

Neutrinos vs. Dark Matter (and what to do about them)

David E. Morrissey (TRIUMF)

with

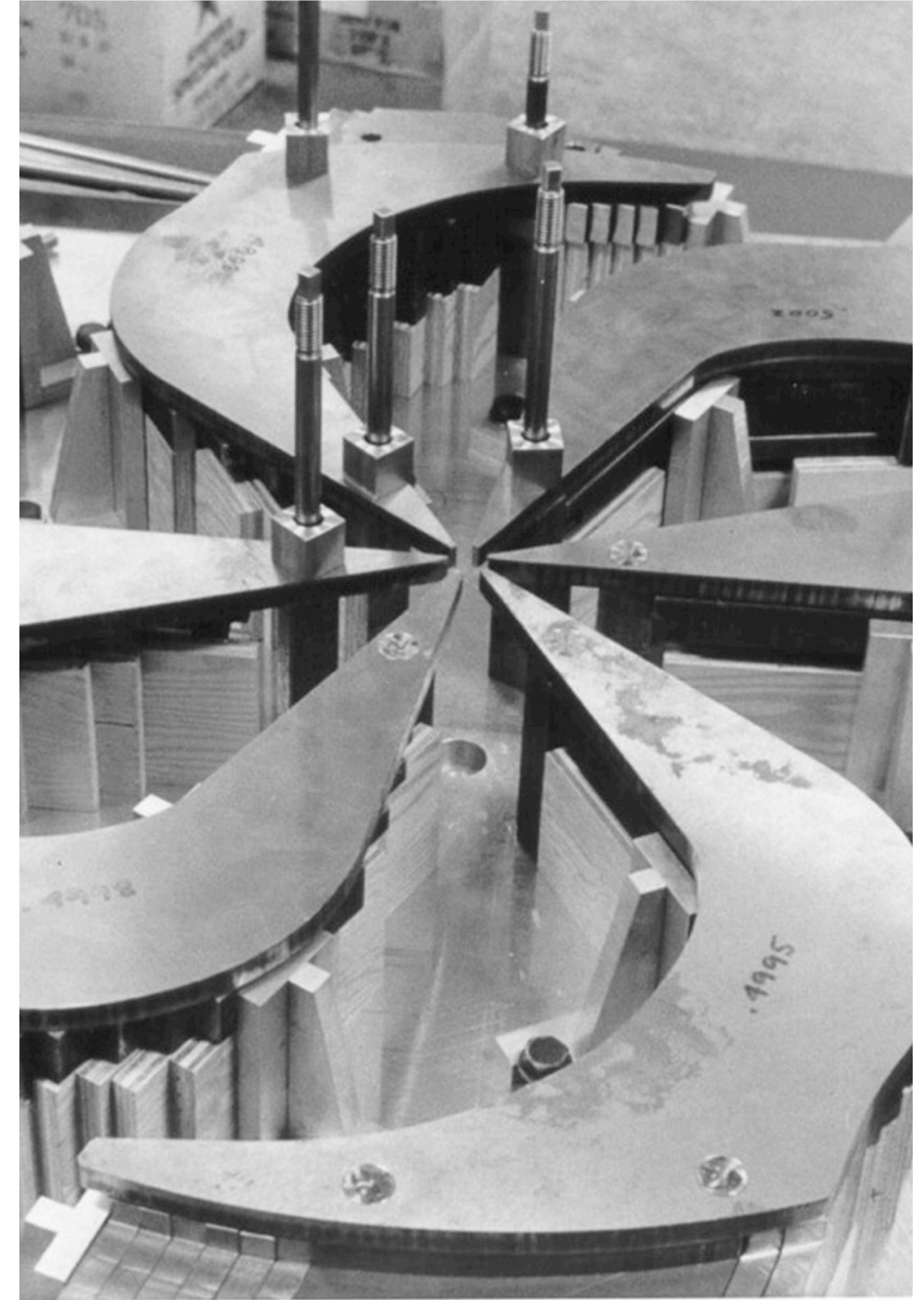
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Navin McGinnis (TRIUMF)

Phys.Rev.D 105 (2022) 3, 03502 [[2108.03248](#)]
+ [[2305.04943](#)]

From Colliders to the Early Universe
2023/05/28



From (My Physics) Early Universe

2

- Inflation, reheating, cooling, phase transitions, BBN, CMB, ...
- **2000:** I arrive at U Chicago for grad school with little detailed knowledge of particle physics. I try out experimental cosmology and condensed matter.
- **2002:** Getting interested in particle theory, I connect with Carlos. He agrees to give me a chance as his first grad student.
- **2002-2005:** We have lots of fun studying beautiful mirrors, electroweak baryogenesis, and more. I also get to work with Marcela.
- **2005-present:** Carlos and Marcela continue to support and inspire me.

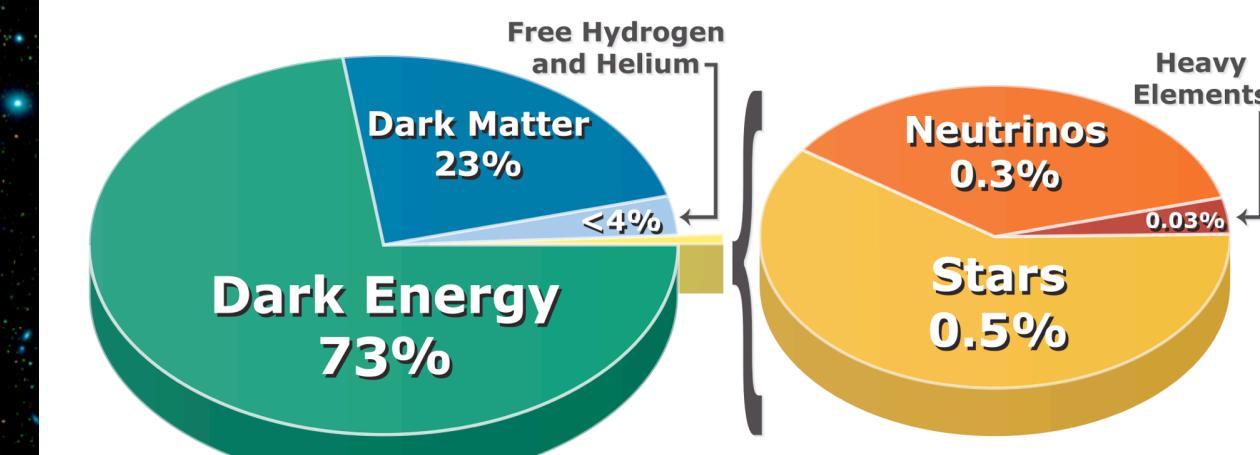
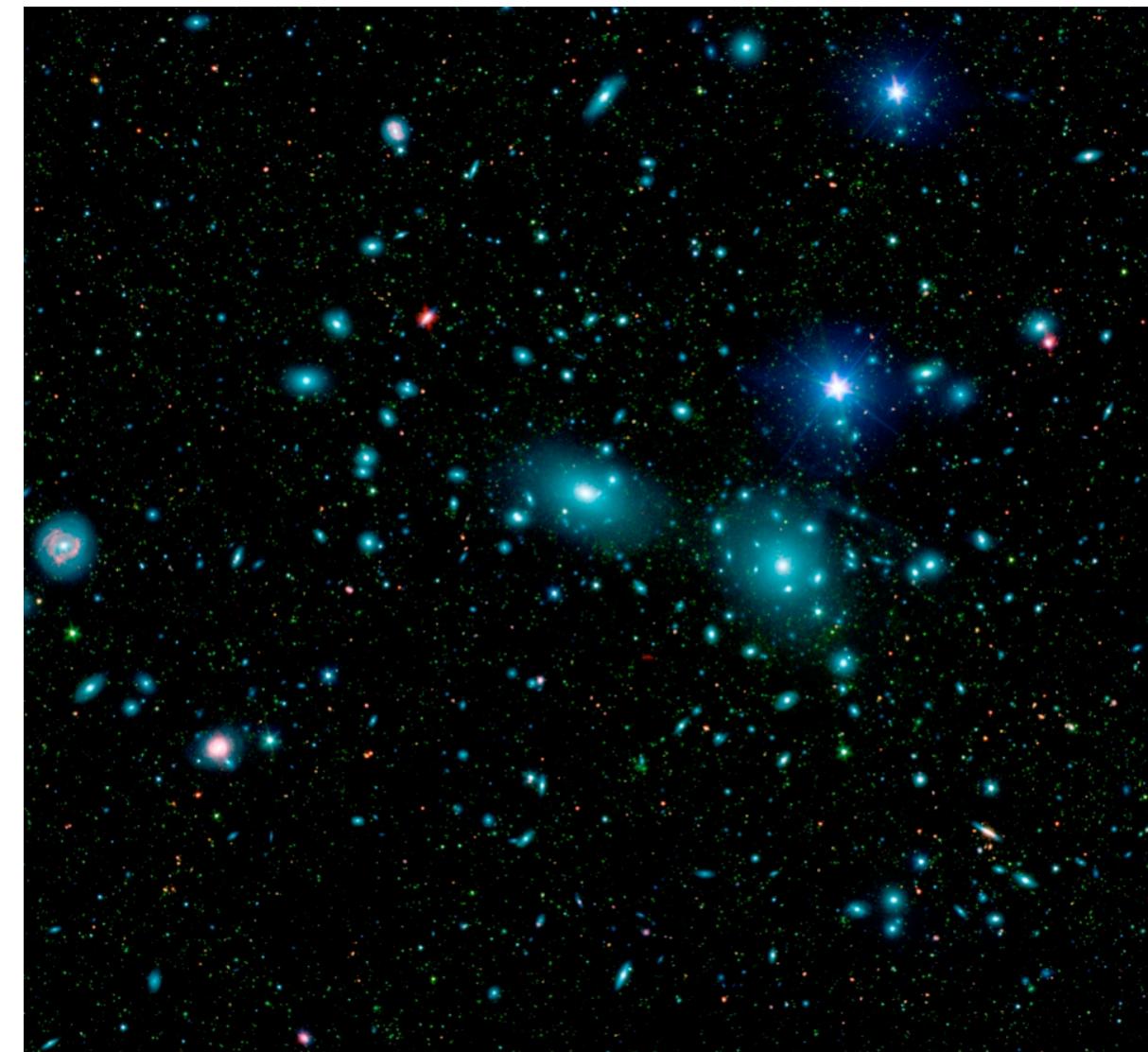
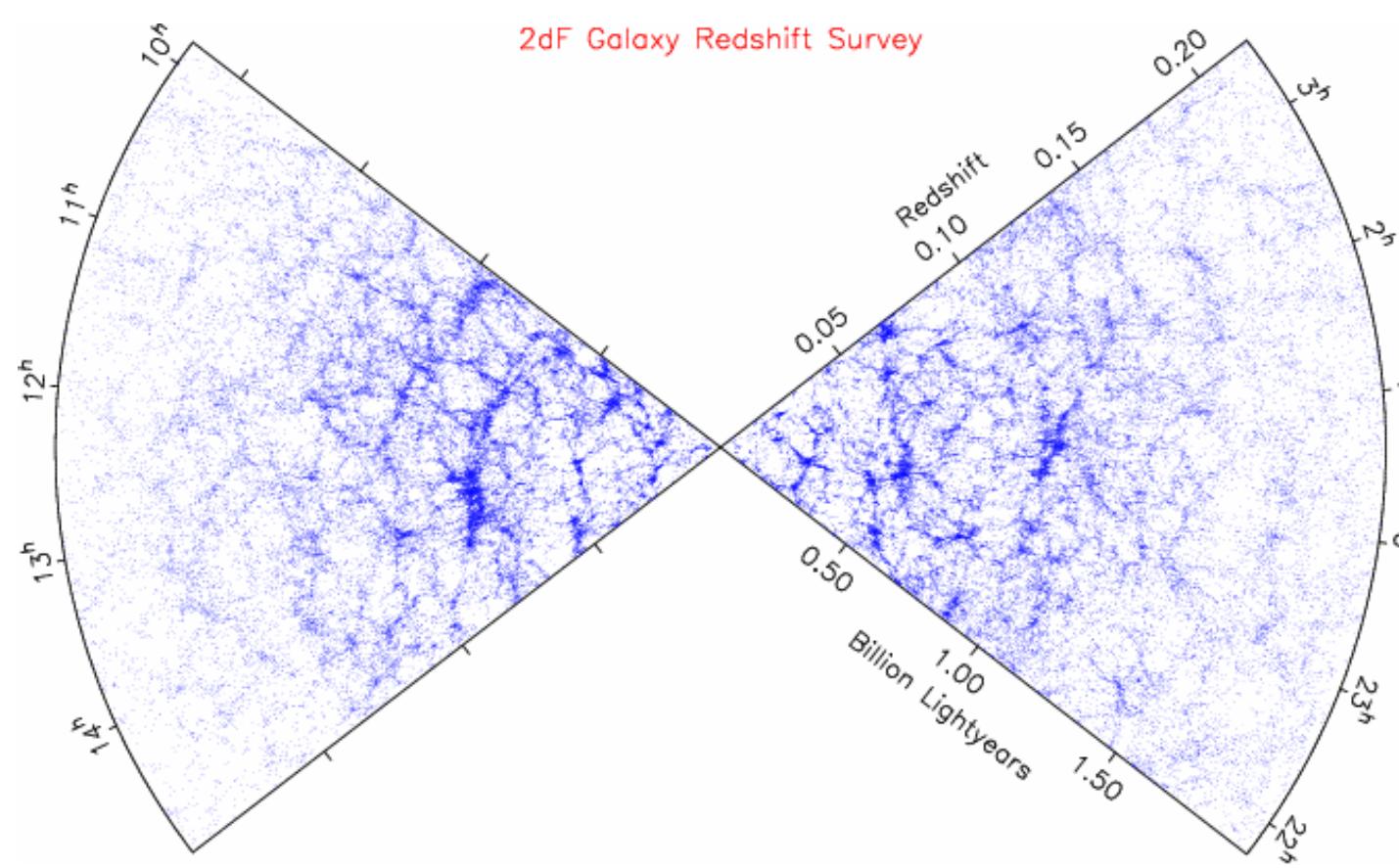
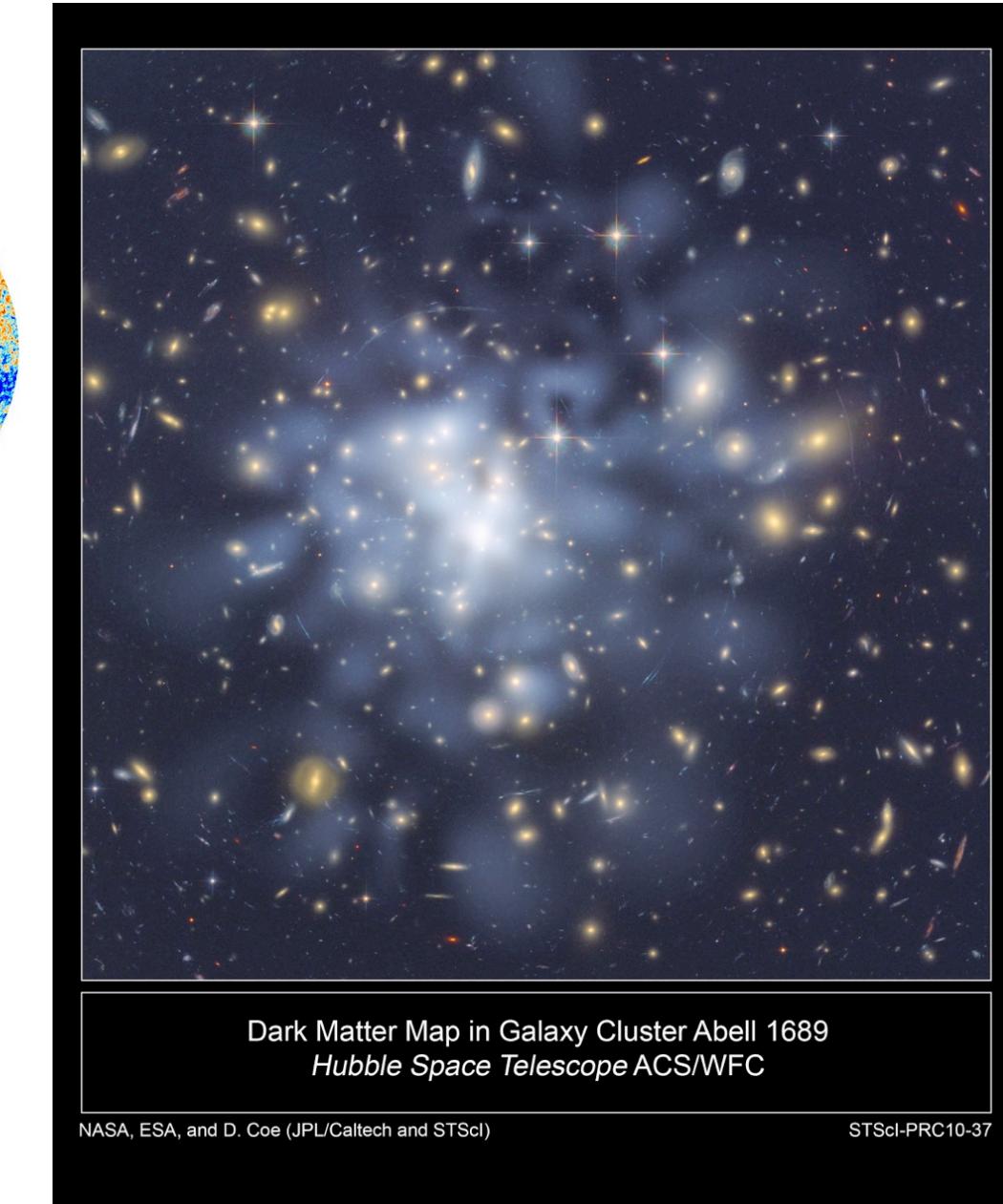
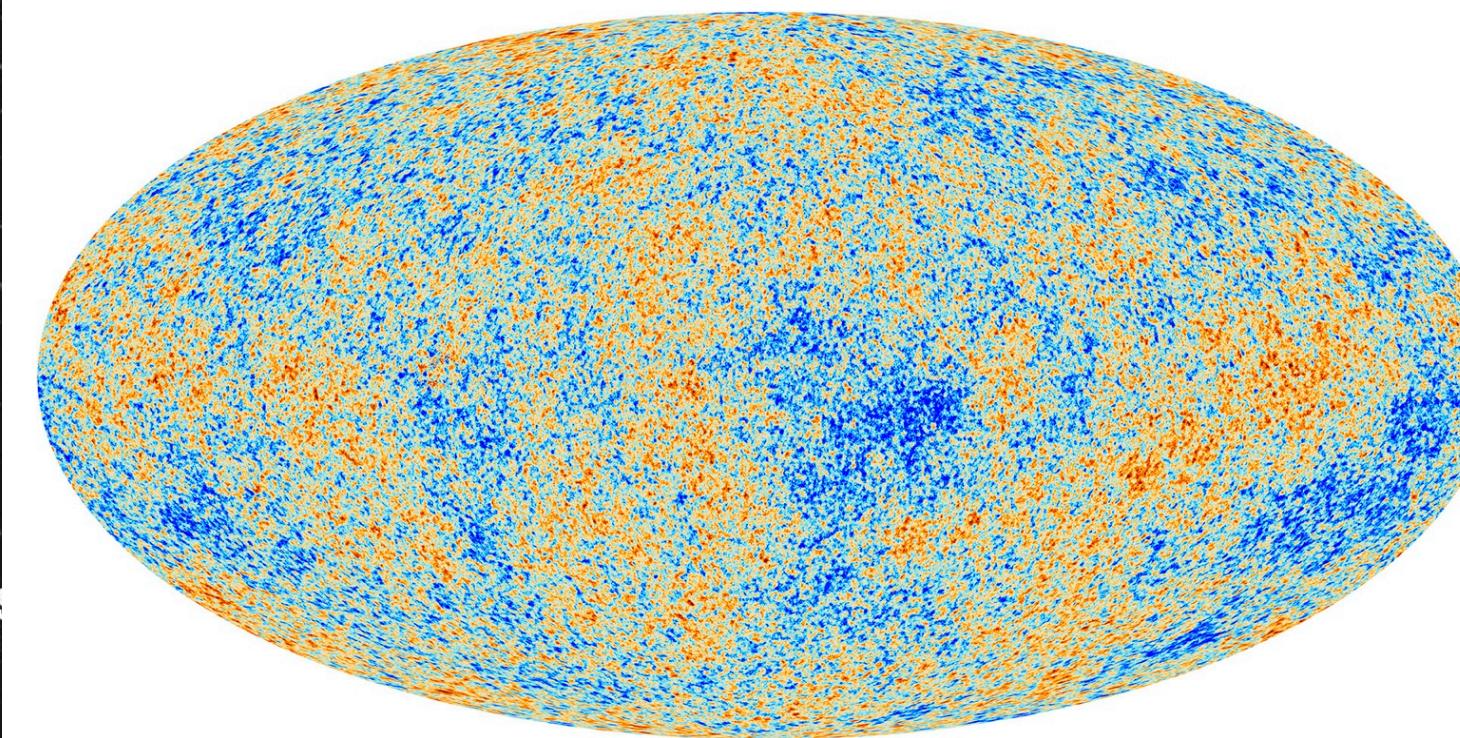
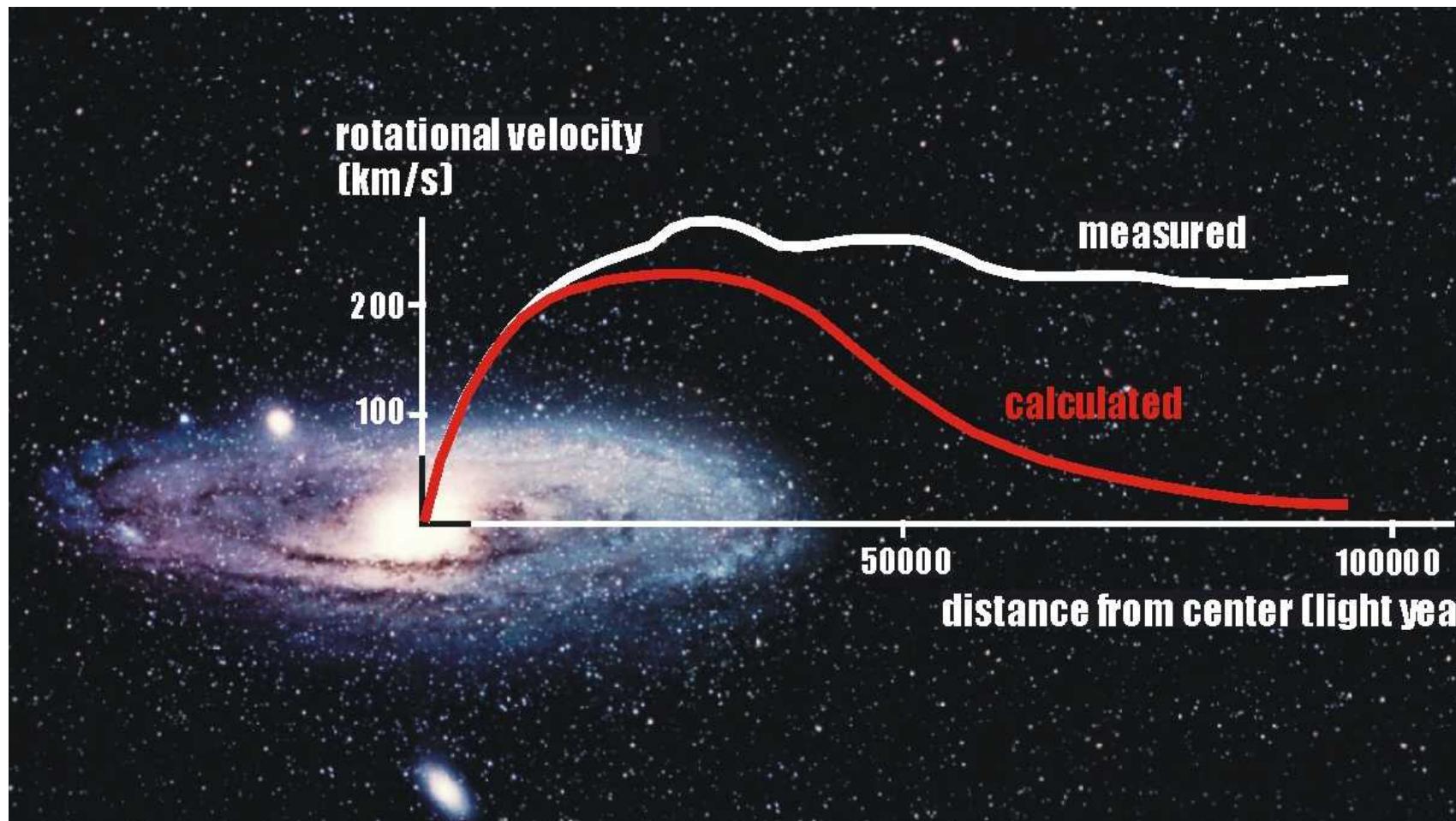
To (Community) Colliders

3

- Marcela and Carlos have fostered and connected a remarkable community.
- As a young graduate student, they helped me connect with many people:
 - Csaba Balázs
 - Ed Berger
 - John Campbell
 - Cheng-Wei Chiang
 - Paddy Fox
 - Graham Kribs
 - Irina Mocioiu
 - Brandon Murakami
 - Eduardo Pontón
 - Géraldine Servant
 - Jing Shu
 - Tim Tait
 - and many more ...

Evidence for Dark Matter

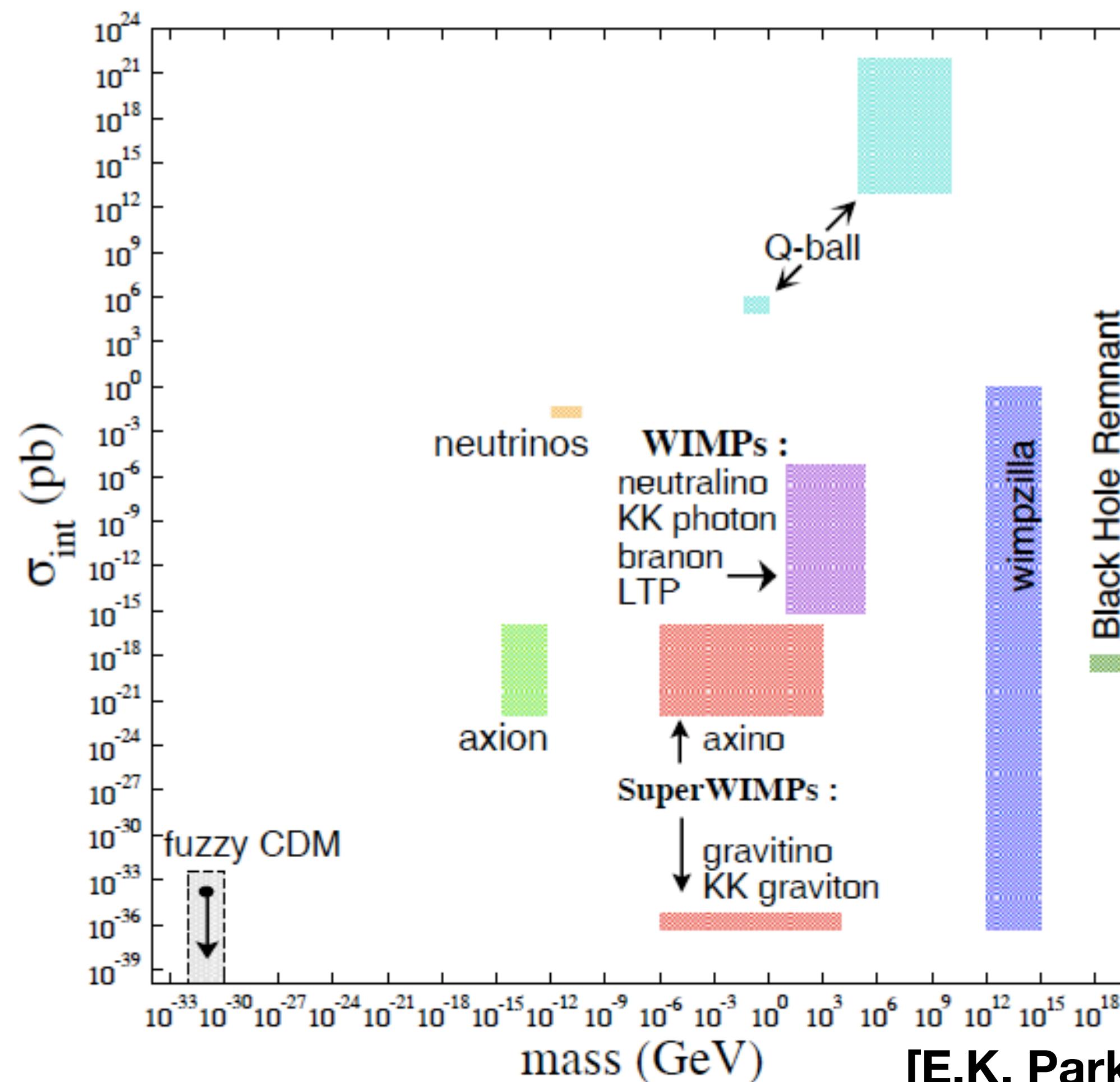
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What is Dark Matter?

5

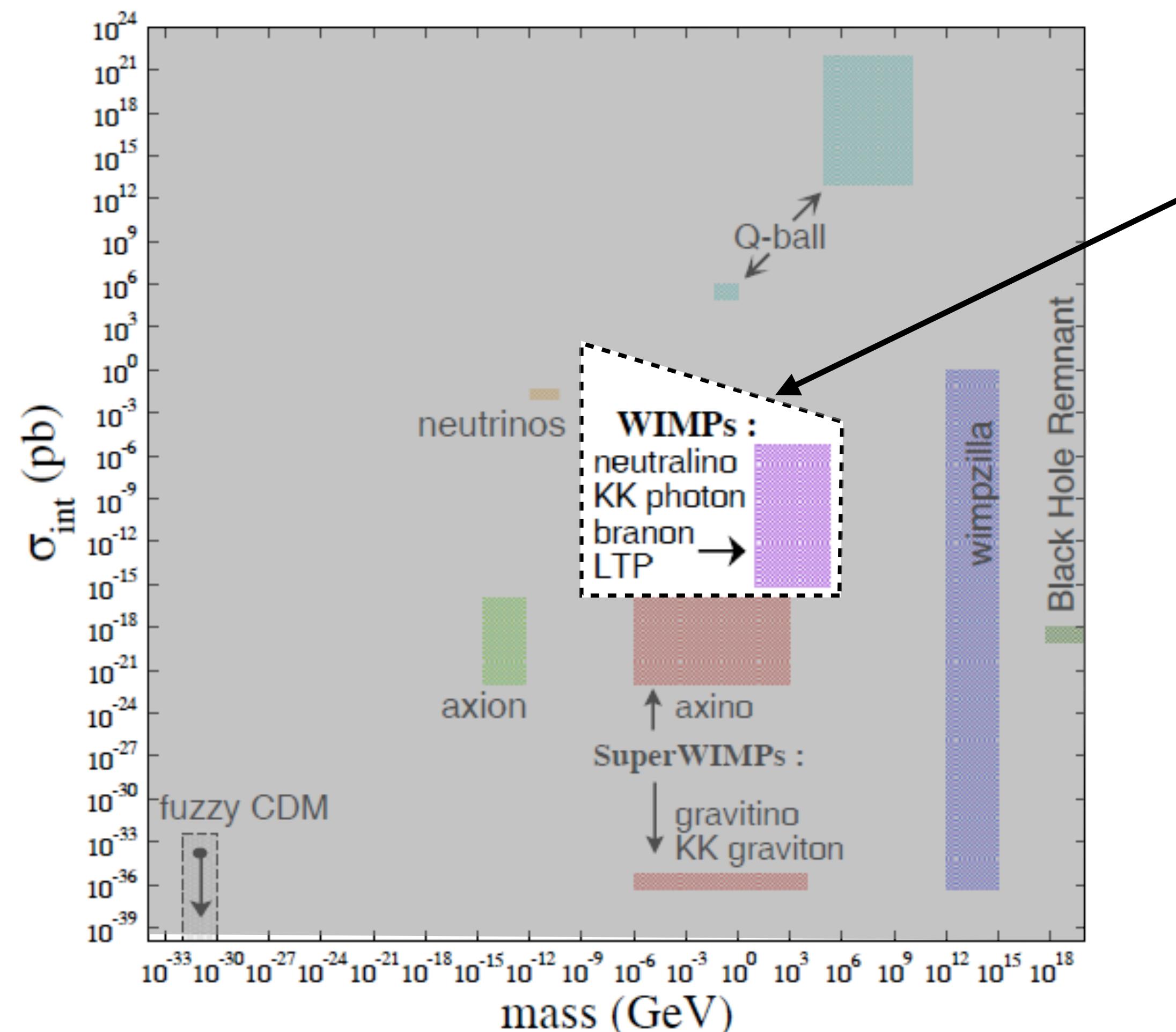
- We don't know!
All evidence comes from gravitational effects on visible matter.



What is Dark Matter?

6

- We don't know!
All evidence comes from gravitational effects on visible matter.



Thermal DM
⇒
**was once in
thermodynamic
equilibrium
with visible matter**

[E.K. Park, HEPAP DMSAG, 2007]

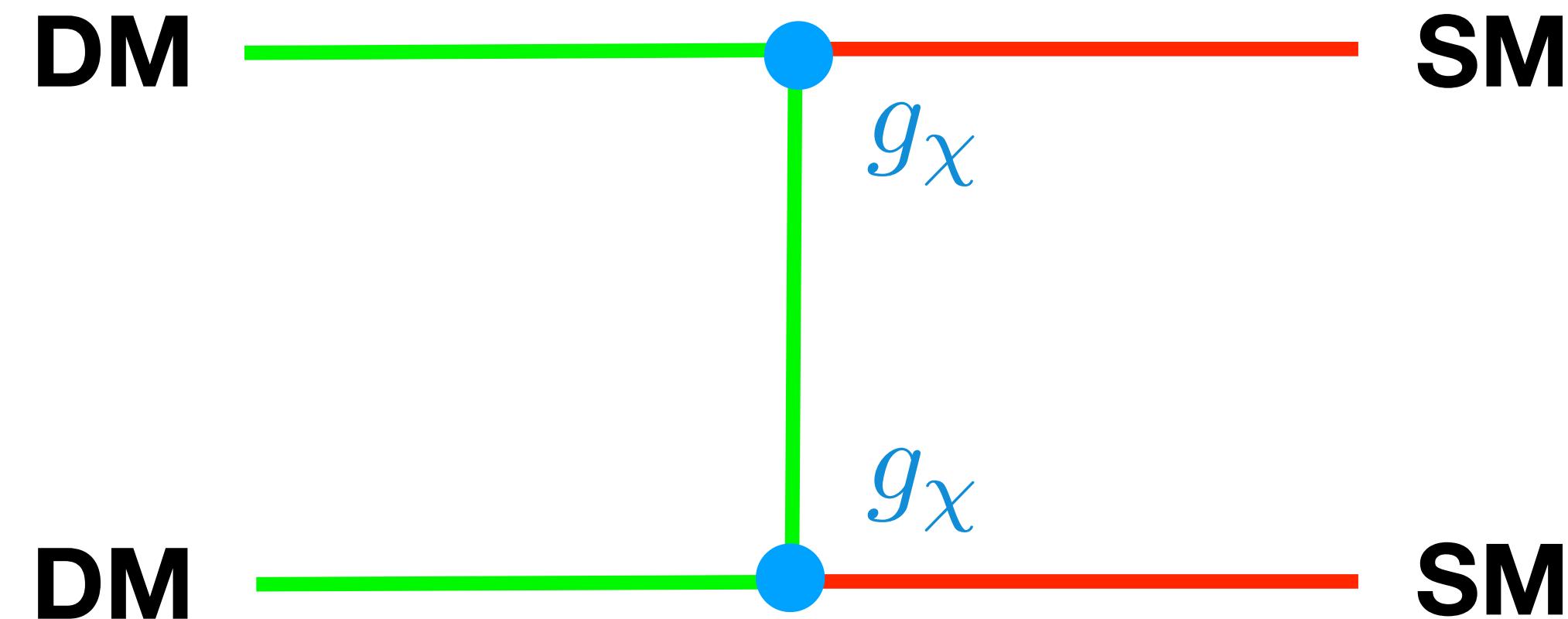
Thermal Dark Matter: Freeze Out

7

- Thermal DM can produce the observed abundance by Freeze Out!

- Requirement: $\langle \sigma_{ann} v \rangle \simeq 3 \times 10^{-26} \text{cm}^3/\text{s}$

- This is determined by particle physics:
e.g.



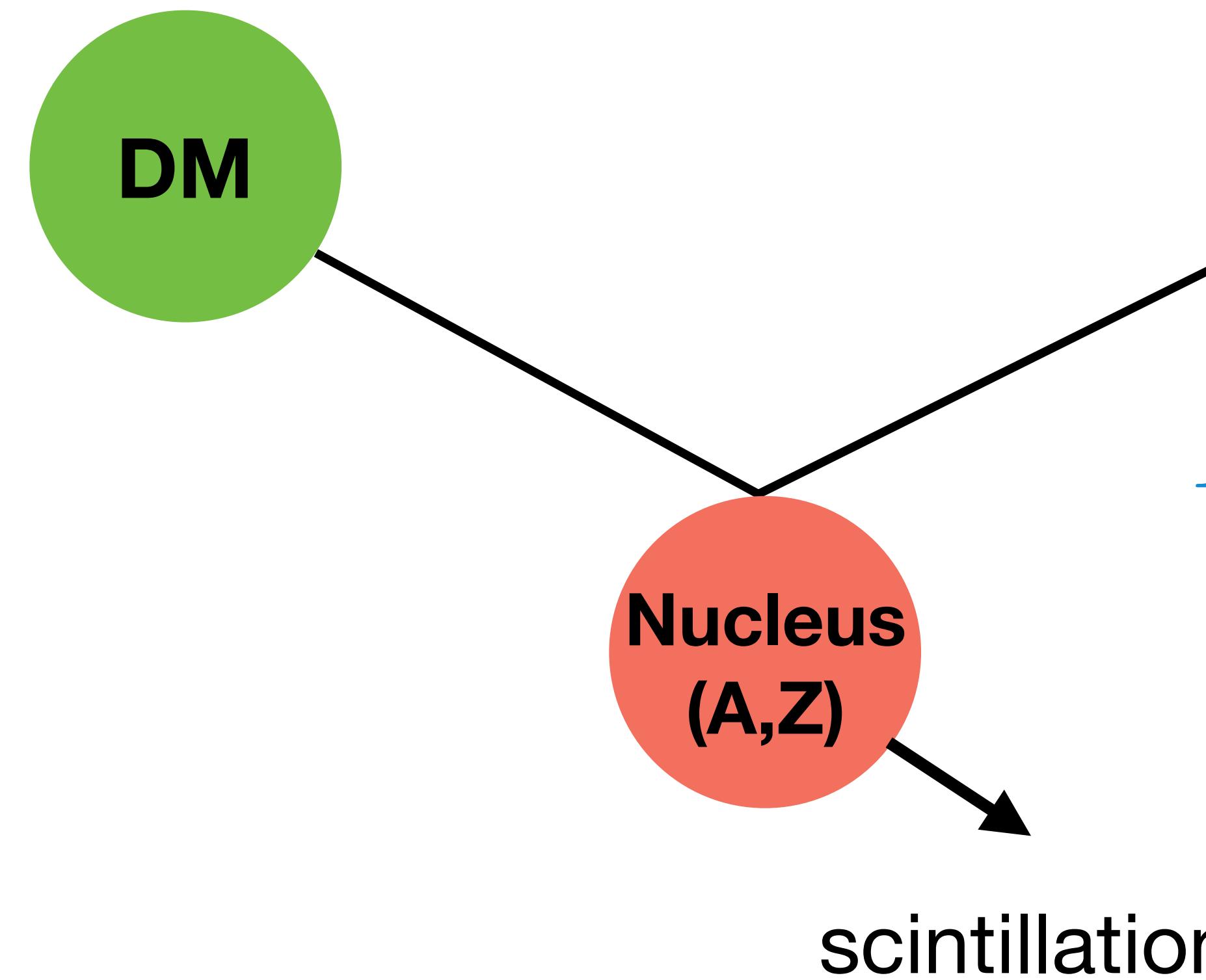
$$\langle \sigma_{ann} v \rangle \simeq \frac{g_\chi^4}{m_\chi^2}$$

- Can work for masses $m_\chi \sim 10 \text{ MeV} - 50 \text{ TeV}$, $g_\chi \gg \text{gravity}$.

Dark Matter Detection in the Lab

8

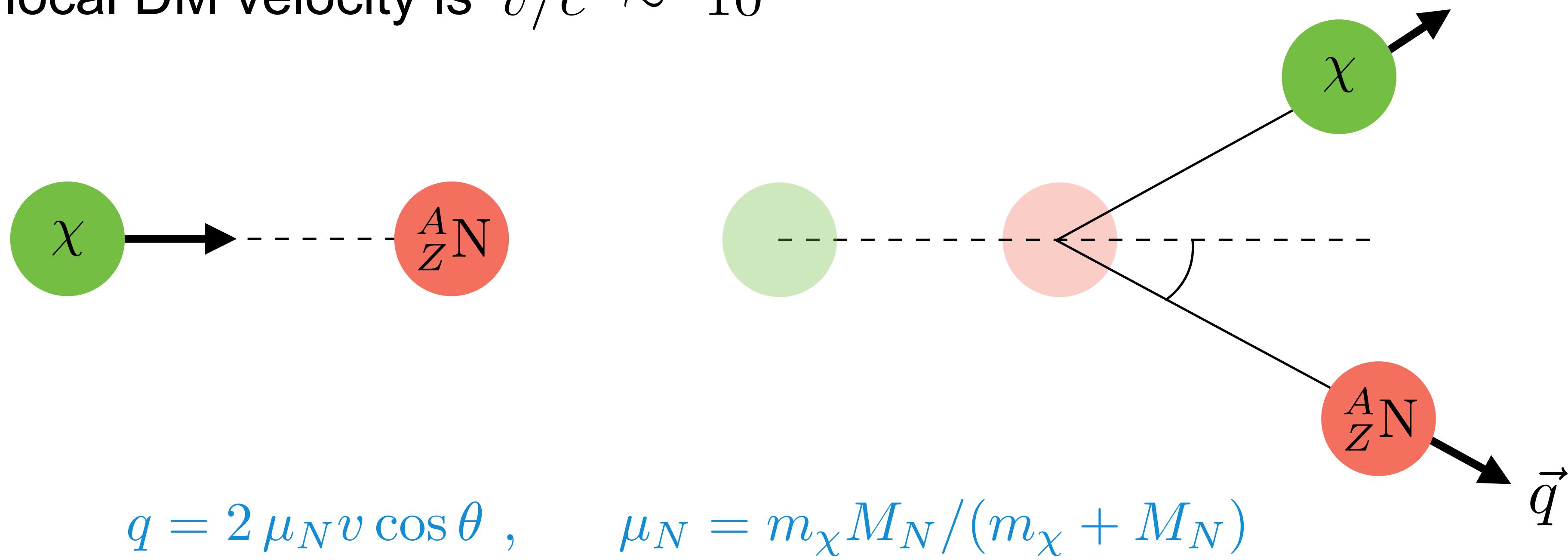
- If DM is all around us and interacts with the SM, it might be detectable!
- The most common detection strategy is to look for **nuclear recoils**.



DM-Nucleus Kinematics

9

- Typical local DM velocity is $v/c \sim 10^{-3}$



$$E_R = \frac{q^2}{2M_N} \lesssim (200 \text{ keV}) \left(\frac{M_N}{100 \text{ GeV}} \right) \left(\frac{\mu_N}{100 \text{ GeV}} \right)$$

DM = χ

DM-Nucleus Interactions

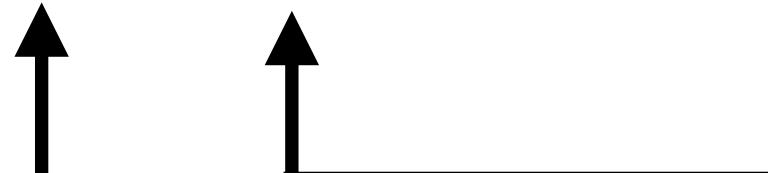
10

- DM-quark interaction → DM-nucleon interaction → DM-nucleus interaction
- In many theories, get a leading DM-nucleon potential of:

$$V_{n\chi}(\vec{x}) = f_n \delta^{(3)}(\vec{x}) \quad \text{spin-independent (SI)}$$

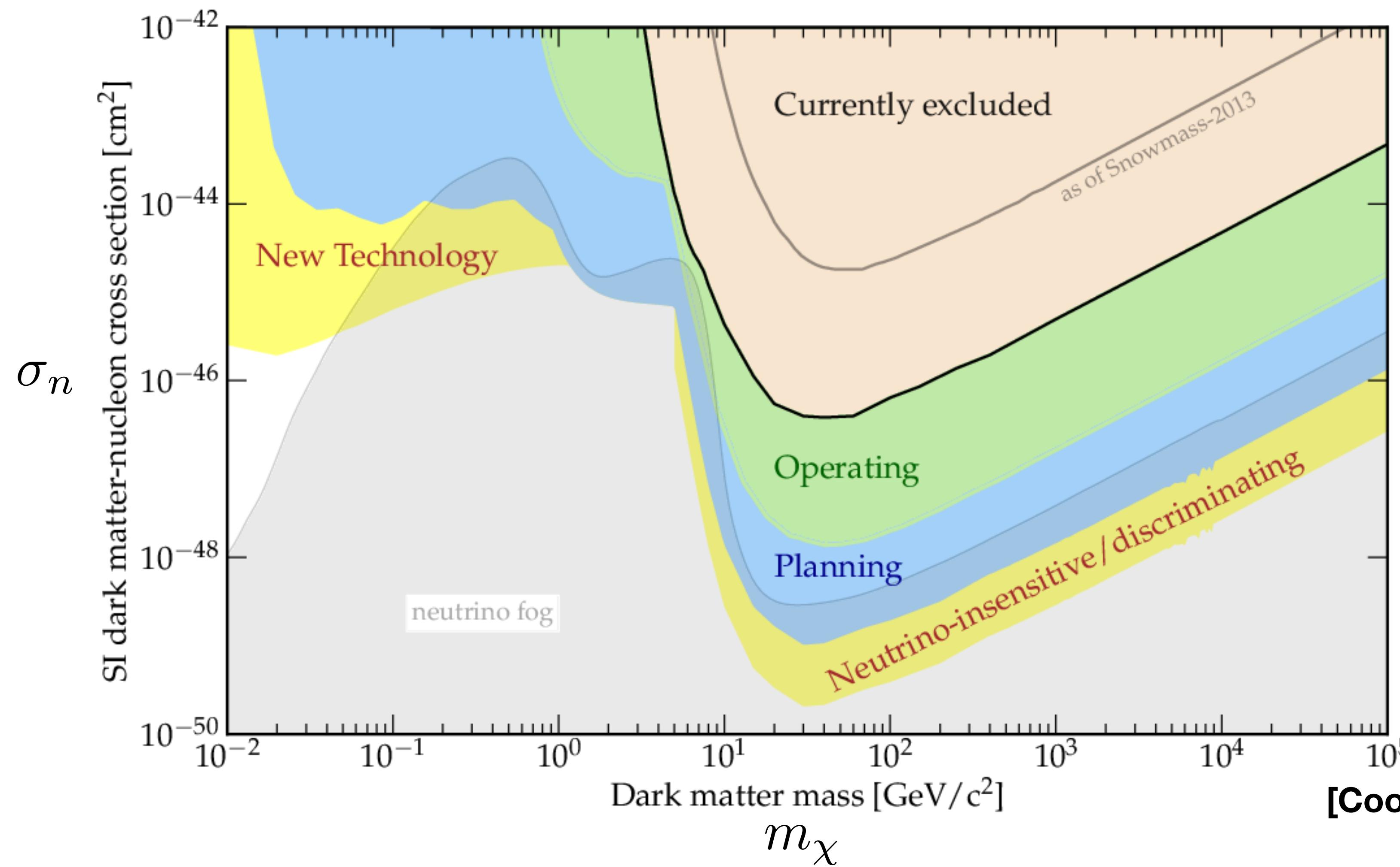
- For **SI** scattering, the cross section on nucleus ${}^A_Z N$ has the form

$$\frac{d\sigma_N}{dE_R} = \frac{A^2}{v^2} \left(\frac{\mu_N}{\mu_n} \right)^2 \sigma_n |F_N(E_R)|^2$$


**DM-nucleon
effective cross section** **nuclear response**

Dark Matter Direct Detection (SI)

- Existing searches have put strong bounds on thermal DM candidates:



Dark Matter Direct Detection (SI)

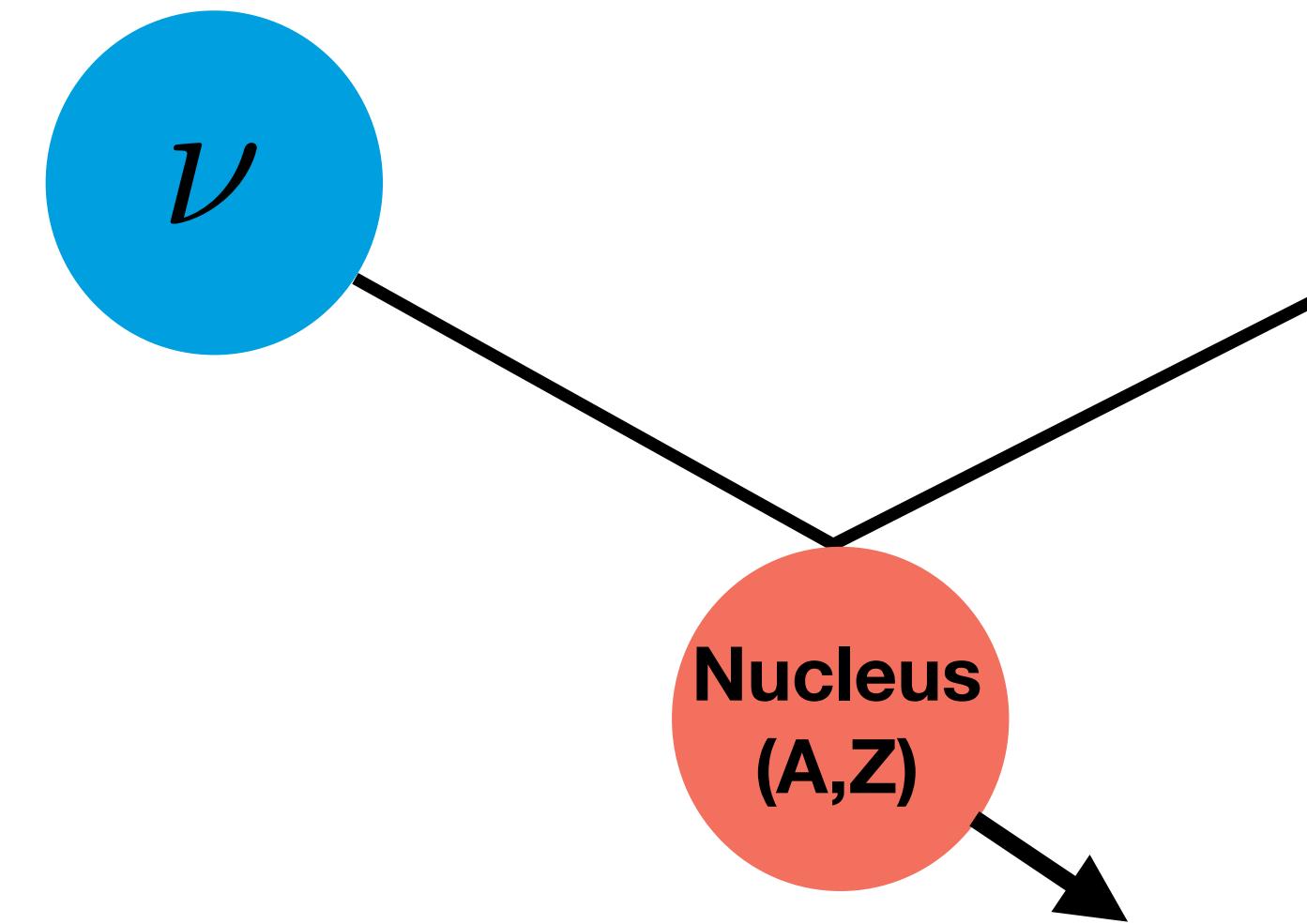
12

- Near future searches for WIMP ($m_\chi \gtrsim 10 \text{ GeV}$) spin-independent DM:
 - **XENONnT**: 8.3 tonnes of liquid **Xe** at Gran Sasso (LNGS)
 - **LZ**: 7 tonnes of liquid **Xe** at Sanford (SURF)
 - **PandaX-4T**: 4 tonnes of liquid **Xe** at Jinping (CJPL)
 - **DarkSide20k**: 20 tonnes of liquid **Ar** at Gran Sasso (LNGS)
- And beyond:
 - **DARWIN**: 40 tonnes of liquid **Xe** at (?)
 - **ARGO**: 300 tonnes of liquid **Ar** at SNOLAB (?)
 - **SuperCDMS**, **SBC**, **NEWS-G**, **SENSEI**, ... at lower masses ($m_\chi \lesssim 10 \text{ GeV}$)

DM Detection and Neutrinos

13

- These experiments aim for near zero instrumental/radiation background.
- But they are getting big enough that they will start to detect **neutrinos** from the sun, supernova, and atmospheric cosmic rays.



- How big is this background? How can it be reduced or mitigated?
Focus here on spin-independent scattering in **Argon** and **Xenon**.

Kinematics: Scattering on Nuclei

14

- Dark Matter:

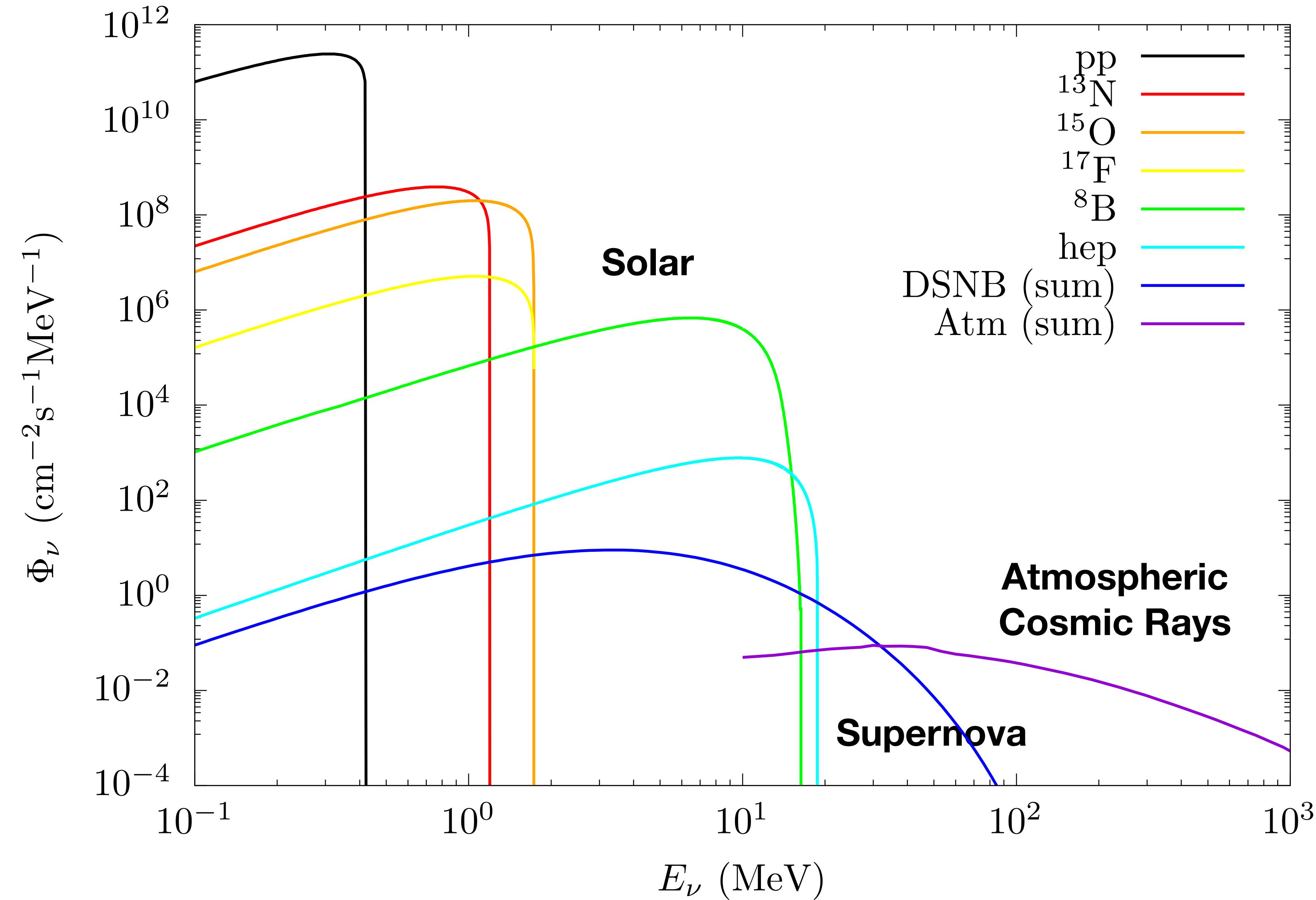
$$\begin{aligned} E_R &\leq 2 \frac{\mu_N^2}{m_N} v^2 \\ &\simeq (200 \text{ keV}) \left(\frac{100 \text{ GeV}}{m_N} \right) \left(\frac{\mu_N}{100 \text{ GeV}} \right)^2 \left(\frac{v}{10^{-3}} \right)^2 \end{aligned}$$

- Neutrino:

$$\begin{aligned} E_R &\leq \frac{2E_\nu^2}{m_N + 2E_\nu} \\ &\simeq (200 \text{ keV}) \left(\frac{E_\nu}{100 \text{ MeV}} \right)^2 \left(\frac{100 \text{ GeV}}{m_N} \right) \end{aligned}$$

- So need to worry about neutrinos with energies in the 10-1000 MeV range.

Neutrino Sources



Neutrino Scattering on Nuclei

16

- Mediated by Z-boson exchange:

$$\frac{d\sigma_{\nu N}}{dE_R} = m_N \frac{G_F^2}{4\pi} Q_W^2 \left[1 - \left(\frac{m_N E_R}{2E_\nu^2} \right) \right] |F_N(E_R)|^2$$



$$Q_W^2 = (A - Z) - Z(1 - 4 \sin^2 \theta_W)$$

nuclear response

- This *coherent neutrino-nucleus scattering* was first observed recently with accelerator neutrinos by the COHERENT experiment in Ar, Cs, and I.

Scattering per Recoil Energy

17

DM:

$$\frac{dN_\chi}{dE_R} = \frac{M T}{m_N} \int d^3v \underbrace{n_\chi f_{lab}(\vec{v}) v}_{\text{DM flux}} \frac{d\sigma_N}{dE_R}$$

$\nu :$

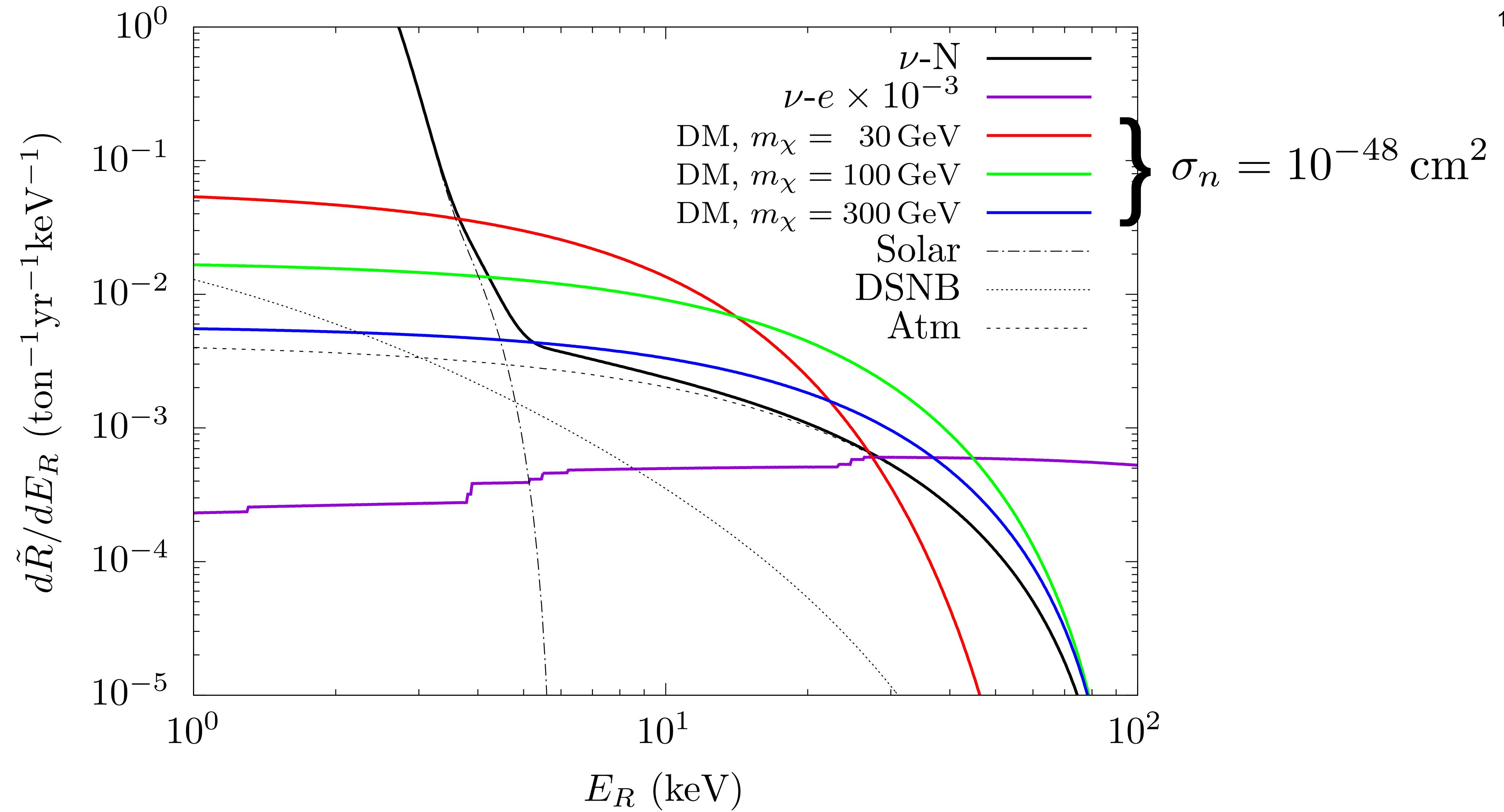
$$\frac{dN_\nu}{dE_R} = \frac{M T}{m_N} \int dE_\nu \underbrace{\Phi_\nu(E_\nu)}_{\nu \text{ flux}} \frac{d\sigma_{\nu N}}{dE_R}$$

$M T = \text{exposure} = \text{mass} \times \text{time}$

$f_{lab}(\vec{v}) = \text{DM velocity distribution}$

$\Phi_\nu(E_\nu) = \text{differential neutrino flux on target}$

Recoil Energy Spectra (Xe)



DM Signal vs. Neutrino Background

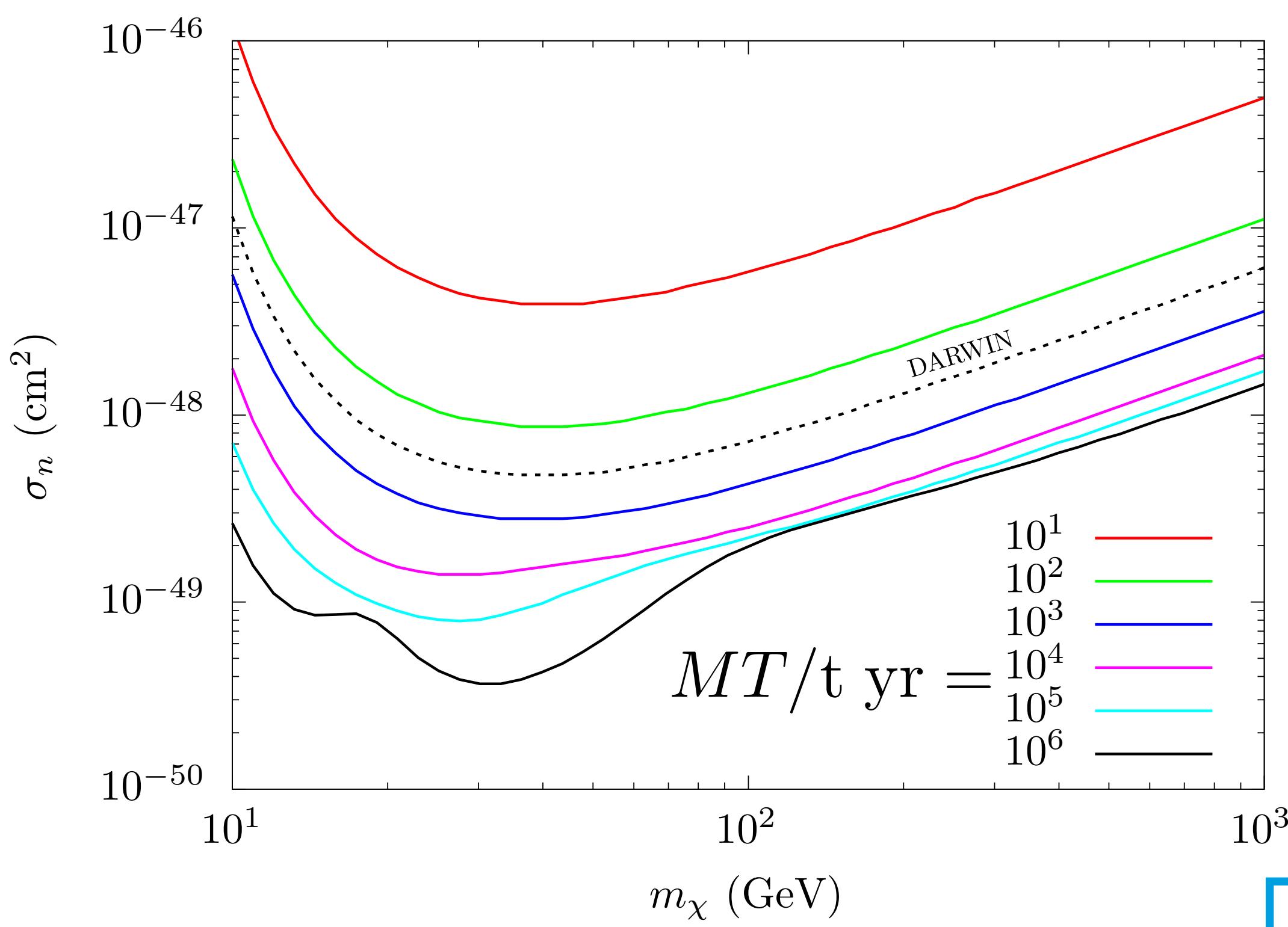
19

- Given total exposure $M T$, what is the maximum sensitivity to σ_n ?
- Define σ_{lim} to be the smallest σ_n for which background only can be excluded.
- Rules of thumb for simple counting:
 - background free: $\sigma_{lim} \propto M T$
 - statistics dominated: $\sigma_{lim} \propto \sqrt{M T}$
 - systematics dominated: $\sigma_{lim} \propto \text{constant}$
- But more information is available in the recoil spectrum — profile likelihood.
e.g. [Monroe + Fisher 2007, Billard et al 2013, O'Hare 2016, ...]

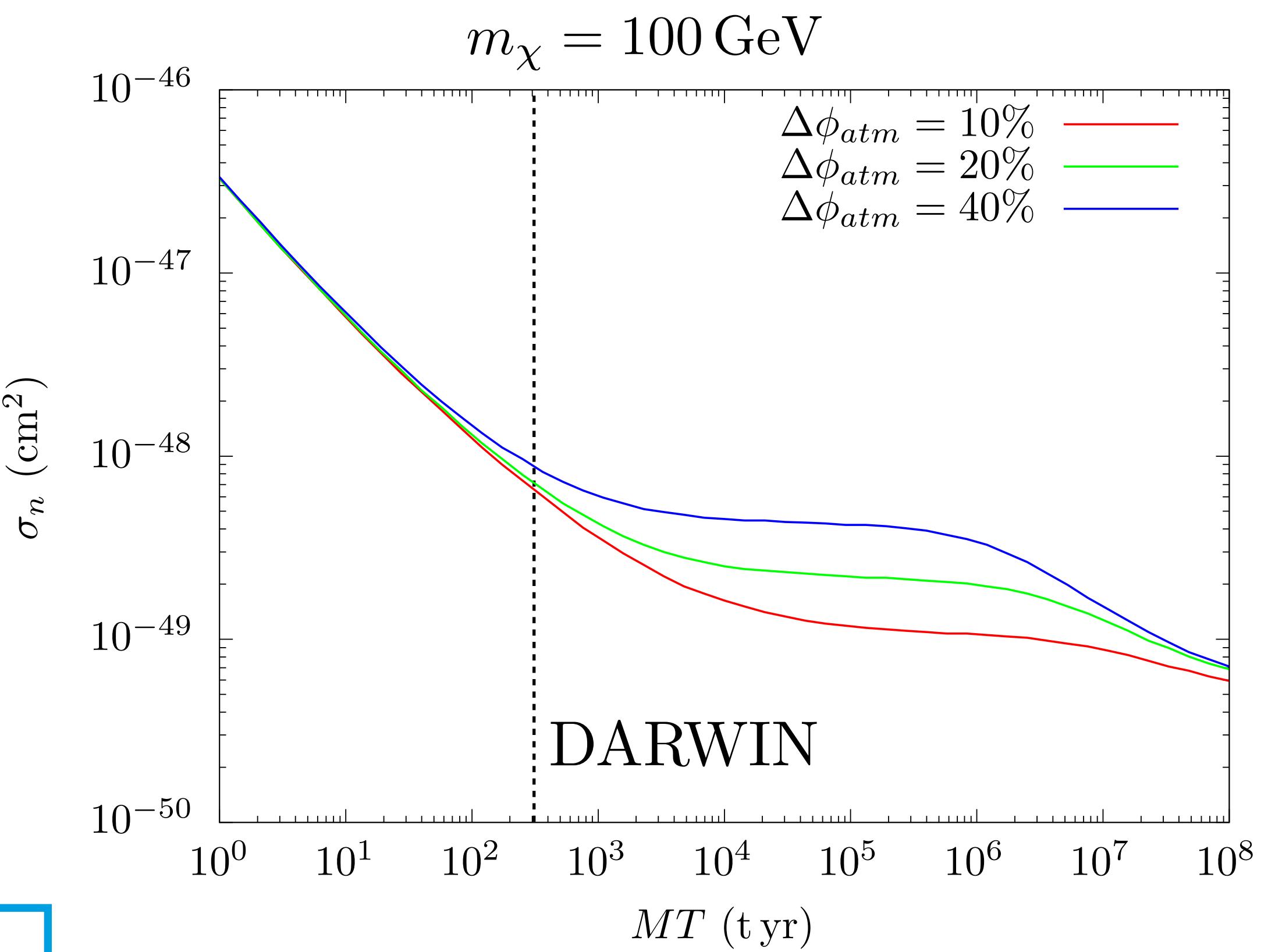
DM Signal vs. Neutrino Background

20

- Updated sensitivities in **Xe** and **Ar** based on projected future detector properties with neutrino-electron scattering and improved flux uncertainties:



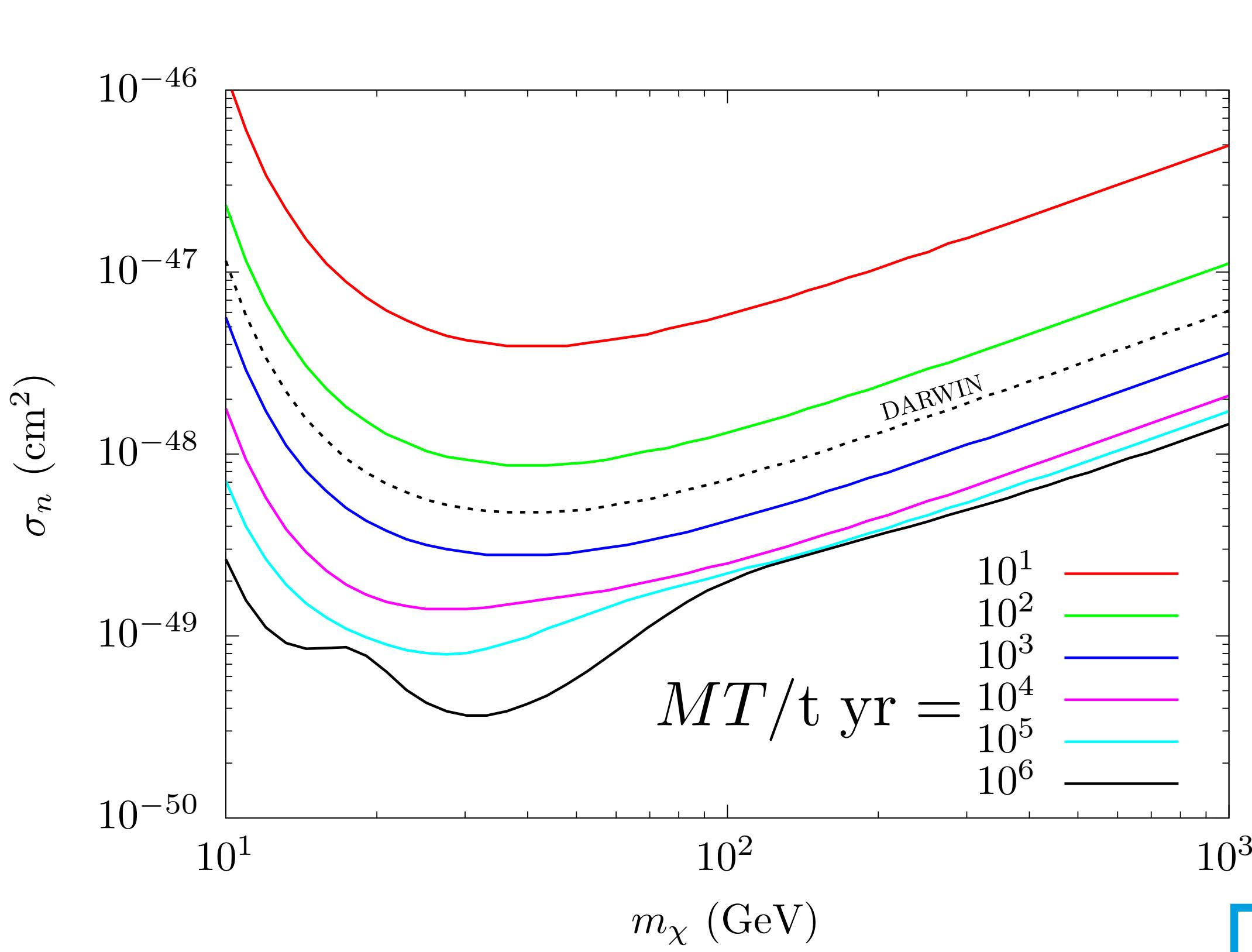
Xe



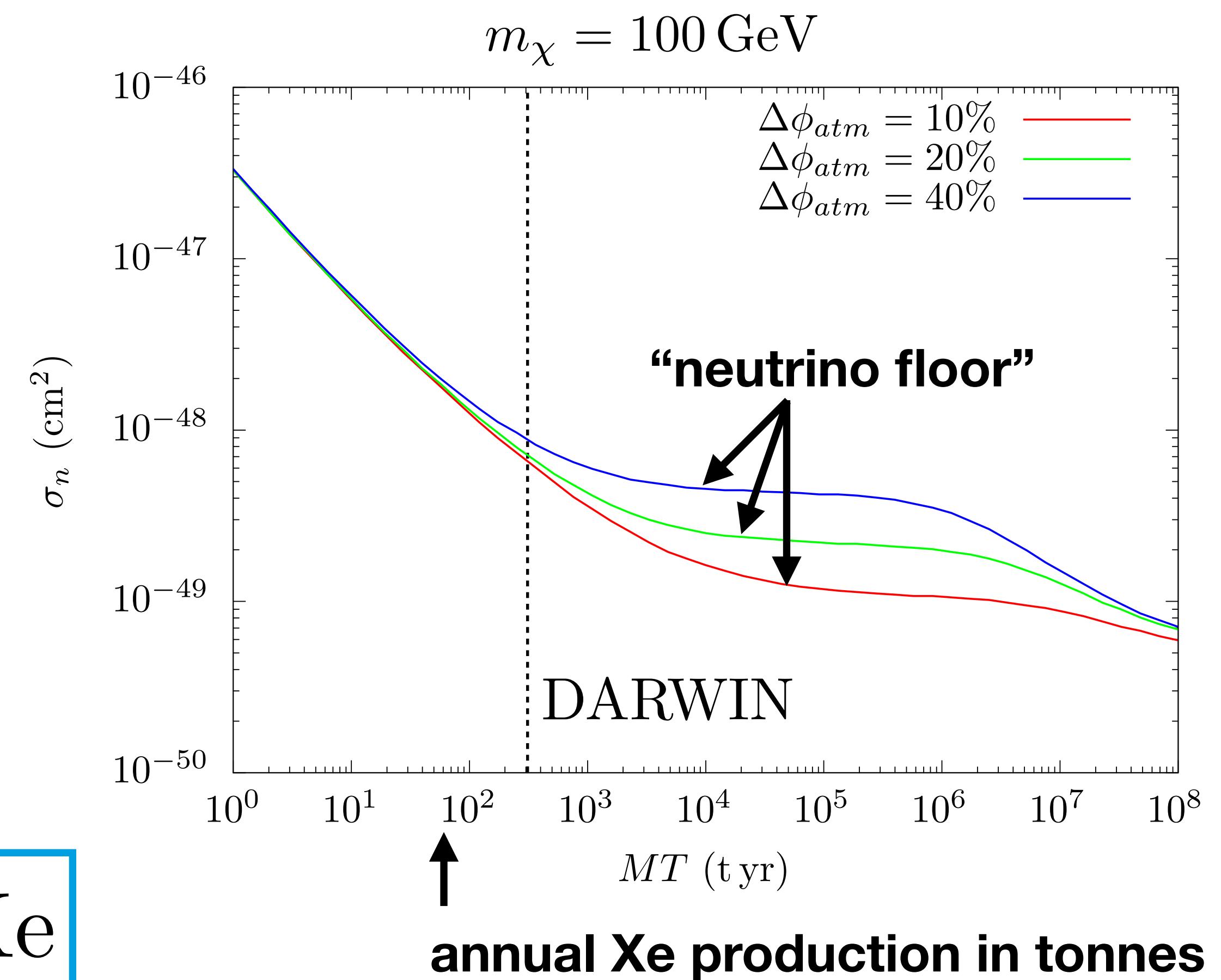
DM Signal vs. Neutrino Background

21

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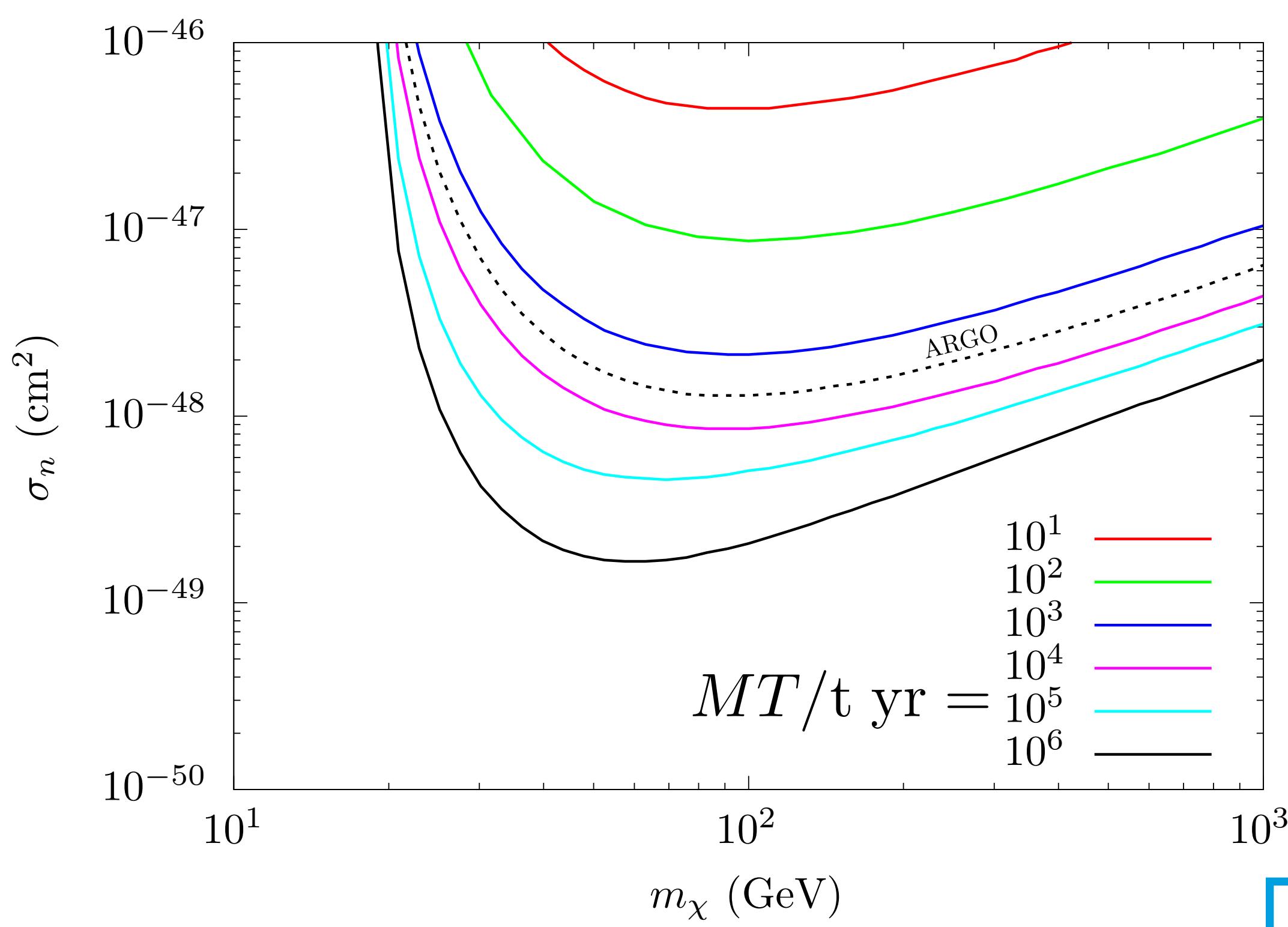
Xe



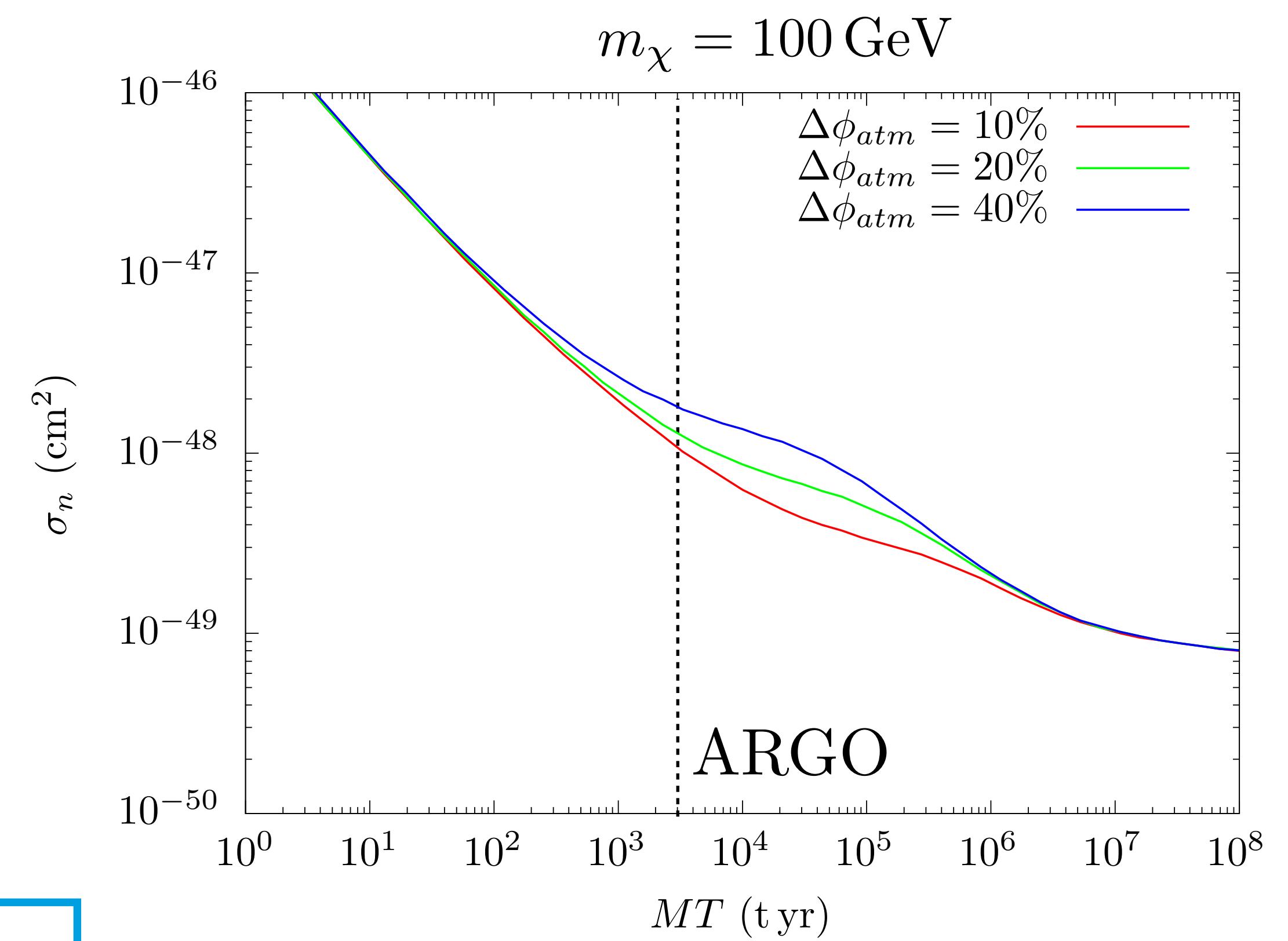
DM Signal vs. Neutrino Background

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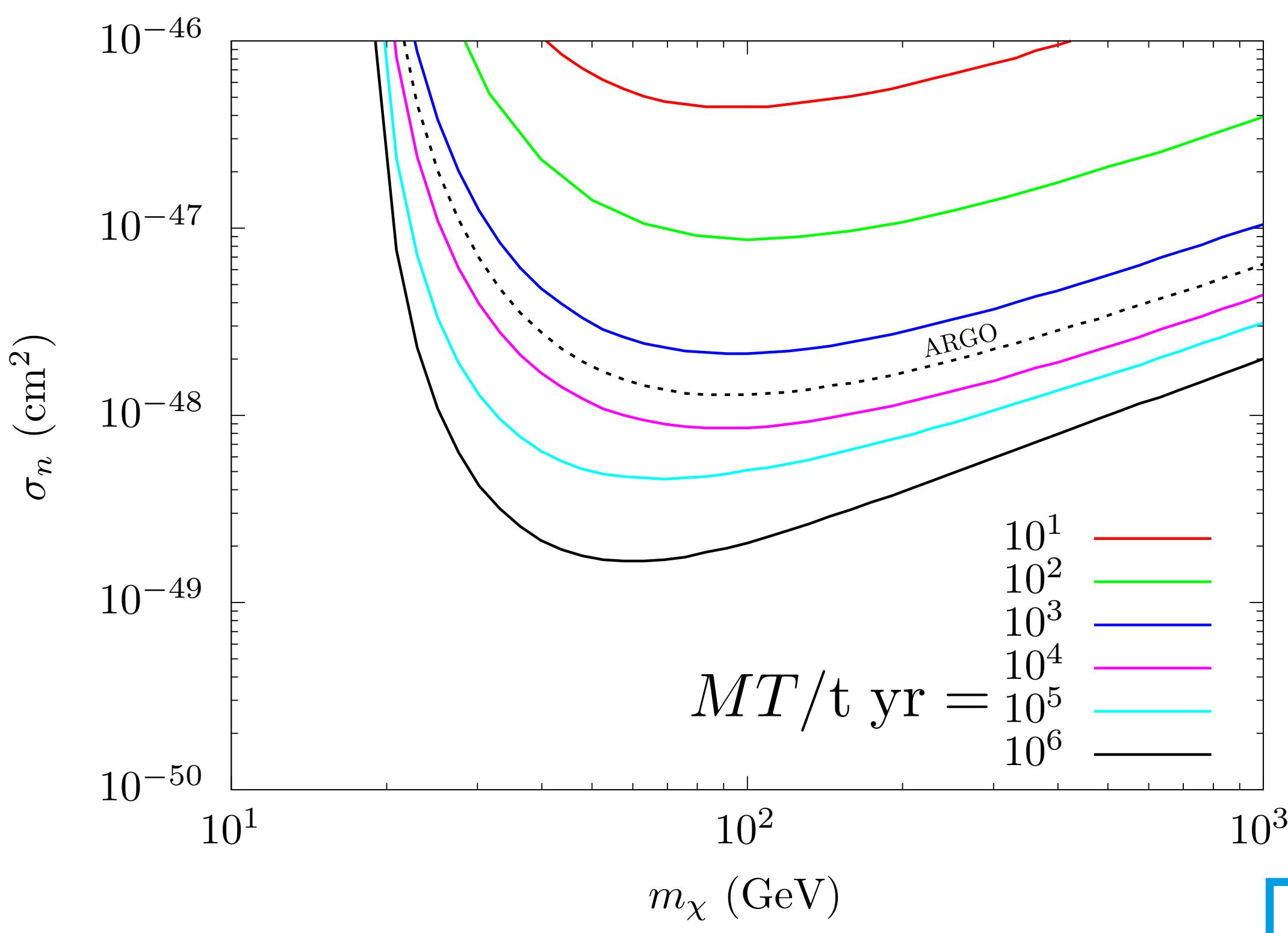
Ar



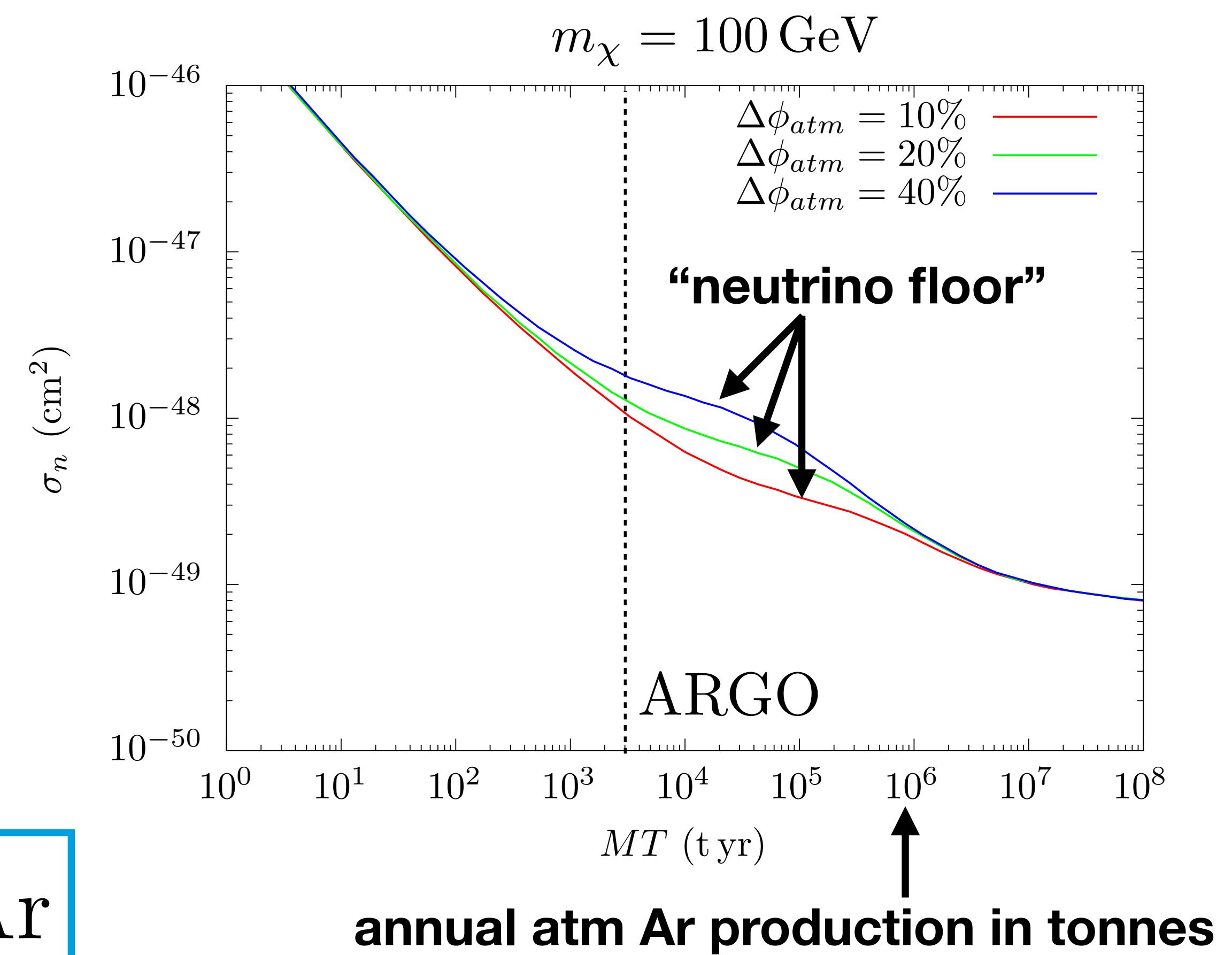
DM Signal vs. Neutrino Background

23

- Updated sensitivities in **Xe** and **Ar** based on projected future detector properties with neutrino-electron scattering and improved flux uncertainties:



Ar

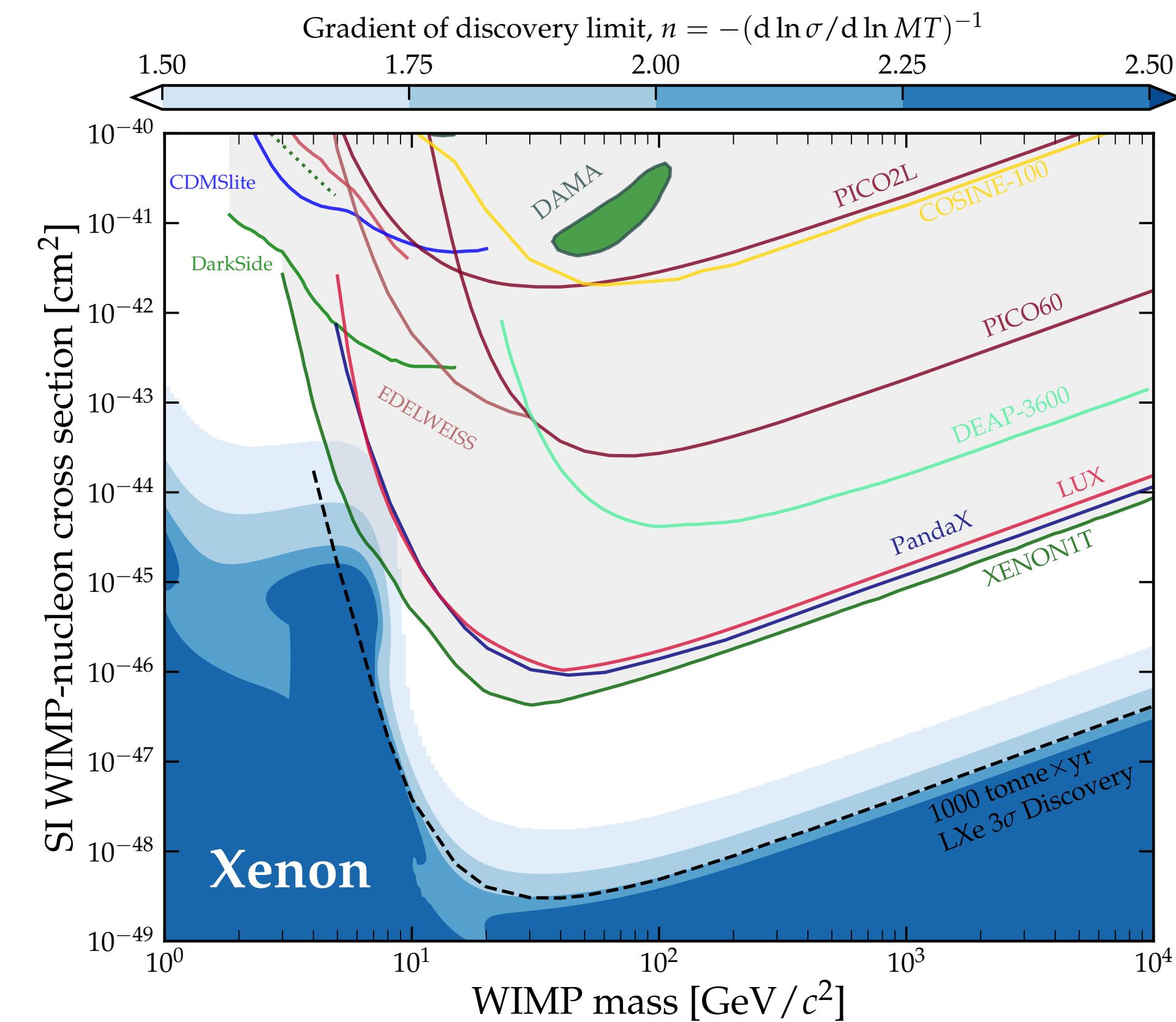


Neutrino Floor or Fog?

24

- The *neutrino floor* in these analyses is not completely impenetrable: at very large exposures, we can “learn” the shape of the background and use spectral information to distinguish it from the DM signal.
- *neutrino floor* → *neutrino fog*
[O’Hare 2021, Snowmass 2022]

$$n = -\frac{d \ln(\sigma_n)}{d \ln(MT)}$$



Neutrino Floor or Fog?

25

- But most analyses so far fix the detector response and neutrino spectral shape and only float the overall normalization in the profile likelihood:

e.g. Neutrino Spectra

$$\frac{d\Phi_{\nu,j}}{dE_\nu} = \phi_j f_j(E_\nu)$$

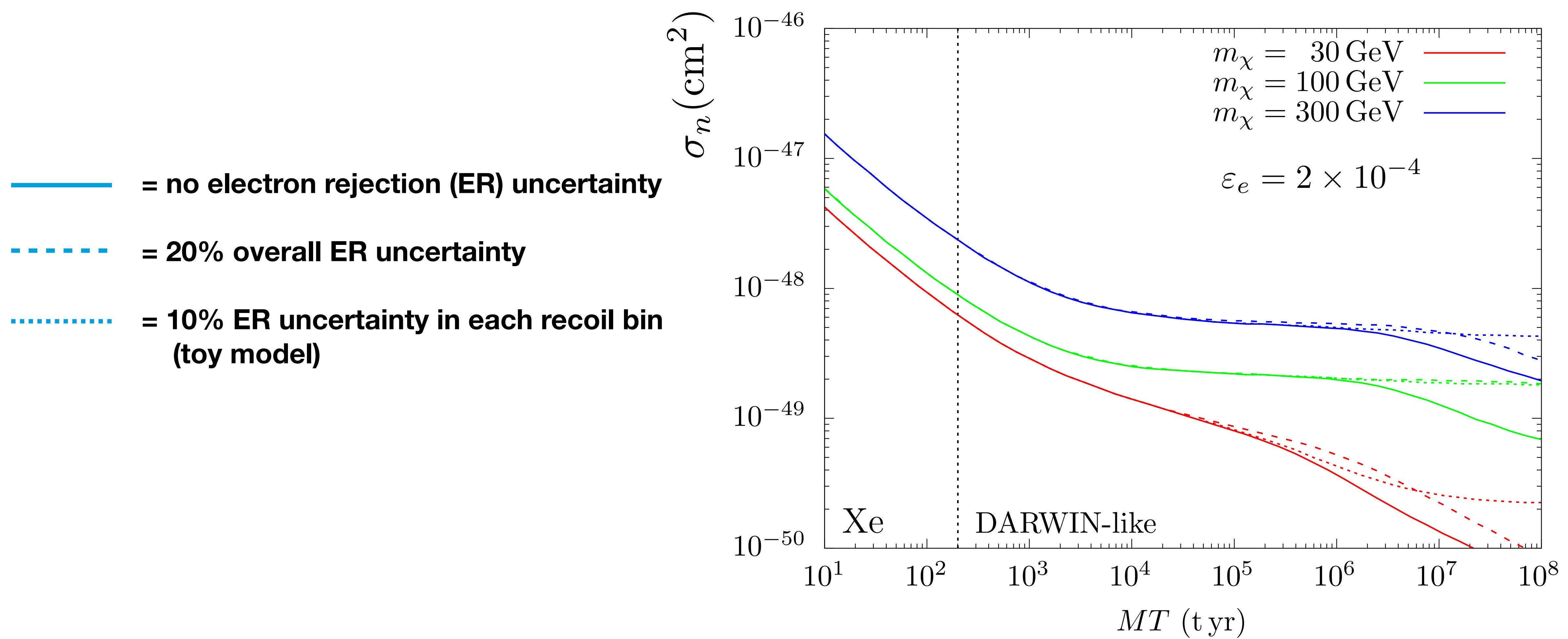
↑ ↑ held fixed
allowed to fluctuate

- Uncertainties in the neutrino spectral shape or the detector response make it much more difficult to separate signal from background using the recoil energy spectral shape information when **S/B $\ll 1$** .

Neutrino Floor or Fog?

26

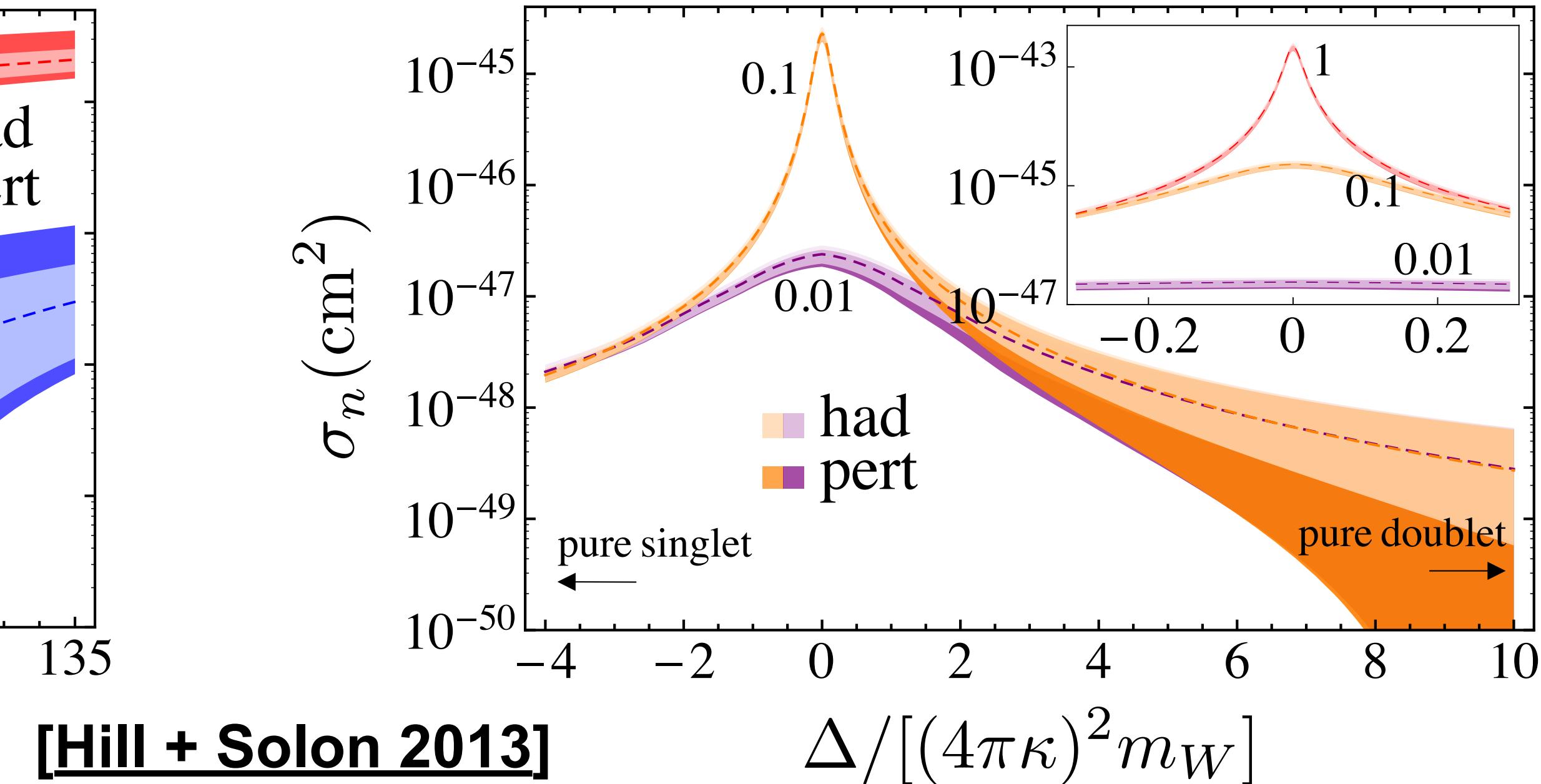
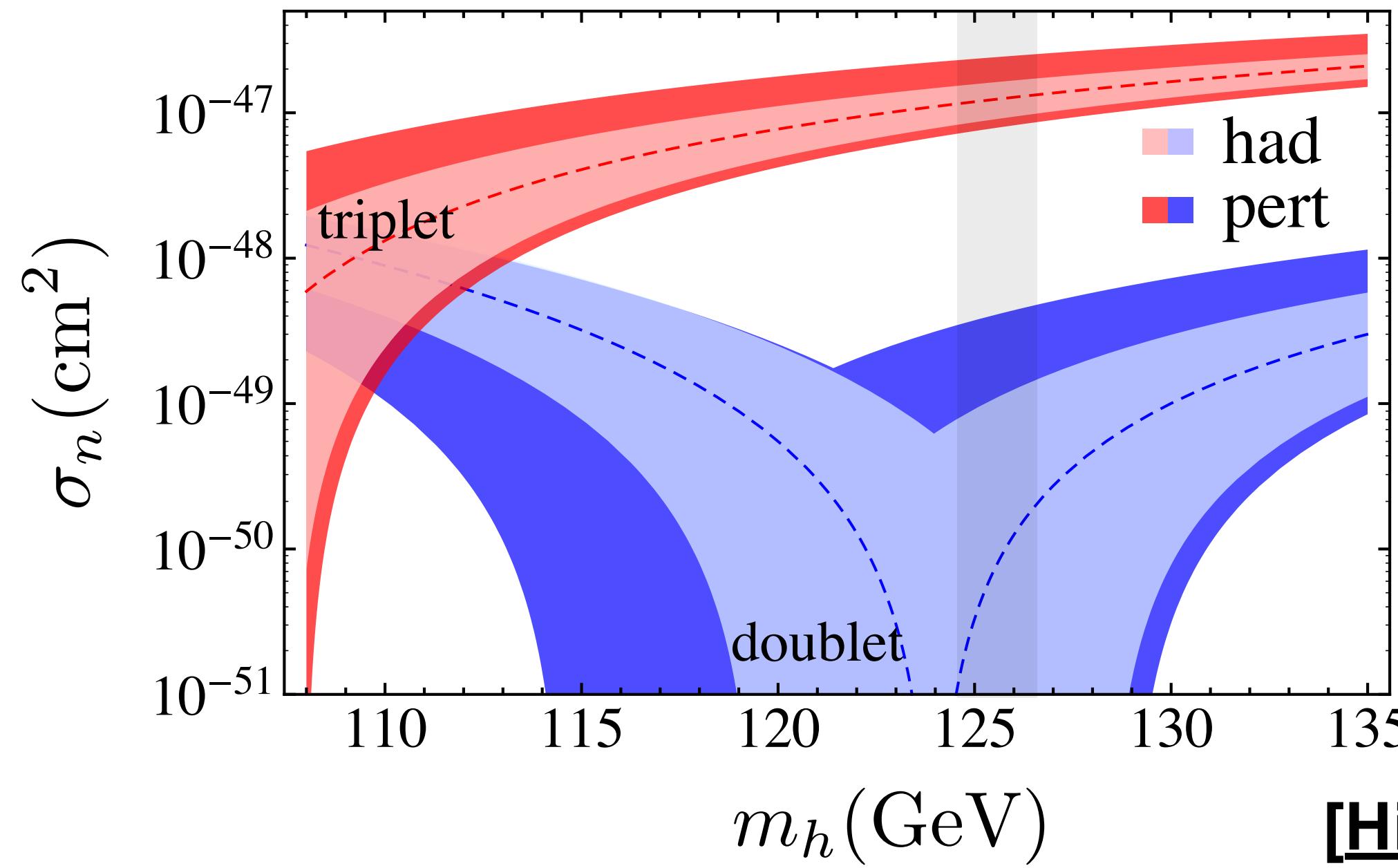
e.g. shape uncertainty in electron recoil rejection ε_e (= 2×10^{-4})



Below the Neutrino Floor

27

- Several well-motivated DM candidates lie below the neutrino floor/fog.
 - e.g. Thermal Higgsino in the Supersymmetric Standard Model (MSSM)
 - correct thermal relic density for $m_\chi \simeq \mu \simeq 1.1$ TeV
 - nucleon scattering mainly via Higgs exchange, $\sigma_n \lesssim 10^{-48} \text{ cm}^2$



Below the Neutrino Floor

28

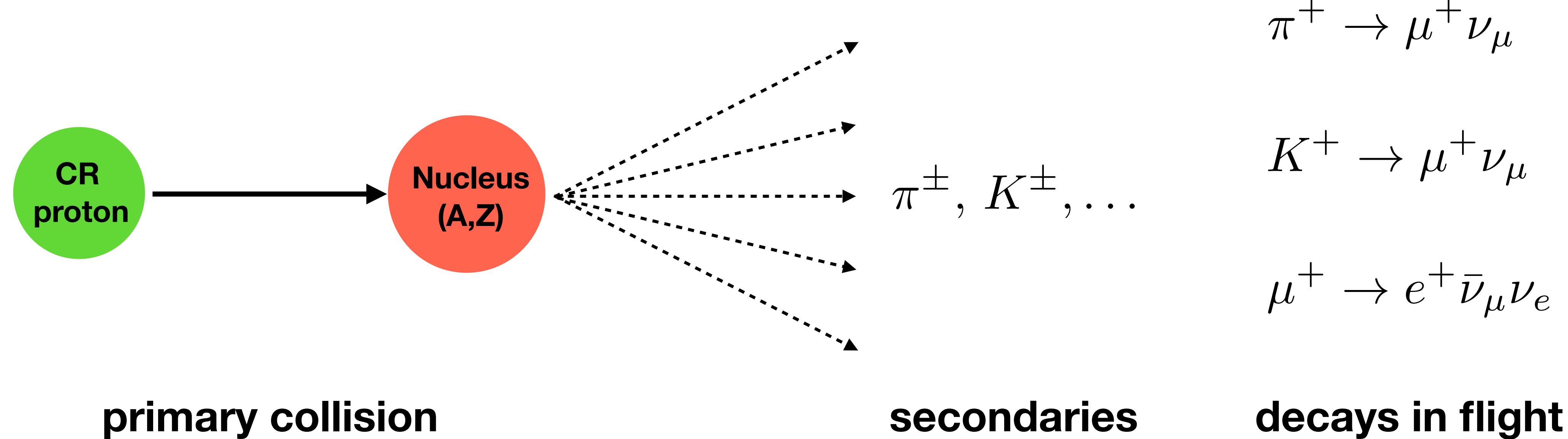
- Several well-motivated DM candidates lie below the neutrino floor/fog.
- Ideas for going beyond it:
 - detectors with directional sensitivity
 - combining data from different detector materials
 - (unrealistically?) large detector volumes
- Another idea: **DM direct detection on the Moon.**

J. Siegrist, “*NASA is going back to the moon. How could physicists collaborate?*”, in Remarks from Funding Agencies to the Snowmass Process: DOE,” Snowmass Community Planning Meeting, October 2020.

Atmospheric Neutrino Production

29

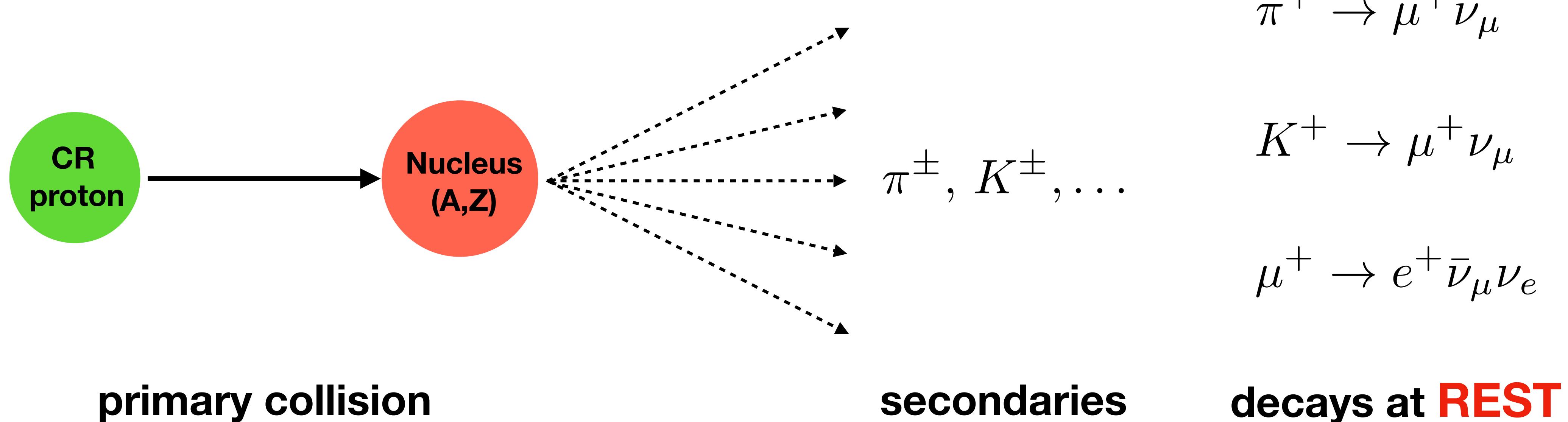
- Atmospheric neutrinos are the dominant neutrino background for $m_\chi \gtrsim 10 \text{ GeV}$
- Neutrinos are produced by cosmic rays hitting the atmosphere.



Moon CR Neutrino Production

30

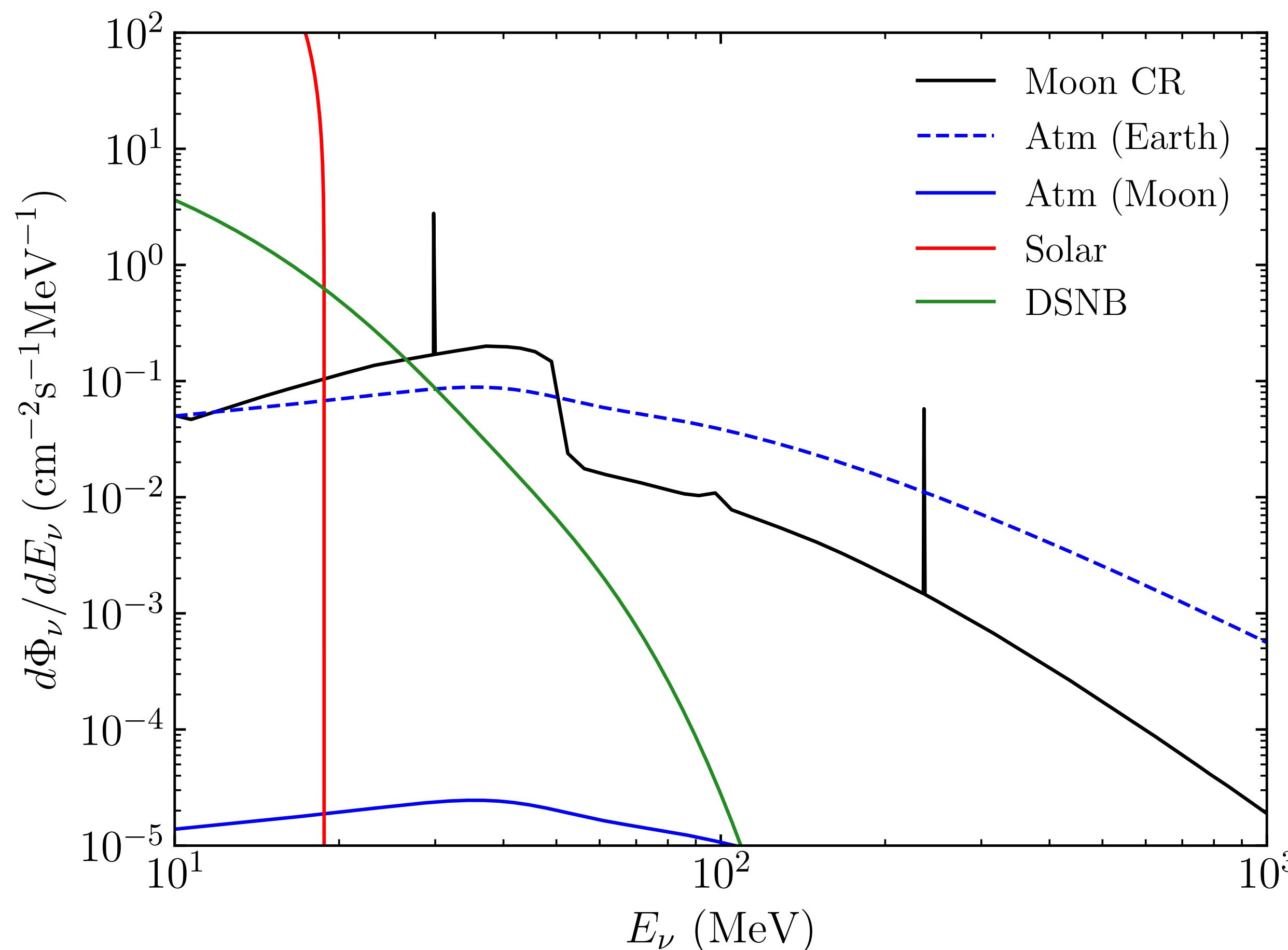
- The Moon has almost no atmosphere.
- Neutrinos are produced by cosmic rays hitting the planetary surface.
- Secondaries are nearly all **stopped** by the medium before decaying.



Neutrino Fluxes on the Moon

31

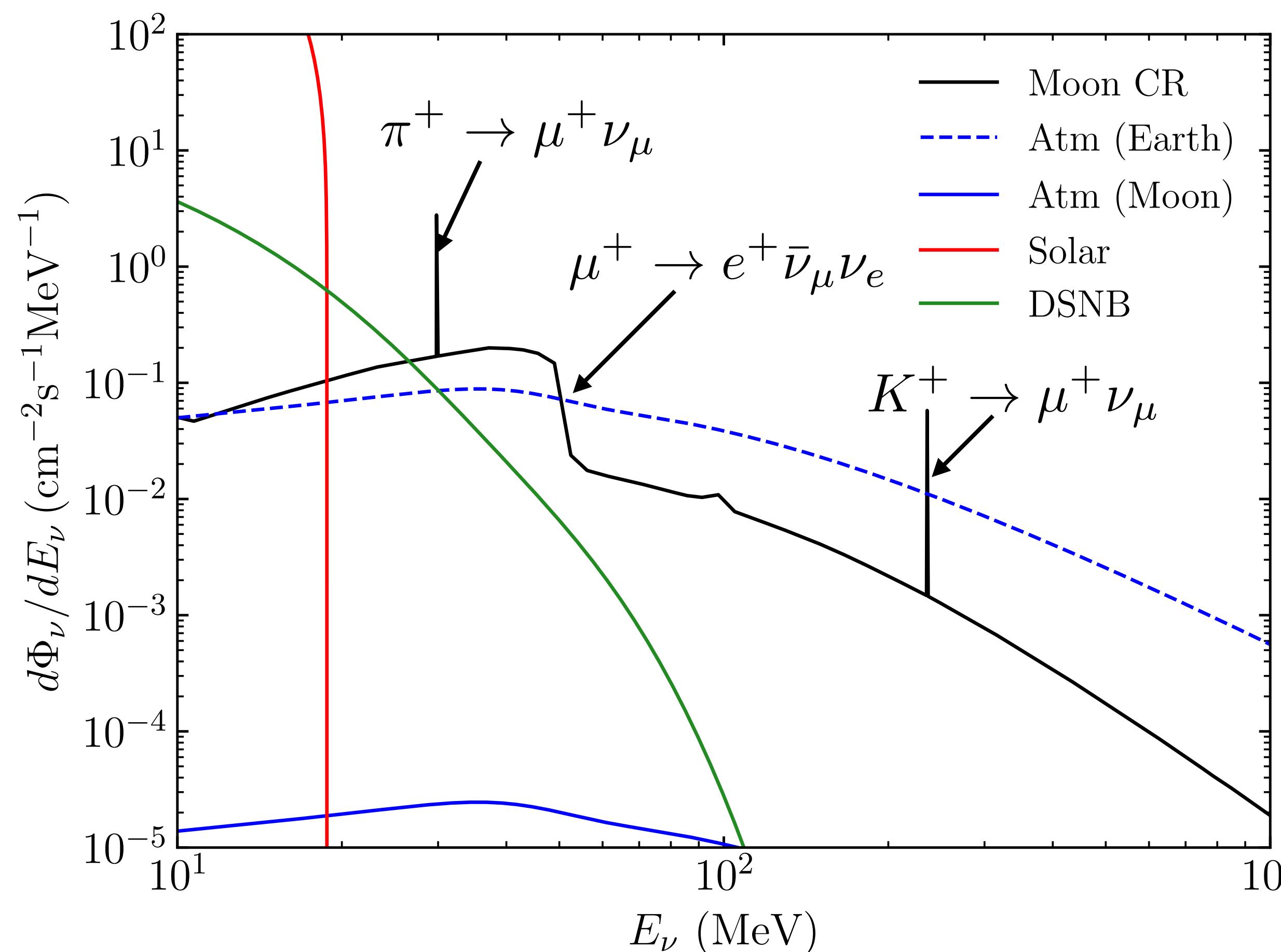
- Calculated by leveraging GEANT Simulations by **[Demidov+Gorbunov 2020]**



Neutrino Fluxes on the Moon

32

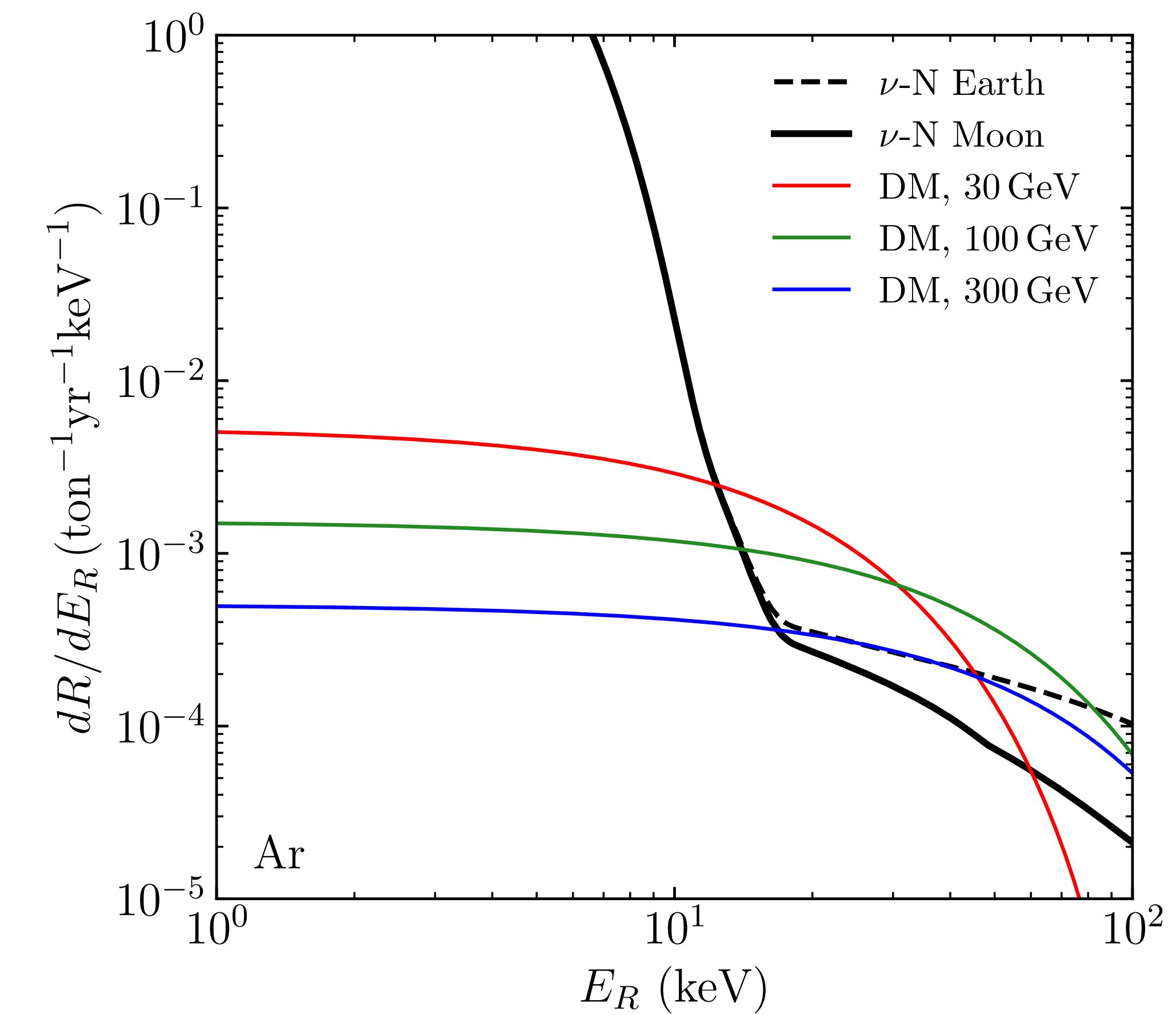
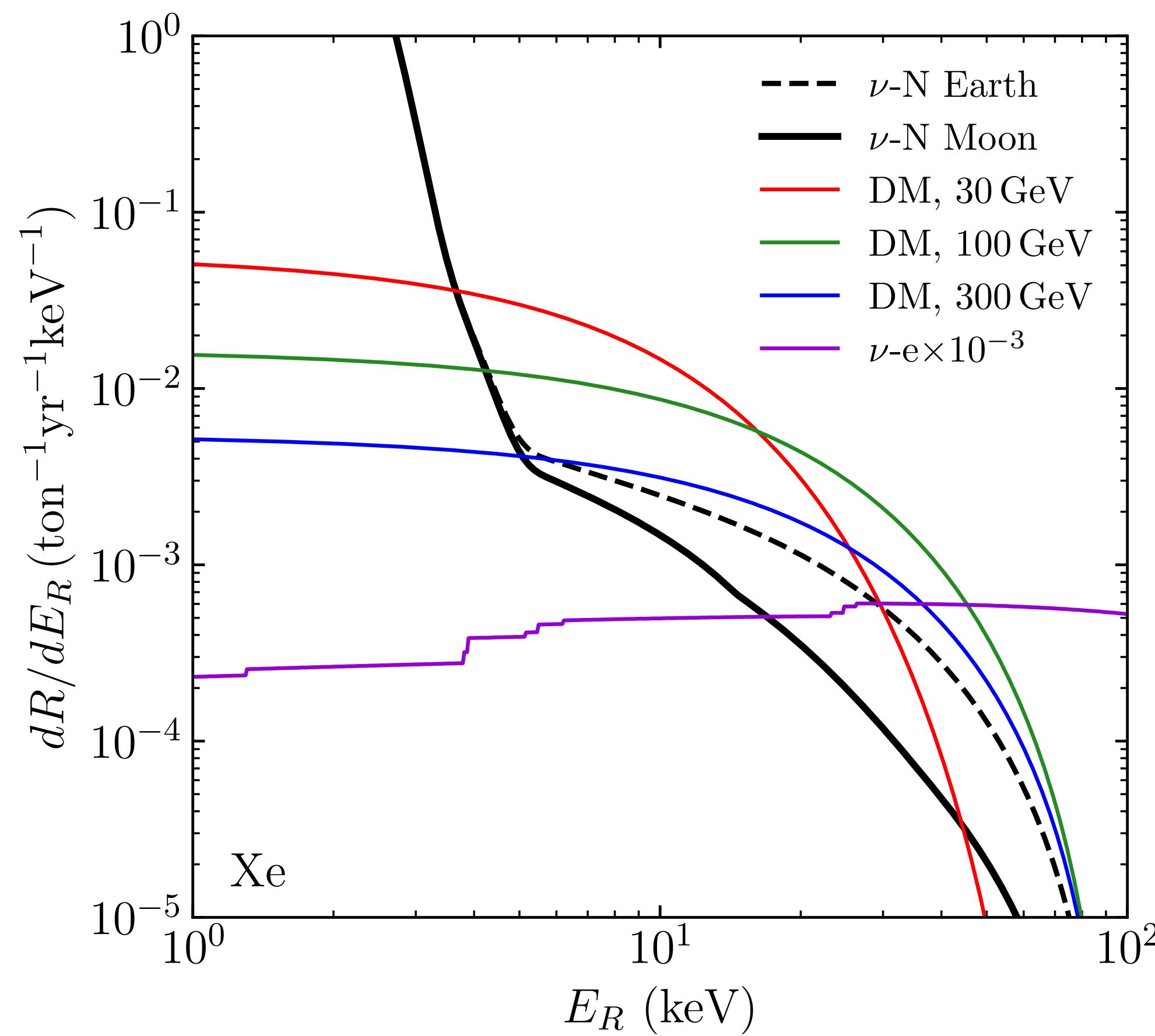
- Calculated by leveraging GEANT Simulations by **[Demidov+Gorbunov 2020]**



DM+ Neutrino Scattering on the Moon

33

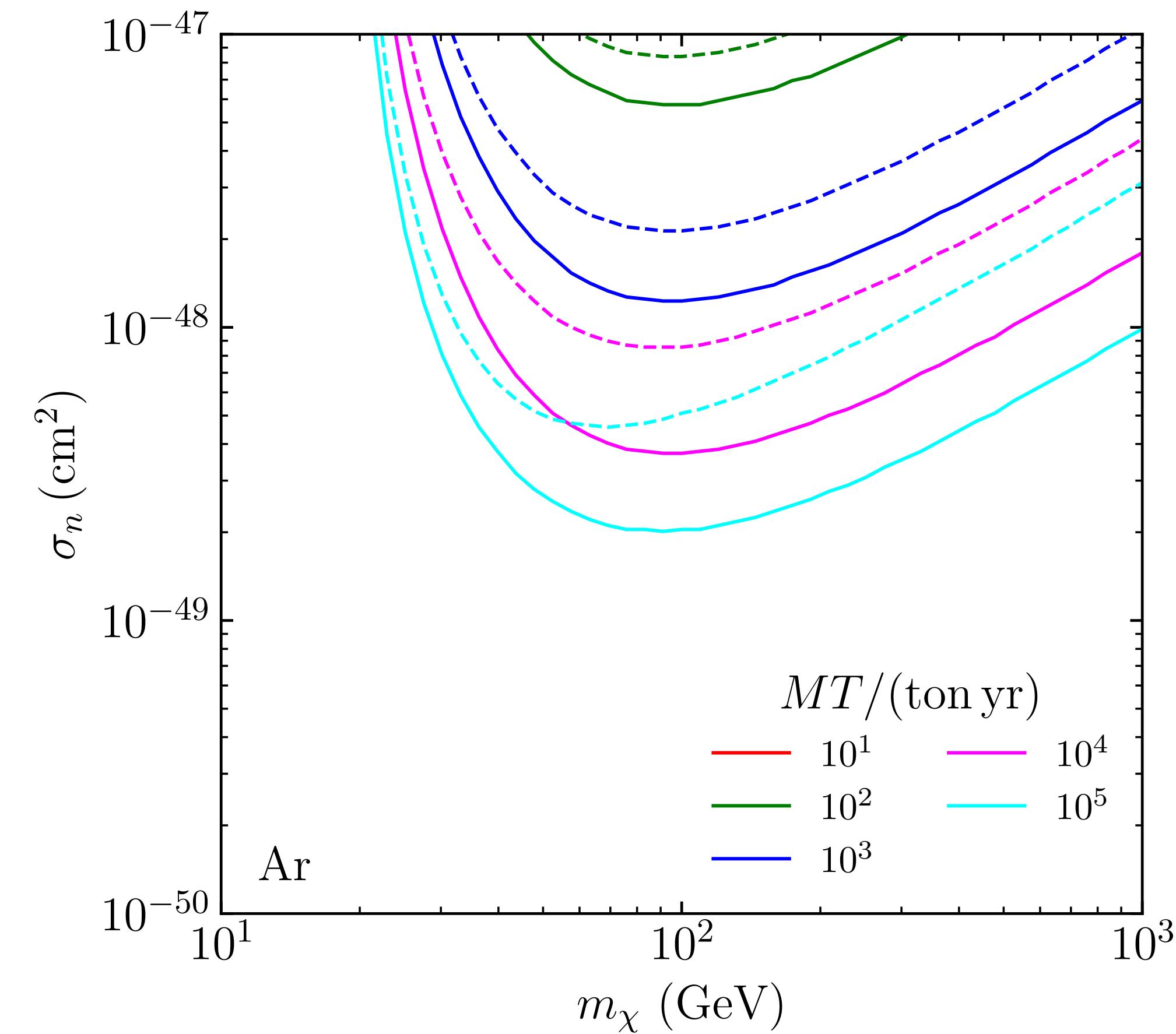
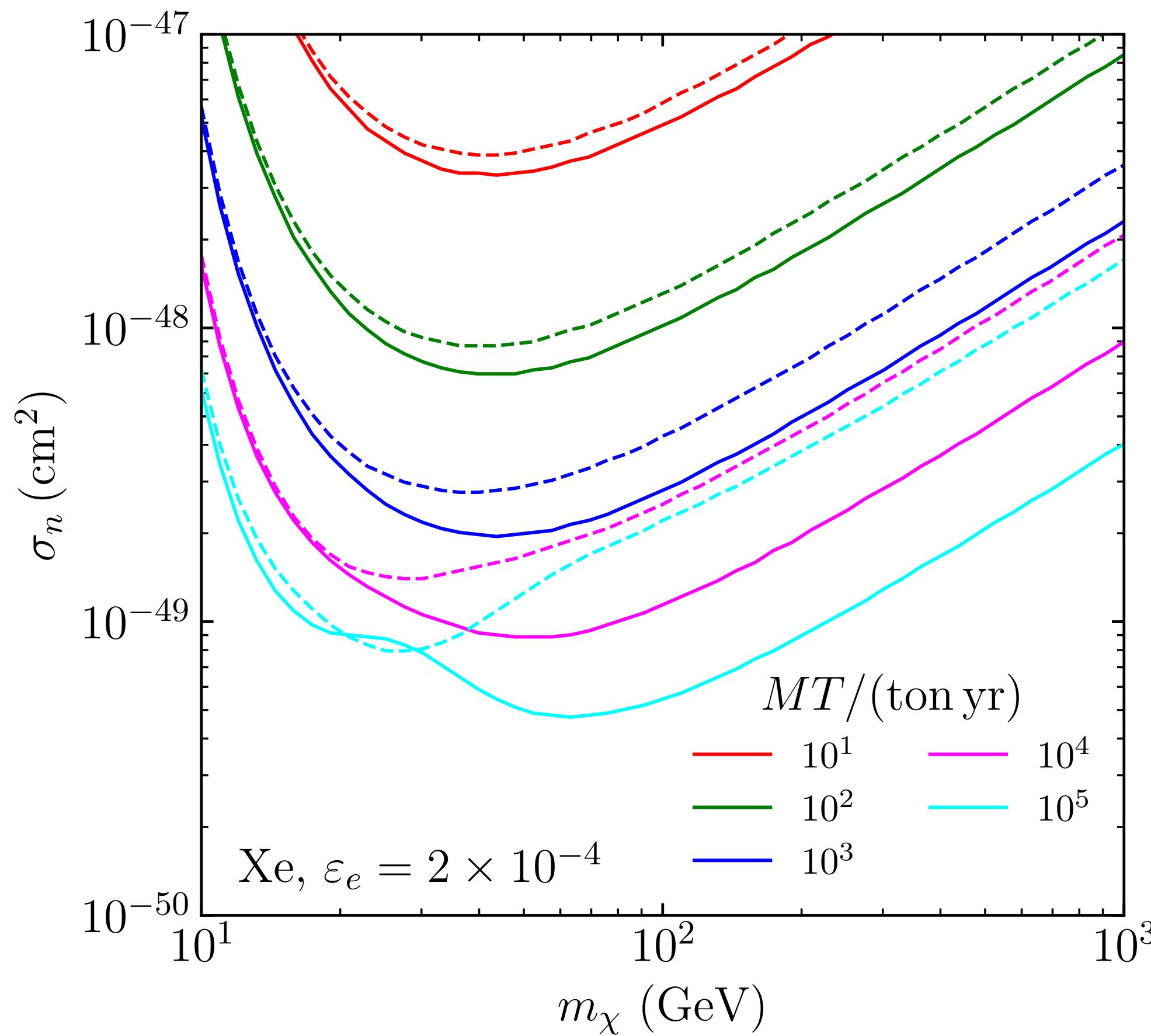
- Effective scattering rates in xenon and argon are reduced relative to Earth.



Dark Matter Sensitivities

34

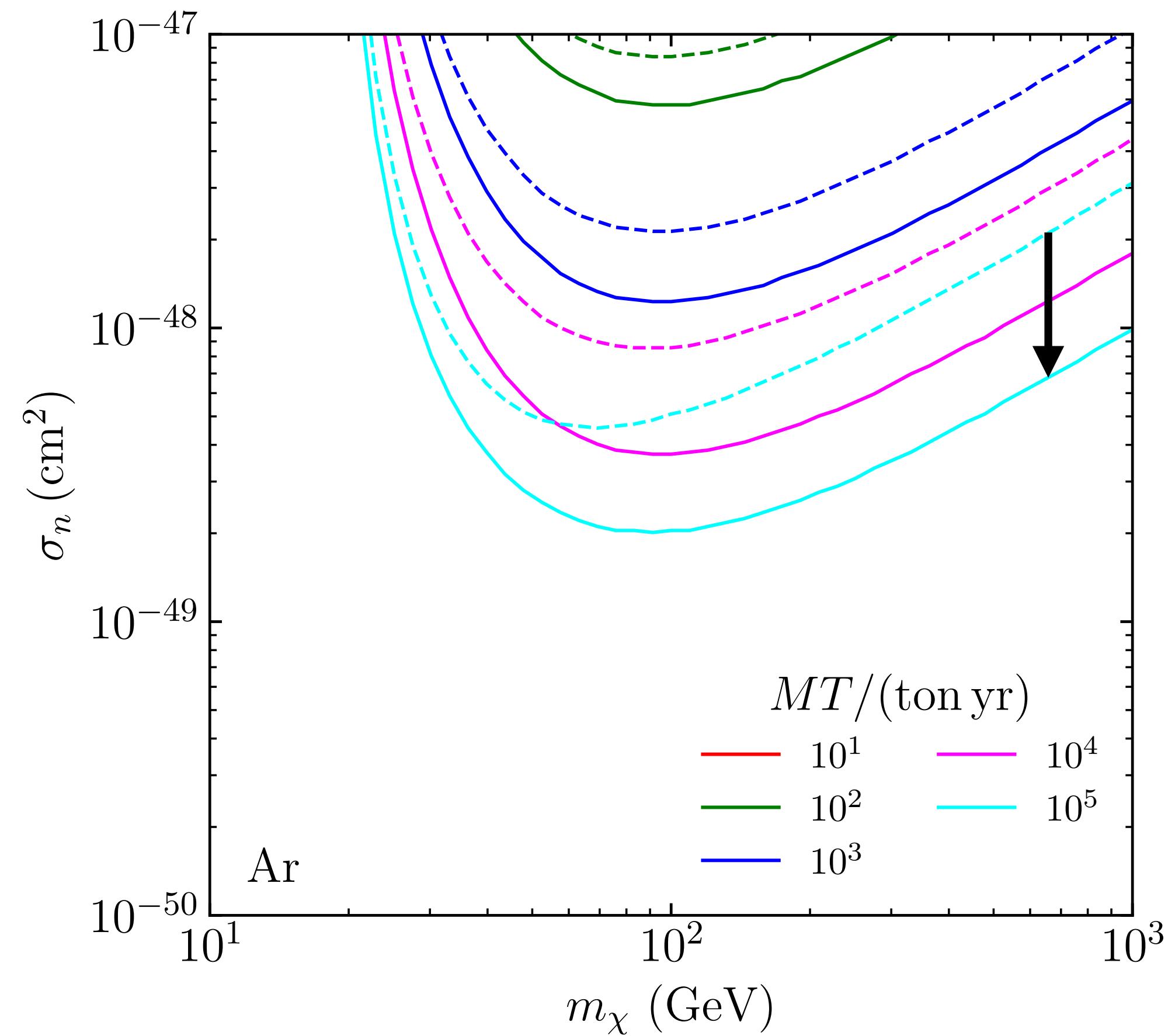
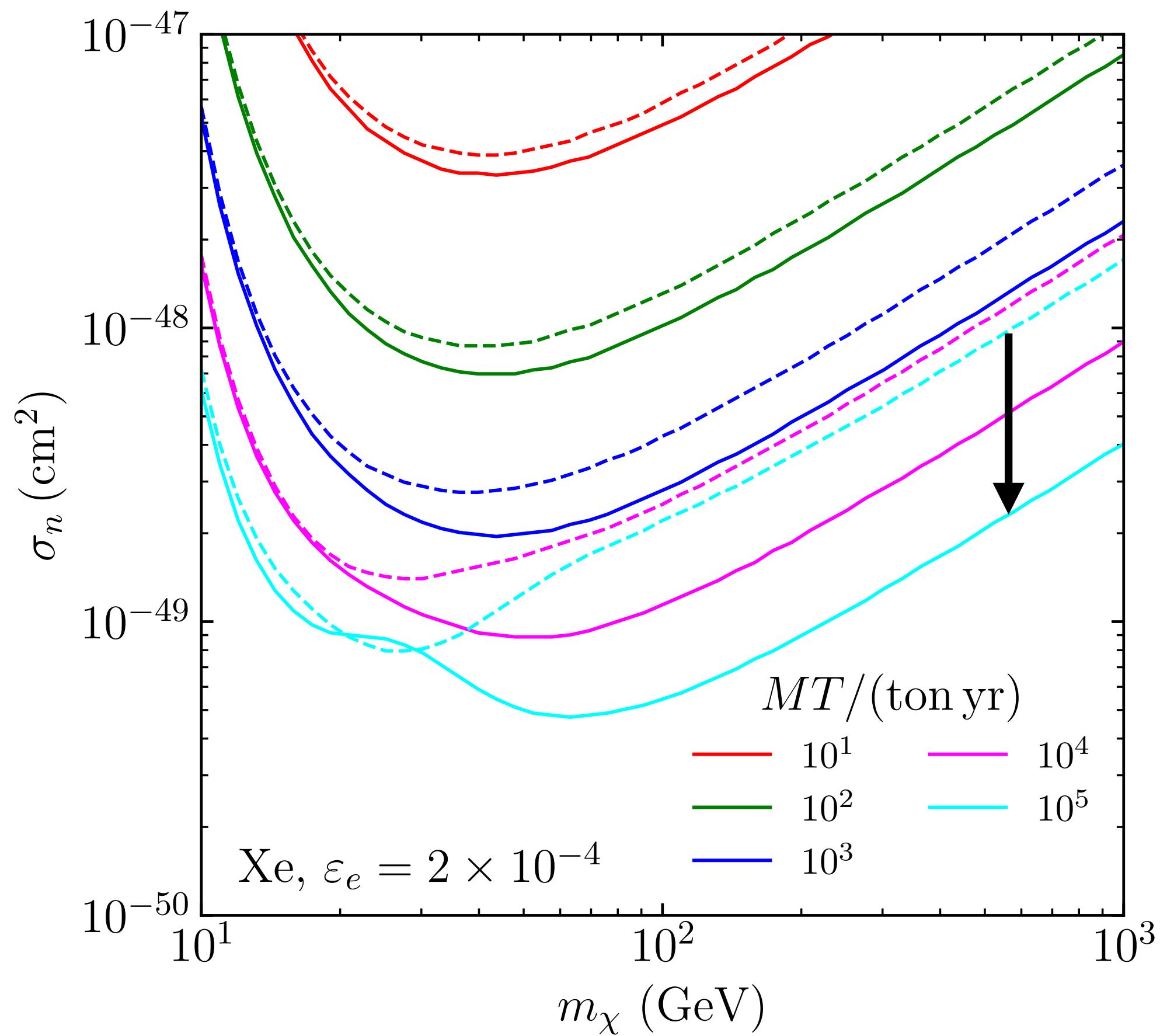
- Significant improvement on Moon (solid) vs. Earth (dashed)!



Dark Matter Sensitivities

35

- Significant improvement on Moon (solid) vs. Earth (dashed)!



Summary

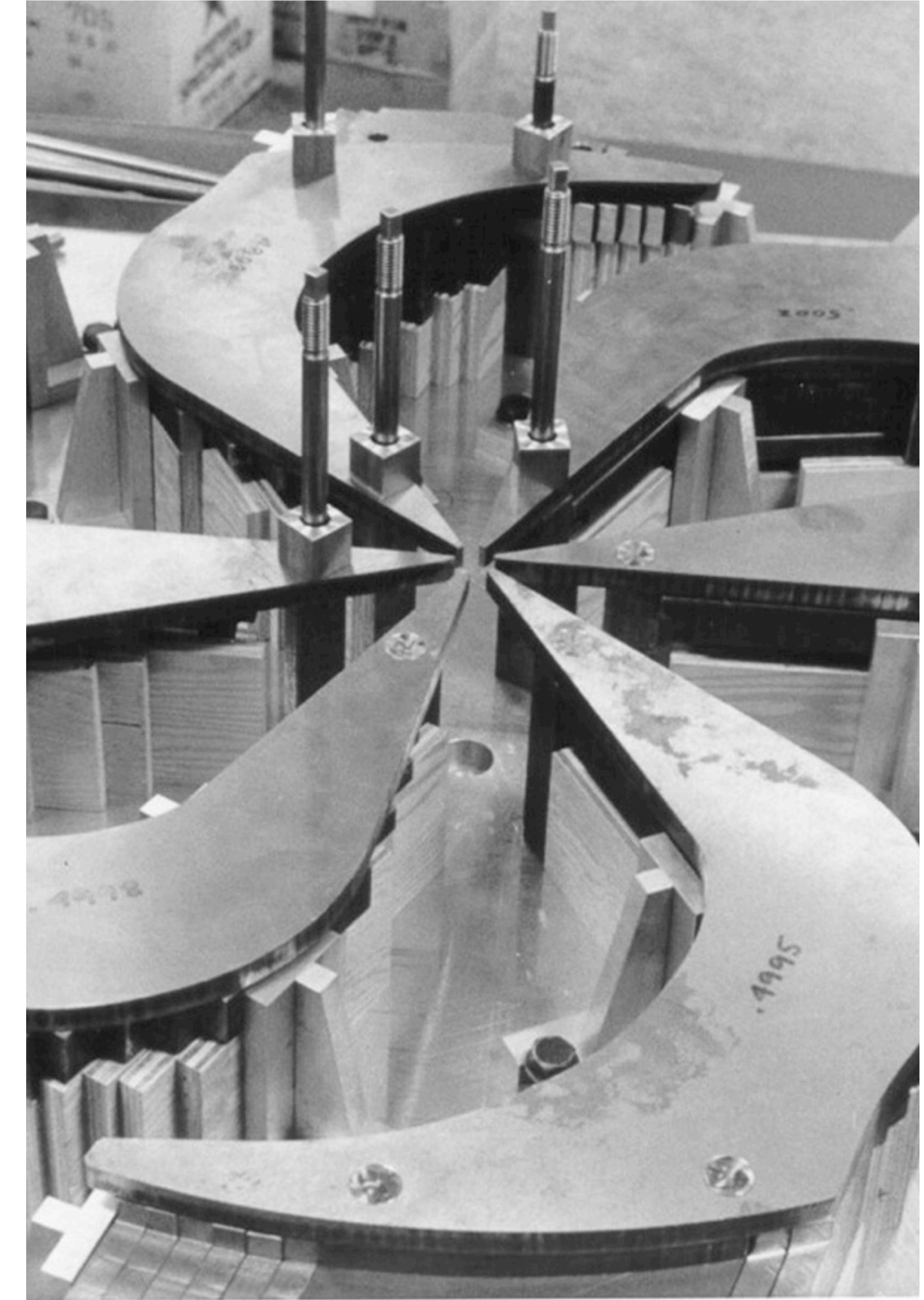
36

- Evidence for dark matter comes from many observations.
We don't know what it is!
- Thermal DM arises naturally through freeze out.
Non-gravitational interactions with matter motivate direct searches.
- Direct detection searches for DM have made amazing progress.
- They will soon face a new challenge from neutrino backgrounds.
- We are looking at ways to reduce them...

Thank you
Merci

www.triumf.ca

Follow us @**TRIUMFLab**

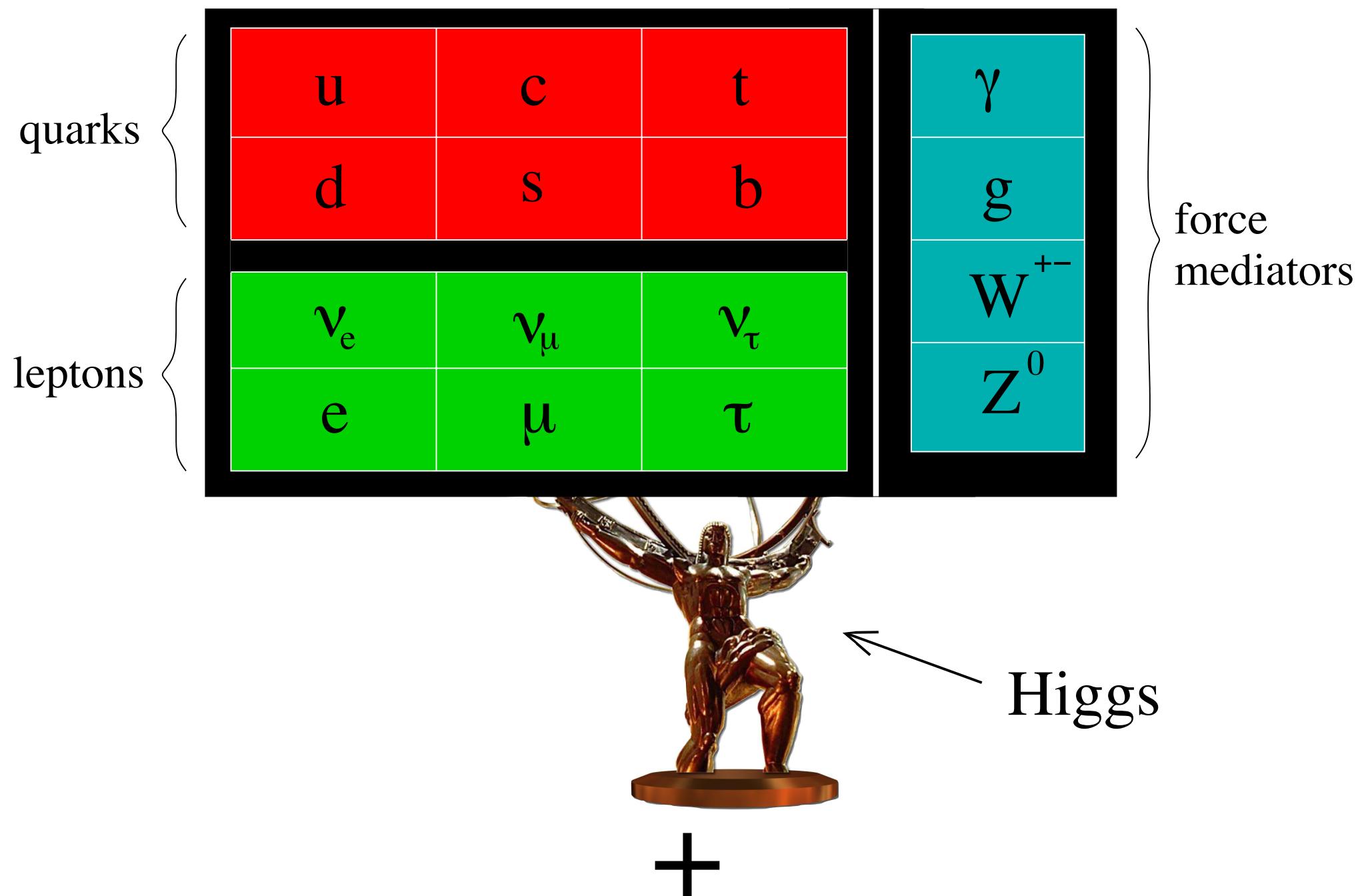


Extra Slides

Extrapolating the SM

39

Does this ...



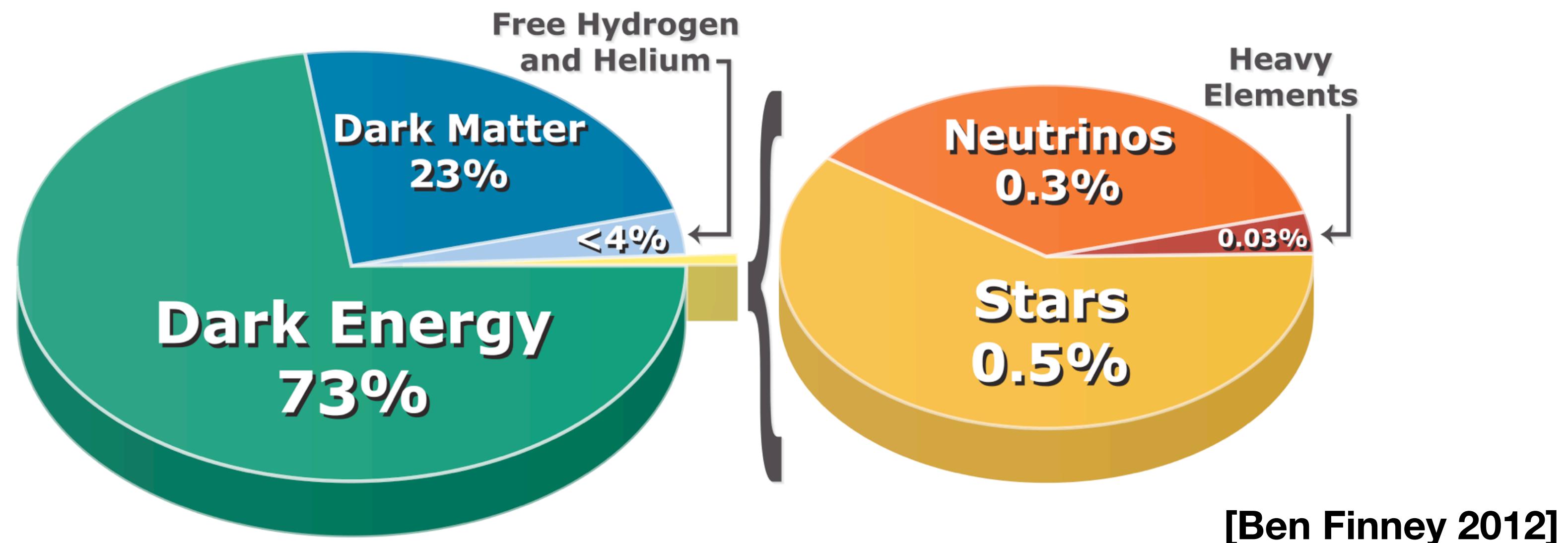
General Relativity

... explain that?

No, apparently

40

- Energy content of the Universe now:

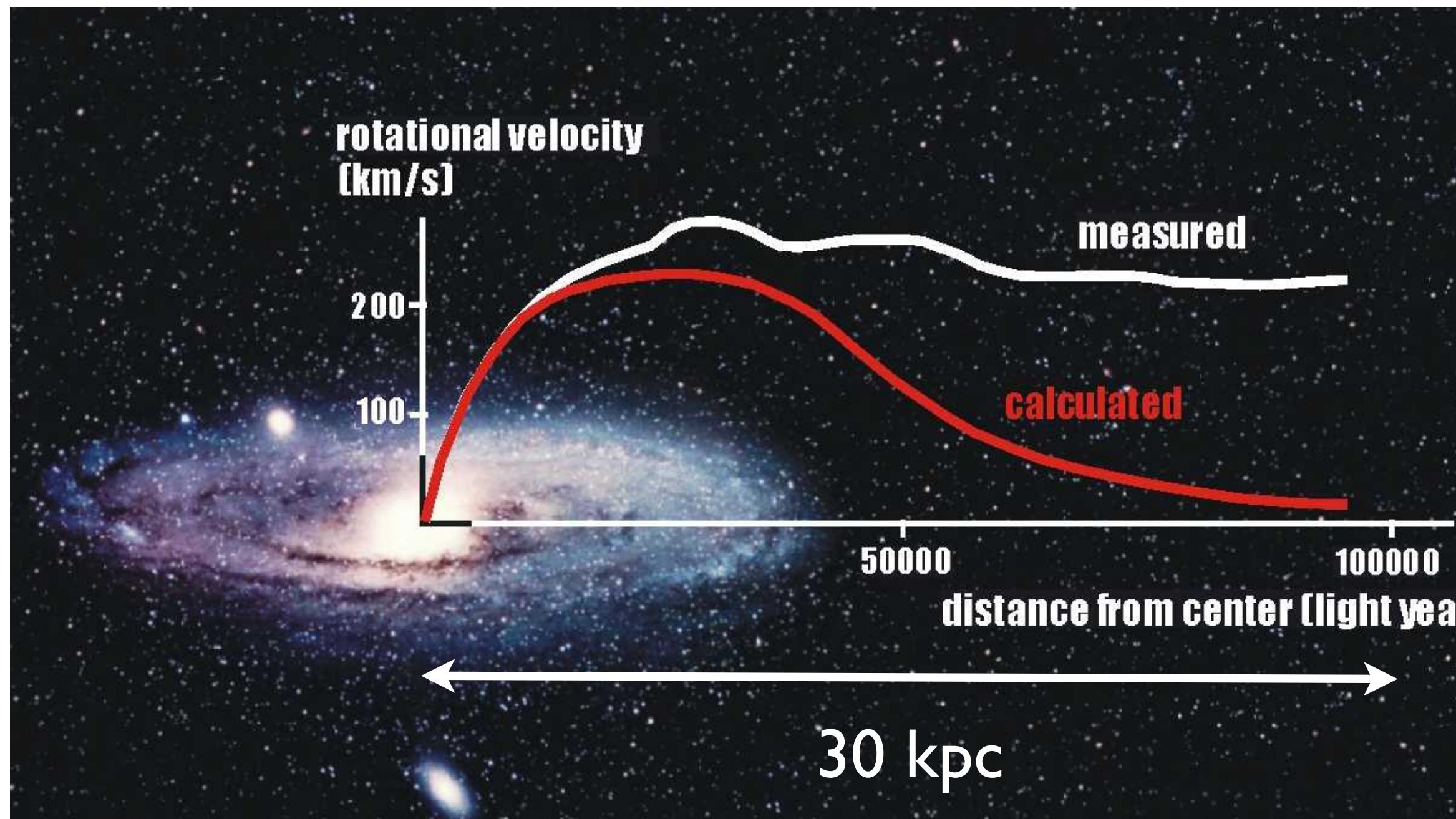


- Only 5% of matter seems to come from stuff in the Standard Model!
- Missing matter = “Dark Matter”

DM Evidence #1: Galaxy Rotation

41

- Many galaxies look like rotating pancakes of stars.
Compare rotation velocity to visible matter enclosed:



- More matter is needed! (Vera Rubin 1970)

DM Evidence #2: Galaxy Clusters

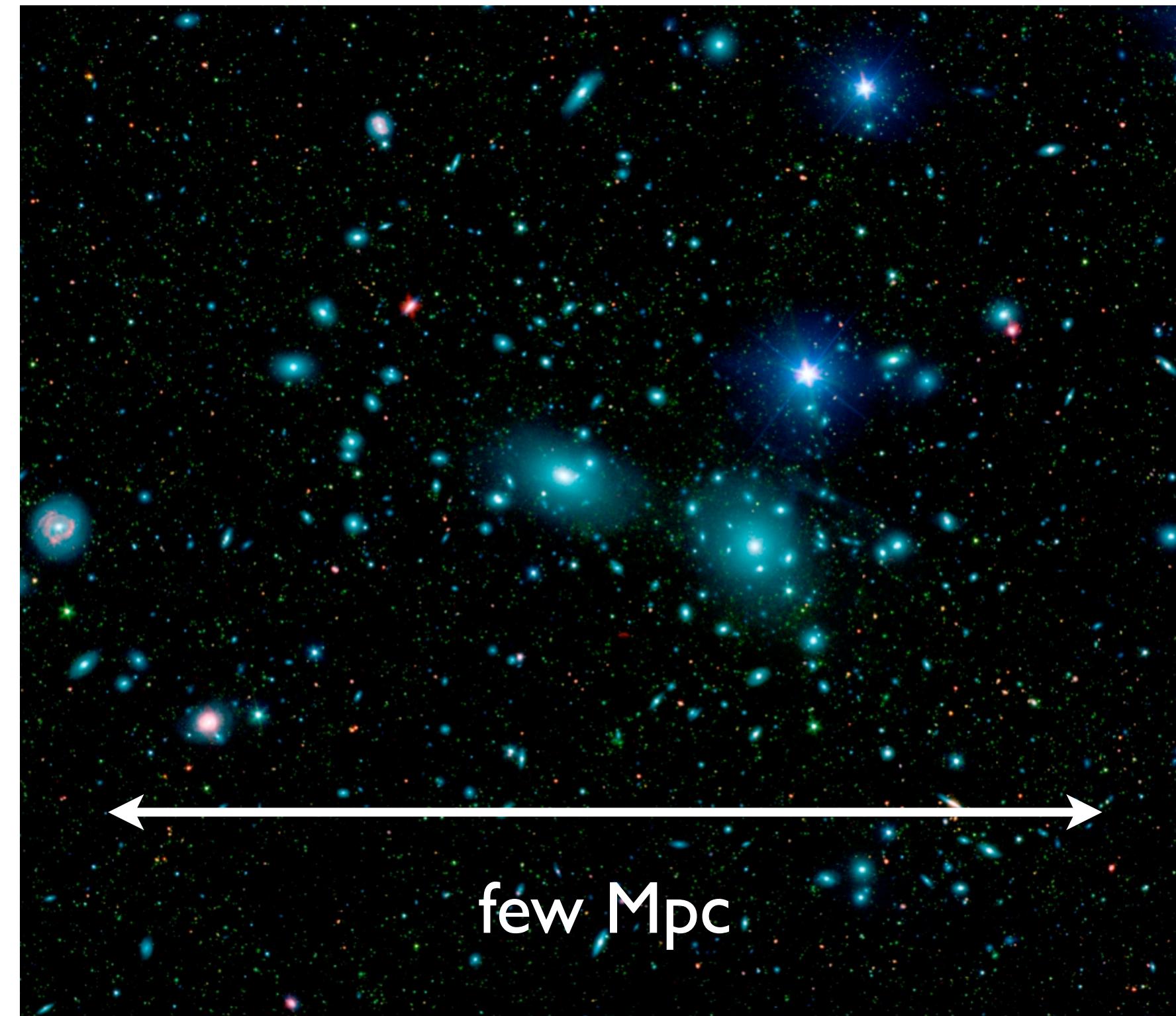
42

- Galaxies are often found within self-gravitating galaxy clusters.
- Virial Theorem:

$$\langle E_{kin} \rangle \sim \langle |V| \rangle$$



$$\langle v_{gal}^2 \rangle \sim \frac{GM_{tot}}{\langle R \rangle}$$

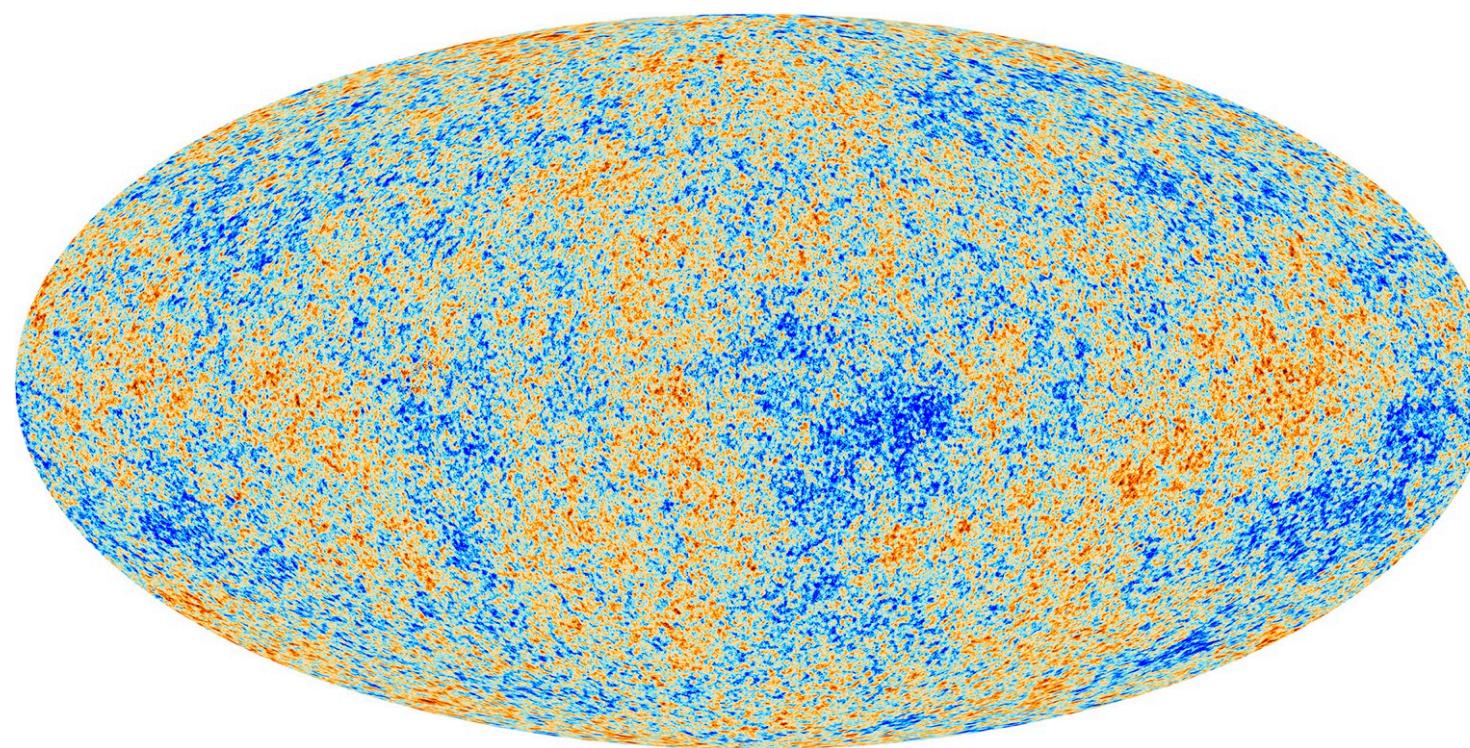


- More matter is needed to explain the observed velocities! (Fritz Zwicky 1933)

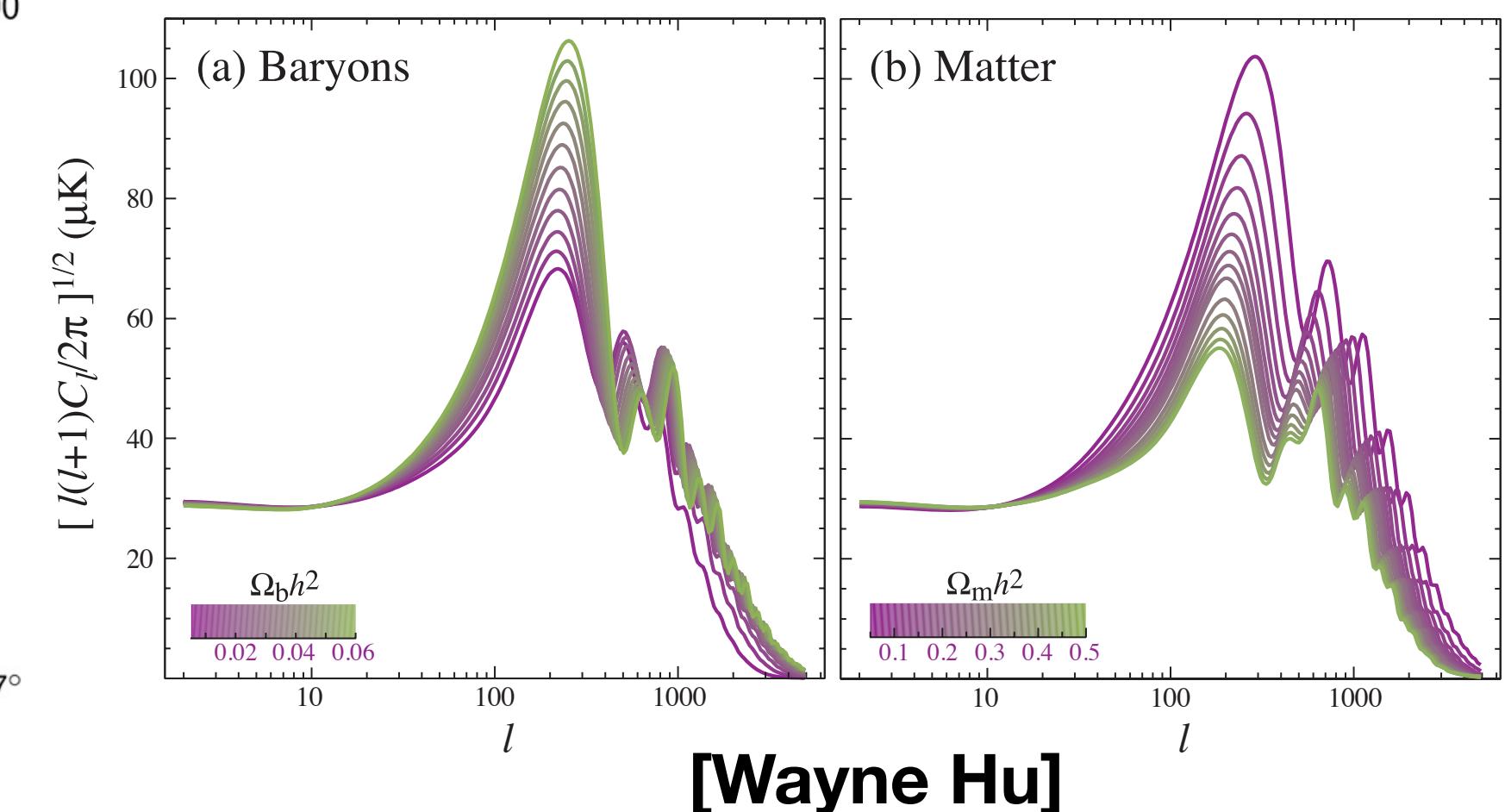
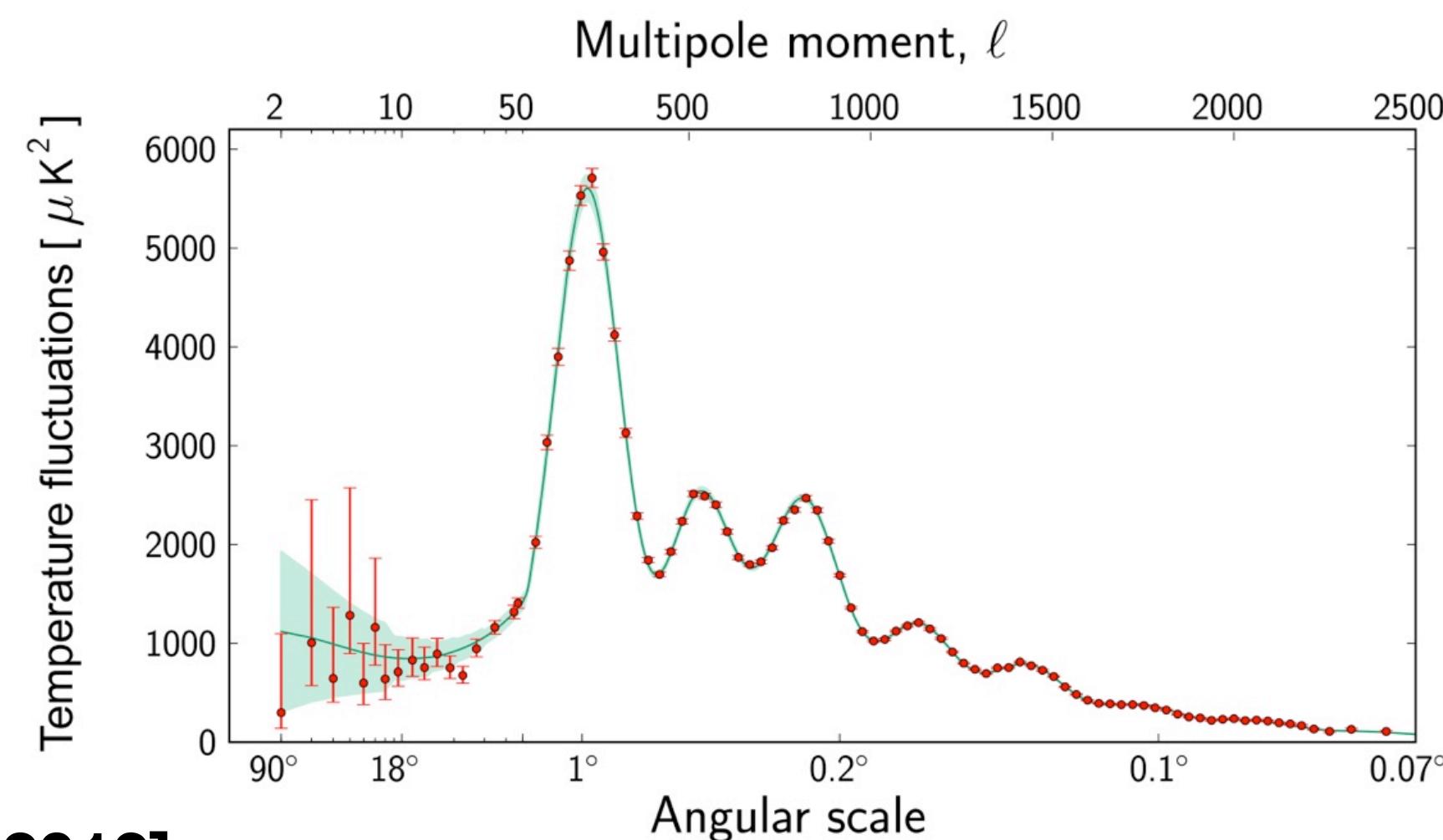
DM Evidence #3: CMB

43

- CMB = Cosmic Microwave Background = 2.725 K photons left from Big Bang
- Temperature fluctuations in the CMB depend on energy content of Universe.



[Planck 2013]



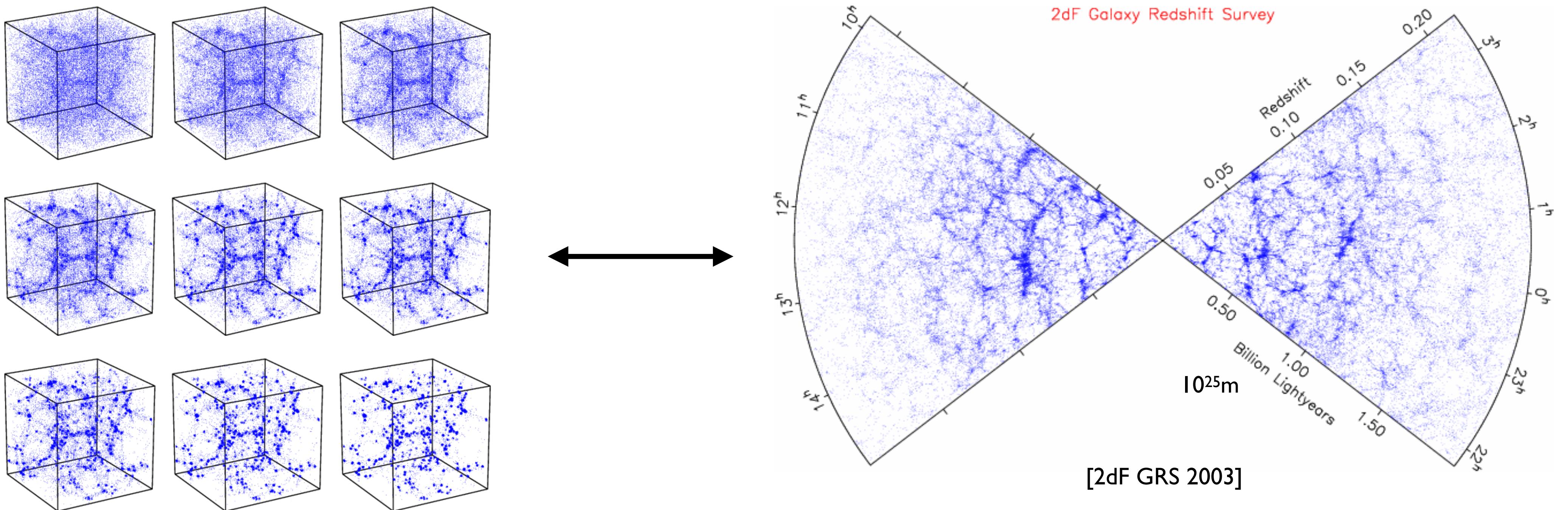
[Wayne Hu]

- Data fits to 30% of energy in matter, but only 5% in regular matter (baryons)!

DM Evidence #4: Cosmic Structure

44

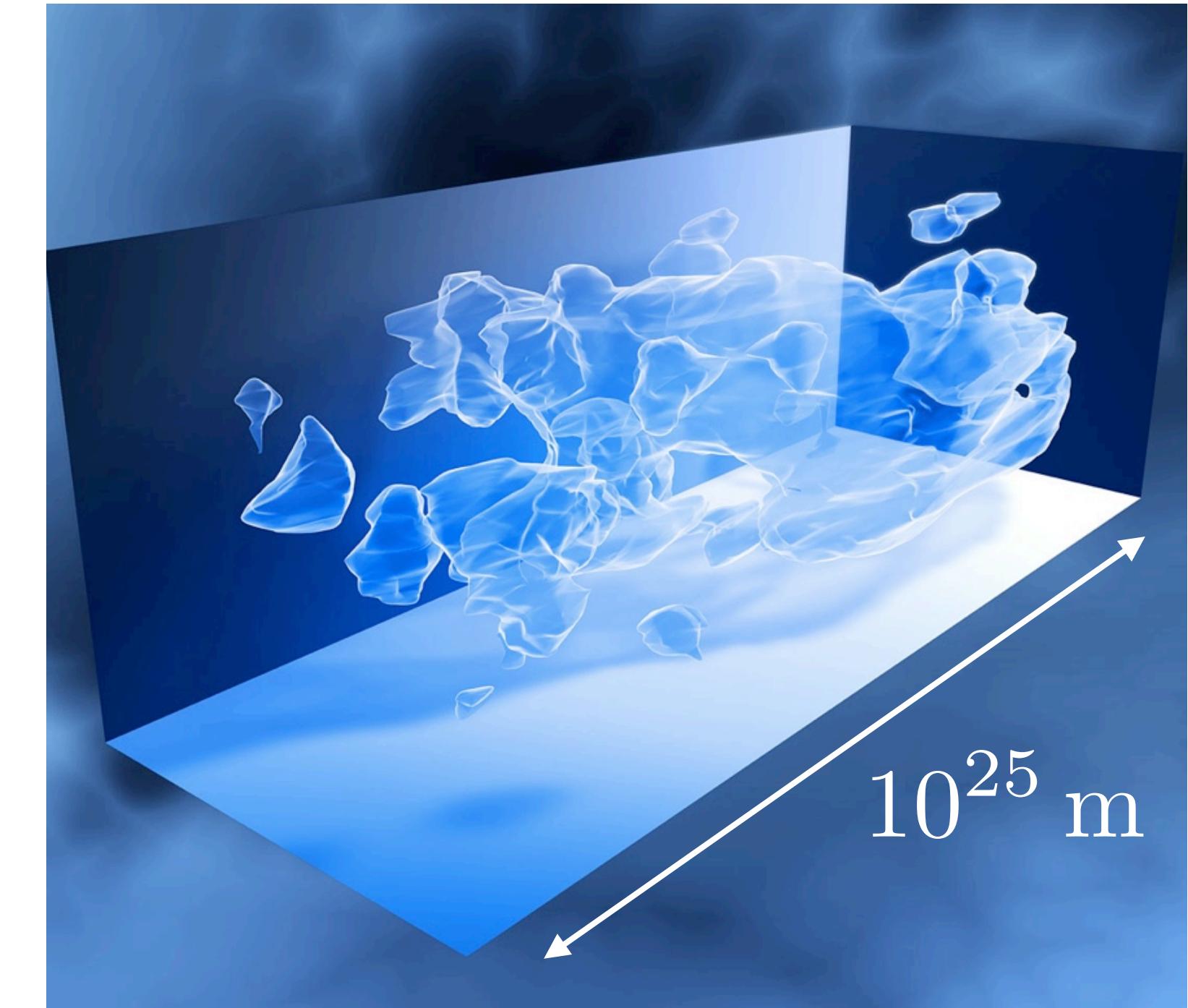
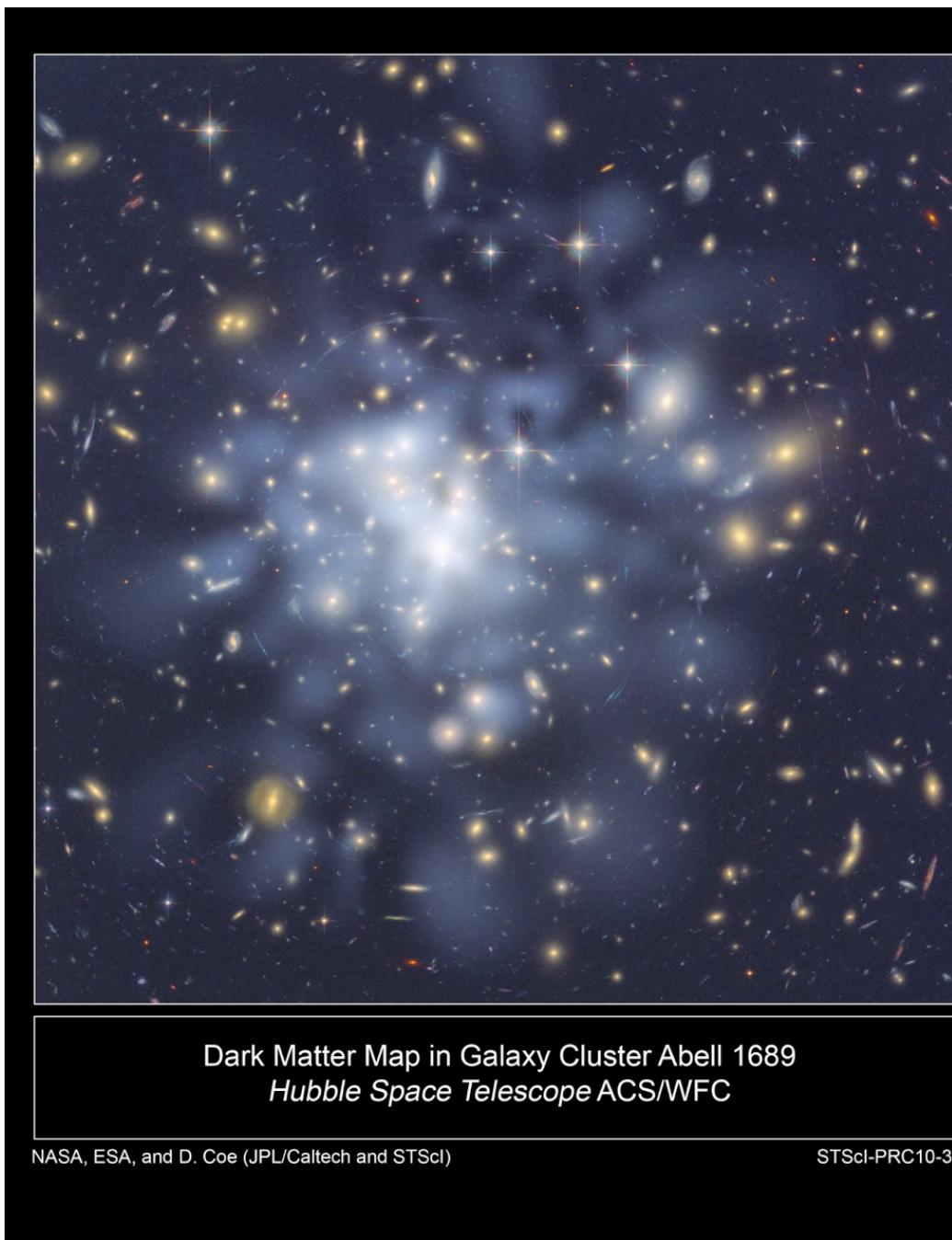
- Visible matter in the cosmos has a structure of “filaments and voids”.
- New (pressureless) dark matter seems to be needed to explain this:
DM collapses gravitationally and pulls visible matter in with it.



DM Evidence #5: Gravitational Lens

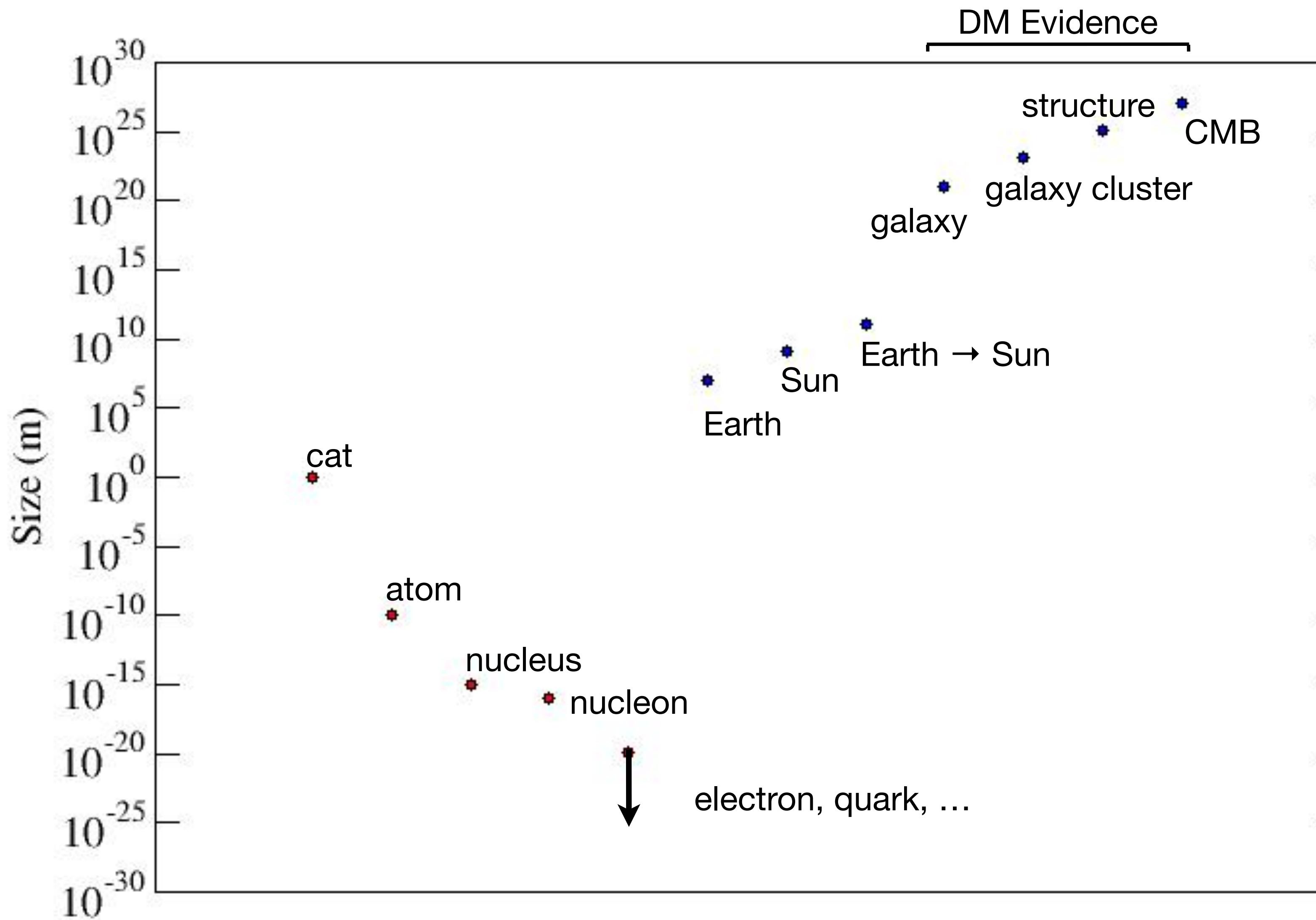
45

- Distant galaxy images are distorted by gravitational lensing.
- The degree of distortion correlates with the amount of matter in between.



- More (matter is needed to explain the lensing seen!

Evidence for Dark Matter



Dark Matter

47

- We don't know how to explain these observations with only the Standard Model and General Relativity.
- **Dark Matter:**
 - there is a new, massive particle with a large density.
 - can account for the data at *all distances!*
- **Modified Gravity:**
 - there are deviations from GR at large distances
 - very challenging (?) to explain the data over all the distances observed
- *Focus on the dark matter explanation today.*

What is Dark Matter?

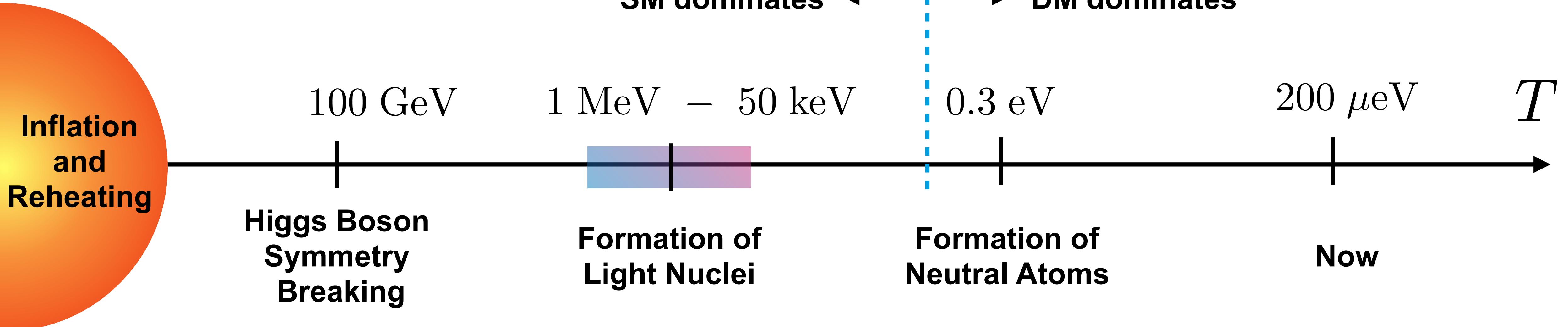
48

- We don't know!
 - All evidence comes from gravitational effects on visible matter.
- But:
 - must not interact too strongly with ordinary matter ("dark")
 - must be non-relativistic today and in the early Universe ("matter")
 - must develop the correct cosmological density (determined from CMB+)
 - must not interact too strongly with itself (for gravitational clumping)

Thermal Dark Matter

49

- Early Universe = hot soup of relativistic particles
As it expanded it cooled off, and some things happened:

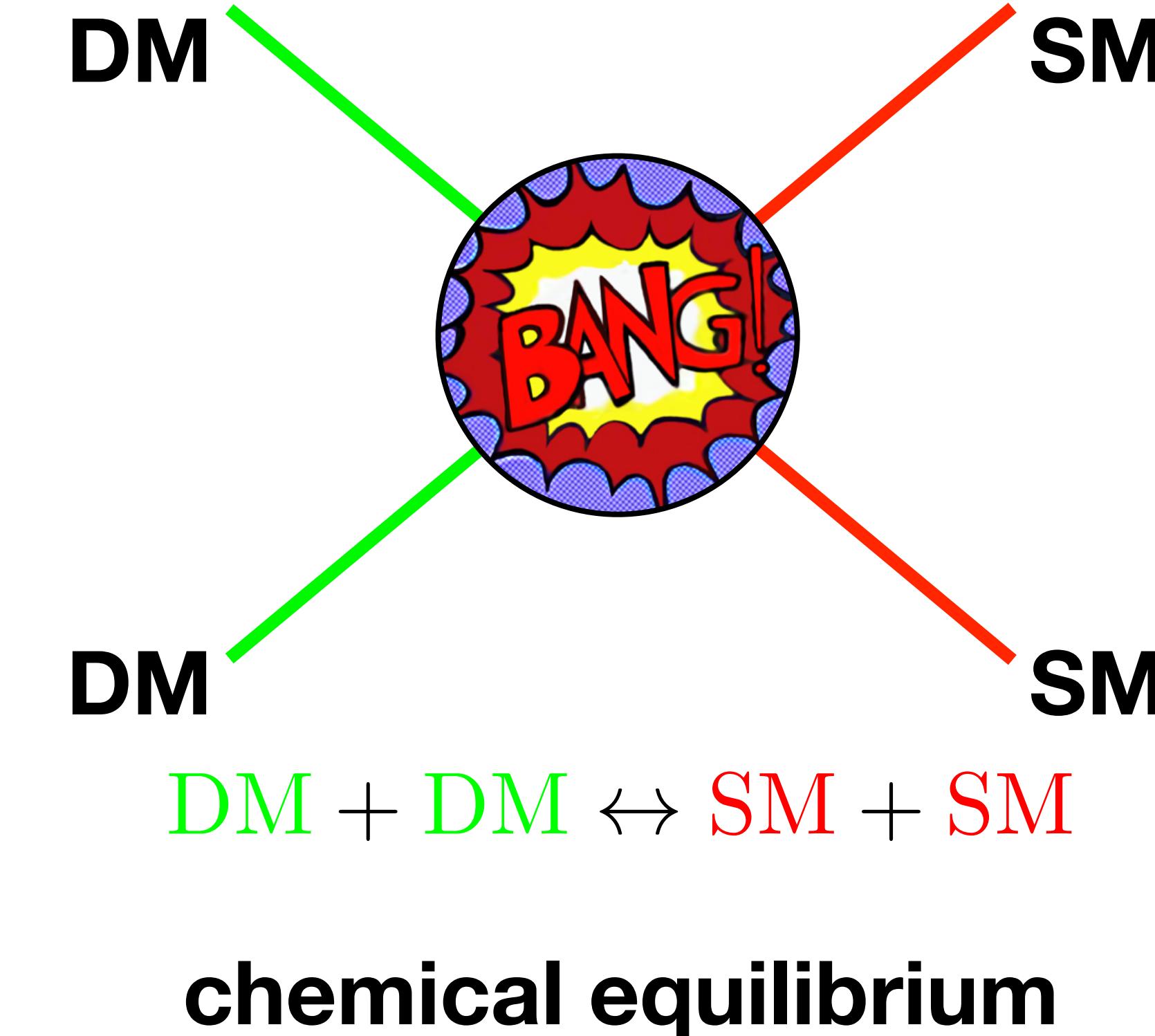
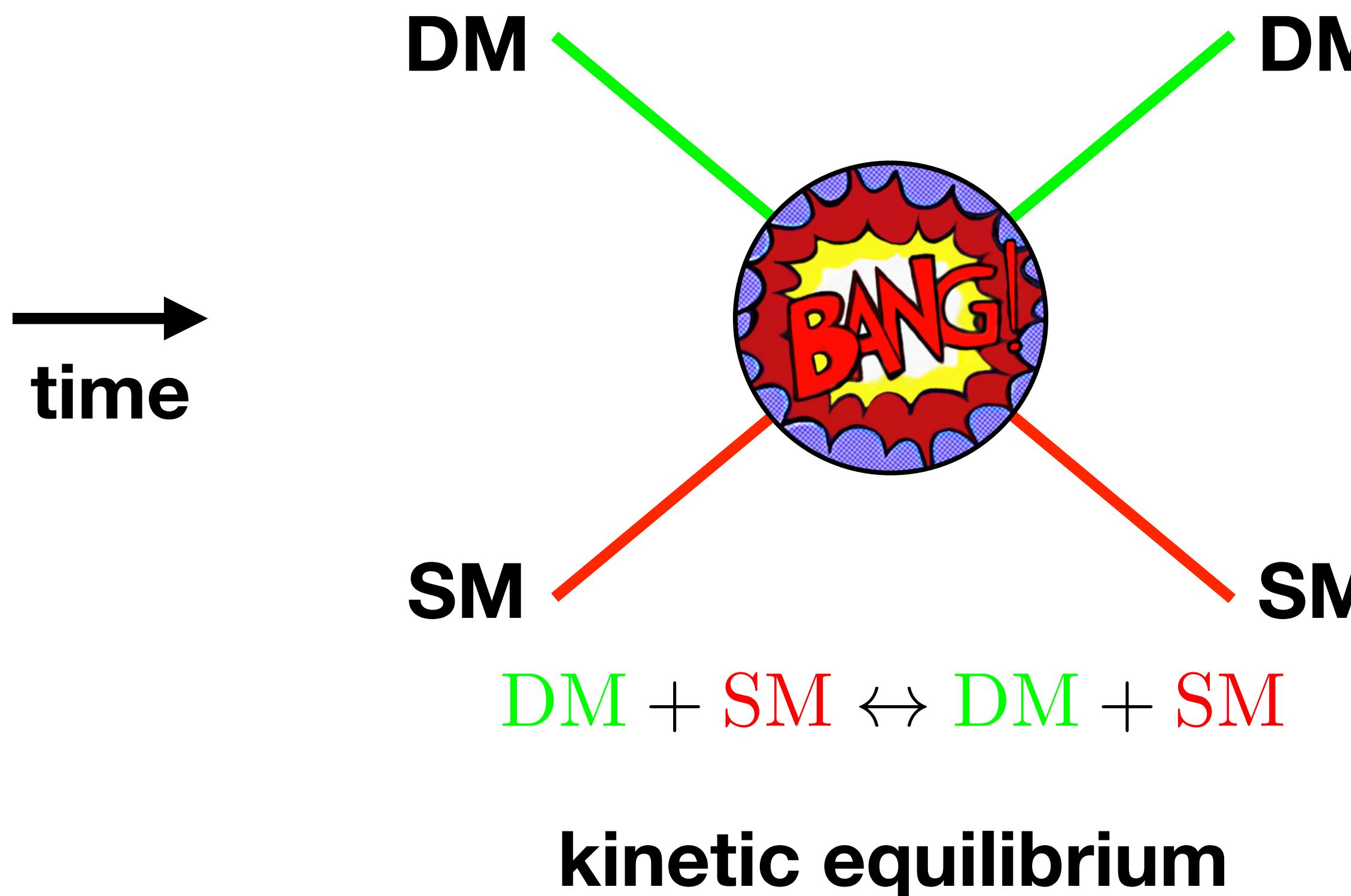


- “**Thermal**” \Rightarrow DM that was once in thermodynamic equilibrium with the SM

Thermal Dark Matter: Equilibration

50

- “Thermal” \Rightarrow DM that was once in thermodynamic equilibrium with the SM
- Equilibrium needs **non-gravitational** interactions between DM and the SM:



Thermal Dark Matter: Equilibration

51

- “Thermal” \Rightarrow DM that was once in thermodynamic equilibrium with the SM
- **Kinetic equilibrium** - DM and SM have the same temperature T .
- **Chemical equilibrium** - number density of DM species of mass m is

$$n_{\text{DM}}^{\text{eq}} \sim \int \frac{d^3 p}{(2\pi)^3} \frac{1}{e^{E/T} \mp 1}, \quad (E = \sqrt{m^2 + p^2}, \hbar = c = k_B = 1)$$

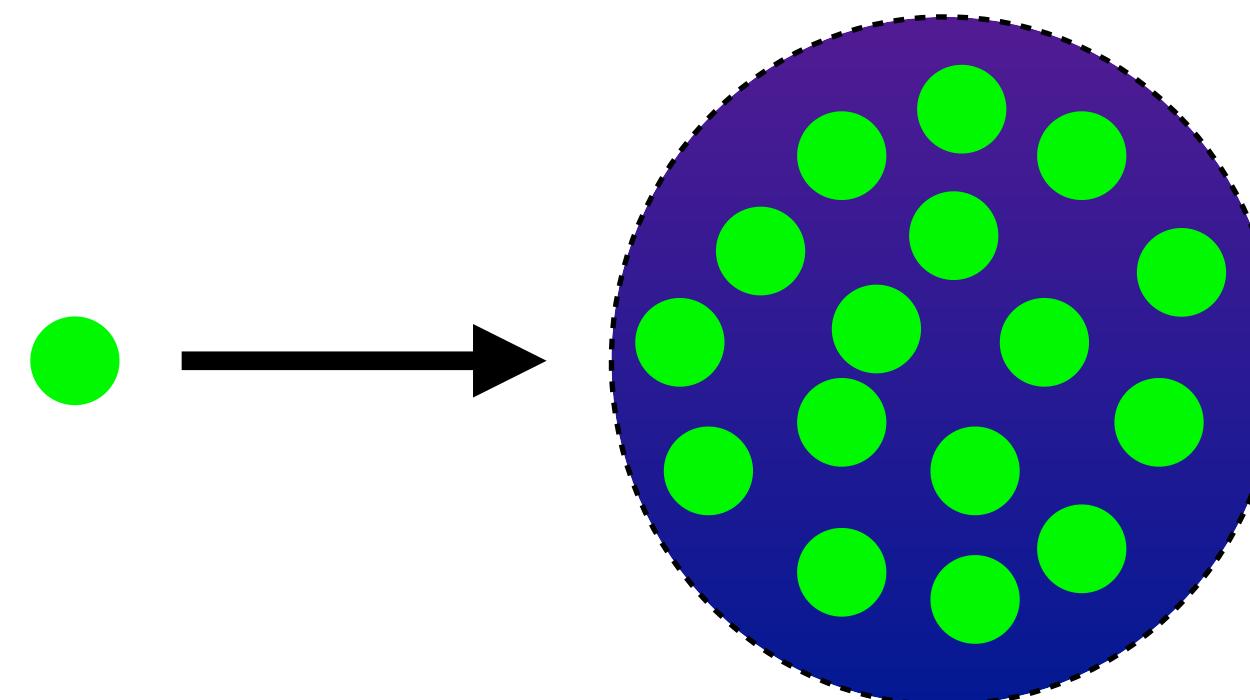
$$\sim \begin{cases} T^3 & ; \quad T \gg m \\ (mT)^{3/2} e^{-m/T} & ; \quad T \ll m \end{cases}$$

Thermal Dark Matter: Freeze Out

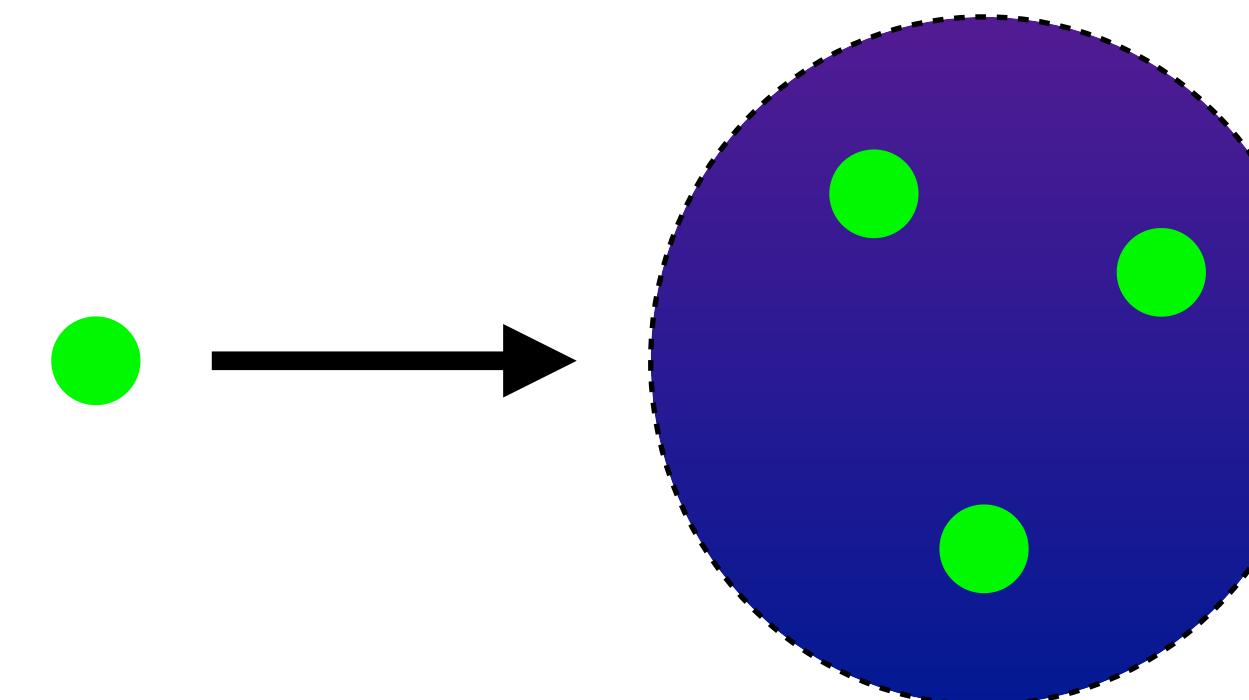
52

- Chemical equilibrium of DM is lost as the Universe cools.
- Reaction rate for DM annihilation $\text{DM} + \text{DM} \rightarrow \text{SM} + \text{SM}$:

$$R_{ann} = \langle \sigma_{ann} v \rangle n_{\text{DM}} \sim (\text{scattering probability}) \times (\text{target density})$$



$$T \gg m \Rightarrow n_{\text{DM}}/T^3 \sim 1$$



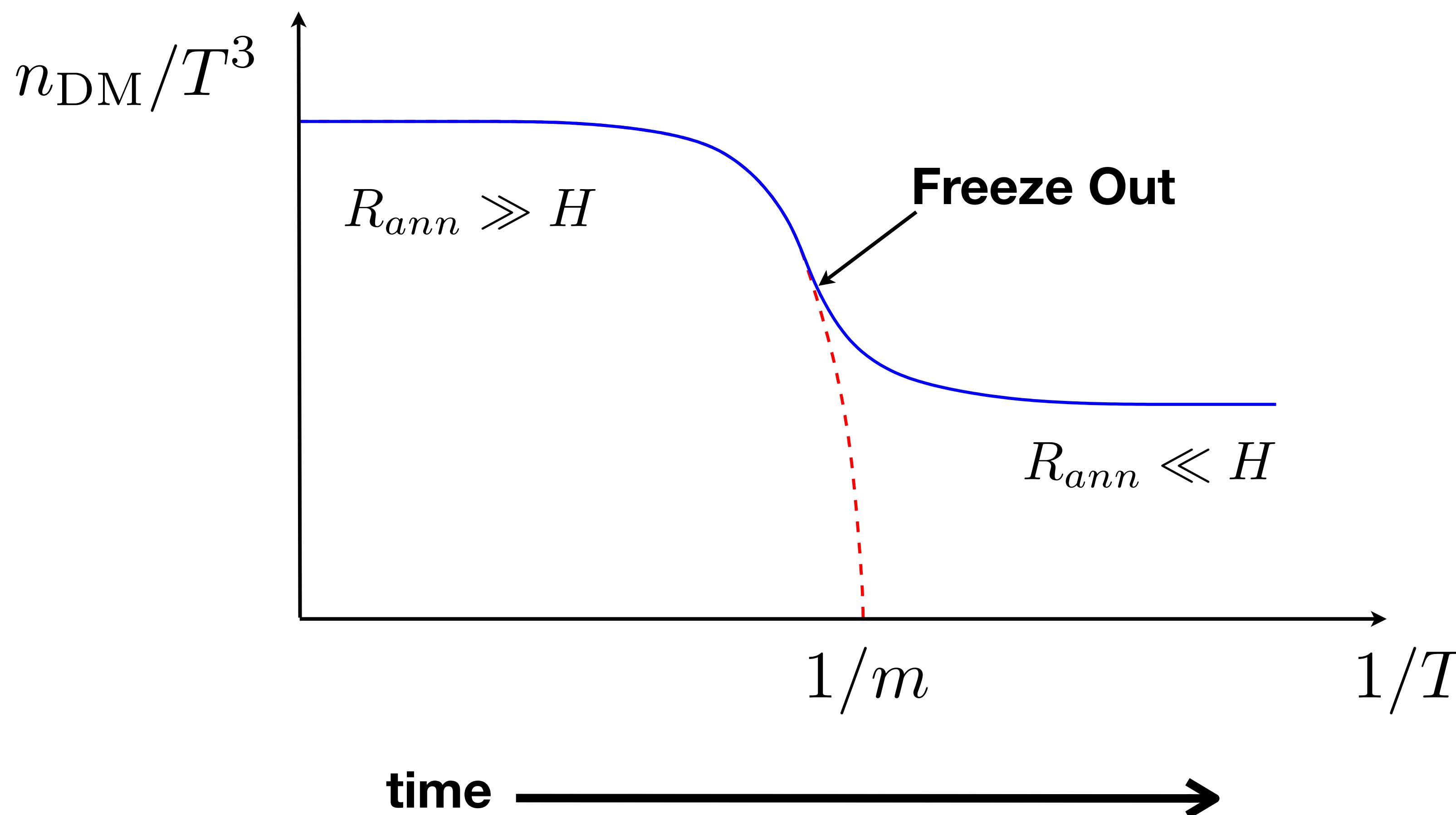
$$T \ll m \Rightarrow n_{\text{DM}}/T^3 \sim e^{-m/T}$$

- Equilibrium requires $R_{ann} > H \simeq 1/\tau_{\text{universe}}$

Thermal Dark Matter: Freeze Out

53

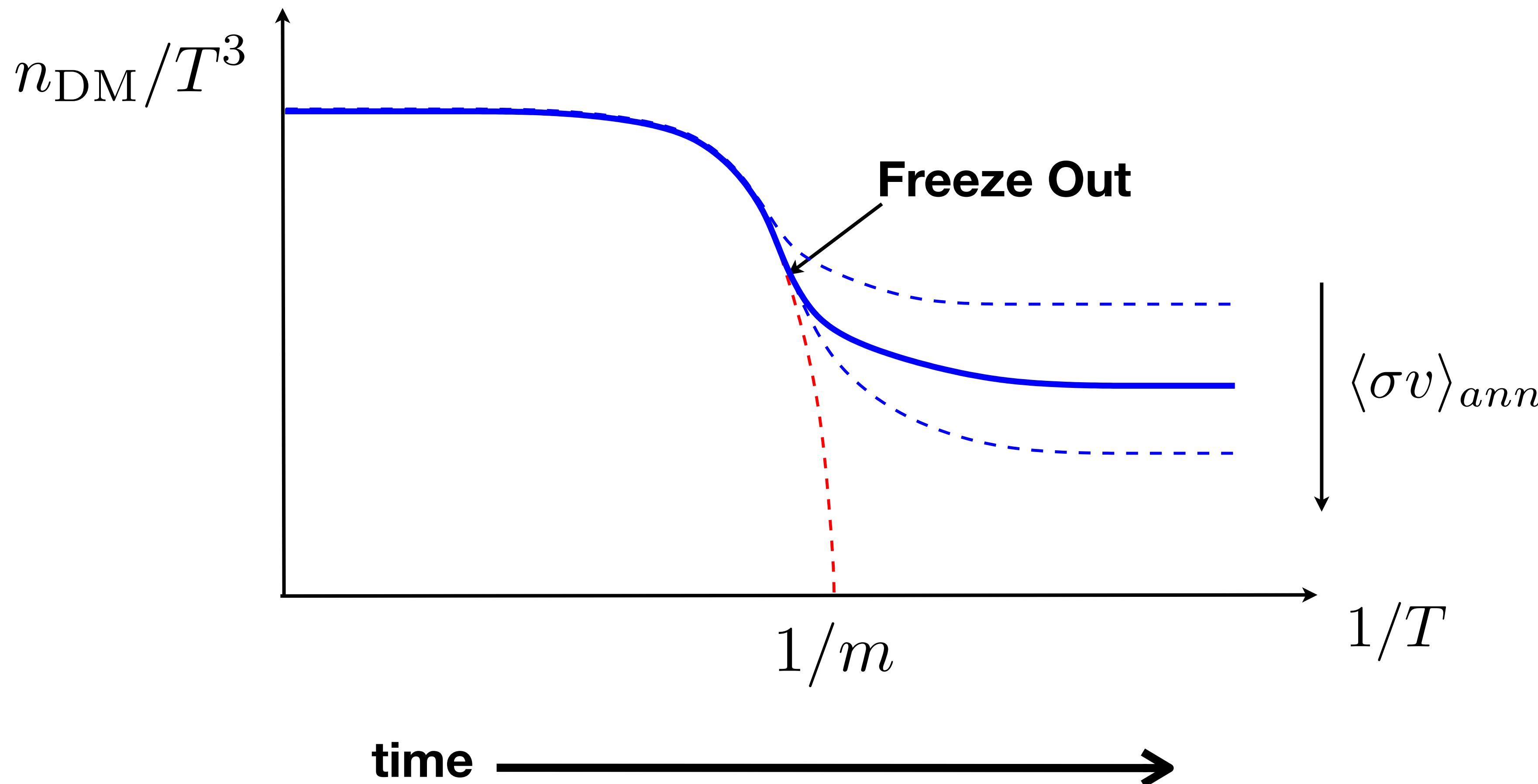
- For moderate DM-SM interaction strength:



Thermal Dark Matter: Freeze Out

- Dark Matter “relic density from freeze out:

$$\frac{n_{\text{DM}}}{n_{\text{obs}}} \simeq \frac{3 \times 10^{-26} \text{cm}^3/\text{s}}{\langle \sigma_{\text{ann}} v \rangle}$$



Thermal Dark Matter: WIMPs

55

- Special case: **WIMP** = Weakly Interacting Massive Particle
 - weak interactions between DM and SM predict $g_{\text{DM}} \sim 0.3$
 - correct density then follows for $m_{\text{DM}} \sim 100 - 3000 \text{ GeV}$
- New particles in this mass range are motivated by Higgs quantum stability!

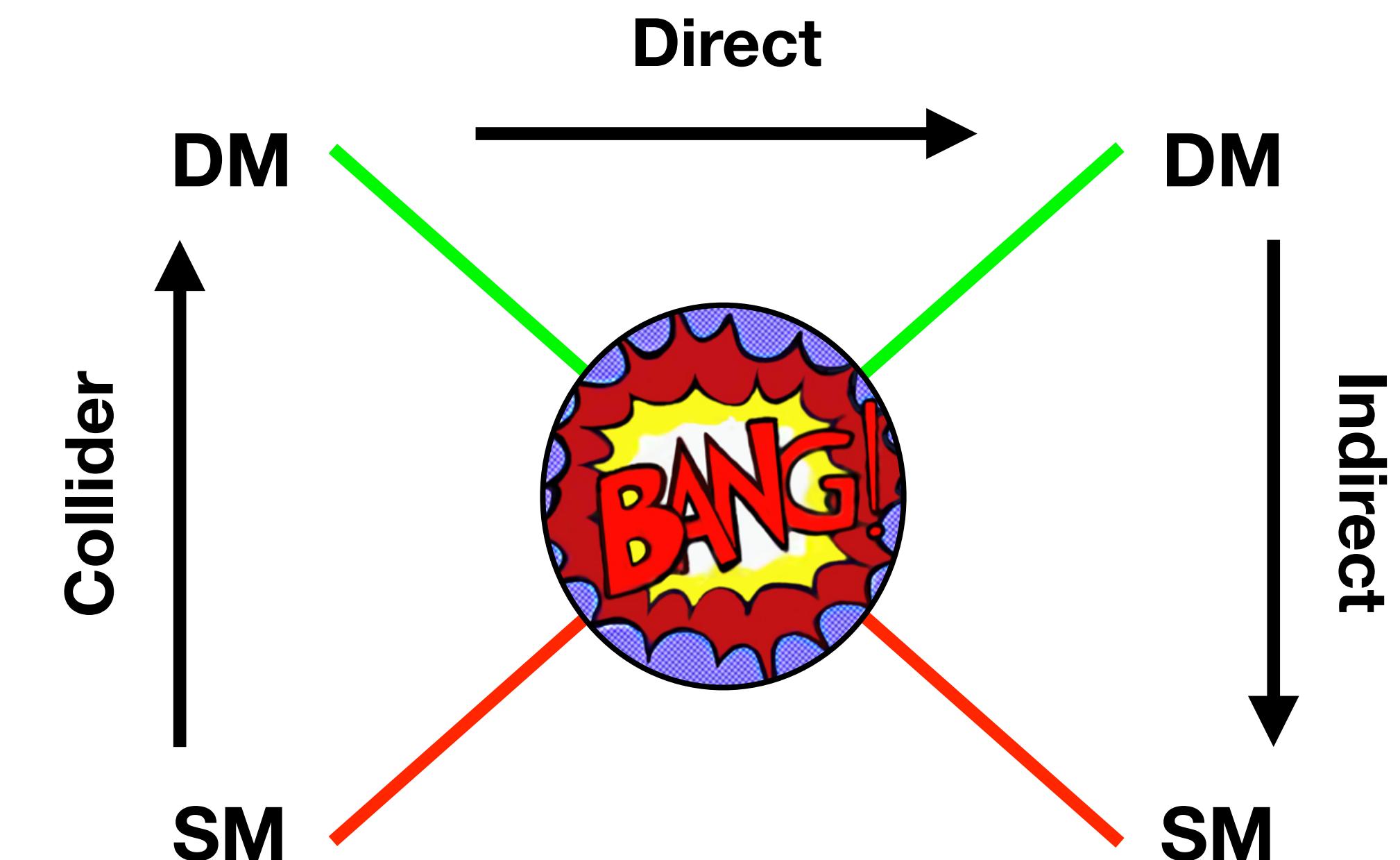
⇒ “WIMP Miracle”

- More generally, thermal freeze out works for $10 \text{ MeV} \lesssim m_{\text{DM}} \lesssim 100 \text{ TeV}$
“WIMP-like Dark Matter”

(Thermal) Dark Matter Detection

56

- We want non-gravitational evidence for dark matter!
This is expected for thermal dark matter.
- Three main approaches:
 1. **Direct Detection**
→ scattering of DM in detectors
 2. **Indirect Detection**
→ cosmic rays and more from DM
 3. **Colliders**
→ create DM in energetic collisions

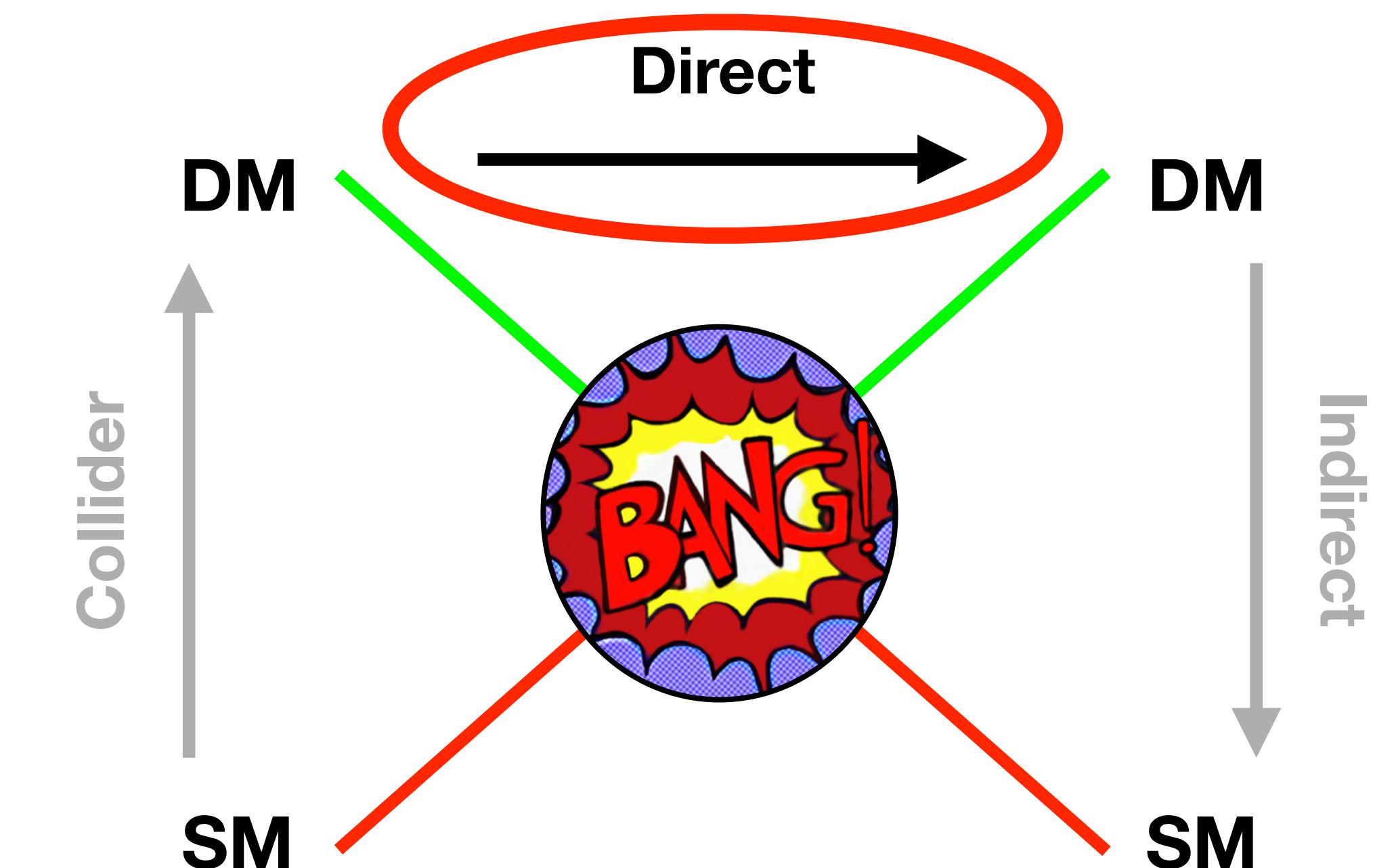


"shake it, break it, make it"

(Thermal) Dark Matter Detection

57

- We want non-gravitational evidence for dark matter!
This is expected for thermal (WIMP) dark matter.
- Three main approaches:
 1. **Direct Detection**
→ scattering of DM in detectors
 2. **Indirect Detection**
→ cosmic rays and more from DM
 3. **Colliders**
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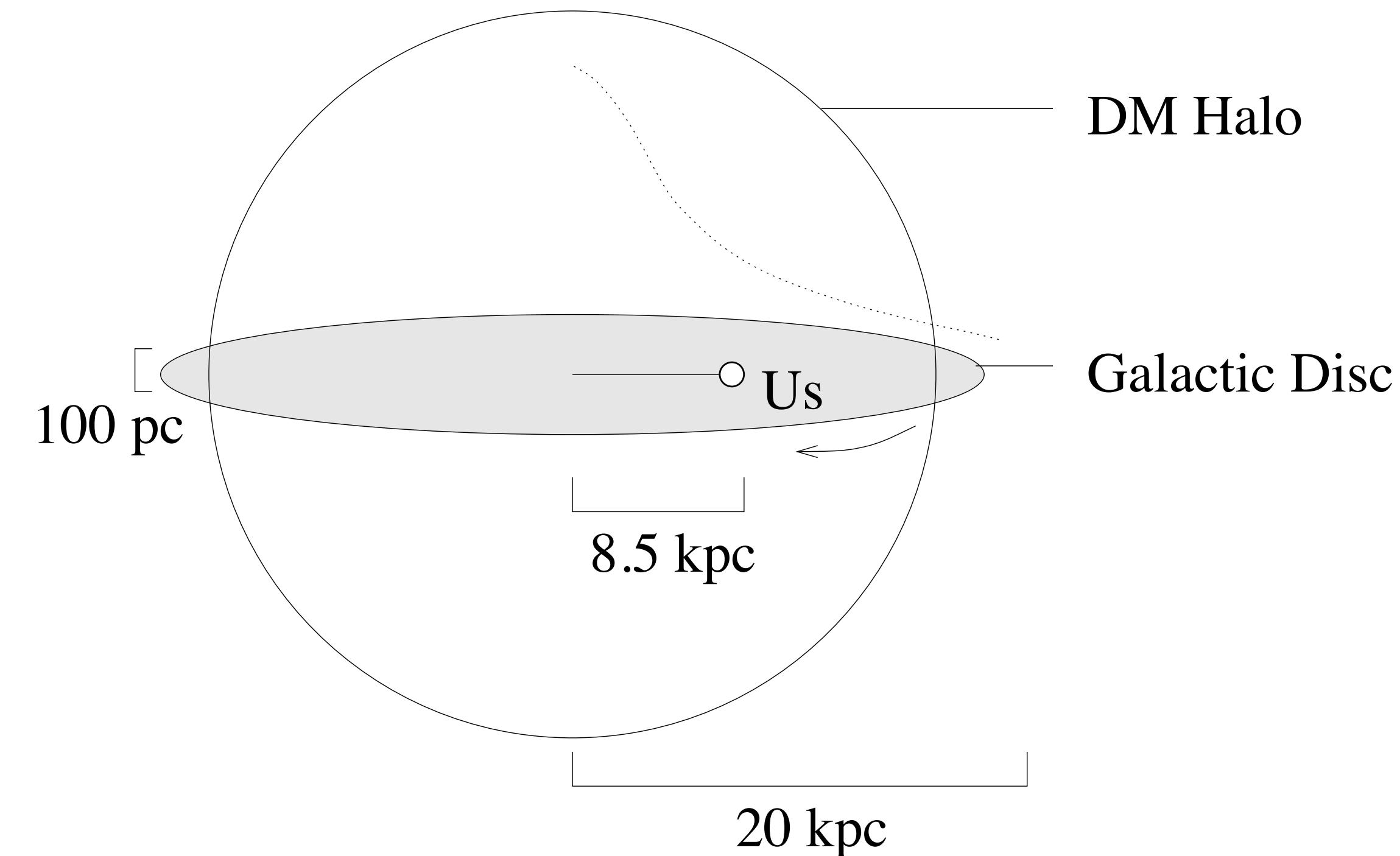


“shake it, break it, make it”

Dark Matter Near Us

58

- If DM exists, we should be surrounded by it.

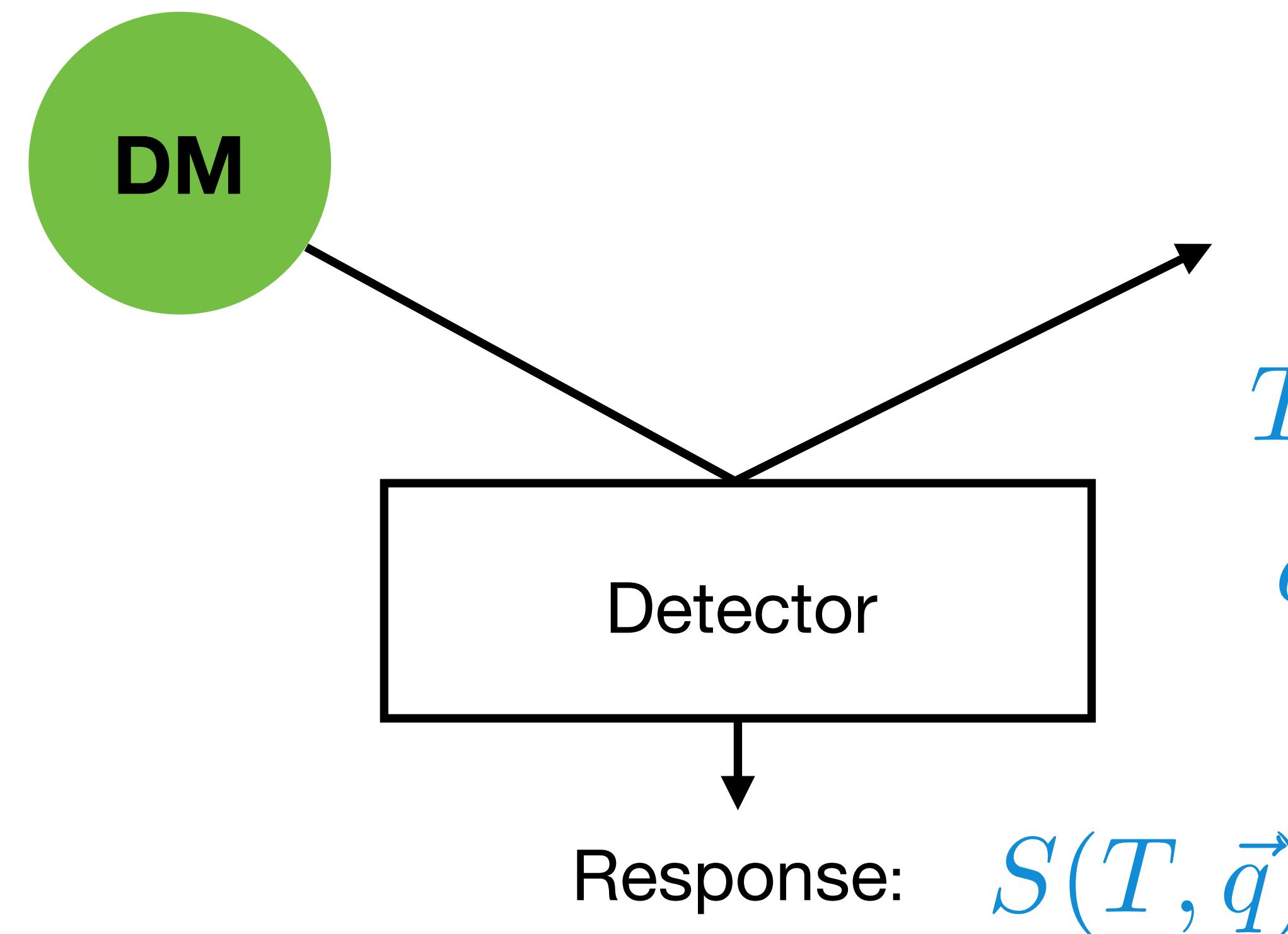


- In our local region: $\rho_{\text{DM}} \simeq 0.3 \text{ GeV/cm}^{-3}$
 $\langle v_{\text{DM}} \rangle \simeq 300 \text{ km/s} \simeq 10^{-3} c$

Dark Matter Detection in the Lab

59

- If DM is all around us and interacts with the SM, it might be detectable!
- Direct Detection: scattering in a detector.



DM-Nucleus Interactions

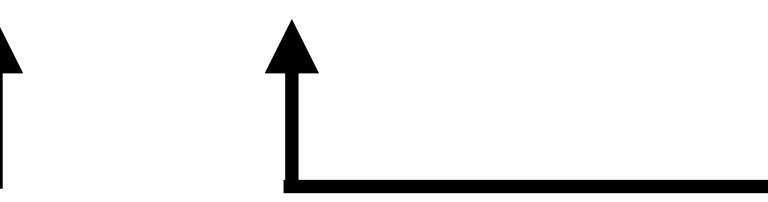
60

- DM-quark interaction → DM-nucleon interaction → DM-nucleus interaction
- In many theories, get a leading DM-nucleon potential of:

$$V_{n\chi}(\vec{x}) = \begin{cases} f_n \delta^{(3)}(\vec{x}) & ; \quad \textbf{spin-independent (SI)} \\ a_n \delta^{(3)}(\vec{x}) (\vec{S}_\chi \cdot \vec{S}_n) & ; \quad \textbf{spin-dependent (SD)} \end{cases}$$

- For SI scattering, the cross section on nucleus ${}_Z^A N$ has the form

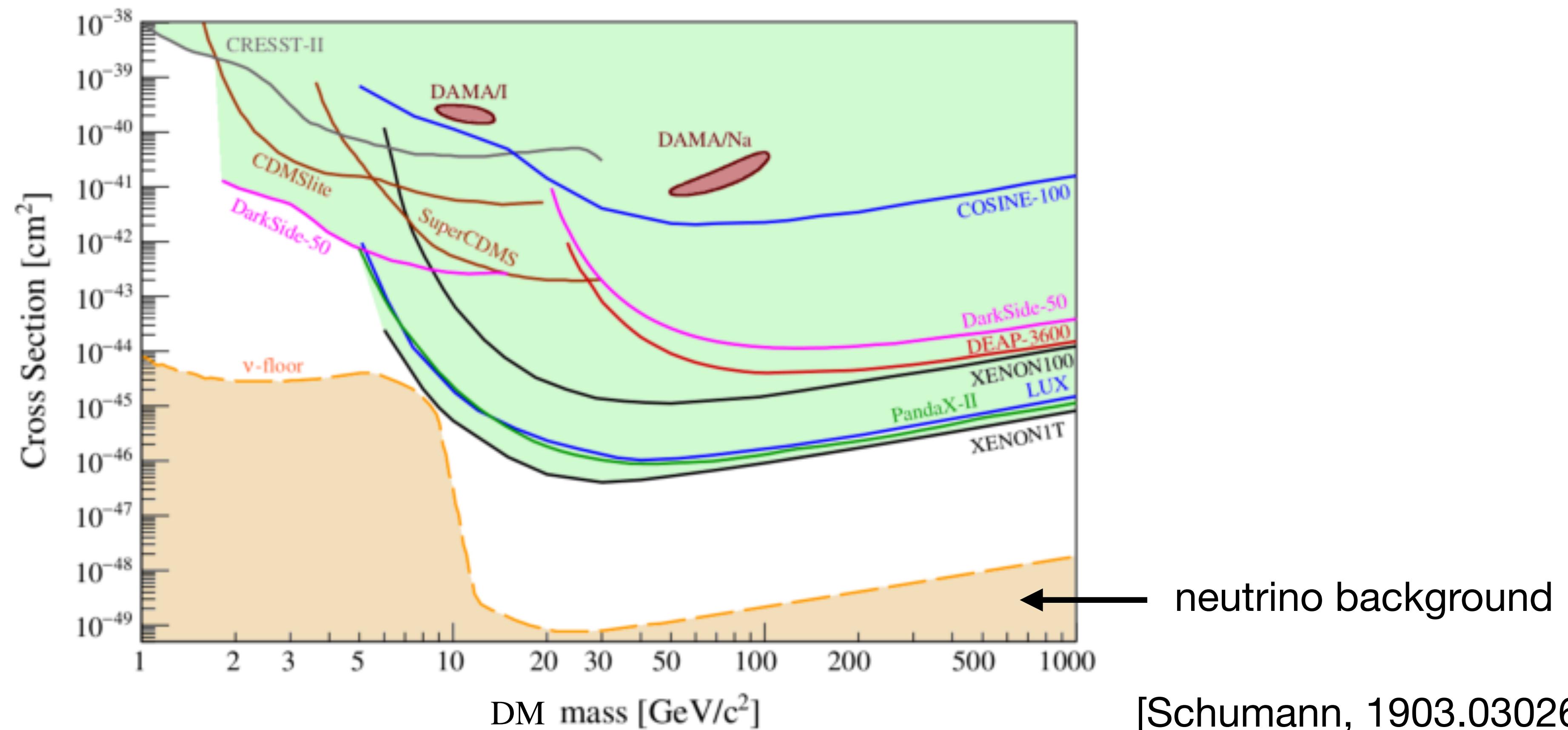
$$\frac{d\sigma_N}{dE_R} = \frac{A^2}{v^2} \left(\frac{\mu_N}{\mu_n} \right)^2 \sigma_n |F_N(E_R)|^2$$


↑
DM-nucleon effective cross section **Nuclear Response**

Dark Matter Direct Detection

61

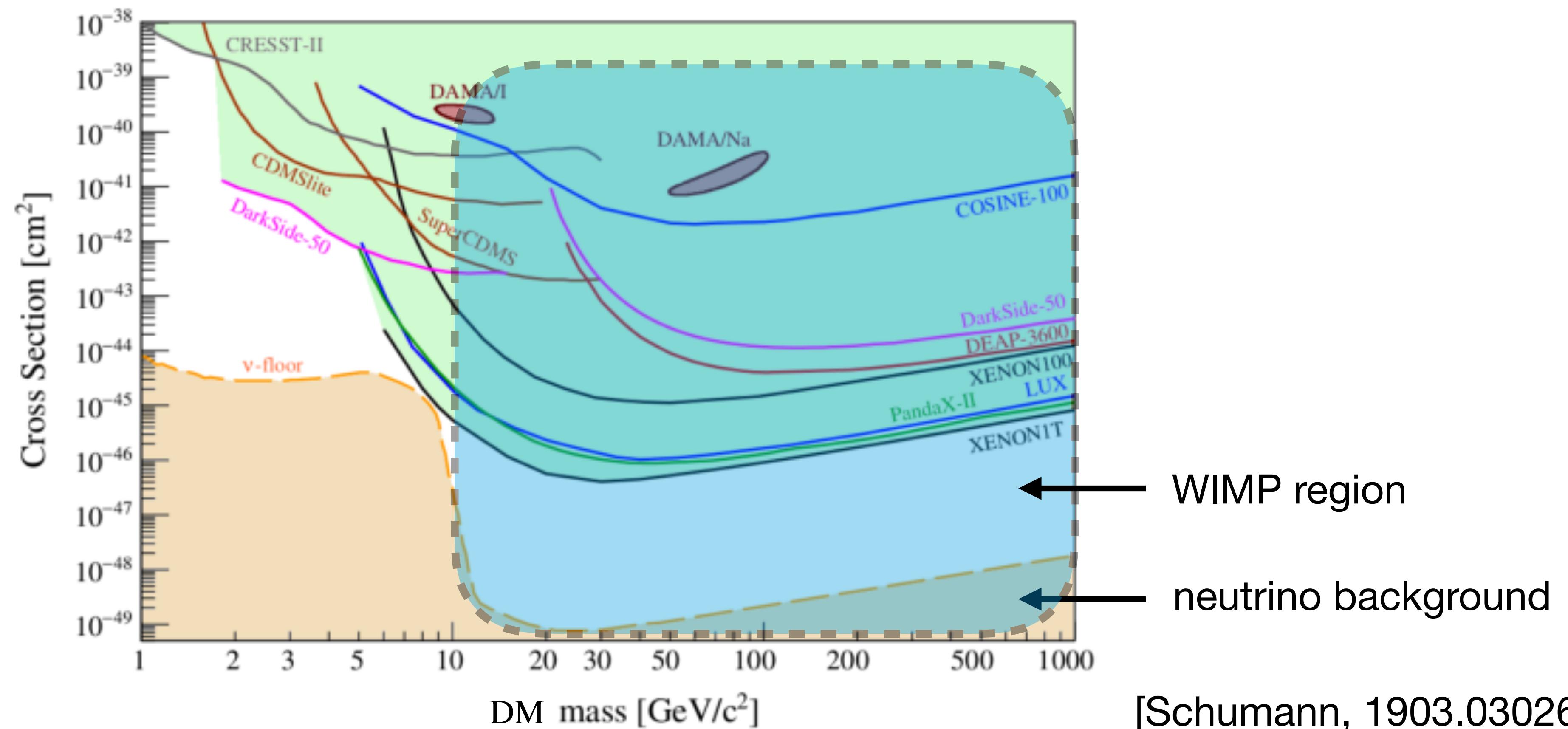
- Searches for DM-nuclear scattering have not seen anything yet.
- For **spin-independent** elastic scattering:



Dark Matter Direct Detection

62

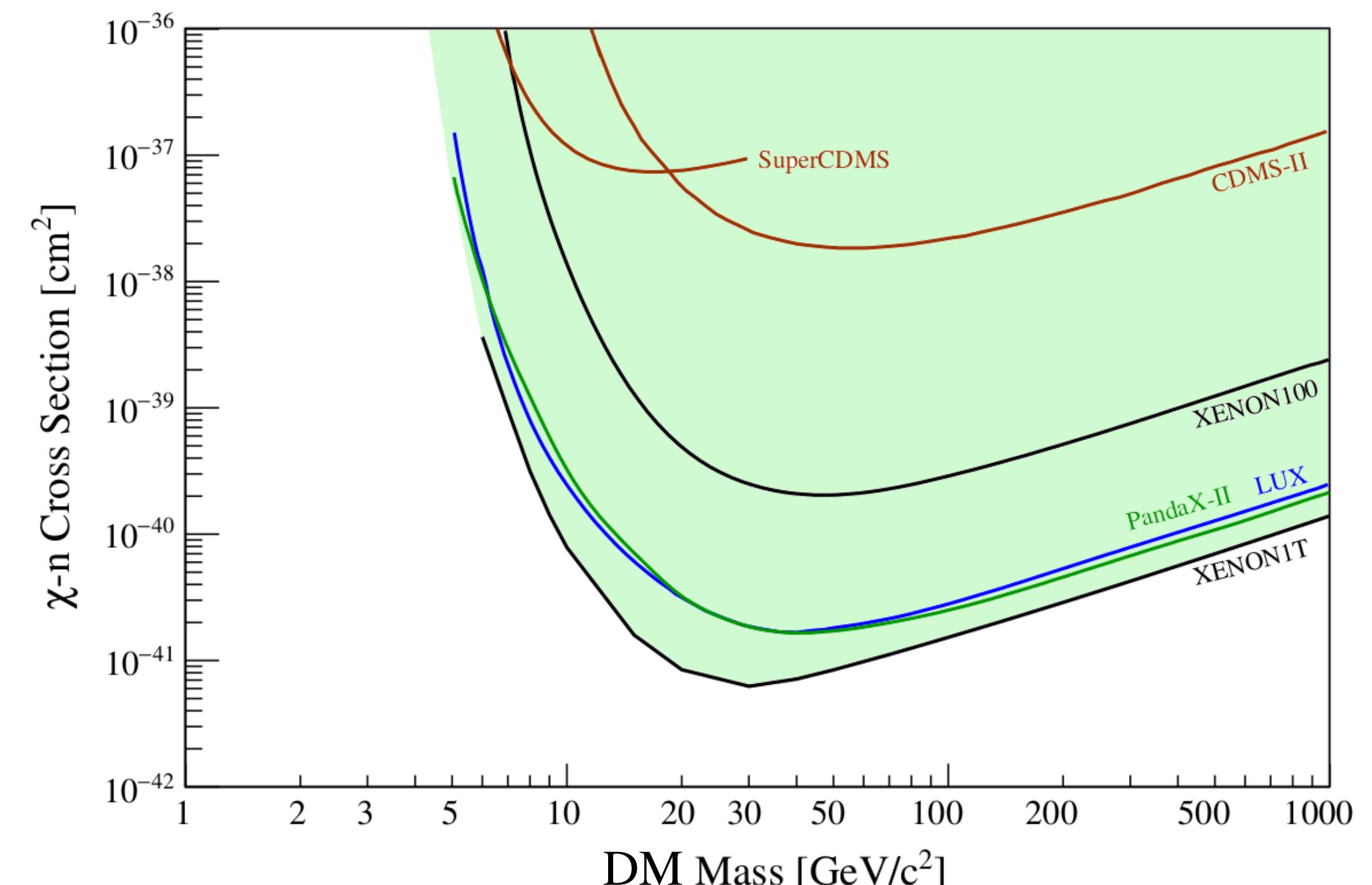
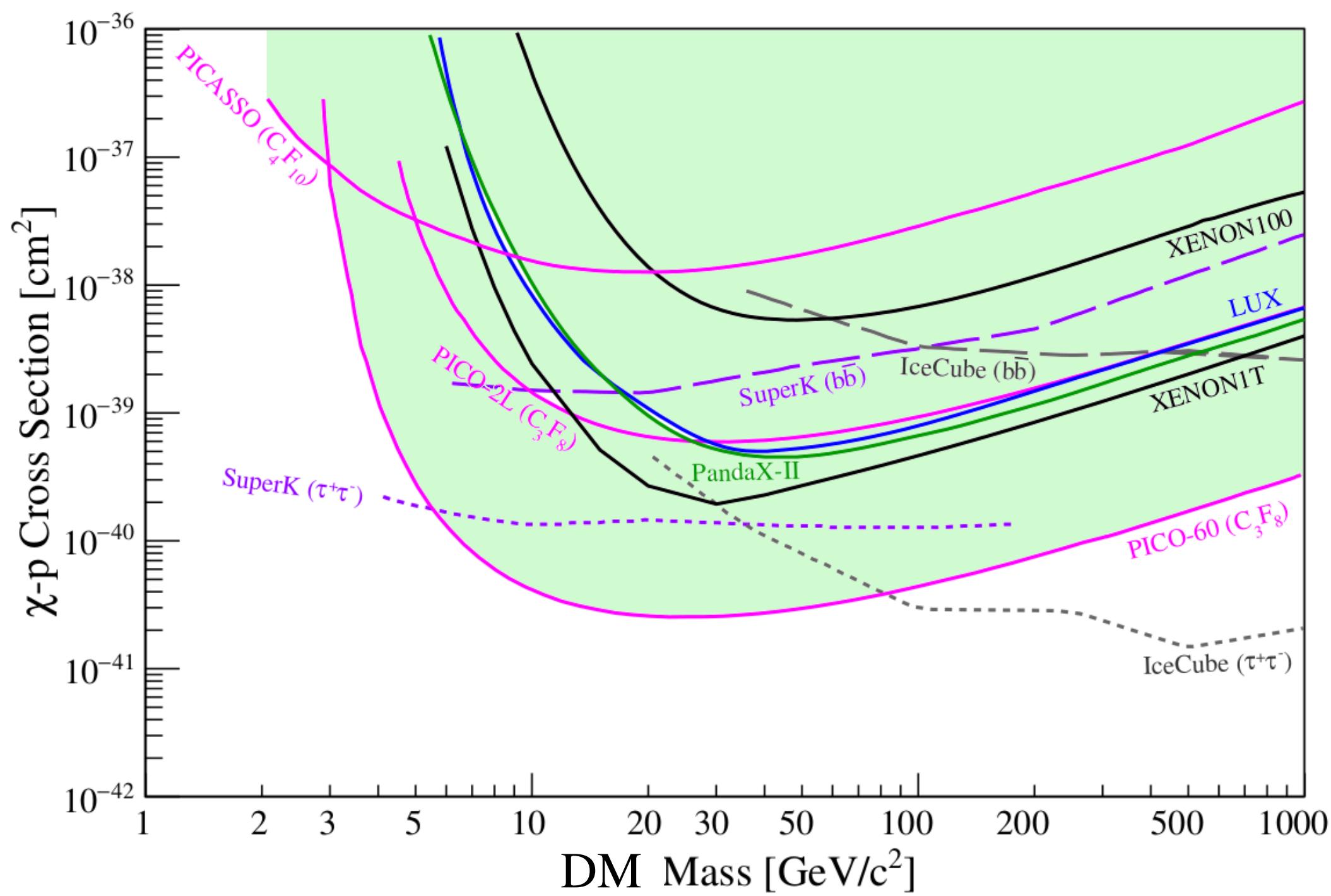
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Dark Matter Direct Detection

63

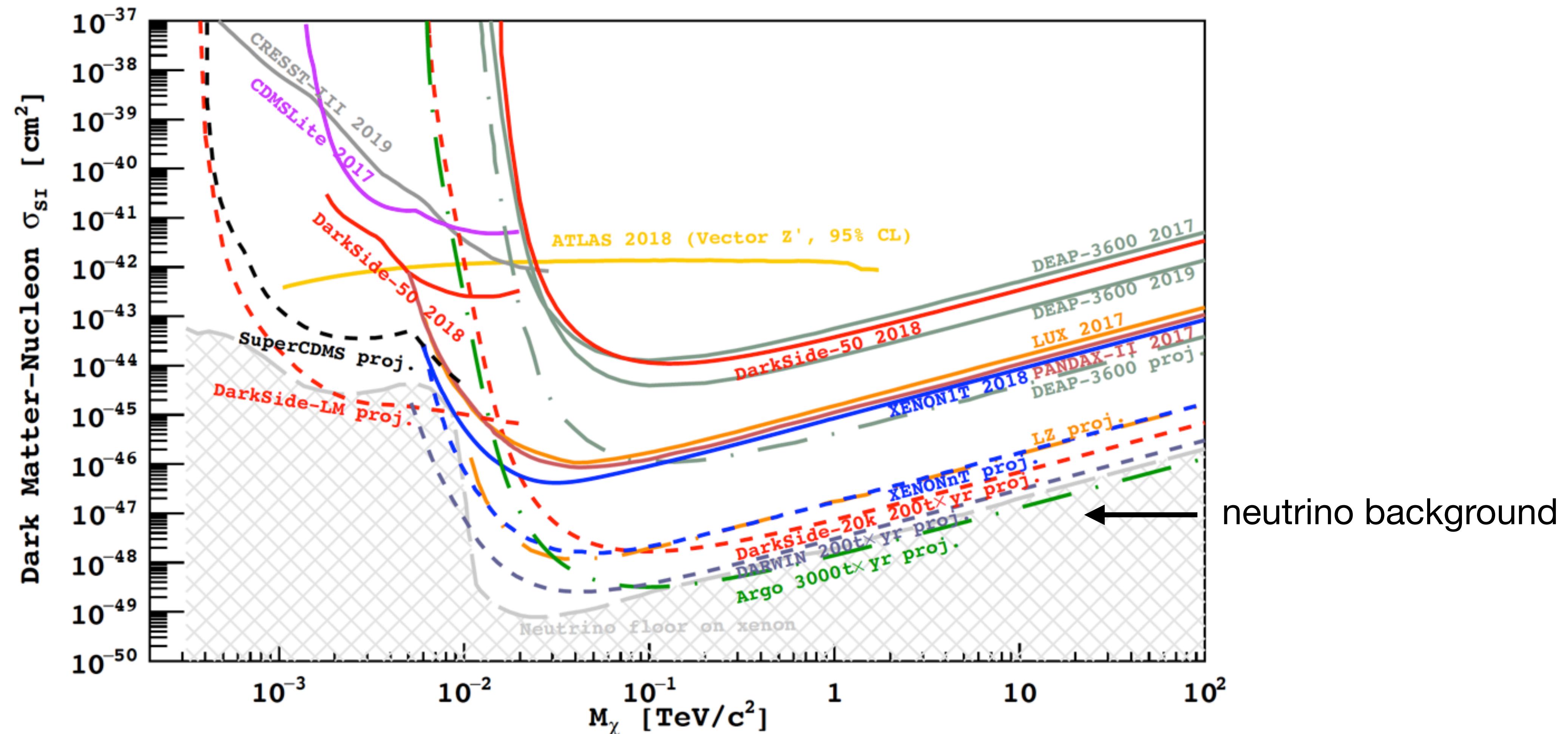
- Searches for DM-nuclear scattering have not seen anything yet.
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Dark Matter Direct Detection

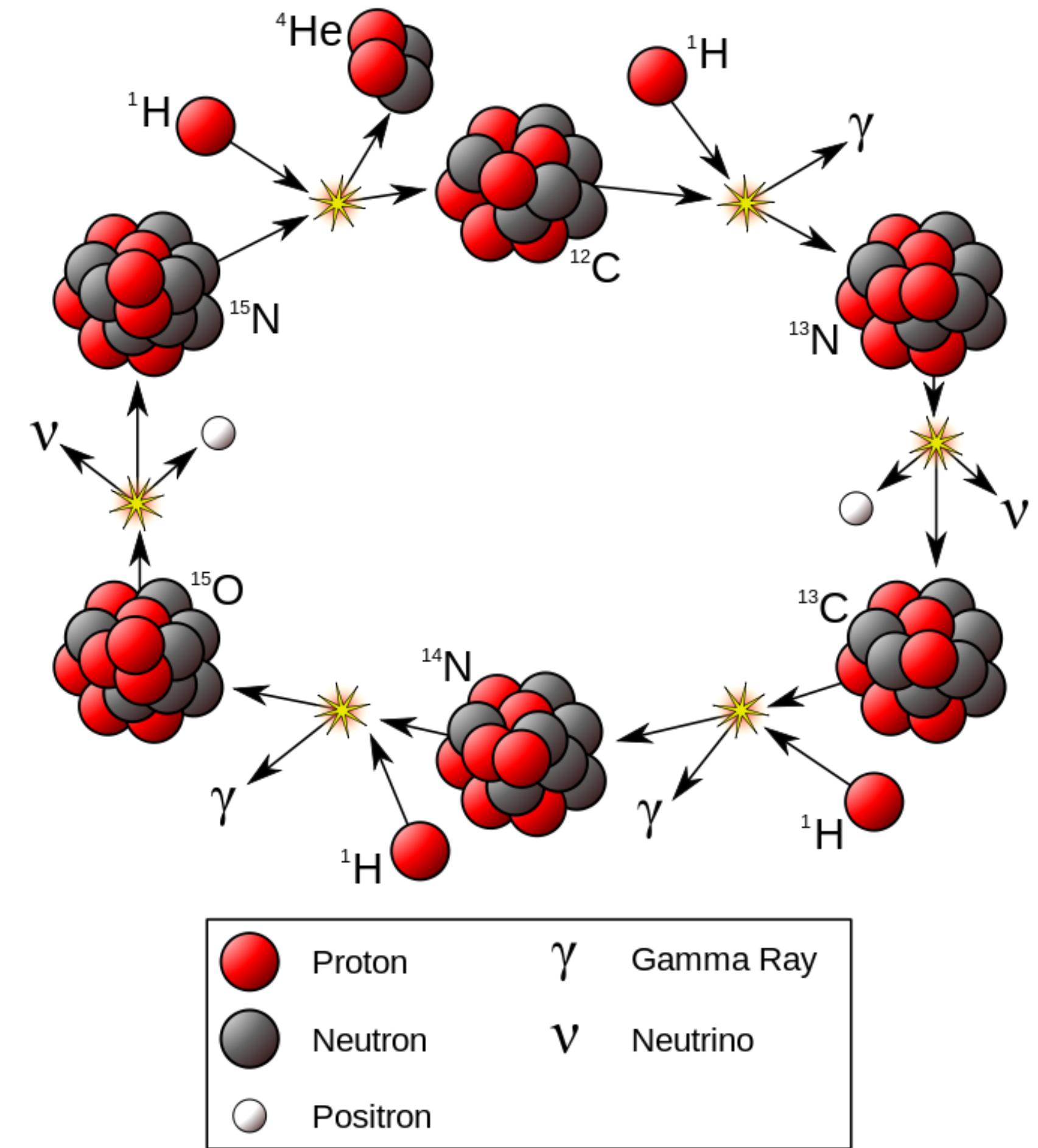
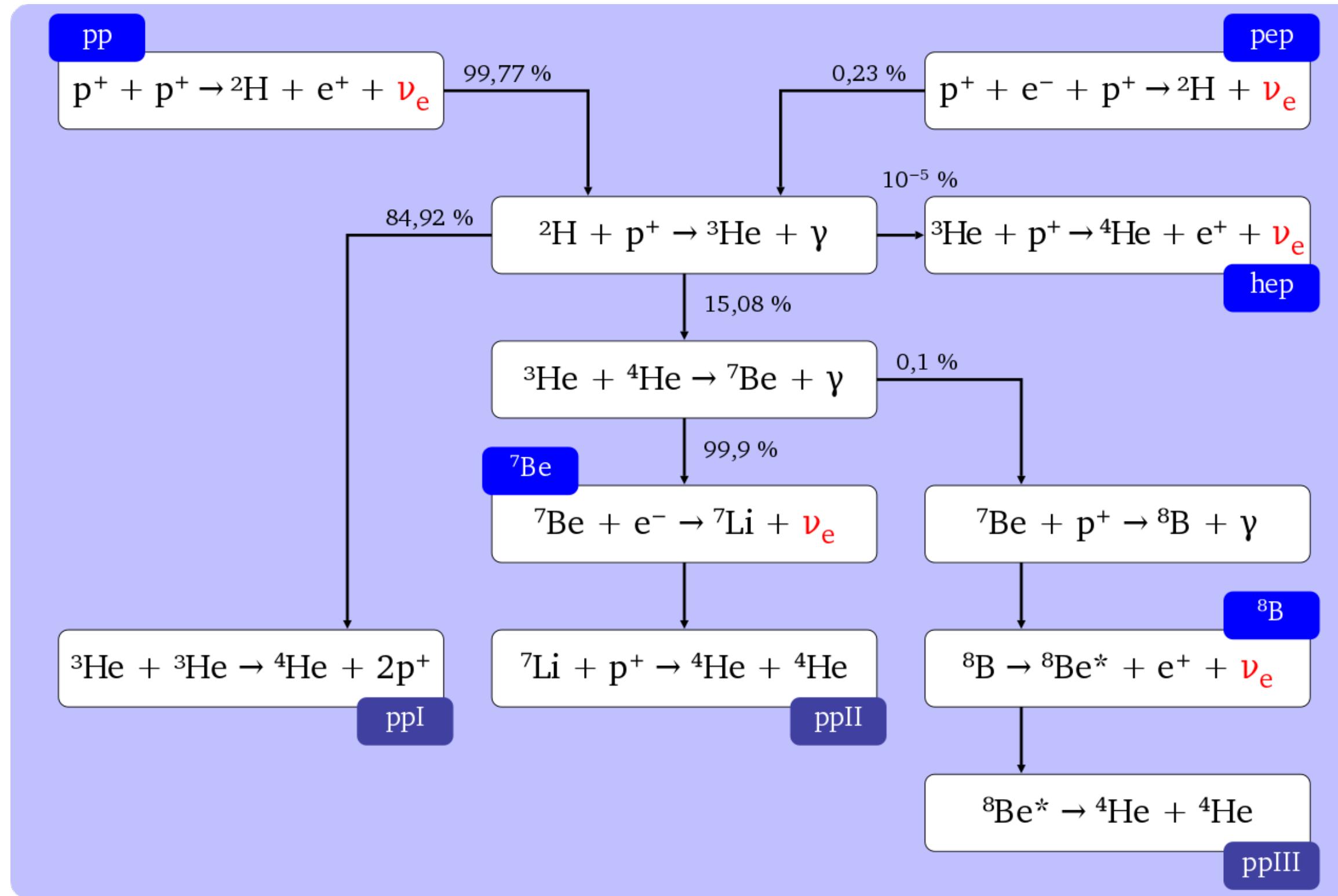
64

- Future projections:



Solar Neutrinos

65



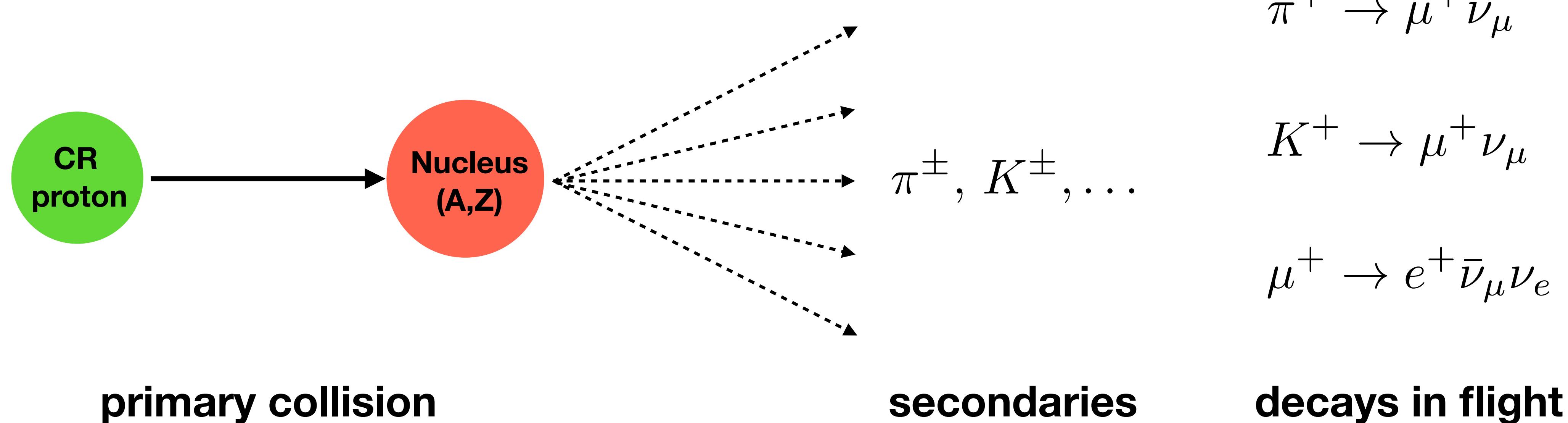
[Dorothy Szam]

[Borb]

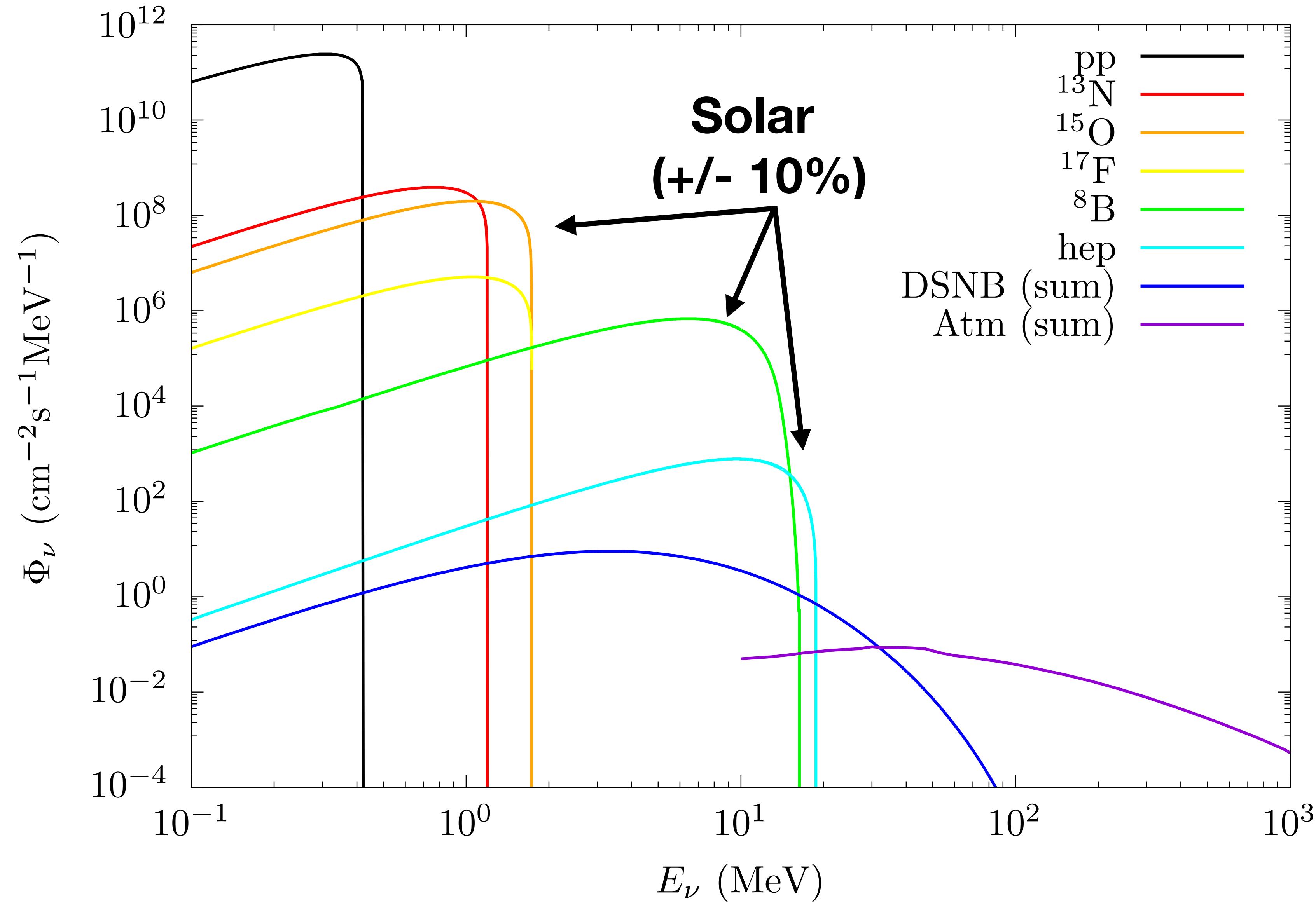
Atmospheric Neutrinos

66

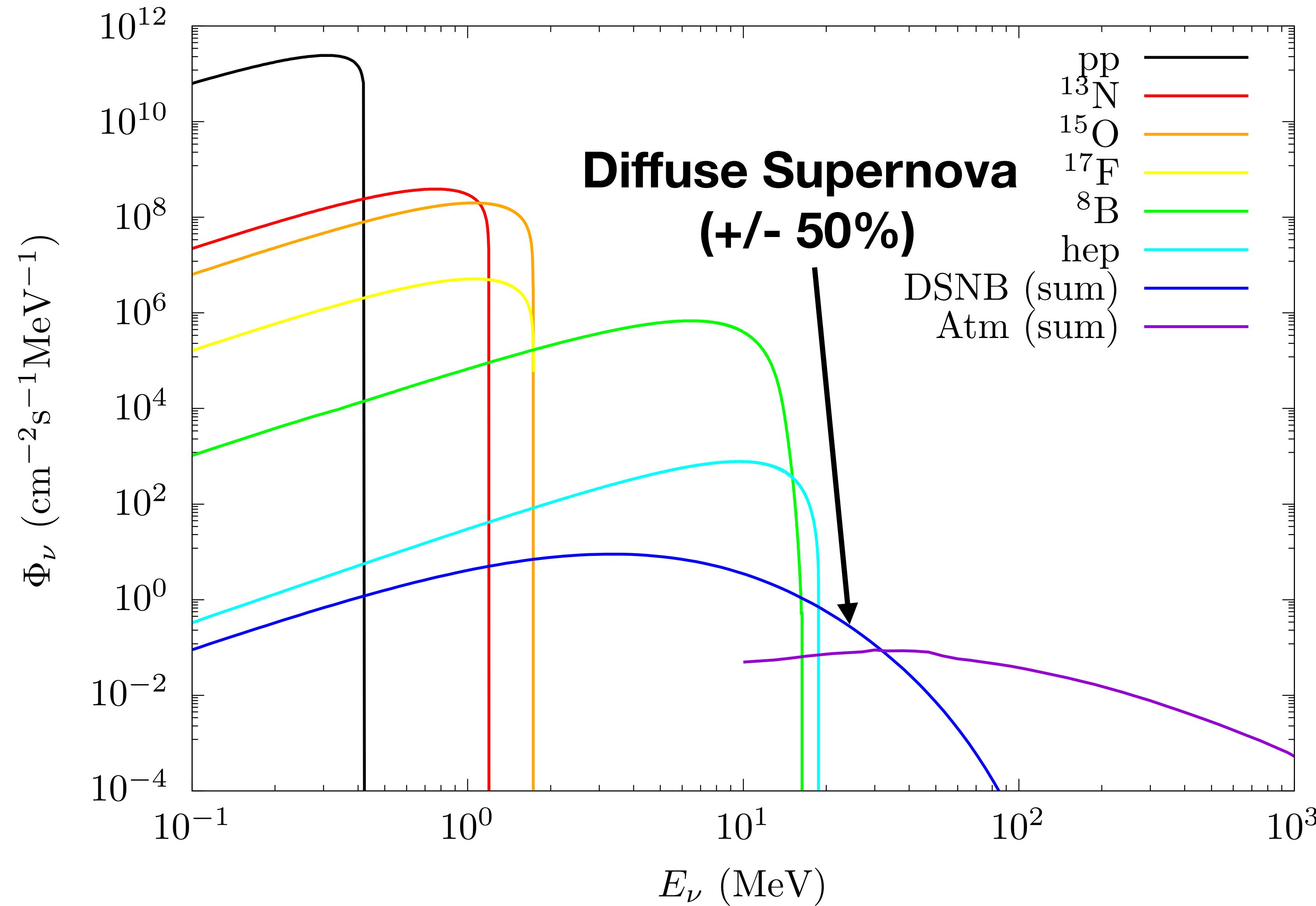
- Atmospheric neutrinos are the dominant neutrino background for $m_\chi \gtrsim 10 \text{ GeV}$
- Neutrinos are produced by cosmic rays hitting the atmosphere.



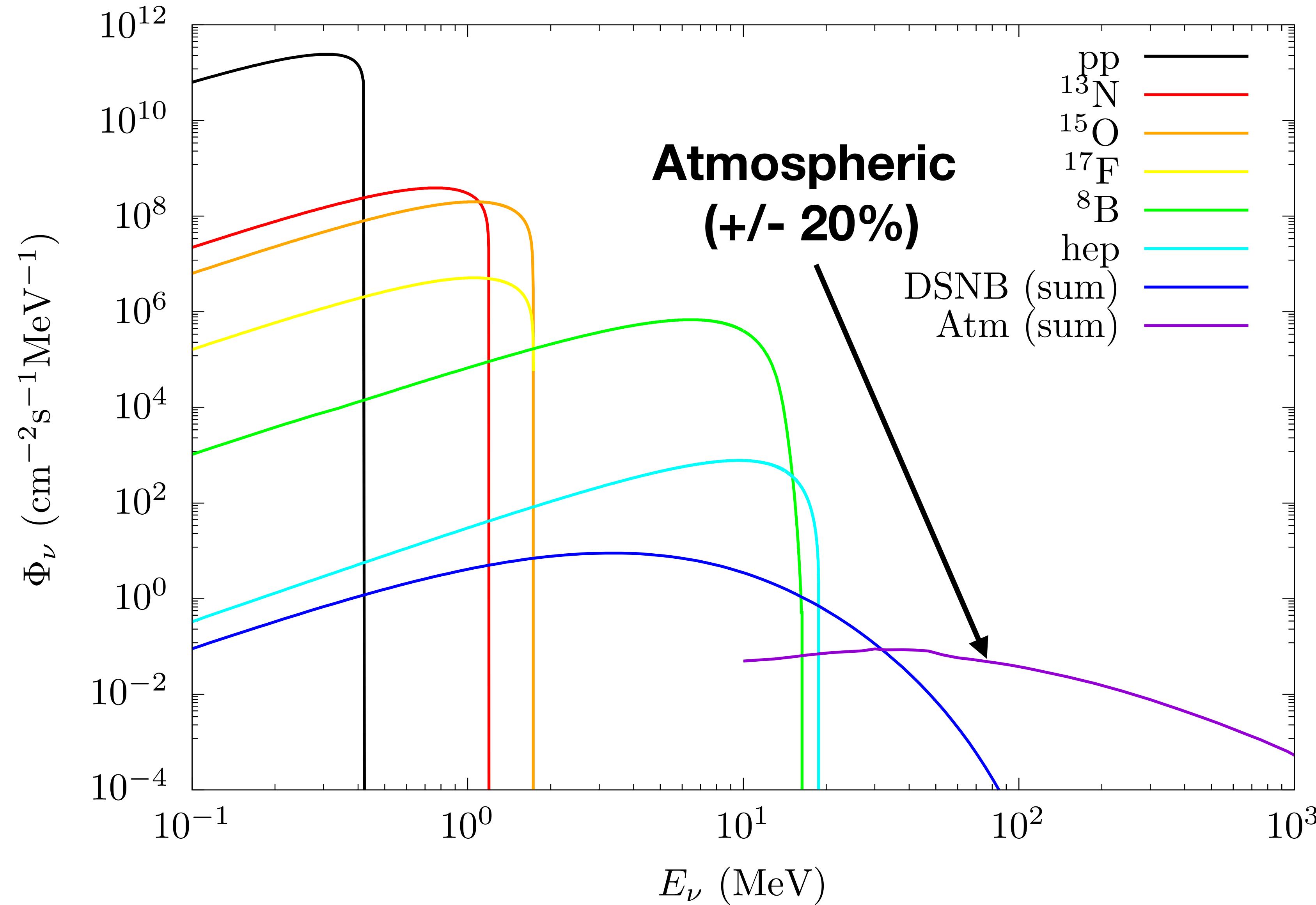
Neutrino Sources



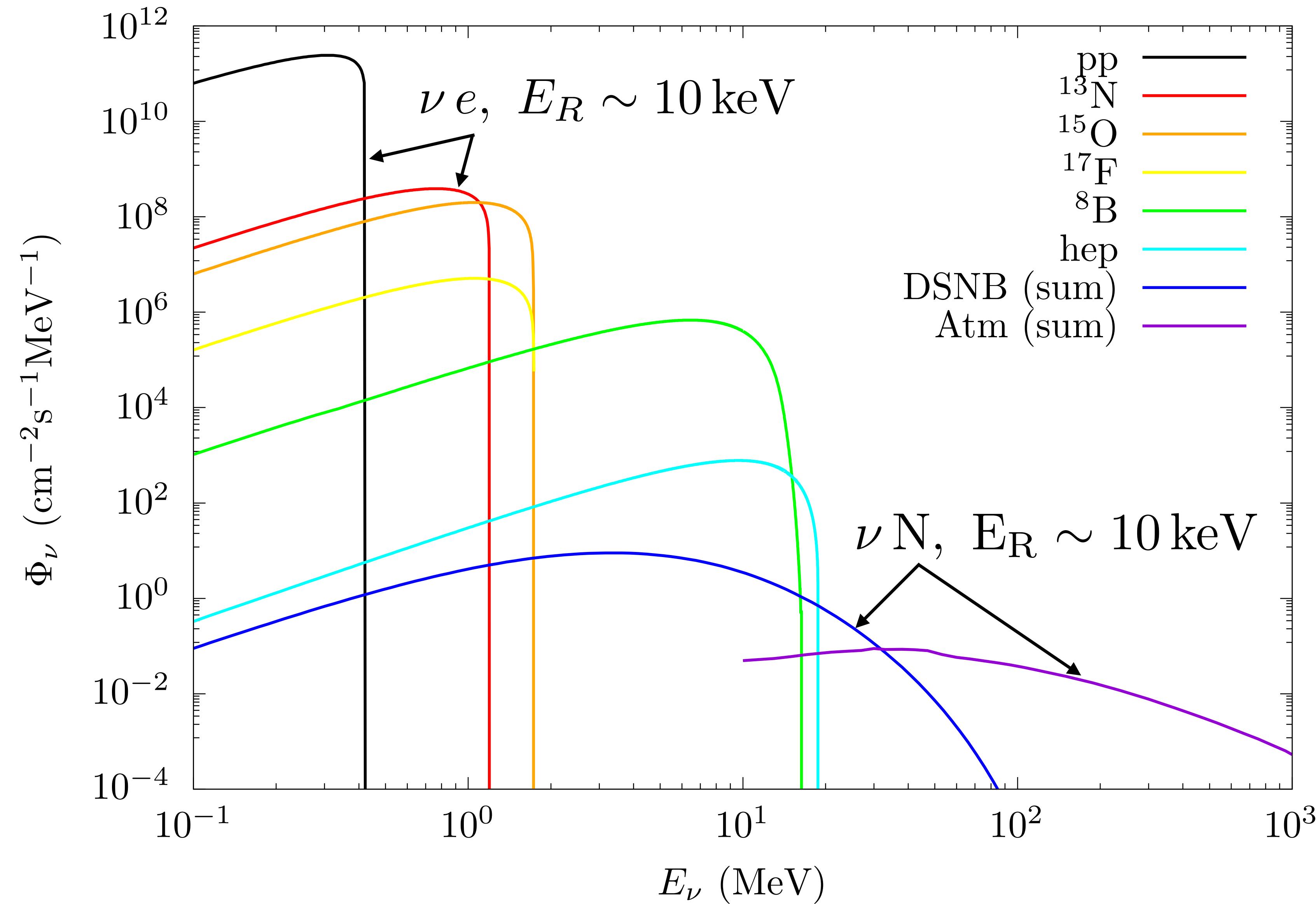
Neutrino Sources



Neutrino Sources

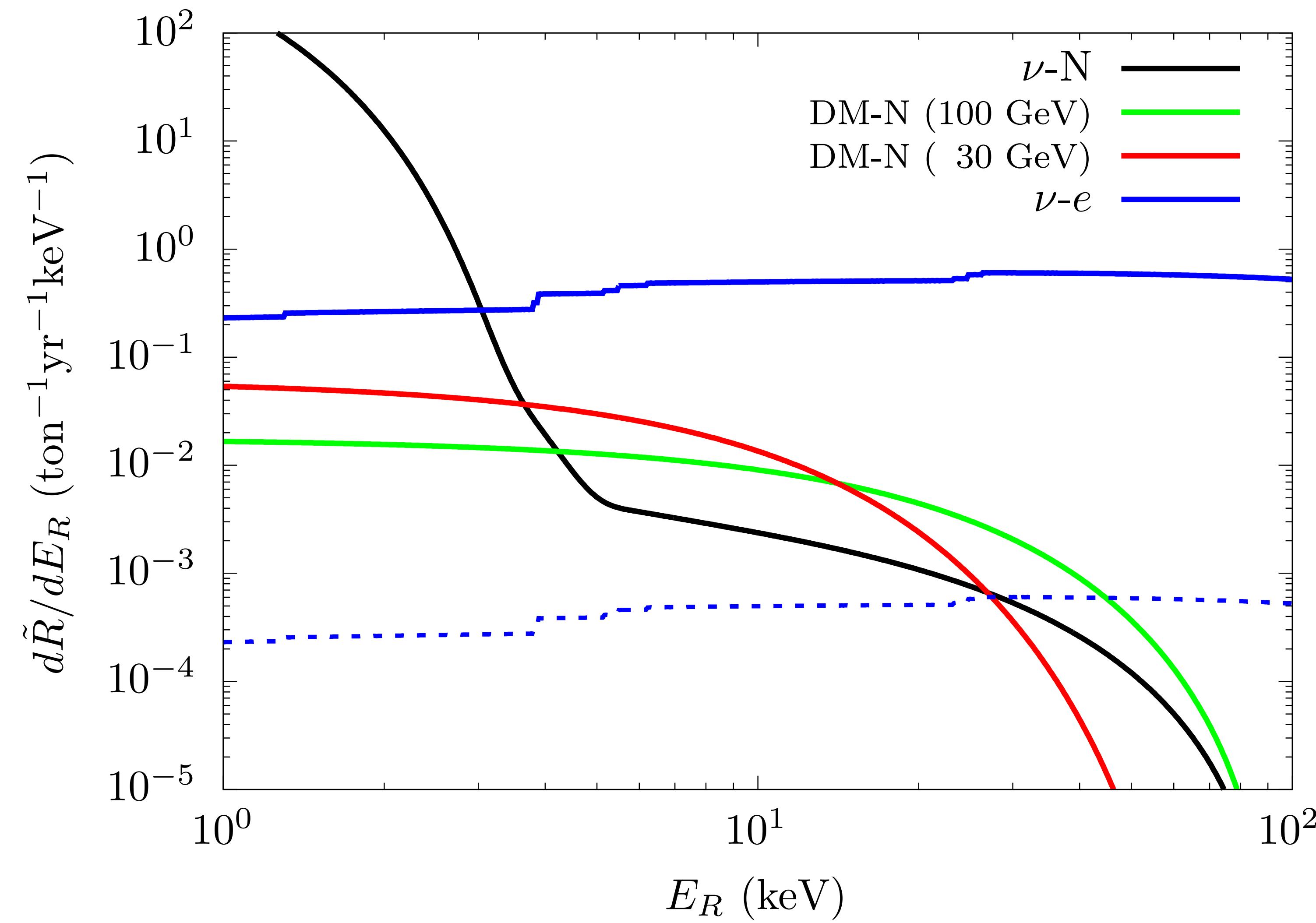


Neutrino Sources



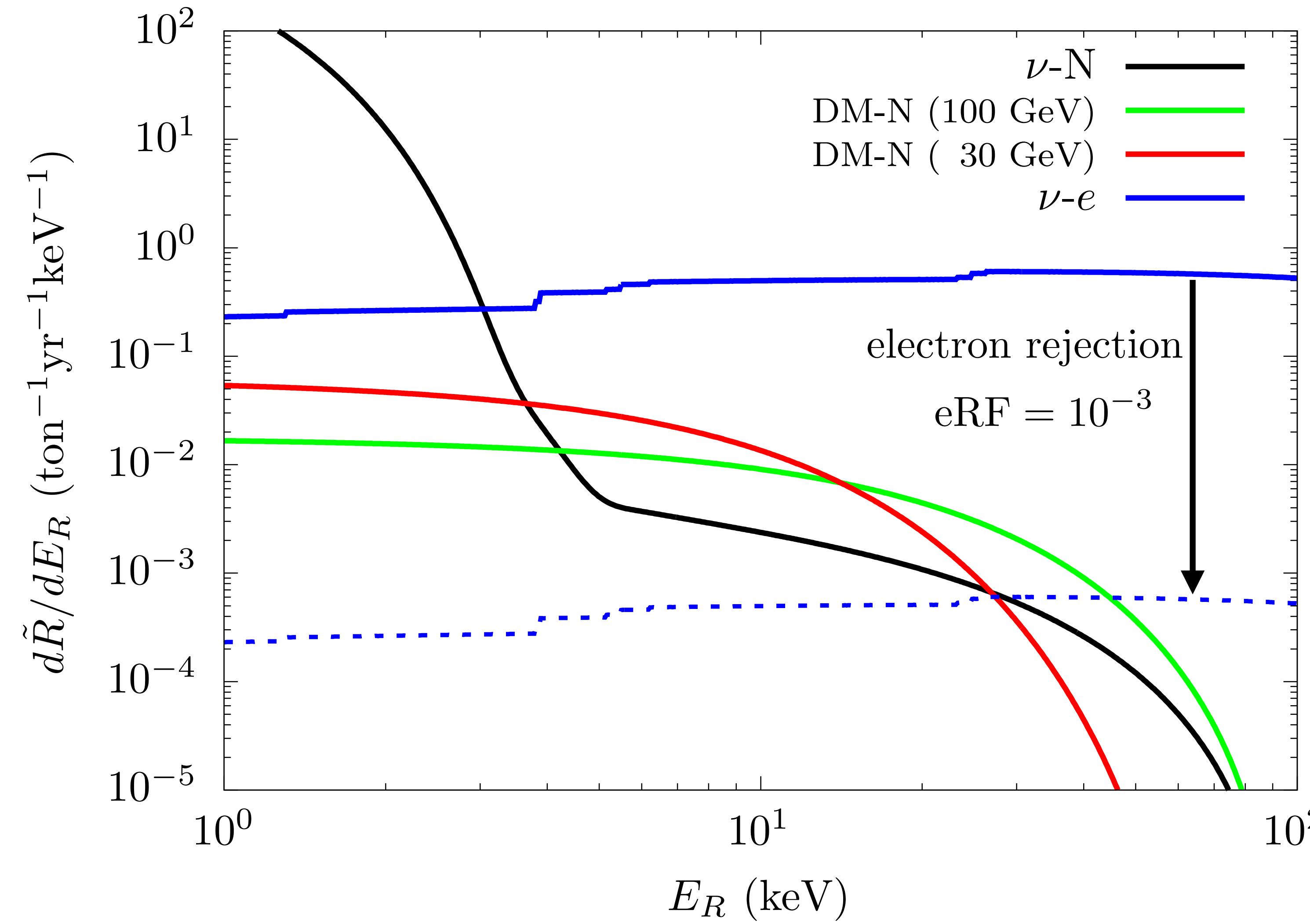
Recoil Energy Spectra (Xe)

71



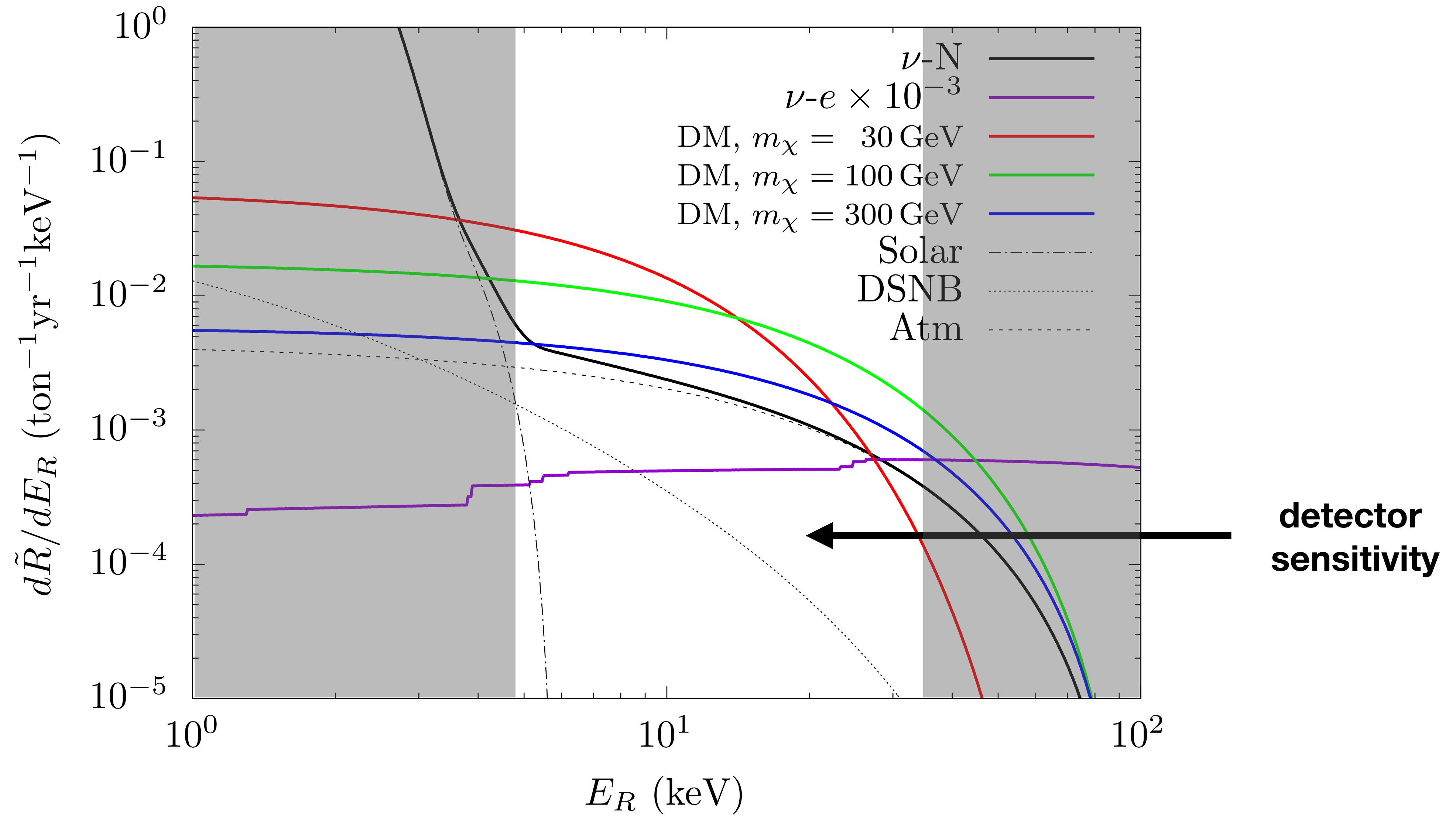
Recoil Energy Spectra (Xe)

72



Recoil Energy Spectra (Xe)

73



Neutrino Floor Calculations

74

- Previous neutrino floor e.g. [Monroe + Fisher 2007, Billard et al 2013, O'Hare 2016, ...]
 - New results:
 - more realistic detector parameters and neutrino fluxes
 - impact of variations in electron rejection power, flux uncertainties
 - sensitivity improvement by combining data from xenon and argon
 - impact of variations in the neutrino spectrum or detector response
 - Note: the *neutrino floor* has been renamed the *neutrino fog*. [O'Hare 2021,
Snowmass 2022]
- We find that spectral shape uncertainties can make it almost impenetrable!

DM Signal vs. Neutrino Background

75

- **Profile Likelihood:**

- Compute (energy binned) likelihood for neutrino fluxes $\{\phi\}$ and DM σ :

$$\mathcal{L}(\sigma, \{\phi\}) = \underbrace{\left[\prod_{i=1}^{N_{bin}} P(N_i | \mu_\chi(\sigma) + \mu_\nu(\{\phi\})) \right]}_{\text{statistics}} \times \underbrace{\mathcal{L}_\nu(\{\phi\})}_{\text{flux uncertainties}}$$

- Find best fit $\{\hat{\phi}\}$ for $\sigma = 0$ hypothesis, compute test statistic:

$$q_0 = -2 \ln \left[\frac{\mathcal{L}(\sigma = 0, \{\hat{\phi}\})}{\mathcal{L}(\sigma, \{\hat{\phi}\})} \right] \sim \text{“discovery significance”}$$

Binning in Recoil Energy

76

- We use (nuclear equivalent) recoil energy bins set by the size of the estimated local detector energy resolution over the region of interest.
- Xenon:
 - ROI = [5,35] keV
 - resolution based on LUX and XENON1T:
- Argon
 - ROI = [55,100] keV (single phase)
 - resolution based on DEAP-3600:

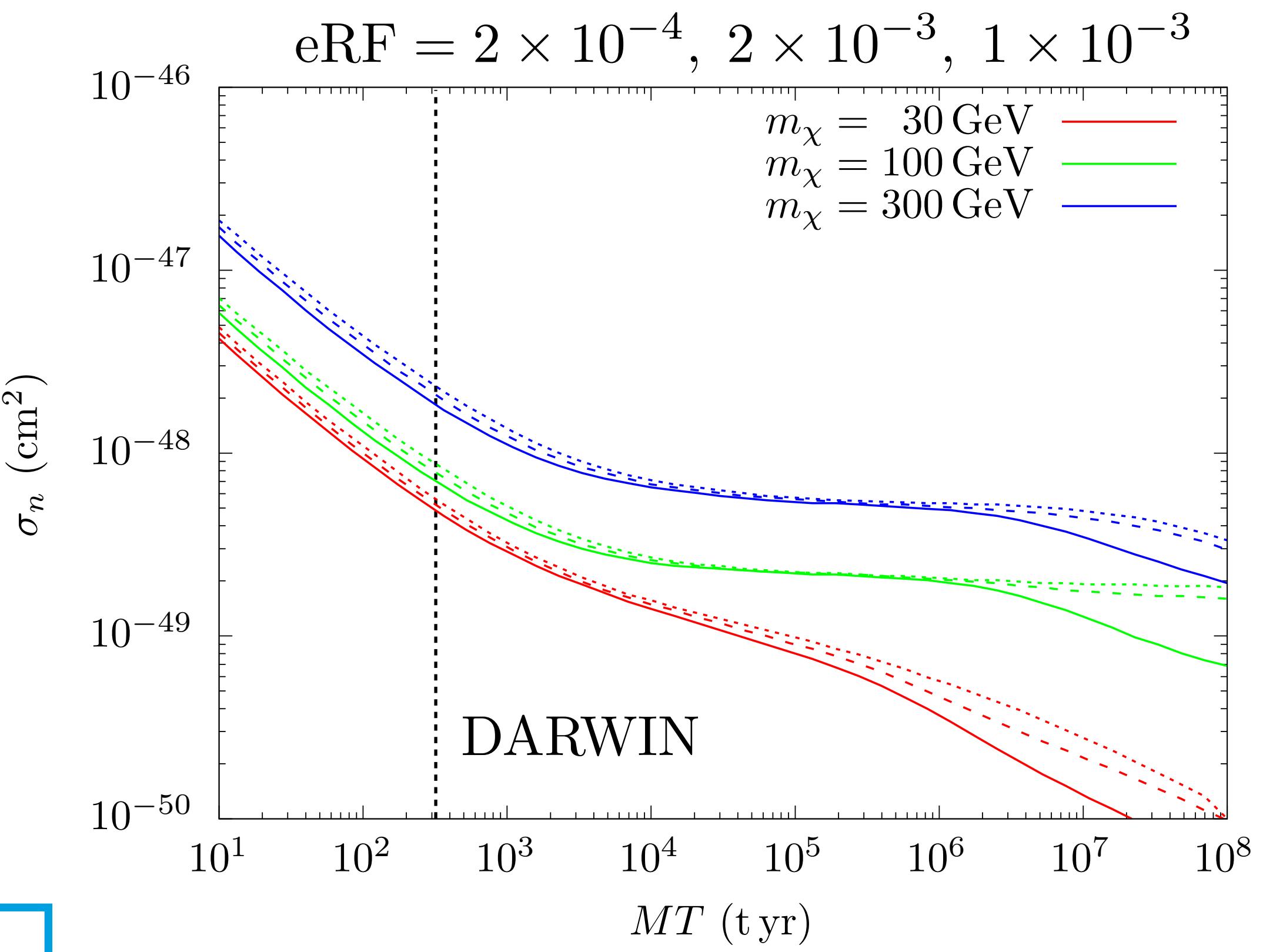
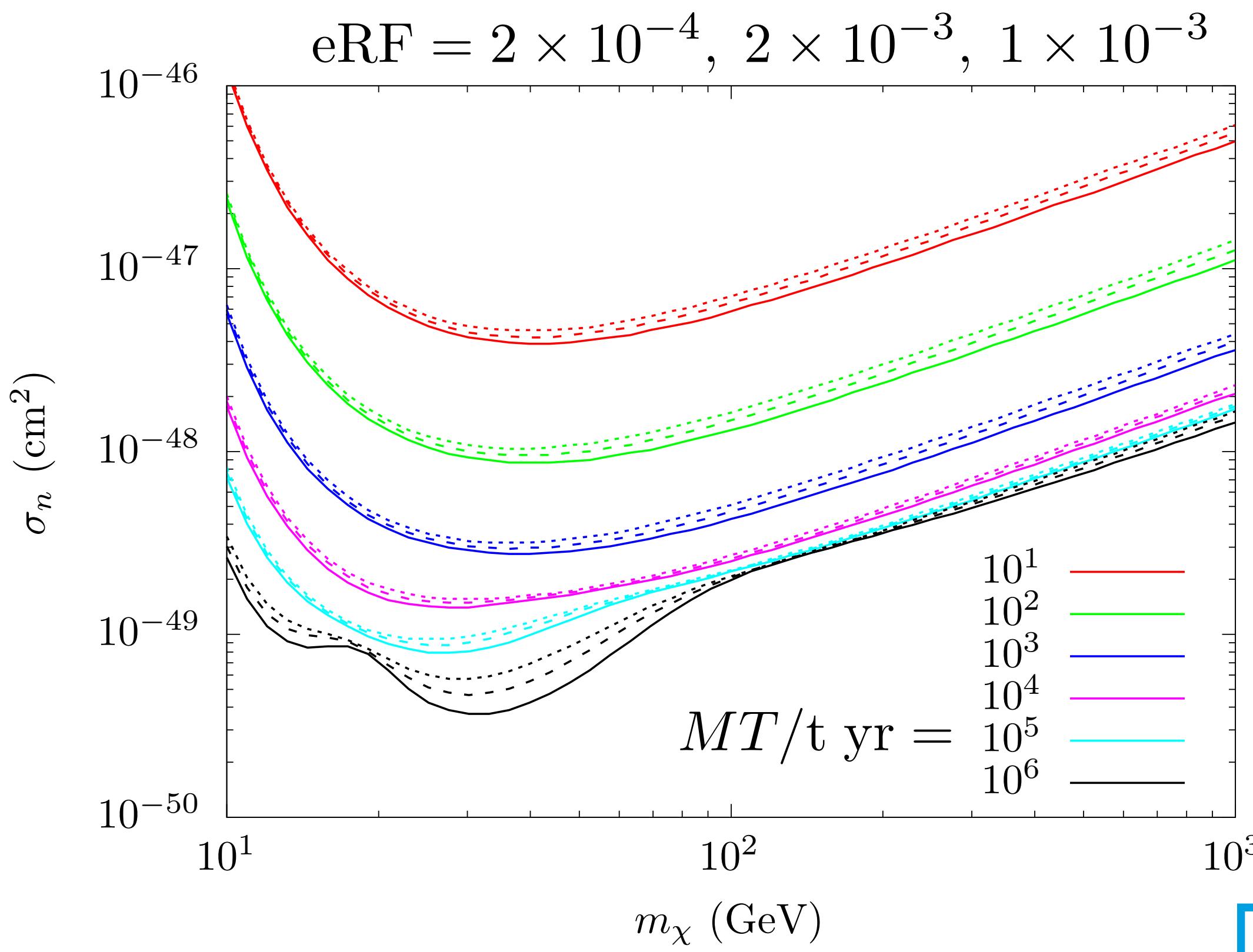
$$\frac{\Delta E_R}{E_R} = 0.80 \left(\frac{\text{keV}}{E_R} \right)^{0.54}$$

$$\frac{\Delta E_R}{E_R} = 1.09 \left(\frac{\text{keV}}{E_R} \right)^{0.55}$$

DM Signal vs. Neutrino Background

77

- Use profile likelihood that uses the spectrum and includes flux uncertainties.
Find smallest DM σ_n that can't be explained by background only.



Xe

Nuclear Recoils vs. Electron Recoils

78

- DM scattering on electrons is unimportant for our analysis ($m_\chi \gtrsim 10 \text{ GeV}$)
- But neutrino-electron scattering can be very significant!
- DM DD experiments work very hard to reject electron recoils:
 - XENON1T: $eRF < 8 \times 10^{-9}$
 - DEAP-3600 (Ar): $eRF \sim 2 \times 10^{-4}$ (?)
 - DARWIN (Xe): $eRF \lesssim 10^{-7}$ (?)
 - ARGO (Ar): $eRF \lesssim 10^{-7}$ (?)

Neutrino-Electron Backgrounds

79

- DM scattering on electrons is unimportant for our analysis ($m_\chi \gtrsim 10 \text{ GeV}$)
- But neutrino-electron scattering can be very significant!
- DM DD experiments work very hard to reject electron recoils:
 - XENON1T: $\varepsilon_e = 3 \times 10^{-3}$ = electron rejection factor (eRF)
 - DEAP-3600 (Ar): $\varepsilon_e < 8 \times 10^{-9}$
 - DARWIN (Xe): $\varepsilon_e \sim 2 \times 10^{-4}$ (?)
 - ARGO (Ar): $\varepsilon_e \lesssim 10^{-7}$ (?)

Electron Recoil Energy Reconstruction

80

- For a given energy transfer in an electron recoil T , the amount of visible energy is typically larger than for a nuclear recoil with the same transfer.
- If an electron recoil is misidentified as a nuclear recoil the reconstructed “nuclear recoil energy” E_R is then

$$T = q_{eff}(E_R) E_R$$

- Model quenching based on NEST + data for Xe and Ar: $q_{eff} \sim 0.2 (E_R/\text{keV})^{0.1}$

Total Neutrino Scattering Rate

81

$$\frac{dR}{dE_R} = N_T \int dE_\nu \Phi_\nu \left(\varepsilon_n \frac{d\sigma_{\nu N}}{dE_R} + \varepsilon_e \frac{d\sigma_{\nu e}^{(Z)}}{dE_R} \right)$$

N_T = # target nuclei

$\Phi_\nu(E_\nu)$ = differential neutrino flux on target

$\varepsilon_n, \varepsilon_e$ = nuclear and electron recoil efficiencies

Neutrino Scattering on Electrons

82

- Neutrino scattering on electrons can also be important!
- Mediated by W and Z bosons for ν_e , Z only for the rest.
- For a free electron (T = neutrino energy transfer):

$$\frac{d\sigma_{\nu_a e}}{dT} \simeq m_e \frac{2 G_F^2}{\pi} Q_{eff,a}^2 , \quad a = e, \{\bar{e}, \mu, \bar{\mu}, \tau, \bar{\tau}\}$$

- Q_{eff} is much larger for ν_e than for the others
- Visible recoil energies arise for smaller E_ν than nuclear scattering.

Kinematics: (Free) Electrons

83

- Dark Matter:

$$q \lesssim 2m_e v \quad (m_\chi \gg m_e)$$
$$T = q^2/2m_e \leq 2m_e v^2/m_\chi$$

- Neutrino:

$$q \lesssim 2E_\nu$$
$$T = q^2/2m_e \leq 2E_\nu^2/m_e$$

- Much more electron recoil energy is available from neutrinos!

Atomic Electrons

84

- Electrons in the target are bound within atoms.
- Free-electron approximation, for $E_R \gg E_B \lesssim Z^2 \alpha^2 m_e$

$$\frac{d\sigma_{\nu e}^{(Z)}}{dT} \simeq Z \frac{d\sigma_{\nu e}^{(free)}}{dT}, \quad T = E_R$$

- Can be shown to hold asymptotically. [Voloshin 2010]
- But this approximation breaks down for Xe and Ar inner electrons!

Atomic Electrons

85

- Electrons in the target are bound within atoms.
- Stepping approximation, for $q \gtrsim q_B \lesssim Z \alpha m_e$

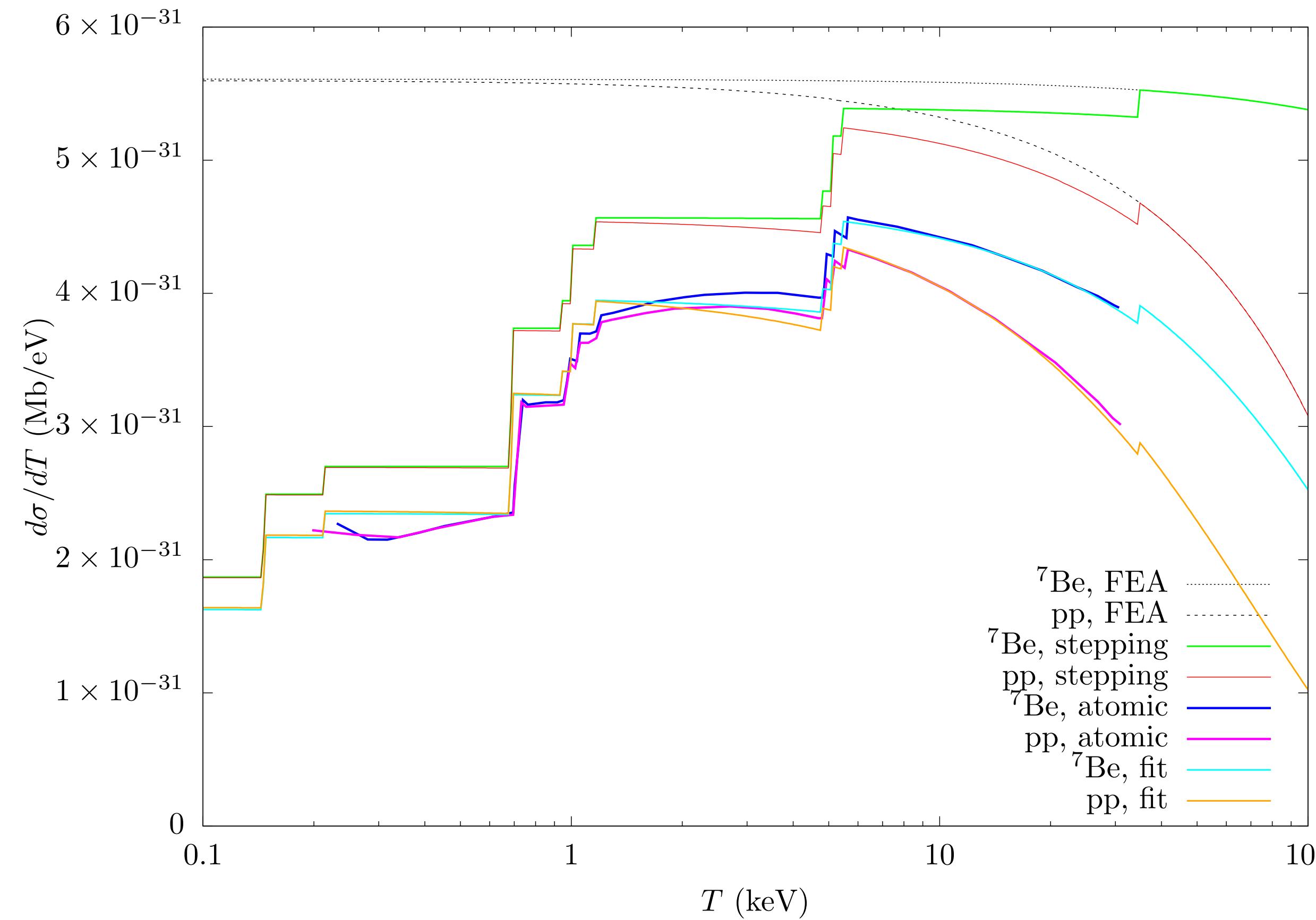
$$\frac{d\sigma_{\nu e}^{(Z)}}{dT} \simeq Z_{eff} \frac{d\sigma_{\nu e}^{(free)}}{dT}$$

$$Z_{eff} = \sum_i \Theta(T - E_{B,i})$$

- Captures the most important atomic features. [Kouzakov, Studenikin, Voloshin 2014]

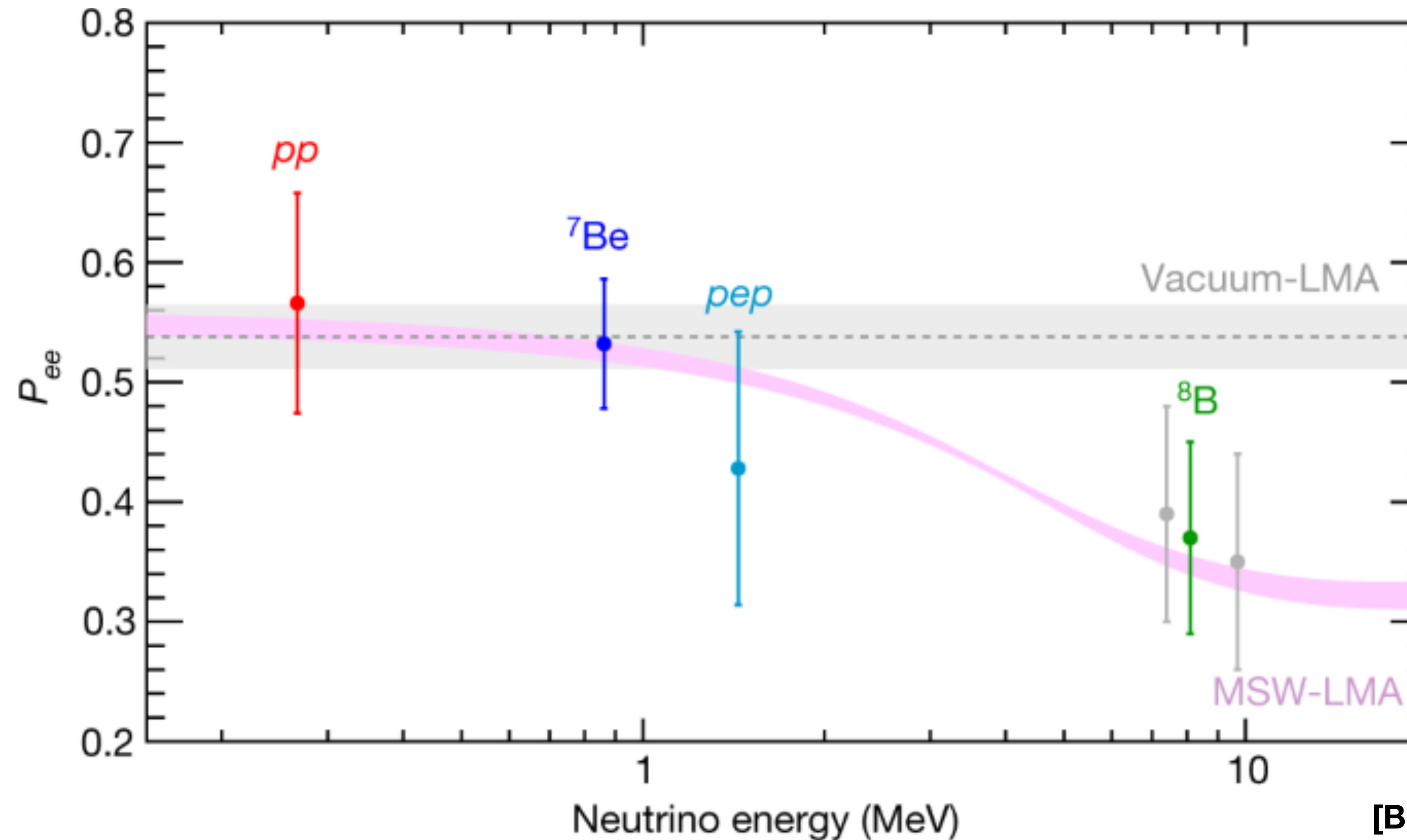
Atomic Electrons

- Electrons in the target are bound within atoms.
- Full atomic calculation for Xe, averaged over main neutrino fluxes:



[Chen et al, 2016]

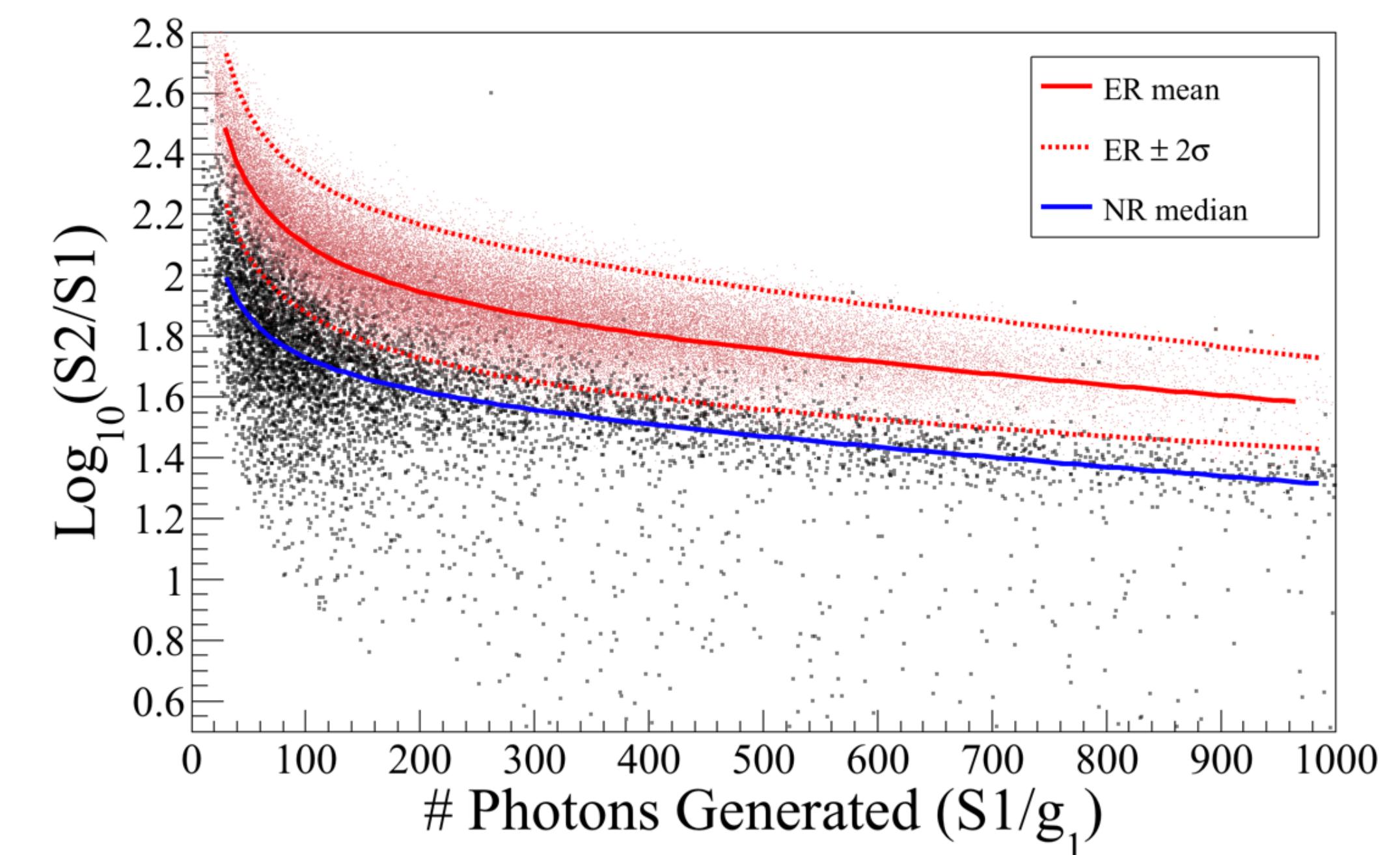
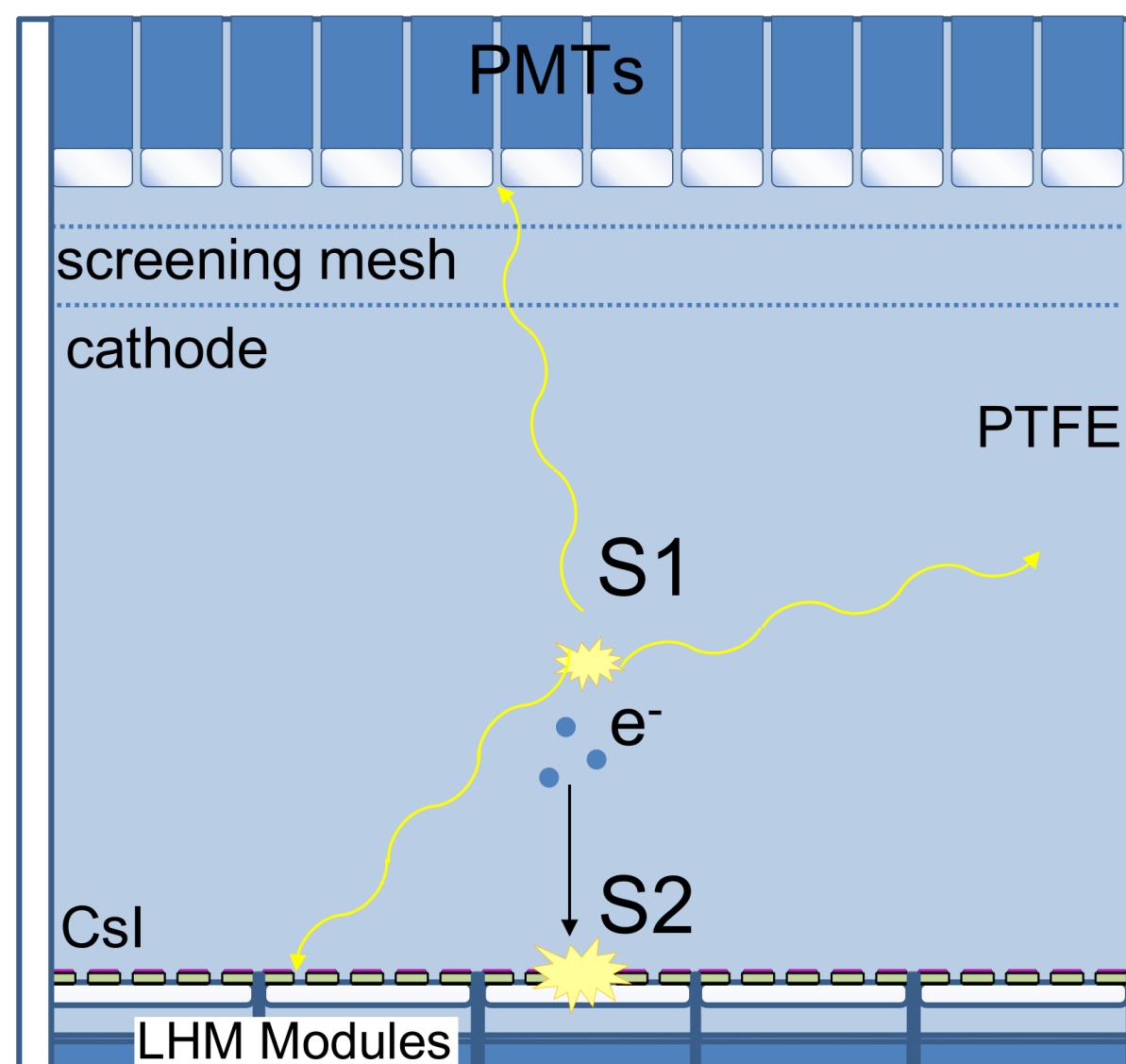
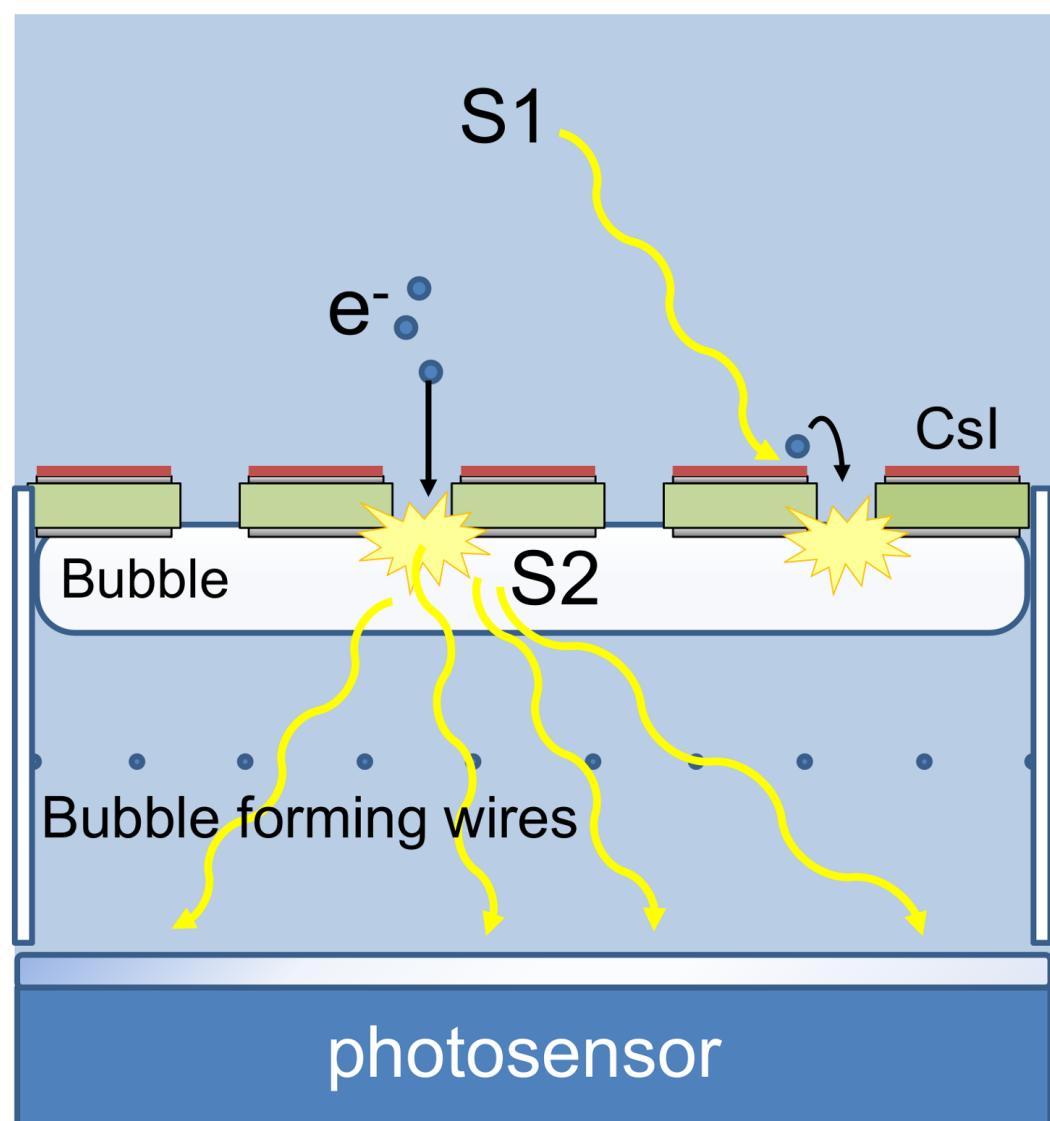
Solar Neutrinos



Electron Rejection in Xe

88

- Compare prompt photons (S1) to slow photons from drifted electrons (S2).



Electron Rejection in Ar

89

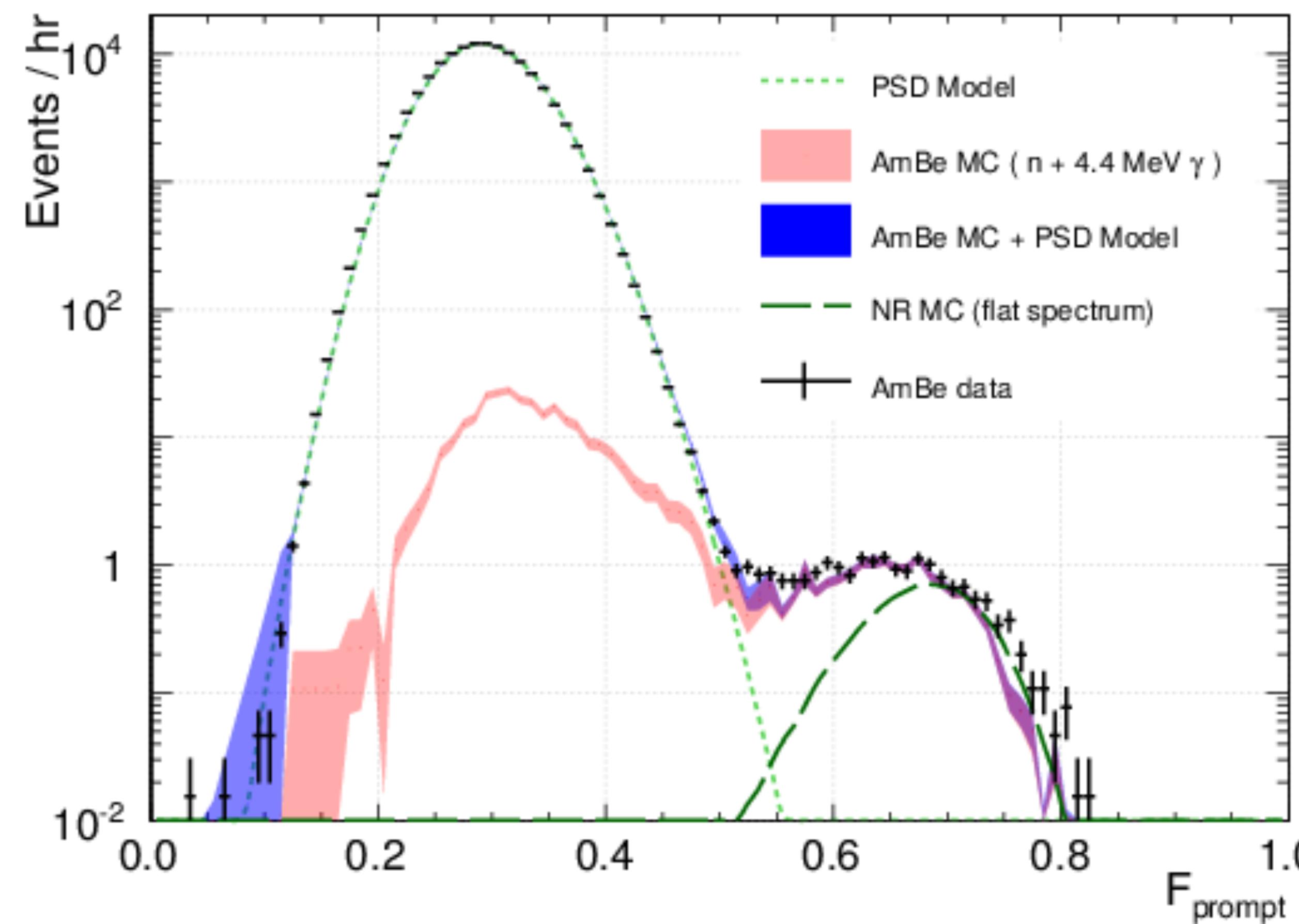
- Use pulse shape discrimination variable F_{prompt} . [Amaudruz, Boulay, ...]
- DM DD experiments typically detect scintillation photons:
 - Ionization/excitation in Ar leads to excited dimers, triplet or singlet.
 - De-excitation produces 128 nm photons.
 - Singlet de-excitation is slow, triplet is fast.
- Nuclear vs. electron recoils produce different numbers of singlets and triplets.
- F_{prompt} captures the time-domain difference in pulse shapes.

Electron Rejection in Ar

90

- Use pulse shape discrimination variable F_{prompt} .

[Amaudruz, Boulay, ...]



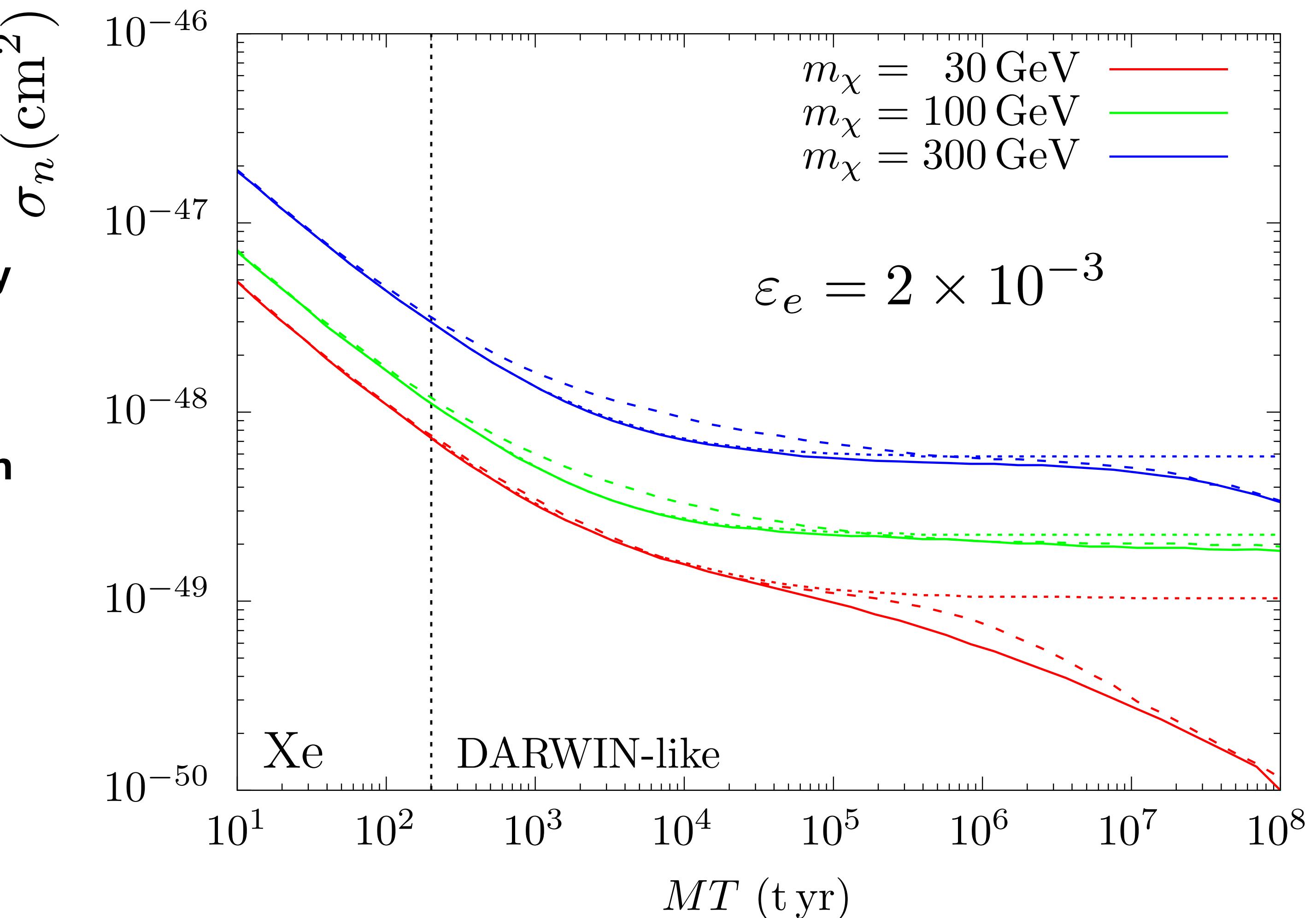
[DEAP-3600 2017]

Neutrino Floor or Fog?

91

e.g. shape uncertainty in electron recoil rejection ε_e (= 2×10^{-3})

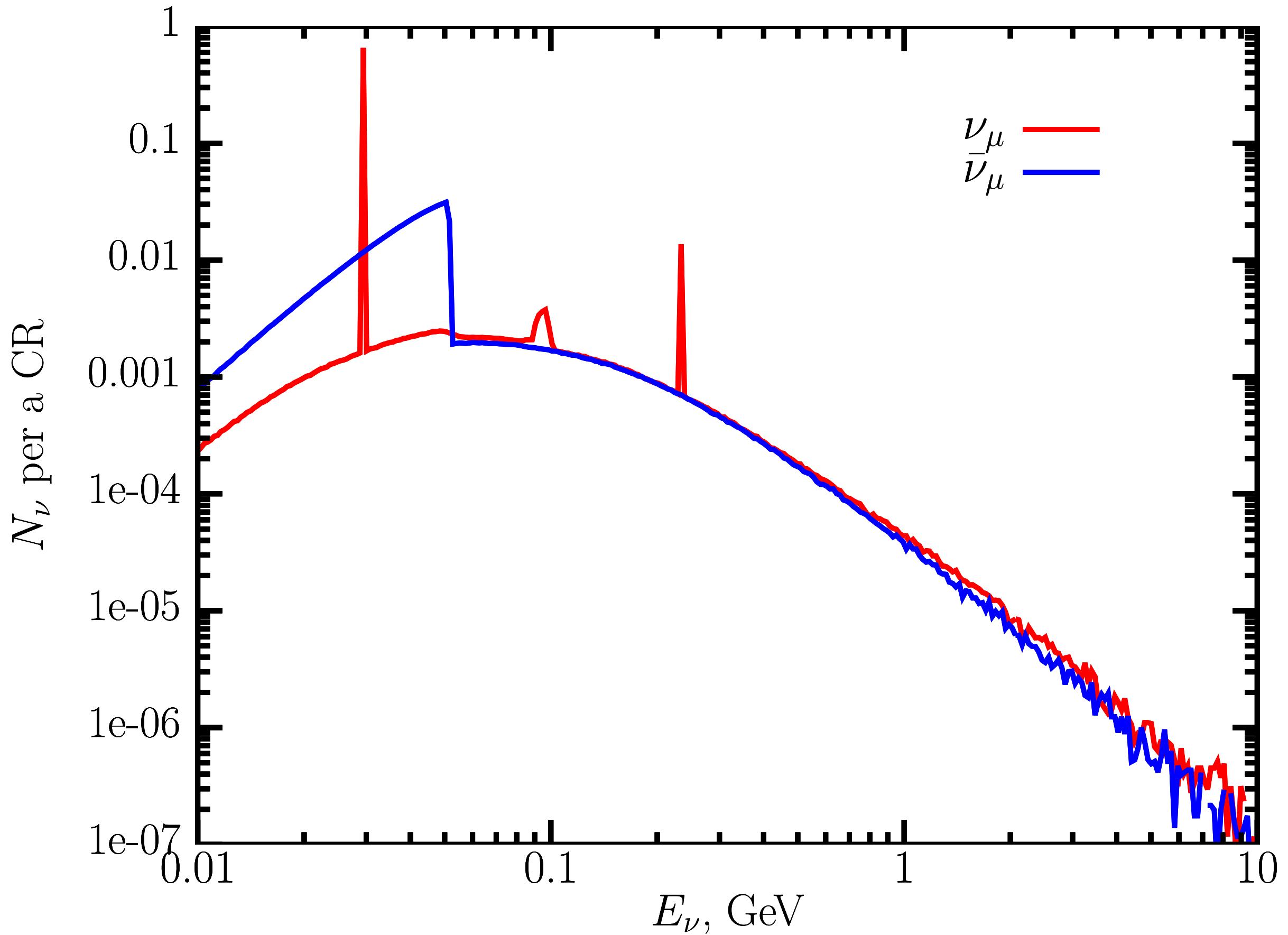
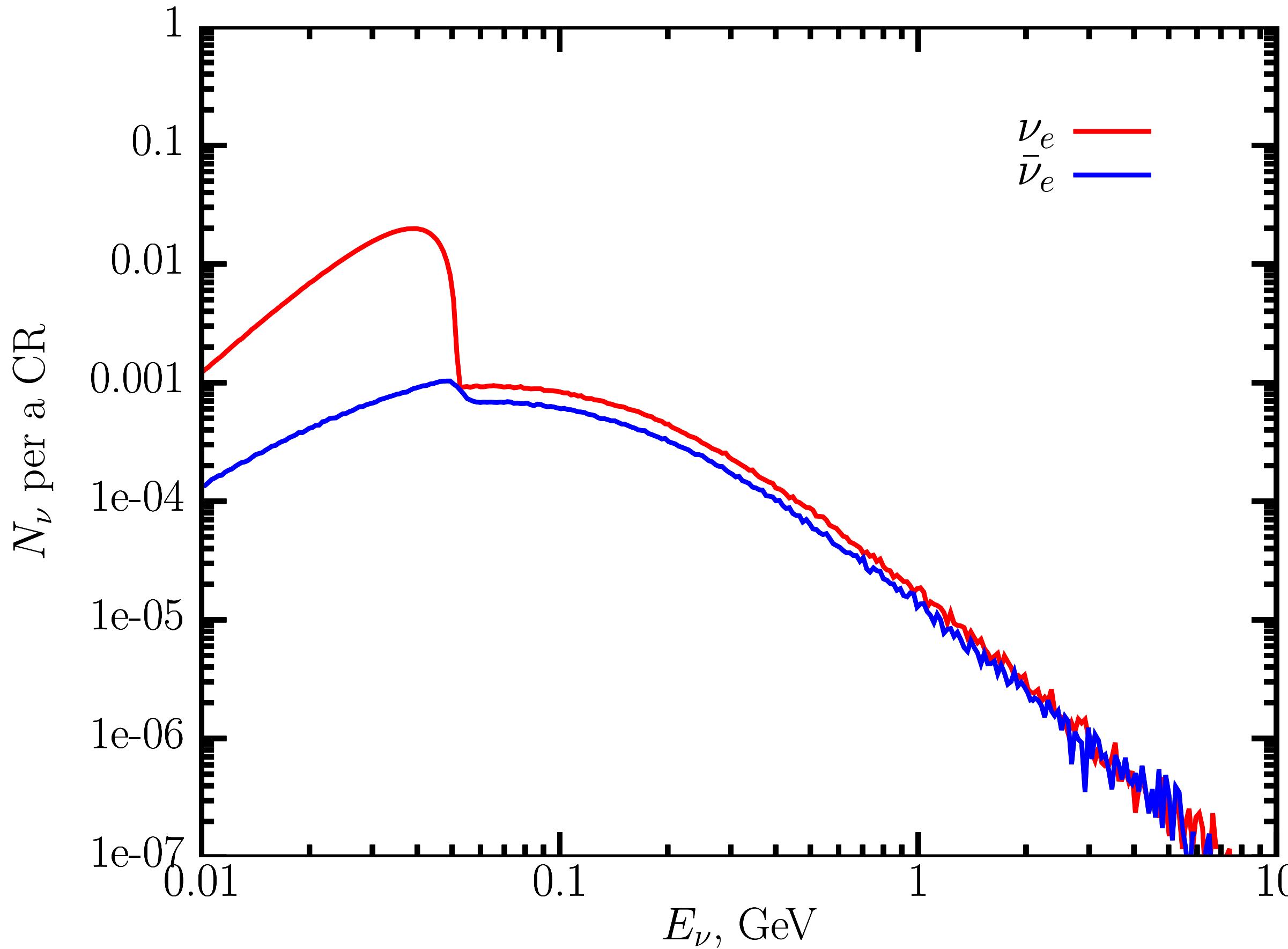
- = no electron rejection (ER) uncertainty
- - -** = 20% overall ER uncertainty
- · -** = 10% ER uncertainty in each recoil bin



Neutrino Production from CRs on the Moon

92

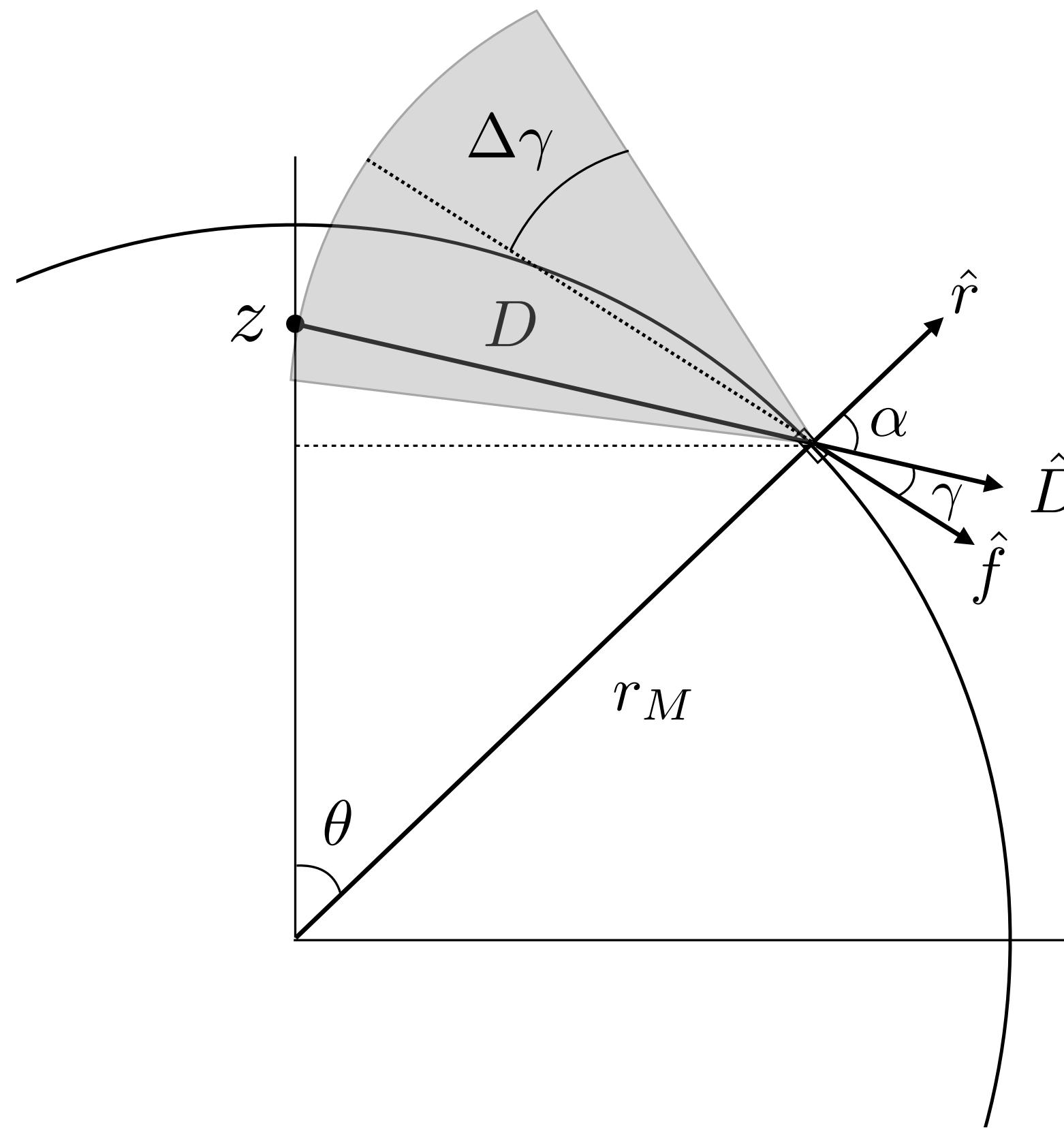
- GEANT4 simulation of # neutrinos per cosmic ray: [Demidov + Gorbunov 2020]



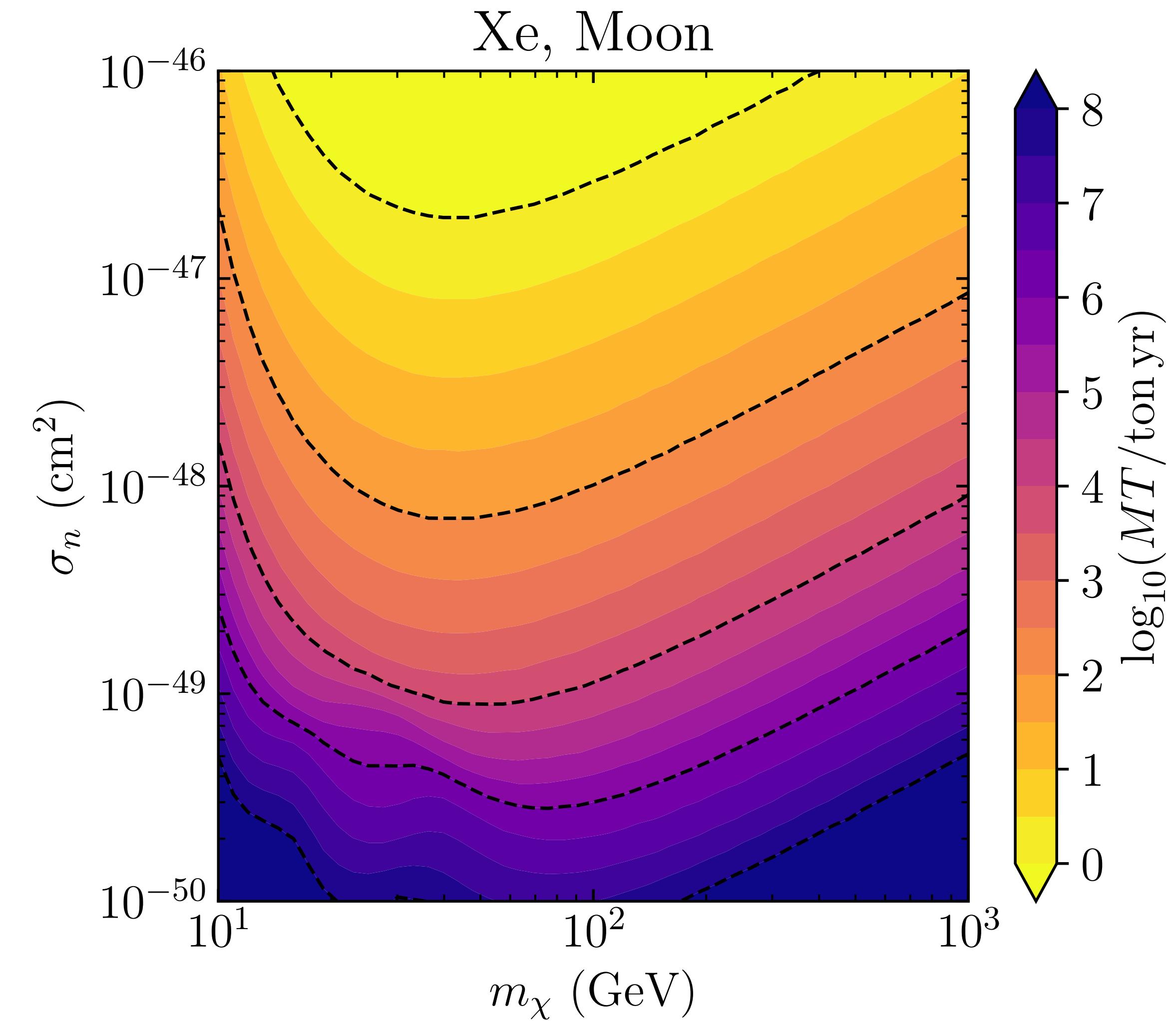
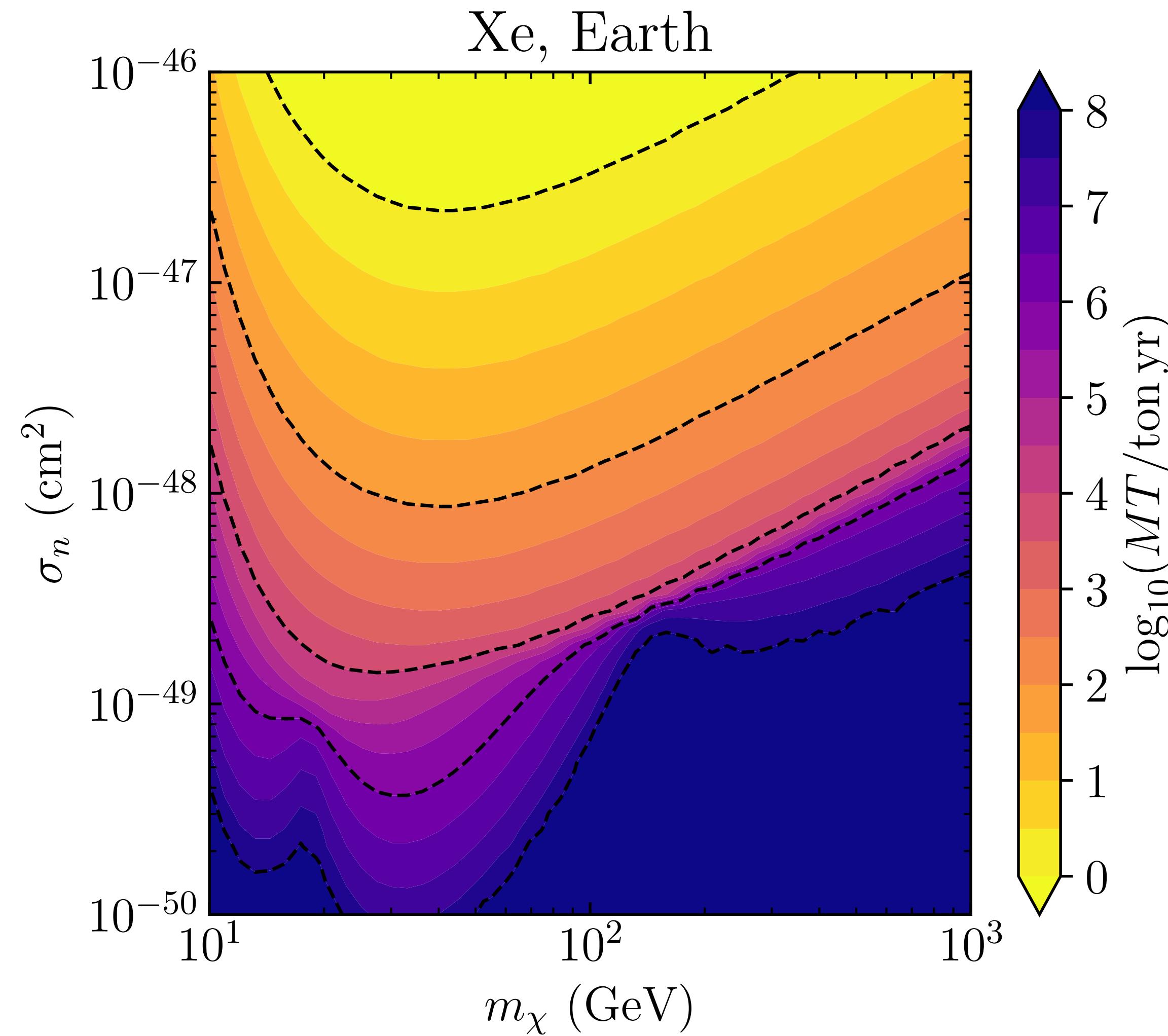
Neutrino Production from CRs on the Moon

93

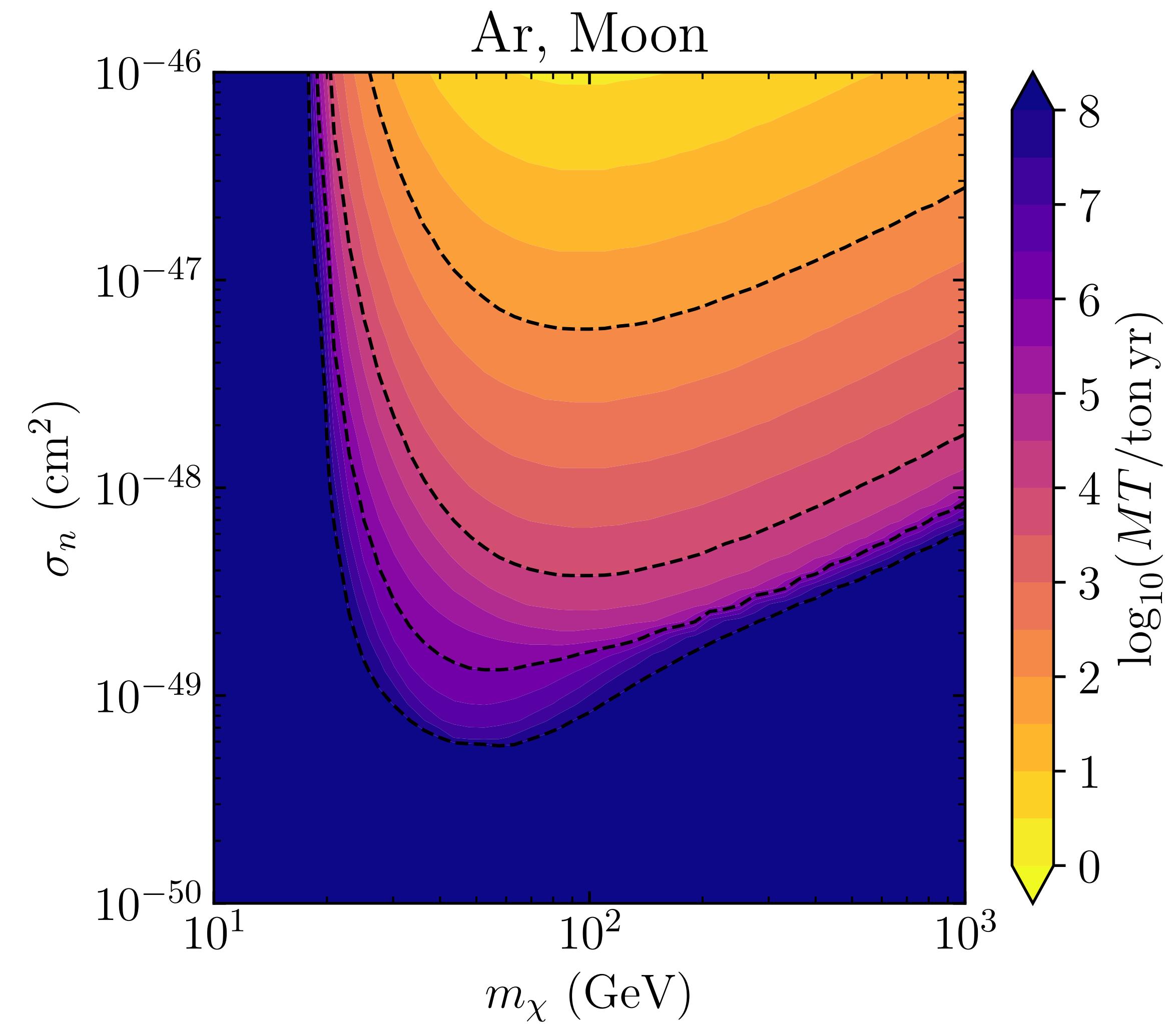
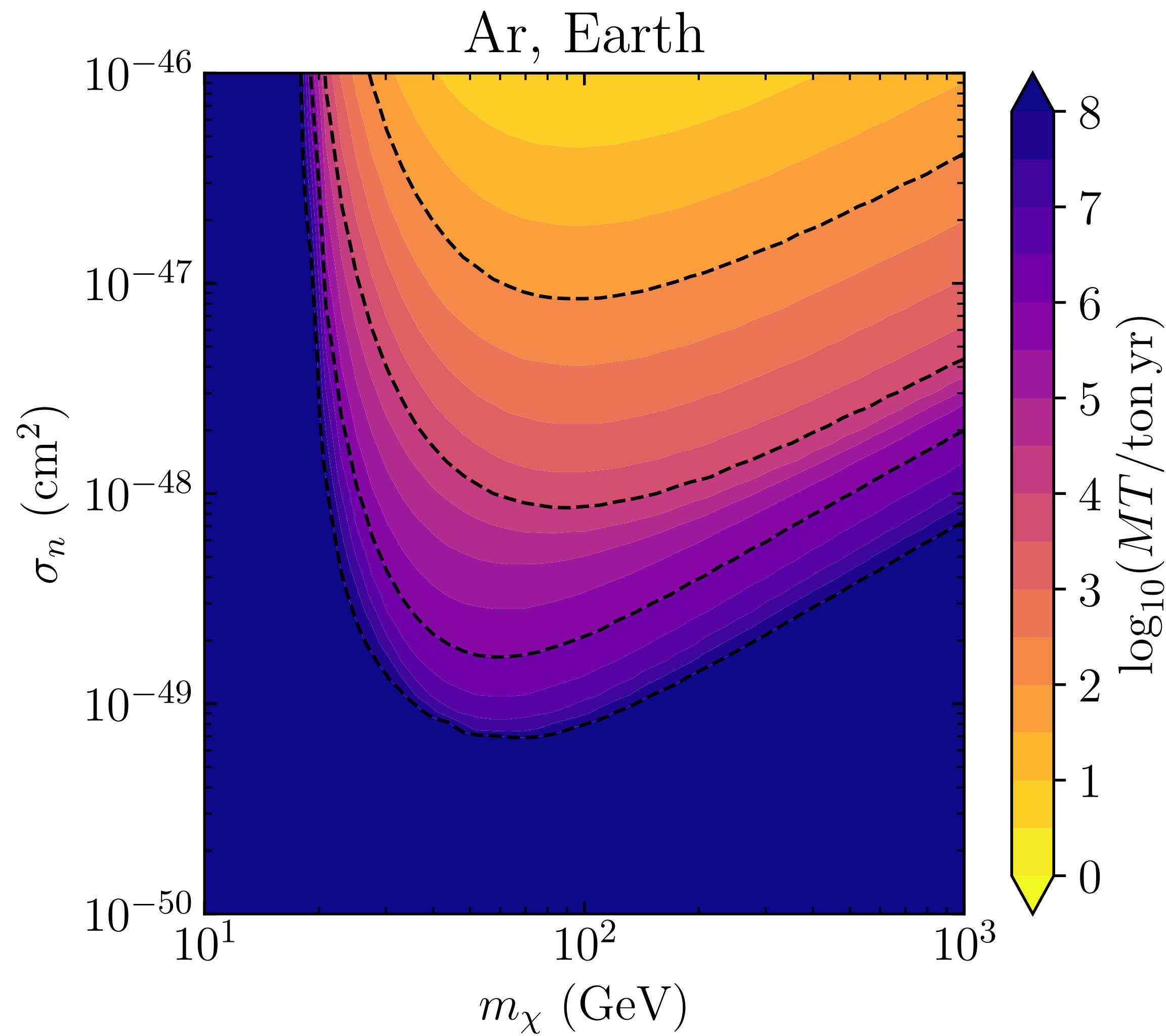
- Neutrinos are created mainly in the first few metres of the Moon surface.
- Treat production as coming from a spherical shell:



SI DM Sensitivity Contours - Xe



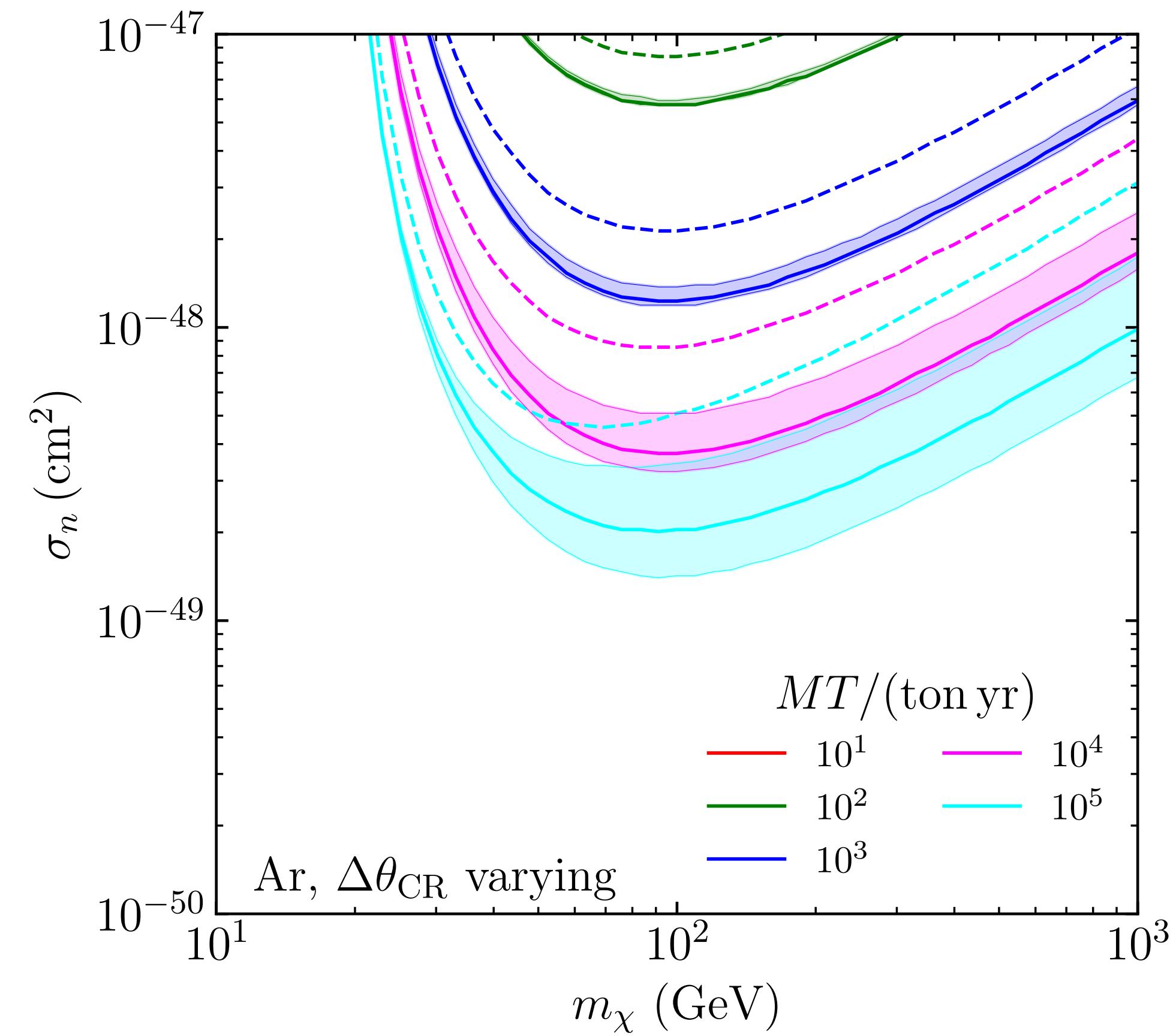
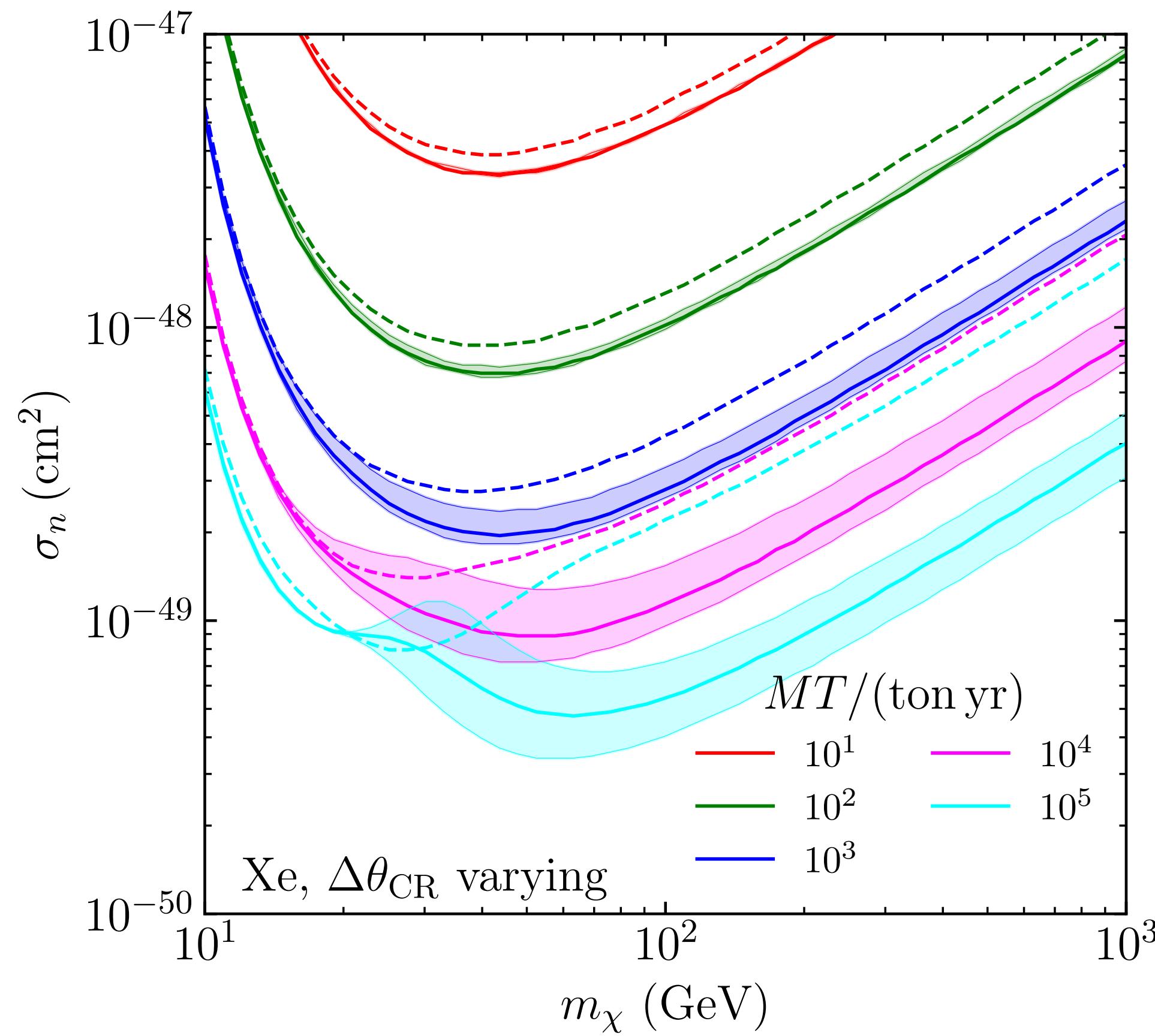
SI DM Sensitivity Contours - Ar



Lunar CR Neutrino Flux Uncertainty

96

- Impact of fractional lunar CR flux uncertainty between 10-40%:



Electron Rejection Factor in Xe

97

- Consider $\varepsilon_e = 2 \times 10^{-4} - 1 \times 10^{-3}$:

