*HEP Seminar, CYCU, 2017/12/05*

# *Indirect Detection of Dark Matter through Neutrinos*


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*JCAP* **01**, 013 (2016)
*Phys.Rev. D* **91**, 033002 (2015)
*JCAP* **10**, 049 (2014)

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- **Part I**
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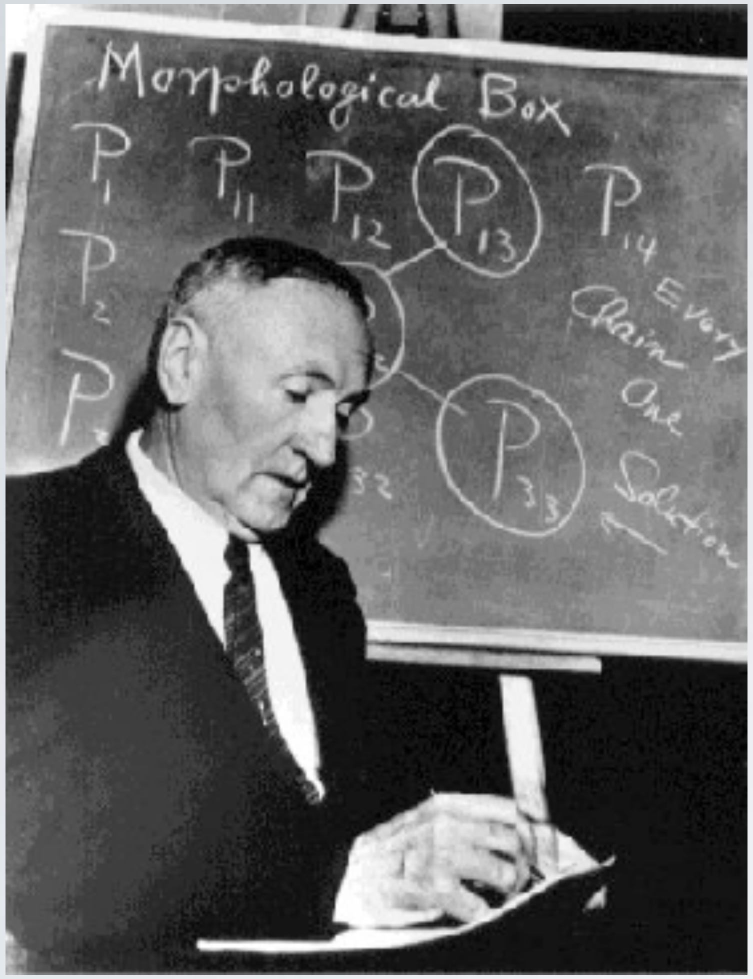
# Contents

# PART I

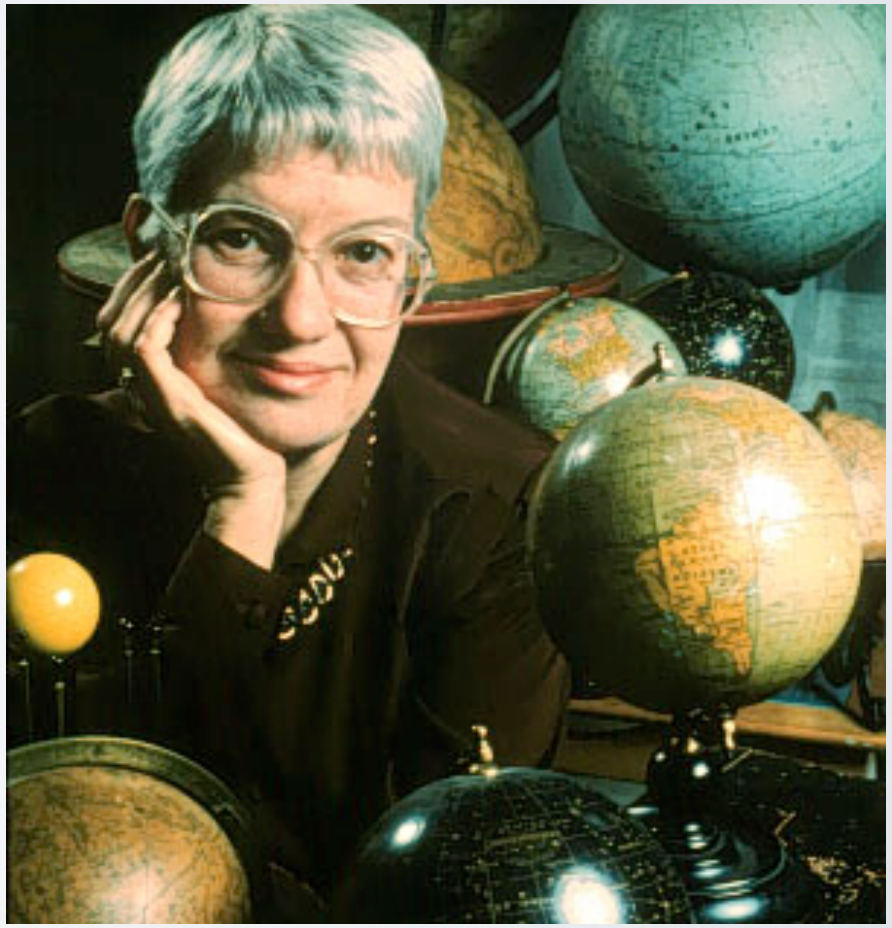
*Beneath the surface*


There is More Matter than the
Matter that Shines




***Fritz Zwicky*** (1898-1974)

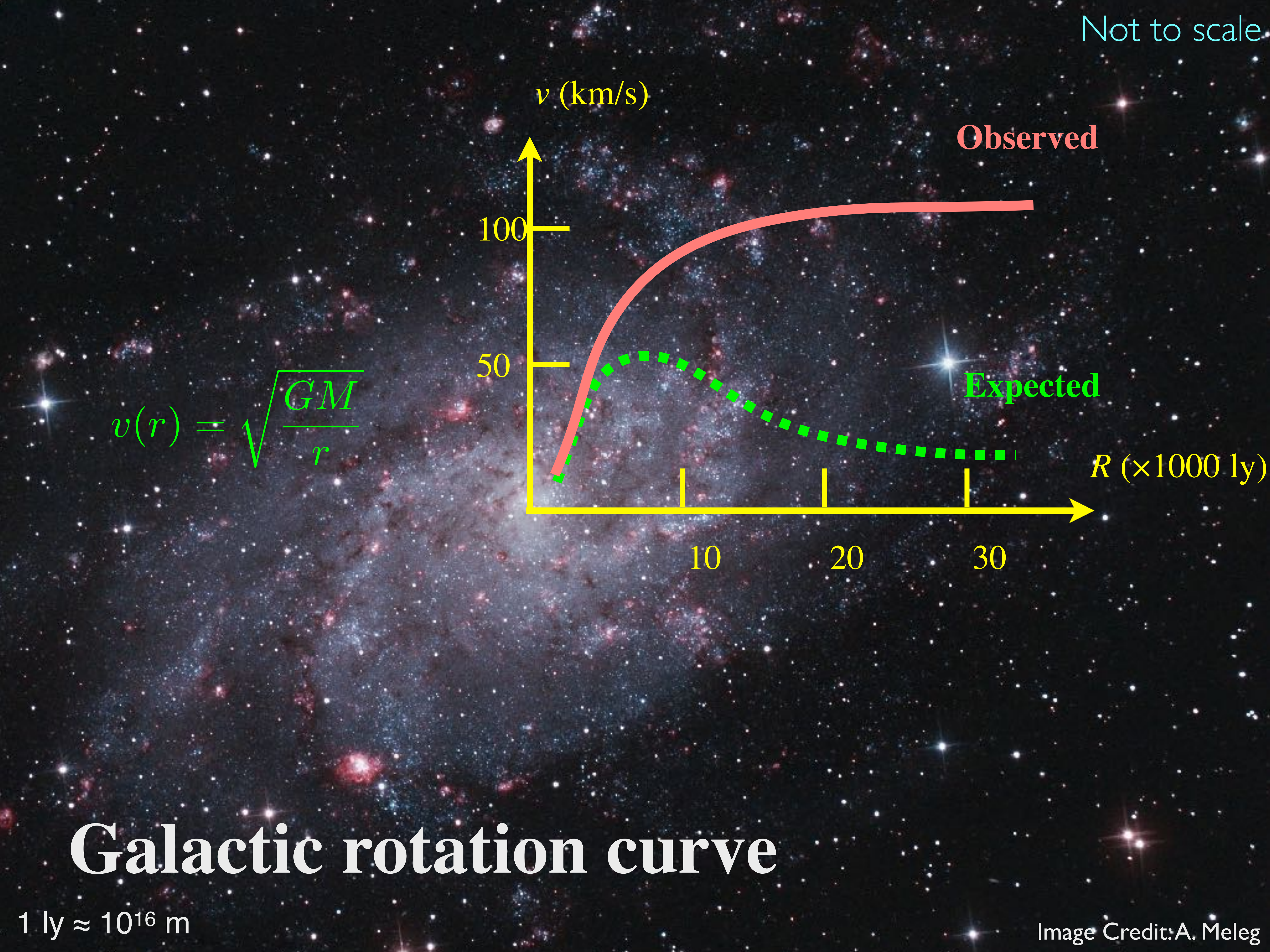
Unseen matter was inferred from the observation of the Coma Cluster in 1933. (*dunkle materie*)
The deduced gravitational mass of the cluster is 400 times greater than the expectation from their luminosity. Most of the matters must be dark.

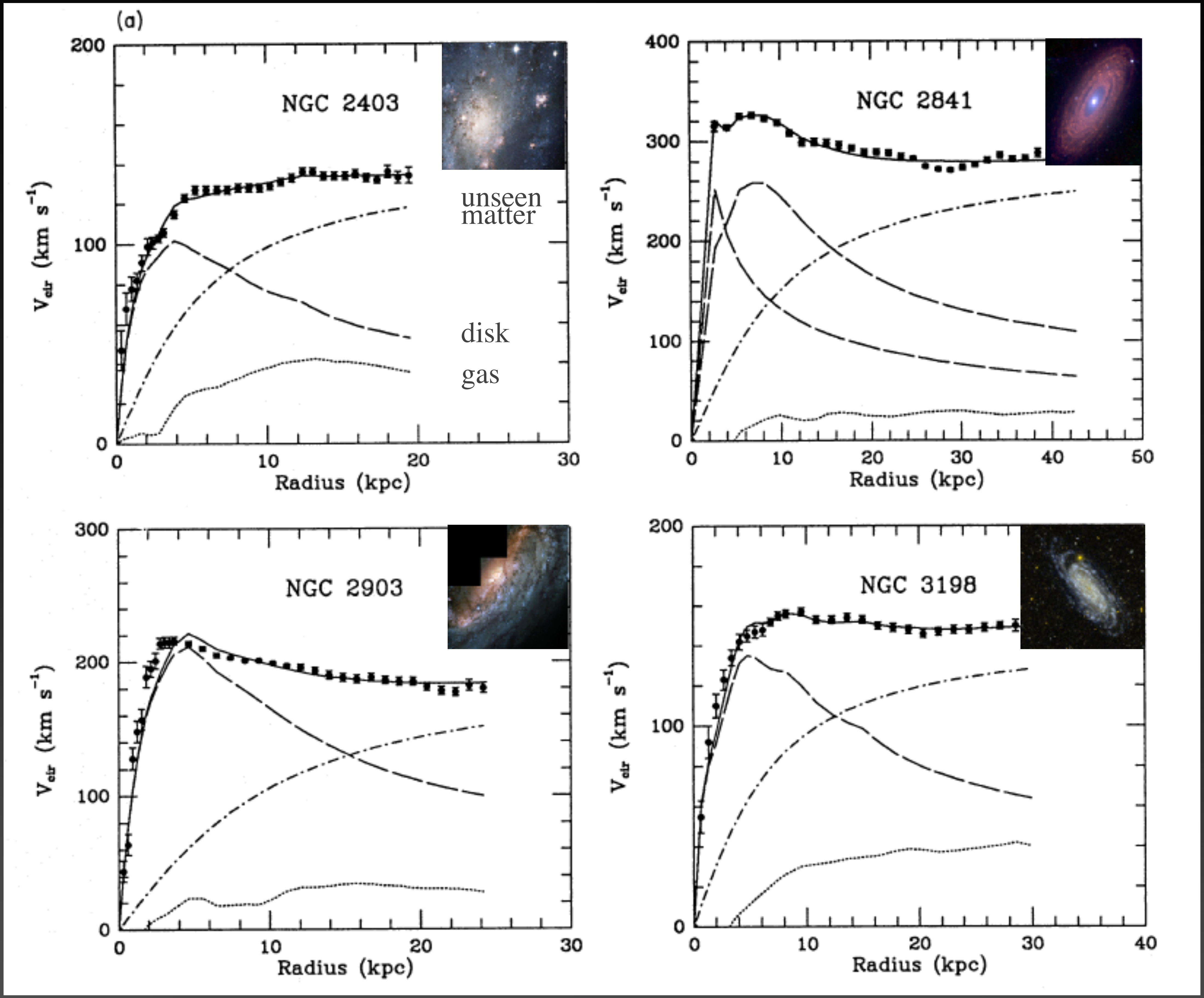


***Vera Rubin*** (1928-2016)

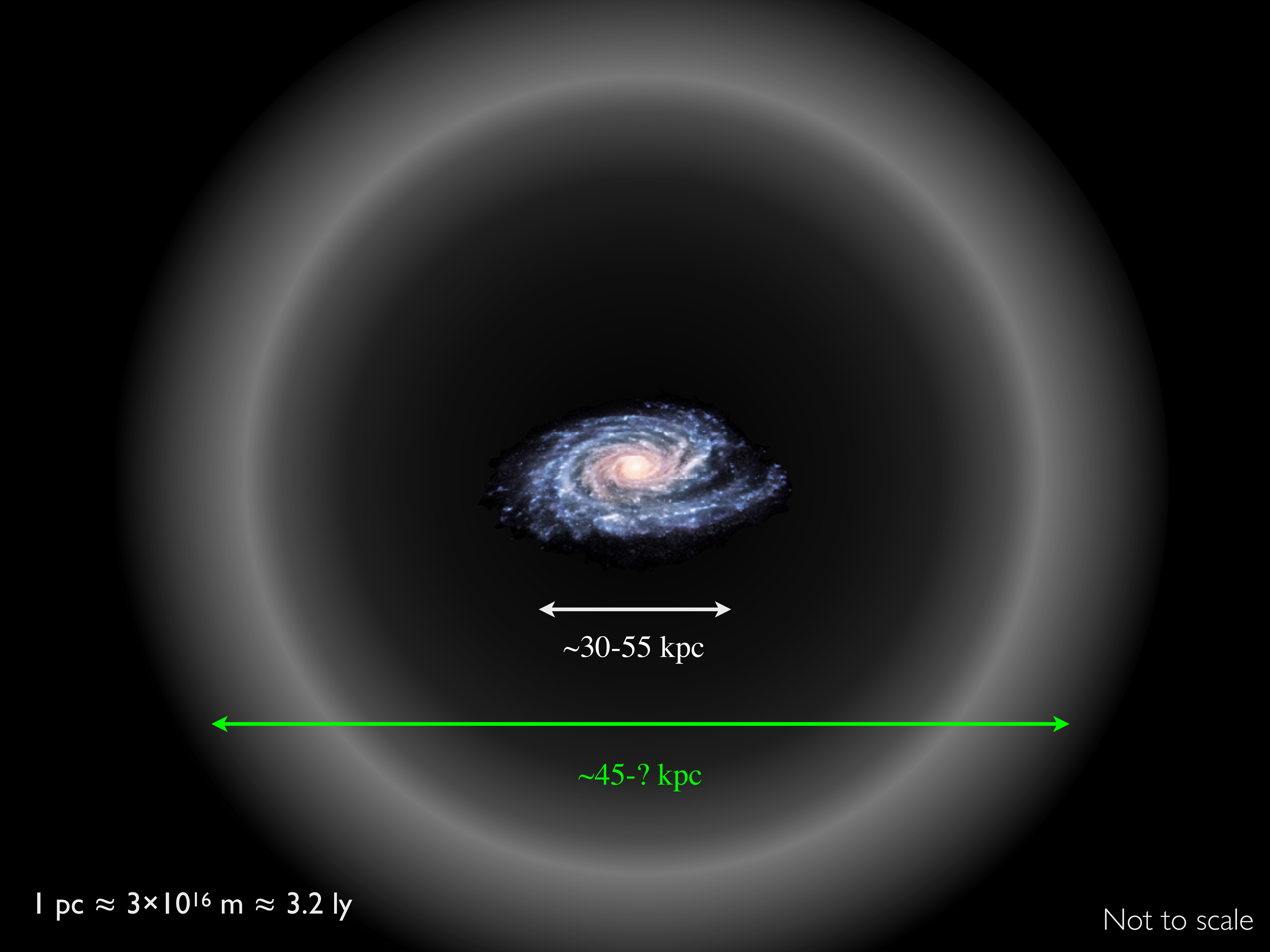
Together with her colleague Kent Ford, they discovered the most stars in spiral galaxies orbit at roughly the same speed. It implied that the galaxy masses grow approximately linearly with radius well beyond the location of most of the stars (galactic bulge).

F. Zwicky, *Astrophys. J.* **86**, 217 (1937)
V. Rubin *et al.*, *Astrophys. J.* **238**, 471 (1980)

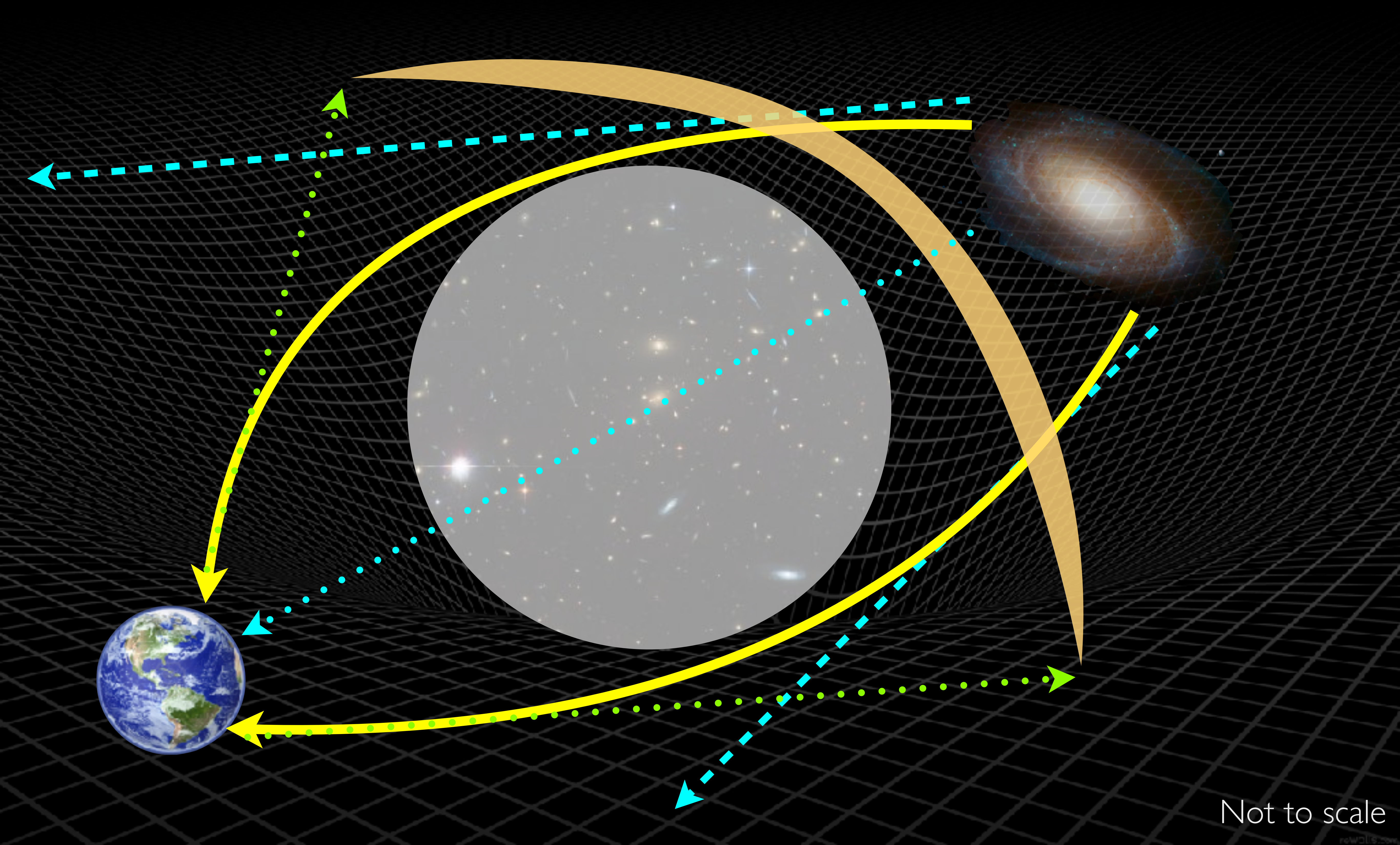

Not to scale
v (km/s)
Observed
100
50
Expected
$v(r) = \sqrt{\frac{GM}{r}}$
R (×1000 ly)
10
20
30
Galactic rotation curve
1 ly ≈ $10^{16}$ m
Image Credit: A. Meleg



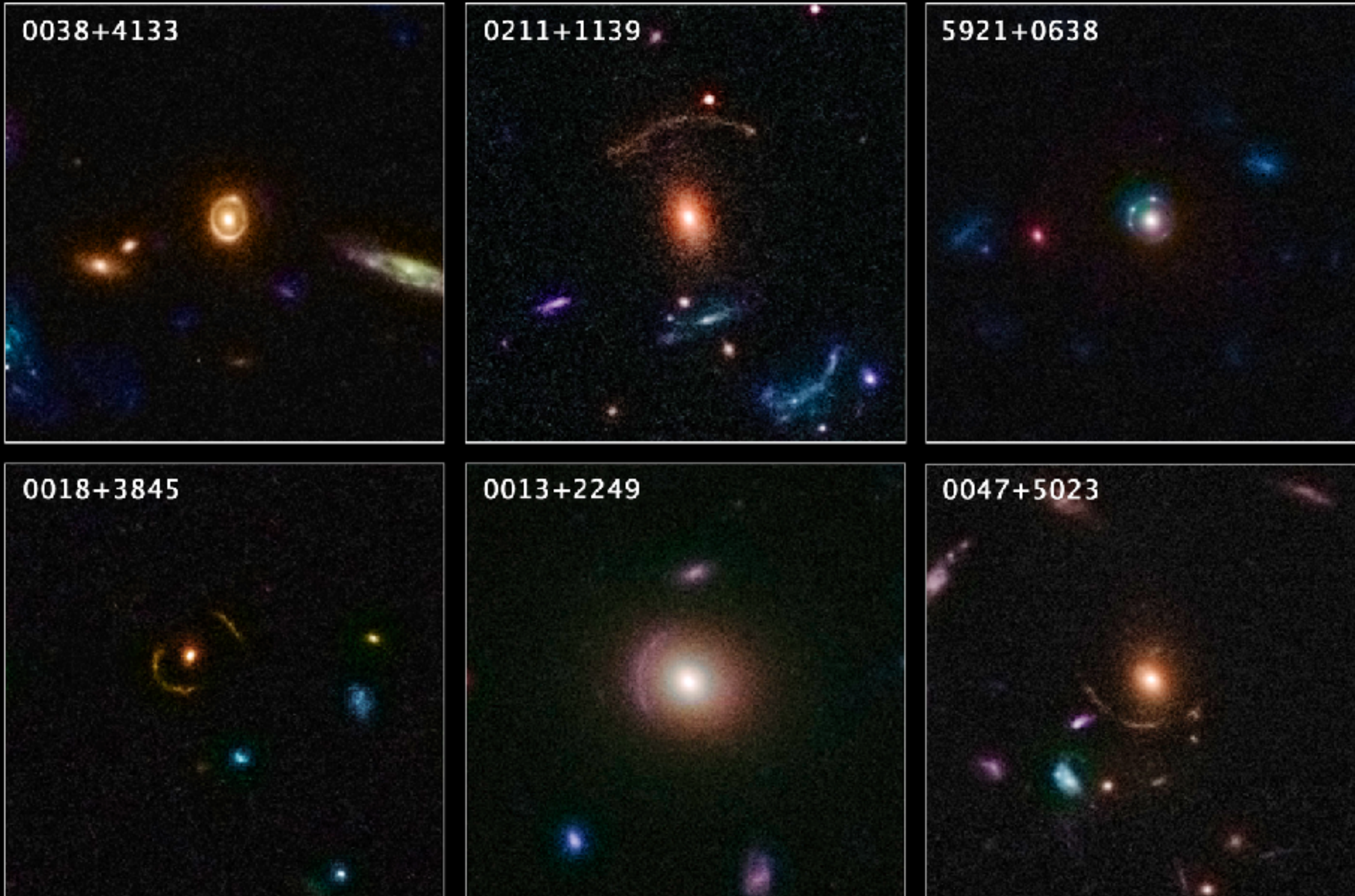

K. G. Begeman *et al.*, *MNRAS* **249**, 523 (1991); Image credit: NASA


~30-55 kpc
~45-? kpc
1 pc ≈ 3×10^16 m ≈ 3.2 ly
Not to scale

# Gravitational lensing



Not to scale



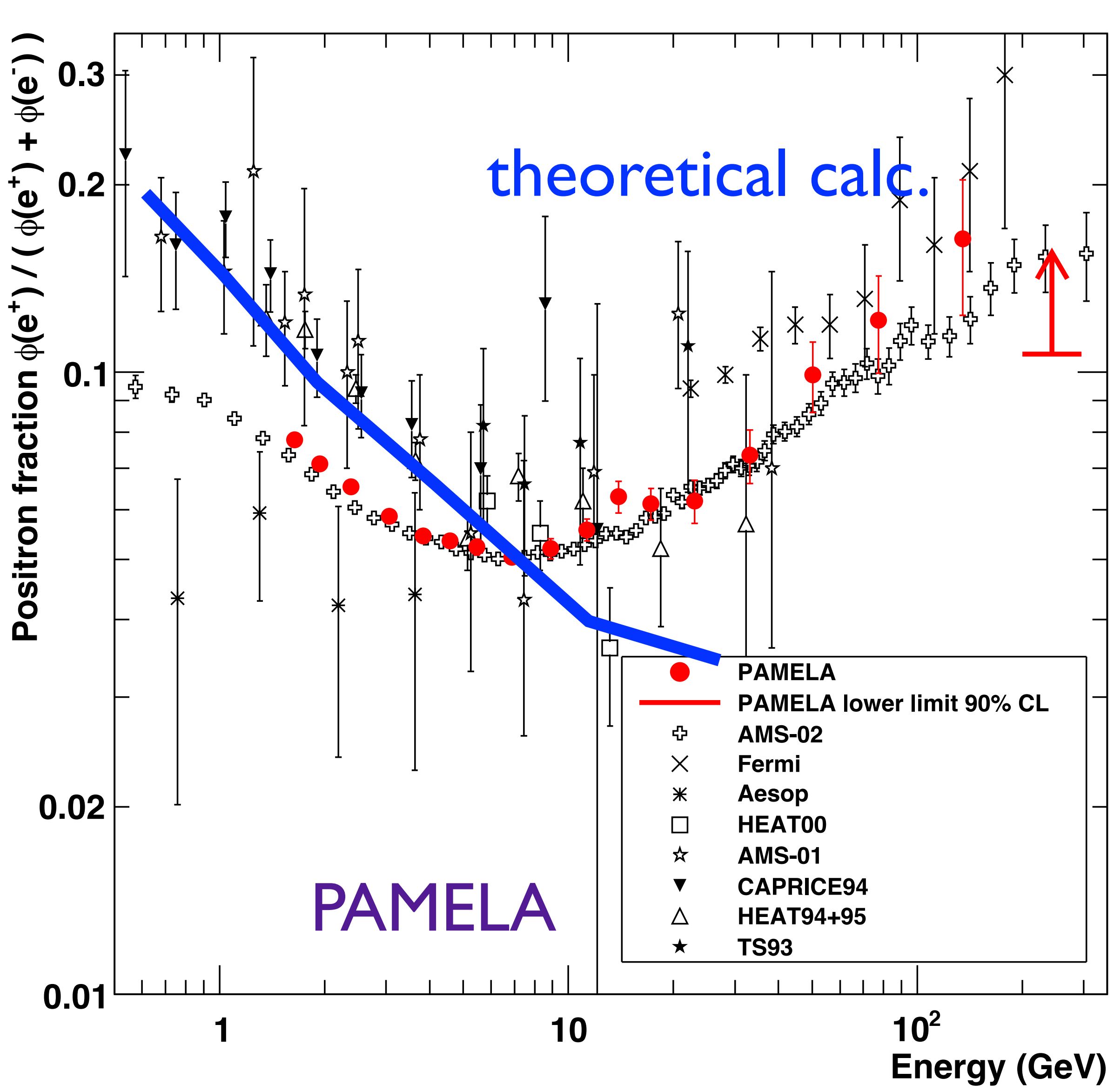

Gravitational Lenses in the COSMOS Survey
*Hubble Space Telescope* ▪ ACS/WFC

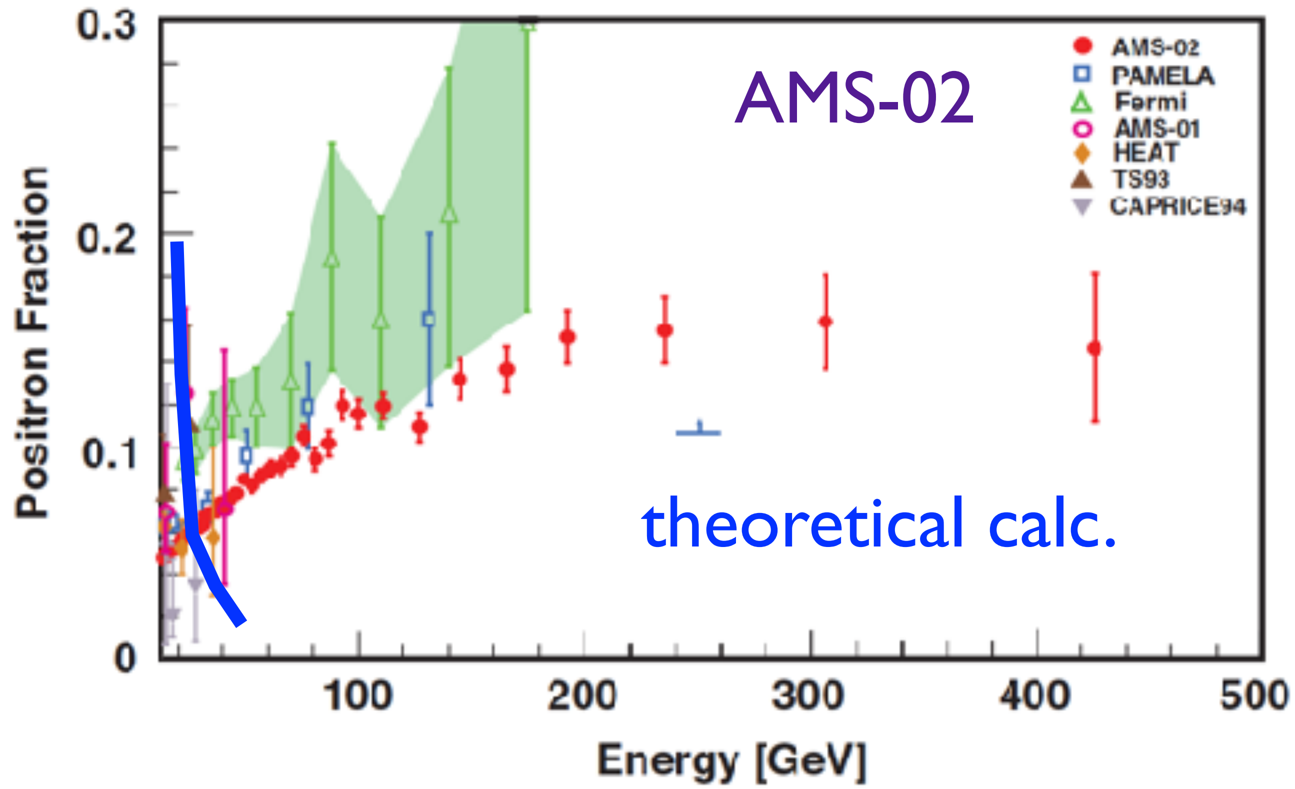
NASA, ESA, C. Faure (Zentrum für Astronomie, University of Heidelberg) and J.-P. Kneib (Laboratoire d'Astrophysique de Marseille)

STScI-PRC08-09

# Possible signatures from DM

O. Adriani *et al.* [PAMELA], *Phys. Rev. Lett.* **111**, 081102 (2013)



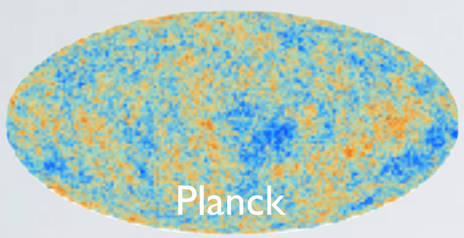



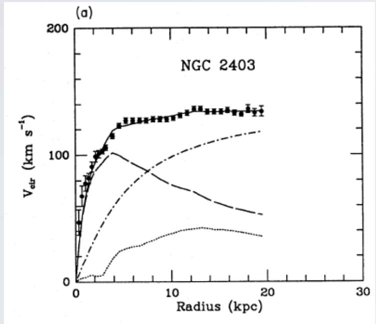

L. Accardo *et al.* [AMS02], *Phys. Rev. Lett.* **113**, 121101(2014)

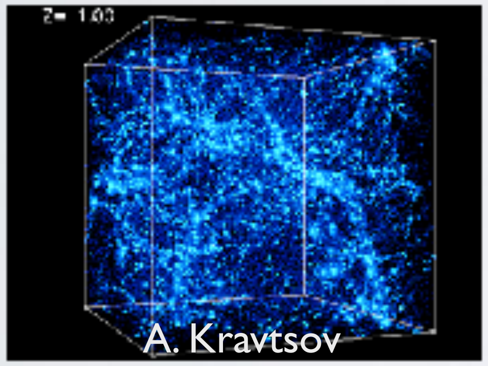
M. Aguilar *et al.* [AMS02], *Phys. Rev. Lett.* **110**, 141102 (2013)
M. Ackermann *et al.* [Fermi], *Phys. Rev. Lett.* **108**, 011103 (2012)
J. Alcaraz *et al.* [AMS], *Phys. Lett. B* **484**, 10 (2000)
and references therein…

# DM at all scales

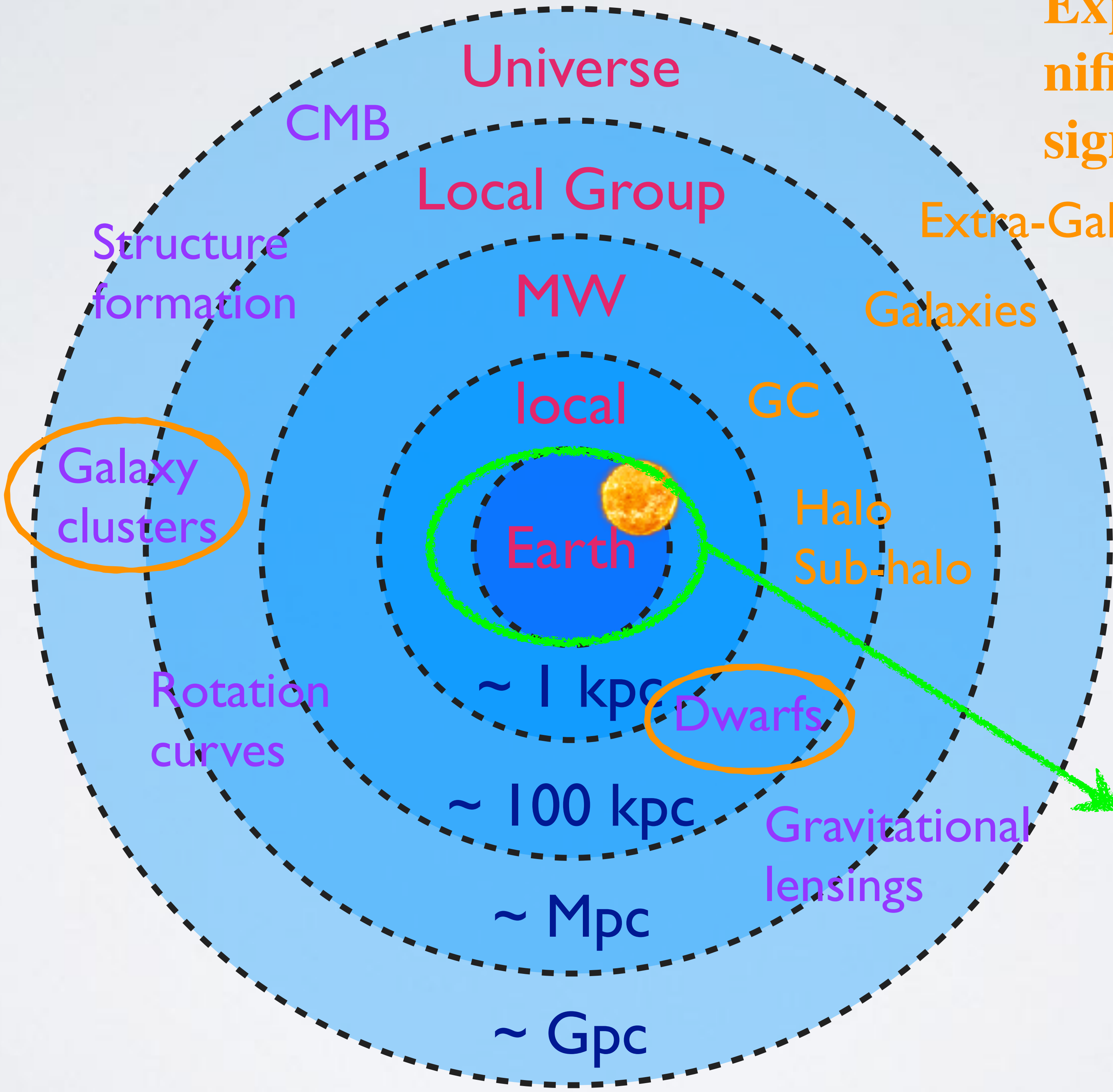
Evidences








**Expected to have significant annihilation signals**

**Our primary concern in this presentation!**

# Elusive Nature of Dark Matter

# Ideas about dark matter

- Basic ideas: Stable, abundant and neutral
- Five times as prevalent as ordinary matter ($\Omega_\chi \approx 0.26$)
- Thermal relic annihilation cross section $\langle \sigma v \rangle = 3\times10^{-26}\ \mathrm{cm^3\ s^{-1}}$
- Moving with non-relativistic velocity (cold) and collisionless among themselves (CCDM)

# Observations vs. simulations

- Simulation inputs:
  - Non-relativistic (cold)
  - Collisionless particles

  } Outcome agrees with large scale structure!

- However, in the small-scale structure:
  - Halo with too cuspy core density  Core-vs-cusp problem
  - Too many satellite galaxies  Missing satellites problem
  - Too massive subhalos  Too-big-to-fail problem

# Resolving the small-scale problems

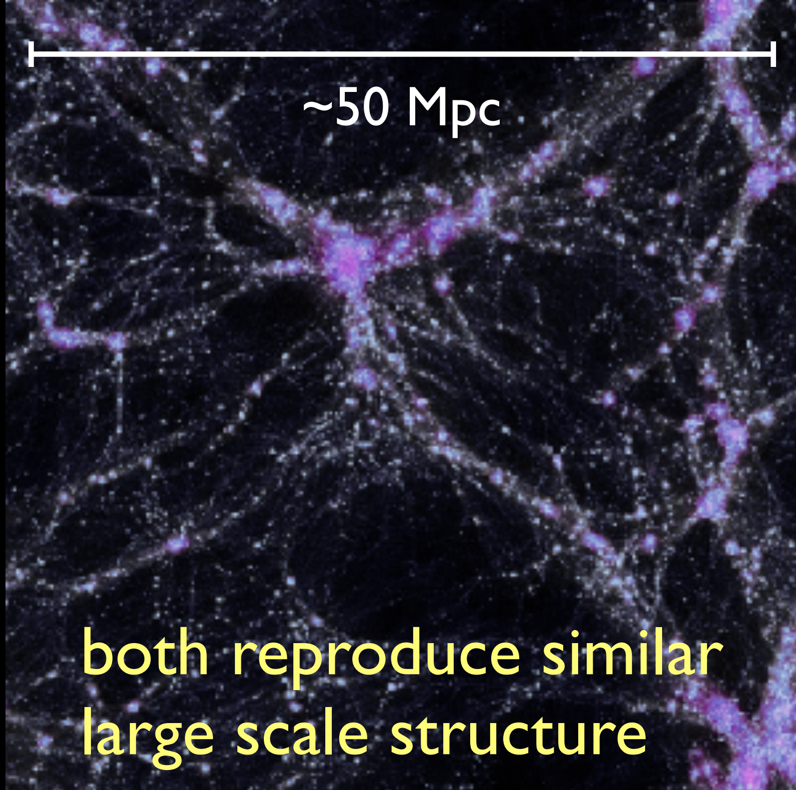

- Introducing the self-interacting DM (SIDM)
- Energy can be transported to the outer halo
- DM does not always sink in the galactic center
- All three difficulties between the simulations and observations can at least be alleviated (not eliminated)

D. N. Spergel *et al.*, *Phys. Rev. Lett.* **84**, 3760 (2000)

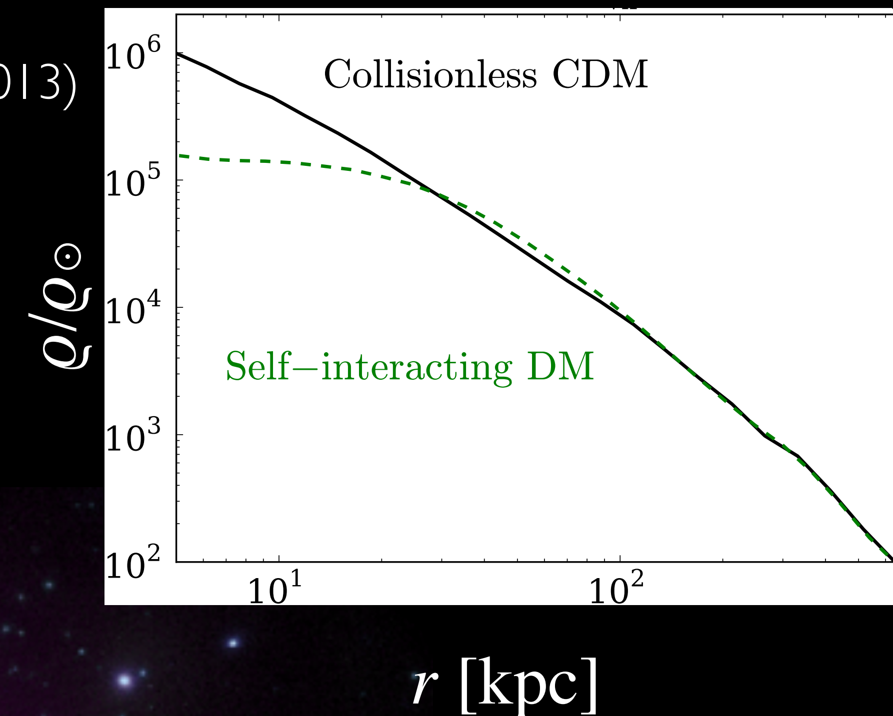
# Alleviating the small-scale problem

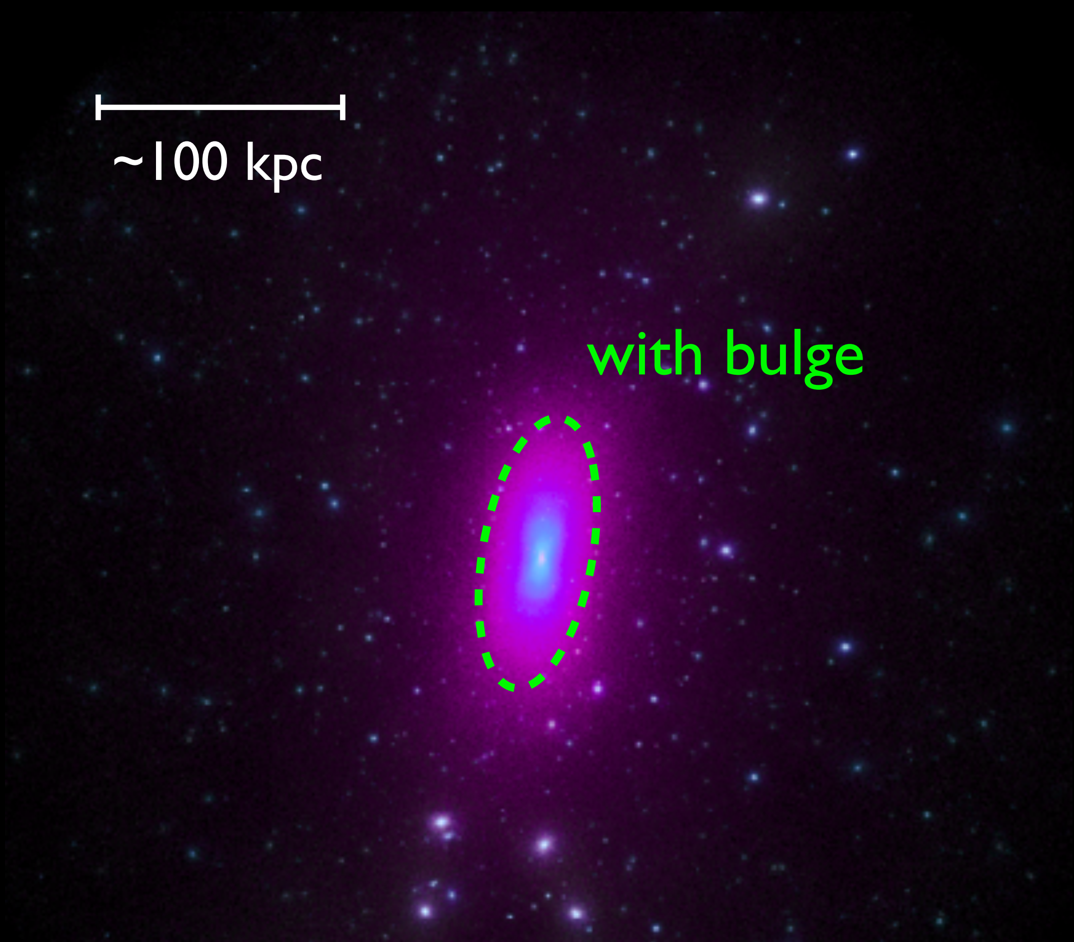
## Core-vs-cusp as an example

M. Rocha *et al.*, *MNRAS* **430**, 81 (2013)
D. H. Weinberg *et al.*, arXiv: 1306.0913 (2013)

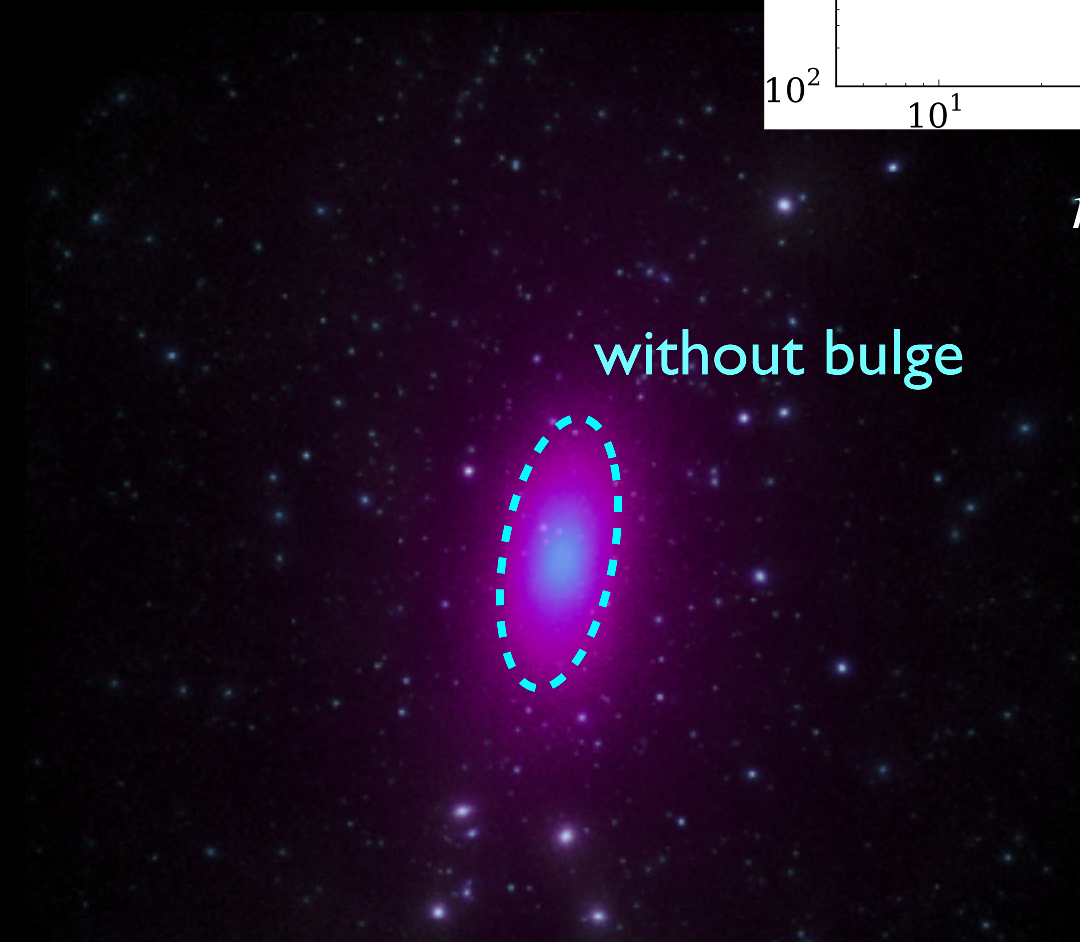



$M_{tot} = 4.2\times10^{13}\ M_\odot$



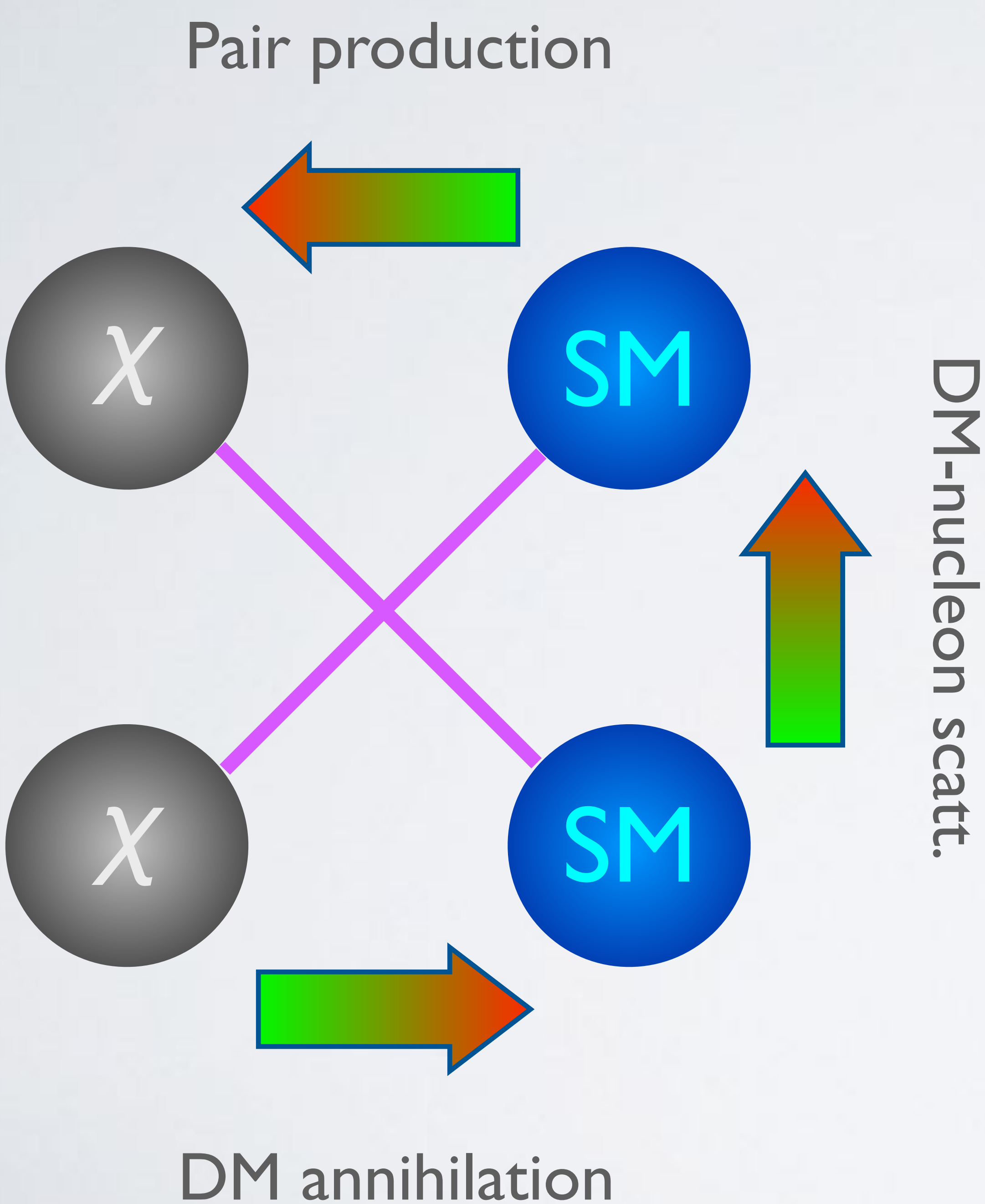




Collisionless DM

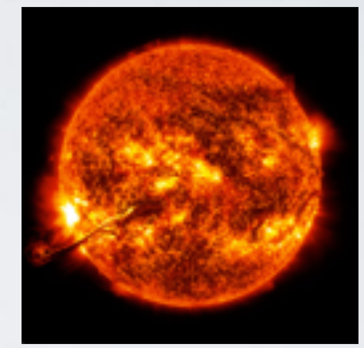



Self-interacting DM: $\sigma_{\chi\chi}/m_\chi \simeq 1$ g cm$^{-3}$

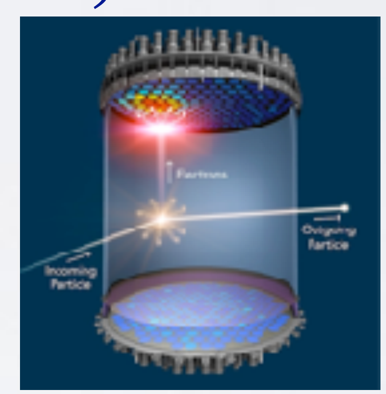
# Possible ways to identify DM



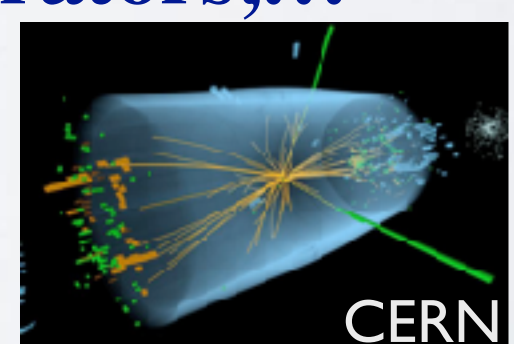

**G.C., Sun, stellar objects,…**



**LUX, XENON, CDMS, DAMA,…**

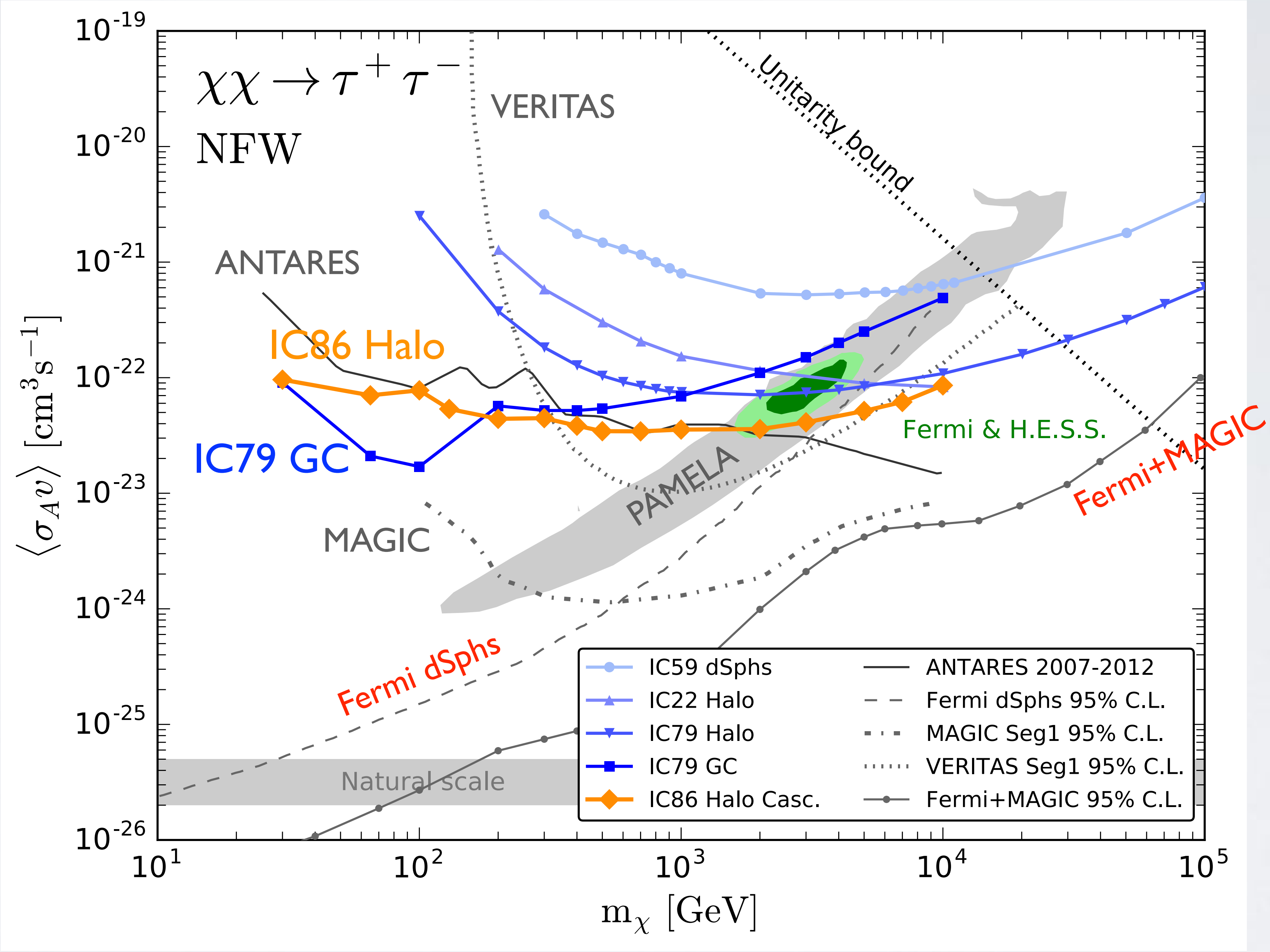



**LHC, Accelerators,…**

M. G. Aartsen *et al.* [IceCube], arXiv: 1606.00209 (2016)

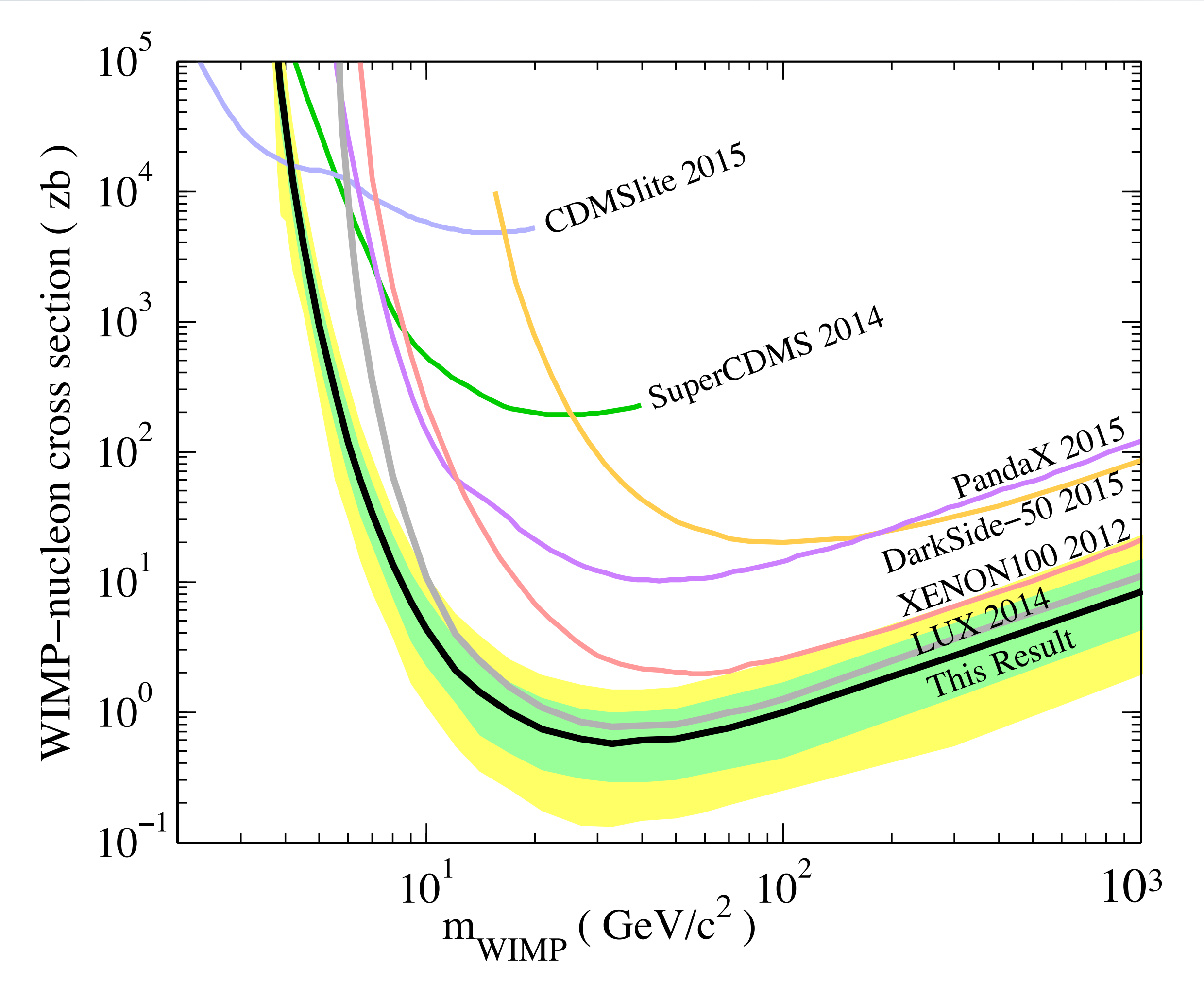
# Indirect search constraint: $\langle \sigma_A v \rangle$

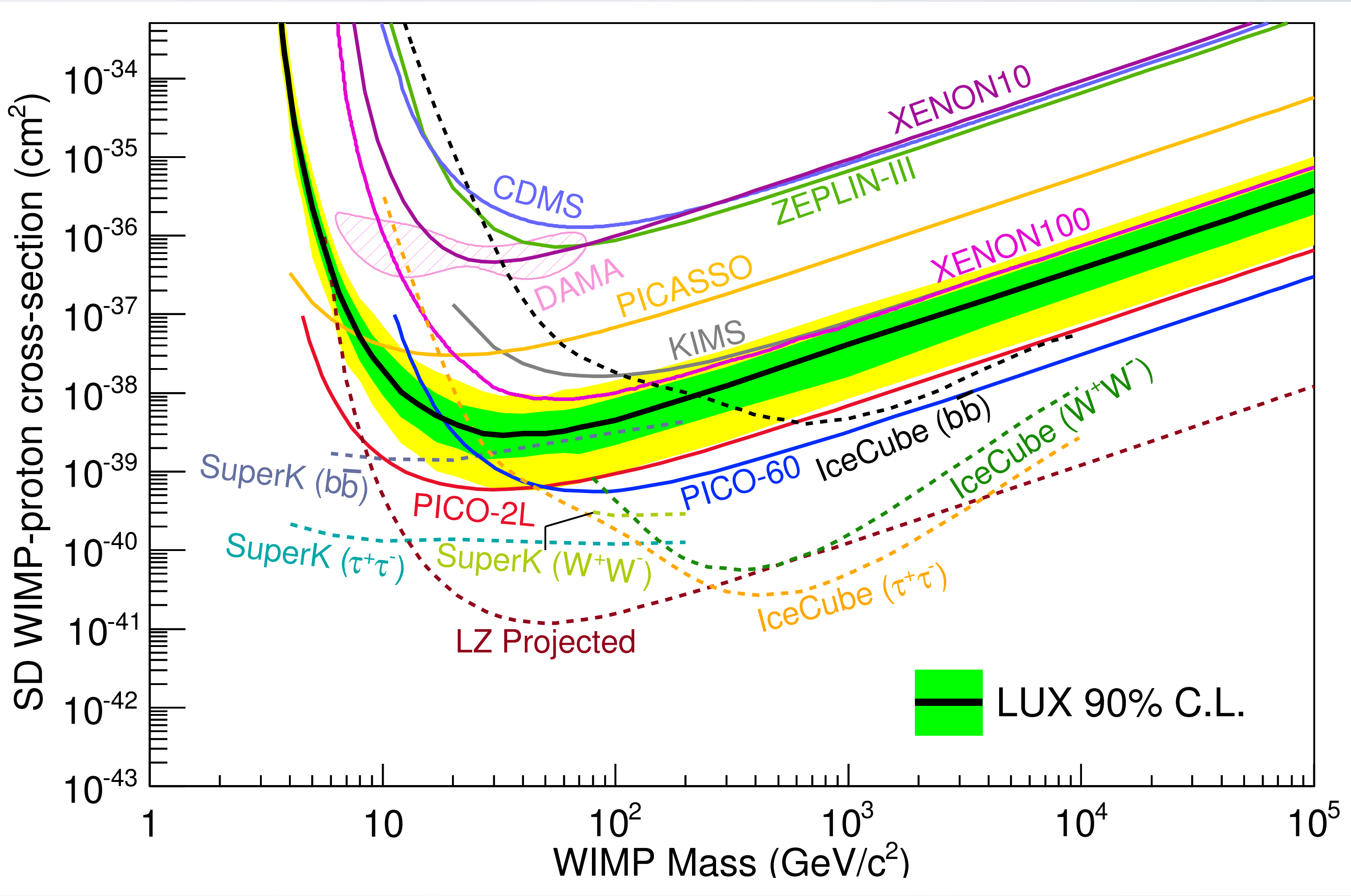




S. Adrián-Martínez *et al.* [ANTARES], *JCAP* **10**, 068 (2015)
R. Abbasi *et al.* [IceCube], *Rhys. Rev. D* **84**, 022004 (2011)
M. G. Aartsen *et al.* [IceCube], *Eur. Phys. J. C* **75**, 20 (2015)
M. G. Aartsen *et al.* [IceCube], *Phys. Rev. D* **88**, 122001 (2013)
M. G. Aartsen *et al.* [IceCube], *Eur. Phys. J. C* **75**, 10 (2015)
M. Ackermann *et al.* [Fermi], *Phys. Rev. D* **89**, 042001 (2014)
J. Aleksić *et al.* [MAGIC], *JCAP* **02**, 008 (2014)
E. Aliu *et al.* [VERITAS], *Phys. Rev. D* **85**, 062001 (2015)
P. Meade *et al.*, *Nucl. Phys. B* **831**, 178 (2010)

# Direct search constraint: $\sigma_{\chi\text{-nucleon}}$



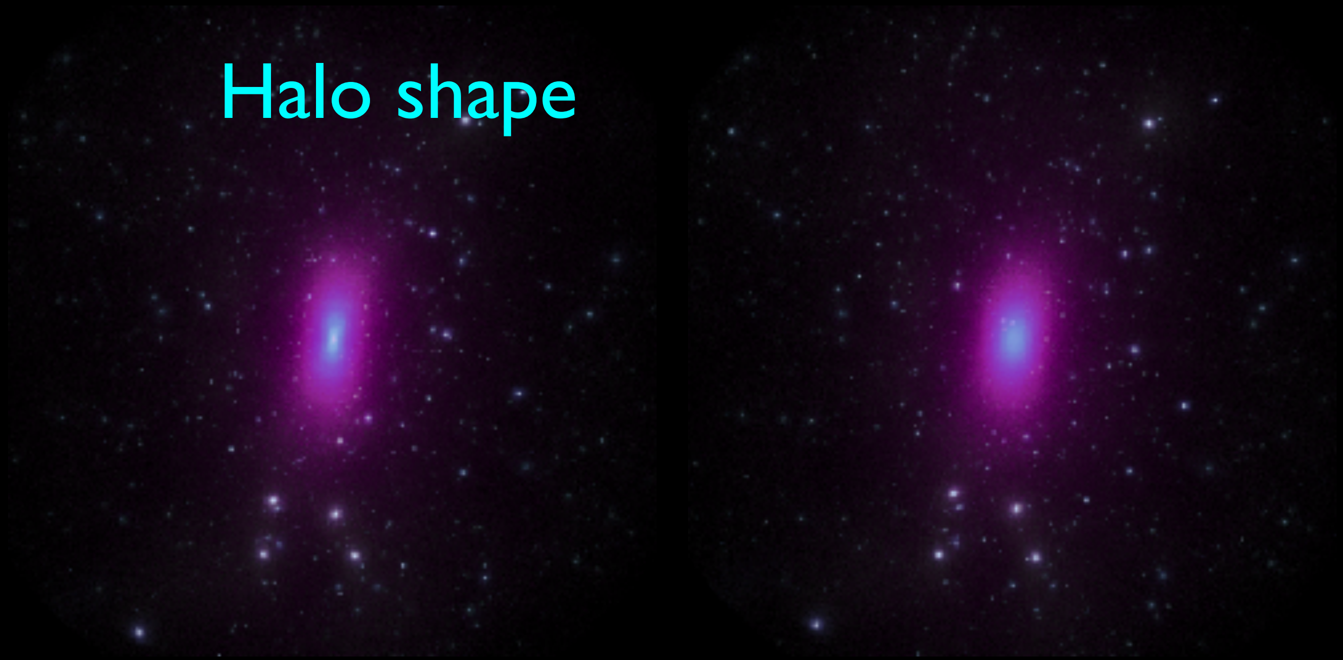

spin-independent

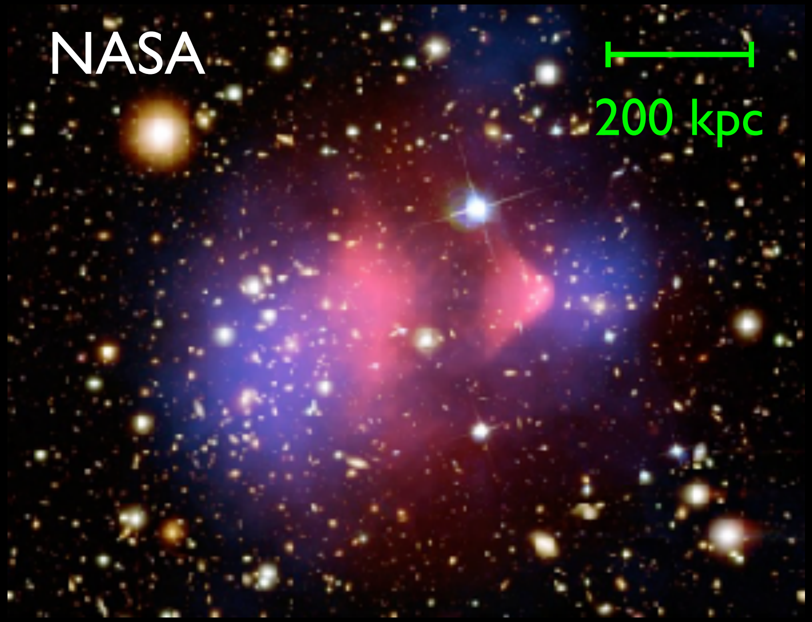
spin-dependent

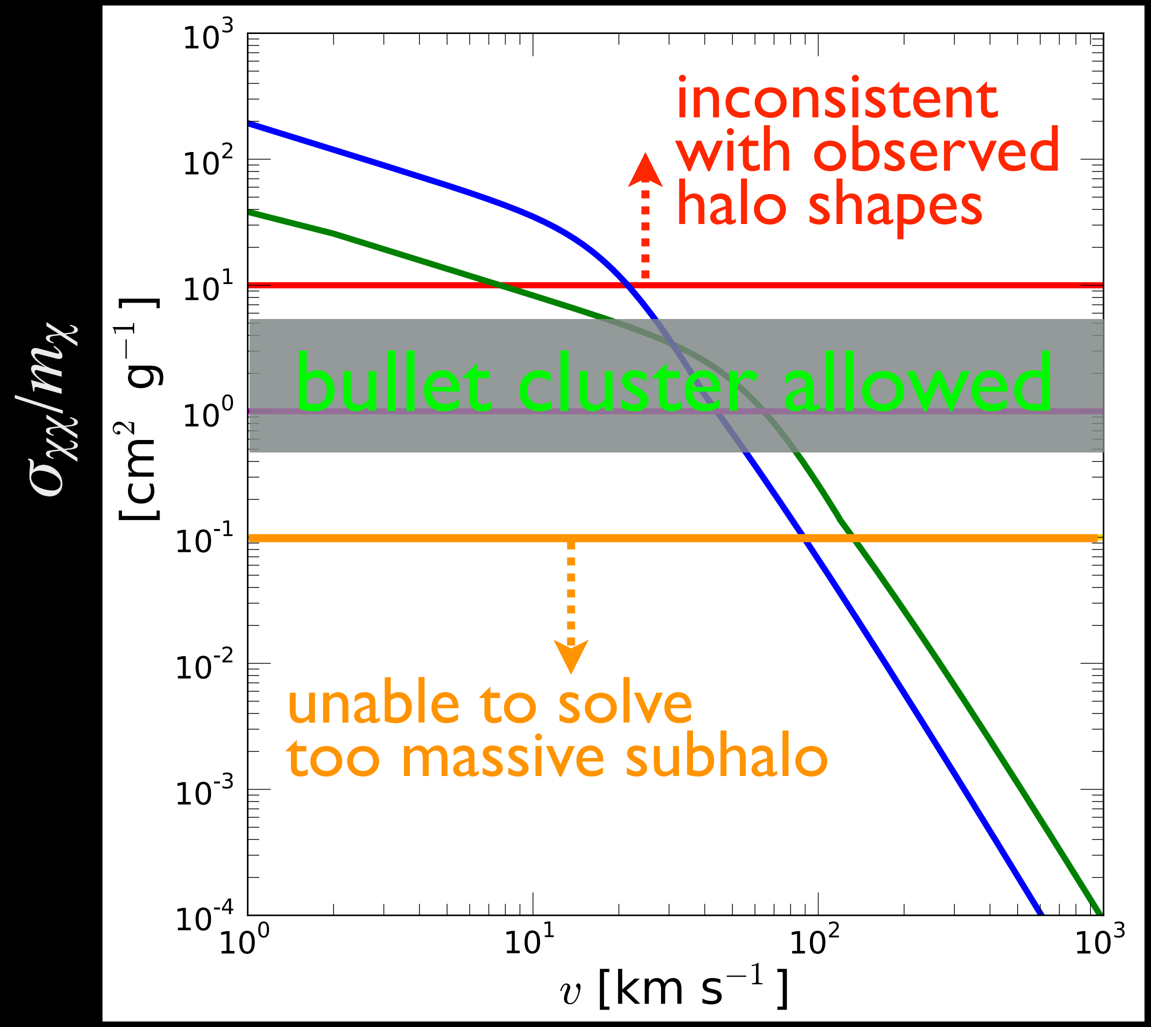

D. S. Akerib *et al.* [LUX], *Phys. Rev. Lett.* **116**, 161301 (2016)
D. S. Akerib *et al.* [LUX], *Phys. Rev. Lett.* **116**, 161302 (2016)
CMS, *Eur. Phys. J. C* **75**, 235 (2015)
S. A. Malik *et al.*, *Phys. Dark Univ.* **9-10**, 51 (2015)
O. Buchmueller *et al.*, *JHEP* **01**, 037 (2015)

M. Rocha *et al.*, *MNRAS* **430**, 81 (2013)
J. Zavala *et al.*, *MNRAS* **431**, L20 (2012)
S.W. Randall *et al.*, *Astrophys. J.* **679**, 1173 (2008)
D. Clowe *et al.*, *Astrophys. J.* **648**, L109 (2006)

# Constraint: $\sigma_{XX}$




Indirect search also has the capability to probe DM self-interaction!

# Connection to the DM searches

- DM annihilation to SM particles

  *Indirect DM search*

- DM-nucleus scattering

  Direct and *indirect DM searches*

- DM-DM scattering

  *Indirect DM search*

- DM pair production

  LHC search

Indirect search can provide sensitivity at ***high*** and ***low*** masses regions as well as the capability to probe $\sigma_{\chi\chi}$

# Brief summary for PART I

- Observational evidences are introduced
- Discrepancies between the observations and simulations
- Resolving the discrepancies: DM self-interaction
- Possible ways to identify DM
- Constraints on cross sections: $\sigma_{\chi\chi}$, $\sigma_{\chi p}$ and $\langle\sigma_A v\rangle$

# Contents

- **Part I**
  - History, observational evidences and experimental constraints
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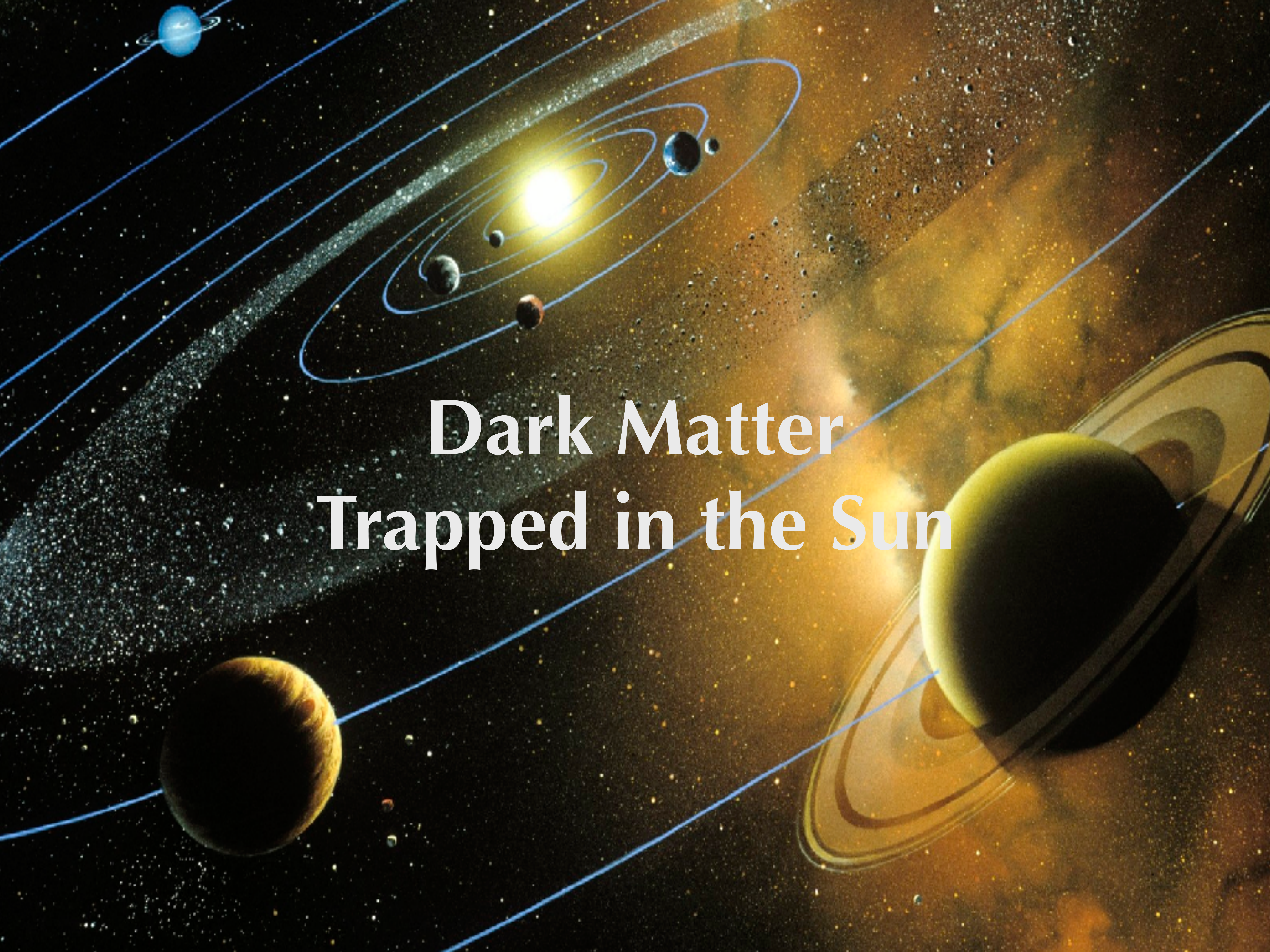
  - Overall summary

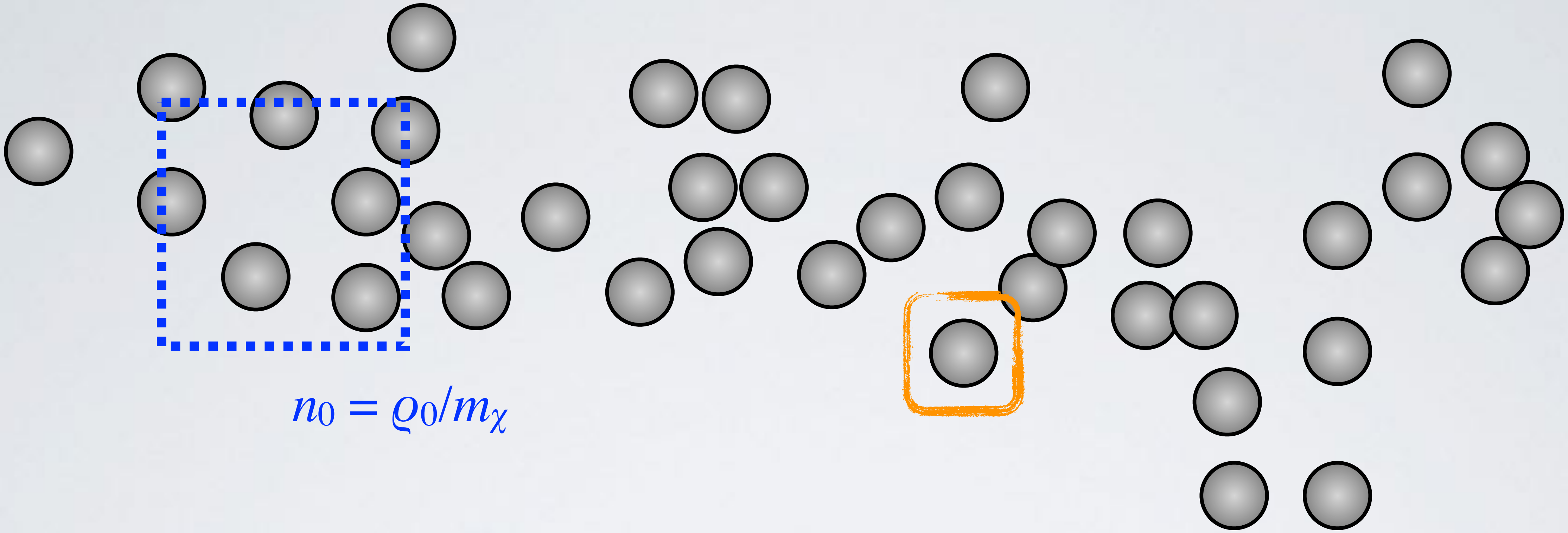
# Part II

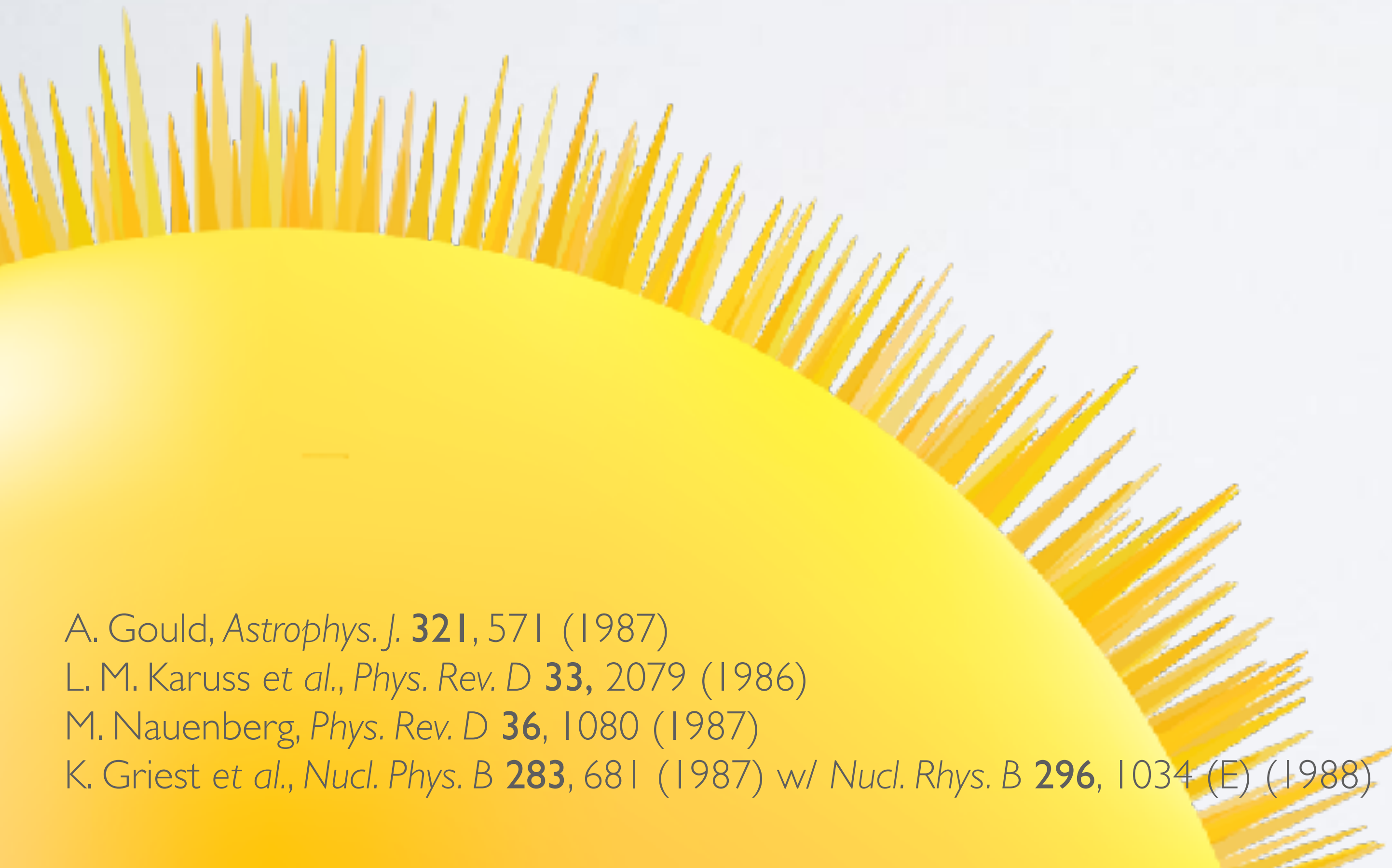
*Looking into the deep space*

# Dark Matter
# Trapped in the Sun

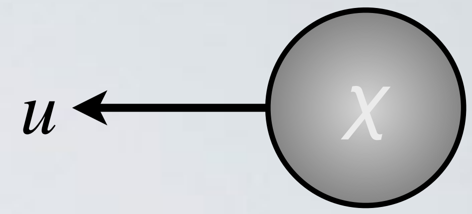


## DM number distribution: $f_\chi(u) = n_0 \times f_u(u)$



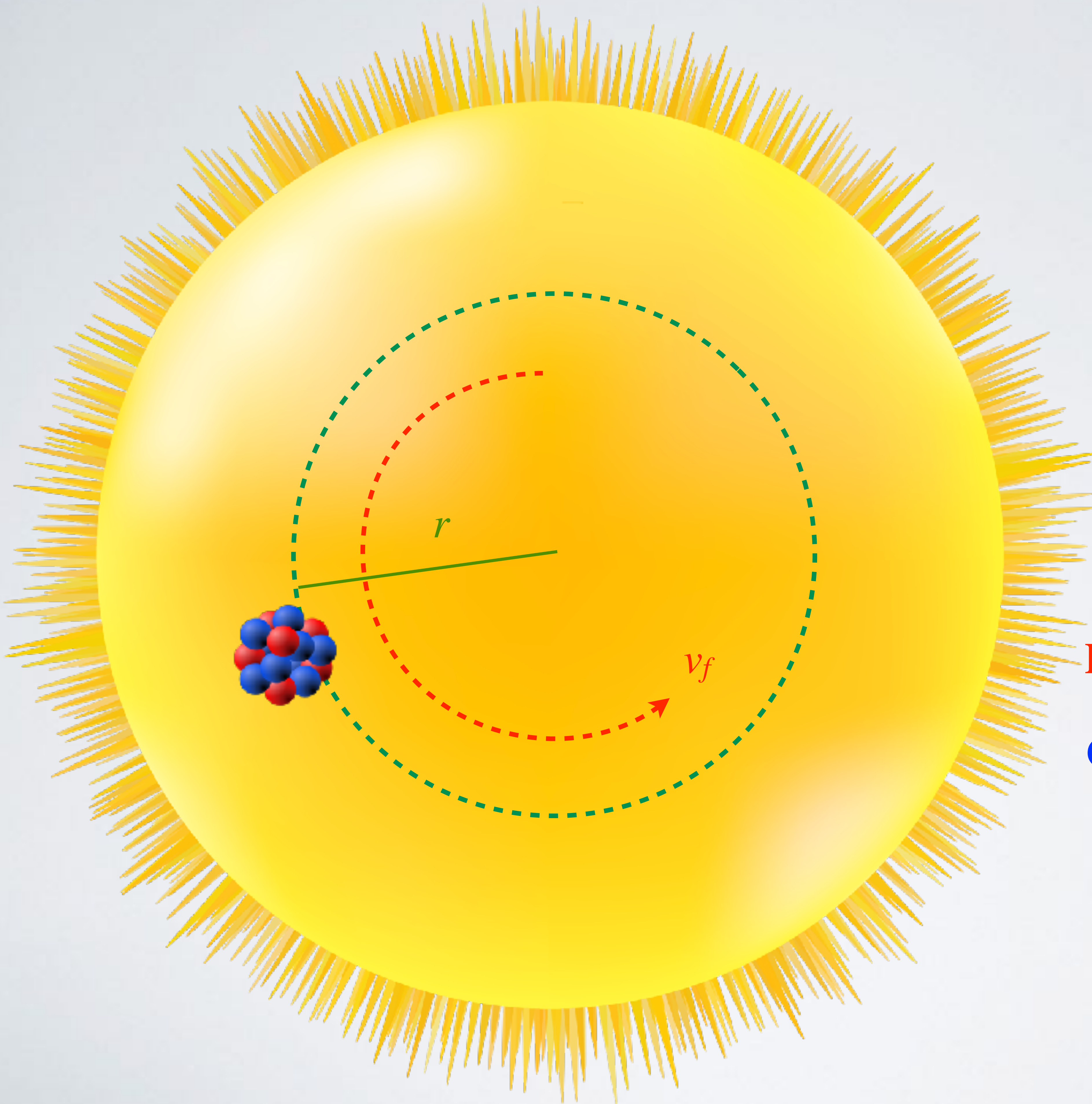



A. Gould, *Astrophys. J.* **321**, 571 (1987)
L. M. Karuss *et al.*, *Phys. Rev. D* **33,** 2079 (1986)
M. Nauenberg, *Phys. Rev. D* **36**, 1080 (1987)
K. Griest *et al.*, *Nucl. Phys. B* **283**, 681 (1987) w/ *Nucl. Rhys. B* **296**, 1034 (E) (1988)




**At layer $r$ :**

$$w = \sqrt{u^2 + v_{\rm esc}^2(r)}$$




**After scattering:**

$$v_f < v_{\rm esc}(r)$$

**DM stays captured**

**Otherwise, escapes**

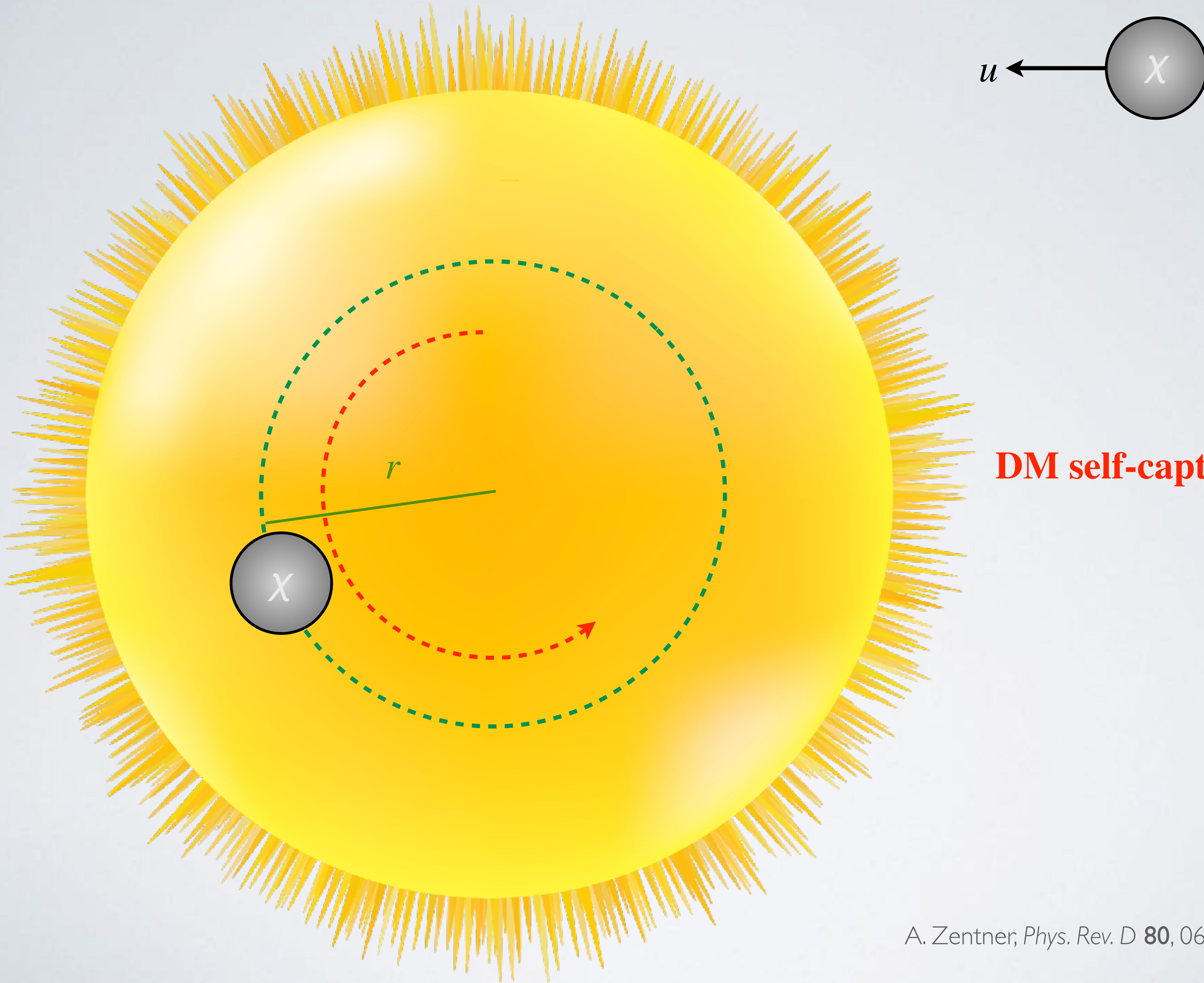
$$v_f > v_{\rm esc}(r)$$

Not to scale

- DM falls into the Sun:
  - Without scattering → escapes
  - Scattered with nucleus → $v_f > v_{esc}$ escapes; $v_f < v_{esc}$ captured
- Probability of $v_f < v_{esc}$ each scattering: $P_{cap}$
- Rate of capture, $\Omega(w) = n_A(r)\sigma_{\chi A} w \times P_{cap}$
- DM capture rate:

$$C_c = \int_{\odot} \int_0^{\infty} \Omega(w) f_\chi(u) du dV$$

A. Gould, *Astrophys. J.* **321**, 560 (1987); *Astrophys. J.* **388**, 338 (1991)
A. Zentner, *Phys. Rev. D* **80**, 063501 (2009)

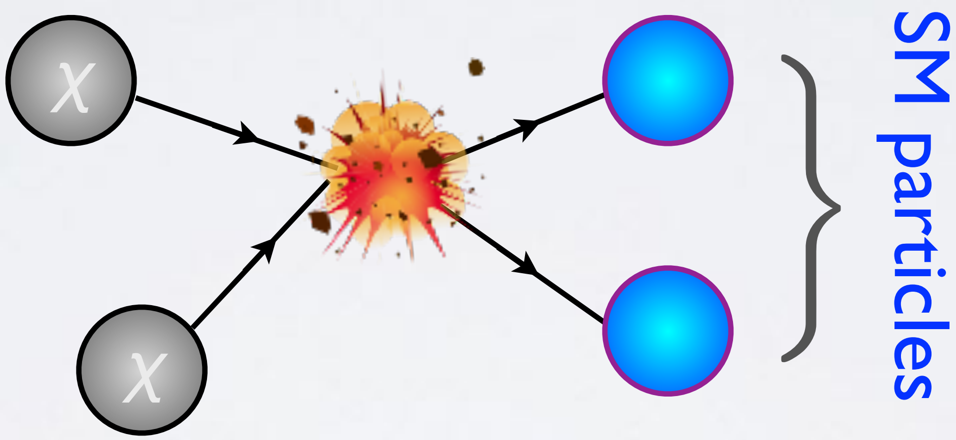



**DM self-capture: $C_s$**

A. Zentner, *Phys. Rev. D* **80**, 063501 (2009)

# DM annihilation

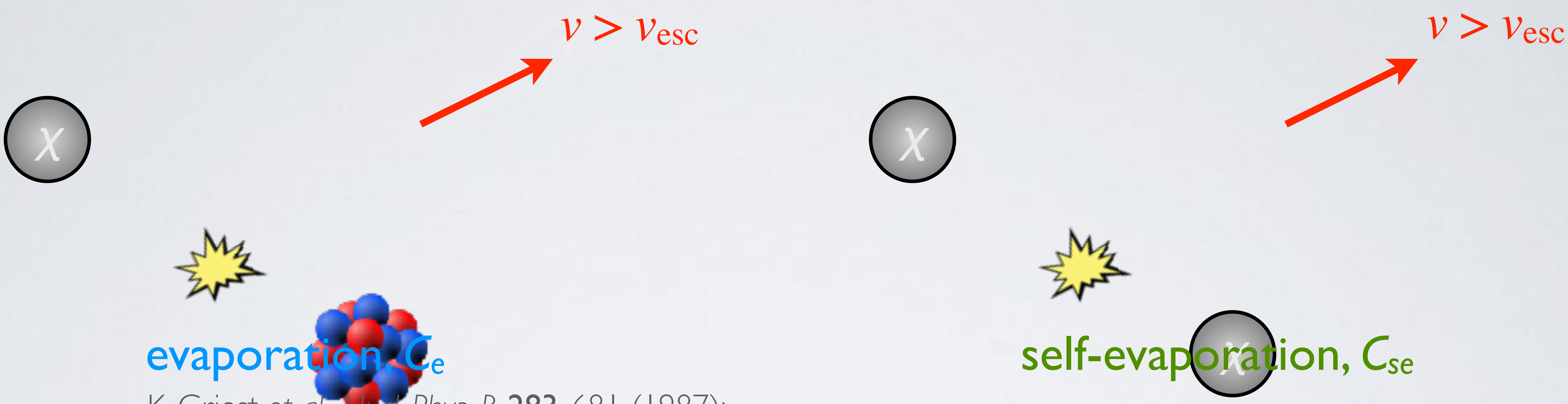
- More DM trapped inside the Sun → Higher DM density
- Chance of collision increases → Triggers the annihilation




- Cause the depletion of DM population
- The pair production of SM particles provides a possibility for detecting signals from DMs in the Sun
- Denoted by $C_a$

K. Griest *et al.*, *Nucl. Phys. B* **283**, 681 (1987) w/ *Nucl. Rhys. B* **296**, 1034 (E) (1988)

# DM evaporation




K. Griest *et al.*, *Nucl. Phys. B* **283**, 681 (1987); *Nucl. Rhys. B* **296**, 1034 (E) (1988)

C.-S. Chen *et al.*, *JCAP* **10**, 049 (2014)

- Trapped DM scatters with nucleus/DM and gain kinetic energy
- If the final velocity $v > v_{esc}$, the DM escapes and causes the depletion of population
- This is called the evaporation and self-evaporation and denoted by $C_e$ and $C_{se}$ respectively
- Numerical studies show that the evaporation effect dominates when $m_\chi \lesssim$ 2~3 GeV
- With self interaction including, it raises up to $m_\chi \lesssim$ 3~4 GeV

- **Capture rates:**
  - Due to nucleus, $C_c$
  - Due to trapped DMs, $C_s$
- **Annihilation rate, $C_a$**
- **Evaporation rates:**
  - Due to nucleus, $C_e$
  - Due to trapped DMs, $C_{se}$

} Increasing population (capture rates)

} Depletion (annihilation and evaporation rates)

} $m_\chi \lesssim 4$ GeV (evaporation rates)

**Gravitational capture**

$$C_c \simeq 3.35 \times 10^{24}\,\mathrm{s}^{-1} \left(\frac{\rho_0}{0.3\,\mathrm{GeV\ cm}^{-3}}\right)\left(\frac{270\,\mathrm{km\ s}^{-1}}{\bar{v}}\right)^3\left(\frac{\mathrm{GeV}}{m_\chi}\right)^2\left(\frac{\sigma_{\chi H}}{10^{-6}\,\mathrm{pb}}\right)$$

**DM self-capture**

$$C_s = \sqrt{\frac{3}{2}} n_\chi \sigma_{\chi\chi} v_{\mathrm{esc}}(R_\odot) \frac{v_{\mathrm{esc}}(R_\odot)}{\bar{v}} \langle \hat{\phi} \rangle \frac{\mathrm{erf}(\eta)}{\eta}$$

**Annihilation**

$$C_a = \langle \sigma v \rangle \frac{V_2}{V_1^2}, \quad V_j \simeq 6.5 \times 10^{28}\,\mathrm{cm}^3 \left(\frac{10\,\mathrm{GeV}}{j m_\chi}\right)^{3/2}\left(\frac{T_\chi}{T_\odot}\right)^{3/2}$$

C.-S. Chen *et al.*, *Phys. Dark Univ.* **14**, 35 (2016)

# Evolution of DM numbers

- The DM population inside the Sun is governed by the equation

$$\frac{dN_\chi}{dt} = C_c + (C_s - C_e)N_\chi - (C_a + C_{se})N_\chi^2$$

K. Griest *et al.*, *Nucl. Phys. B* **283**, 681 (1987);
C.-S. Chen *et al.*, *JCAP* **10**, 049 (2014)

- With the solution

$$N_\chi(t) = \frac{C_c \tanh(t/\tau_A)}{\tau_A^{-1} - (C_s - C_e)\tanh(t/\tau_A)/2}$$

- $\tau_A$ is the equilibrium timescale = $1/\sqrt{C_c(C_a + C_{se}) + (C_s - C_e)^2/4}$

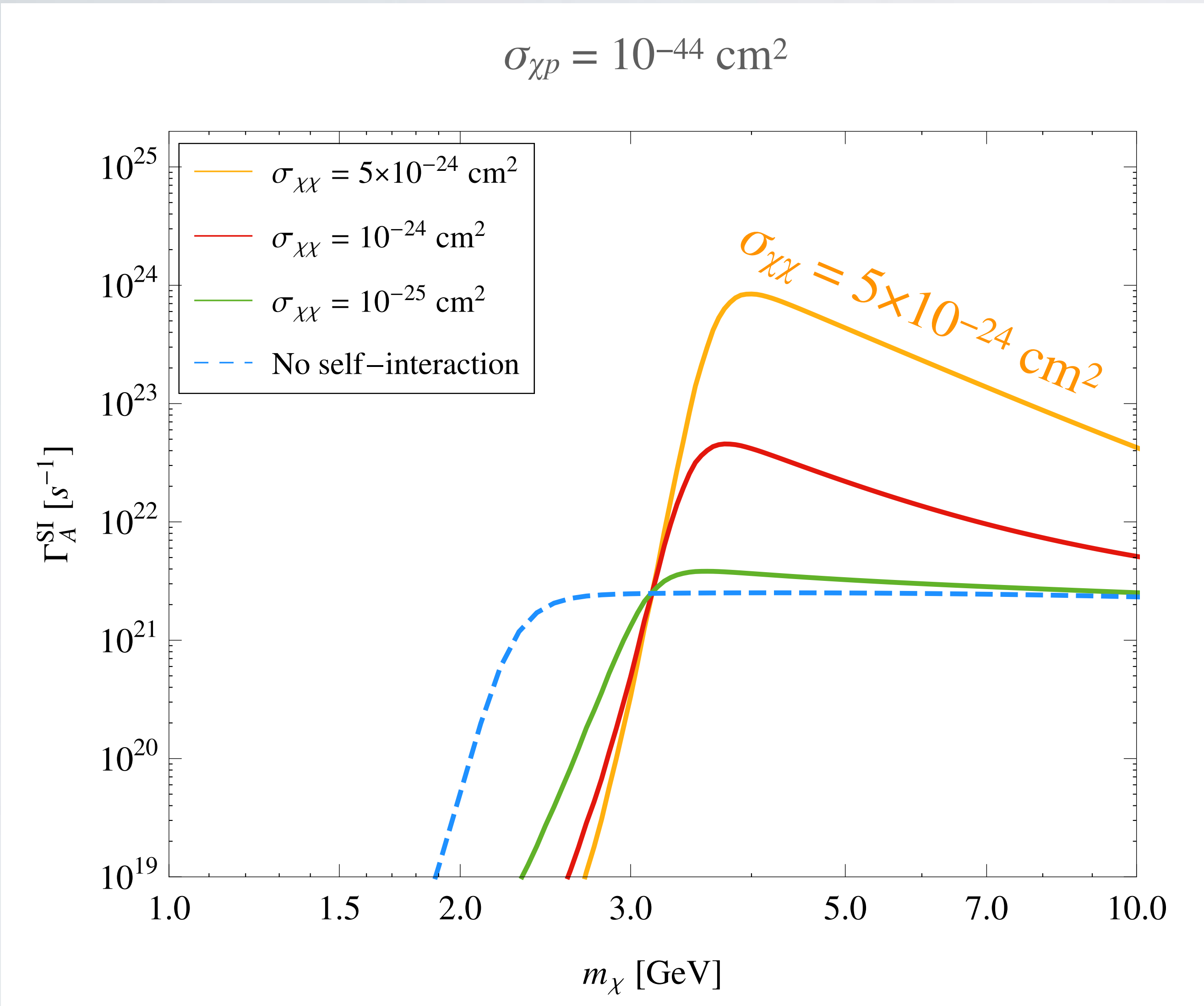
- In the absence of evaporations, when $t \gg \tau_A$, $N_\chi$ approaches a constant

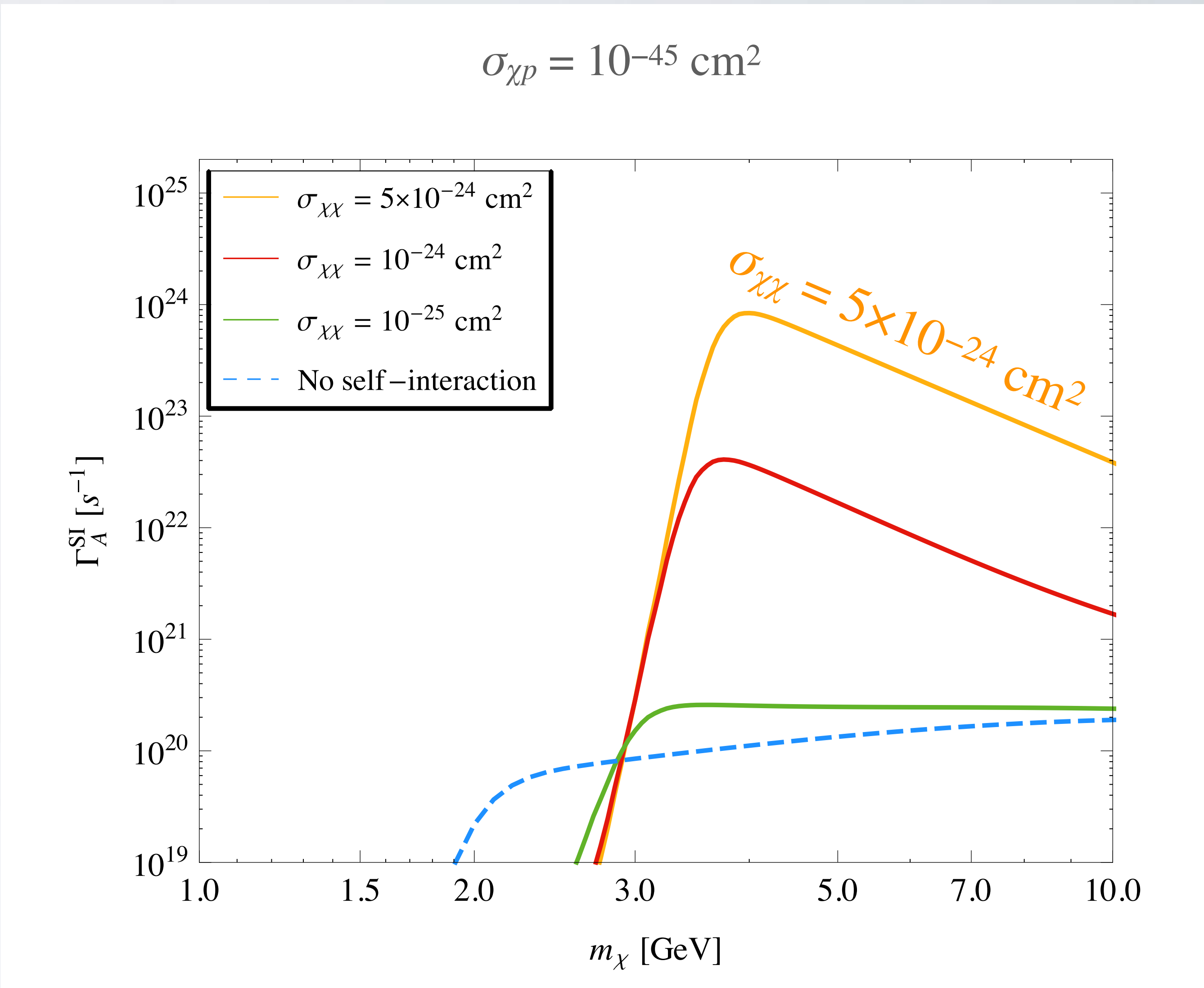
$$N_\chi^{\rm eq} = \sqrt{\frac{C_c}{C_a}}\underbrace{\left(\sqrt{\frac{R}{4}} + \sqrt{\frac{R}{4} + 1}\right)}_{\text{correction due to self-interaction}} \qquad R \equiv \frac{C_s^2}{C_c C_a}$$

$\ll 1$, $C_c$ dominance

$\gg 1$, $C_s$ dominance

# Total annihilation in the Sun




Total annihilation rate: $\Gamma_A = \frac{1}{2} C_a N_{\chi,\mathrm{eq}}^2 \begin{cases} \frac{1}{2}\frac{C_s^2}{C_a} & R \gg 1, \text{ determined by } C_s \\ \frac{1}{2} C_c & R \ll 1, \text{ determined by } C_c \end{cases}$

# Brief summary for PART II

- Formalism for the evolution of DM population in the Sun is given
- When self-interaction is dominant, the total annihilation rate is determined by self-interaction only
- Notion of heat transfer between DMs is briefly mentioned. Its implications can be found in *Phys. Dark Univ.* 14, 35 (2016)

# Contents


Part III
There is strong shadow
where there is much light

# Detection instruments

- *Undeflected* by the interstellar EM fields
- All interstellar media are almost *transparent* to neutrinos
- They carry nearly *original energy information* from the production point

**Neutrino detectors**

- ANTARES, NESTOR, NEMO, KM3NeT,…
- IceCube, PINGU,…
- Baikal,…
- Super-K, Hyper-K, KamLAND, JUNO,…

**Gamma-ray telescopes**

- MAGIC, H.E.S.S., VERITAS,…
- Fermi-LAT,…
- CTA, Gamma-400,…

**Anti-matter satellites**

- PAMELA, ATIC, PPB-Bets,…
- AMS-02

**Others**

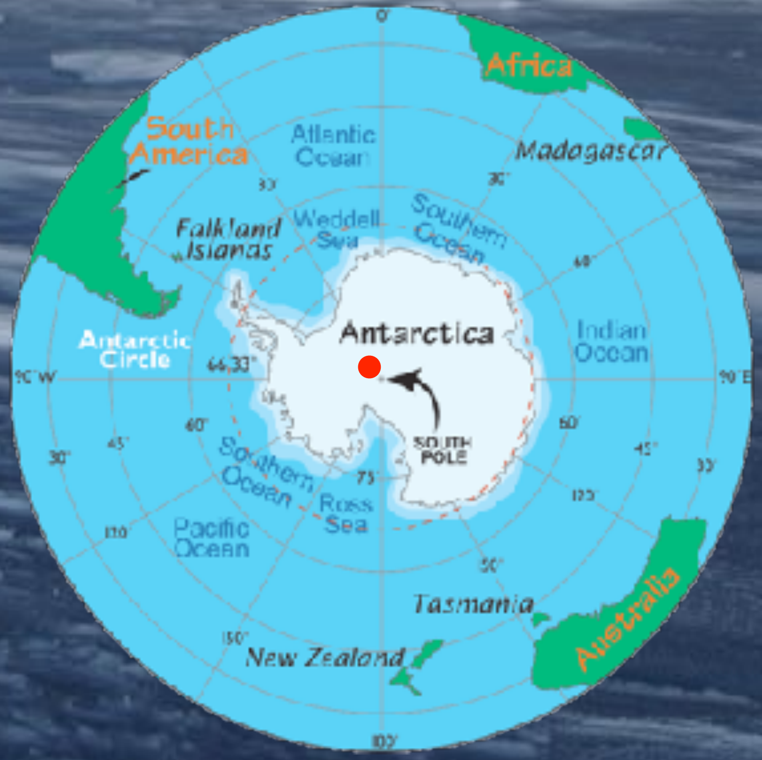
- x-ray, radio,…


Image Credit: J. Yang [IceCube Collab.]

Location: 89° 59′ 24″ S
63° 27′ 11″ W
Near Amundsen–Scott South Pole Station (90° S, 0° E)


~29°

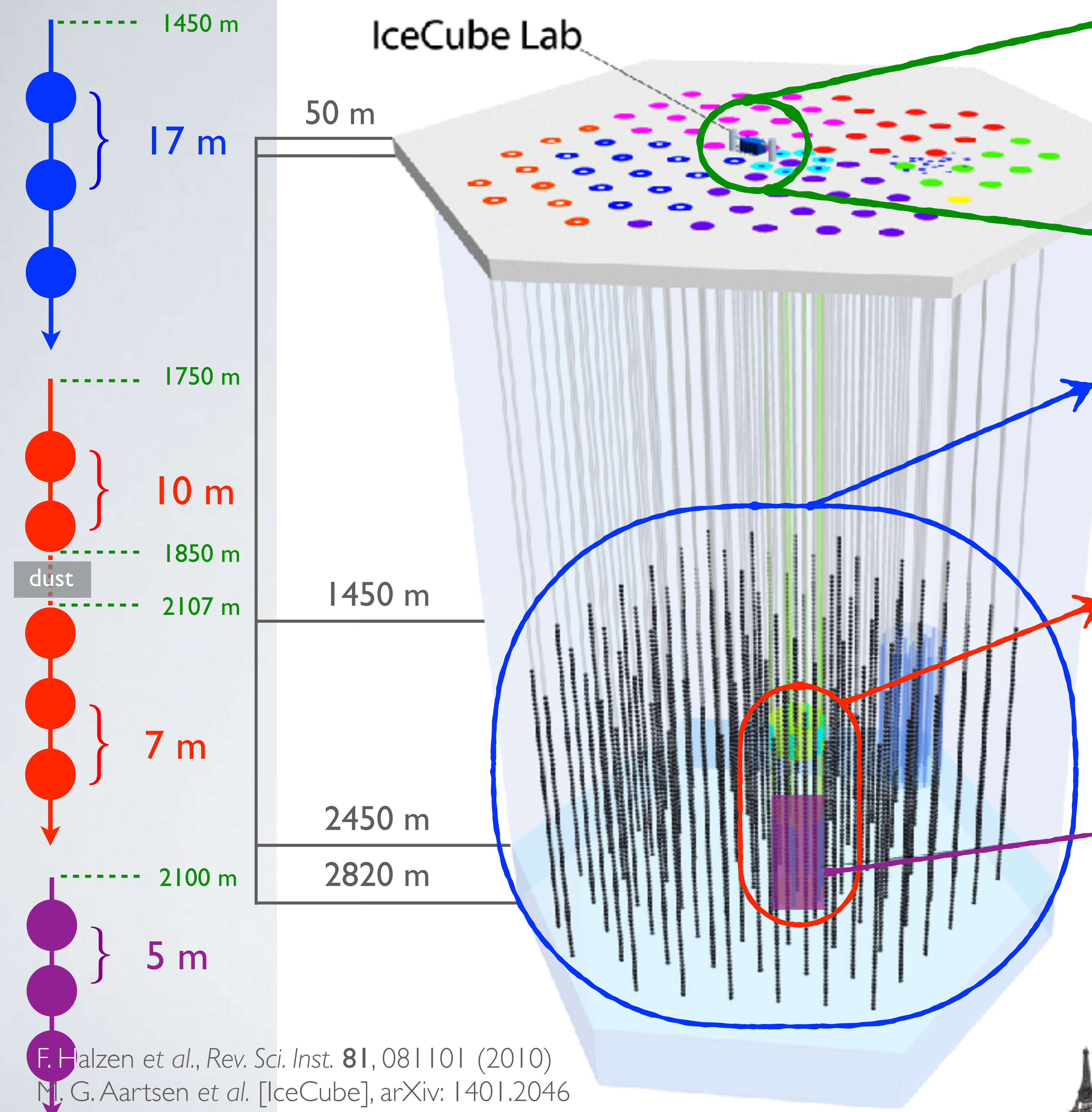
~23.5°

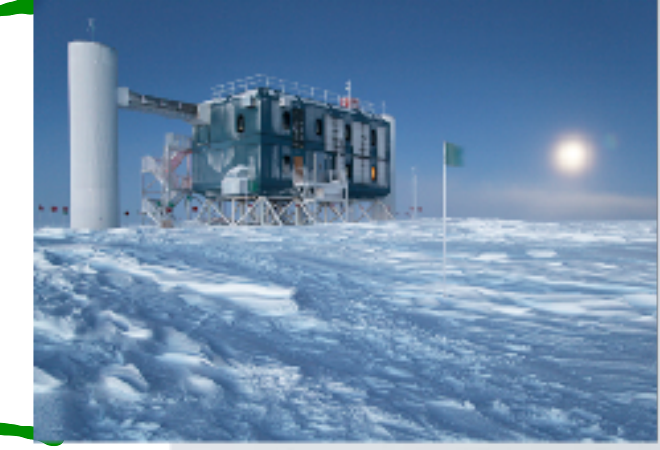



IceCube indirect DM Search:

- G.C. is about 29° above the horizon always
- The Sun is 23.5° above/below the horizon

Not to scale



**IceCube array:**
86 strings with 60 optical sensors on each string. Total 5160 optical sensors.

**DeepCore array:**
8 additional strings with total 480 optical sensors optimized @ 10~100 GeV.

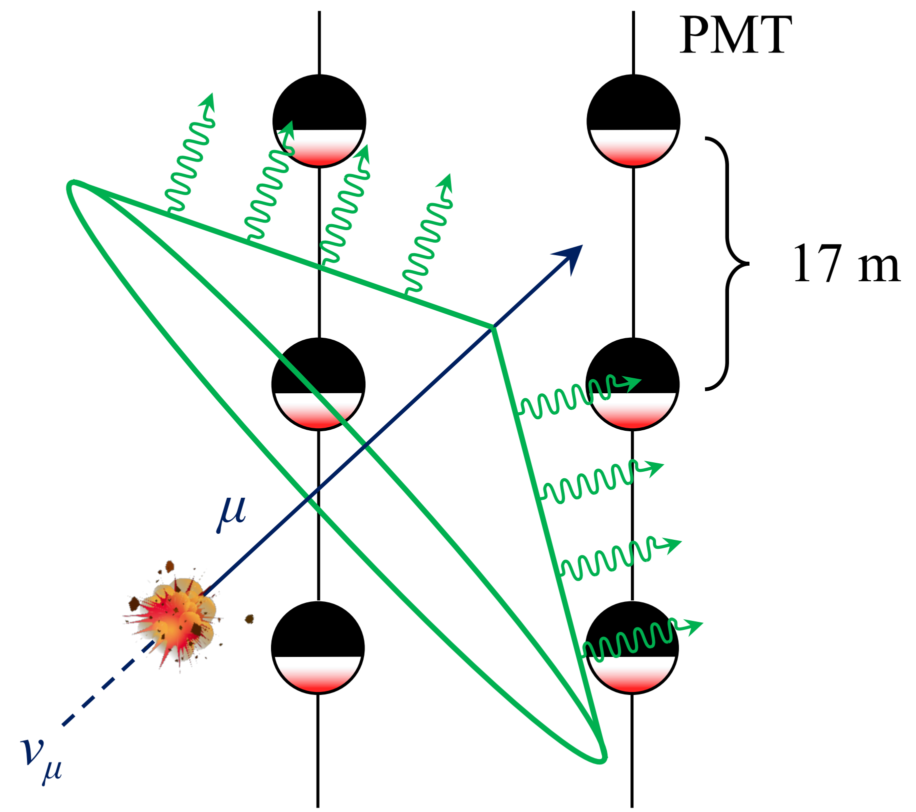
**PINGU array (~2020):**
40 additional strings with total 2400 optical sensors optimized @ 1~15 GeV.

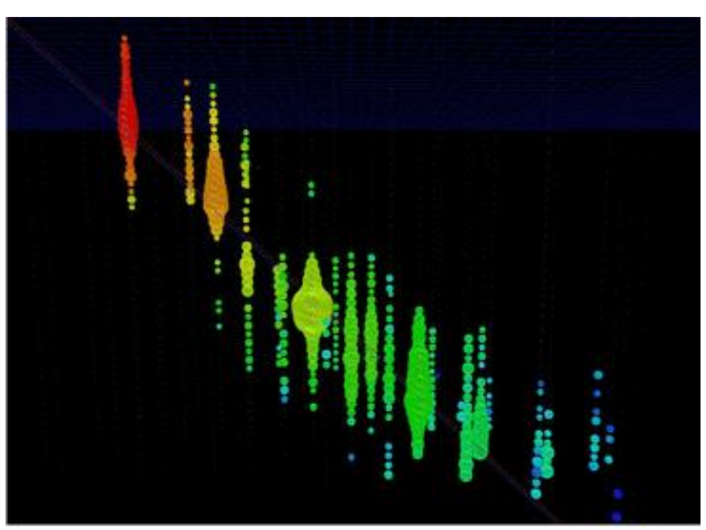

F. Halzen *et al.*, *Rev. Sci. Inst.* **81**, 081101 (2010)
M. G. Aartsen *et al.* [IceCube], arXiv: 1401.2046

## Track

$$\nu_\mu + N \longrightarrow \mu + X$$

*X*: hadronic shower

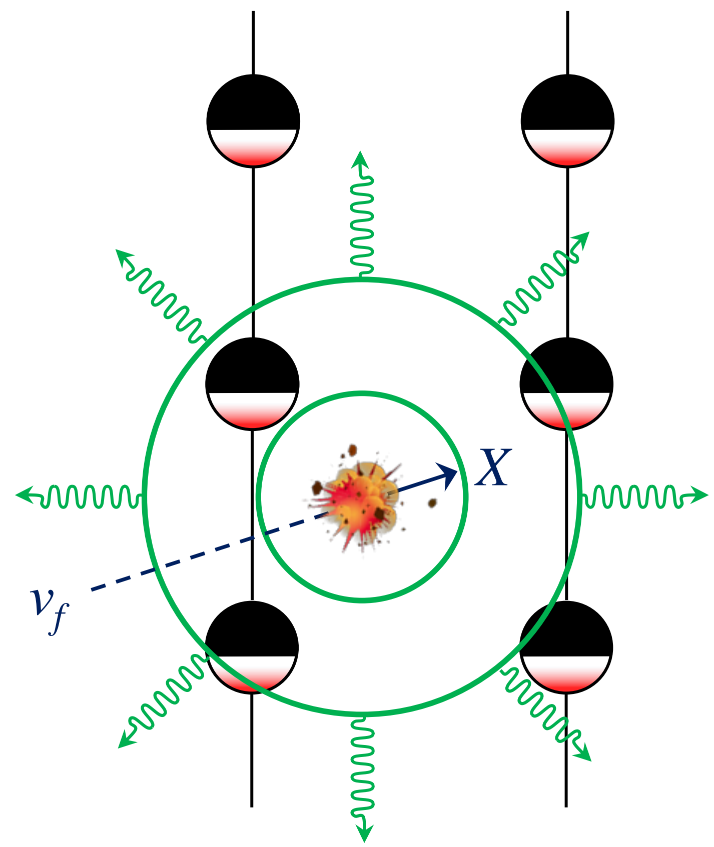


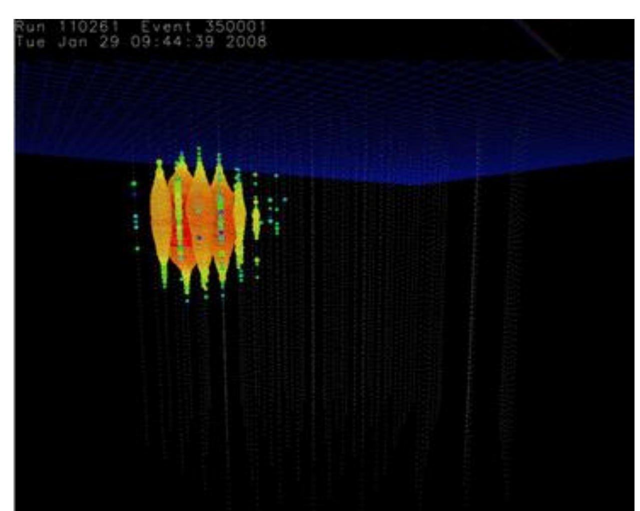



## Cascade

$$\nu + N \longrightarrow \nu + X$$

$$\nu_{e,\tau} + N \longrightarrow e/\tau + X$$

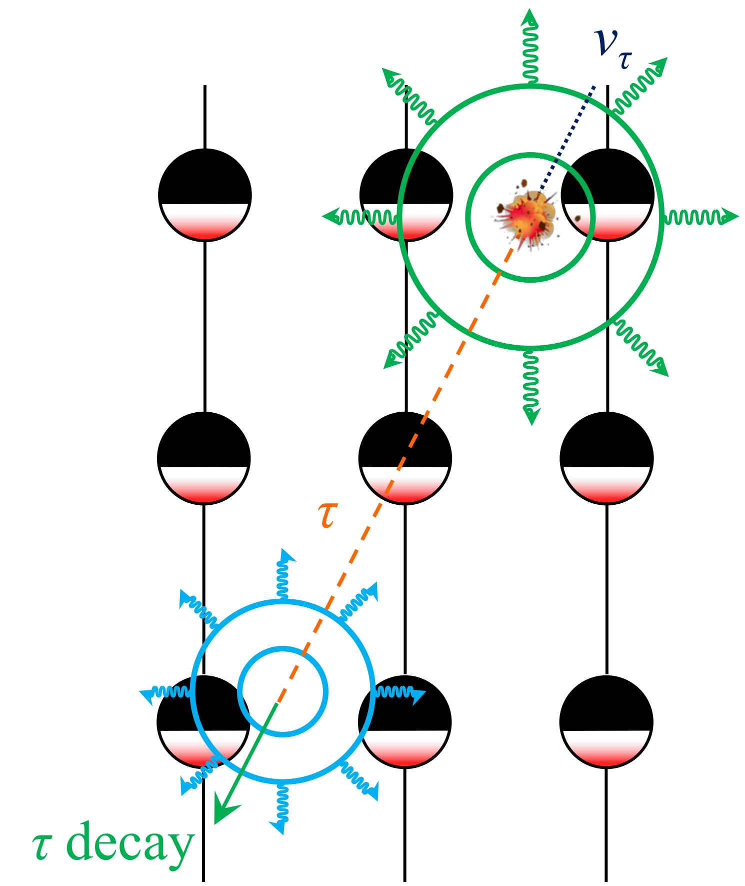


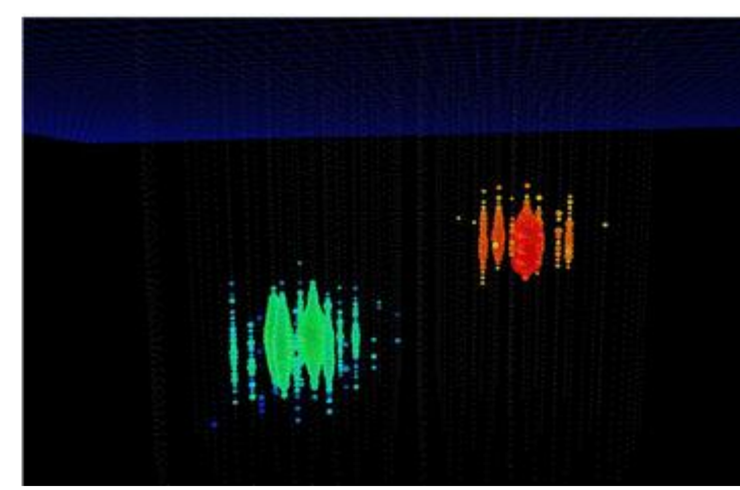




## Double-bang

$$\nu_\tau + N \longrightarrow \tau + X$$

$$\hookrightarrow \nu_\tau + \nu + X$$



extreme high energy $\nu_\tau$
up to PeVs (simulated)

F. Halzen *et al.*, *Rev. Sci. Inst.* **81**, 081101 (2010)/Reillustrated

# Effective area

- IceCube has no definite boundary
- An effective volume (boundary) should be defined by

$$V_{\text{eff}} = \frac{N_{\text{recon}}}{N_{\text{gen}}} \times V_{\text{gen}}$$

- The efficiency of transforming the *energy differential neutrino flux* [GeV$^{-1}$ cm$^{-2}$ s$^{-1}$] into the event number

$$\text{Event} = T \int dE \, \frac{d\Phi}{dE} \times V_{\text{eff}}(E) \times \rho N_A \times \sigma(E)$$

- The effect area (detector acceptance) is defined as

$$V_{\text{eff}}(E) \rho N_A \sigma(E) \equiv A_{\text{eff}}(E) \quad [\text{cm}^2]$$

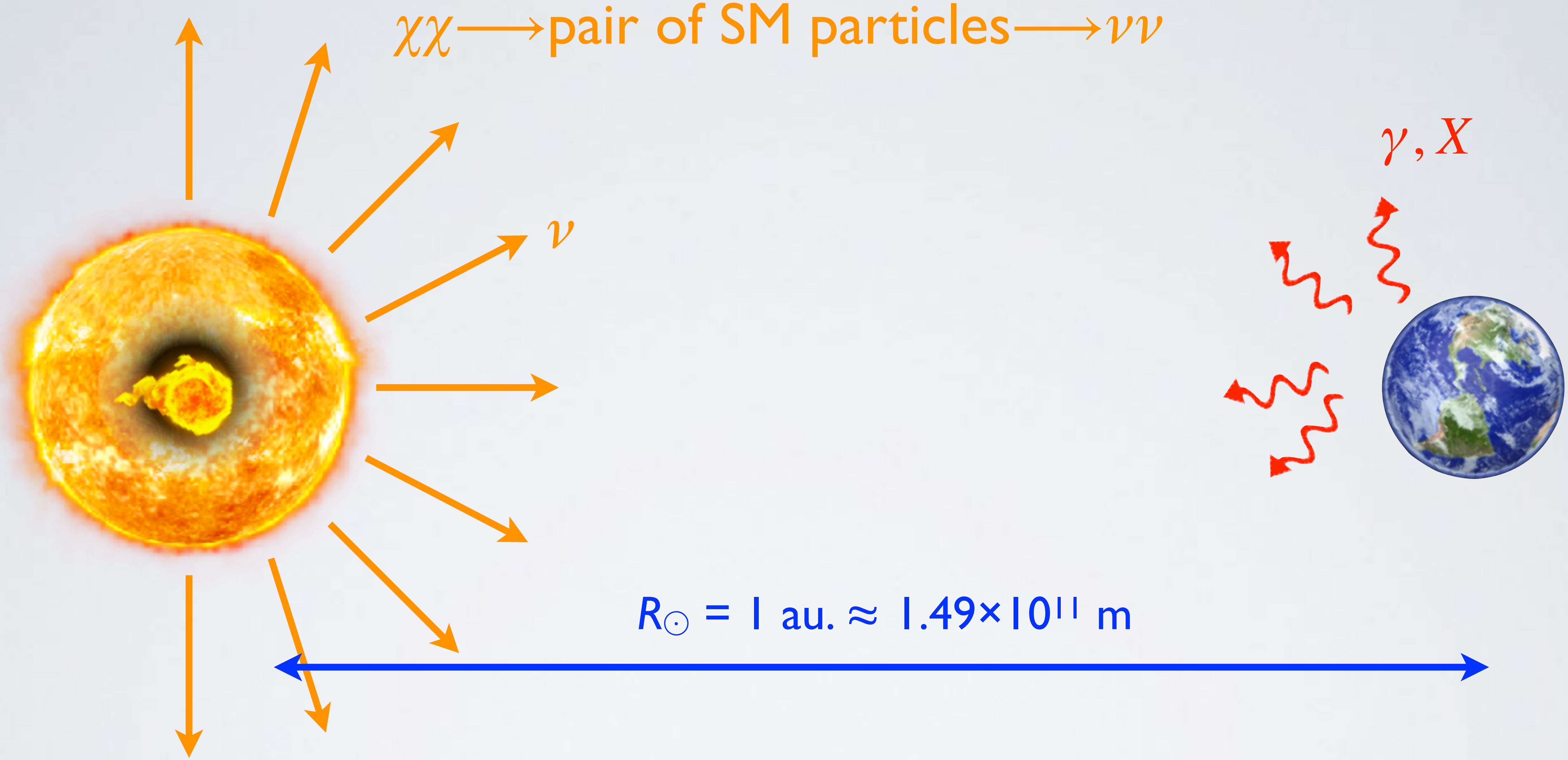
Provided by the IceCube Collaboration

# IceCube and Indirect Dark Matter Search

Image Credit: IceCube Collab.

# How we measure the signals

Model-independent framework

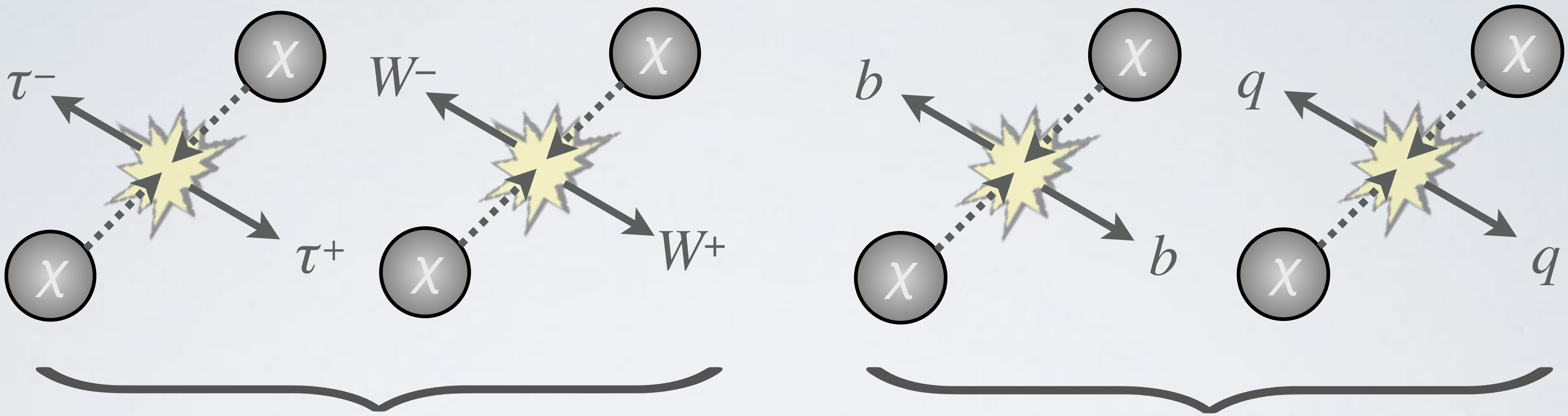



$$\Gamma_A \sum_f B_f \left(\frac{dN_{\nu_j}}{dE_{\nu_j}}\right)_f \times \frac{P_{\nu_j\to\nu_i}(E_\nu)}{4\pi R_\odot^2} = \frac{d\Phi_{\nu_i}}{dE_{\nu_i}}$$

$\nu$-yields per second | propagation | flux

# Neutrinos produced from DM annihilation

**Channels:** $B_f(\tau\tau)$ + $B_f(WW)$ + $B_f(bb)$ + $B_f(qq)$ + … = 1




**Hard channels**

**Soft channels**

High energy neutrinos from DM annihilation

$\nu\nu$ $\tau^+\tau^-$ $W^+W^-$ $bb$ $qq$ $e^+e^-$

most high energy neutrinos

fewest neutrinos

C. Rott, talk at CosPA (2013)

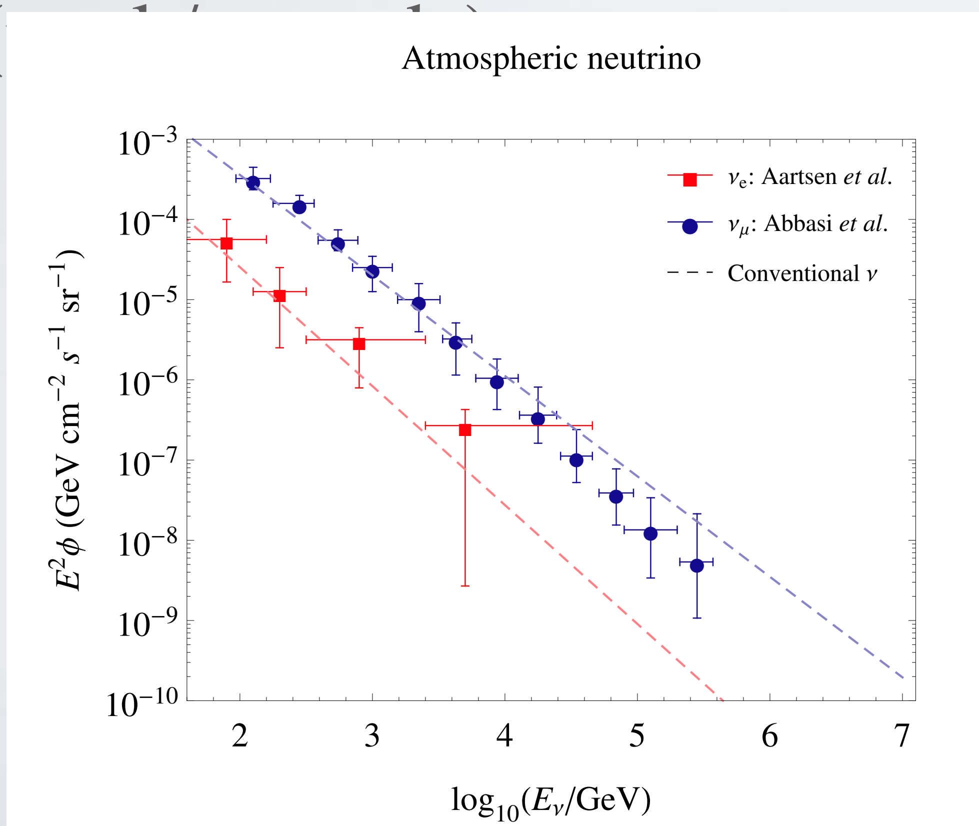
MeV neutrinos raised from $\pi/K$ multiplications

C. Rott *et al.*, *Phys. Rev. D* **88**, 055005 (2013)

N. Bernal *et al.*, *JCAP* **08**, 011 (2013)

# Atmospheric neutrino

- Generated by the cosmic ray inte
acting with the atmospheric nucl
- Pions and muons are generally pr
duced and decay subsequently
- Primary backgrounds in the IceCube are $\nu_e$ (cascade) and $\nu_\mu$
(




M. Honda *et al.*, *Phys. Rev. D* **75**, 043006 (2007)
M. G. Aartsen et al. [IceCube], *Phys. Rev. Lett.* **110,** 151105 (2013)

TABLE VIII: Neutrino flux ($m^{-2}sec^{-1}sr^{-1}GeV^{-1}$) for $0.4 > \cos\theta_z > 0.3$

| | Kamioka | | | | Sudbury | | | | Gran Sasso | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $E_\nu$ (GeV) | $\nu_\mu$ | $\bar{\nu}_\mu$ | $\nu_e$ | $\bar{\nu}_e$ | $\nu_\mu$ | $\bar{\nu}_\mu$ | $\nu_e$ | $\bar{\nu}_e$ | $\nu_\mu$ | $\bar{\nu}_\mu$ | $\nu_e$ | $\bar{\nu}_e$ | *Norm* |
| 1.000 | 12.81 | 12.43 | 6.78 | 5.65 | 17.48 | 17.24 | 9.97 | 7.91 | 16.35 | 15.93 | 8.94 | 7.25 | $10^1$ |
| 1.259 | 7.78 | 7.50 | 4.11 | 3.37 | 9.88 | 9.68 | 5.58 | 4.37 | 9.46 | 9.19 | 5.20 | 4.16 | $10^1$ |
| 1.585 | 46.19 | 43.94 | 24.12 | 19.49 | 55.21 | 53.30 | 30.51 | 23.59 | 53.74 | 51.55 | 29.21 | 23.10 | 1 |
| 1.995 | 26.76 | 25.06 | 13.68 | 10.91 | 30.50 | 28.81 | 16.30 | 12.49 | 29.98 | 28.16 | 15.80 | 12.32 | 1 |
| 2.512 | 15.21 | 13.98 | 7.50 | 5.89 | 16.57 | 15.42 | 8.55 | 6.49 | 16.27 | 15.03 | 8.25 | 6.36 | 1 |
| 3.162 | 8.38 | 7.59 | 3.97 | 3.09 | 8.89 | 8.11 | 4.38 | 3.28 | 8.74 | 7.94 | 4.24 | 3.24 | 1 |
| 3.981 | 44.88 | 40.07 | 20.30 | 15.66 | 47.11 | 41.80 | 21.82 | 16.19 | 46.49 | 41.46 | 21.39 | 16.25 | $10^{-1}$ |
| 5.012 | 23.67 | 20.76 | 10.10 | 7.70 | 24.47 | 21.29 | 10.54 | 7.87 | 24.14 | 21.22 | 10.49 | 7.90 | $10^{-1}$ |
| 6.310 | 12.32 | 10.64 | 4.91 | 3.70 | 12.47 | 10.74 | 4.98 | 3.74 | 12.38 | 10.72 | 4.98 | 3.74 | $10^{-1}$ |
| 7.943 | 63.40 | 54.11 | 23.35 | 17.54 | 63.19 | 53.98 | 23.26 | 17.49 | 63.33 | 54.03 | 23.25 | 17.49 | $10^{-2}$ |
| 10.00 | 32.32 | 27.25 | 10.90 | 8.19 | 32.29 | 27.23 | 10.88 | 8.18 | 32.31 | 27.23 | 10.88 | 8.18 | $10^{-2}$ |

TABLE XXII: $\nu_\mu$ flux ($m^{-2}sec^{-1}sr^{-1}GeV^{-1}$) above 10 GeV

| | $\cos\theta_z$ | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $E_\nu$ (GeV) | 1.–.9 | .9–.8 | .8–.7 | .7–.6 | .6–.5 | .5–.4 | .4–.3 | .3–.2 | .2–.1 | .1–.0 | *Norm* |
| $1.000\times10^1$ | 2.557 | 2.625 | 2.703 | 2.799 | 2.911 | 3.052 | 3.232 | 3.482 | 3.824 | 4.172 | $10^{-1}$ |
| $1.259\times10^1$ | 1.295 | 1.331 | 1.370 | 1.419 | 1.479 | 1.554 | 1.646 | 1.778 | 1.964 | 2.166 | $10^{-1}$ |
| $1.585\times10^1$ | 0.654 | 0.673 | 0.694 | 0.720 | 0.751 | 0.789 | 0.840 | 0.906 | 1.009 | 1.121 | $10^{-1}$ |
| $1.995\times10^1$ | 3.297 | 3.397 | 3.505 | 3.653 | 3.811 | 4.001 | 4.269 | 4.612 | 5.154 | 5.807 | $10^{-2}$ |
| $2.512\times10^1$ | 1.659 | 1.710 | 1.770 | 1.848 | 1.930 | 2.033 | 2.167 | 2.349 | 2.627 | 2.997 | $10^{-2}$ |
| $3.162\times10^1$ | 0.831 | 0.858 | 0.891 | 0.931 | 0.974 | 1.033 | 1.100 | 1.197 | 1.340 | 1.542 | $10^{-2}$ |
| $3.981\times10^1$ | 4.144 | 4.291 | 4.463 | 4.663 | 4.898 | 5.205 | 5.572 | 6.091 | 6.852 | 7.935 | $10^{-3}$ |
| $5.012\times10^1$ | 2.055 | 2.136 | 2.225 | 2.329 | 2.457 | 2.612 | 2.819 | 3.085 | 3.482 | 4.051 | $10^{-3}$ |
| $6.310\times10^1$ | 1.014 | 1.056 | 1.104 | 1.161 | 1.228 | 1.308 | 1.420 | 1.556 | 1.762 | 2.059 | $10^{-3}$ |
| $7.943\times10^1$ | 0.499 | 0.519 | 0.545 | 0.576 | 0.609 | 0.653 | 0.710 | 0.783 | 0.897 | 1.054 | $10^{-3}$ |
| $1.000\times10^2$ | 2.443 | 2.551 | 2.679 | 2.838 | 3.012 | 3.248 | 3.541 | 3.930 | 4.524 | 5.345 | $10^{-4}$ |

# Event rate and sensitivities

- The event rates in IceCube:

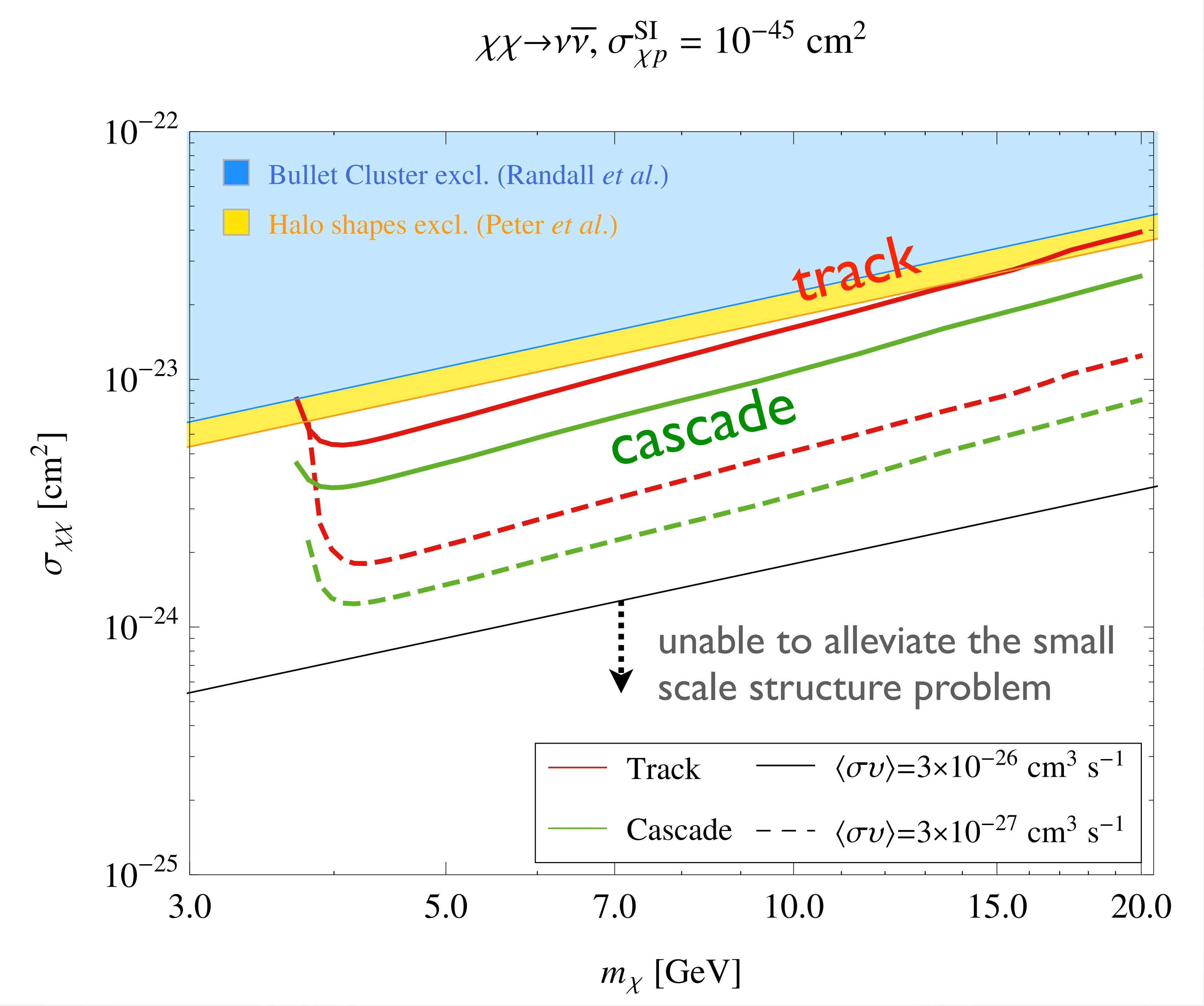
$$N_\nu(m_\chi) = \int_{E_{\rm th}}^{m_\chi} \frac{d\Phi_\nu}{dE_\nu} A_{\rm eff}(E_\nu) dE_\nu$$

$$N_{\rm atm}(E_\nu^{\rm max}) = \int_{E_{\rm th}}^{E_{\rm max}} \frac{d\Phi_\nu^{\rm atm}}{dE_\nu} A_{\rm eff}(E_\nu) dE_\nu$$

- Generally $E_\nu^{\rm max} = m_\chi$ for comparison
- The sensitivity is taken to reach $2\sigma$ detection significance in 5 years

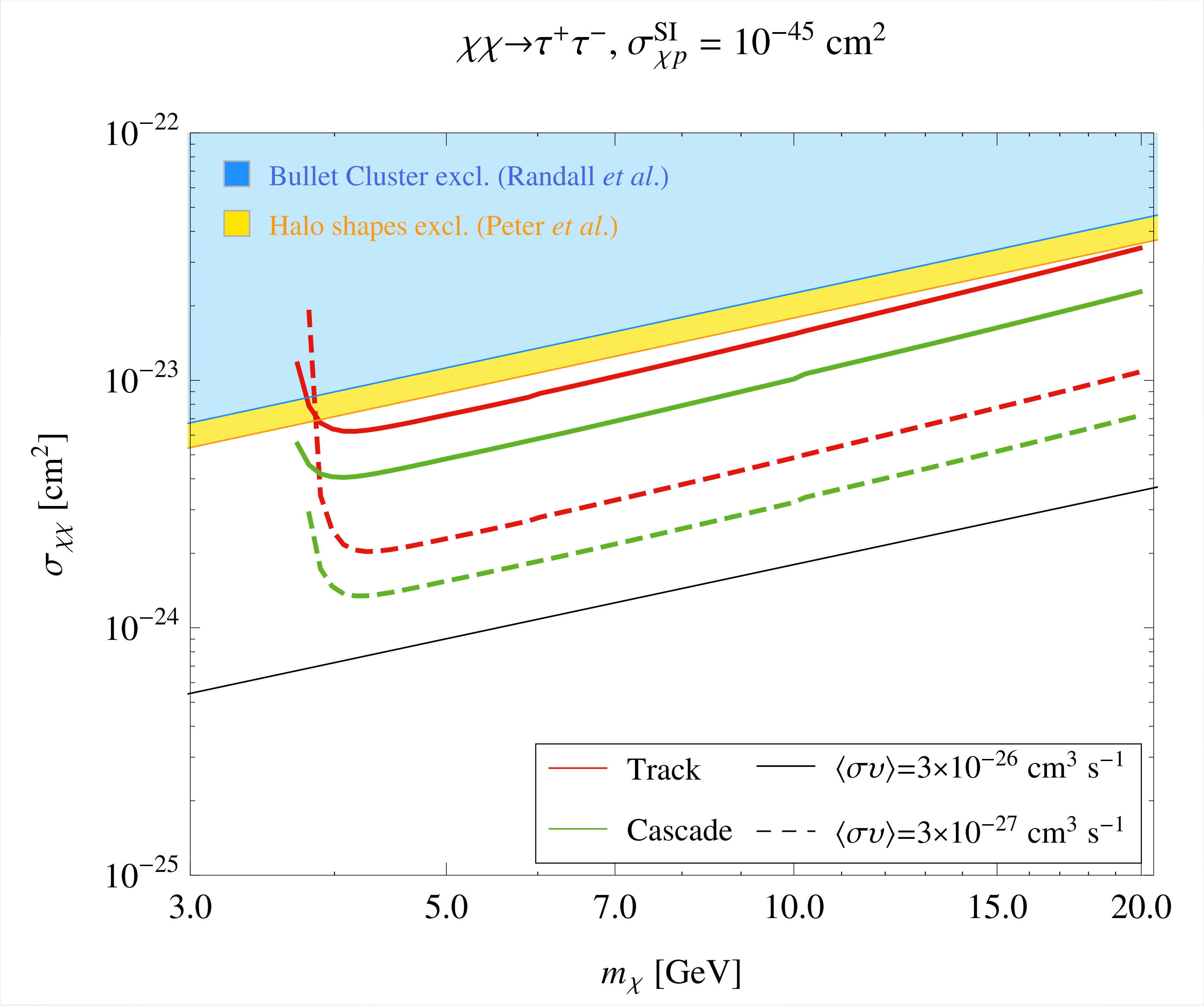
| | Track | | Cascade | |
|---|---|---|---|---|
| $E_{max}$ [GeV] | Bkg | DM | Bkg | DM |
| 5 | 7146 | 76 | 9874 | 90 |
| 10 | 10280 | 91 | 13775 | 105 |
| 50 | 21680 | 132 | 21803 | 132 |
| 70 | 23584 | 138 | 23111 | 136 |
| 100 | 26610 | 146 | 24363 | 140 |

# Sensitivity on $\sigma_{\chi\chi}$: Solar DM




$$\Gamma_A = \frac{1}{2}\frac{C_s^2}{C_a}$$

# Sensitivity on $\sigma_{\chi\chi}$: Solar DM

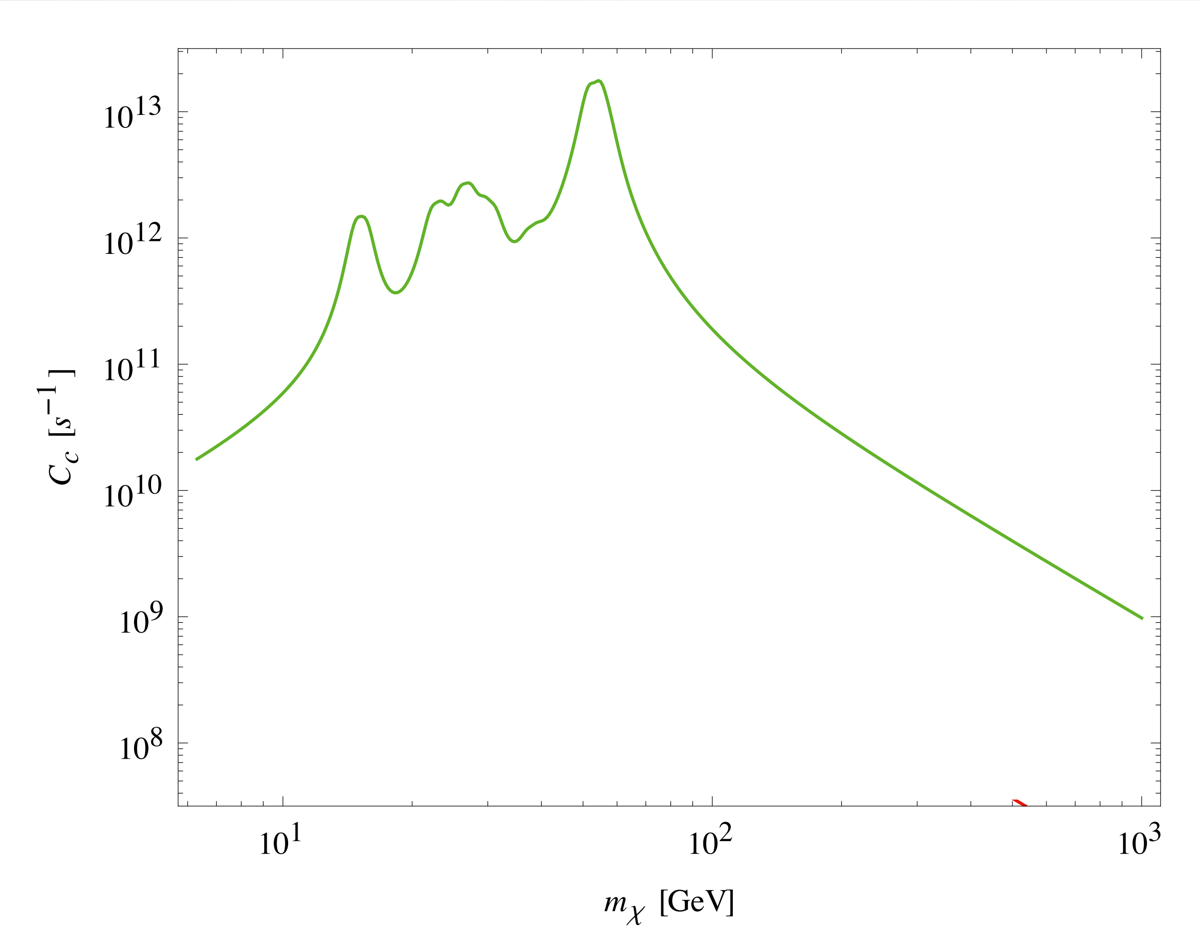


# What about Earth?

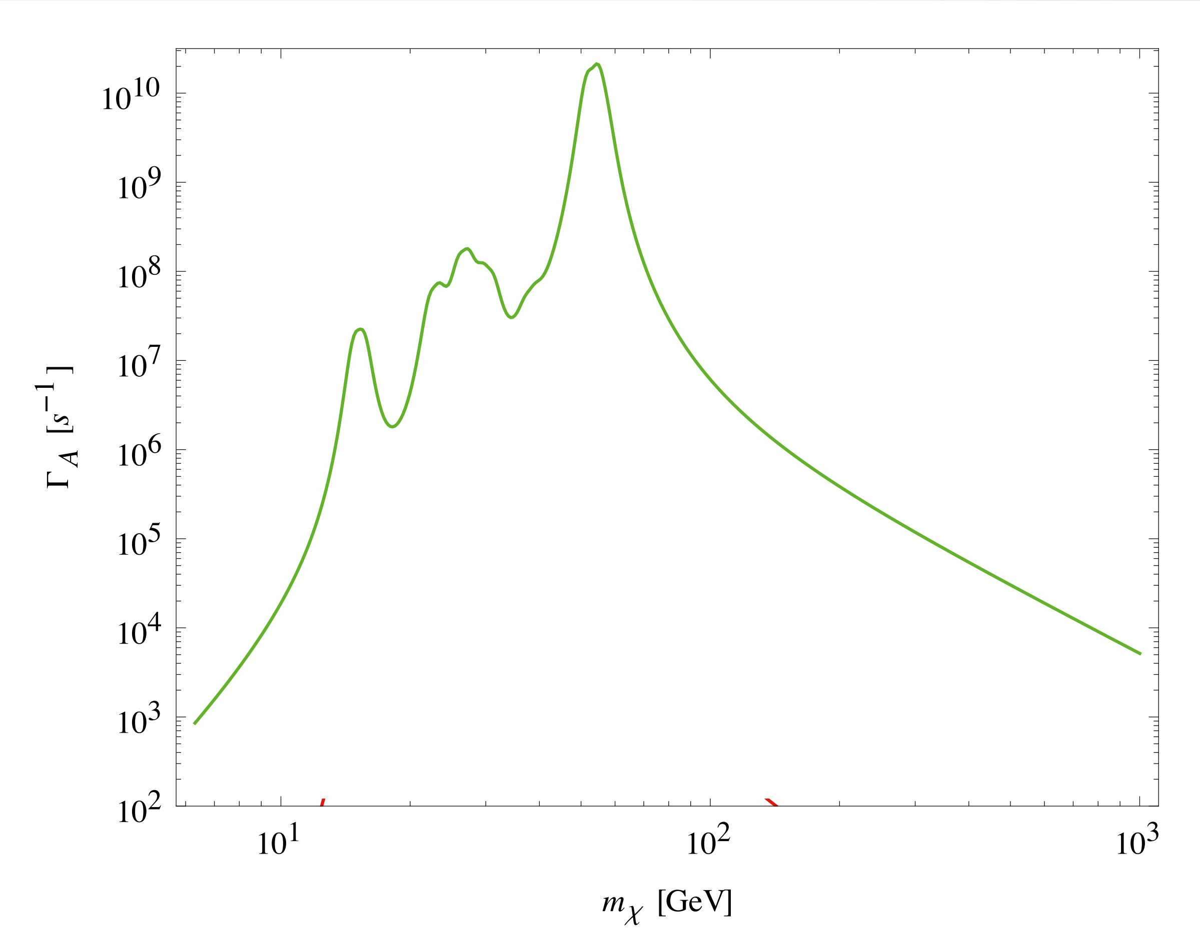
- Solar neutrinos suffer from severe attenuation when $E_\nu > 500$ GeV
- Sun is not an ideal place for examining high mass DM
- Earth density is much smaller, so does the radius
- Attenuation effect is not significant in the Earth
- Atmospheric background is strongly suppressed at TeV range and greater
- Earth is an ideal place for probing high mass DM

# DM in the Earth

Capture

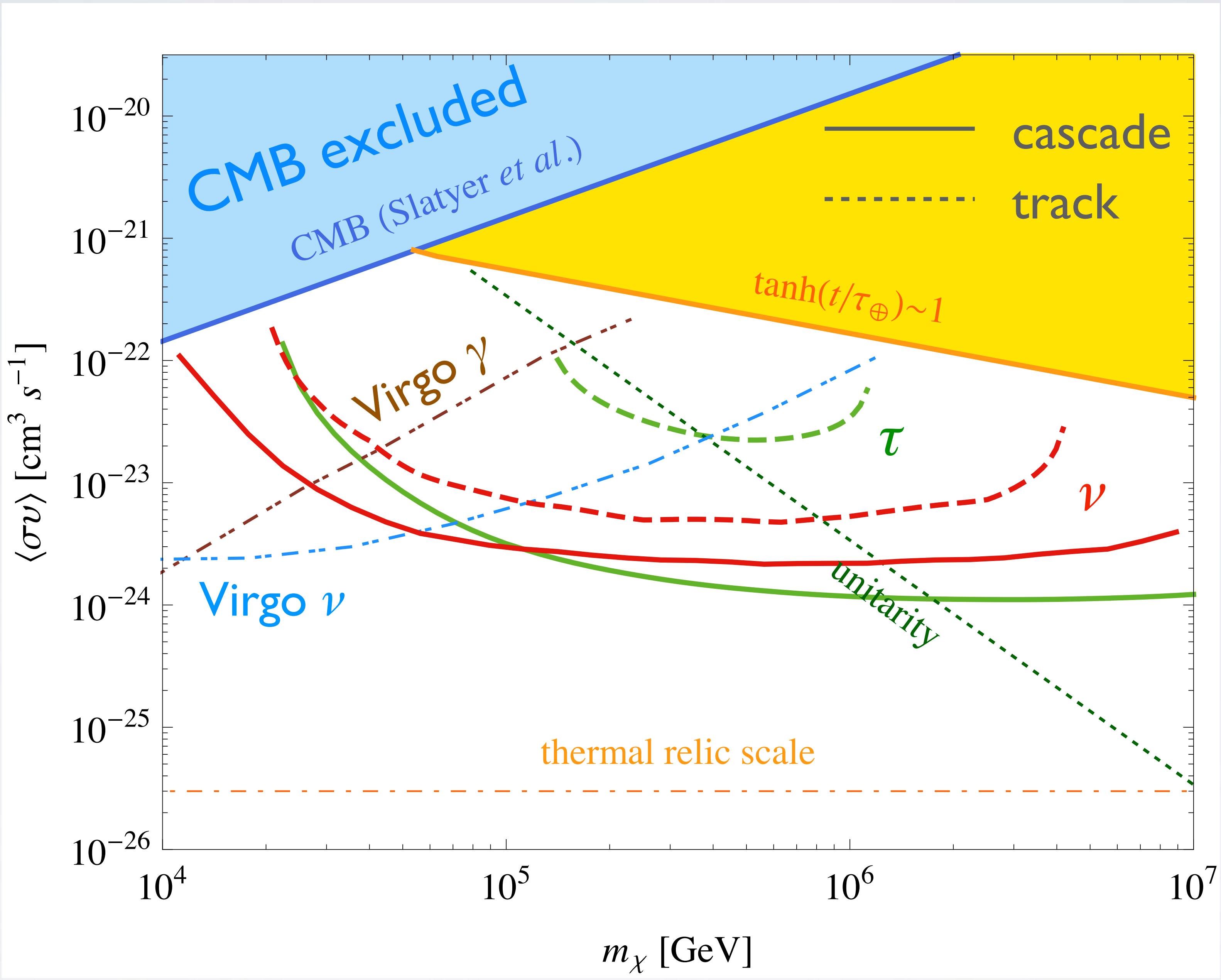



Annihilation




- Ignoring evaporation and self-interaction effects
- $\langle \sigma v \rangle = 3\times10^{-26}$ cm$^3$ s$^{-1}$
- $\sigma_{\chi p} = 10^{-45}$ cm$^2$
- Earth DM is not in the $N_\chi$ equilibrium state

# Sensitivity on $\langle \sigma v \rangle$: heavy $m_\chi$ at Earth

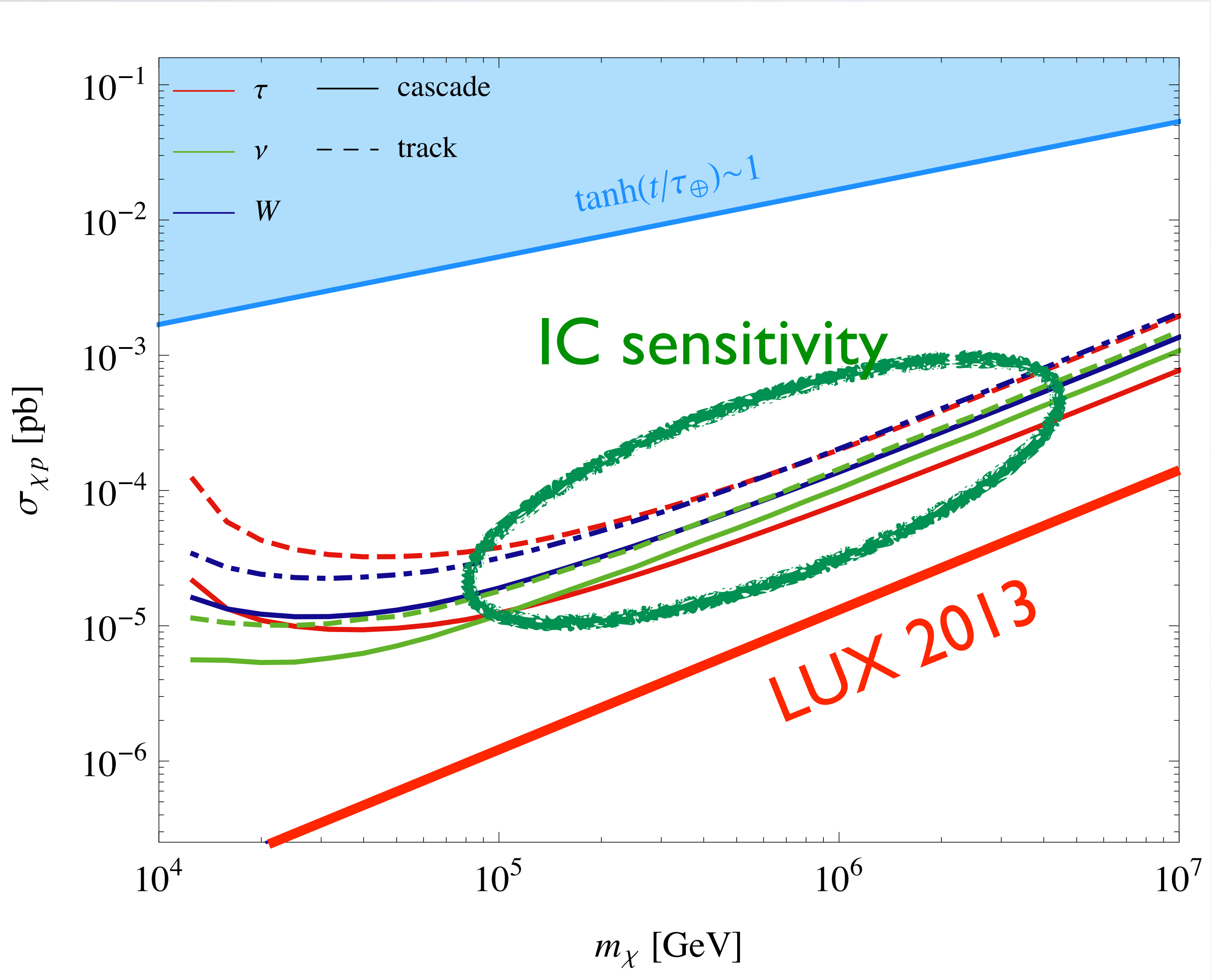



- $\sigma_{\chi p}$ is taken from LUX upper bound

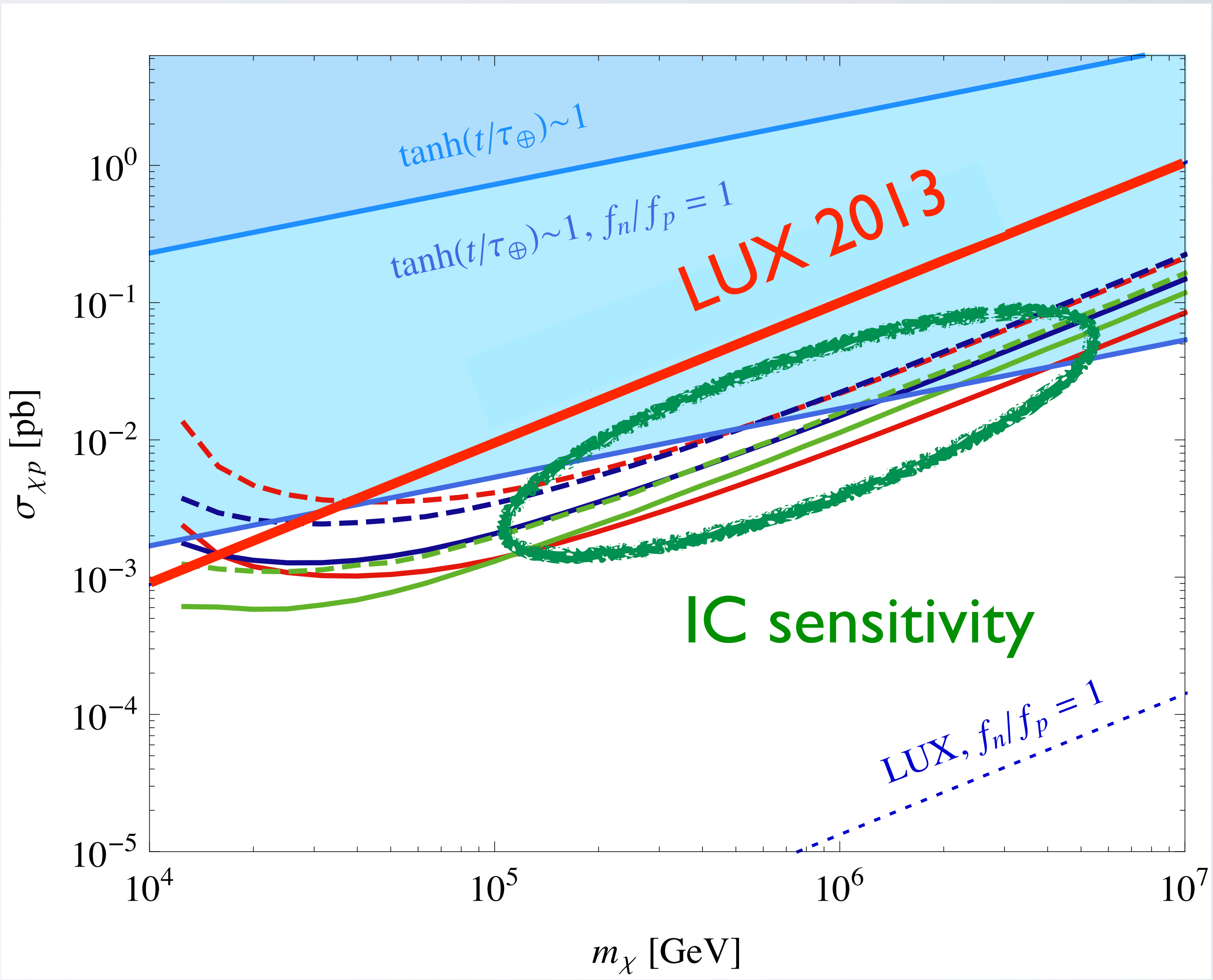
T. R. Slatyer *et al.*, *Phys. Rev. D* **80**, 043526 (2009)
M. Murase *et al.*, *JCAP* **02**, 028 (2013)
G.-L. Lin *et al.*, *Phys. Rev. D* **91**, 033002 (2015)

# Sensitivity on $\sigma_{\chi p}$: heavy $m_\chi$ at Earth

$f_n/f_p = 1$




$f_n/f_p = -0.7$




- $\langle \sigma v \rangle$ is taken to be $3\times10^{-26}$ cm$^3$ s$^{-1}$
- Above the LUX constraint line is excluded
- With isospin violation, IC sensitivities are much stringent than the direct search

# IceCube and indirect DM search

- High $m_\chi$ ➞ By observing Earth DM
- Low $m_\chi$ ➞ By observing Solar DM
- IceCube has the capability to probe $\sigma_{\chi\chi}$, $\sigma_{\chi p}$ and $\langle \sigma_A v \rangle$
- In this talks, we only focus on the model-independent analysis

# Contents


Summary

# In closing…

- Evidences of dark matter are introduced
- The formalism for the evolution of DM population in the Sun
- The thermal transport between DM and nucleus will alter the evolution process
- IceCube neutrino detector and its role in the DM indirect search
- Various IceCube sensitivities are presented