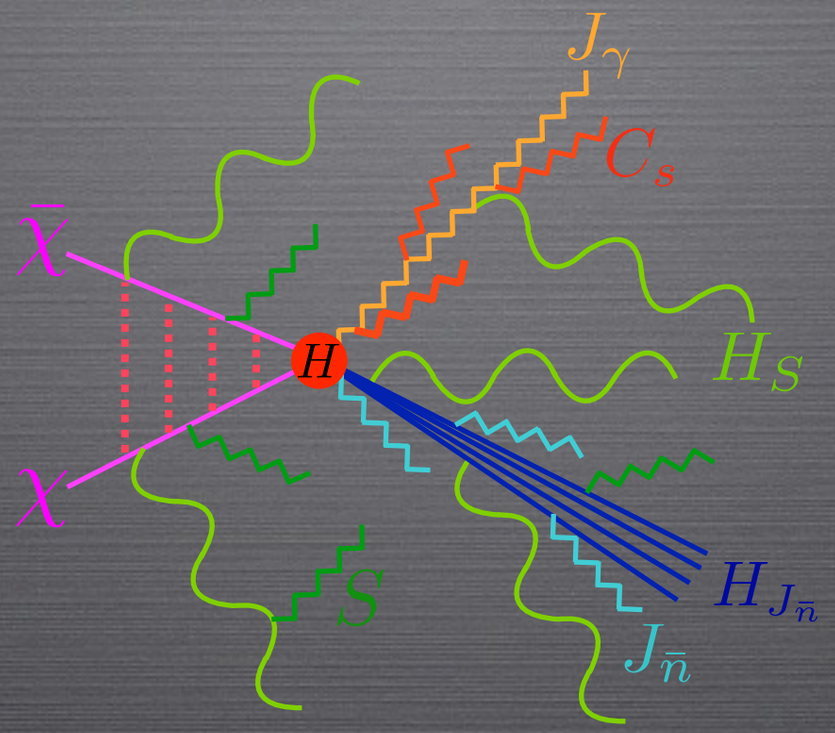
Precision Dark Matter Spectra for Cherenkov Telescopes



Nick Rodd

1712.07656, 1808.04388, and to appear (this week!)

w/ Matthew Baumgart, Timothy Cohen, Emmanuel Moulin, Ian Moult, Lucia Rinchiuso, Tracy R. Slatyer, Mikhail P. Solon, Iain W. Stewart, Varun Vaidya

TeVPA, 27 August 2018

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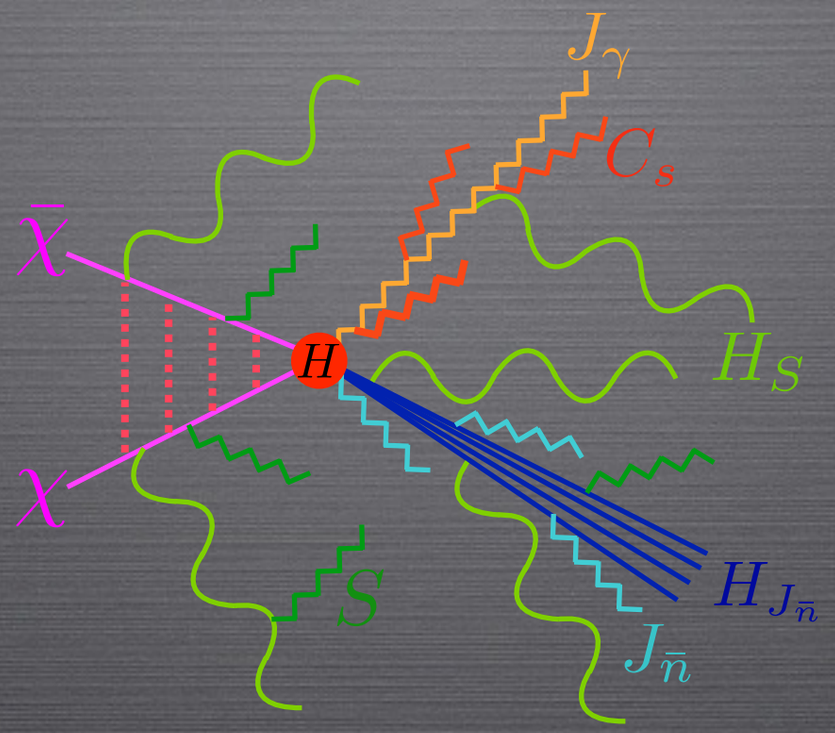


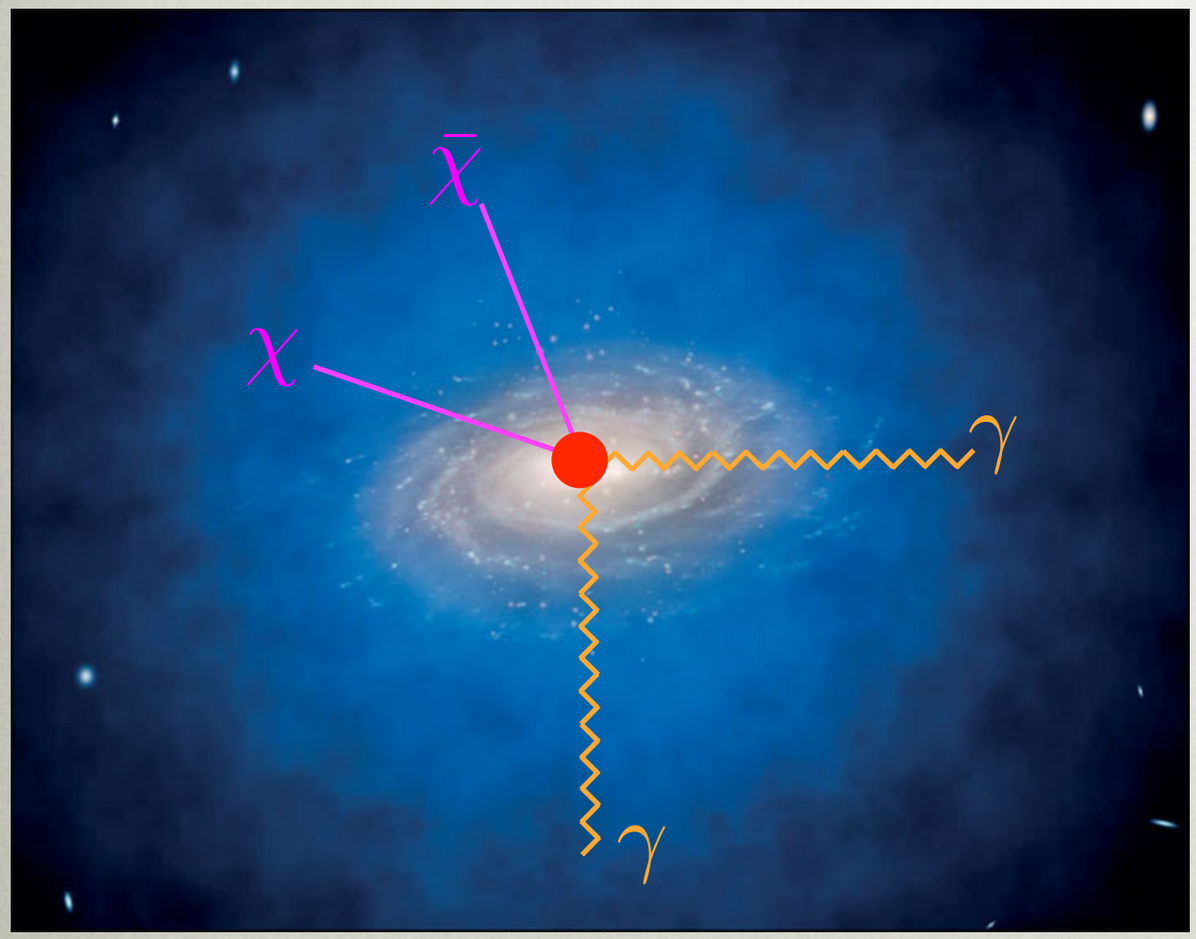
Nick Rodd

1712.07656, 1808.04388, and to appear (this week!)
w/ HDMA Collaboration

TeVPA, 27 August 2018

Discovering TeV Dark Matter

- χ: **Wino (3 TeV),** Higgsino (1 TeV), SU(2) Quintuplet (10 TeV)
- Simple, compelling DM models - how can we test them?



Discovering TeV Dark Matter

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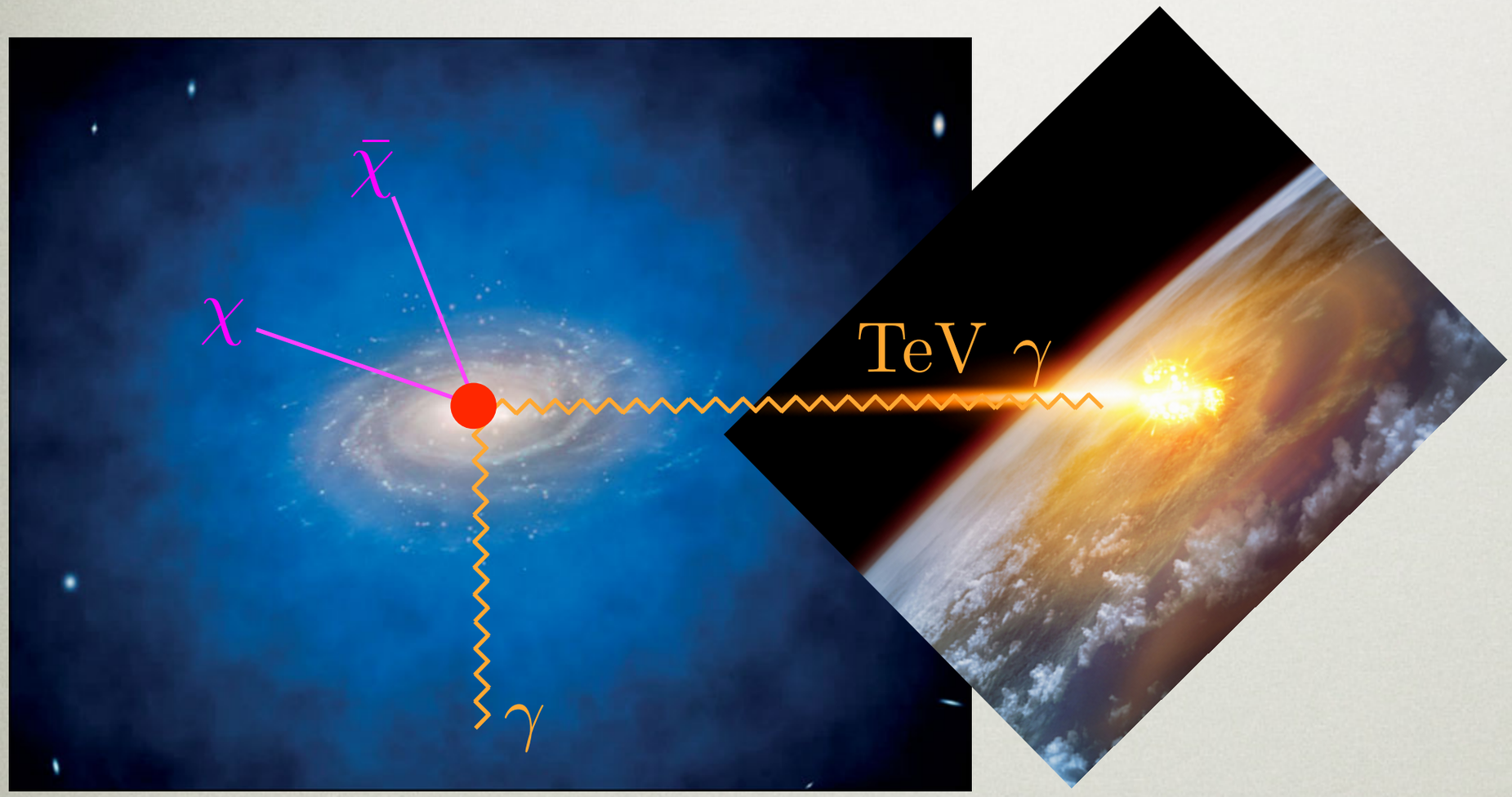

Discovering TeV Dark Matter

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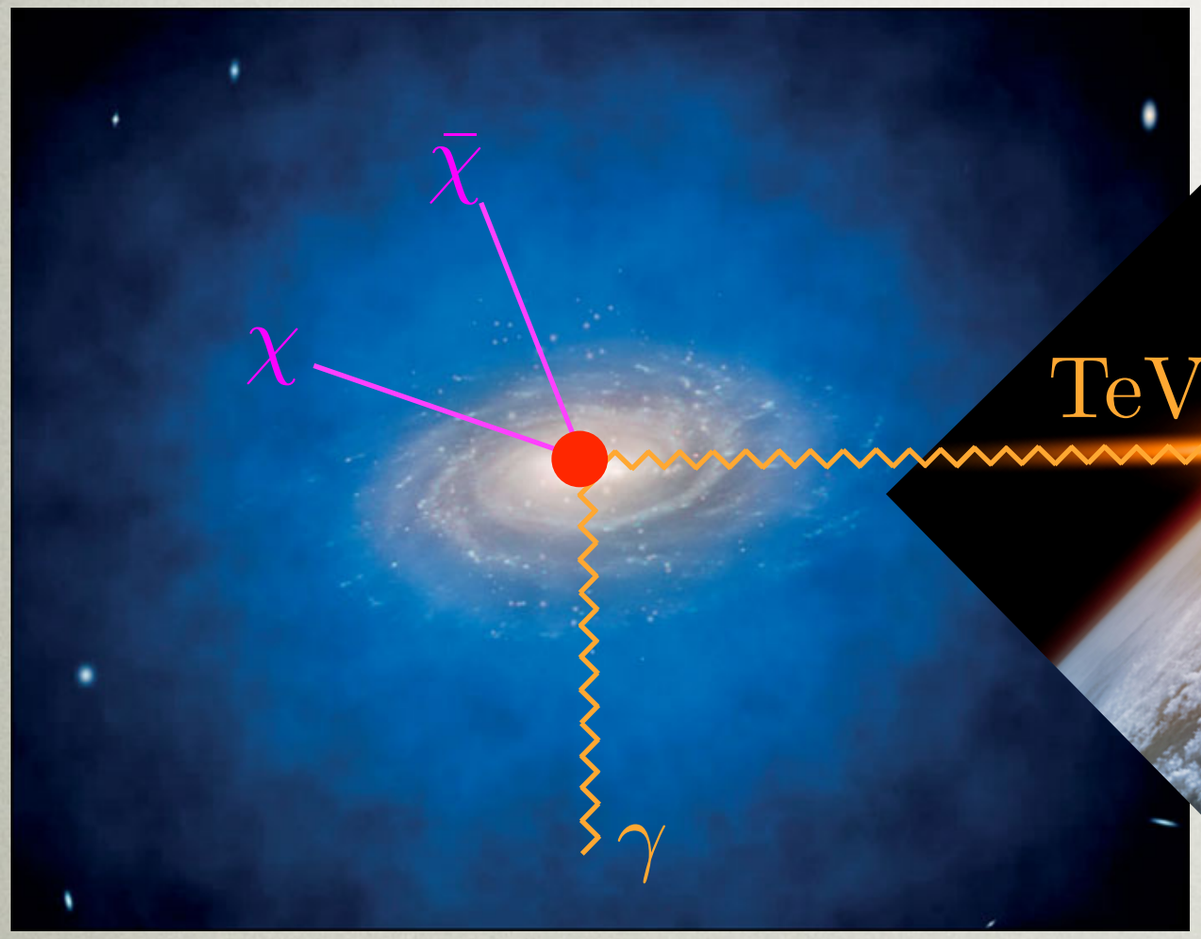
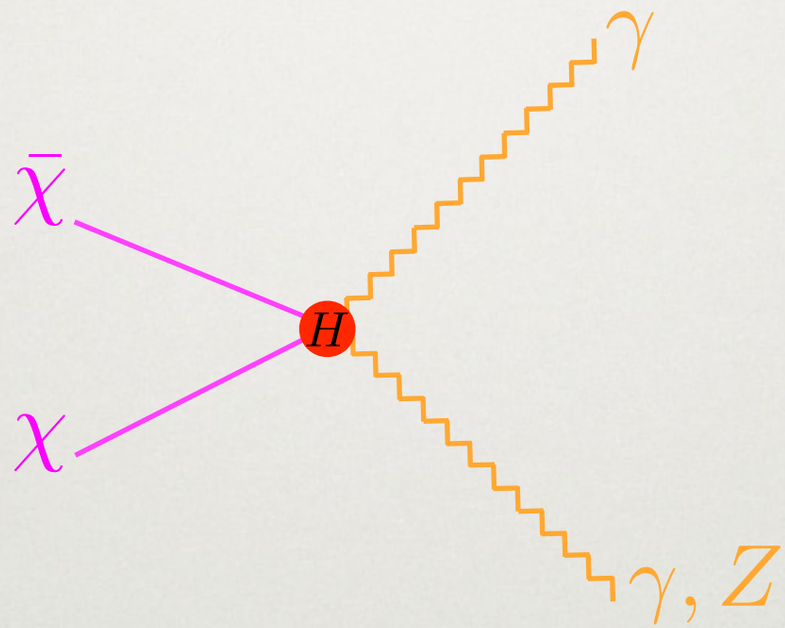
- Annihilation ➜ TeV photons ➜ **Cherenkov Telescopes**



Gamma Ray Lines

- What rate and spectrum of photons does the wino predict?
- Line long known prediction, e.g. [Bergstrom, Ullio `97]



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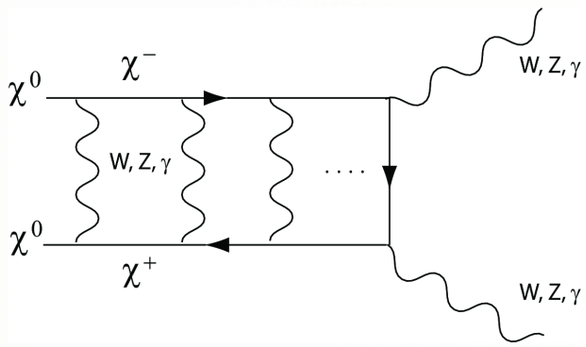
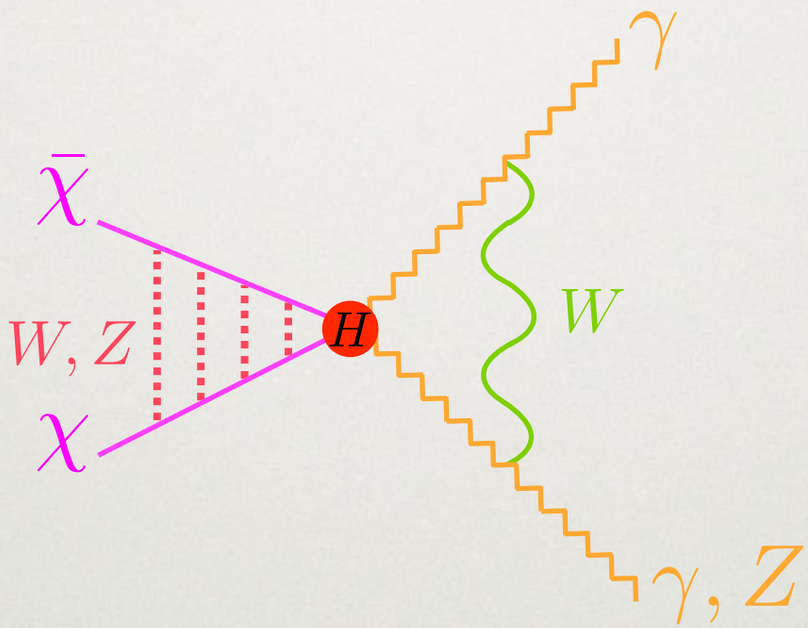
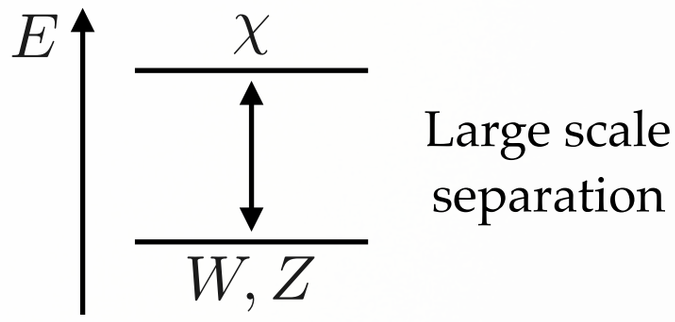
Sommerfeld



[Arkani-Hamed, Finkbeiner, Slatyer, Weiner `08]



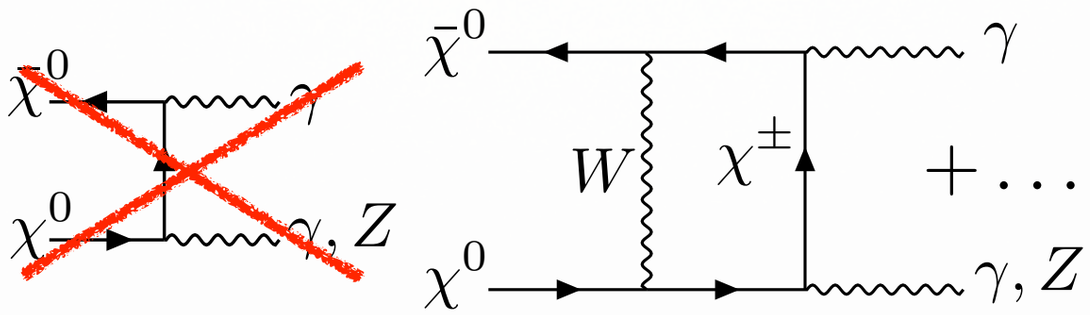
Sudakov Logs



[Bauer, Cohen, Hill, Solon `14]
[Ovanesyan, Slatyer, Stewart `14]
[Ovanesyan, **NLR**, Slatyer, Stewart `16]

Sommerfeld image from [Bergström `12]

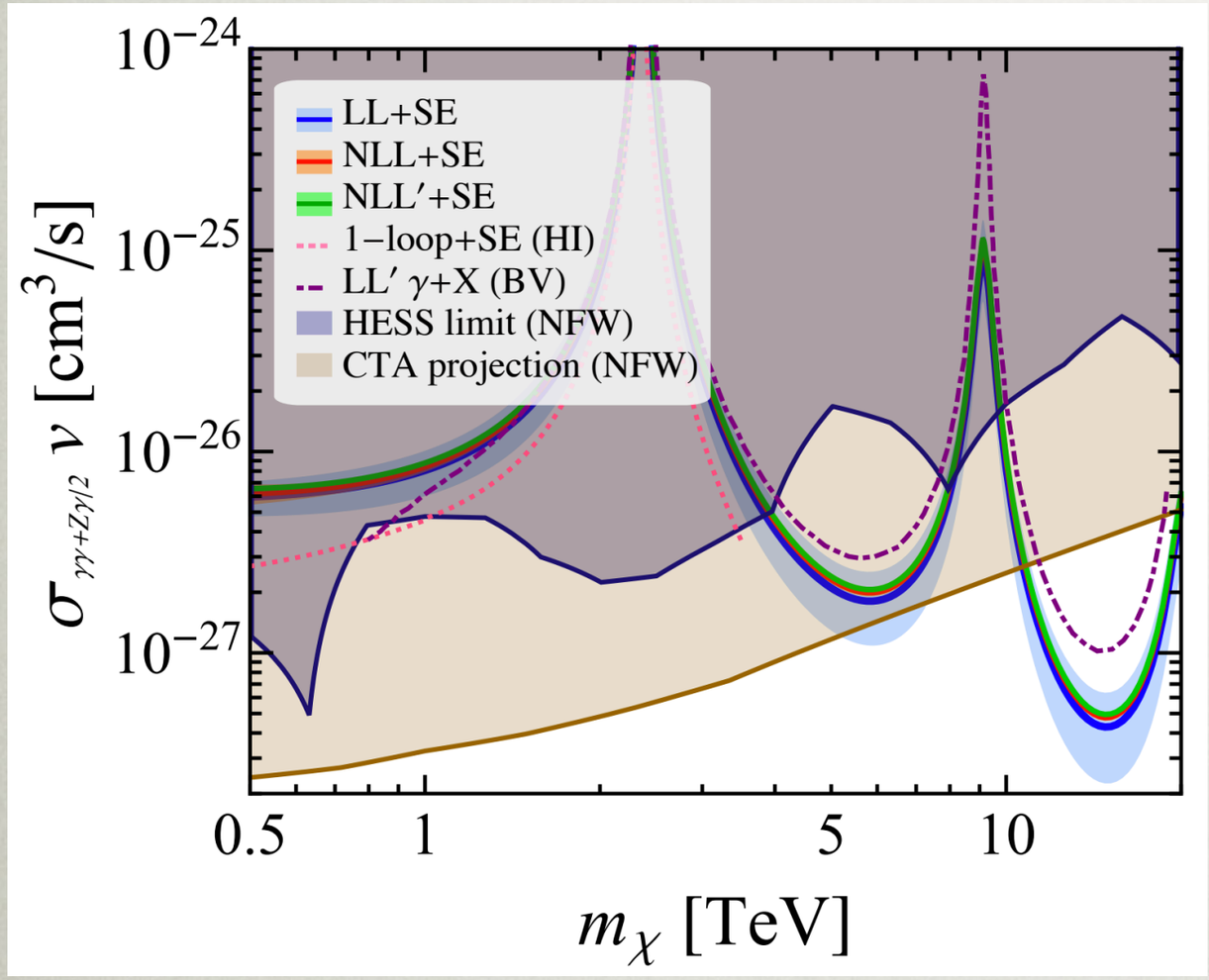
Fixed Order $\langle \sigma v \rangle$



[Hryczuk, Iengo `11]

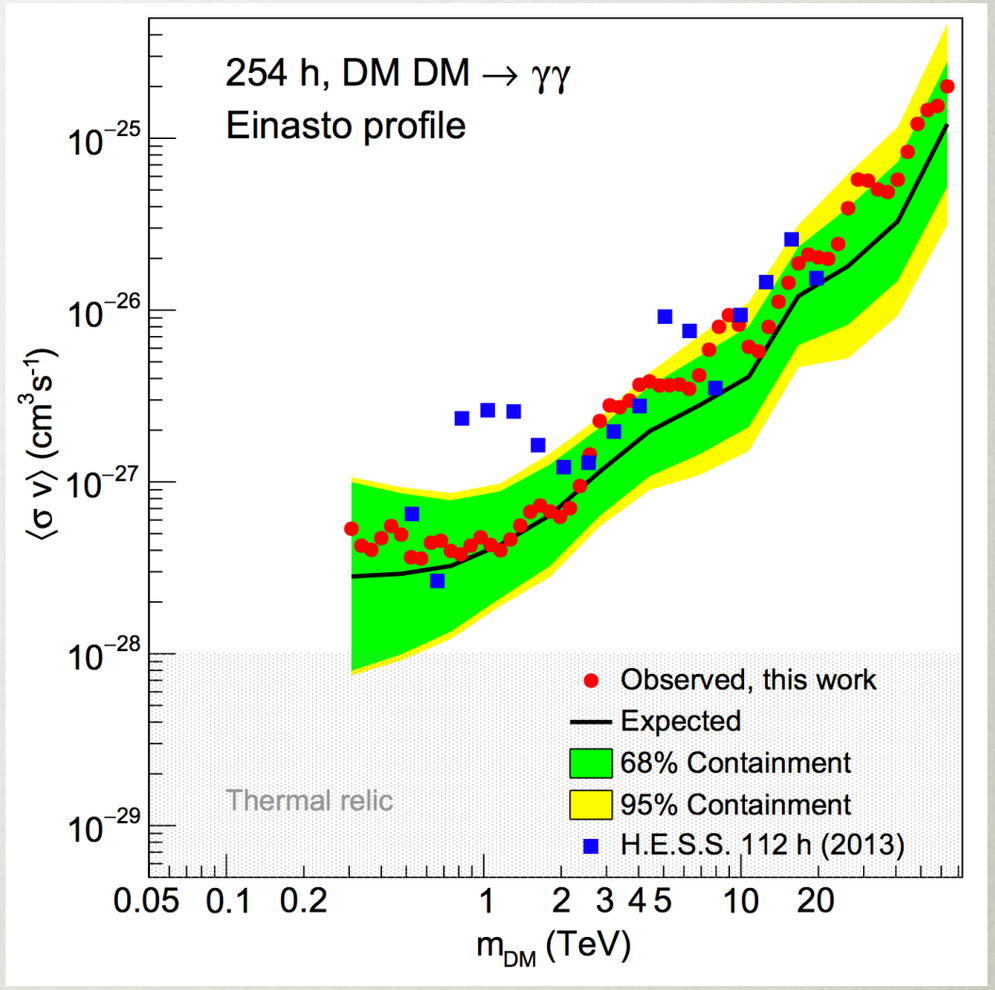
Gamma Ray Lines

Theory Prediction



[Ovanesyan, **NLR**, Slatyer, Stewart `16]

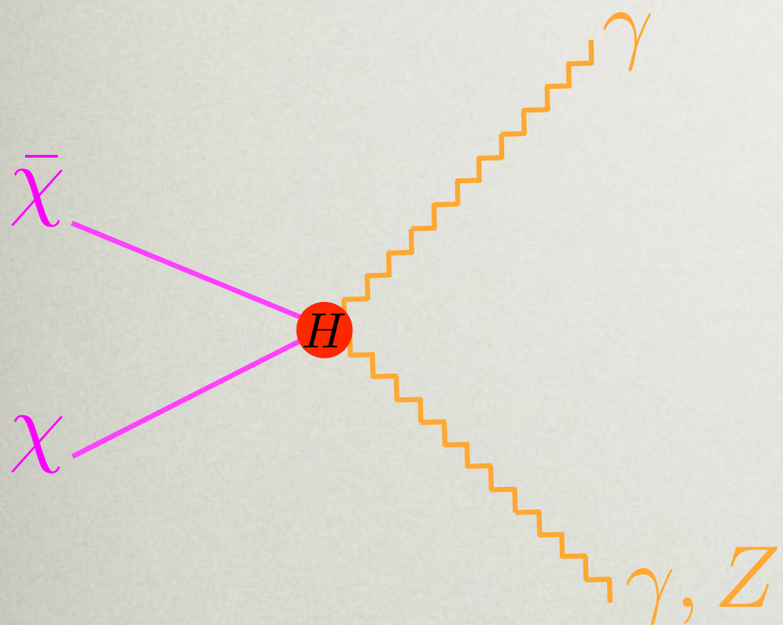
Experimental Limit

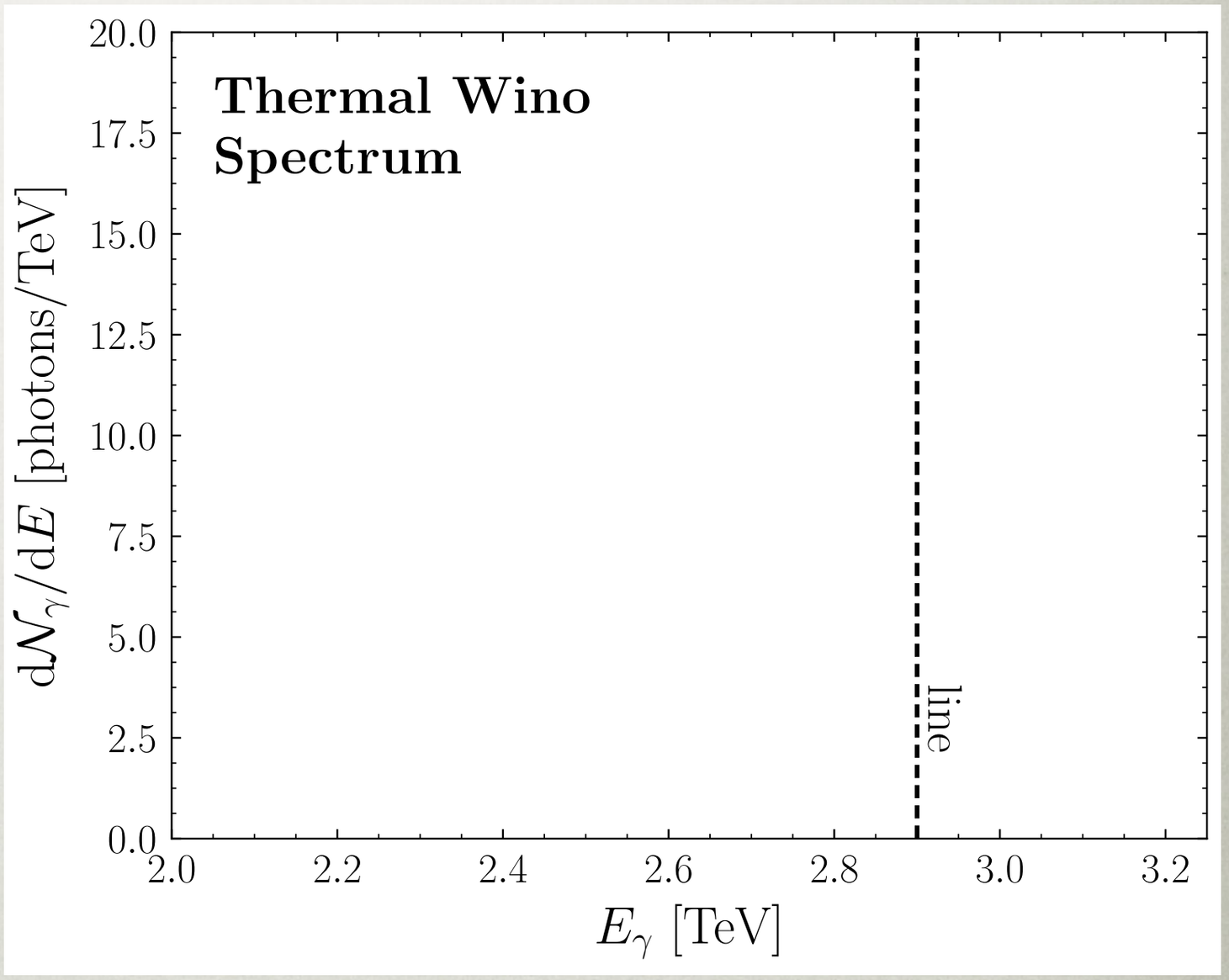


[H.E.S.S. `18]

- Not looking great for the wino!
- Escape route: cored DM density

Endpoint Spectrum



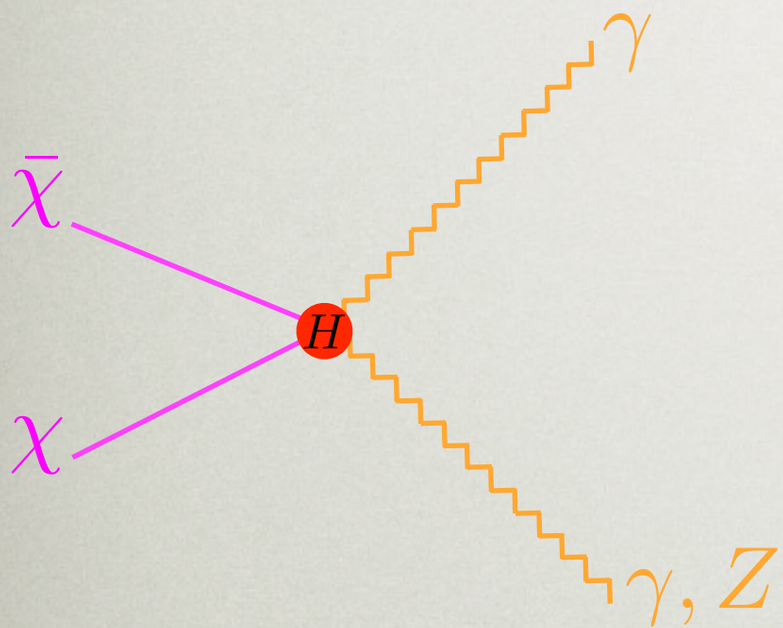


Thermal wino

$m_\chi = 2.9 \pm 0.1$ TeV

[Beneke et al `16]

Endpoint Spectrum



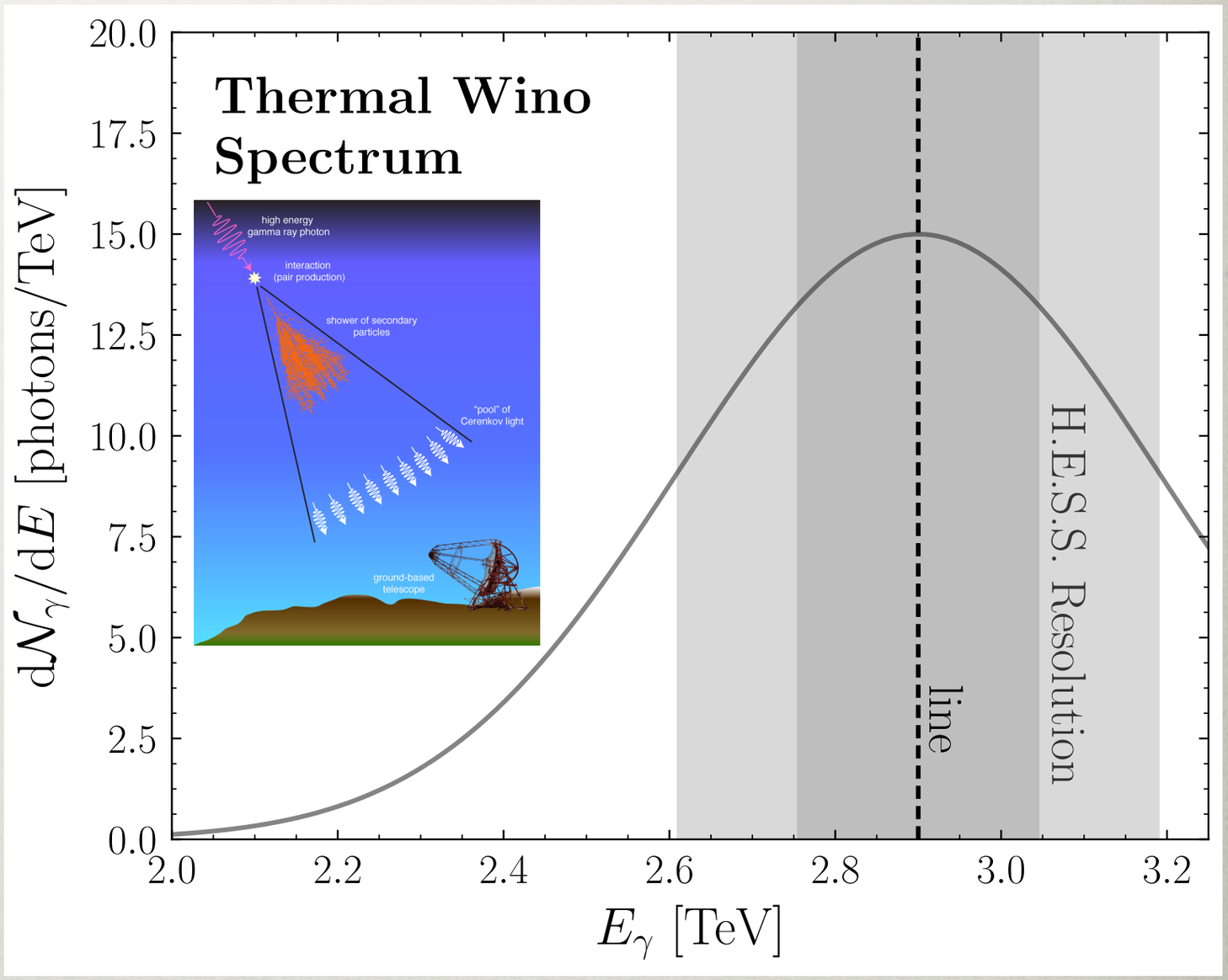
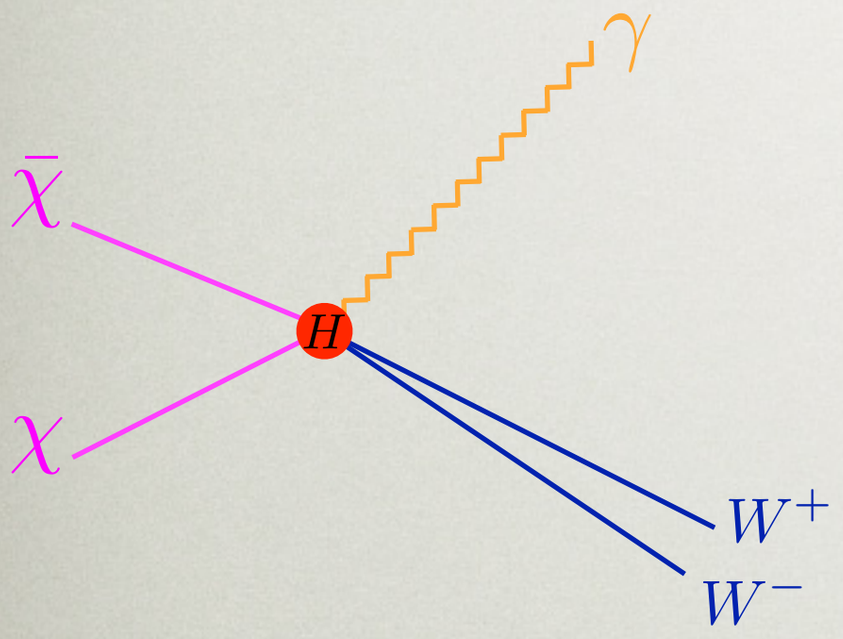
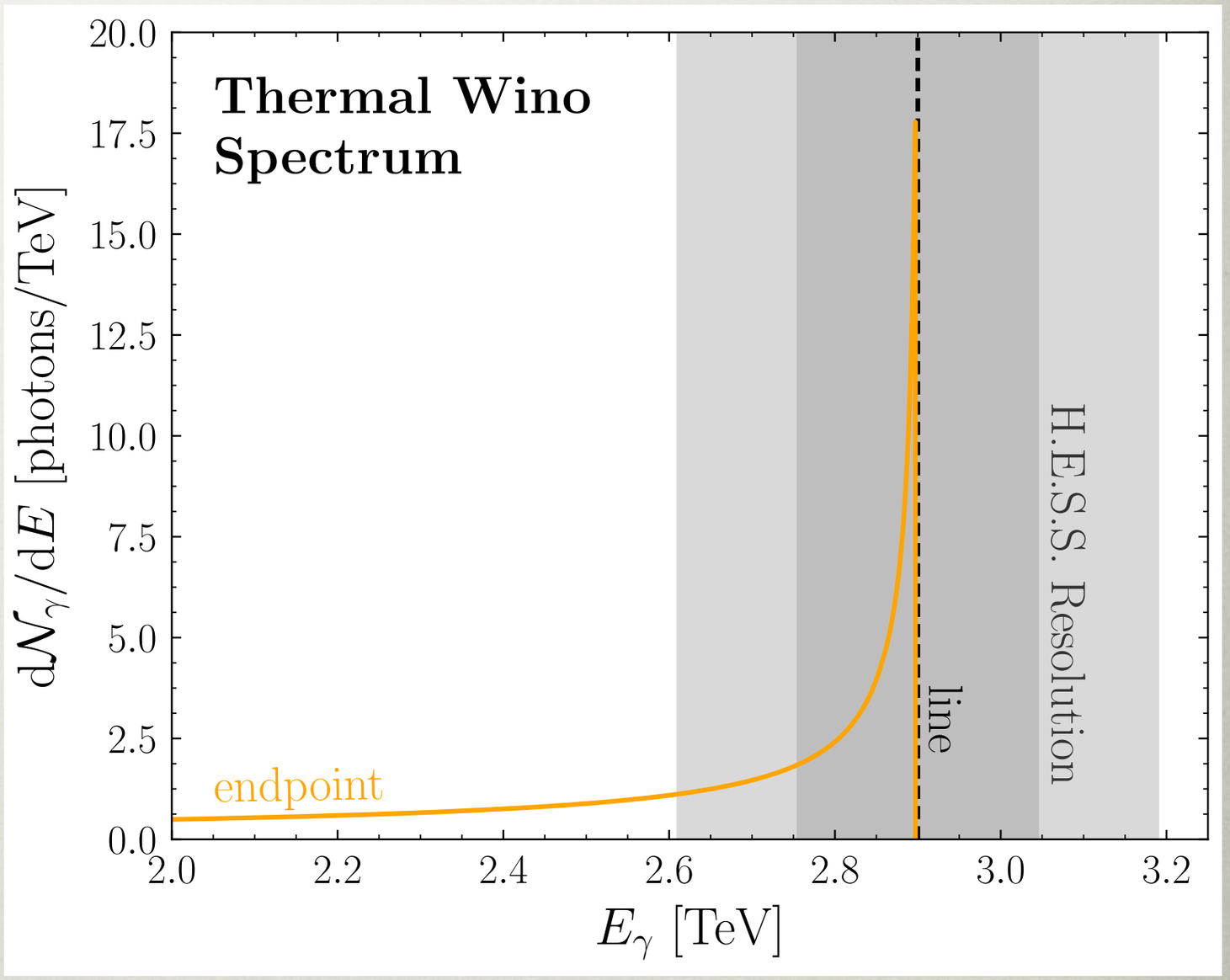


Image from by NASA's Imagine the Universe; telescope image from the H.E.S.S. Collaboration

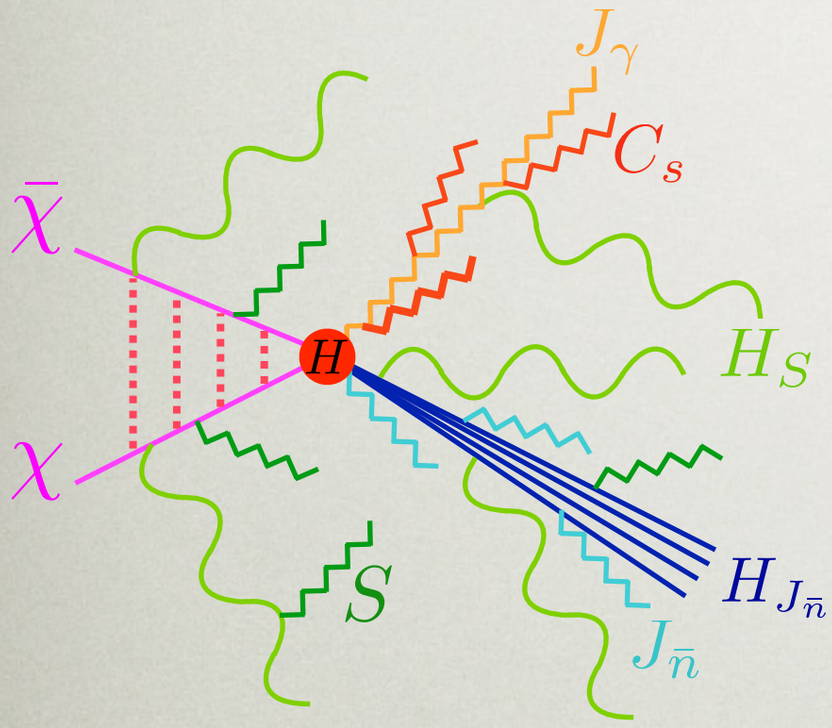
Endpoint Spectrum

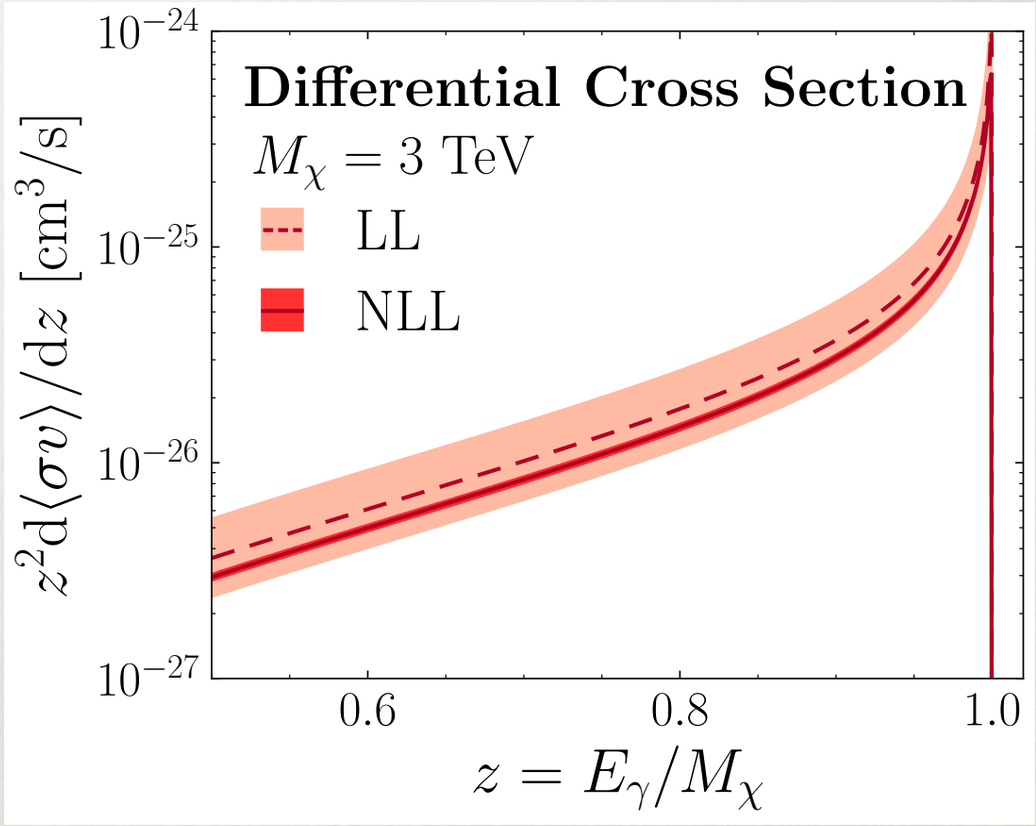




Endpoint Spectrum

- All photons: $(1-z) \ll 1;\ z = E_\gamma / M_\chi$
- [1712.07656] we derived the relevant modes for the endpoint spectrum

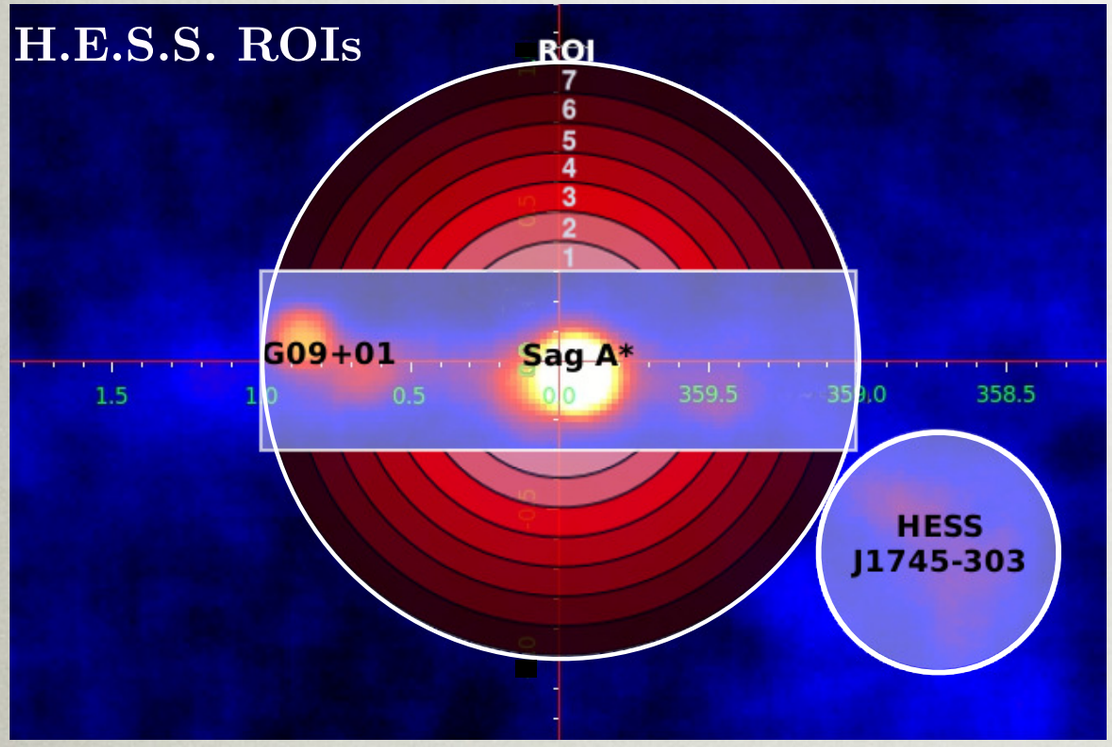


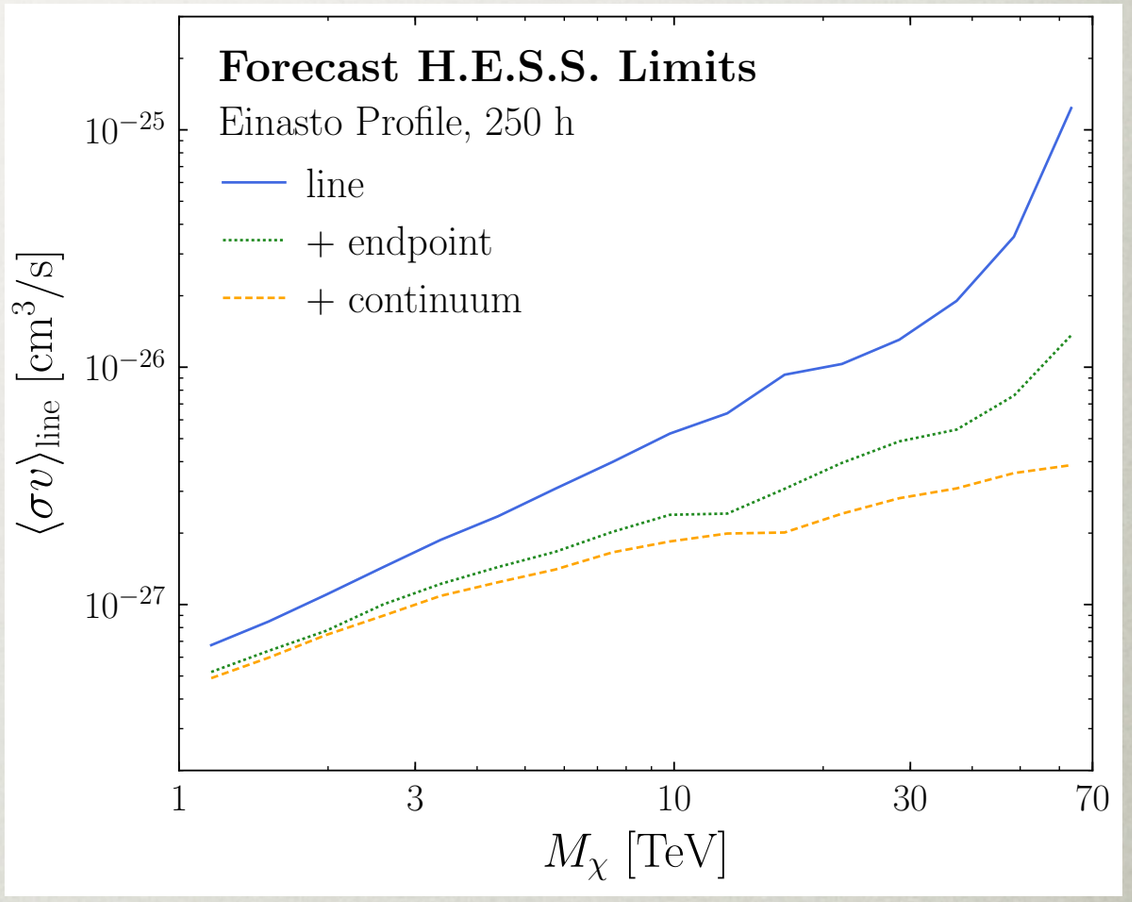


- Analytically calculated LL spectrum w/ modern EFT techniques
- Extended to NLL in [HDMA `18, to appear], theory errors: $\mathcal{O}(5\%)$

Endpoint At H.E.S.S.

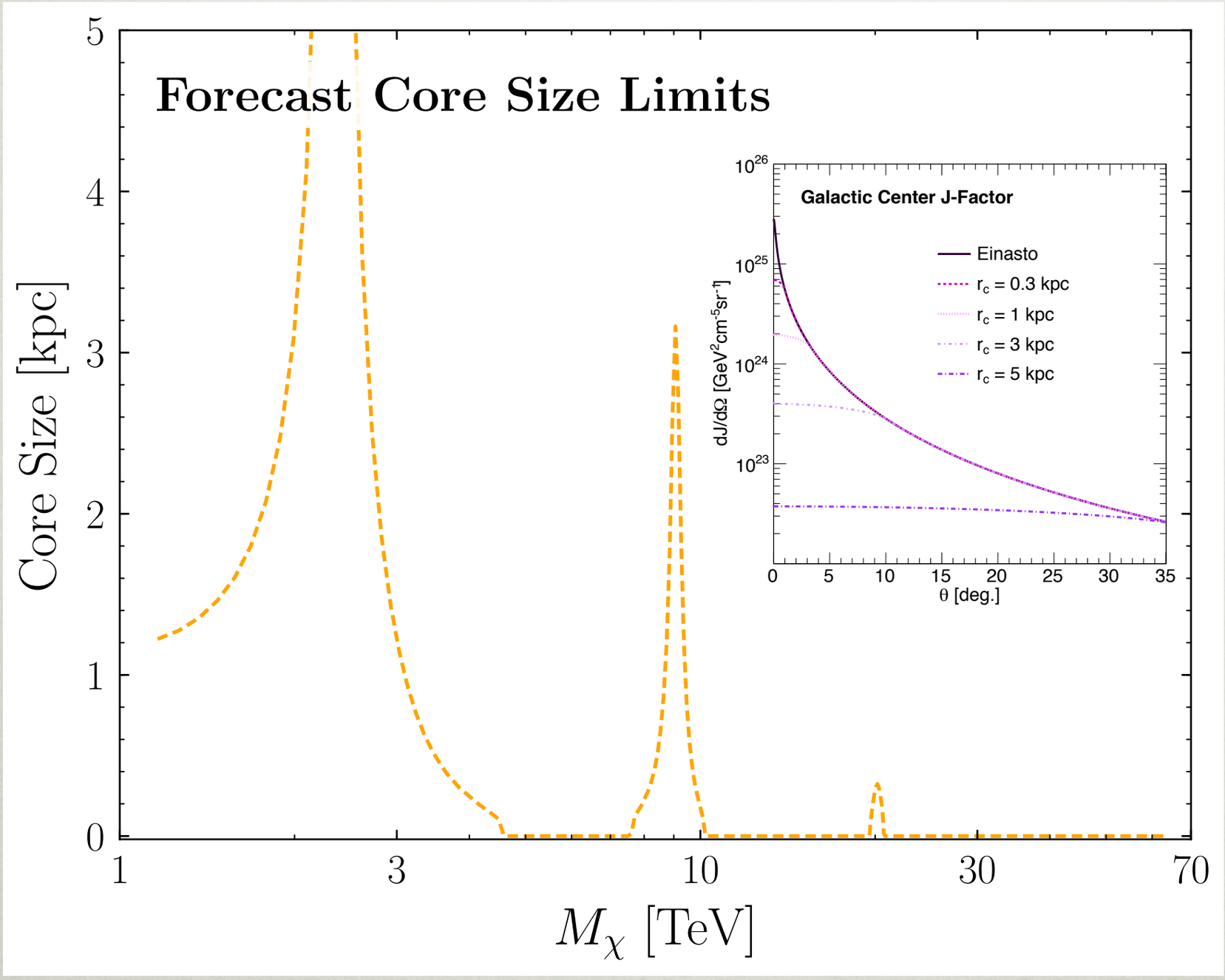
- [1808.04388] we performed a realistic H.E.S.S. forecast including the endpoint





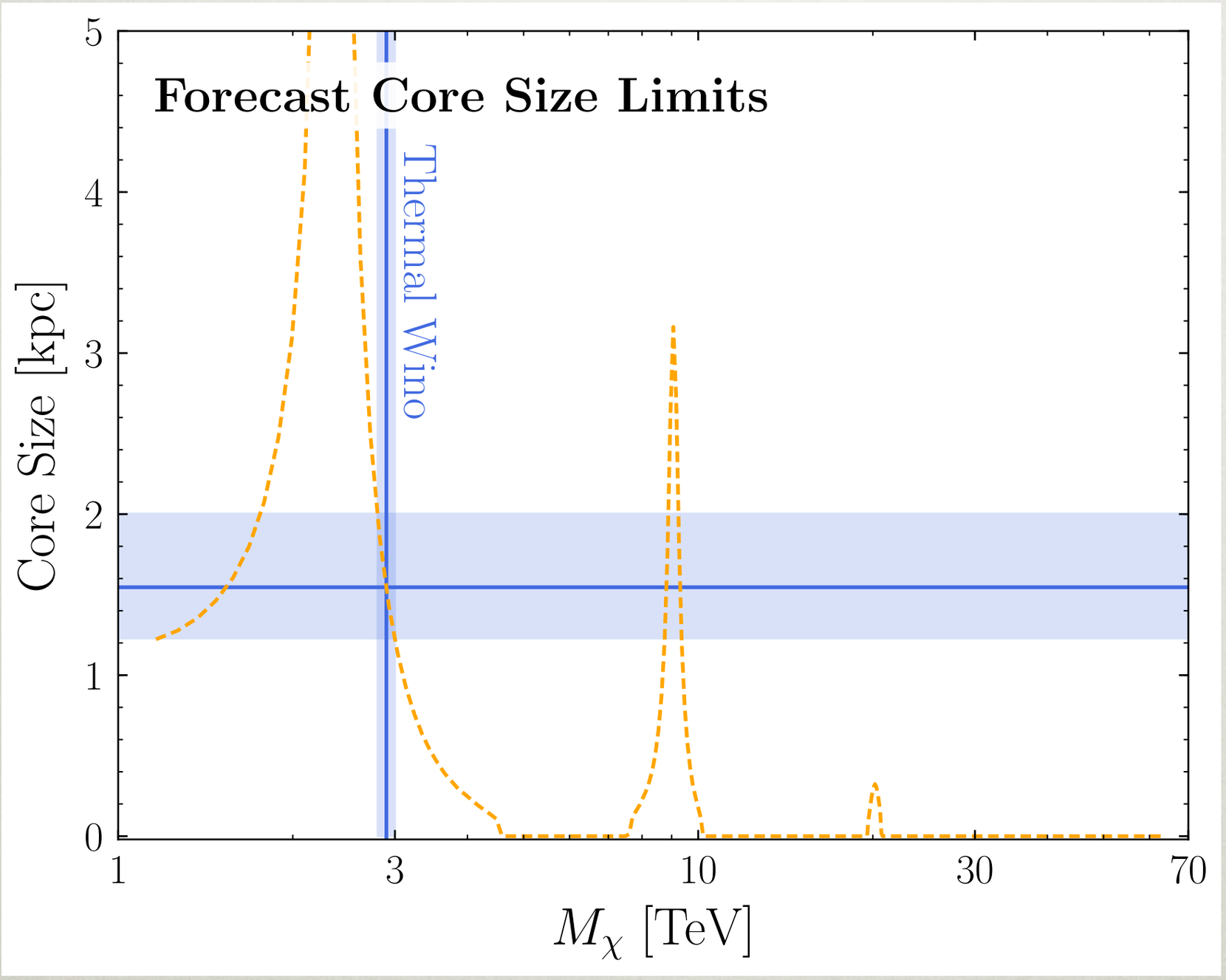
- Followed strategy published in [H.E.S.S., 1805.05741]

Wino Implications



[HDMA 1808.04388]

Wino Implications



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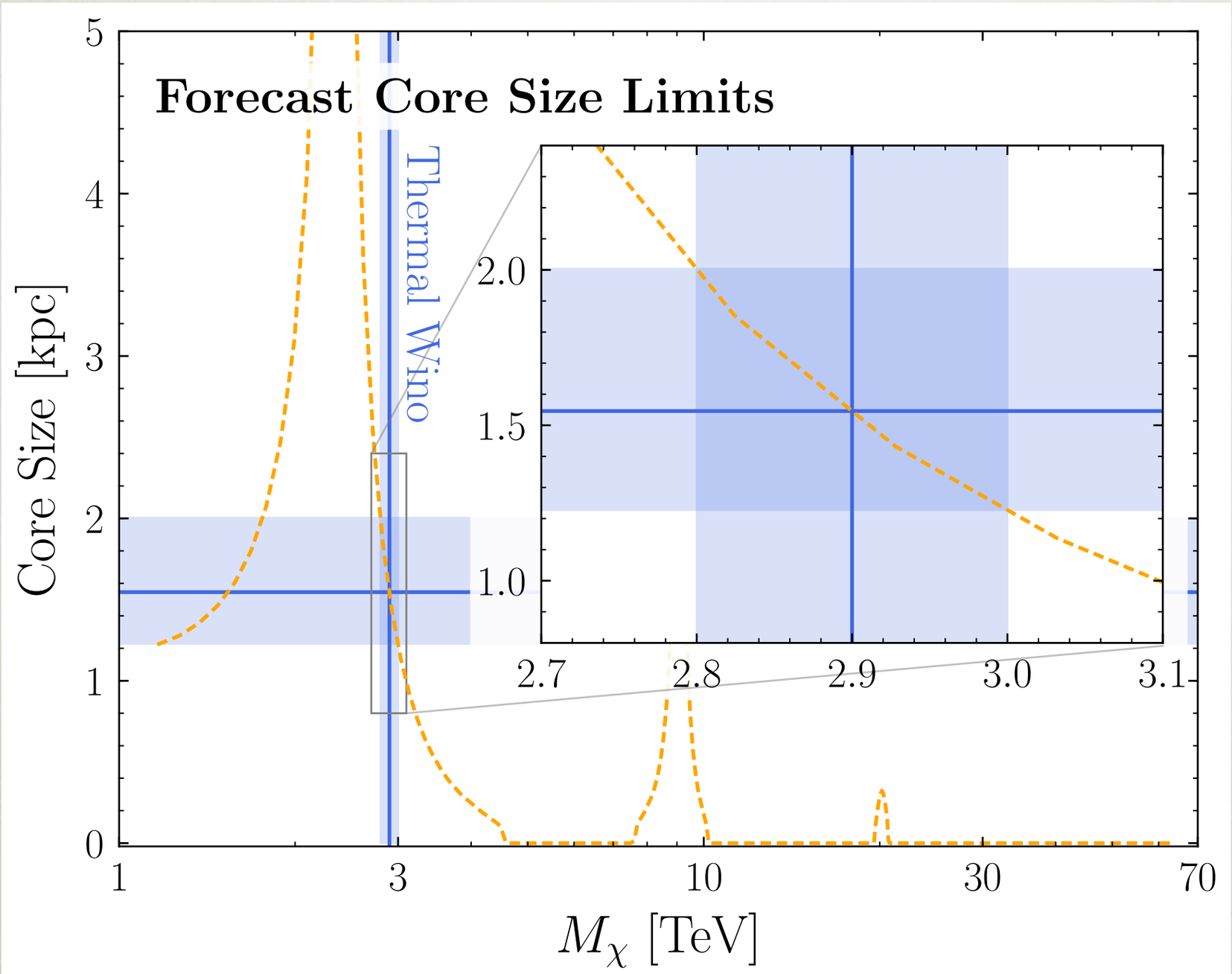
[HDMA 1808.04388]

Wino Implications



[HDMA 1808.04388]

Bulge measurements suggest $r_c \lesssim 2$ kpc (for NFW)

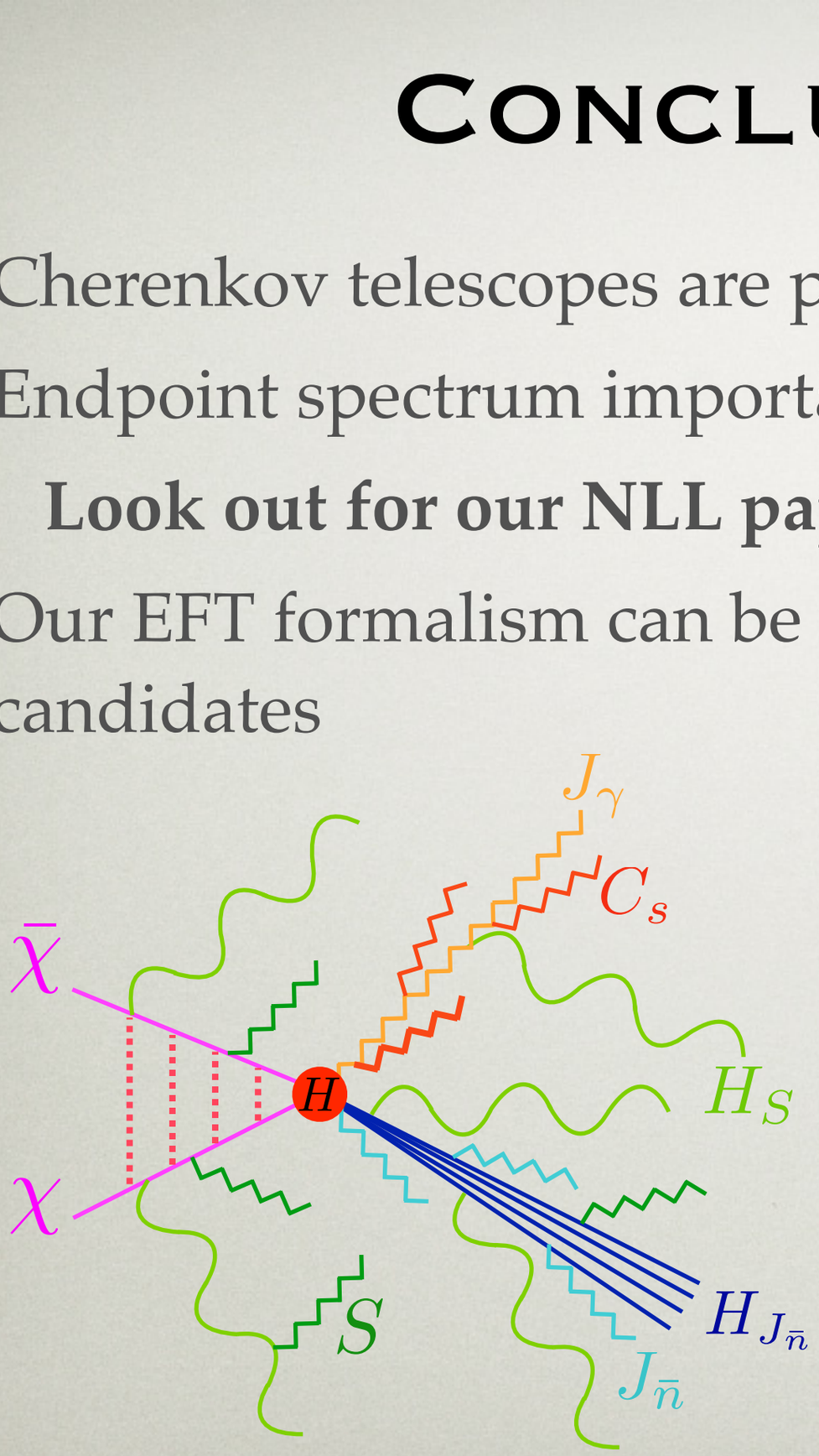
[Hooper `15]

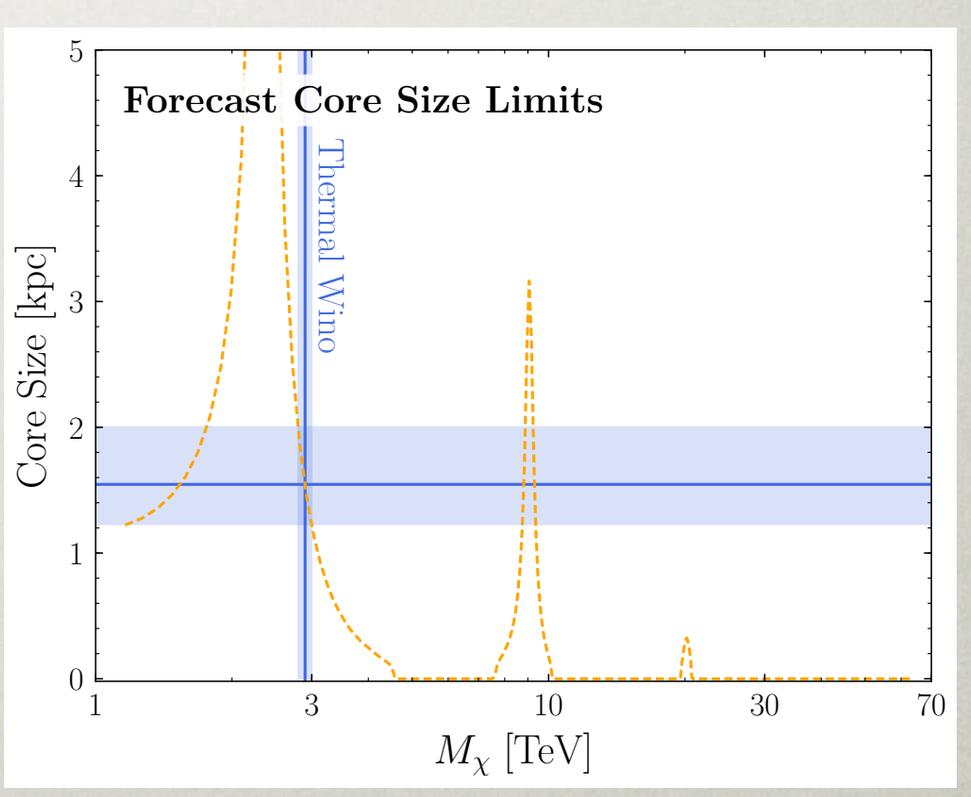
Simulations show cores $\mathcal{O}(1\ \text{kpc})$

[Chan et al `15]

Conclusion

- Cherenkov telescopes are probing the TeV DM hypothesis
- Endpoint spectrum important point of theory prediction
  - **Look out for our NLL paper this week!**
- Our EFT formalism can be applied to many other TeV DM candidates



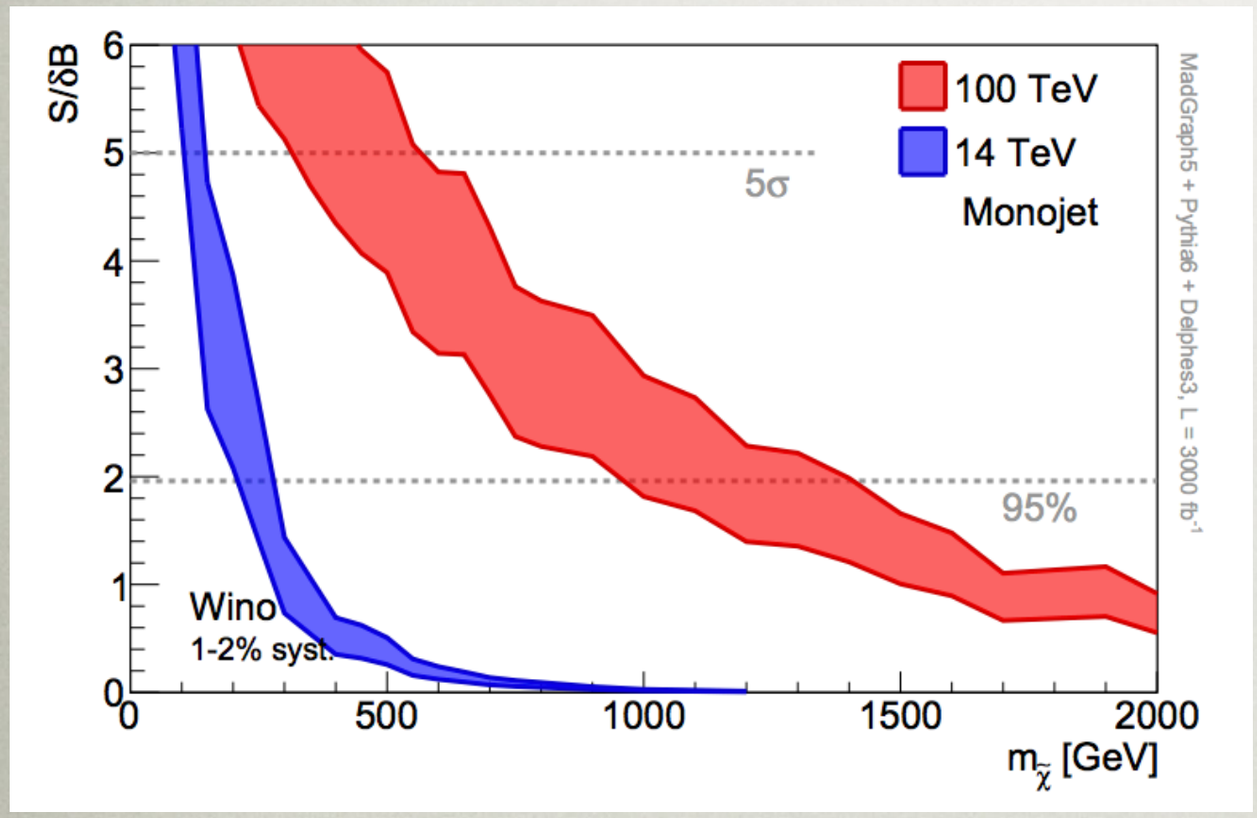


Backup Slides

The Elusive Wino

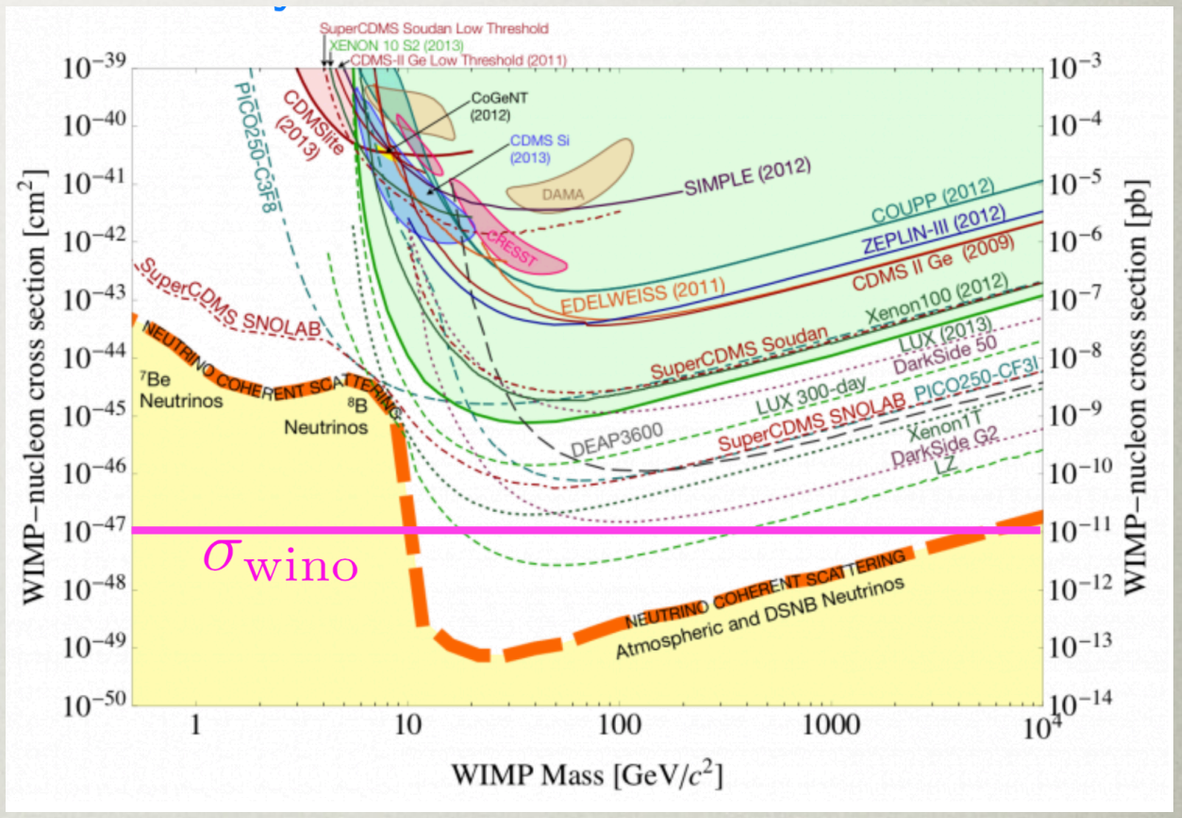
- Wino is hard to probe other than with indirect detection!

Monojet Wino Limits



[Low, Wang `14]

Direct Detection Limits



Definition of $\langle \sigma v \rangle_{\mathrm{line}}$

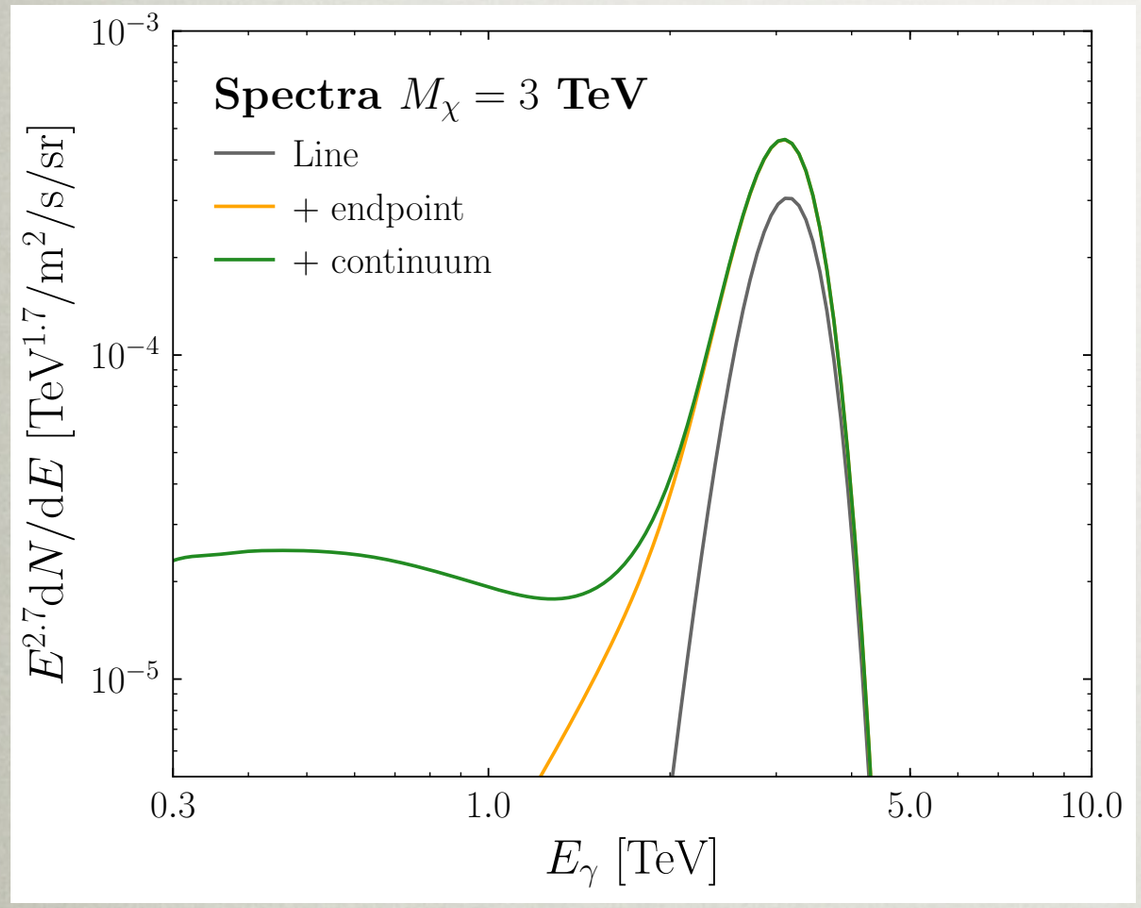
- Instead of the total cross section, usually set limits on

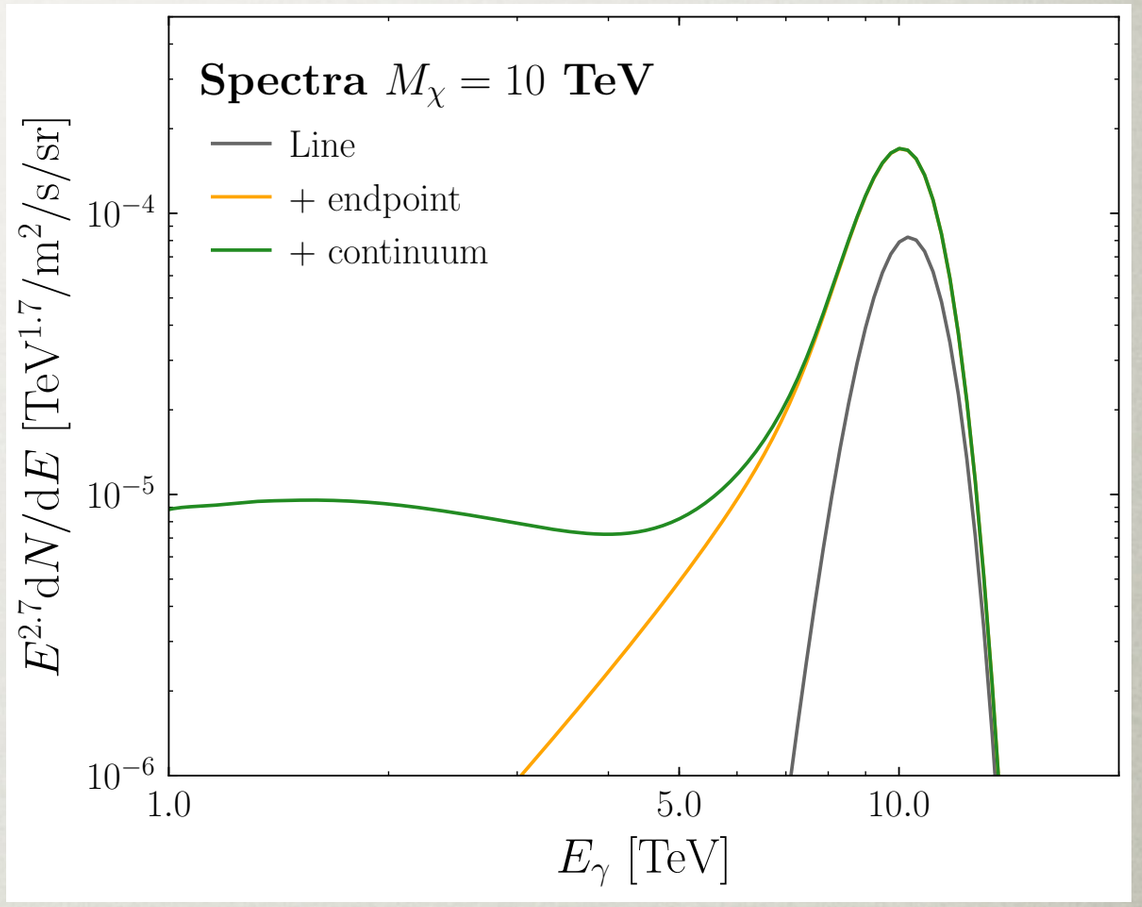
$$\langle \sigma v \rangle_{\mathrm{line}} = \langle \sigma v \rangle_{\gamma\gamma} + \frac{1}{2} \langle \sigma v \rangle_{\gamma Z}$$

- In terms of which we can define an "effective spectrum"

$$\frac{\mathrm{d}\langle \sigma v \rangle}{\mathrm{d}E} = \langle \sigma v \rangle_{\mathrm{line}} \left[2\delta \left(E - m_{\mathrm{DM}} \right) + \left(\frac{\mathrm{d}\mathcal{N}_\gamma}{\mathrm{d}E} \right)^{\mathrm{endpoint}} \right]$$

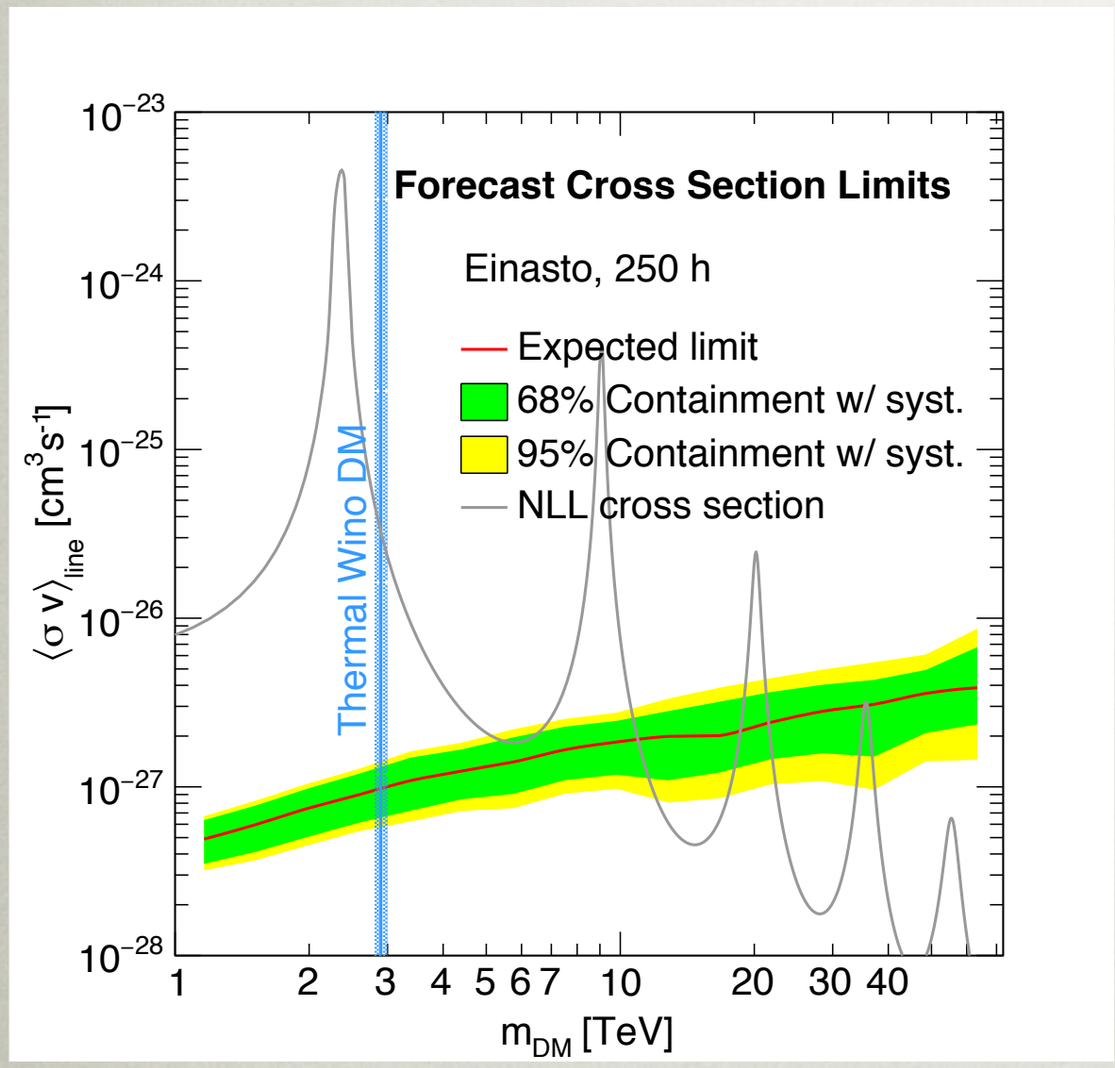
Continuum Emission

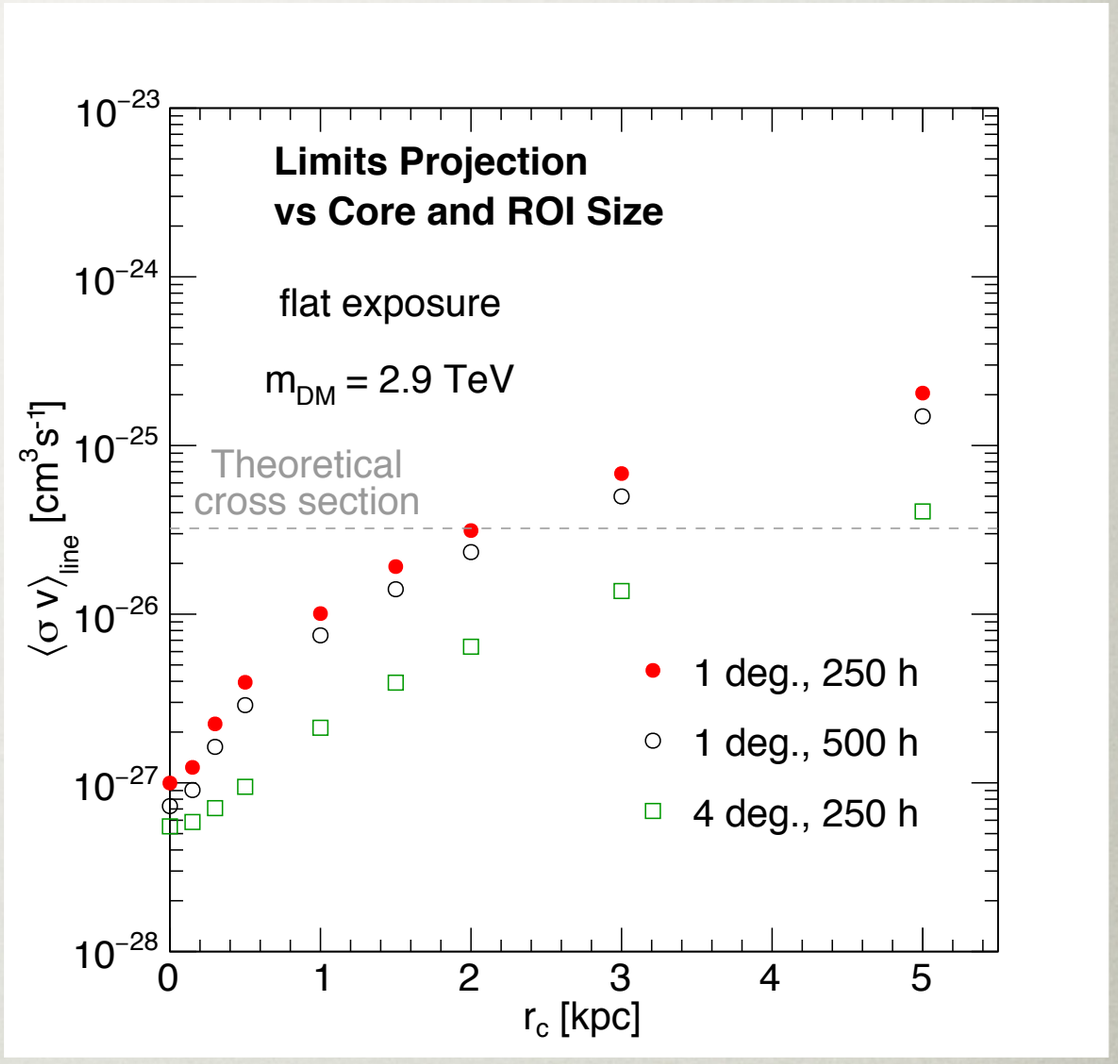




[HDMA 1712.07656]

Further Forecast Results

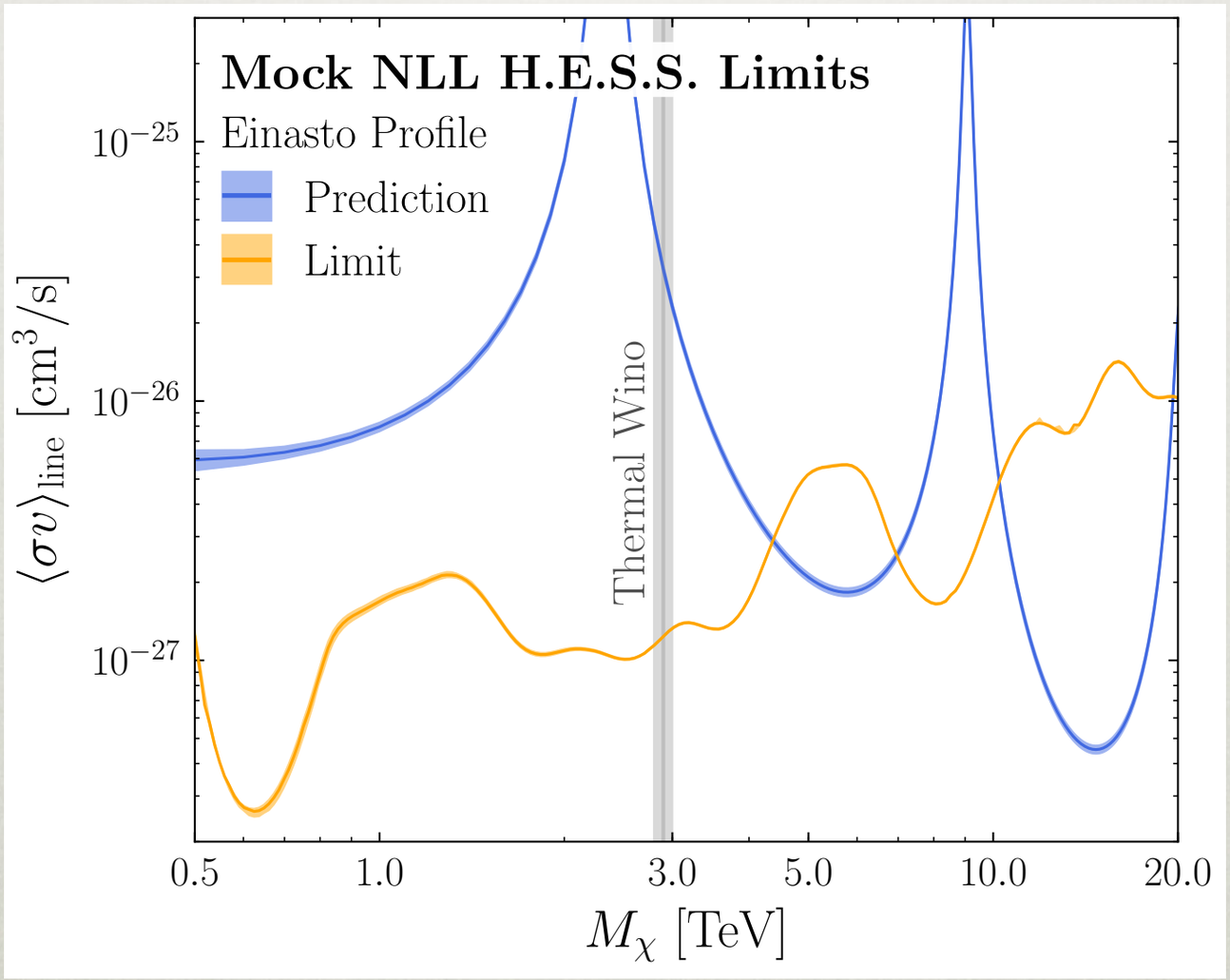




[HDMA 1808.04388]

Theory Uncertainty

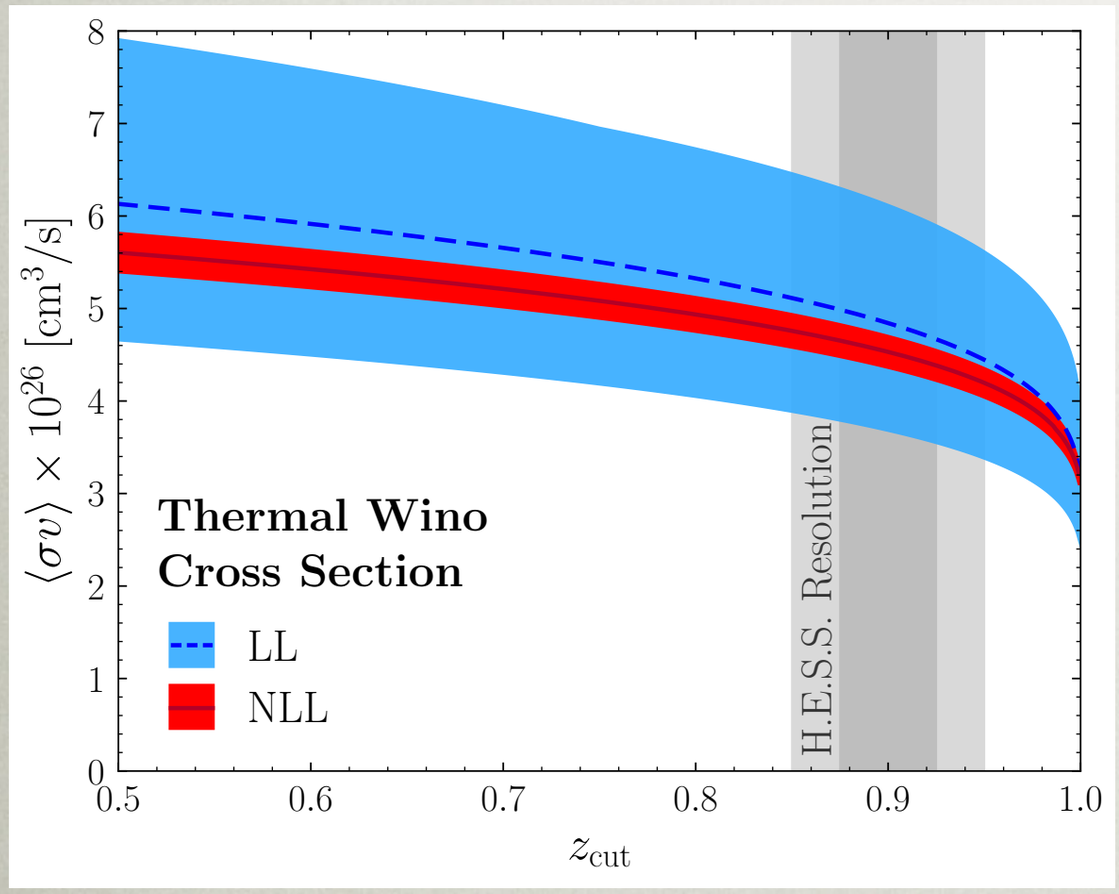
- Theory uncertainty on line prediction and mock limit at $\mathcal{O}(5\%)$

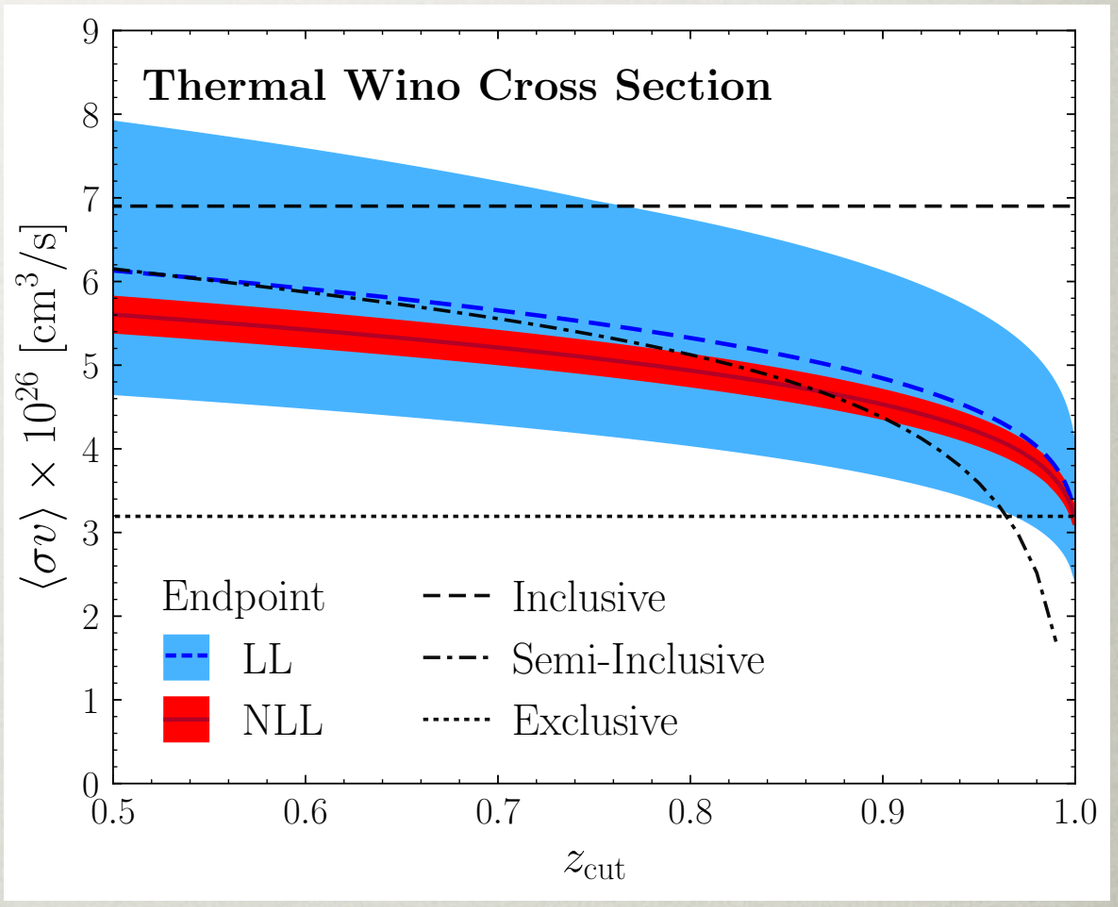


[HDMA NLL, to appear]

Cumulative Cross Section

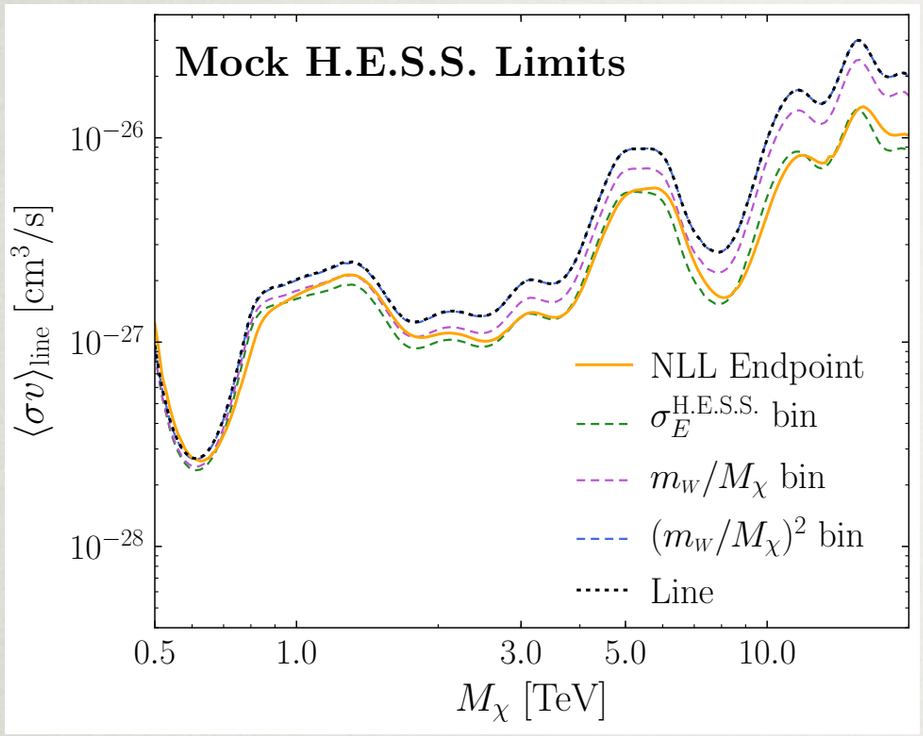
$$\sigma(z_{\rm cut}) = \int_{z_{\rm cut}}^{1} \mathrm{d}z \, \frac{\mathrm{d}\sigma}{\mathrm{d}z}$$

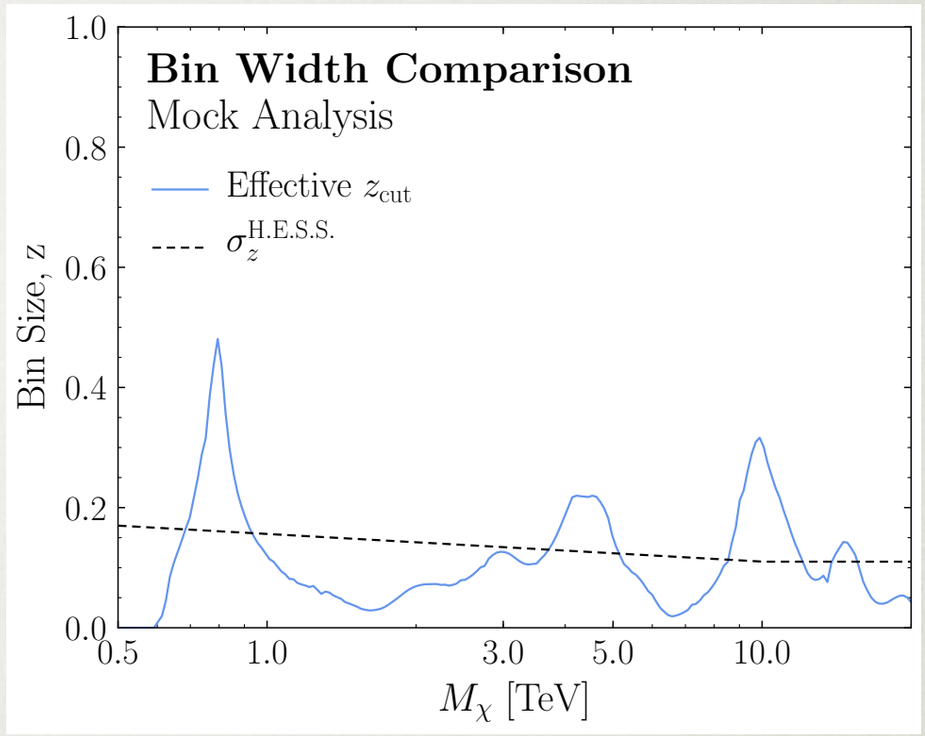


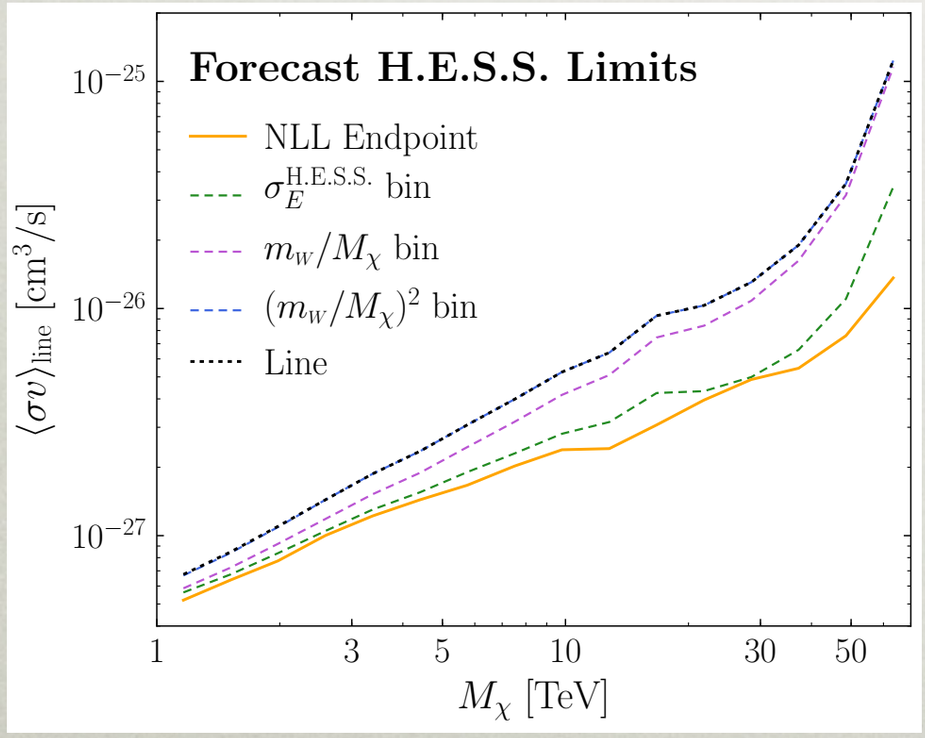


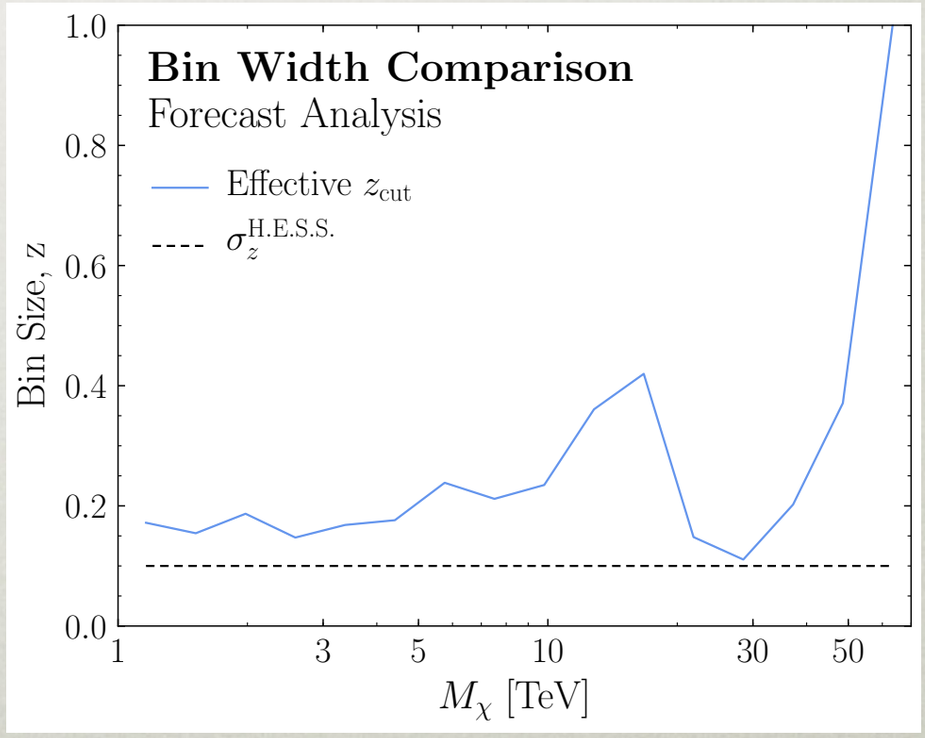
[HDMA NLL, to appear]

Comparison to Effective Bin Size









[HDMA NLL, to appear]

LL Analytic Expression

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}z}\right)^{\mathrm{LL}} = \underbrace{4\,|s_{0\pm}|^2\,\hat{\sigma}^{\mathrm{LL}}_{\mathrm{line}}\,\delta(1-z)}_{\text{Line}} + \underbrace{\frac{2\,\alpha_W}{\pi}\,\frac{\hat{\sigma}^{\mathrm{LL}}_{\mathrm{line}}}{1-z}\,e^{\frac{4\,\alpha_W}{\pi}\,L_J^2(z)}\left\{F_1\Big(3\,L_S(z)-2\,L_J(z)\Big)e^{\frac{-3\,\alpha_W}{\pi}\,L_S^2(z)}-2\,F_0\,L_J(z)\right\}}_{\text{Endpoint}}$$

$$\hat{\sigma}^{\mathrm{LL}}_{\mathrm{line}} = \frac{\pi\,\alpha_W^2\,\sin^2\theta_W}{2\,m_{\mathrm{DM}}^2\,v}\exp\left[-\frac{4\,\alpha_W}{\pi}\,\ln^2\left(\frac{m_W}{2\,m_{\mathrm{DM}}}\right)\right]$$

$$L_J(z) = \ln\left(\frac{m_W/m_{\mathrm{DM}}}{2\,\sqrt{1-z}}\right)\Theta\left(1-\frac{m_W^2}{4\,m_{\mathrm{DM}}^2}-z\right)$$

$$L_S(z) = \ln\left(\frac{m_W/m_{\mathrm{DM}}}{2\,(1-z)}\right)\Theta\left(1-\frac{m_W}{2\,m_{\mathrm{DM}}}-z\right)$$

$$F_0 = \frac{4}{3}\,|s_{00}|^2 + 2\,|s_{0\pm}|^2 + \frac{4\,\sqrt{2}}{3}\,\Re\Big(s_{00}\,s_{0\pm}^*\Big)$$

$$F_1 = -\frac{4}{3}\,|s_{00}|^2 + 2\,|s_{0\pm}|^2 - \frac{4\sqrt{2}}{3}\,\Re\Big(s_{00}\,s_{0\pm}^*\Big)$$

$$\Big\langle 0\Big|\,\chi^{0\,T}\,i\sigma_2\,\chi^0\,\Big|(\chi^0\chi^0)_S\Big\rangle = 4\sqrt{2}\,m_{\mathrm{DM}}\,s_{00}\,,$$

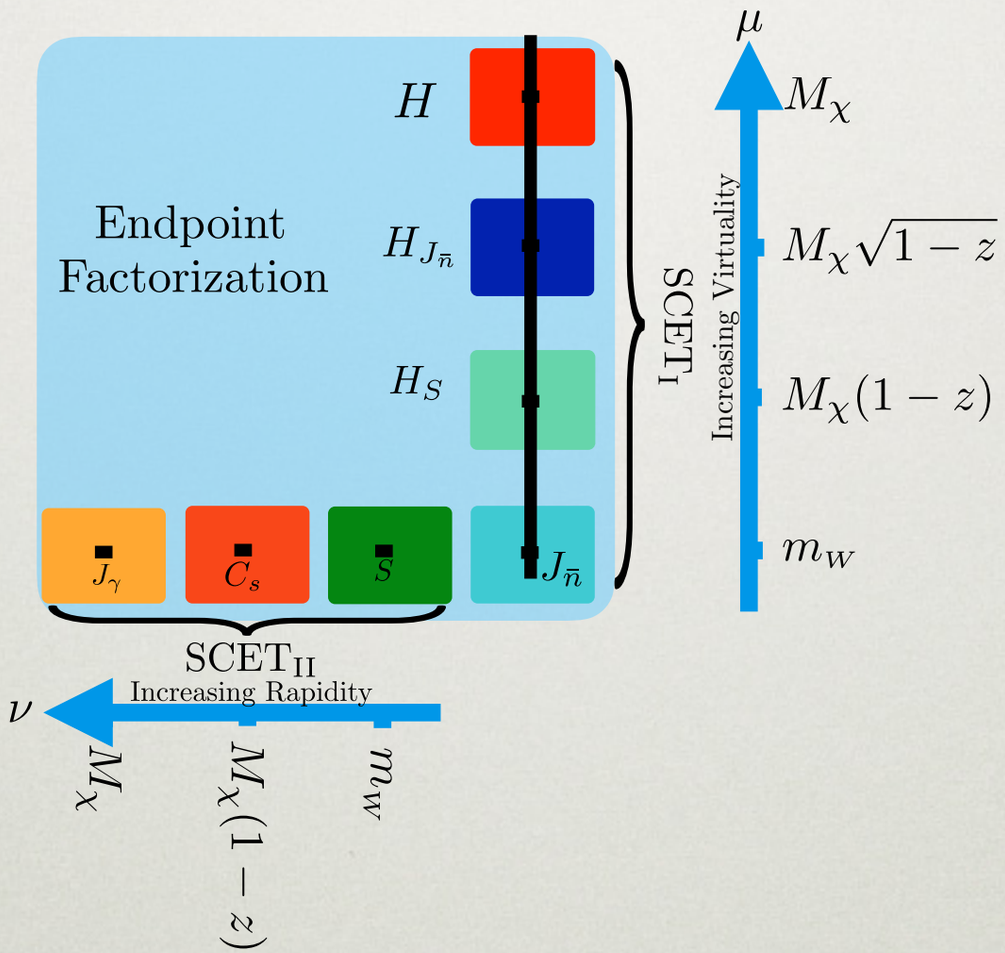
$$\Big\langle 0\Big|\,\chi^{+T}\,i\sigma_2\,\chi^-\,\Big|(\chi^0\chi^0)_S\Big\rangle = 4\,m_{\mathrm{DM}}\,s_{0\pm}$$

- See [1712.07656], NLL expression more complex, still analytic

Endpoint Factorization Formula

$$\left(\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}z}\right)^{\mathrm{NLL}} = H(M_\chi,\mu)\, J_\gamma(m_W,\mu,\nu)\, J_{\bar{n}}(m_W,\mu,\nu)\, S(m_W,\mu,\nu)$$

$$\times H_{J_{\bar{n}}}(M_\chi, 1-z, \mu) \otimes H_S(M_\chi, 1-z, \mu) \otimes C_S(M_\chi, 1-z, m_W, \mu, \nu)$$



- Proven at LL in [1712.07656]
- Extended to NLL in [HDMA NLL, to appear]