Astrophysical Sources as Dark Matter Detectors

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Physics 492: Honors
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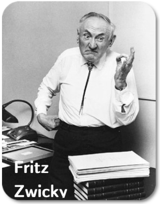
Where did it all begin?



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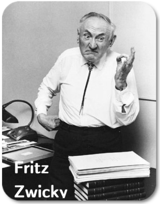

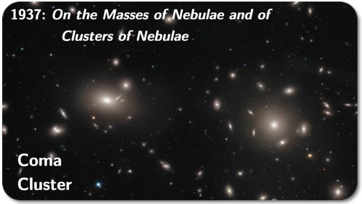

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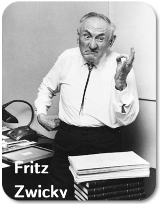

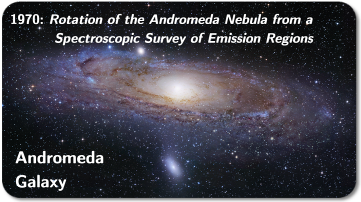

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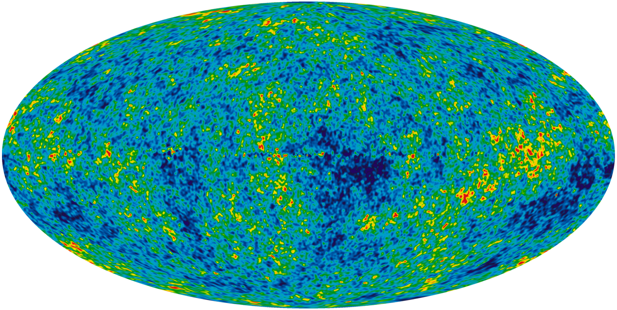
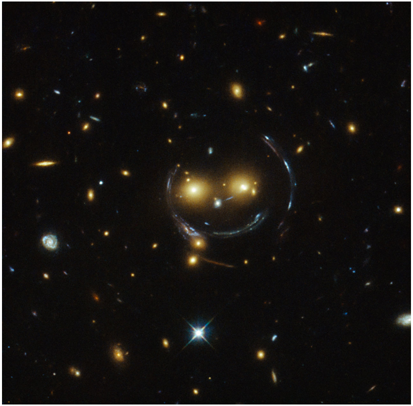


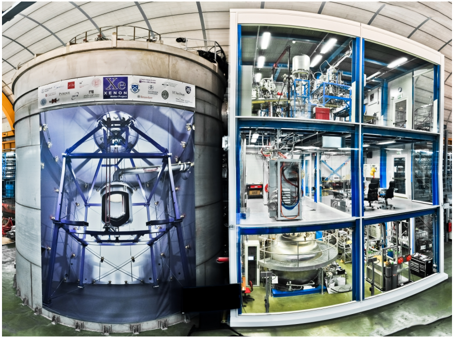
Cosmic Microwave Background Radiation, WMAP.

Where are we now?



"Smiling" image of a galaxy cluster with lensed background galaxies.

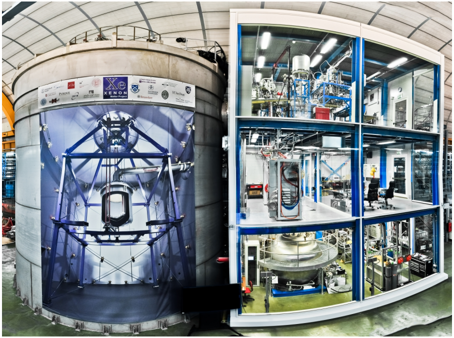
Hitting the Neutrino Floor



XENON1T Direct Detection Experiment.

Hitting the Neutrino Floor

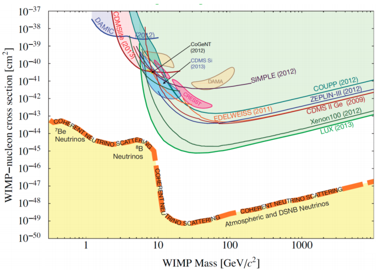
- Dark matter direct detection experiments are slowly reaching the limits of the instruments – DSNB **neutrino noise is becoming an issue.**



XENON1T Direct Detection Experiment.

So what do we do?

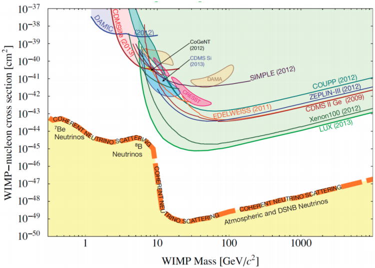
- If dark matter direct detection is slowly becoming obsolete, how can we probe to lower cross section bounds?



Cross section bounds from direct detection.

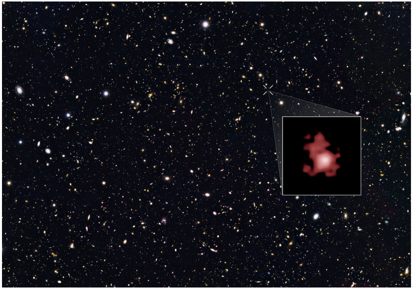
So what do we do?

- If dark matter direct detection is slowly becoming obsolete, how can we probe to lower cross section bounds?
- **Look to astrophysics!**



Cross section bounds from direct detection.

Other motivations!



GN-z11: $z \sim 11$, with a super massive black hole at its center.

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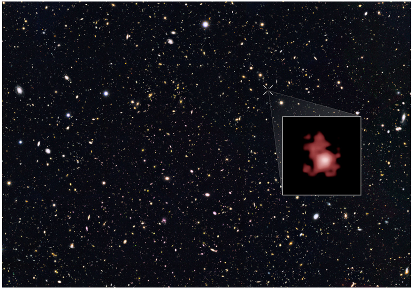

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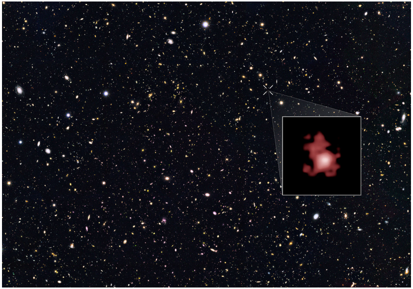
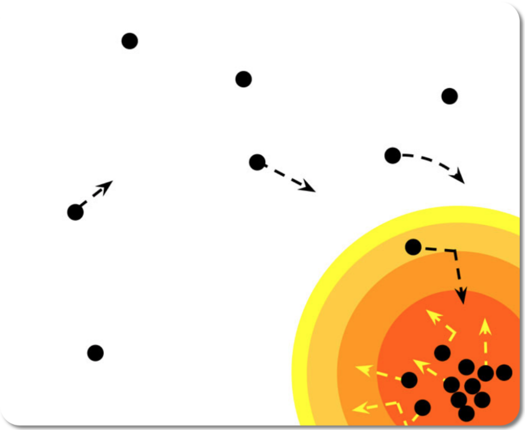


GN-z11: $z \sim 11$, with a super massive black hole at its center.

- Freese, Iocco, Taoso, Gondolo, Gould, and more: **Dark stars.**
- Explanation of super massive black holes?

Mutliscatter Capture “Derivation”



Schematic of multiscatter capture.

With that in mind...

On paper:

$$\begin{aligned}\text{Cap. Rate (N Scatters)} = &\text{(stellar parameters)} \times \\ &\text{(prob. of scattering)} \times \\ &\text{(prob. of being captured by those scatters)}\end{aligned}$$

With that in mind...

On paper:

$$\text{Cap. Rate (N Scatters)} = (\text{stellar parameters}) \times (\text{prob. of scattering}) \times (\text{prob. of being captured by those scatters})$$

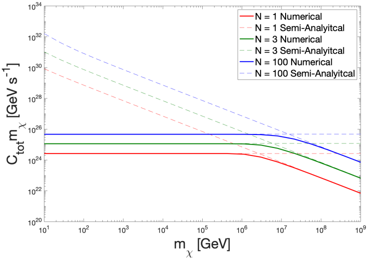
In practice:

$$C_N = \pi R^2 p_N(\tau) \frac{\sqrt{2} n_\chi}{\sqrt{3\pi}\bar{v}} \left(\left(2\bar{v}^2 + 3v_{esc}^2\right) - \left(2\bar{v}^2 + 3v_N^2\right) \exp\left(-\frac{3\left(v_N^2 - v_{esc}^2\right)}{2\bar{v}^2} \right) \right)$$

$$C_{tot} = \sum_{N=1}^{\infty} C_N$$

Observational Effects (NS)

- Dark matter annihilation provides an additional luminosity source for the neutron star L_{DM}.



$L_{DM} = C_{tot} m_\chi$ in neutron stars.

Constraining DM Properties (NS)

- This luminosity becomes important for **old neutron stars** so that DM has thermalized and annihilation is in equilibrium.

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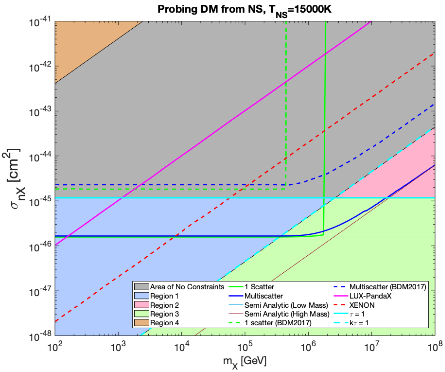
- This luminosity becomes important for **old neutron stars** so that DM has thermalized and annihilation is in equilibrium.
- $\rightarrow$ Leading to constraints on m_χ and σ_χ for a given ρ_χ.



One more piece of physics needed

The **Eddington Luminosity** is the maximum luminosity a star can have while preserving hydrostatic equilibrium.

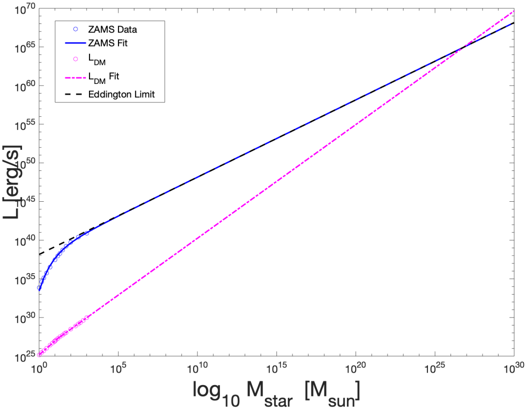
$$\boxed{L_{Edd} = 3.7142 \times 10^4 \left(\frac{M_\star}{M_\odot}\right) L_\odot}$$

Observational Effects (Pop. III)

- Harder to deal with:

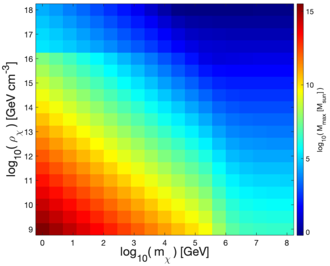
$$\text{Bounds} \rightarrow \begin{cases} L_{edd}(M_{max}) = L_{DM}(M_{max}) + L_{nuc}(M_{max}) & : \text{Strong Limit} \\ L_{edd}(M_{max}) = L_{DM}(M_{max}) & : \text{Weak Limit} \end{cases}$$

Observational Effects (Pop. III)

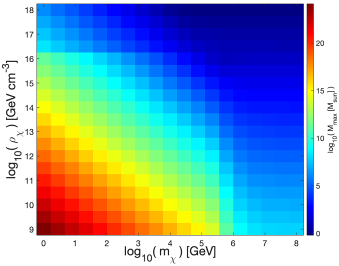


$10^2\, GeV\, DM.$

Mass Constraints (Pop. III)



Strong limit.



Weak limit.

Constraints from Pop. III Stars

- What happens if we observe an Eddington limited star?

$$L_{DM} \propto \sigma_\chi \rho_\chi M_\star^3 / m_\chi R_\star^2$$

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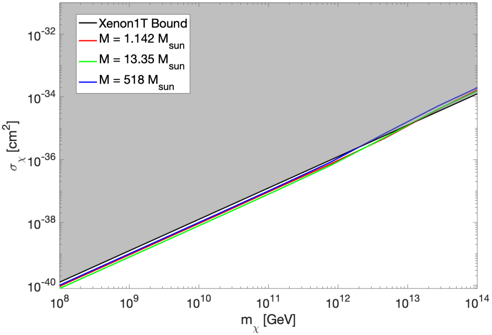

Key takeaways...

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Direct detection experiments are quickly approaching the sensitivity of **background neutrinos.**

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Astrophysical sources can be used to constrain the dark matter interaction cross section σ_χ.

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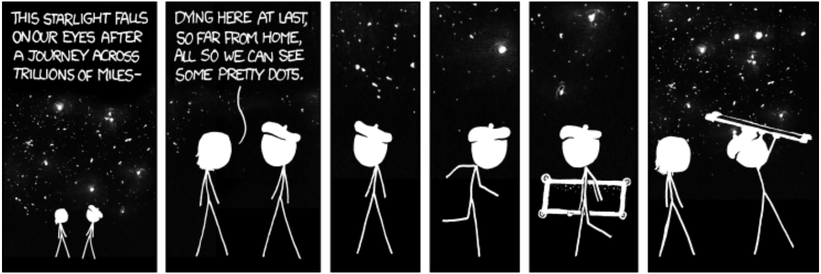
Takeaway 2

Astrophysical sources can be used to constrain the dark matter interaction cross section σ_χ.

Takeaway 3

Neutron stars and Population III stars are promising objects to **probe dark matter below the neutrino floor** and beyond the Standard Model.

Thank you!


THIS STARLIGHT FALLS ON OUR EYES AFTER A JOURNEY ACROSS TRILLIONS OF MILES-
DYING HERE AT LAST, SO FAR FROM HOME, ALL SO WE CAN SEE SOME PRETTY DOTS.

Approximate and Semi-Analytic Calculations

$$C_N = \sqrt{24\pi} p_N(\tau) n_\chi G M_\star \frac{1}{\bar{v}} \left(1 - \left(1 + \frac{2A_N^2 \bar{v}^2}{3v_{esc}^2}\right) e^{-A_N^2}\right) \tag{1}$$

where

$$A_N^2 = \frac{3v_{esc}^2 N m_n}{\bar{v}^2 m_\chi} \tag{2}$$

$$\mathsf{C}^{\mathsf{k}} m_\chi = \begin{cases} \pi R^2 \frac{\sqrt{2} n_\chi}{\sqrt{3\pi}\bar{v}} \left(2\bar{v}^2 + 3v_{esc}^2\right) \frac{k(k+3)}{(n_T \sigma_n \chi 2R)^2} m_\chi & ; \frac{3\left(v_N^2 - v_{esc}^2\right)}{2\bar{v}^2} \gg 1, k < \tau \\ \pi R^2 \frac{\sqrt{3} n_\chi}{\sqrt{2\pi}\bar{v}^3} 3 v_{esc}^4 z_i 4 m_N \frac{2}{\tau^2} \left[\frac{k(k+1)(k+2)}{3} + z_i \frac{4m_N}{m_\chi} \frac{k(k+1)(k+2)(3k+1)}{12}\right] & ; \frac{3\left(v_N^2 - v_{esc}^2\right)}{2\bar{v}^2} \ll 1, k < \tau \\ \pi R^2 \frac{\sqrt{2} n_\chi}{\sqrt{3\pi}\bar{v}} \left(2\bar{v}^2 + 3v_{esc}^2\right) m_\chi & ; \frac{3\left(v_N^2 - v_{esc}^2\right)}{2\bar{v}^2} \gg 1, k > \tau \\ \pi R^2 \frac{\sqrt{3} n_\chi}{\sqrt{2\pi}\bar{v}^3} 3 v_{esc}^4 z_i 4 m_N \left[\frac{2\tau}{3} + z_i \frac{4m_N}{m_\chi} \frac{\tau^2}{2}\right] & ; \frac{3\left(v_N^2 - v_{esc}^2\right)}{2\bar{v}^2} \ll 1, k > \tau \end{cases} \tag{3}$$

Intricacies for Exotic Objects

$$\sigma \rightarrow \sigma_{n\chi} \frac{M_N^4}{m_n^4} F^2\left(\langle E_R \rangle\right) \tag{4}$$

$$C_N \rightarrow \frac{C_N}{1 - \frac{2GM}{Rc^2}} \tag{5}$$

$$\chi = \left[1 - \left(1 - \frac{2GM}{Rc^2}\right)^{1/2}\right] \tag{6}$$

$$v_{esc} \rightarrow \sqrt{2\chi} \tag{7}$$

Neutron Star Constraint Criterion

$$m_x C_N = L_{DM} = 4\pi\sigma_0 R^2 T_{NS}^4 \left(1 - \frac{2GM}{Rc^2}\right)^2 \tag{8}$$

leads to:

$$\sum_N p_N(\tau)\left(1 - \left(1 + \frac{2A_N^2 \bar{v}^2}{3v_{esc}^2}\right)e^{-A_N^2}\right) = \mathrm{const}\frac{T_{NS}^4}{\rho X} \tag{9}$$

which is essentially:

$$L_{sources} + (\text{heat rate}) = L_{radiated} \tag{10}$$

In equilibrium, (heat rate) $= 0$. With no sources (WD, NS), we get the constraint that we are claiming.

Future Work on Pop. III Stars

- We assumed a cross section σ_χ in calculating capture rate for Pop. III stars as a proof of concept.
- We then were able to extract the cross section that we assumed $\rightarrow$ proof of concept.
- **Future work:** Make no assumptions about the cross section and see what the plot below would look like:

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