Solar Dark Matter
Production & Detection

Chuan-Yang Xing
邢传阳

arxiv:240x.xxxxx
with Shao-Feng Ge, Jie Sheng, Chen Xia

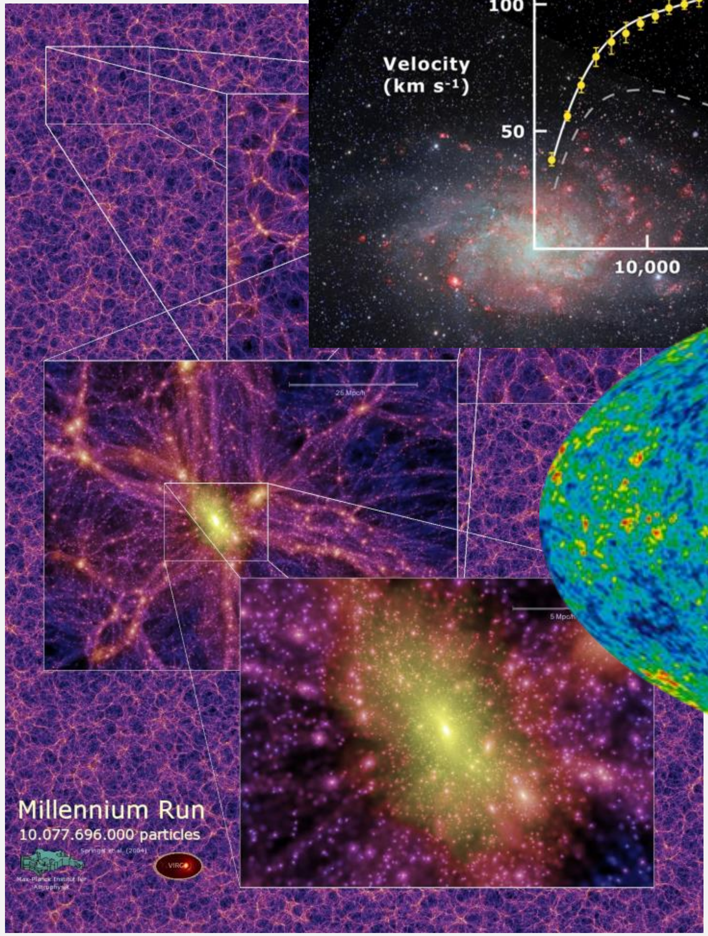
李政道研究所
TSUNG-DAO LEE INSTITUTE

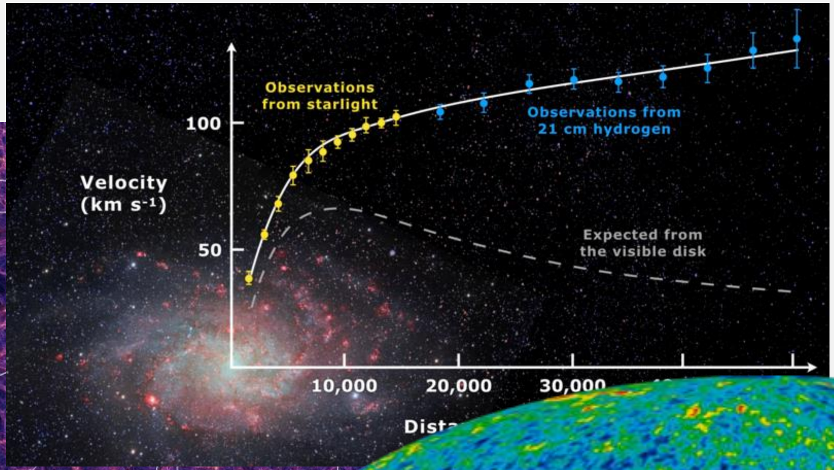
2023年紫金山暗物质研讨会@NNU
2023/12/31

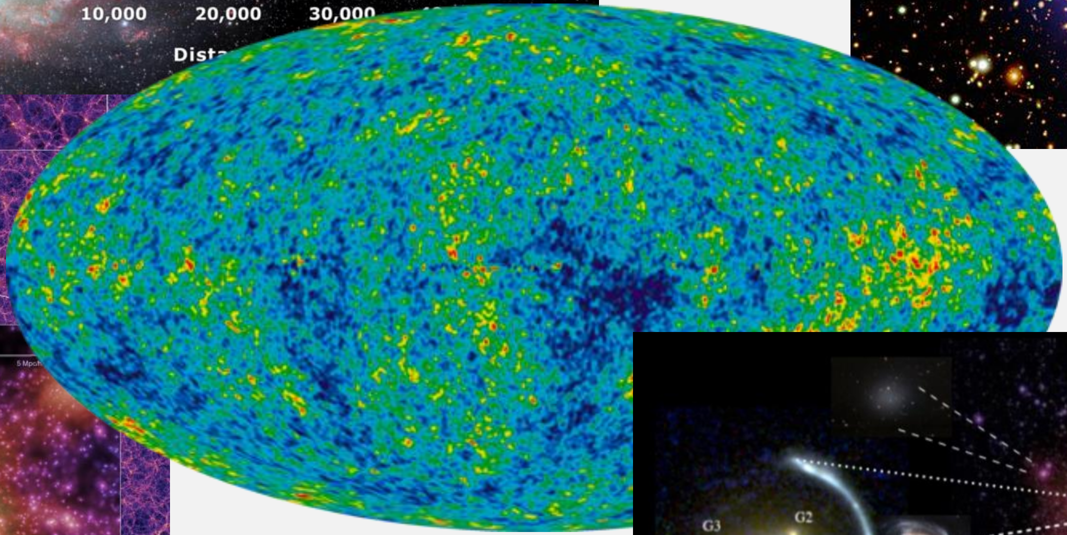
Solar Dark Matter:

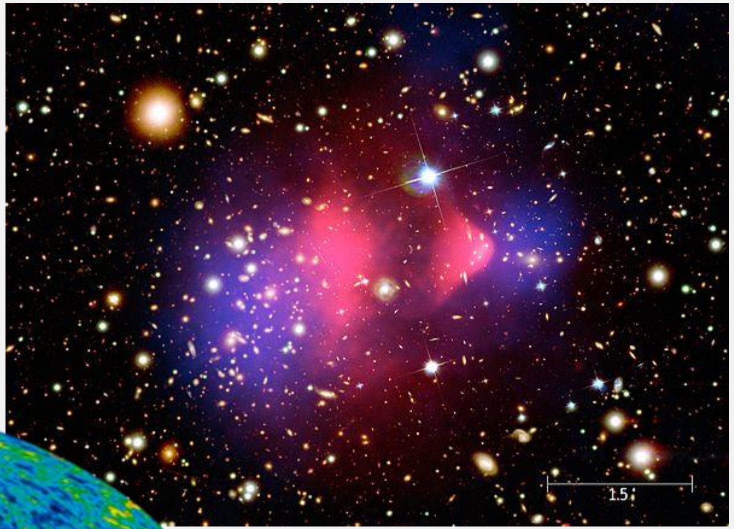
1. Motivation
2. Production
3. Attenuation
4. Detection
5. Conclusion

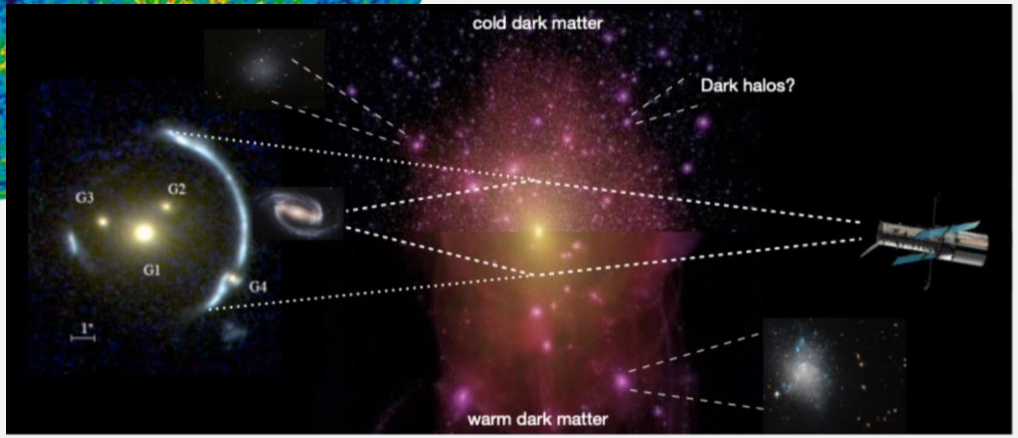
DM Evidence


Millennium Run
10.077.696.000 particles


Observations from starlight
Observations from 21 cm hydrogen
Velocity (km s⁻¹)
100
50
Expected from the visible disk
10,000
20,000
30,000

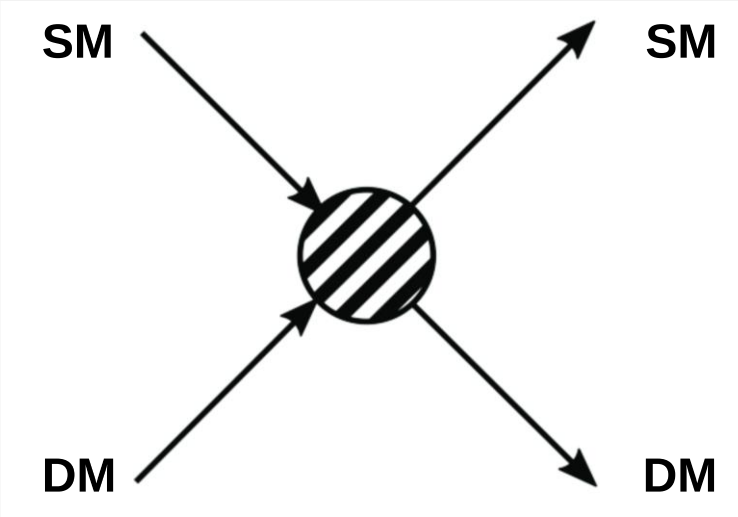


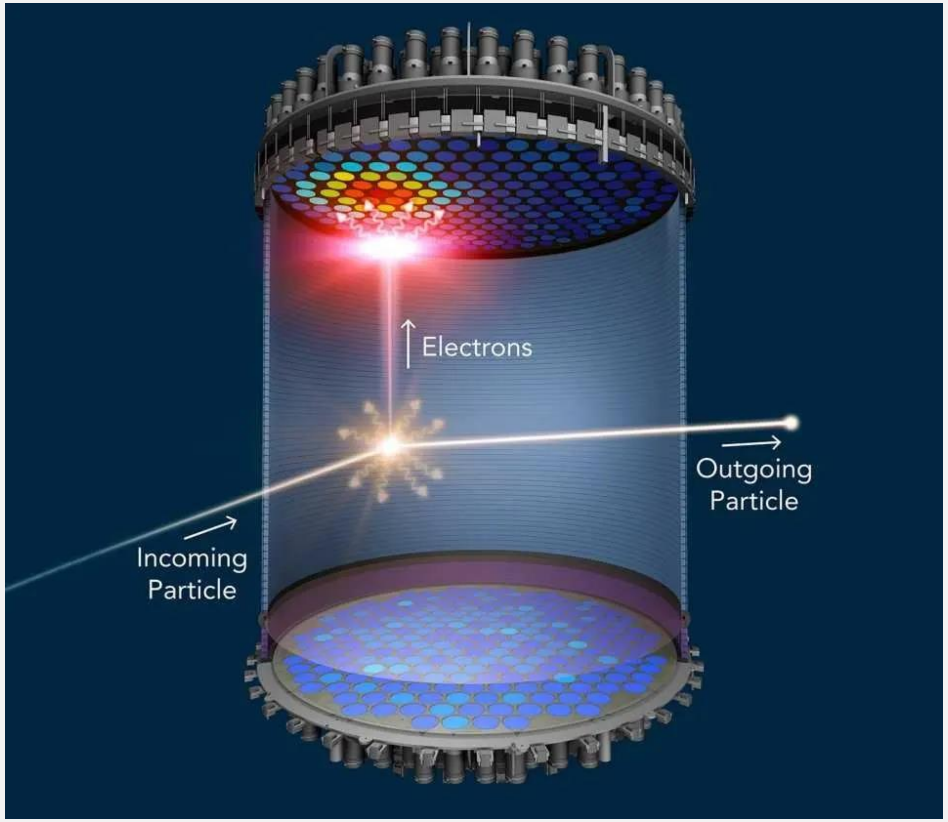



cold dark matter
Dark halos?
G3
G2
G1
G4
warm dark matter

Scattering → Production

Assumption:





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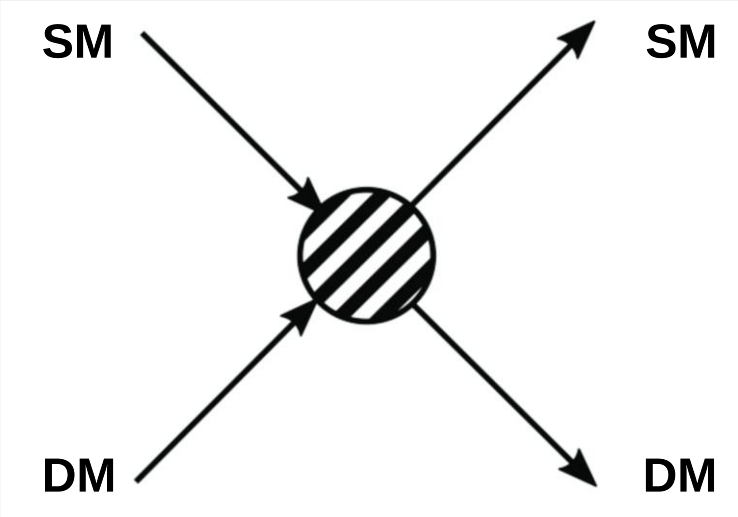
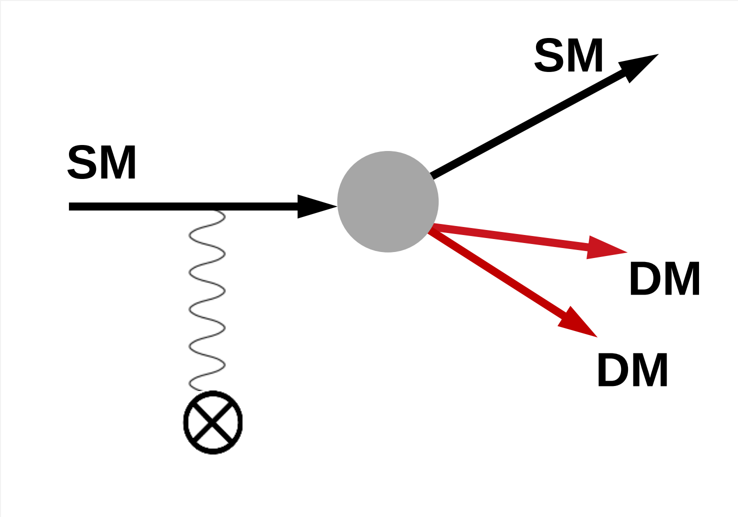


Production:



DM Production

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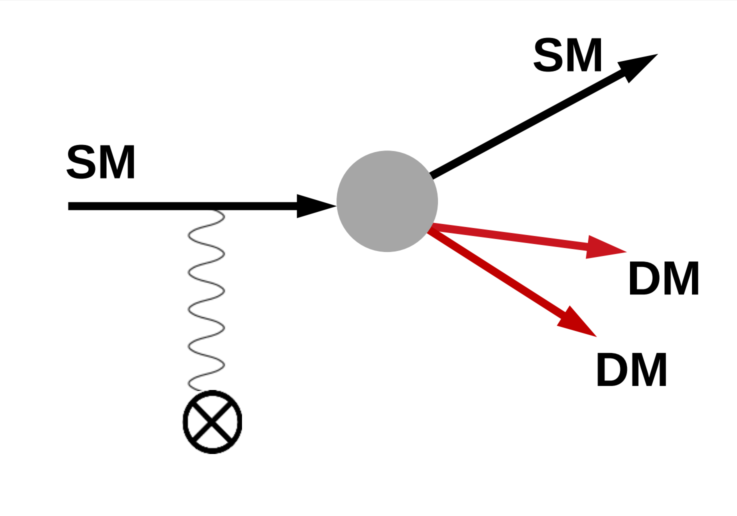
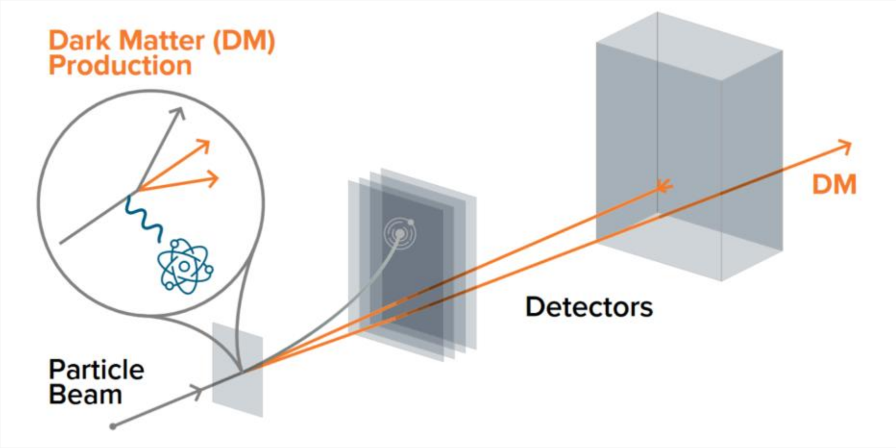
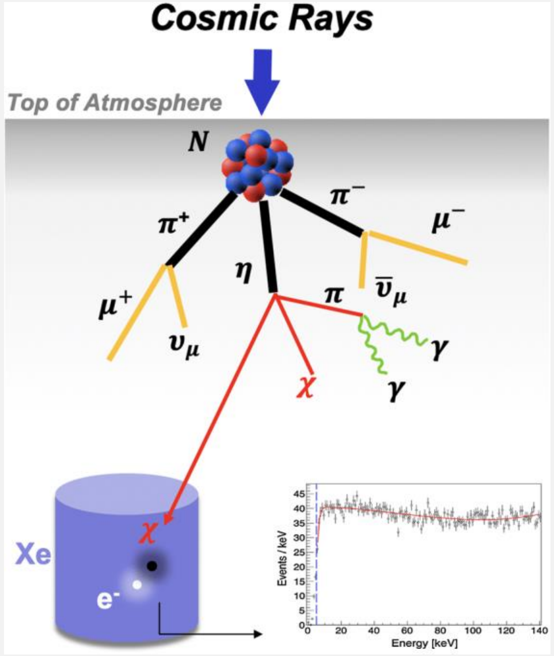
Production:



1. Collider / Beam Dump



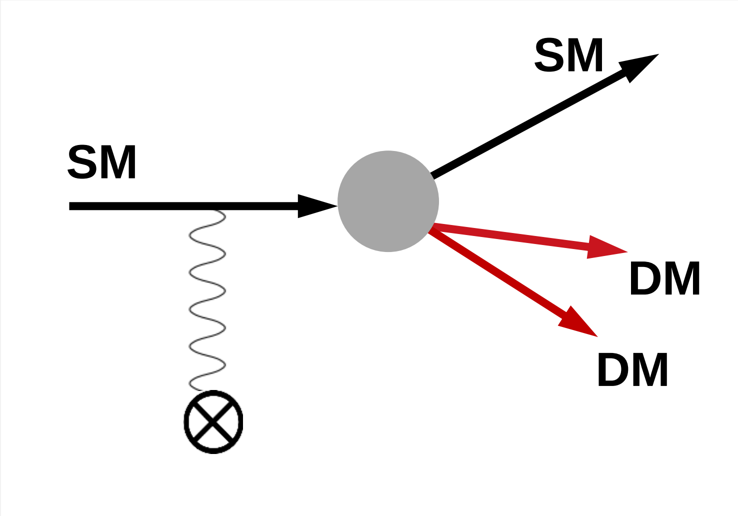
2. Atmospheric DM



Su, Wang, Wu, Yang, Zhu, PRD 102, 115028 (2020)

DM Production In the SUN

Production:

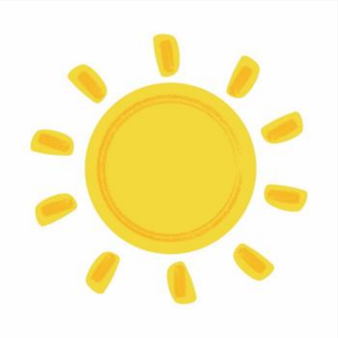


DM produced in the SUN???

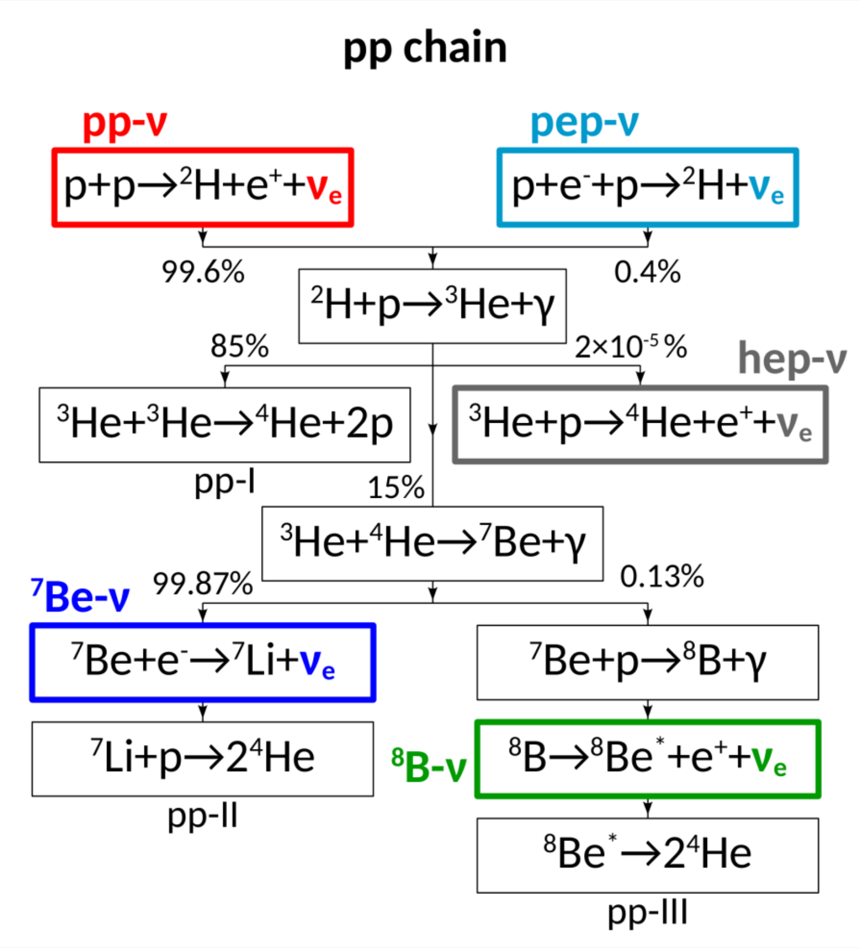
DM Production In the SUN

Nuclear Reaction: pp Chain

Look into the Sun:



Standard Solar Model



Borexino Collaboration, Nature volume 562, 505–510 (2018)

DM Production In the SUN

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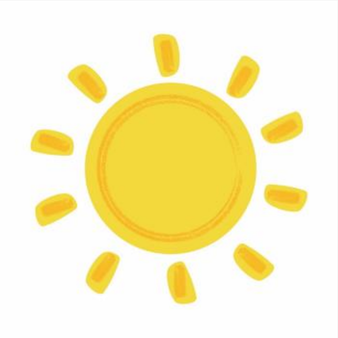

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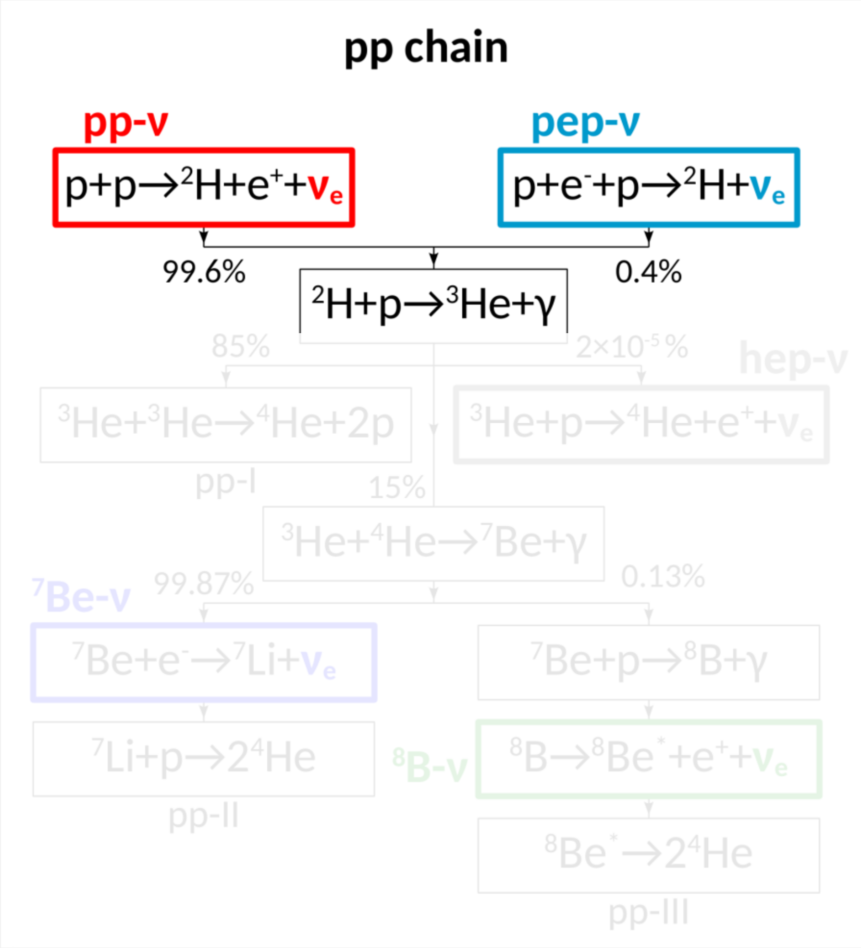

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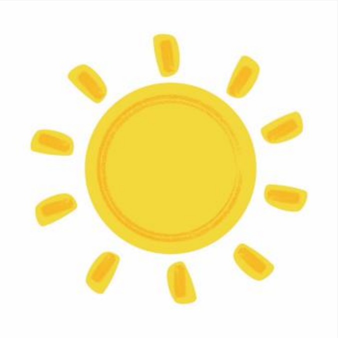

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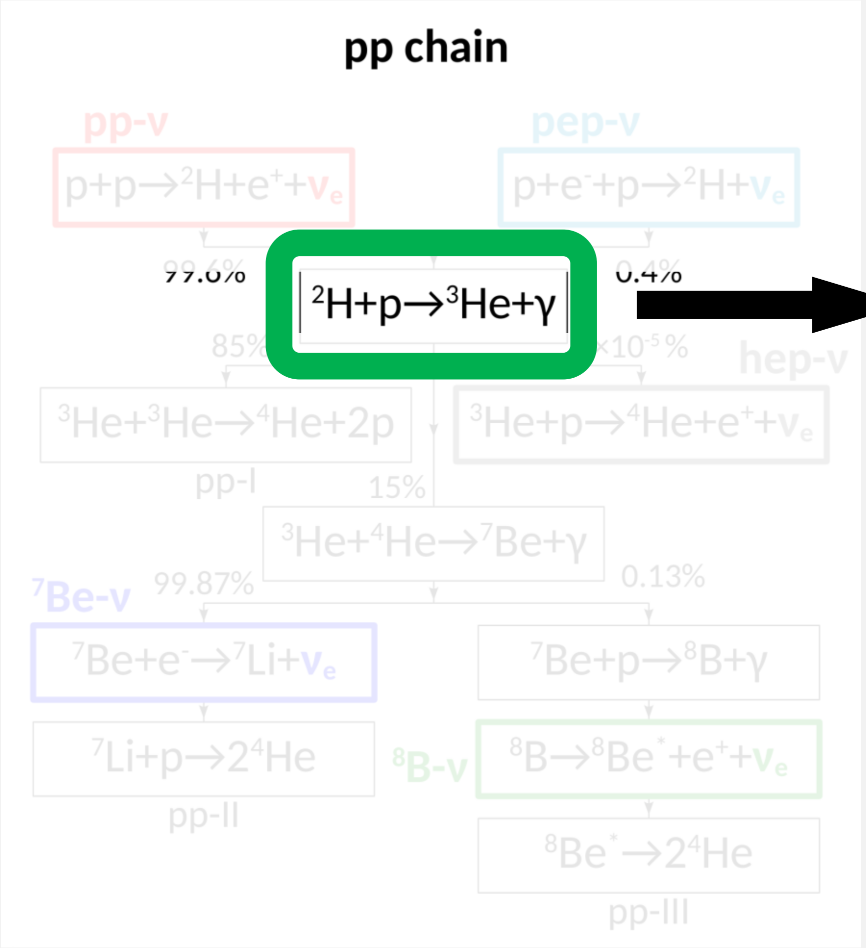
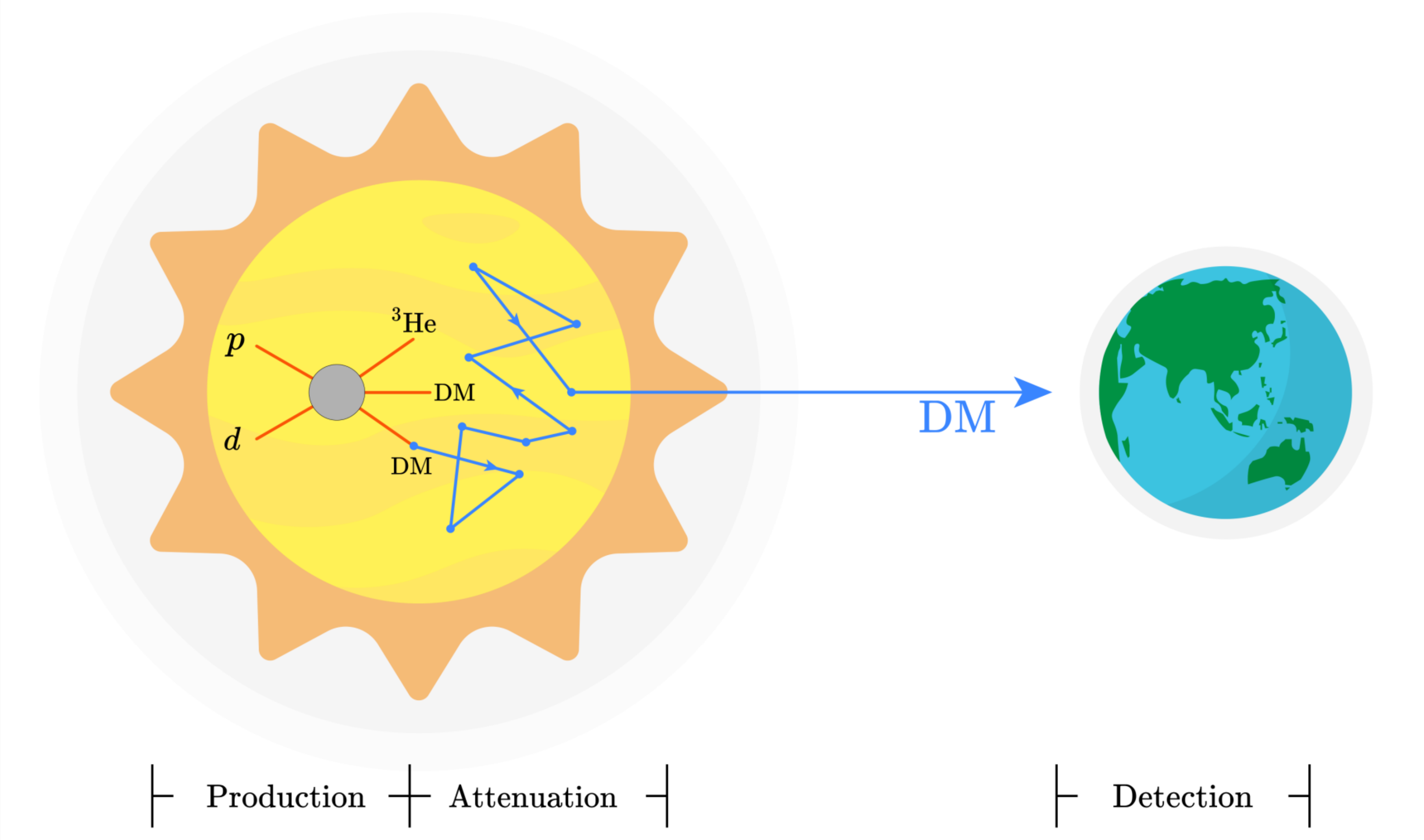


$$^{2}\mathrm{H} + p \to {}^{3}\mathrm{He} + \mathrm{DM} + \mathrm{DM}$$

Borexino Collaboration, Nature volume 562, 505–510 (2018)

Solar DM Overview



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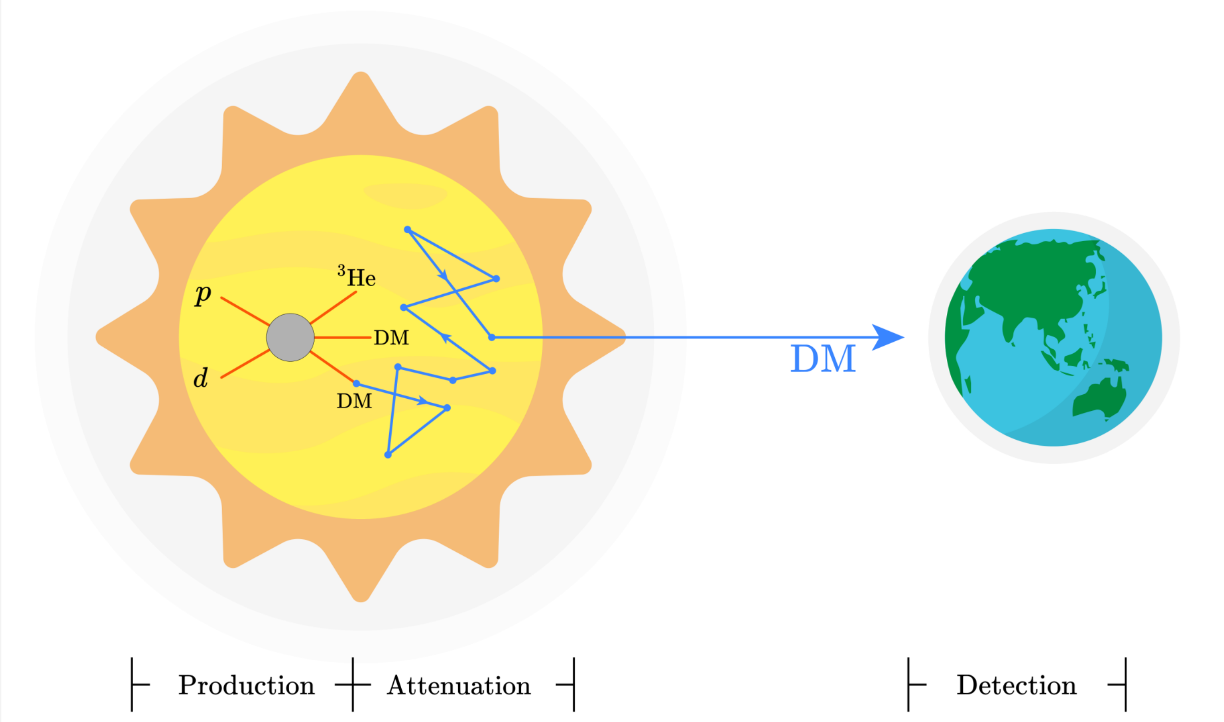


Nuclear Fusion

$$^{2}\mathrm{H} + p \to {}^{3}\mathrm{He} + \gamma$$

σ_γ

$$^{2}\mathrm{H} + p \to {}^{3}\mathrm{He} + \mathrm{DM} + \mathrm{DM}$$

σ_{DM}

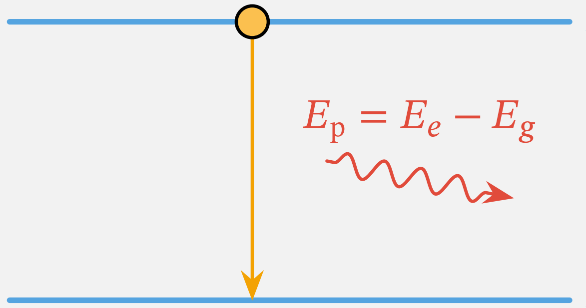
Nuclear Fusion

Bertulani, CPC 156 (2003) 123-141

Quantum mechanics: consider a potential between p & H^2

$$^{2}\mathrm{H} + p \rightarrow {}^{3}\mathrm{He} + \gamma$$

σ_γ



$^{2}\mathrm{H} + p$ (initial ionized state)

$^{3}\mathrm{He}$ (final ground state of p&H^2)

similar to recombination: $p + e \rightarrow \mathrm{H} + \gamma$

$$^{2}\mathrm{H} + p \rightarrow {}^{3}\mathrm{He} + \mathrm{DM} + \mathrm{DM}$$

σ_{DM}

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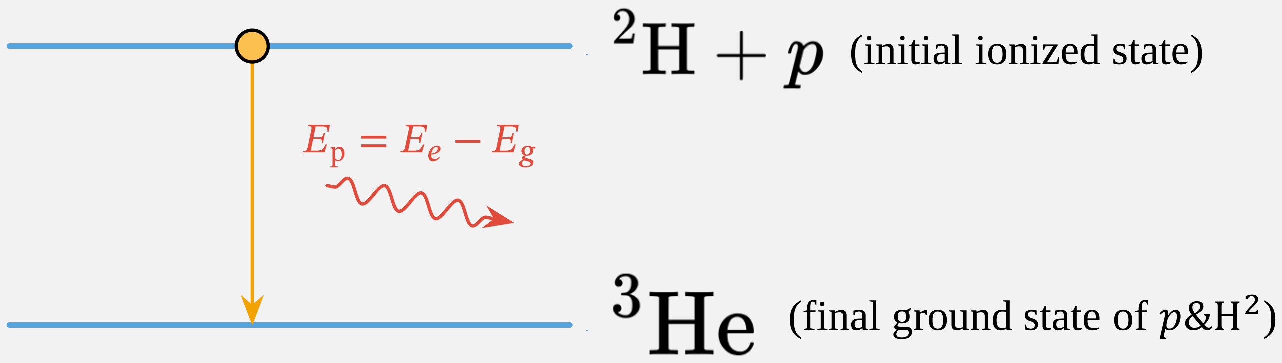

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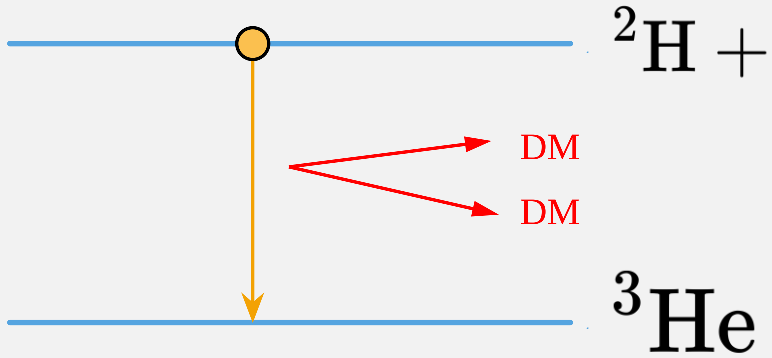
σ_{DM}



$E_{\mathrm{DM}} = 5.5\ \mathrm{MeV}$

Nuclear Fusion

nuclear potential — spin-orbital coupling — Coulomb potential

$p-\mathrm{H}^2$ Potential: $$V(\mathbf{x}) = V_0(x) + V_S(x)(\mathbf{l}\cdot\mathbf{s}_p) + V_C(x).$$

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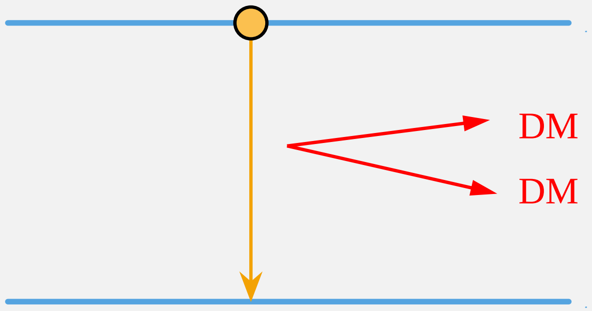

$^2\mathrm{H} + p$ — Initial state WF: ϕ_i

$^3\mathrm{He}$ — Final state WF: ϕ_f

$$\mathcal{M} \sim \langle \phi_f \mid \mathcal{O} \mid \phi_i \rangle \Rightarrow \sigma_{\mathrm{DM}}$$

$$\mathcal{O} \Longleftarrow \mathcal{L}_{\mathrm{DM}}$$

Nuclear Fusion

nuclear potential — spin-orbital coupling — Coulomb potential

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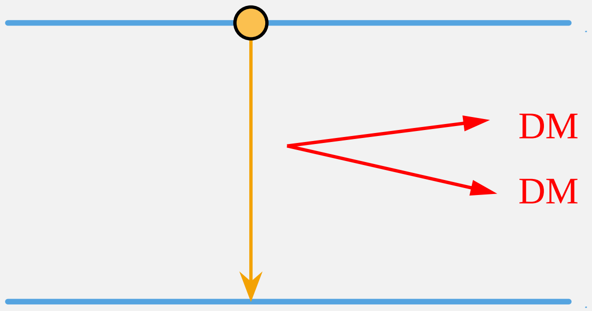

$^2\mathrm{H} + p$

Initial state WF: ϕ_i

$^3\mathrm{He}$

Final state WF: ϕ_f

$$\mathcal{L} = \frac{1}{\Lambda}\chi^*\chi\bar{p}p,$$

$$\mathcal{M} \sim \langle \phi_f \mid \mathcal{O} \mid \phi_i \rangle \Rightarrow \sigma_{\mathrm{DM}}$$

$$\mathcal{M} = \frac{1}{3\Lambda}\mathbf{q}\cdot\langle f|\,\mathbf{x}\,|i\rangle\,.$$

$\mathbf{q} \equiv \mathbf{p}_\chi + \mathbf{p}_{\chi^*}$

$$\mathcal{O} \Longleftarrow \mathcal{L}_{\mathrm{DM}}$$

Production Rate

DM production rate:

p-H^2 photon rate

$$\frac{d^2 n_{\rm DM}}{dt dE_{\rm DM}} \sim \frac{2}{\sigma_\gamma}\frac{d\sigma_{\rm DM}}{dE_{\rm DM}} \times \frac{dn_\gamma}{dt}$$

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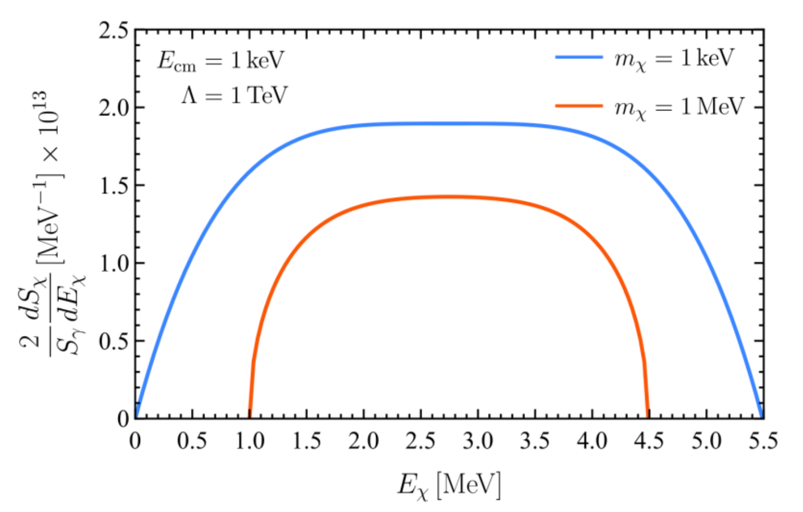

note: $S \propto \sigma$

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DM production rate:

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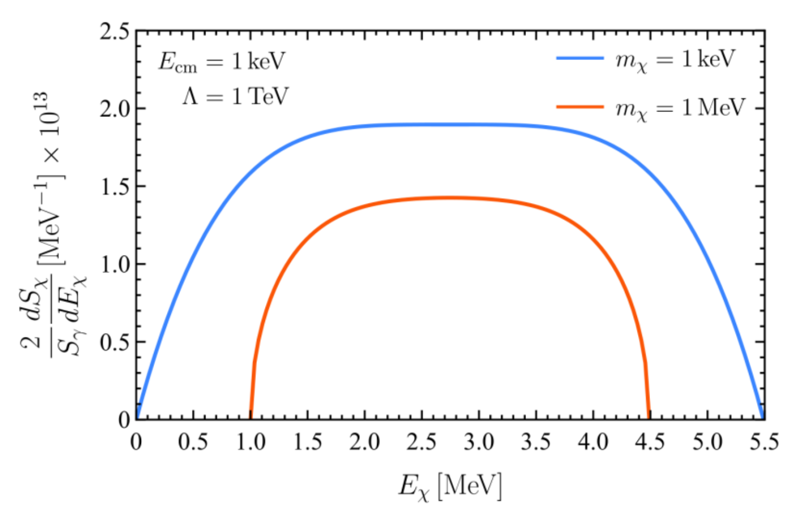

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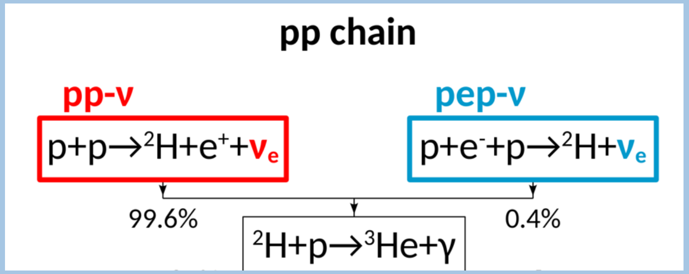
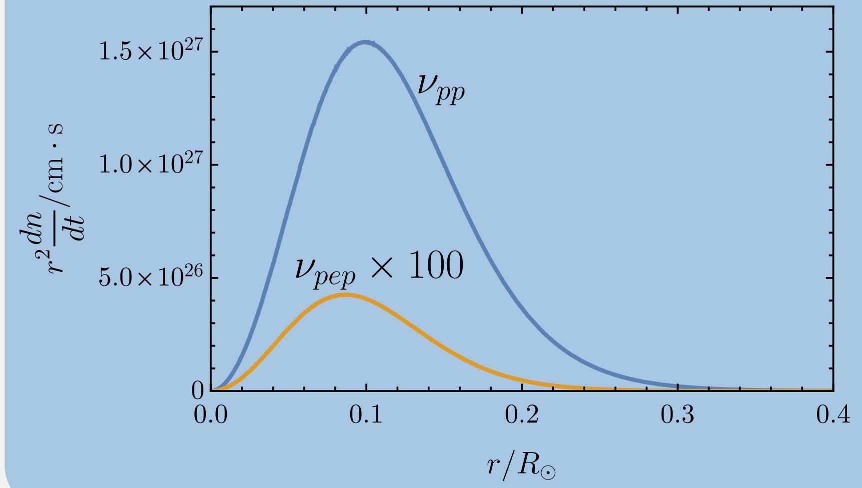
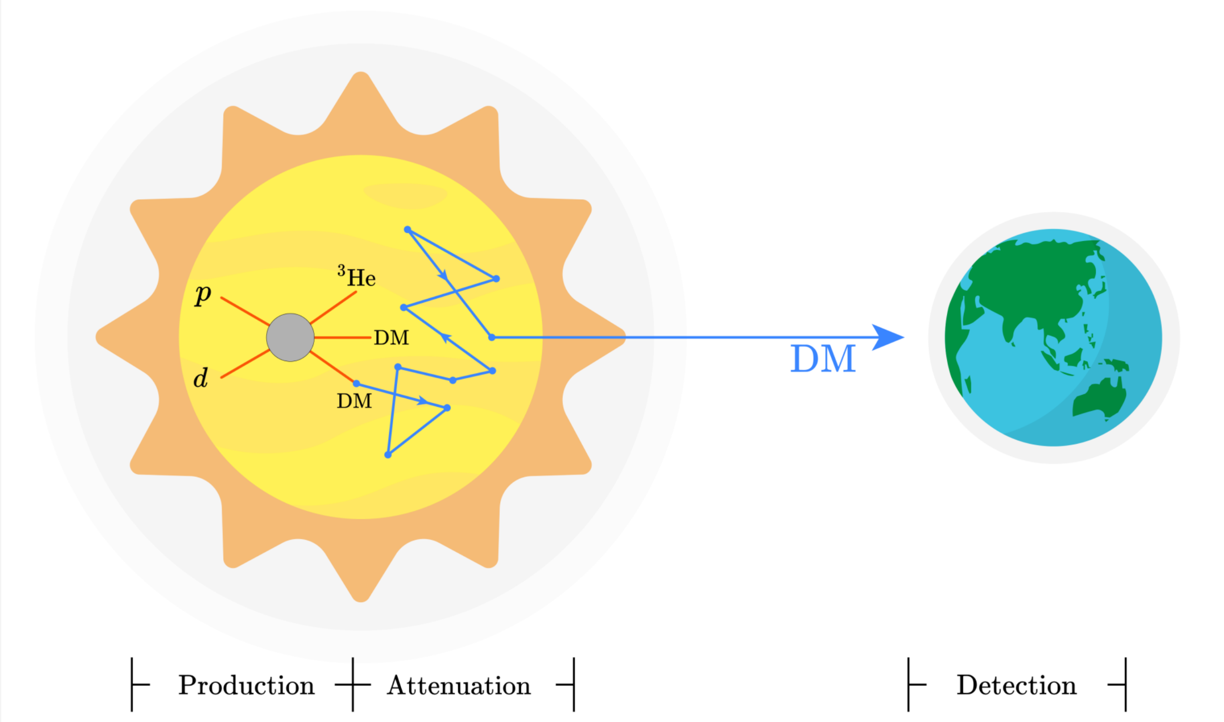


$$\frac{dn_\gamma}{dt} \sim \frac{dn_\nu^{pp}}{dt} + \frac{dn_\nu^{pep}}{dt}$$

(from solar model)



Solar Dark Matter:



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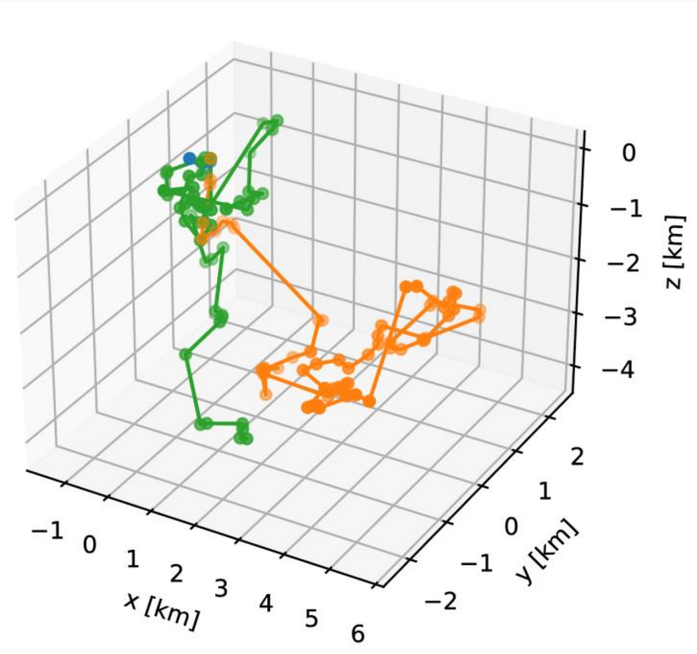
1. Monte Carlo



C. Xia, private communication

computationally expensive

Modeling the Scattering

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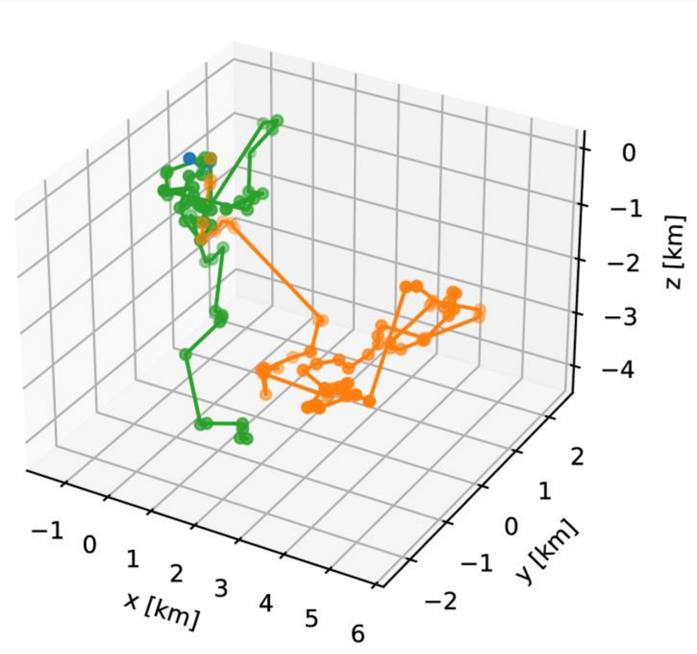
1. Monte Carlo



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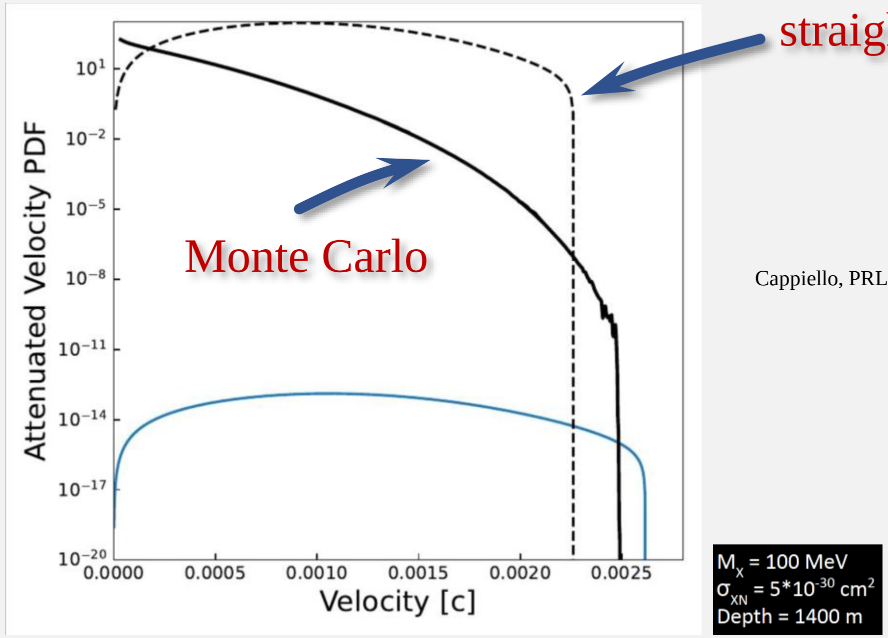
2. Straight-line Approximation



Cappiello, PRL 130, 221001 (2023)

invalid for large scattering xsec

See also NQ Song's talk

Analytical
&
Accurate

??

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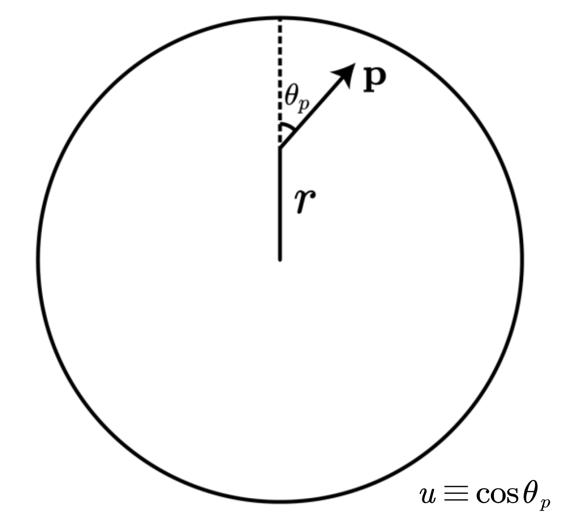
Boltzmann Equation Method

key function: **Distribution** $f(\mathbf{r}, \mathbf{p}, t) = f(r, u, E_{\mathrm{DM}})$



Boltzmann Equation Method

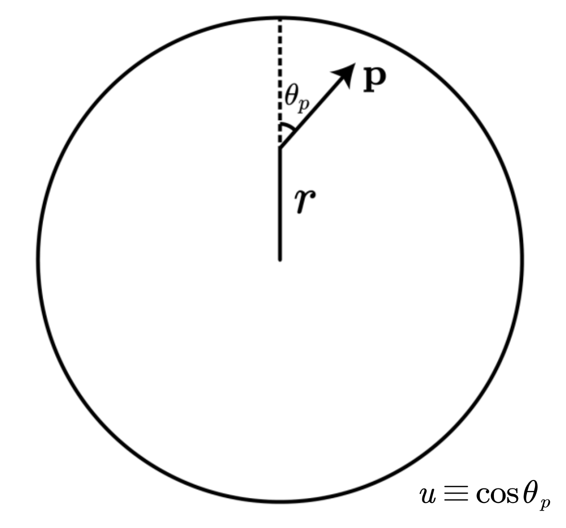
key function: **Distribution** $f(\mathbf{r},\mathbf{p},t) = f(r,u,E_{\rm DM})$

$$\mathbf{L}[f] = \mathbf{C}_{\rm scat}[f] + \mathbf{C}_{\rm prod}$$

Liouville Operator: propagation

Collision Terms: interaction

Kolb, Turner, The Early Universe



The Boltzmann Equation

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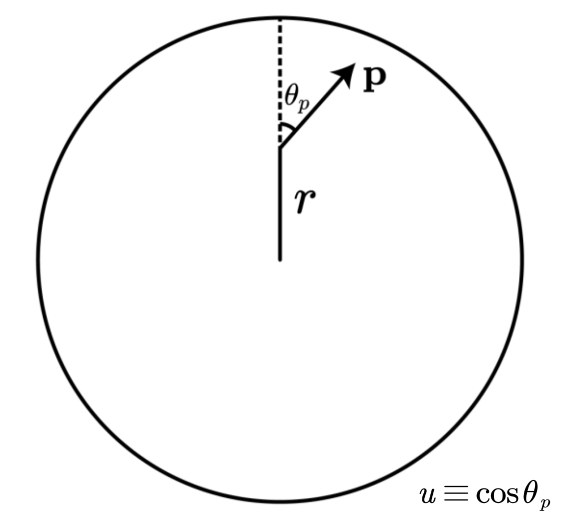

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$$\hat{\mathbf{L}}[f_\chi] = |\mathbf{p}_\chi| \left(u \frac{\partial f_\chi}{\partial r} + \frac{1-u^2}{r}\frac{\partial f_\chi}{\partial u} \right)$$

$$\mathbf{C}_{\mathrm{prod}} = \frac{2\pi^2}{g_\chi |\mathbf{p}_\chi|} \frac{d^3 N_\chi}{dt dE_\chi dV_\odot}$$

$$\mathbf{C}_{\chi p}[f_\chi^i] = -\frac{1}{2}\int d\Pi_p^i d\Pi_\chi^f d\Pi_p^f (2\pi)^4 \delta^4(p_\chi^i + p_p^i - p_\chi^f - p_p^f) \left(\overline{|\mathcal{M}|^2_{\chi p}} (f_\chi^i f_p^i - f_\chi^f f_p^f) \right)$$

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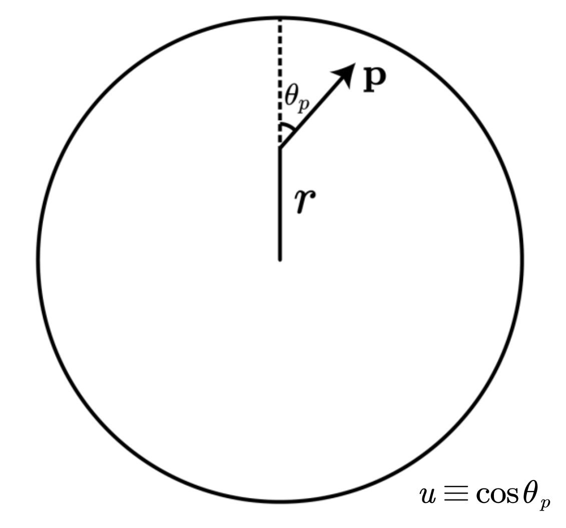

Boundary Condition

$$f(R_\odot, u, E_\chi) = 0, \quad \text{for} \quad u \leq 0$$

No particle goes in at the surface.

Boltzmann Equation Method

key function: **Distribution** $f(\mathbf{r},\mathbf{p},t) = f(r,u,E_{\rm DM})$

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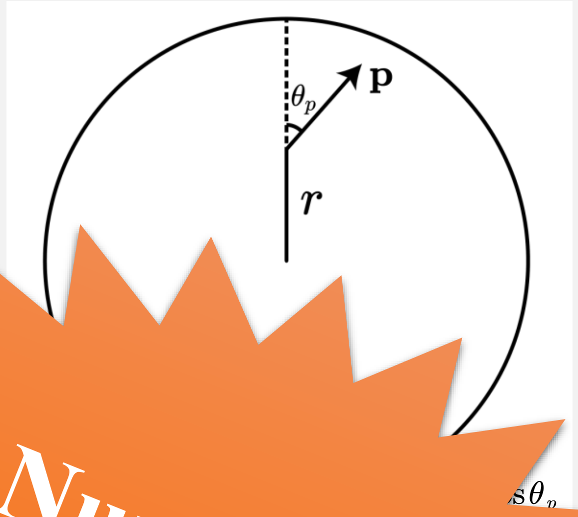
Liouville Operator: propagation

Collision Terms: interaction



Kolb, Turner, The E…

Numerical Solution

Boundary Condition

$$f(R_\odot, u, E_\chi) = 0, \quad \text{for} \quad u \le 0$$

No particle goes in at t… su…e

Approximation

Scattering Collision Term: **5-fold integration**

$$d\Pi = \frac{g}{(2\pi)^3}\frac{d^3\mathbf{p}}{2E},$$

$$\mathbf{C}_{\chi p}[f_\chi^i] = -\frac{1}{2}\int d\Pi_p^i d\Pi_\chi^f d\Pi_p^f (2\pi)^4 \delta^4(p_\chi^i + p_p^i - p_\chi^f - p_p^f)\left(\overline{\overline{|\mathcal{M}|^2_{\chi p}}}(f_\chi^i f_p^i - f_\chi^f f_p^f)\right)$$

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Approximation: $m_p \sim \text{GeV}$ $E_\chi, |\mathbf{p}_\chi|, |\mathbf{p}_p| \sim \text{MeV}$ **Expansion over $\frac{1}{m_p}$**

$$\mathbf{C}^{(1)}_{\chi p}[f_\chi] \approx -|\mathbf{p}_\chi| n_p \sigma^{\text{LO}}_{\chi p} f_\chi(r, u, E_\chi)\left(1 - \frac{2E_\chi}{m_p}\right),$$

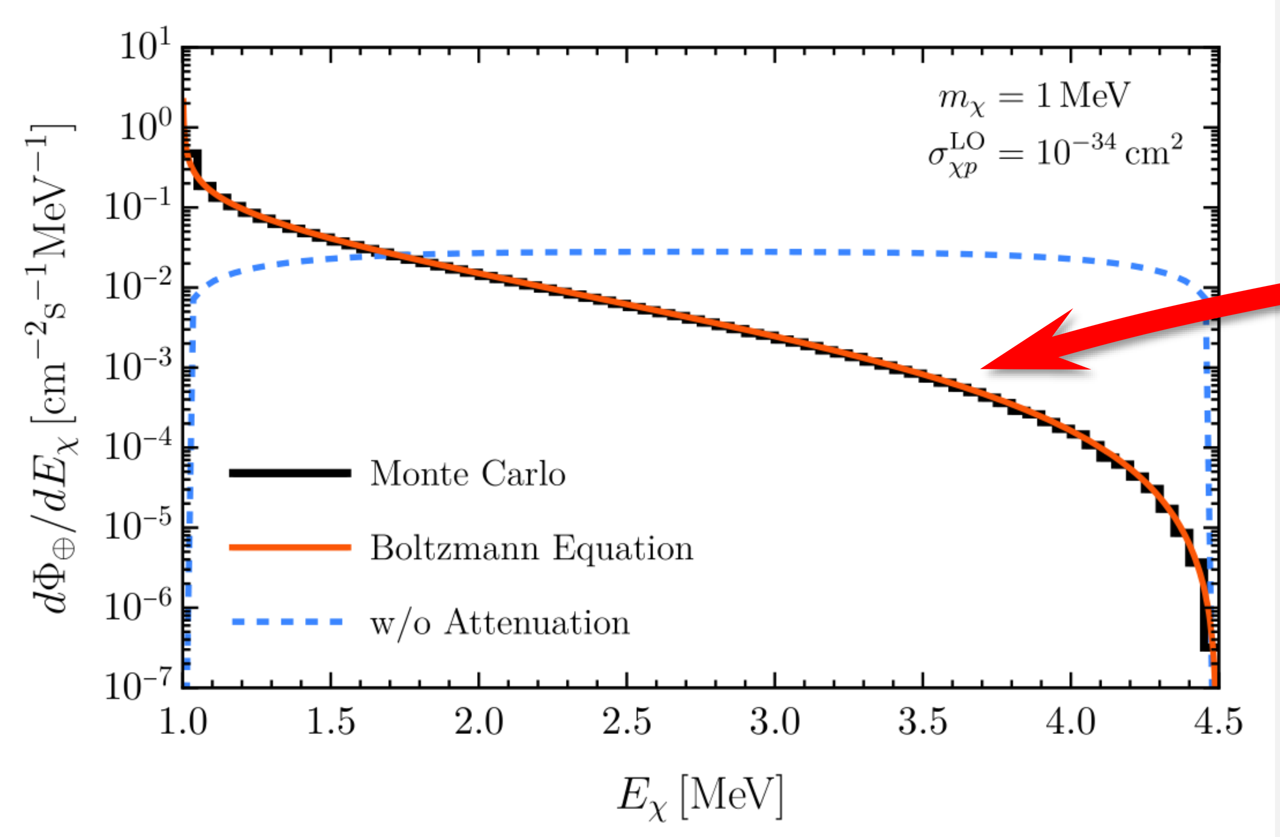
$$\mathbf{C}^{(2)}_{\chi p}[f_\chi] \approx |\mathbf{p}_\chi| n_p \sigma^{\text{LO}}_{\chi p}\int \frac{du'}{2} f_\chi(r, u', \bar{E}'_\chi)\left(1 + \frac{2E_\chi}{m_p}(1 - uu')\right)$$

$\mathbf{C}_{\chi p}[f] \equiv \mathbf{C}^{(1)}_{\chi p}[f] + \mathbf{C}^{(2)}_{\chi p}[f]$

DM Flux

DM Flux @ Earth:

$$\frac{d\Phi_\oplus}{dE_\chi} = \frac{R_\odot^2}{4\pi^2 \mathrm{AU}^2} |\mathbf{p}_\chi|^2 \int_0^1 du\, u f(R_\odot, u, E_\chi),$$



Monte Carlo & Boltzmann Equation

Perfect Alignment

Solar Dark Matter:

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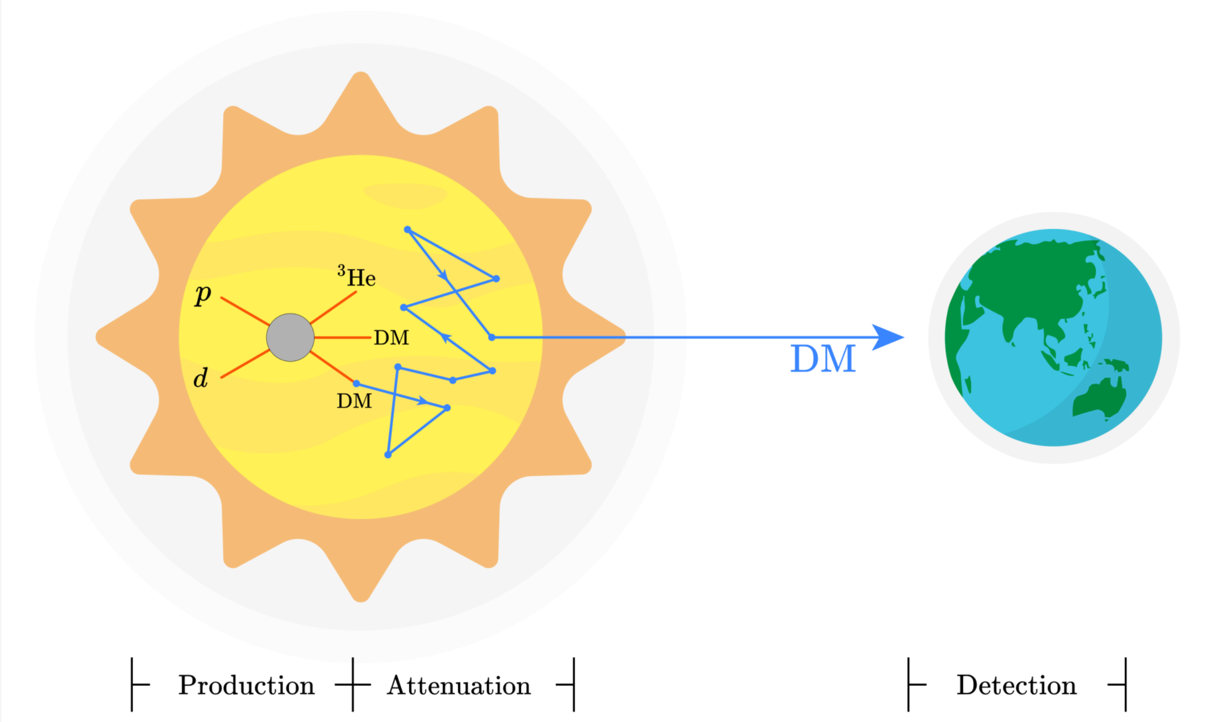
2. Production
3. Attenuation
4. **Detection**
5. Conclusion



Detection

Xenon Detector: $E_{\mathrm{NR}}^{\mathrm{xenon}} \simeq 0.4\,\mathrm{keV}\,.$ Below the threshold

Argon Detector: $E_{\mathrm{NR}}^{\mathrm{argon}} \simeq 1.5\,\mathrm{keV}\,.$ DarkSide-50 threshold ✓ sensitivity ✗

Detection

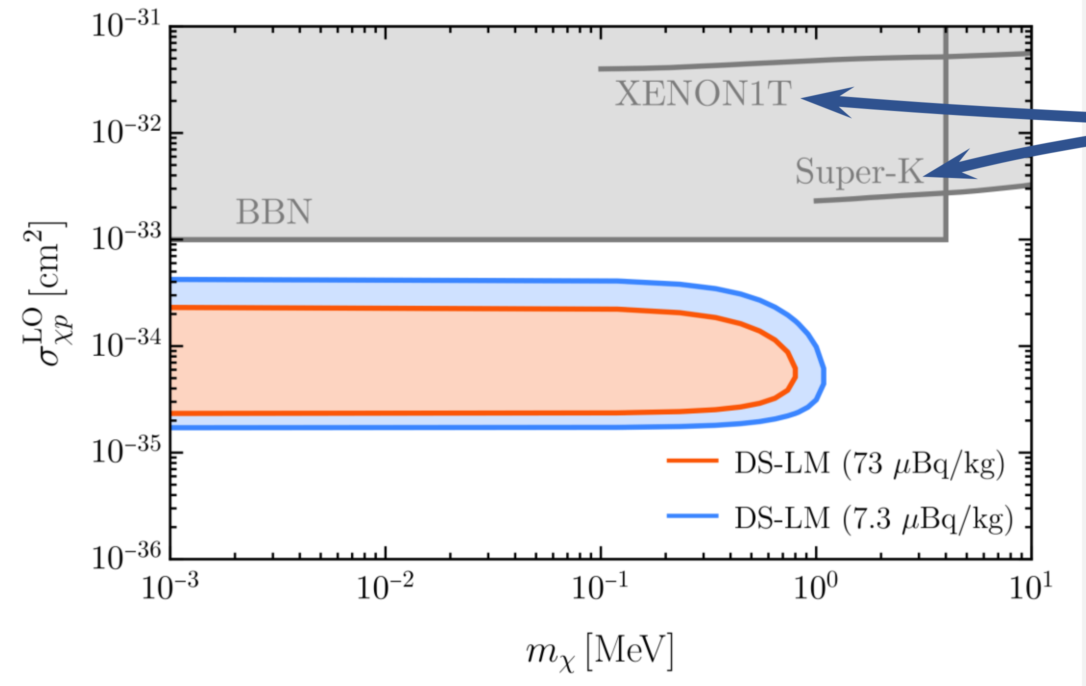
Xenon Detector: $E_{\rm NR}^{\rm xenon} \simeq 0.4\,{\rm keV}.$ Below the threshold

Argon Detector: $E_{\rm NR}^{\rm argon} \simeq 1.5\,{\rm keV}.$ DarkSide-50 threshold ✓ sensitivity ✗

GADM Collaboration, PRD 107, 112006 (2023)

DarkSide-LowMass

Future follow-up of DarkSide-50



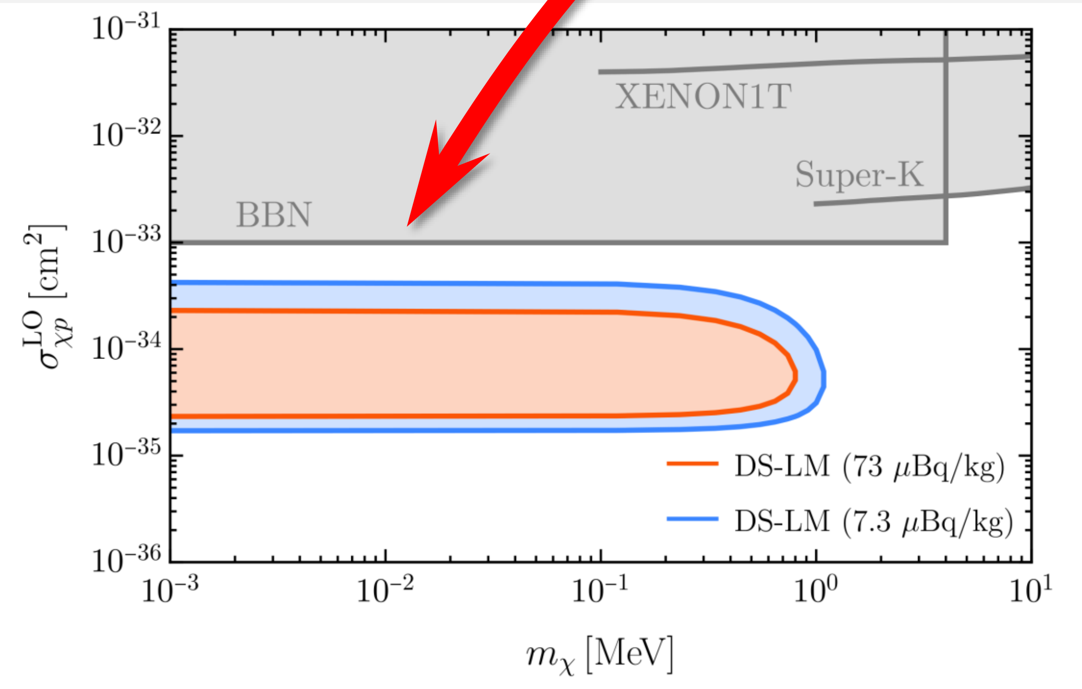
Cosmic-Ray Boosted DM

Light DM in BBN

1. Light & Thermal DM: BBN excluded $m_{\rm DM} \lesssim 1\,{\rm MeV}$ Sabti, Alvey, Escudero, Fairbairn, Blas, JCAP 01 (2020) 004

2. Light but Decoupled & Diluted DM: BBN consistent $T_{\rm dec} \sim 10\,{\rm MeV}$

Evans, Ghalsasi, Gori, Tammaro, Zupan, JHEP 02 (2020) 151



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Conclusion:

Solar DM can be

$$^{2}\mathrm{H} + p \to {}^{3}\mathrm{He} + \mathrm{DM} + \mathrm{DM}$$

Produced

Attenuated

Detected

Thanks!