An Introduction to Indirect Detection of WIMP Dark Matter

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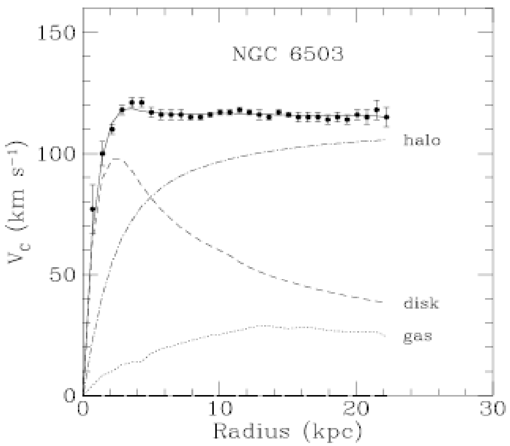
Outline

- Brief introduction to DM, WIMP, and indirect detection
- Charged particle signals induced by DM
- High energy photon signals induced by DM
- Neutrino signals induced by DM
- Summary

Gravitational evidence

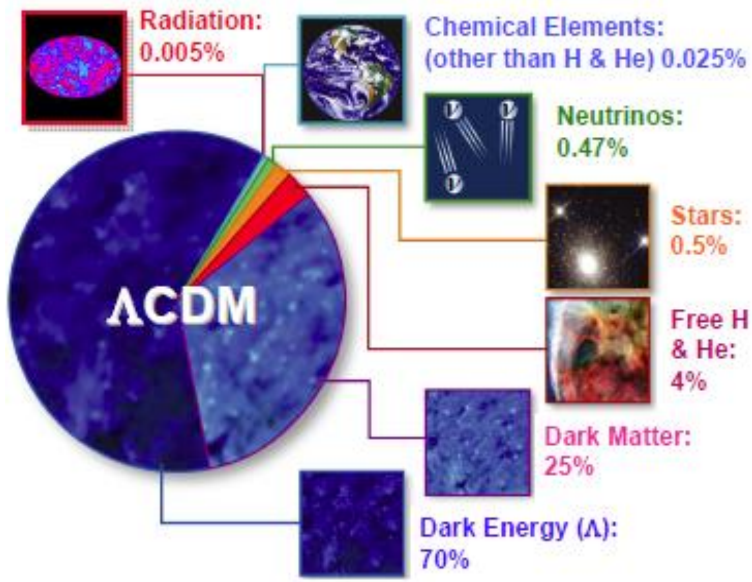
- Too many evidences of DM, but all are gravitational.



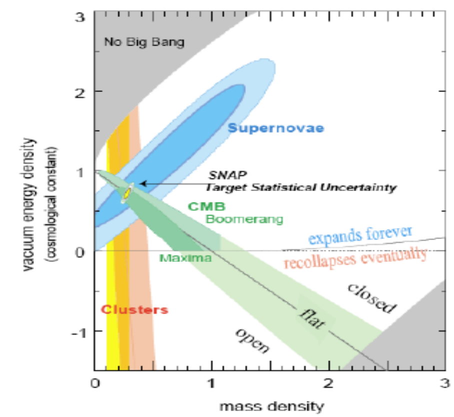
Rotation curve of galaxy

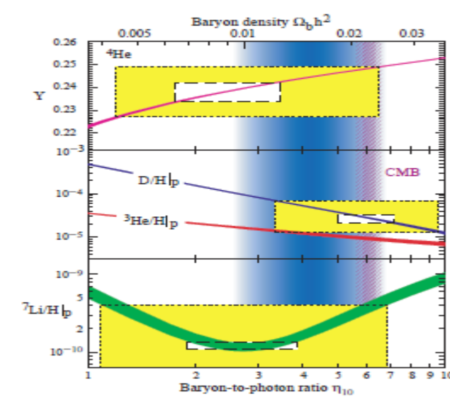
$$v(r) = \sqrt{GM / r} \propto r^{-1/2}$$

$$v(r) \propto r, \rho(r) \propto r^{-2}$$

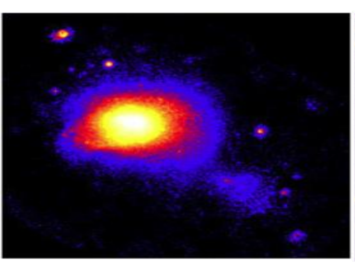


Supernova,
CMB, Large scale



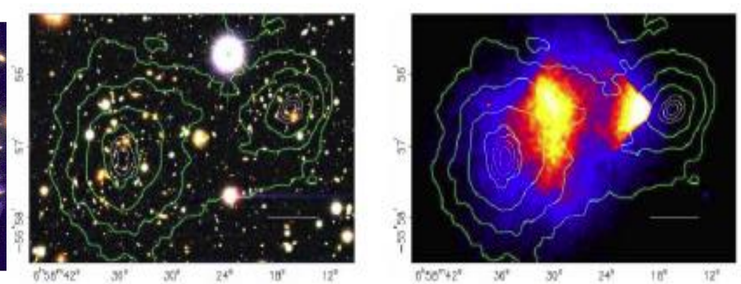


BBN



X-ray hot gas

gravitational lensing



bullet cluster

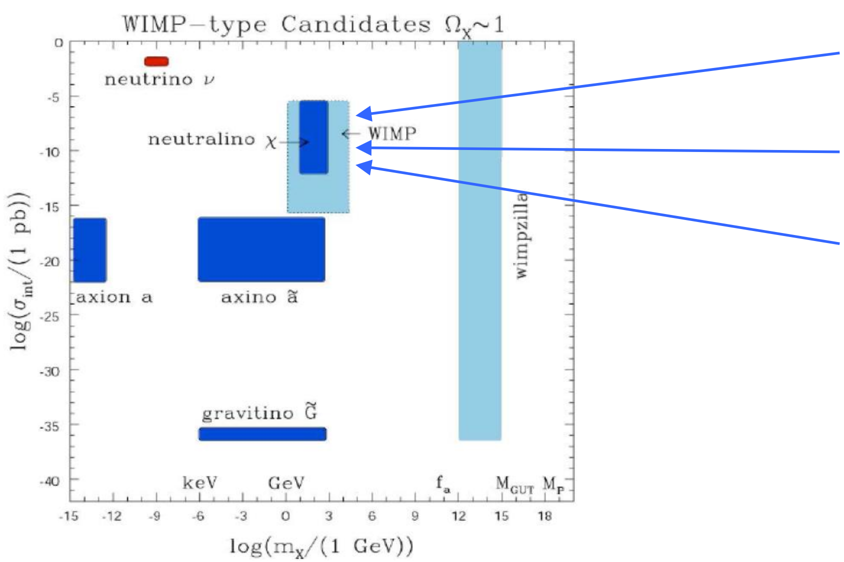
Properties of DM

known

- Stable (never decay or lifetime>>10^{17}s)
  indicate new discrete symmetry (unknown!)
- Weakly interaction with matter
  electric/color neutral
- Relic density

- Cold DM: m>>kT favored
  WIMP, axion …
  warm DM
  sterile neutrino
  hot DM: m<<kT excluded
  SM neutrino

Unknown: mass, coupling, spin, CP, particle spectrum……



- lightest Supersymmetric particle (LSP) :
  neutralino, sneutrino, gravitino,
- Lightes Kaluza-klein particle (LKP) :
  kk-photon, kk-neutrino, kk-graviton…
- little Higgs model
- Neutrino/sterile neutrino
- Axion, ALP, dark photon
- Q-ball, Wimpzilla, Mirror particle, single scalar, inner Higgs, hidden sector particle, millicharged DM ……

WIMPs

- Boltzmann equation $L(f) = C(f)$

$$\frac{dn}{dt} = -3Hn - \langle\sigma v\rangle(n^2 - n_{\rm eq}^2)$$

- Thermal production (freeze-out mechanism)

$$\Omega_{DM} h^2 \approx 0.1 \left(\frac{x_f}{20}\right)\left(\frac{100}{g_*}\right)^{1/2}\left(\frac{3\times 10^{-26}\, cm^3/s}{\langle\sigma v\rangle}\right)$$

Observed relic density

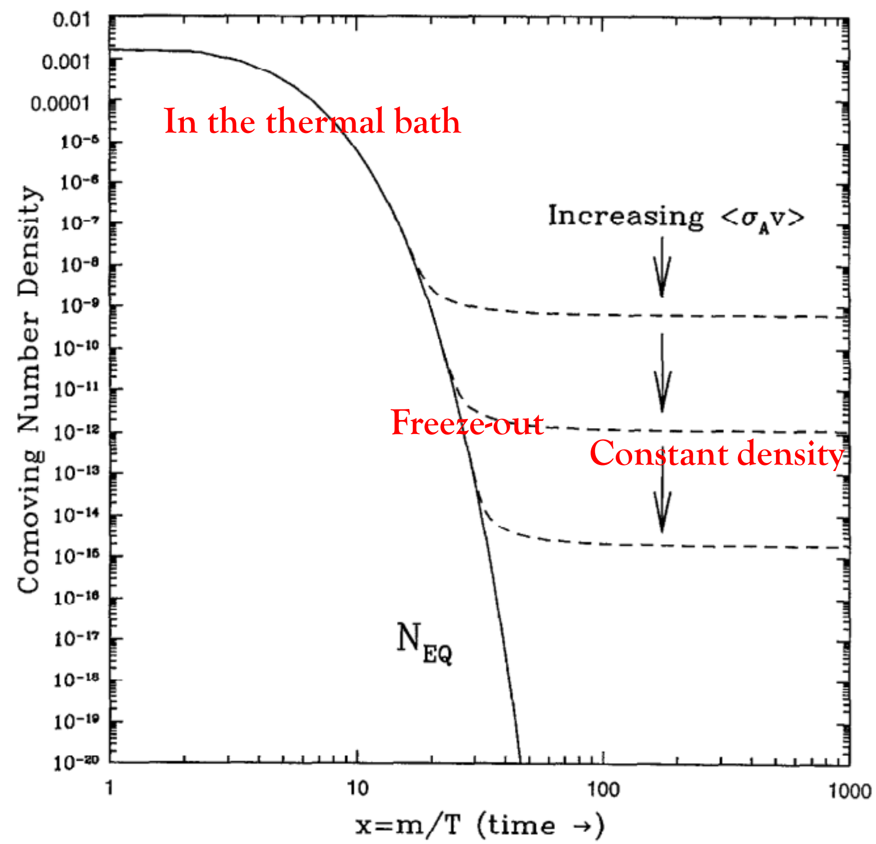
Natural value

$$\langle\sigma v\rangle \approx 10^{-26}\, cm^3/s \left(\frac{\alpha}{10^{-2}}\right)^2 \left(\frac{10^2\, GeV}{m_{DM}}\right)^2$$

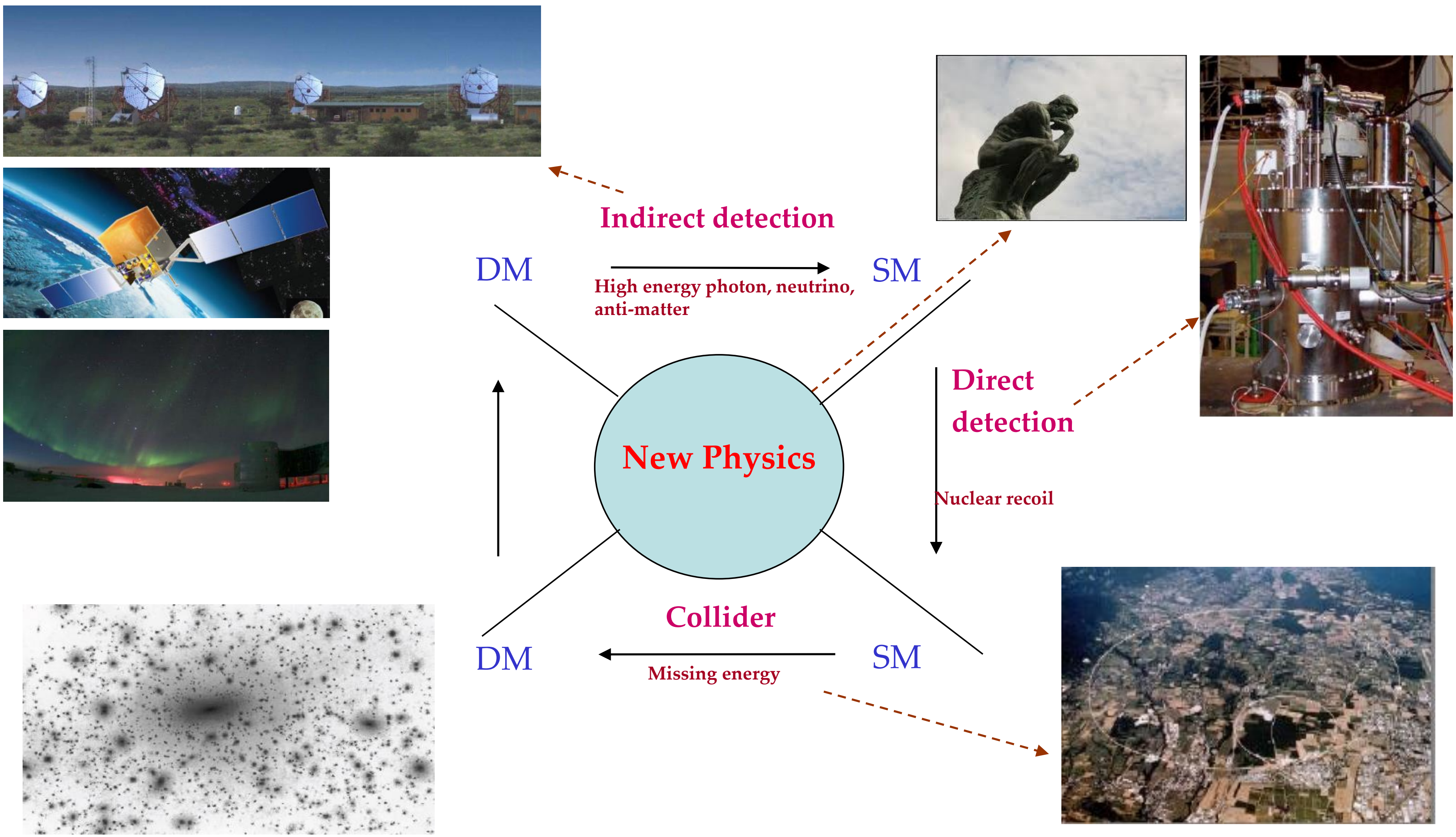
Weakly Interacting Massive Particles

WIMP miracle !

Predicted by many Beyond Standard Models

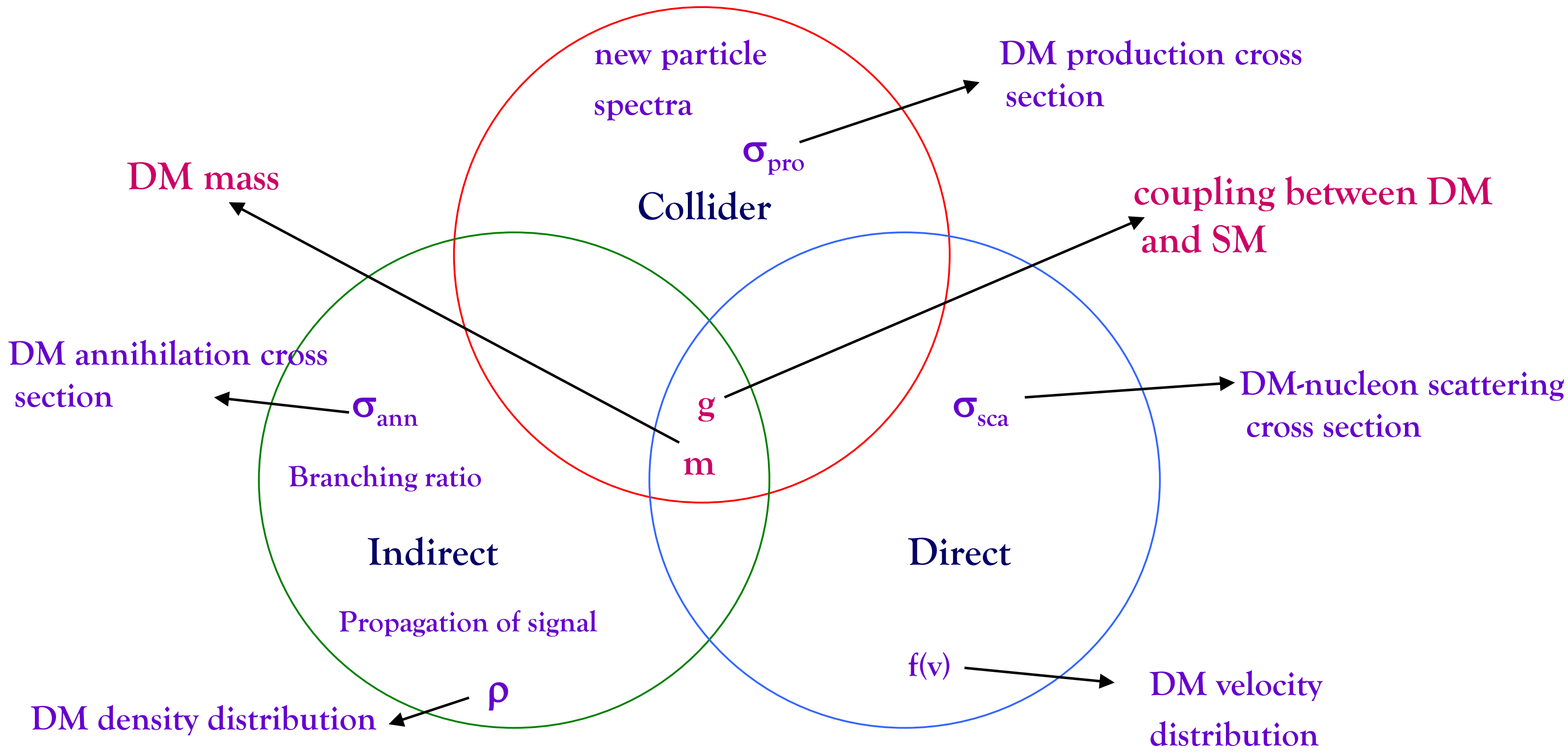


Detection of (WIMP) DM



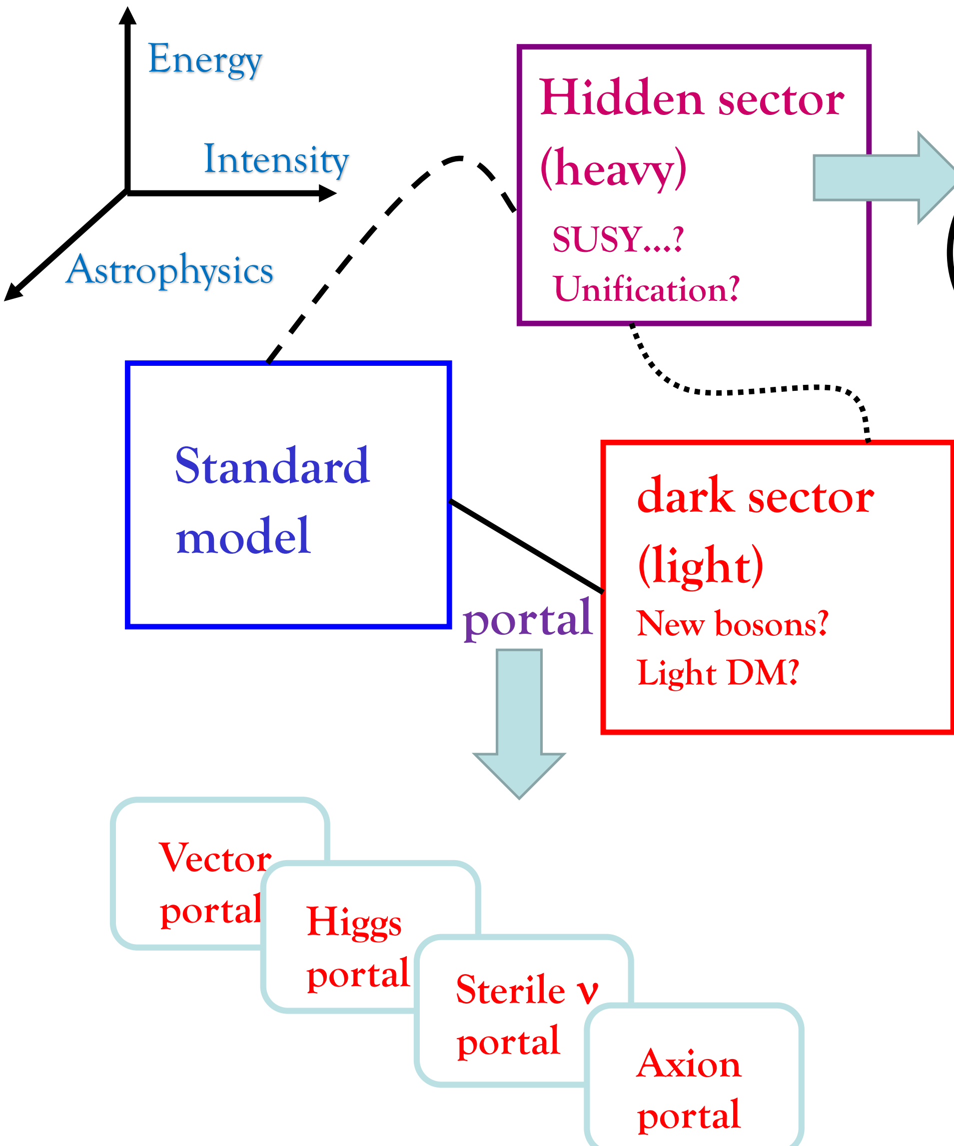
Astronomical (Large structure survey, N-body simulation….)

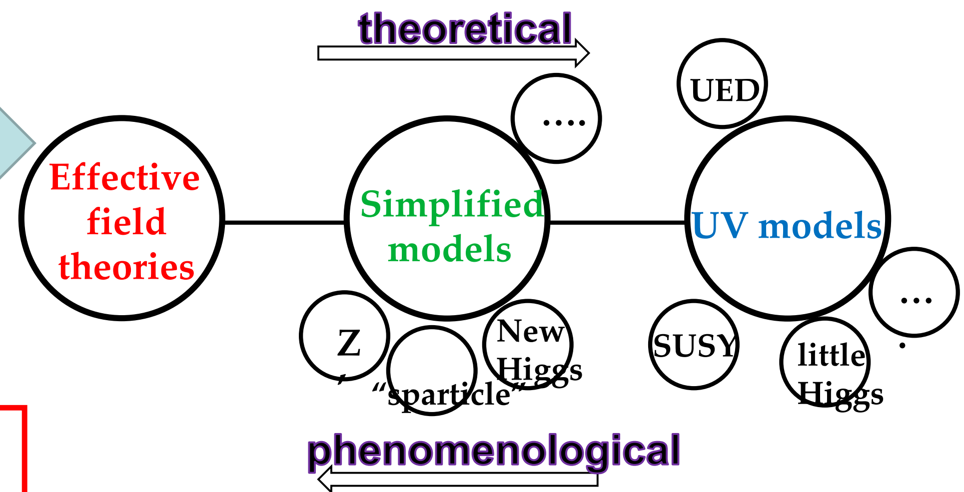
(WIMP) DM phenomenology



- Key Point: DM-SM interaction and particle spectrum defined by new physics.
- Method: analyze the DM signal and sensitivity of DM detection experiments.
- Results:
  - (1)Use known data to constrain available DM model.
  - (2)Build self-consistent model to explain the experiment results.
  - (3)Predict possible signals in the future DM detection experiments.

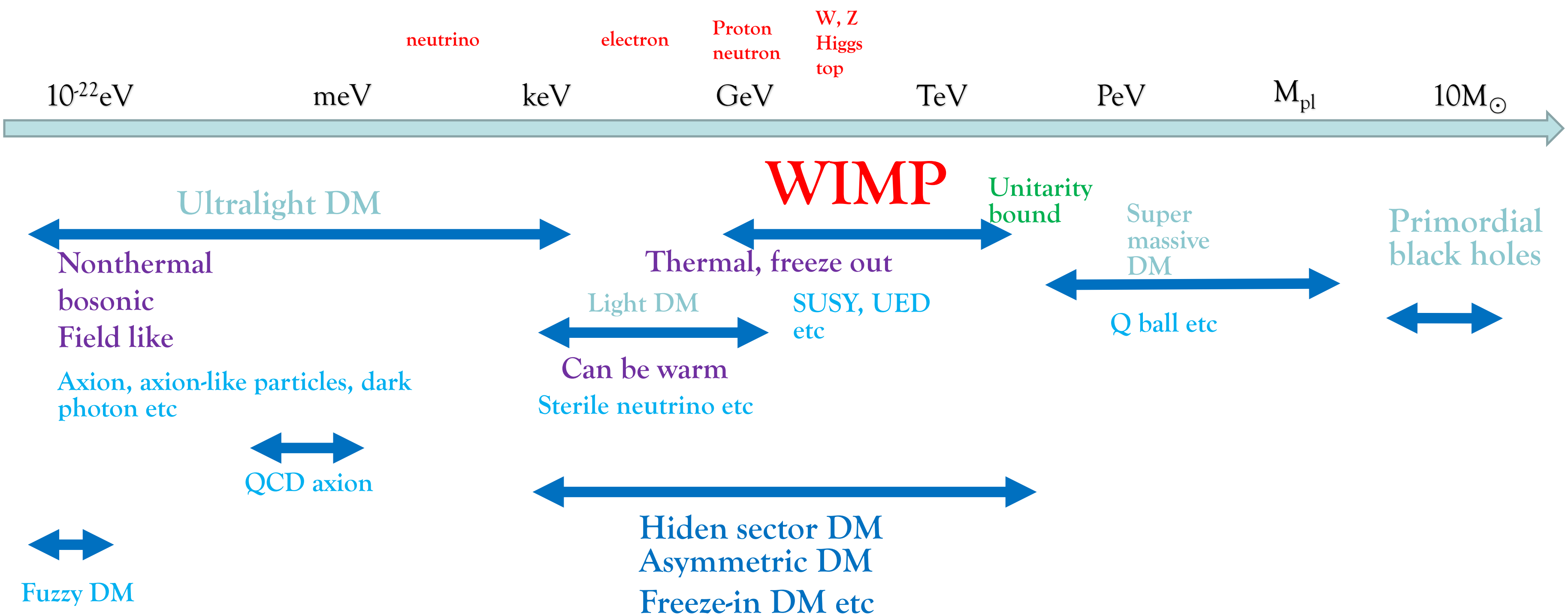
Theoretical framework





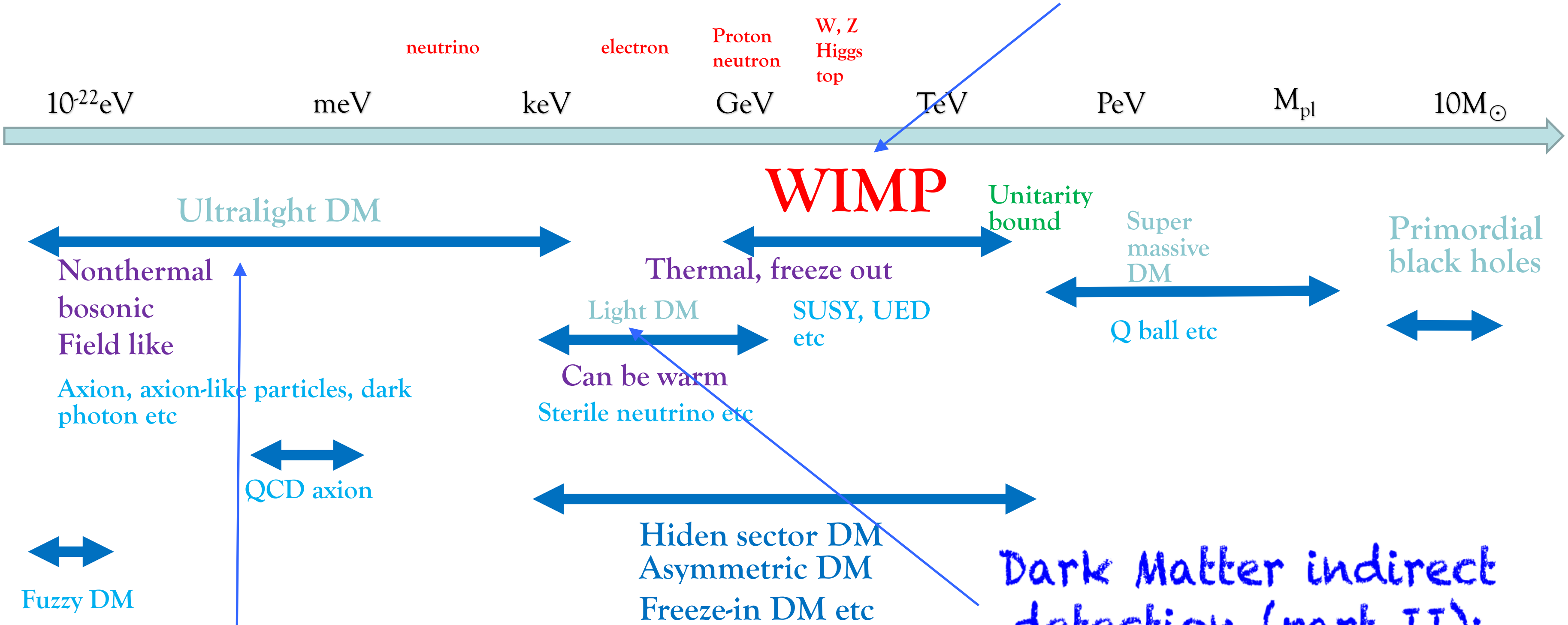
- Many BSM models guided by the naturalness principle predict WIMPs
- However, ordinary WIMPs have been strictly constrained by many current experiments.
- DM particles may interact with SM particles through some portals (mediators).
- There may be many new particles in the hidden/dark sector.
- Light or ultralight DM models are well motivated. There are large parameter regions uncovered by current experiments.

Landscape of DM



Landscape of DM

I focus on here m_{DM} ~ O(1) GeV-O(10^2) TeV



Dark Matter indirect detection (part II): sub-GeV Dark Matter

Yue-Lin Sming Tsai
(Purple Mountain Observatory)

Many nice lectures are here

e.g. from Prof. Q. L. Yang, J. Shu, Y. Zhao, Q. Yuan, J. Liu……

Indirect detection

Dark matter annihilates/decays in ________________ to

a place

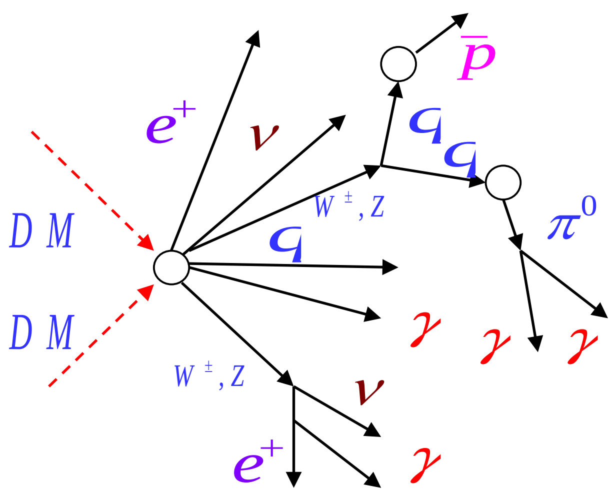
__________ , which are detected by________________ .

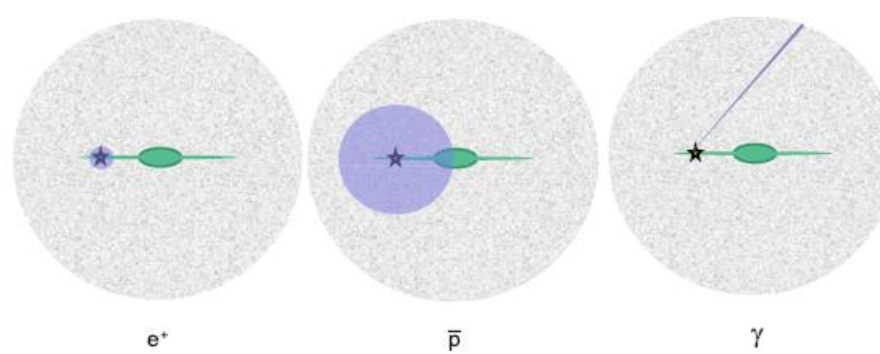
particles

an experiment

J. L. Feng

- Signals: (high energy) charged particles, photons, and neutrinos.
- Very different propagation, statistics, and backgrounds,





Signal flux

- Primary signal flux at the position of DM annihilation (source term)

$$\left(\frac{dN}{dE}\right)^A \propto \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\left(\frac{dN}{dE}\right)_i^A \times \rho^2$$

Particle factor

Astrophysics factor

thermally averaged cross section

May be enhanced by some factor, namely

Boost Factor

Initial signal spectrum per annihilation

use PYTHIA, PPPC4DMID, HDMSpectra…

DM distribution profile

NFW, Einasto, Cored…

DM local density

~0.4 GeV/cm^3

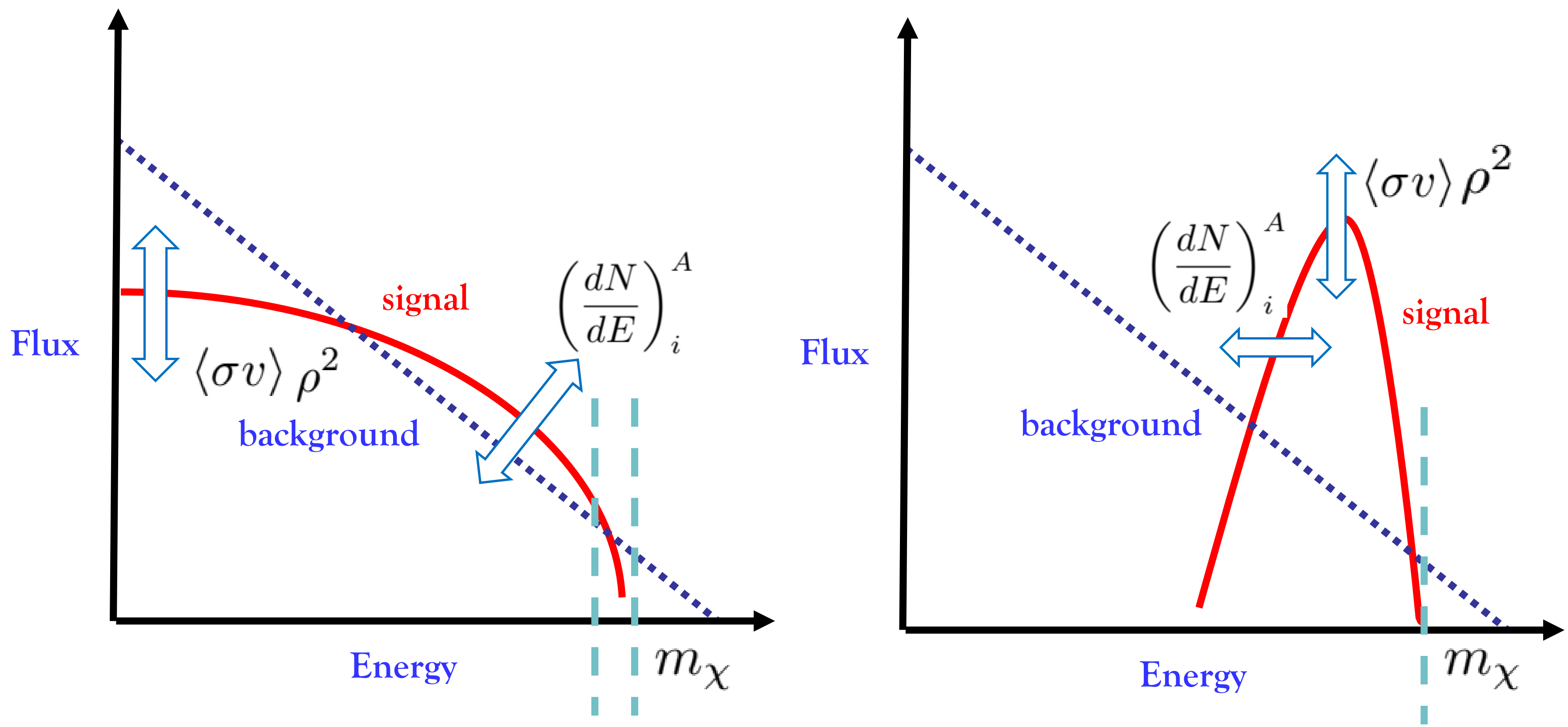
- Primary signal flux of DM decay

$$\left(\frac{dN}{dE}\right)^D \propto \frac{1}{4\pi}\frac{1}{\tau_\chi m_\chi}\left(\frac{dN}{dE}\right)_i^D \times \rho$$

lifetime of DM

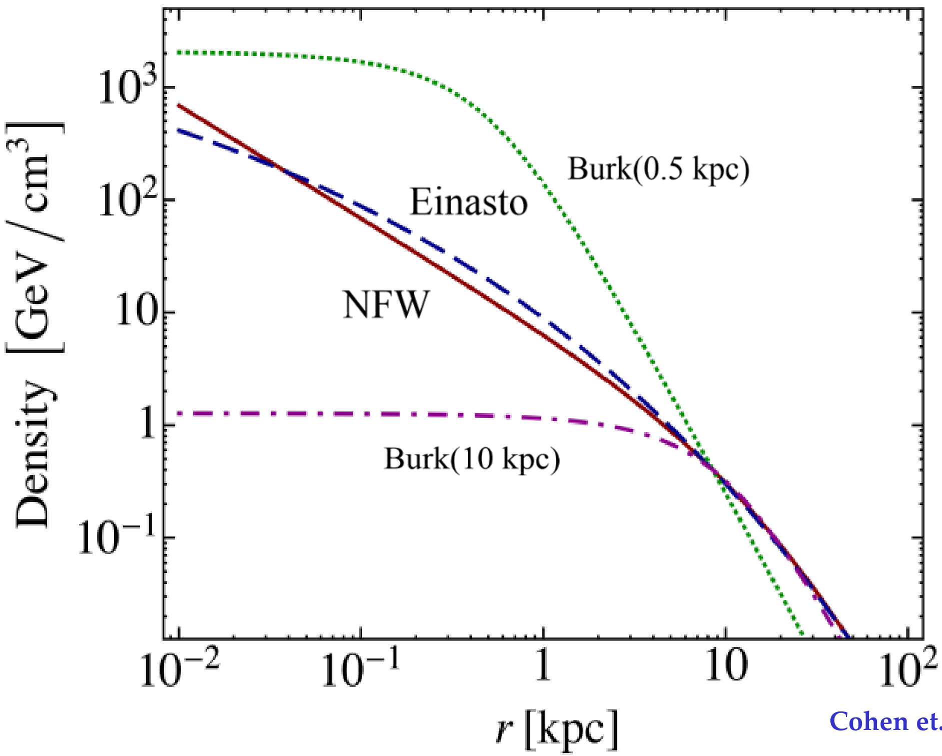
- Propagation and secondary signal production would modify the flux.

Signal flux



- Expect to find an excess above the background.
- Better to search for hard spectra and line spectra.
- DM signal spectrum has a cut-off at DM mass.

DM distribution



Cohen et. al, 1307.4082

Navarro-Frenk-White (NFW)

$$\rho_{\rm NFW}(r) = \frac{\rho_0}{(r/r_s)\,(1+r/r_s)^2}$$

Einasto

$$\rho_{\rm Ein}(r) = \rho_0 \exp\left[-\frac{2}{\gamma}\left(\left(\frac{r}{r_s}\right)^{\gamma} - 1\right)\right]$$

Burkert

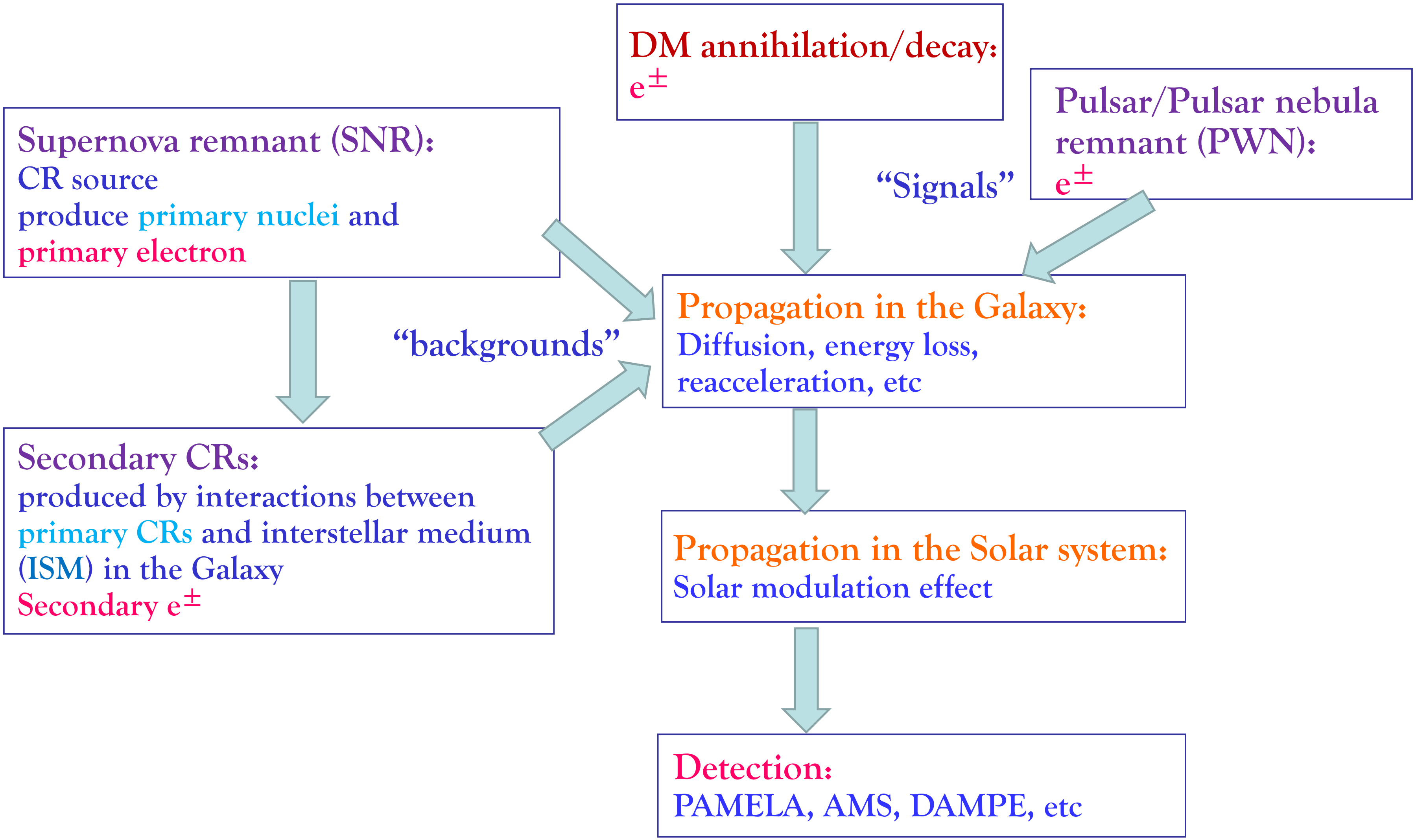
$$\rho_{\rm Burk}(r) = \frac{\rho_0}{(1+r/r_s)(1+(r/r_s)^2)}$$

- The form of the spatial distribution of DM is almost universal at different scales.
- Can be derived from N-body simulation.
  N-body simulation focuses on gravity interaction between DM; but baryons are also important.
- NFW and Einasto profiles are consistent with simulation and widely adopted in studies.
  These profiles have a sharp distribution in the inner halo.
- Some observations of dwarf galaxies indicate a cored profile.

Charged particles

Cosmic ray $e^{\pm}$

- Production->Propagation->Detection



Propagation equation

- Key point: solve the propagation equation to derive the flux of charged CRs

$$\frac{\partial}{\partial t}\frac{dn}{dE} = \nabla\cdot\left[D(E,\vec{x})\nabla\frac{dn}{dE}\right] + \frac{\partial}{\partial E}\left[b(E,\vec{x})\frac{dn}{dE}\right] + Q(E,\vec{x},t)$$

differential flux — diffusion effect — energy loss effect — source term

- It is possible to add several other effects in the equation, such as convection, reacceleration, fragmentation, and decay, etc.

- Boundary condition: assume CRs propagate in a cylindrical "diffusive region" containing the Galactic disk with R ~O(10) kpc and h ~O(1) kpc.

- The contributions of the propagation effects for different CR species are different.

- Exact solutions can be derived by using the numerical package, e.g. Galprop.

Propagation effects

- **Diffusion:** described by the energy dependent diffusion coefficient contributed by scattering between CRs and random component of magnetic fields

$$D(E) \sim D_0 \left(\frac{E}{E_0}\right)^{\delta}$$

D_0 and δ are determined by the fit to CR data, such as the flux ratio of boron to carbon (B/C); E_0 is taken at O(1) GeV.

typical time scale: $\tau_{\rm diff} \sim \frac{R^2}{D_0} \cdot E^{-\delta}$

- **Energy loss:** described by the energy dependent energy loss coefficient for $e^{\pm}$, the main contributions are from inverse Compton scattering (ICS) and synchrotron radiation. Therefore b(E) is determined by the energy density of the Galactic radiation backgrounds and magnetic field.

$$b_e(E) \simeq b^0_{\rm IC} \left(\frac{u_{\rm ph}}{1\ {\rm eV/cm^3}}\right) \cdot E^2 + b^0_{\rm sync} \left(\frac{B}{1\ \mu{\rm G}}\right) \cdot E^2 \qquad \tau_{\rm loss} \sim \frac{E}{b(E)}$$

for proton, this effect can be neglect.

Profumo, 1301.0952

Solution for background

- For the steady-state diffusion equation,

$$0 = -\frac{\psi}{\tau_{\rm diff}} - \frac{\psi}{\tau_{\rm loss}} + Q \qquad \frac{\mathrm{d}n}{\mathrm{d}E} = \psi(\vec{x}, E, t)$$

  the solution is $\psi \sim Q \cdot \min[\tau_{\rm diff},\ \tau_{\rm loss}]$

- For the primary CR proton, take $Q \sim E^{-2}$

  Since $\tau_{\rm diff} \ll \tau_{\rm loss}$, we have $\psi \sim E^{-2} \cdot E^{-\delta} \sim E^{-2.7}$

- For the primary CR electron, take $Q \sim E^{-2}$

  at low energy $\psi \sim Q \cdot \tau_{\rm diff} \sim E^{-2} \cdot E^{-\delta} \sim E^{-2.7}$

  at high energy $\psi \sim Q \cdot \tau_{\rm loss} \sim E^{-2} \cdot \frac{E}{E^2} \sim E^{-3}$

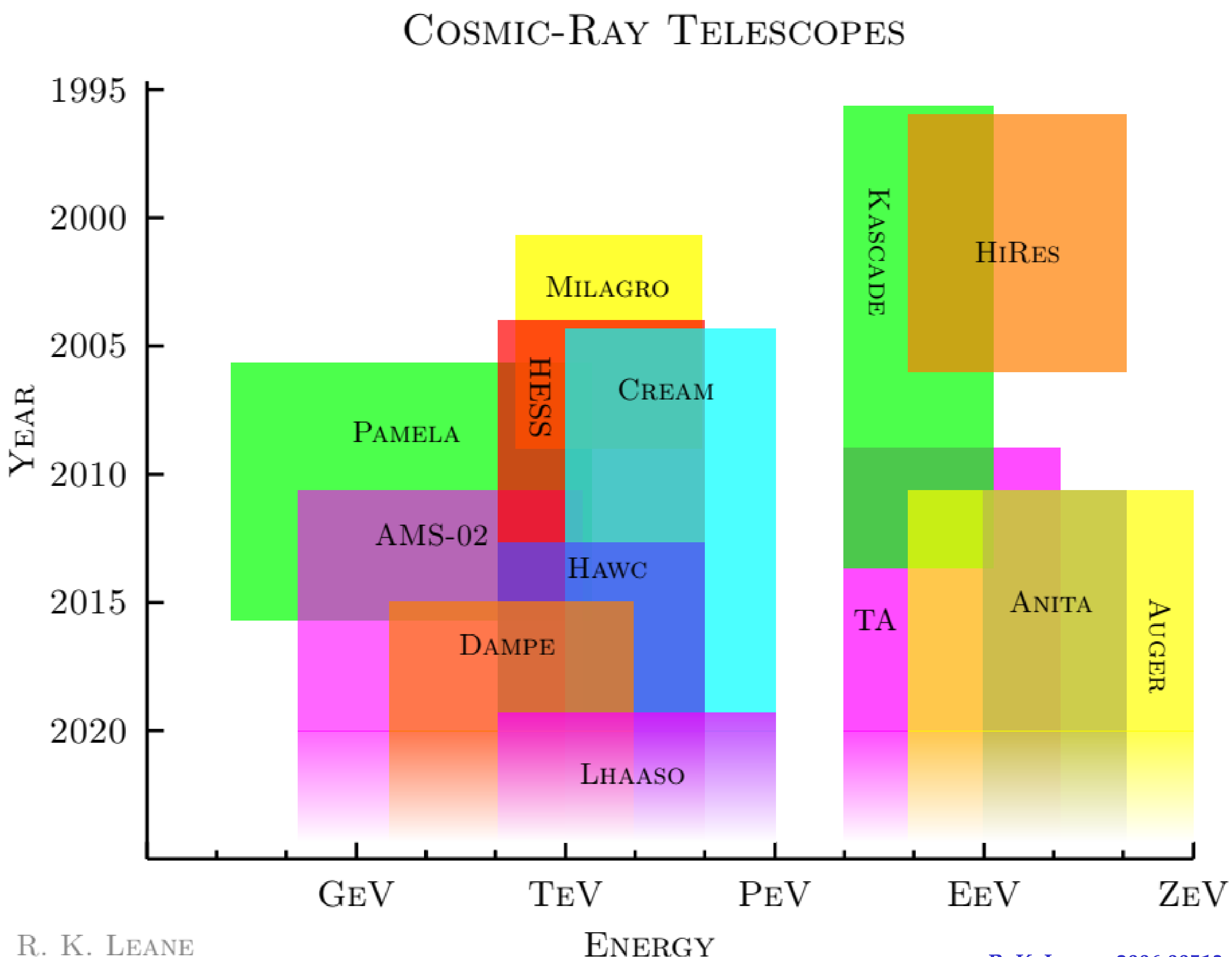
- For the secondary CR $e^{\pm}$, the source term is given by the spectrum of primary proton $Q_p \sim E^{-2.7}$, we have $\psi \sim E^{-3.4}$

  the ratio of the secondary positron to primary electron

$$\frac{\psi_{e^+}}{\psi_{e^-}} \sim E^{-\delta}$$

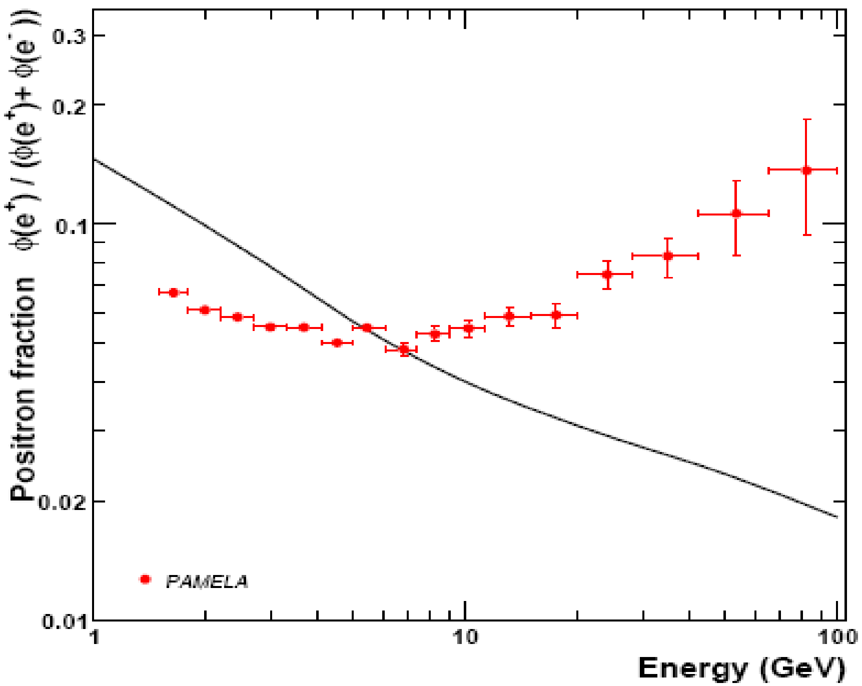
Profumo, 1301.0952

Experiments

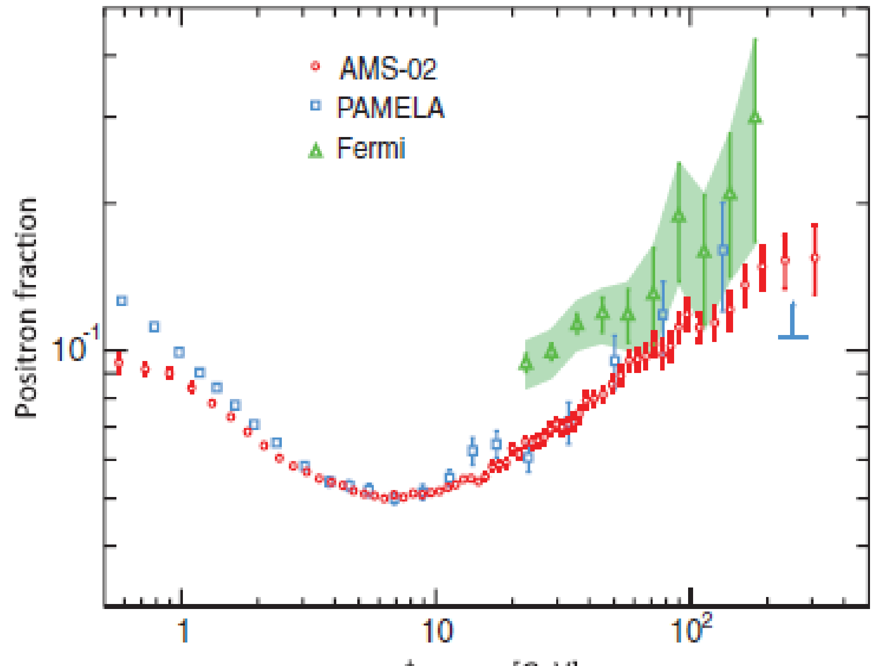


R. K. Leane, 2006.00513

Anomalous CR $e^{\pm}$



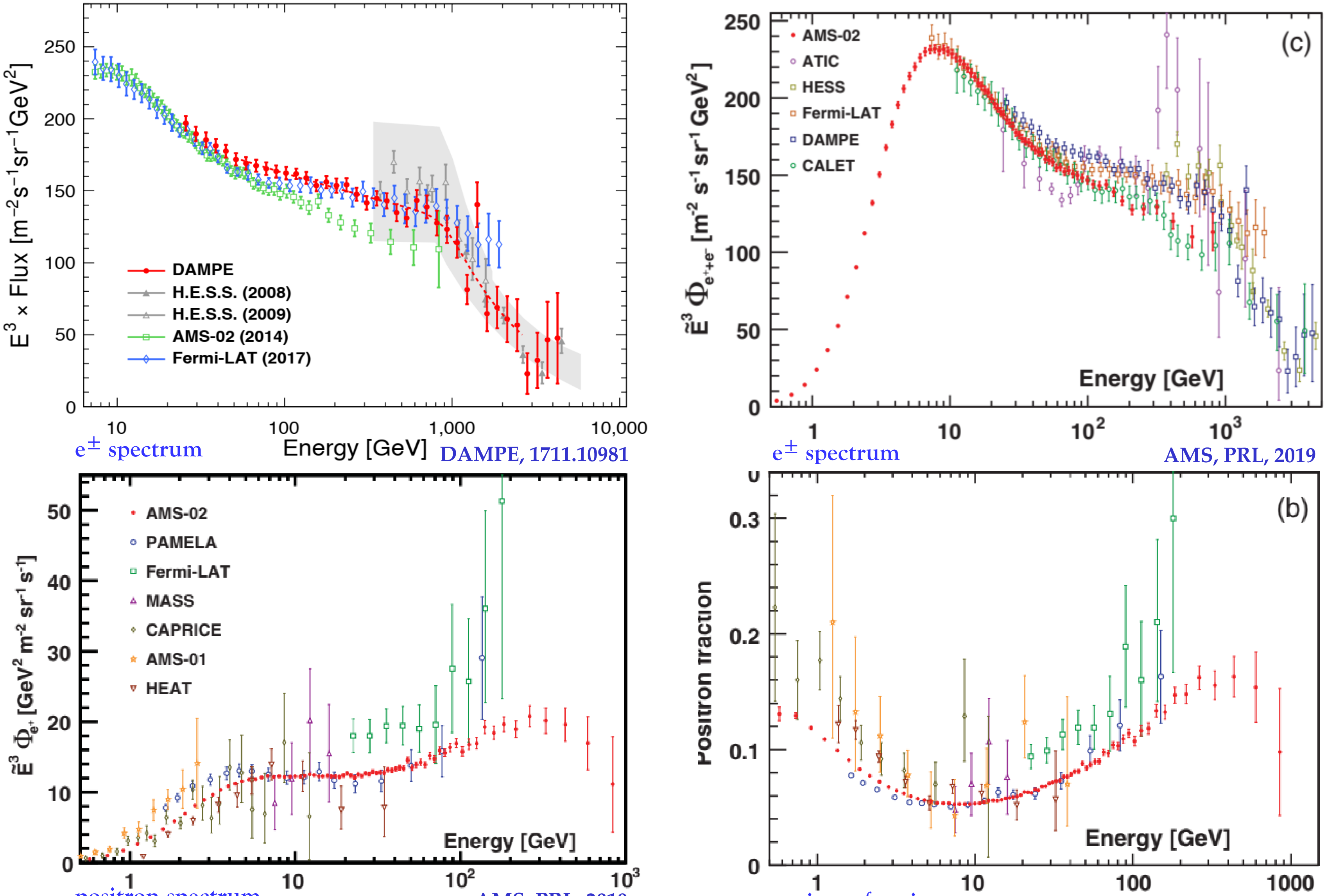
PAMELA, 0810.4995



AMS, PRL, 2013

- The high enegy CR $e^{\pm}$ observations cannot be explained by the primary CR electron and secondary CR $e^{\pm}$.
- Require exotic $e^{\pm}$ sources in the Galaxy.
- Several experiments have confirmed this excess.

Anomalous CR e$^{\pm}$



e$^{\pm}$ spectrum — DAMPE, 1711.10981

e$^{\pm}$ spectrum — AMS, PRL, 2019

positron spectrum — AMS, PRL, 2019

positron fraction

Exotic $e^{\pm}$ Sources

- Dark matter annihilation/decay

Source term for annihilation $$Q_A(\mathbf{r}, E) = \frac{\langle\sigma v\rangle_A \rho^2(r)}{2m_{\rm DM}^2}\frac{dN}{dE}$$

Source term for decay $$Q_D(\mathbf{r}, E) = \frac{1}{\tau_{\rm DM}}\frac{\rho(r)}{m_{\rm DM}}\frac{dN}{dE}$$

Continuously distributed in the Galaxy and independent of time

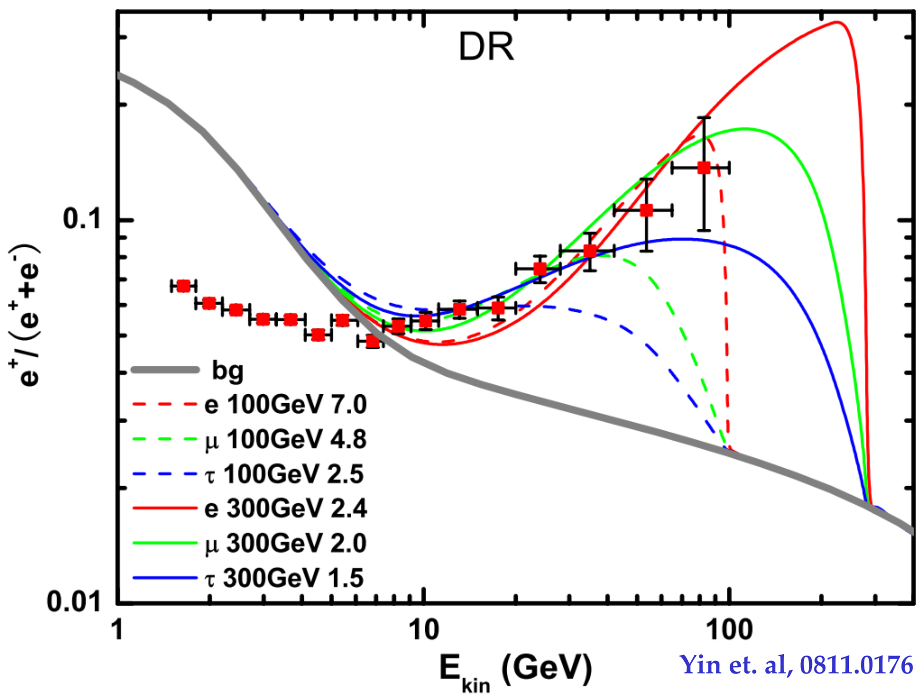
- Pulsar/PWN

$$Q(E, r, t) = Q_0 E^{-\alpha}\exp(-E/E_{\rm cut})\delta(r - r_0)\delta(t - t_0)$$

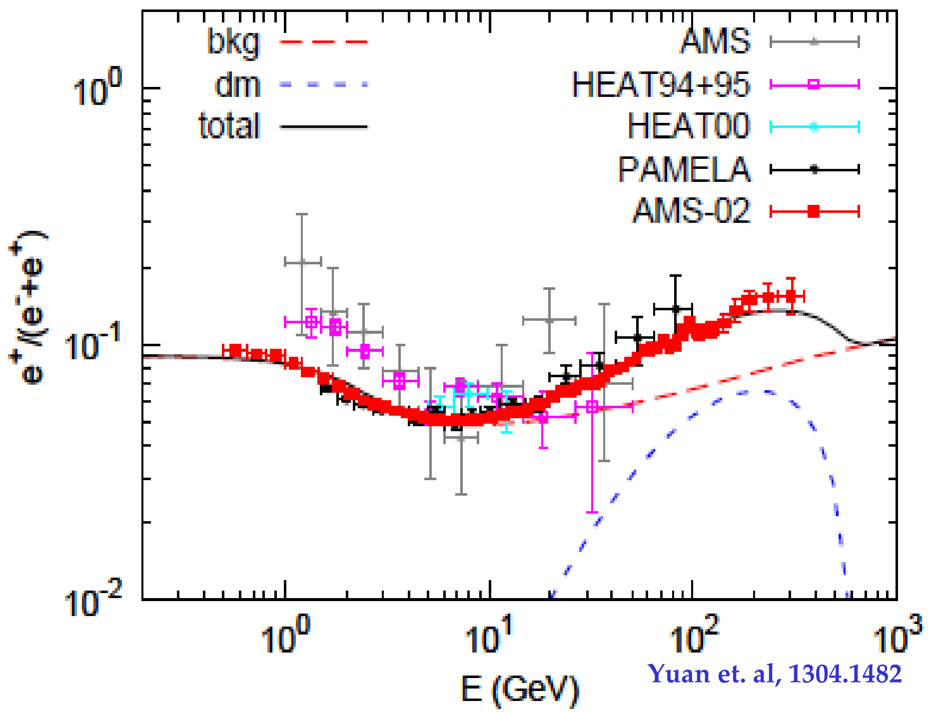
Discrete source and burst-like injection

Solution $\psi \propto Q \cdot \exp\left(-\left(\frac{r}{r_{\rm diff}}\right)^2\right)$ $\quad r_{\rm diff} \simeq \sqrt{D(E)\cdot t}$

DM interpretation



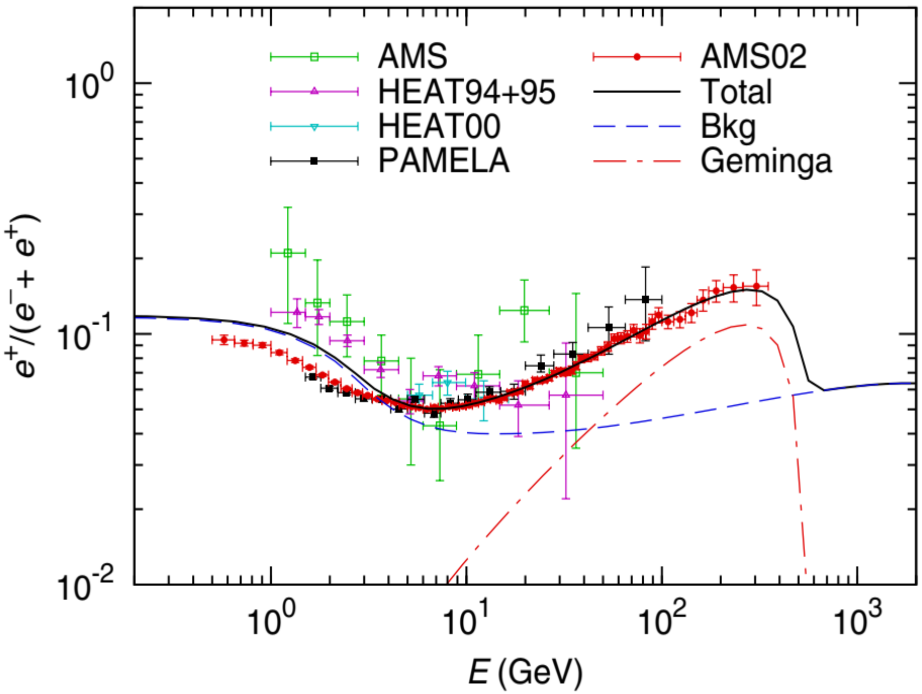
Yin et. al, 0811.0176

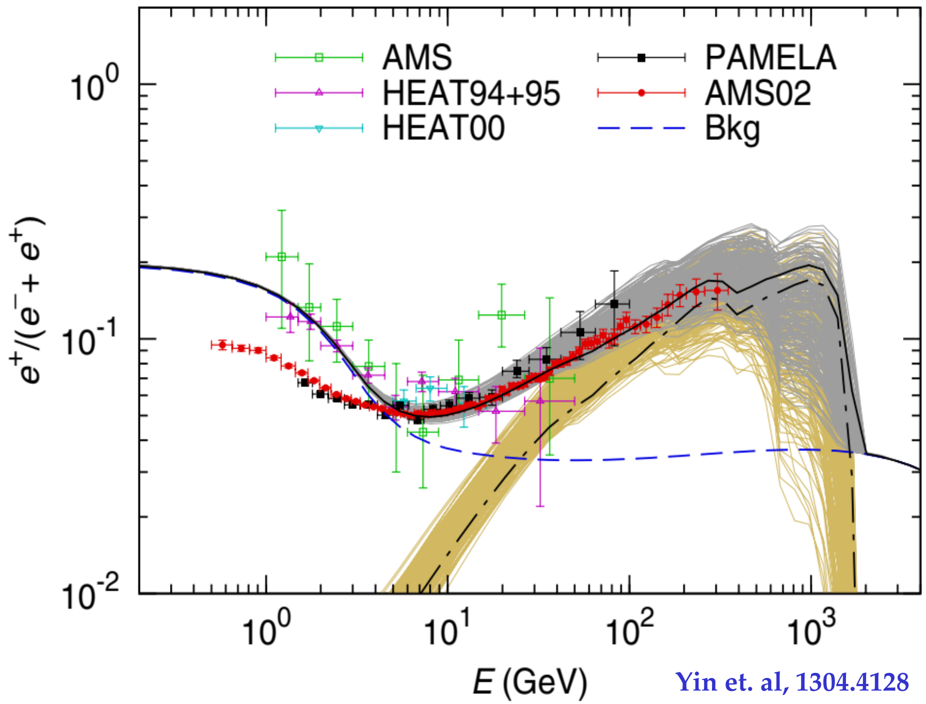


Yuan et. al, 1304.1482

- Require large boost factor for the annihilating DM ~O(10^3).
  Sommerfeld effect, Breit-Wigner effect, non-thermal DM ……
- Or require long life time of the decaying DM ~O(10^{26})s.
  high order operators at the very high energy scale, e.g. M_{GUT} ~10^{16} GeV
- Require "leptophilic" DM.
- Unfortunately, the corresponding parameter regions are strictly constrained by the gamma-ray observations

Pulsar/PWN interpretation

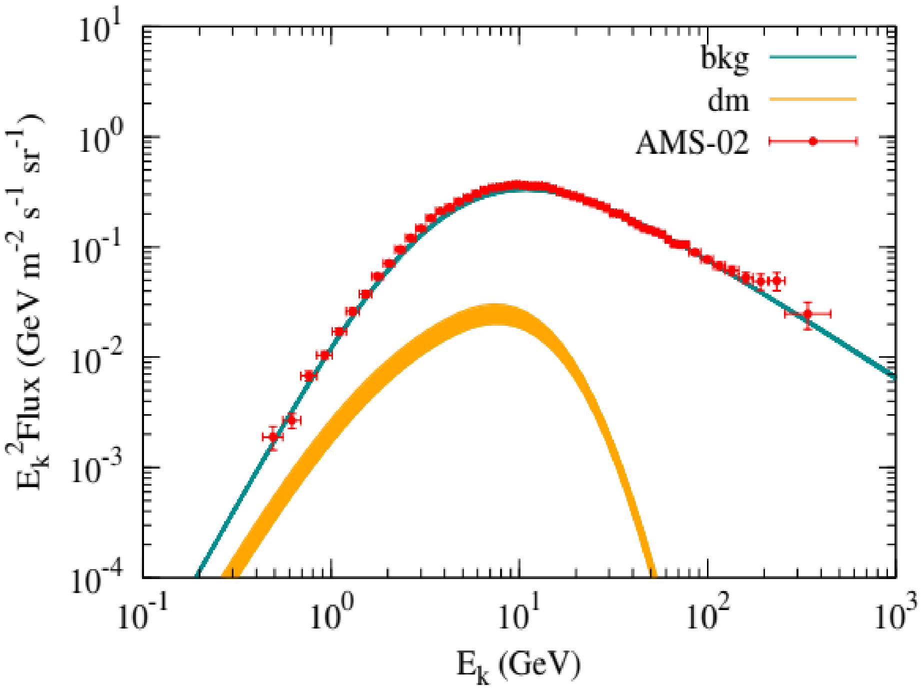


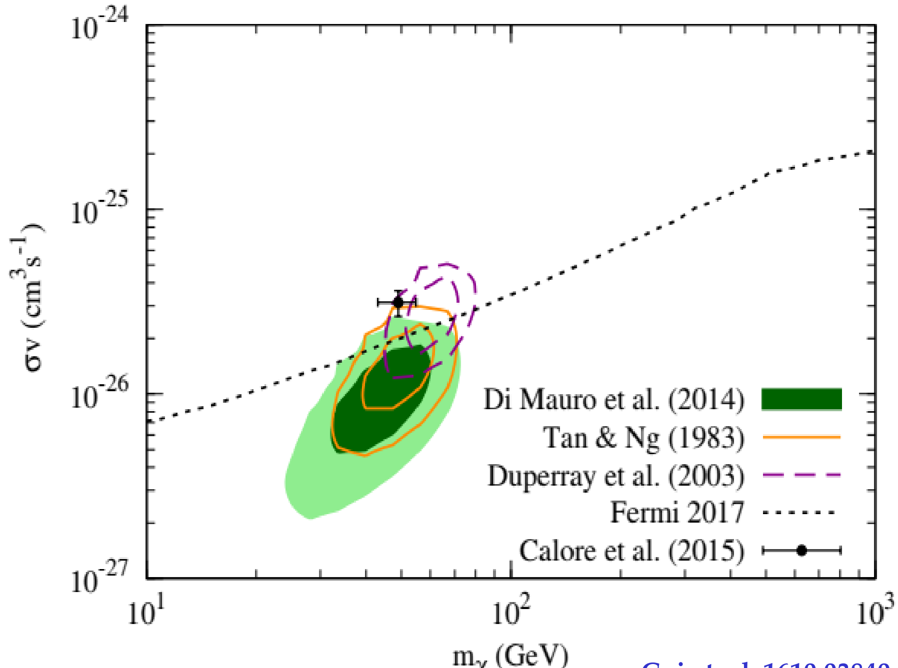


Yin et. al, 1304.4128

- Can be explained by a single nearby pulsar with age ~ $O(10^5)$ yr and distance <1 kpc.
- Can also be explained by the contribution from many pulsars.
- No constraint from the associated gamma-ray emission.
- The injection mechanism of high energy $e^{\pm}$ from PWN to ISM remains unclear.
- Recent observations and studies show that the propagation of $e^{\pm}$ around pulsar/PWN may be complicated. Uncertainties exist.

CR anti-proton

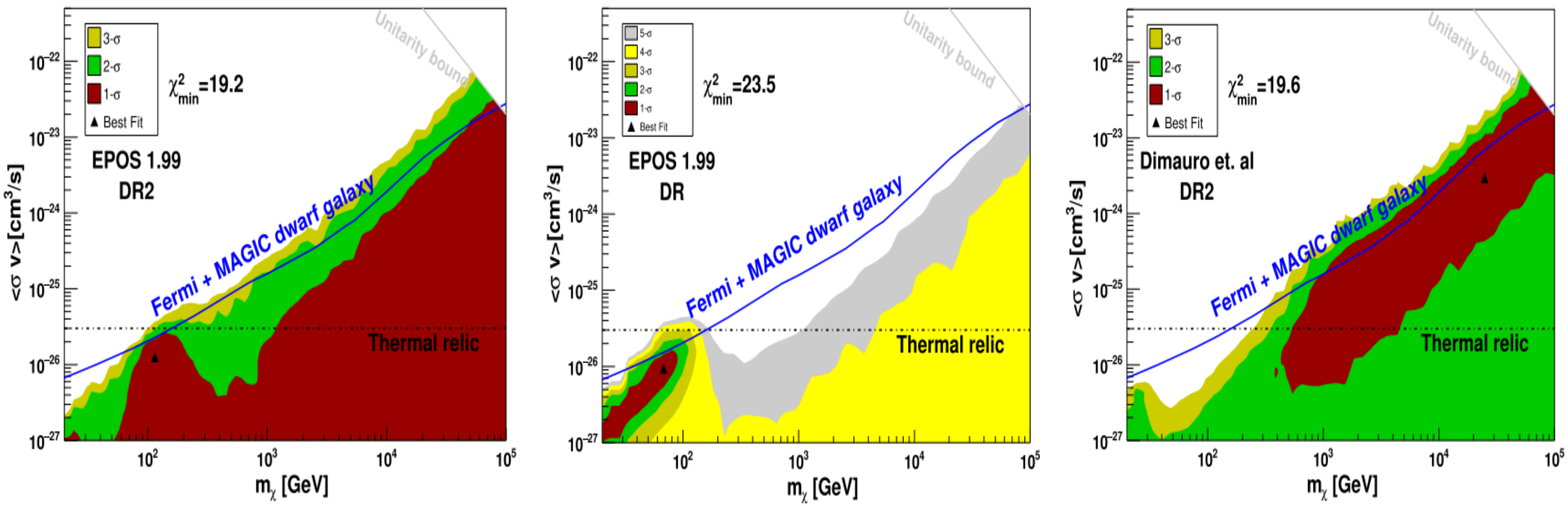




Cui et. al, 1610.03840

- The main CR anti-protons are expected to the secondary anti-protons. The astrophysical source is difficult to directly produce anti-protons.
- There seems no significant excess in the AMS-02 data at high energies above $O(10^2)$ GeV.
- In 2016, two studies (1610.03071,1610.03840, published in PRL) claimed an excess at ~O(10) GeV in the AMS-02 data.
- This excess is also found in many other studies. It can be explained by an annihilating DM with a mass ~O(10) GeV and an annihilation cross section of about natural value.

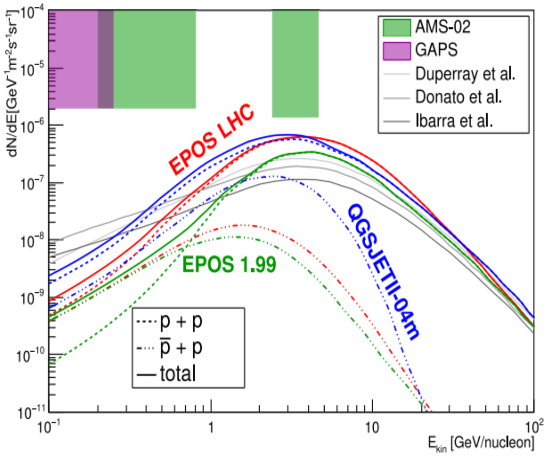
CR anti-proton

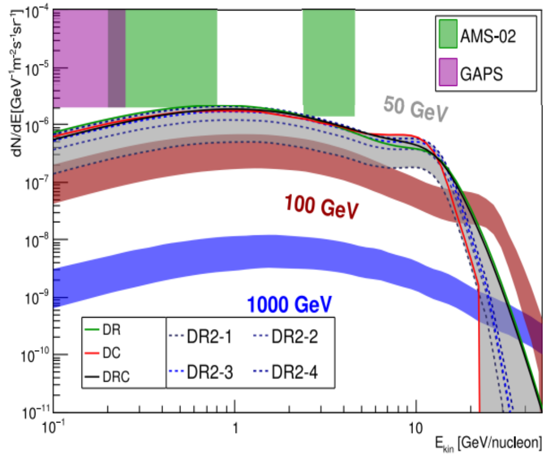


Lin et. al, 1903.09545

- The significance of the excess depends on several theoretical inputs:
  - Model of strong interaction: determine the production of secondary anti-proton.
  - Propagation model: modify the spectra of signal and background.
  - Modulation model: modify the low energy CR spectra.
- For some models, the data even indicate a high-energy excess. But corresponding DM region is severely constrained by gamma-ray observations.
- Some studies show that including the error covariance of data could reduce the significance of the low energy excess.
- The AMS-02 results can also be used to set constraint on the DM annihilation cross section.

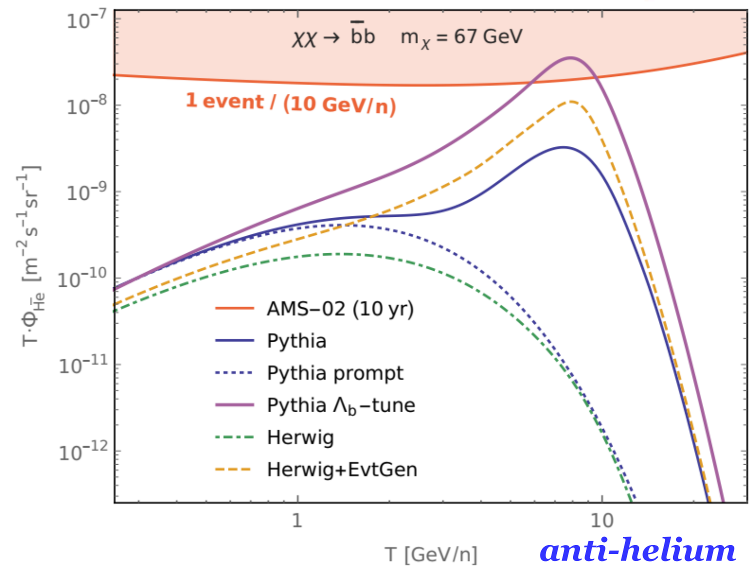
Anti-deuteron and anti-helium





anti-deuteron

Lin et. al, 1801.00997



anti-helium

Winkler, Linden, 2006.16251

- The formation of an antimatter nucleus requires several antimatter nucleons are very close to each other in the phase space.
- Therefore antimatter nuclei are very difficult to be produced in astrophysical processes and the corresponding background is ultra-low.
- The high energy jet induced by DM annihilation/decay can produce antimatter nuclei.
- The flux of antimatter nuclei also depends on the model of strong interaction and propagation model. Also depend on the coalescence model describing how antimatter nucleons form a nucleus.
- The anti-proton signals of DM are correlated to anti-deuteron and anti-helium signals.
- Such signals can be investigated by AMS and GAPS.

Photons (γ-rays)

Photon signal from DM

- Little energy loss and trajectory deflection during the propagation; easily detected. preserve the information of the nature and distribution of the DM.
- Complicated backgrounds in the Galaxy.
- Primary signal flux of DM annihilation

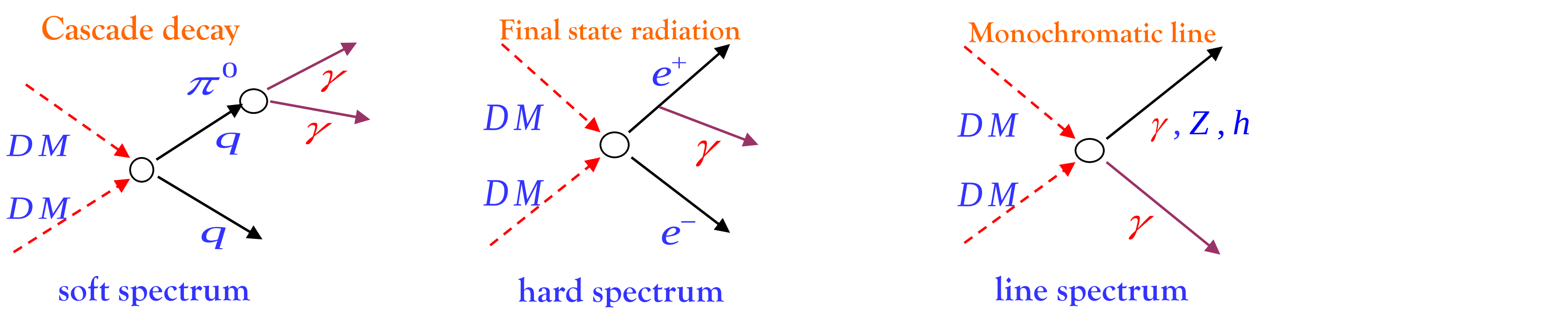
$$\left(\frac{dN}{dE}\right)^A = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\left(\frac{dN}{dE}\right)_i^A \times \boxed{\int d\Omega \int_{\mathrm{l.o.s.}} dl \;\; \rho^2[r(l,\psi)]}$$

J factor: determines the strength of the signal; depends on the DM distribution of source

- Primary signal flux of DM decay

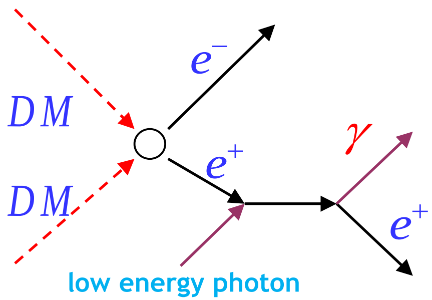
$$\left(\frac{dN}{dE}\right)^D = \frac{1}{4\pi}\frac{1}{\tau_\chi m_\chi}\left(\frac{dN}{dE}\right)_i^D \times \boxed{\int d\Omega \int_{\mathrm{l.o.s.}} dl \;\; \rho[r(l,\psi)]}$$ ← **D factor**

- Primary processes. Mainly focus on **gamma-ray** signals for WIMP.

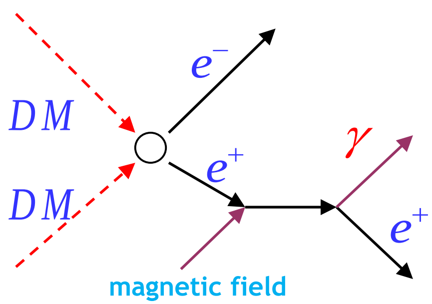


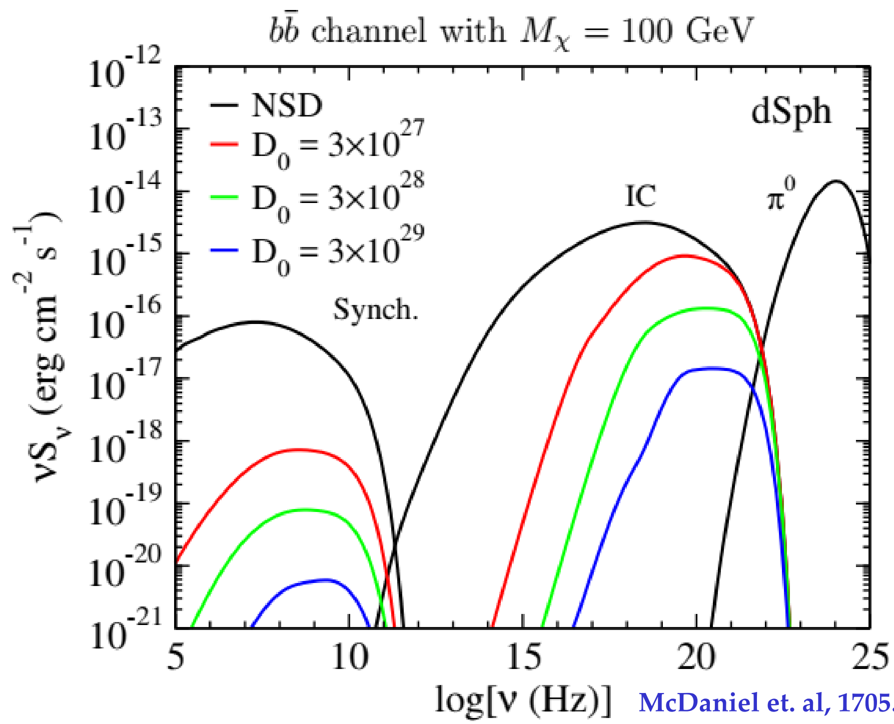
Multi-wavelength signals

Inverse Compton scattering



Synchrotron radiation





McDaniel et. al, 1705.09384

- Secondary emission processes: primary $e^{\pm}$ from DM annihilation/decay interact with other matter during propagation in astrophysical systems and produce photons at lower energies.
- Include inverse Compton scattering, synchrotron, bremsstrahlung, and Coulomb energy loss.
- Signals from radio to X-ray. The corresponding detection have good resolution.
- Flux depends on the environment of astrophysical systems. Uncertainties!

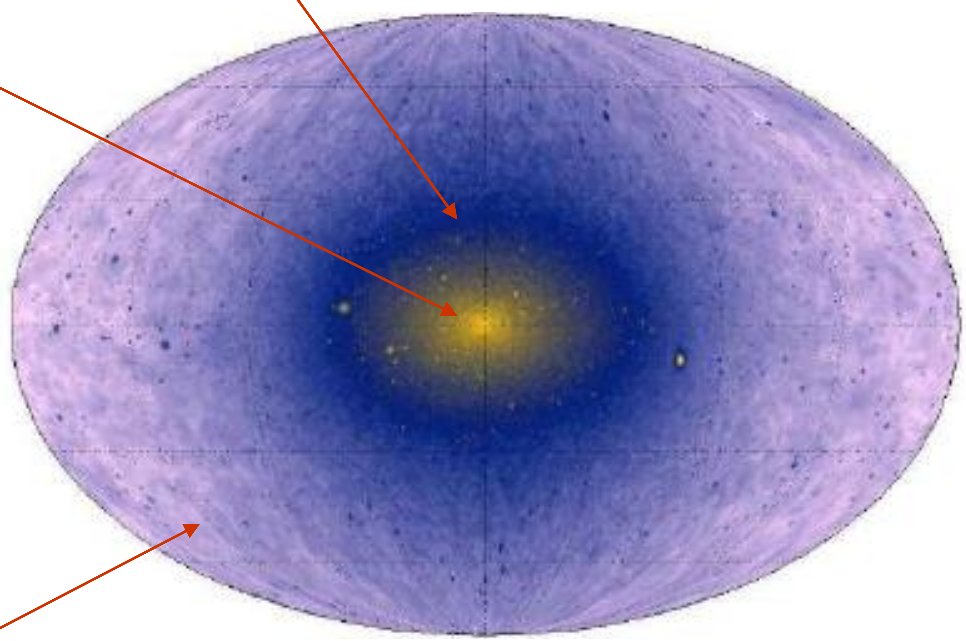
Targets

- Searching signals from dense DM regions

Galactic halo
large statistics galactic background

Galaxy cluster
good source id
low statistics

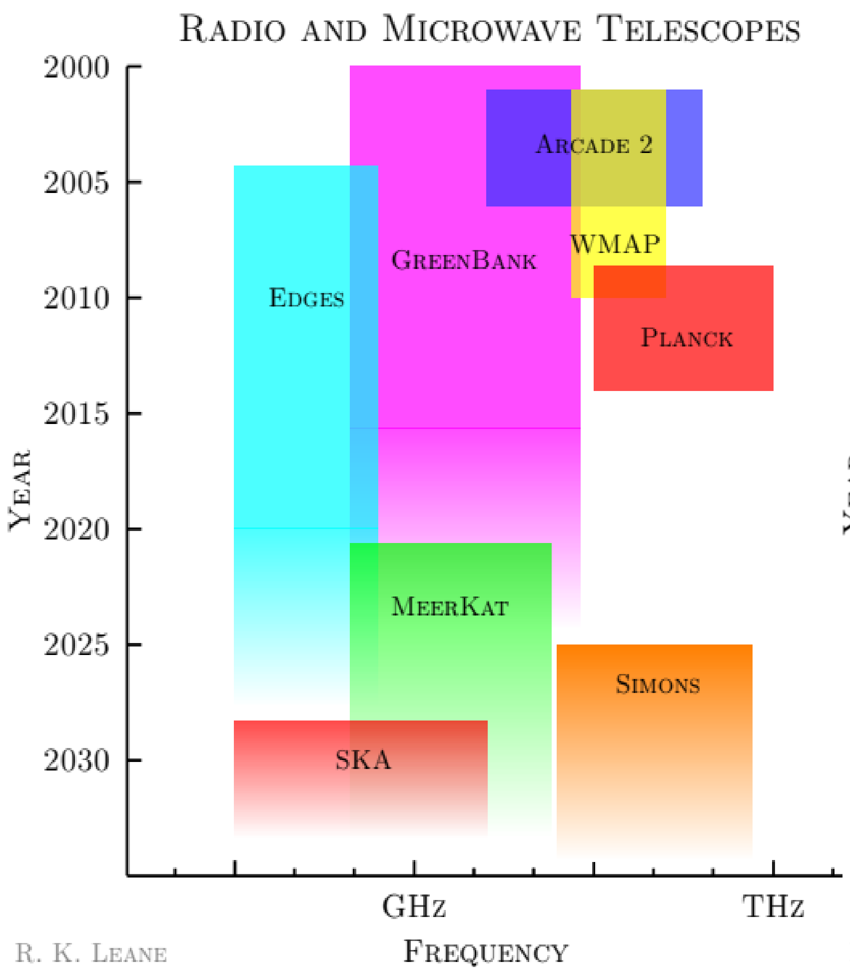
Galactic center
very large statistics
too many astrophysical source and
confusion/diffusion background

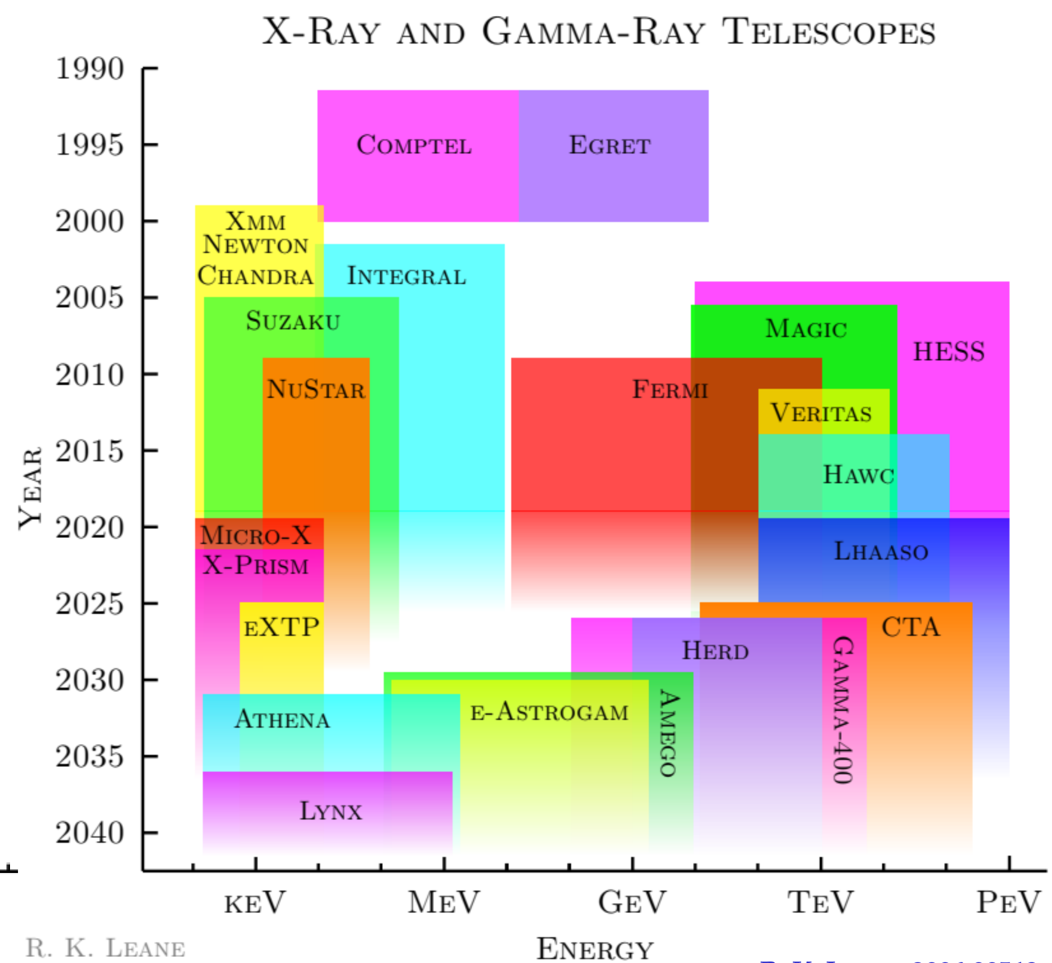


Diffuse extra-galactic
large statistics
extra-galactic/galactic background

Dwarf Spheroidal satellite galaxy (DSph)
low background, good source id

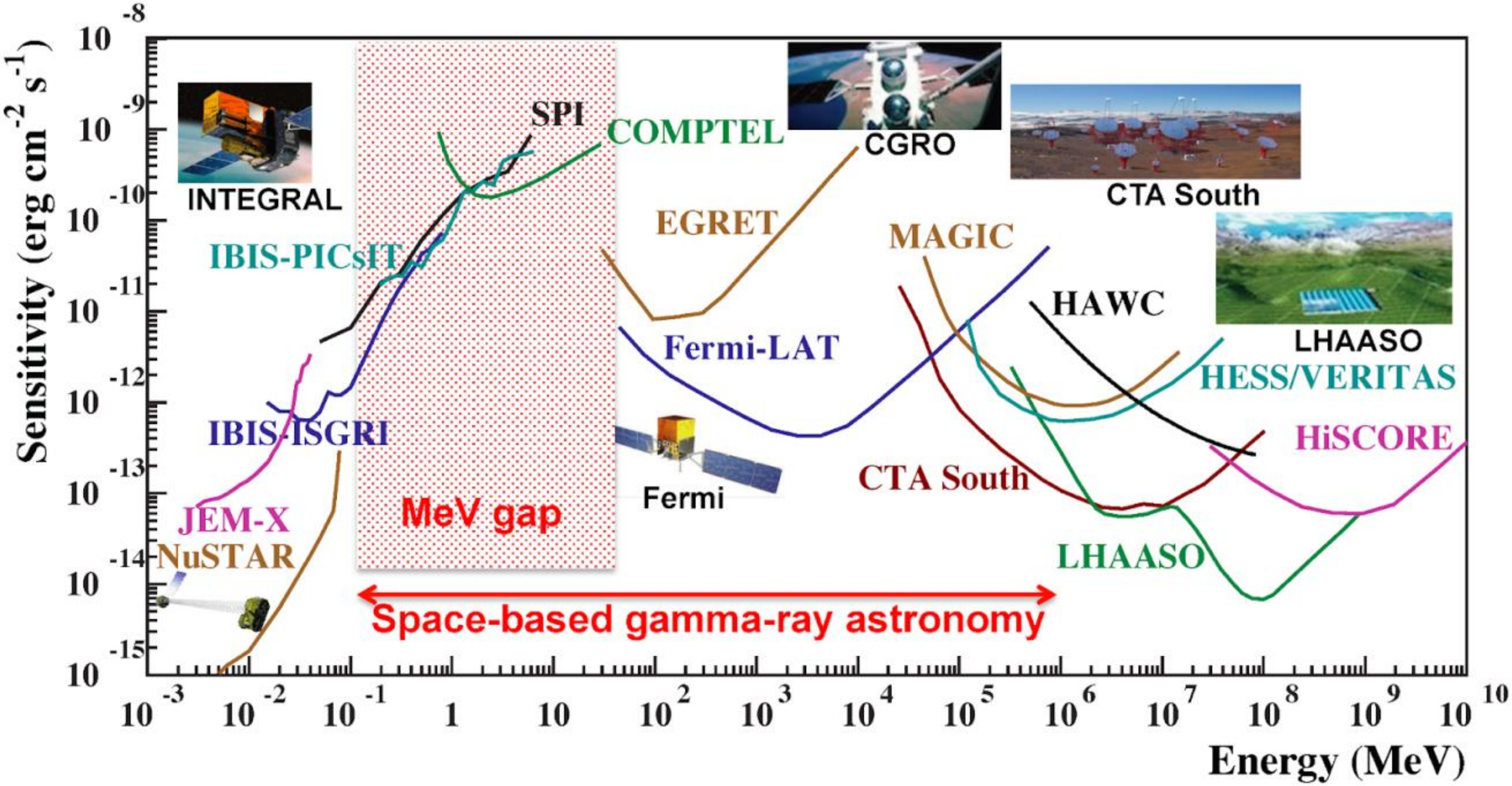
Experiments





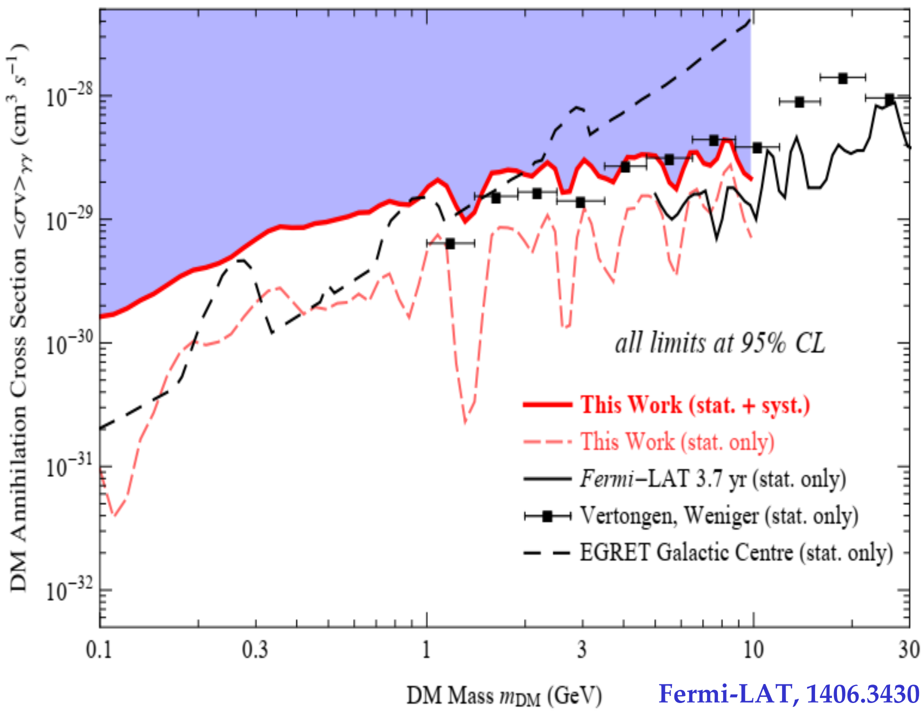
R. K. Leane, 2006.00513

Sensitivity of high energy detection

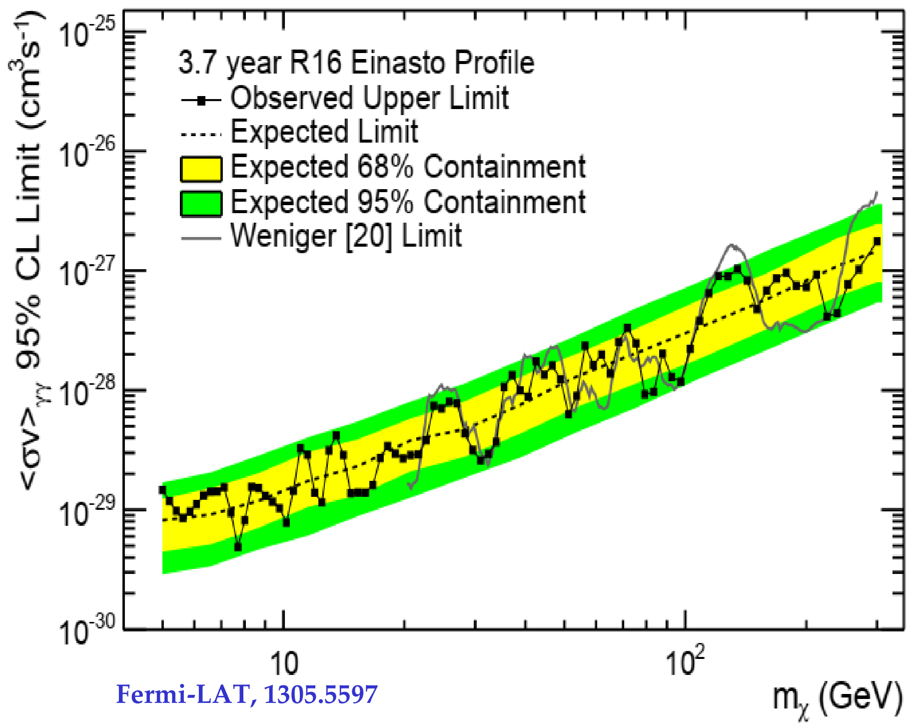


Caputo, TAUP2021

Gamma-ray spectral line



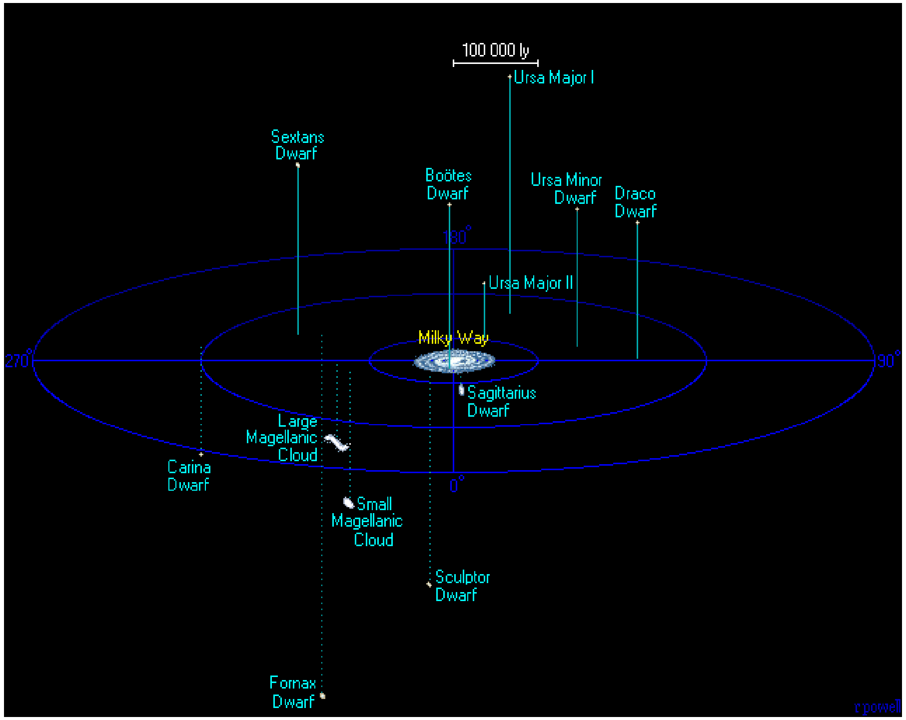
Fermi-LAT, 1406.3430



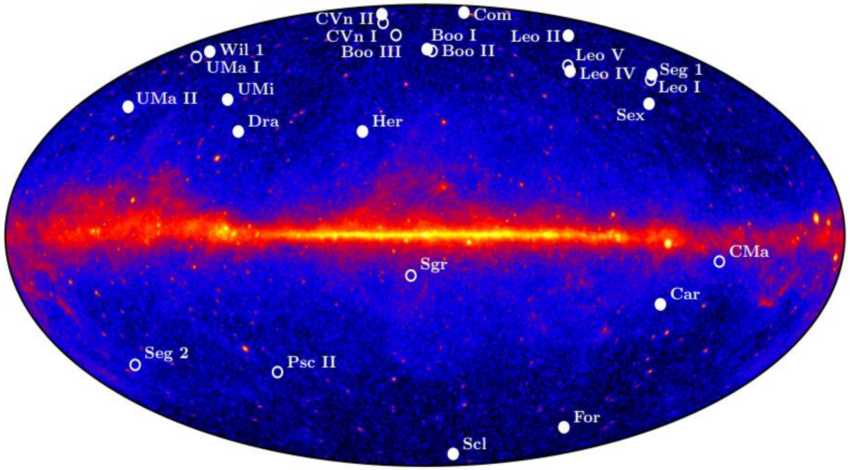
Fermi-LAT, 1305.5597

- In theory, DM annihilation at loop level or decay could produce such signal.
- There is no astrophysical process that can produce gamma-ray spectral line. Therefore, if such signal is detected, it should be resulted from DM annihilation/decay.
- For annihilation, search for the Galactic Center; for decay, search for halo.
- In 2012, some studies showed there seems an excess at ~130GeV in the GC in the Fermi-LAT data. However, this excess was not confirmed by the following studies.
- Can be detected by DAMPE and HERD.

Dwarf Spheroidal satellite galaxies



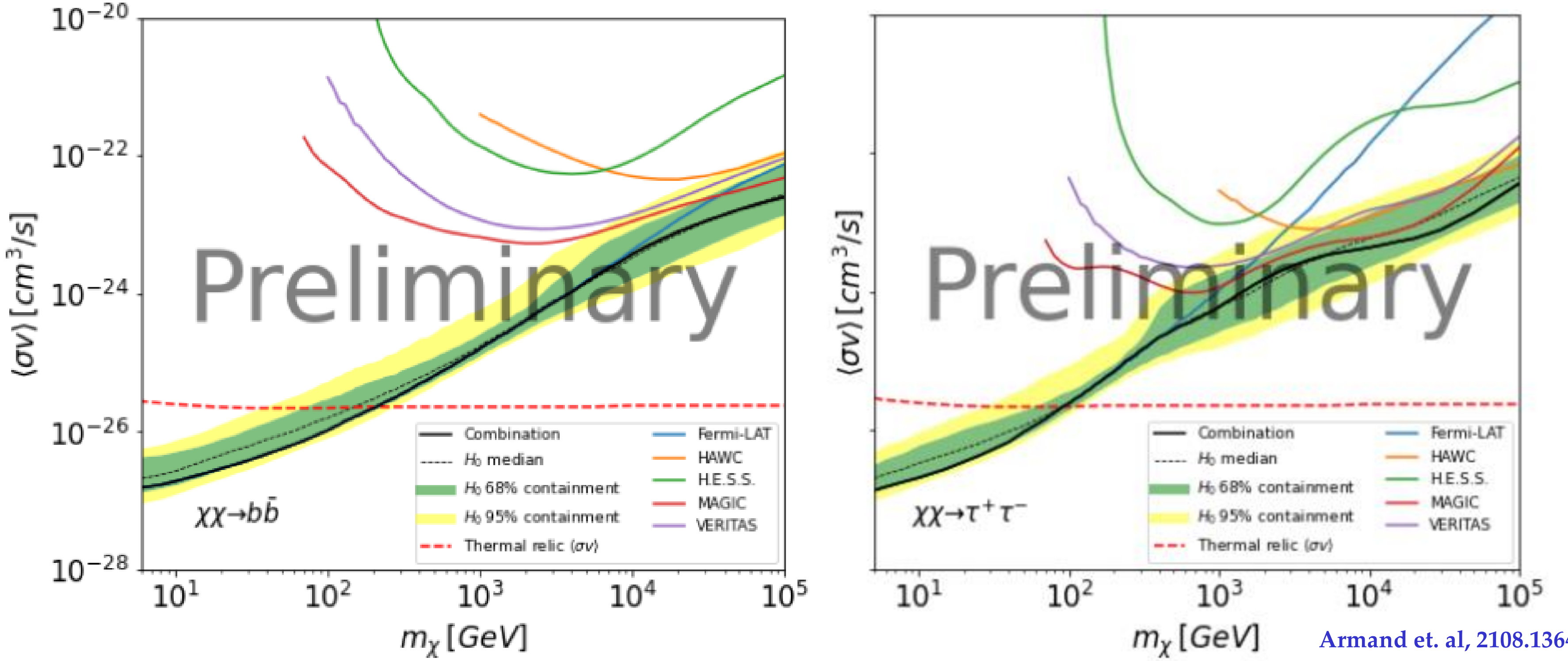
http://www.atlasoftheuniverse.com/sattelit.html



Fermi-LAT, 1310.0828

- The dominant component of dSph is DM->large J factor
- Nearby sources->large J factor
- Low component of gas and dust->almost background free
- The DM profile can be derived from the Jeans analysis using the kinematic observation results.
- Several large ultra-faint dSphs were discovered in recent years by DES. Future surveys, like LSST, may discover more such sources.

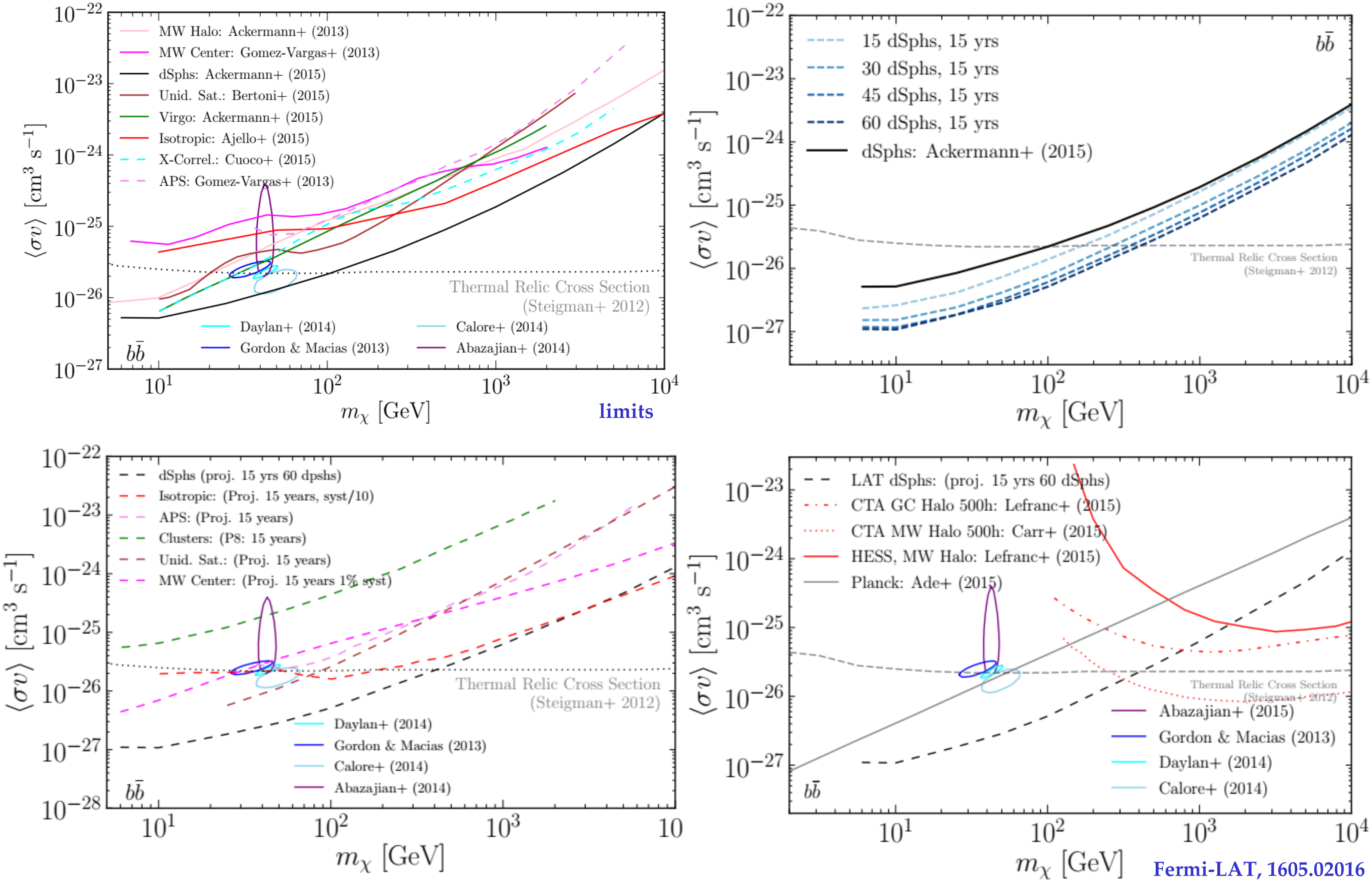
Limit from dSphs



Armand et. al, 2108.13646

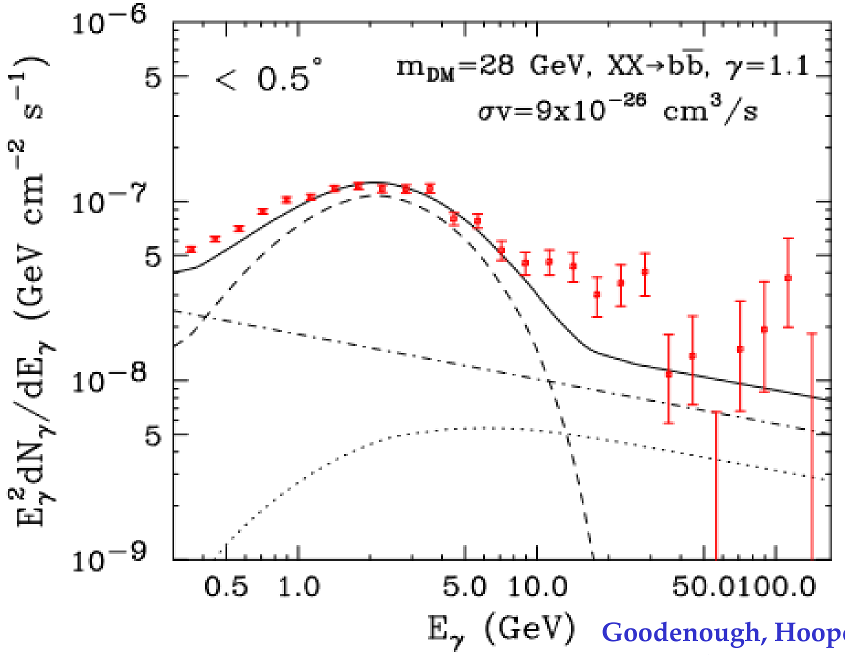
- Limit can be derived from the joint analysis using the results from several experiments.
- The above limits base on the observations of Fermi-LAT, HWAC, H.E.S.S., MAGIC, and VERITAS. The observations of 20 dSphs are considered in the combined analysis.
- The ground-based gamma-ray experiments investigate very high energy gamma-ray. Therefore, they set constraint for very heavy DM.
- The uncertainties of the J-factor should be considered.

Prospect

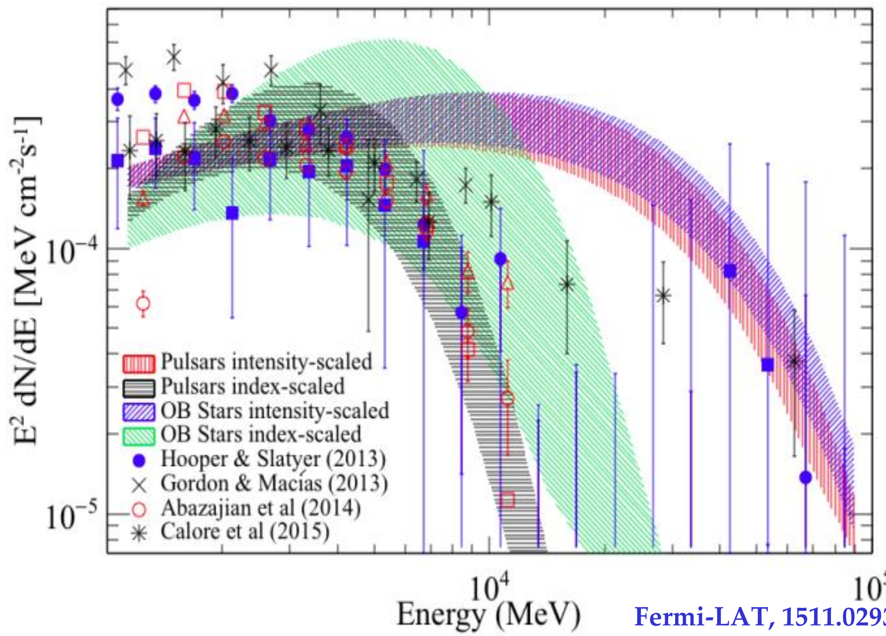


Fermi-LAT, 1605.02016

Galactic Center excess



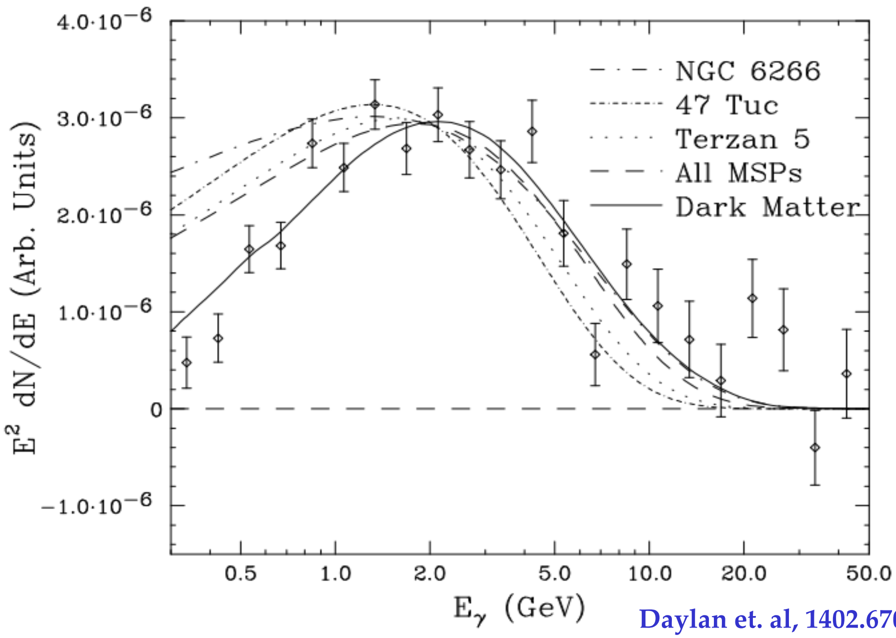
Goodenough, Hooper, 0910.2998



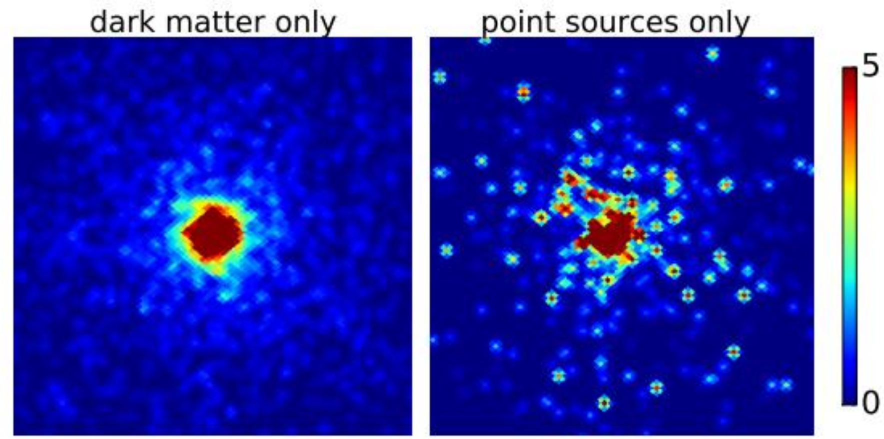
Fermi-LAT, 1511.02938

- Galactic Center has very dense DM distribution and very large J-factor.
  But backgrounds are also very complicated (point sources and diffuse gamma-ray).
- One study in 2009 showed that there is a Galactic Center excess (GCE) in the Fermi-LAT data at ~GeV.
- This excess has been confirmed by many studies (after 2012).
- The energy spectrum can be explained by an annihilating DM with a mass ~O(10) GeV and an annihilation cross section of about the natural value.
- The spatial distribution of GCE is also consistent with a NFW profile.
- GCE can also be interpreted by a population of point sources, like millisecond pulsars (MSPs). See e.g. Yuan, Zhang, 1404.2318.

Galactic Center excess



Daylan et. al, 1402.6703



Lee et. al, 1412.6099

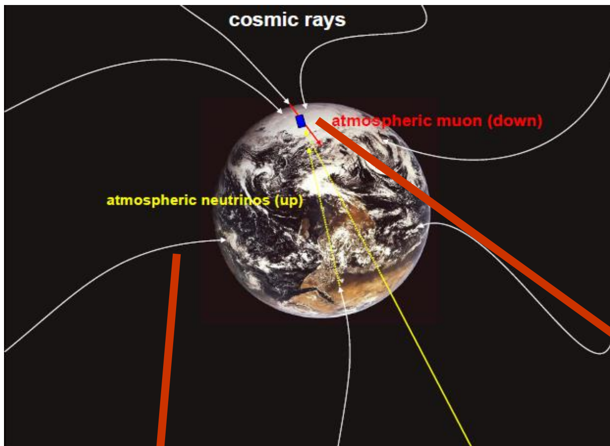
- Spectrum of MSP is consistent with the data (except at sub-GeV).
- However, the known MSPs cannot explain the flux of GCE. Require more un-resolved MSPs below the threshold of point-source detection of Fermi-LAT.
- The spatial distributions of signal for the DM and MSP hypotheses are different.

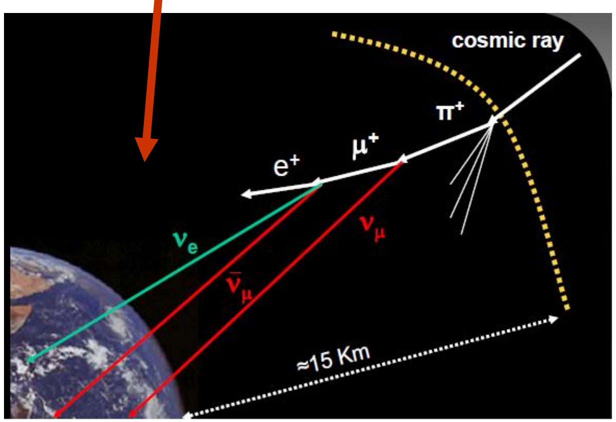
  Can be tested by the photon statistics.
- In 2015, two studies based on different analyzing methods (1506.05104,1506.05124, published in PRL) claimed that the GCE is explained by point sources.
- However, such conclusions are challenged by some recent analyses (e. g. 1911.12369, 2002.12370, published in PRL).
- The origin of GCE remains debatable. Many studies are on-going. See e.g. 2203.06859.

Neutrinos

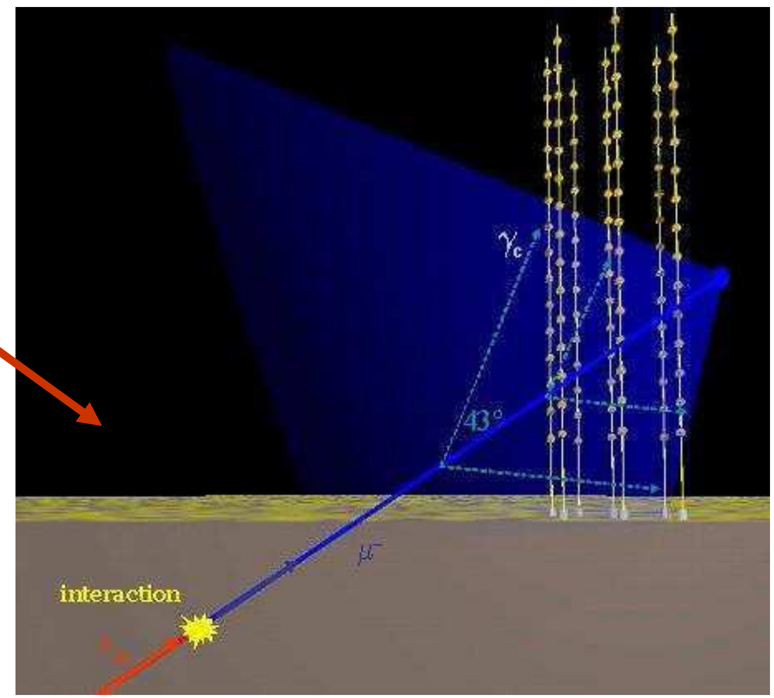
High energy neutrino detection

- Very little energy loss and trajectory deflection during the propagation , preserve the information of the nature and distribution of the DM.
- Weakly interaction, difficult to detect, require very large volume of detector



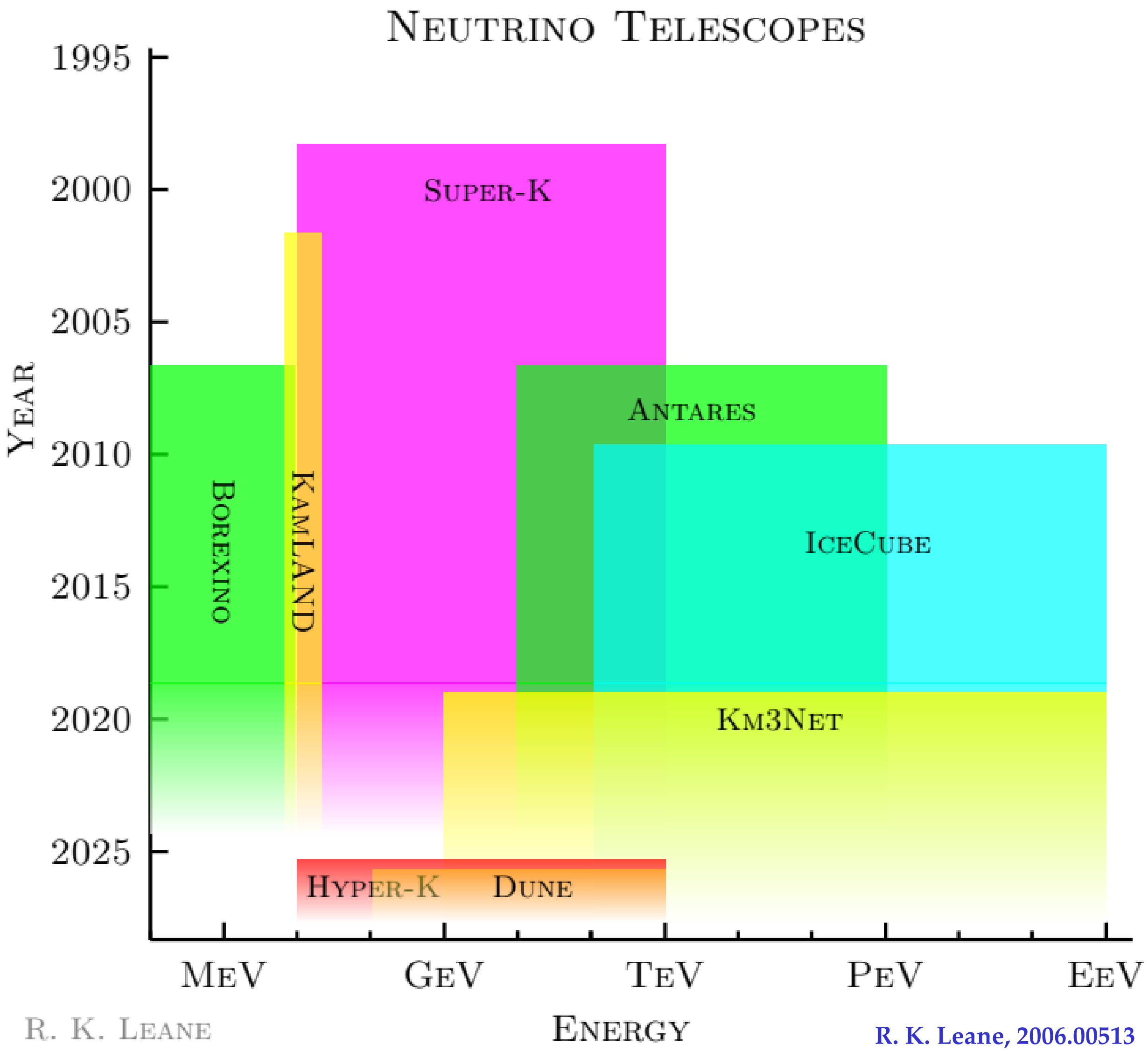


- Detector is set in the deep underground/ice/sea (Super-k/IceCube/Antares).
- Focus on upgoing events



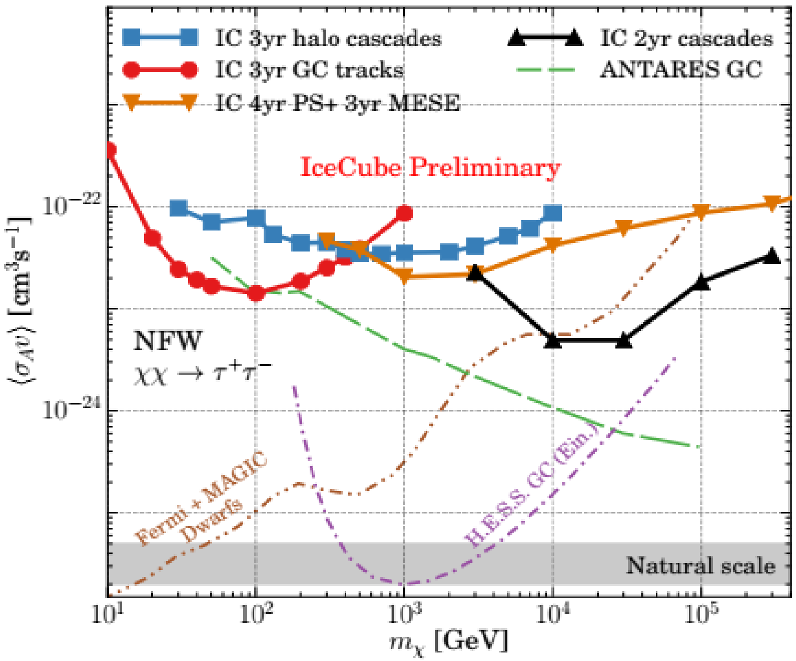
- Large atmospheric neutrino background, Require high direction resolution
- Cherenkov detector : detect Cherenkov emission from the charged leptons induced by neutrinos

Experiments

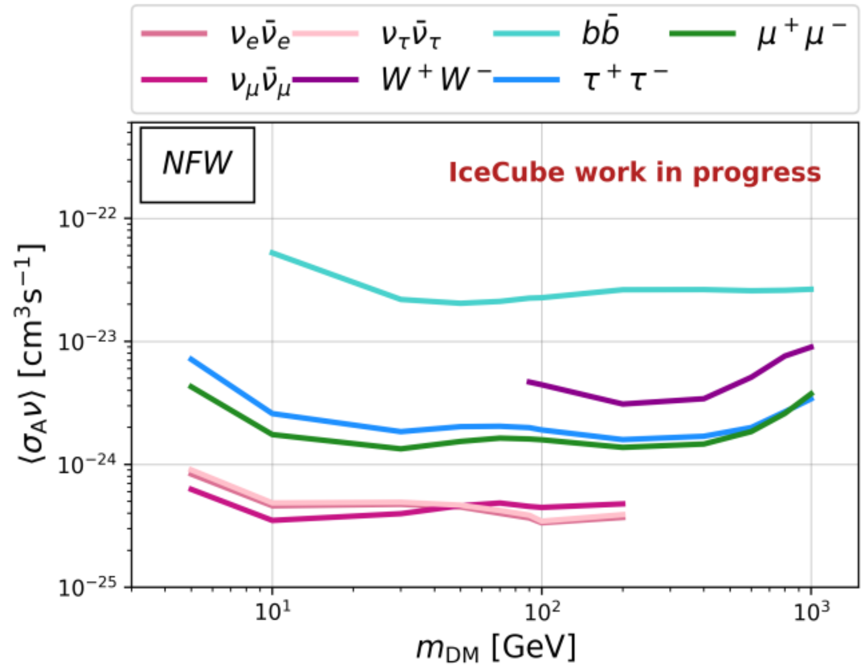


R. K. Leane, 2006.00513

Limit from cosmic neutrino



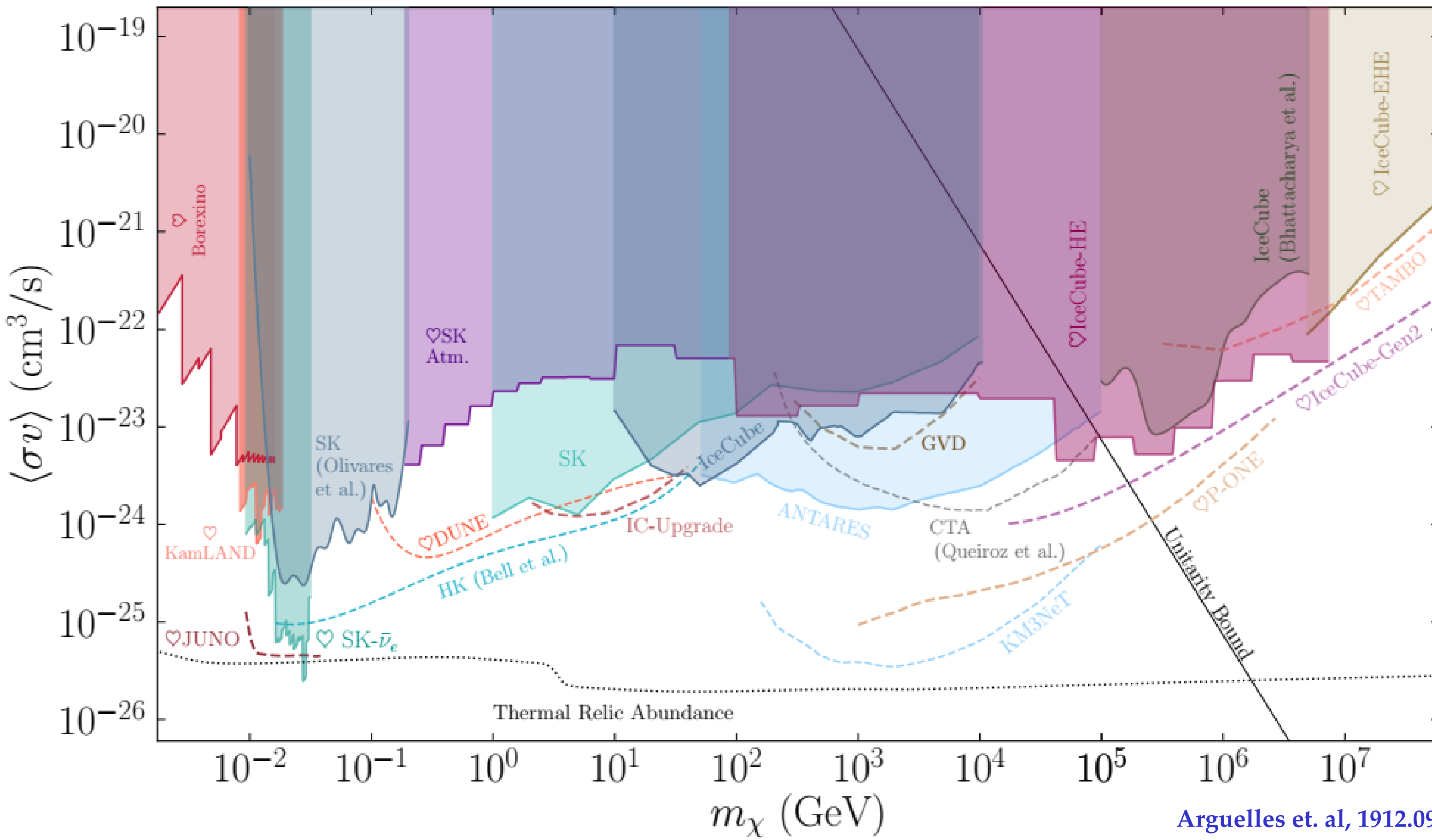
IceCube, TAUP 2017



IceCube, 2107.11224

- The search strategies for cosmic neutrino signals resulting from DM annihilation/decay in astrophysical systems are similar to photon signals from DM.
- The expressions of two signal fluxes are also similar.
- However, since the neutrinos are very difficult to detect compared with the photons, the corresponding limits are weaker.
- Large volume neutrino detectors are suitable to detect very high energy neutrinos. Thus favor heavy DM; the corresponding limit can be competitive with those from other detections.

Limit from cosmic neutrino



Arguelles et. al, 1912.09486

- Limits and sensitivities for DM annihilation to νν in the Galaxy and extra-galactic halos

Solar Neutrino from DM annihilation

DM is free in the Galaxy with MB distribution

↓ attracted by solar system's gravitation

DM-nucleon scatters in the Sun

↓ DM loss energy

DM is trapped in the core of Sun

↓ reach equilibrium

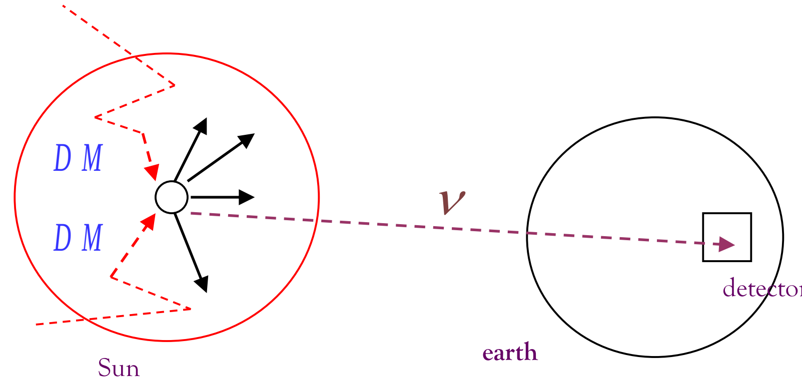
DM annihilate in the Sun

↓ neutrinos escape, propagate to the earth

Neutrinos interact with matter near the detector

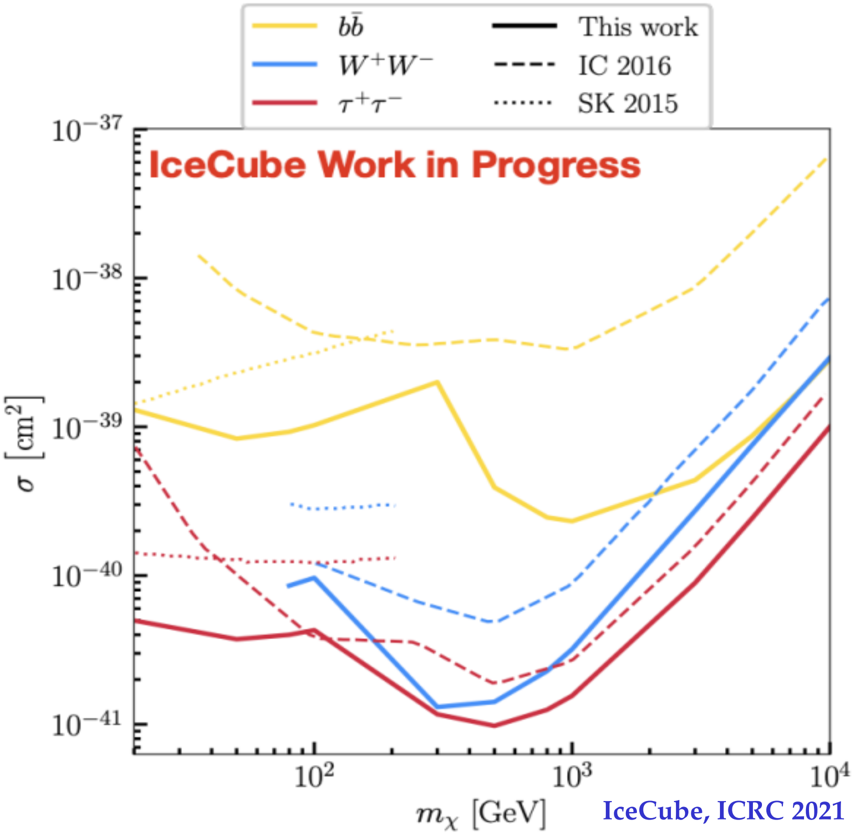
↓ produce muons

Detect Cherenkov light induced by muons

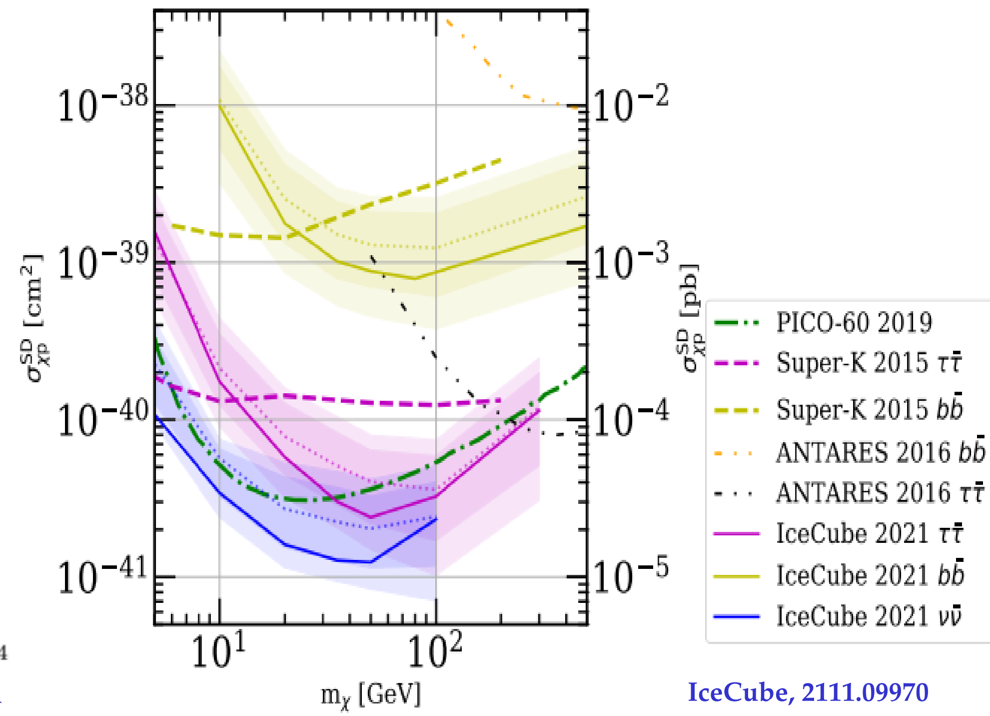


- DM annihilate rate is determined by capture rate and then DM-nucleon scattering.
- Detect DM-nucleon scattering cross section and branching ratio of DM annihilating to neutrinos.
- Constrain DM annihilate channel to WW, ZZ, tt and νν.
- Main background is from atmospheric neutrino induced by cosmic rays.
- Similar process can also happen in the center of the Earth.

Limit from solar neutrino



IceCube, ICRC 2021



IceCube, 2111.09970

- Focus on spin-dependent DM-nucleon scattering cross section.
- Limit can be compared with those from direct detection.

Summary

- WIMPs are well-motivated in new physics models and easy to detect.

- However, WIMP signal has not been confirmed by experiments. Thus many (indirect detection) experiments have set very stringent constraints for WIMPs.

- Some indirect detection experiments reported some anomalous signals which could explained by WIMPs.

- The interpretations of these anomalies strongly depend on the knowledge of high energy astrophysical processes. Some anomalies favor an astrophysical interpretation, while some are still under debate.

- Future experiments and studies may provide new clues to WIMPs.

Some references and recommended readings

- Lectures (in arXiv)
  - S. Profumo, TASI 2012 lectures on astrophysical probes of dark matter, 1301.0952.
  - D. Hooper, TASI lectures on indirect searches for dark matter, 1812.02029.
  - T. Slatyer, Les Houches lectures on indirect detection of dark matter, 2109.02696.
- Snowmass2021 Cosmic Frontier White Paper
  - K. K. Boddy et. al, Astrophysical and cosmological probes of dark matter, 2203.06380.
  - R. K. Leane et. al, Puzzling excesses in dark matter searches and how to resolve them, 2203.06859.
  - S. Ando et. al, Synergies between dark matter searches and multiwavelength/ multimessenger astrophysics, 2203.06781.
- Talks
  - J. S. Gaskins, Indirect dark matter searches, SLAC Summer Institute 2014.
  - T. Slatyer, Dark matter indirect detection, SLAC Summer Institute 2020.
  - F. Calore, Indirect detection of dark matter, TAUP 2021.

Thank you