Dark lepton superfluid in proto-neutron stars

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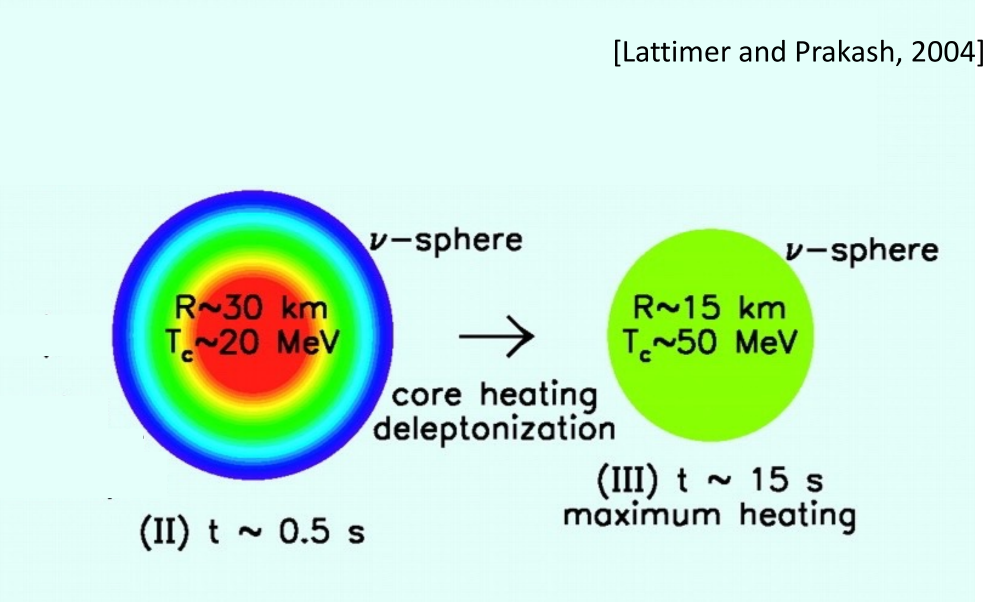
Core-collapse supernovae are unique laboratories

- Extreme conditions in proto-neutron stars (PNS)
  - Baryon number density $n_B \sim n_0 = 0.16\ \mathrm{fm}^{-3}$;
  - Temperature $T_{\mathrm{PNS}} \sim 20 - 50$ MeV;
  - Neutrinos are trapped for $\tau_{\mathrm{diff}} \sim 20$ s;
  - Maximum Lepton chemical potential $\mu_L = \mu_{\nu_e} \sim 200$ MeV.

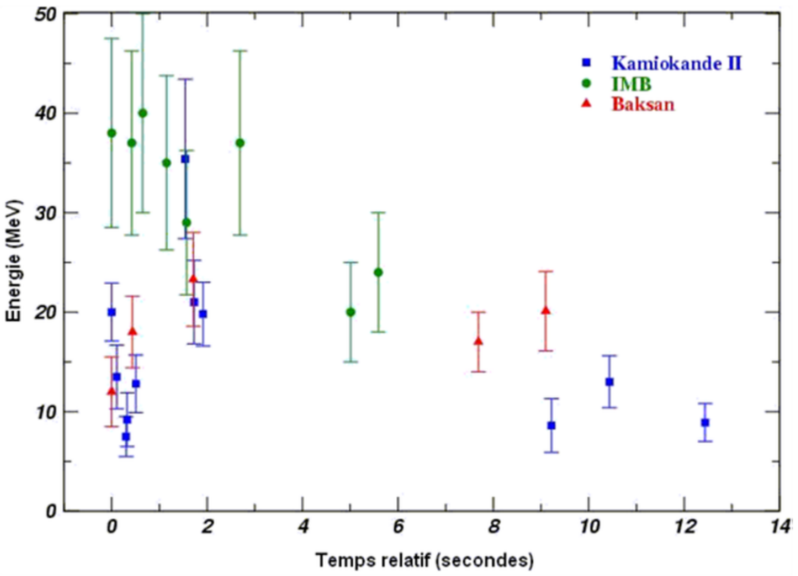


Similar conditions could be encountered in binary NS mergers

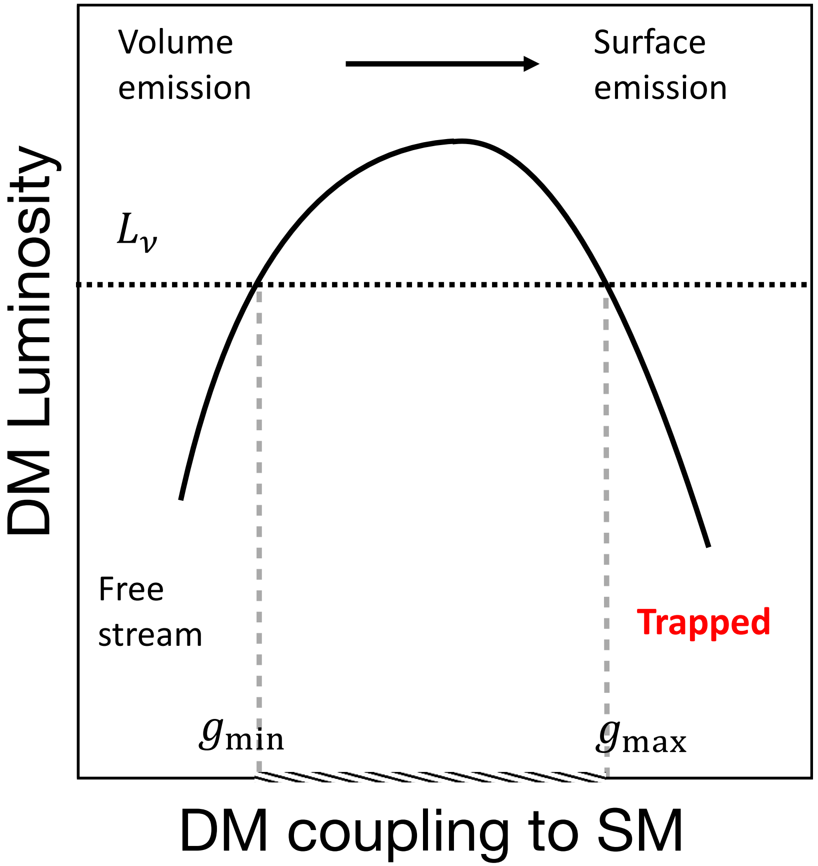
Cooling constraints on light DM

e.g., [Raffelt *et al*, Phys.Rev.Lett. 60 (1988)]

- Extra cooling from new light (mass $\lesssim T_{\text{PNS}}$) particles alters ν emissions



Neutrinos from SN1987A



- What about the trapping regime?

Why neutrino portal dark matter?

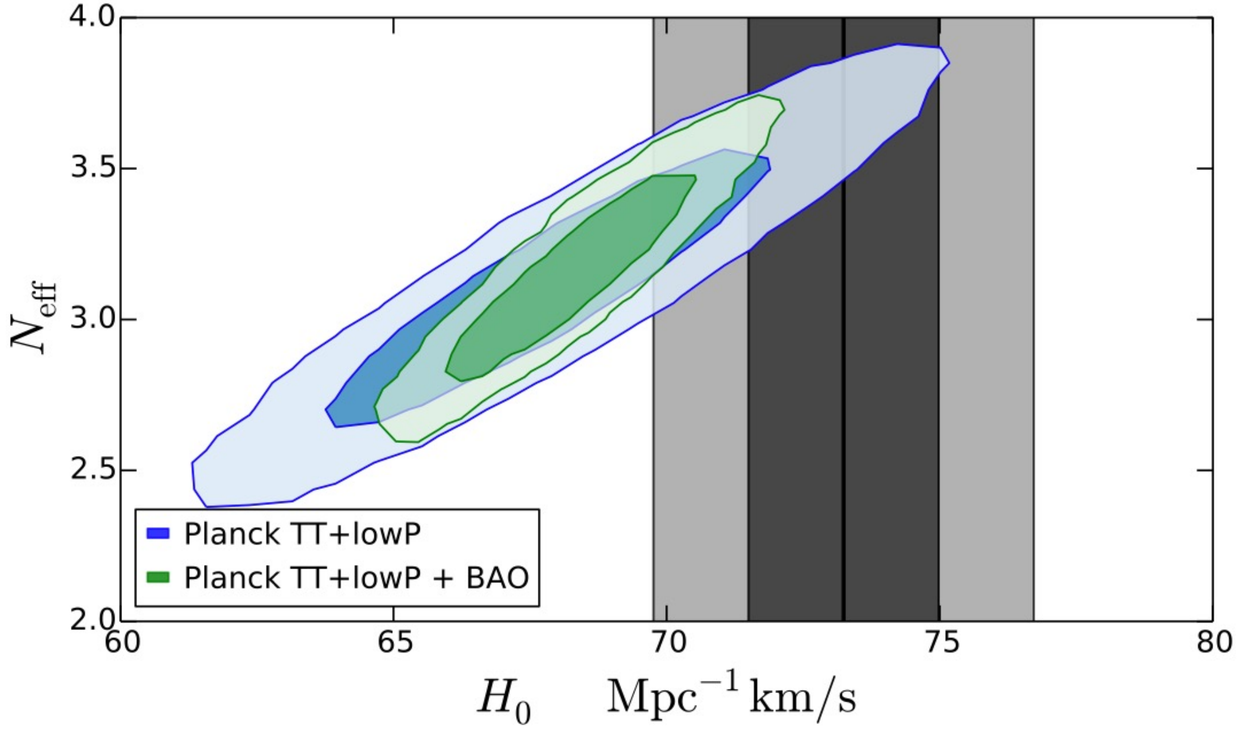
- Theory: BSM physics expected
  - Neutrino mass model? CP violation? …
- Phenom: hints from labs and the cosmos
  - Short baseline neutrino anomalies (LSND, MiniBooNE), …
  - Strong neutrino self-interactions may solve the Hubble tension (~4σ):

	CMB (Planck 2018)	Local measurements (BAO, Cepheids, Type Ia SNe)
H_0 $(\mathrm{km\,s^{-1}Mpc^{-1}})$	67.9 ±1.3	74.03 ± 1.42

[1903.07603], [1807.06209], …

Neutrino self-interaction alleviates the Hubble tension (?)

- The proposal: large late time $\Delta N_{\mathrm{eff}} \sim 1$ (requires additional dark sector physics)

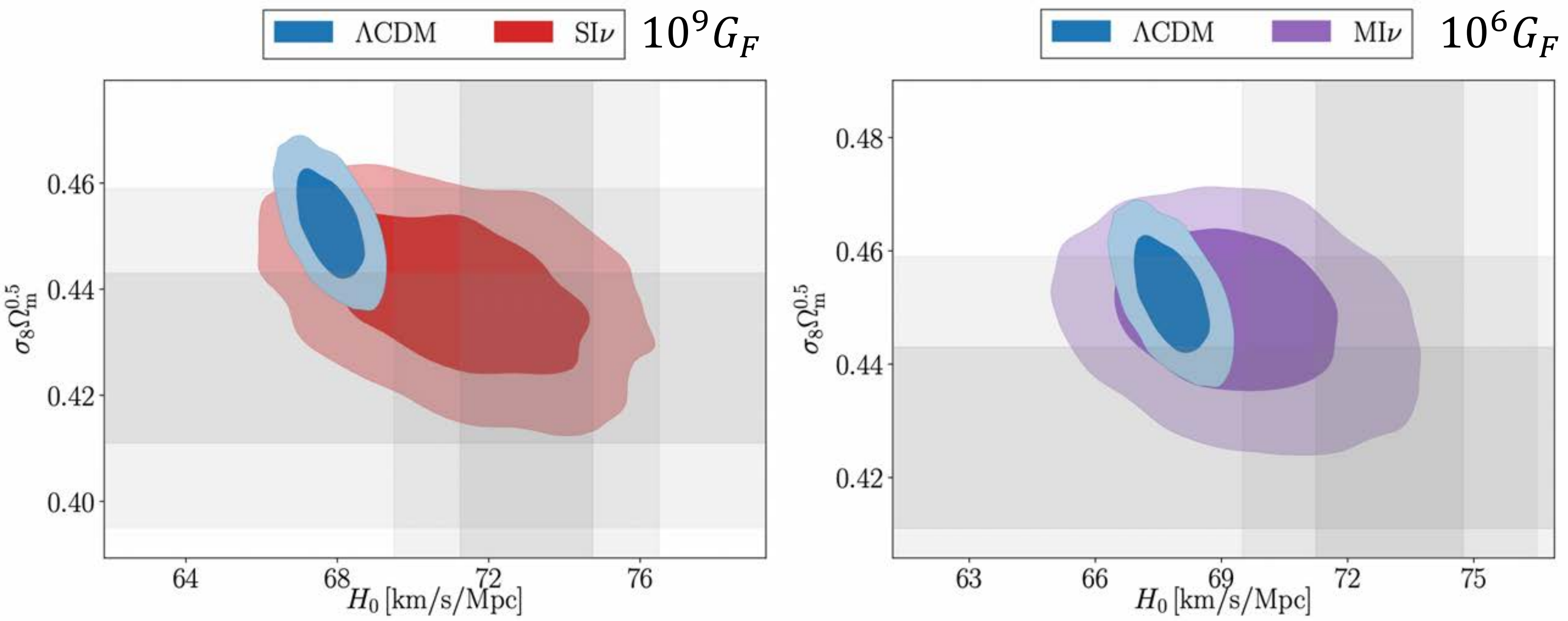


[1607.05617]

- But this damps the amplitude of matter density fluctuations at small scales

Neutrino self-interaction (?) alleviates the Hubble tension (?)

- Neutrino self-interaction suppresses ν free-streaming until T ~ eV;



	SIν	MIν
$\sum m_\nu$(eV)	$0.42^{+0.17}_{-0.20}$	$0.40^{+0.17}_{-0.23}$
$N_{\rm eff}$	4.02 ± 0.29	3.79 ± 0.28
$G_{\rm eff}$	$(4.7^{+0.4}_{-0.6}\rm MeV)^{-2}$	$(89^{+171}_{-61}\rm MeV)^{-2}$

[Kreisch *et al*, 1902.00534]

- Also ameliorates the σ_8 tension through degeneracies among params in the CMB fit

- Strong interaction strength implies light mediators: $10^6 G_F \sim \frac{\mathcal{O}(1)}{\mathcal{O}(100\ \rm MeV)^2}$

Model: sub-GeV ν-portal scalars

- Gauge neutral scalar ϕ carrying lepton number 2:

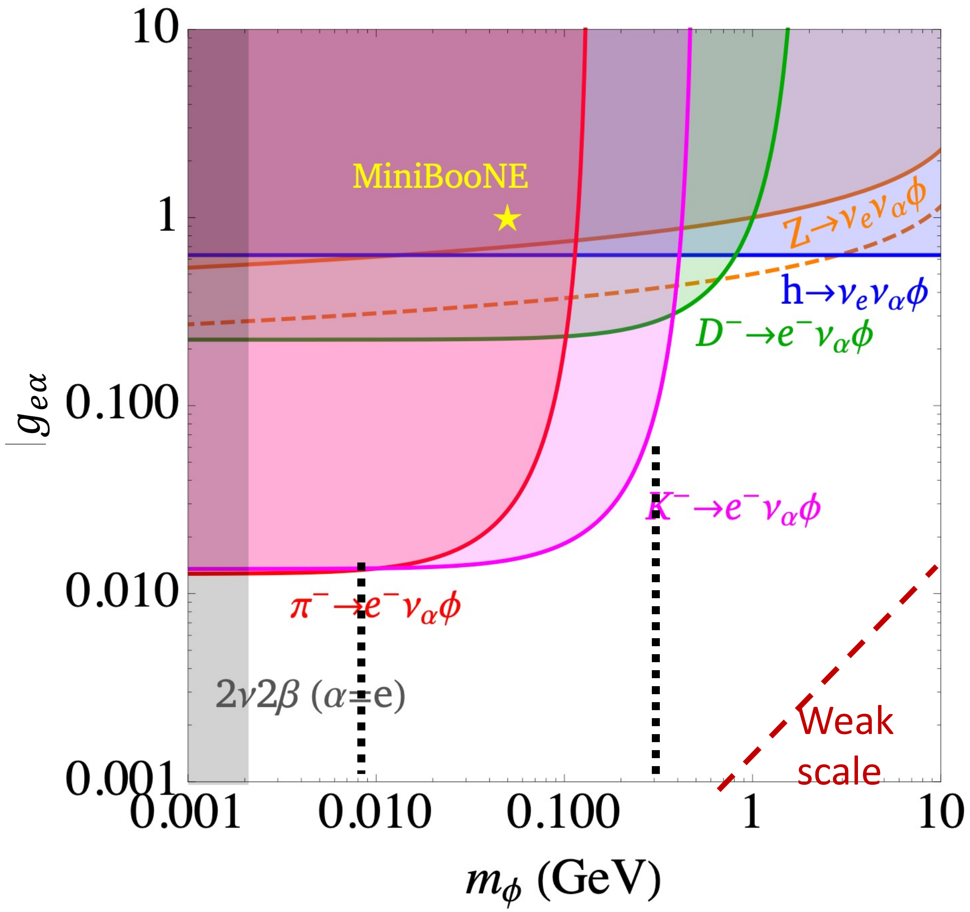
$$\mathcal{L}_{\text{eff, int}} \supset -\frac{g_{\alpha\beta}}{2}\nu_\alpha\nu_\beta\phi^* + \text{h.c.} - m_\phi^2\phi\phi^* - \frac{\lambda}{4}(\phi^*\phi)^2$$

- Generated from dimension-6 operator after EWSB:

$$\frac{f_{\alpha\beta}}{\Lambda^2}(L_\alpha\widetilde{H})(L_\beta\widetilde{H})\phi^* + \text{h.c.} \qquad L=(\nu_l, l^-)^T$$

[Burgess and Cline, 1994], [Berryman *et al*, 2018], …

- Expect large couplings: $|g| \sim f_{\alpha\beta}\frac{v^2}{\Lambda^2} \sim O(1)$
- Astro and laboratory constraints:
  - ΔN_{eff} during Big Bang nucleosynthesis: $m_\phi \gtrsim 10$ MeV (?);
  - Supernovae production: $m_\phi \lesssim 300$ MeV;
  - Focus on $g \equiv g_{ee} \lesssim 10^{-2}$ in this talk; $g \gtrsim 10^{-6}$ satisfies the SN cooling bound.



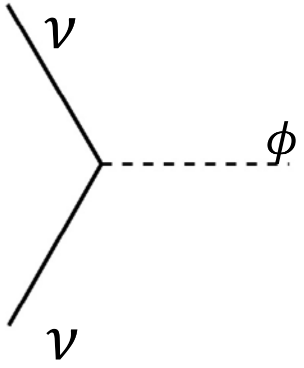
[Berryman *et al*, 1802.00009]

[de Gouvea *et al*, 1910.01132]

Production, Thermalization, and Condensation

➢ Rapid ϕ production in abundance

- $\frac{\mathrm{d}n_\phi}{\mathrm{d}t} \sim 10^{61}\ \mathrm{s}^{-1}\mathrm{km}^{-3} \times \left(\frac{g}{10^{-3}}\right)^2 \left(\frac{m_\phi}{50\ \mathrm{MeV}}\right)^2 \left(\frac{\mathrm{T}}{30\ \mathrm{MeV}}\right)$;

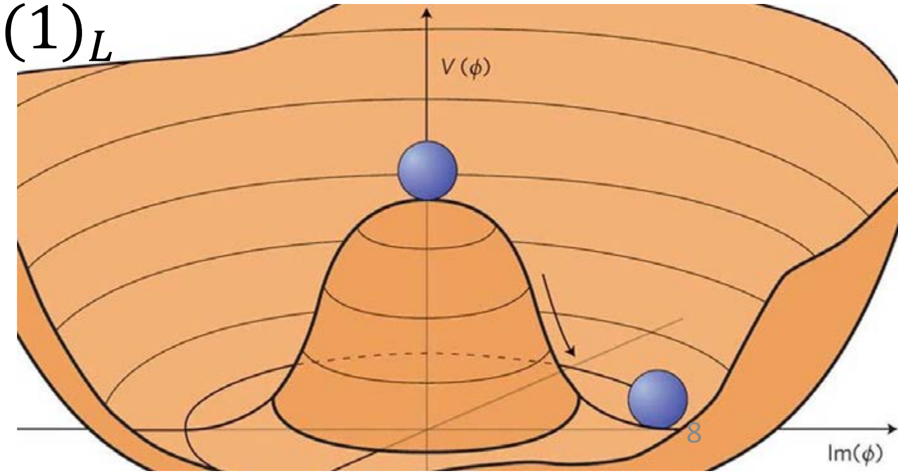


➢ Trapping and thermalization: $\phi \to \nu\nu$

- Mean free path: $\lambda_\phi \sim 10^{-9}\ \mathrm{km} \times \left(\frac{10^{-3}}{g}\right)^2 \left(\frac{50\ \mathrm{MeV}}{m_\phi}\right)^2 \left(\frac{E_\phi}{20\ \mathrm{MeV}}\right)$;
- Equilibrium characterized by chemical potential $\mu_\phi = 2\mu_L = 2\mu_{\nu_e}$;

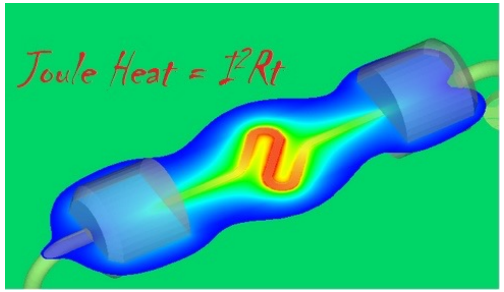
➢ Bosons condense when $\mu_\phi \geq m_\phi$: spontaneously broken $U(1)_L$

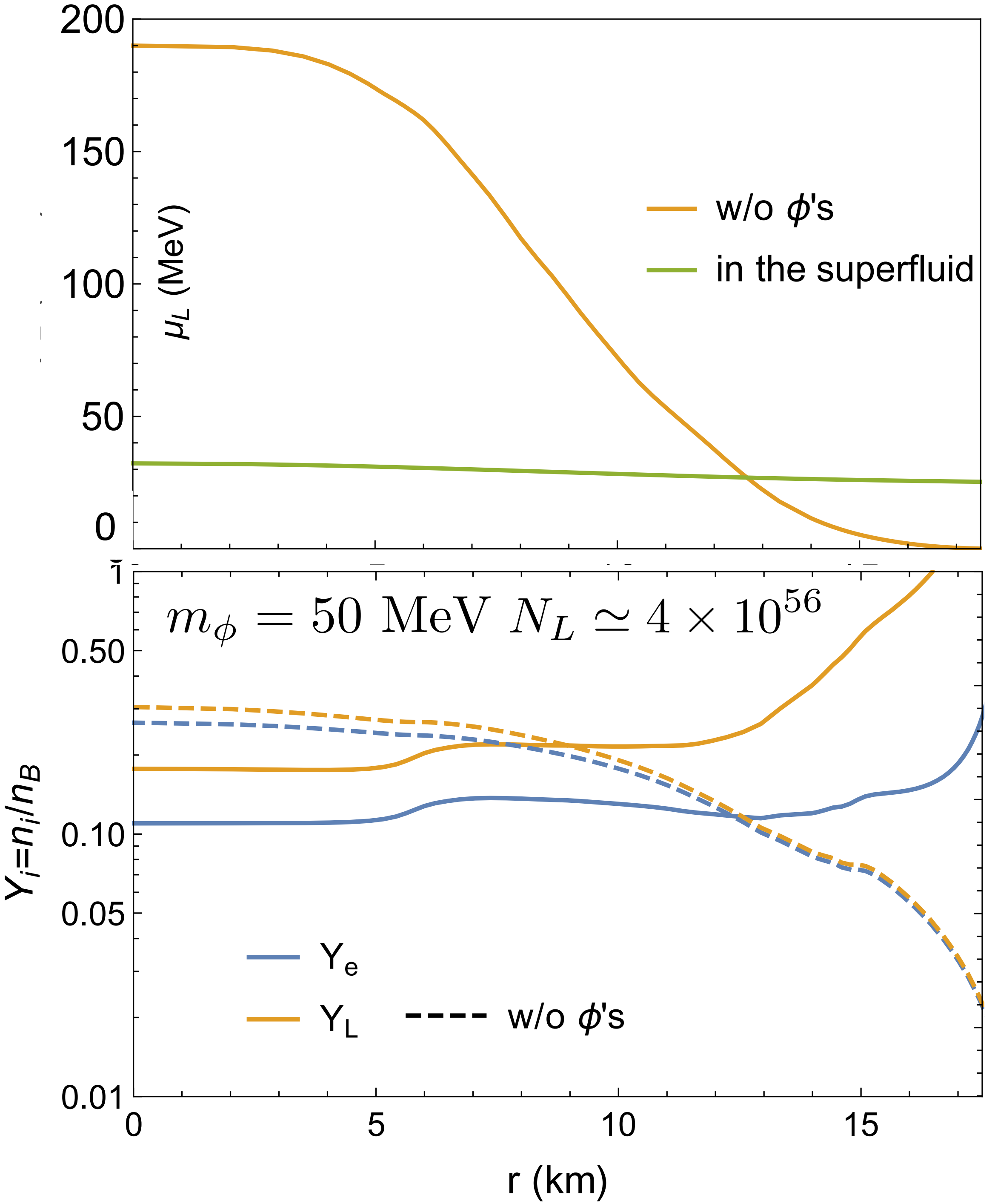
- $V_{\mathrm{eff}}(\phi) = (m_\phi^2 - \mu_\phi^2)\phi^*\phi + \frac{\lambda}{4}(\phi^*\phi)^2$ minimized by a finite vev;
- The ground state is a lepton number superfluid.



Astrophysical Implications

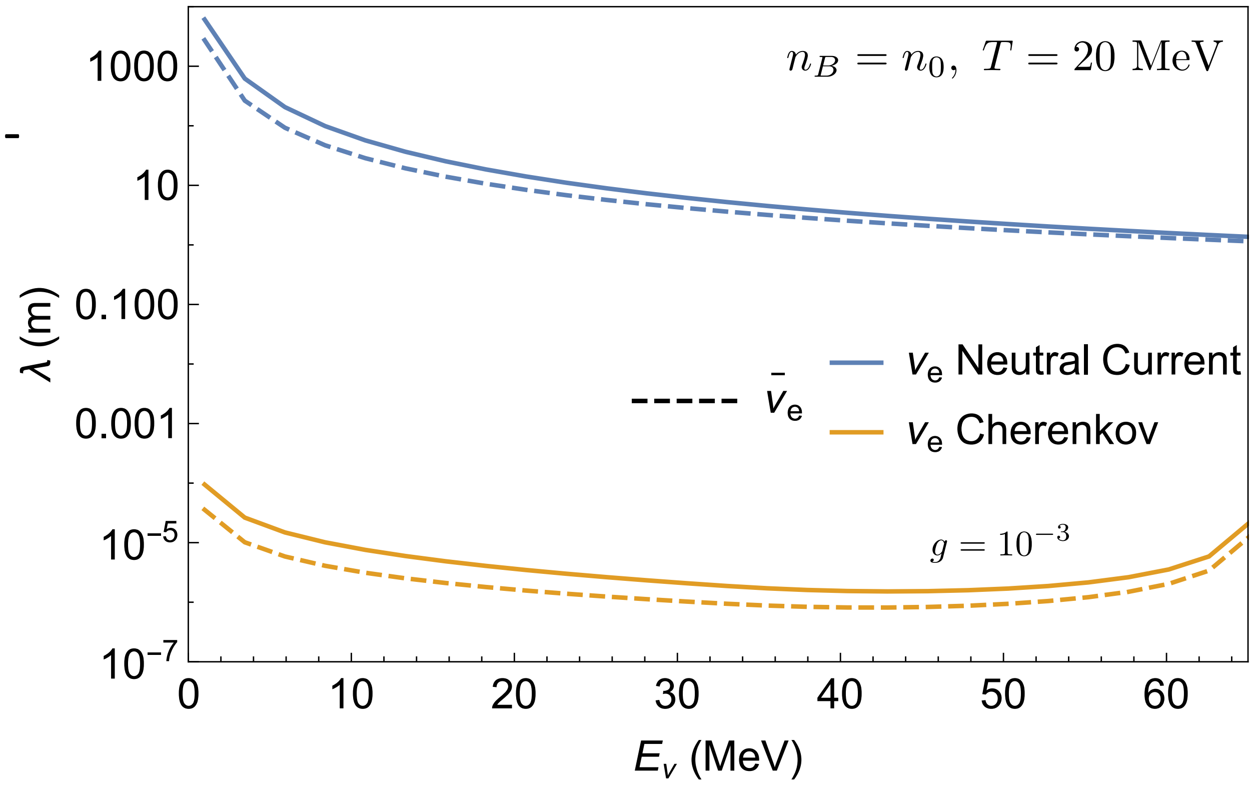
- Instantaneous L transport by the superfluid
  - In standard scenarios ν diffusion takes ~ 20 s
  - Superfluid mandates a constant* μ_L
- Could lower maximum T attainable
  - Suppressed Joule heating





Astrophysical Implications

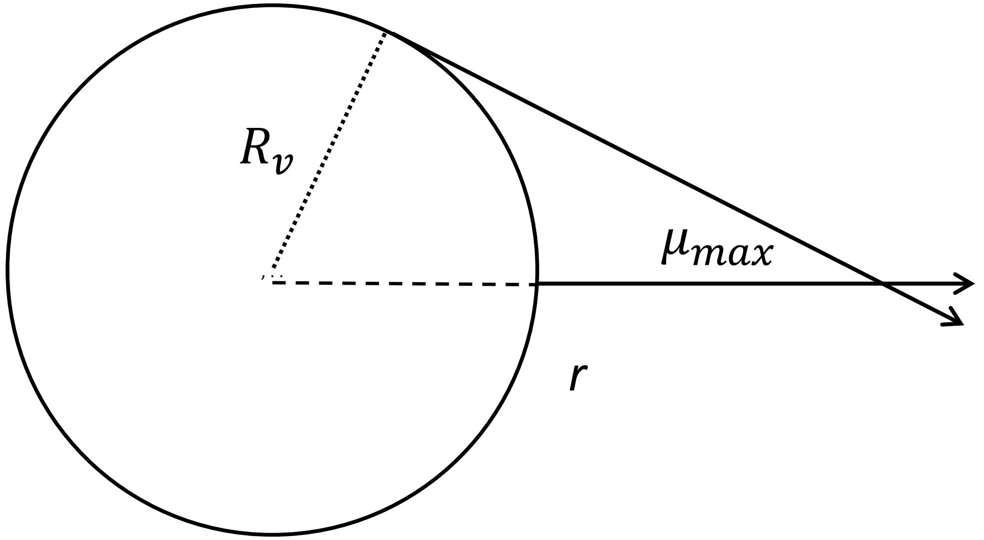
- Reduce thermal conductivity
  - Neutrinos dominate heat transport;
  - In the standard scenario determined by neutral-and charged-current reactions:
    - Scattering: $\nu_X + N \to \nu_X + N,\ X = e, \mu, \tau$
    - Absorptions: $\nu_e + n \to e^- + p,$
      $\bar{\nu}_e + p \to e^+ + n$, …
  - Goldstone mode J enables Cherenkov radiation $\nu_e \to \nu_e\, J$, shortens ν_e mean free path.



- Similar reductions could apply to μ and τ.

Astrophysical Implications: neutrino decoupling

The Bulb Model



$$f(E_\nu, r, \mu) = f_\nu(E_\nu)\xi^2 \frac{\Theta(\mu - \sqrt{1-\xi^2})}{1-\sqrt{1-\xi^2}}$$

$$\xi = \frac{R_\nu}{r}, \quad \mu = \left\langle \frac{\vec{p}}{|\vec{p}|}, \hat{r} \right\rangle$$

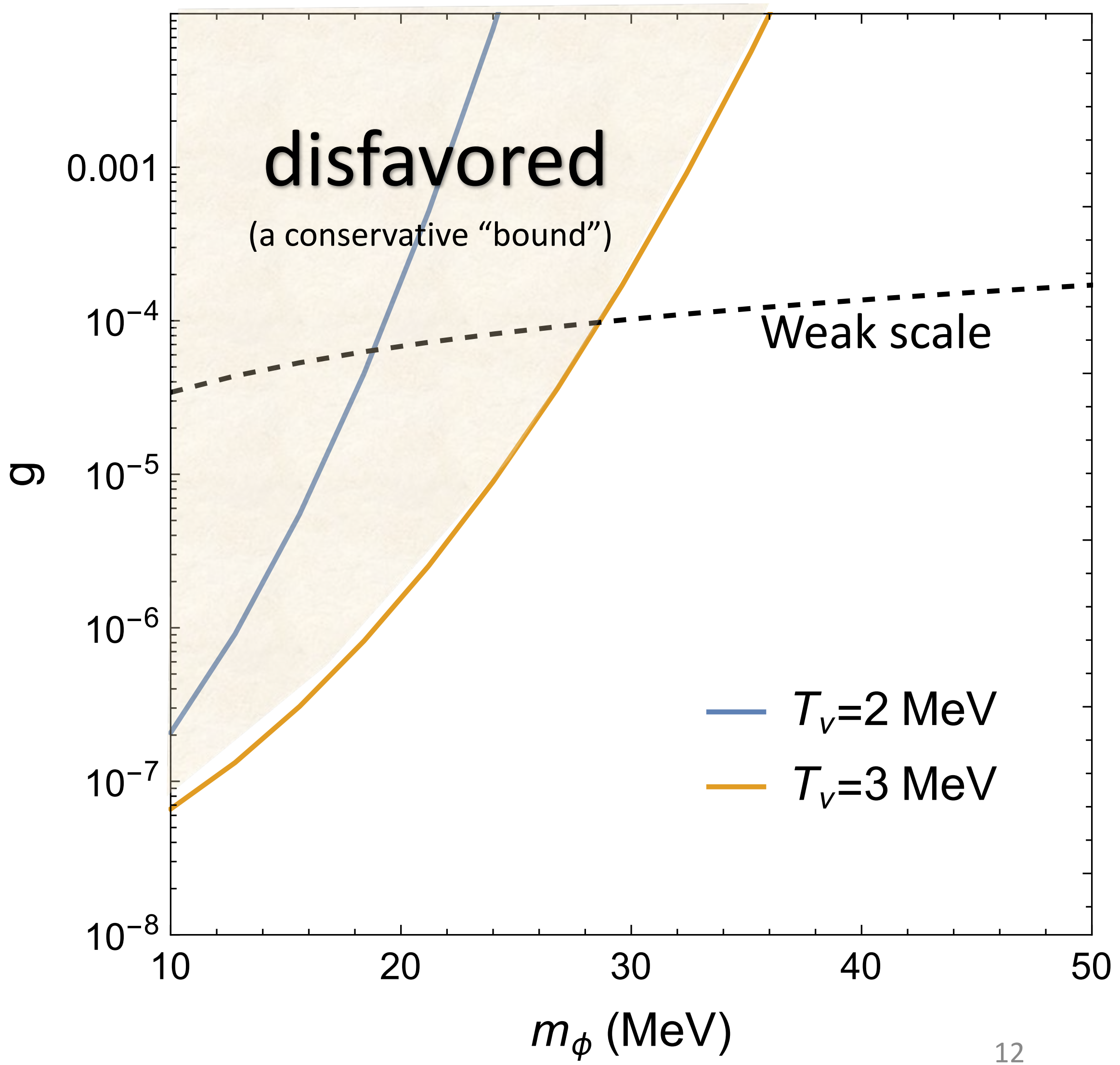
- Decoupling occurs outside condensed regions where $\mu_L \approx 0$
  - Large flux at the superfluid edge, recedes quickly to smaller radii.
- ϕ's are still important
  - (stronger-than-)Weak-scale interactions could dominate decoupling: $\nu\nu \to \phi$ at $\mathcal{O}(g^2)$.
- The neutrino bulb model assumes
  - R_ν independent of E_ν;
  - Perfect blackbody spectrum;

Astrophysical Implications: neutrino decoupling

- Optical depth determines decoupling radius:

$$\tau(E=3T_\nu)=\int_{R_\nu}^{\infty}\frac{\mathrm{d}r}{\lambda(E=3T_\nu,r)}=\frac{2}{3}$$

- Low T_ν (large R_ν) might be in tension with SN1987
  - fix luminosity around $L_\nu \approx 3\times 10^{51}$ ergs/s;
  - Bayesian analysis favors $T_{\bar{\nu}_e} \gtrsim 3$ MeV (e.g. [arxiv:0107260])
- Mostly symmetric between ν_e and $\bar{\nu}_e$:
  - lowers n/p ratio, bad for r-processes
- Self-consistent simulations are required!



Summary and Outlooks

- Interesting phenom for new Weak scale neutrino interactions; Strong neutrino self-interactions highly unlikely (for e and μ);

- Core-collapse supernovae remains a powerful laboratory; In medium effects could be important for dark matter phenom;

- Dark lepton superfluid may drastically change the PNS composition and transport properties;

- Self-consistent simulations can identify observable signatures in neutrino signals;

- Extensions: coupling involving μ and τ flavors and flavor non-conservations; Effects on BBN? During core-collapse?