Heating the dark matter halo with dark radiation from supernovae

Stefan Vogl

based on arXiv:2411.18052
with Xun-Jie Xu (IHEP, Beijing)

universität freiburg

SNII as laboratory for new physics

- high density and temperature 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 $\rightarrow$ access to core via neutrinos from SN 1987A
- few events but roughly consistent with expected cooling of proto-neutron star
- limits often based on cooling argument (Raffelt criterion)

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
  $\rightarrow$ search for e.g gamma rays

  see e.g talks by Francesca, Jorge, Eike

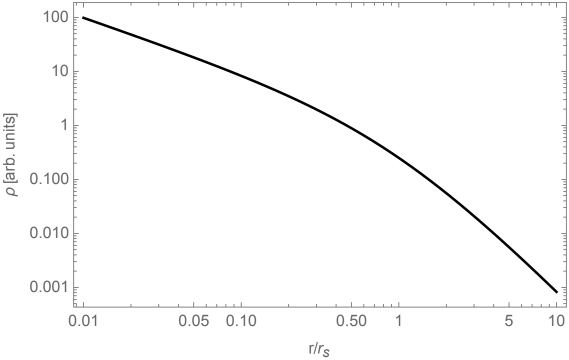
  $\rightarrow$ search for interactions with detectors at earth

  see e.g talks by Andres, David

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

Dark Matter Halo

NFW profile



- N-body simulations predict a universal shape of dark matter halos: NFW profile

$$\rho_{NFW} = \frac{\rho_0 r_s^3}{r(r + r_s)^2}$$

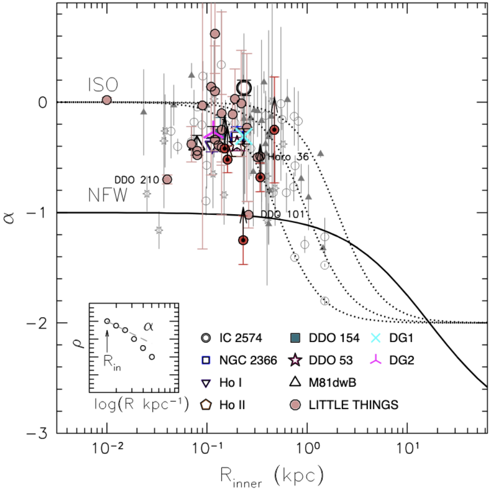
- ρ proportional $1/r$ at small r, inner slope $\alpha = -1$ (dark matter cusp)

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

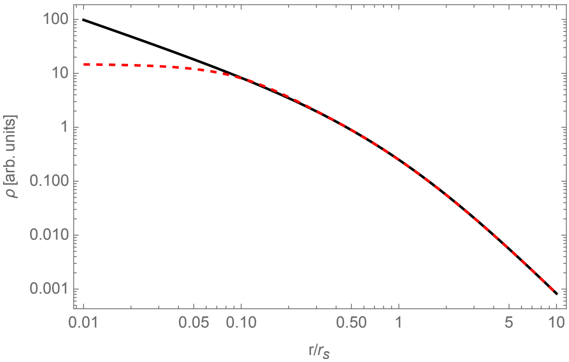
Dark matter cores



Oh et al 2015, 1502.01281

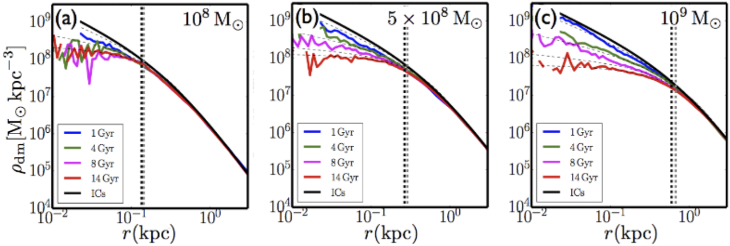
- some observations prefer slopes $\alpha = 0$, i.e DM cores

Cored profile



- flat inner profile ($\alpha = 0$), size controlled by core radius r_c
- can form due to baryon feedback or non standard dark matter properties ($\rightarrow$ self-interacting dark matter, fuzzy dark matter ...)

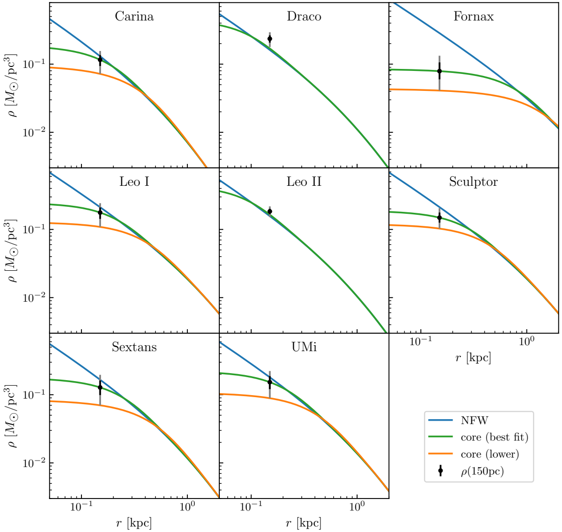
Simulations with baryon feedback



Baryon feedback can transform an originally NFW cusp into a core

Read et al ’15, 1508.04143

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

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

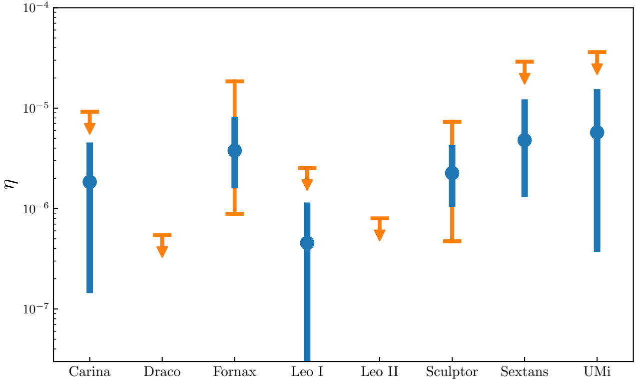
- taking upper limit on $r_c \rightarrow \Delta E_{max} \sim 10^{51}$ to 10^{54} erg

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 $8m_\odot \lesssim m_* \lesssim 40m_\odot$ 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 particle?
- Can they travel astrophysical distances?
- Can they deposit their energy in the dark matter halo?

Benchmark models

Consider a set of simple, well motivated benchmark models for production in SN

- dark photon
- dark Higgs
- Z' from $B - L$
- Z' from $L_\mu - L_\tau$

and couple all of them to dark matter

For illustration: focus on dark photon now

Production in SN

- dark photons couples to proton and electron
- production in SN dominated by
  - nucleon bremsstrahlung: $p + n \to p + n + Z'$
  - semi-Compton scattering: $\gamma + e^- \to Z' + e^-$
- significant ($\mathcal{O}(1)$) energy fraction is possible, compare SN1987A bound

Lifetime

- dark photons are not stable
- typical distance to decay $l = \gamma\beta/\Gamma$
  $\Rightarrow$ Can particle travel astrophysical distances of $\mathcal{O}$(kpc)?
- direct couplings to electrons but not neutrinos or photons
  - for $2m_e \leq m_{Z'}$: relatively quick decays to e^+e^-
  - for $2m_e > m_{Z'}$: fairly slow, loop induced to decay to 3γ
- for $2m_\chi < m_{Z'}$ decay to DM possible
  instantaneous decay to dark matter for relevant couplings g_χ with BR=100%

$\Rightarrow$ split in parameter space between these options

Optical depth

- Z' (or DM from its) decay must scatter on halo DM to transfer energy
- probability of scattering controlled by optical depth τ

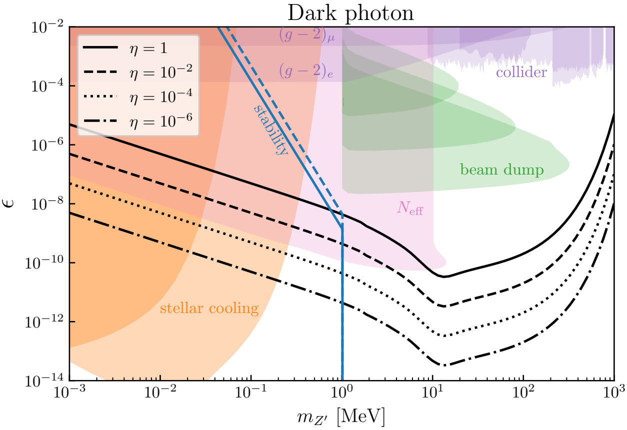
$$\tau \approx \frac{\sigma}{m_\chi} \int \rho dl$$

- for density profiles of cored halos $\tau \geq 1$ for

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

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

Putting everything together



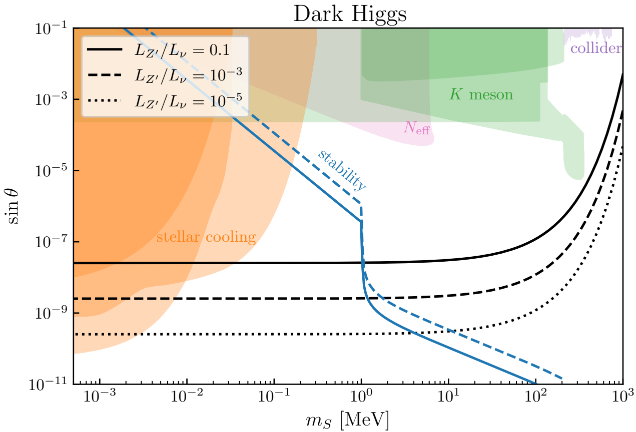
Testable parameter space: Dark Photon

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

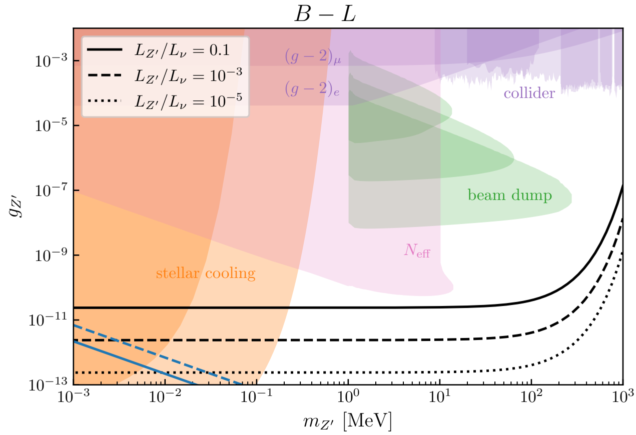
Backup material

Testable parameter space: Dark Higgs

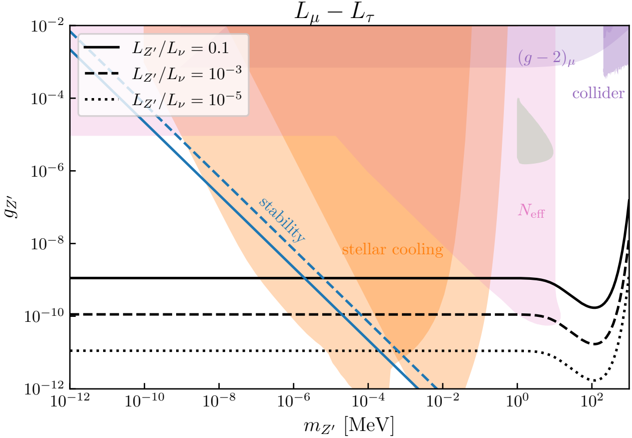


Even more space for dark Higgs

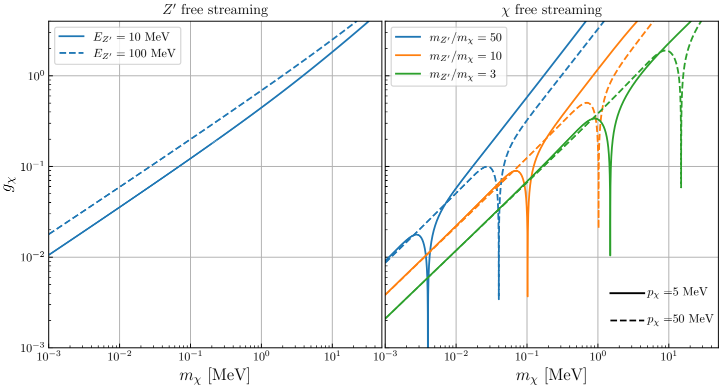
Testable parameter space: $U(1)_{B-L}$



Testable parameter space: $U(1)_{L_\mu - L_\tau}$



Limits on g_{DM}



energy loss via scattering on halo dark matter

- Z' stable: Z' DM $\rightarrow$ Z' DM scattering (Compton-like cross section)
- Z' decays to DM : DM DM $\rightarrow$ DM DM scattering (Bhabha/Moeller-like scattering cross section)

for $\tau \geq 1$: $m_{DM} \lesssim 100$ MeV and sizeable g_χ