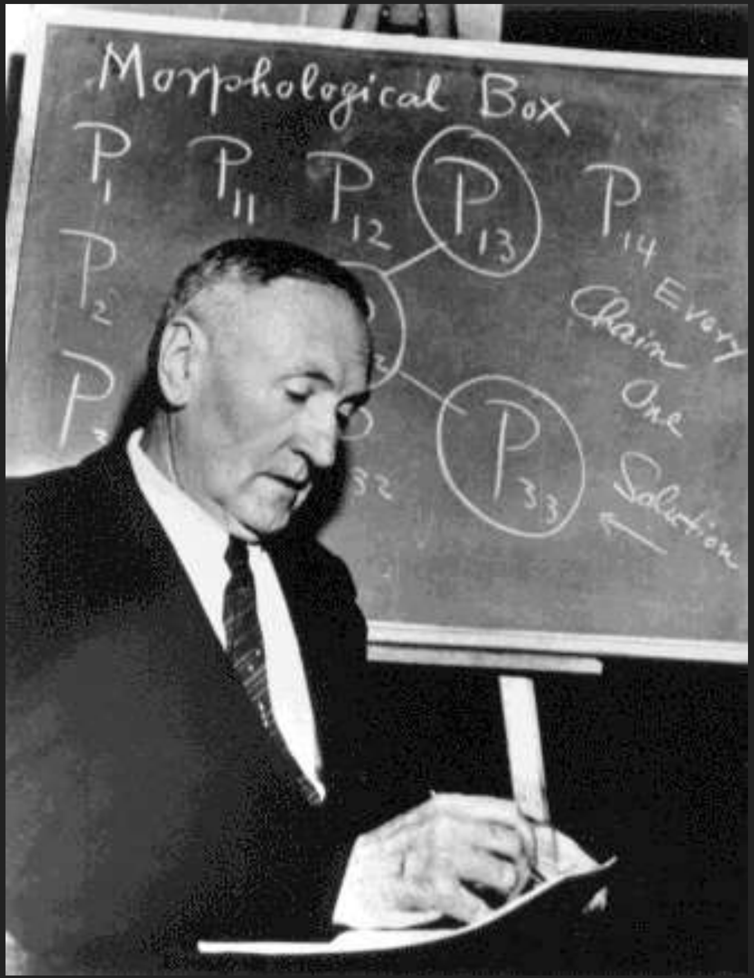
Yen-Hsun Lin (林彥勳)
Institute of Physics, Academia Sinica

NCTS-TCA SSP Mini-Workshop
July 5-7, 2021

Detecting Dark Matter

Methods and Sensitivities

quoted from Wiki

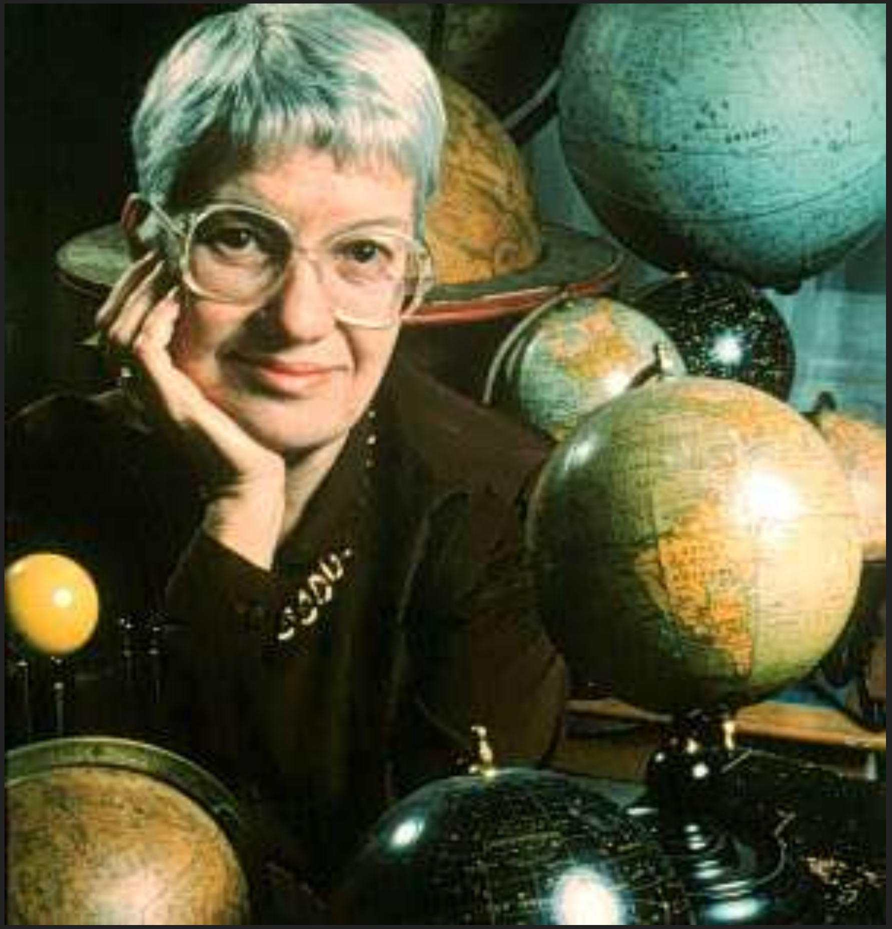


Fritz Zwicky (1898-1974)

Unseen matter was inferred from the observation of the Coma Cluster in 1933. (*dunkle materie*)
The deduced gravitational mass of the cluster is 400 times greater than the expectation from their luminosity. Most of the matters must be dark.

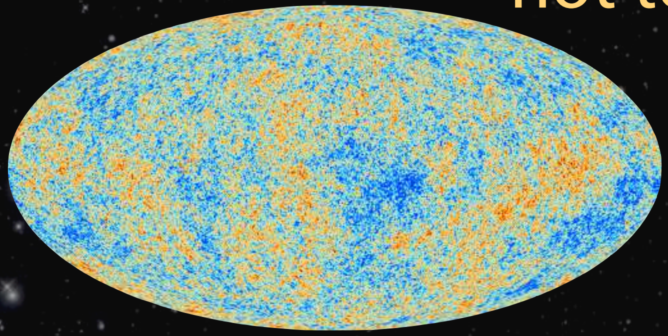
Vera Rubin (1928-2016)

Together with her colleague Kent Ford, they discovered the most stars in spiral galaxies orbit at roughly the same speed. It implied that the galaxy masses grow approximately linearly with radius well beyond the location of most of the stars (galactic bulge).



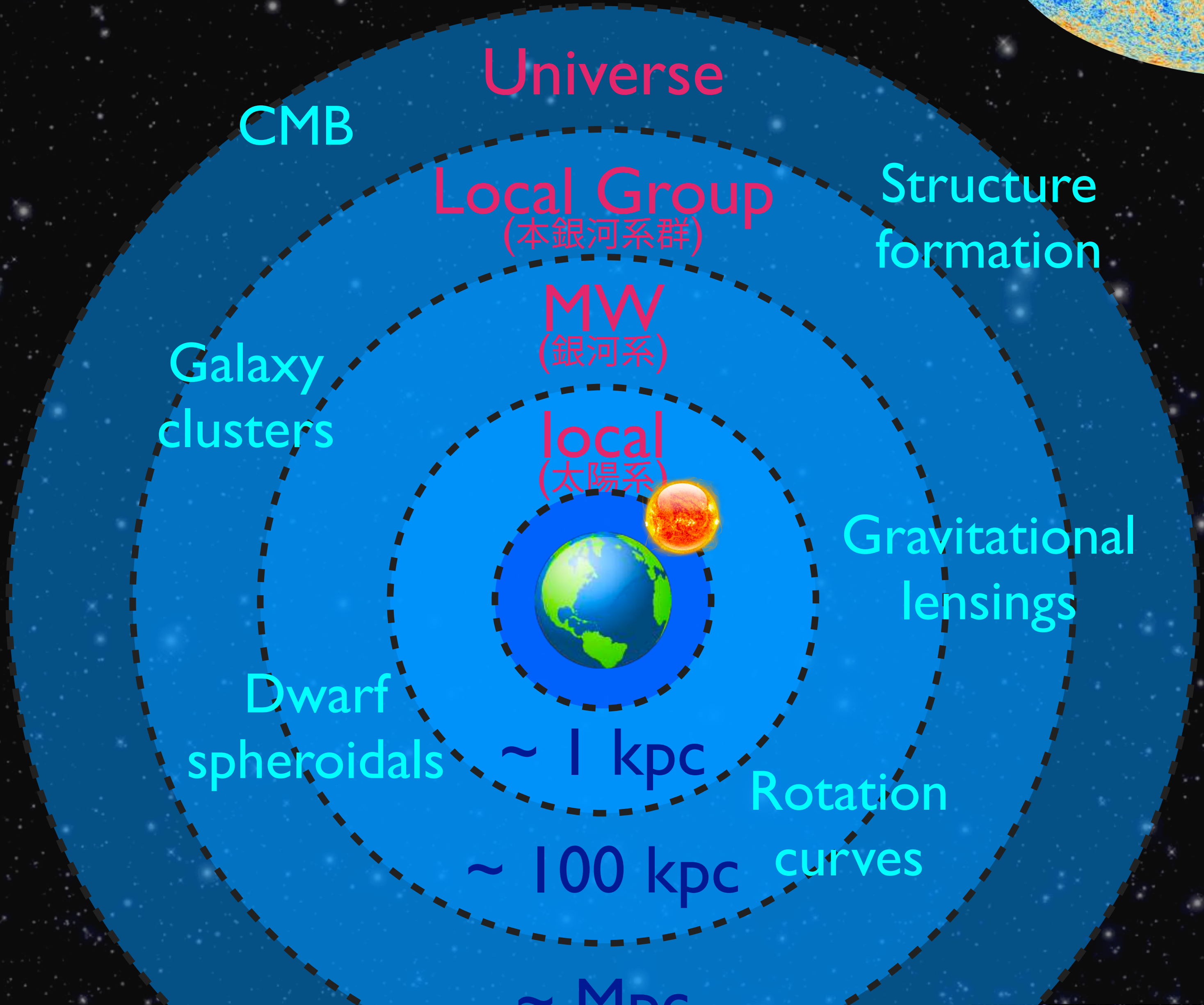
Dark matter is ***ubiquitous*** in the Universe!

not to scale



More ancient

Larger space



Universe

CMB

Local Group
(本銀河系群)

Structure formation

MW
(銀河系)

Galaxy clusters

local
(太陽系)

Gravitational lensings

Dwarf spheroidals

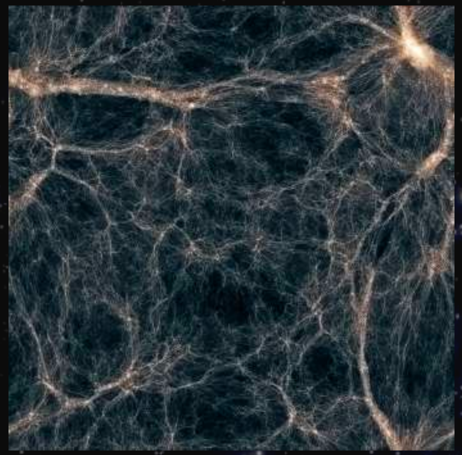
~ 1 kpc

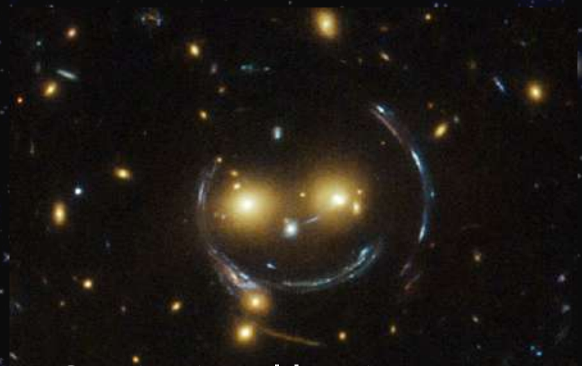
Rotation curves

~ 100 kpc

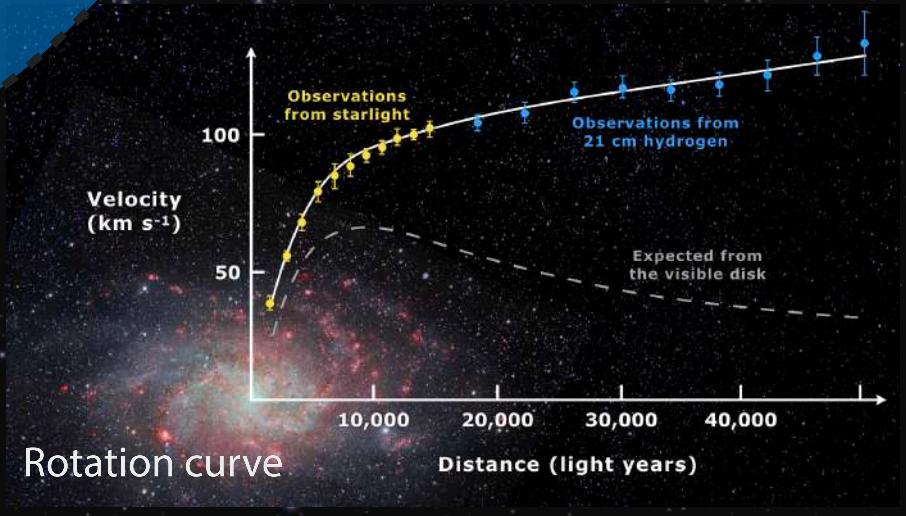
~ Mpc

~ Gpc





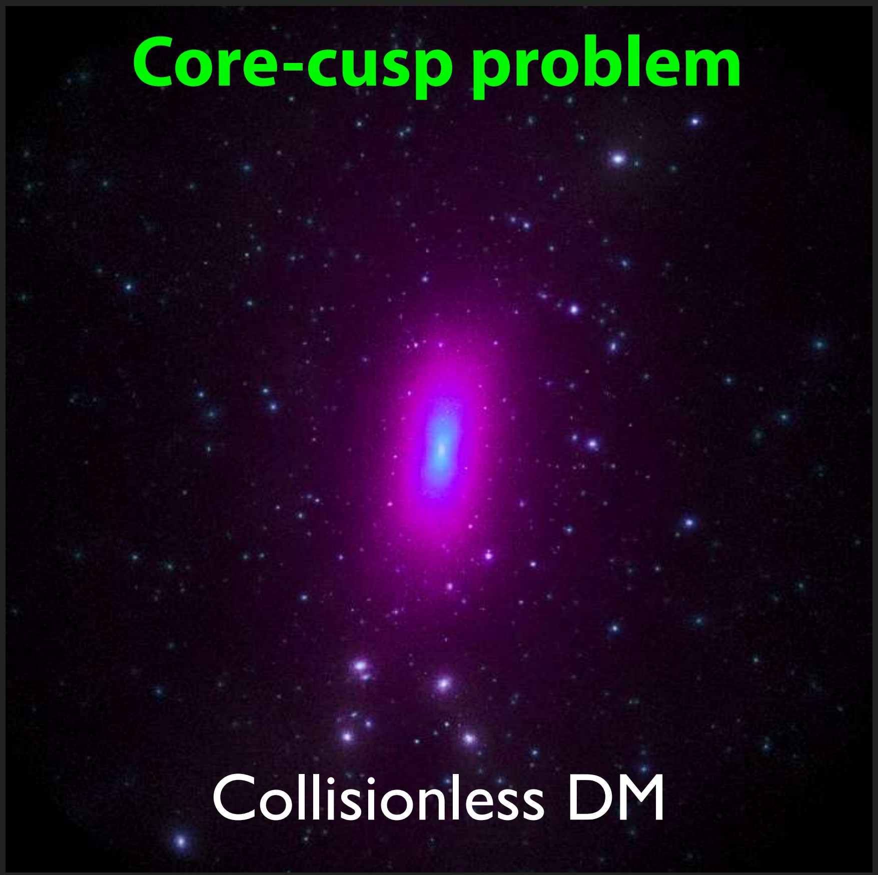
Gravitational lensing



Rotation curve

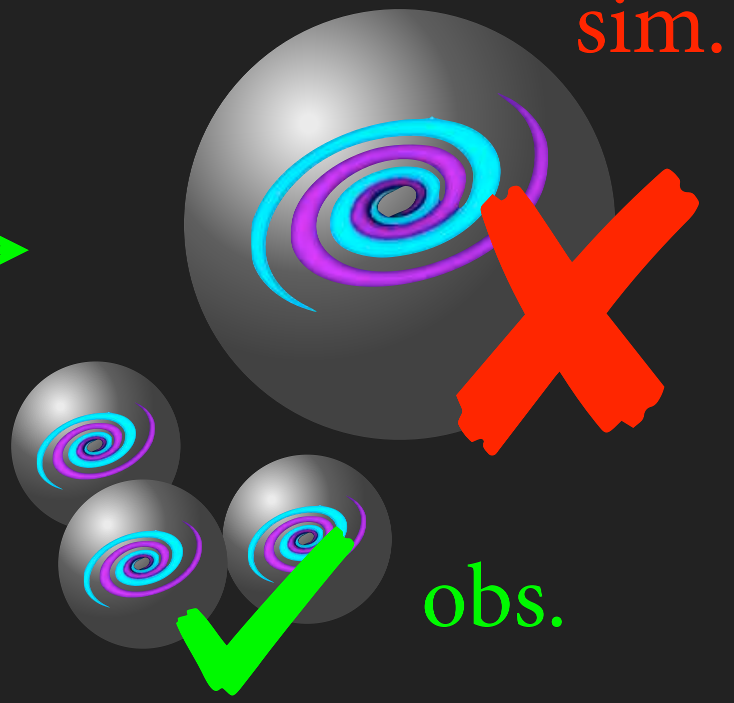
$1\,\mathrm{pc} \approx 2.06 \times 10^{5}\,\mathrm{AU} \approx 3.08 \times 10^{16}\,\mathrm{m}$

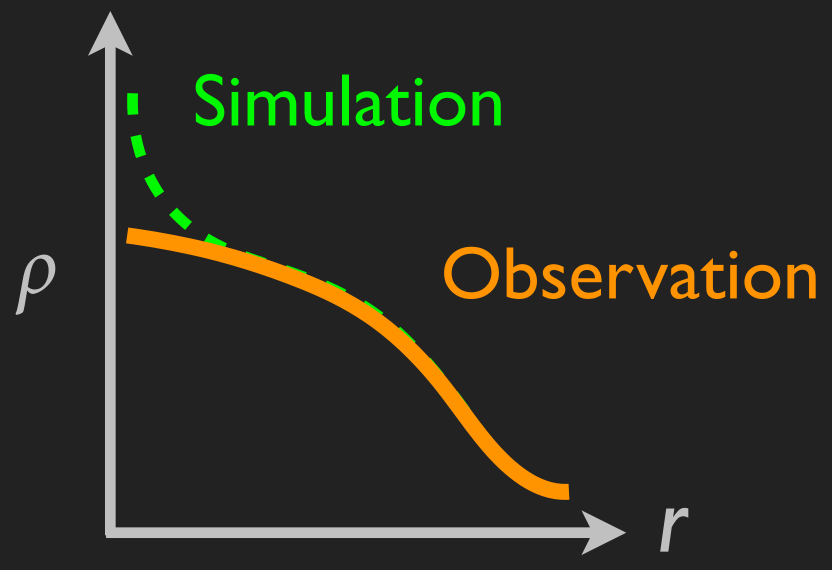
Core-cusp problem



Missing satellite

Too-big-to-fail





Satellite number

simulation ~ $O(10^3)$

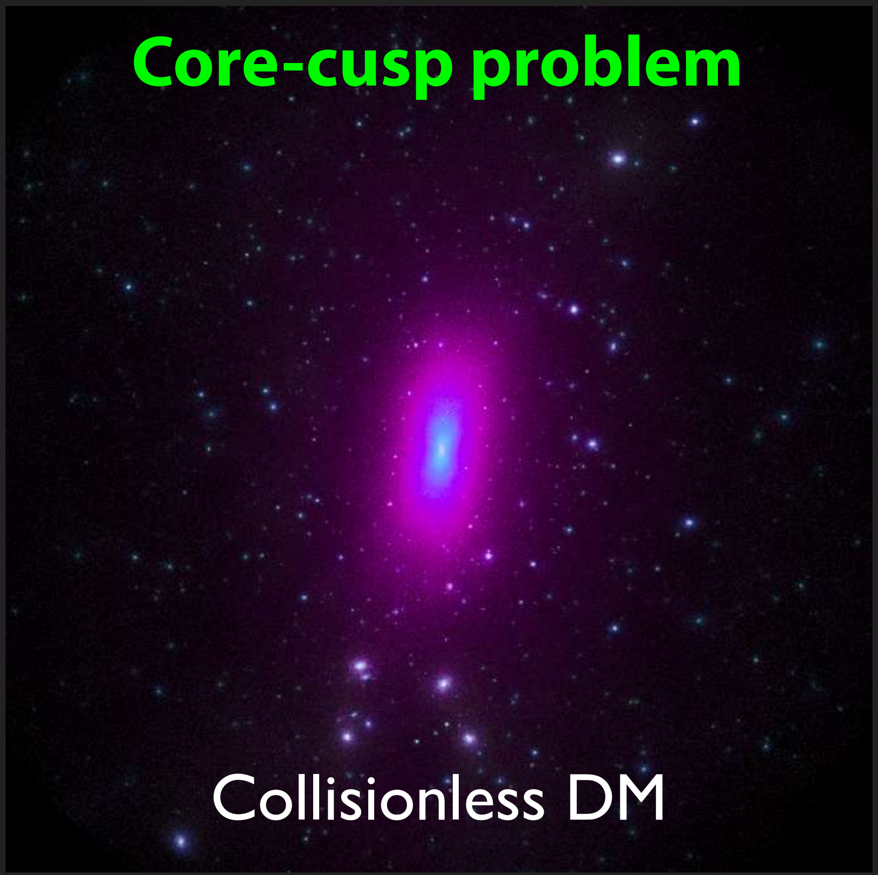
observation ~ dozens

We didn't see any satellite as massive as predicted by the *N*-body sim.

Bullock et al. (2017)
Tulin et al. (2018)

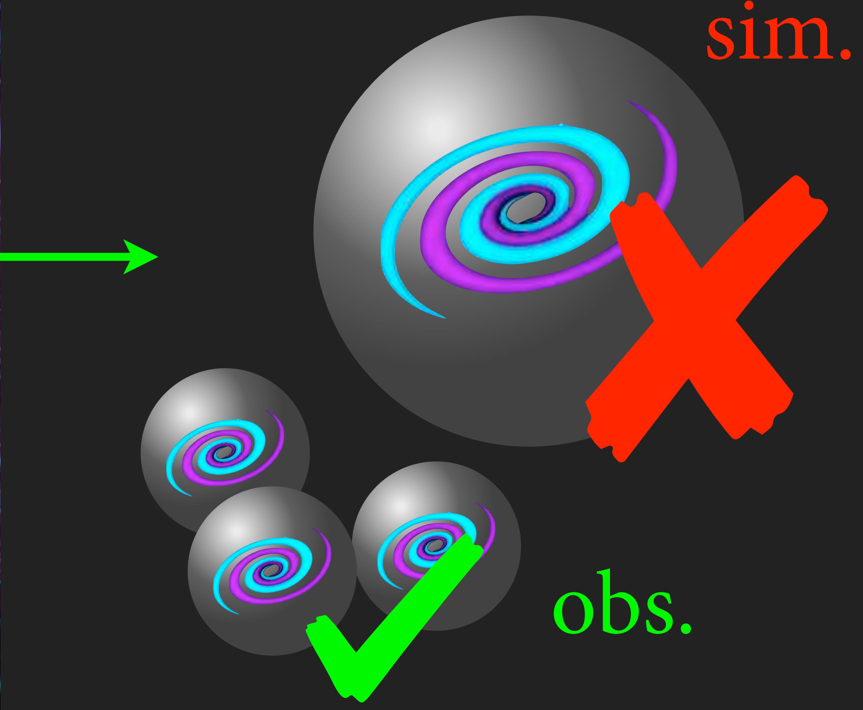
not to scale

Core-cusp problem



Missing satellite

Too-big-to-fail

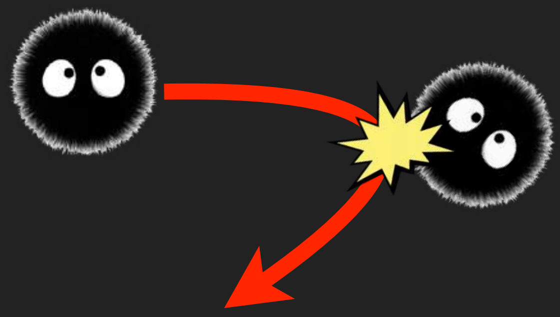


To alleviate these small-scale problem:

Dark matter (DM) self-interaction

Not only gravity!

$$10^{-25}\,\frac{\mathrm{cm}^2}{\mathrm{GeV}} \leq \frac{\sigma_{\chi\chi}}{m_\chi} \leq 10^{-23}\,\frac{\mathrm{cm}^2}{\mathrm{GeV}}$$



Bullock et al. (2017)
Tulin et al. (2018)

not to scale

Outline

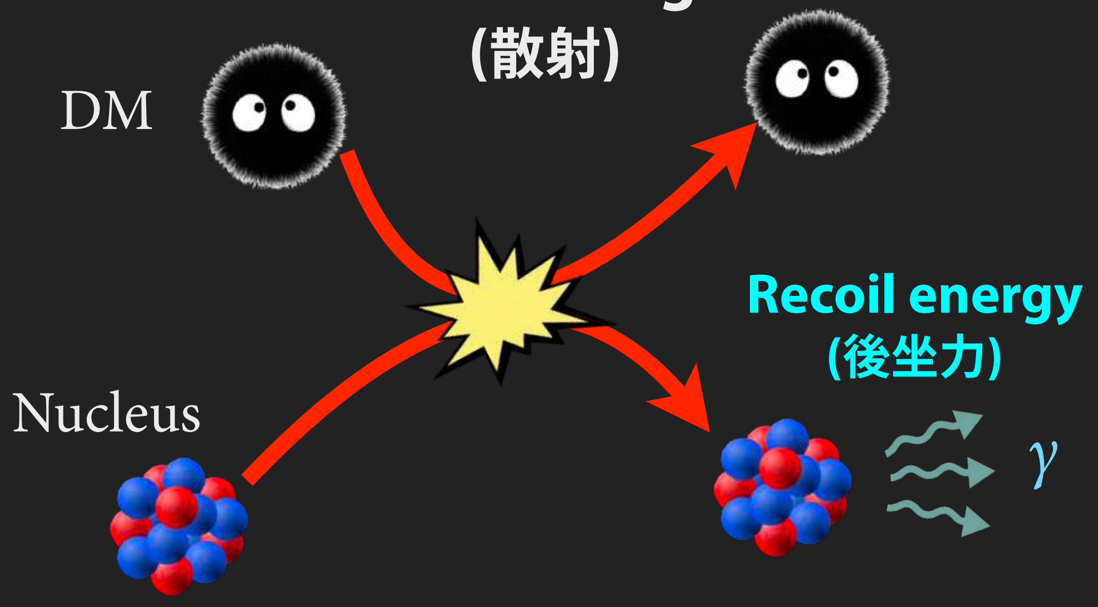
- **Part I: Introduction**
  - DM concept and traces in the Universe
  - Hints beyond collisionless DM
- **Part II: Detection methods**
  - Direct detection
  - Indirect detection
  - Production in the colliders (not covered)
  - Topics that are not covered in this talk
- **Summary**

> *There is strong shadow where*
> *there is much light*
>
> — J. W. von Goethe (1749-1832)

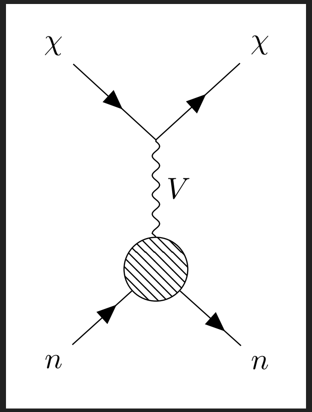
Behind the veil of darkness

- Dark *matter* → mass m_χ
- To *measure* → DM-SM *interaction* → cross section σ

Scattering (散射)



Recoil energy (後坐力)



Kinetic + *Z*-mass mixing model

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\varepsilon_\gamma}{\cos\theta_W}B_{\mu\nu}V^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu}$$

$$\mathcal{L}_{\text{mass}} = \frac{1}{2}m_Z^2 Z_\mu Z^\mu - \varepsilon_Z m_Z^2 Z_\mu V^\mu + \frac{1}{2}m_V^2 V_\mu V^\mu$$

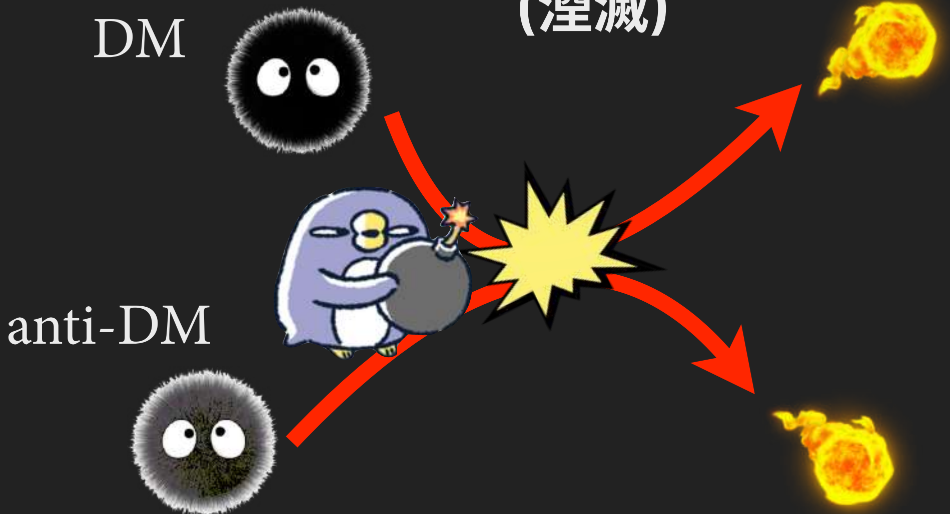
INCONCLUSIVE

Interacting portal between DM & SM

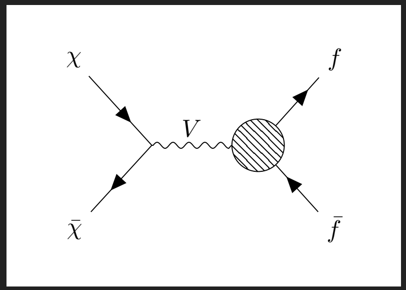
$$\mathcal{L}_{\text{int}} = \left(\varepsilon_\gamma e J_\mu^{\text{EM}} + \tilde{\varepsilon}_Z \frac{g_2}{\cos\theta_W} J_\mu^{\text{NC}}\right) V^\mu$$

and so many other theories…

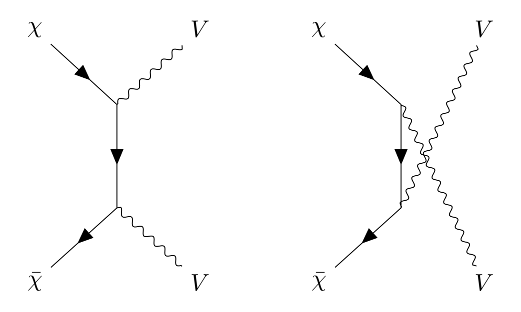
Annihilation (湮滅)

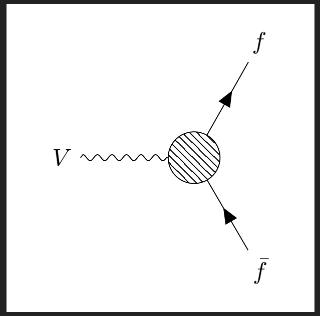


Standard Model particles



or



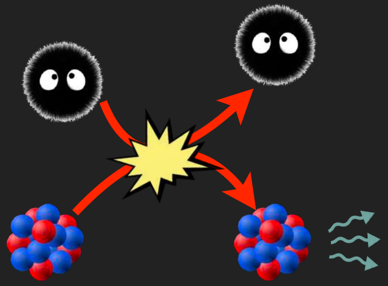


not to scale

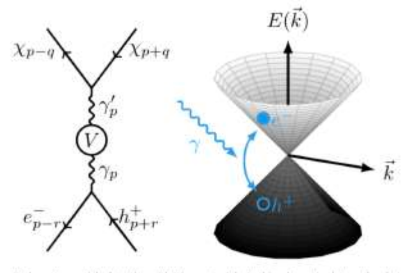
CDEX Collab.
LUX Collab.
SENSEI Collab.
XENON Collab.
Essig+ (2015)
Hochberg+ (2015)
Hochberg+ (2016)
Geilhufe+ (2019)
Kim+ (2020)
Kahn+ (2020)
Knapen+ (2020)
…

Method 1: Direct detection

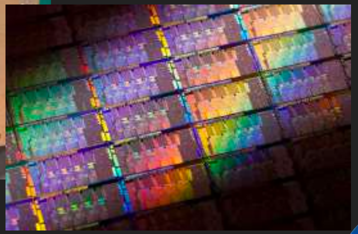
- Dark *matter* → mass m_χ
- To *measure* → DM-SM *interaction* → cross section σ

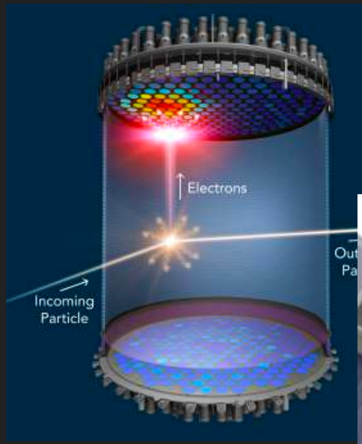


superconductor/graphene
(超導體/石墨烯)
Dirac matter…



semiconductor (半導體)
skipper CCD





liquid xenon
(液態氙)

dentist's X-ray/CT scan

electron

neutron/proton

(電子伏特 eV)
m_χ

keV

collective effects
phonon/plasmon
magnon/e^- Cooper pair…

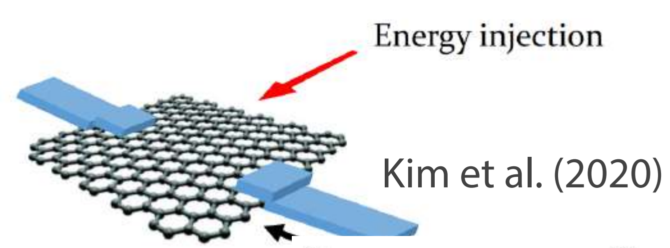
MeV

electron recoils
ionization
Migdal effect…

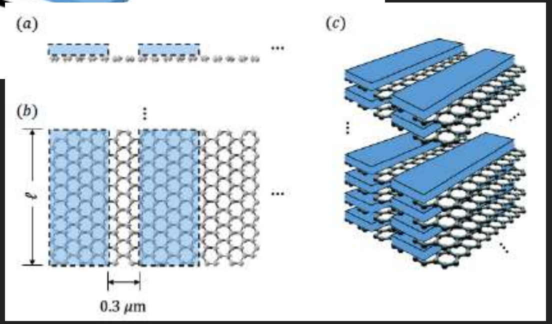
GeV

nucleus recoils

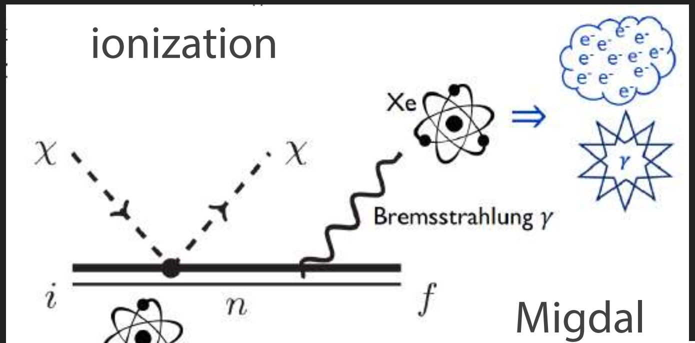
> TeV



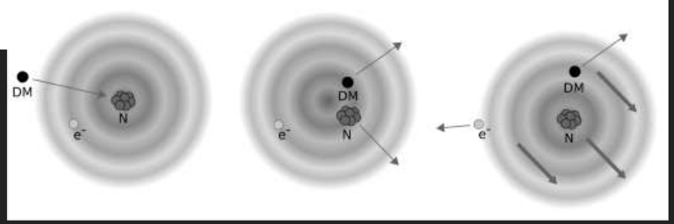
Kim et al. (2020)

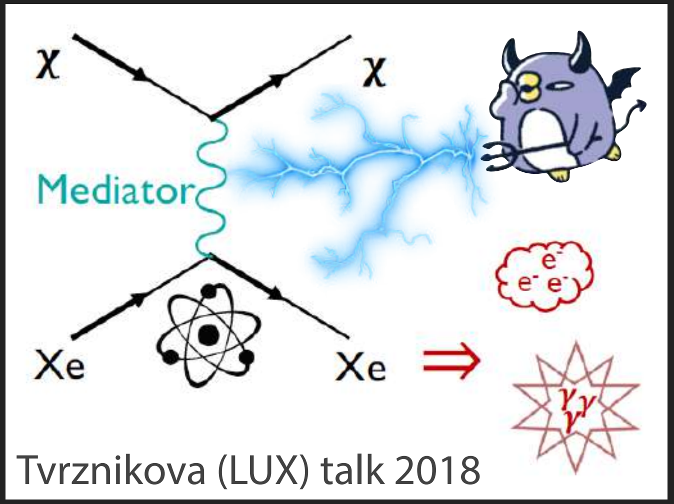


ionization



Migdal





Tvrznikova (LUX) talk 2018

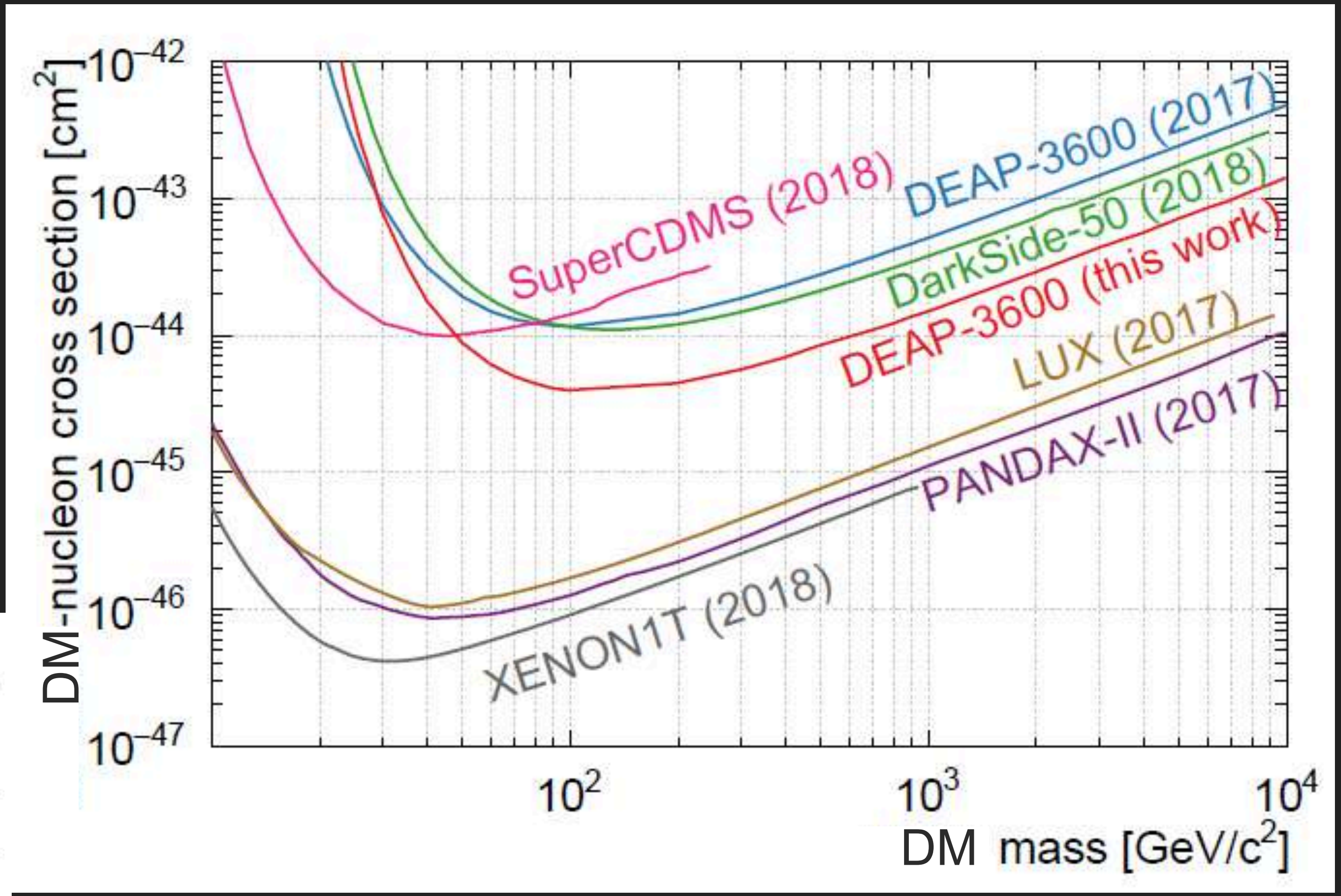
$1\,\text{GeV} \approx 1.6 \times 10^{-27}\,\text{kg}$

not to scale

Direct detection sensitivity

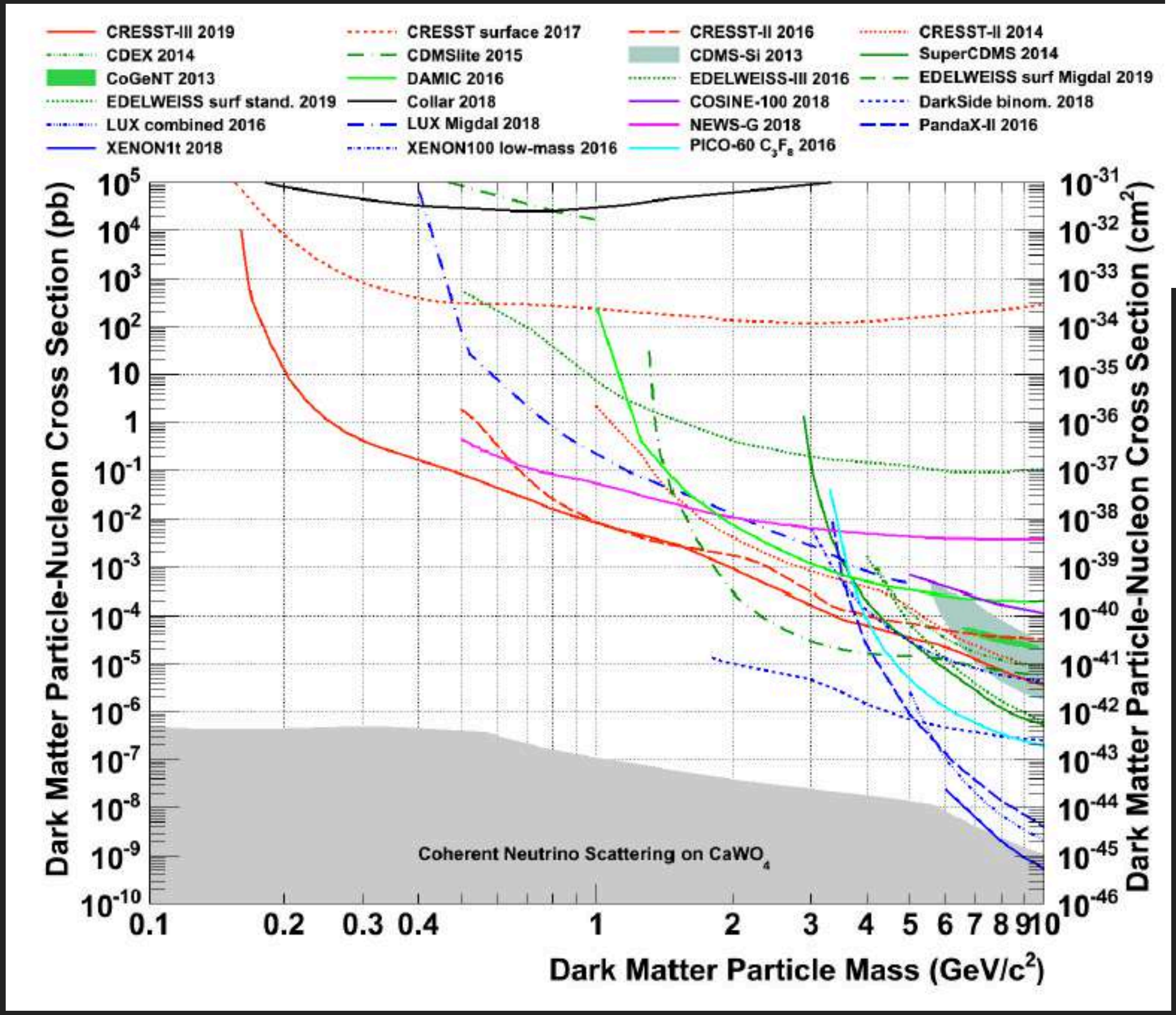
1 GeV ~

DM mass heavier than 10 GeV



- Null result → upper limit
- Heavy DM → $\sigma_{\chi n} \sim 10^{-46}$ cm^2
- Light DM → $\sigma_{\chi n} \sim 10^{-35}$ cm^2

0.1 GeV < DM mass < 10 GeV



Rate
反應率

$$\frac{dR}{dE_R} = \frac{\rho_0}{2m_\chi}\frac{\sigma_{\chi A}}{\mu_A^2}F^2(q)\int\frac{f(v)}{v}d^3v$$

SI
自旋無關

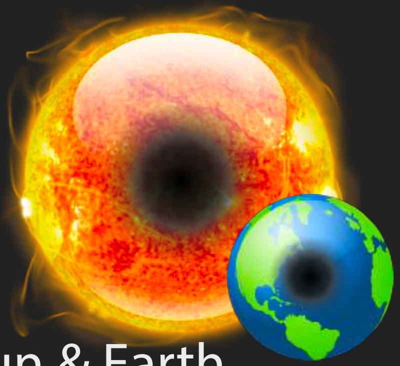
$$\sigma^{\mathrm{SI}}_{\chi A}(q=0) \approx \frac{\mu_A^2}{\mu_p^2}\sigma^{\mathrm{SI}}_{\chi p}A^2$$

SD
自旋相關

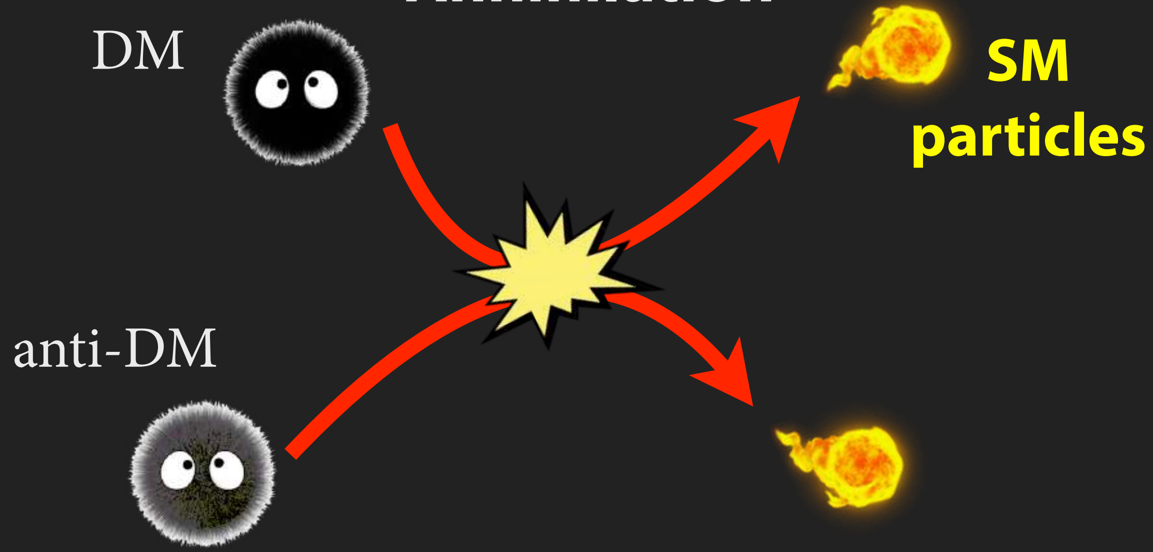
$$\sigma^{\mathrm{SD}}_{\chi A}(q=0) \approx \frac{\mu_A^2}{\mu_p^2}\sigma^{\mathrm{SD}}_{\chi p,n}\left[\frac{4}{3}\frac{J+1}{J}(a_p\langle S_p\rangle + a_n\langle S_n\rangle)^2\right]$$

Method 2: Indirect detection

MW center



Sun & Earth



Annihilation

DM

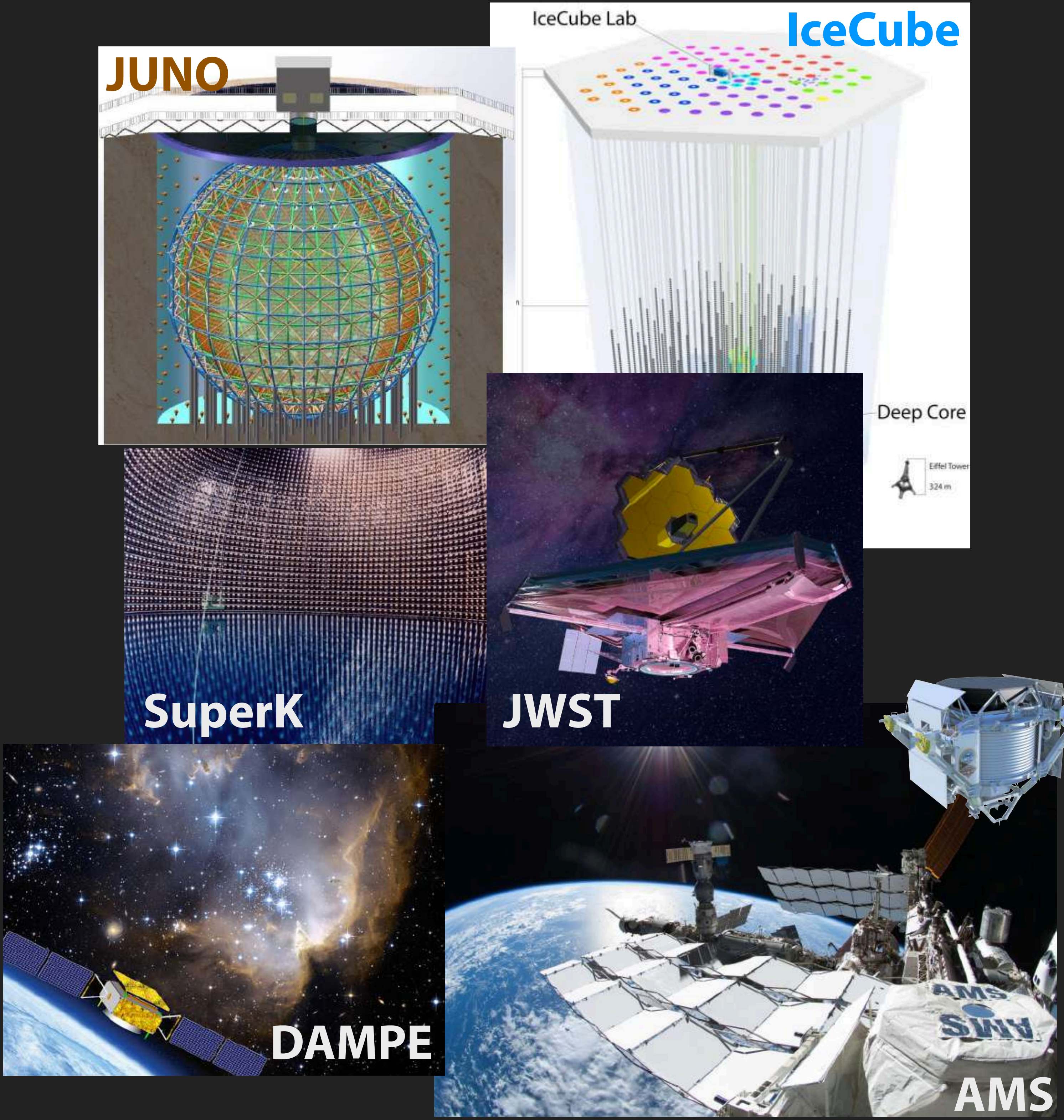
anti-DM

SM particles

Neutron star

Red giant

Supernova



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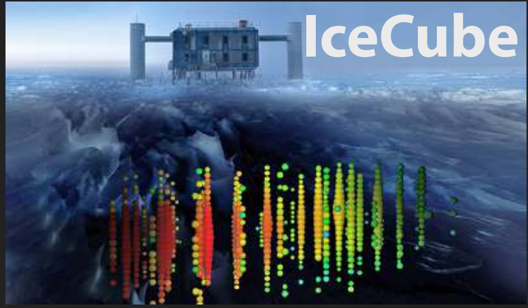
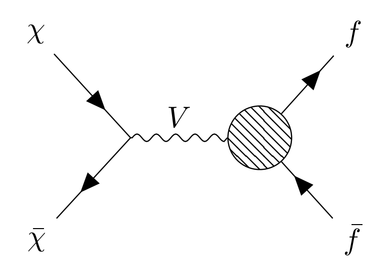
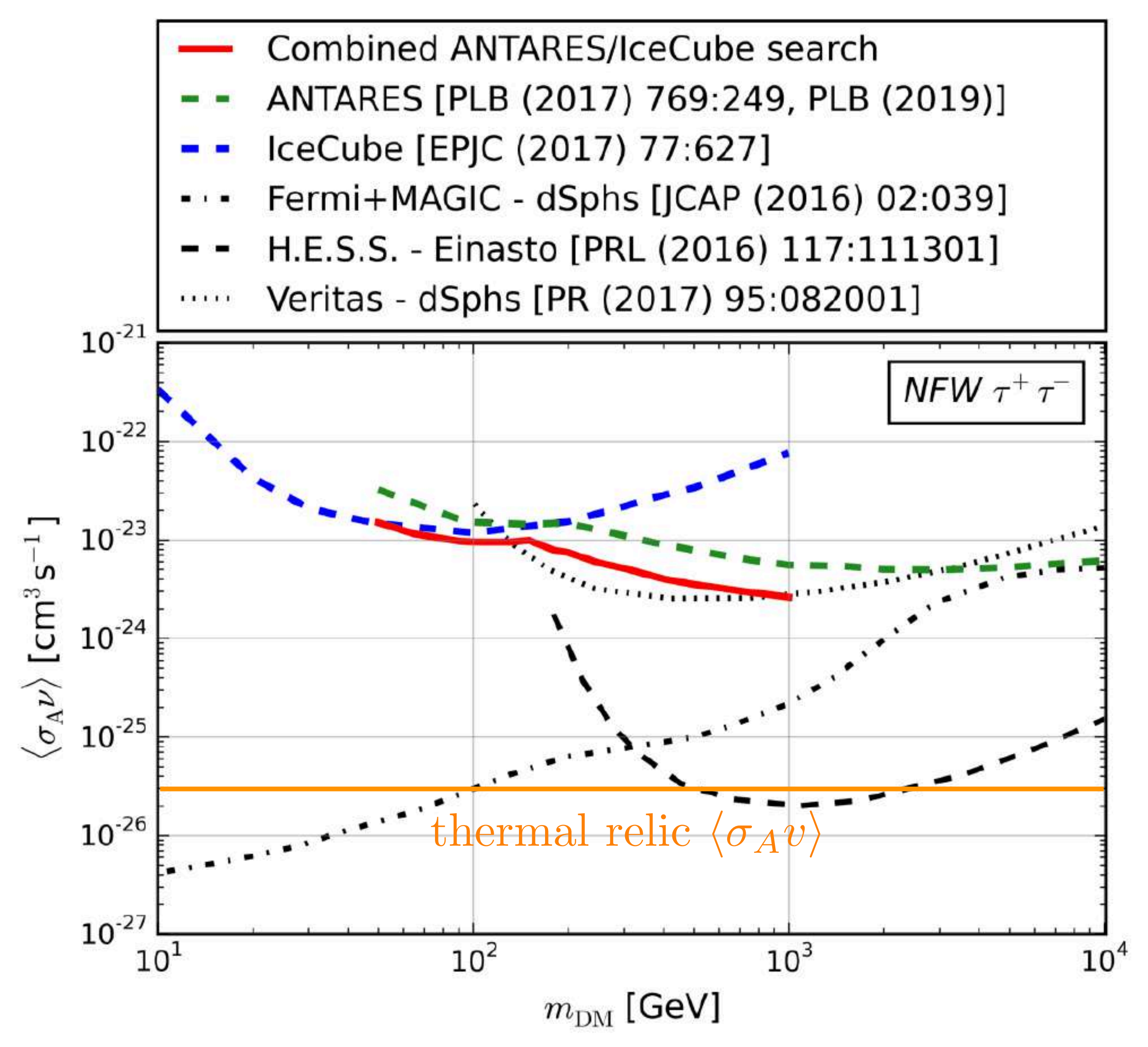
Indirect detection sensitivity: MW



MW center



$= \langle \sigma_A v \rangle$ DM annihilation cross section



Albert et al. (2020)

- MW DM density profile (NFW)

$$\rho_\chi(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1+\frac{r}{R_s}\right)^2}$$

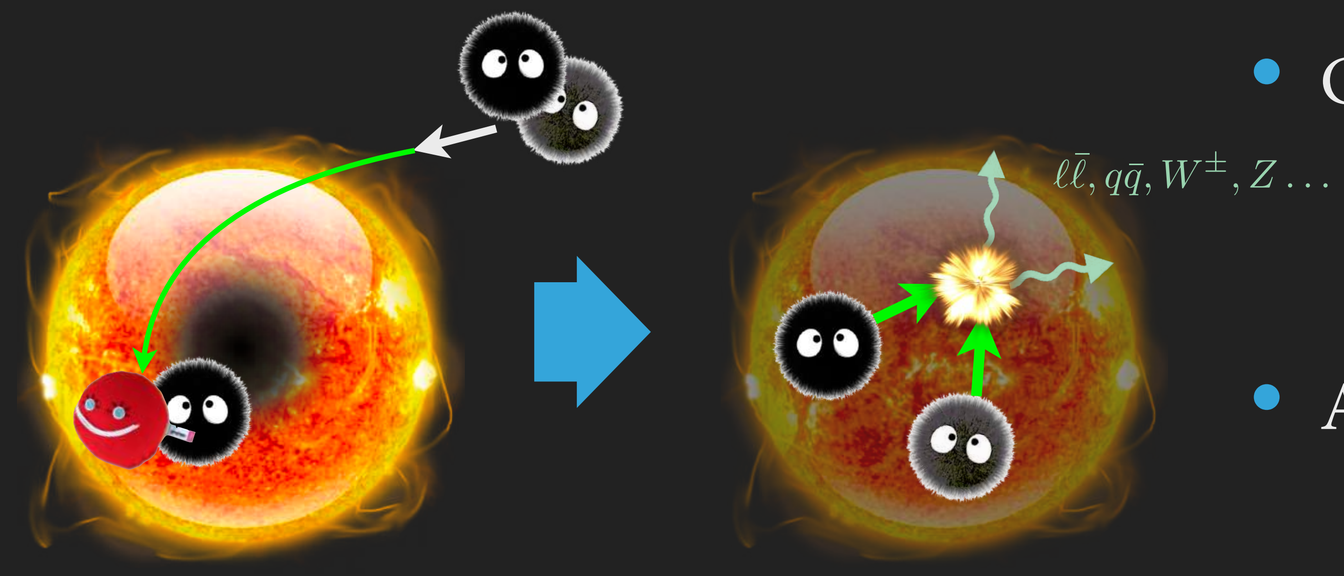
- The neutrino flux at the Earth generated from DM annihilation

$$\frac{d\Phi_{\nu_i}}{dE_{\nu_i}} = \frac{\Delta\Omega}{4\pi}\frac{\langle \sigma_A v \rangle}{2m_\chi^2}\sum_f B_f \frac{dN^f_{\nu_i}}{dE_{\ni i}} R_\odot \rho_\chi^2 \mathcal{J}_2(\Delta\Omega)$$

- Various annihilation channels are investigated with different detectors: $\ell\bar{\ell}, q\bar{q}, \gamma, W^\pm, Z \ldots$
- Nothing is found so far

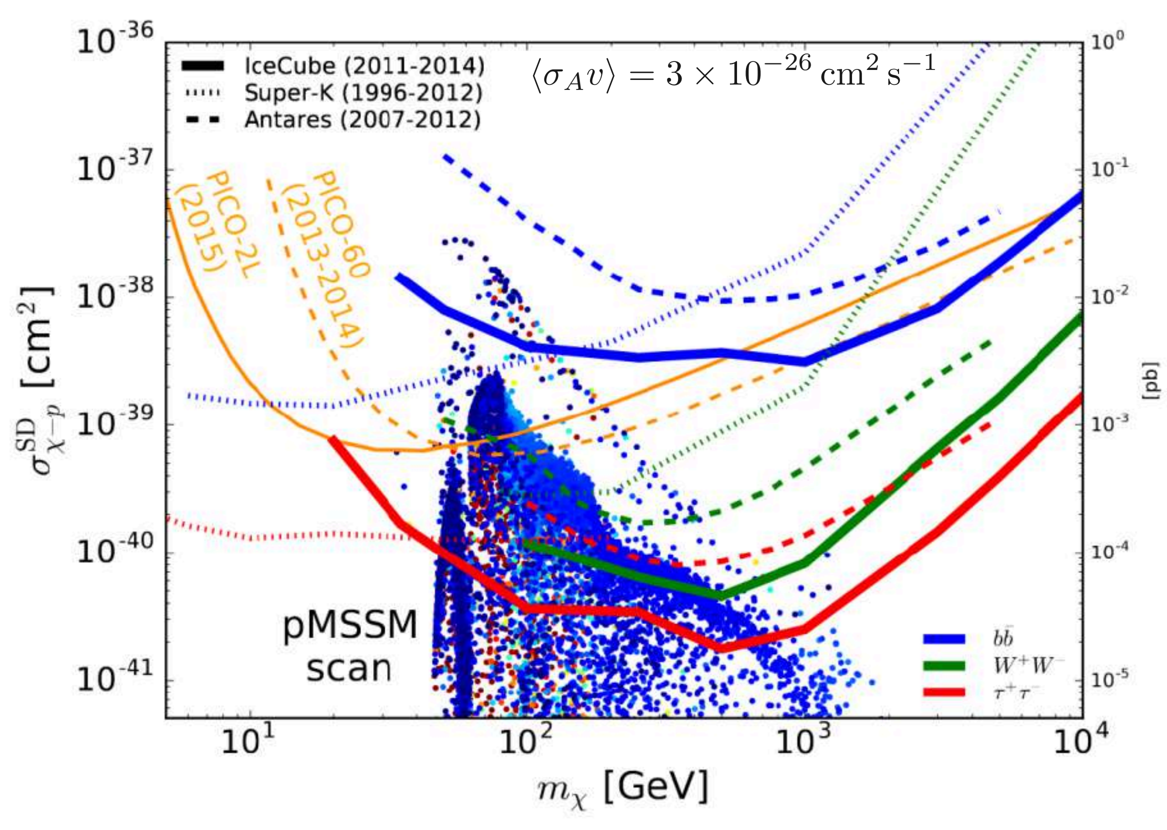
→ upper limit

Indirect detection sensitivity: Sun



Capture

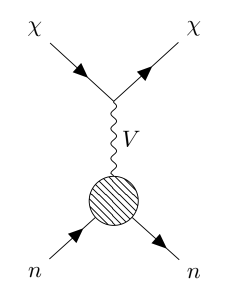
Annihilation



Aartsen et al. (2016)

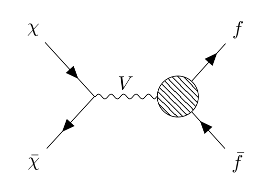
- Capture process: DM-nucleon scattering

$$C_c \propto \frac{\rho_\chi}{m_\chi}\frac{1}{\langle v_\chi \rangle}\sum_A F_A(m_\chi)\sigma_{\chi A}\frac{m_V^4}{(m_V^2+q^2)^2}$$



- Annihilation process: DM + antiDM

$$C_a = \langle \sigma_A v \rangle \frac{\int n_\chi^2(r)d^3r}{(\int n_\chi(r)d^3r)^2}$$



- Total of DM number N_χ in the Sun

$$\frac{dN_\chi}{dt} = C_c - C_a N_\chi^2 \rightarrow \boxed{\Gamma_A = \frac{1}{2}C_a N_\chi^2}$$

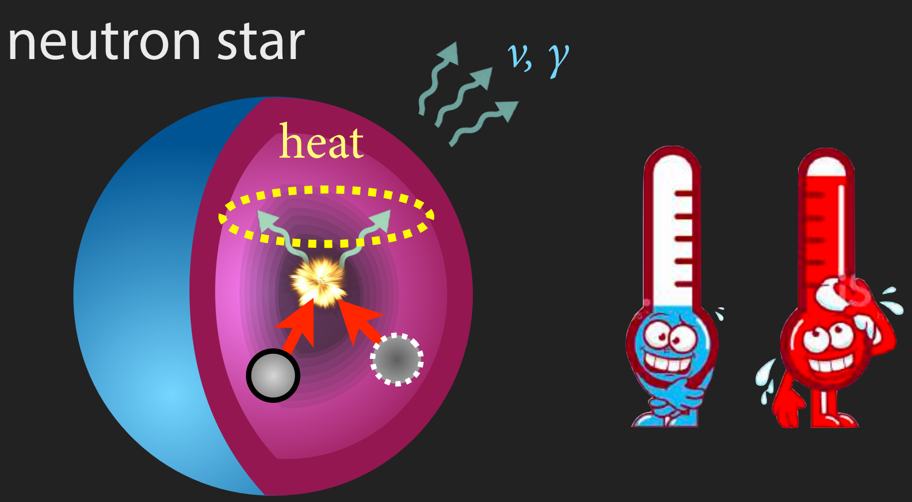
total annihilation rate

- The associated neutrino event N_ν at the detector

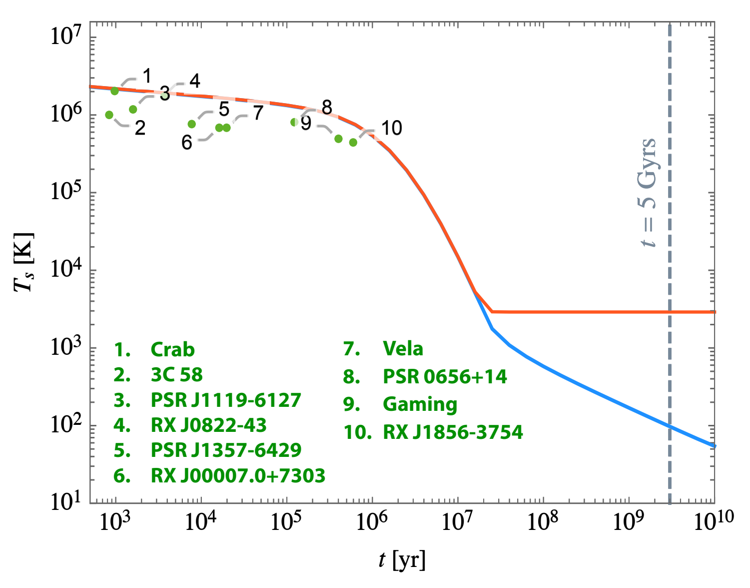
$$N_\nu = \int \frac{d\Phi_{\nu_i}(\Gamma_A)}{dE_{\nu_i}} A_\nu^{\rm eff}(E_\nu)dE_\nu$$

- Sun's advantage: it is sensitive to both
  - DM-nucleon cross section $\sigma_{\chi n}$
  - DM annihilation cross section $\langle \sigma_A v \rangle$

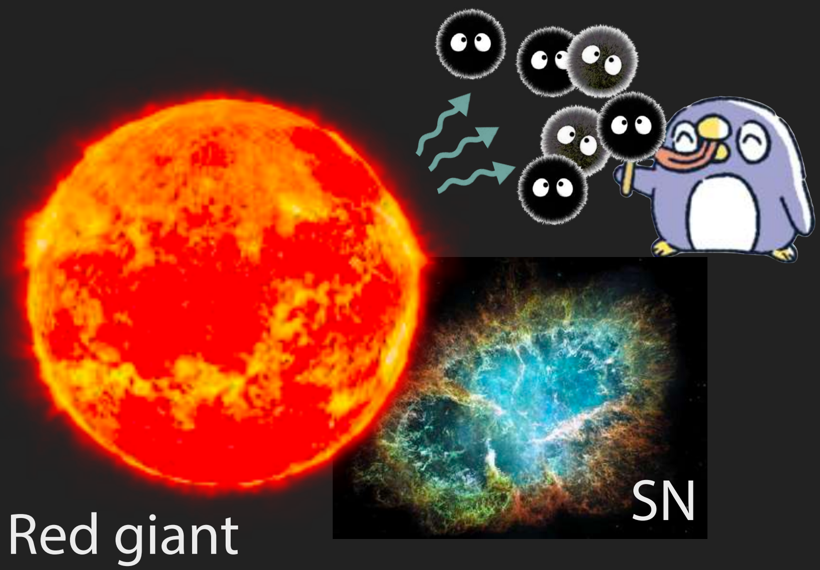
Other probes to the dark sector



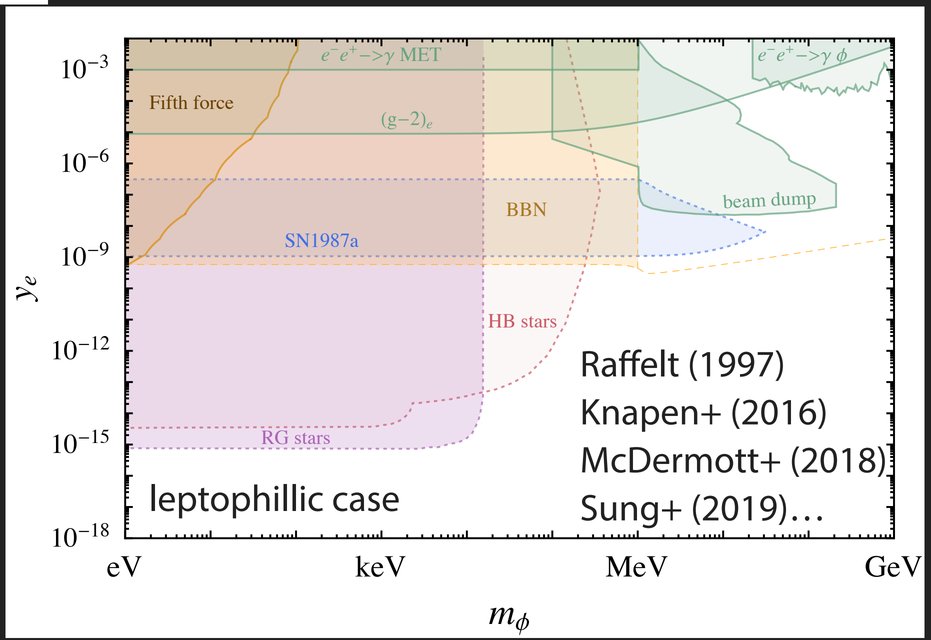
Kouvaris+ (2007), Lin+ (2021)…



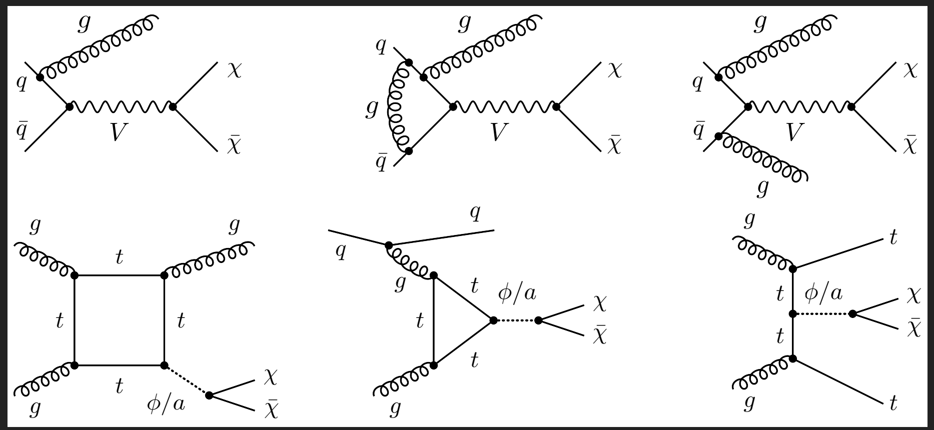
- Extra heating ϵ_χ generated via DM annihilation in the neutron star
- It could counterbalance the cooling of the star
- How strong the extra heating is that depends on the coupling strength between DM and SM



- Extra heat dissipation ϵ_χ' caused by dark particle emission
- DM could be produced along with neutrino during SN
- It dims the SN neutrino luminosity



Raffelt (1997)
Knapen+ (2016)
McDermott+ (2018)
Sung+ (2019)…

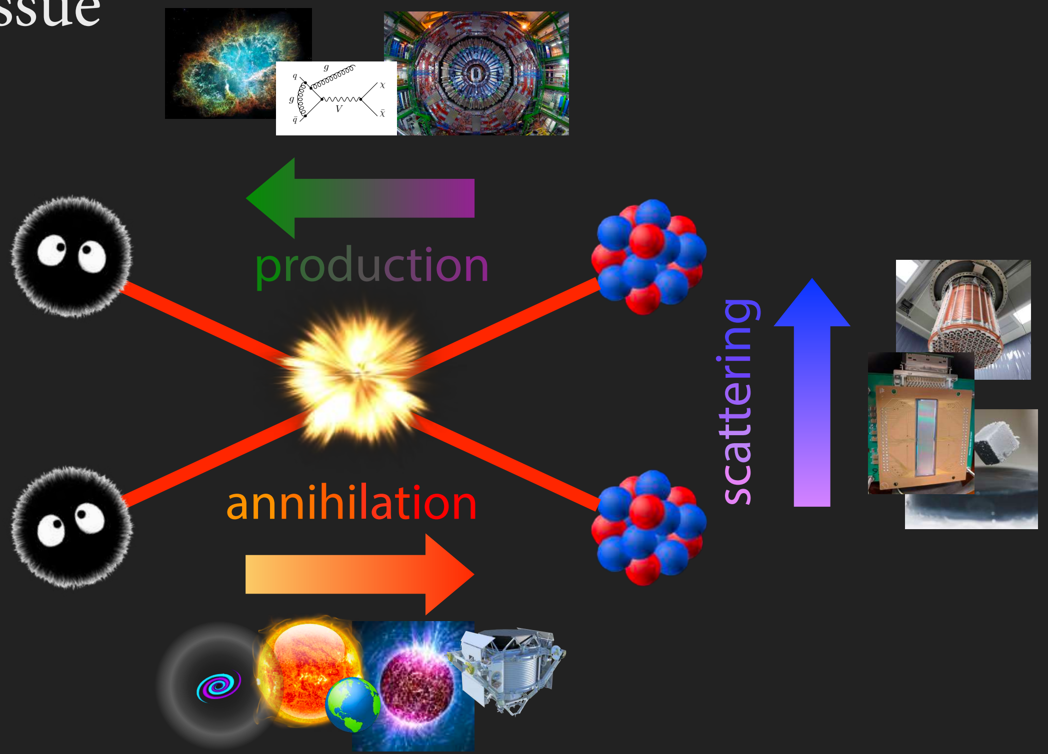


Abdallah et al. (2015)

- Create dark particles in the colliders, eg. LHC, Belle II…etc
- Searching missing momentum in mono-jet events

Brief summary

- Particle essence of DM is still elusive: knowledge in particle physics is inadequate
- Various ways to tackle this issue



- Not yet covered topics:
  - Axion-like DM: DM mass ~ eV and even much smaller
  - Non-annihilating DM: portal through decay or other effects?
  - DM self-interaction: Addressed by small-scale observation, any particle side implication?
  - What's the underlying theory? Too many now, none is proved correct
  - ……

Kouvaris+ (2011)
McDermott+ (2011)
Bramante+ (2013)
Ellis+ (2018)
Nelson+ (2019)
Gresham+ (2019)
Dasgupta+ (2020)
Lin+ (2020)
Bauswein+ (2021)
…