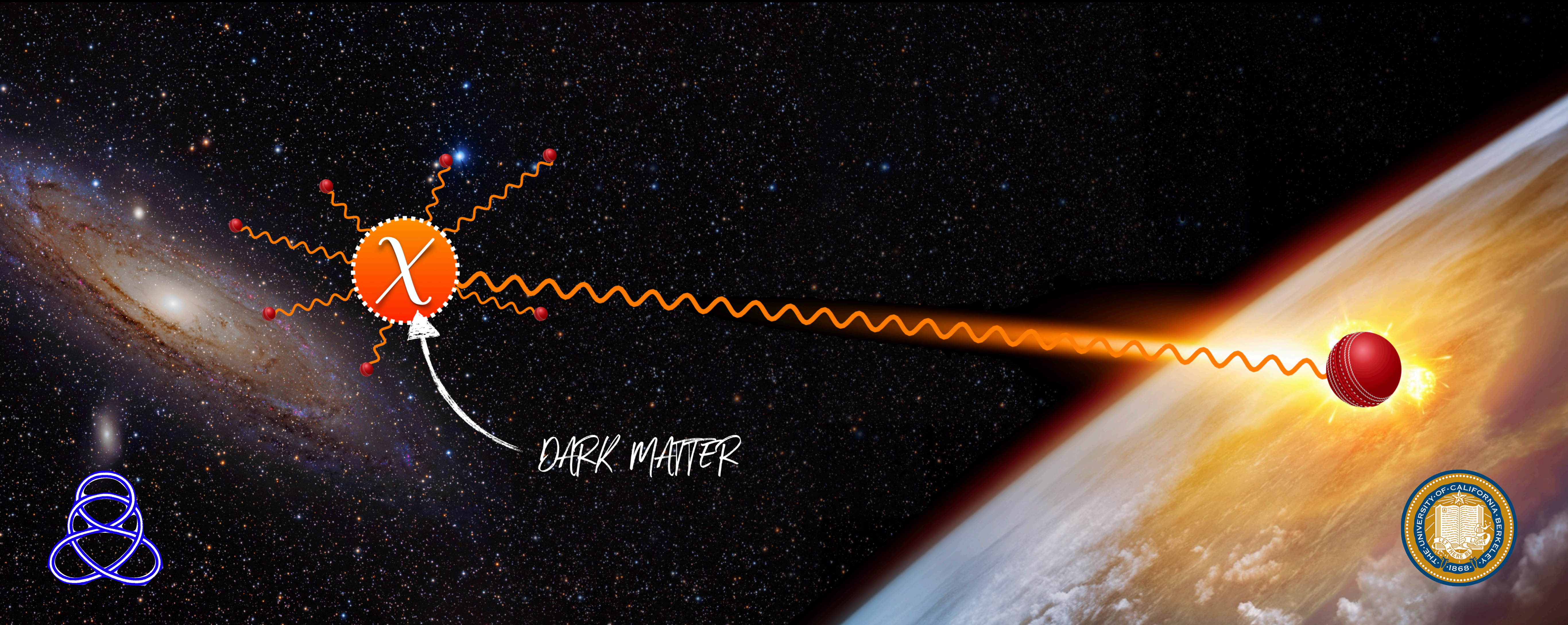
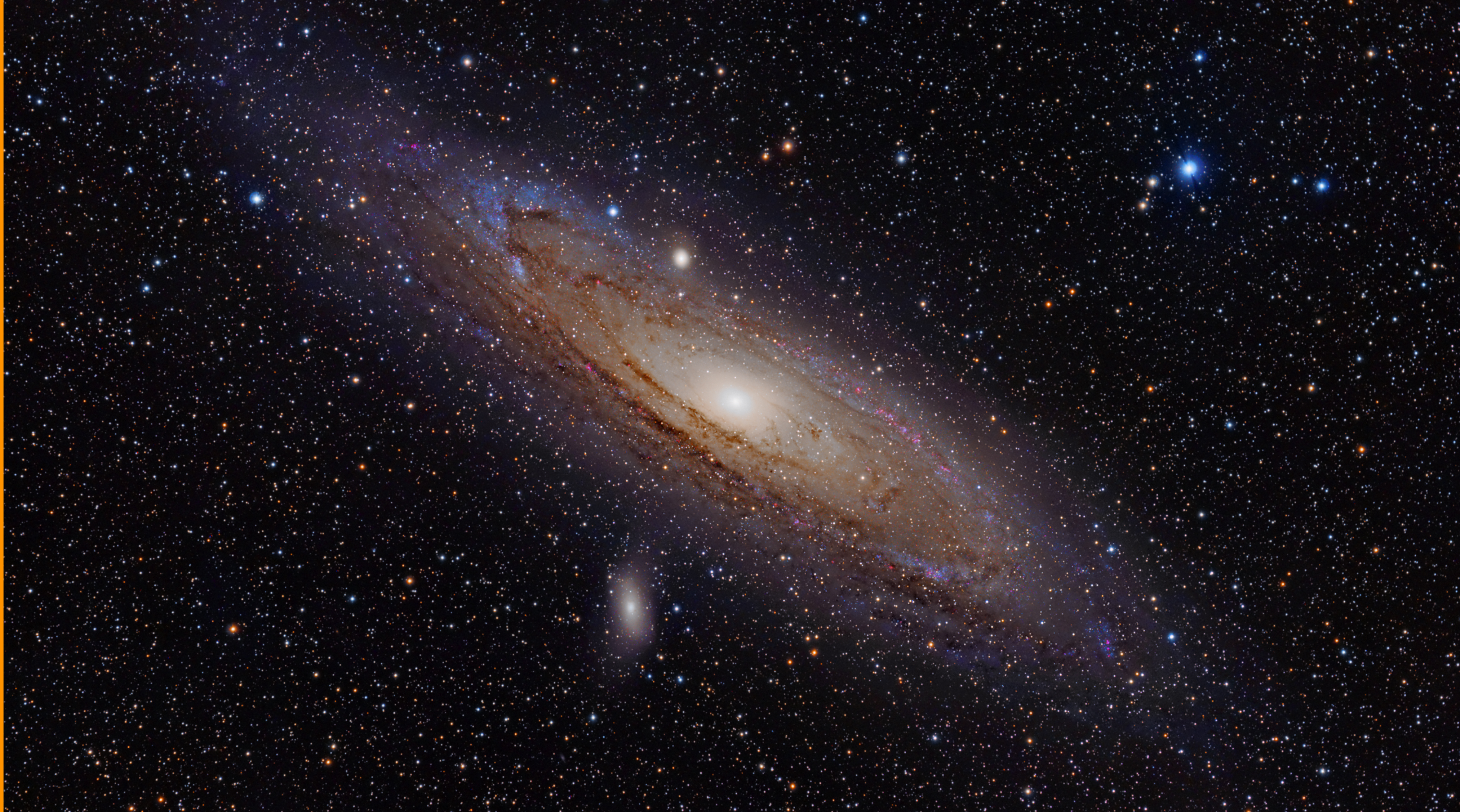
Searching for the Heaviest Particle in the Universe

NICK RODD | XIX NEUTRINO TELESCOPE WORKSHOP | 24 FEBRUARY 2021



The Mystery of Dark Matter



[Rubin, Ford ApJ 1970]

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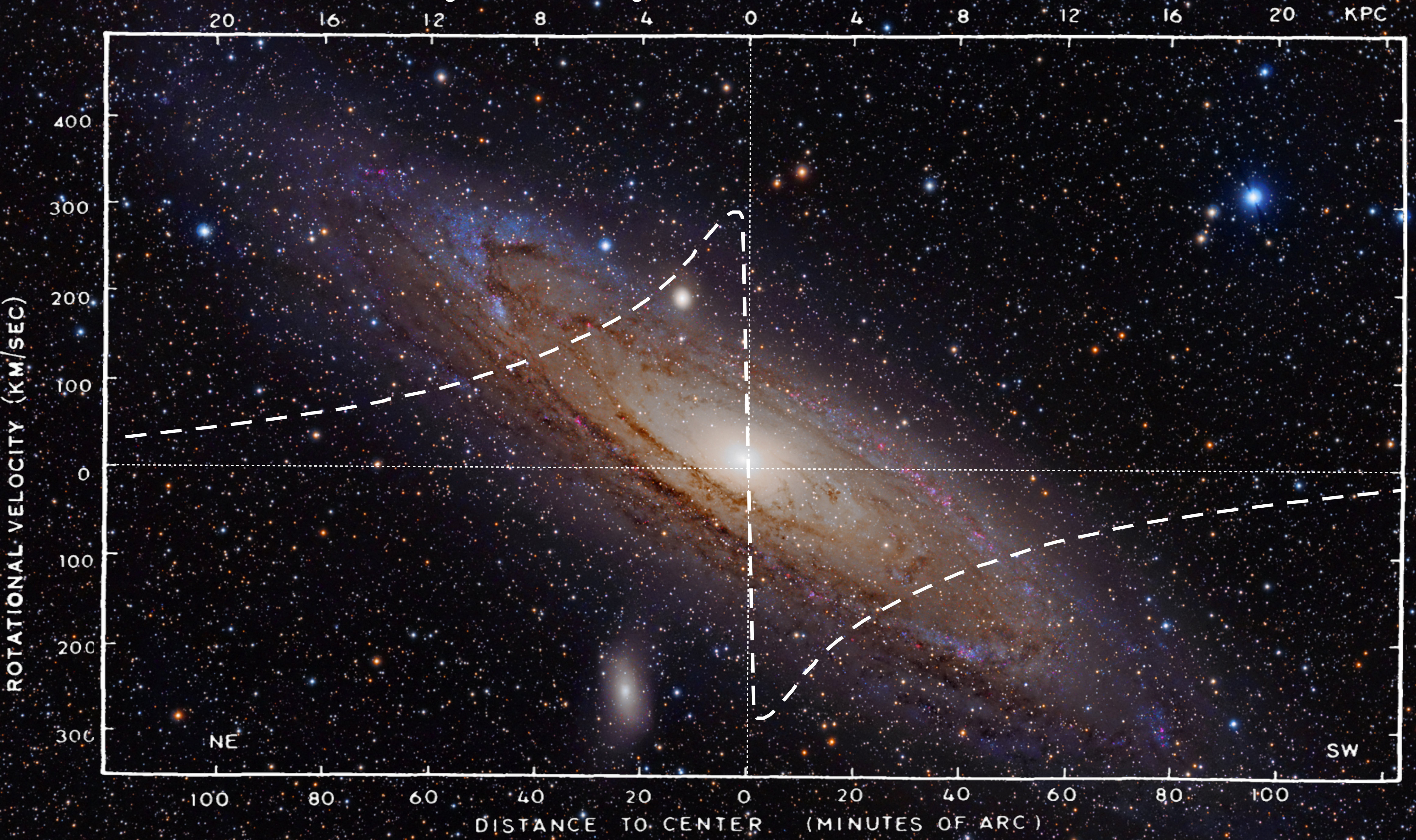
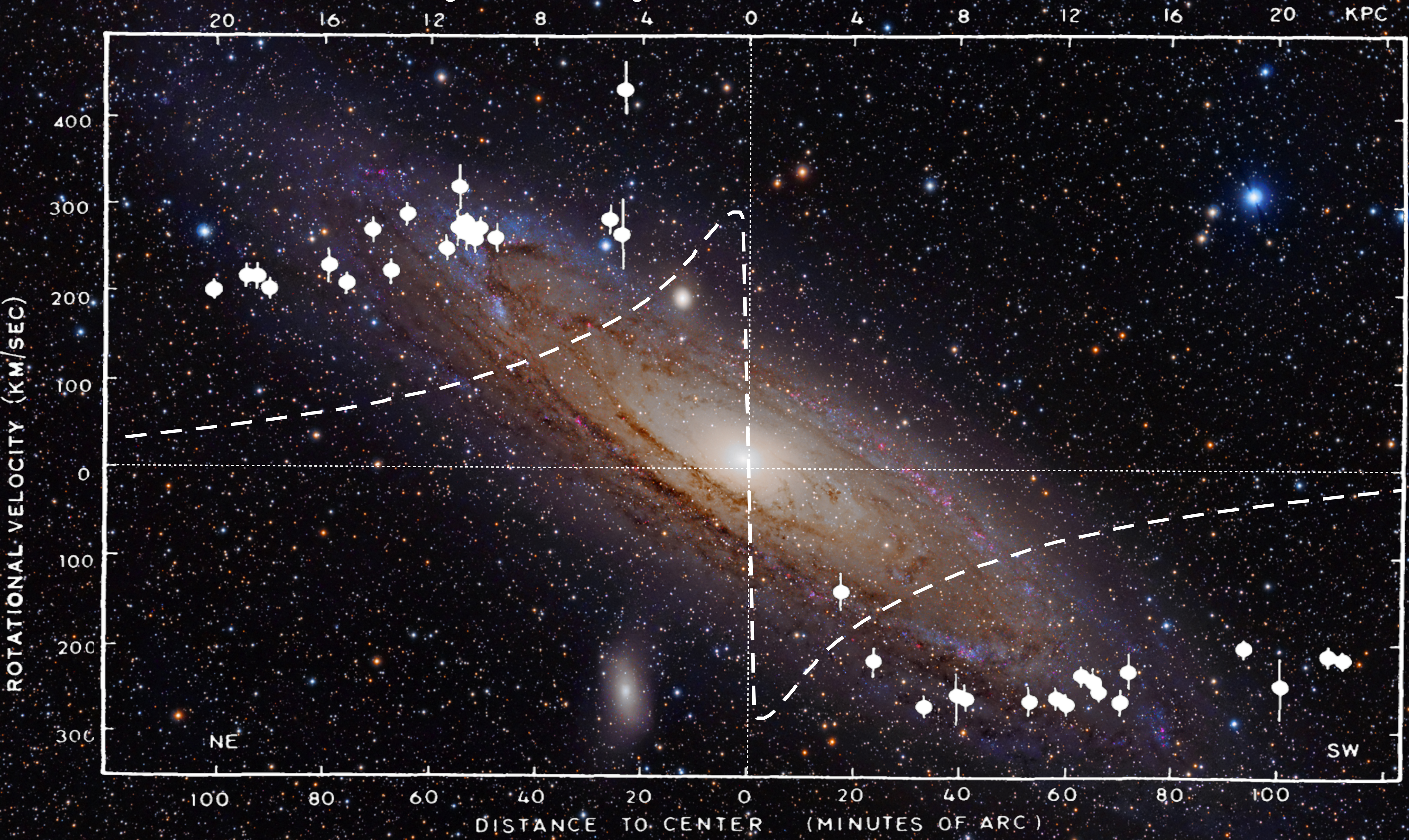


[Rubin, Ford ApJ 1970]

The Mystery of Dark Matter



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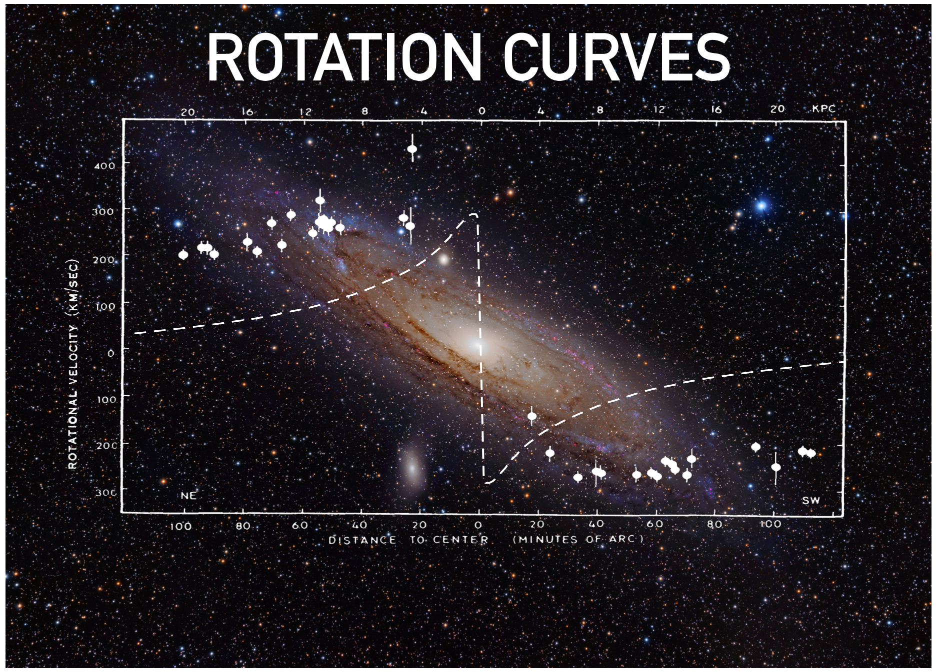
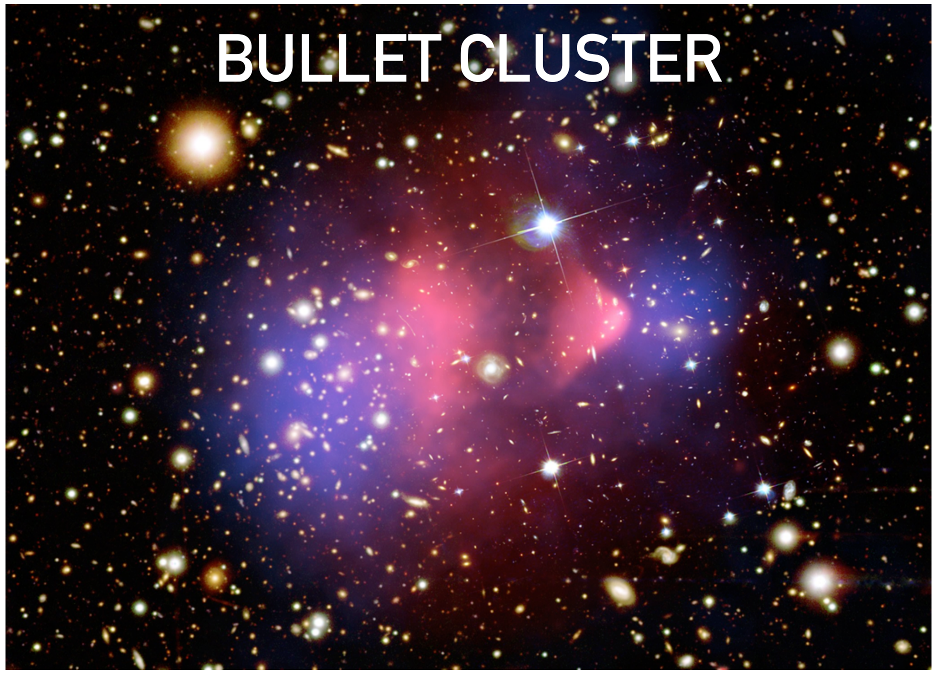
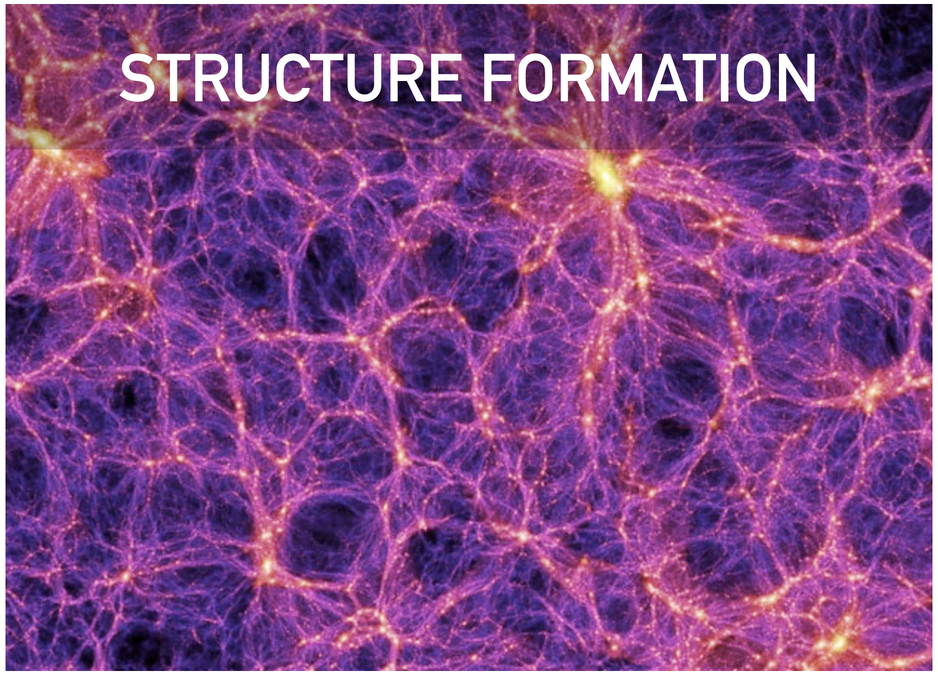
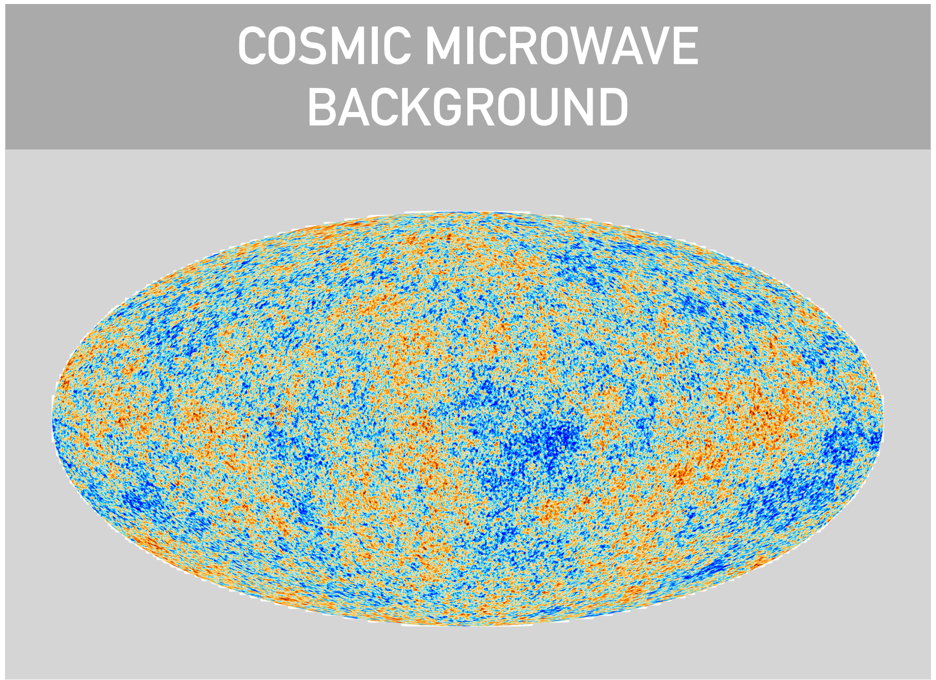


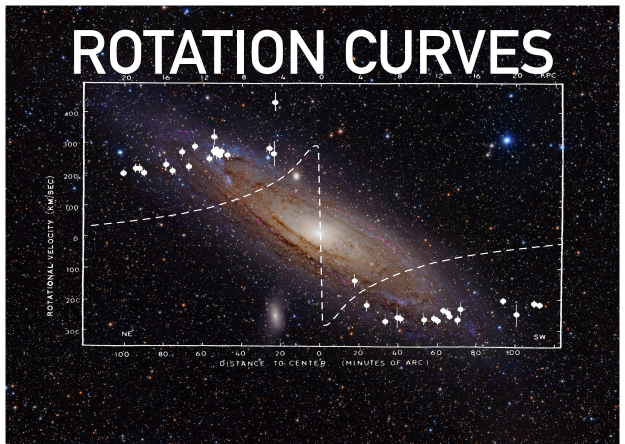


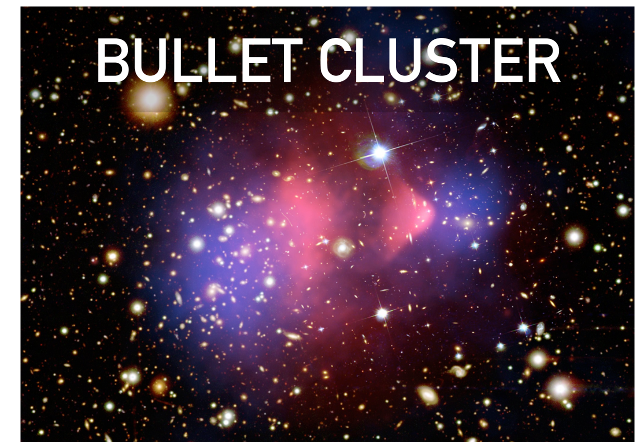


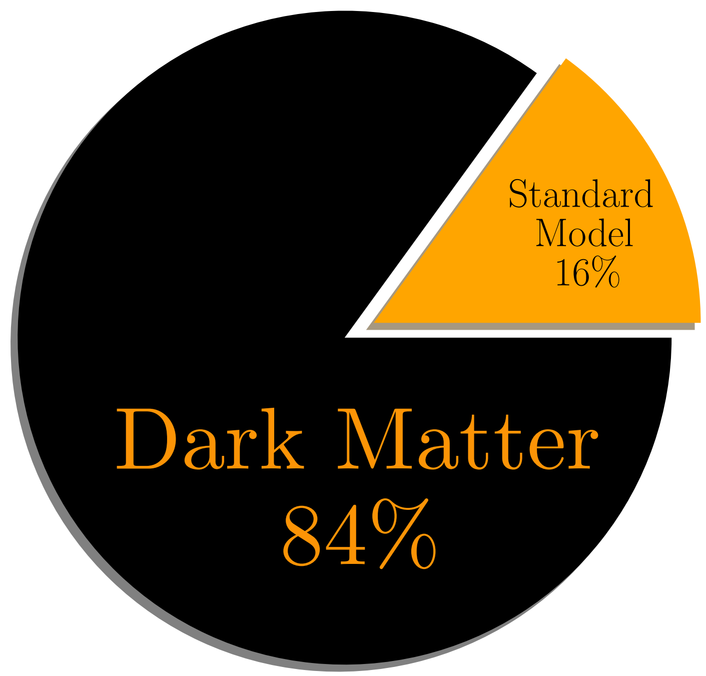


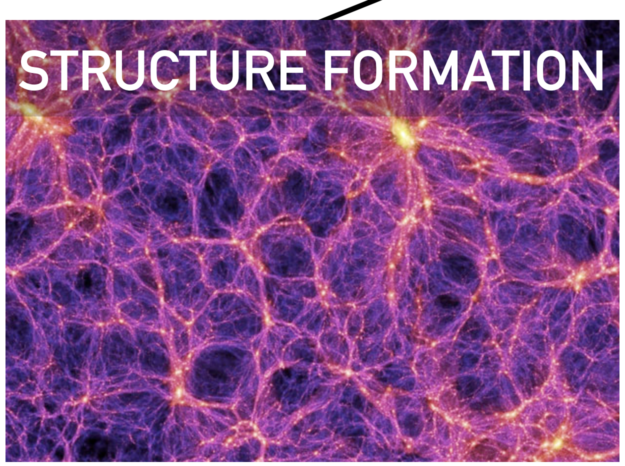
See also Gianfranco Bertone
"Multimessenger fingerprint of Dark Matter"
talk last Friday

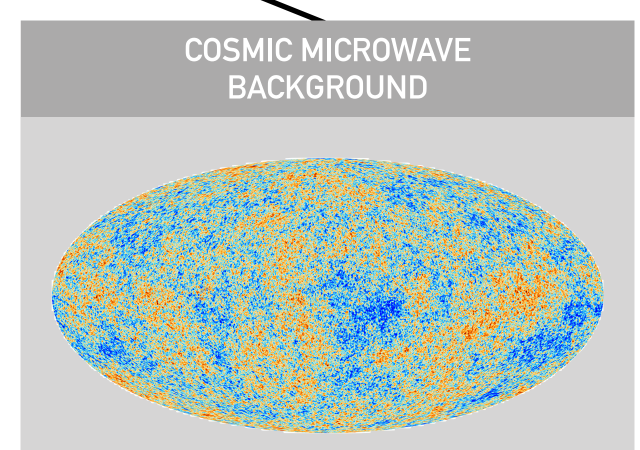
The Mystery of Dark Matter











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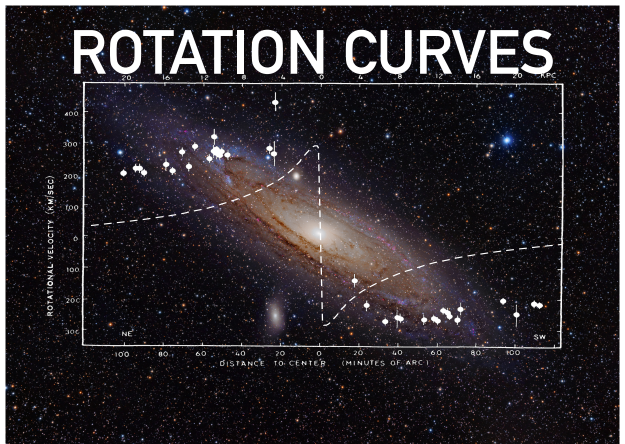

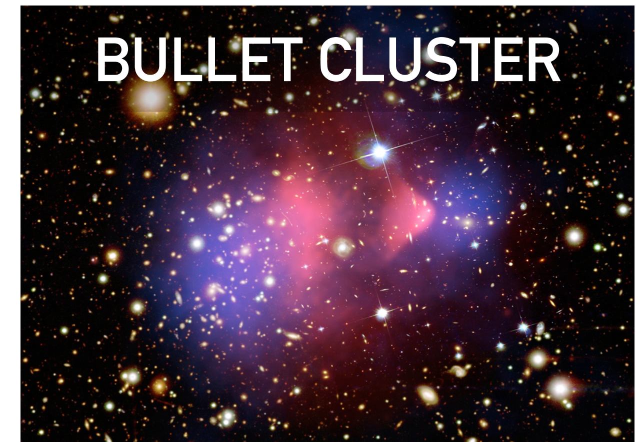

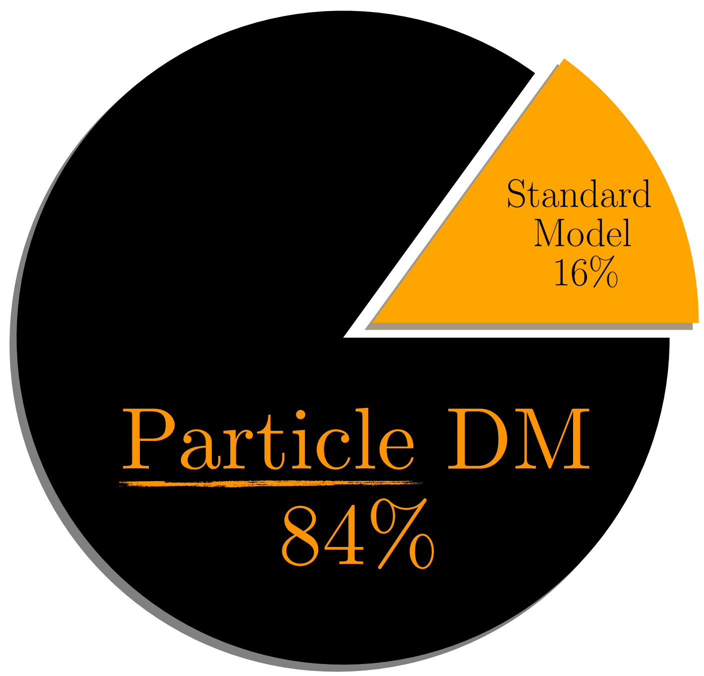

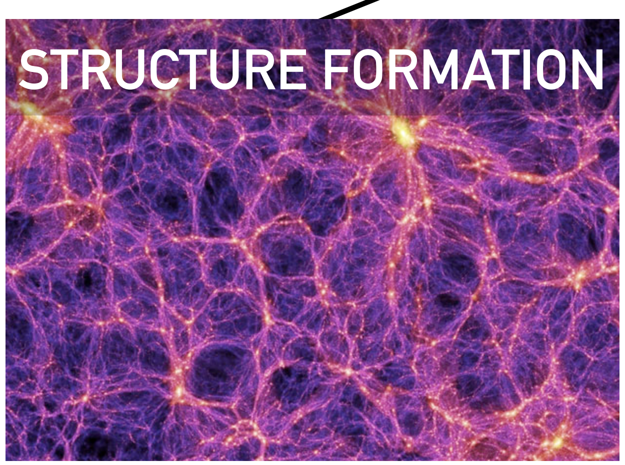

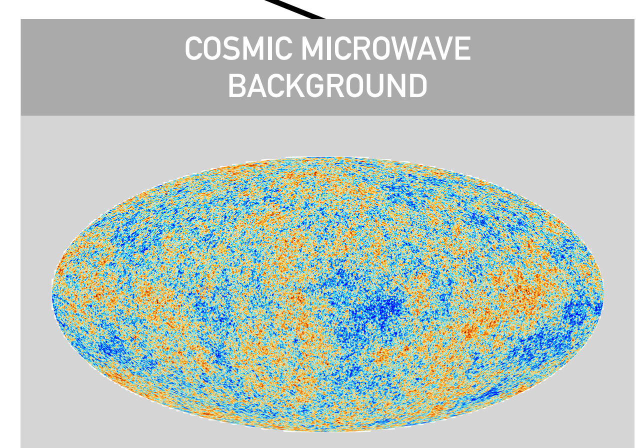

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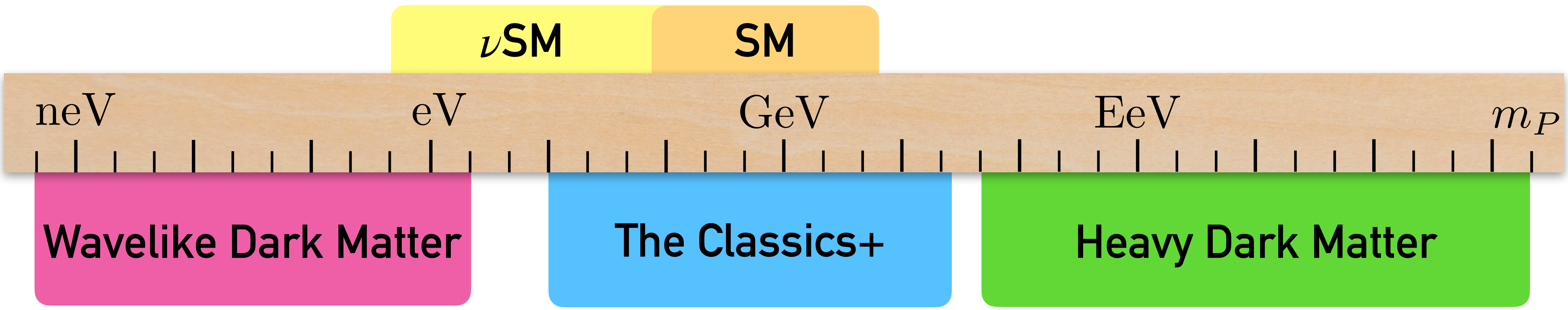
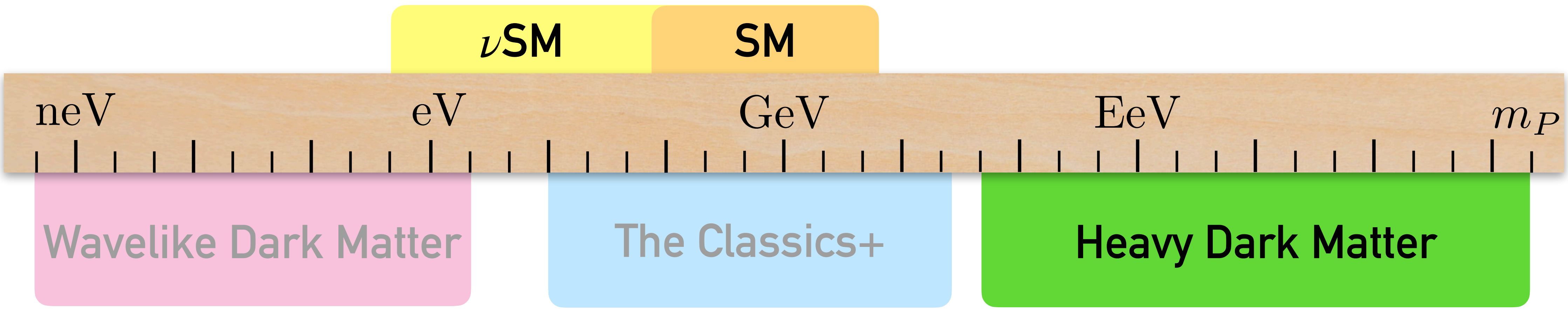
The Dark Matter Landscape



What is the Dark Matter mass?

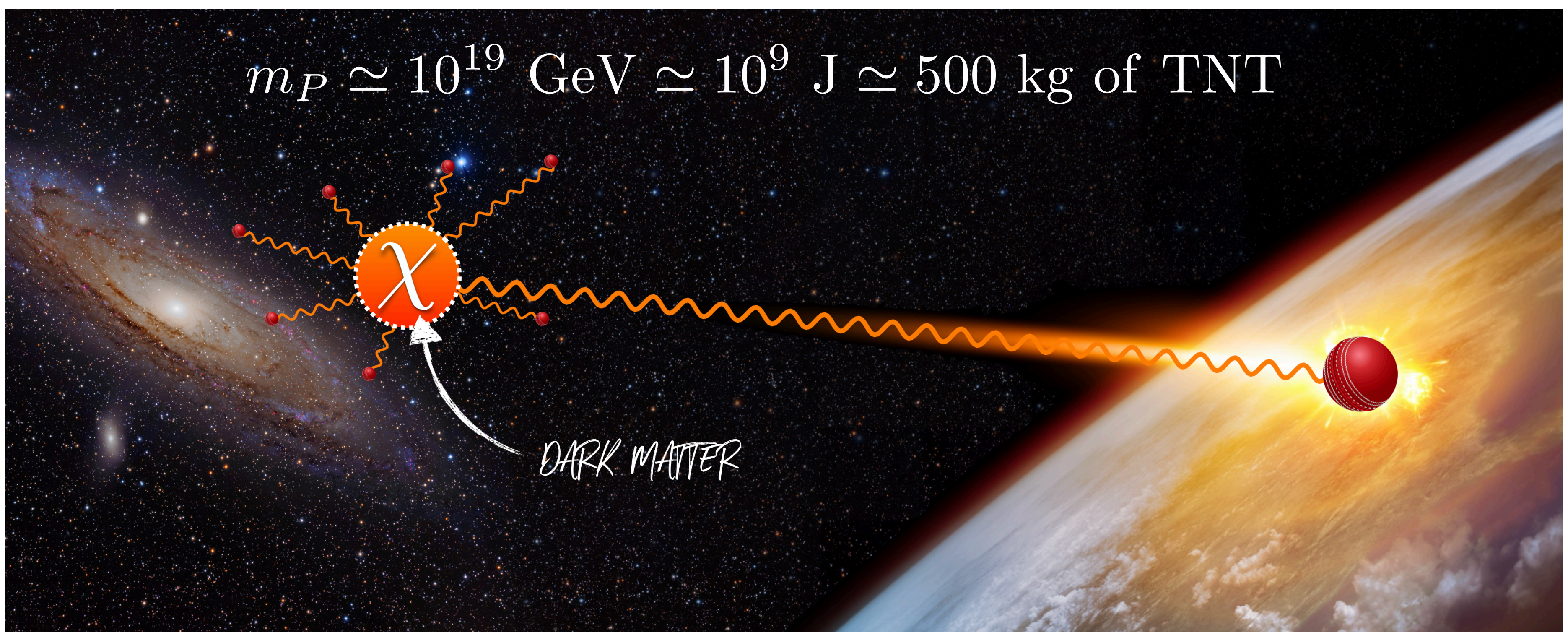
The Dark Matter Landscape



What is the Dark Matter mass?

The Search for Heavy Dark Matter

$$n_{\rm sun}^{\rm DM} \sim 10^{-4} \left(\frac{m_P}{m_{\rm DM}} \right) \text{ particles/km}^3$$



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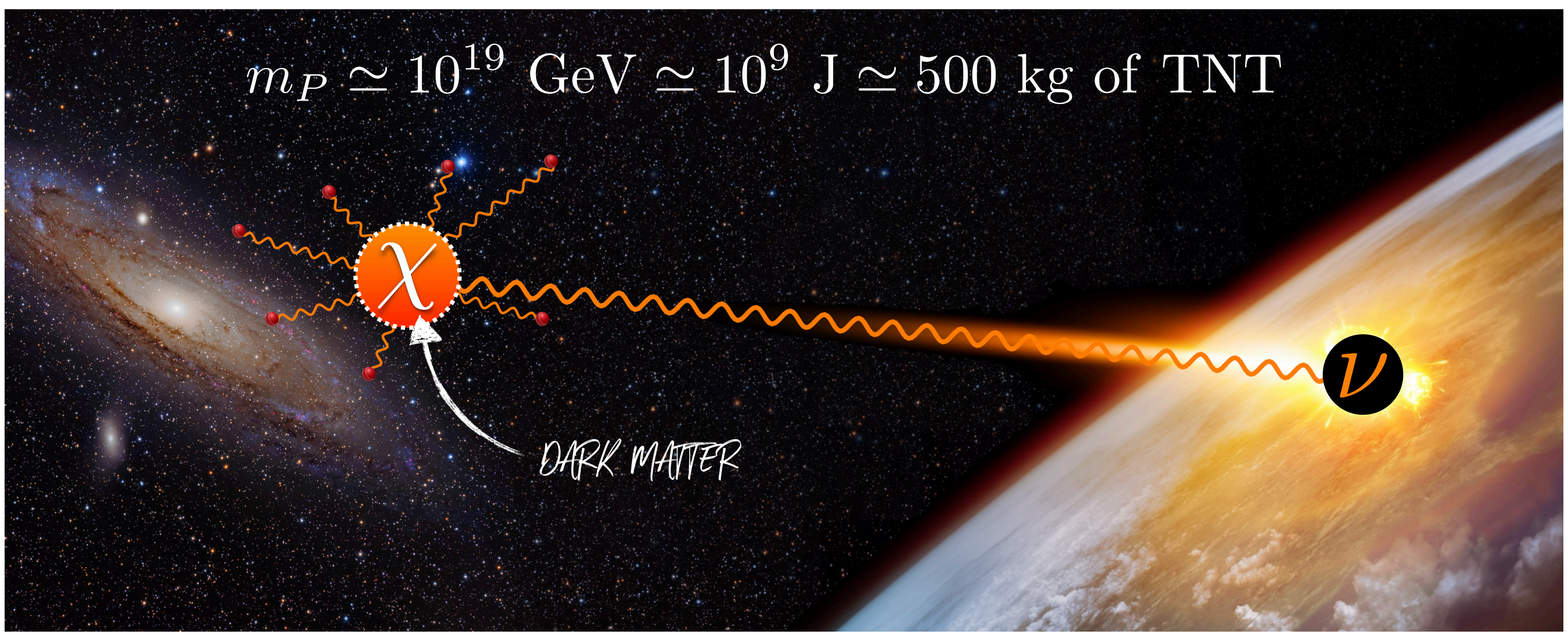
Heavy Dark Matter



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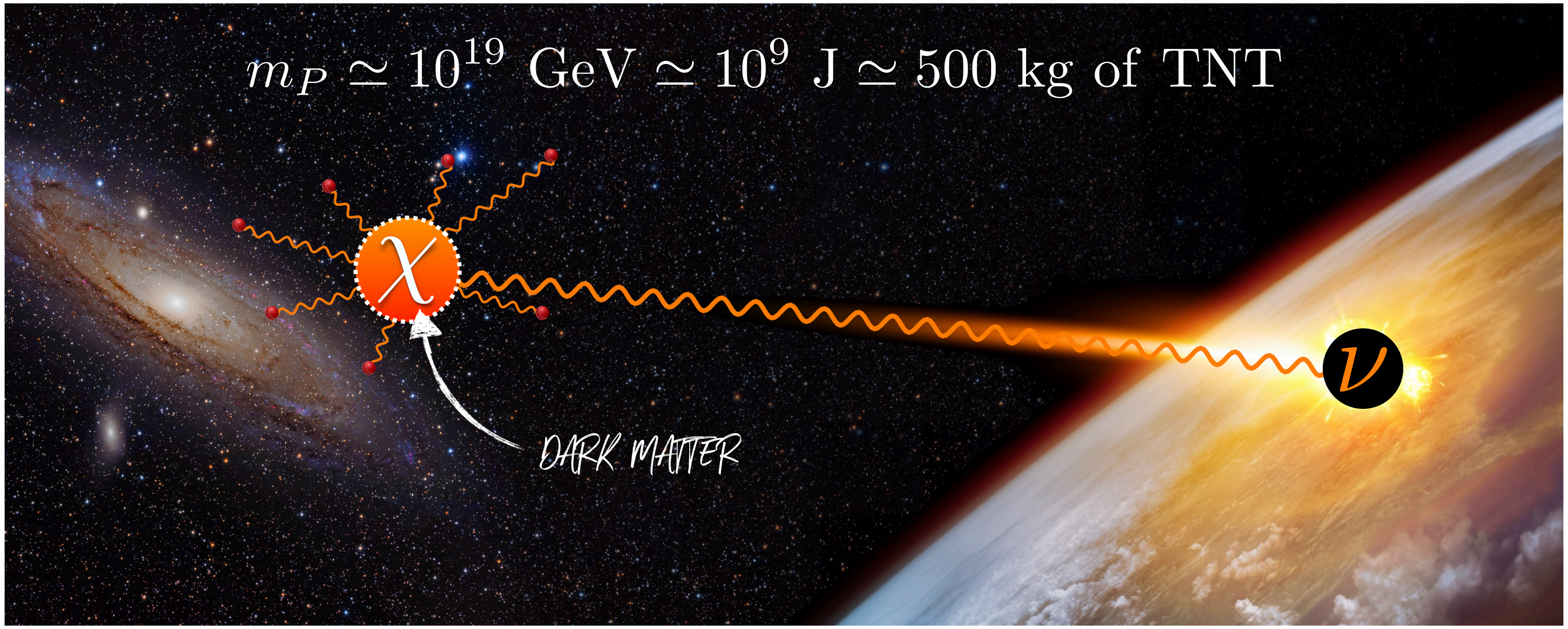

This is Indirect Detection

Outline

Goal is to answer three questions

Outline

1. Why consider heavy dark matter? UV and IR motivations

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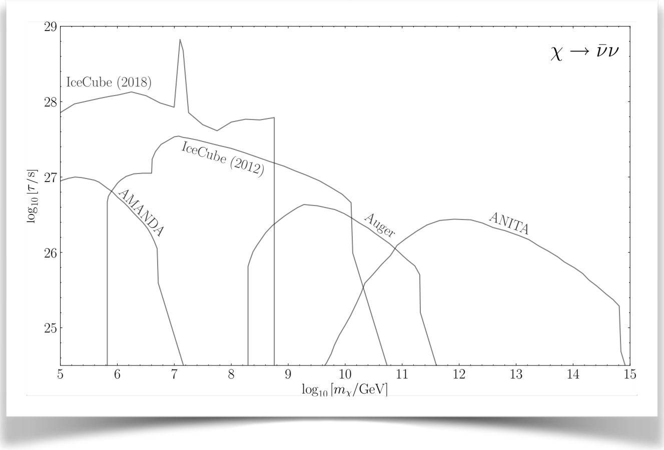
1. **Why** consider heavy dark matter? UV and IR motivations

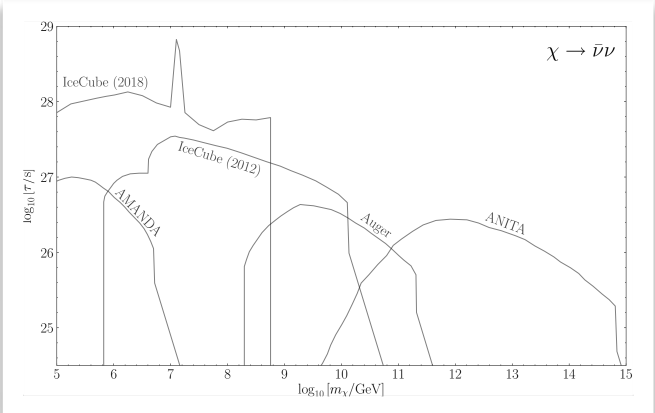
2. **How** can we find it? Landscape of neutrino telescopes



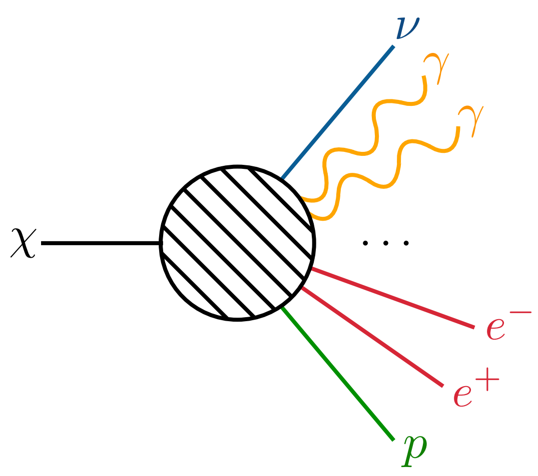
Outline

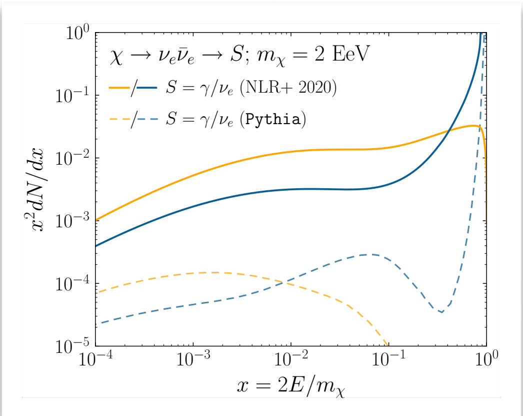
1. **Why** consider heavy dark matter? UV and IR motivations

2. **How** can we find it? Landscape of neutrino telescopes



3. **What** are we looking for? The particle physics of the decay





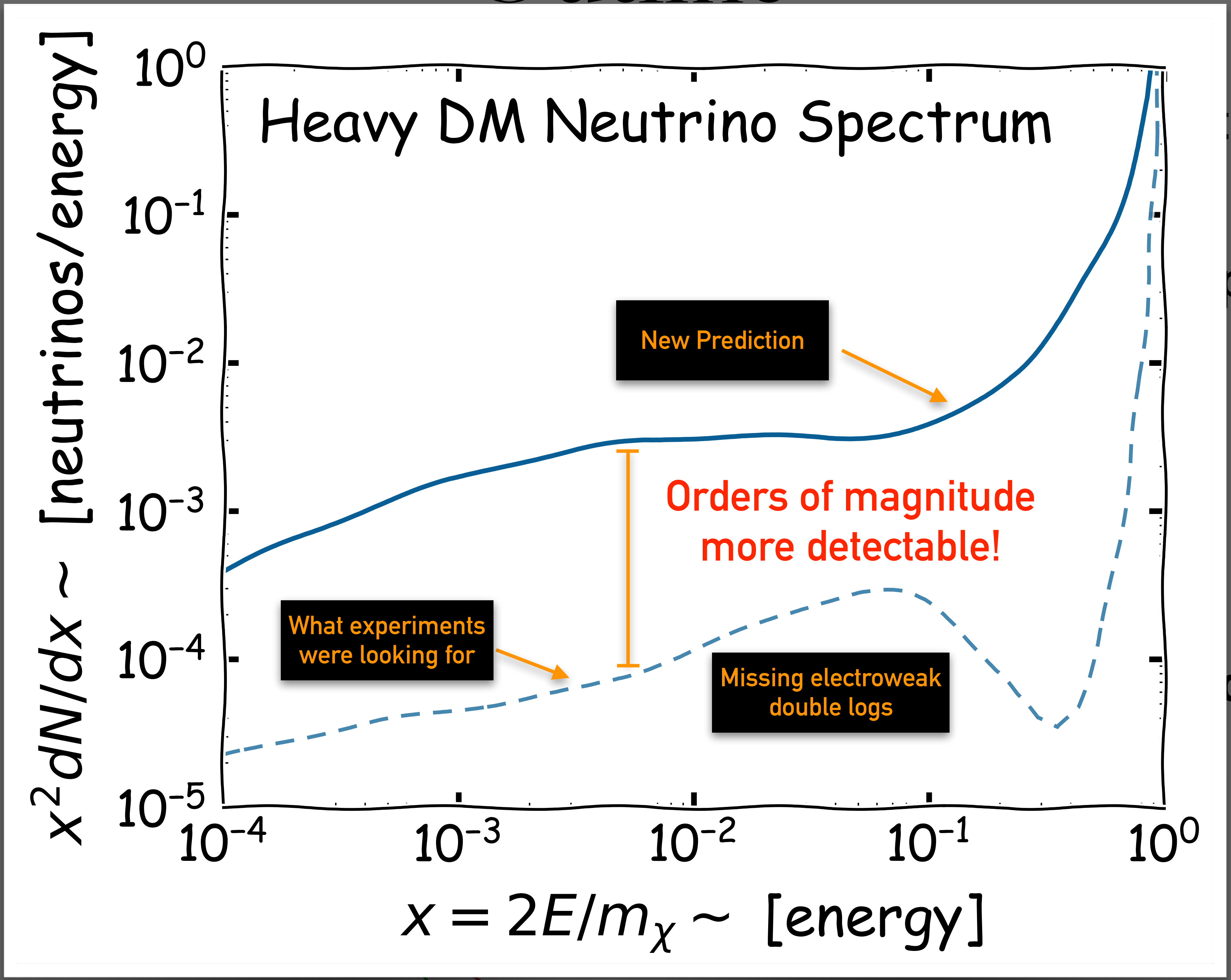
[Bauer, NLR, Webber 2020]

Outline

1 ... ions

... pes

3. ... decay



e^+

p

[Bauer, NLR, Webber 2020]

UV Motivation

~limit on thermal dark matter
[Griest, Kamionkowski PRL 1990]

Non-thermal production

Freeze-in [Hall+ JHEP 2010], produced during reheating [e.g. Chung+ PRD 1998], gravitational particle production [e.g. Chung+ JHEP 2019], …

Decay through e.g. Planck suppressed operators

For scaling see [Cohen, NLR+ PRL 2017]

Many recent ideas

[Contino+ JHEP 2019], [Babichev+ PLB 2019], [Kim+ PRL 2019], [Dudas+ PRD 2020], [Kramer+ 2020], [Hambye+ PLB 2020], [Garcia+ PRD 2020], …

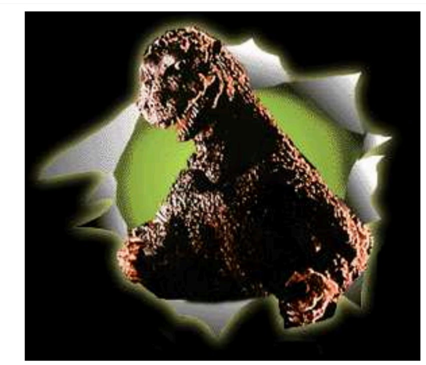
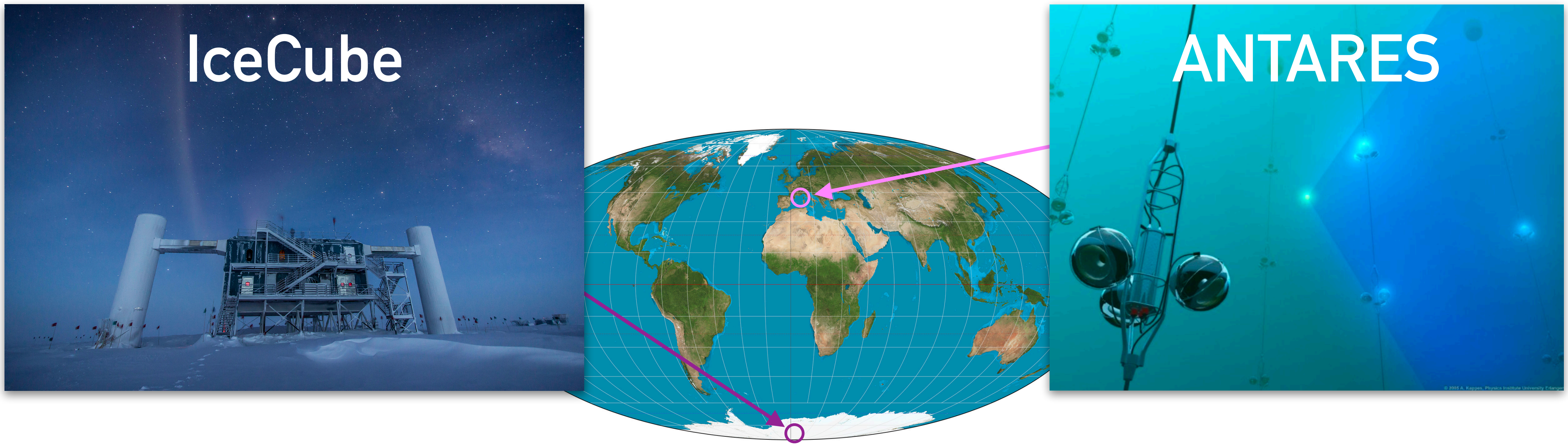


Figure 7. Dark matter may be much more massive than usually assumed, much more massive than wimpy WIMPS, perhaps in the WIMPZILLA class.

[Kolb+ AIP 1998]

IR Motivation

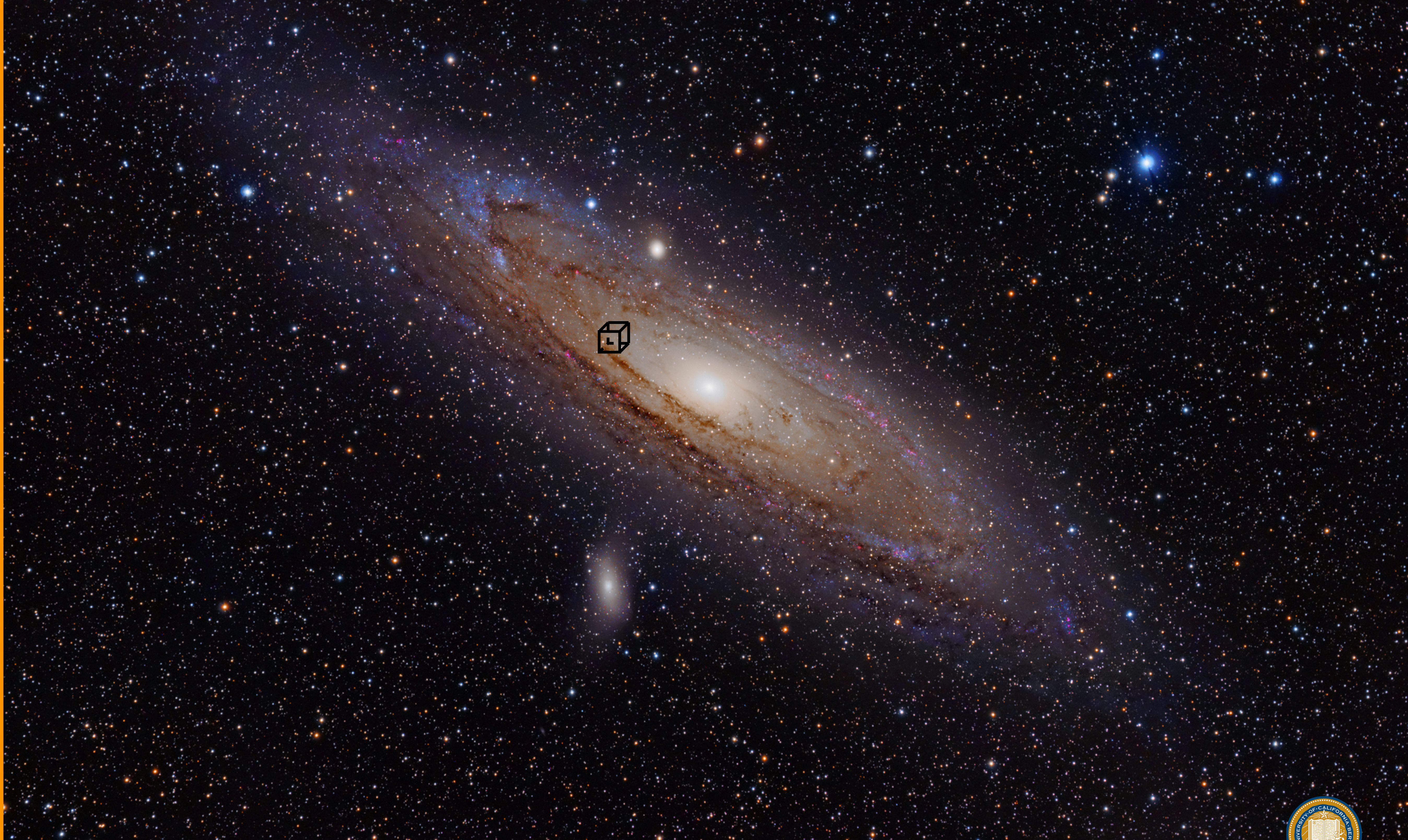


+ many more existing and upcoming instruments

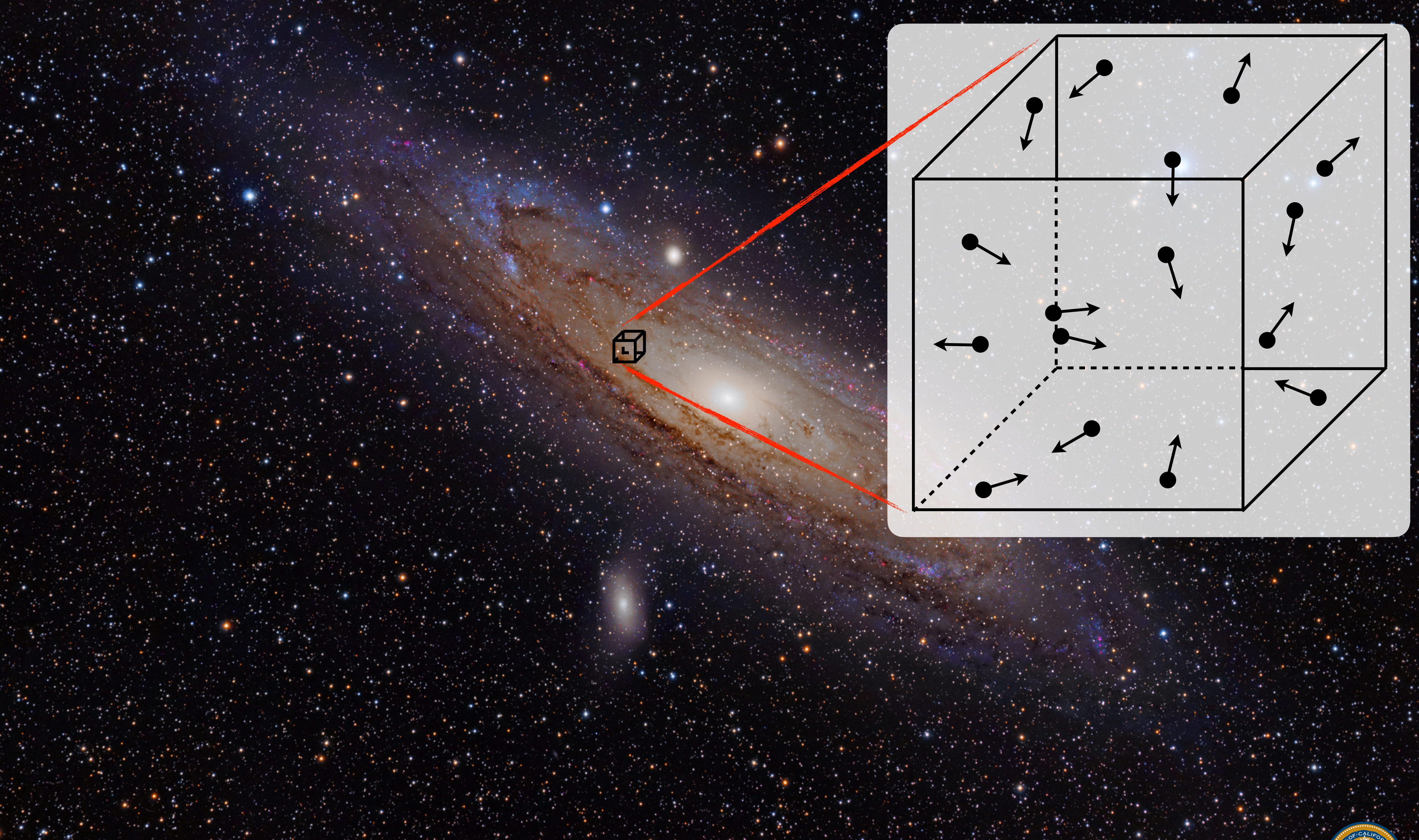
The search for Heavy Dark Matter is a multi-messenger problem, see e.g.
[Ishiwata+ JCAP 2020]
[Cohen, NLR+ PRL 2017]

Heavy Dark Matter

Heavy Dark Matter



Heavy Dark Matter



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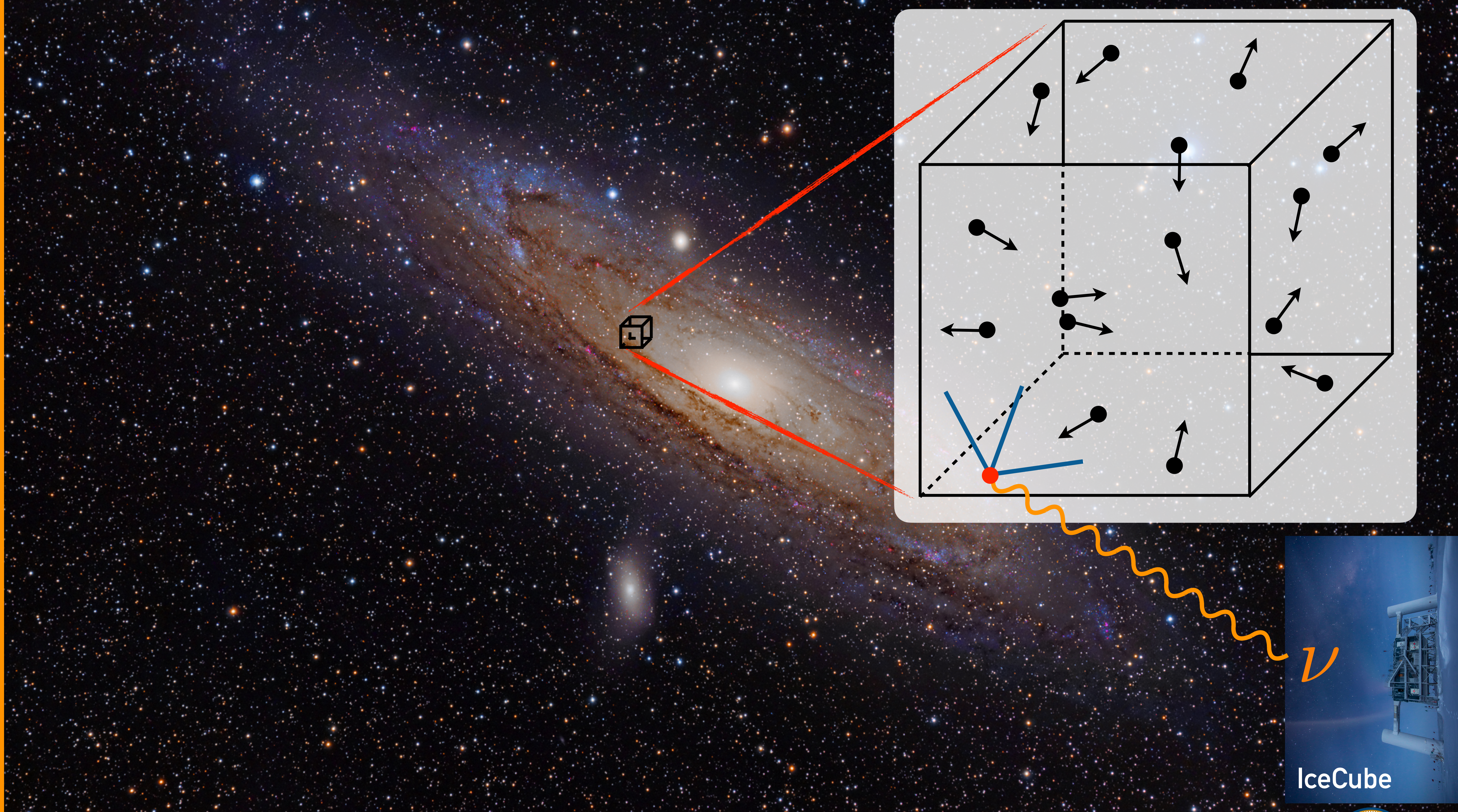

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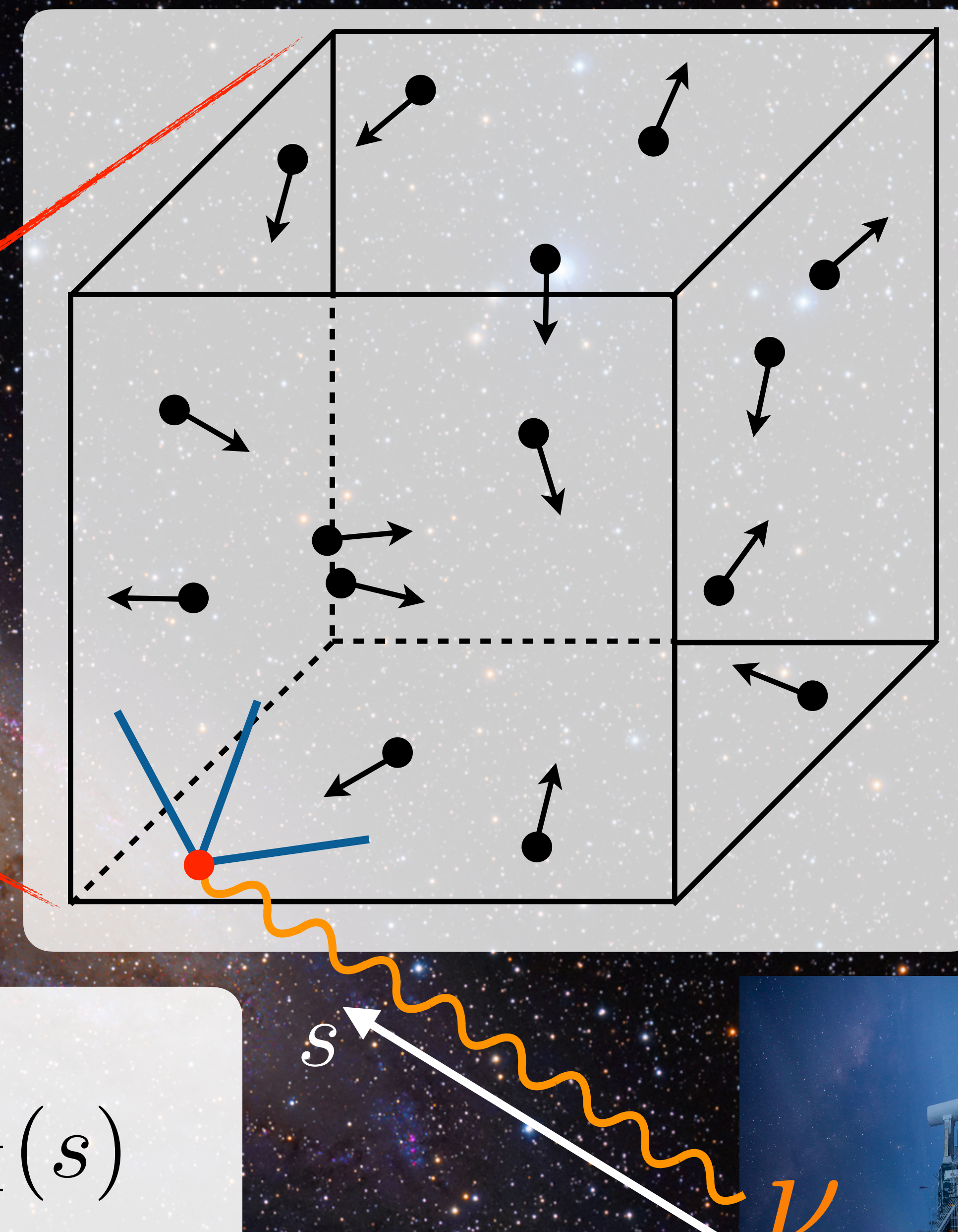
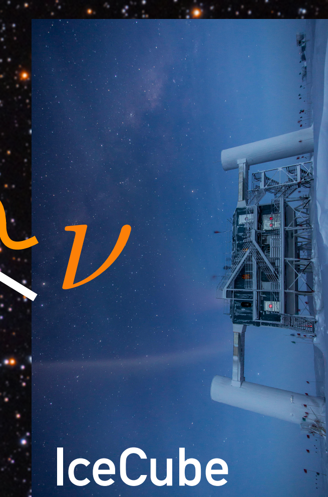




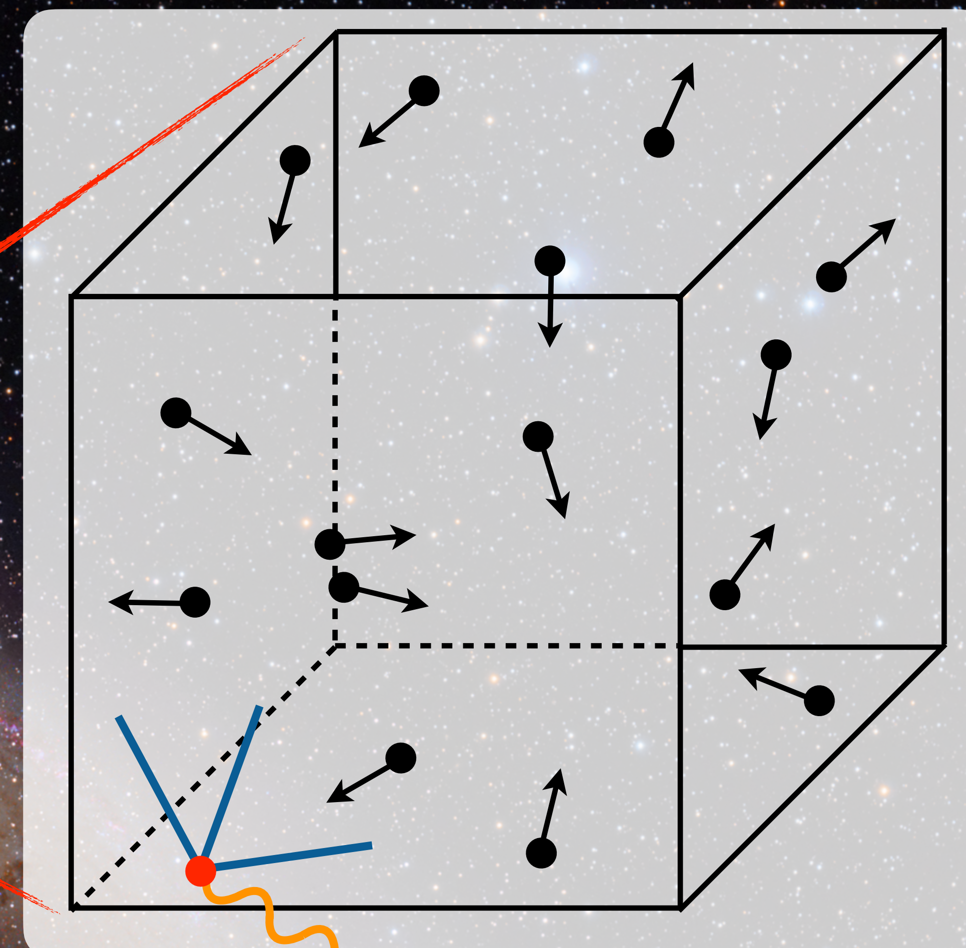
The Indirect Detection Flux

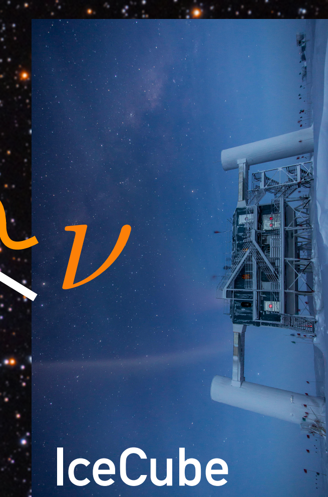
$$\Phi = \frac{1}{4\pi \, m_\chi \tau} \int dE \, \frac{dN}{dE} \times \int ds \, \rho_{\rm DM}(s)$$

The Dark Matter flux in $[\nu/\text{cm}^2/\text{s}/\text{sr}]$

For details, see [Lisanti, NLR+ PRD 2018]

Heavy Dark Matter



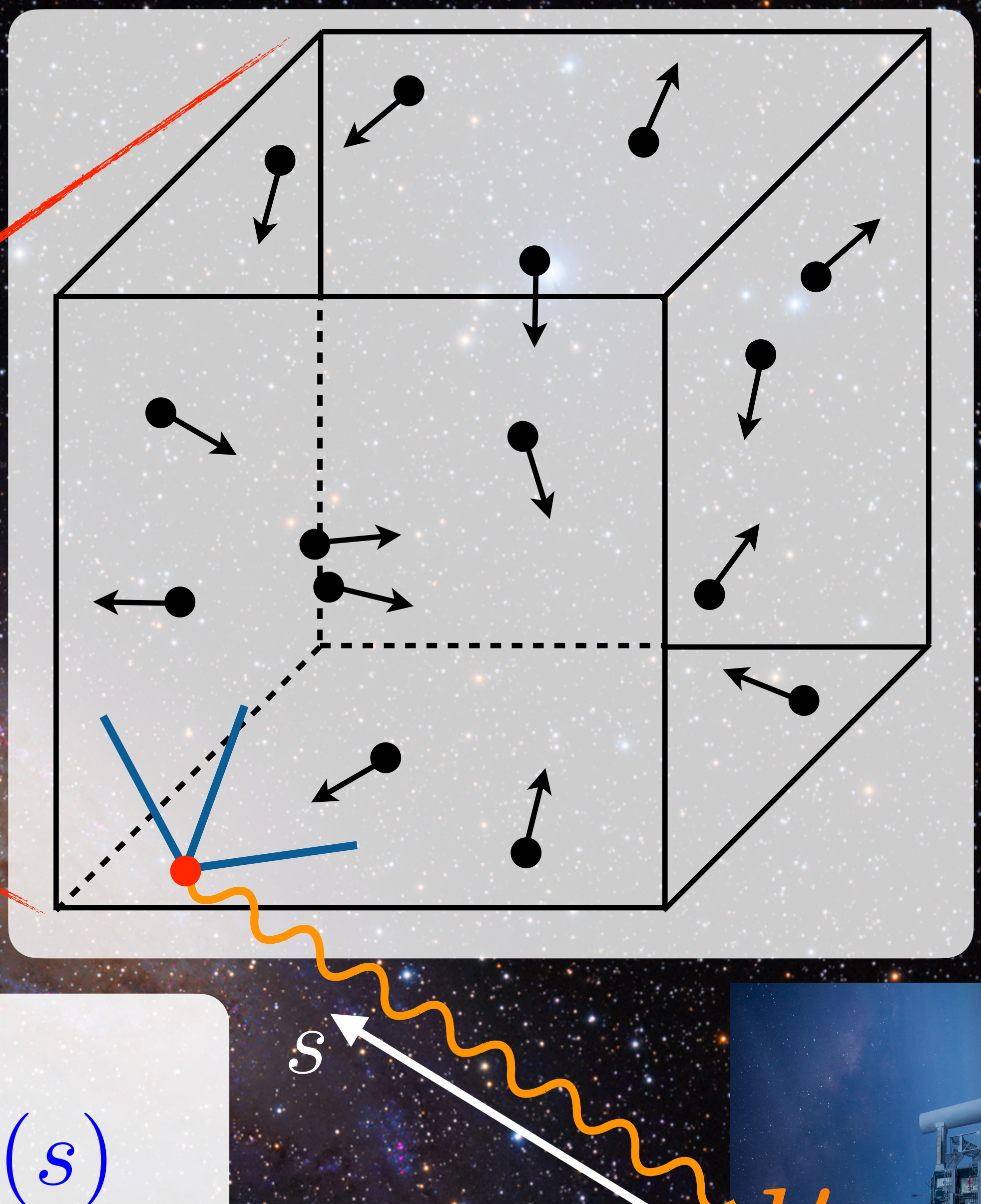


The Indirect Detection Flux

$$\Phi = \underbrace{\frac{1}{4\pi\, m_\chi \tau} \int dE\, \frac{dN}{dE}}_{\text{Particle Physics}} \times \underbrace{\int ds\, \rho_{\mathrm{DM}}(s)}_{\text{Astrophysics}}$$

For details, see [Lisanti, NLR+ PRD 2018]

Heavy Dark Matter



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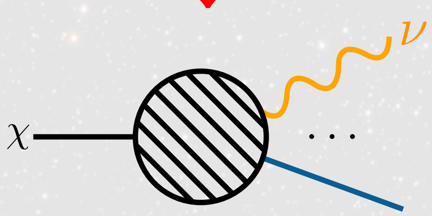
We will revisit!



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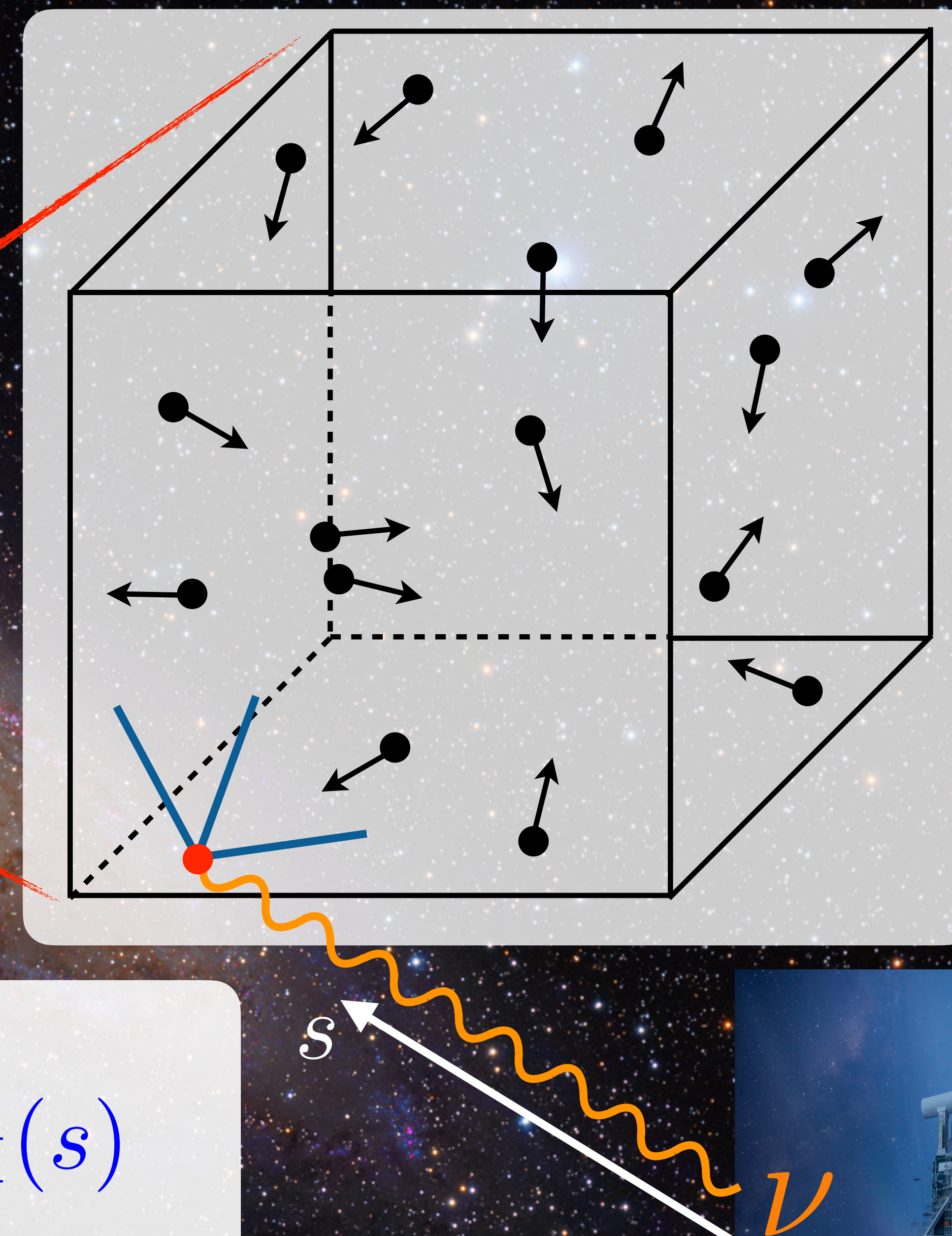

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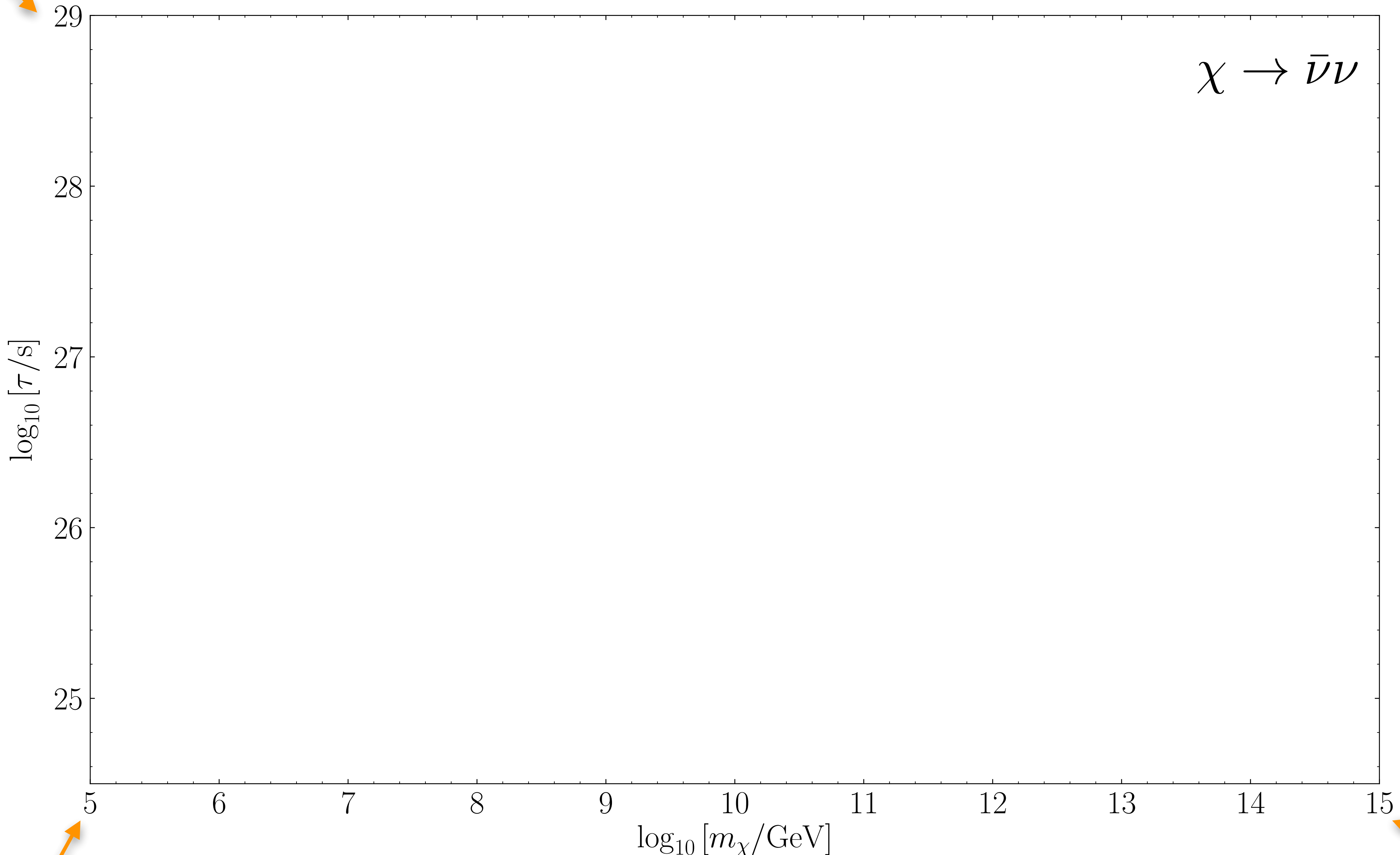
We will revisit!

For details, see [Lisanti, NLR+ PRD 2018]

Landscape

$\gg t_U$ ~ limit on $\chi \rightarrow$ relativistic [DES 2020]

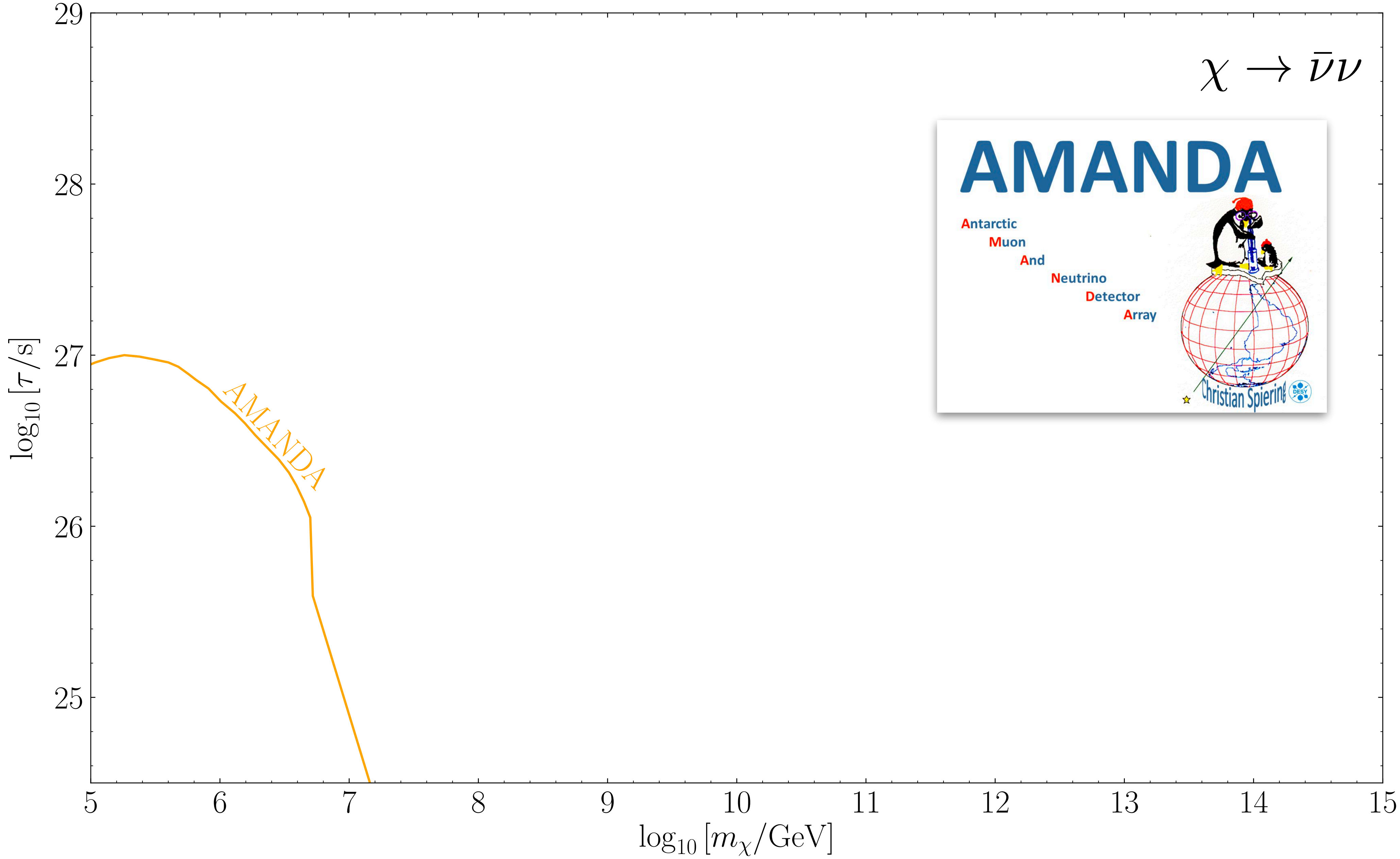


~GUT Scale

~Unitarity Limit [Griest, Kamionkowski PRL 1990]

Limits reproduced from [Esmaili, Ibarra, Peres JCAP 2012]

Landscape



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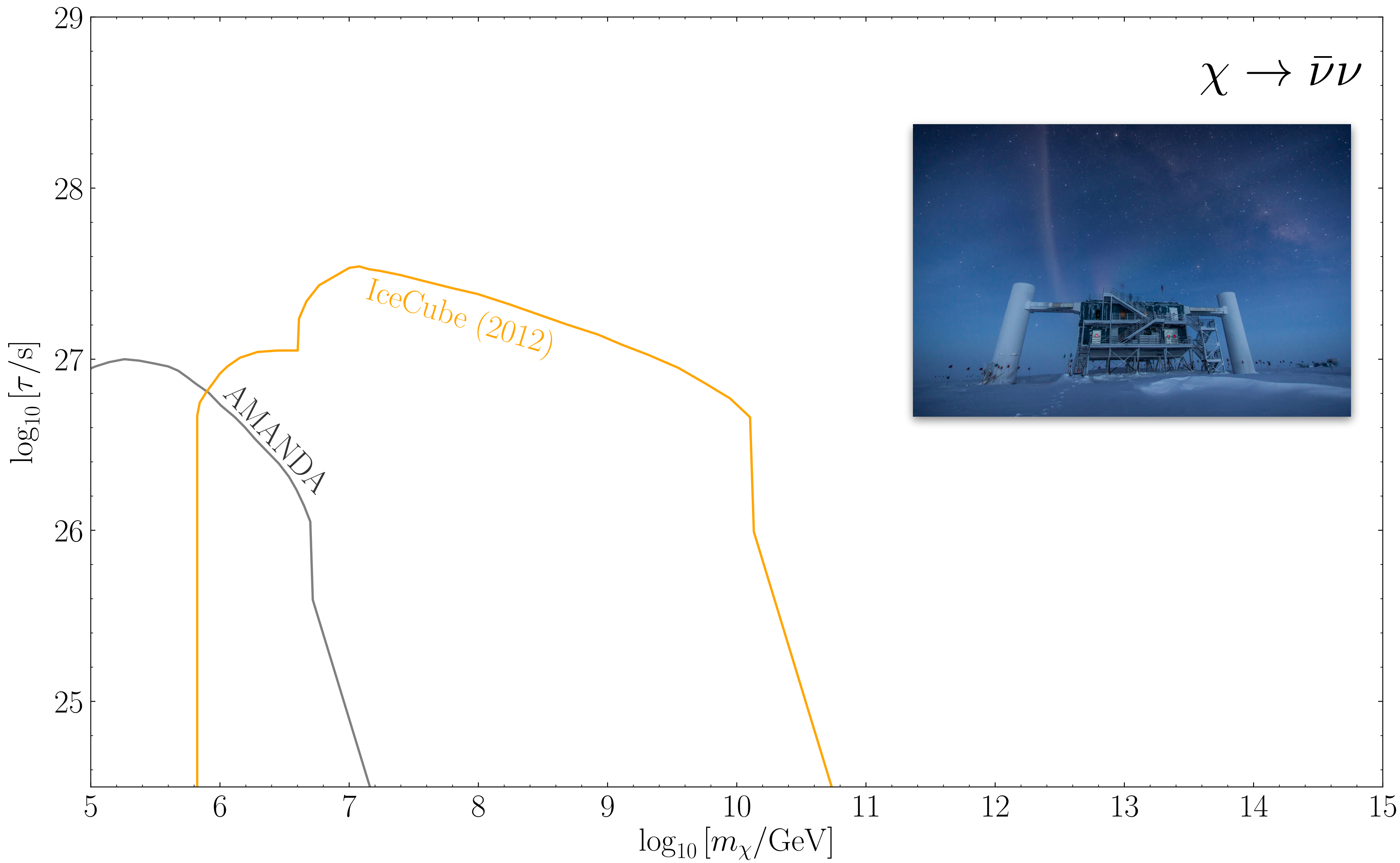

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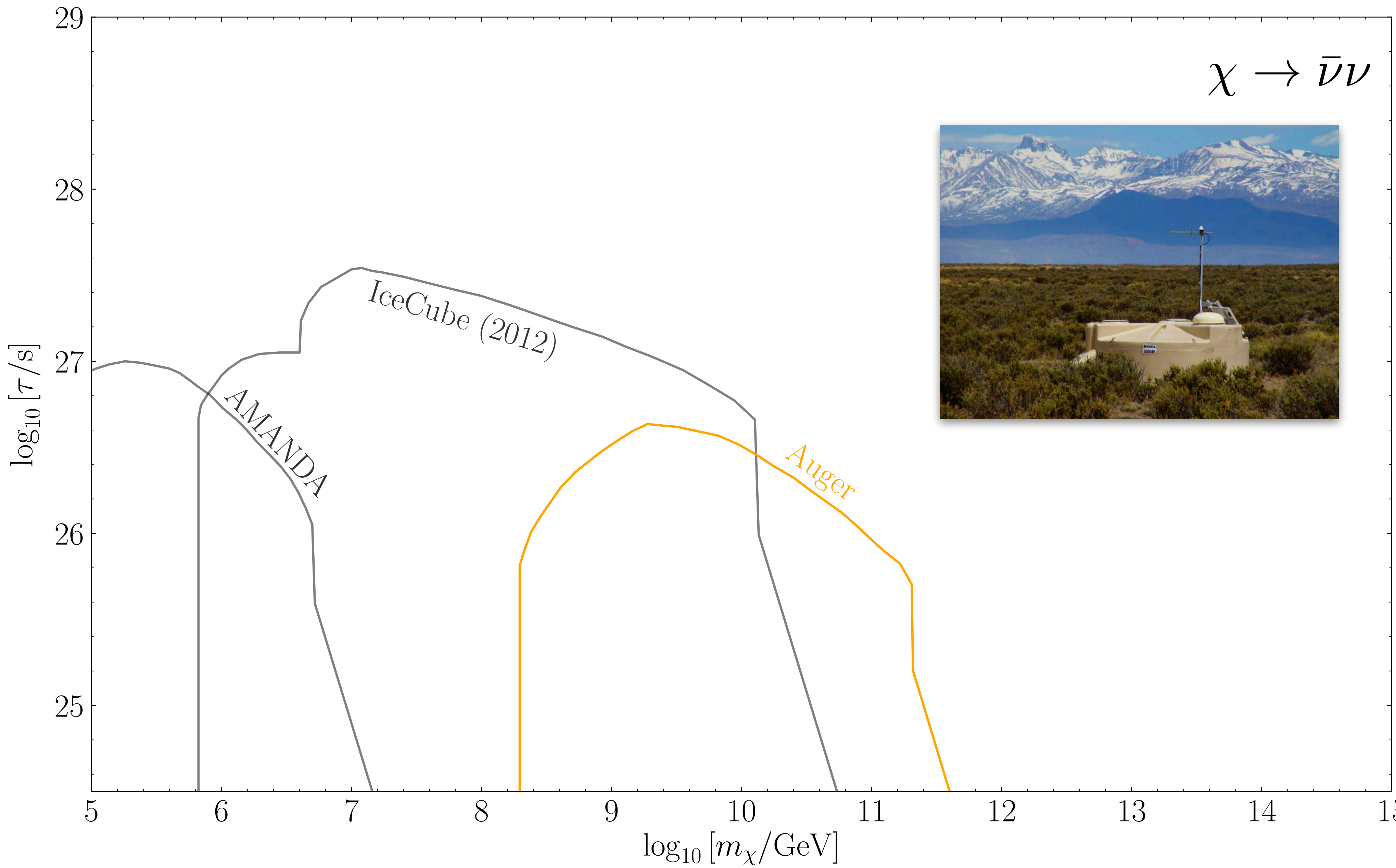

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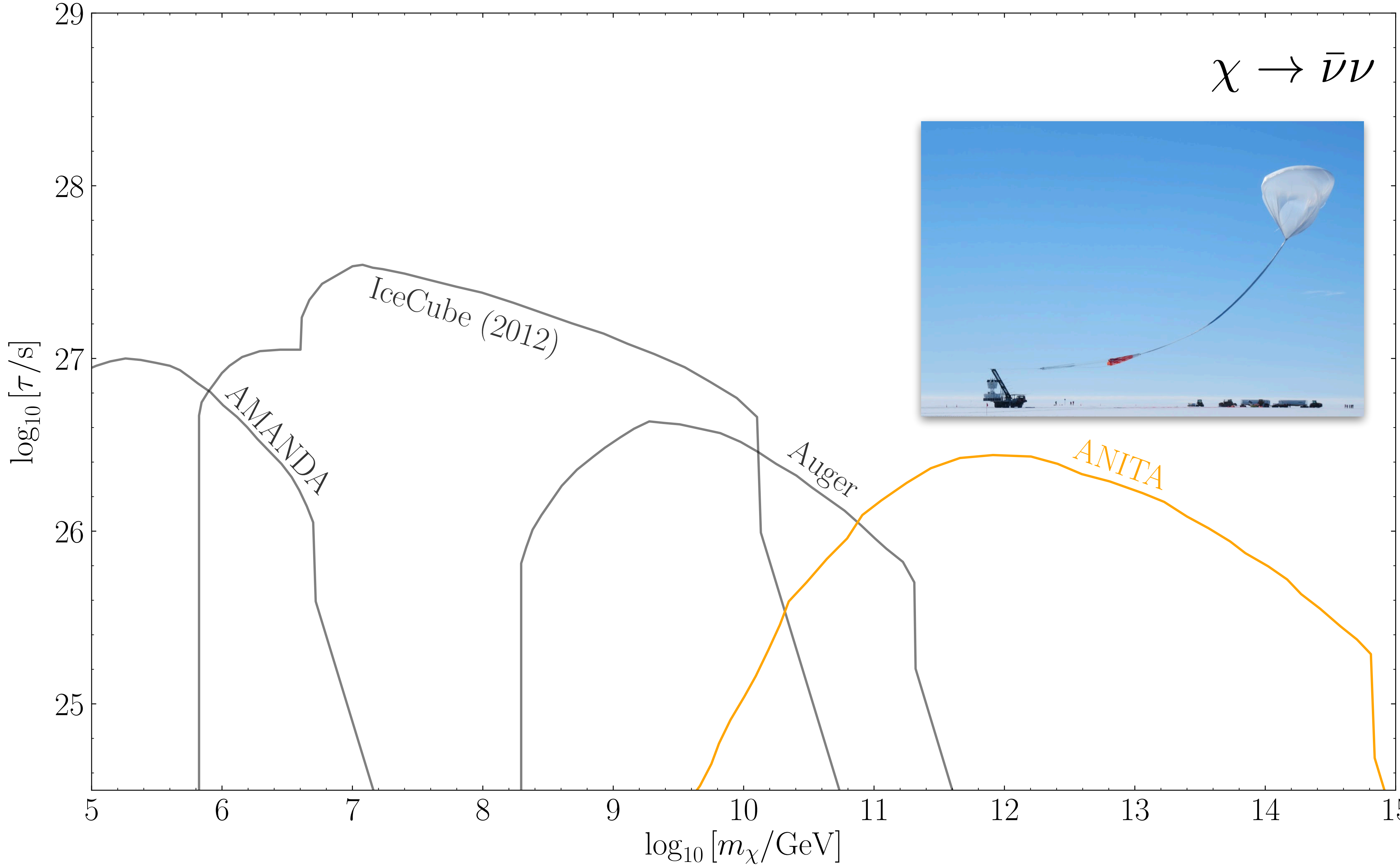

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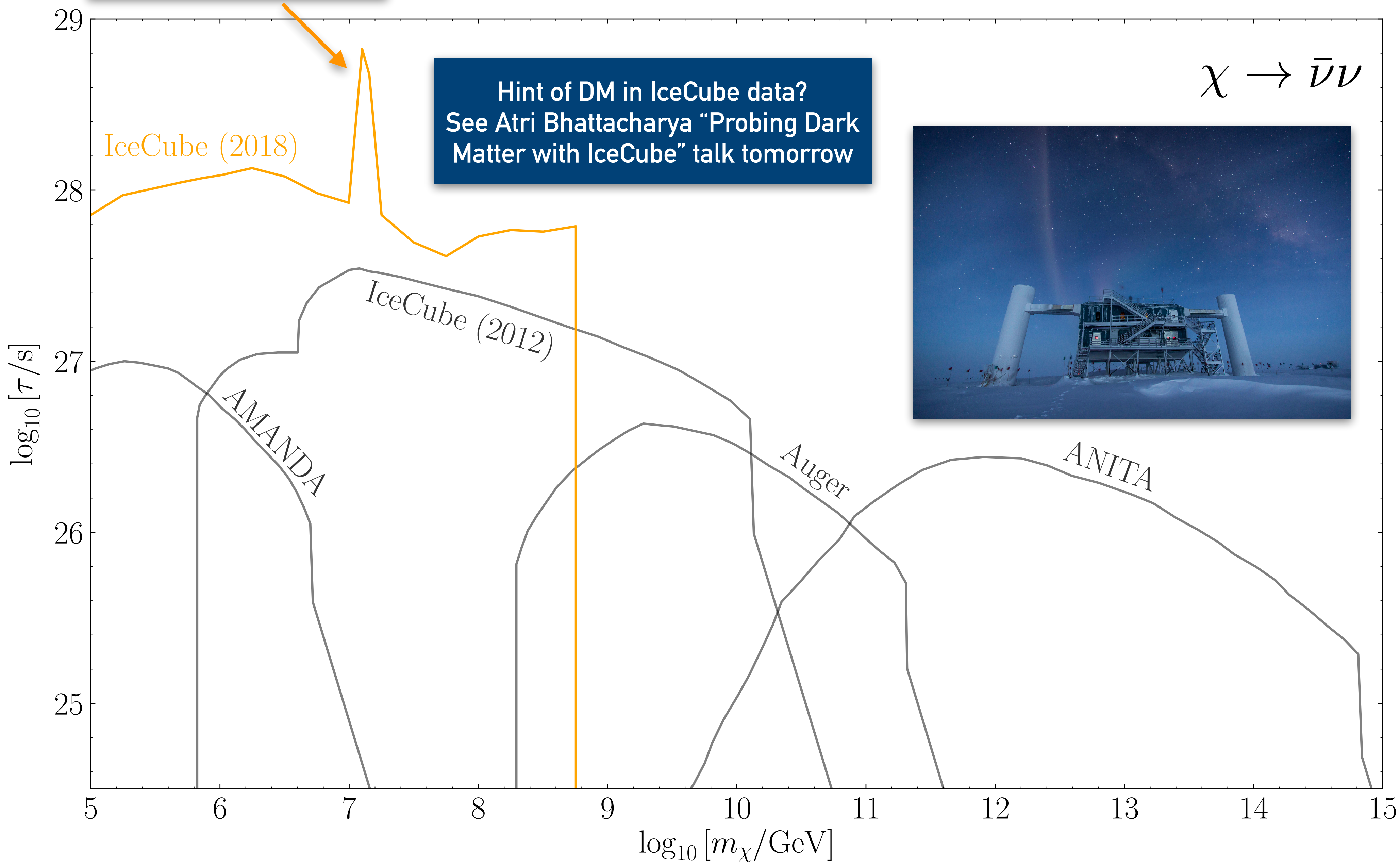
Landscape

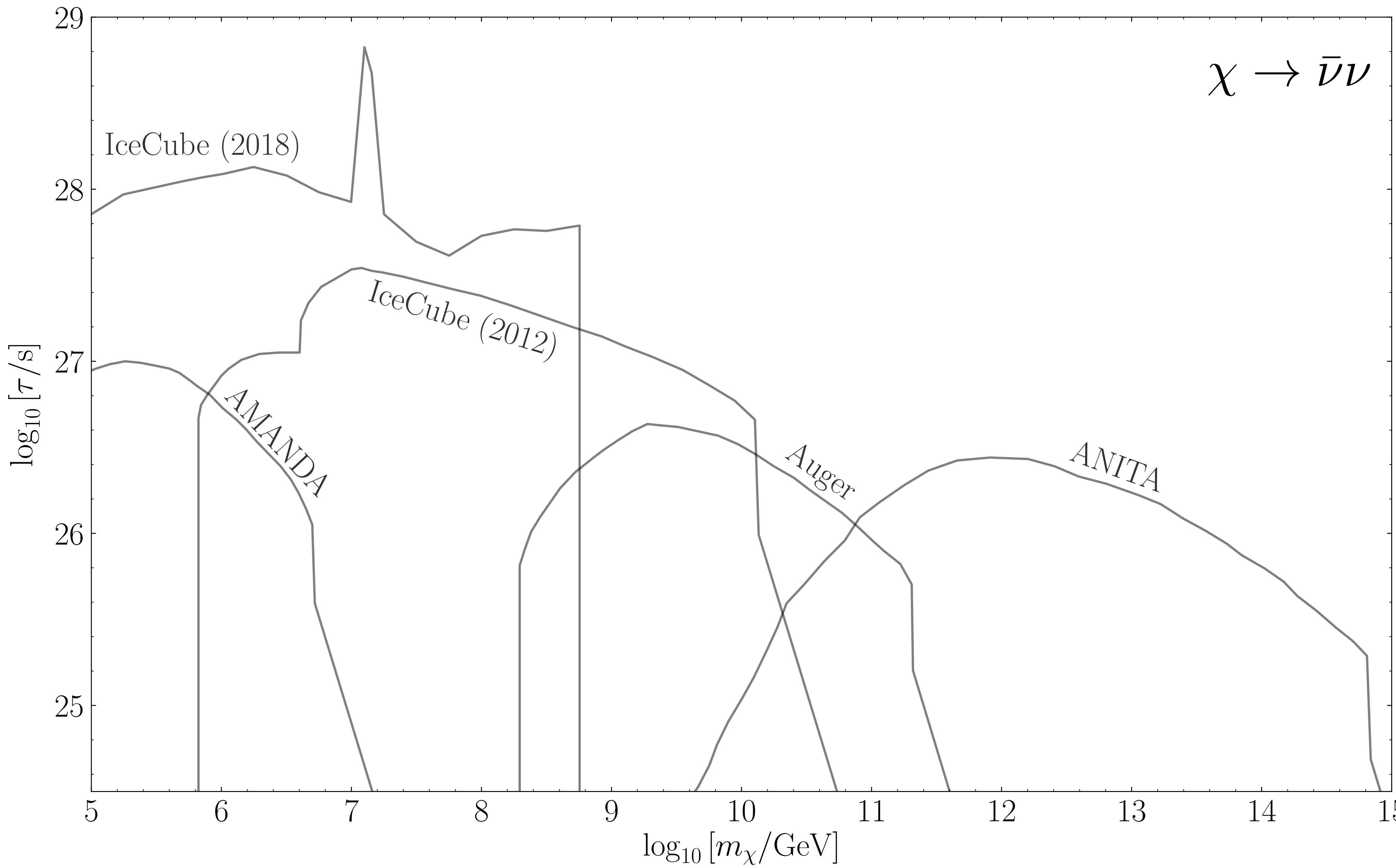
Enhanced sensitivity due to Glashow resonance



Hint of DM in IceCube data? See Atri Bhattacharya "Probing Dark Matter with IceCube" talk tomorrow

Limits reproduced from [Esmaili, Ibarra, Peres JCAP 2012] & [IceCube EPJC 2018]

Landscape



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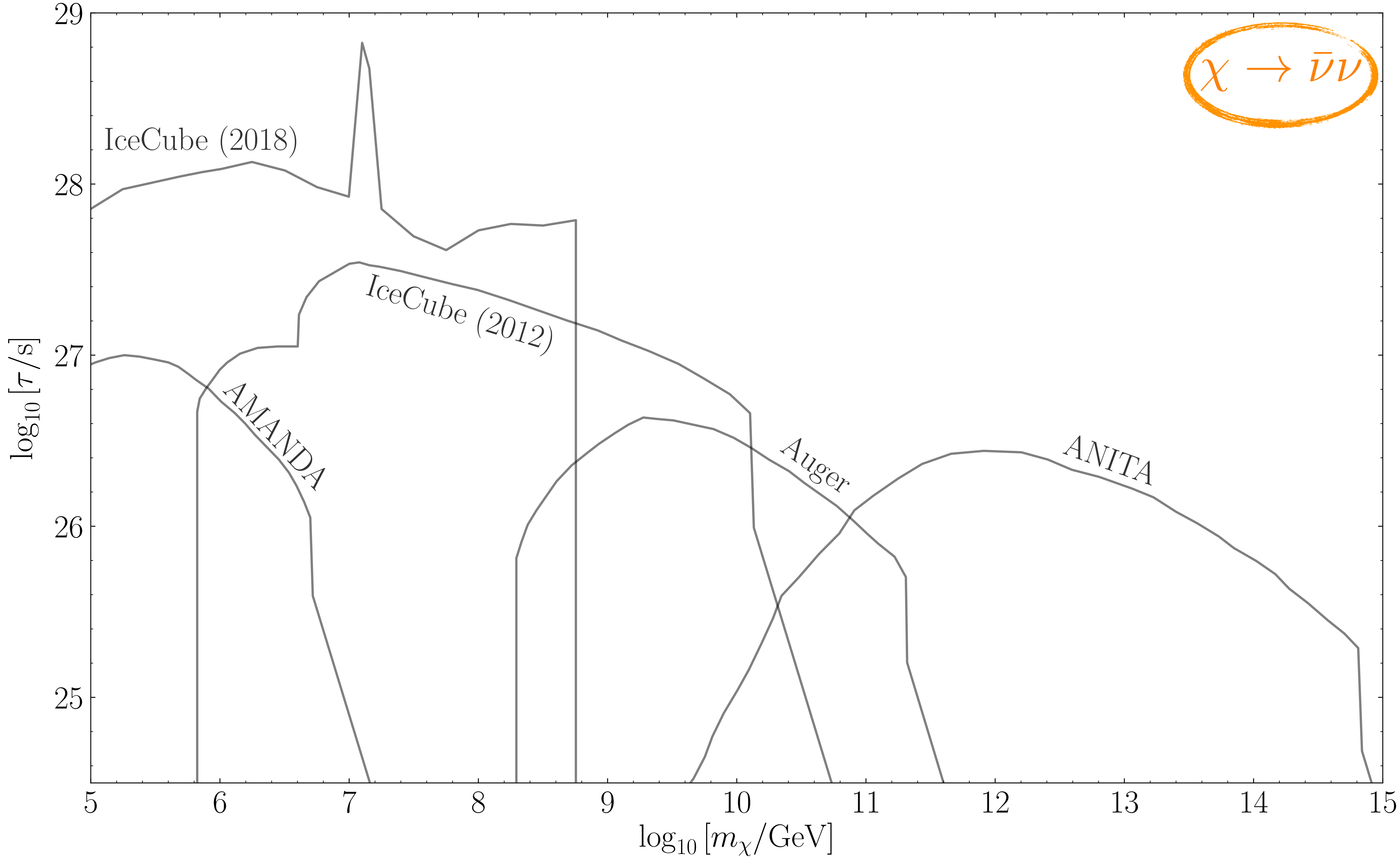

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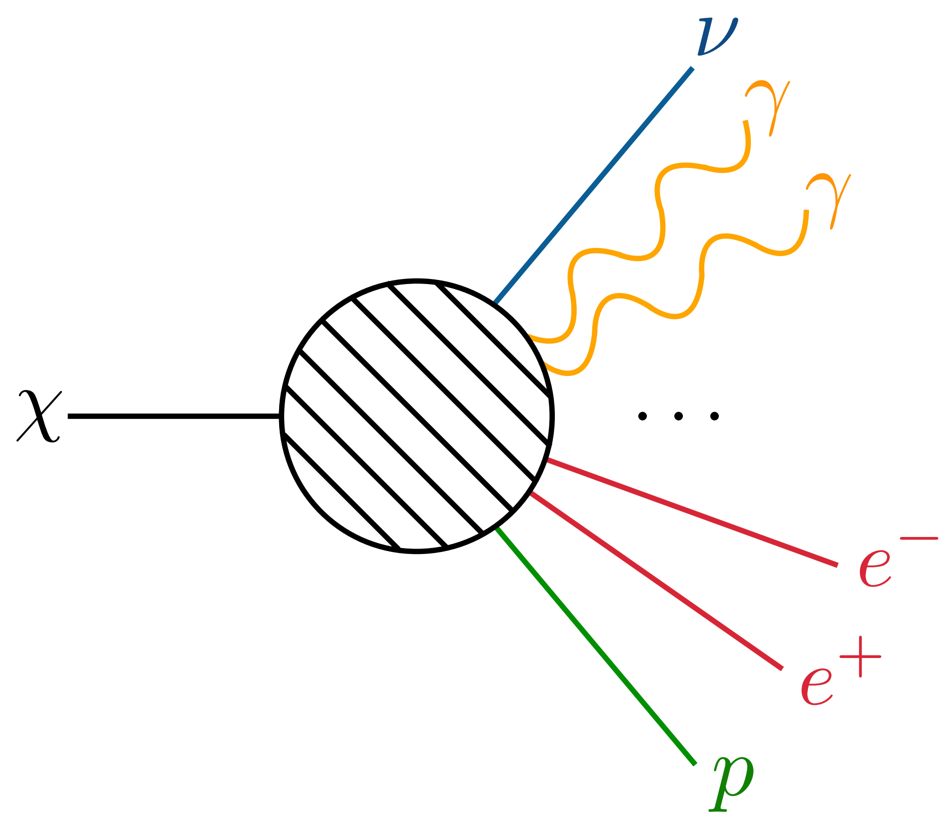
The Calculation

Indirect Detection Flux

$$\Phi = \frac{1}{4\pi m_\chi \tau} \int dE \, \frac{dN}{dE} \times D$$

Dark Matter flux the experiments can detect

Distribution of the signal flux over the sky



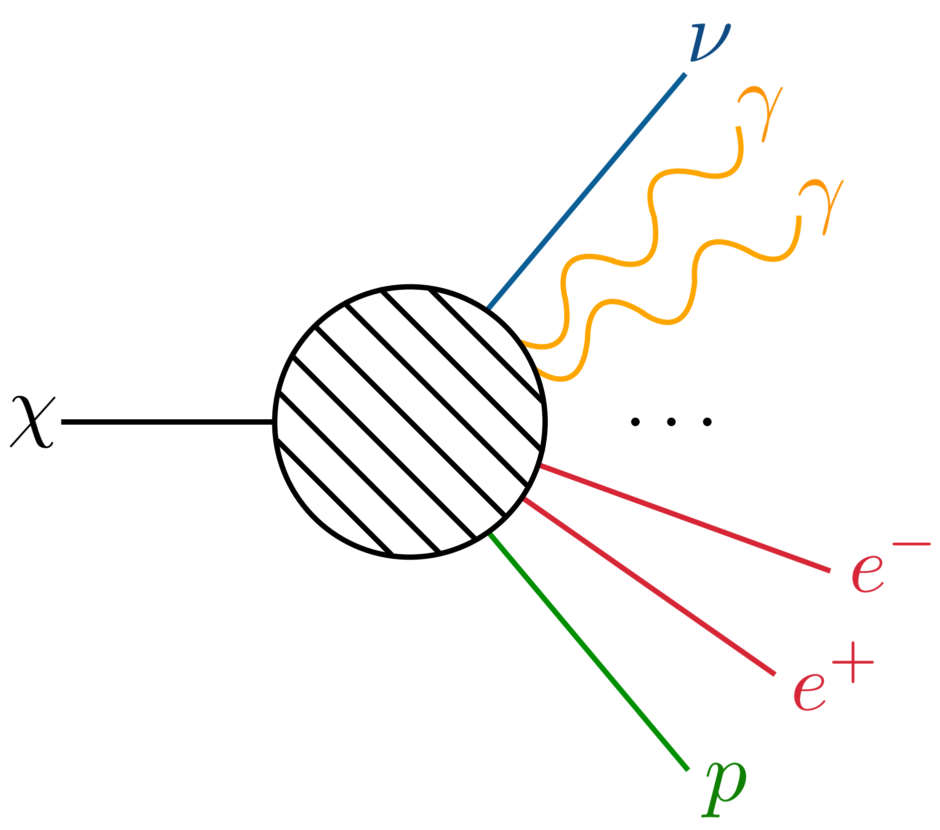
[Bauer, NLR, Webber 2020]

The Calculation

Indirect Detection Spectrum

$$\frac{dN}{dE} = \frac{1}{\Gamma_0}\frac{d\Gamma}{dE}(\chi \to S + \ldots)$$

$$= \nu,\ \gamma,\ e^{\pm},\ p,\ \bar{p},\ {}^{3}\overline{\mathrm{He}},\ \ldots$$



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The Calculation

Indirect Detection Spectrum

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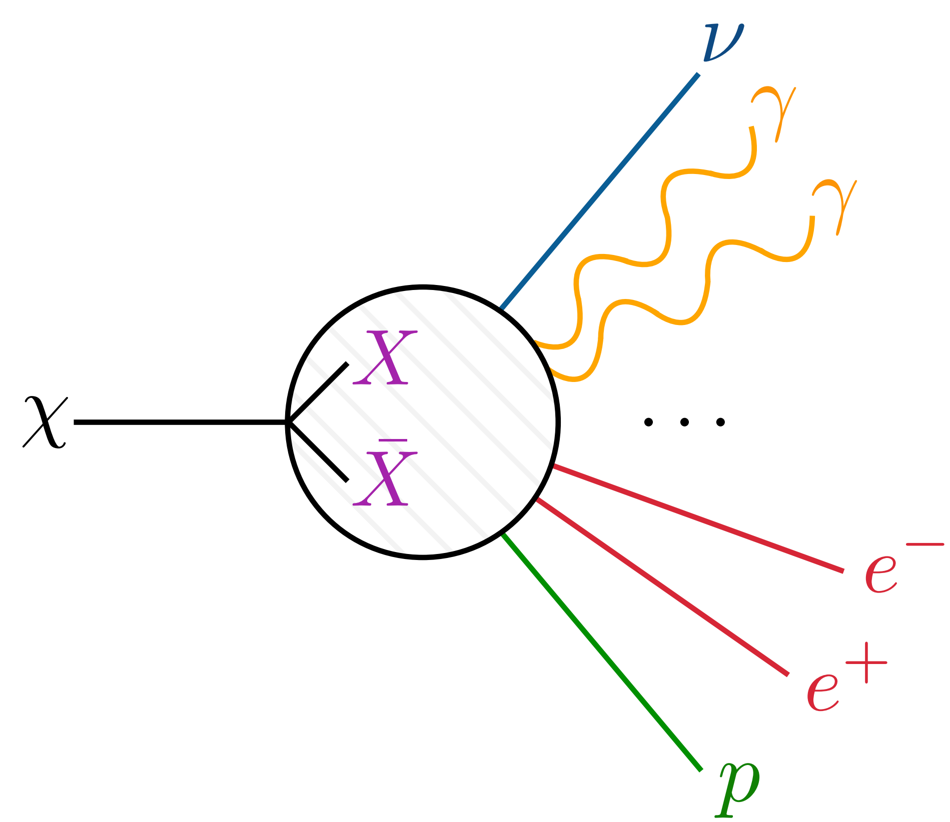

[Bauer, NLR, Webber 2020]

The Calculation

Approach before our work

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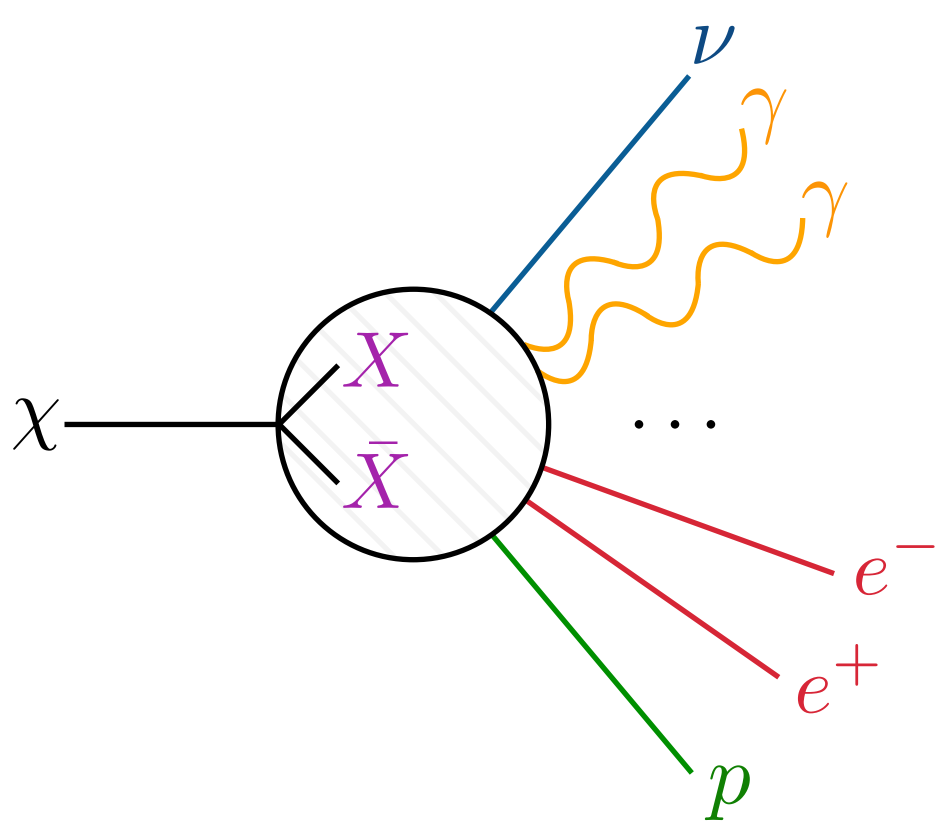

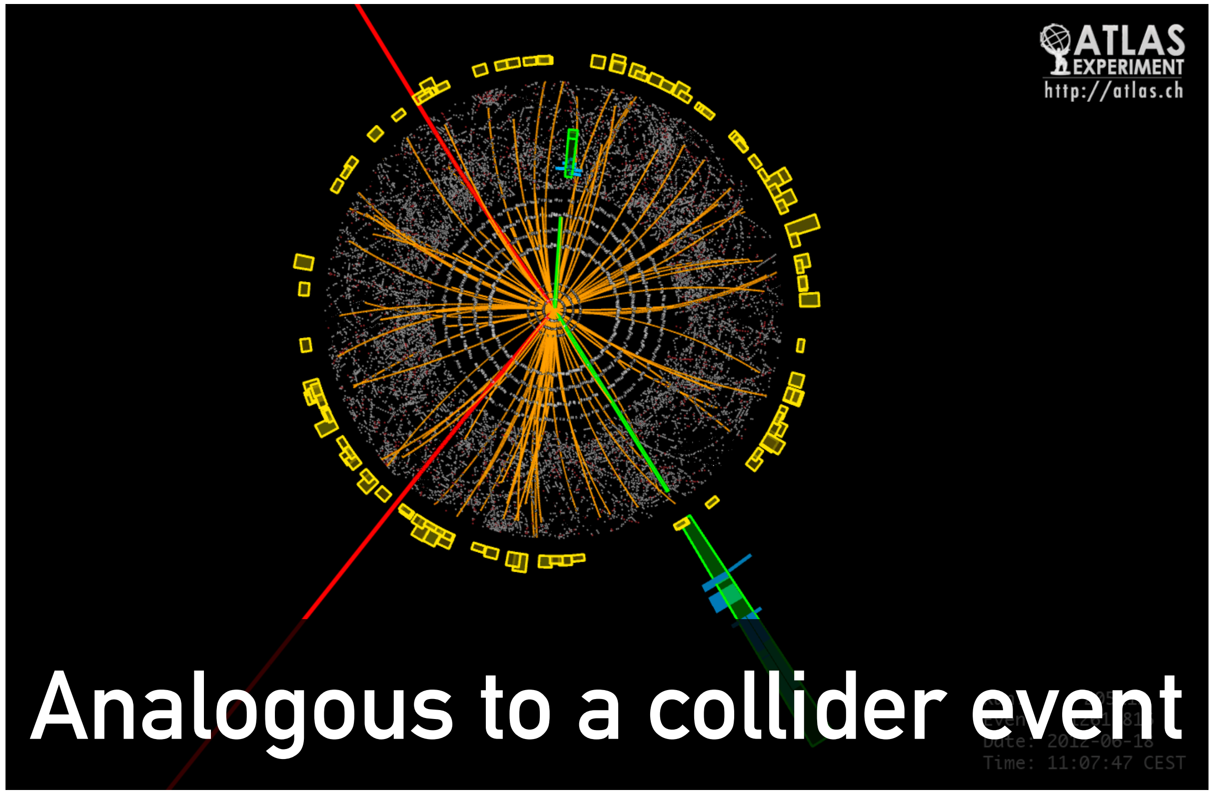

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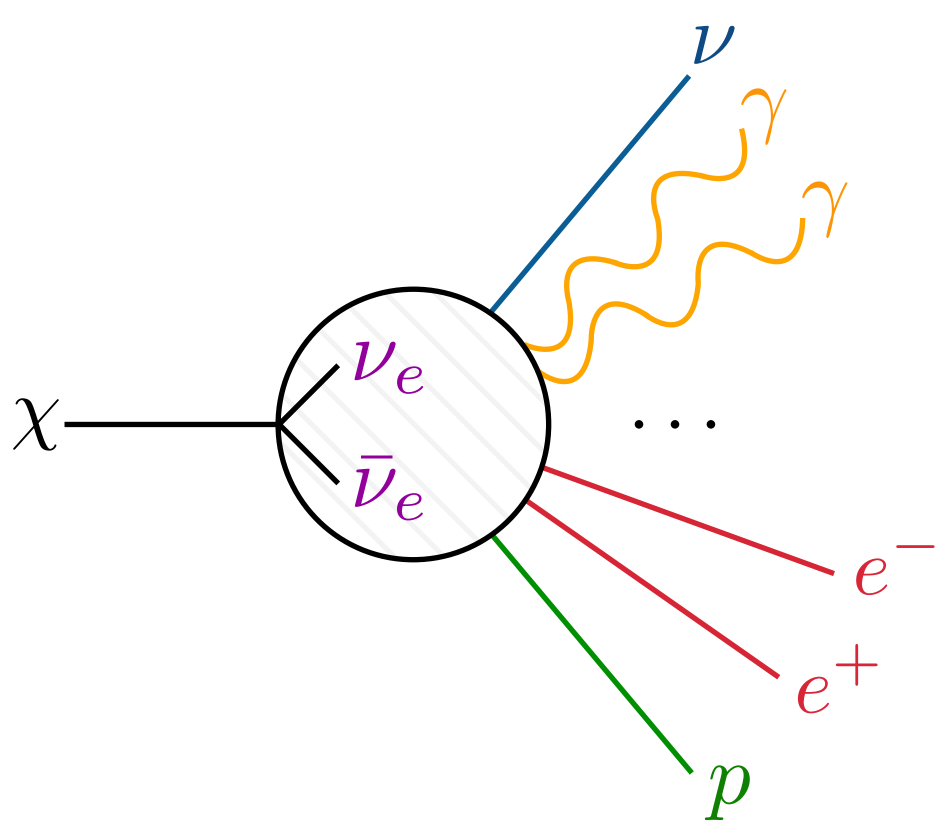

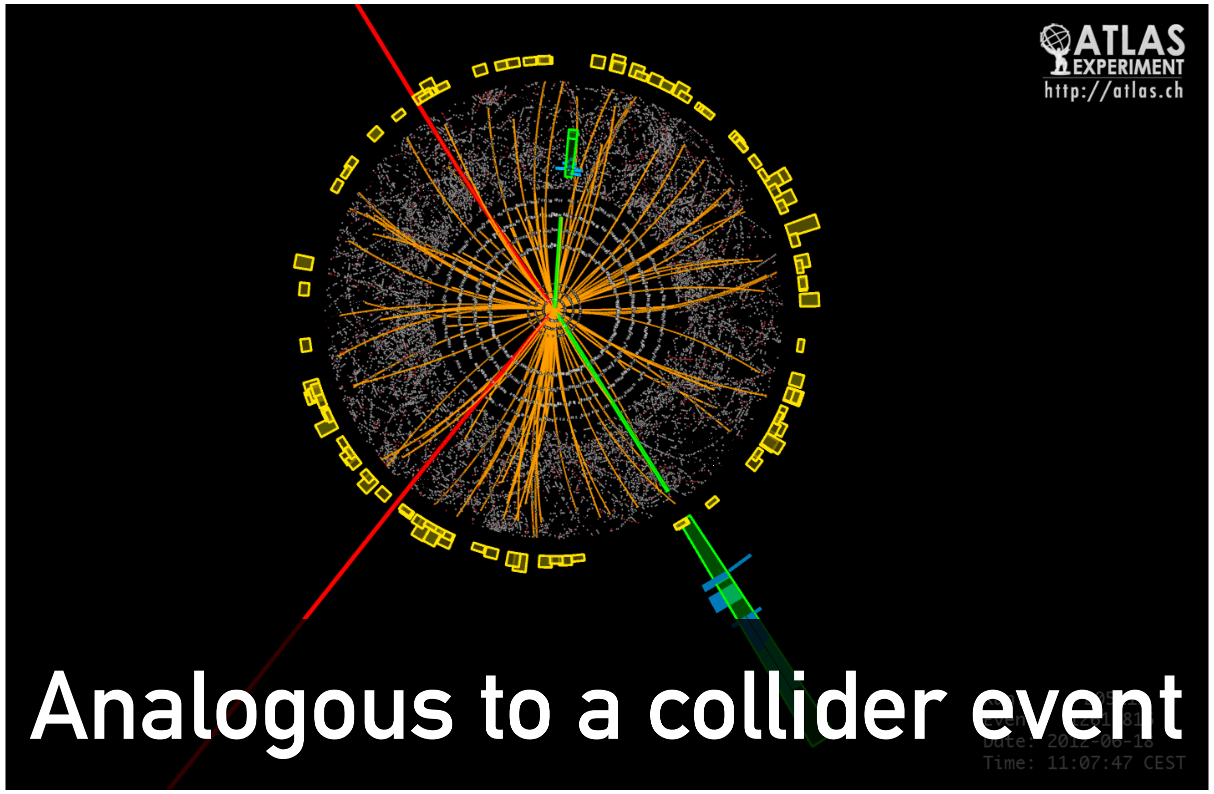

For explicit model, see e.g. [Berghaus+ JHEP 2019], [Dudas+ PRD 2020]

[Bauer, NLR, Webber 2020]

The Calculation

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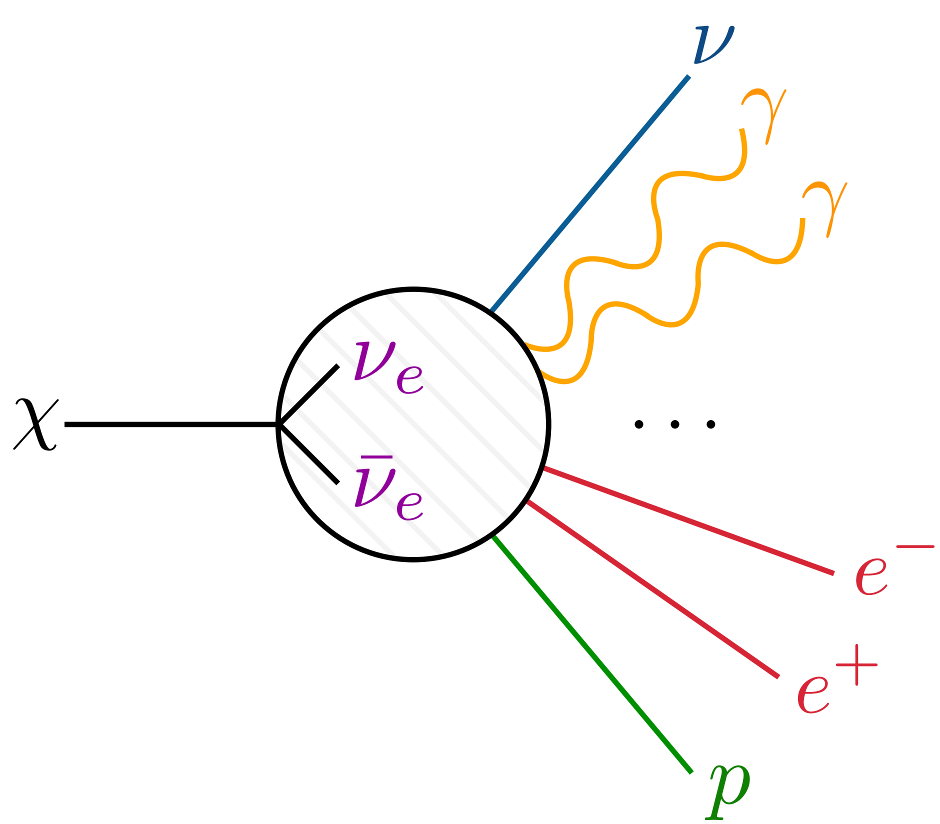

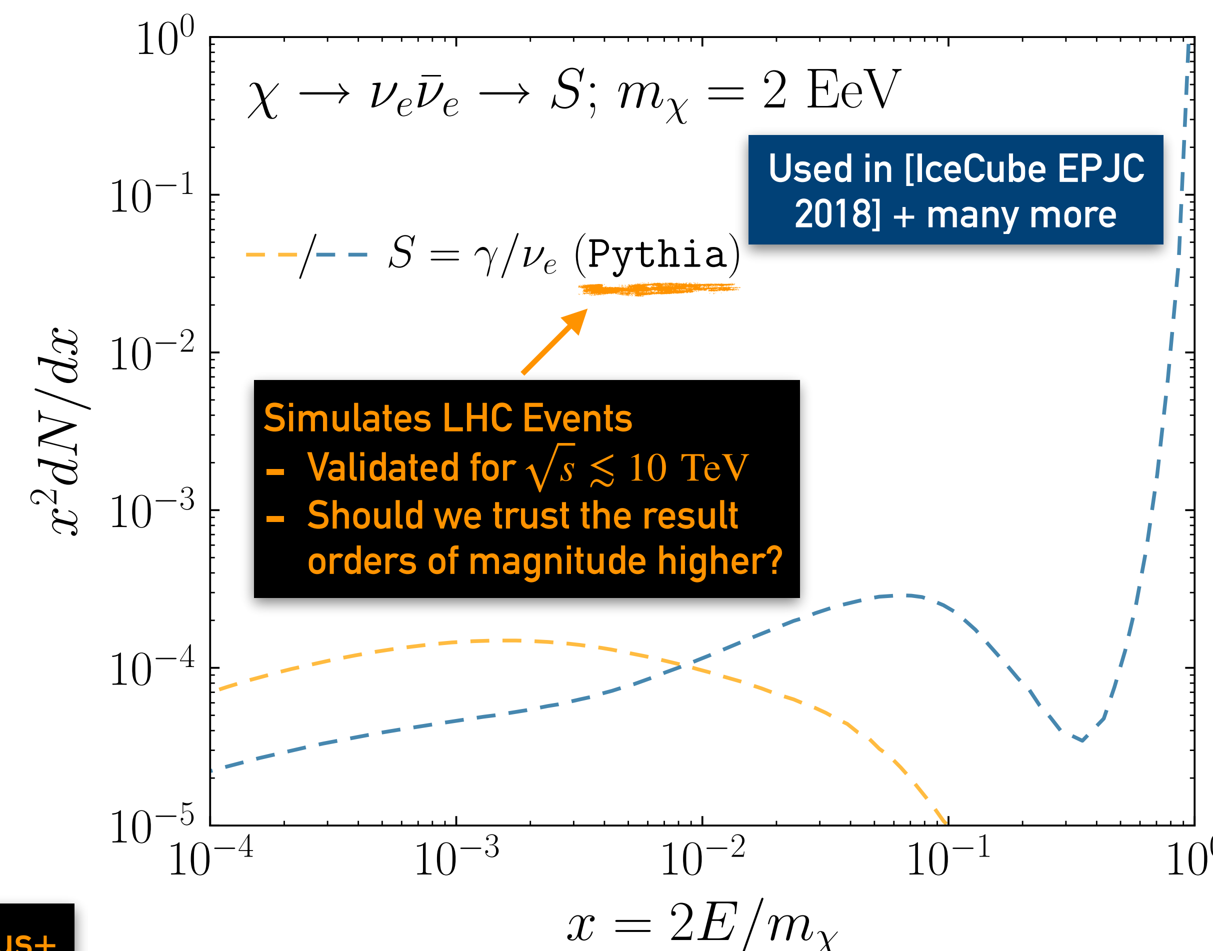

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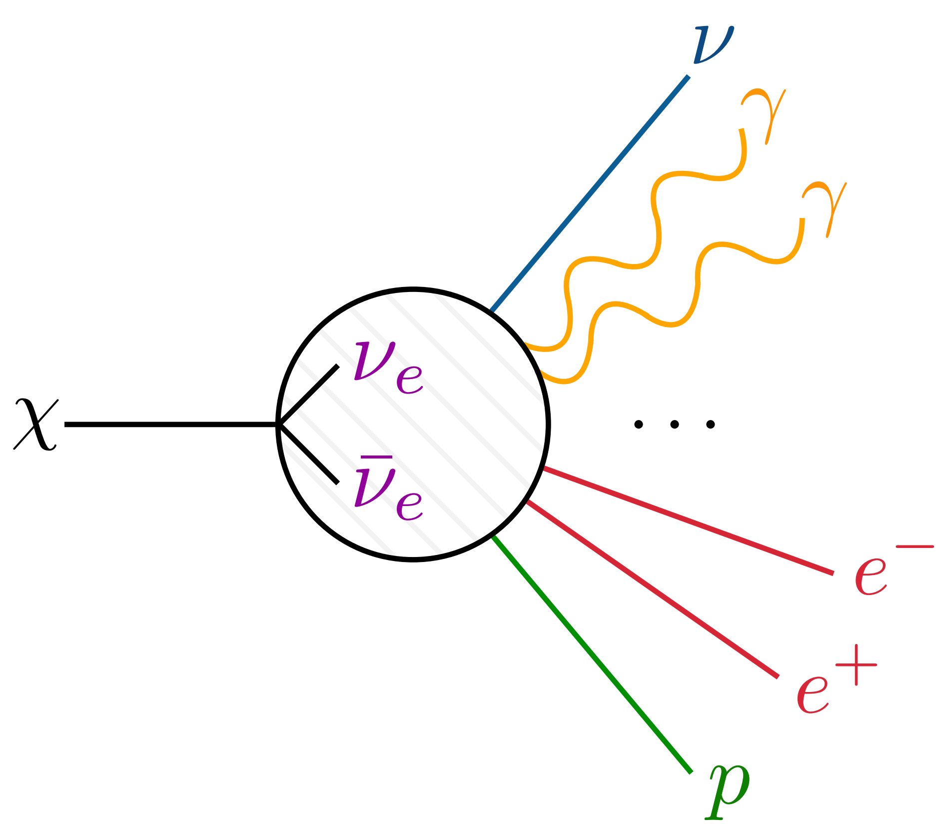
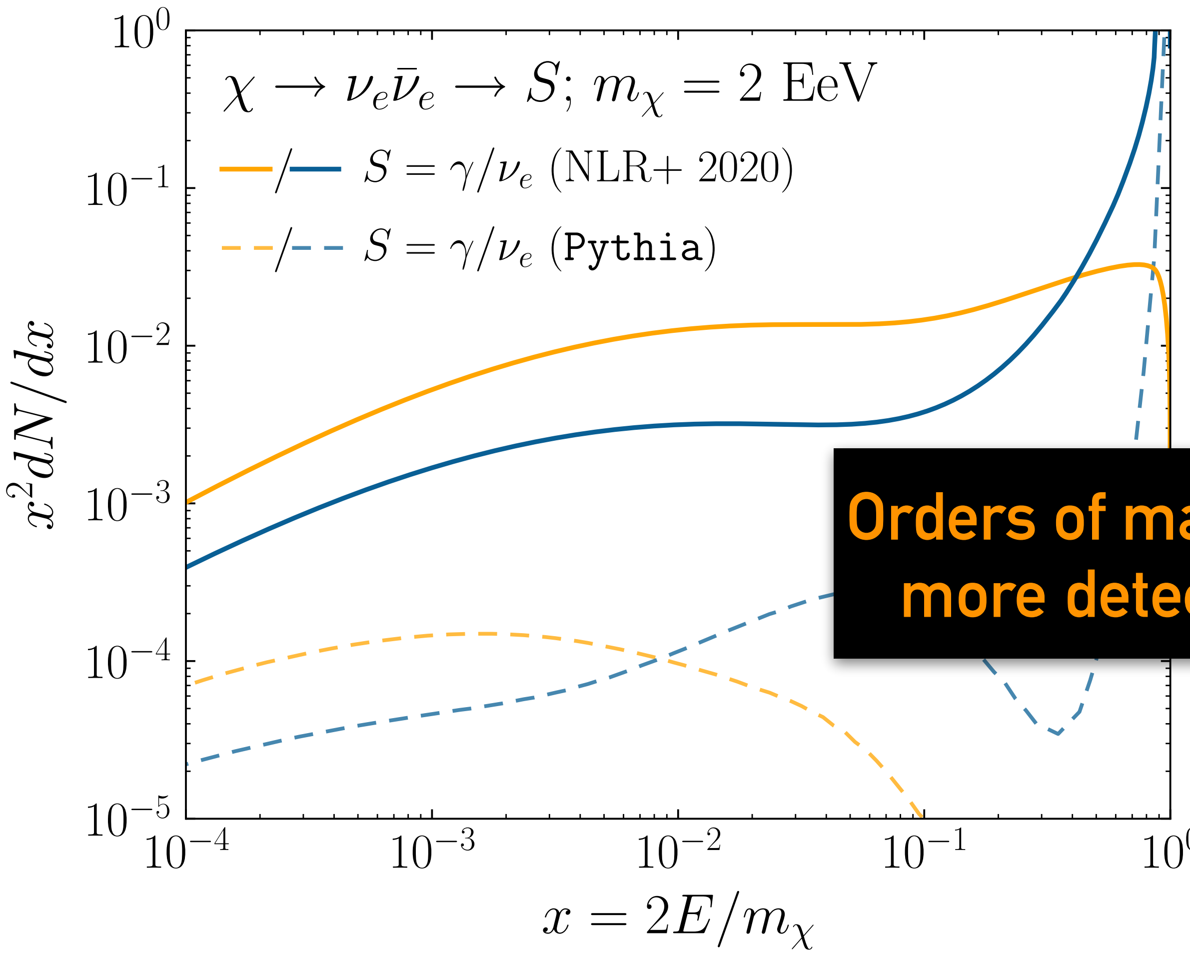
Approach before our work

$$\frac{dN}{dE} = \frac{1}{\Gamma_0}\frac{d\Gamma}{dE}(\chi \to \nu_e \bar{\nu}_e \to S + \ldots)$$





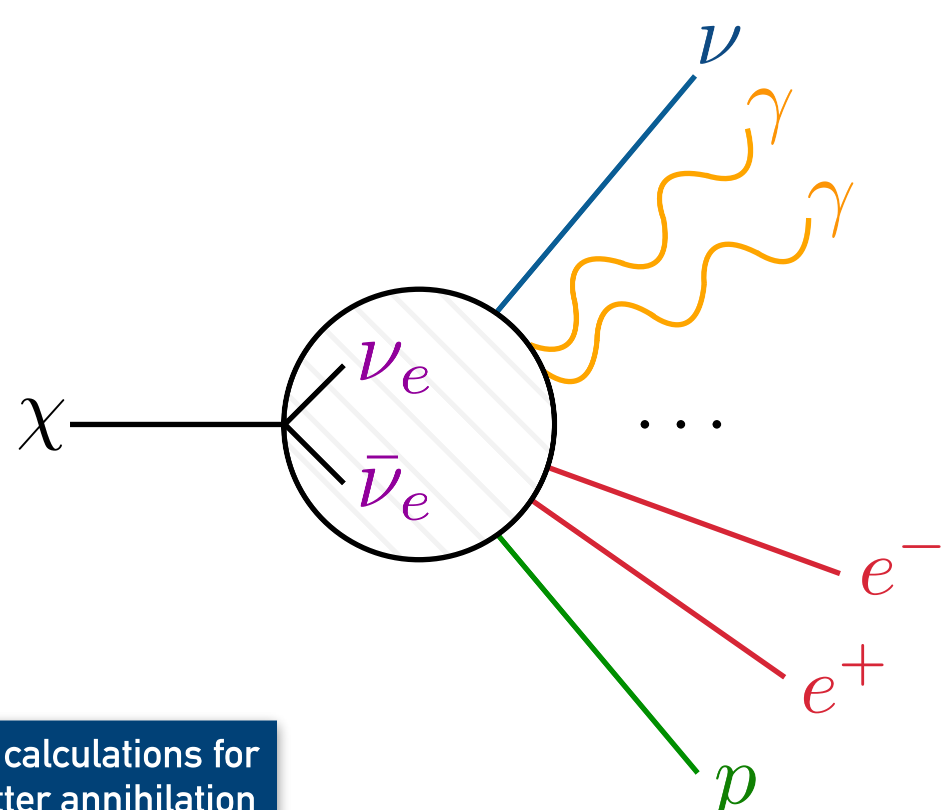
Orders of magnitude more detectable!

[Bauer, NLR, Webber 2020]

The Calculation

A new formalism

$$\frac{dN}{dx}$$



Fragmentation Function: $d_j^i(x;\, \mu_{\rm UV}, \mu_{\rm IR})$

$$p\left({}^{j}\xrightarrow[E]{} \bullet \xrightarrow[xE]{} {}^{i} \right)$$

$\sim$ the probability $j \to i$ with energy fraction x as $\mu = \mu_{\rm UV} \to \mu_{\rm IR}$

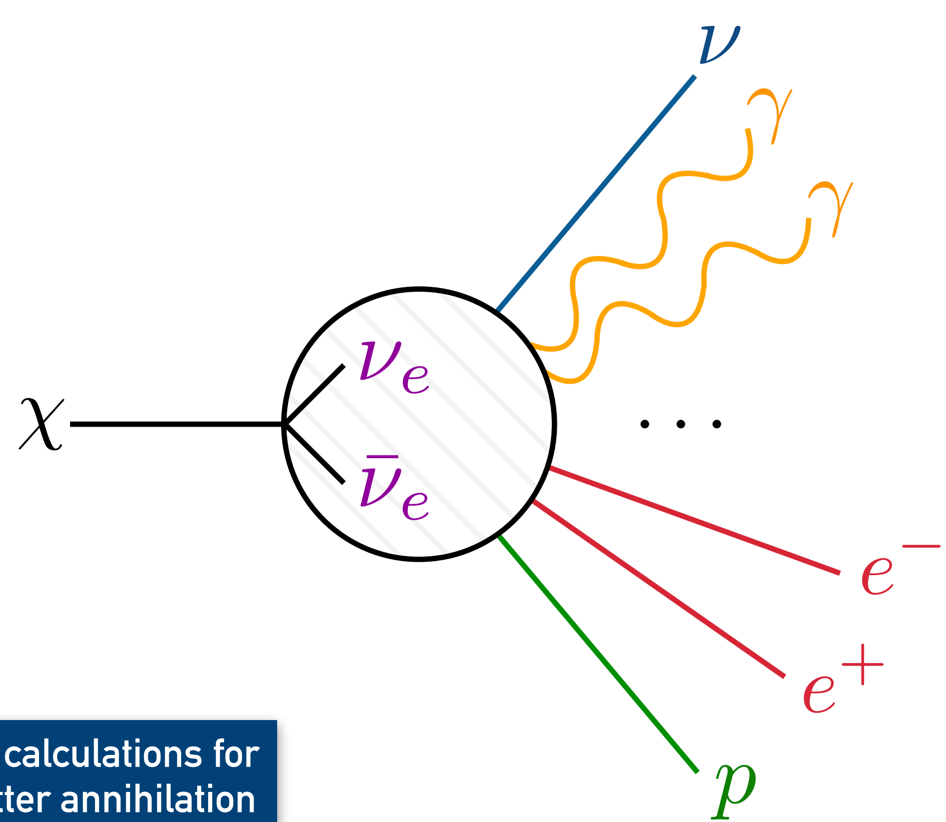
c.f. SCET calculations for dark matter annihilation [NLR+ JHEP 2019] [NLR+ JHEP 2018] [NLR+ PRD 2017]

[Bauer, NLR, Webber 2020]

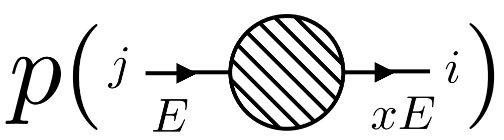
The Calculation

A new formalism

$$x\frac{dN}{dx} = d^S_{\nu_e}(x;\, m_\chi, 0) + d^S_{\bar{\nu}_e}(x;\, m_\chi, 0)$$



Fragmentation Function: $d^i_j(x;\, \mu_{\rm UV}, \mu_{\rm IR})$



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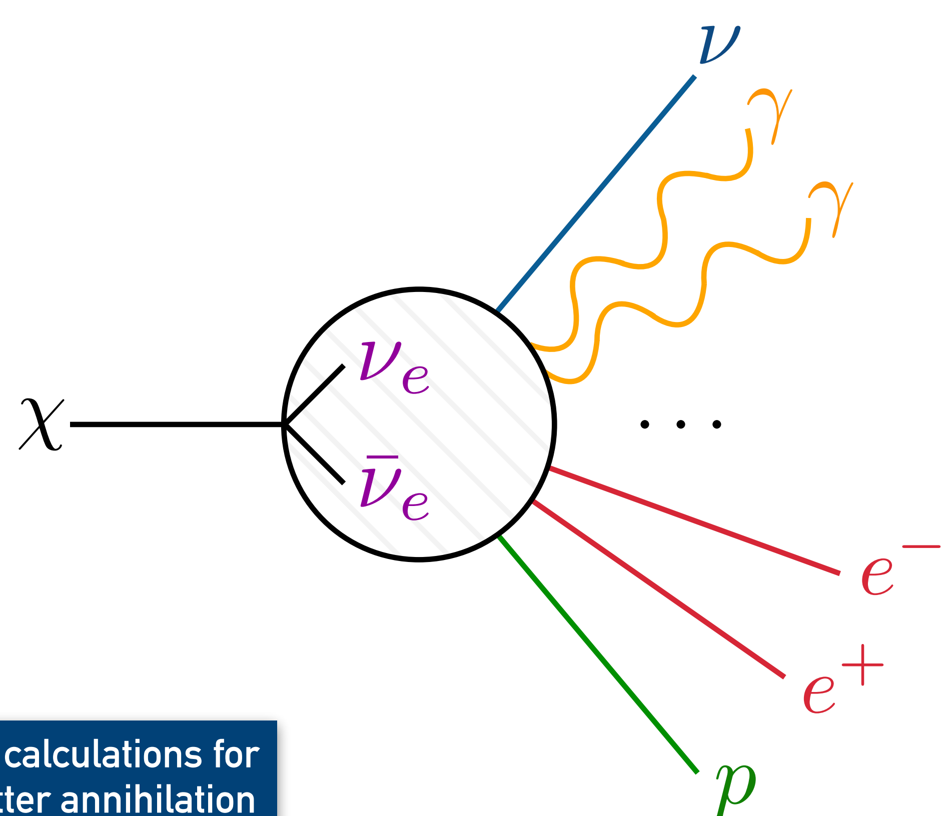
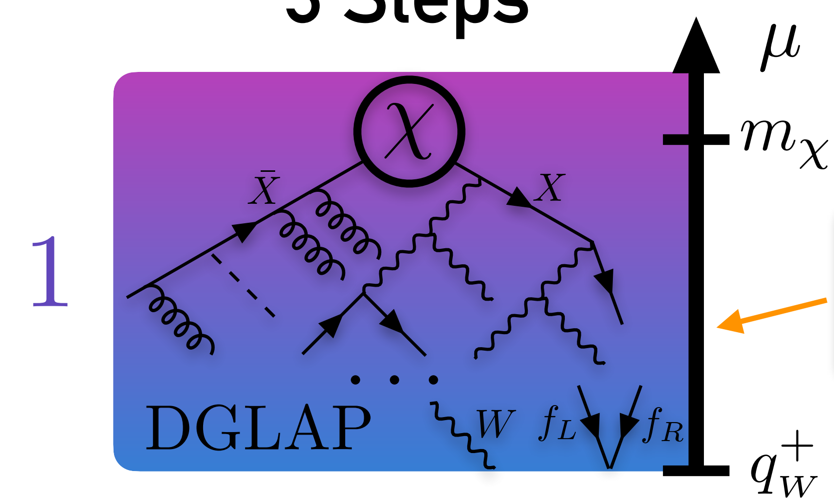


3 Steps



Full unbroken Standard Model - includes effects missing in Pythia

c.f. SCET calculations for dark matter annihilation
[NLR+ JHEP 2019]
[NLR+ JHEP 2018]
[NLR+ PRD 2017]

[Bauer, NLR, Webber 2020]

The Calculation

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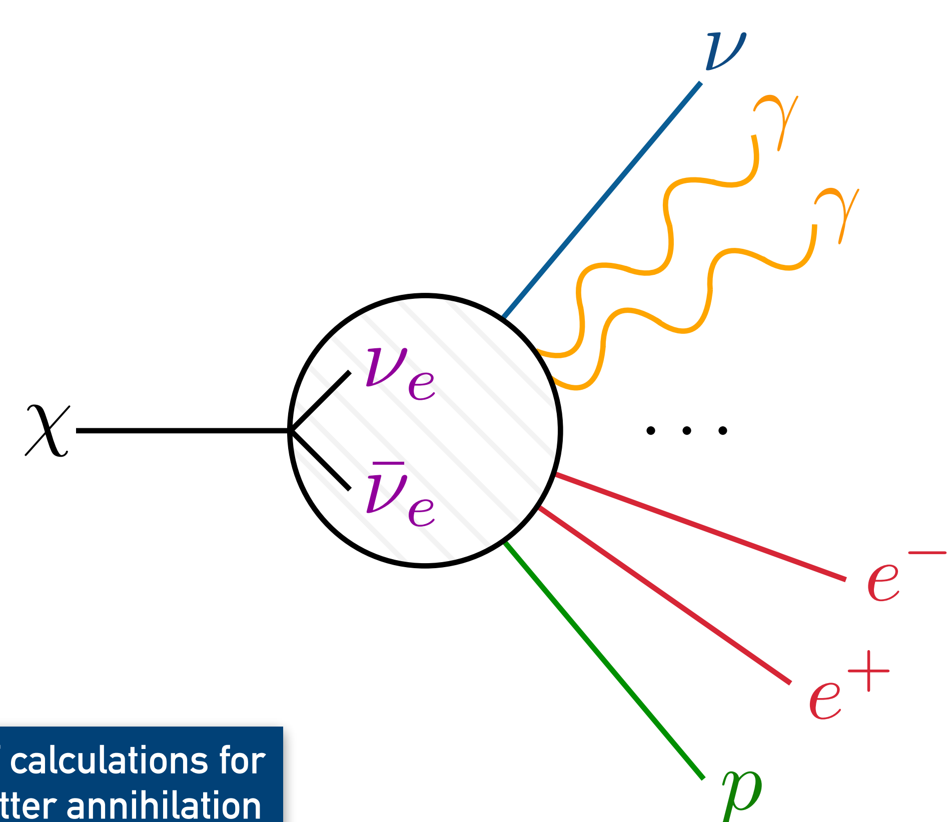

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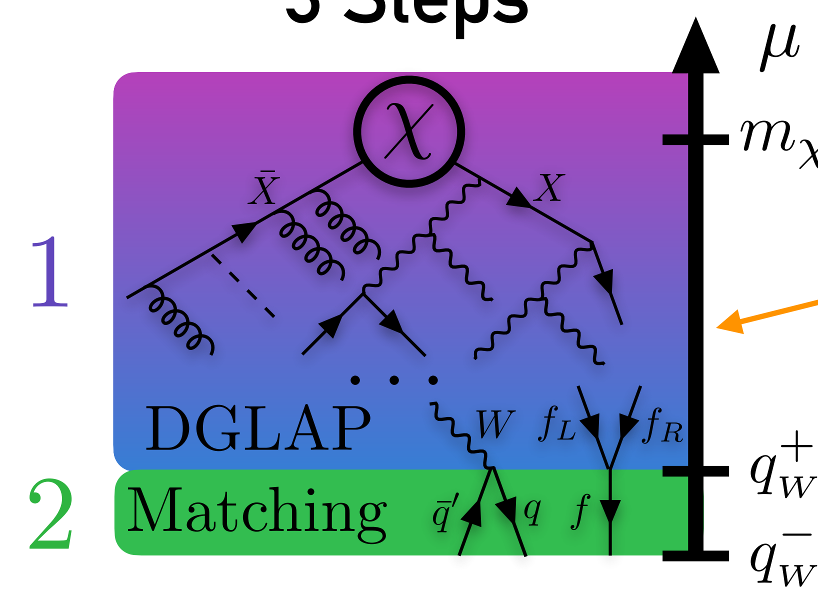

Full unbroken Standard Model - includes effects missing in Pythia

Matching through Electroweak scale

c.f. SCET calculations for dark matter annihilation
[NLR+ JHEP 2019]
[NLR+ JHEP 2018]
[NLR+ PRD 2017]

[Bauer, NLR, Webber 2020]

The Calculation

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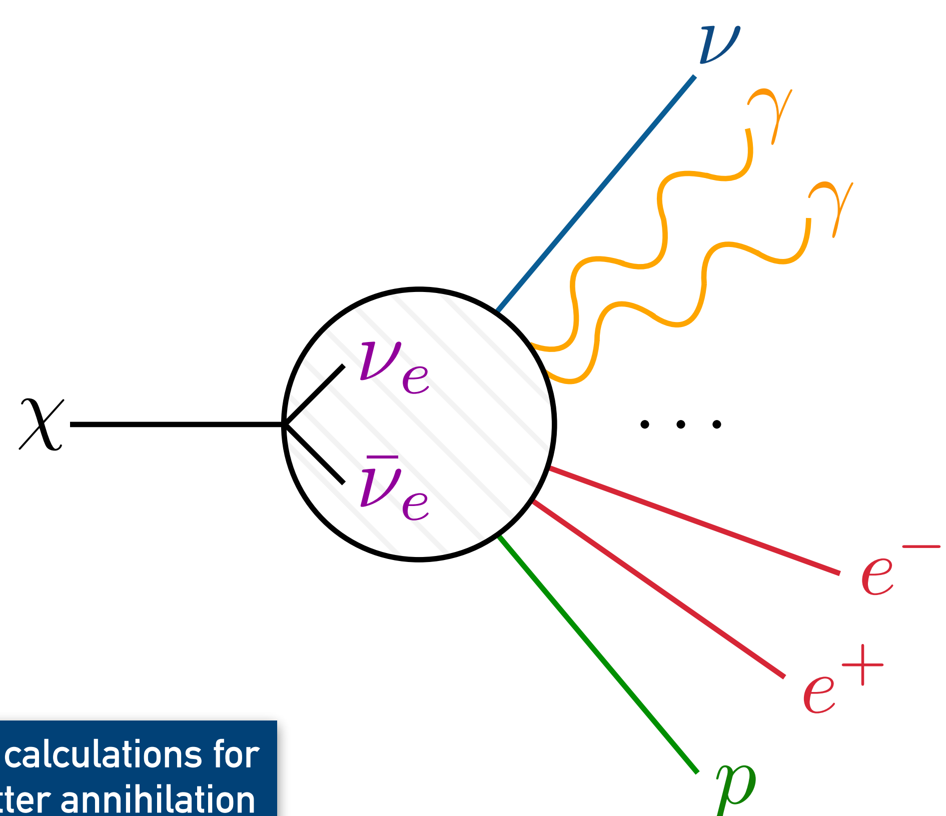
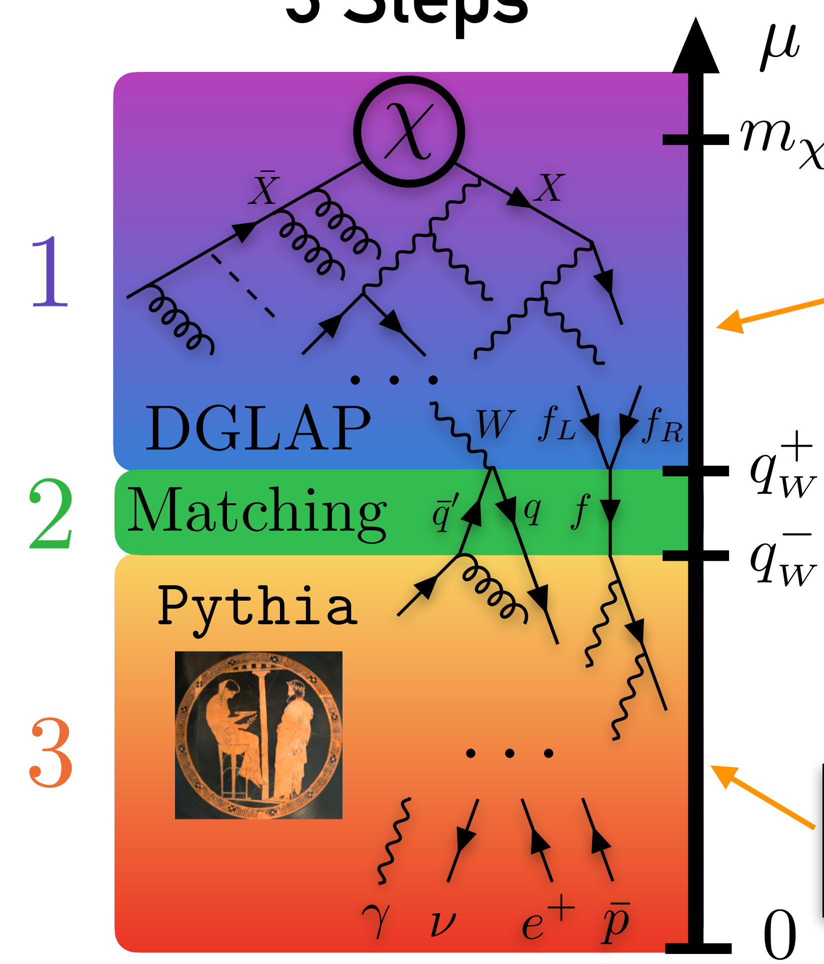


3 Steps



Full unbroken Standard Model - includes effects missing in Pythia

Matching through Electroweak scale

Includes hadronization, relevant due to e.g. $\pi^0 \to \gamma\gamma$

c.f. SCET calculations for dark matter annihilation
[NLR+ JHEP 2019]
[NLR+ JHEP 2018]
[NLR+ PRD 2017]

[Bauer, NLR, Webber 2020]

The Calculation

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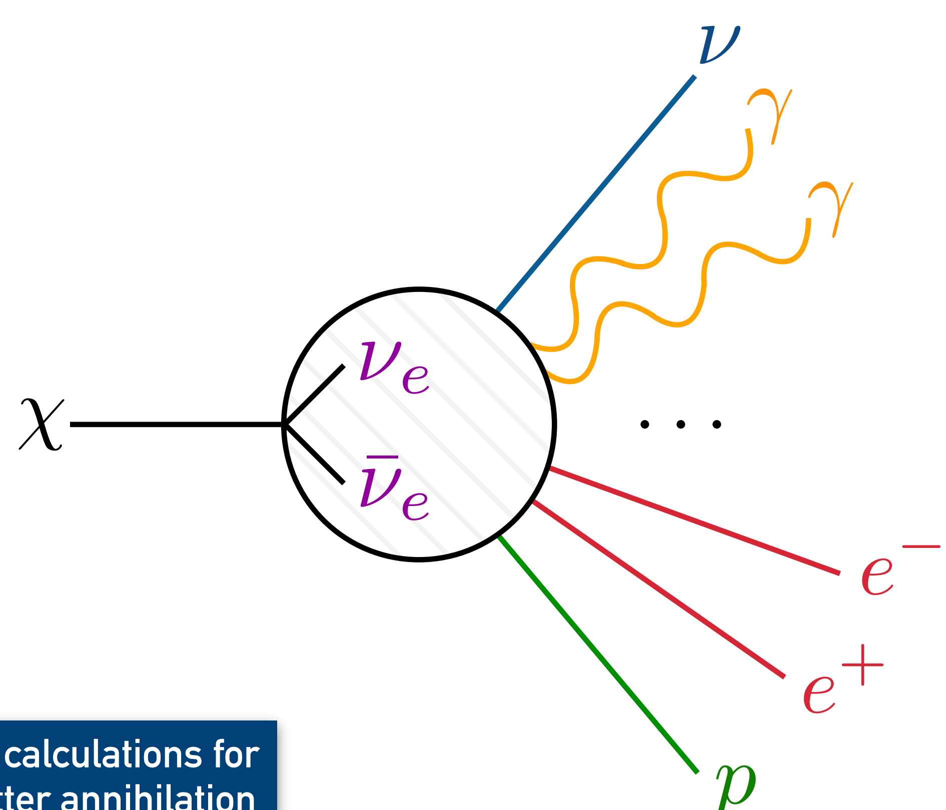
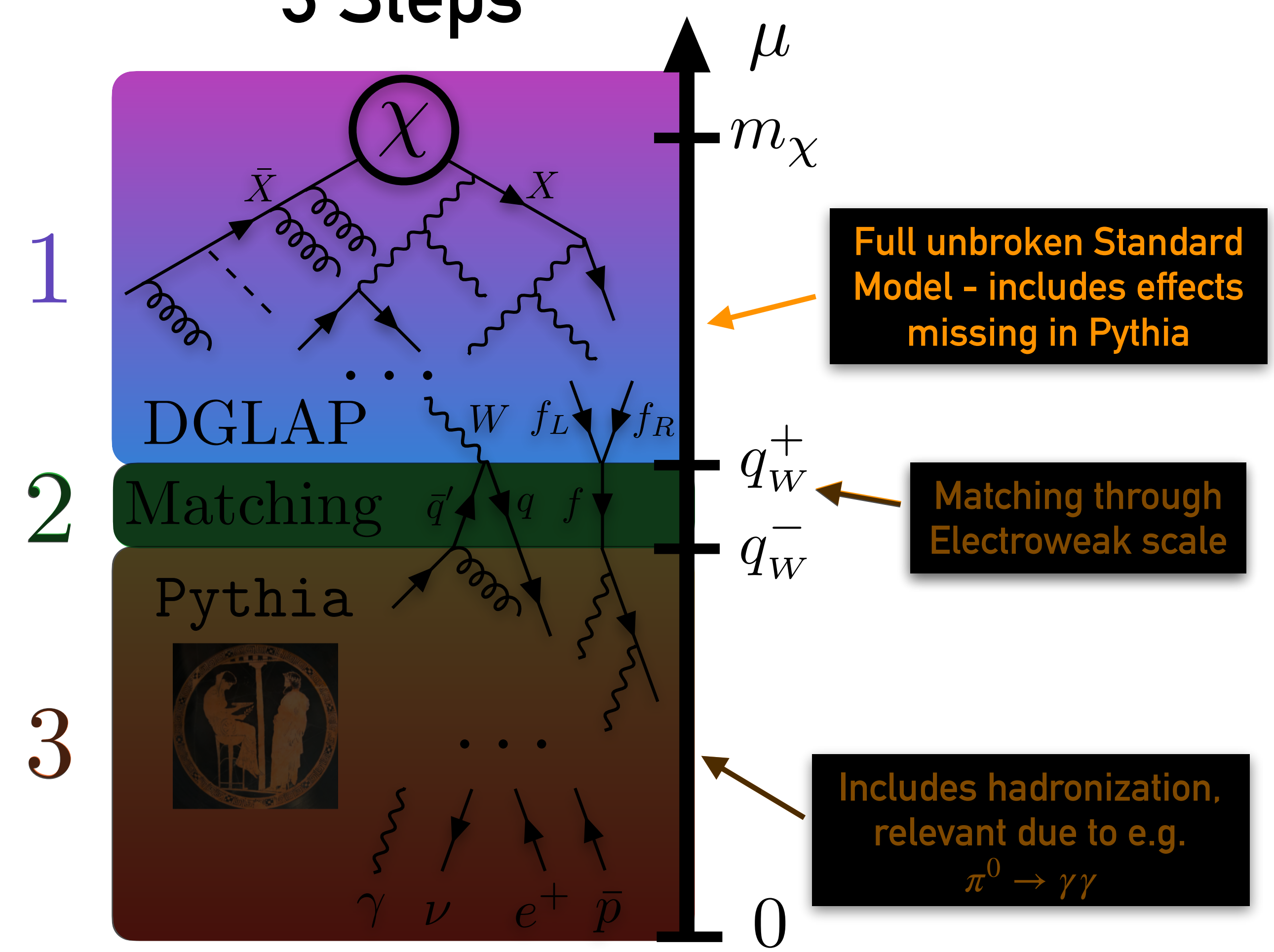


3 Steps

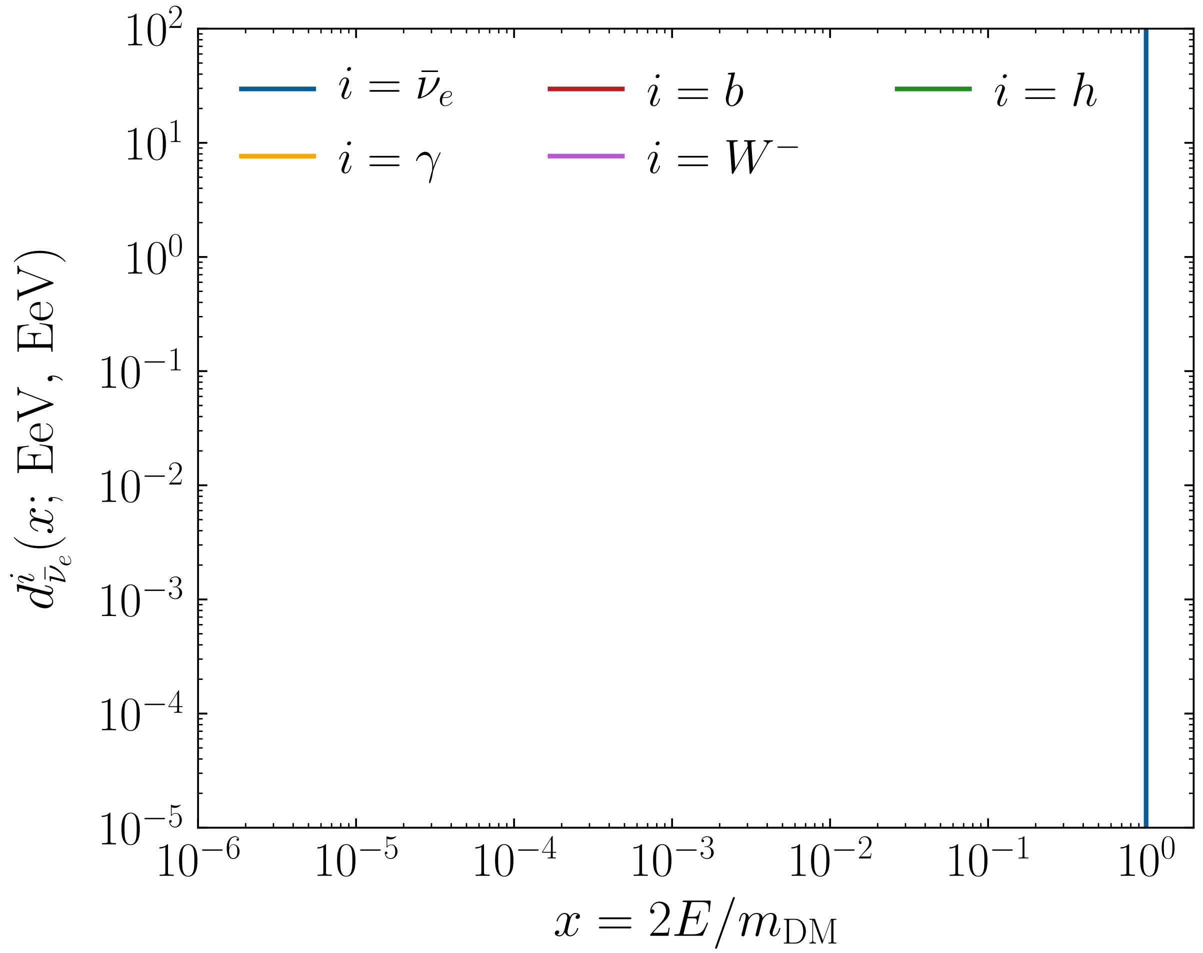


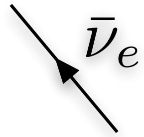
c.f. SCET calculations for dark matter annihilation
[NLR+ JHEP 2019]
[NLR+ JHEP 2018]
[NLR+ PRD 2017]

[Bauer, NLR, Webber 2020]

DGLAP Evolution

$$d^i_{\bar{\nu}_e}(x;\, m_\chi, m_\chi) = \delta^i_{\bar{\nu}_e}\delta(1-x)$$





[Bauer, NLR, Webber 2020]

DGLAP Evolution

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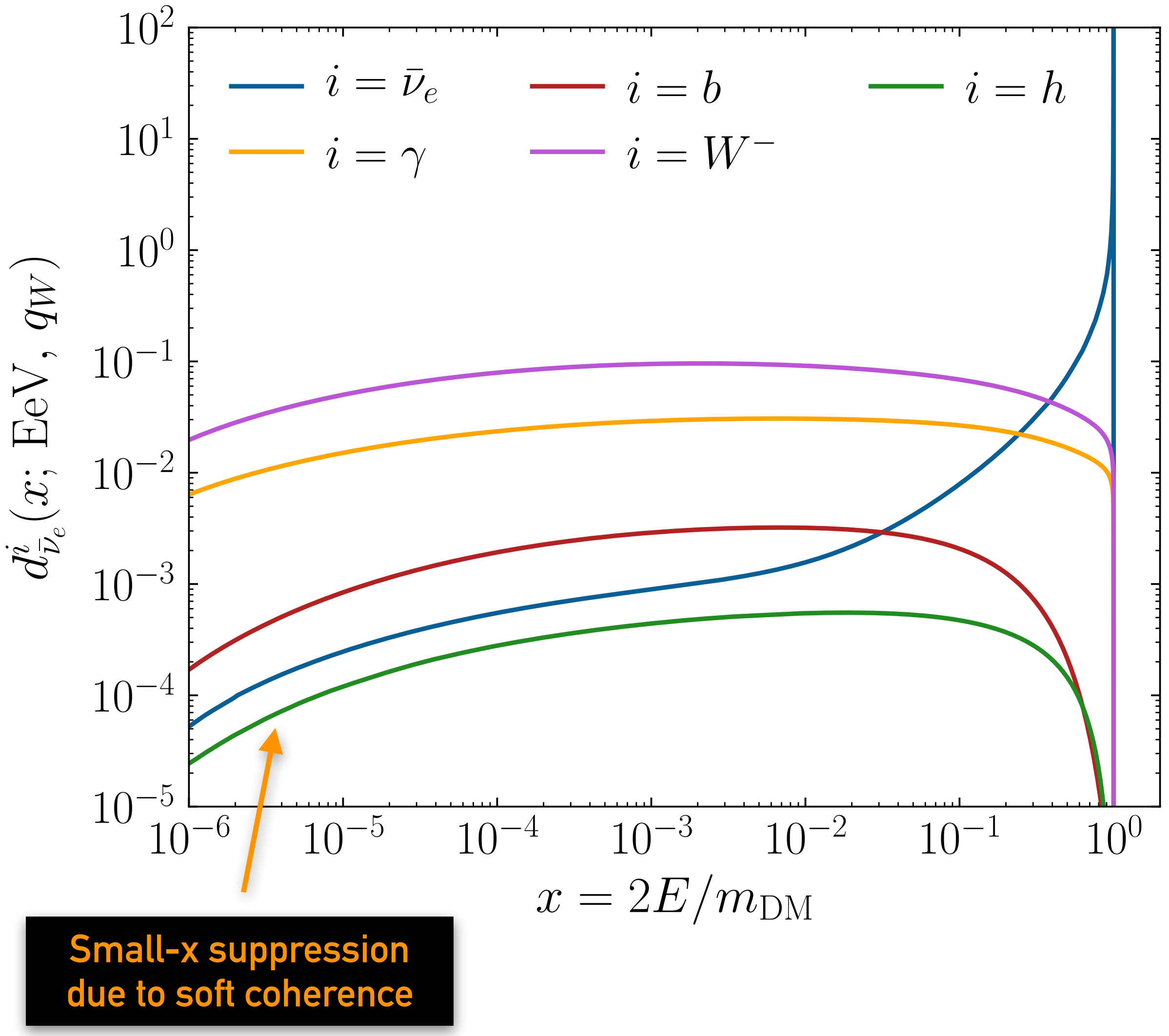
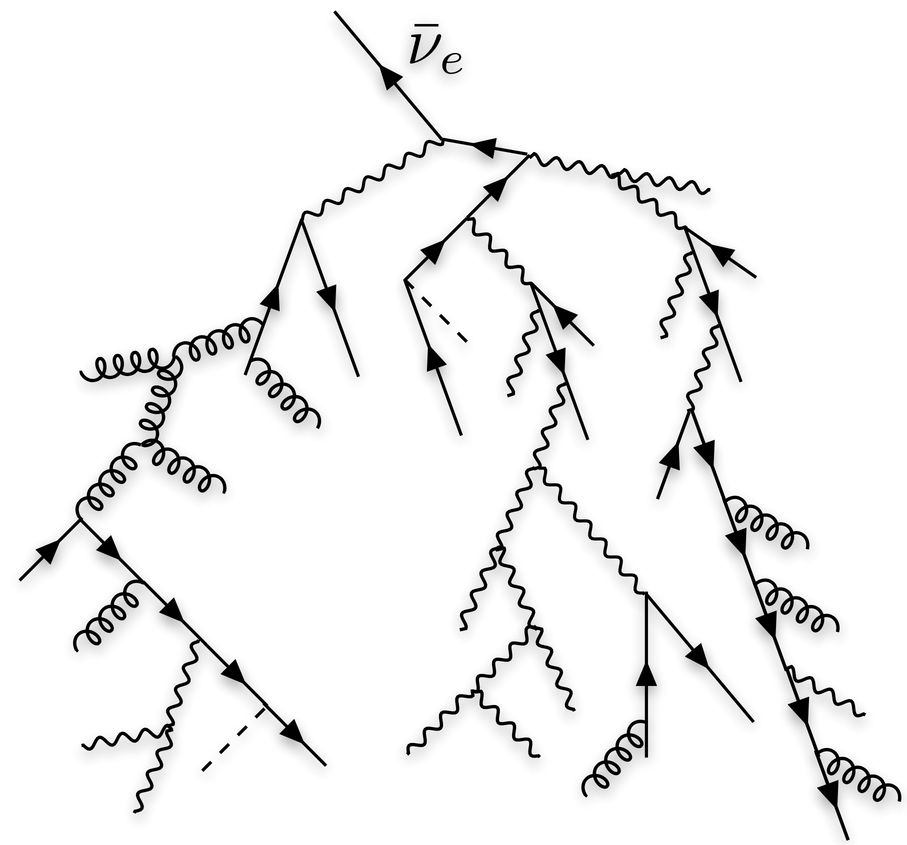
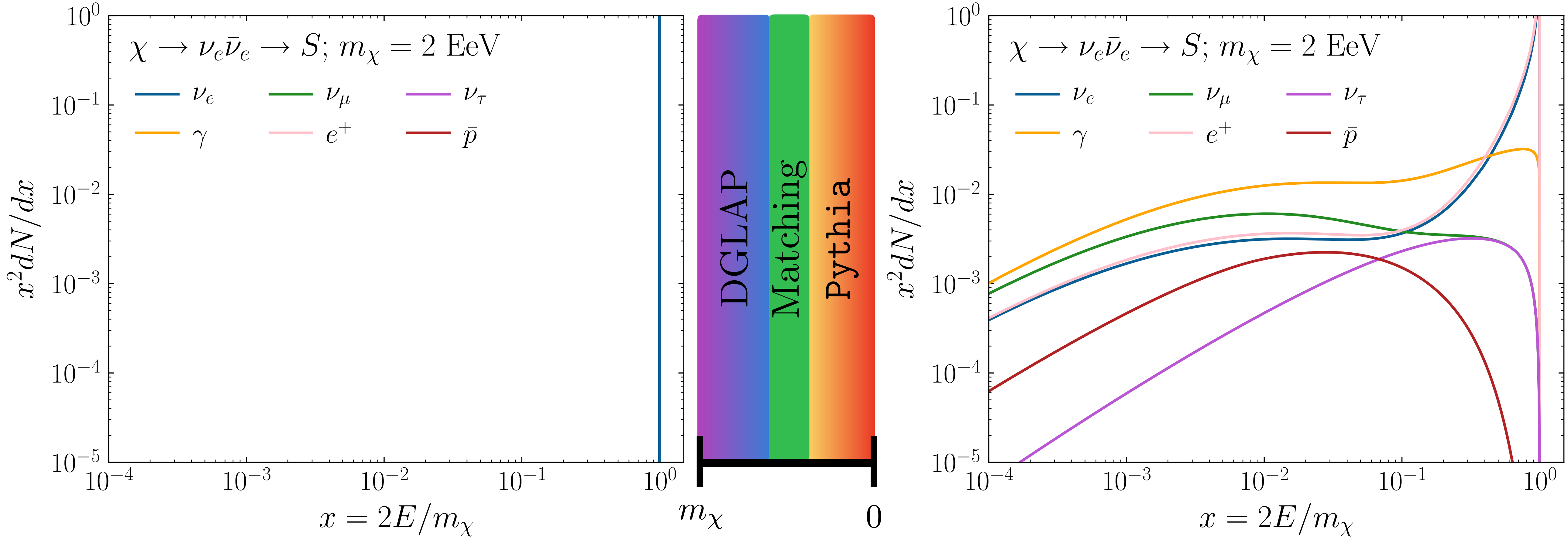




[Bauer, NLR, Webber 2020]

The Results

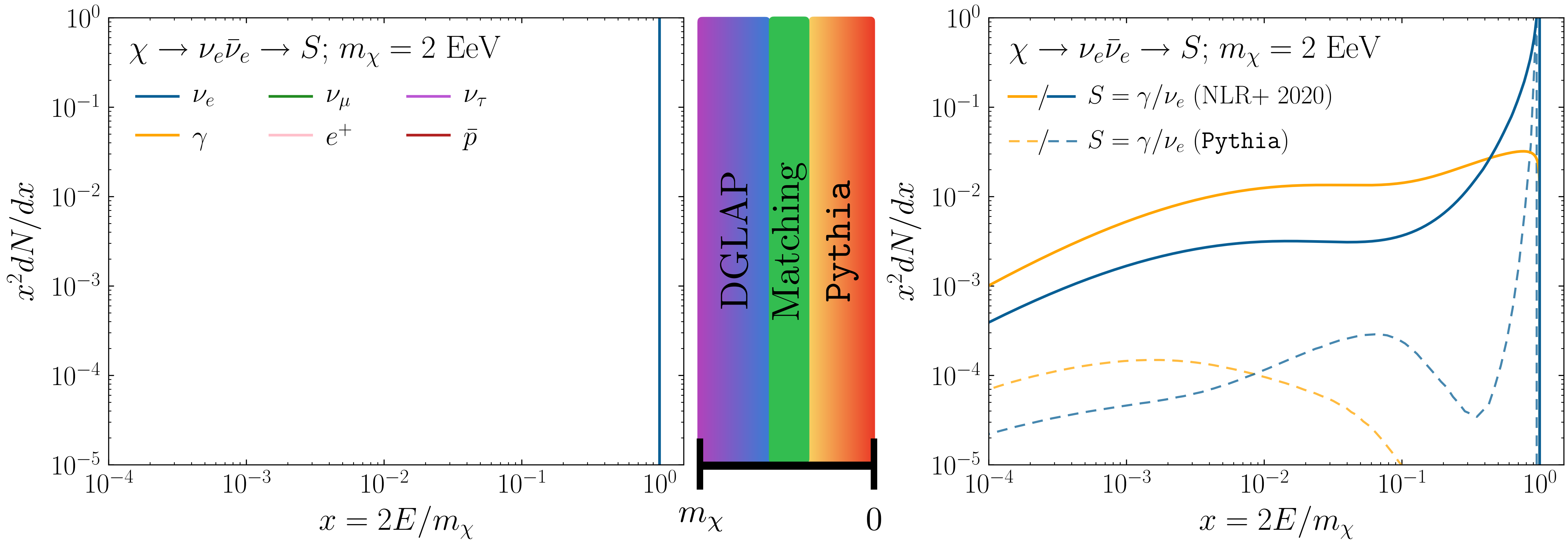
Rich Spectrum of Final States



[Bauer, NLR, Webber 2020]

The Results

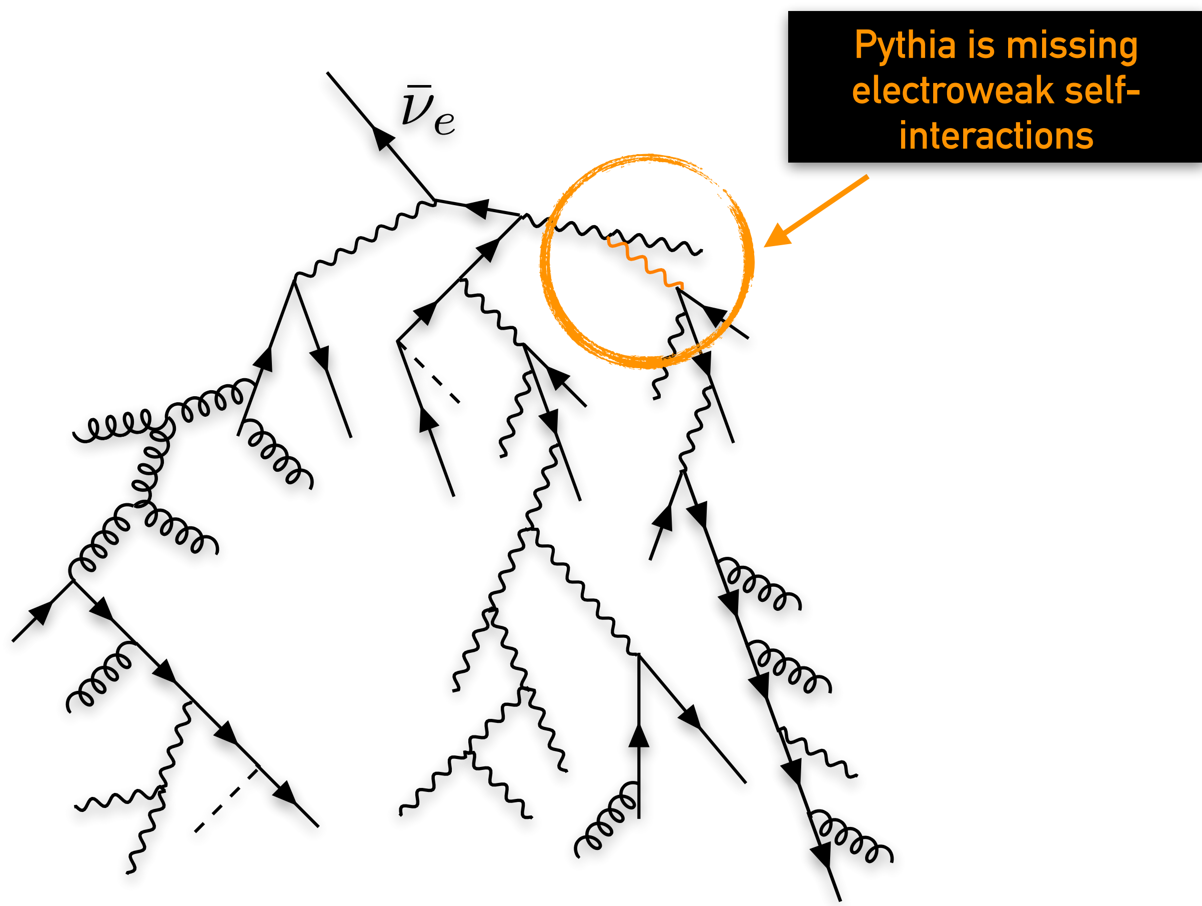
Dramatic difference for the experimental flux

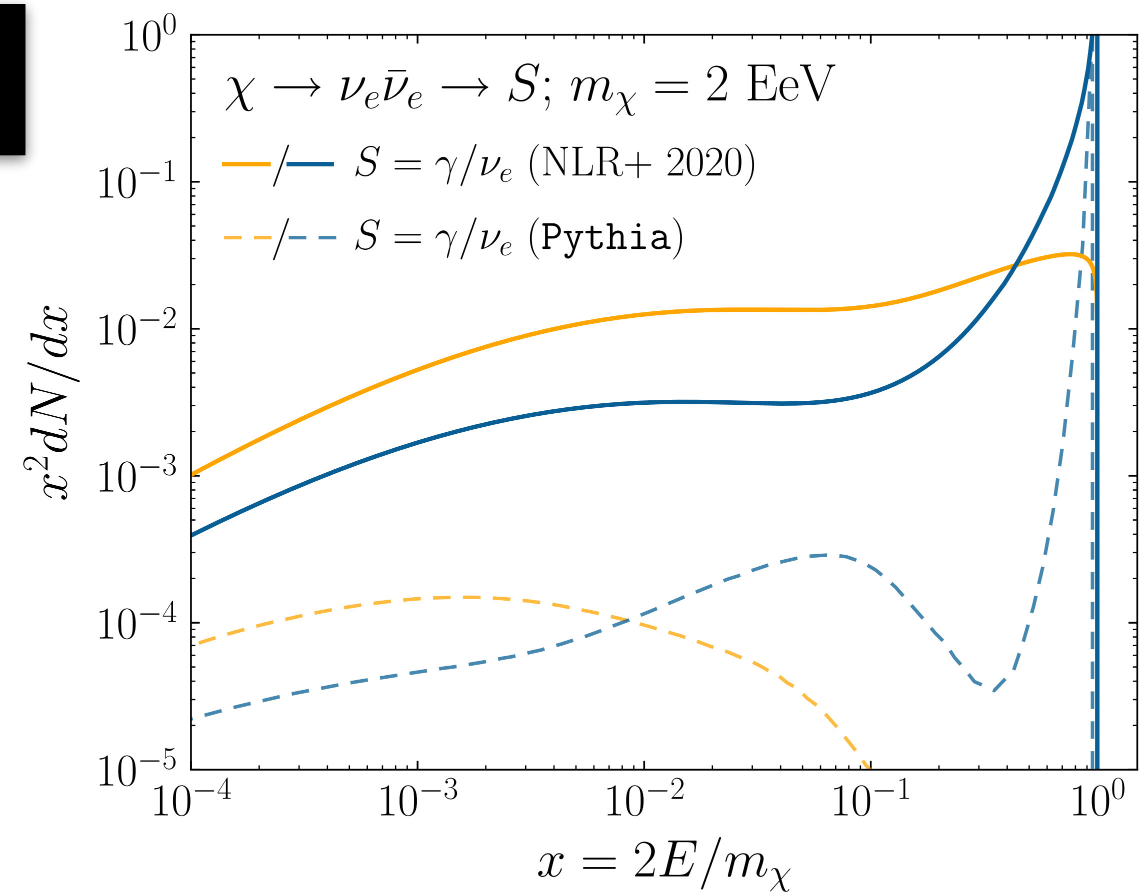


[Bauer, NLR, Webber 2020]

The Results

Why the large disagreement?

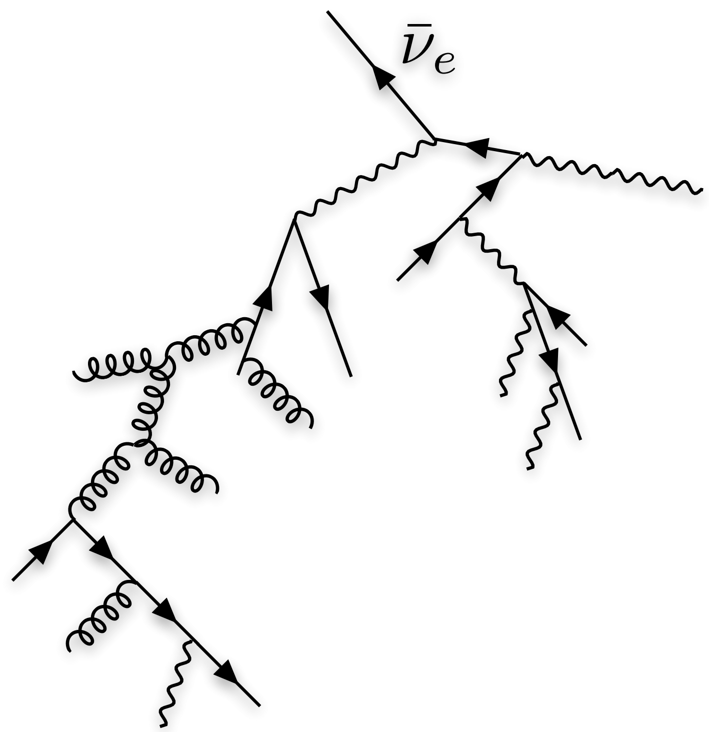


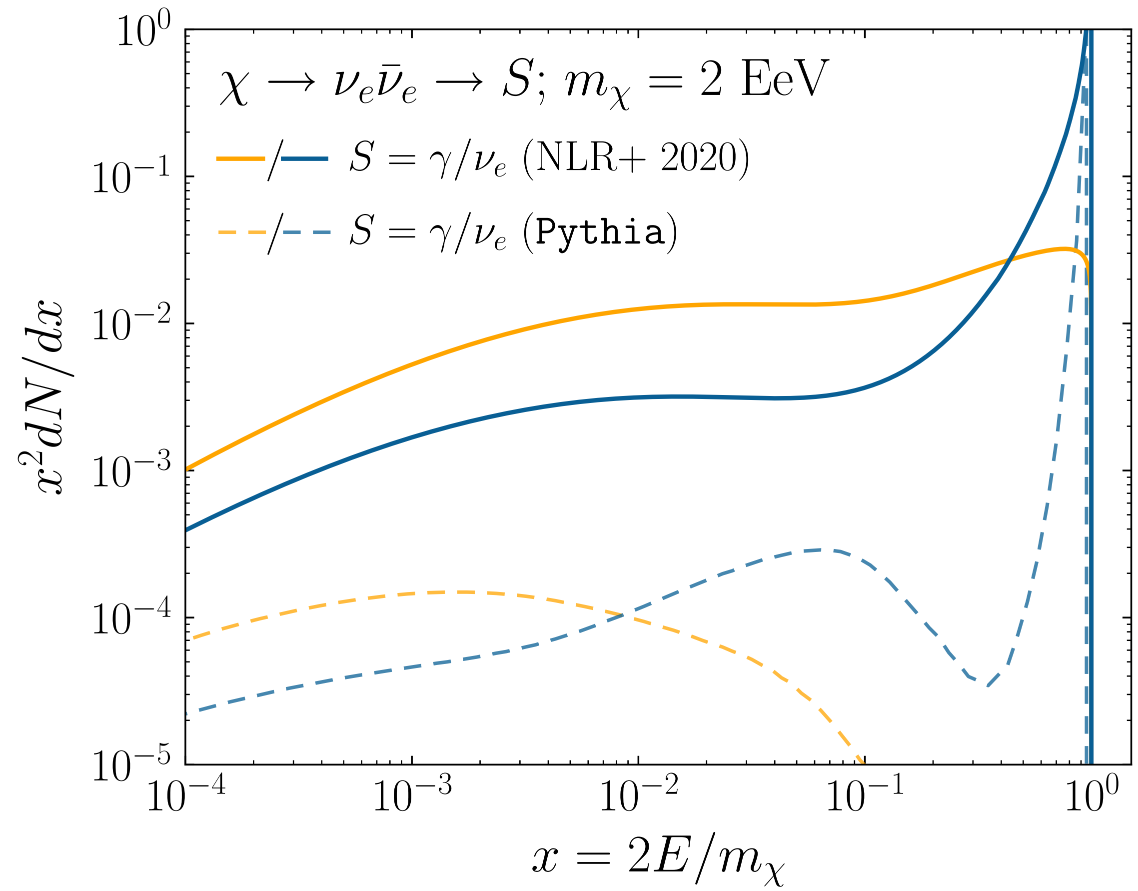


[Bauer, NLR, Webber 2020]

The Results

Key electroweak double logs not resummed





[Bauer, NLR, Webber 2020]

The Results

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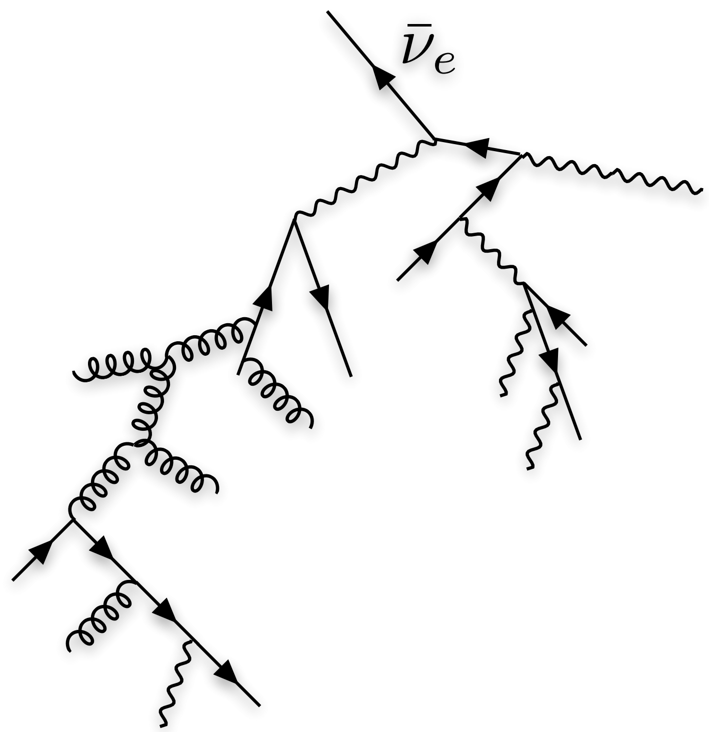
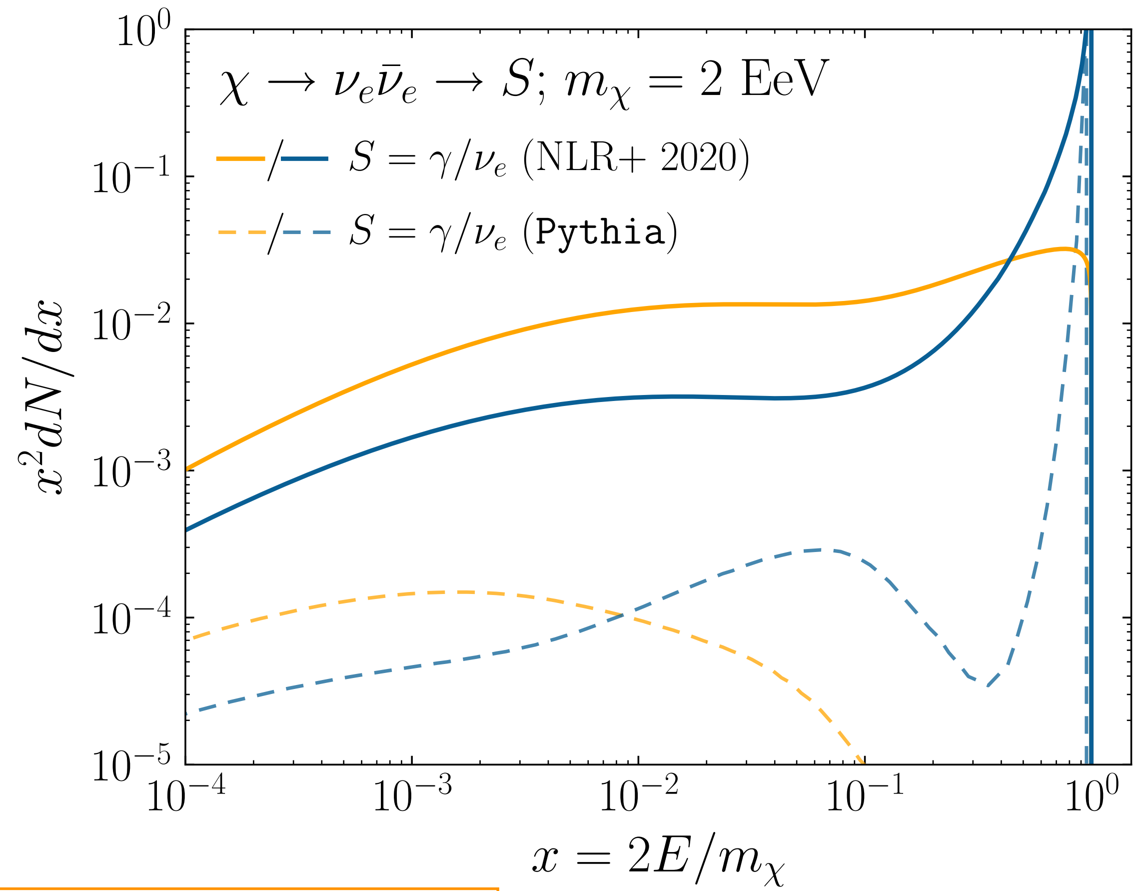


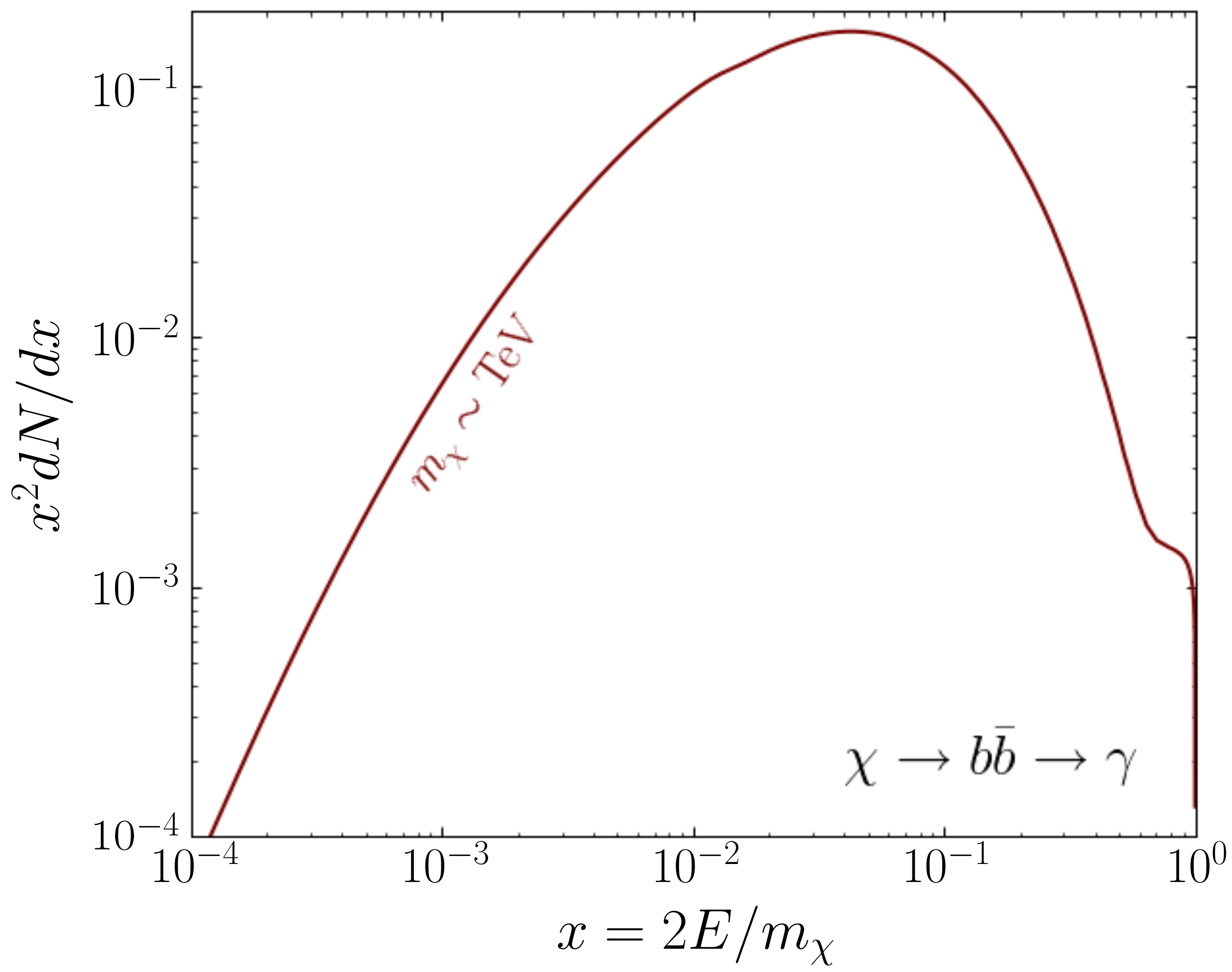


Missing contributions of the form

$$\exp[\alpha_2 \ln^2(m_\chi/q_W)] \sim 1000$$

[Bauer, NLR, Webber 2020]

The Results



[Bauer, NLR, Webber 2020]

The Results

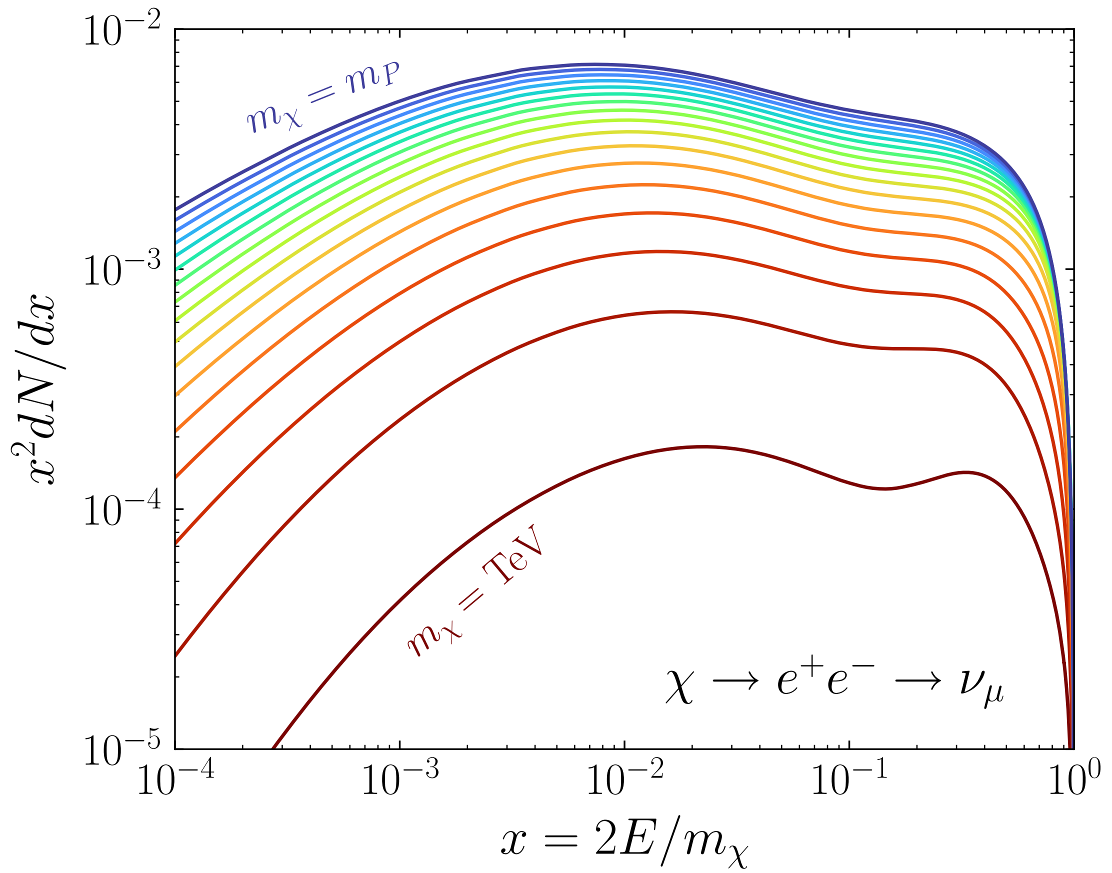
README.md

github.com/nickrodd/HDMSpectra

HDMSpectra

Dark Matter Spectra from the Electroweak to the Planck Scale

License MIT arXiv 2007.15001



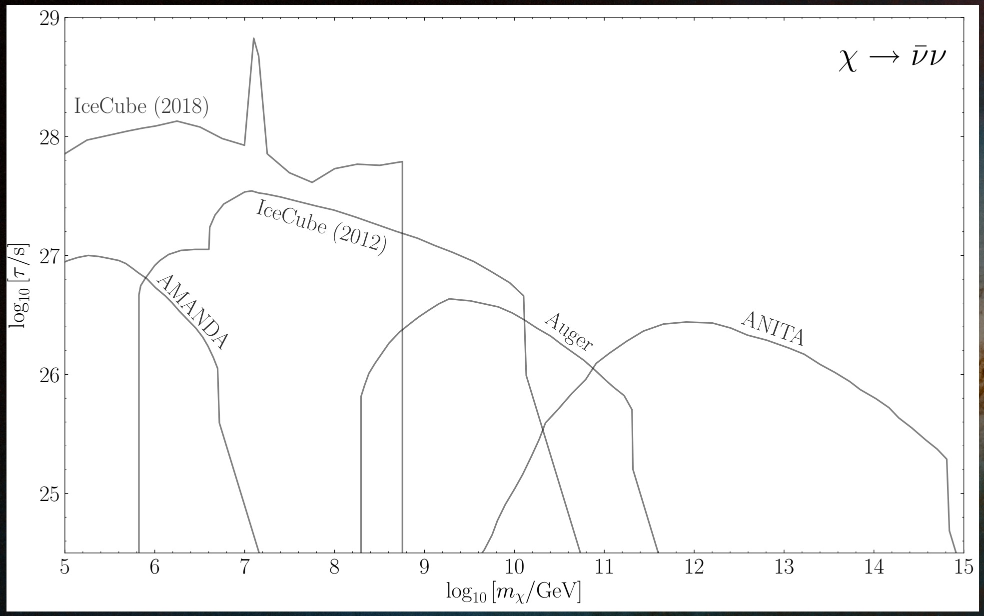
Adopted by IceCube [Liu+ JCAP 2020]

See Jeff Lazar "Searching for Dark Matter from the Sun with Ten Years of IceCube Data" talk on Tuesday

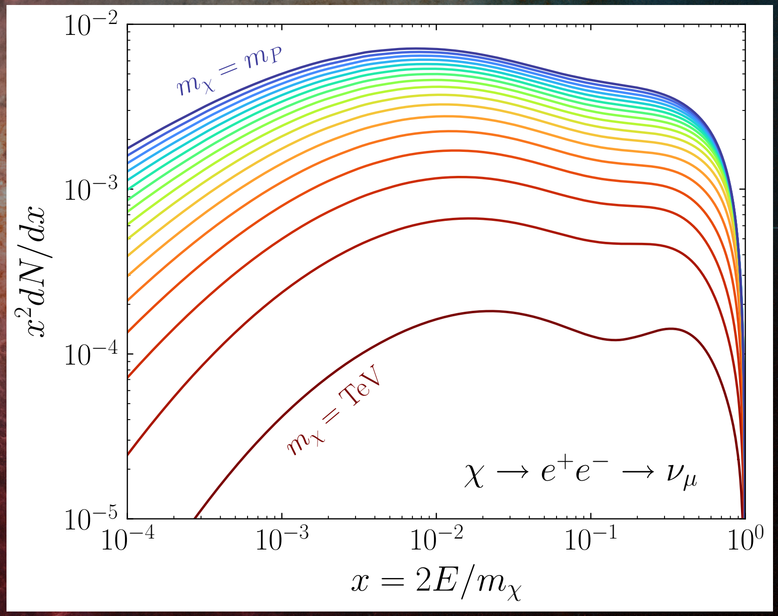
[Bauer, NLR, Webber 2020]

Conclusion

Experiment



Theory

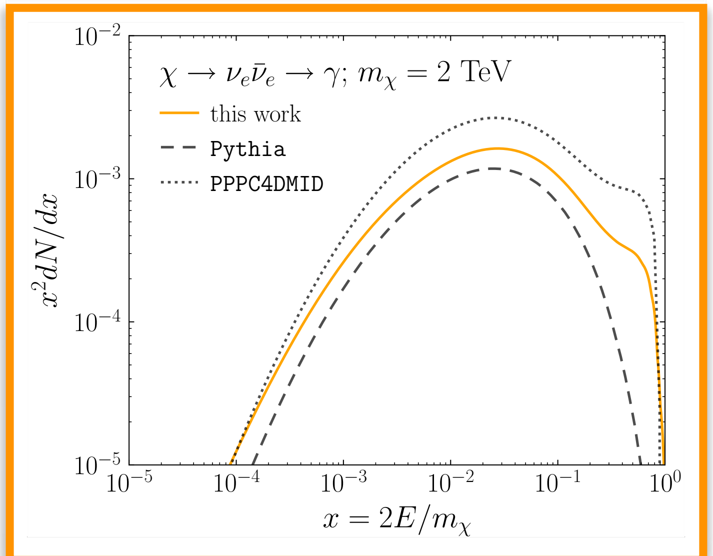


Backup Slides

Looking Forward

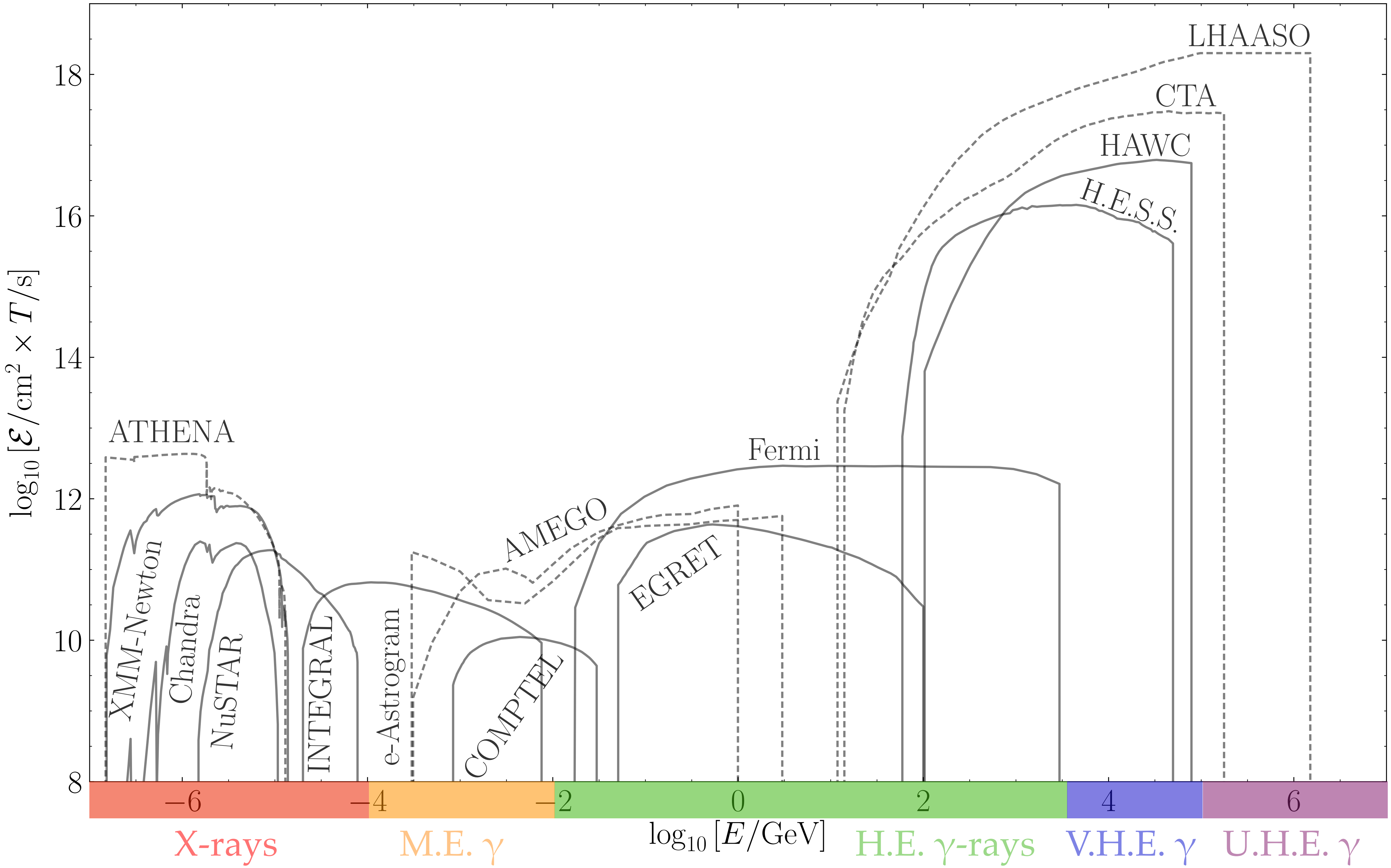
Many directions to build on these results

- Improve soft coherence (required for NLL)
- Fixed order matching (disagreements at $m_\chi \sim \text{TeV}$)
- Coherent showering (e.g. B/W^3 mixing)
- Propagation effects (what spectrum reaches Earth?)
- Additional UV input (e.g. charged DM, SUSY threshold)
- ...

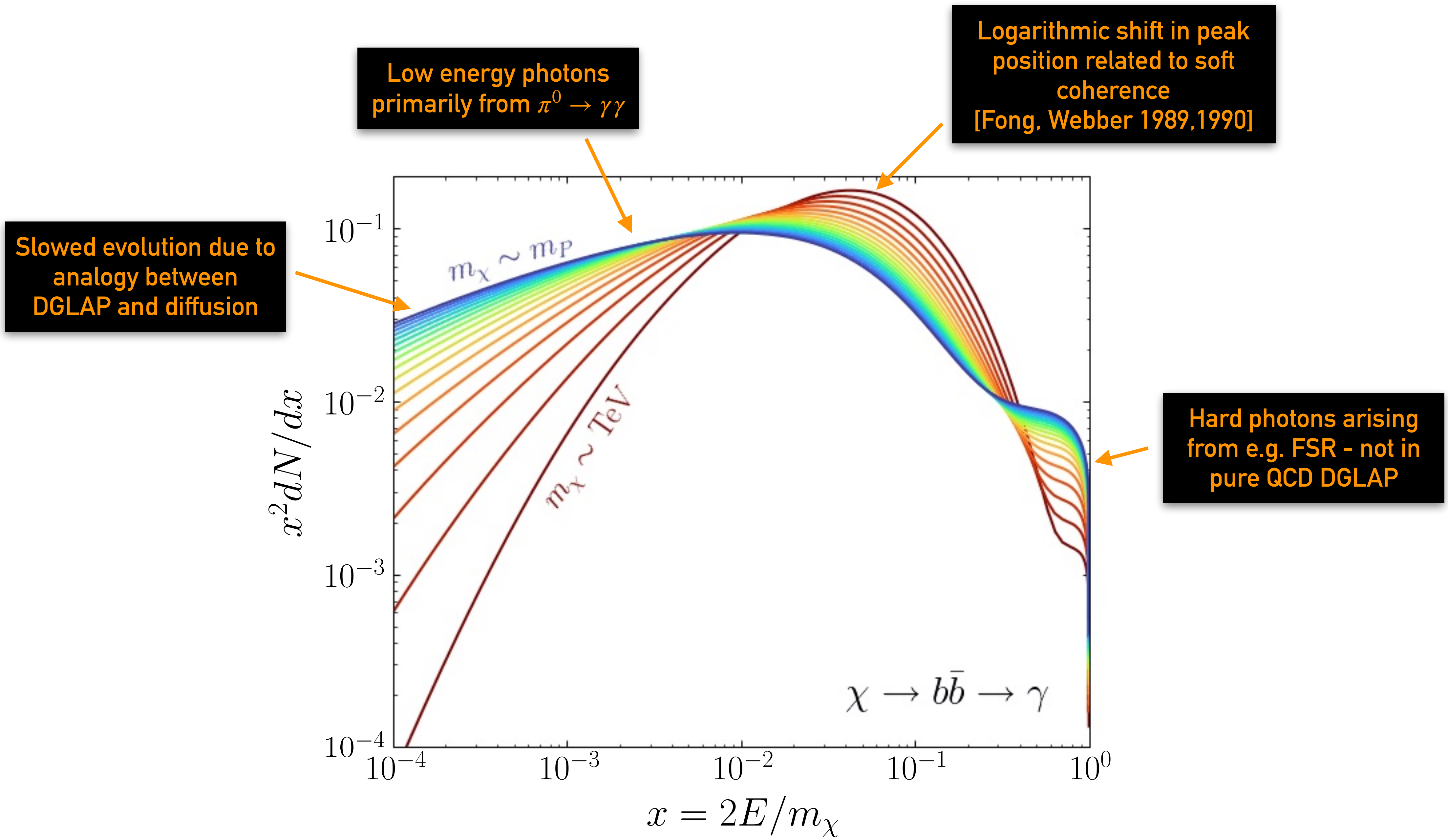


[Bauer, NLR, Webber 2020]

Photon Landscape



The Results



[Bauer, NLR, Webber 2020]

DGLAP ↔ Diffusion

Expand near $z \simeq 1$

$$\frac{\partial}{\partial \ln \mu} d(x;\, \mu) \simeq \frac{2C\alpha}{\pi} \left[\zeta(2) \frac{\partial}{\partial \ln x} + \zeta(3) \left(\frac{\partial}{\partial \ln x} \right)^2 + \ldots \right] d(x;\, \mu)$$

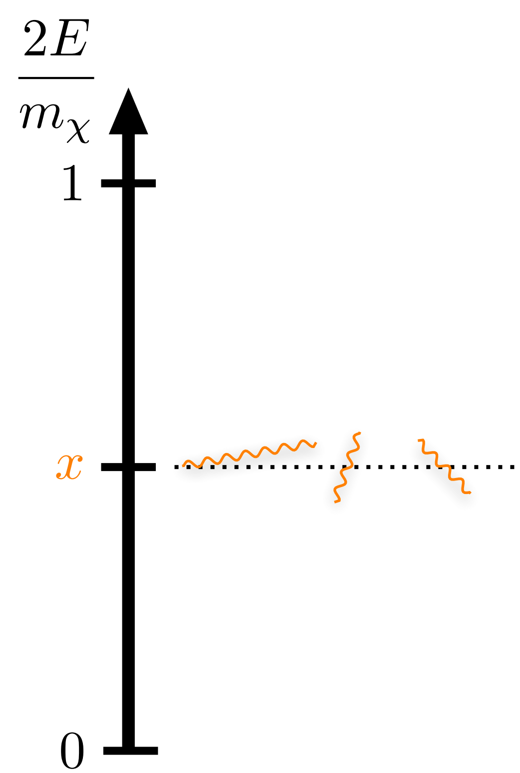
Like diffusion equation with $t = \ln \mu$

Also why in truth we evolve from low scale up,
otherwise evolution is unstable

[Bauer, NLR, Webber 2020]

DGLAP Evolution

$$\mu \frac{\partial}{\partial \mu} d(x;\ \mu)$$

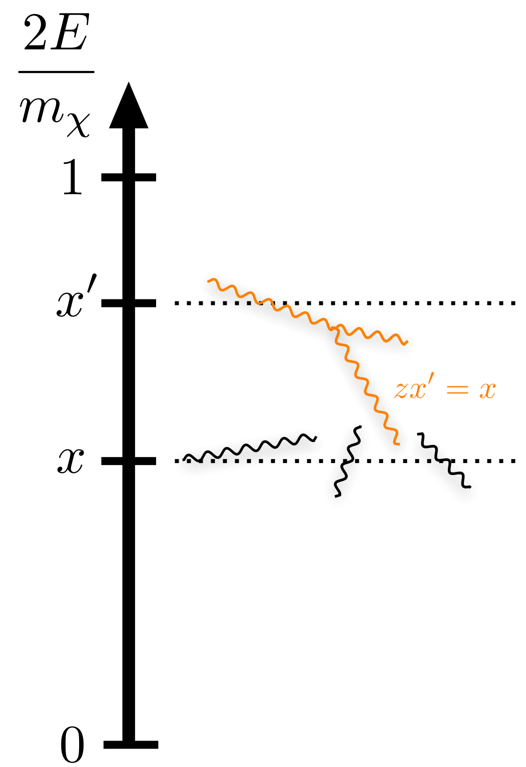


[Bauer, NLR, Webber 2020]

DGLAP Evolution

Dominant effect from $1 \to 2$ splittings

$$\mu \frac{\partial}{\partial \mu} d(x;\, \mu) = \frac{\alpha}{\pi} \int_x^1 \frac{dz}{z} \hat{P}(z) d(x/z;\, \mu)$$



[Bauer, NLR, Webber 2020]

DGLAP Evolution

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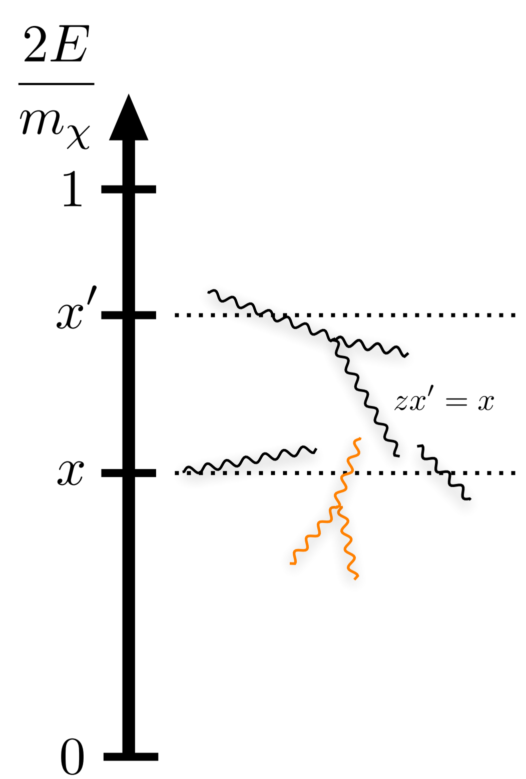
$$\mu \frac{\partial}{\partial \mu} d(x;\, \mu) = \frac{\alpha}{\pi} \int_x^1 \frac{dz}{z}\, \hat{P}(z) d(x/z;\, \mu) - \frac{\alpha}{\pi} d(x;\, \mu) \int_0^1 dz\, \hat{P}(z)$$



[Bauer, NLR, Webber 2020]

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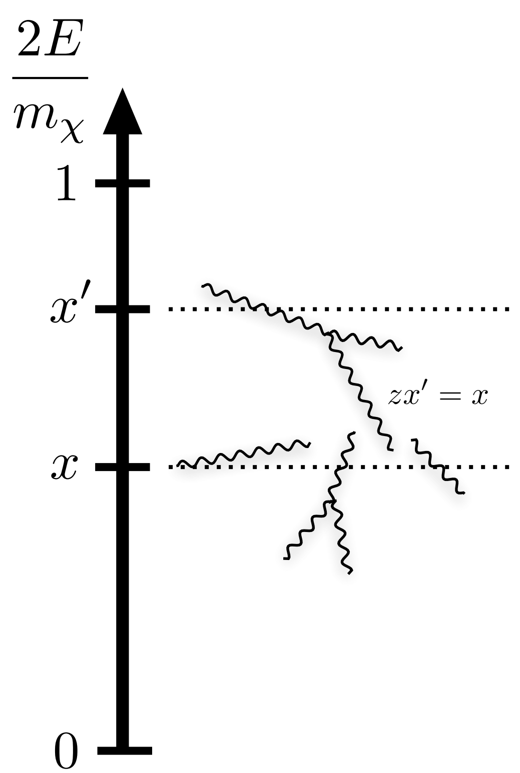
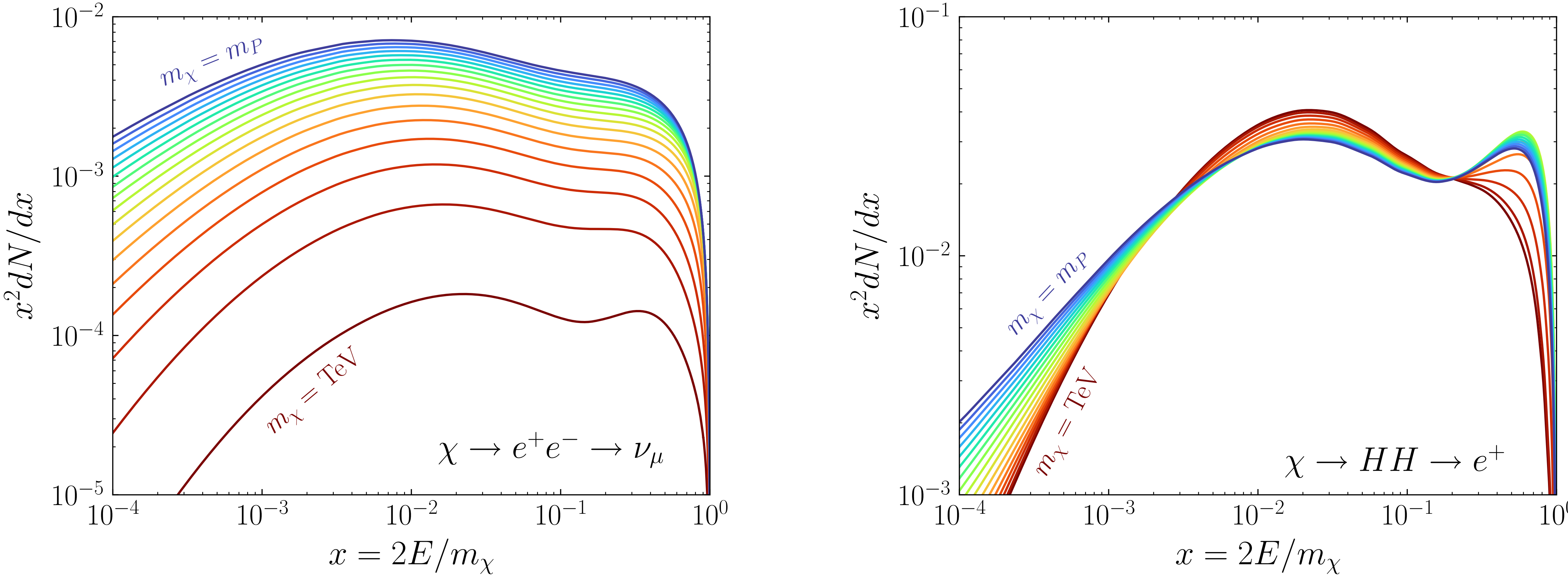


Need result for the full Standard Model - 2,204 coupled Fragmentation Functions

Build on efforts for a 100 TeV collider,
e.g. [Manohar, Waalewijn JHEP 2018], [Bauer, Webber JHEP 2019]
and push on to the Planck scale

[Bauer, NLR, Webber 2020]

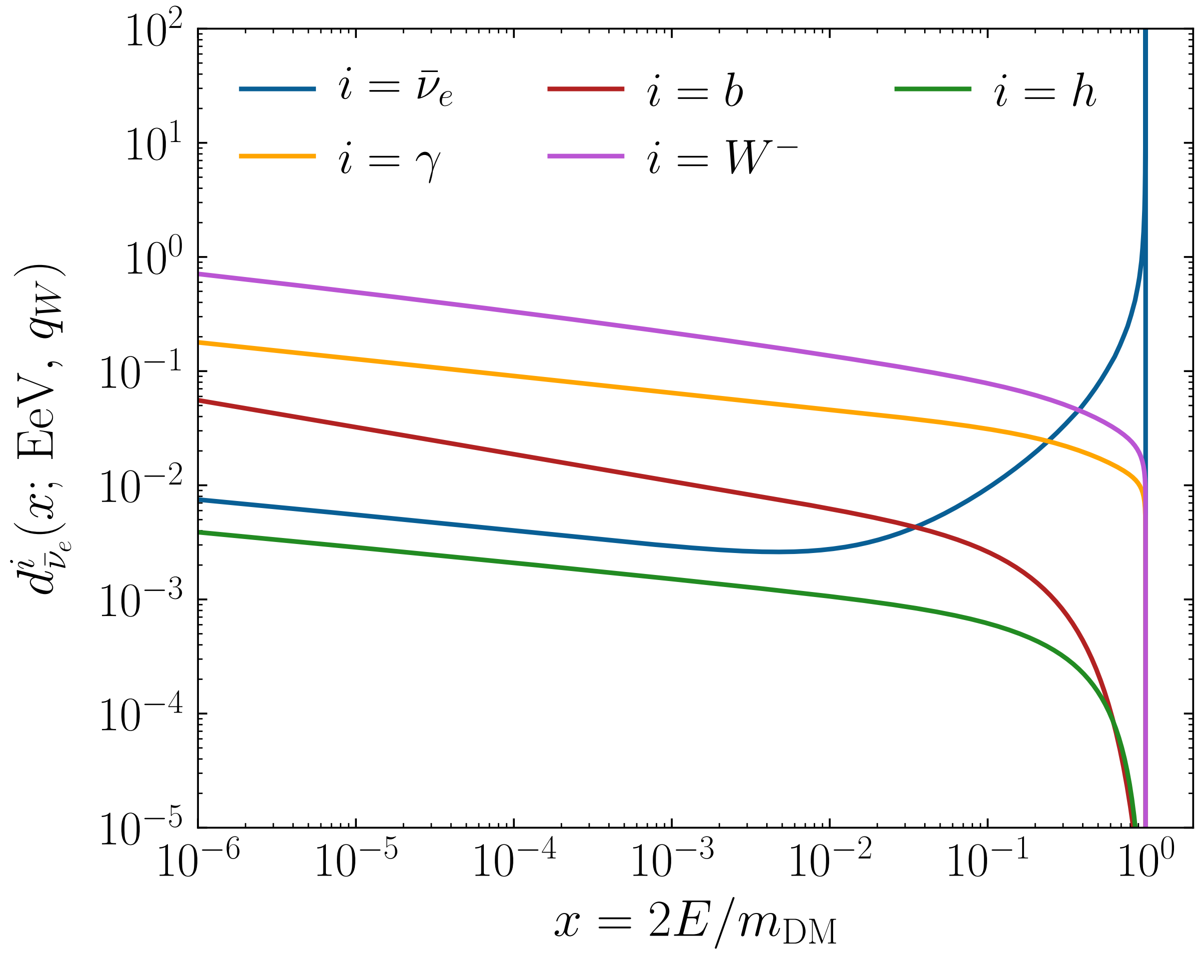
Additional Results

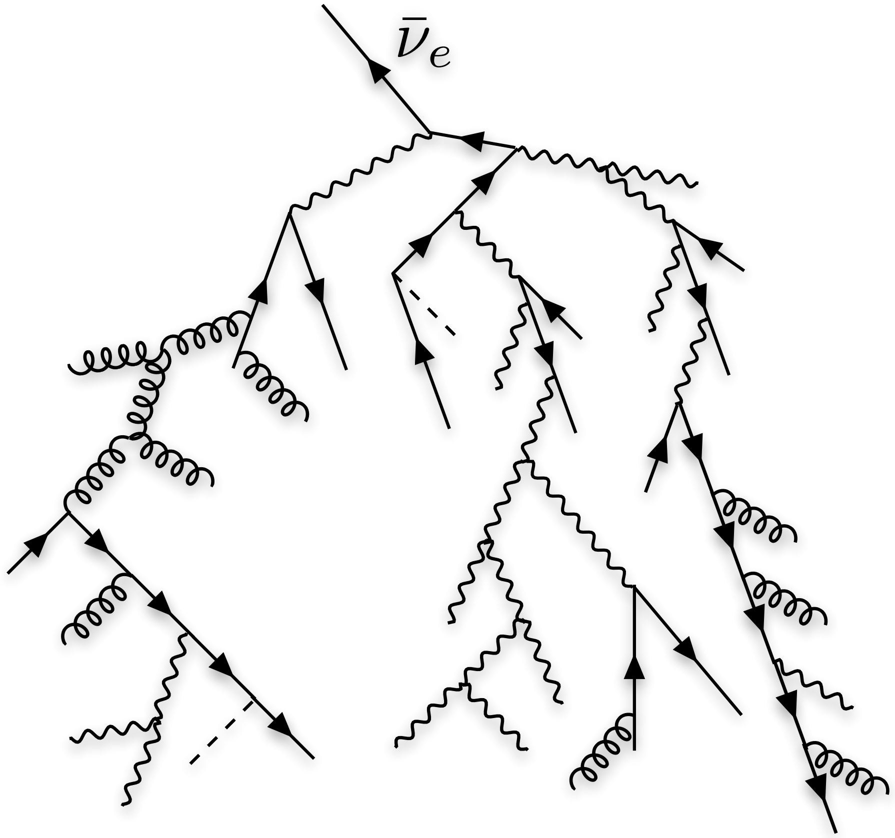


[Bauer, NLR, Webber 2020]

Soft Coherence

$$d^i_{\bar{\nu}_e}(x;\, m_\chi, m_\chi) = \delta^i_{\bar{\nu}_e}\delta(1-x)$$





[Bauer, NLR, Webber 2020]

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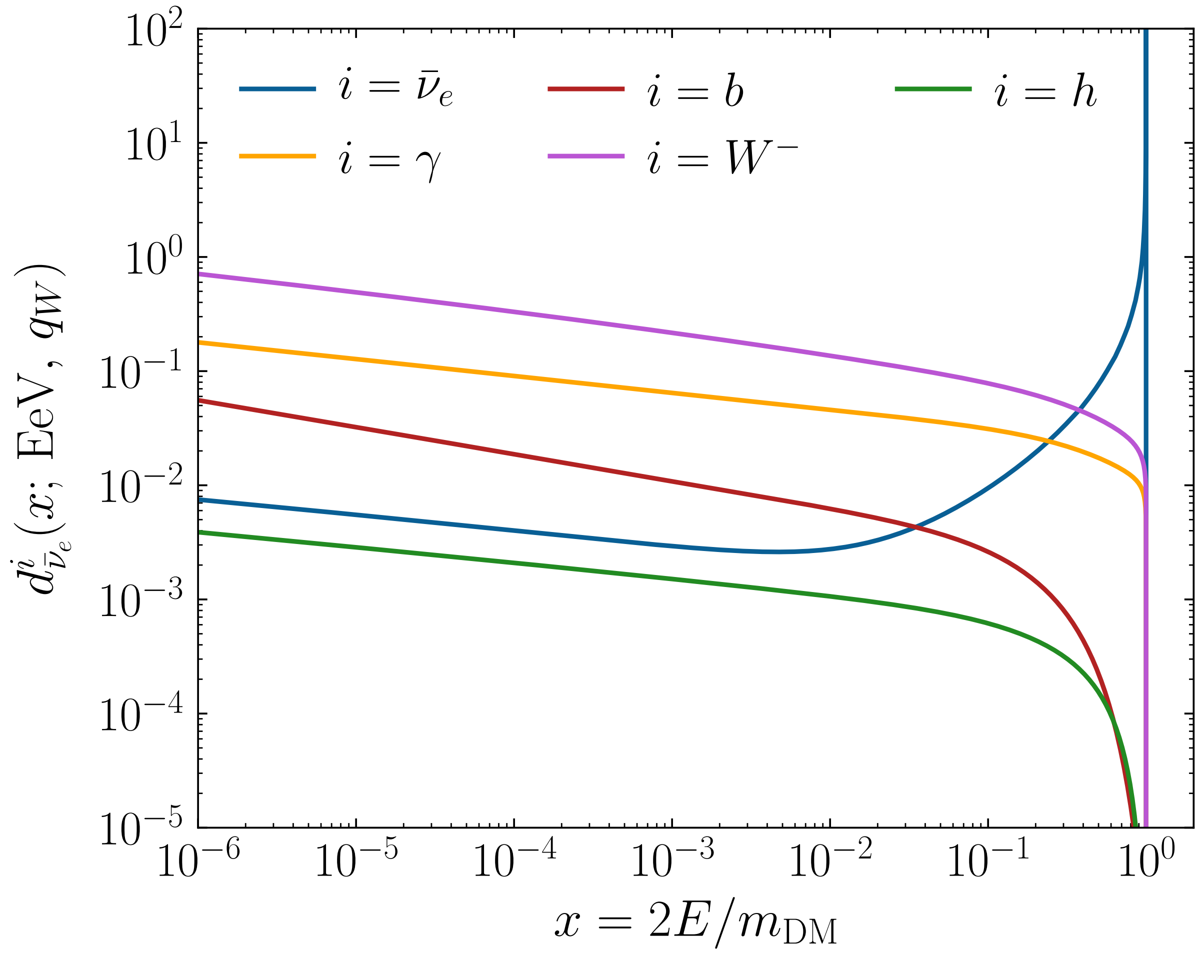

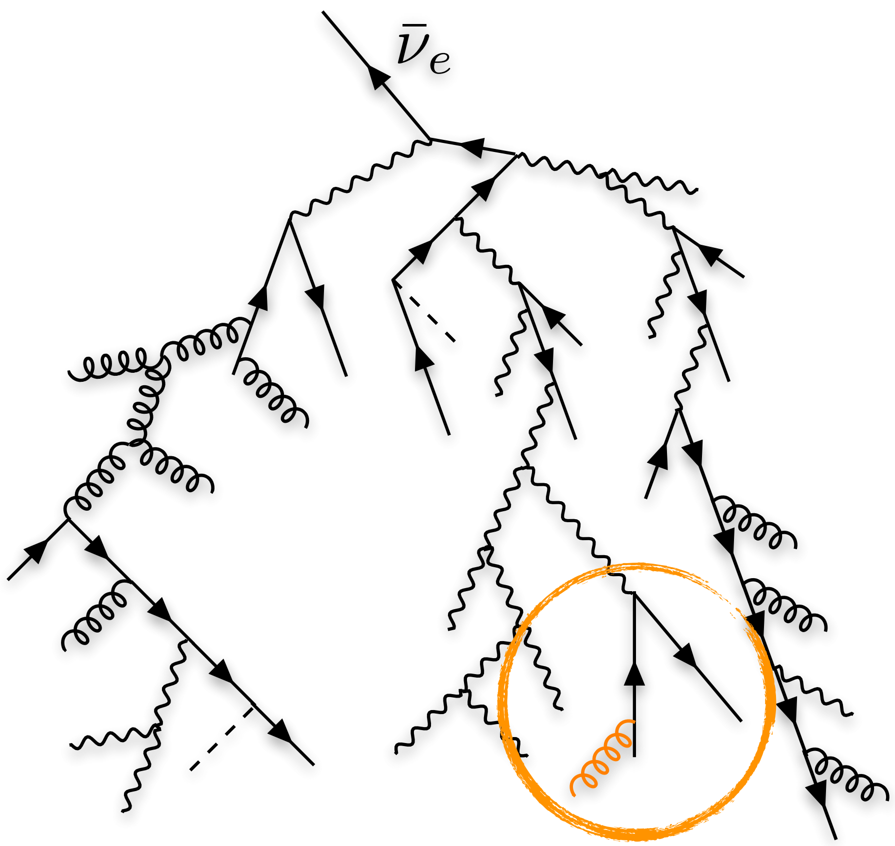

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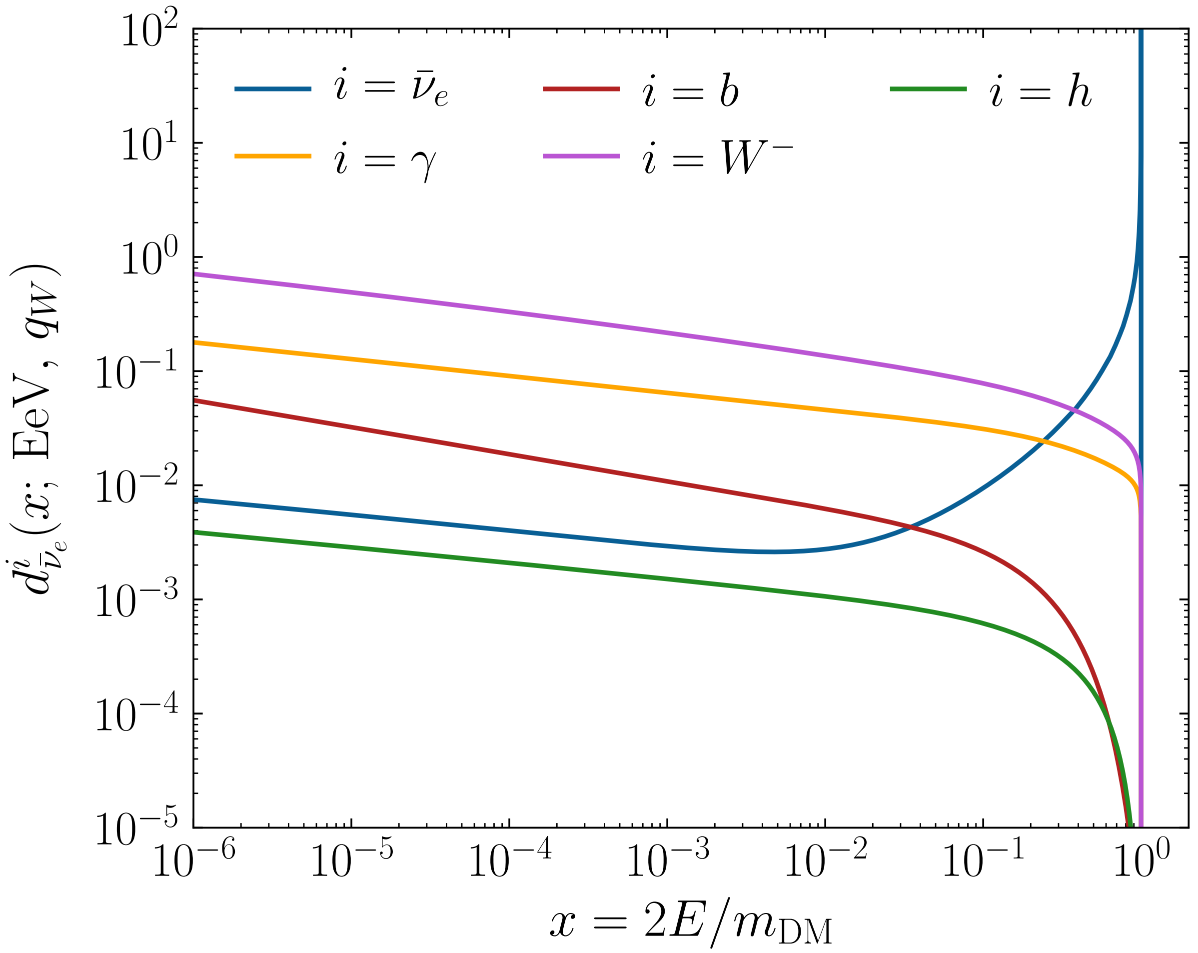

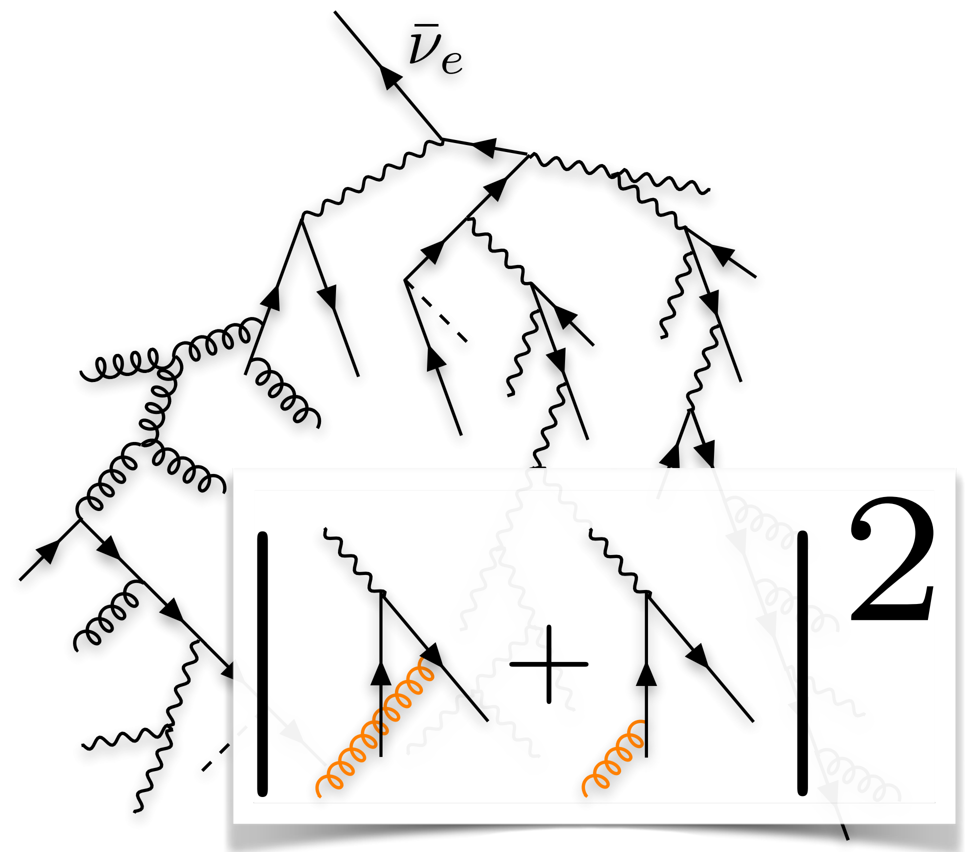

[Bauer, NLR, Webber 2020]

Soft Coherence

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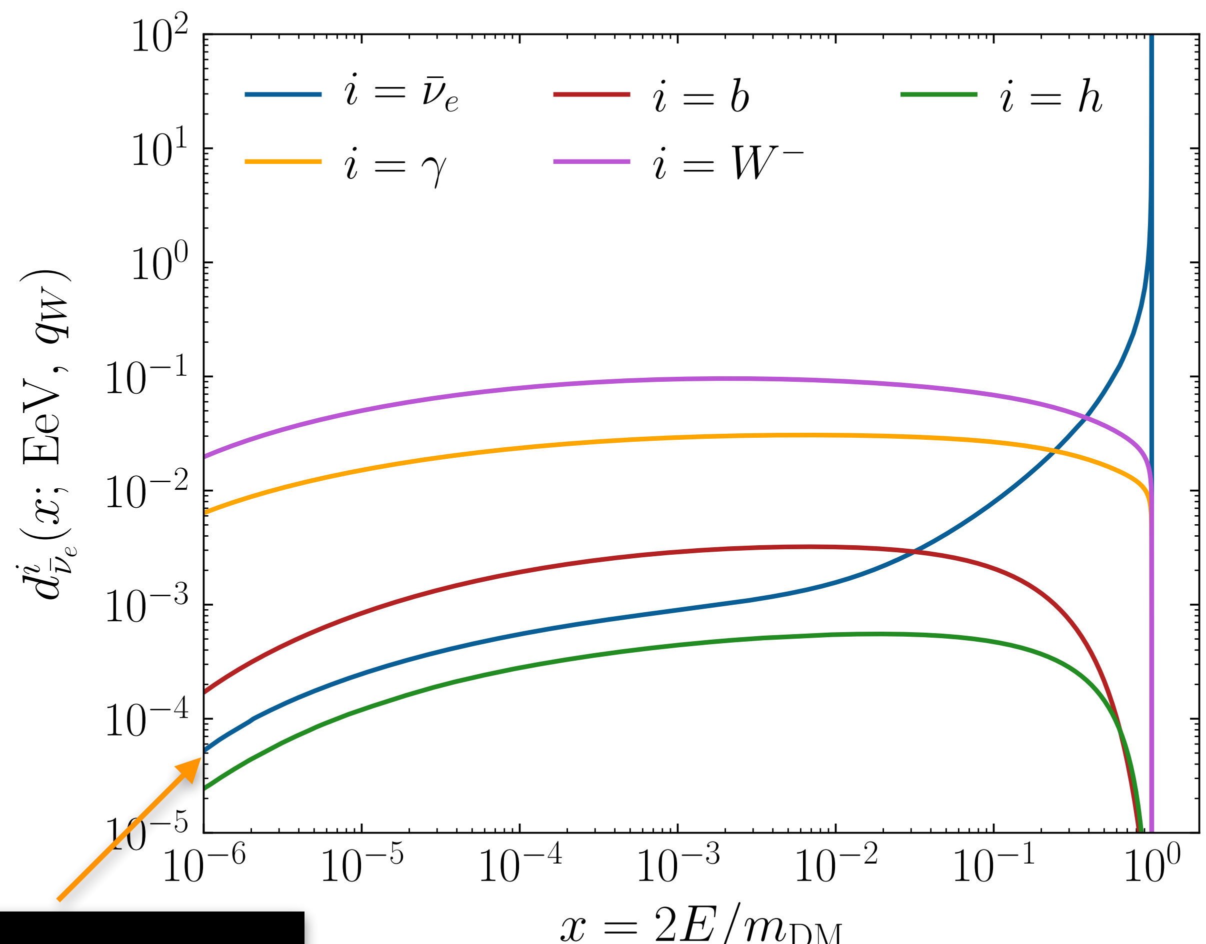
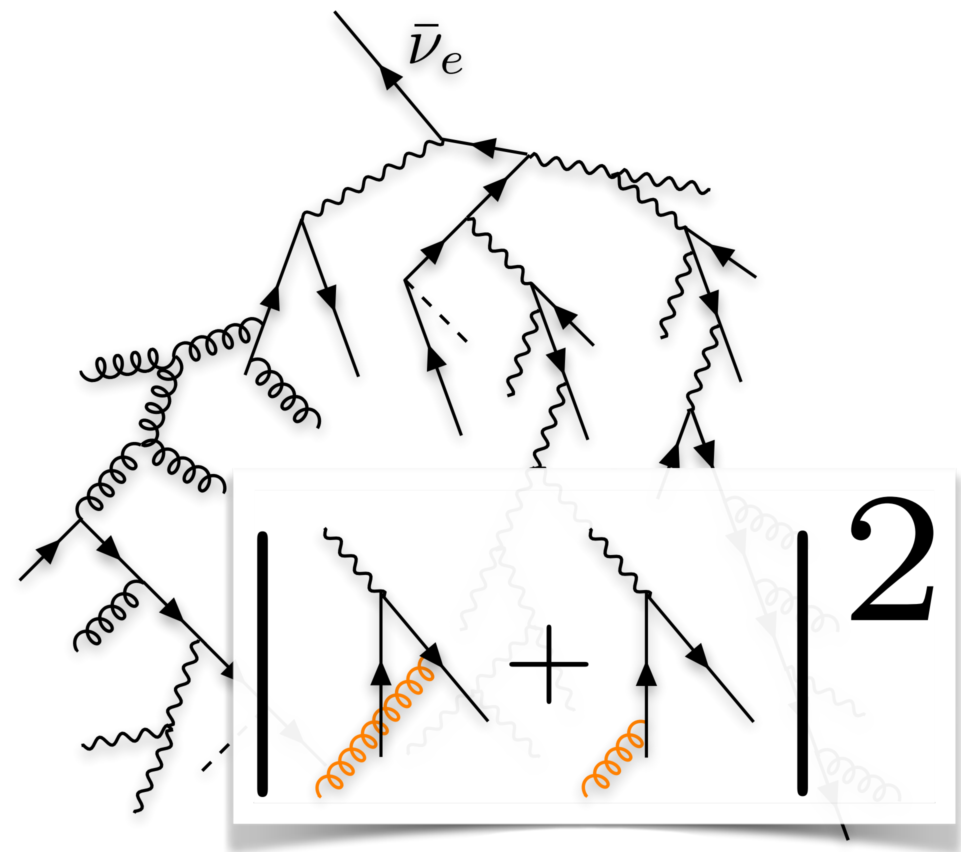


Small-x suppression due to soft coherence - destructive interference!



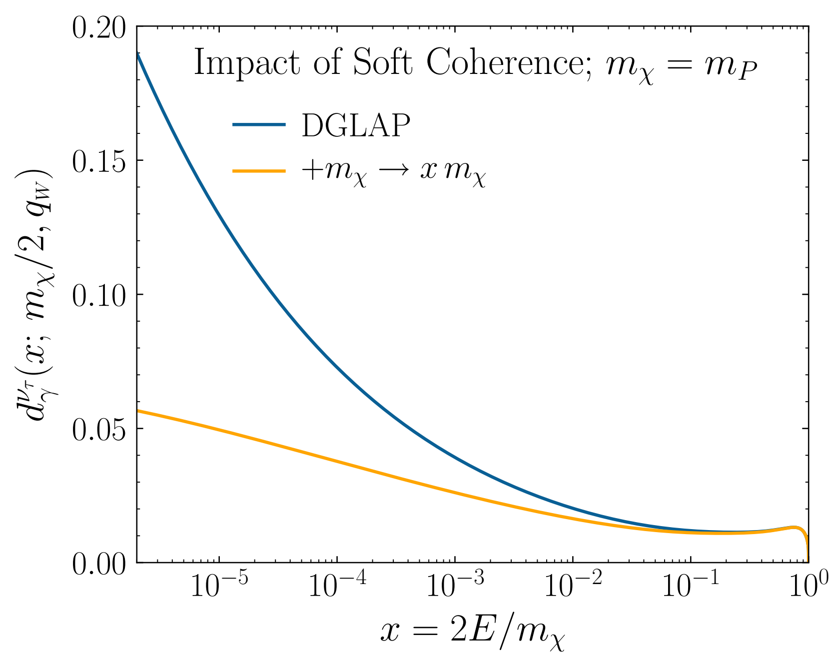
[Bauer, NLR, Webber 2020]

Soft Coherence

- [Bassetto, Ciafaloni, Marchesini 1983]

$$xD_g(x;\,Q) = \delta(1-x) + \sum_{n=1}^{\infty} \frac{(C_A\alpha_3/\pi)^n}{n!(n-1)!}\left(\ln\frac{Q^2x^2}{Q_0^2}\right)^n\left(\ln\frac{1}{x}\right)^{n-1}$$

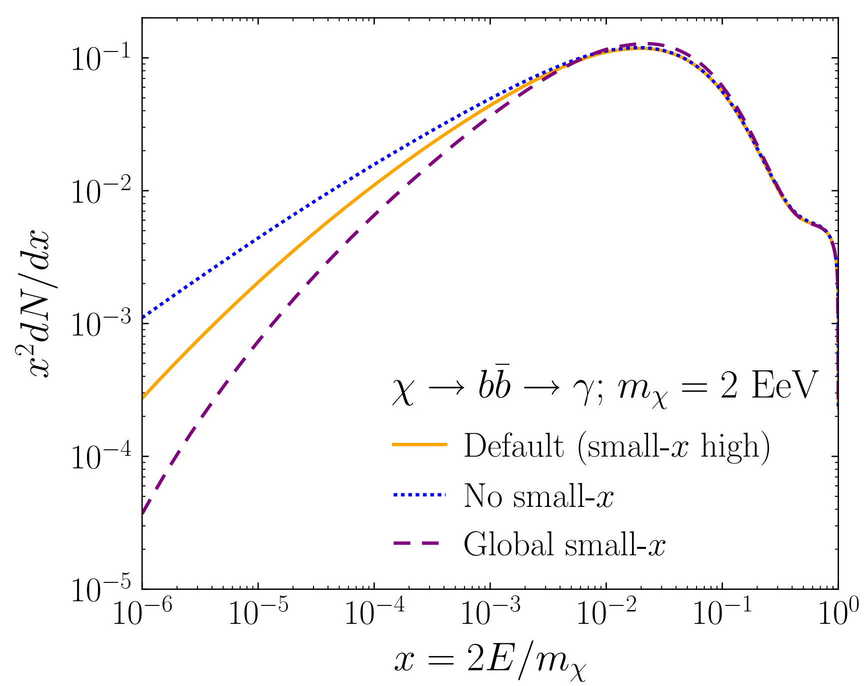
- This result satisfies a DGLAP equation, but with:

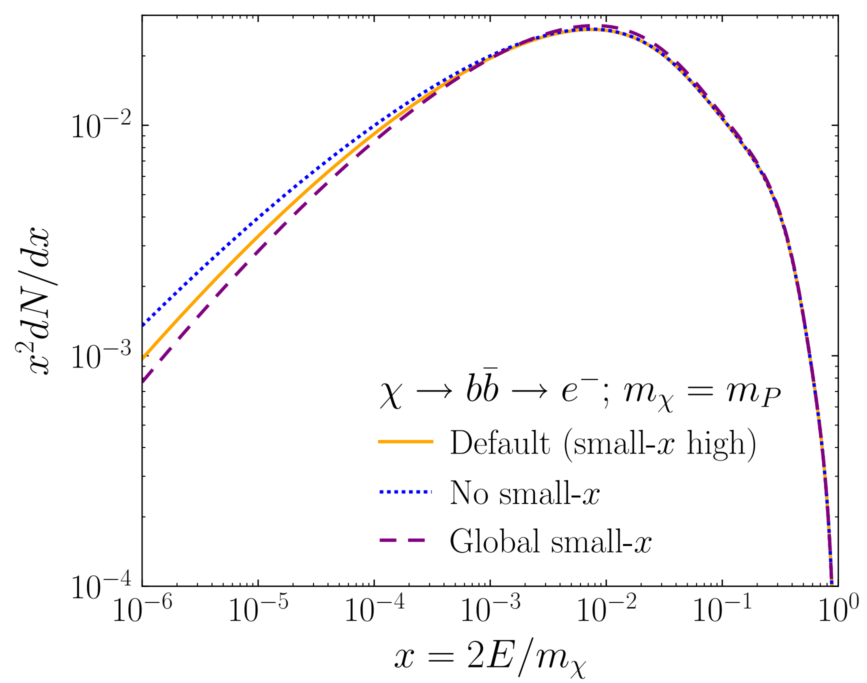


We also factor out the SU(2) double logs from the substitution

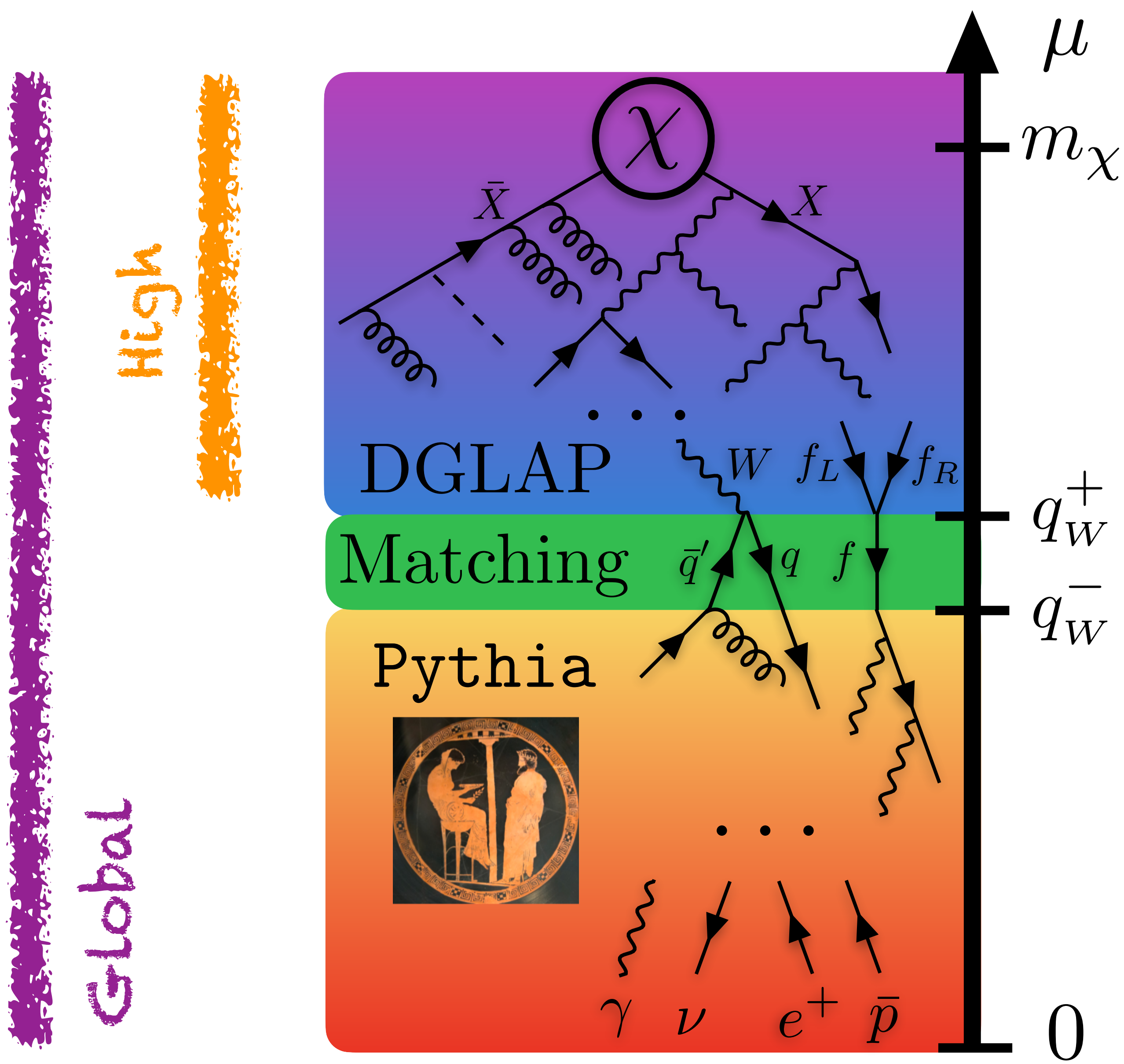
[Bauer, NLR, Webber 2020]

Soft Coherence



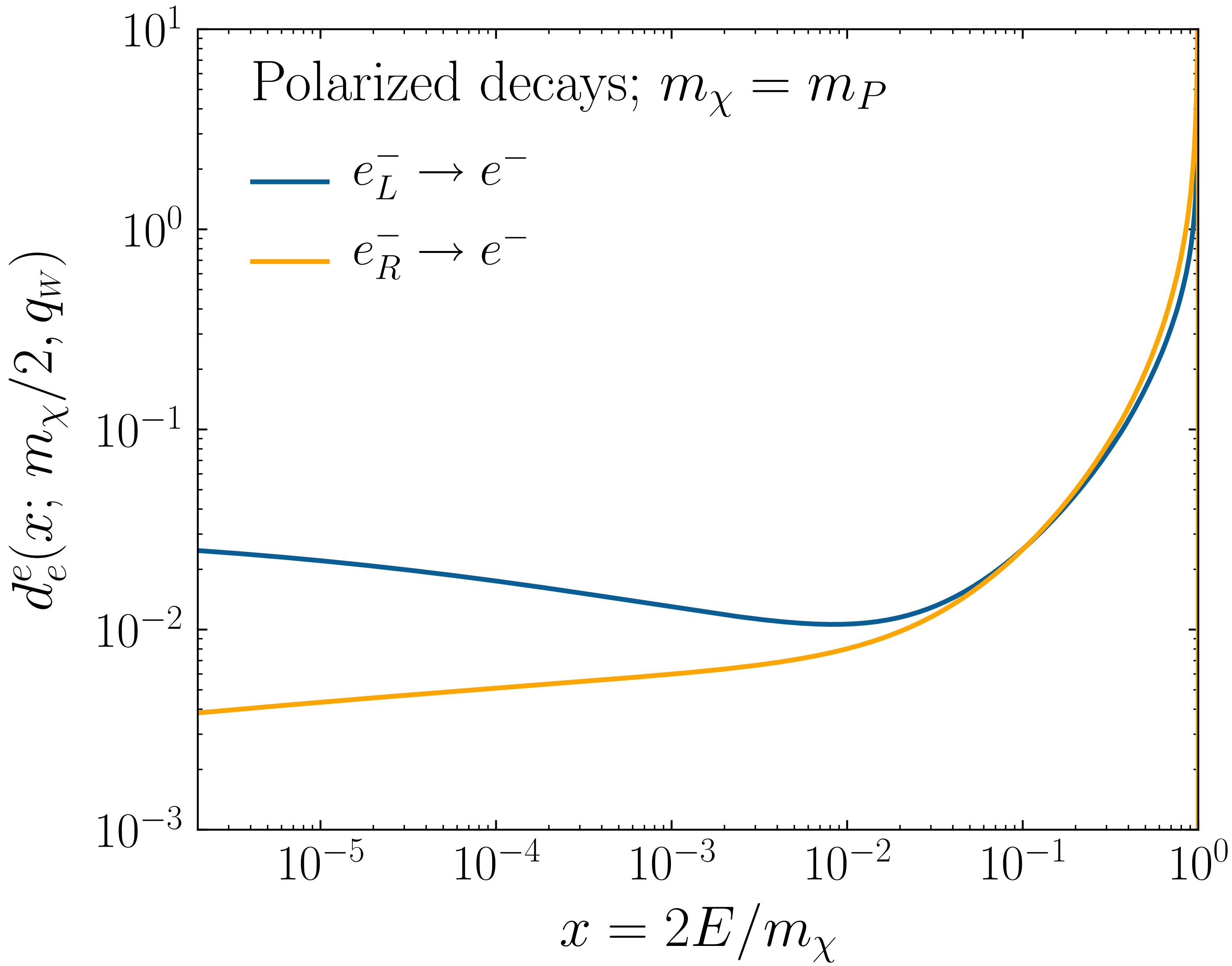


- Where should it be applied?



[Bauer, NLR, Webber 2020]

Importance of Polarization



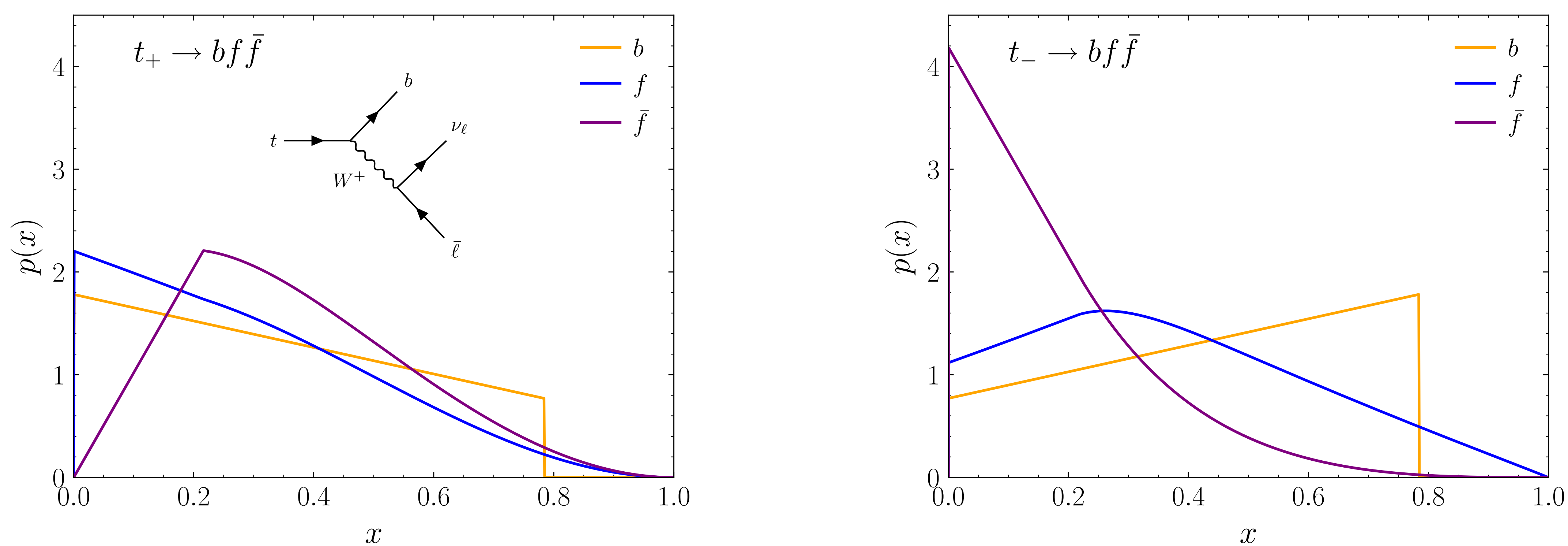
[Bauer, NLR, Webber 2020]

Weak Matching

- **Exploit FF convolution property**

$$d(x;\, m_\chi, q_W^-) = \int_x^1 \frac{dz}{z} d(z;\, m_\chi, q_W^+) d(x/z;\, q_W^+, q_W^-)$$
$$= d(x;\, m_\chi, q_W^+) \otimes d(x;\, q_W^+, q_W^-)$$

- **Most states do not evolve, EW scale states (Z, W, h, t) decay**
- **Must account for polarized decays, all analytically**

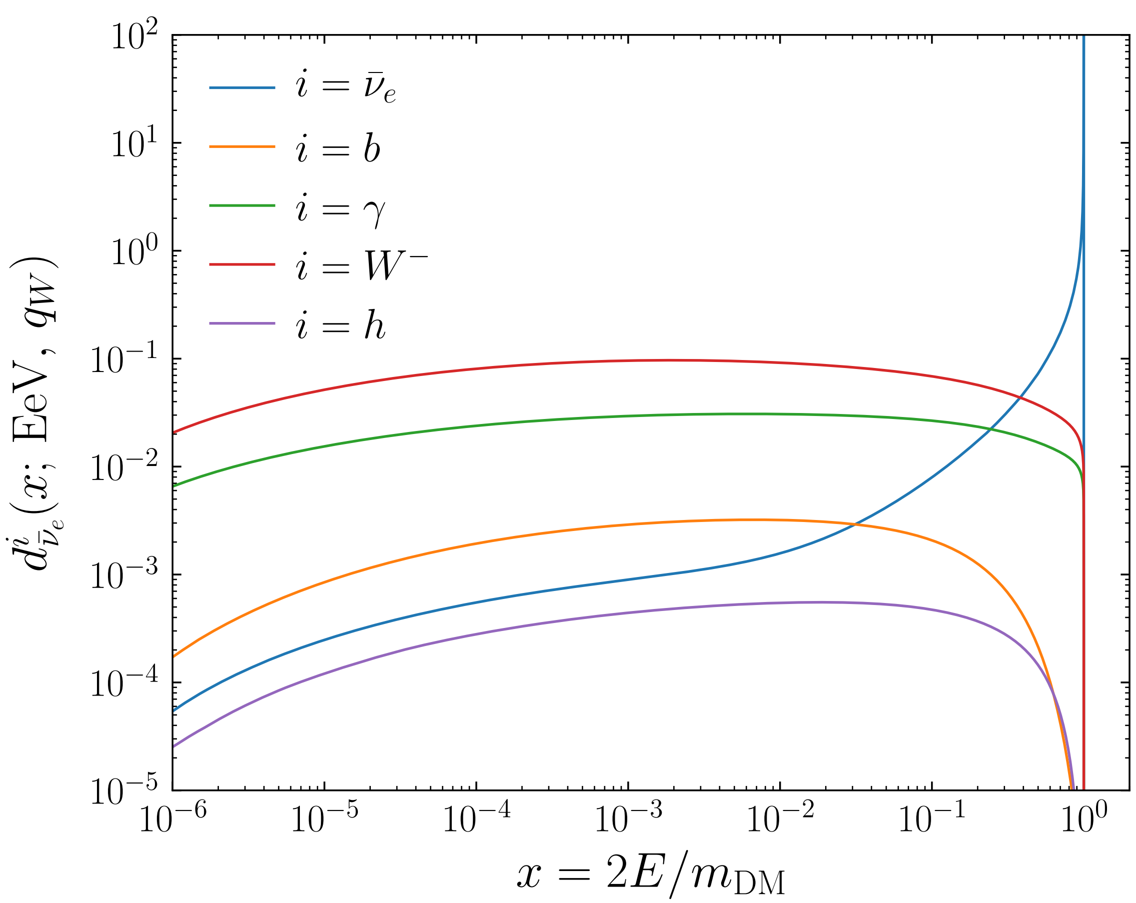


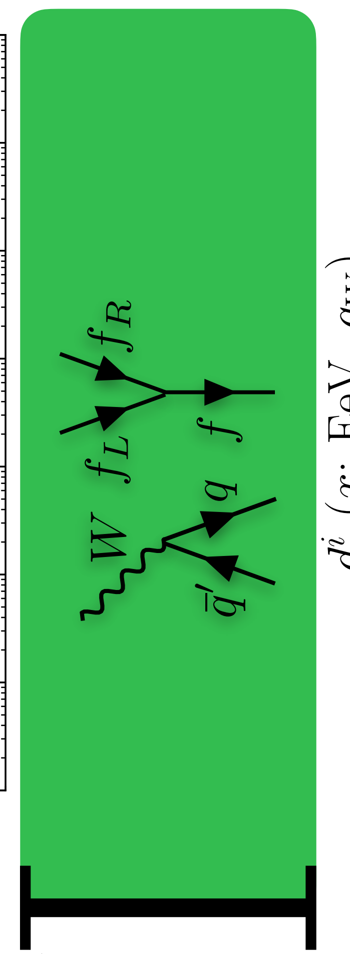
[Bauer, NLR, Webber 2020]

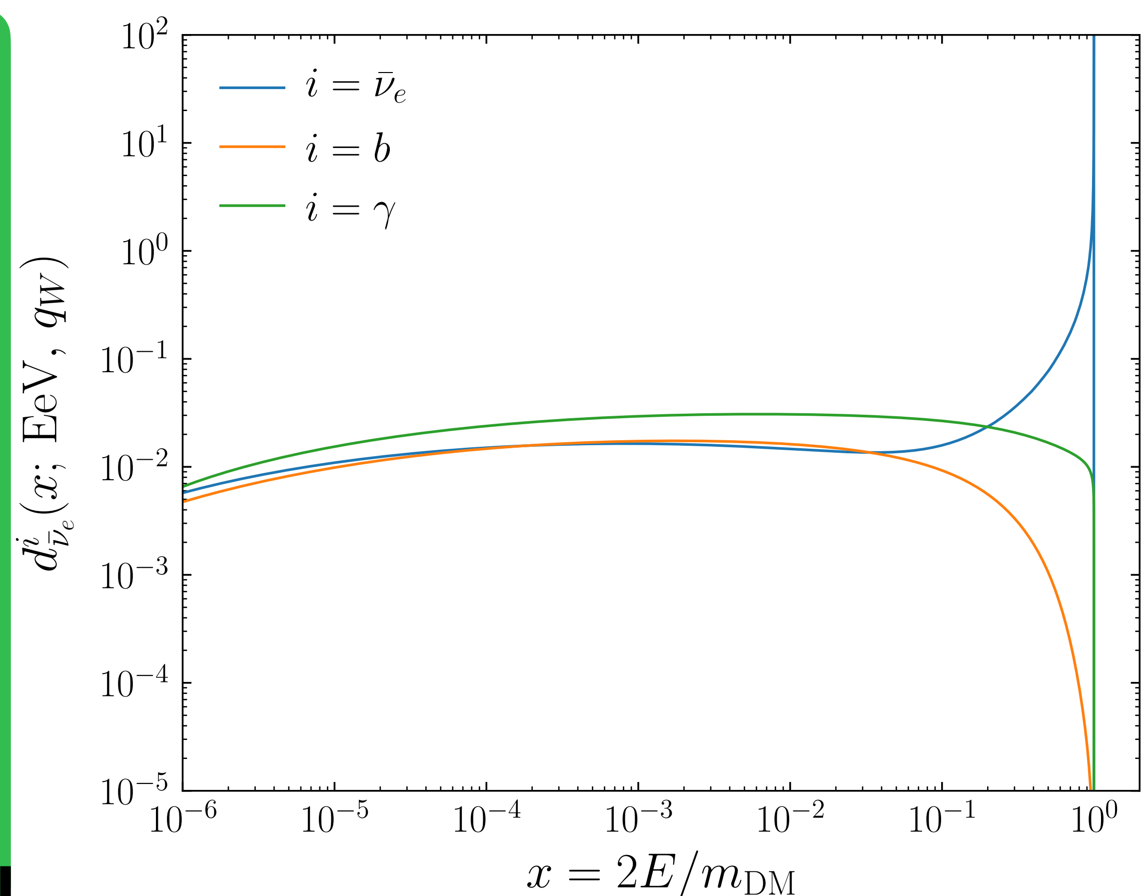
Weak Matching

Impact on the spectra

$$d(x;\, m_\chi, q_W^-) = d(x;\, m_\chi, q_W^+) \otimes d(x;\, q_W^+, q_W^-)$$







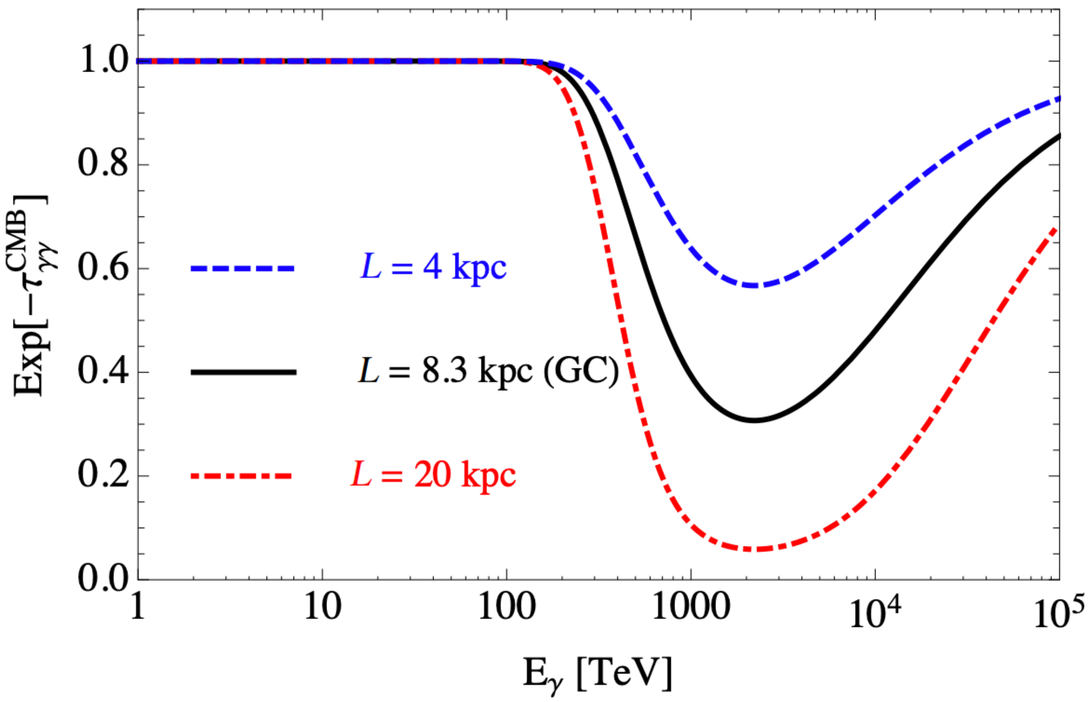
q_W^+ q_W^-

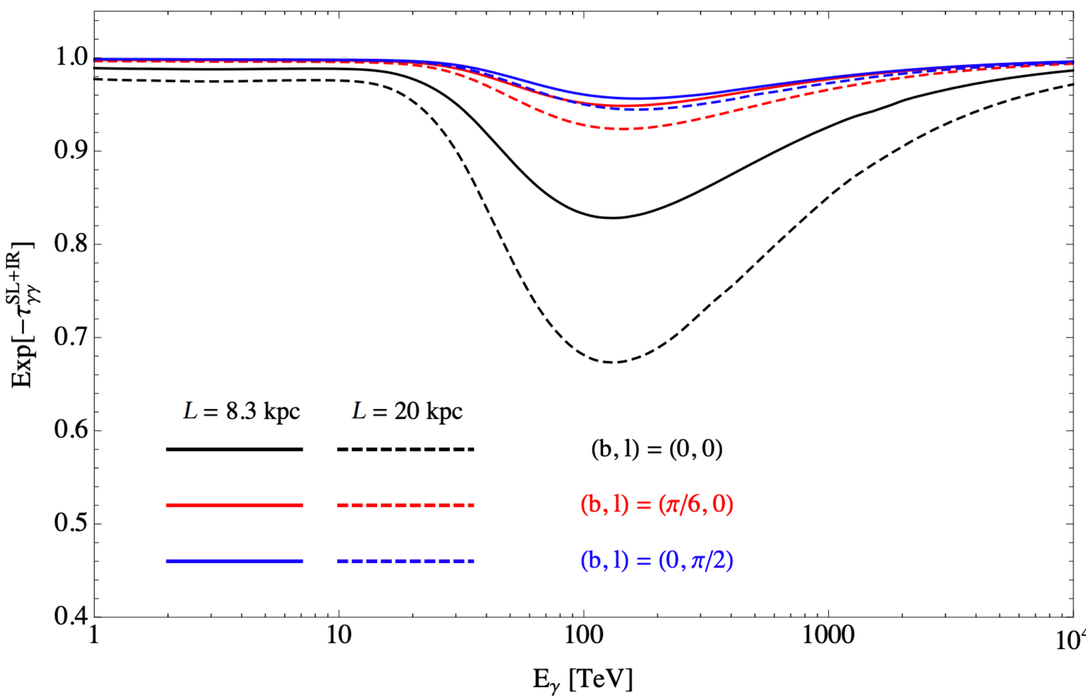
Matching

[Bauer, NLR, Webber 2020]

Propagation Effects

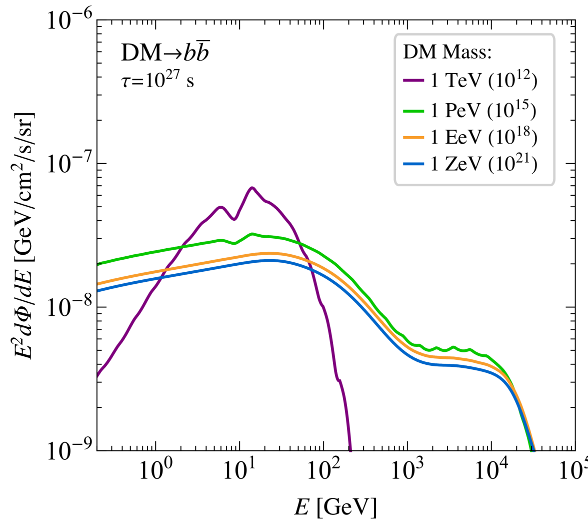
Will a photon make it to Earth?





[Esmailia, Serpico 1505.06486]

What we actually see:

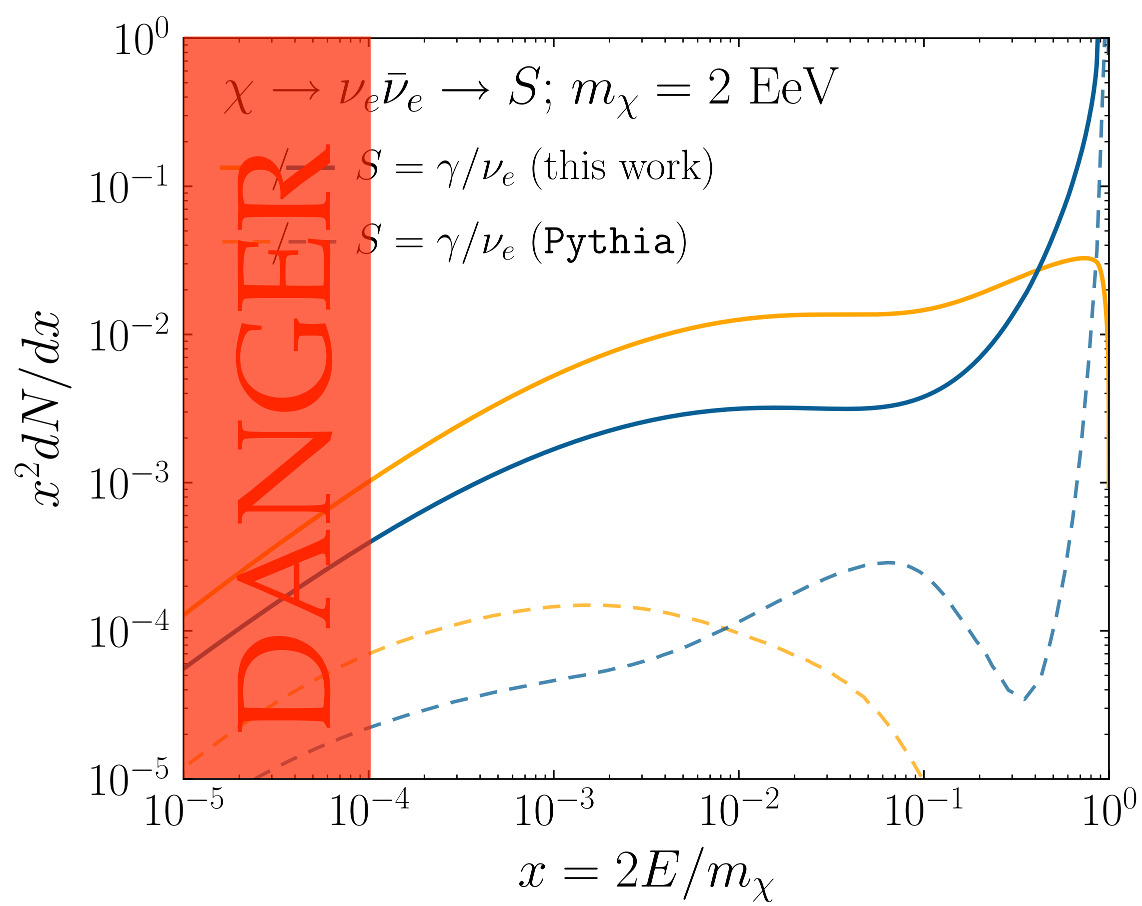


[NLR+ PRL 2017]

[Bauer, NLR, Webber 2020]

Uncertainties

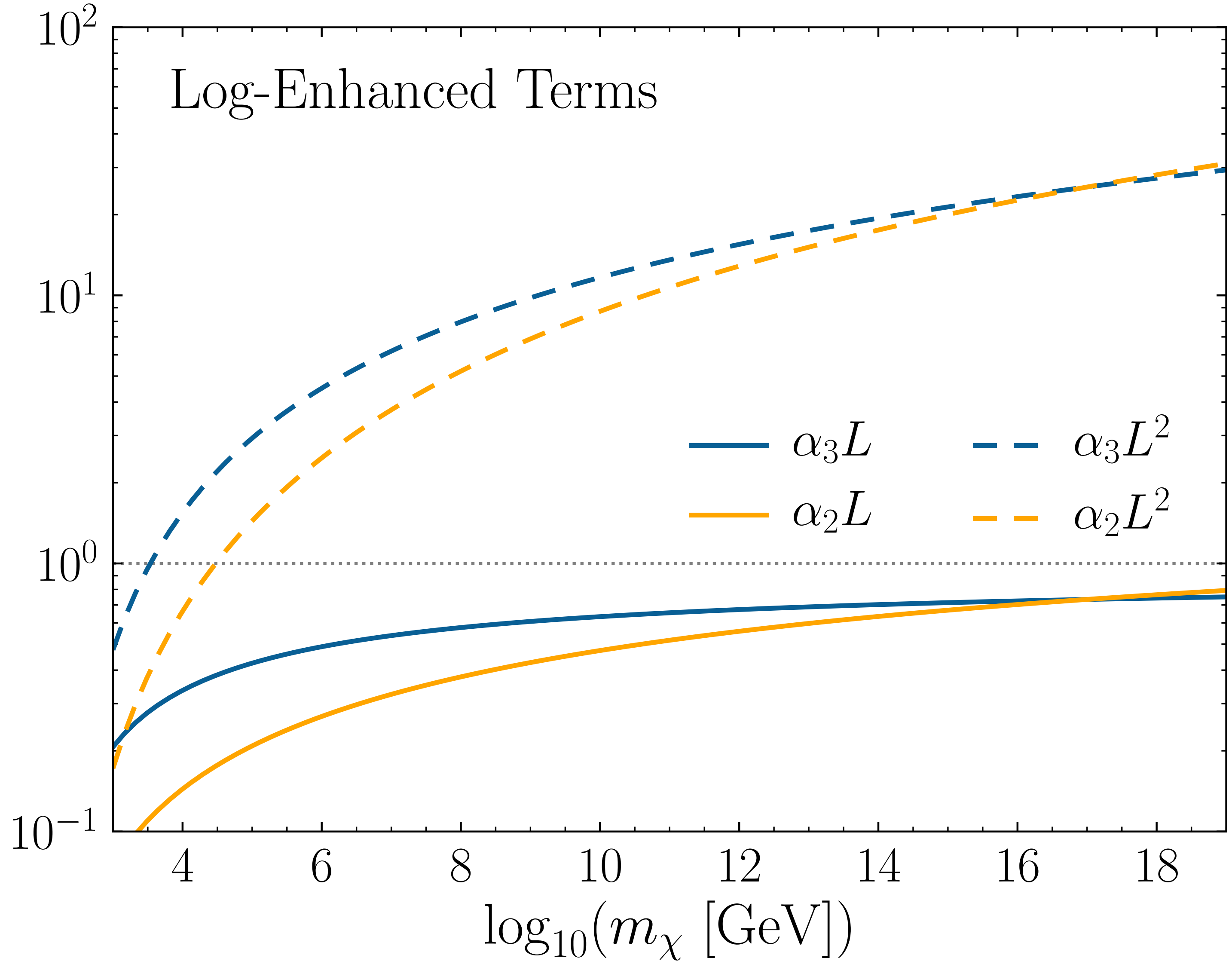
- Missing a complete treatment of (soft) QCD single logs
- Large corrections for $\alpha_s L \sim 1$, i.e. $x \approx e^{-1/\alpha_s} \approx 10^{-4}$
- Simple argument, only an estimate of where results break



[Bauer, NLR, Webber 2020]

Uncertainties

- Size of missing αL logs at higher dark matter masses



NB: include running couplings

[Bauer, NLR, Webber 2020]

Electroweak Double Logs

Terminals on DGLAP equations

$$\mu \frac{\partial}{\partial \mu} d(x;\, \mu) = \frac{\alpha}{\pi} \int_x^{z_{\max}} dz\, \hat{P}(z) d(x/z;\, \mu) - \frac{\alpha}{\pi} d(x;\, \mu) \int_0^{z_{\max}} dz\, \hat{P}(z)$$

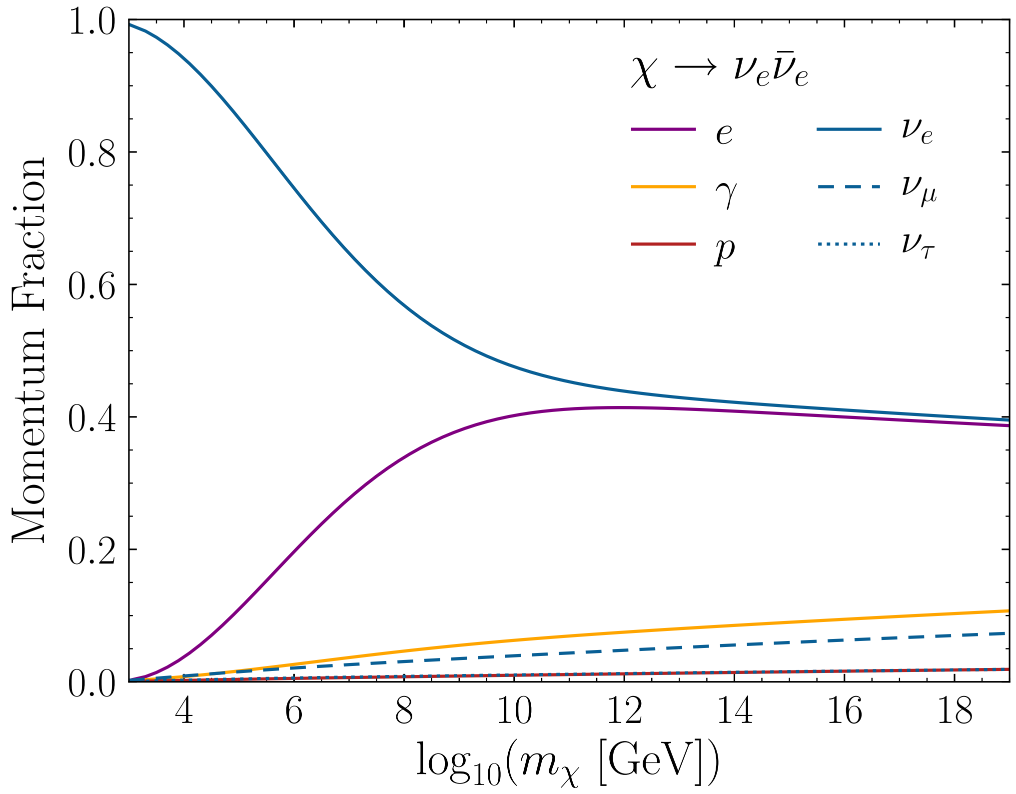
$$z_{\max} = \begin{cases} 1 - m_V/\mu & \text{for } U(1)_Y, SU(2)_L \\ 1 & \text{otherwise} \end{cases}$$

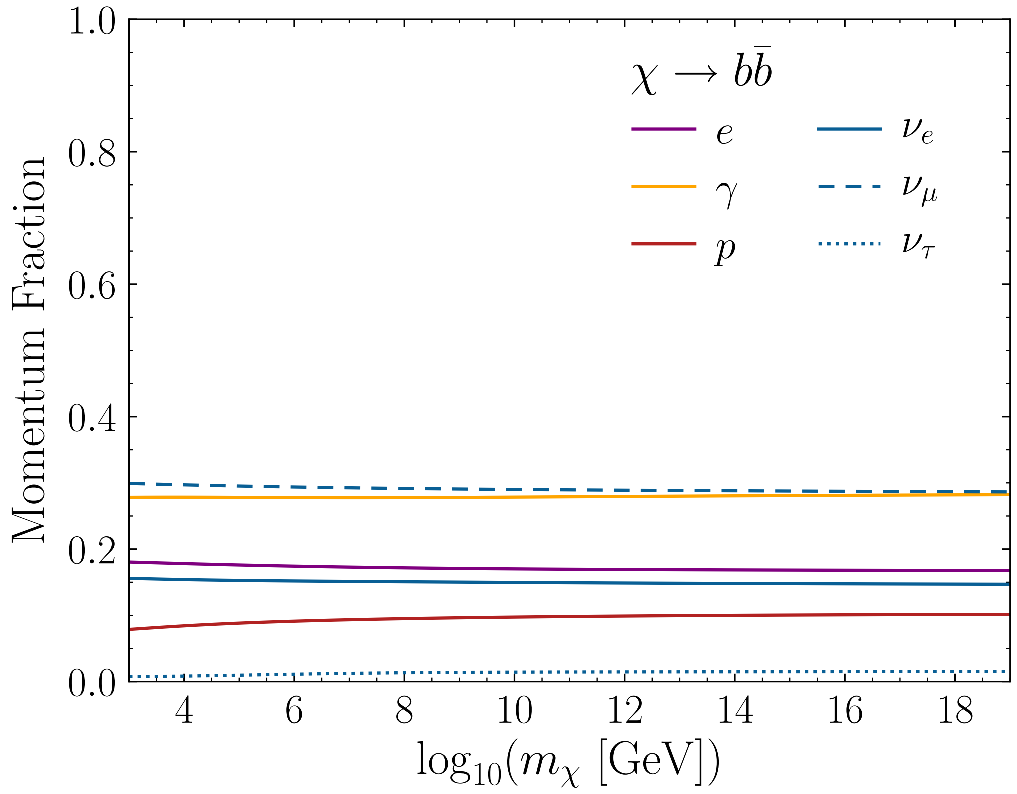
Origin of the EW double logs

c.f. SCET_{II} treatment of the same physics [Manohar, Waalewijn 1802.08687]

[Bauer, NLR, Webber 2020]

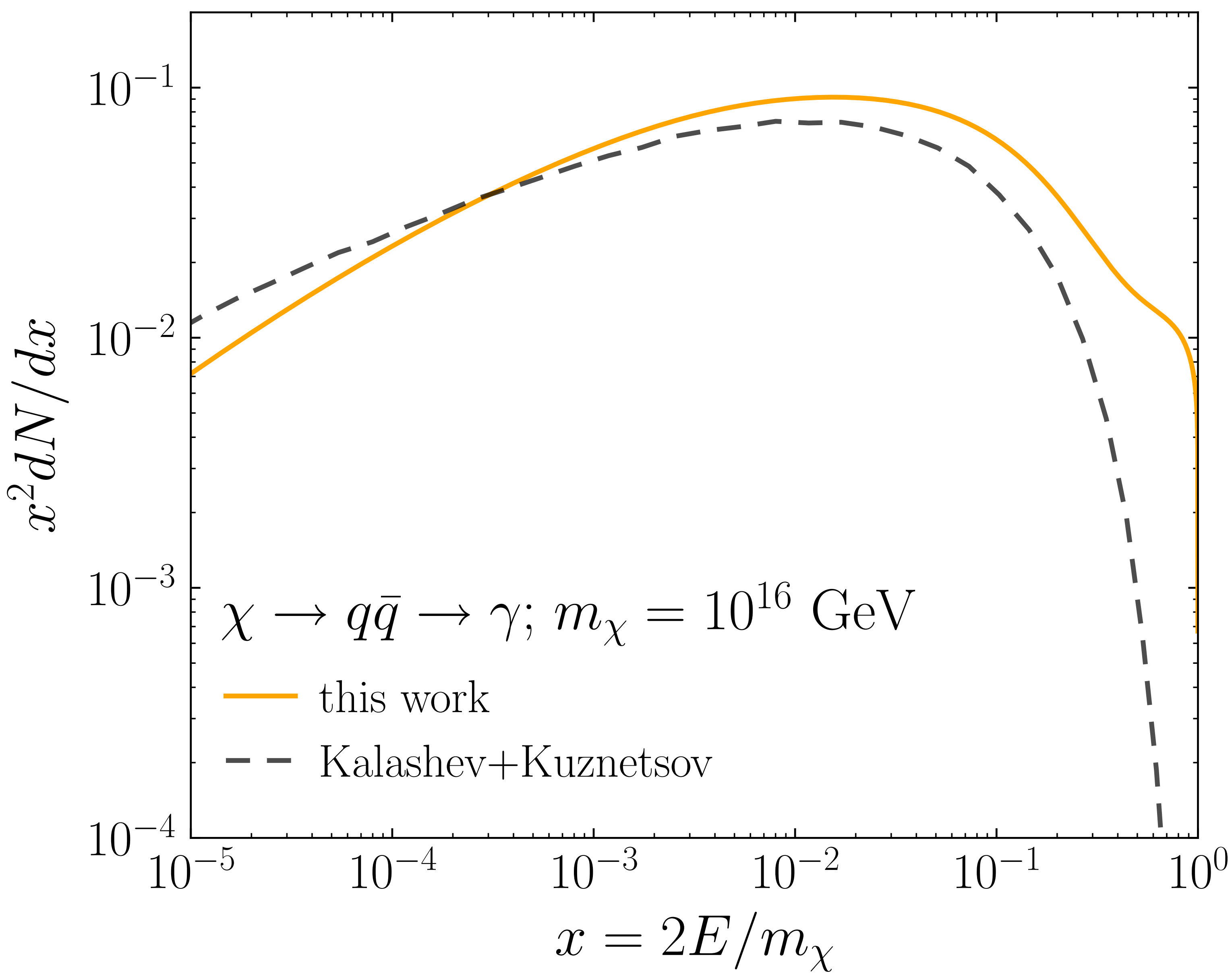
Momentum Fractions





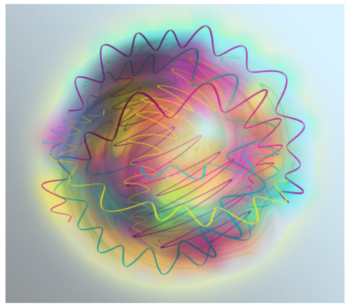
[Bauer, NLR, Webber 2020]

Hadronic Results



[Bauer, NLR, Webber 2020]

Explicit Model: Glueball



- Glueballs: lowest lying state of a hidden sector containing only a confining SU(N) gauge theory (dark QCD)
  - Naturally long lived and thereby a DM candidate
  - Mass at the confinement scale - for SU(3) unifying with the SM can get m~100 TeV
- Lowest order coupling to the standard model is dim-6

$$\mathcal{L} \supset \frac{\lambda'}{\Lambda^2} G'_{\mu\nu} G'^{\mu\nu} |H|^2 \;\rightarrow\; \lambda' \frac{\Lambda^3_{\mathrm{QCD}'}}{\Lambda^2} \phi_{G'} |H|^2$$

- The lifetime then comes out as:

$$\tau \approx 5 \times 10^{27}\ \mathrm{s} \left(\frac{3}{N'} \frac{1}{4\pi\lambda'} \right)^2 \left(\frac{\Lambda}{m_{\mathrm{pl}}} \right)^4 \left(\frac{100\mathrm{TeV}}{\Lambda_{\mathrm{QCD}'}} \right)^5$$

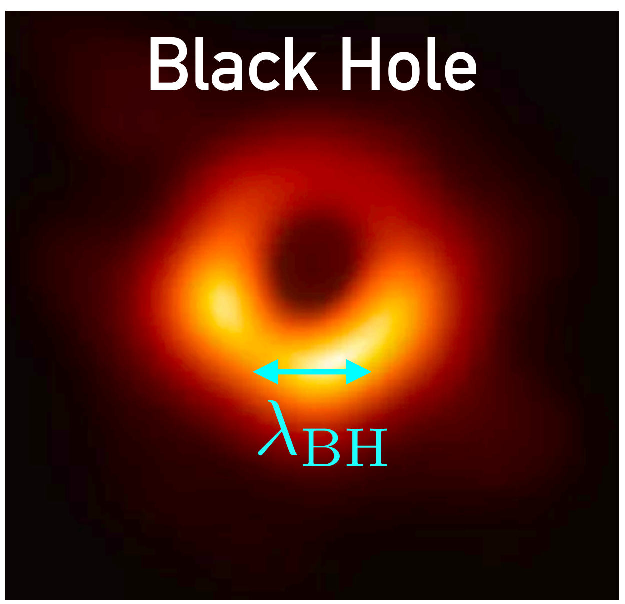
See e.g. [hep-ph/0008223], [1402.3629], [1605.08048], [1609.02151]
Recent examples, [1811.06975], [1812.03516], [1906.00981], [2003.02846], [2003.04900], [2003.04936]

[Bauer, NLR, Webber 2020]

Heavy Dark Matter

$$n_{\rm sun}^{\rm DM} \sim 10^{-4} \left(\frac{m_P}{m_{\rm DM}} \right) \text{ particles/km}^3$$

Heavy Dark Matter



$$\lambda_{\rm DM} \sim \frac{1}{m_{\rm DM}} \Leftrightarrow \lambda_{\rm BH} \sim m_{\rm DM}$$

$$m_{\rm DM} = m_P \sim 10^{28} \text{ eV} \approx 0.02 \ \mu\text{g}$$

Composite or Black Hole DM could be even heavier

[Bauer, NLR, Webber 2020]