The First Stars in The Universe as Dark Matter Laboratories

SCAN ME

SCAN ME

Authors: Cosmin Ilie,[1] Caleb Levy,[1] Jacob Pilawa,[2] and Saiyang Zhang[3]

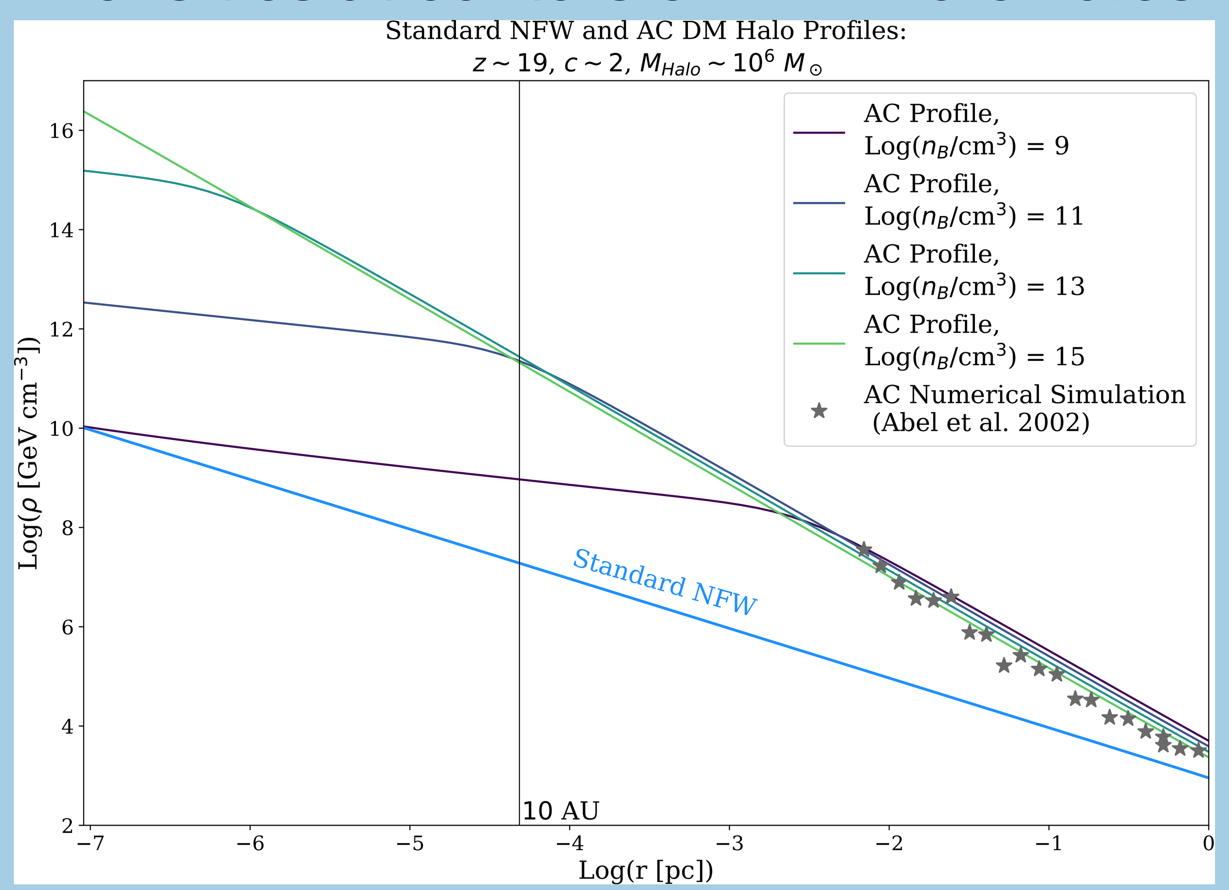
Affiliations: [1] Colgate University; [2] University of California, Berkeley; [3] University of Texas, Austin

Abstract: Based on the effects of captured Dark Matter heating we show that the mere observation of the first nuclear burning stars (PopIII stars) in the universe can be used to place tight constraints on the strength of the interaction between dark matter and regular, baryonic matter. Intriguingly, we find that this approach can be used to probe the Spin Dependent (SD) Dark Matter-proton interaction cross section below the neutrino fog that will soon affect direct detection experiments. Additional strengths of this approach is probing sub-GeV (annihilating) Dark Matter, where direct detection experiments suffer for a degradation of their constraining power.

First stars, birds-eye view:

- None observed yet, so far they remain theoretical constructs.
- Expected to form at z~[25,15] out of the collapse of primordial (zero metallicity) molecular H gas clouds at center of DM halos [1].
- A protostar forms roughly when heating (from collapse or other sources) overcomes cooling.
- Low cooling mechanisms (primarily molecular H cooling)
- If DM heating plays a significant role: Dark Stars (DS) form [2,3]. See also talk by Katherine Freese on Thursday (Session 5) and poster by Jillian Paulin
- If DM heating plays no role ⟶ Population III (PopIII) stars (the primary focus of this poster. For details see [4,5])
- PopIII stars: a few per DM halo and can be as heavy as $1000 M_\odot$ [6]

DM Densities at centers of DM micro halos:



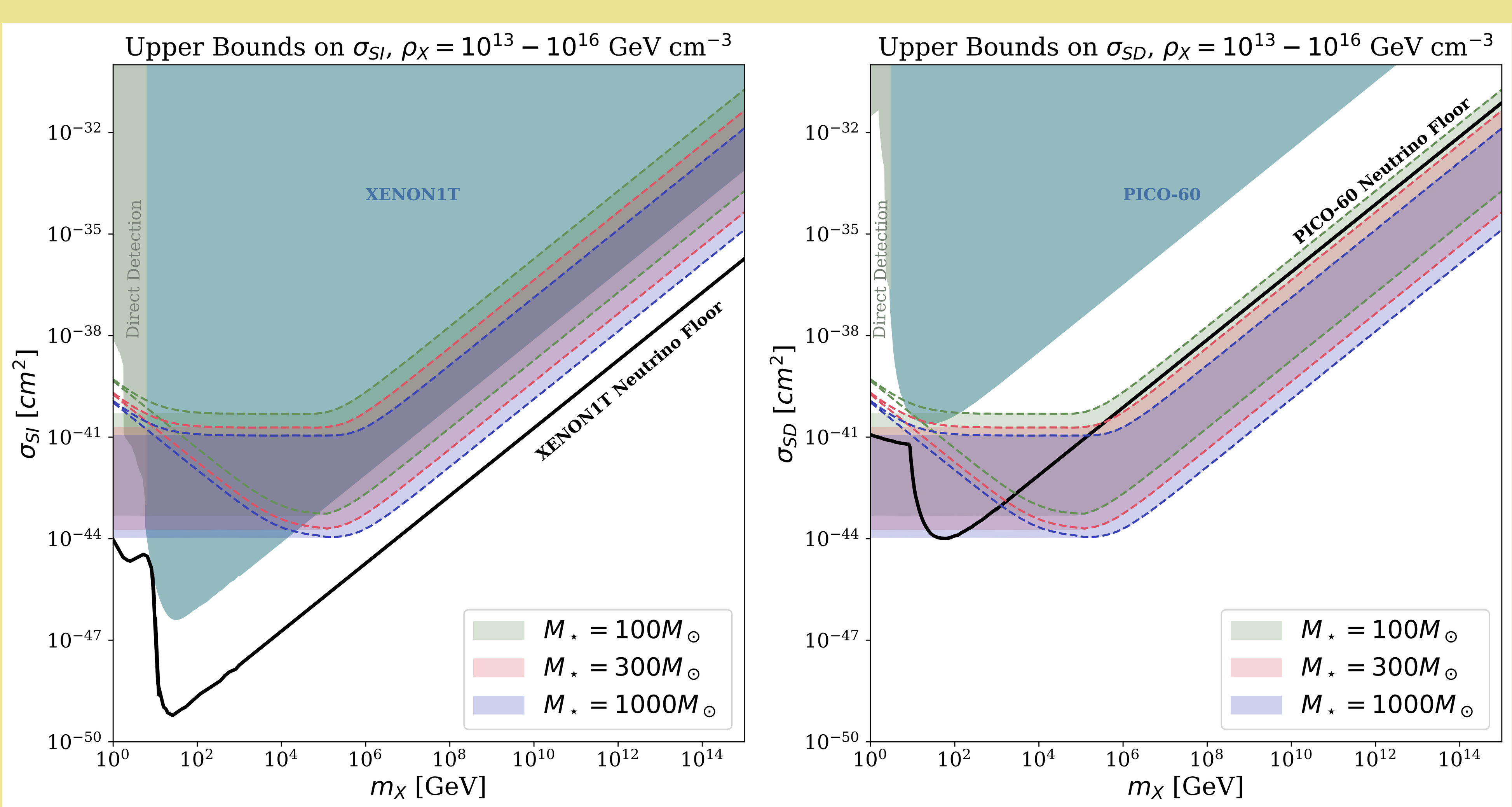
- Most PopIII stars will form well within 10 AU of DM halo center
- DM densities at locations where PopIII stars form are enhanced by Adiabatic Contraction (AC) (see Fig above)
- If AC persists until collapse of cloud to $n_B \simeq 10^{15}\ cm^{-3}$ DM density at location of PopIII stars can be as high as $10^{16} GeVcm^{-3}$

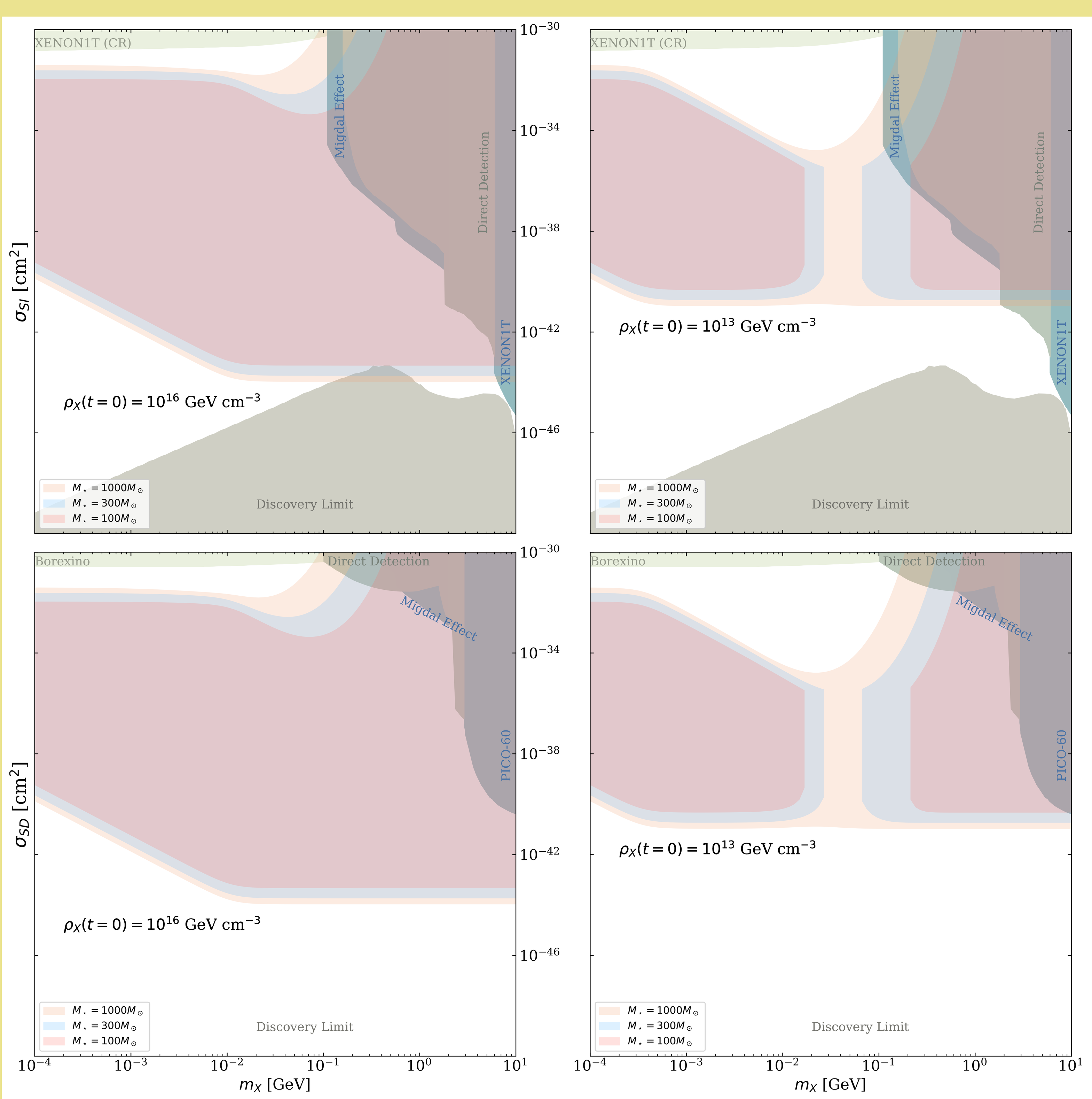
Method:

- Assume observation of PopIII stars with mass ranging from 100 to 1000 $M_\odot$
- Assume $\rho_X \in [10^{13}, 10^{16}]\ GeVcm^{-3}$
- The Eddington Limit is recast as a condition on the maximum amount of DM heating from captured DM by a PopIII star
- Max DM heating is converted to bounds on DM-proton scattering cross section

Main Results:

- In the two panel Figure (below) we plot our forecast bounds based on the Method described above, for DM particle mass $m_X \gtrsim 1 GeV$
- In the four panel Figure (to the right) we plot our forecast bounds for the Co-SIMP[7] sub-GeV DM model.
- In each case we contrast against direct detection experiment bounds and the neutrino floor (aka fog).
- For more details of our work see [4,5] or scan the QR codes in the title box.





References:

1. Volker Bromm, “Formation of the First Stars,” *Rept.Prog.Phys.* 76 (2013) 112901 • e-Print: 1305.5178 [astro-ph.CO]
2. Doug Spolyar, Katherine Freese, and Paolo Gondolo, “Dark matter and the first stars: a new phase of stellar evolution," *Phys.Rev.Lett.* 100 (2008) 051101 • e-Print: 0705.0521 [astro-ph]
3. Katherine Freese, Cosmin Ilie, Doug Spolyar, Peter Bodenheimer, Monica Valluri, Peter Bodenheimer, "Supermassive Dark Stars: Detectable in JWST," *Astrophys.J.* 716 (2010) 1397-1407 • e-Print: 1002.2233 [astro-ph.CO]
4. Cosmin Ilie, Caleb Levy, Jacob Pilawa, Saiyang Zhang, “Constraining dark matter properties with the first generation of stars," *Phys.Rev.D* 104 (2021) 12 • e-Print: 2009.11474 [astro-ph.CO]
5. Cosmin Ilie, Caleb Levy, Jacob Pilawa, Saiyang Zhang, "Probing below the neutrino floor with the first generation of stars," e-Print: 2009.11478 [astro-ph.CO]
6. Shingo Hirano, Takashi Hosokawa, Naoki Yoshida, Hideyuki Umeda, Kazuyuki Omukai, “One Hundred First Stars : Protostellar Evolution and the Final Masses,” *Astrophys.J.* 781 (2014) 60-81 • e-Print: 1308.4456 [astro-ph.CO]
7. Juri Smirnov and John F. Beacom, “New Freezeout Mechanism for Strongly Interacting Dark Matter,” *Phys.Rev.Lett.* 125 (2020) 13, 131301 • e-Print: 2002.04038 [hep-ph]