QCD & New Physics in Extreme Astrophysical Environments: Neutron Stars & their Mergers

Chair:	Nicole Bell
Panel members:	Susan Gardner Anthony Thomas Steven Harris

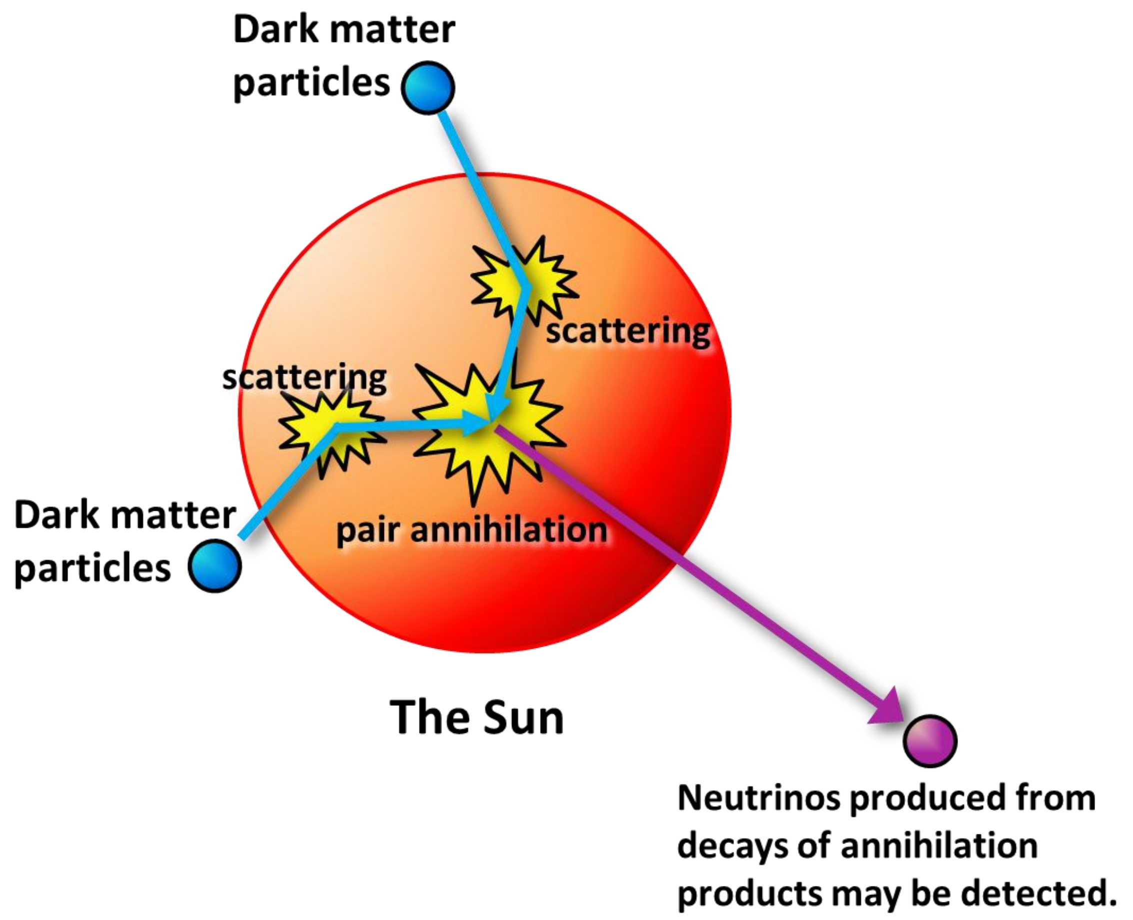
QCD & New Physics in Extreme Astrophysical Environments: Neutron Stars & their Mergers

- What lurks in the heart of a neutron star? Can they contain dark matter?
- What effects would “dark” neutron decays have? What can we learn about such DM ?
- How can neutron star observations constrain QCD-like hidden sectors?
- What new physics can we learn from gravitational wave detections (in NS mergers)?
- What new constraints emerge on axions from the study of neutron star mergers?

- What is the maximum NS mass?
- To what extent do NS possess strangeness? Can we generate heavy NS with hyperons?
- Is there a transition to deconfined quark matter?
- Can we observe evidence of QCD phase transition, under what conditions?
- How do GW observations constrain the EoS?
- Can we observe prompt black hole formation?

Dark Matter Capture in Stars

→ an alternative approach to Dark Matter Direct Detection experiments



Due to their extreme density, ***neutron stars*** capture dark matter ***very*** efficiently.

Capture probability saturates at order unity when the cross section satisfies the **geometric limit**

$$\sigma_{th} \sim \pi R^2 \frac{m_n}{M_*} \sim 10^{-45} \mathrm{cm}^2$$

Neutron Stars → Black holes?

Kouvaris; Kouvaris & Tinyakov; McDermott, Yu & Zurek; Bramante, Fukushima & Kumar; NFB, Petraki & Melatos; Bertone, Nelson & Reddy; and others.

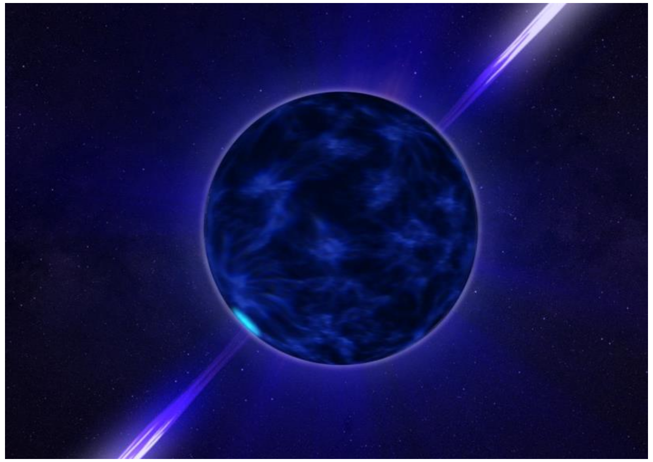
Can neutron stars accumulate so much dark matter they would collapse to black holes?

Yes, provided that:

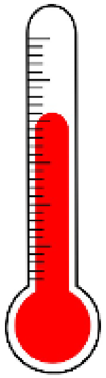
- No annihilation (e.g. asymmetric dark matter, with DM-antiDM asymmetry))
- DM is bosonic (and condenses to a small self gravitating BEC), or
- DM is fermionic with attractive self-interactions, and
- No repulsive-self interactions that prevent collapse (even very very tiny self-interaction is enough) NFB, Petraki & Melatos, PRD 2013

→ Black hole formation is possible for non-annihilating dark matter, while unlikely for typical WIMP-like dark matter

Neutron star heating



- **Capture of dark matter** (plus subsequent energy loss)
  → DM ***kinetic energy*** heats neutron star ~ **1700K** **(Baryakhtar et al)**
- **Annihilation** of thermalized dark matter
  → DM ***rest mass energy*** heats neutron star ~ **additional 700K**

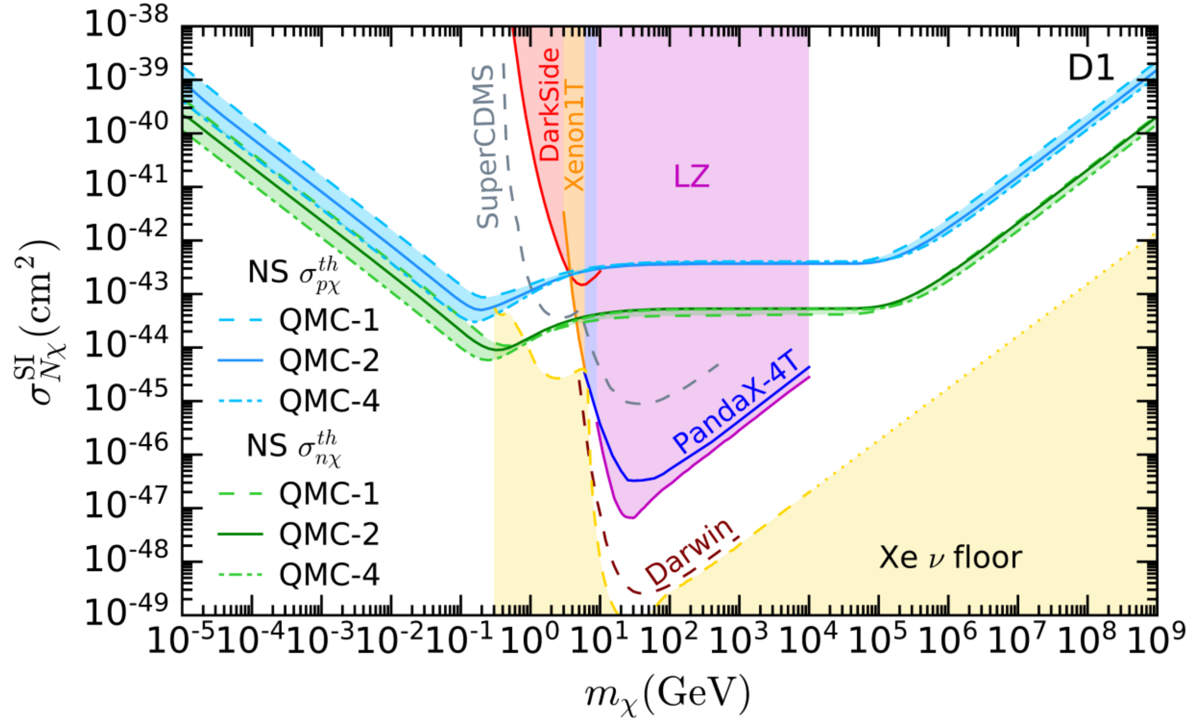


Coolest known neutron star (PSR J2144-3933) has a temperature of ~ 4.2×10^4 K.

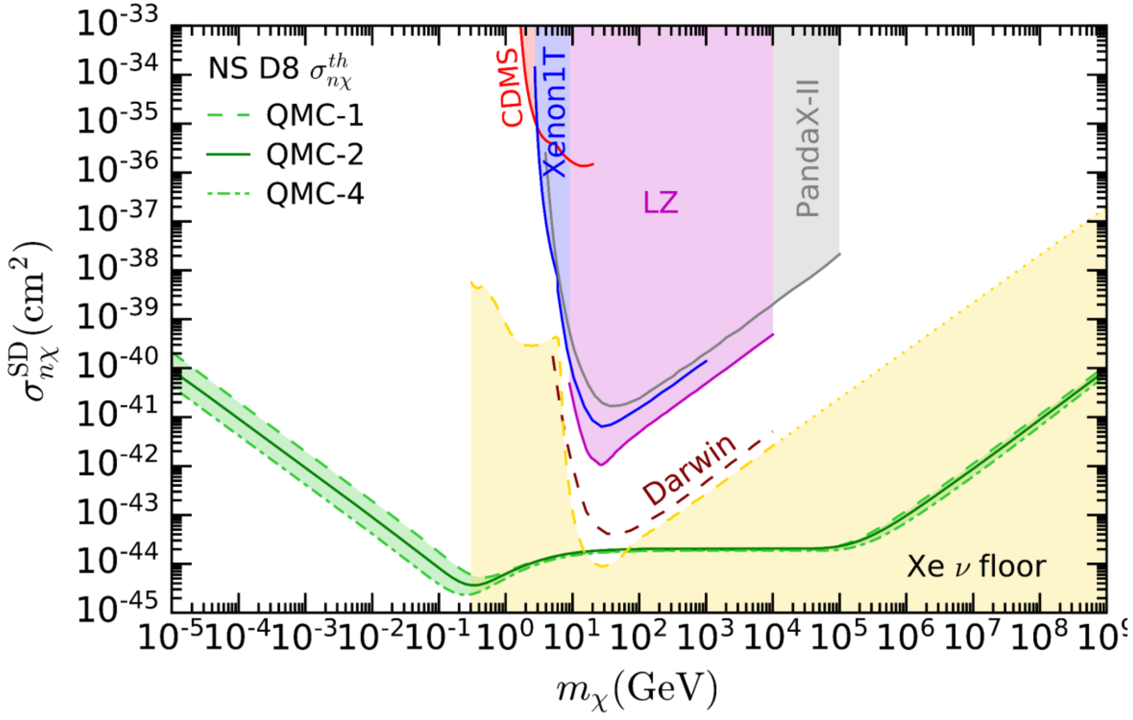
Old isolated neutron stars should cool to: 1000 K after ~ 10 Myr
100 K after ~ 1 Gyr

NS Heating Sensitivity:

Spin-independent DM-nucleon scattering



Spin-dependent DM-nucleon scattering



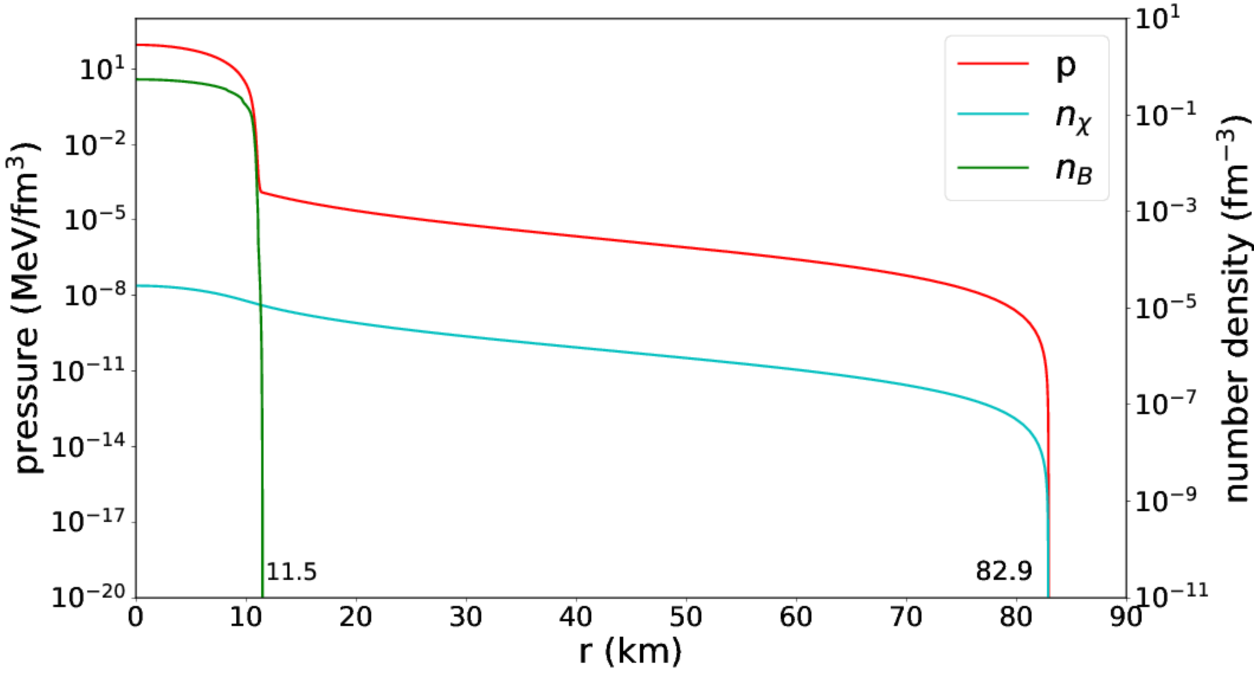
Anzuini, NFB, Busoni, Motta, Robles, Thomas and Virgato, JCAP 11, 056 (2021)

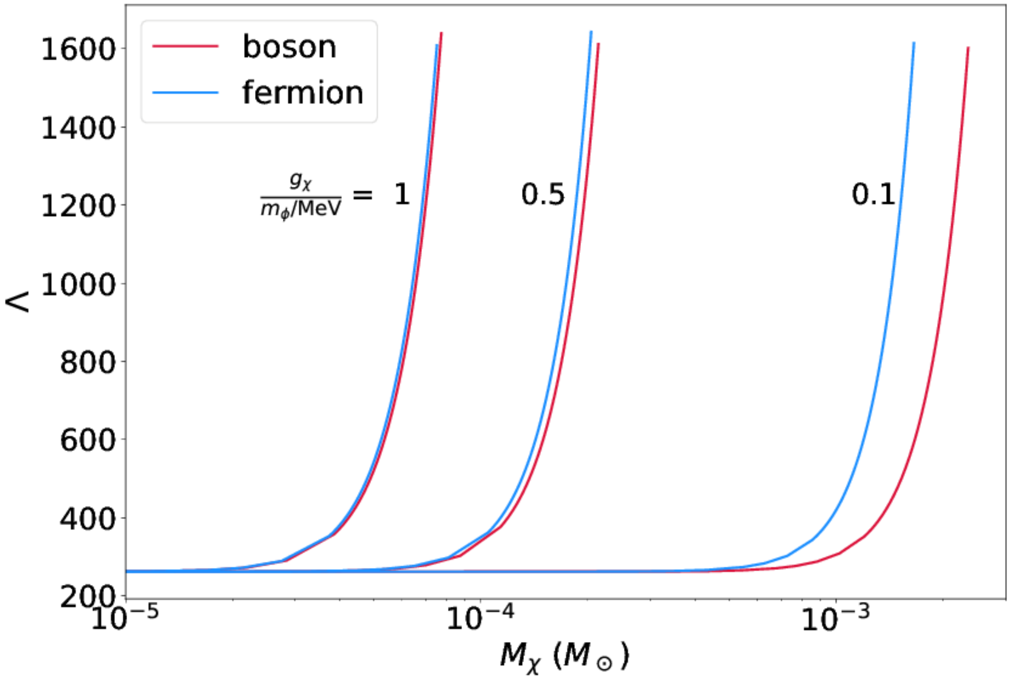
Neutron star mergers → gravitational waves

Nelson, Reddy & Zhou, JCAP 07, 012 (2019)

- Light DM + light mediators (MeV scale)
- Either femionic DM (degeneragy pressure) or bosonic with repulsive self-interactions
  - ➢ **DM component extents to large radii → NS dark matter halo**

- Increases the NS tidal deformability, Λ.
  - ➢ LIGO observation of NS-NS merger, GW170817, constrains $\Lambda < 800$
  - ➢ strong bounds, even for small DM component $\sim 10^{-4} M_{\odot}$





Light Dark Matter

Recently there was a very interesting proposal from Fornal and Grinstein (1801.01124).

Originated in long-standing puzzle concerning free neutron lifetime:

- Measurement for trapped n's: 879.6 ± 0.6 sec
- Measurement in beam decay : 888.0 ± 2.0 sec

This *3.5σ discrepancy* solved by existence of new decay mode, which would not be seen in the beam decay experiment

$$n \longrightarrow \text{Dark Matter } (\chi) + \text{something}$$

"Something" not a photon : Tang *et al*., Los Alamos 1802.01595

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Light Dark Matter (cont.)

- There are very strict limits on the mass of the new DM particle. It should be within an MeV or so of the neutron mass. For the case

$$n \longrightarrow \chi + \varphi$$

with χ carrying baryon number and φ also dark,

$$937.9 \text{ MeV} < m_\chi + m_\varphi < 939.565 \text{ MeV}$$

- Serebrov *et al.,* 1802.06277 also claim this particle would resolve a reactor anti-neutrino anomaly
- Also nice discussion of tension with best value of neutron axia charge by Czarnecki *et al.,* 1802.01804 (constrains but does not rule out the explanation)

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

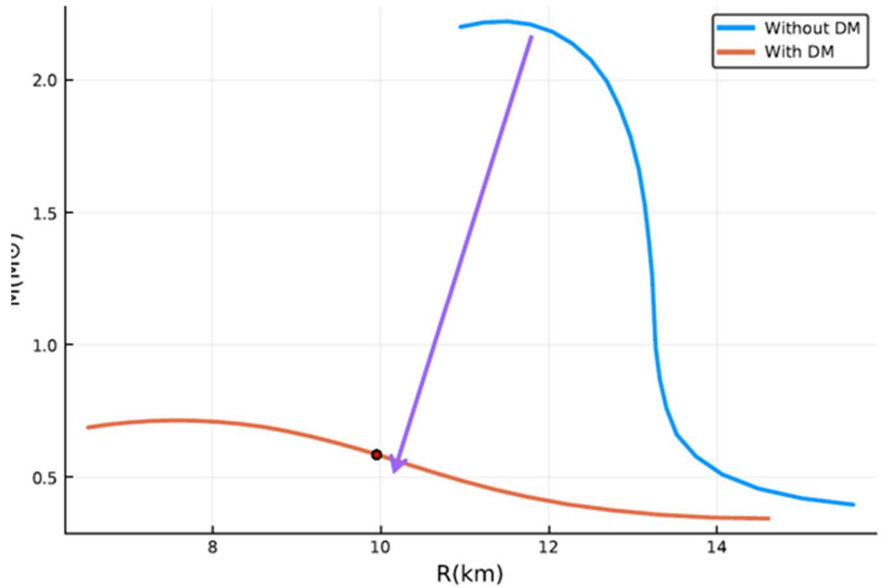
Compatibility of Fornal-Grinstein Hypothesis with Neutron Star Properties?

- A rush of papers
  - McKeen *et al.*, 1802.08244
  - Motta *et al.*, 1802.08427
  - Baym *et al.*, 1802.08282
- All reach a similar conclusion
- I follow the work of Motta, Guichon and Thomas (1802.08427)
- If such a dark matter particle exists neutrons high in the Fermi sea of a neutron star will be unstable
- This will replace high energy/pressure neutrons with lower energy/pressure dark matter particles: Consequences?

Dark matter particles must have strong repulsive interaction: like omega in NN force

Solve Tolman-Oppenheimer-Volkoff Equations

- Maximum allowed mass for stable neutron star drops from 2.21 $M_\odot$ to 0.7 $M_\odot$
- But cannot even get that as maximum stable star goes to just 0.58 $M_\odot$



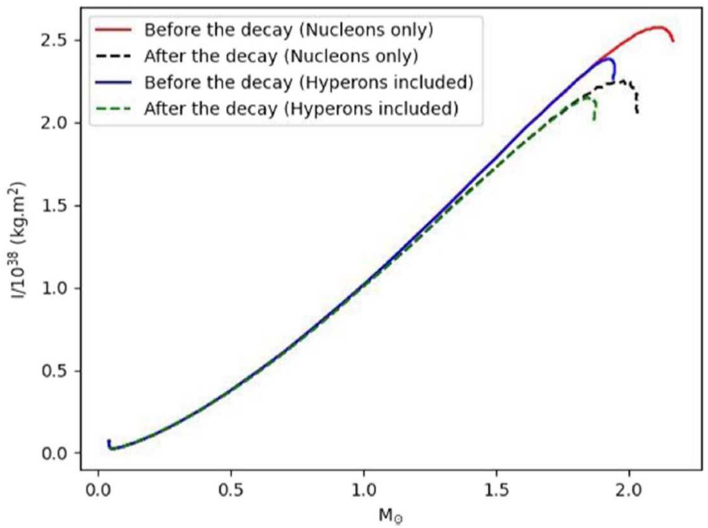
Motta et al., 1802.08427

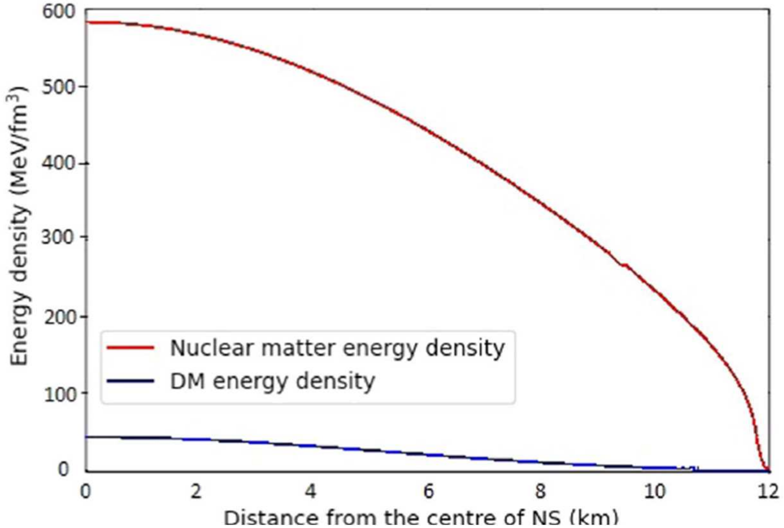
Alternative due to Strumia (JHEP 2022)

$n \longrightarrow \chi\chi\chi$ **with m_χ very close to m_n /3**

No repulsive interaction needed.

Moment of inertia decreases after decay: hence star spins up and gets hotter!





Husain and Thomas, J. Phys. G: Nucl. Part. Phys. **50** (2023) 015202

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DARK MATTER PARTICLE PHYSICS

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Dark Decay Models [Fornal & Grinstein, 2018]

Minimal ingredients, considered broadly

At lower energies…

[Alonso-Alvarez et al., 2022]

$$\mathcal{O}_{abc} = u_a d_b d_c \chi$$

— to induce visible-dark baryon mixing

Dark Decays of Hadrons

Neutron decay anomaly	$\mathcal{O} = u\,d\,d\,\chi$	$m_{\rm DS} \lesssim m_n$
Hyperon dark decays (this work)	$\mathcal{O} = u\,d\,s\,\chi$	$m_{\rm DS} \lesssim m_\Lambda$
B-Mesogenesis	$\mathcal{O} = u\,d\,b\,\chi$	$m_{\rm DS} \lesssim m_B$

CLAS, BESIII, SN1987A

[Elor, Escudero, Nelson, 2019;
Elor & McGehee, 2021;...]

largest dark sector mass

$$\mathcal{L}_1^{\rm eff} = \bar{n}\left(i\partial\!\!\!/ - m_n + \frac{g_n e}{2m_n}\sigma^{\mu\nu}F_{\mu\nu}\right)n$$

$$+\bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \varepsilon(\bar{n}\chi + \bar{\chi}n)$$

mediates $n \to \chi\gamma$ (or $\Lambda \to \chi\gamma$) and more

Energy Loss Observables

Can be particularly sensitive to new physics, such as dark matter capture, BSM decays

Observables include…

Pulsar spin down measurements…

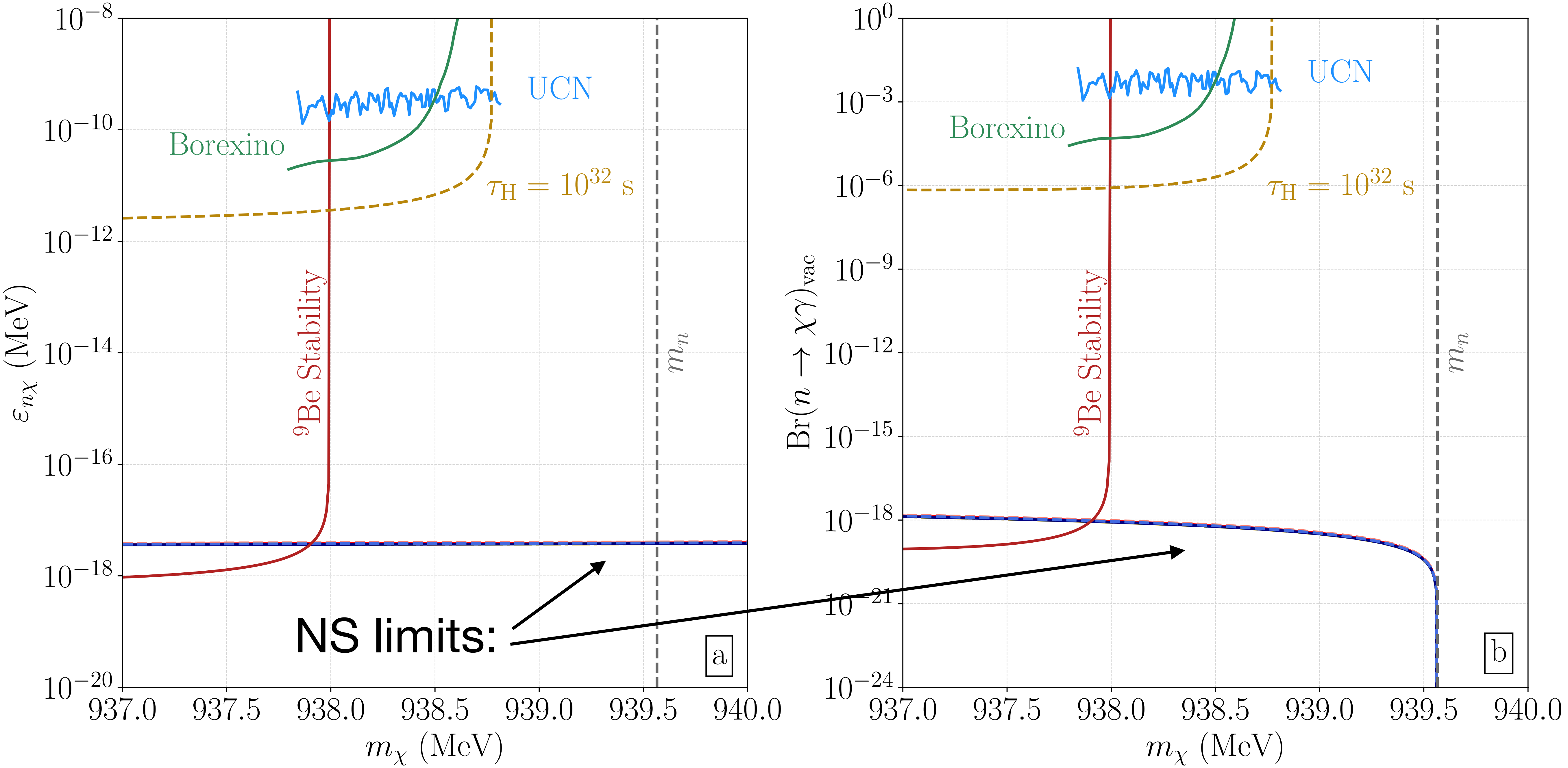
Measurements of pulsar binary orbital period decay rates
(Recall Hulse-Taylor binary pulsar, GR test!)…

Temperature measurements of the cooling history of a neutron star (or a white dwarf)…

G. Bussoni, talk in F

These effects *constrain* the BSM possibilties…

Exclusion Limits (at 2σ)



N.B. dark sector choices

[J. Berryman, SG, M. Zakeri, PRD 109, 023021 (2024)]

The Theory of Neutron Stars
is not settled

Much ongoing discussion, also at QCHSC 24!

QCD @ $T = 0; \rho_c \simeq (1 - \text{few})\, \rho_0$

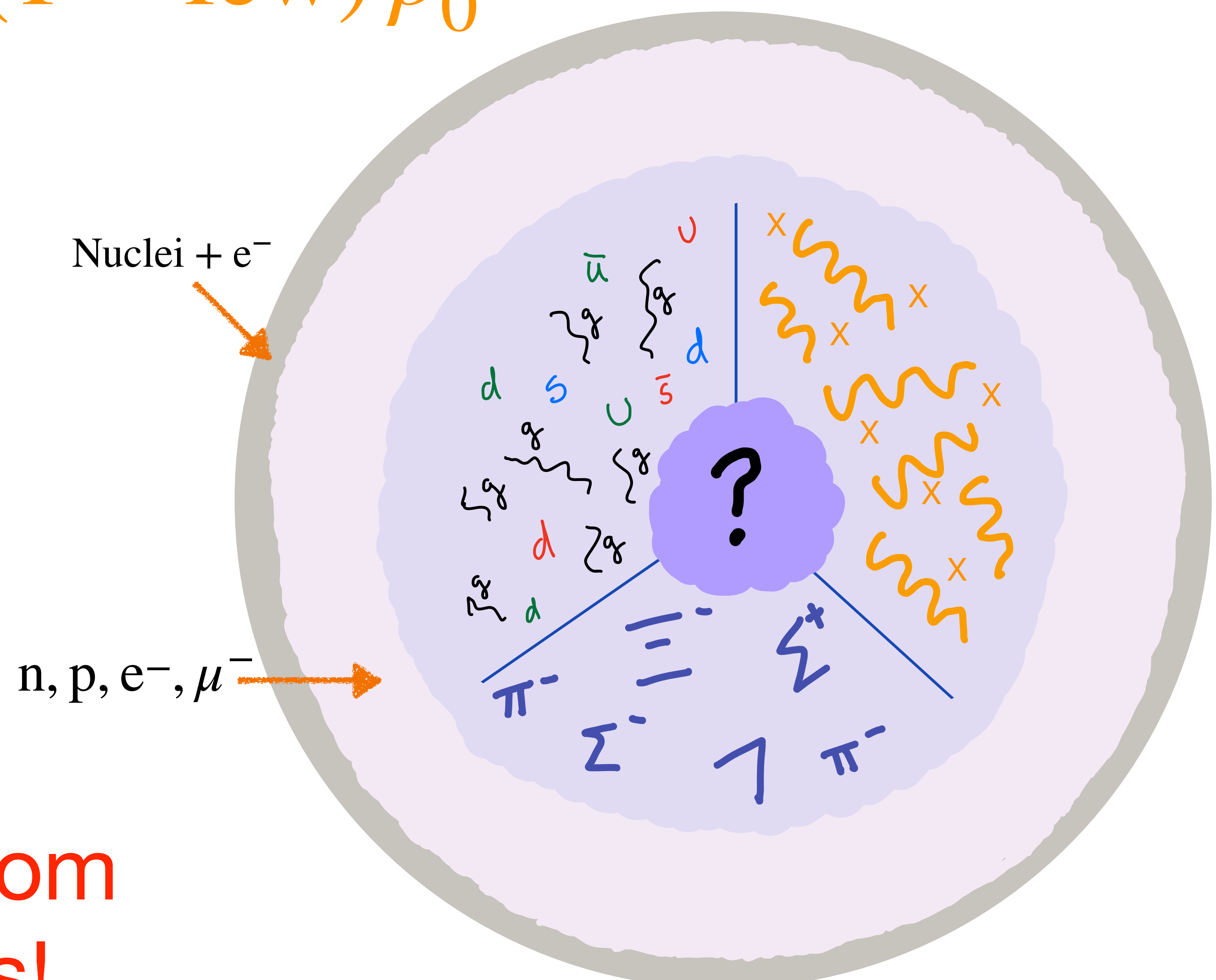
Description?

EoS?

Role of Hyperons?

Observed ns's already constrain dark matter, dark sector models!

Further constraints from studies of energy loss!



[Berryman, SG, & Zakeri, 2022; after Baym & Pethick, 1975]

Hyperons in Neutron Star Cores?

- Nuclear matter traditionally n, p and e
- Charge neutral so $\mu_n = \mu_p + \mu_e$
- But density in typical NS reaches 2-3 times nuclear matter density (i.e. 0.32 to 0.48 fm^{-3})
- Fermi level of n's higher than m_Λ AND time to form core in supernova explosion ~seconds
- Whereas WEAK interactions, which can change strangeness take nano-seconds:
  hence hyperons CAN appear
- They are stable because decays are forbidden by the Pauli Principle

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The Hyperon Puzzle

- Energetically hyperons must appear
- But when new species appears the momentum of lowest energy level ~zero
- Hence the pressure is lower than nucleons alone
- A high mass NS requires high pressure in the core and this appears impossible if hyperons are present
- How are 2 M_o NS possible?

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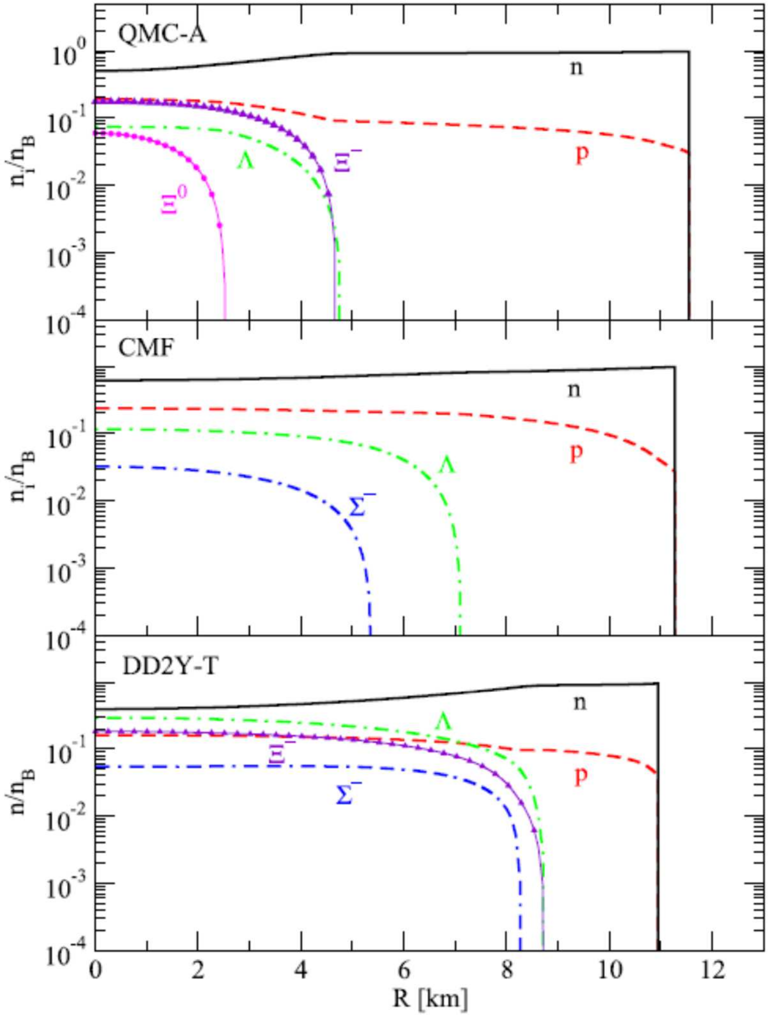
Radial Distribution of Hyperons In Heavy NS



CMF: Papazoglou et al. (1999)

DD2Y-T : Typel et al. (2010)

MNRAS **502**, 3476–3490 (2021)

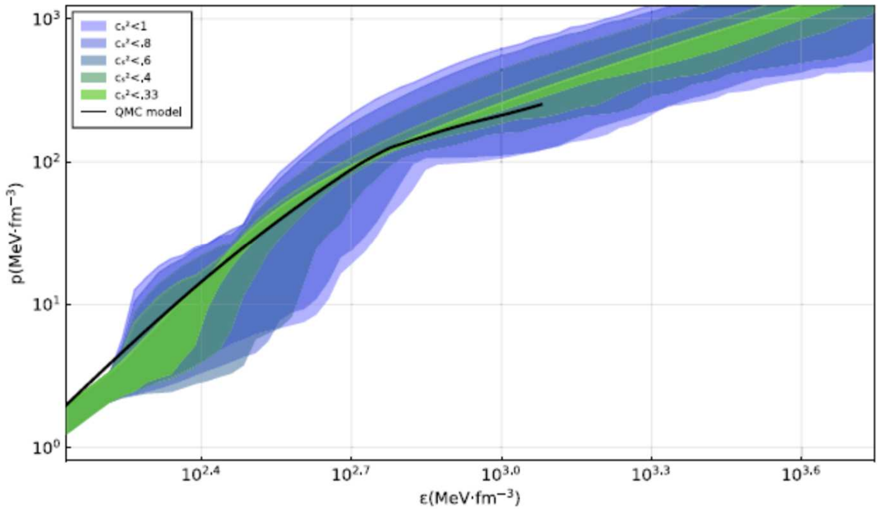
ELSEVIER

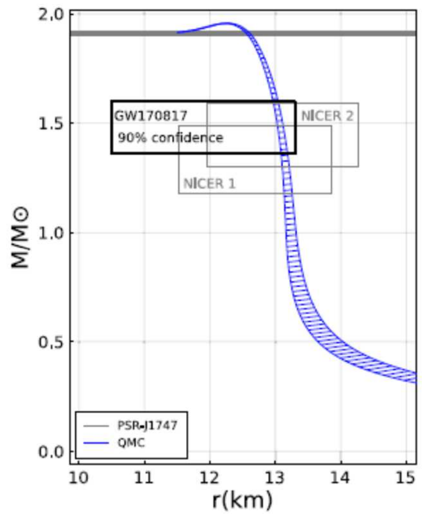
Nuclear Physics A 1009 (2021) 122157

www.elsevier.com/locate/nuclphysa

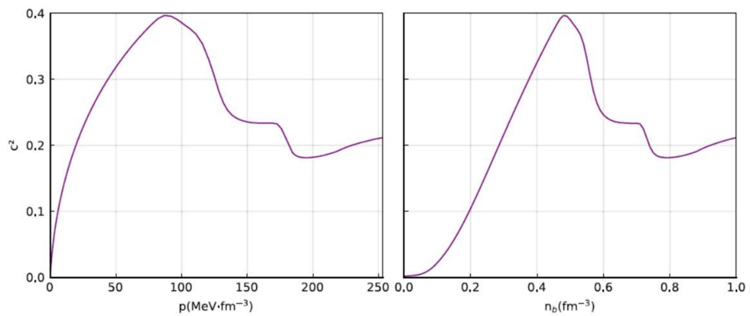
On the sound speed in hyperonic stars

T.F. Motta [a,*], P.A.M. Guichon [b], A.W. Thomas [a]





Follow up on Annala et al., Nature Physics (2020) model independent EoS based on speed of sound interpolation between low and high density
- claim low value implies quark matter



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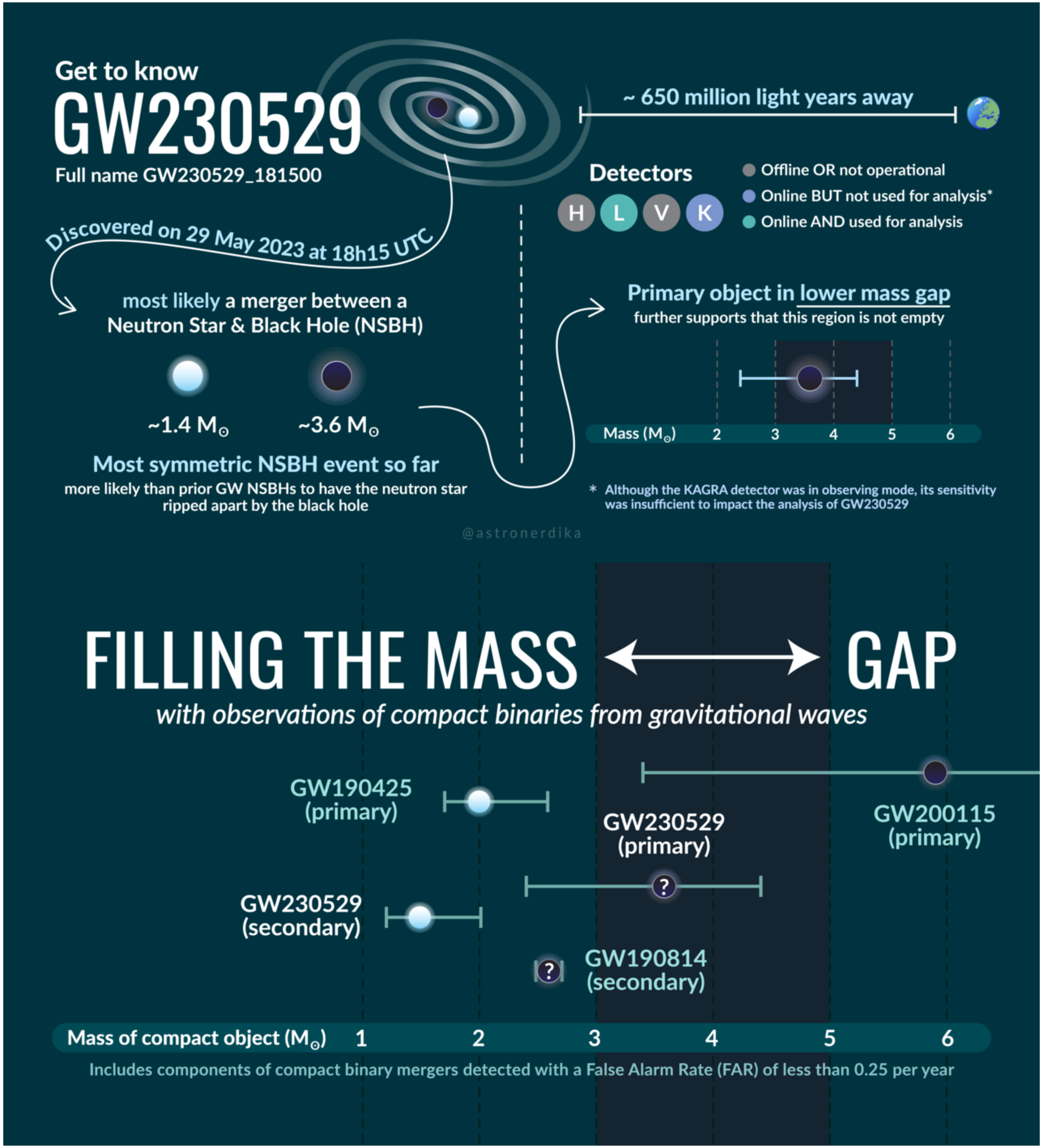


Neutron star or black hole?

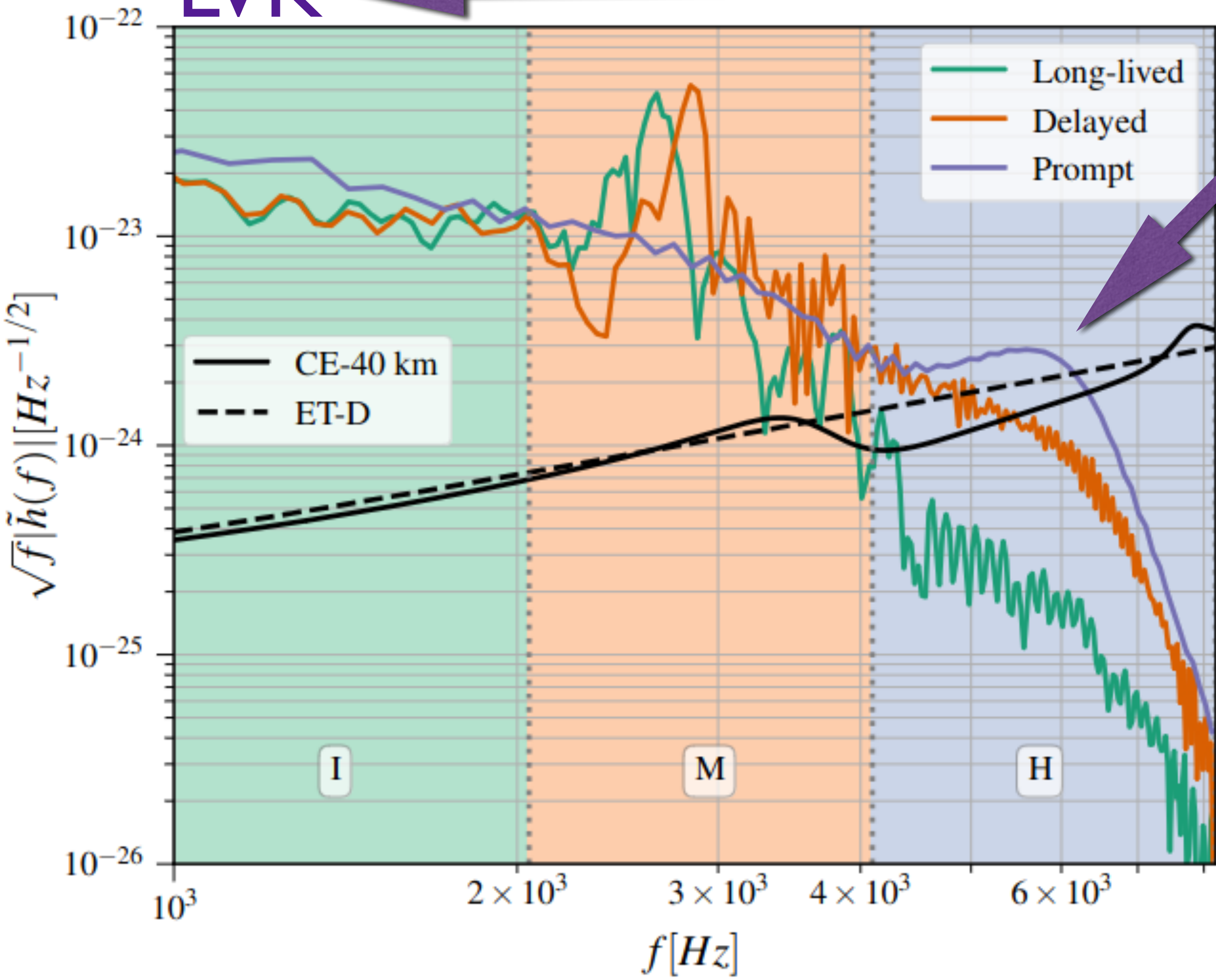
NS/BH transition speaks to EoS, rotation, …

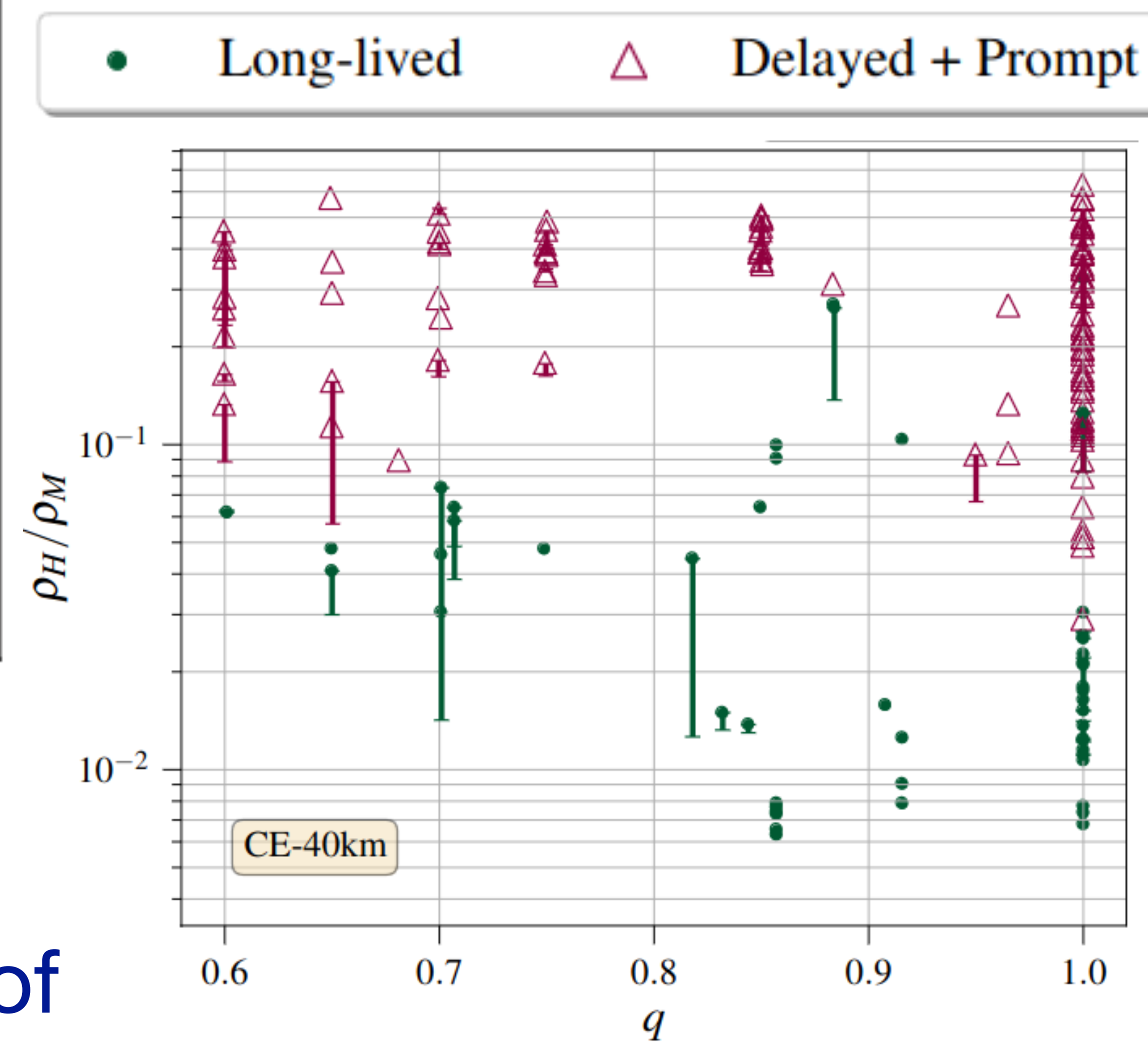
Improvements in sensitivity opens new windows on new physics

https://www.ligo.caltech.edu/news/ligo20240405

Direct Detection of Black Hole Formation

LVK





[Arnab Dhani, Radice, Schuette-Engel, SG+, PRD 109 044071 (2024)]

Detectability of QCD phase transitions also possible

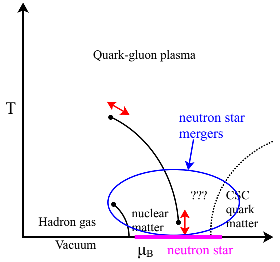
[Aviral Prakash ..., PRD 109 103008 (2024)]

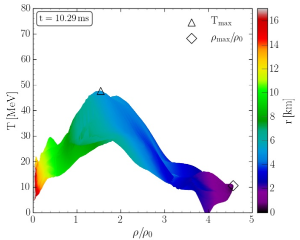
N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries PHYSICS FRONTIER CENTER

NSF

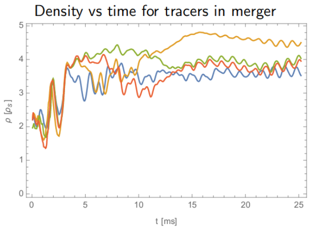
What do neutron star mergers offer that neutron stars don't?

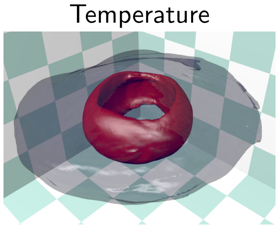
1) Probe interior of QCD phase diagram



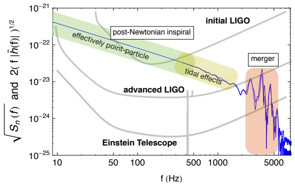


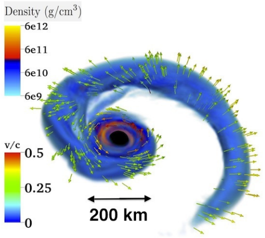
2) Dramatic variation of thermodynamic properties





3) Unique multimessenger observables





How can BSM physics show up in NS mergers? (1/3)

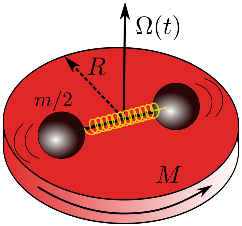
1) BSM particles that are trapped/accumulated in the merger remnant

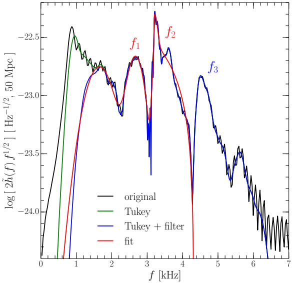
   a) Oscillation modes

   b) Transport properties

2) BSM particles that escape the merger remnant

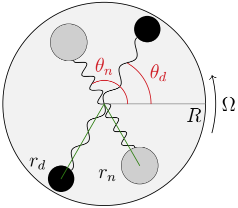
GW spectrum without DM

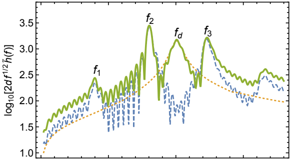




Takami, Rezzolla, Baiotti arXiv:1412.3240

GW spectrum with DM





Ellis, Hektor, Hütsi, Kannike, Marzola, Raidal, Vaskonen, arXiv:1710.05540

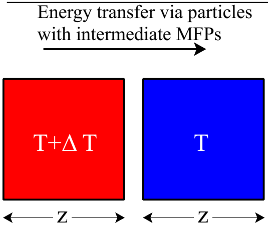
Dark matter fluid changes properties of GW spectrum from NS merger

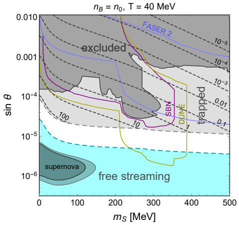
How can BSM physics show up in NS mergers? (2/3)

1) BSM particles that are trapped/accumulated in the merger remnant
   a) Oscillation modes
   b) Transport properties
2) BSM particles that escape the merger remnant

Energy dissipation from compression and resultant reequilibration.

Thermal conductivity (& shear viscosity)

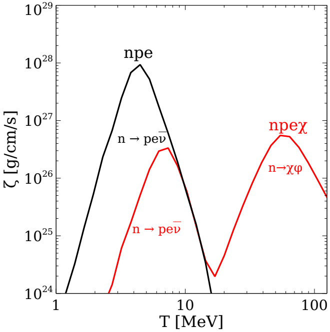




Trapped BSM particles could enhance thermal conductivity or shear viscosity.
Effects: Slow down differential rotation, and ???

Bulk viscosity

Neutron lifetime anomaly: To reconcile, maybe neutron decays into dark sector (e.g. $n \to \chi\phi$)



Novel neutron decay yields high bulk viscosity at high T.

How can BSM physics show up in NS mergers? (3/3)

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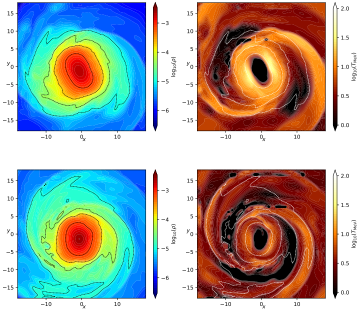
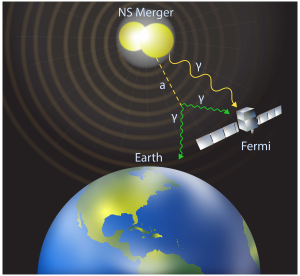
Cooling from axion emission



Remnant cools, but no change in GW signal.
Cooling could effect ν emission and thus, kilonova

Decay of emitted axions



Emitted axions can decay to photons, generating an additional EM signal in NS mergers.
Fermi-LAT constrains axions from GW170817.

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