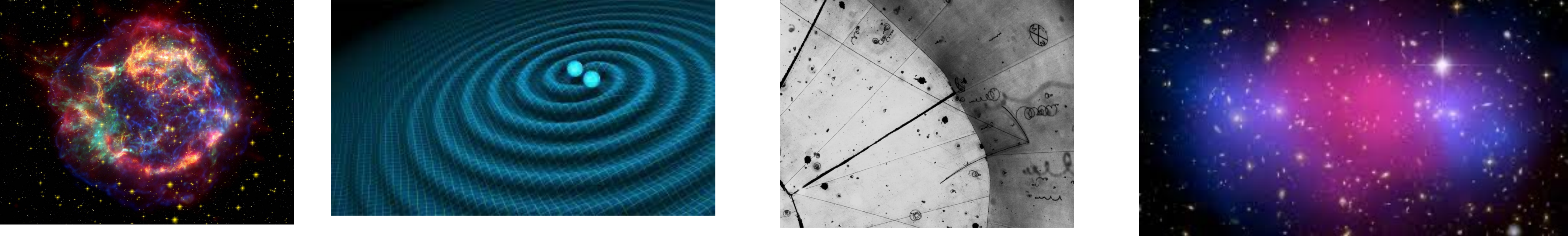


Dark Matter Signatures in Neutron Stars

Dake Zhou

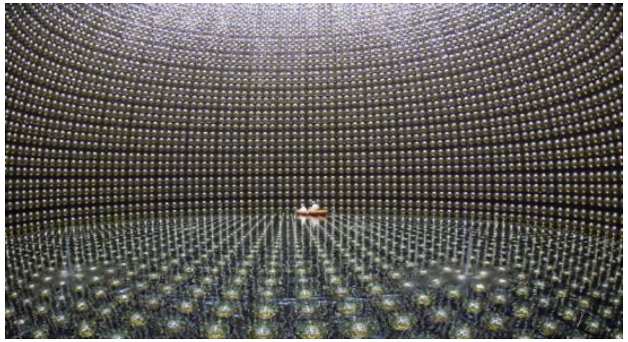
N3AS
Network for Neutrinos,
Nuclear Astrophysics,
and Symmetries
PHYSICS FRONTIER CENTER

NSF

Neutron stars are ideal laboratories

- ➢Extreme conditions: nurturing ground for exotics (dark?)
  - Dense: $\rho \sim 10^{19}$ kg/m^3 (dense QCD)
  - Compact: $\mathrm{M/R} \sim 0.3$ (strong gravity)
  - Hot: $T \sim 50$ MeV, opaque to ν's (supernovae and kilonovae)
  - $B \sim 10^{12}$ T (magnetars), high spin (millisecond pulsars), …
- ➢Multimessenger observations: a window to the unknown (dark?)

…



How may neutron stars get DM?

- Accretion is inefficient, probably w/o detectable effects

$$M_{\rm accretion} \sim 10^{-16} \left(\frac{\rho_\chi}{\rm GeV/cm^3}\right) \left(\frac{\sigma_{\chi n}}{10^{-45}{\rm cm}^2}\right) \left(\frac{\rm t}{10^8\ \rm yrs}\right)\ M_\odot$$

  - Exceptions:
    - Thermalized bosonic DM could induce gravitational collapse

$$M_{\rm crit} \approx M_{\rm pl}^2/m_\chi \sim 10^{-16} \left(\frac{100\ \rm GeV}{m_\chi}\right)\ M_\odot$$

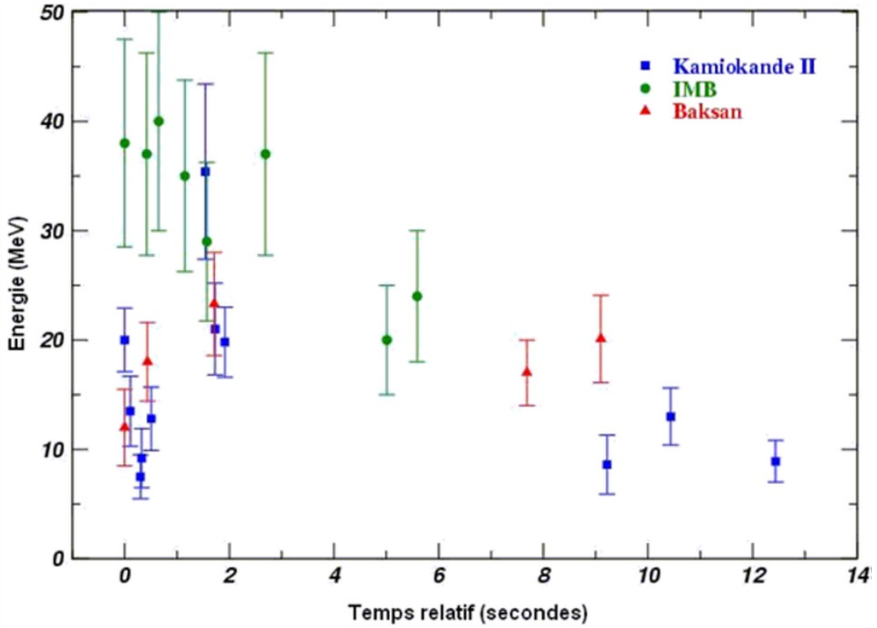
[Goldman and Nussinov 1989], [Kouvaris and Tinyakov 2010], [Bertoni et al 2013], [Bramante et al 2013], [Jamison 2013]…

    - Primordial BHs [Abramowicz et al 2009],[Fuller et al 2017],… , compact dark objects alike, …

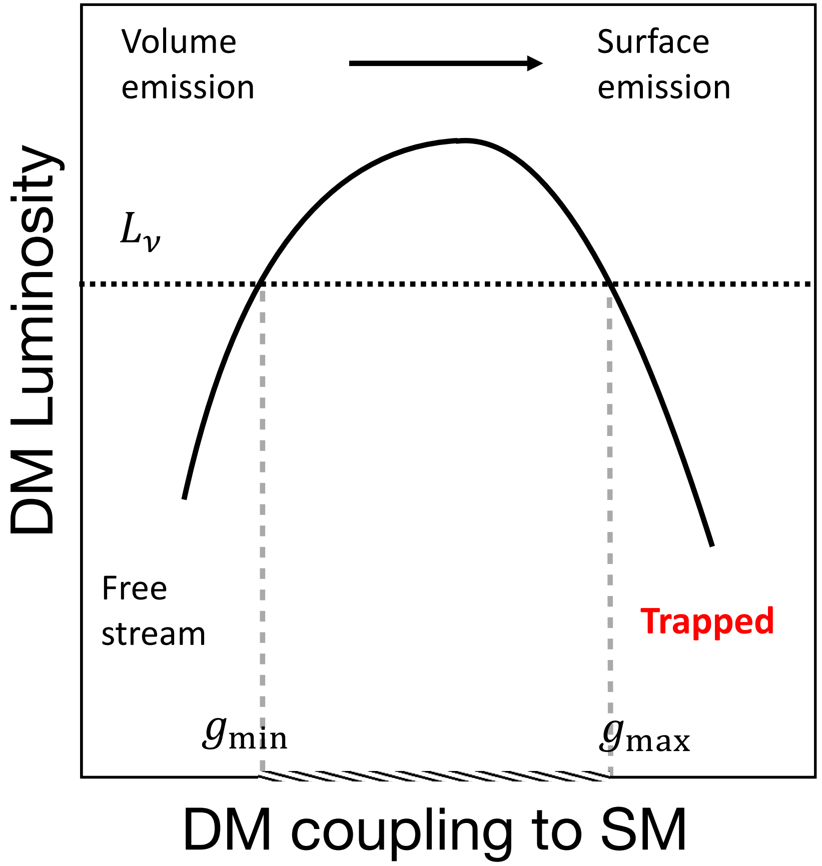
- In situ: produced/converted from SM species in the star and remains trapped

DM production in proto-neutron stars

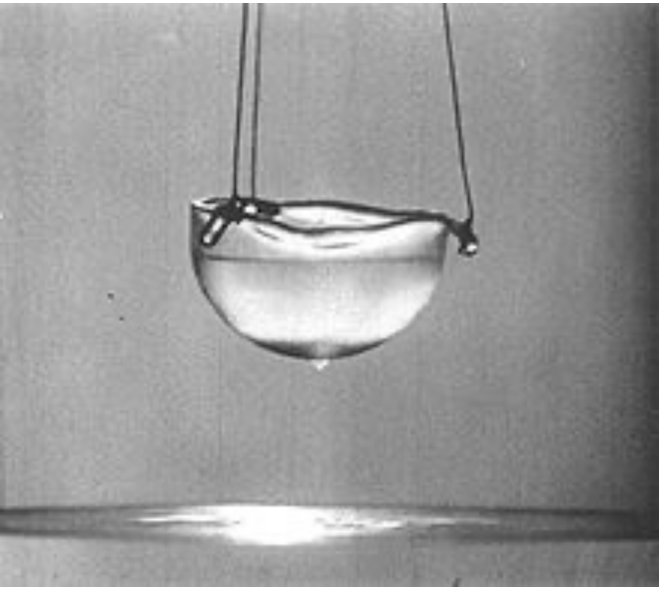
- ➢ Cooling bound: Extra cooling from new light particles alters ν emissions [Raffelt *et al*, Phys.Rev.Lett. 60 (1988), …]

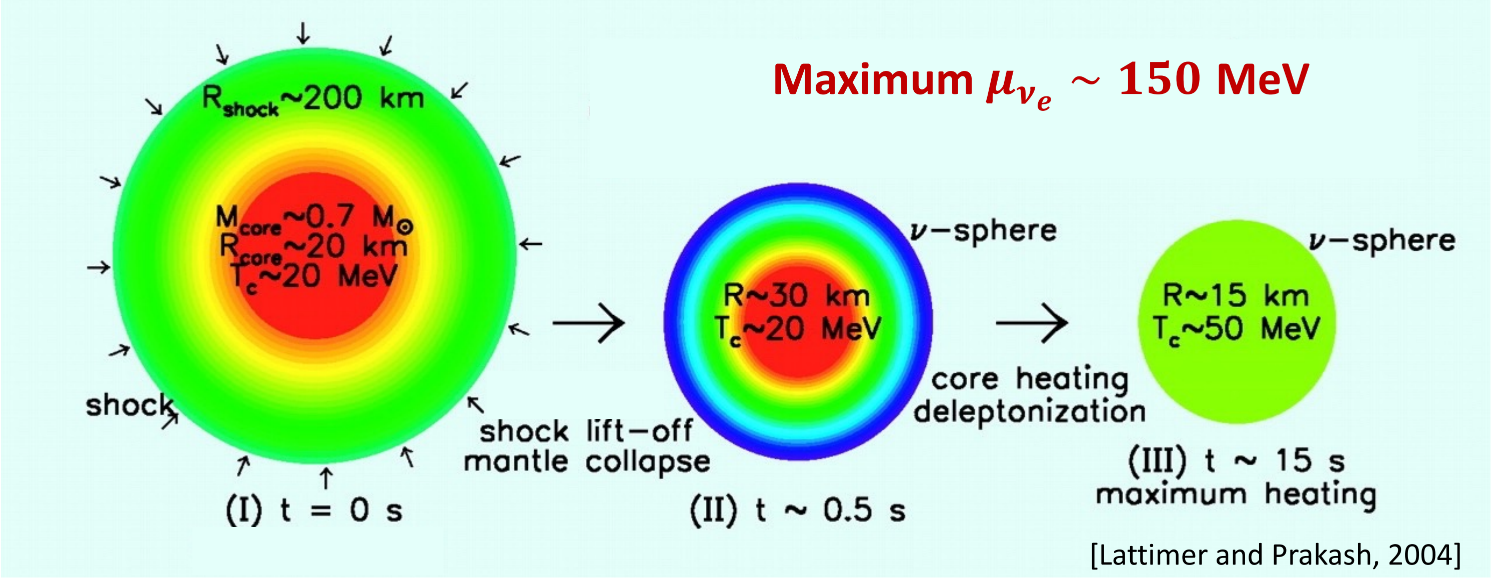


Neutrinos from SN1987A



- ➢ Trapping: gravity $(v_{esc}\sim 0.6)$, self-interaction, matter effect (B, L, γ…)
  - Relevant for other types of stars too (see talks last week)





Maximum $\mu_{\nu_e} \sim 150$ MeV

[Lattimer and Prakash, 2004]

Dark Lepton Superfluid in Proto-Neutron Stars

[Sanjay Reddy and **DZ**, *PRD* 105 (2022) 2, 023026, arxiv: 2107.06279]

Model: ν-portal bosons

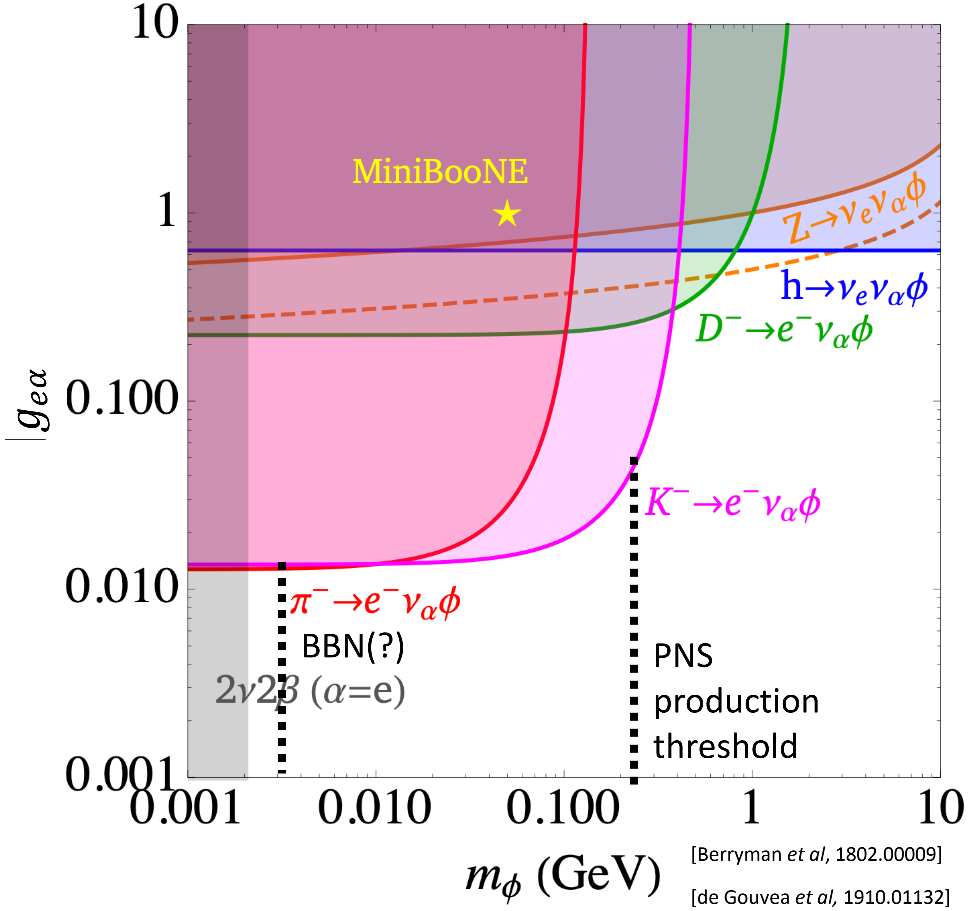
- Gauge neutral scalar ϕ carrying lepton number 2:

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

  - Generated from dimension-6 operator after EWSB

$$\frac{f_{\alpha\beta}}{\Lambda^2}(l\tilde{H})(l\tilde{H})\phi^* + \text{h. c.}$$

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



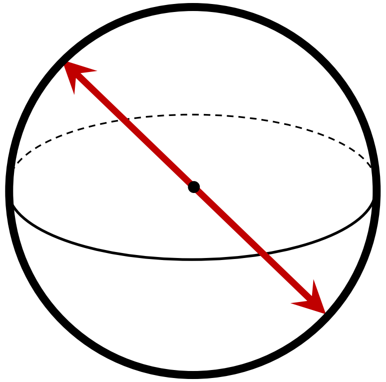
[Berryman *et al*, 1802.00009]

[de Gouvea *et al*, 1910.01132]

- Rich phenomenology:
  - Many astro and laboratory constraints;
    Focus on $g \equiv g_{ee} \lesssim 10^{-2}$ in this talk
  - Strong ($10^6 G_F$) neutrino self-interaction + N_{eff} ~4 resolves the Hubble tension(?) [Kreisch et al, 1902.00534], …

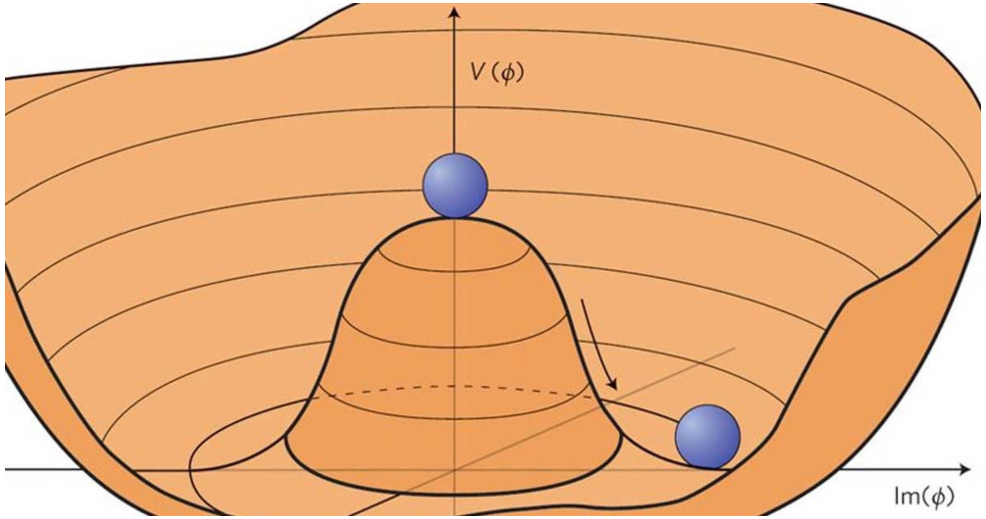
Production, Thermalization, and Condensation

- Rapid ϕ production in abundance $\nu\nu \to \phi$
  - $\frac{\mathrm{d}n_\phi}{\mathrm{d}t} \sim 10^{61}\ \mathrm{s}^{-1}\mathrm{km}^{-3} \times \left(\frac{g}{10^{-3}}\right)^2 \left(\frac{m_\phi}{50\ \mathrm{MeV}}\right)^2 \left(\frac{\mathrm{T}}{30\ \mathrm{MeV}}\right)$
- Trapping and thermalization: $\phi \to \nu\nu,\ \nu\phi \to \nu\phi, \ldots$
  - 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 $U(1)_L$
  - $V_{\mathrm{eff}}(\phi)$ minimized by a finite VEV; Goldstone boson as the flat direction
  - The ground state is a lepton number superfluid



ϕ produced in the ground state

ν_e Fermi sphere

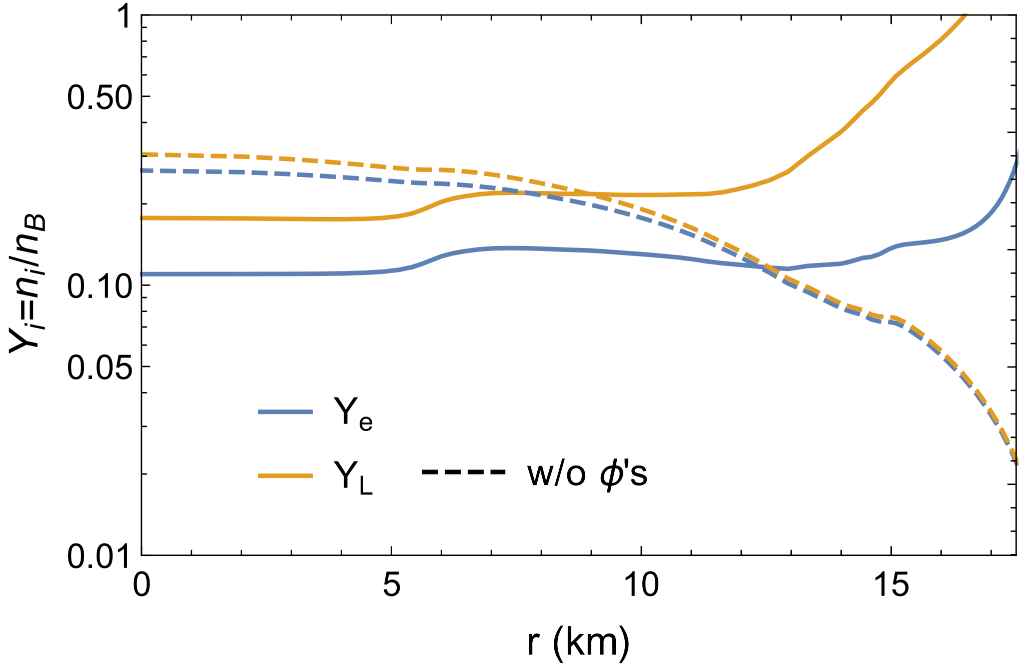


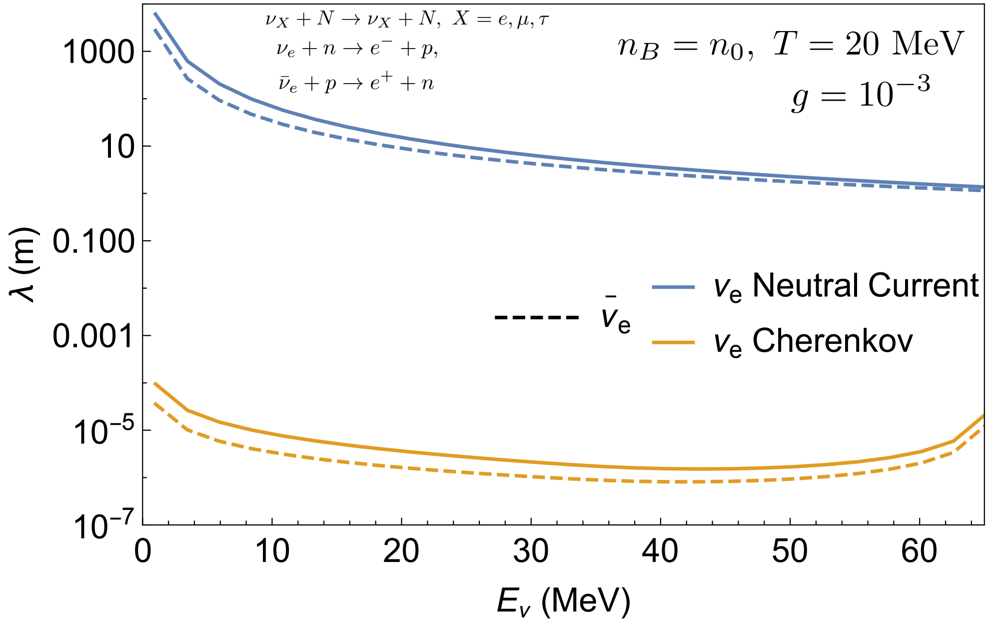
Astrophysical Implications

- Instantaneous L transport by the superfluid:
  - Suppress Joule heating: lower maximum T attainable
- Alter PNS compositions: change n-to-p ratios
- Reduced thermal conductivity
  - The Goldstone mode couples strongly to ν_e's; linear dispersion

$$\omega = \sqrt{\frac{\mu_\phi^2 - m_\phi^2}{3\mu_\phi^2 - m_\phi^2}}\, k + \mathcal{O}(k^3)$$

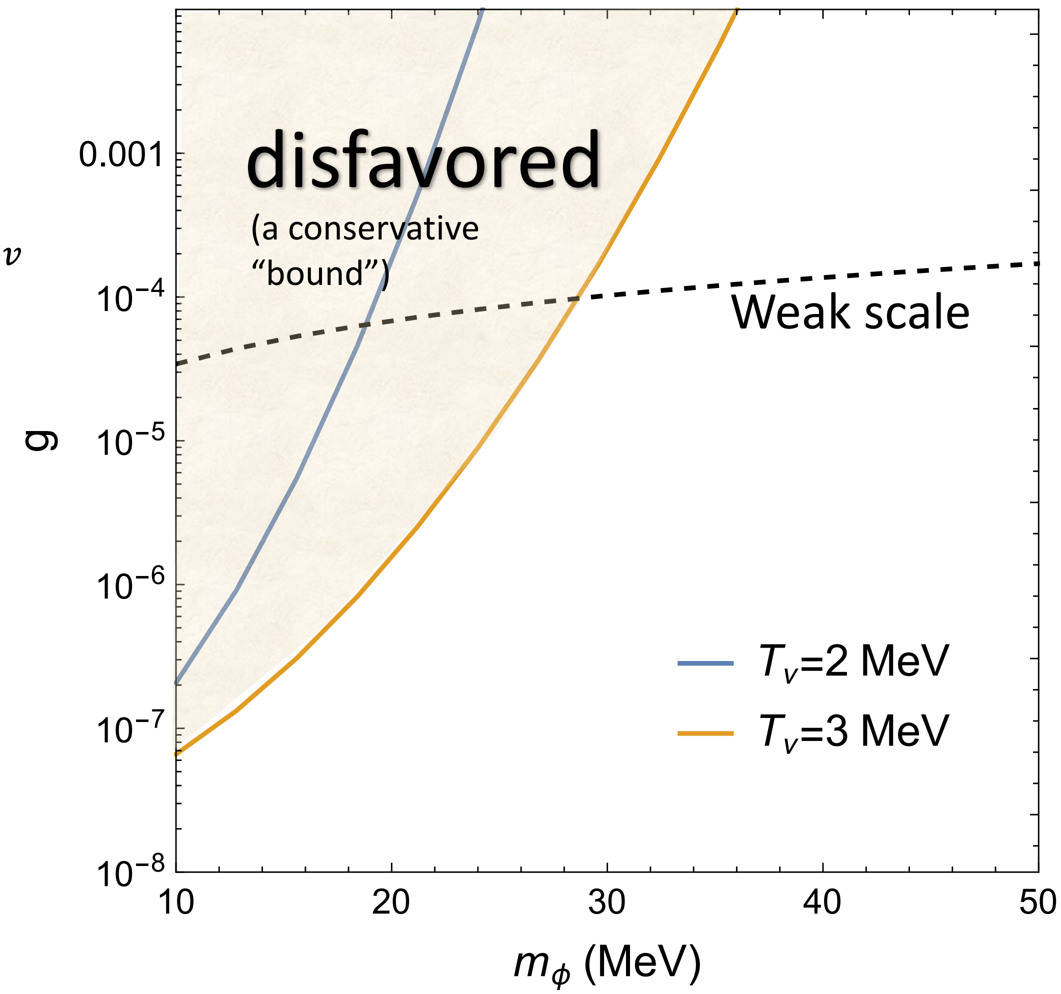
  - Cherenkov radiation $\nu_e \to \nu_e J$ shortens ν_e mean-free-path
- Need simulations to identify potential observables





Observable: neutrino signal

- Neutrino decoupling sensitive to new Weak-scale forces
    - Insensitive to the condensate, generic to νSI models
    - Relates T_ν and interaction strength through bulb model & fixed L_ν
- "bound": Low T_ν (large R_ν) in tension with SN1987
    - Bayesian analysis favors $T_{\bar{\nu}_e} \gtrsim 3$ MeV (e.g. [arxiv:0107260])
- Side effect: reduced asymmetry between ν_e and $\bar{\nu}_e$
    - lower n/p ratio in ν driven winds, bad for r-processes
- Self-consistent simulations required to refine these
    - Feedback; condensate; BNS mergers? …



Retention of DM

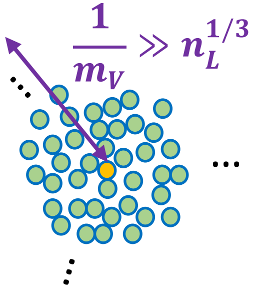
[Ann Nelson, Sanjay Reddy, **DZ**, *JCAP* 07 (2019) 012]
[Sanjay Reddy and **DZ**, in preparation]

- Can the dark particles remain trapped for longer?
  - The dark lepton bosons will evaporate and leave the star as ν's over ~20 s
- Couple the (vector) boson V^{μ} to Dirac fermion χ carrying L

$$\mathcal{L}_{\text{eff}} \supset \mathcal{L}_{\text{eff},\nu V} + \bar{\chi}(i\gamma^{\mu}\partial_{\mu} - g_{\chi}\gamma^{\mu}V_{\mu} - m)\chi$$

- Non-zero net lepton number in the star preferably selects χ over $\bar{\chi}$

$$E_{\bar{\chi}} - E_{\chi} = \frac{2g_{\chi}g_{L}}{m_V^2}\, n_L \simeq 10\ \text{MeV}\ \frac{g_{\chi}g_L}{10^{-4}} \left(\frac{\text{MeV}}{m_V}\right)^2 \frac{n_L}{0.1\ \text{fm}^{-3}}$$



  - Could also work for other SM charges in the star (e.g., B current in *JCAP* 07 (2019) 012, arxiv:1803.03266)

Charge separation and retention

[Sanjay Reddy and **DZ**, in preparation]
[Ann Nelson, Sanjay Reddy, **DZ**, *JCAP* 07 (2019) 012]

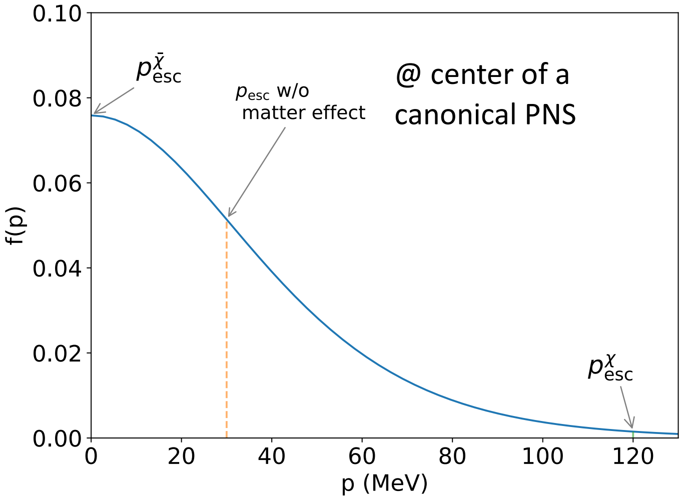
- Symmetric production, **asymmetric trapping**
  - A 1D estimate: escape velocities as trapping criterion

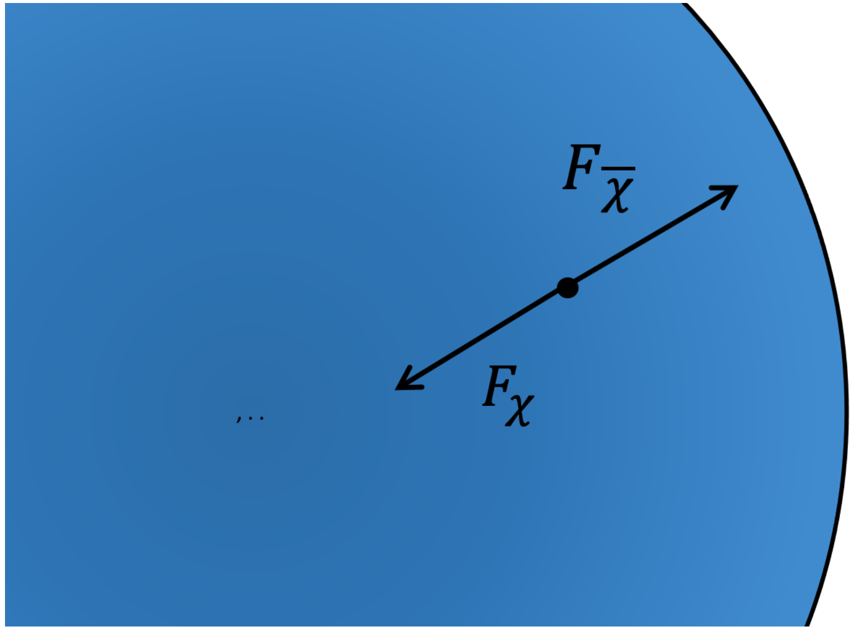
$$E_{\chi,\mathrm{kin}} + E_{\chi,\mathrm{matter}} + E_{\chi,\mathrm{grav}} = 0$$

  - Eg: 80% retention rate for χ, 1% for $\overline{\chi}$ (whole star average)

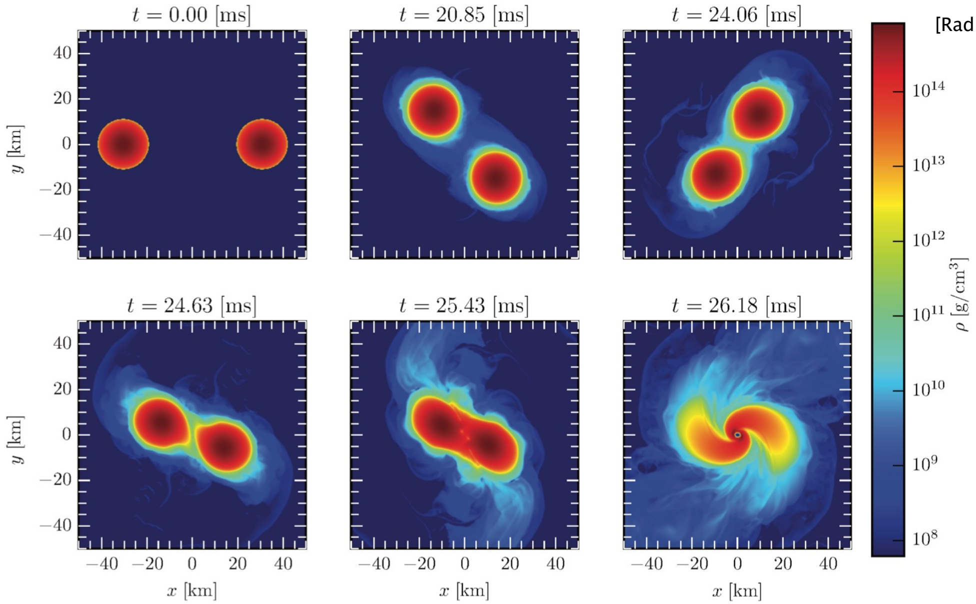
$$m_\chi = 50\ \mathrm{MeV},\ m_V = 1\ \mathrm{MeV}$$
$$g_\chi g_L = 10^{-4},\ T = 20\ \mathrm{MeV}$$

  - Net dark matter: $\lesssim 0.01\ M_\odot$

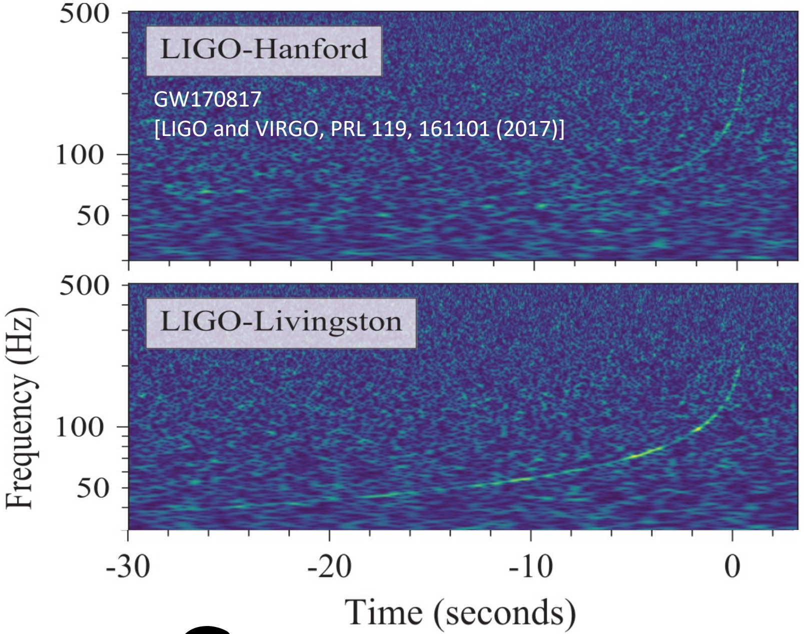




- Are there observables associated with these trapped DM?



[Radice *et al*, 1502.00551]

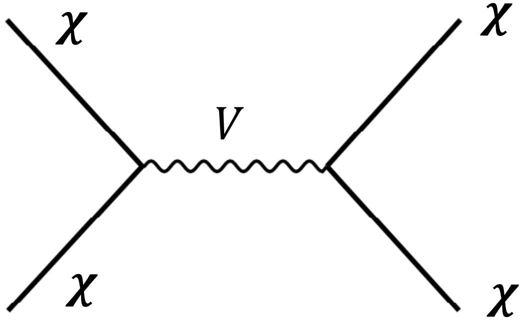


GW170817
[LIGO and VIRGO, PRL 119, 161101 (2017)]

Dark Halo around Neutron Stars and Gravitational Waves

[Ann Nelson, Sanjay Reddy, **DZ**, *JCAP* 07 (2019) 012, arxiv:1803.03266]

Dark halo from self-interacting DM



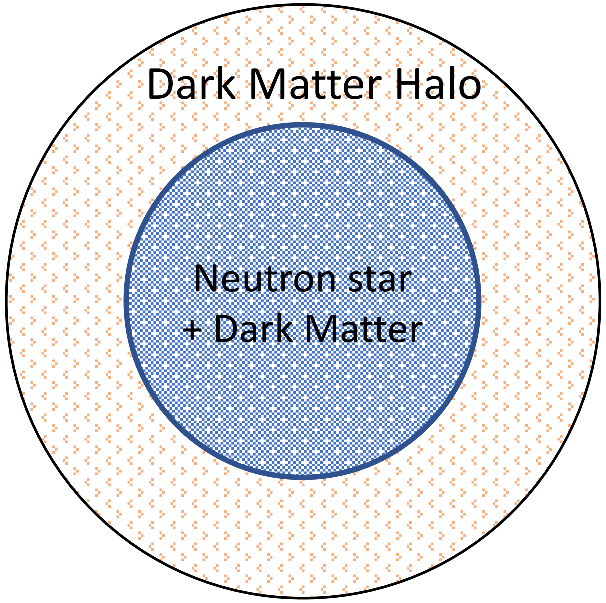
- (strong) DM self-interactions from the vector mediator
  - Light (sub-GeV) fermions charged under massive U(1) (B,L,B-L,…)

$$\mathcal{L} \supset \bar{\chi}(i\partial\!\!\!/ - g_\chi V\!\!\!/ - m_\chi)\chi + \frac{1}{2}m_V^2 V^\mu V_\mu - \frac{1}{4}V^{\mu\nu}V_{\mu\nu}, \quad V_{\mu\nu} = (\partial_\mu V_\nu - \partial_\nu V_\nu)$$

  - Charged bosons could work too

$$\mathcal{L} \supset \partial^\mu \phi^* \partial_\mu \phi - m_\phi^2 \phi^* \phi - g V^\mu (\phi^* \partial_\mu \phi - \phi \partial_\mu \phi^*)$$

- Can form stable halos around NS
- Halo modifies gravitational wave emissions from binary NS inspirals
  - Small monopole, but large quadrupole contributions $M_{\rm DM} \lesssim 10^{-2} M_{\rm NS}$



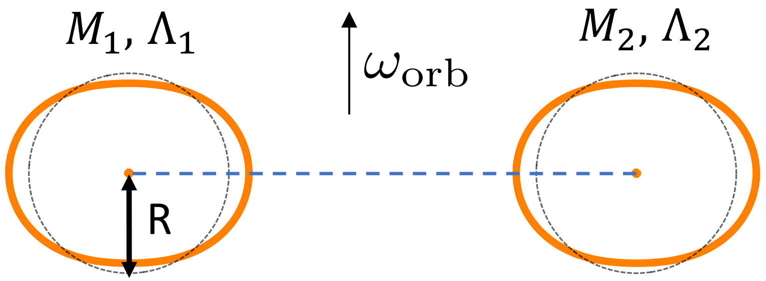
[A. Nelson, S. Reddy, **DZ**. JCAP 1907 (2019) 012]

GW emission from compact binary inspirals

➢Point particle dynamics: leading order Post-Newtonian Expansion

- Chirp:

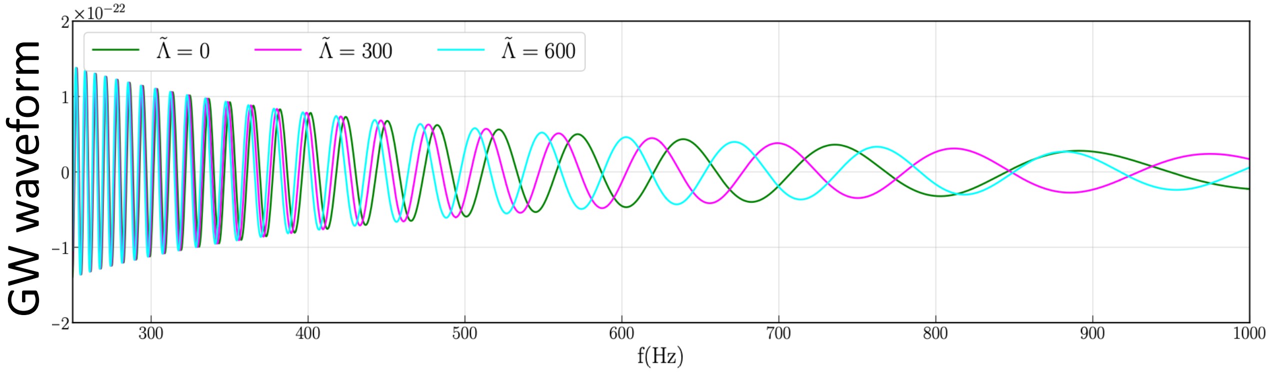
$$\frac{\mathrm{d}f_{\mathrm{GW}}}{\mathrm{d}t} = \frac{96}{5}\pi f_{\mathrm{GW}}^2 \left(\pi G \mathcal{M}\right)^{5/3} \qquad \mathcal{M} = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$$



➢Finite size effect: tidal deformability Λ

$$\Delta\Psi^{\mathrm{tidal}} \propto -v^5 \tilde{\Lambda},$$ [E. Flanagan and T. Hinderer, PRD 77 021502 (2007)]

$$\tilde{\Lambda} = \frac{16}{13}\frac{(M_1 + 12M_2)M_1^4\Lambda_1 + (12M_1 + M_2)M_2^4\Lambda_2}{(M_1 + M_2)^5}$$

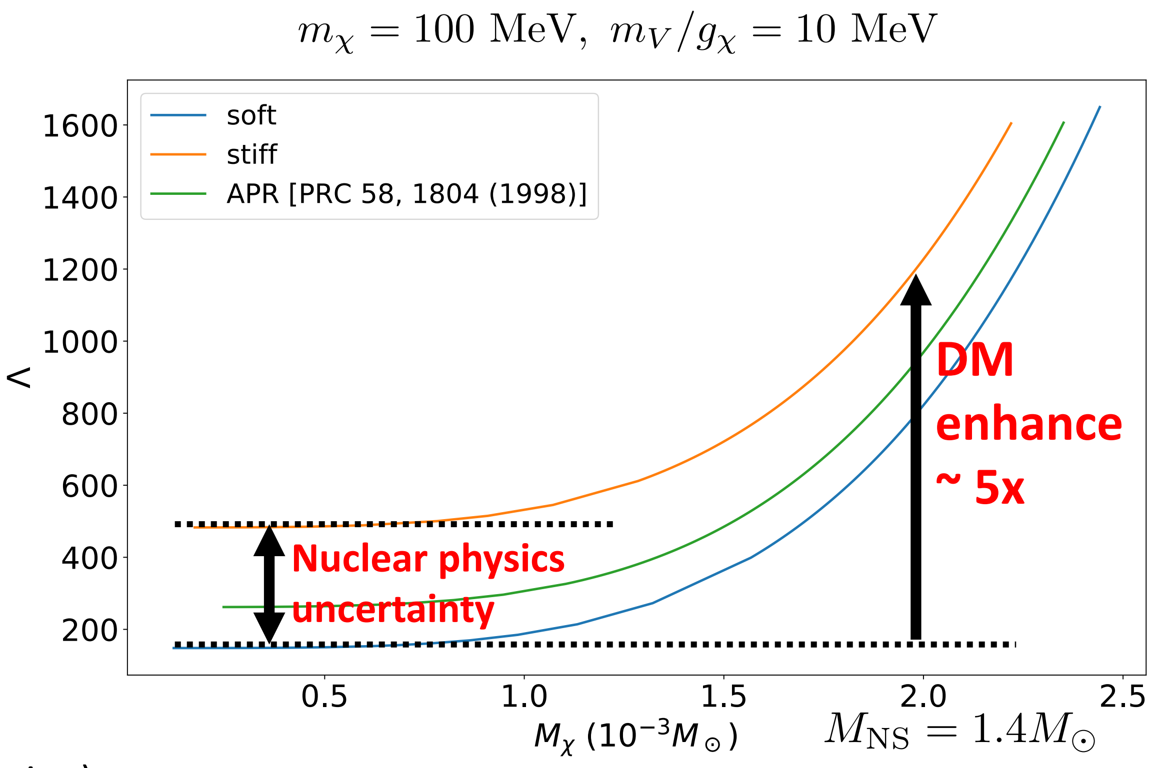


[Chatziioannou, 2020]

- E.g., GW170817: $\tilde{\Lambda} = 300^{+500}_{-190}$ [LIGO and VIRGO, PRX 9 011001 (2019)]

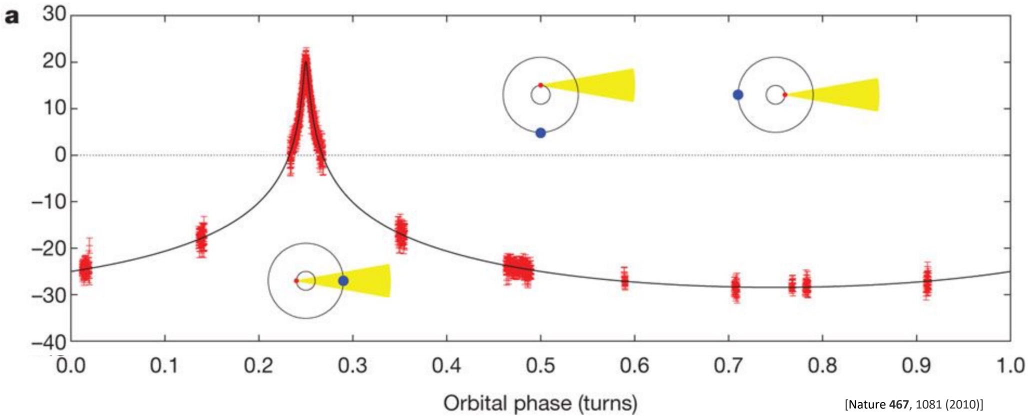
Dark halos and gravitational waves

- Halos predict large Λ or large variability in Λ
  - Nuclear/QCD uncertainties are subdominant
  - Precise measurements of Λ expected in near future
    - LIGO A+ (in ~5 years): O(100) events, ΔΛ~100
    - 3G (in ~15 years): O(1000) events, ΔΛ~20
- If found, venue for study interacting dark sector
  - Variability in Λ shend light on couplings to SM (capture/production)
  - Insights on SIDM: intriguing galactic scale implications
    - Velocity-dependent $\sigma_{\chi n}$ & small-scale structure puzzles [Kaplinghat et al 2016],…
    - exception: Fermi pressure alone is sufficient for light fermions ($\lesssim$ 50 MeV)

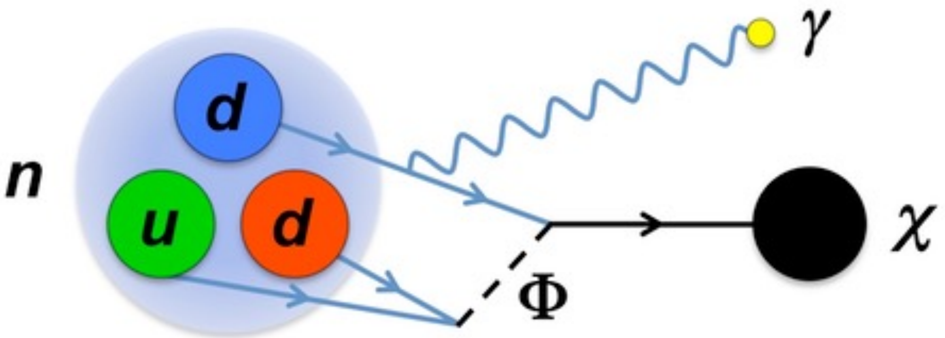


[A. Nelson, S. Reddy, **DZ**. JCAP 1907 (2019) 012]

Post-Newtonian treatment breaks down when halos touch; Need simulations!



[Nature **467**, 1081 (2010)]



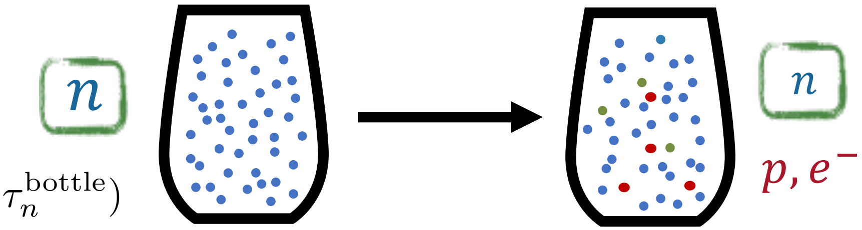
Neutron Stars Exclude Light Dark Baryons

[David McKeen, Ann Nelson, Sanjay Reddy, **DZ**, *PRL.* 121 (2018) 6, 061802]

Dark Neutrons and the Neutron Decay Puzzle $n \to p + e + \bar{\nu}_e$

- **"Bottle":**

(magnetic trap is similar)

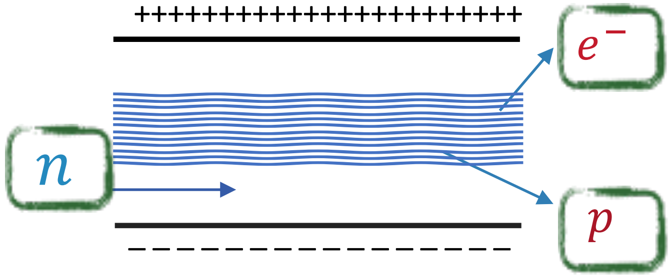


$P_{\text{survival}}(t) = \exp(-t/\tau_n^{\text{bottle}})$

$$\tau_n^{\text{bottle}} = 879.6 \pm 0.6 \text{ s}$$

[W. Mampe, *et al*, JETP Lett. 57, 82 (1993)] [A. Serebrov *et al*, Phys. Lett. B 605, 72 (2005)] [A. Pichlmaier, *et al*, Phys. Lett. B693, 221 (2010)] [A. Steyerl et al, Phys. Rev. C 85, 065503 (2012)] [S. Arzumanov *et al*, Phys. Lett. B745, 79 (2015)]

- **"Beam":**



$P_{\text{decay}}(t) = 1 - \exp(-t/\tau_n^{\text{beam}})$

$$\tau_n^{\text{beam}} = 888.0 \pm 2.0 \text{ s}$$

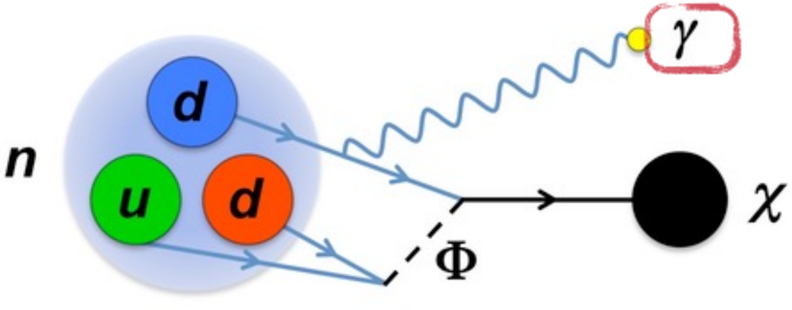
[J. Byrne and P. G. Dawber, Europhys. Lett. 33, 187 (1996)]
[A. T. Yue *et al*, Phys. Rev. Lett. 111, 222501 (2013)]

4σ tension!

- **One Solution:** $n \to \chi + \ldots$

Be^9 and χ stable: $937.90 \text{ MeV} < m_\chi < m_p + m_e = 938.87 \text{ MeV}$

[Z. Tang *et al.* Phys. Rev. Lett. 121, 022505 (2018)] Not Found!



[B. Fornal and B. Grinstein, PRL. **120**, 191801 (2018)]

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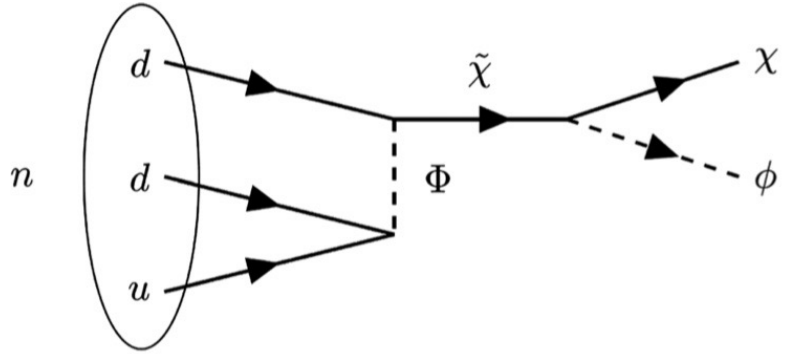
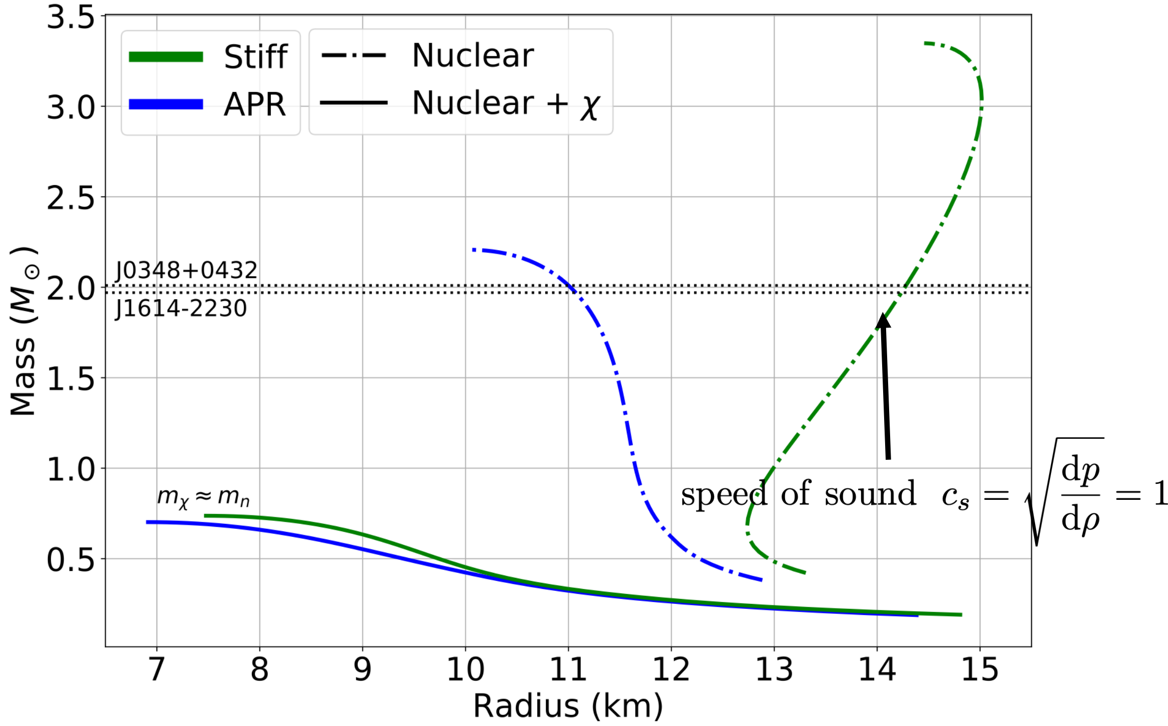


…

Neutron Star Constraints

- Thermalization even for tiny mixings
  - $t_{\text{th}} \ll t_{\text{NS}} \sim 10^6 - 10^8 \text{yrs}$
- In equilibrium $\mu_\chi = \mu_n$, χ's dominate:
  - Short range nn interactions are repulsive
  - n-> $\chi + \cdots$ is energetically favorable
- In equilibrium EOS governed by Fermi gas of χ
  - Significant reductions to maximum NS masses
  - Unless $m_\chi \gtrsim 1.2$ GeV (irrelevant to the lifetime puzzle) or χ's have significant self-repulsion



[McKeen, Nelson, Reddy, **DZ**, PRL. 121, 06180 (2018)]

Summary and Outlook

- In situ production/trapping can be a significant source of DM in (neutron) stars
  - Matter effects could enhance/suppress production and trapping
  - Non-standard accretion scenarios merit further investigations
- Multimessenger observations as new probes of DM through imprints on stellar structure, composition, and transport phenomena
  - Robust constraints on dark baryons from NS observations despite unknown QCD physics
  - Future GW detections may reveal dark halos, unraveling interacting dark sector
  - Simulations account for DM feedback are crucial in validating SNe constraints/observables