Heating the dark matter halo with dark radiation from supernovae

Stefan Vogl

based on JCAP 07 (2025) 058 [arXiv:2411.18052]
with Xun-Jie Xu (IHEP, Beijing)

universität freiburg

SNII as laboratory for new physics

- nuclear density and $T = \mathcal{O}(10)$ MeV in core makes SN potentially efficient producers of light, very weakly coupled new physics, e.g. axions, dark photons, sterile neutrinos ...
- dynamics in core shielded by mantle $\rightarrow$ most constraints based on one observation: neutrinos from SN 1987A
- few events but roughly consistent with expected cooling of proto-neutron star
- limits typically based on "Raffelt criterion": luminosity in new physics less than neutrino luminosity

Can we do better?

- neutrino observations: wait for next galactic SN

  $\Rightarrow$ Need other observables if we want to do more now.

- produced particle can escape and decay/convert to SM

  see e.g 1702.02964, 1903.07923 ...

- What happens if the energy goes to the dark sector? Can SN energy injection affect DM observables at a detectable level?

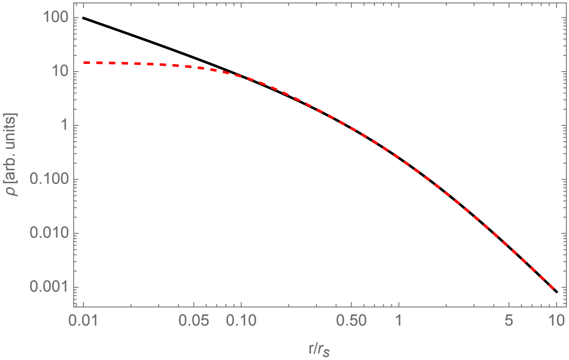
Dark Matter Halo

Density profiles of dwarfs spheroidals

photo for Fornax dwarf galaxy

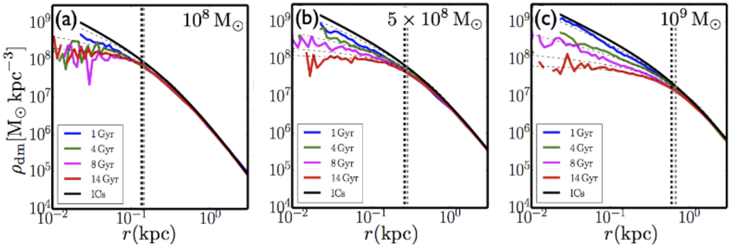
- velocity distribution of stars traces gravitation potential, i.e. mass profile
- overall mass dominated by dark matter
- can determine density profile from stellar kinematics

Cuspy vs cored profile



- expectation from DM only simulations: NFW profile
- observations: some dwarfs prefer a core
- some physics missing:
  - non-standard DM, e.g. fuzzy, self-interacting, ...
  - astrophysics: baryon feedback

Simulations with baryon feedback



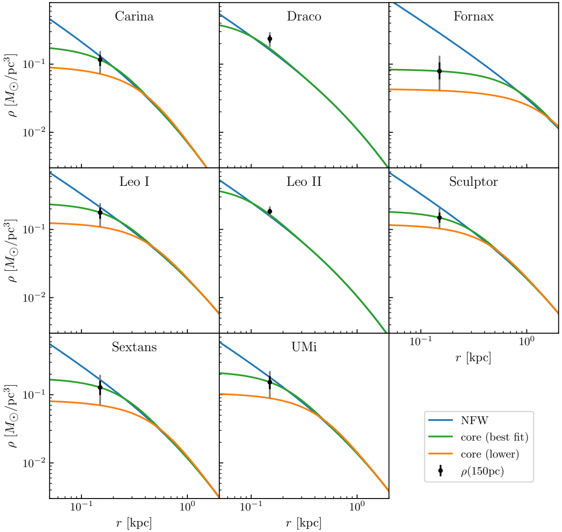
Read et al '15, 1508.04143

- Baryon feedback can transform an originally NFW cusp into a core
- Baryon feedback is gas flows driven by SN explosions

see also talk by A. Di Cintio

rather inefficient process $\Rightarrow$ What about direct energy injection?

Dwarf spheriodal halo profiles



input data from Read et al '18, 1808.06634

Gravitational binding energy

- cored halos have more material at larger radius $\Rightarrow$ less gravitational binding energy
- need additional energy to transform a cuspy to a cored halo
- ΔE is a function of r_c
- from gravitational binding energy and virial theorem

$$\Delta E = 8\pi G \int dr\, r\, [M_c(r)\rho_c(r) - M_{NFW}(r)\rho_{NFW}(r)]$$

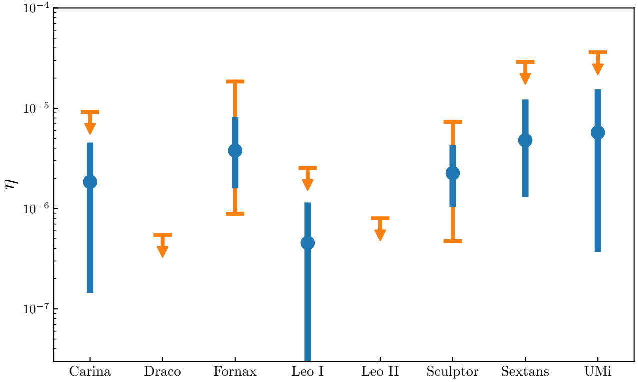
- taking upper limit on $r_c \to \Delta E_{max} \sim 10^{51}$ to 10^{54} erg

SN as energy sources

- type II (core collapse) supernova typically release about 3×10^{53} erg of which only about 1% goes into visible explosion
- all stars with $8 m_\odot \lesssim m_* \lesssim 40 m_\odot$ explode on time scales much less than age of galaxy
  $\Rightarrow$ only need to know fraction of stars in this mass range and overall stellar mass
- stellar mass: measured
- mass distribution of stars: assume Kroupa initial mass mass function, $\approx 3 \times 10^{-3}$ stars in right mass range

$$E_{tot} \approx 2.5 \frac{M_*}{m_\odot} \times 10^{51} \text{ erg with } M_* \sim 10^6 m_\odot$$

Allowed energy fractions



10^{-5} of energy released by SN sufficient to produce cores in excess of observations

Particle physics

Key questions

- Can we produce enough exotic particles?
- Can they travel astrophysical distances?
- Can they deposit their energy in the dark matter halo?

Consider benchmark model:

- here: dark Higgs, i.e. singlet scalar mixed with Higgs and coupled to dark matter
- results qualitatively similar for: dark photon, $B - L$ and $L_\mu - L_\tau$

Answers

- Can we produce enough exotic particles?

Efficient production via nucleon bremsstrahlung and semi-Compton. $\mathcal{O}(1)$ of SN energy emitted in s for $\sin\theta \approx 10^{-7}$.

- Can they travel astrophysical distances?

Yes, if $m_s < 2m_e$. Alternative: for $2m_\chi < m_s$ we have fast decays to DM. DM can travel across the halo.

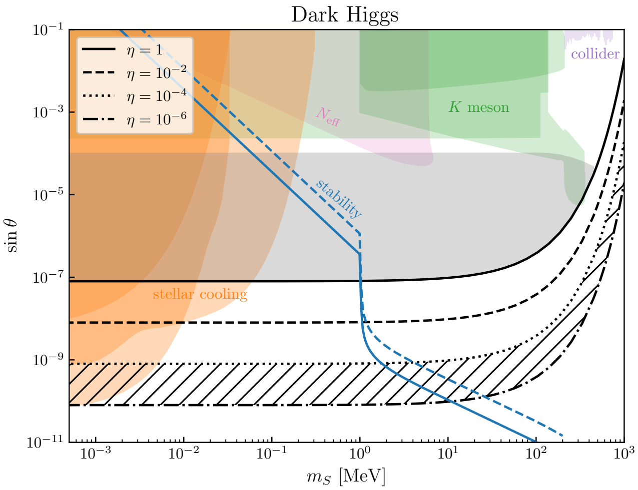
- Can they deposit their energy in the dark matter halo?

For efficient scattering in halo we need:

$$\sigma \gtrsim (1-2) \times 10^{-25}\text{cm}^2 \cdot \frac{m_\chi}{\text{MeV}}$$

largish cross section: need $m_{DM} \lesssim 100$ MeV and $g_{DM} \gtrsim 0.01$ - 1

Putting everything together



Testable parameter space

Conclusions

- total energy release from SN explosions over lifetime of galaxy is huge
- for $\mathcal{O}(1)$ energy absorbed dwarf galaxies sensitive to $\approx 10^{-5}$ of total energy release
- conditions for sufficient energy release and efficient absorption possible in a range of simple benckmark models (dark photon, dark Higgs, $B - L$, $L_\mu - L_\tau$)
- halo shape allows testing couplings well beyond usual SN1987a bound, two orders of magnitude improvements possible