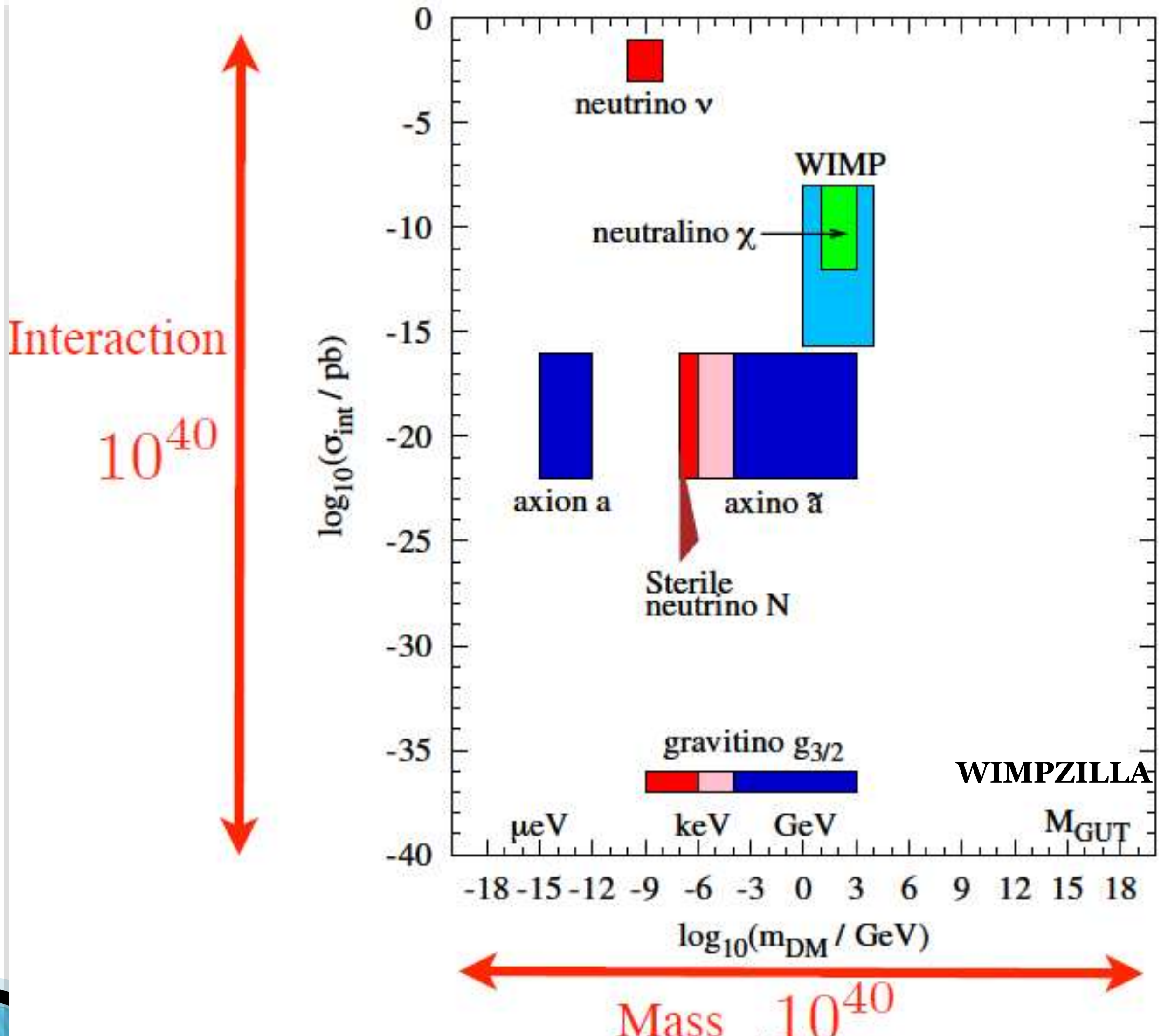
- ❖ The free streaming of DM from dense regions to under-dense regions smoothes out inhomogeneities inside the scale, smaller than the free steaming length scale, λ_f.
- ❖ Neutrinos (hot DM) with m~eV: $\lambda_f \sim 600$ Mpc.

  → Galaxies (10~100 kpc) cannot form.
- ❖ For structure formation, $\lambda_f << 1$ Mpc.
- ❖ Warm DM: $\lambda_f \sim 1$ Mpc.

Candidates from BSM

- ❖ Supersymmetry: neutralino, gravitino, sneutrino, axino
- ❖ Extra dimension: Kaluza-Klein particle
- ❖ Strong CP problem: axion
- ❖ Extended ν sector: sterile (RH) neutrino
- ❖ WIMPZILLA
- ❖ …

Ranges

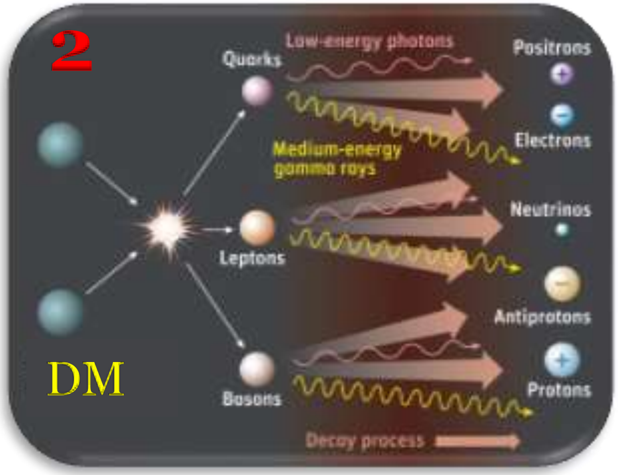


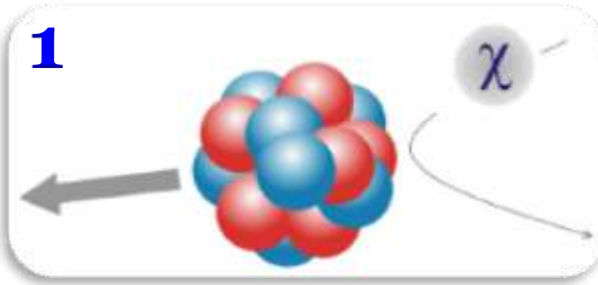
Interaction
10^40
0
-5
-10
-15
-20
-25
-30
-35
-40
log10(σint / pb)
neutrino ν
WIMP
neutralino χ
axion a
axino ã
Sterile neutrino N
gravitino g3/2
WIMPZILLA
μeV
keV
GeV
MGUT
-18 -15 -12 -9 -6 -3 0 3 6 9 12 15 18
log10(mDM / GeV)
Mass 10^40

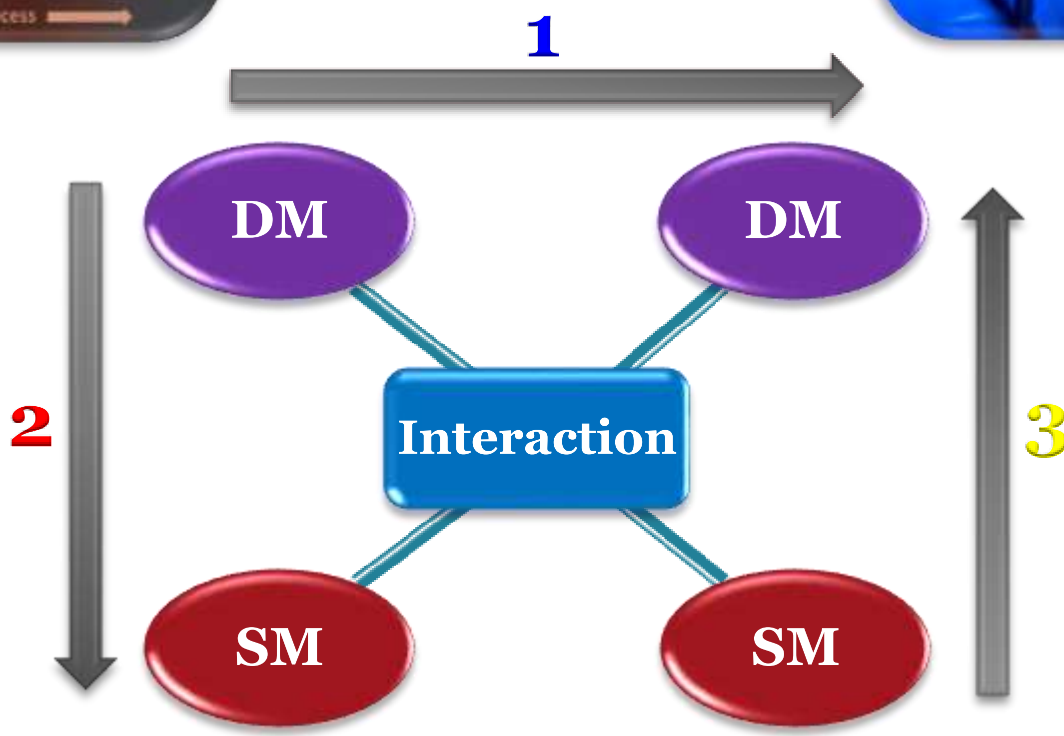

Dark Matter?


"LOTS OF THINGS ARE INVISIBLE, BUT WE DON'T KNOW HOW MANY BECAUSE WE CAN'T SEE THEM."

DM Search Strategies

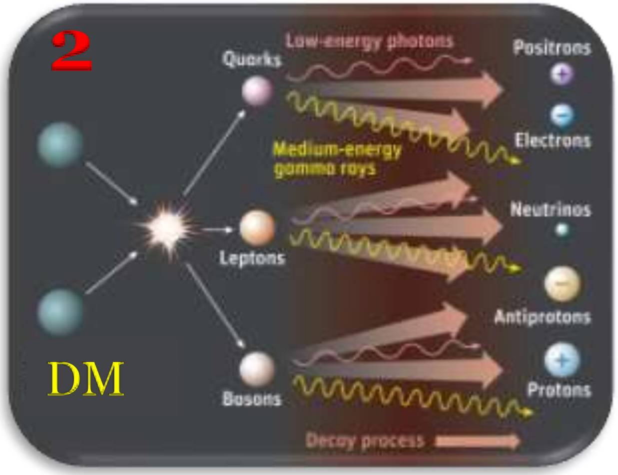


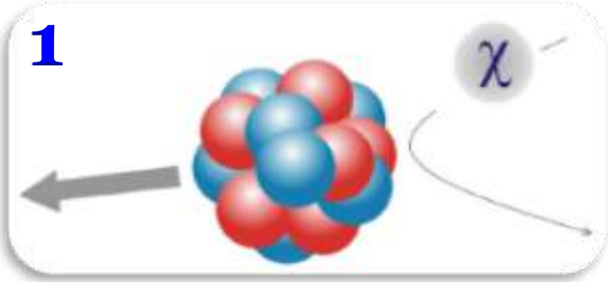


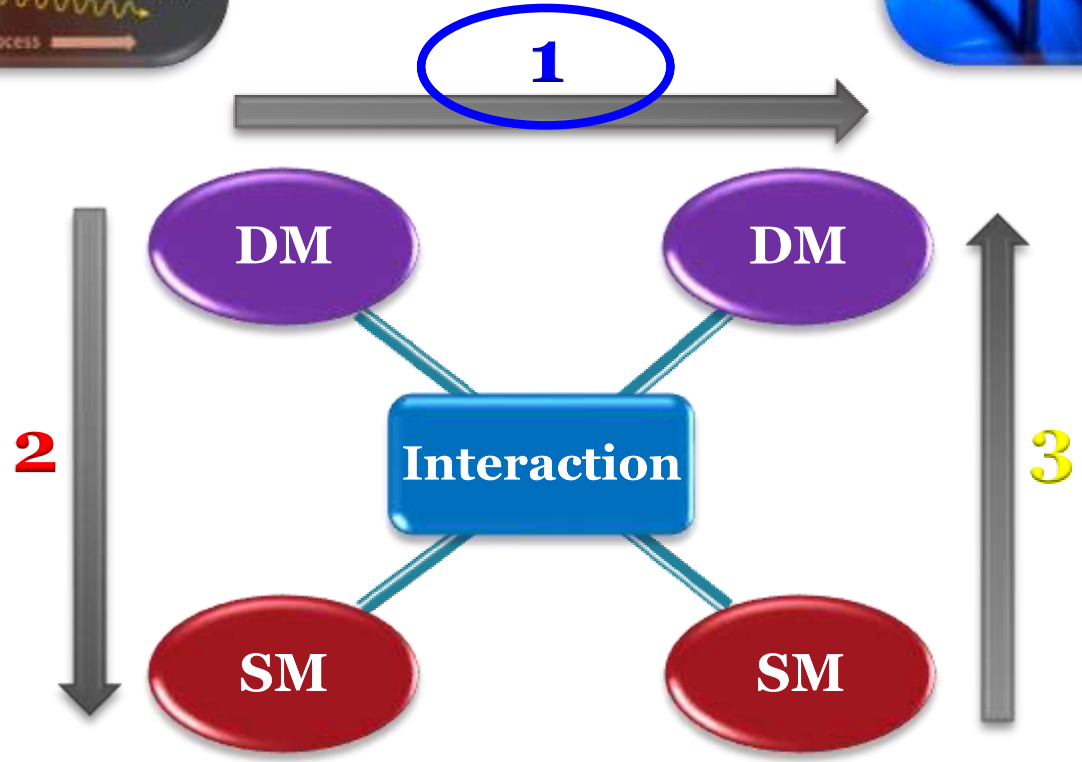


3. DM Direct Searches

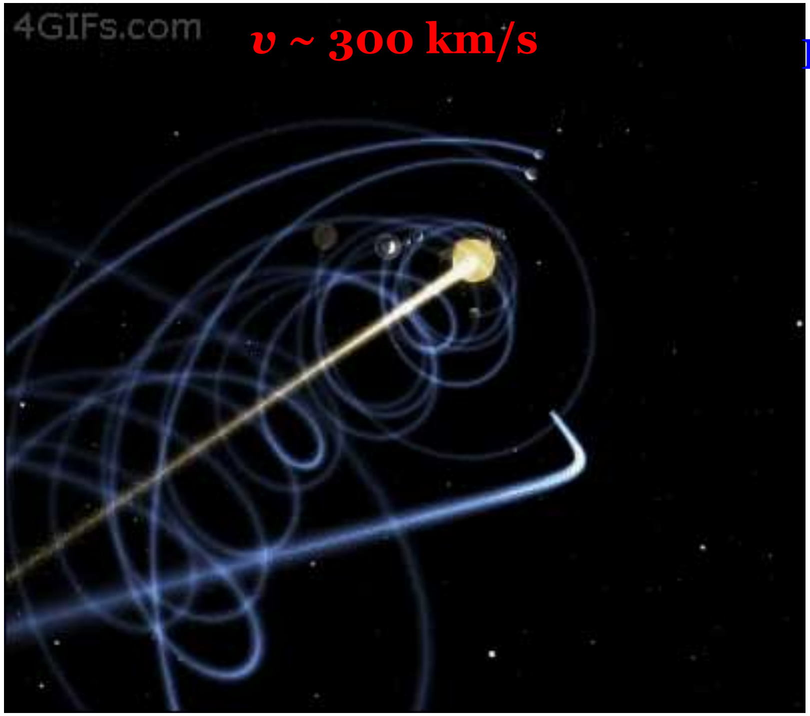
DM Direct Detection







Human vs Dark Matter

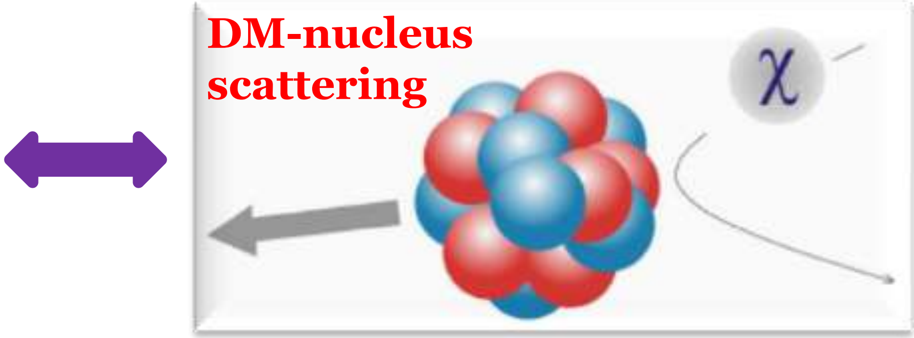


- When $m_{DM} \sim m_p \sim 0.94$ GeV: $300\ \mathrm{km/s} \times \dfrac{0.4\ \mathrm{GeV/cm^3}}{0.94\ \mathrm{GeV}} \times 60\ \mathrm{cm} \times 170\ \mathrm{cm}$

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

- $\sim 10^{11}$ DM's penetrate our body per second!

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

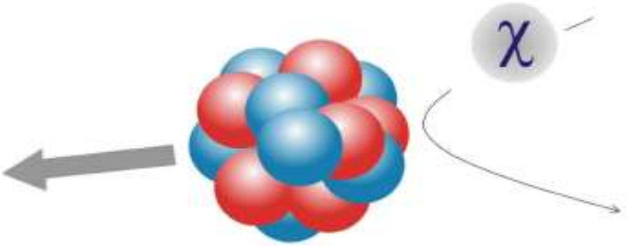
❖ Challenges: very small E, small event rate, large backgrounds

DM direct detection

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

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:

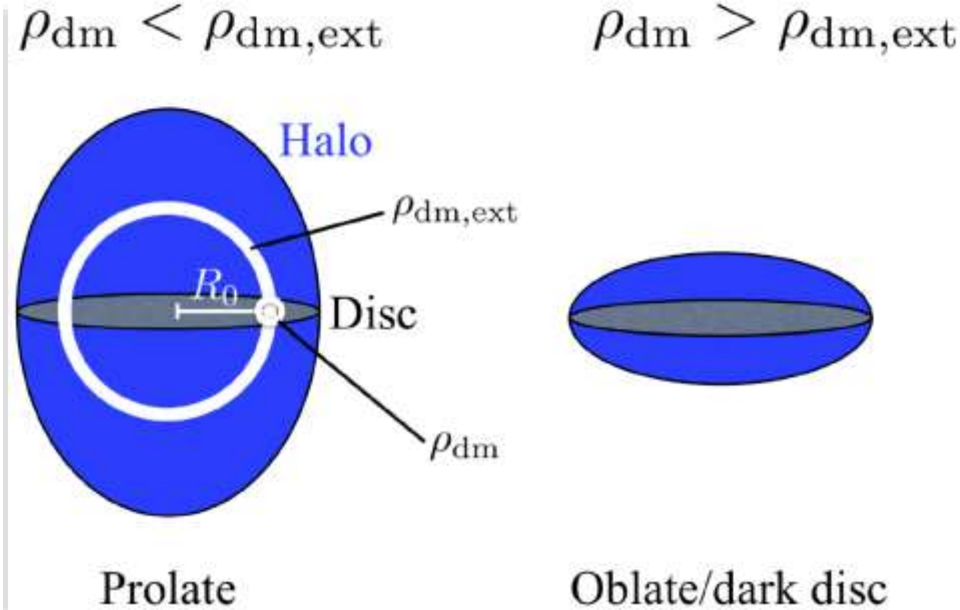
$$\frac{dN}{dE_R}(t) \propto \frac{\rho_\chi}{m_\chi}\int_{v>v_{\min}} d^3v\,\frac{d\sigma}{dE_R}\,v\,f_\oplus(\vec{v},t)$$

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

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: extrapolating ρ_{DM} from the rotation curve
- Recently, there have been attempts to bridge two scales.

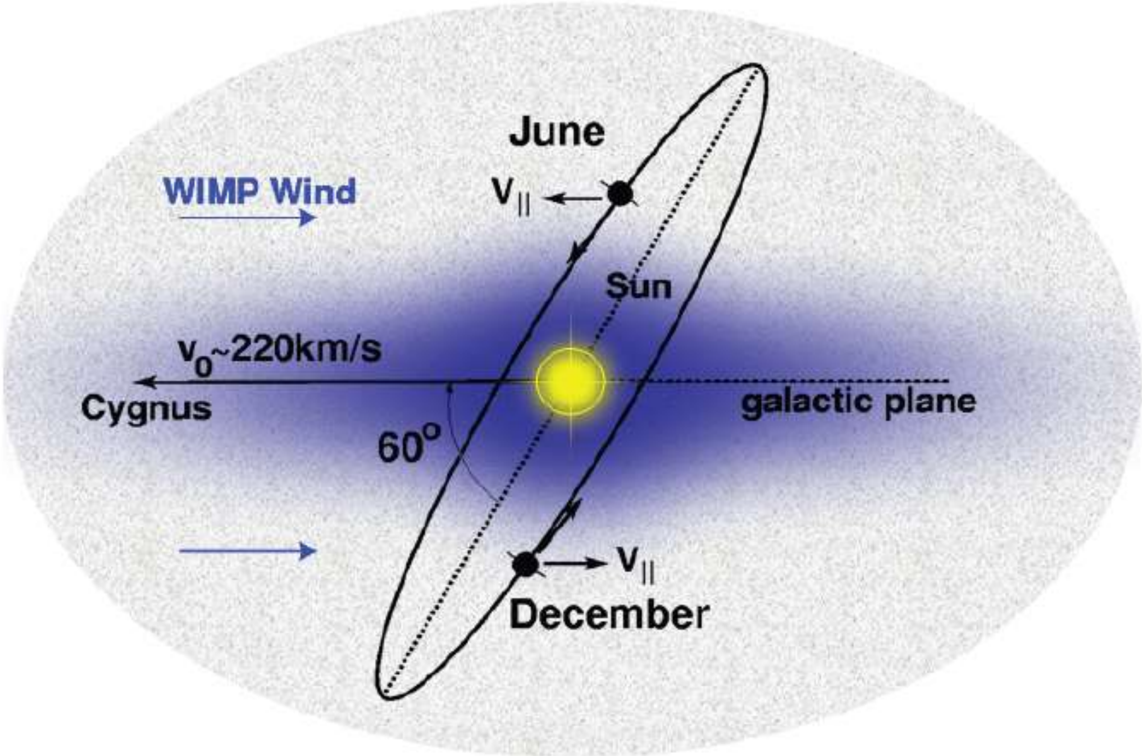
DM velocity distribution

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

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

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

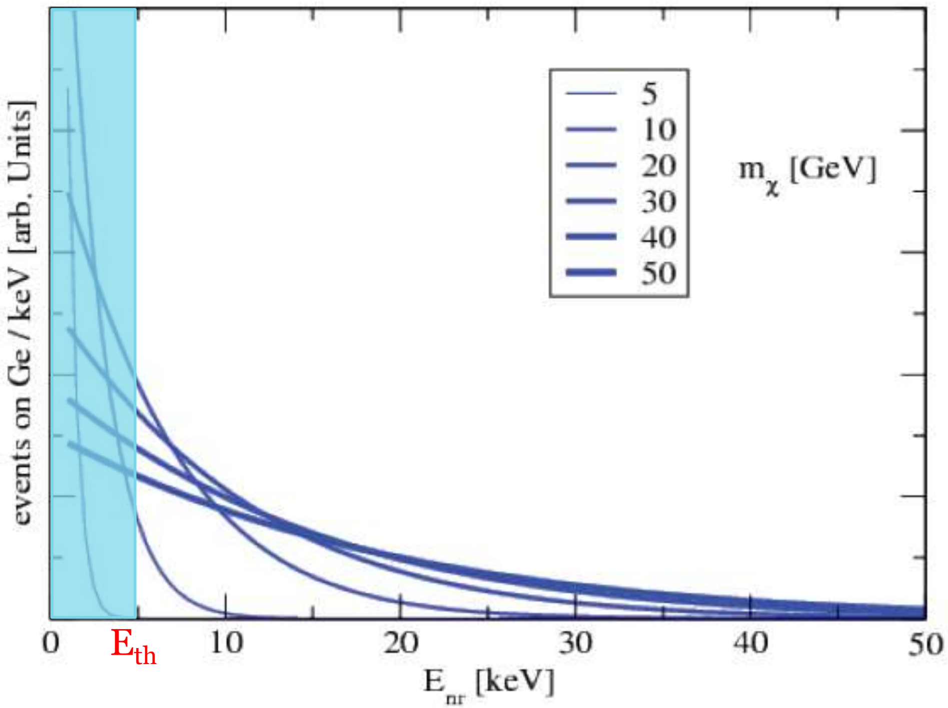
earth velocity: $\vec{v}_\oplus(t)$ with $v_\oplus \approx 30\,\mathrm{km/s}$



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



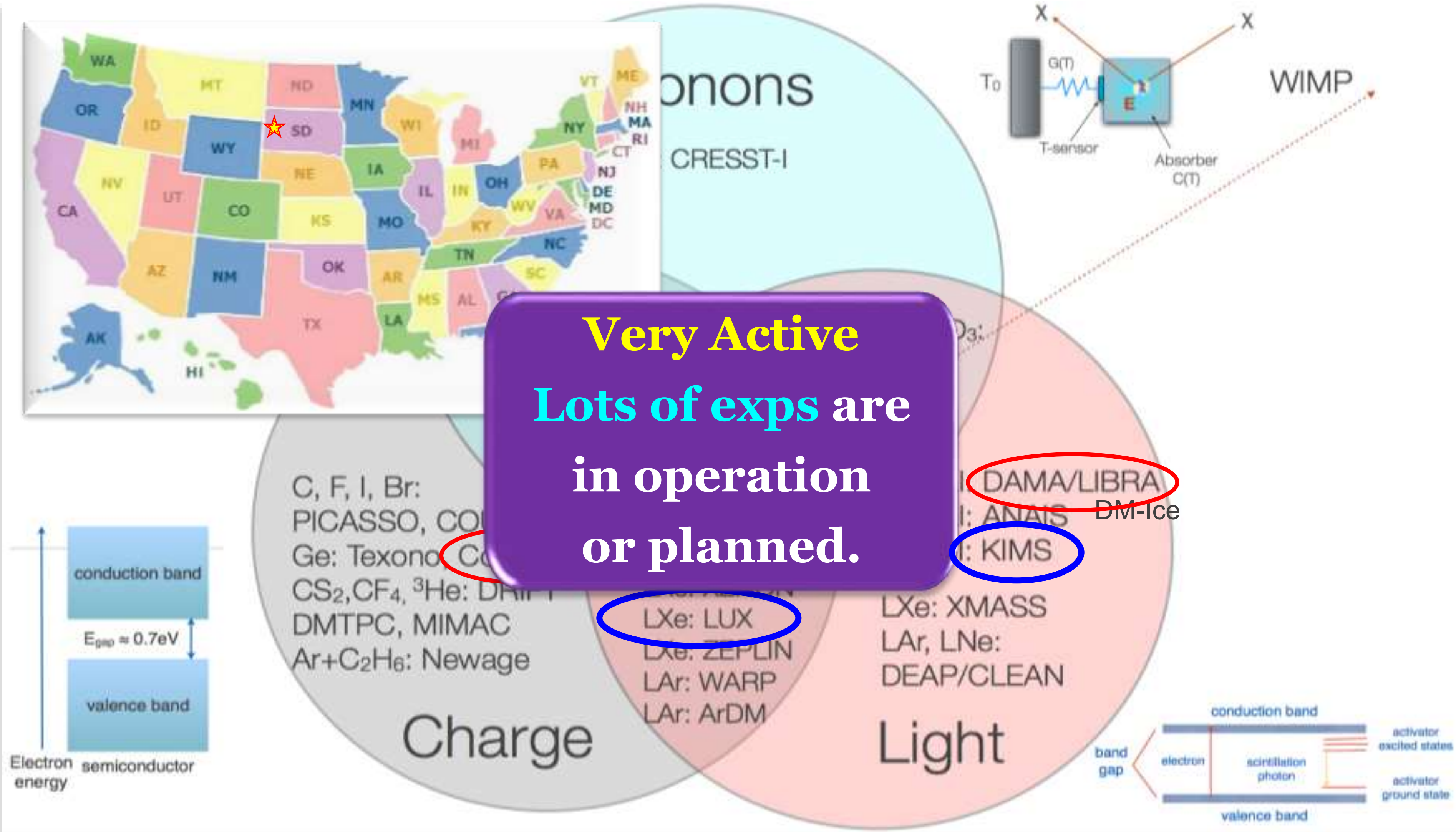
$m_\chi \ll M$:

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

spectrum gets shifted to low energies for low WIMP masses

$\Rightarrow$ energy threshold is crucial

Detection Techniques



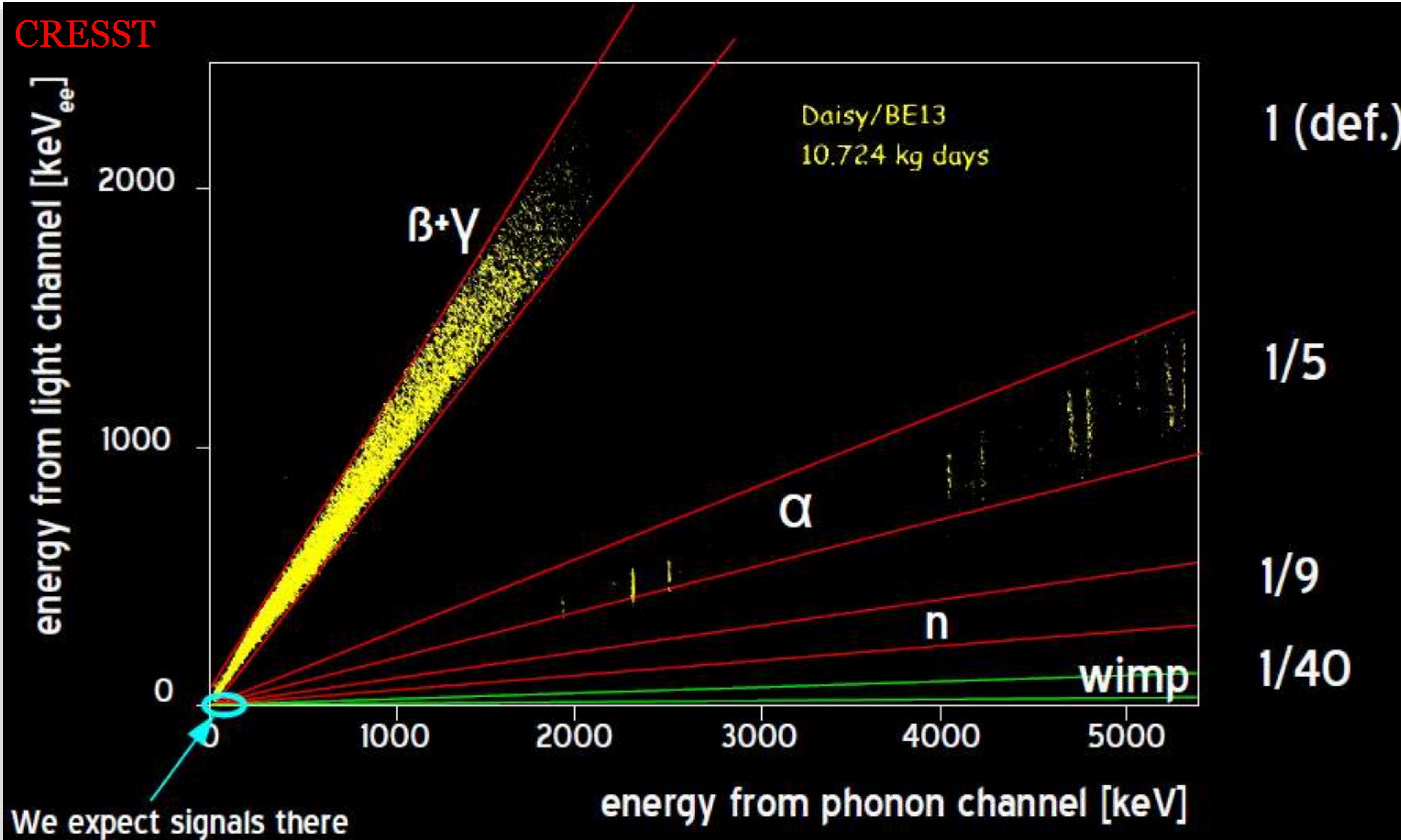
Very Active

Lots of exps are in operation or planned.

Direct Detection in Korea

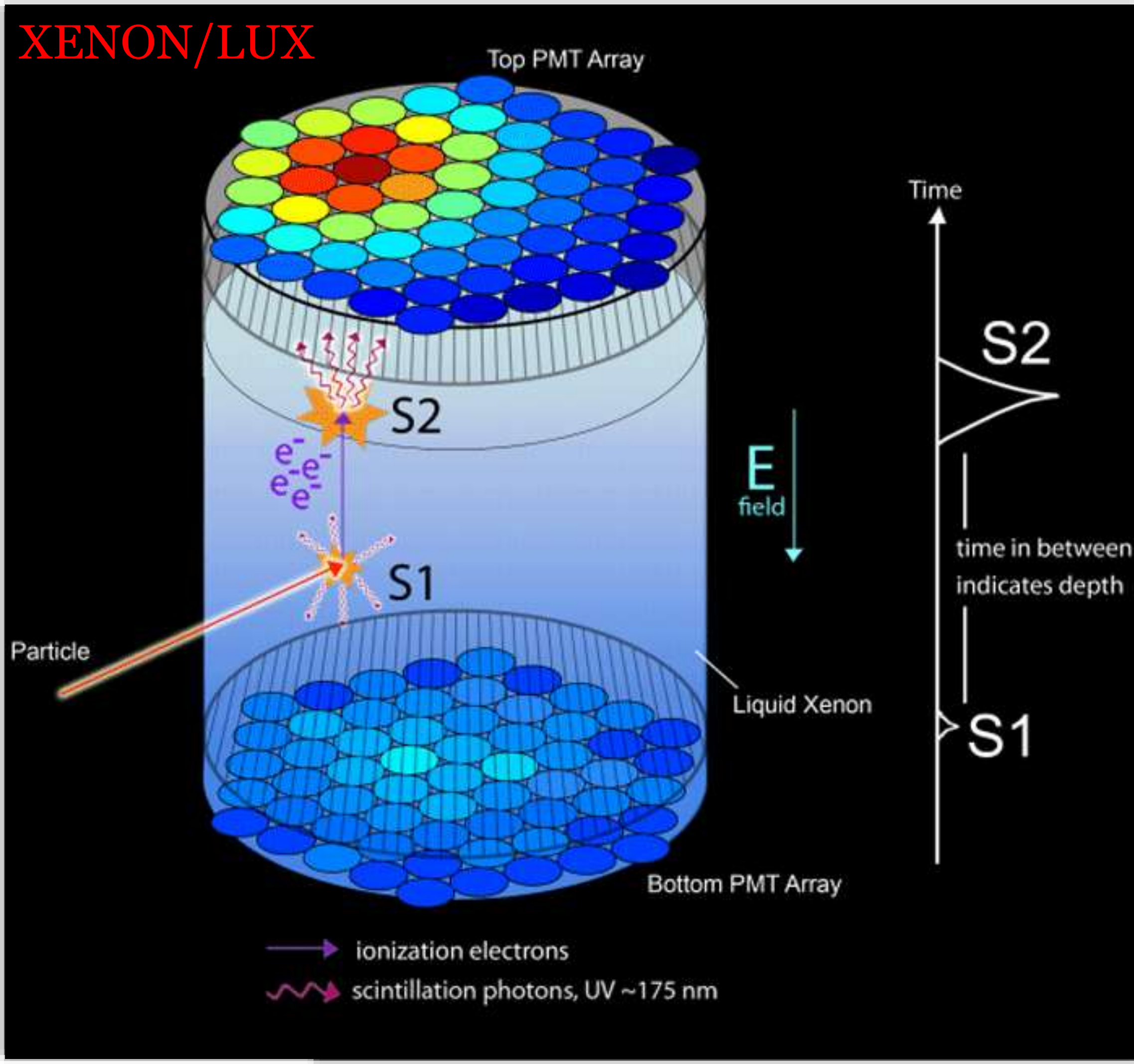
- ❖ Center for Underground Physics (CUP) of IBS (Daejeon): Yangyang & Taebaek(?)

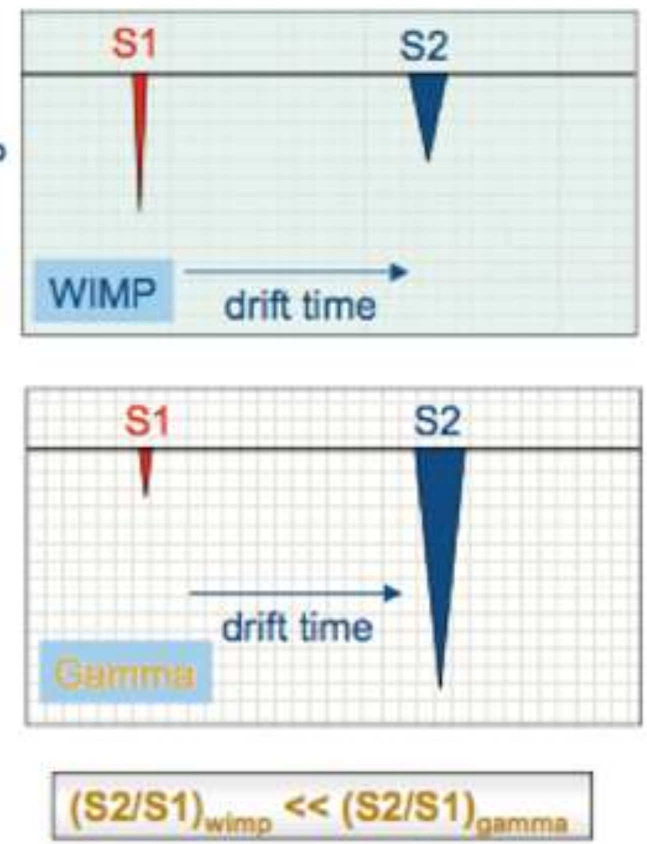
Event Discrimination



G. Deuter, Eurograd Workshop, Sept. 2010

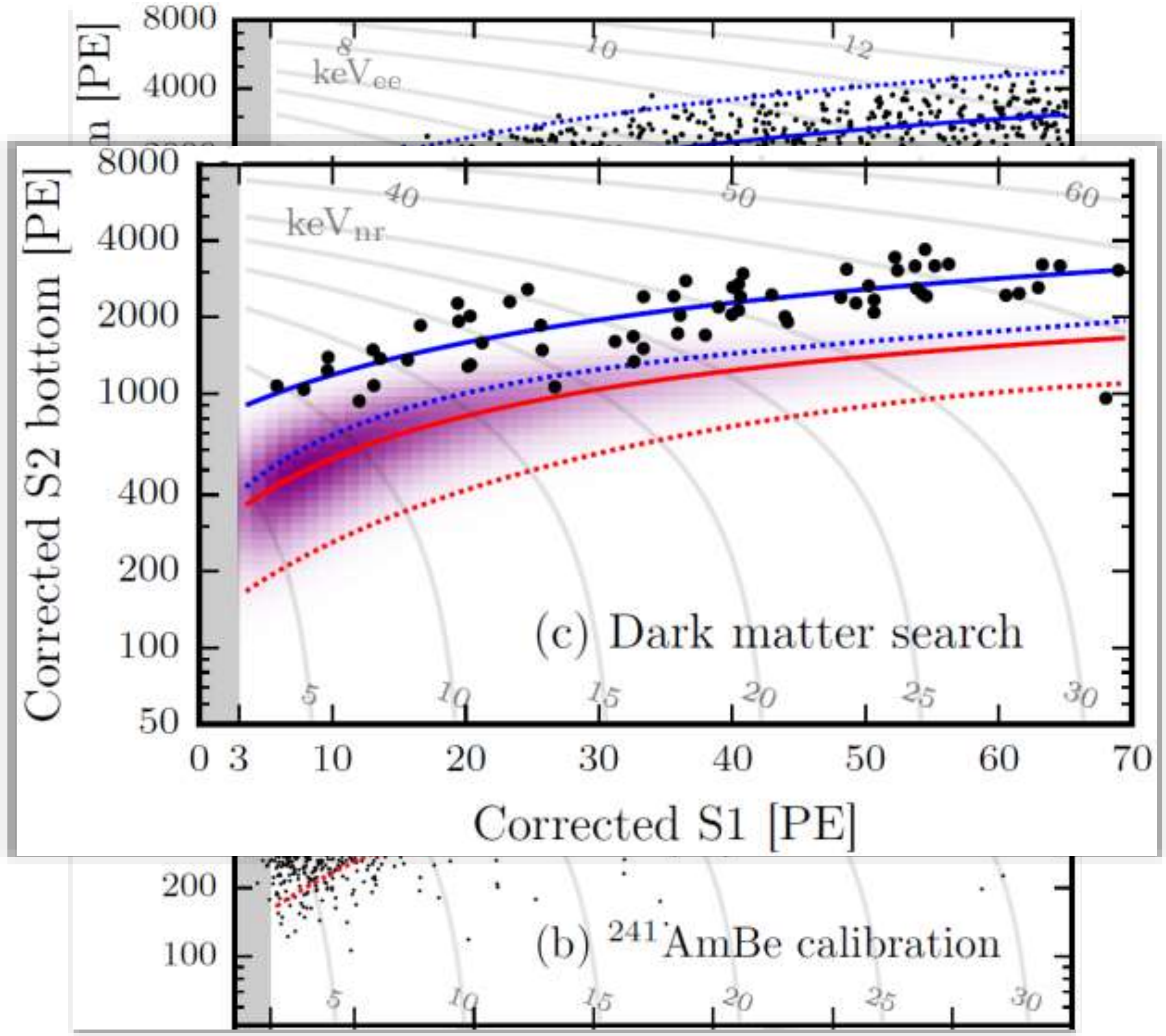
Event Discrimination





Calibration

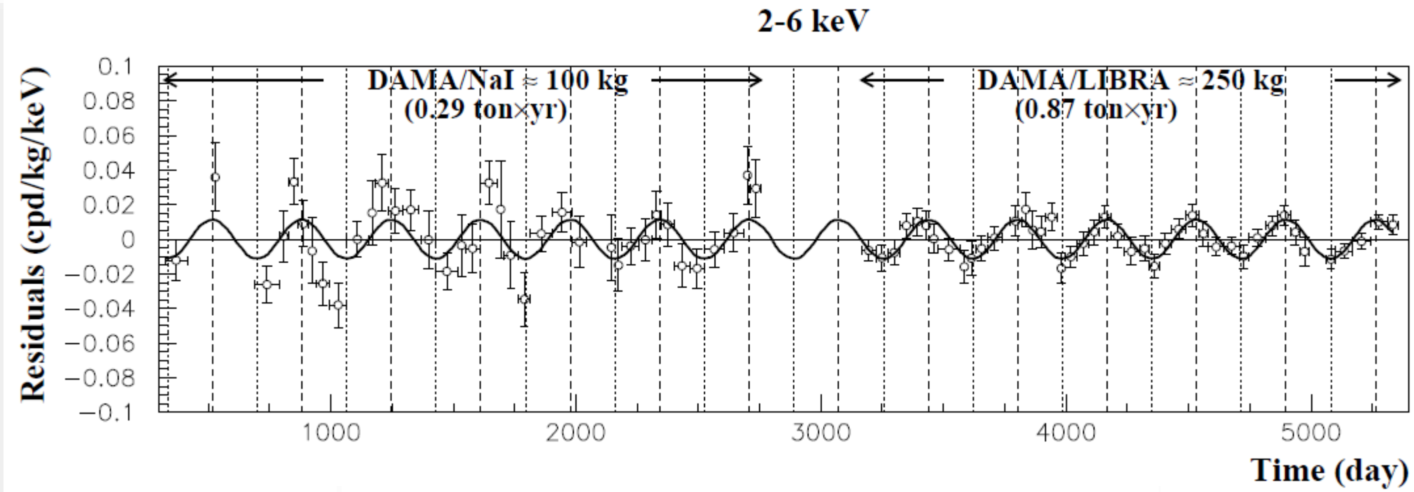
XENON1T,
arXiv:1705.06655

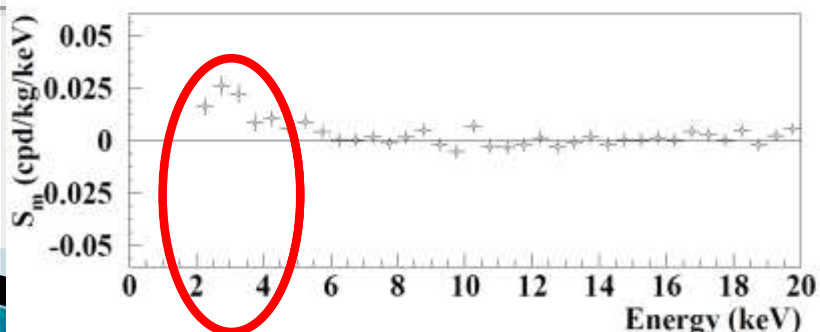


Annual Modulation

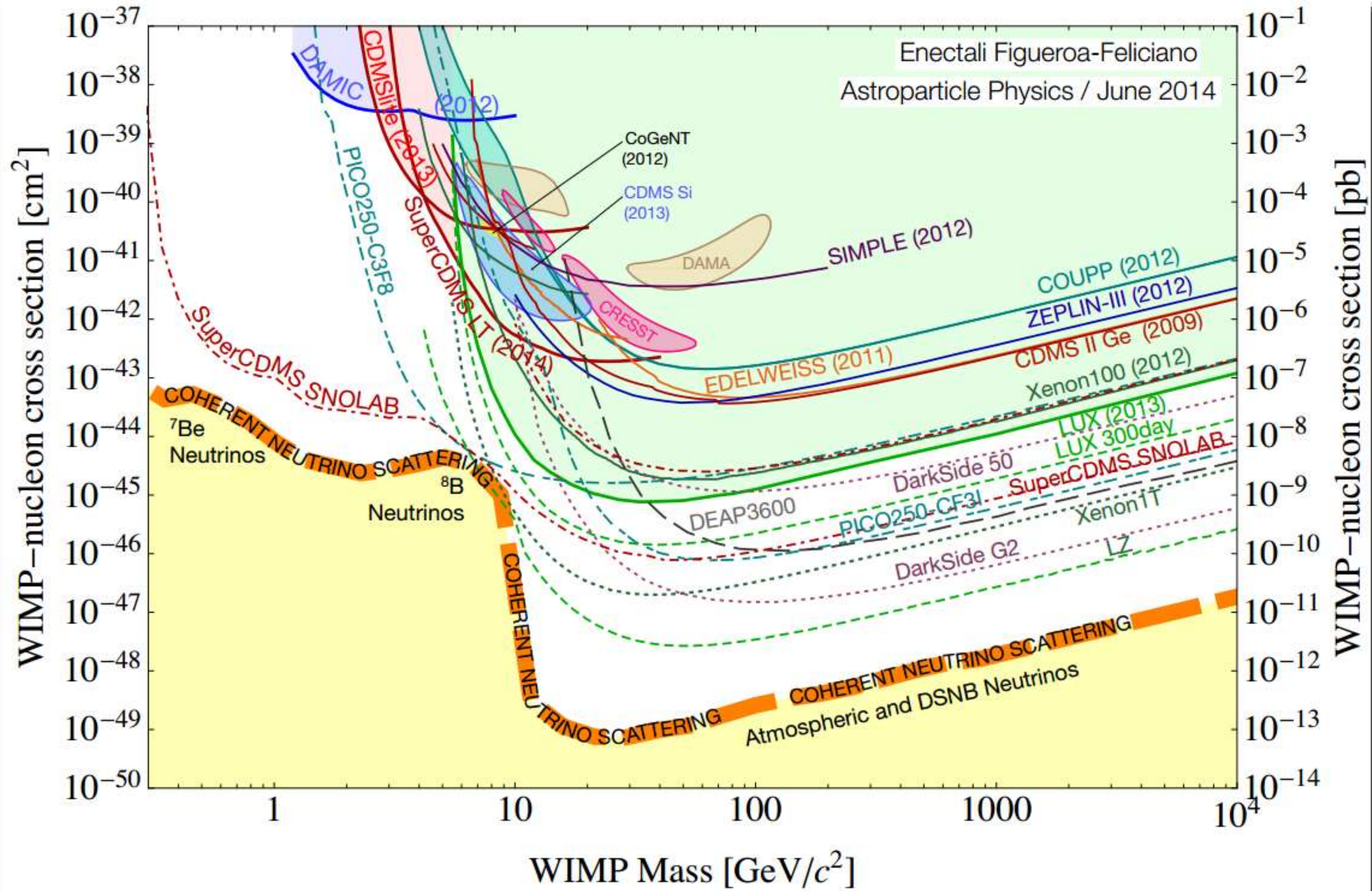
DAMA, EPJC73:2648 (2013)

- 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 (9.3 σ significance).
- 14 annual cycles, modulation amplitude: 0.0112 ± 0.0012 in the (2-6) keV
- Phase: 144 ± 7 days (cf. June 2nd), Period: 0.998 ± 0.002 yr



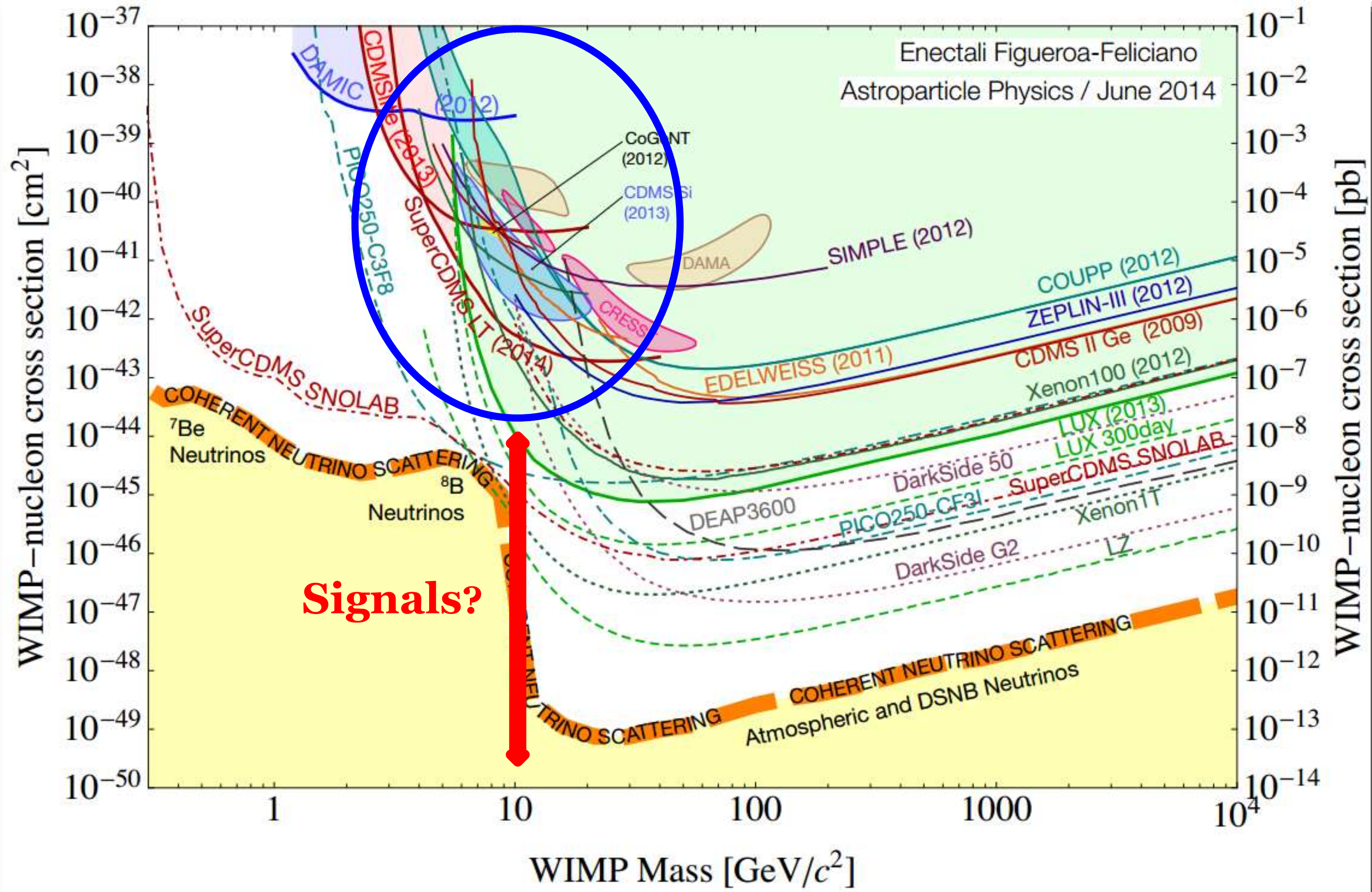


Status (2013)



Enectali Figueroa-Feliciano
Astroparticle Physics / June 2014
WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]
DAMIC
(2012)
CDMSlite (2013)
PICO250-C3F8
SuperCDMS LT (2014)
CoGeNT (2012)
CDMS Si (2013)
DAMA
CRESST
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
LUX 300day
DarkSide 50
SuperCDMS SNOLAB
PICO250-CF3I
DEAP3600
Xenon1T
DarkSide G2
LZ
SuperCDMS SNOLAB
COHERENT NEUTRINO SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
Atmospheric and DSNB Neutrinos

Status: Hints of ~10 GeV DM?



Suggested Ideas

❖ **Isospin-violating DM (IVDM):**

Giuliani, PRL (2005)

- DM can couple differently to p's and n's: $f_p \neq f_n$

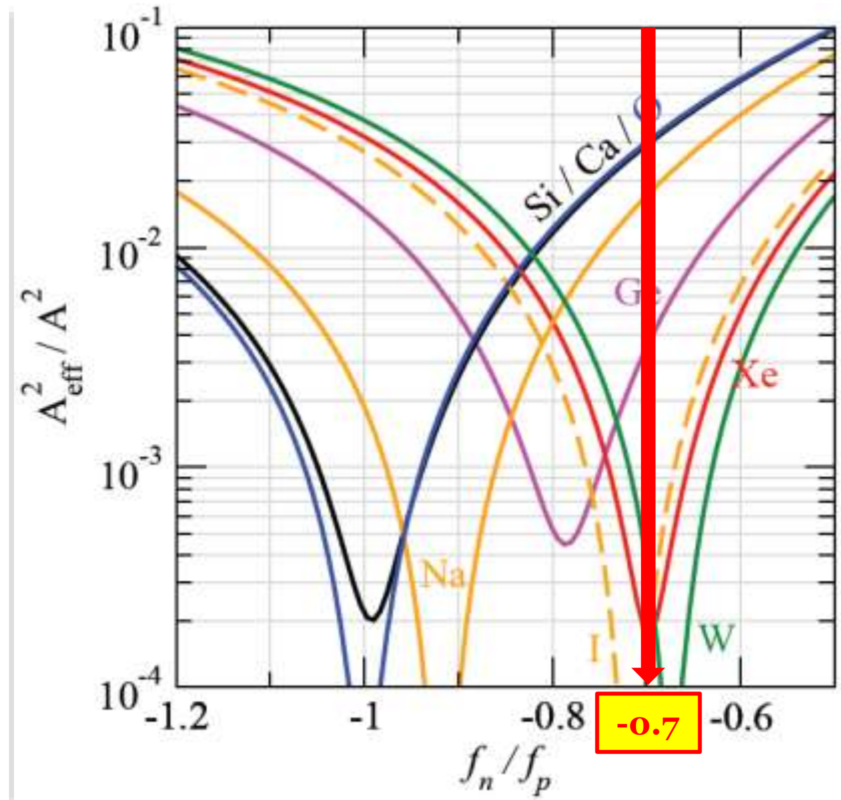
  If $f_p f_n < 0$, cancellation between two contributions

$$\sigma^{\mathrm{SI}} = \frac{[Z f_p + (A-Z) f_n]^2}{f_p^2} \frac{\mu_{\chi N}^2}{\mu_{\chi p}^2} \sigma_p^{\mathrm{SI}}$$

- Effective nuclear mass number:

$$A_{\mathrm{eff}}^2 \equiv \sum_{i \in \mathrm{isotopes}} 2 r_i [Z \cos\theta + (A_i - Z)\sin\theta]^2$$

$\tan\theta = f_n/f_p$, r_i: relative abundance



Kopp et al., JCAP (2012)

IVDM via a Double Portal

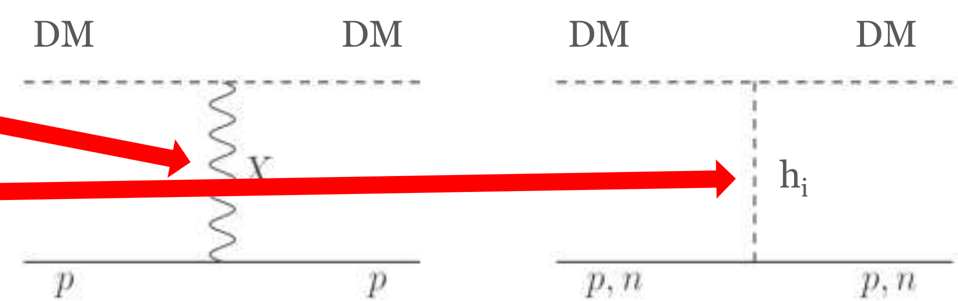
JCP, Belanger, Goudelis, Pukhov
JCAP (2014)

- **Isospin-violating DM (IVDM)**:

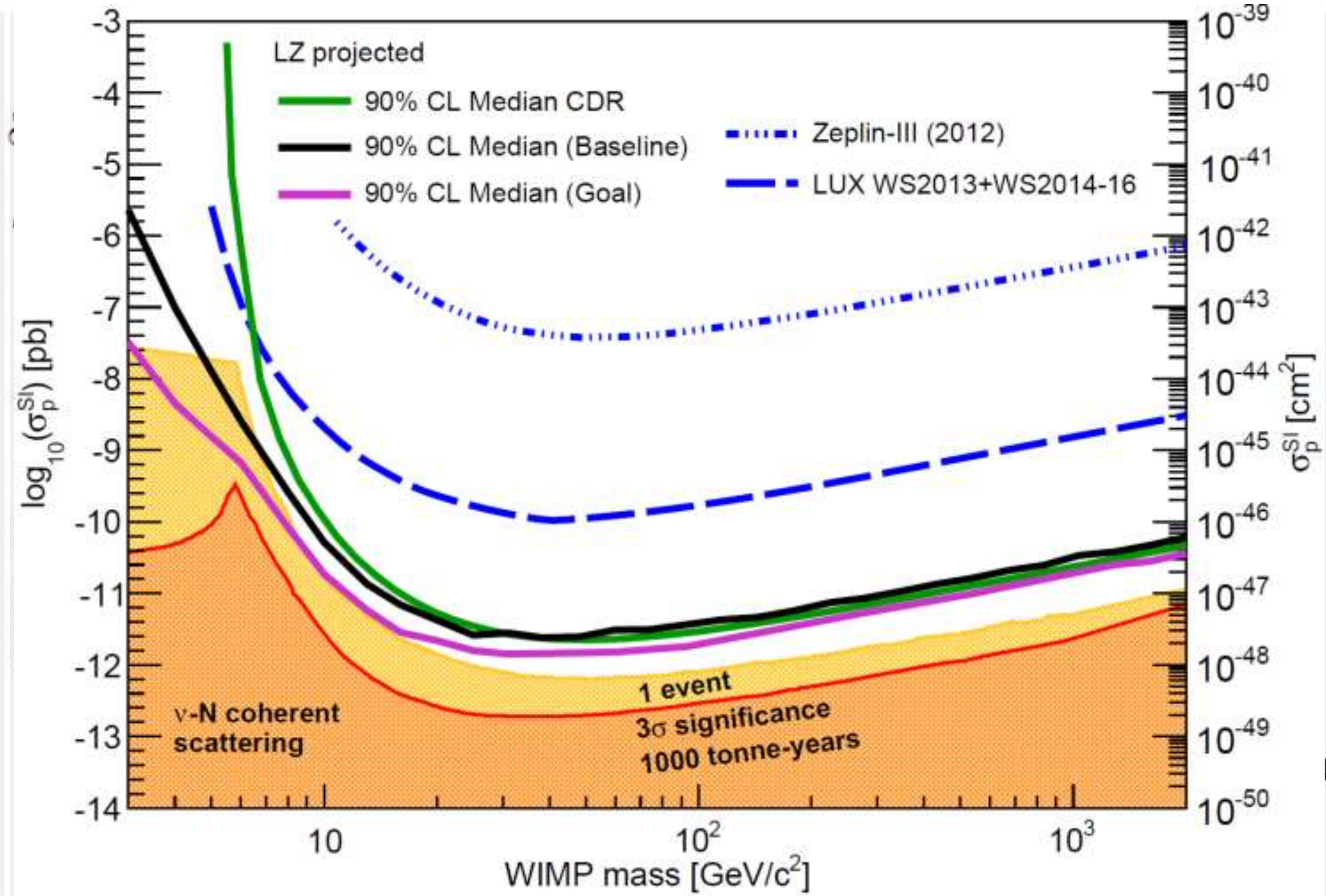
$$\sigma_{\mathrm{DM}-N} \propto [Z f_p + (A-Z) f_n]^2$$

- A hidden DM with a double portal interaction:

$$\mathcal{L} \supset \mathcal{L}_{SM} - \frac{1}{2} \sin\epsilon\, \hat{B}_{\mu\nu} \hat{X}^{\mu\nu} - \lambda_{SH} S^\dagger S H^\dagger H$$



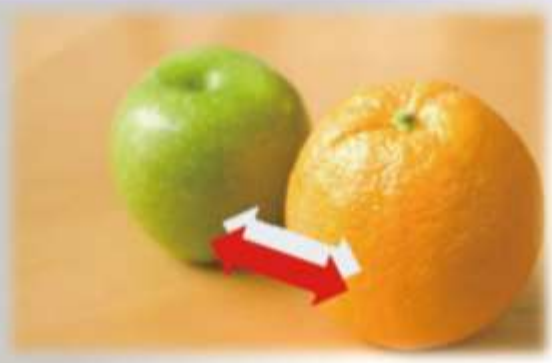
Updated Direct Detection Status



What DAMA people thought

About interpretation

See e.g.: Riv.N.Cim.26 n.1(2003)1, IJMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD84(2011)055014, JMPA28(2013)1330022



...models...
- Which particle?
- Which interaction coupling?
- Which EFT operators contribute?
- Which Form Factors for each target-material?
- Which Spin Factor?
- Which nuclear model framework?
- Which scaling law?
- Which halo model, profile and related parameters?
- Streams?
- ...

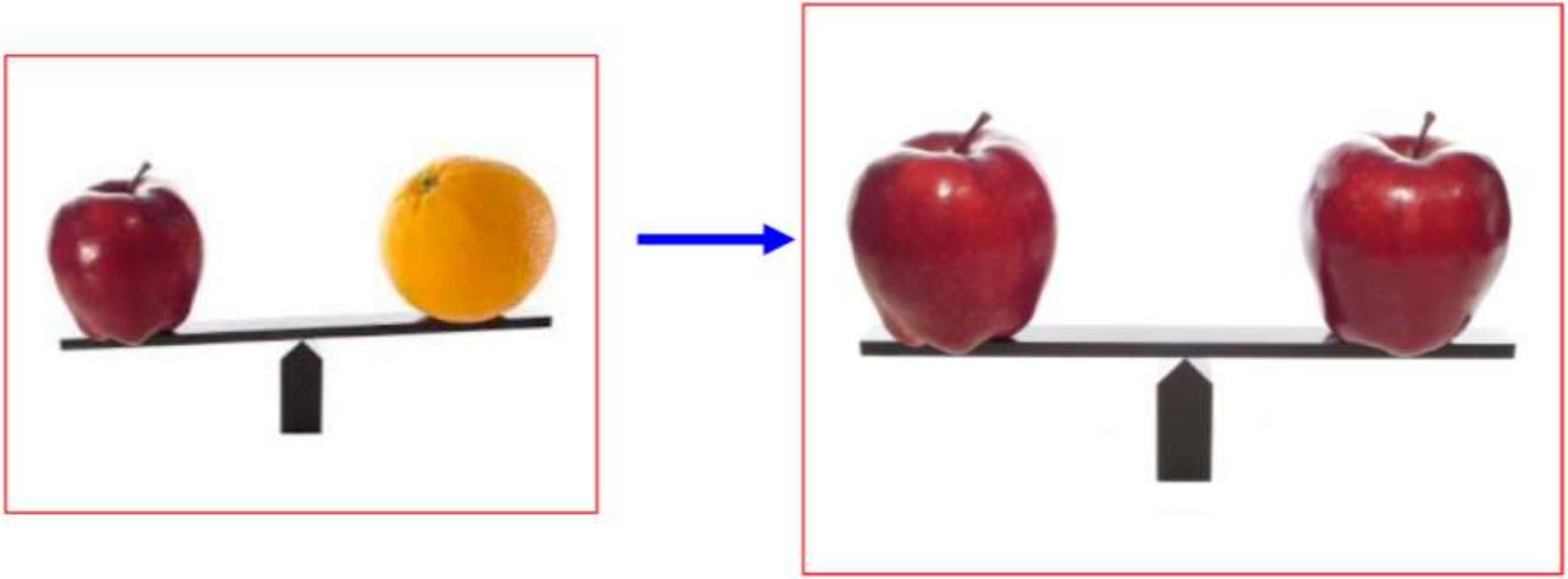
...and experimental aspects...
- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities
- Efficiencies
- Definition of fiducial volume and non-uniformity
- Quenching factors, channeling
- ...

Uncertainty in experimental parameters, as well as necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with a fixed set of assumptions and parameters' values are intrinsically strongly uncertain.

No experiment can be directly compared in model independent way with DAMA

Riccardo Cerulli @TAUP2016

Best way to prove/refute DAMA/LIBRA's result



- Exactly same experiment!!
- Need to understand why DAMA/LIBRA shows modulation (WIMP?)
  - It is possible that underline cause of DAMA signals might be due to another exciting physics.

Global NaI(Tl) efforts

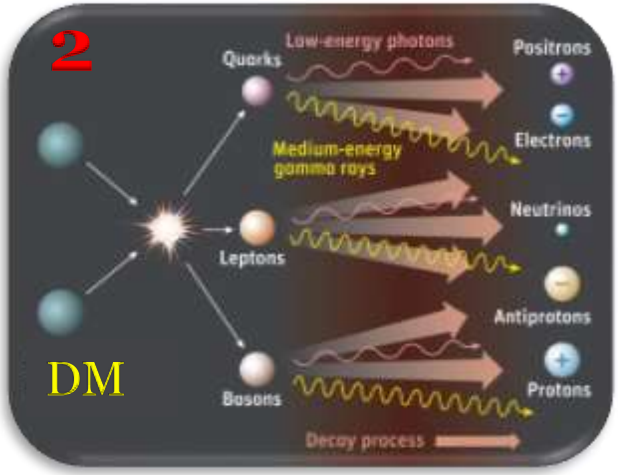
Hyun Su Lee @ DSU 2017

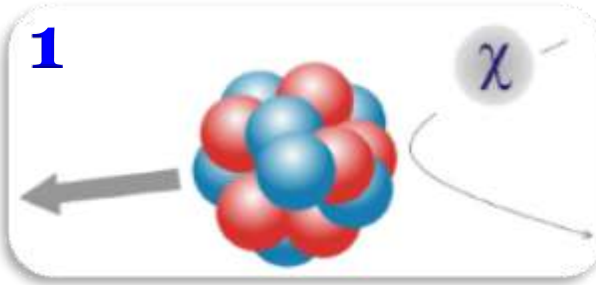
COSINE Project

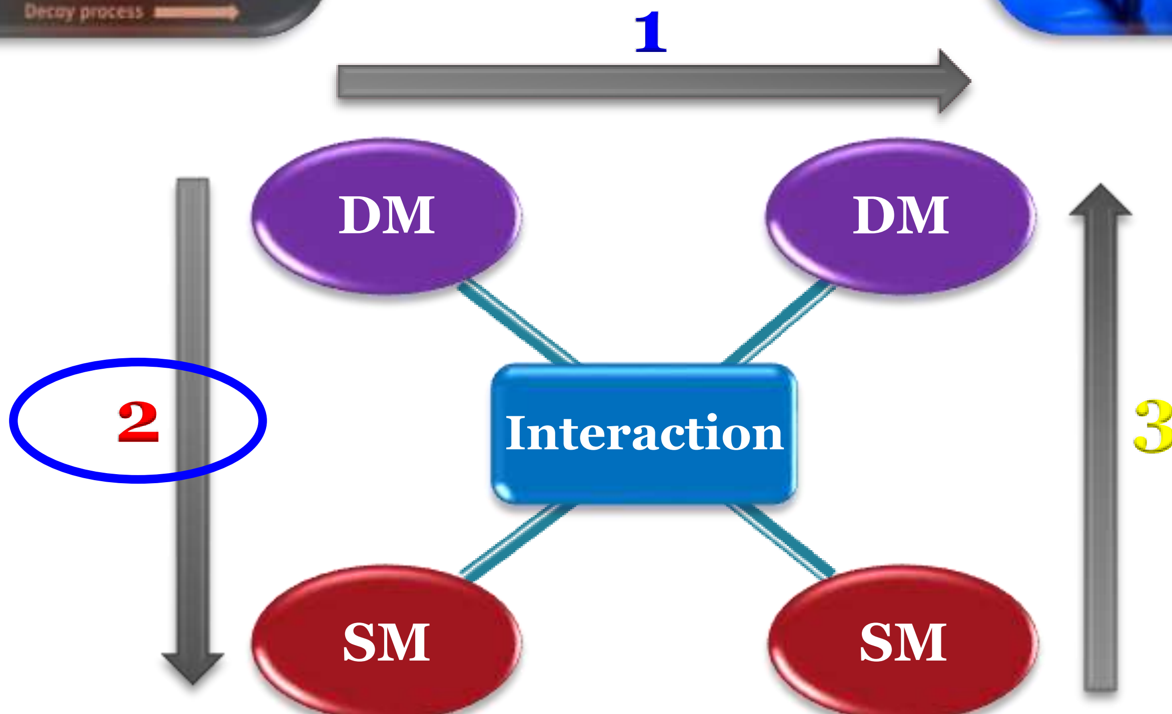
KIMS and DM-Ice joint effort to search for dark matter interactions in NaI(Tl) scintillating crystals. (Goal to **reproduce DAMA/LIBRA**)

4. DM Indirect Searches

DM Indirect Detection



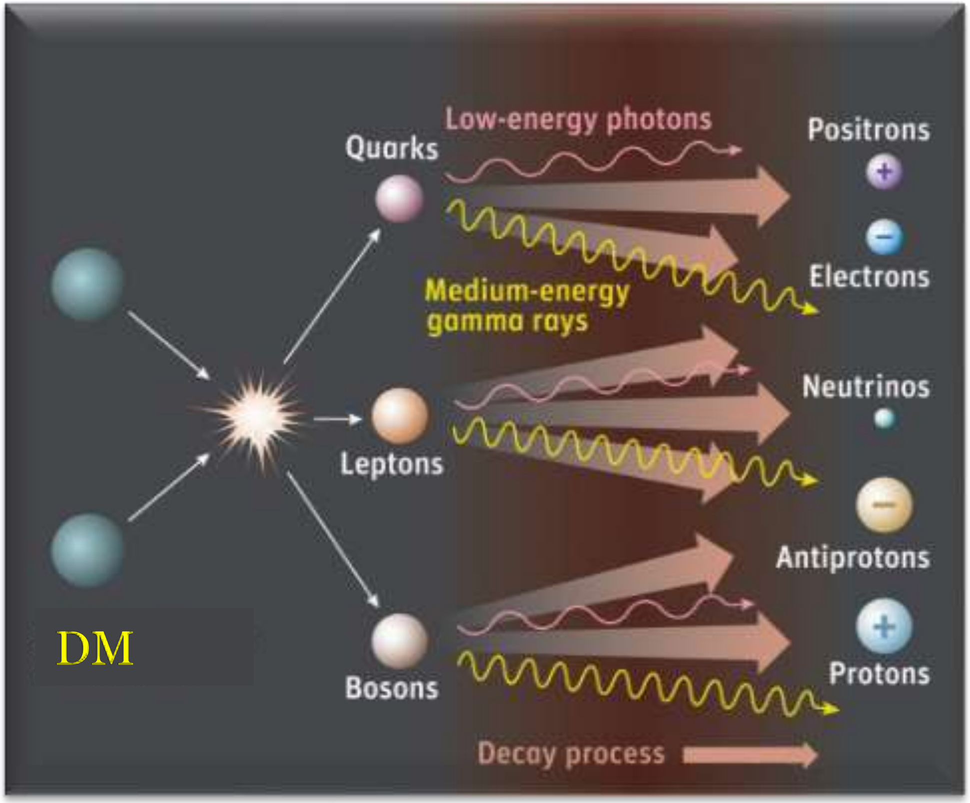




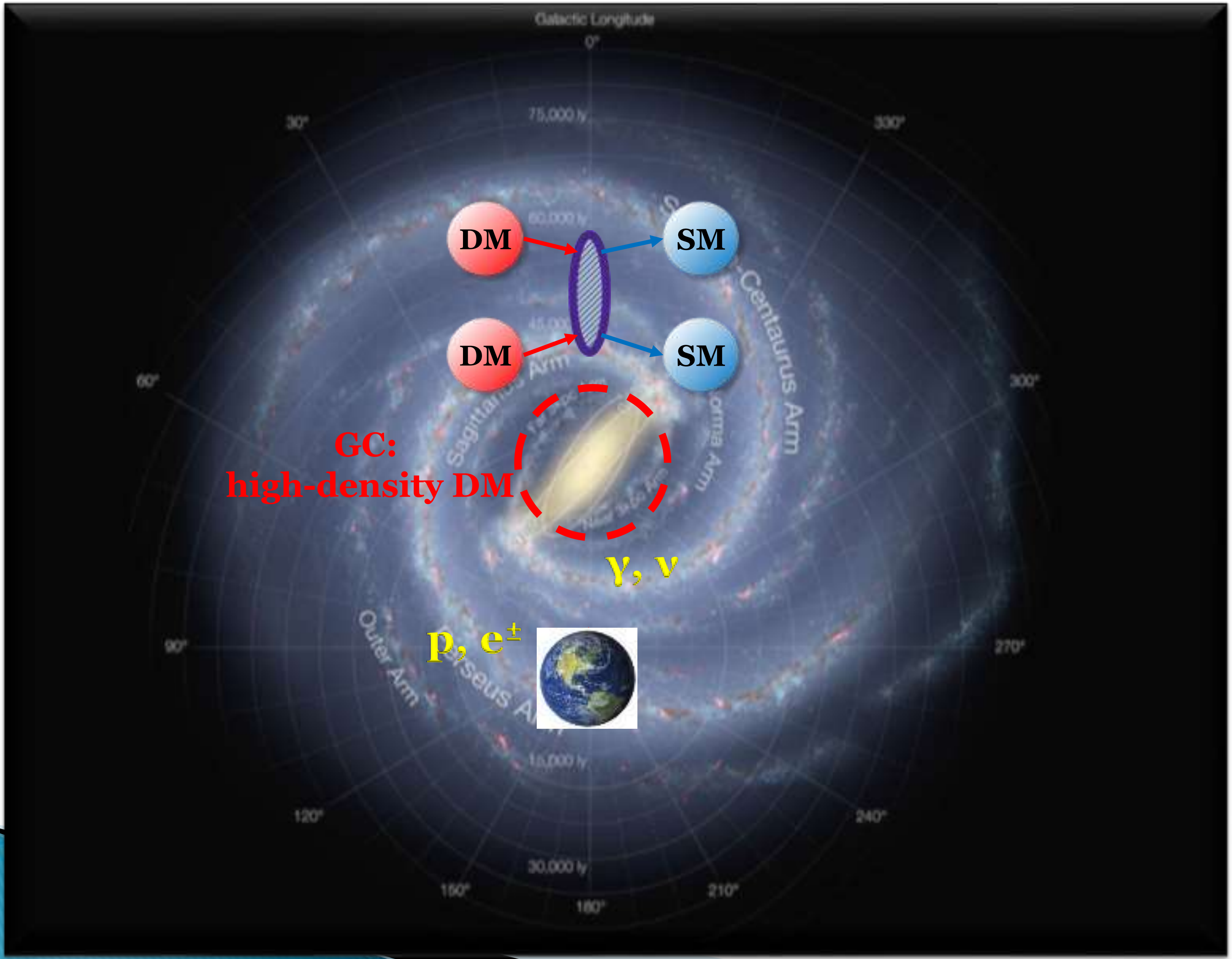
Indirect Detection

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

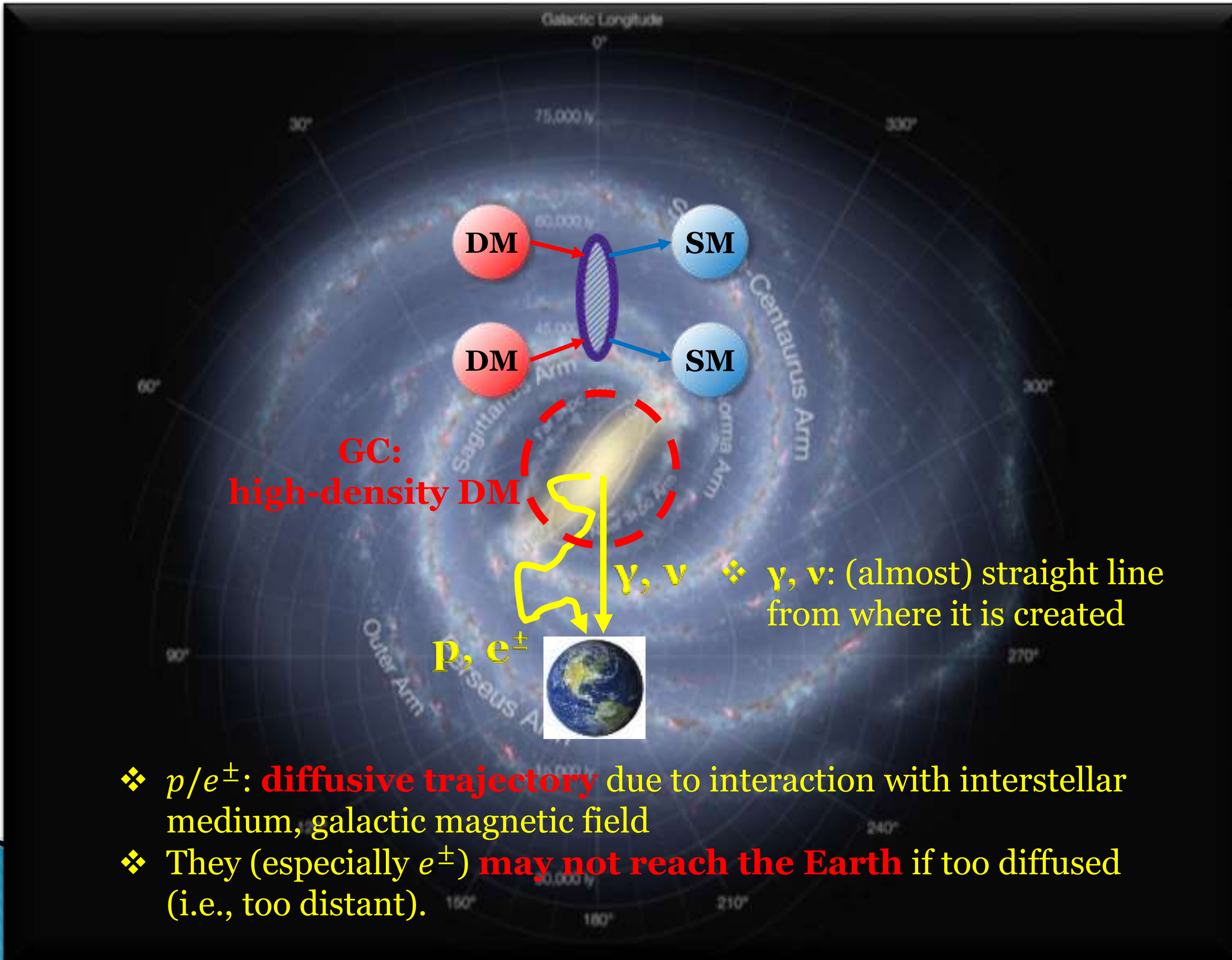
❖ Not conclusive evidence: backgrounds from other sources



Indirect Detection: Cosmic-Rays

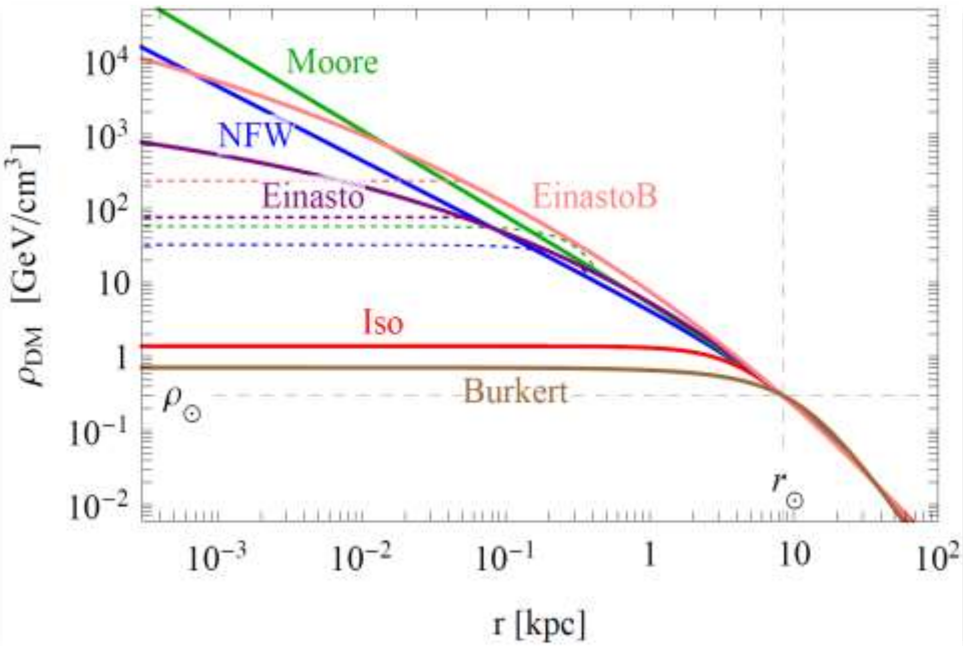


Indirect Detection: Cosmic-Rays



- ❖ γ, ν: (almost) straight line from where it is created
- ❖ $p/e^{\pm}$: **diffusive trajectory** due to interaction with interstellar medium, galactic magnetic field
- ❖ They (especially $e^{\pm}$) **may not reach the Earth** if too diffused (i.e., too distant).

DM Halo Profiles



- NFW: $(\alpha, \beta, \gamma)=(1, 3, 1)$

$$\rho(r) = \rho_0 \left(\frac{r_0}{r}\right)^{\gamma} \left(\frac{1+(r_0/r_s)^{\alpha}}{1+(r/r_s)^{\alpha}}\right)^{\frac{\beta-\gamma}{\alpha}}$$

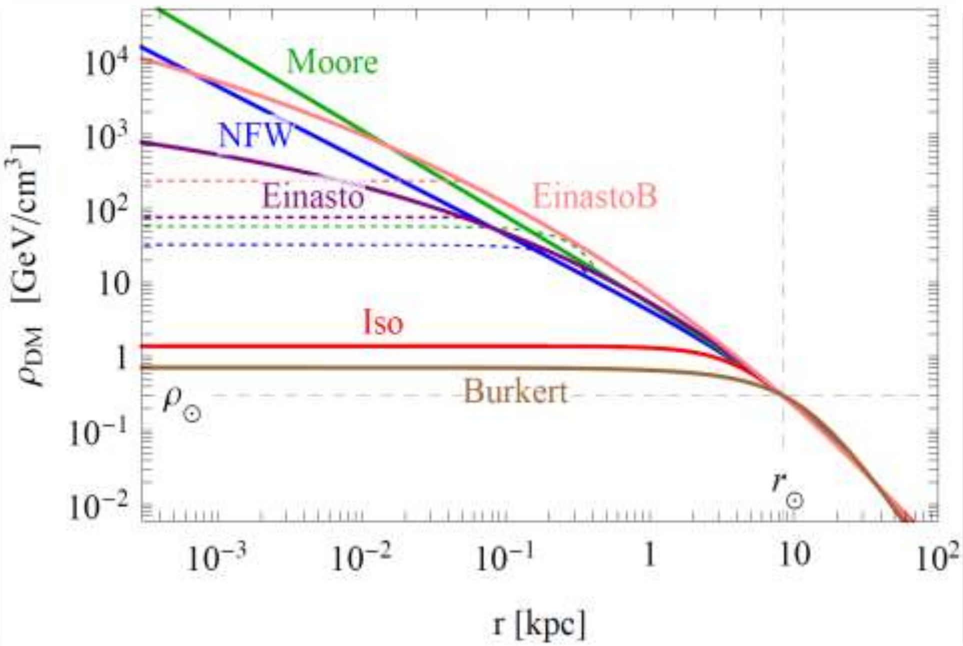
- Einasto

$$\rho(r) = \rho_e Exp\left[-d_n\left(\left(\frac{r}{r_c}\right)^{\frac{1}{n}} - 1\right)\right]$$

ρ_e: the density at the radius r_e

r_e defines a vol. containing ½ of $mass_{tot}$

DM Halo Profiles



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ρ_e: the density at the radius r_e

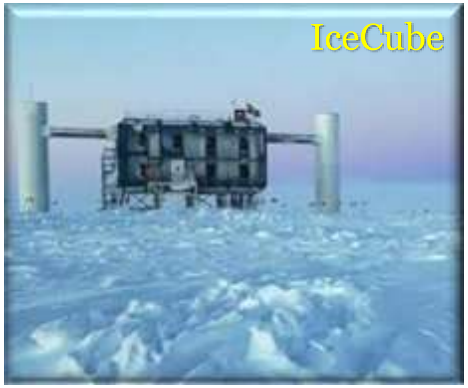
r_e defines a vol. containing ½ of $mass_{tot}$

❖ “Cusp vs Cored” problem:

- ➢ CDM N-body simulations → cusp profile
- ➢ Dwarf galaxies indicate cored profile.

Cosmic-Ray Experiments

- Ground-based
  MAGIC, HESS, CTA, IceCube, Super-K, Hyper-K, …
- Balloon-based:
  ATIC, PPB-BETS, …
- Satellite-based:
  AMS, Chandra, Fermi-LAT, PAMELA, XMM-Newton, Hitomi, ASTROGAM, …
  - ✓ Great sensitivity to cosmic-ray signals
  - ✓ Better chance to have the information for extracting DM properties



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^+ excess
  - XMM-Newton (X-ray): 3.5 keV line
  - IceCube (ν): PeV events
  - …

Hints from Cosmic-Rays?

❖ DM signatures in cosmic-ray observations?

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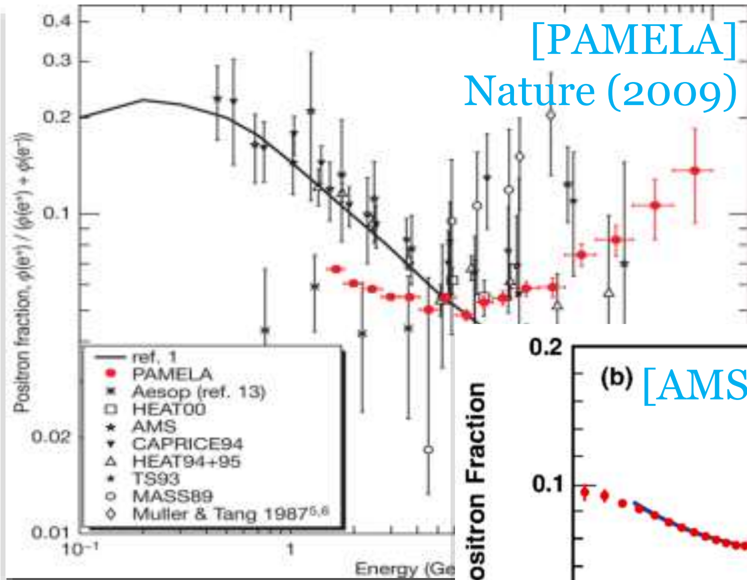
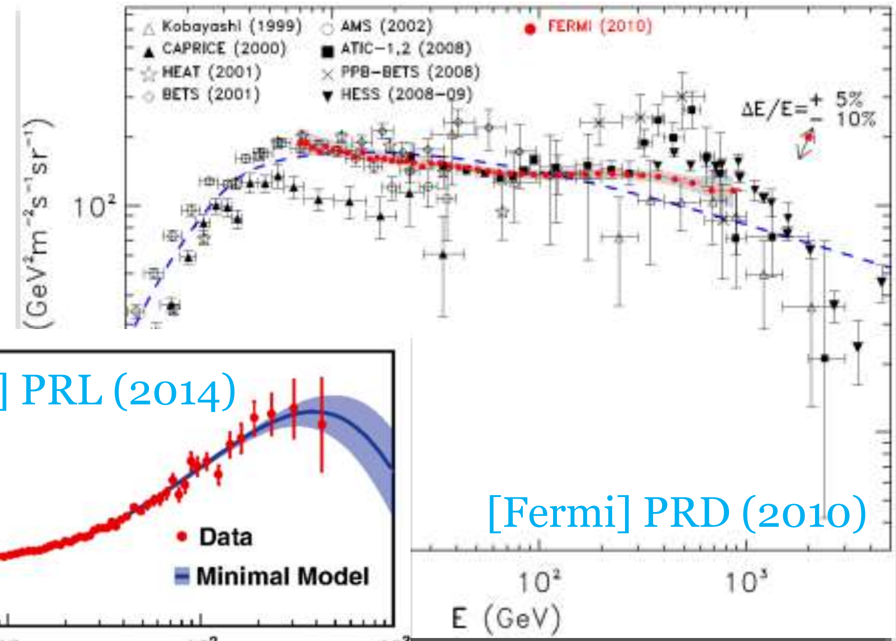
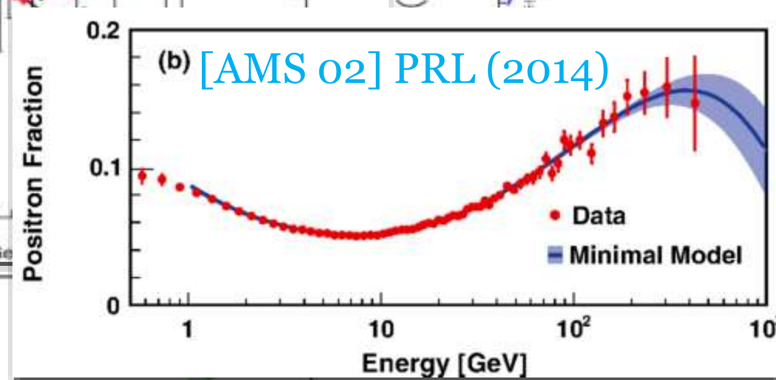
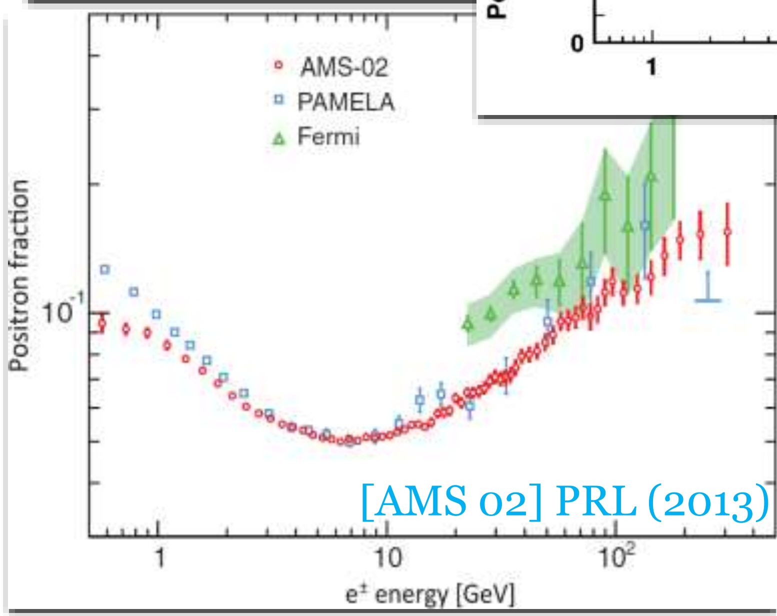
- …

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





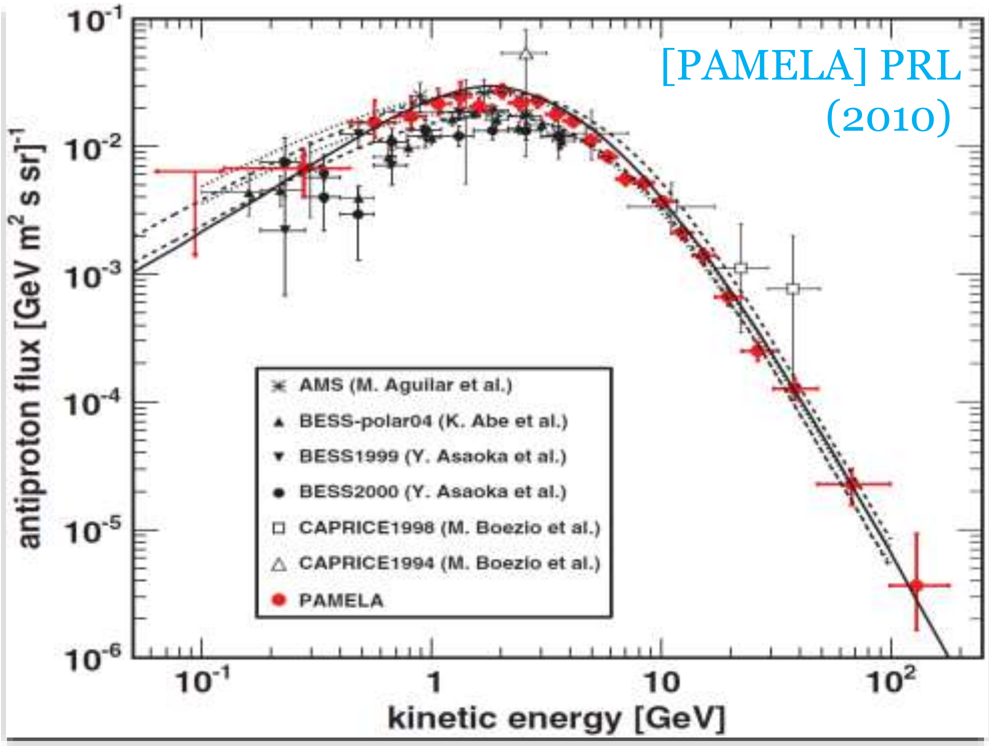




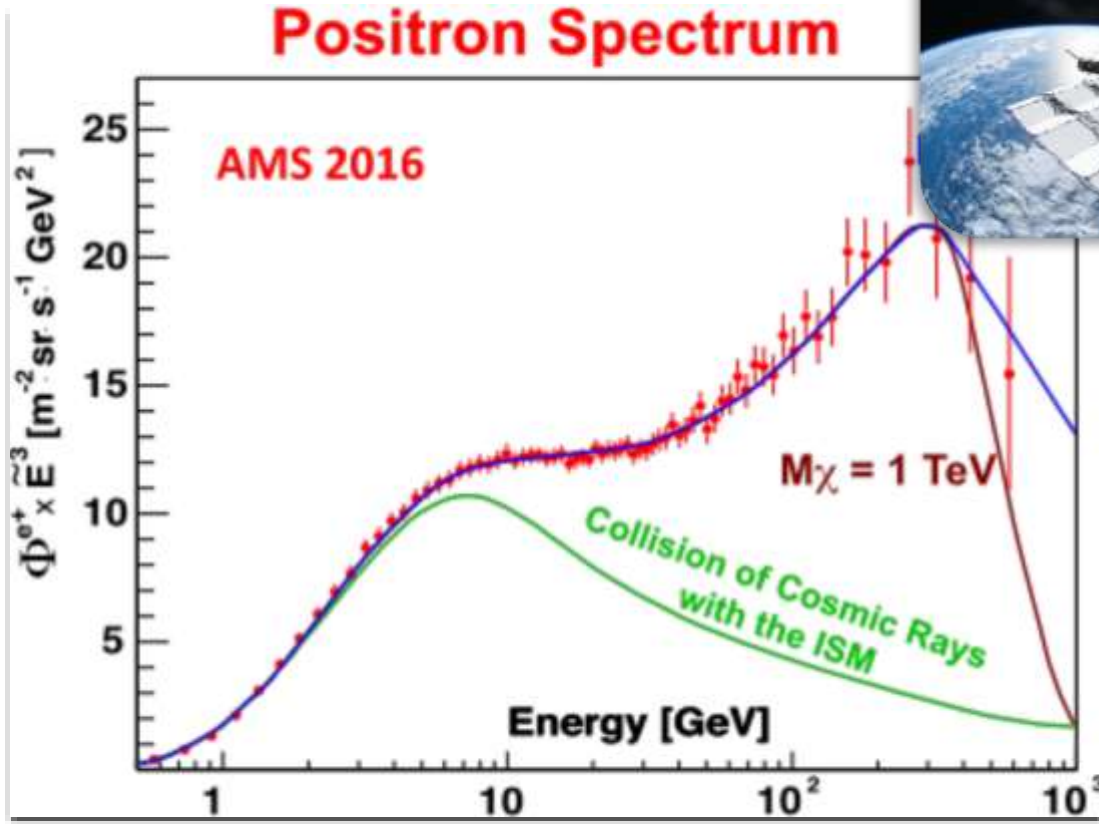
- ❖ PAMELA, Fermi-LAT, AMS-02:
  ➔ Excess in e^+/e^- fraction and $e^+ + e^-$ flux
- ❖ Require new sources of e^+ & e^-

Maybe not in anti-p

- ❖ Excess in e^+/e^- fraction and e^++e^- flux, but (maybe) not in anti-proton flux



e^+ Excesses: AMS02 in 2016



DM Ideas for e^- & e^+

- **Leptophilic DM ideas**:

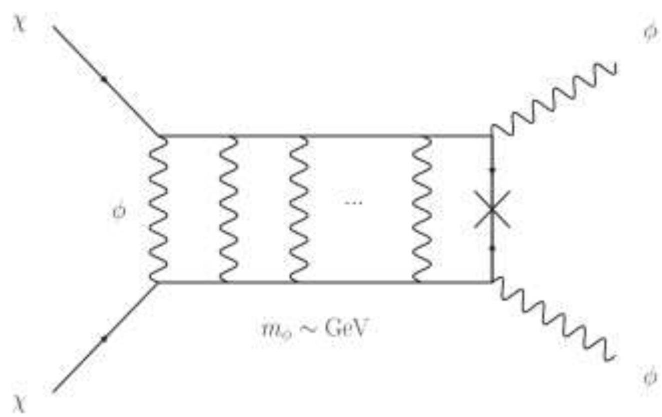
  Lepton-flavored DM, sub-GeV mediator, two DM components,

  Dirac gaugino DM, split-UED, …

- DM annihilating into sub-GeV mediator

  → Decay to p & $\bar{p}$ is kinematically forbidden, Sommerfeld enhancement

1^{st}: Used for neutralino DM by Hisano et al.



Chun & **JCP**, JCAP (2009)

Arkani-Hamed et al., PRD (2009)

A series of works
on general EWDM
in collaboration with EJ Chun

Importance of γ-rays

- Preserve spatial information about their sources

  & travel long distance (vs. $e^{\pm}$, $p^{\pm}$, ...)
- Spectrum at the detector similar to the injection spectrum
- Photons can be measured very easily & precisely (vs. ν's)
- Relatively efficient S/B discrimination in searches for γ-ray signatures
- Signatures in E_γ play a major role in DM searches.

(monochromatic peak and/or continuous bump signals)

γ-rays from Dark Matter

- γ-ray signal from DM annihilation is described by

$$\Phi_\gamma(E_\gamma,\psi) = \frac{dN_\gamma}{dE_\gamma}\frac{\langle\sigma v\rangle}{8\pi m_X^2}\int_{\text{los}}\rho^2(r)dl$$

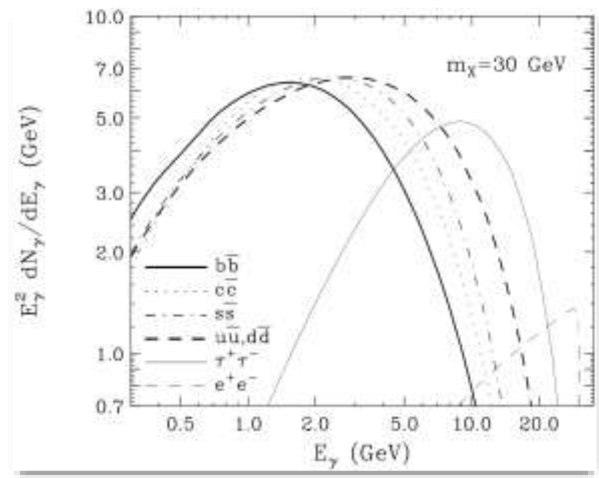
1) Distinctive peak or bump-like spectrum

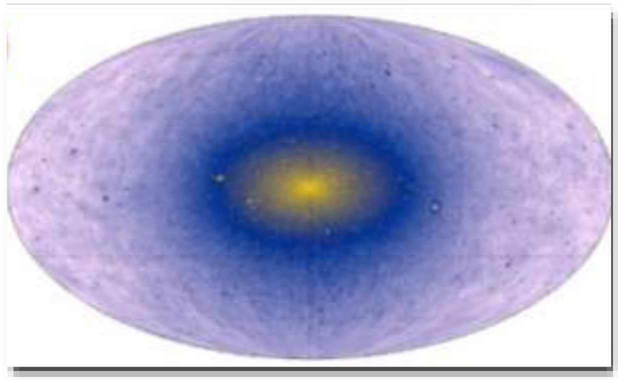
2) Normalization of the signal

3) Signal concentrated around the GC,

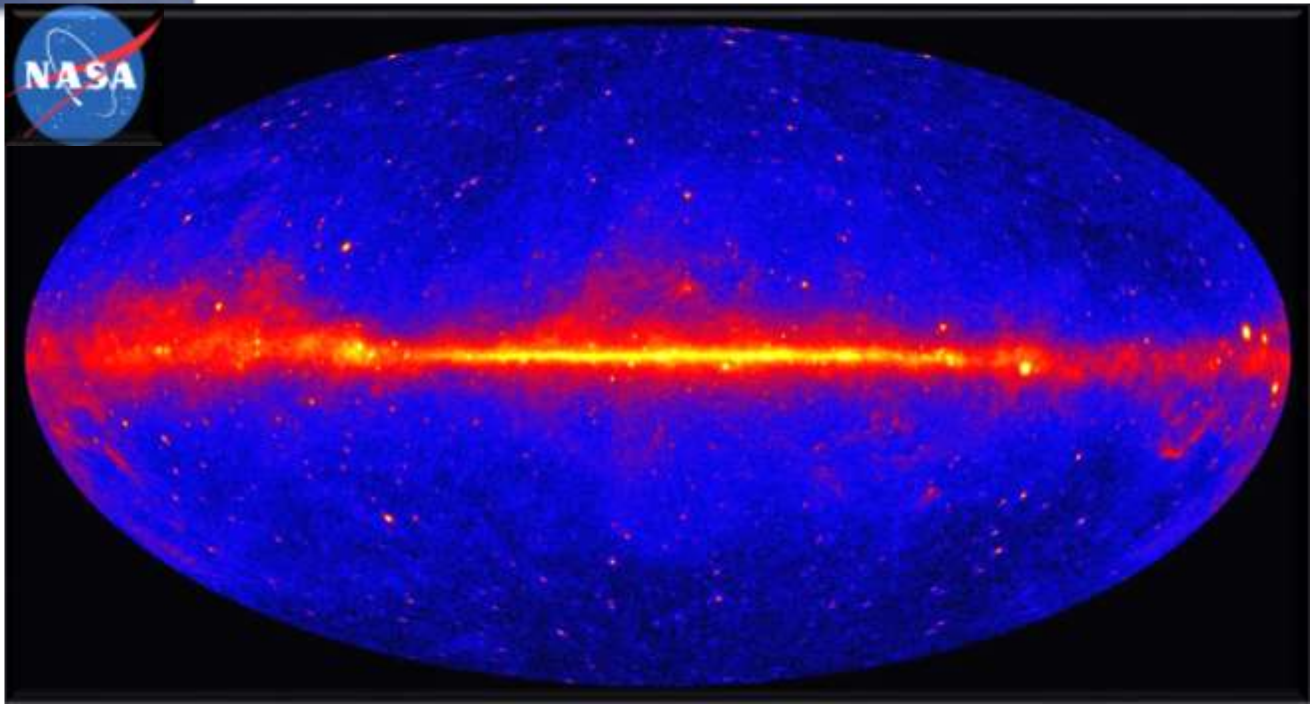
Spherical symmetry,

Morphology determined by the DM distribution

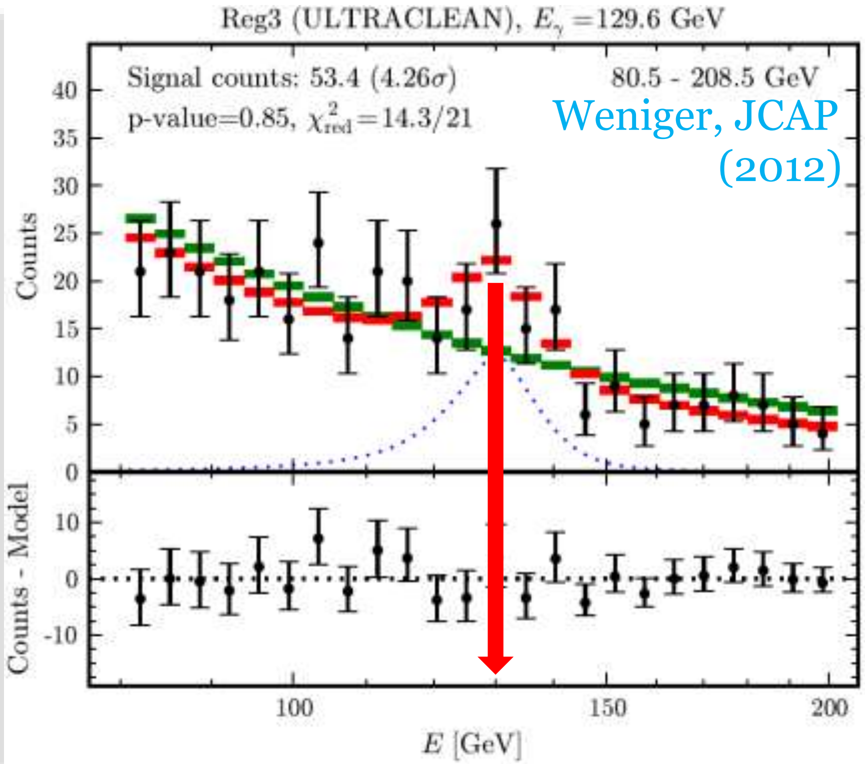


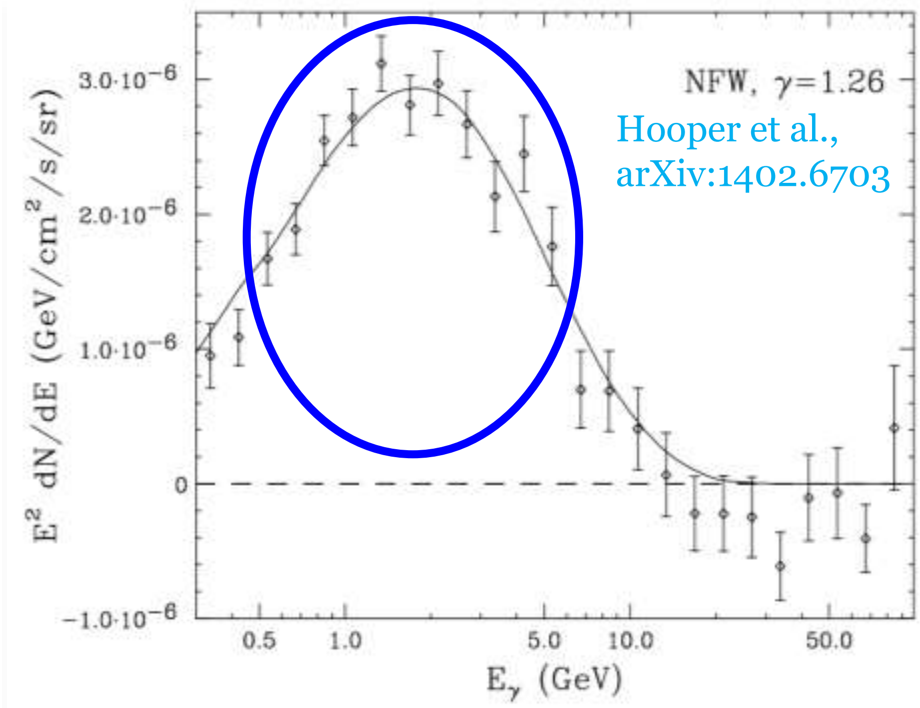


Fermi-LAT All Sky Map



γ-rays by Fermi-LAT

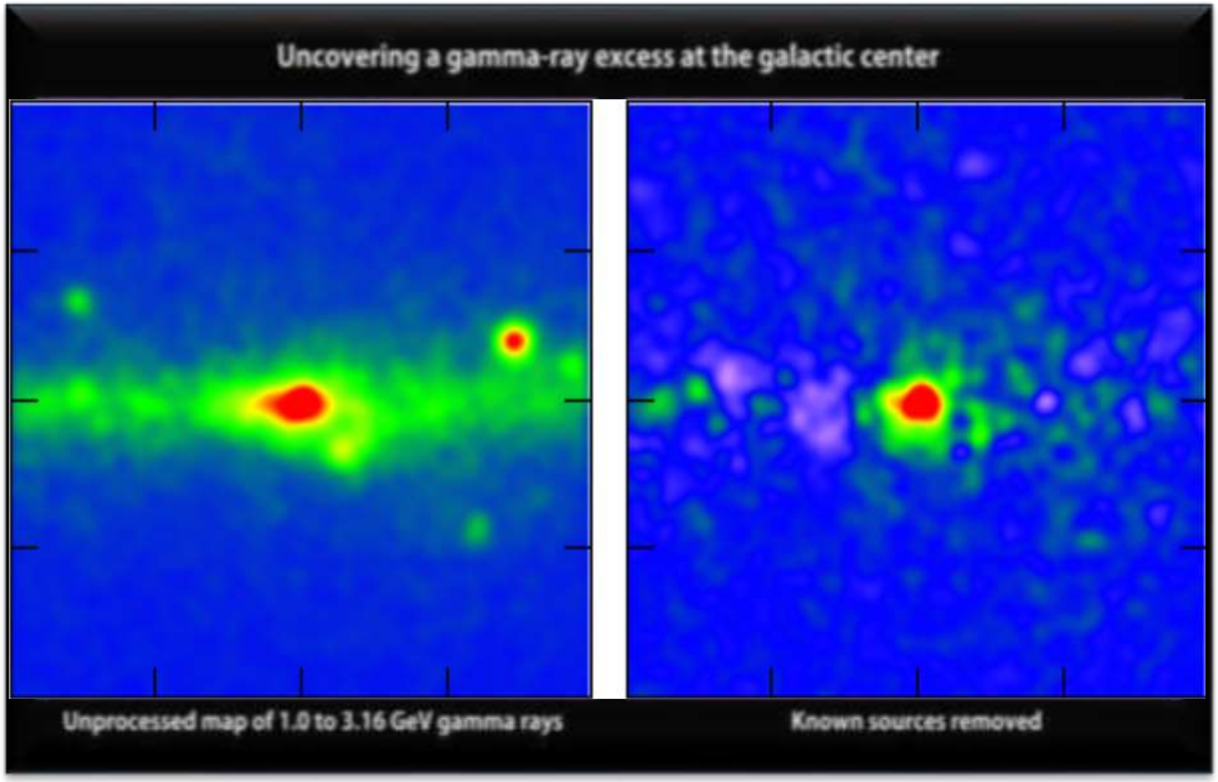




- ❖ γ-ray line (Gaussian peak) at $E_\gamma \approx 130$ GeV

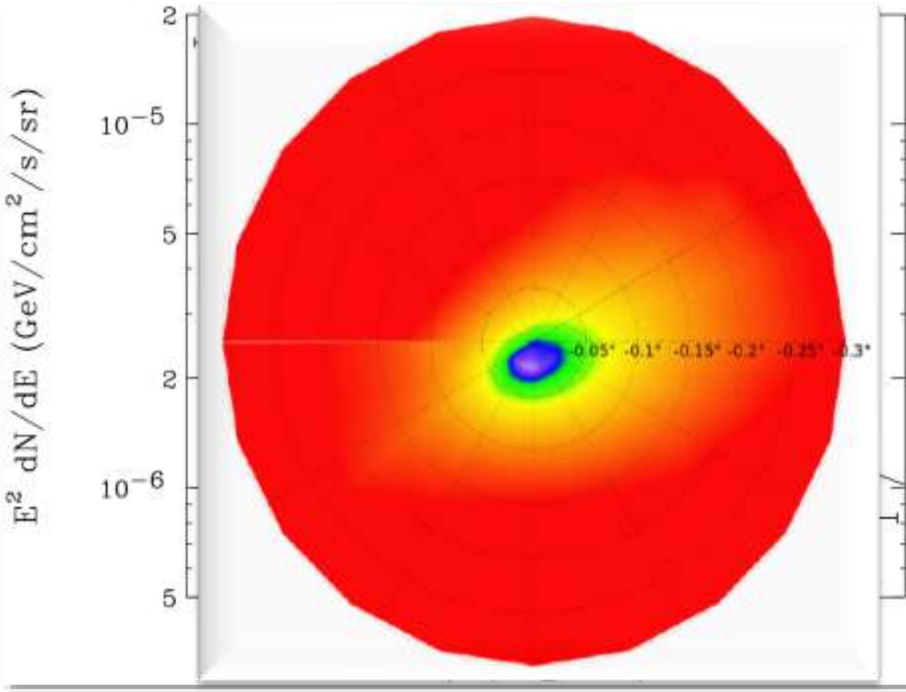
- ❖ Gamma-ray excess around $E_\gamma \approx O$(GeV)
- ❖ Signal: extended to > 10° from the GC
- ❖ Consistent with the dynamical center of the Milky Way

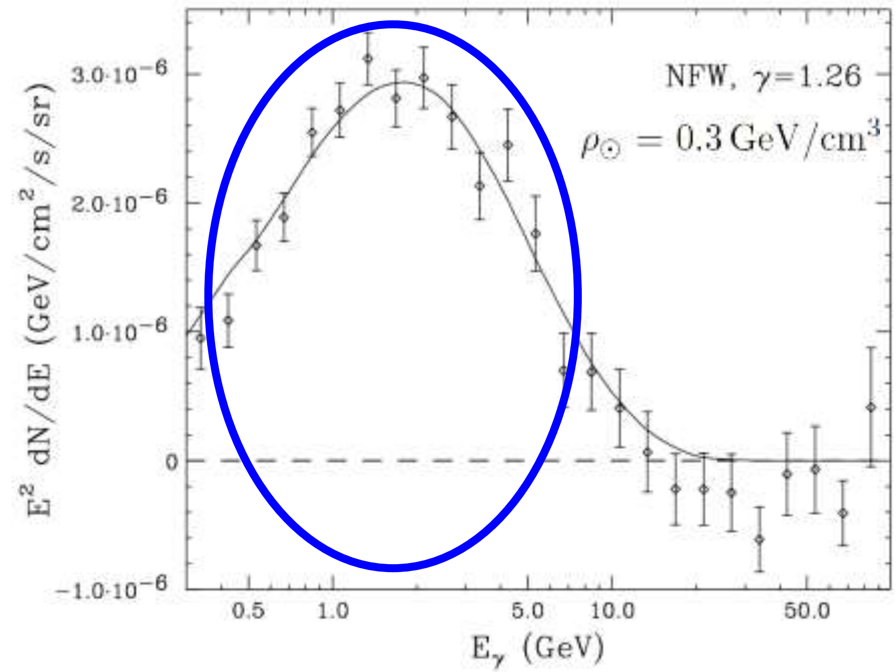
GeV γ-rays from Galactic Center



arXiv:1402.6703

Features of Fermi GeV Excess

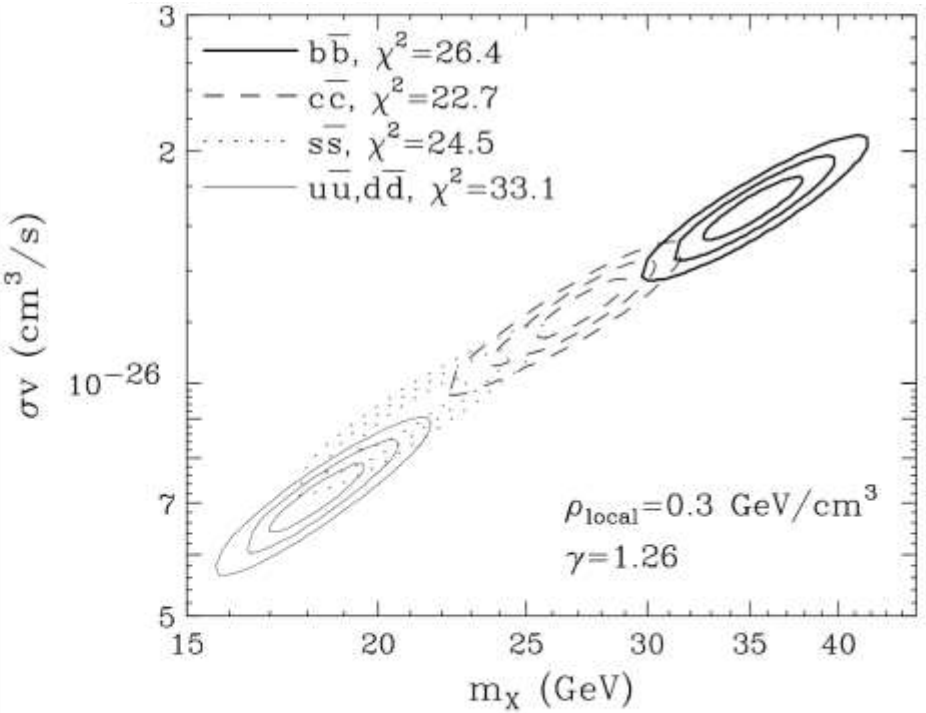


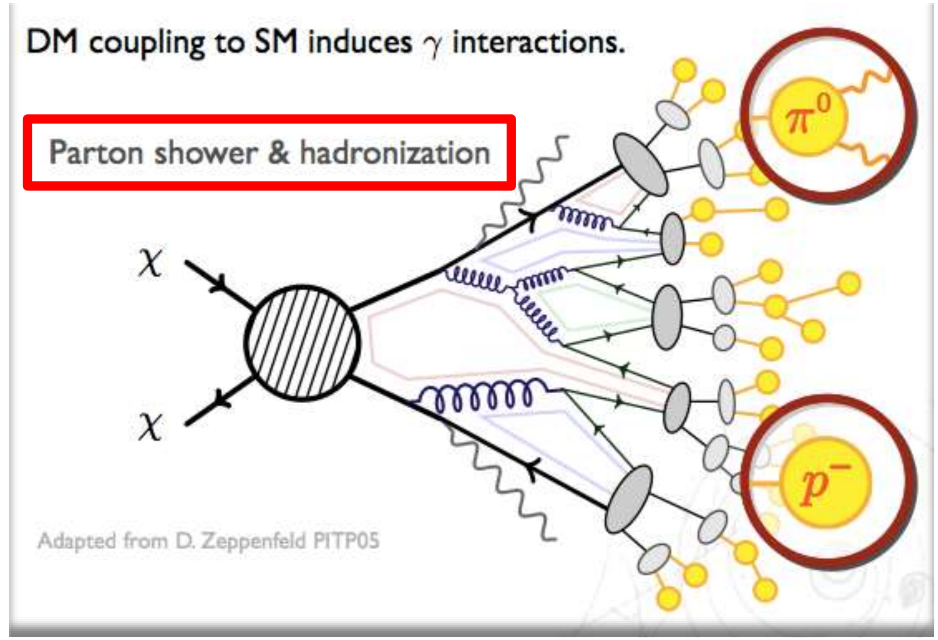


- Signal: extended to > 10° from the GC → disfavor point sources
- Consistent with the dynamical center of the Milky Way (< 0.05°)
- The spectrum of the excess peaks at 1-3 GeV.

arXiv:1402.6703

Bump: Preferred Final States



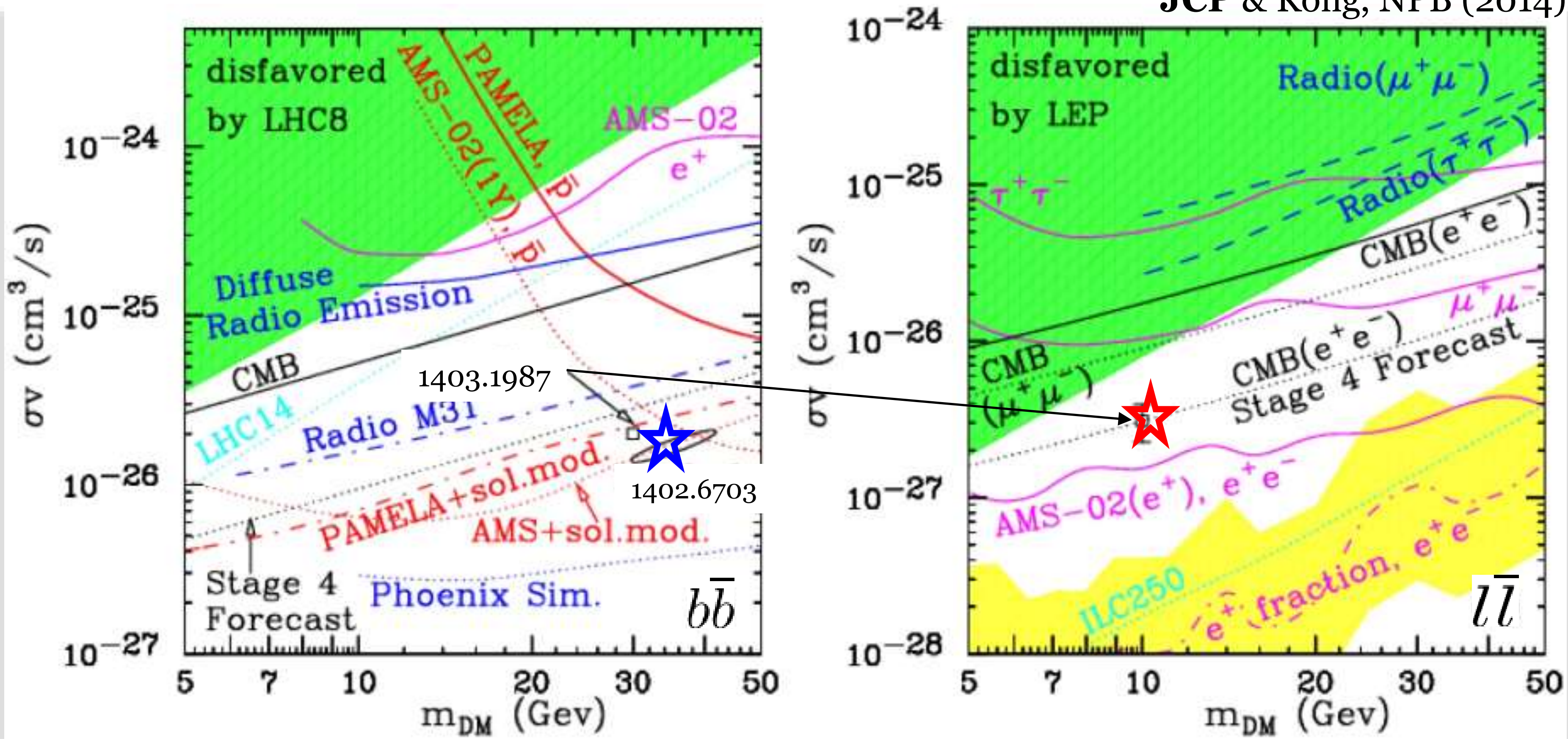


- The spectrum is in good agreement with the predictions from 20-40 GeV DM mostly annihilating to quarks (fragmentation, IC, bremsstrahlung, ...).
- Required cross section is ~ 0.7-2.1 · 10^{-26} cm³/s

arXiv:1402.6703

Constraints on DM Interpretations

JCP & Kong, NPB (2014)

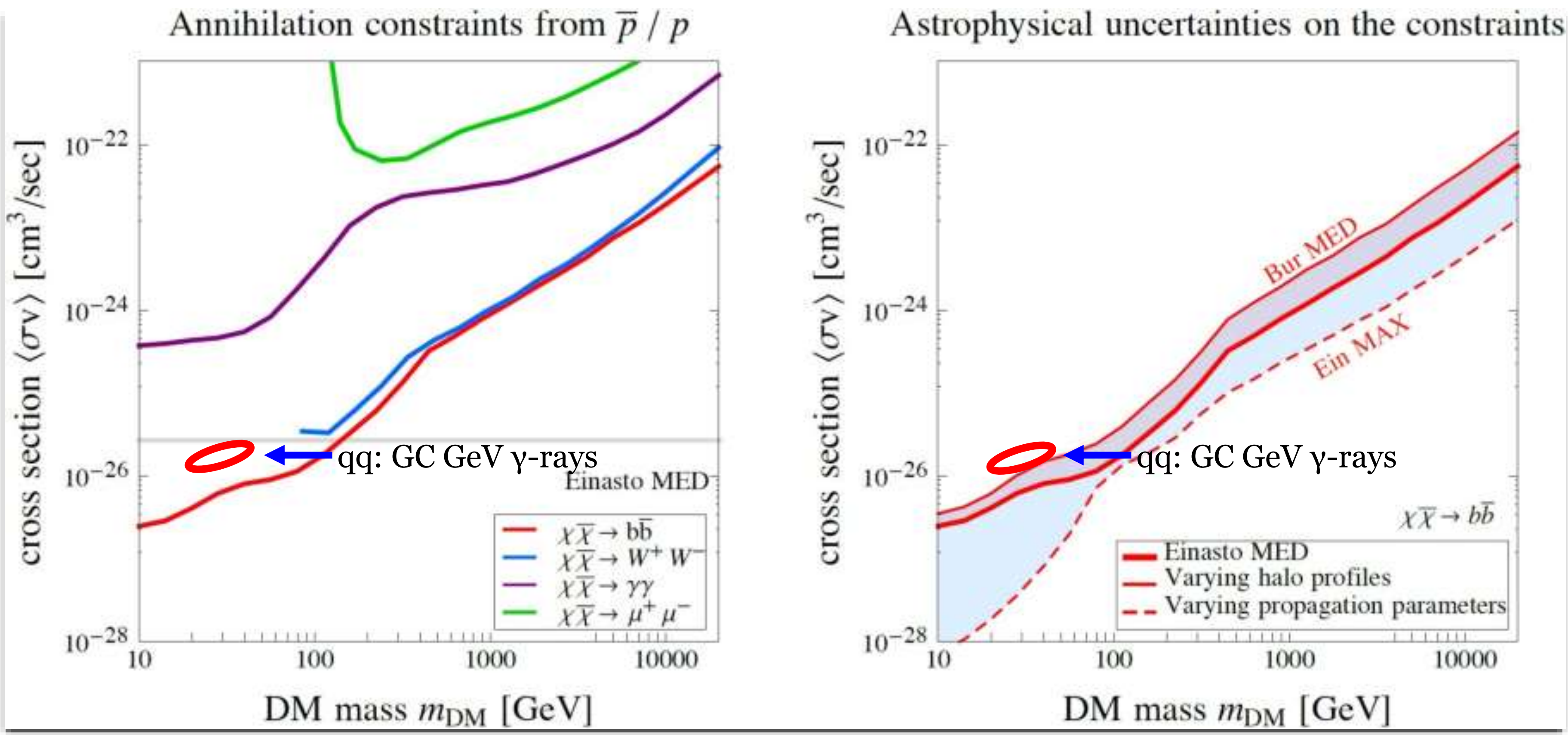


➢ DM couplings to 1st (2nd) generation of SM fermions: disfavored!

(Maybe even not b-quark)

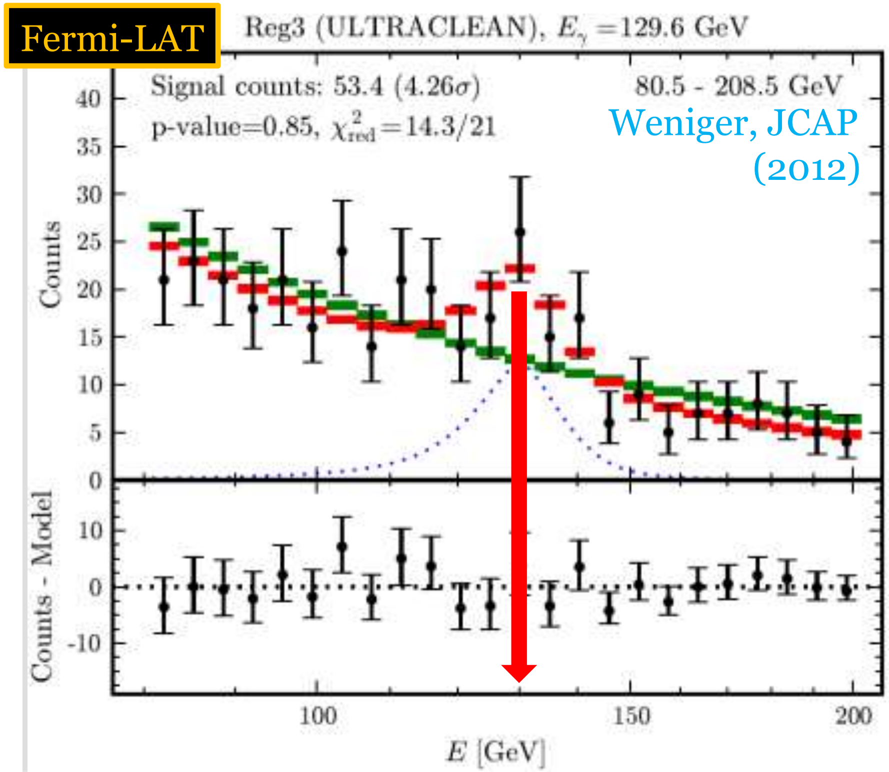
New Limits from AMS-02

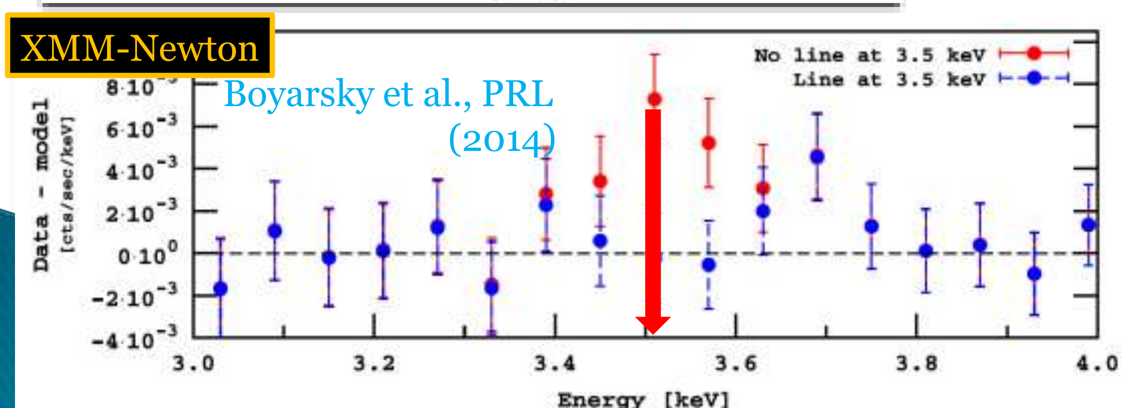
Cirelli et al., arXiv:1504.04276



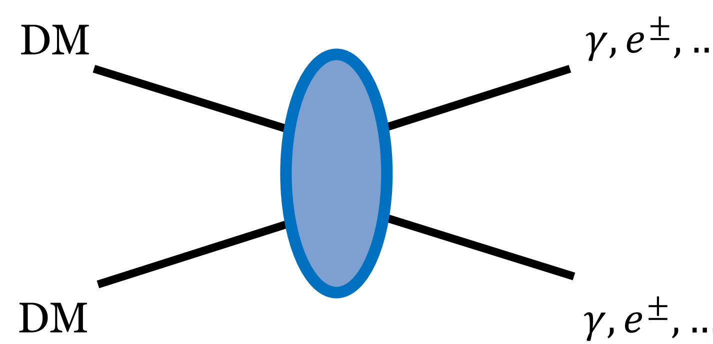
- Based on the recent AMS-02 anti-p/p data
- **q-final states are disfavored!** (**regardless of mediator**)

Line-like Excesses

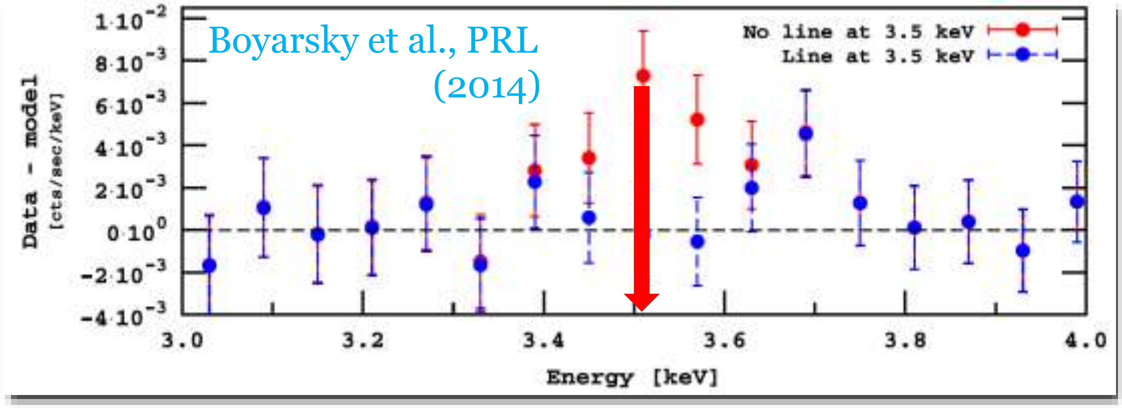




- 3.5 keV line, 511 keV line, 130 GeV line, ...
- **Typical DM interpretation**
  - ✓ DM: directly annihilates/decays into 2 (stable) SM particles, γ+X
  - ✓ The location of the line is identified as the (double) mass of DM
  - ✓ Width of the line is instrumental

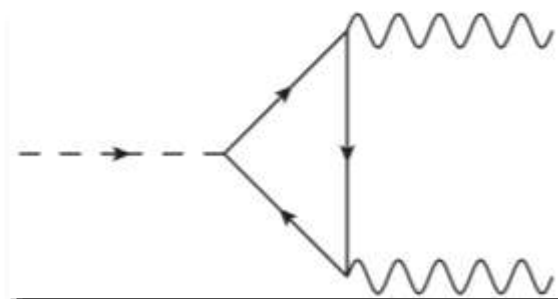


3.5 keV Lines



- Indications at 3.2σ (Andromeda) and 2.3σ (Perseus) from XMM-Newton
- γ line (Gaussian peak) at $E_\gamma \approx 3.5$ keV

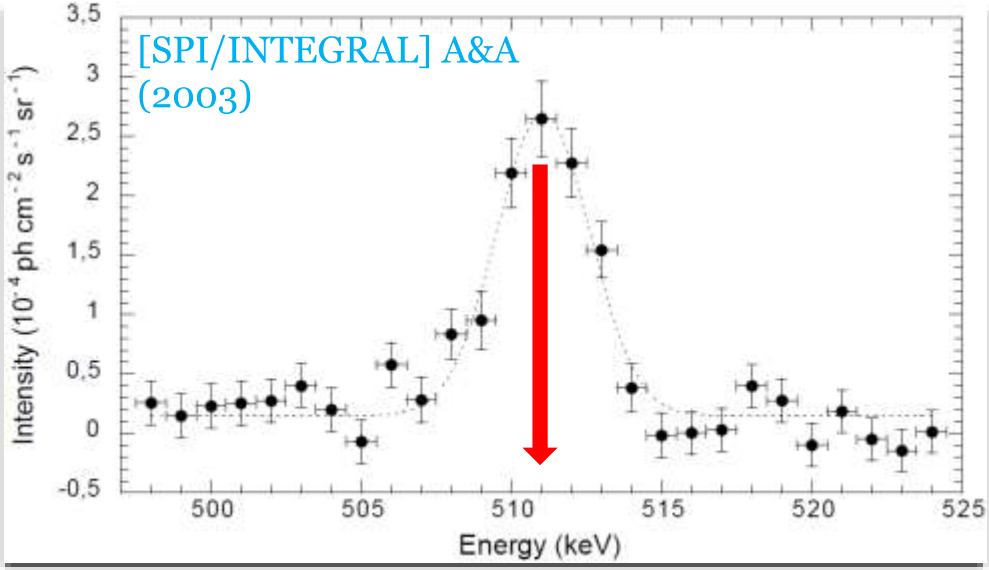
  → DM: directly annihilate/decay into photon + X

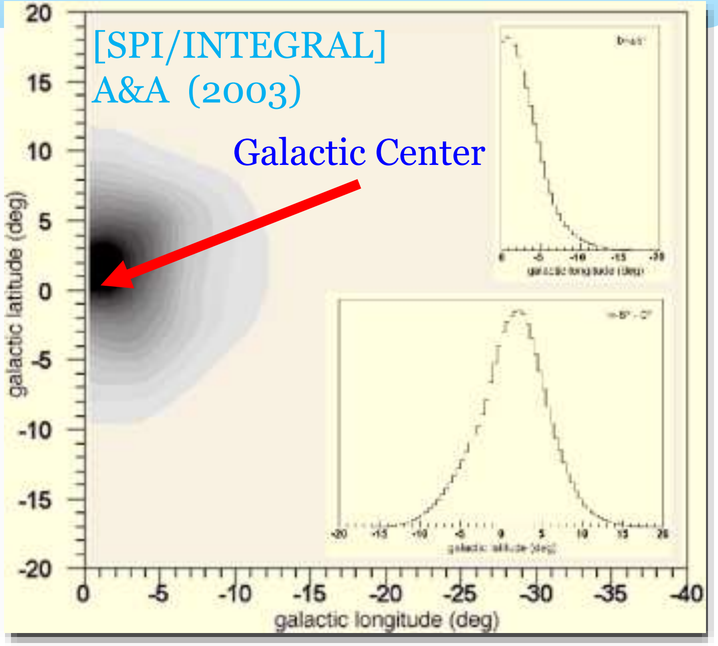


- Decay models: sterile *ν*, axion-like particles, axino, ...

Alternative mechanism for cosmic-ray peaks based on extended DM:
Doojin Kim & **JCP**, PLB (2015)

511 keV γ-ray Line





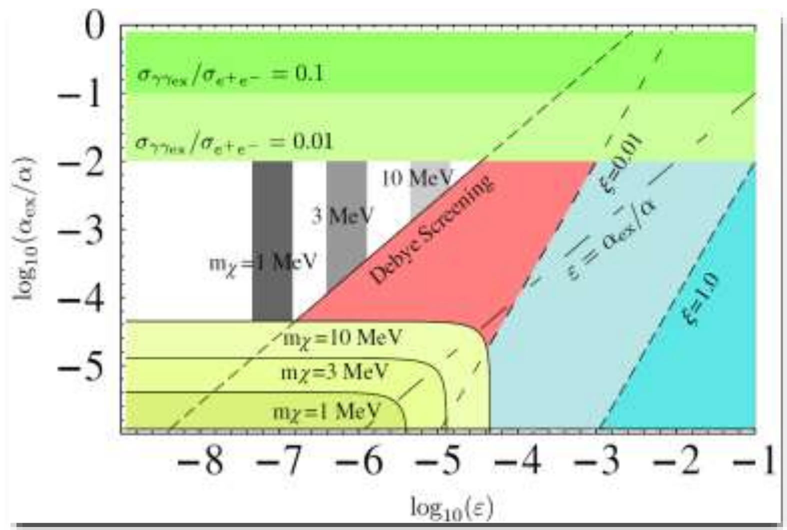
$m_e = 510.99892$ keV

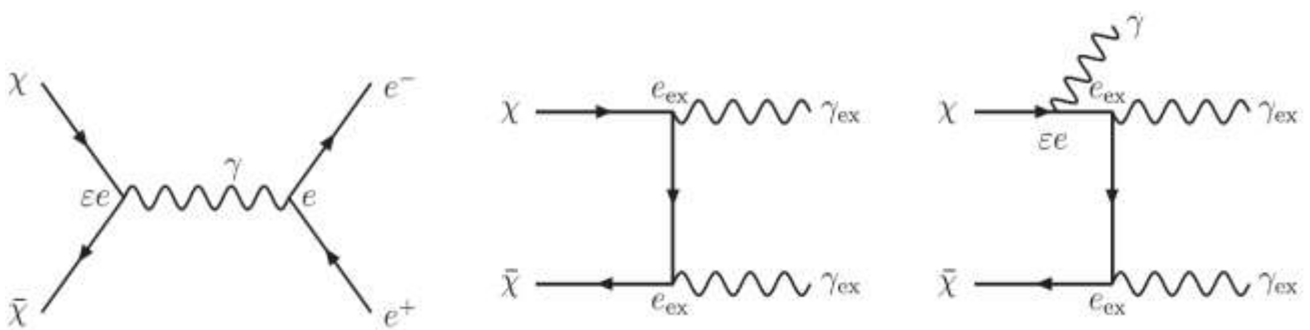
instrument	year	flux $[10^{-3}\ ph\ cm^{-2}\ s^{-1}]$	centroid $[keV]$
HEAO-3	1979 – 1980	1.13 ± 0.13	510.92 ± 0.23
HEXAGONE	1989	1.00 ± 0.24	511.33 ± 0.41
TGRS	1995 – 1997	1.07 ± 0.05	510.98 ± 0.10
SPI/INTEGRAL	2003–	1.02 ± 0.10	$511.06^{+0.17}_{-0.19}$

e^+ Sources for 511 keV γ-rays

Huh, Kim, **JCP** & Park, PRD (2008)

- Particle physics:
  - Light DM annihilation or decay
    - → Axino, Sterile neutrino, Milli-charged DM, …
  - Others → Exciting heavy DM, …





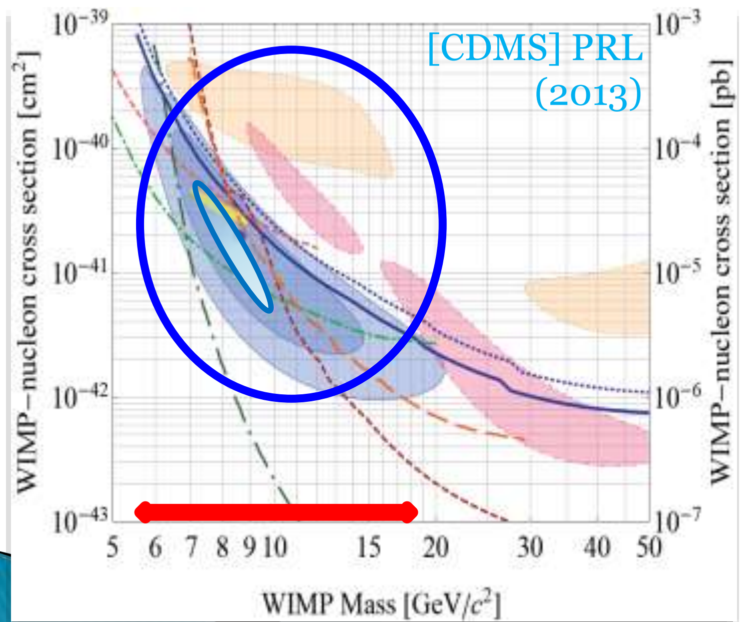
Direct searches & γ-rays: 10GeV?

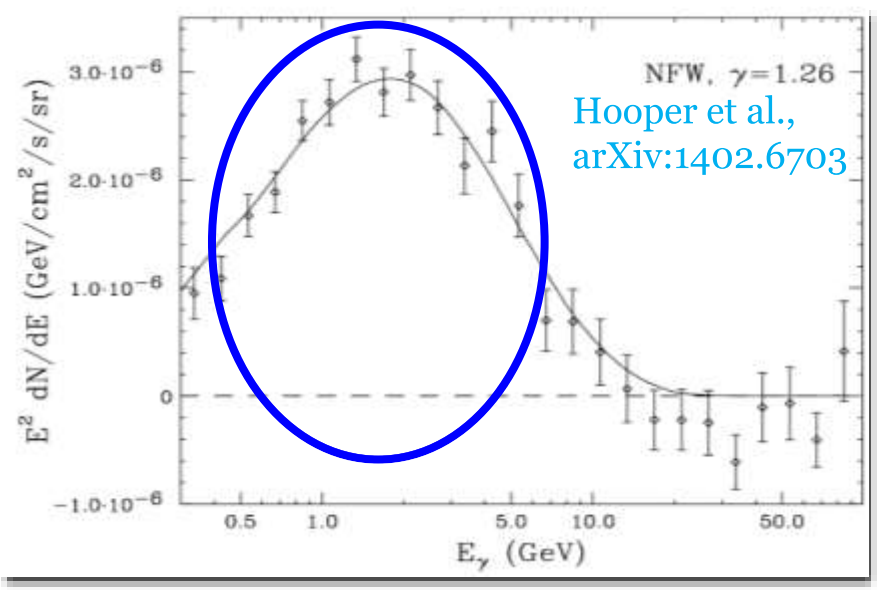
Kyae & **JCP**, PLB (2014)

- DM direct searches & γ-ray observations similarly favor light DM: ~ 10 GeV.

- They can be explained in a common **framework**.

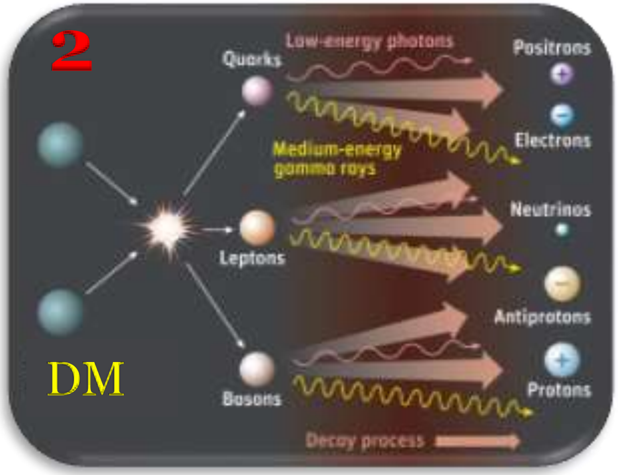
  → ~10 GeV Fermion/scalar DM with a *O*(TeV) complex scalar mediator

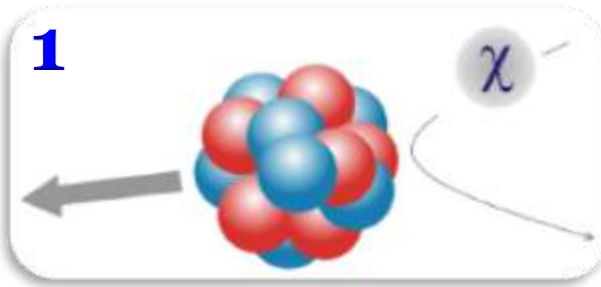


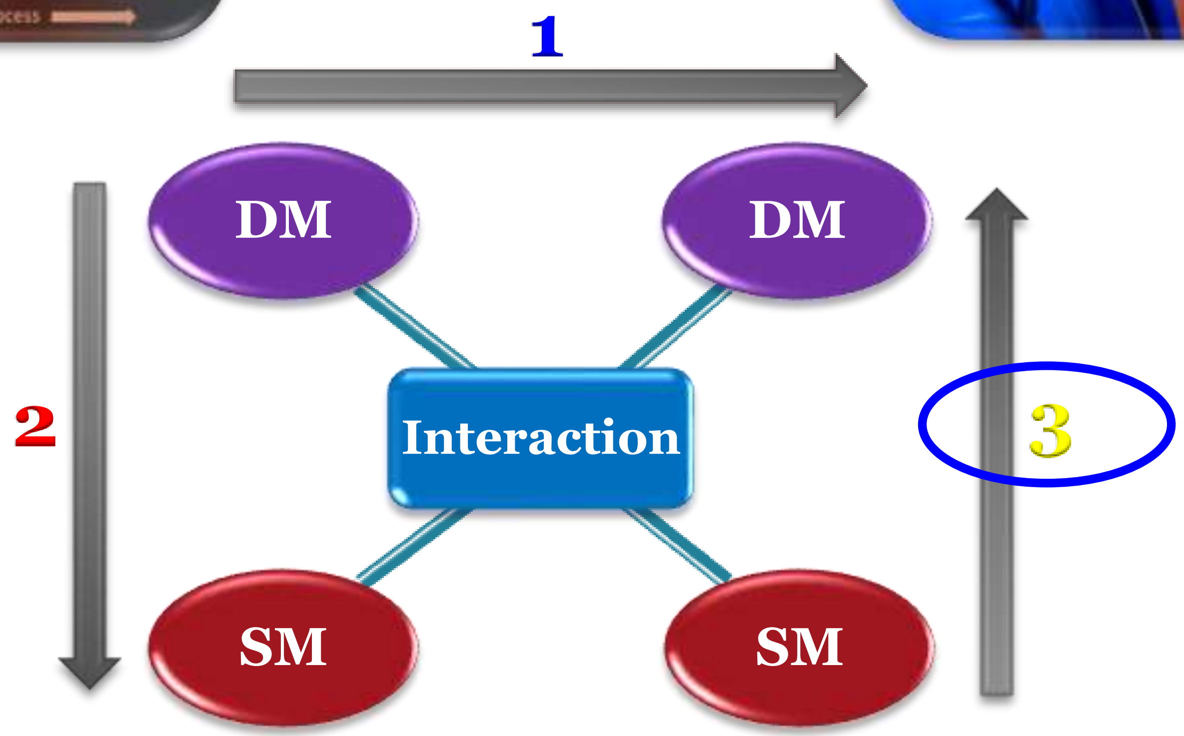


5. DM & Collider

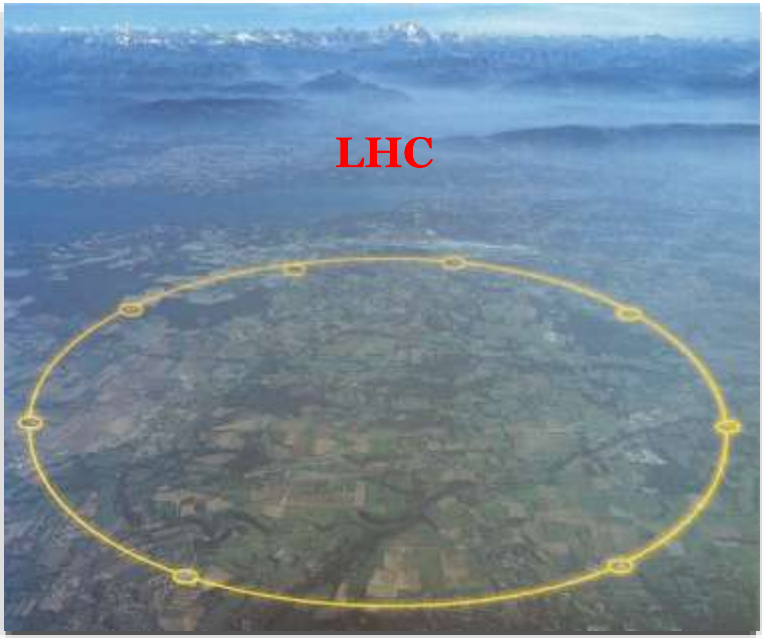
DM Production @ Colliders





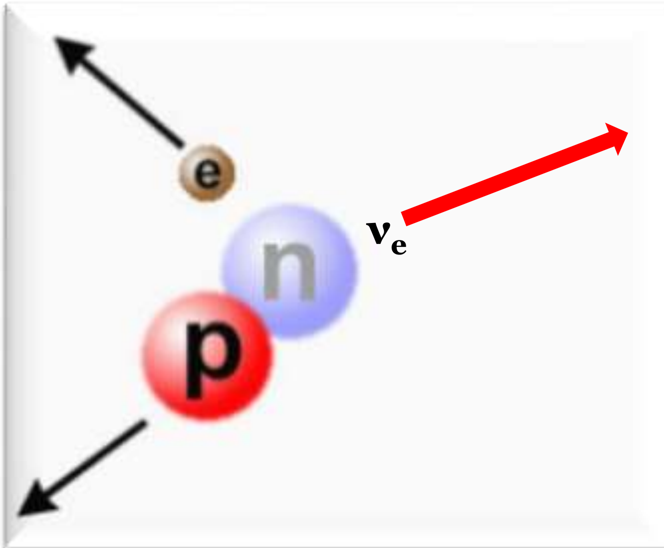


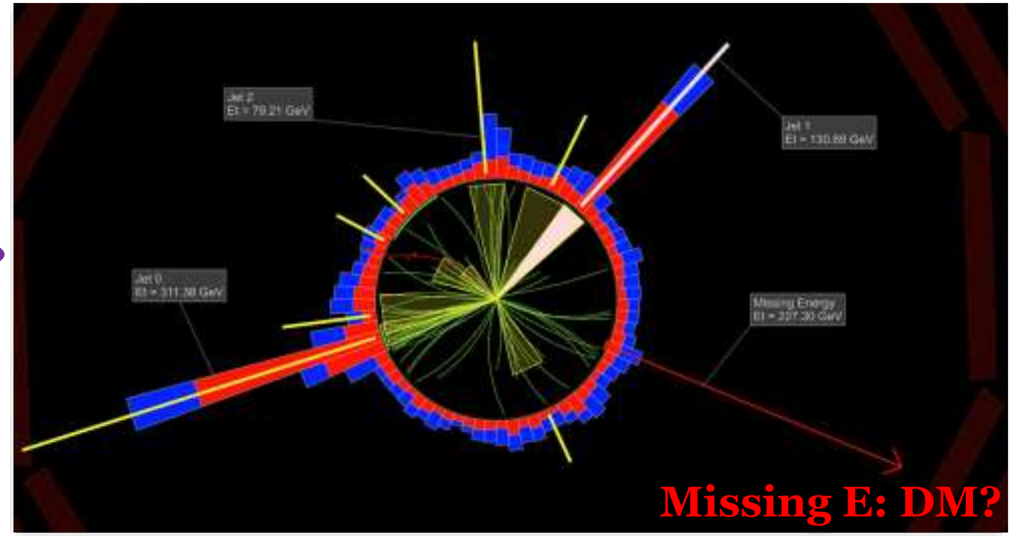
Collider Physics: LHC



- Production of heavy new particle (e.g. super-partner, Z', t', ...) may be seen at the LHC
- LHC Run I (7-8 TeV): no conclusive evidence of DM yet
- LHC Run II (13-14 TeV): upgrade of the LHC has been completed, now running!

DM at Colliders





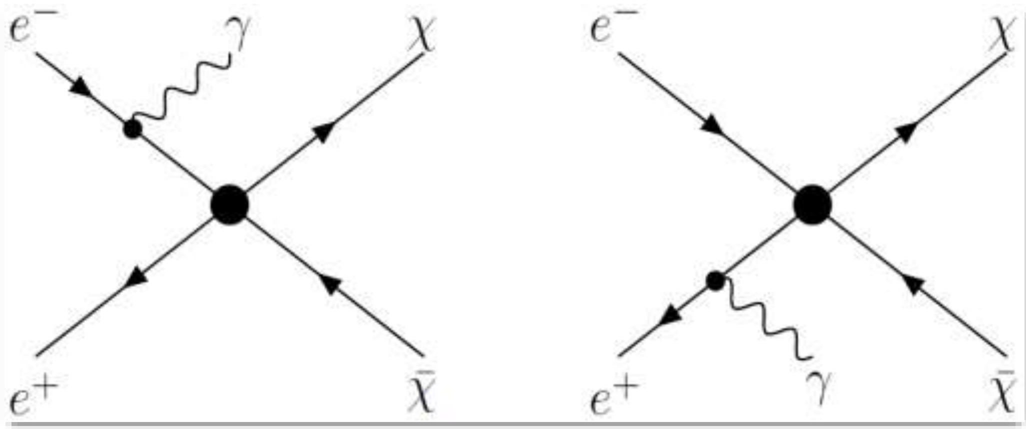
Pauli(1930) Fermi(1932)

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

  → regarded as Missing E

Collider Limits

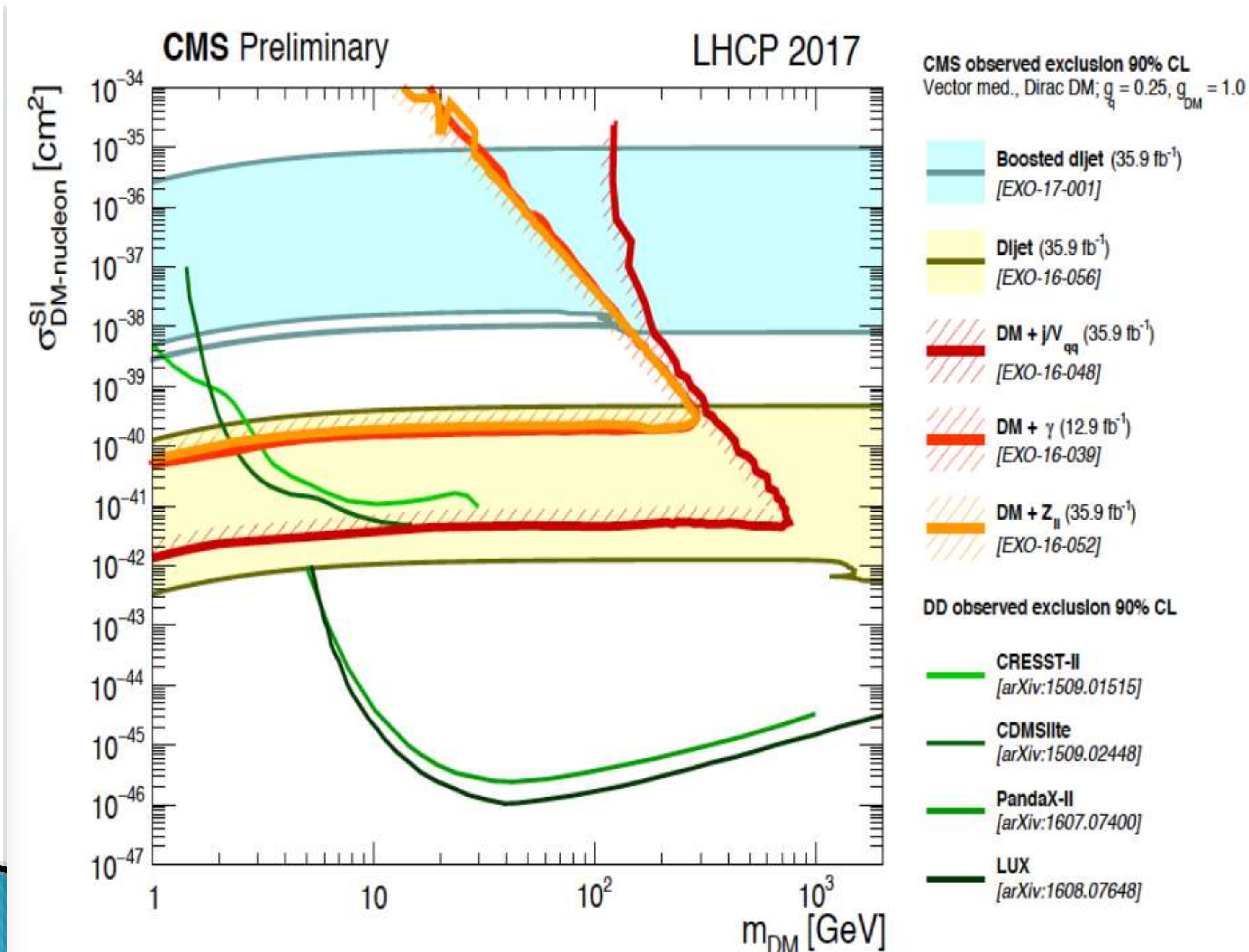
JCP & Kong, NPB (2014)



- LEP(ILC): mono-γ+E_T & LHC: mono-j+E_T
  - → limits on $\sigma_{\chi N}$ & $<\sigma v>_{\chi\chi \to ll,\, qq,\, \ldots}$
- b, t-quarks flavored DM: mono-b+E_T more effective

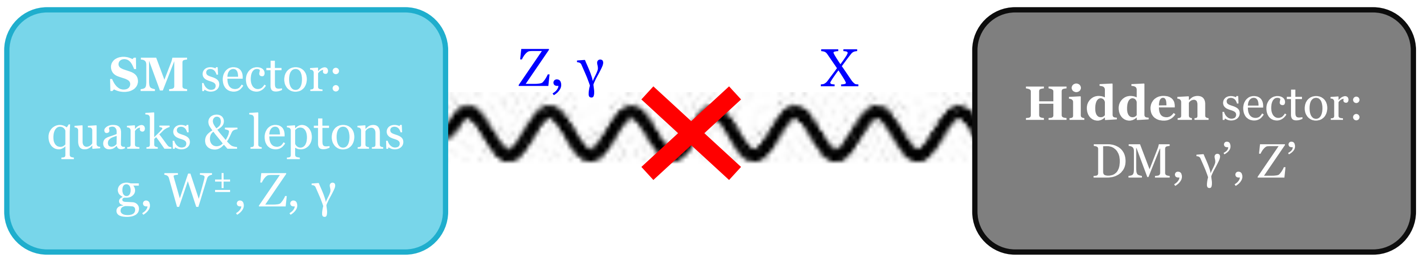
Constraints on DM models

CMS (LHC) Limits



Light DM & Hidden $U(1)_X$

- Motivations for light DM & hidden γ/Z':
  - ✓ e^+ excess (PAMELA, AMS-02), 511 keV γ line (SPI/INTEGRAL), $(g-2)_\mu$, …
  - ✓ Limitations of DM direct searches (E_{th})
- Hidden light sector (new force & particles): e.g. $U(1)_X$



- $U(1)_Y$ & $U(1)_X$ can mix ← kinetic mixing

$$\mathcal{L} \supset -\frac{1}{2}\sin\epsilon\, X_{\mu\nu}F^{\mu\nu}$$

Huh, Kim, **JCP** & Park, PRD (2008)

Light DM & Hidden $U(1)_X$

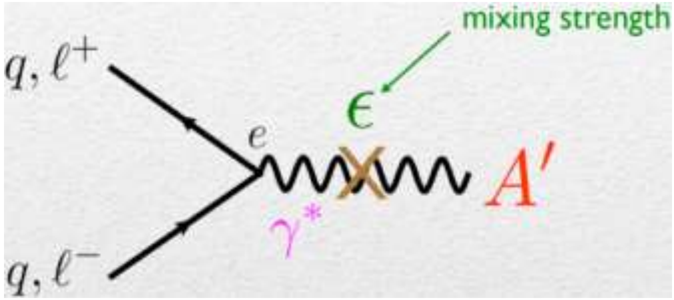
- Hidden $U(1)_X$ & DM

E.J. Chun, **JCP** & S. Scopel, JHEP (2011)

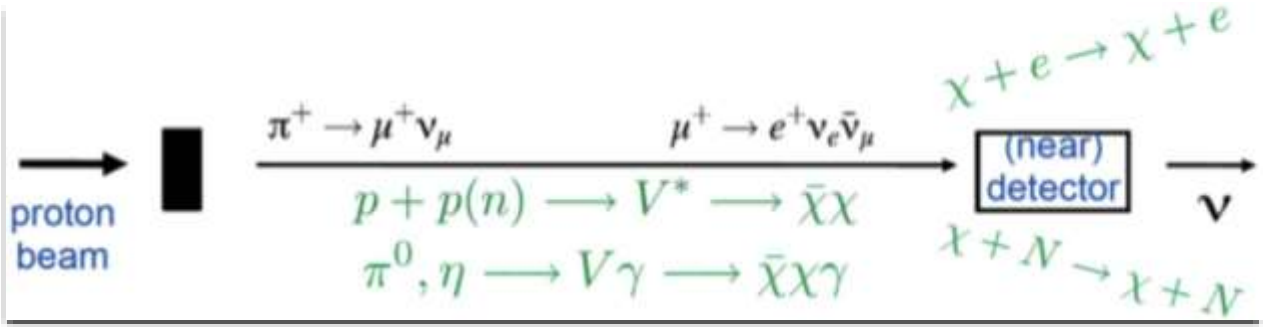
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\sin\epsilon\,\hat{B}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{4}\hat{X}^{\mu\nu}\hat{X}_{\mu\nu} - g_X\hat{X}^{\mu}\bar{\psi}\gamma_{\mu}\psi + \frac{1}{2}m_{\hat{X}}^2\hat{X}^2 + m_{\psi}\bar{\psi}\psi$$

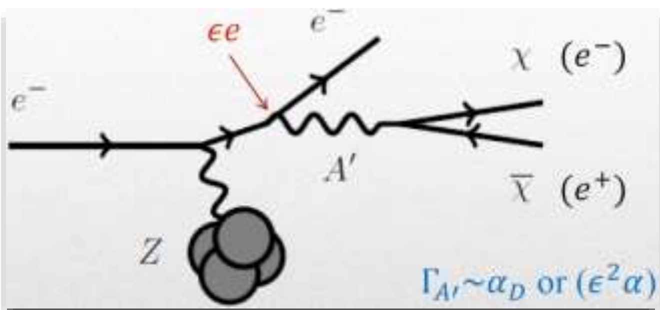
- Low-E & EW constraints:$(g-2)_\mu$, ρ parameter, atomic parity violation, EWPT, …

- Collider limits: LEP, LHC, …



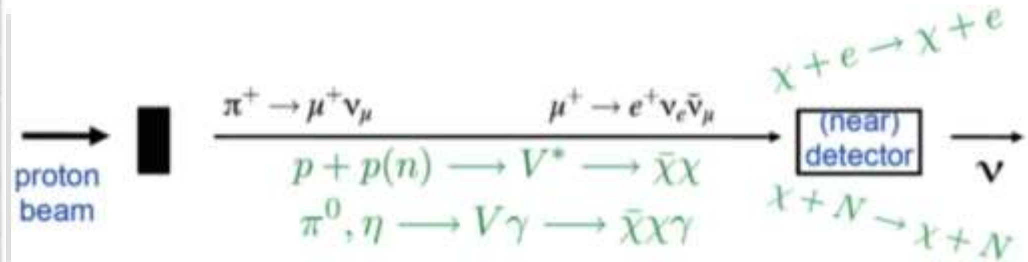
DM @ Fixed Target Experiments

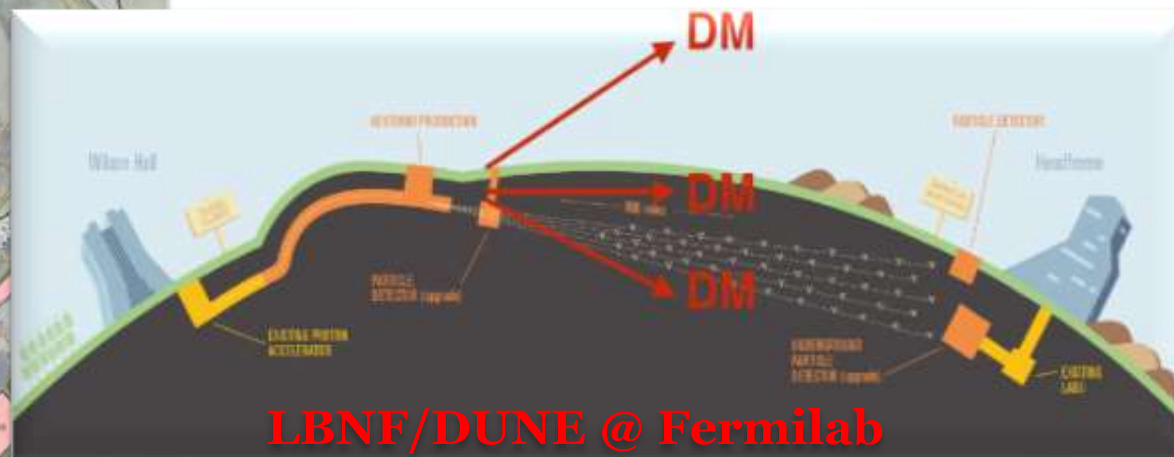




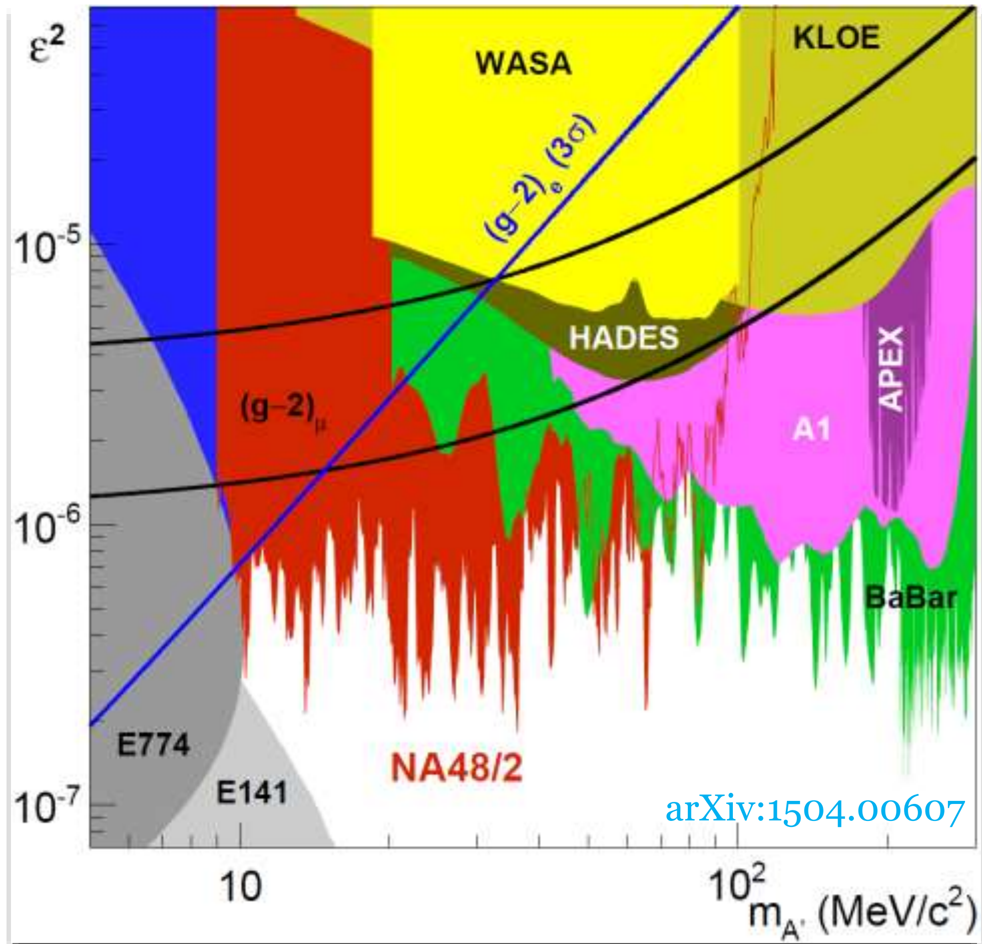
- p/e beam dump ➔ Z', DM production
- Original purpose: *ν* production
- Upcoming Exps.: SHiP (CERN), NOVA/MicroBooNE/DUNE (Fermilab), APEX/HPS/DarkLight/BDX (J-Lab), …

Future Fixed Target Exps.



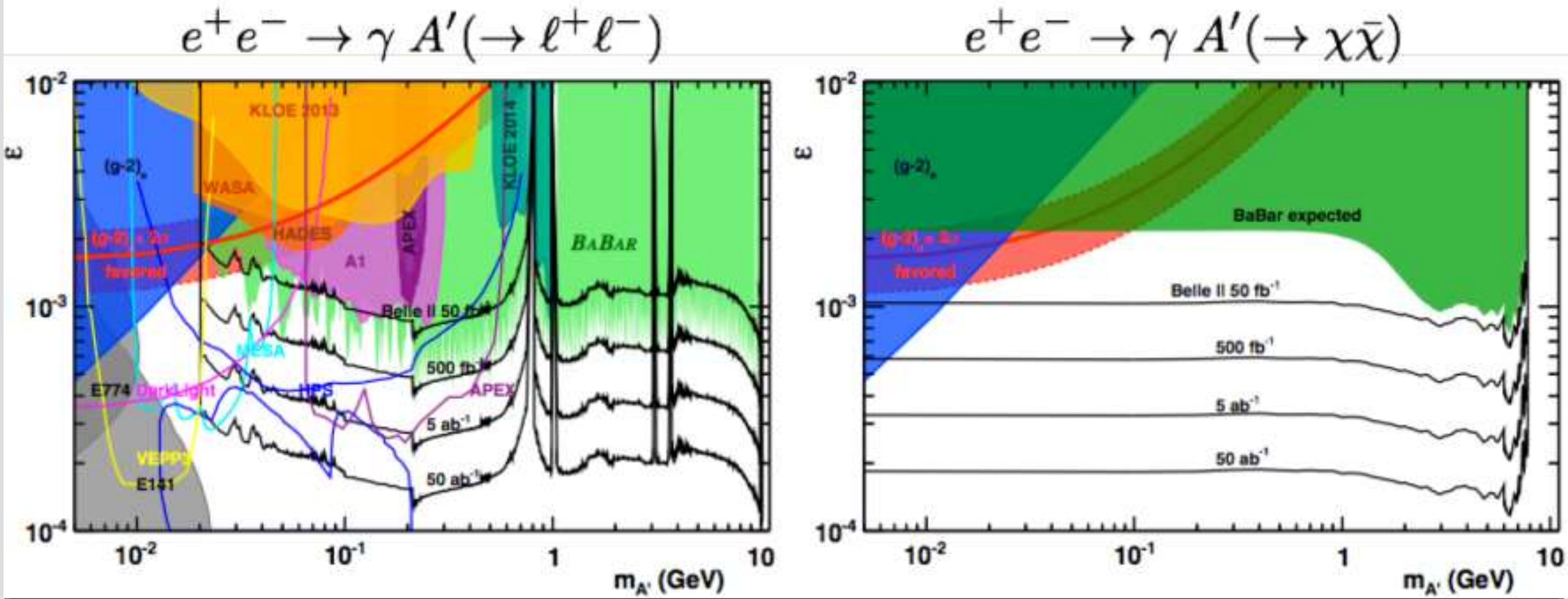


Current Status



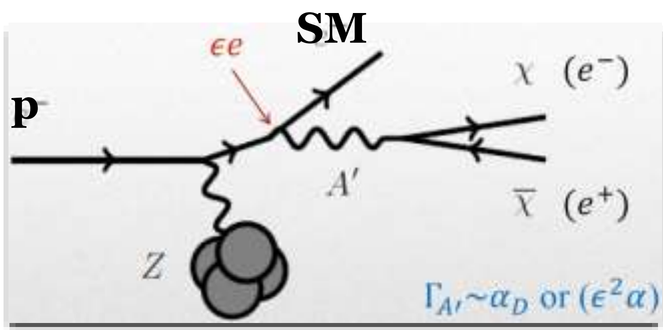
Belle II

Prospects with Belle II

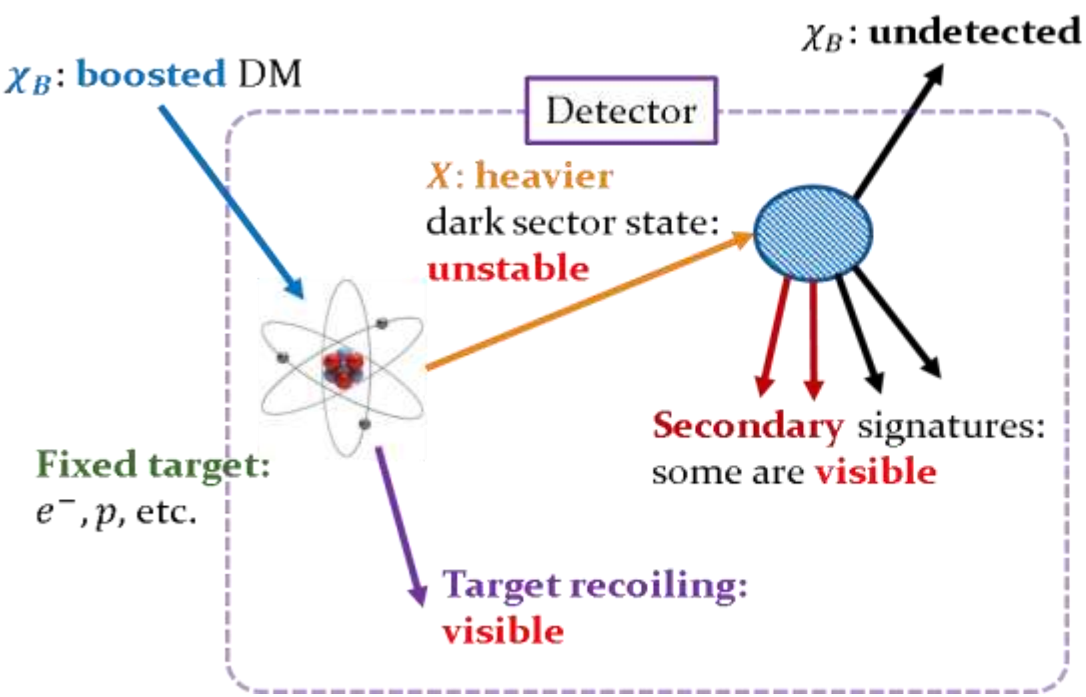


From Y. Kwon' talk

DM "Colliders"



D. Kim, **JCP** & S. Shin (2016)

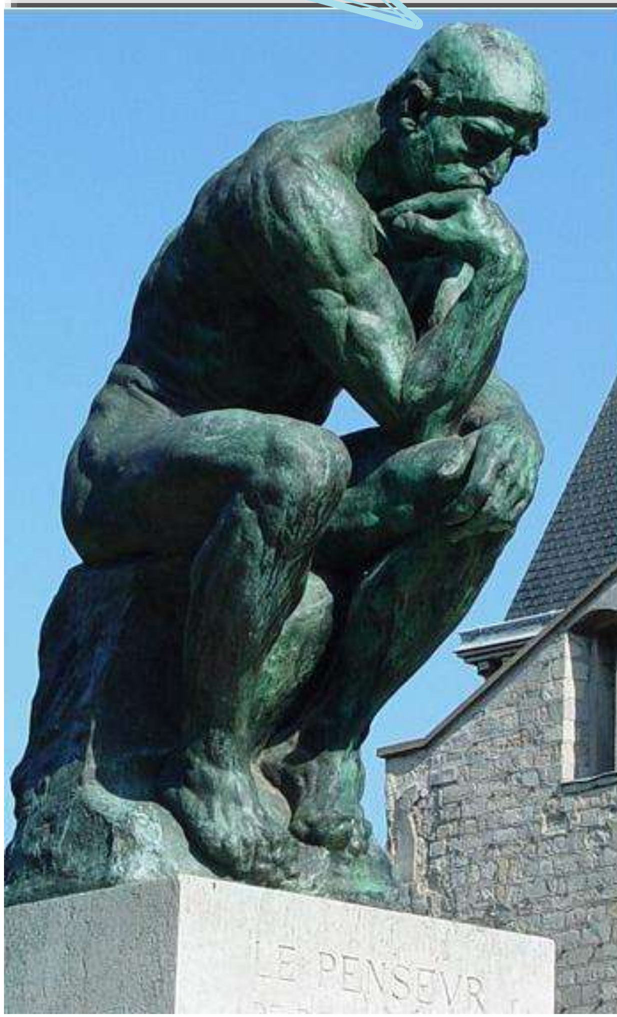


Follow-ups in collaborations with experimentalists (DUNE, SHiP, ...)

- Target recoil (like in typical DM direct detection exp.) + secondary visible signatures ➔ **more** handles, (relatively) **background-free**
- **Complementary** to standard DM direct searches
- **Boosted DM sources** needed: BDM scenarios, fixed target experiments, etc.

Higgs @ LHC !

Dark Matter ?



Summary

- Particle physics: to find fundamental interactions and elements
- DM: clear sign of new physics (particle) beyond the Standard Model
- Nature of DM: one of the most important problems in 21C