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X17 Research Group

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SCHOOL OF PHYSICS

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Few new concepts of nuclear physics in a Neutron Star environment

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Outline

^{8}Be and ^{4}He as physics Lab
ATOMKI experiment – results

X17 Boson

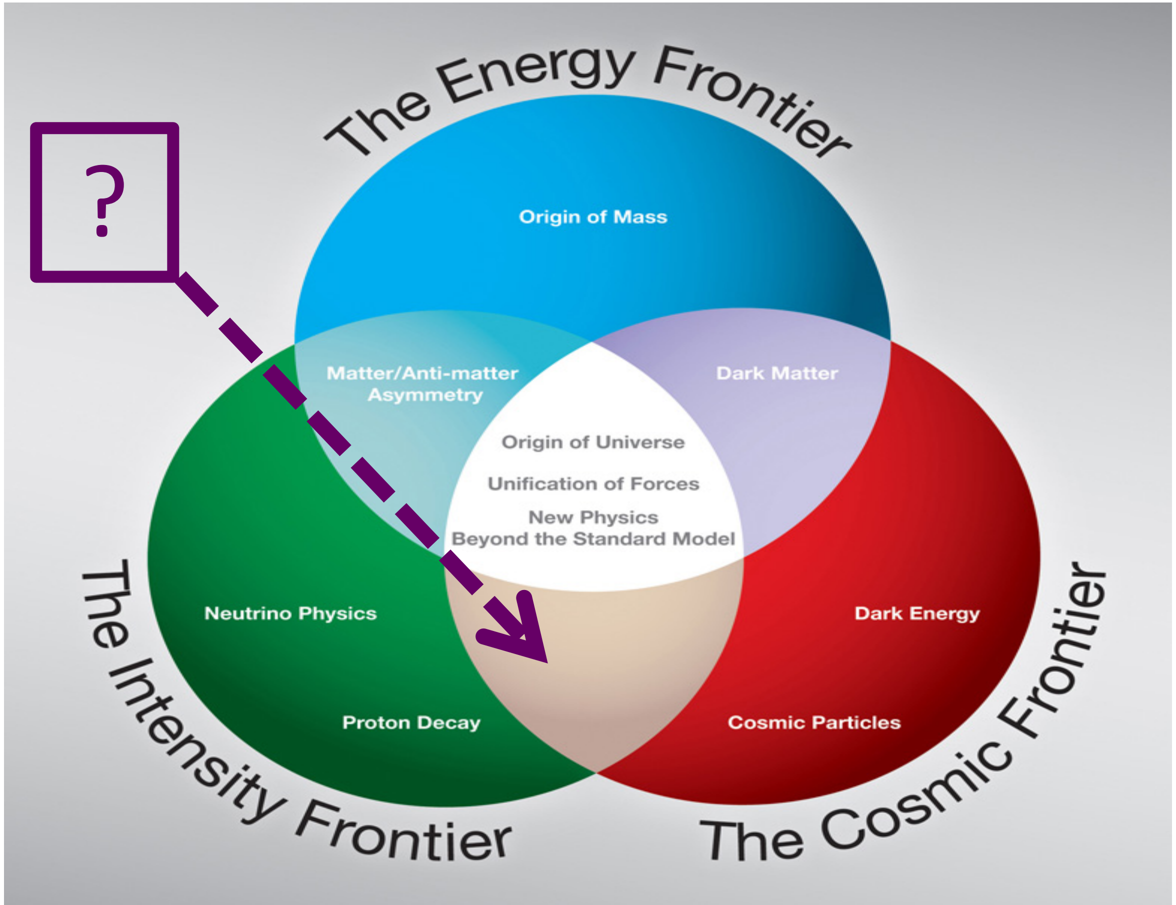
The VPL (Veselský- Petousis-Leja) model and
the X17 boson in a Neutron Star environment

Scenario 1

Hyper-Heavy elements in
a Neutron Star environment

Scenario 2

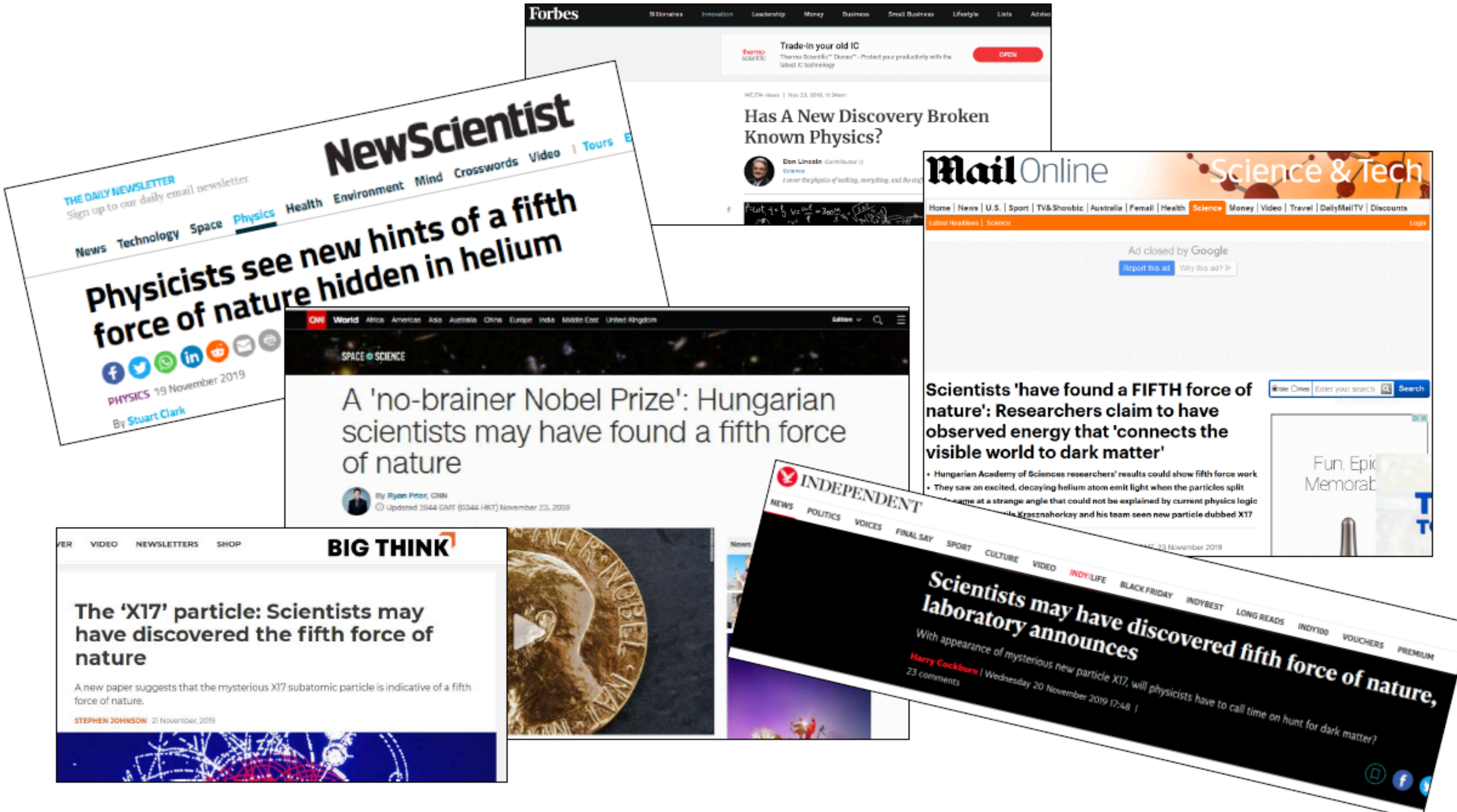
Why are we interested so much ?



Its an open opportunity for

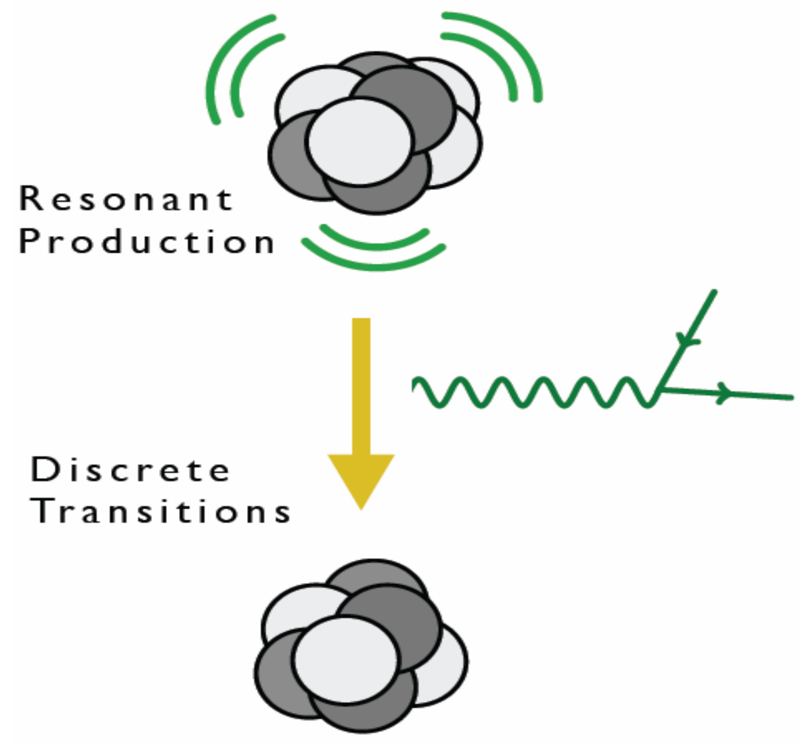
NEW REVOLUTIONARY PHYSICS

The X17 Boson



$^{8}Be^{*}$ and $^{4}He^{*}$ as a new physics lab

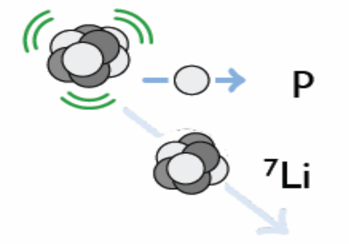
- The $^{8}Be^{*}$ nucleus is composed of: 4 protons and 4 neutrons (2p+2n for $^{4}He^{*}$).
- Excited states can be produced through p + ^{7}Li (p+^{3}H), with high statistics.
- Excited states decay to ground state with relatively large energies (≈ 20 MeV).
- $^{8}Be^{*}$ and $^{4}He^{*}$ nuclear transitions provide interesting probes of light to weakly-coupled particles.



^{8}Be* decay

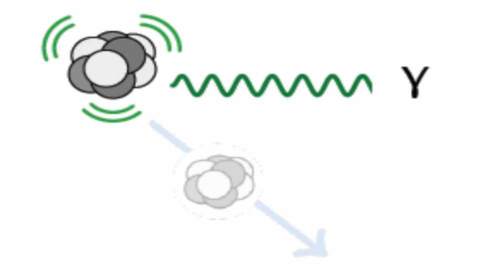
- **Hadronic**

  B(p ^{7}Li) ≈ 100%



- **Electromagnetic**

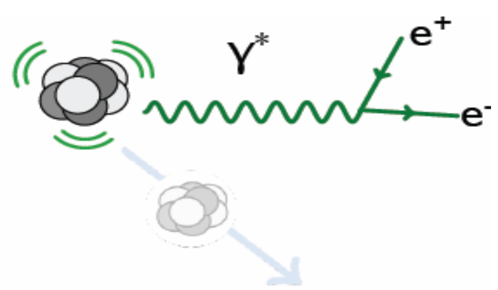
  B(^{8}Be --> γ) ≈ 1.5 x 10^{-5}



- **Internal Pair Creation (IPC)**

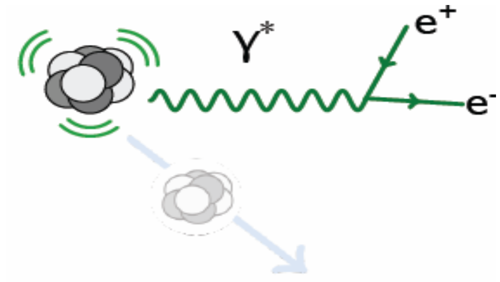
  B(^{8}Be --> e^+ e^-) ≈ 5.5 x 10^{-8}

  τ ≤ 10^{-13} sec “short lived”

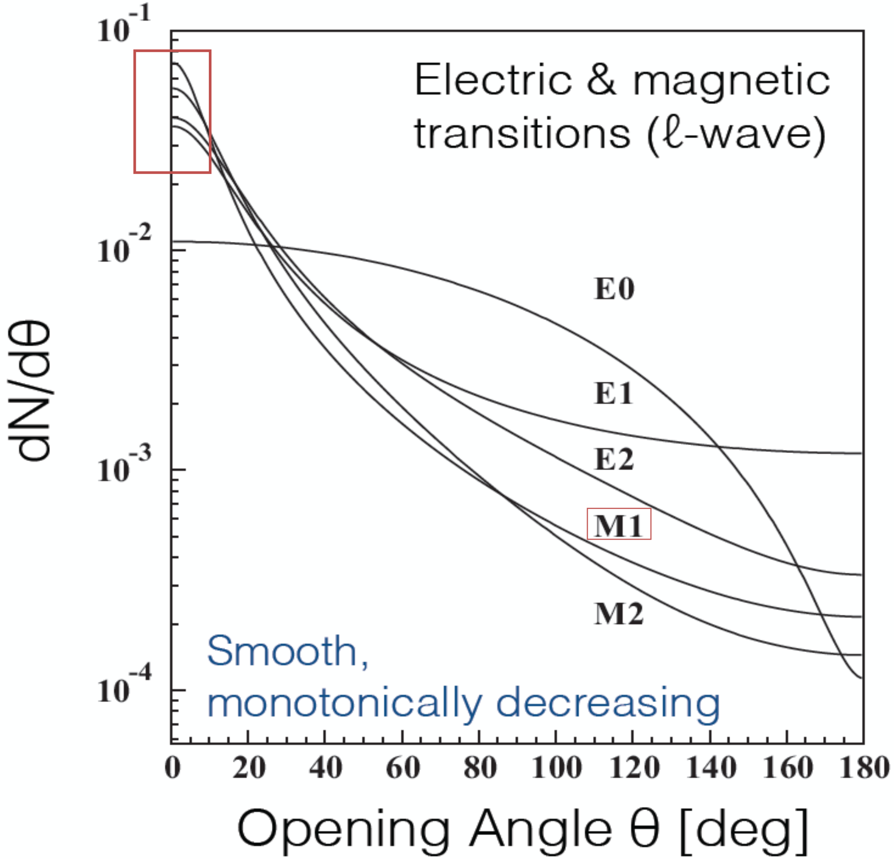


^{8}Be* decay

- Internal Pair Creation (IPC)
  $B(^{8}Be \rightarrow e^{+} e^{-}) \approx 5.5 \times 10^{-8}$



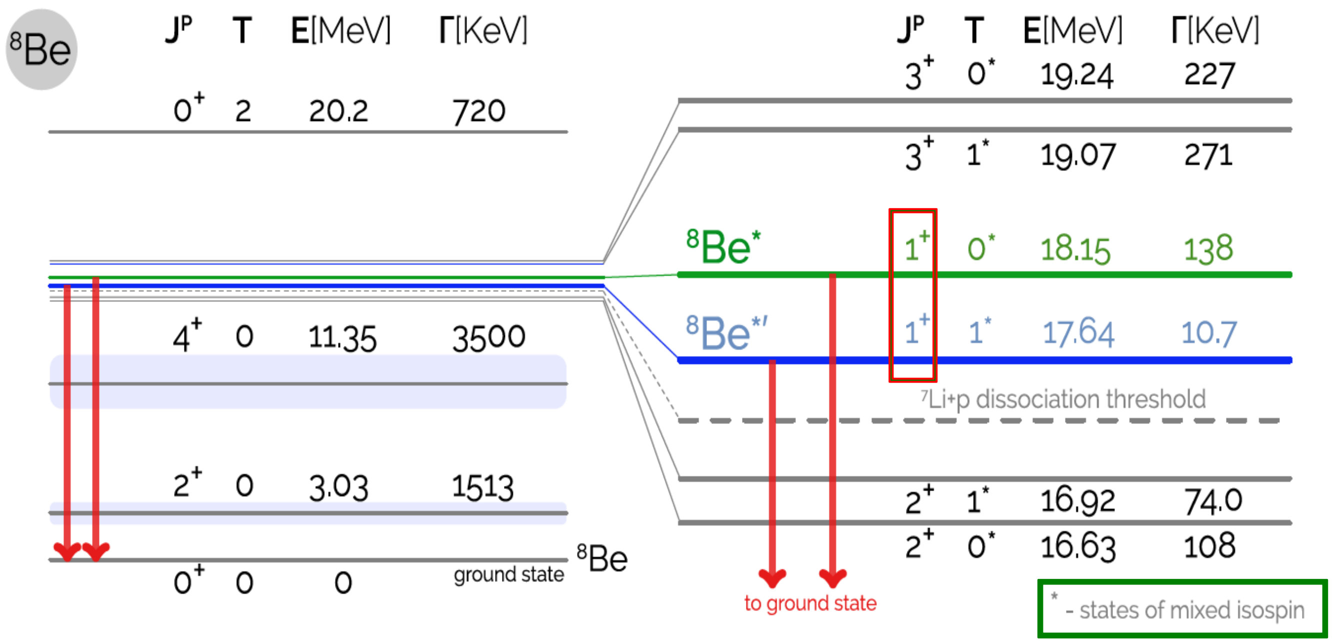
For $e^{+}e^{-}$ pair produced by a virtual photon the $dN/d\theta$ sharply peaks at low θ and is expected to decreasing monotonically as a function of θ.



Gulyas et al. (2015); Rose (1949)

The ^{8}Be*spectrum

- Many excited states with different spins and isospins.
- Of special interest: the **^{8}Be* (18.15)** and **^{8}Be*' (17.64)** states.

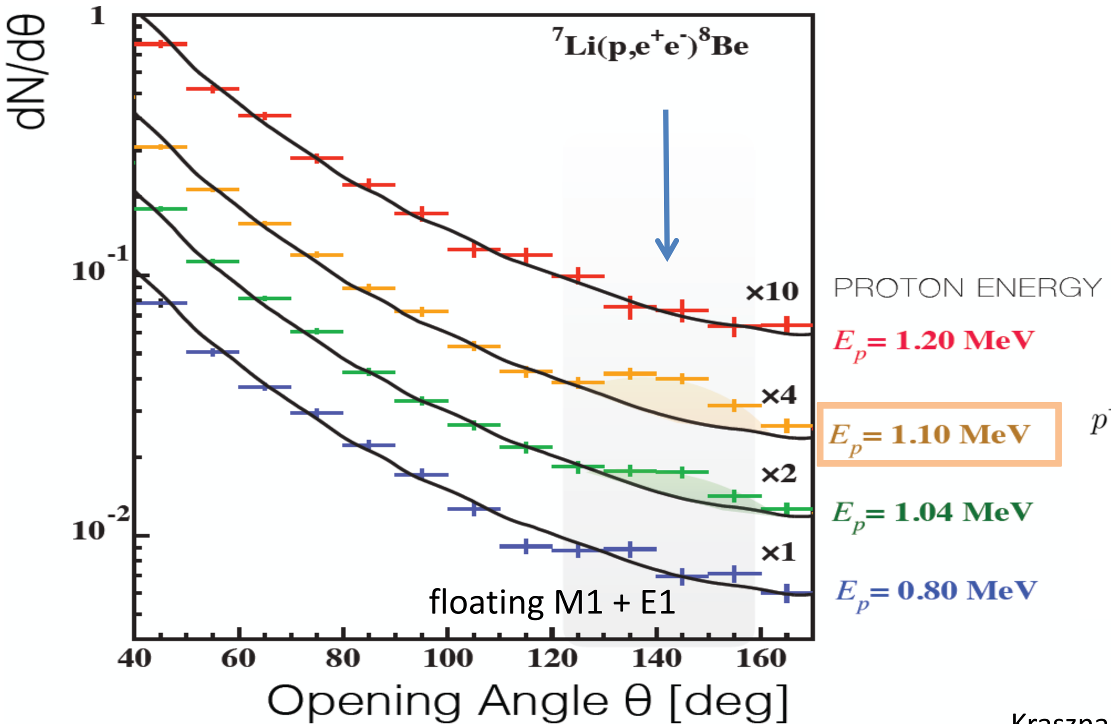


Tilley et al. (2004) and Wiringa et al. (2013)

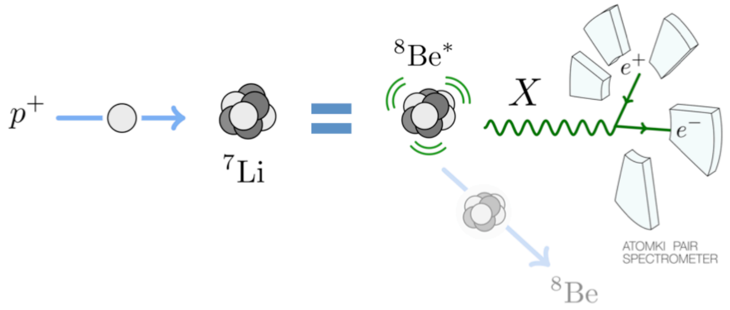
Feng et al. Phys. Rev. Lett. 117, 071803 (2016)

The ATOMKI results

- A bump at near the **140^0** was observed as one passes through the ^{8}Be* resonance.
- Background Fluctuations Probability: 5.6×10^{-12} ---> (6.8σ)



15μg/cm^2 thick LiF_2
700 μg/cm^2 thick LiO_2
evaporated on 10μm Al



Krasznahorkay et al. PRL 116, (2016)

Feng et al. Phys. Rev. Lett. 117, 071803 (2016)

The ATOMKI results

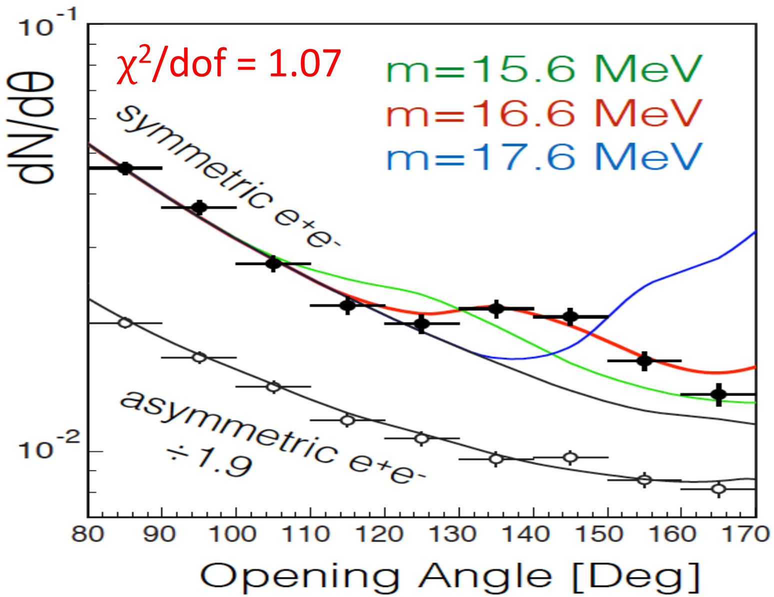
- The θ (and m_{ee}) distributions can be explained by postulating a new particle and the decay **^{8}Be* --> ^{8}Be+X**, followed by **X -- > e^+e^-**
- Best fit parameters: $M_X = 16.7 \pm 0.35\ (\text{stat})\ \pm 0.5\ (\text{sys})\ \text{MeV}$

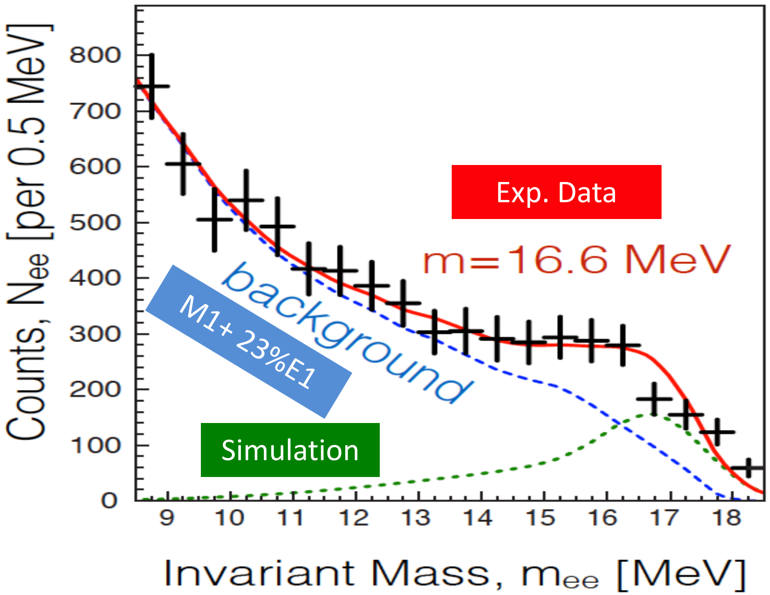
$$\mathcal{B} \equiv \frac{\text{BR}(^8\text{Be}^* \to X + {}^8\text{Be})}{\text{BR}(^8\text{Be}^* \to \gamma + {}^8\text{Be})} \times \text{BR}(X \to e^+e^-) = 5.8\times10^{-6}$$

1

Krasznahorkay et al. PRL 116, (2016)

Feng et al. Phys. Rev. Lett. 117, 071803 (2016)



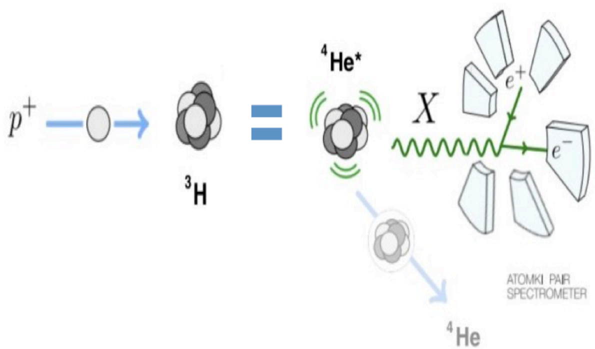


Same anomaly using another target (^3H)

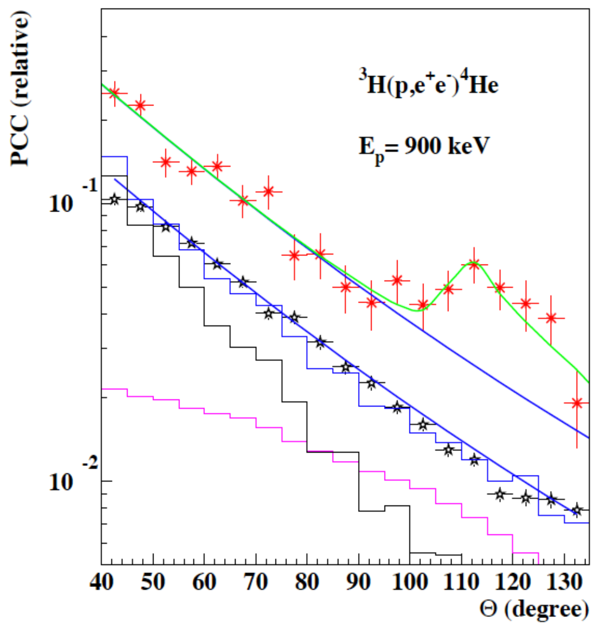
$^3H(p,\gamma)^4He^*$

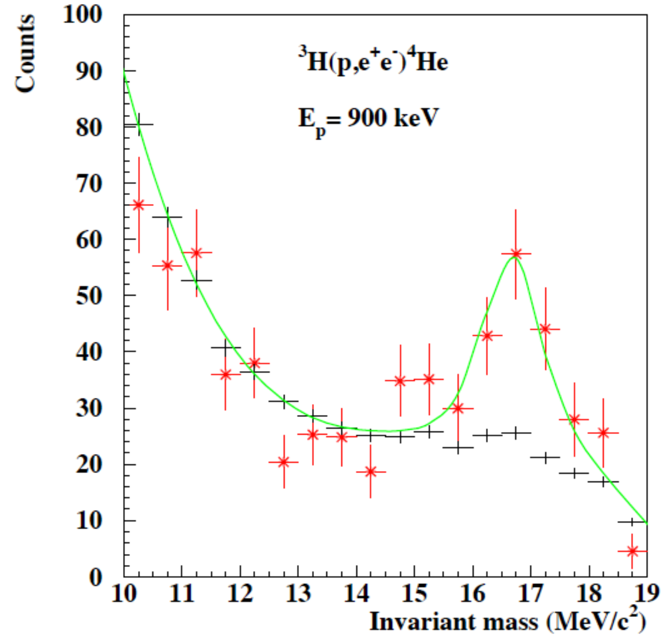
- A proton beam E_p = 900 keV with a typical current of 1.0 μA strikes on a ^3H target.
- e^+e^- pairs showed a peak at **115^0**, supporting the creation and decay of the X17 particle with mass of **m_X = 16.84 ± 0.16(stat) ± 0.20(syst) MeV** (7.1σ)

Feng et al. Phys. Rev. Lett. 117, 071803 (2016)



^3H target absorbed in a 3mg/cm^2 thick Ti layer evaporated onto a 0.4 mm thick Mo disk.





A. Krasznahorkay et al. Phys. Rev. C **104**, 044003 (2021) 10.1103/PhysRevC.104.044003

Scenario 1

The VPL (Veselský- Petousis - Leja) model and the X17 Boson in a Neutron Star environment

https://doi.org/10.1088/1361-6471/ac09db Journal of Physics G (2021)

https://doi.org/10.1103/PhysRevC/106/L012802 EPJ Web of Conferences 252, 04008 (2021)

Submitted to MDPI- Journal - Symmetry (2022)

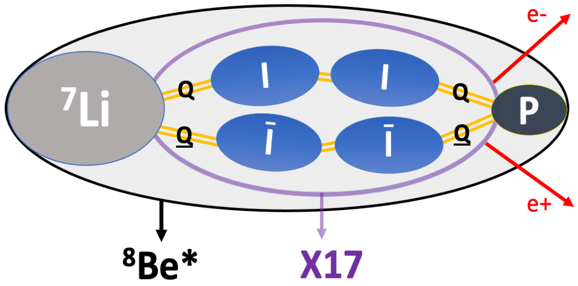
The VPL (Veselský - Petousis - Leja) model

We present a hypothesis that the anomaly in the folding angle of e^-e^+ pairs:

- Can be related to the cluster structure of the decaying state

We propose that the potentially observed X17 boson:

- Can mediate the nucleon-nucleon interaction
- Low-energy regime of QCD
- Weakly bound cluster states p+^{7}Li and p+^{3}H



We make use of:

- EoS of SNM (vector meson m_v=17 MeV)
- RMF theory of nuclear force
- QHD-I
- Incompressibilities K_0=245-260 MeV
- Couplings g_v, g_s << 1

$$\epsilon = \frac{g_v^2}{2m_v^2}\rho_N^2 + \frac{m_s^2}{2g_s^2}(m_N - m_N^*)^2 + \frac{\kappa}{6g_s^3}(m_N - m_N^*)^3 + \frac{\lambda}{24g_s^4}(m_N - m_N^*)^4 + \frac{\gamma}{(2\pi)^3}\int_0^{k_F} d^3k\sqrt{k^2 + (m_N^*)^2}$$

K_0	m_v	m_s	g_v	g_s	κ	λ
MeV	MeV	MeV			MeV	
245	17.	25.58	0.2407	0.4666	0.0039	-0.001396
250	17.	25.58	0.2417	0.4703	0.00398	-0.001316
260	17.	25.58	0.2417	0.4684	0.00374	-0.001204

https://doi.org/10.1088/1361-6471/ac09db (Journal of Physics G)

The VPL (Veselský - Petousis - Leja) model

Based on concepts of chiral symmetry breaking:

- Reduction of the rest mass of a pseudoscalar particle from physical value m_π=135 MeV to m_X=17 MeV
- Equivalence in reduction of the quark mass from dynamical value ~ 310 MeV down to current quark mass ~ 5 MeV

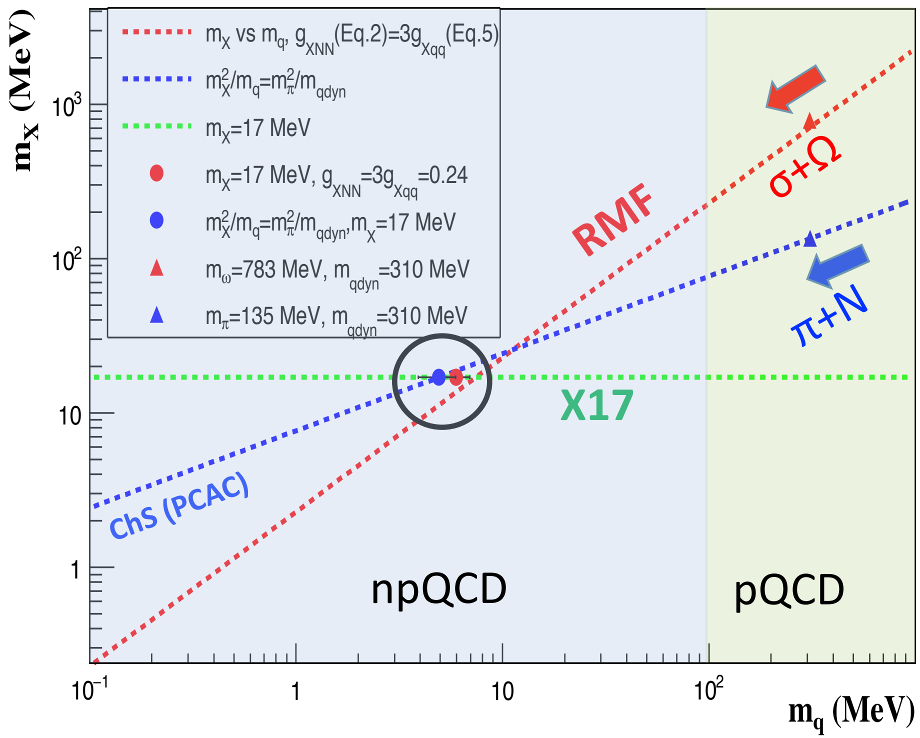
Possible observation of a X17 boson may suggest:

- The existence of a new scale in QCD
- Chiral symmetry restoration

It might be related to:

- The interaction between nucleons at distance, mediated by instantons.
- Possibly a bounce into a false instanton vacuum (a QM tunneling into a metastable vacuum and back), where the mechanism based on instanton model can occur.

https://doi.org/10.1088/1361-6471/ac09db (Journal of Physics G)



$$(\frac{m_N}{m_s})^2 g_s^2 = 357.4$$
$$(\frac{m_N}{m_v})^2 g_v^2 = 273.8 \quad (2)$$

$$\frac{m_X^2}{m_{q,curr}} \simeq \frac{m_\pi^2}{m_{q,dyn}} \quad (4)$$

$$g_{Xqq} = \frac{g_A m_{q,curr}}{f_\pi} \quad (5)$$

The VPL (Veselský - Petousis - Leja) model

QCD vacuum and Instanton Liquid Model (ILM)

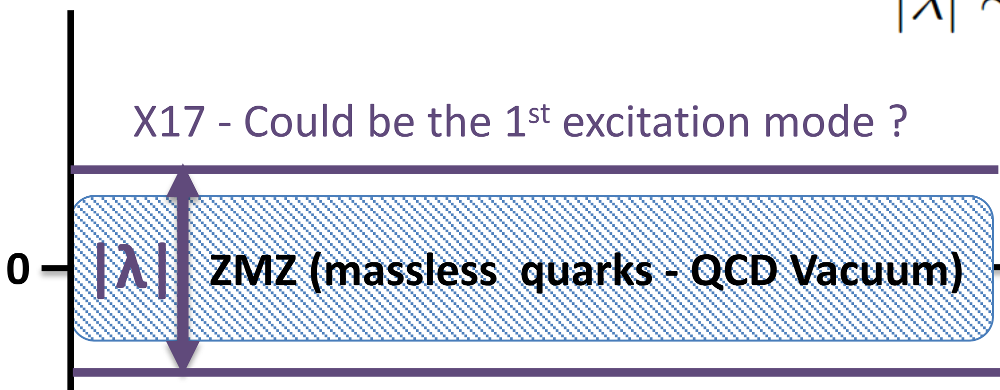
The physics of the non-perturbative vacuum of strong interaction started even before QCD.

Nambu and Jona-Lasinio (NJL) inspired by BCS theory of superconductivity, have qualitatively explained that strong enough attraction of quarks can break $SU(N_f)_A$ chiral symmetry spontaneously and, among many other effects, create near-massless pion's. Chiral effective Lagrangian's and related theory have lead to one important input, a nonzero quark condensate **$\langle q\bar{q}\rangle \neq 0$**

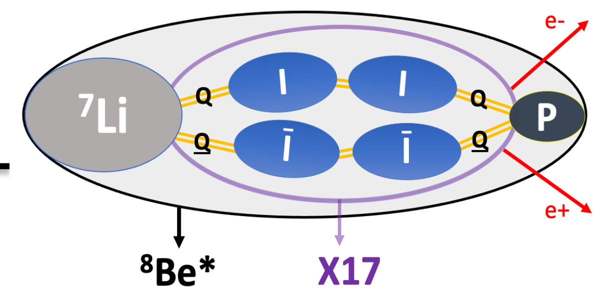
Another explanation of chiral symmetry breaking by the instanton ensemble is based on the collectivization of the **instanton zero modes**, into the so called **"zero mode zone" (ZMZ)**. Due to nonzero matrix elements of the Dirac operator, near-zero Dirac eigenvalues are residing within a strip of small width¨:

E. Shuryak and I. Zahed arXiv:2110.15927v1

$$|\lambda| \sim \mathrm{width\,(ZMZ)} \sim \frac{\rho^2}{R^3} \sim 20\,\mathrm{MeV}$$



ρ = 1/3 fm
R = 1 fm



The X17 boson in a Neutron Star environment

$$\frac{dP}{dr} = \frac{-G}{c^2}\frac{(P+\epsilon)(m+\frac{4\pi r^3 P}{c^2})}{r(r-\frac{2Gm}{c^2})}$$

$$\frac{dm}{dr} = 4\pi r^2 \frac{\epsilon}{c^2}$$

$$\epsilon = \frac{g_v^2}{2m_v^2}\rho_N^2 + \frac{m_s^2}{2g_s^2}(m_N - m_N^*)^2 + \frac{\kappa}{6g_s^3}(m_N - m_N^*)^3$$
$$+\frac{\lambda}{24g_s^4}(m_N - m_N^*)^4 + \frac{\gamma}{(2\pi)^3}\int_0^{k_F} d^3k\sqrt{k^2 + (m_N^*)^2}$$

$$P = \frac{g_v^2}{2m_v^2}\rho_N^2 - \frac{m_s^2}{2g_s^2}(m_N - m_N^*)^2 + \frac{\kappa}{6g_s^3}(m_N - m_N^*)^3$$
$$+\frac{\lambda}{24g_s^4}(m_N - m_N^*)^4 + \frac{1}{3}\frac{\gamma}{(2\pi)^3}\int_0^{k_F} d^3k\frac{k^2}{\sqrt{k^2 + (m_N^*)^2}}$$

$$\frac{m_X^2}{m_{q,curr}} \simeq \frac{m_\pi^2}{m_{q,dyn}}$$

$$g_{Xqq} = \frac{g_A m_{q,curr}}{f_\pi}$$

The X17 boson in a Neutron Star environment

- The reported X17 MeV boson has been investigated in the context of its possible influence to the neutron star structure.

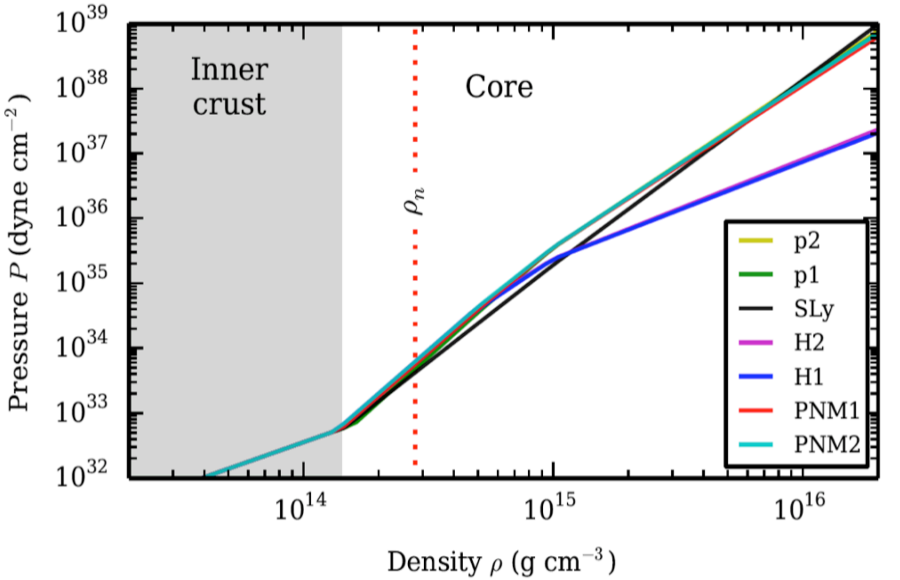
- We implemented the m_v=17 MeV to the nuclear equation of state using different incompressibility values K_0=245 MeV and K_0=260 MeV solving the Tolman-Oppenheimer-Volkov equations.

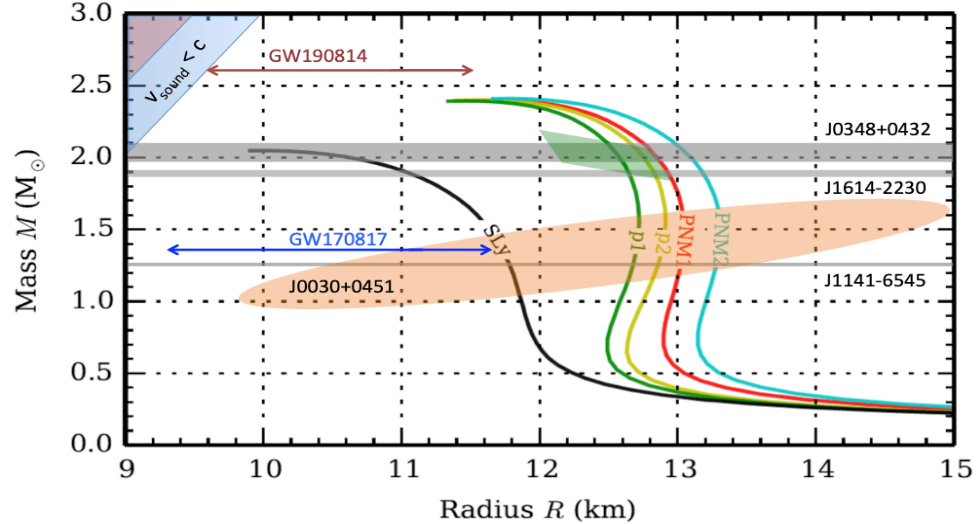
- We estimated an upper limit of $M_{TOV} \approx 2.4 M_{\odot}$ for a non-rotating neutron star with span in radius 11.5 km ≤ R ≤ 14 km.

- Moving away from the β-equilibrium with admixture of 10% protons we simulated possible softening of equation of state due to hyperons, we saw that our estimated limits fit quite well inside the newest reported studies, coming from the neutron stars merge procedure.

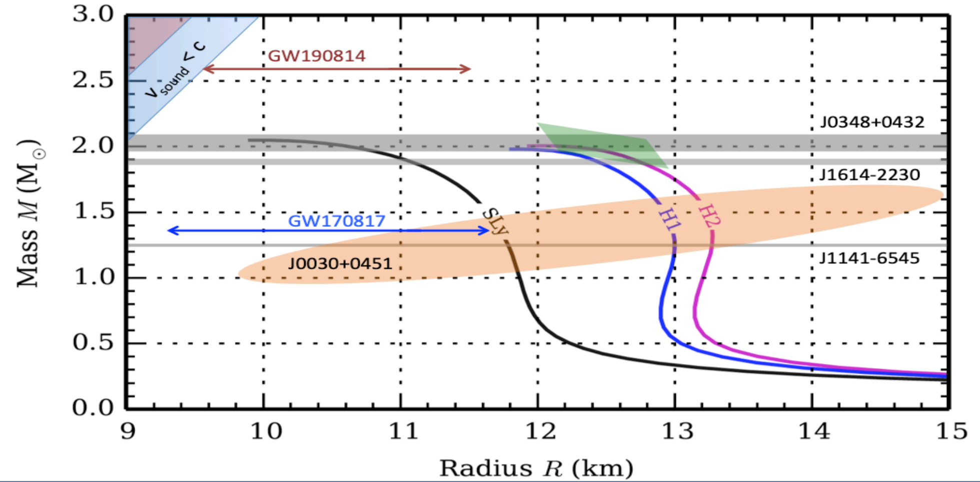
Petousis. V, Veselský. M, Leja. J, EPJ Web of Conferences 252, 04008 (2021)

The X17 boson in a Neutron Star environment





Models	a_0	Γ_1	Γ_2	Γ_3	K$_0$(MeV)	Note
PNM1	34.600	3.350	3.170	2.497	245	Pure.nucl.matt
H1	34.600	3.350	2.570	1.497	245	Hyperons sim
p1	34.553	3.470	3.307	2.546	245	10% of protons
PNM2	34.642	3.348	3.040	2.534	260	Pure.nucl.matt
H2	34.642	3.348	2.440	1.534	260	Hyperons sim
p2	34.593	3.530	3.177	2.500	260	10% of protons



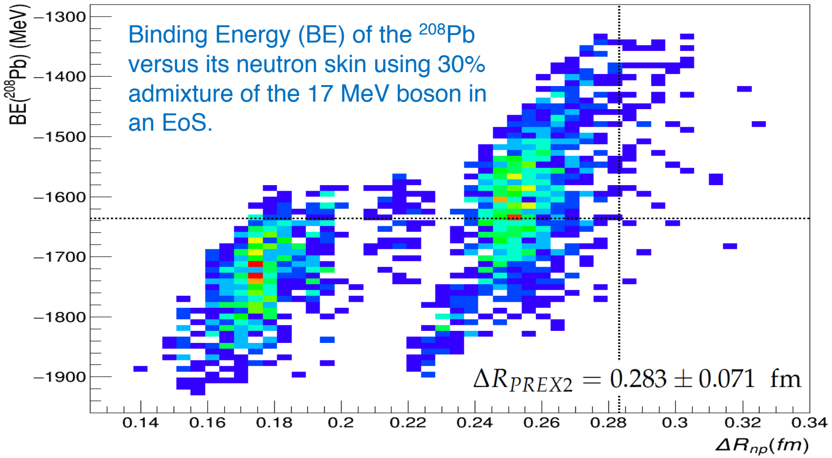
The X17 boson in a Neutron Star environment

$$L_{MFT} = \overline{\psi}\{i\partial^{\mu}\gamma_{\mu} - g_v V_0 \gamma_0 - (M - g_s \Phi_0)\}\psi - \frac{1}{2}m_s^2\Phi_0^2 - \frac{1}{3!}k\Phi_0^3 - \frac{1}{4!}\lambda\Phi_0^4$$
$$\boxed{+\frac{1}{2}m_{\omega}^2(1-q)^2V_0^2 + \frac{1}{2}m_X^2 q^2 V_0^2}$$

$$m_v^{*2} = (q^2 m_X^2 + (1-q)^2 m_\omega^2)$$

$$\Delta R = R_n - Rp$$

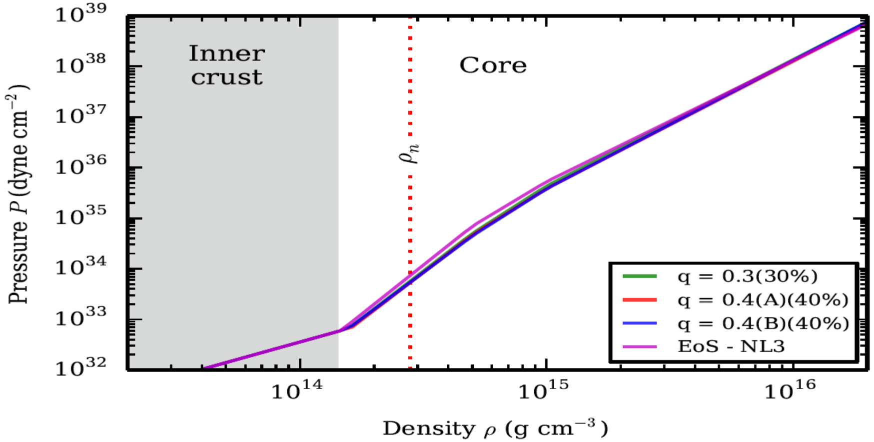
- Main goal was to set parameter sets that satisfy all the observable constraints. Several combinations of parameters appeared to satisfy these constraints.
- We used parameter sets with 17 MeV boson admixture ranging between 20% to 40%.
- The 20% admixture failed to satisfy constraints from heavy ion collisions.
- Parameter sets with admixture of 30% to 40% satisfied all the constraints.
- Such observation can have physical meaning.

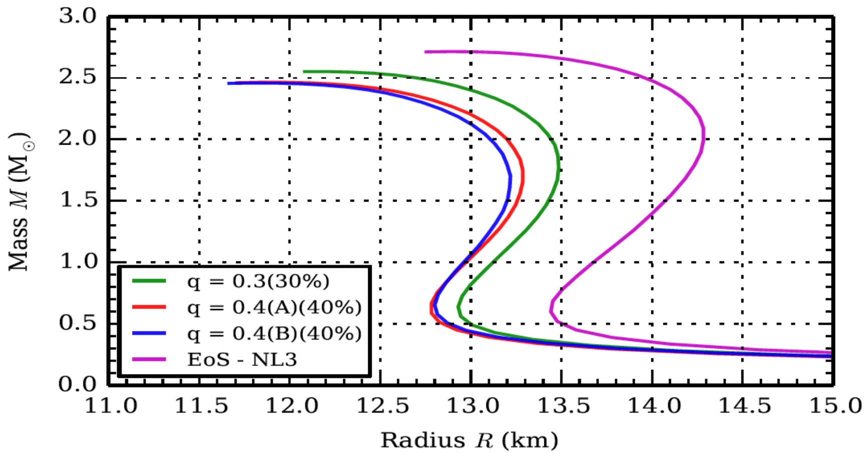


K_0	q	κ	λ	g_v	g_s	$m^*_v[MeV]$	$m_\sigma[MeV]$
235.95	0.3	21.50	-163.33	8.38	9.20	547.77	482.16
269.14	0.4(A)	11.00	-50.00	6.85	7.23	469.55	391.44
257.50	0.4(B)	11.50	-60.00	6.85	7.23	469.55	391.44

EoS q-admixture (%)	a_0	Γ_1	Γ_2	Γ_3	K_0(MeV)
0.3 (30%)	34.703	3.741	3.118	2.497	235.95
0.4(A) (40%)	34.673	3.744	3.036	2.517	269.14
0.4(B) (40%)	34.653	3.643	3.095	2.540	257.50
NL3 (0%)	34.846	3.872	2.925	2.394	332

The X17 boson in a Neutron Star environment





- In summary, we implemented a hypothetical 17 MeV boson to a nuclear equation of state (EoS) and observe that only instances with admixture 30% - 40% satisfy all the constraints.

- The successful EoS result in a radius around 13 km for a neutron star with mass $1.4M_\odot$ and in maximum mass of around $2.5M_\odot$.

- The values of these results are in a good agreement with recent measurement by NICER.

- The obtained value of maximum mass is also in agreement with the recently reported mass of a pulsar and potentially also with the mass remnant of the gravitational wave event GW190814.

- Thus, it appears that these EoS satisfy all the existing experimental constraints and can be considered as universal equations of state of nuclear matter.

Scenario 2

Hyper-Heavy elements in a Neutron Star environment

Physical Review C, **106**, L012802 (2022)
https://doi.org/10.1103/PhysRevC/106/L012802

Hyper - Heavy elements in a Neutron Star environment

The Constrained Molecular Dynamics (CoMD)

$$V_{vol} = \frac{T_0}{\rho_0}\delta(\boldsymbol{r_i} - \boldsymbol{r_j})$$

$$V_3 = \frac{2T_3\rho^{\sigma-1}}{(\sigma+1)\rho_0^{\sigma}}\delta(\boldsymbol{r_i} - \boldsymbol{r_j})$$

$$V_{sym} = \frac{\alpha_{sym}}{\rho_0}\delta(\boldsymbol{r_i} - \boldsymbol{r_j})(2\delta_{\tau_i,\tau_j} - 1)$$

$$V_{sur} = \frac{C_s}{\rho_0}\nabla^2_{\langle \boldsymbol{r_i}\rangle}\delta(\boldsymbol{r_i} - \boldsymbol{r_j})$$

$$V_{coul} = \frac{e^2}{||\boldsymbol{r_i} - \boldsymbol{r_j}||}$$

V_{vol} Volume term

V_3 Three-body term

V_{sym} Symmetry term

V_{sur} Surface term

V_{coul} Coulomb repulsion

C_s Surface parameter

$\rho_0 = 0.16\ \mathrm{fm}^{-3}$ Saturation density

$\alpha_{sym} = 32$ MeV Symmetry

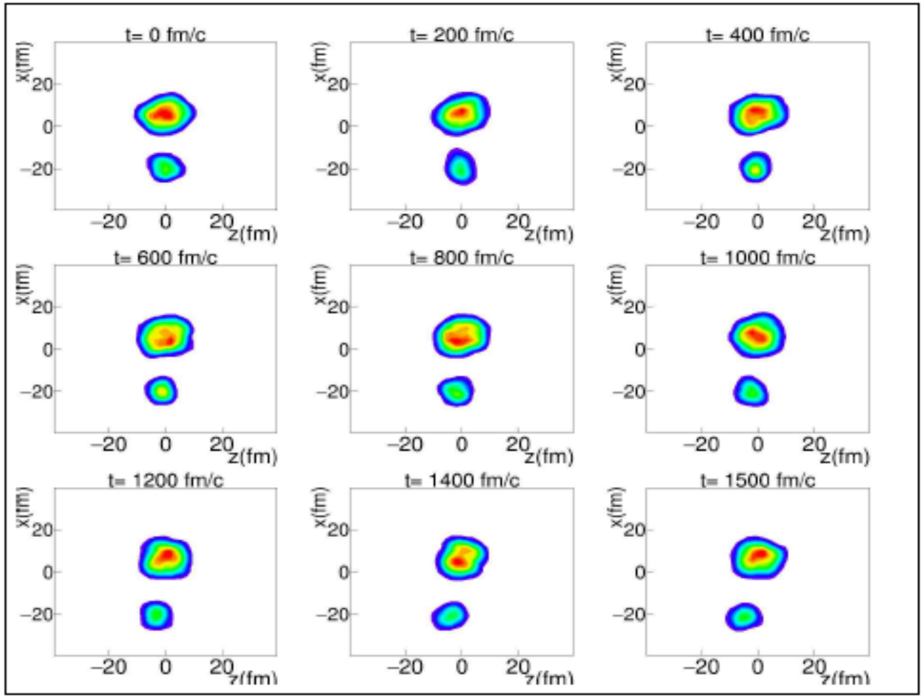
$C_s/\rho_0 = 0$ Surface – density ratio

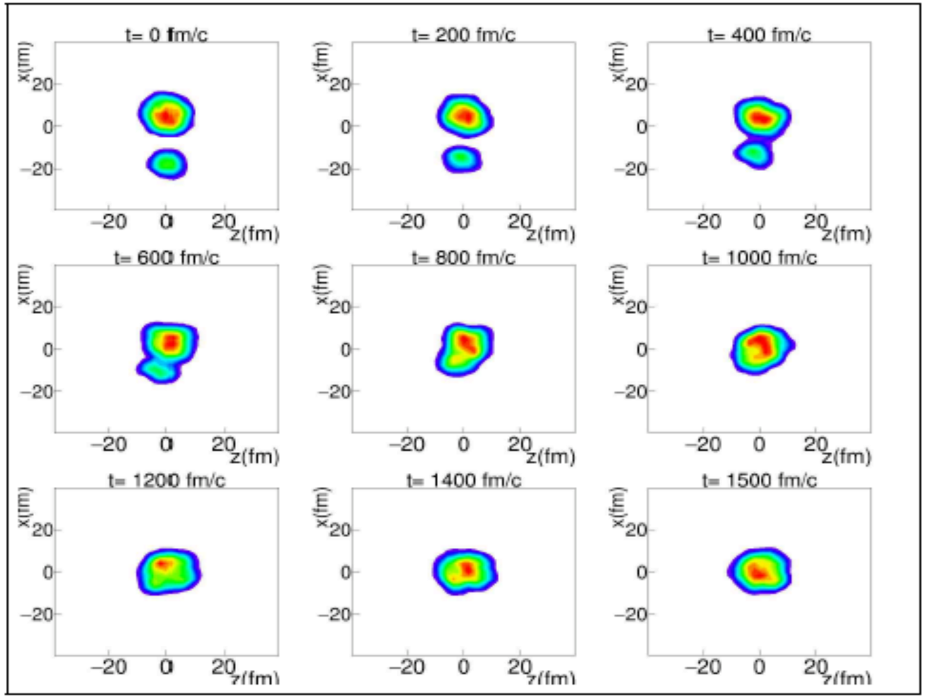
Gaussian wave-packets

$$f(\boldsymbol{r},\boldsymbol{p}) = \frac{1}{(2\pi\sigma_r\sigma_p)^3} e^{-\frac{(\boldsymbol{r}-\langle \boldsymbol{r_j}\rangle)^2}{2\sigma_r^2}} e^{-\frac{(\boldsymbol{p}-\langle \boldsymbol{p_j}\rangle)^2}{2\sigma_p^2}}$$

Veselský. M, Petousis. V, Moustakidis. Ch, Souliotis. G. A, Bonasera. A (2022)
(Submitted to PRC Letters)

Hyper - Heavy elements in a Neutron Star environment

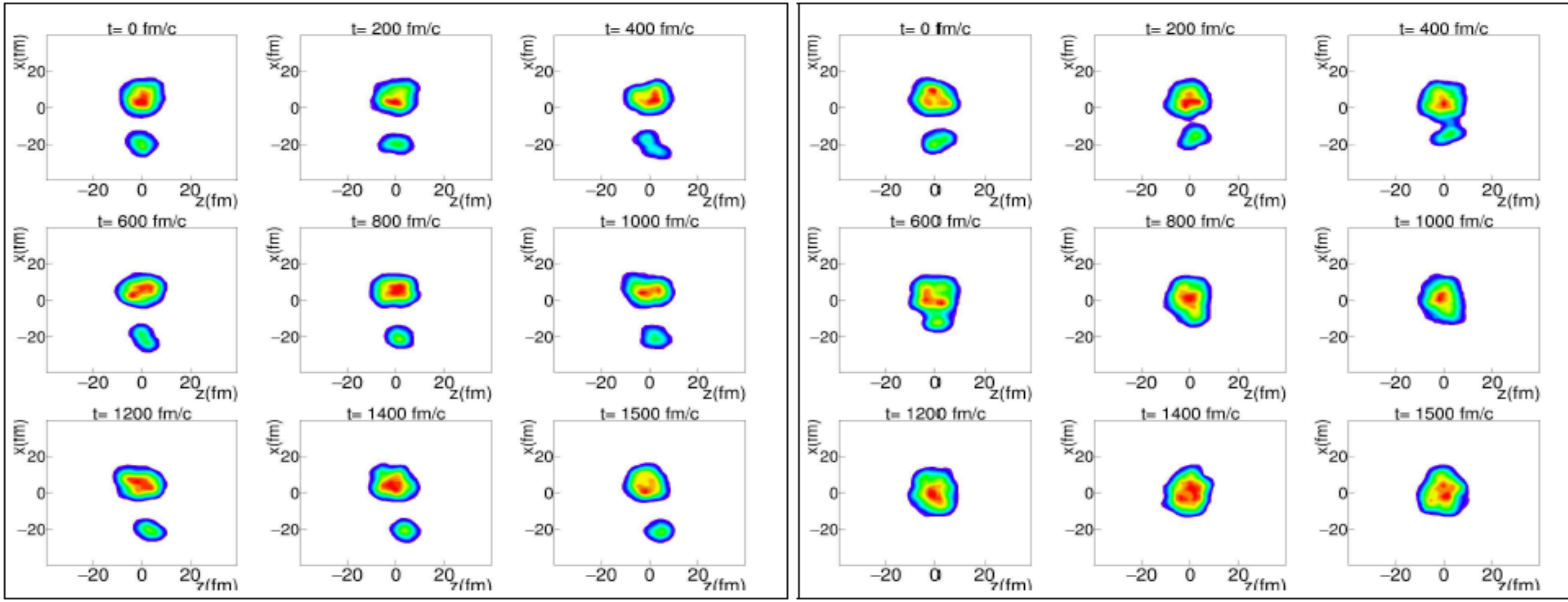




- **Without nucleonic medium**

Typical evolution of nucleonic density for central collision ^{140}Ni+^{460}U calculated using the CoMD code at beam energy 1.25 MeV/nucleon (Left panel) and 1.5 MeV/nucleon (Right panel). A **Coulomb interaction cutoff 2 fm**, incompressibility K_0 = 254 MeV and a **soft density dependence of symmetry energy** were used. Scattering due to a "neutron wind" dominates at lower beam energy (Left panel), while **fusion dominates at higher beam energy (Right panel)**.

Hyper - Heavy elements in a Neutron Star environment

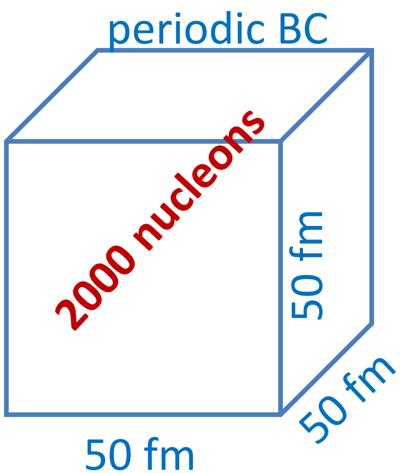


- **Without nucleonic medium**

Typical evolution of nucleonic density for central collision ^{140}Ni+^{460}U calculated using the CoMD code at beam energy 1.25 MeV/nucleon (Left panel) and 1.5 MeV/nucleon (Right panel). A **Coulomb interaction cutoff 2 fm**, incompressibility K_0 = 254 MeV and a **stiff density dependence of symmetry energy** were used. Scattering due to a "neutron wind" dominates at lower beam energy (Left panel), while **fusion dominates at higher beam energy (Right panel)**.

Hyper - Heavy elements in a Neutron Star environment

- **With nucleonic medium**



- To simulate conditions inside neutron stars, CoMD was further modified to introduce a low-density nucleonic background by placing 2000 nucleons inside a box with periodic boundary conditions.

- The size of the box was initially set to 50x50x50 fm^3, corresponding to approximately one tenth of saturation density $\rho_0 = 0.16\ fm^{-3}$

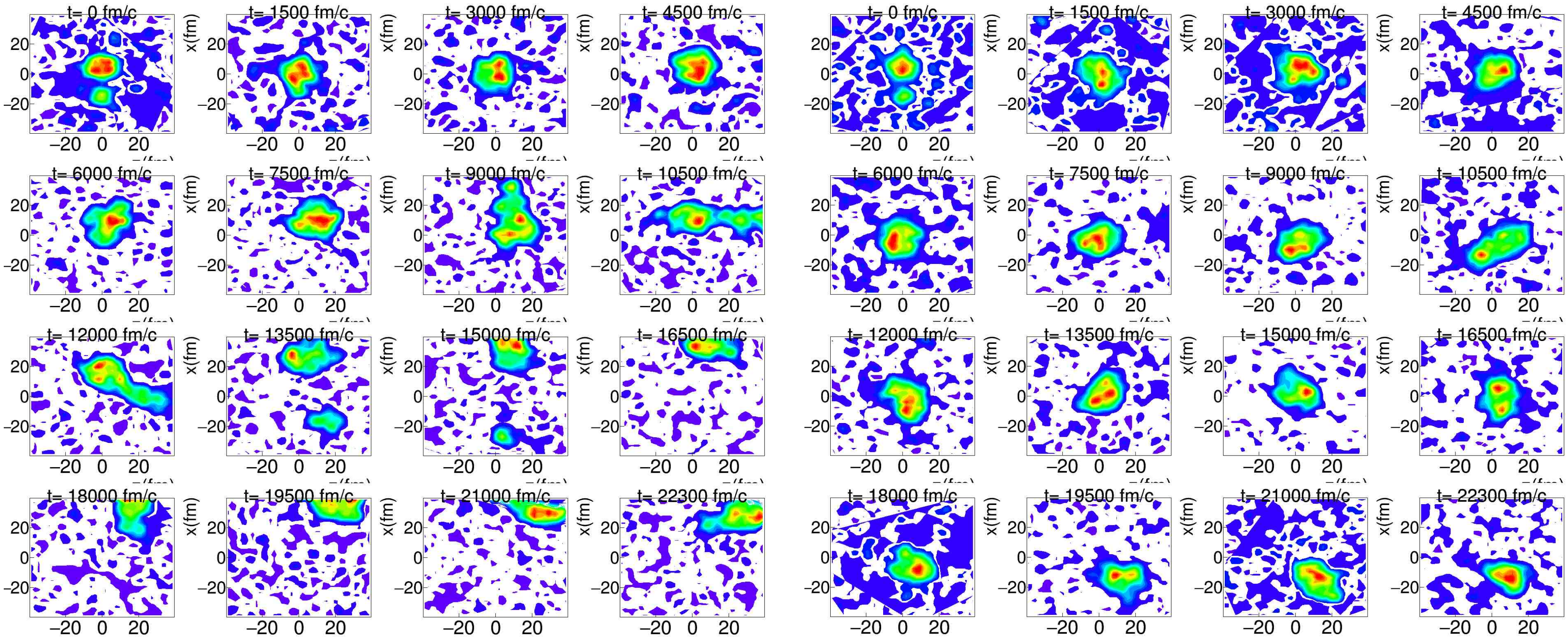
- The cutoff of Coulomb interaction was set correspondingly to the Debye-Hückel length at given density and proton fraction of nuclear medium (10%).

$$\lambda_D = \sqrt{\frac{\epsilon_0}{n_e q_e^2/T_e + n_p q_p^2/T_p}}$$

- The Debye-Hückel formula used in this work assumes classical protons (10%). This approximation can be justified for lowest values of density of the proton background, where assumed temperature of around 1 MeV it is comparable to Fermi energy. All the possible reactions proceed within an s-wave, and thus the fusion probabilities will be the same.

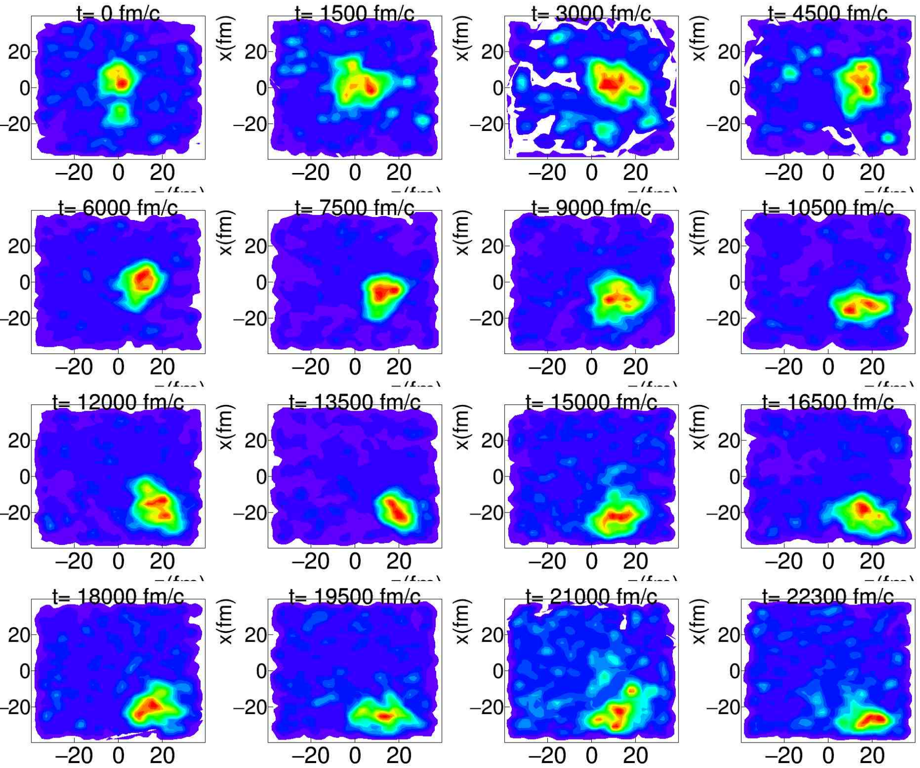
- The simulations lead to the confirmation that the "neutron wind" observed previously was unphysical and practically there is no fusion barrier down to beam energy corresponding to typical neutron star temperature 10^8 -10^9 K (10 - 100 keV).

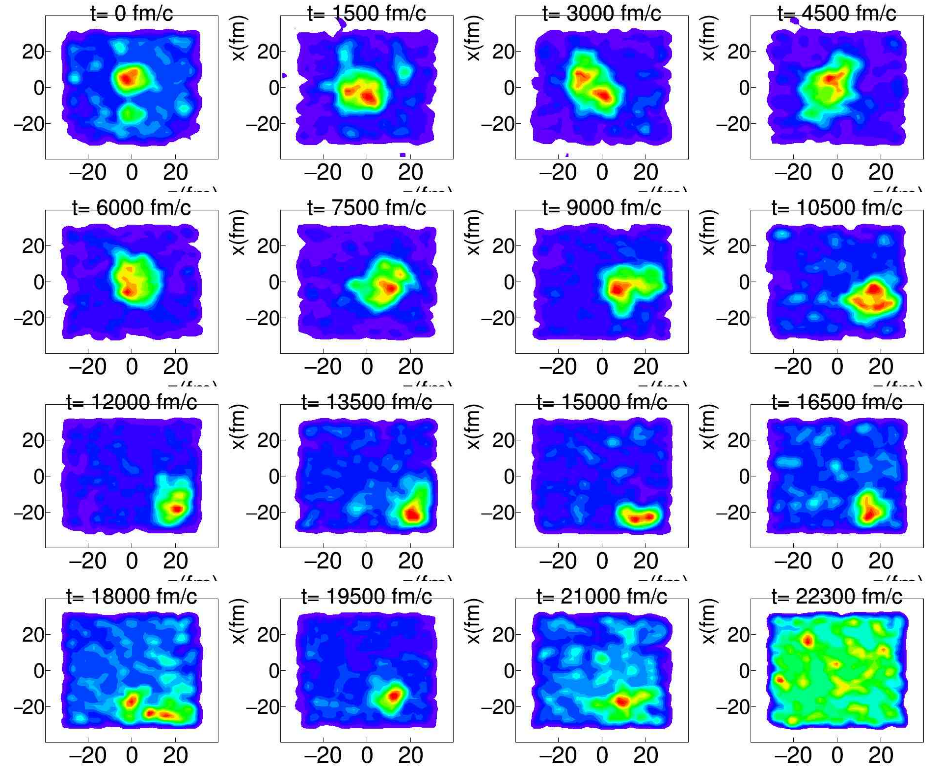
Hyper - Heavy elements in a Neutron Star environment



Evolution of the system ^{140}Ni+^{460}U in the nucleon bath with 10% proton concentration calculated using the CoMD code at beam energy 0.01 MeV/nucleon and **Coulomb interaction cutoff at 10, 7 fm** (from left to right), corresponding to nucleon bath densities **$\rho_0/100$, $\rho_0/50$**, respectively. Incompressibility is K_0 = 254 MeV and a **stiff density dependence of symmetry energy** were used. The initial distance is 25 fm. Timescale up to 25000 fm/c (10^{-20} s).

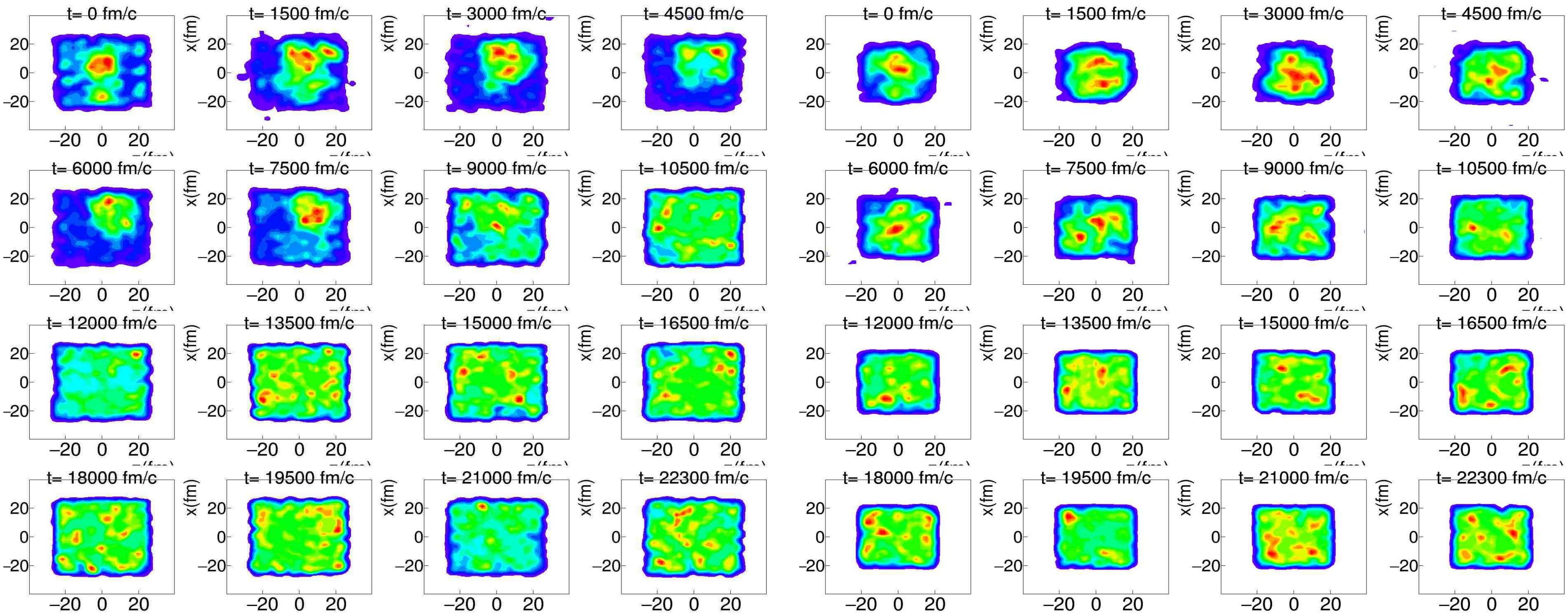
Hyper - Heavy elements in a Neutron Star environment





Evolution of the system ^{140}Ni+^{460}U in the nucleon bath with 10% proton concentration calculated using the CoMD code at beam energy 0.01 MeV/nucleon and **Coulomb interaction cutoff at 5, 4 fm** (from left to right), corresponding to nucleon bath densities **$\rho_0/30$, $\rho_0/17$**, respectively. Incompressibility is K_0 = 254 MeV and a **stiff density dependence of symmetry energy** were used. The initial distance is 25 fm. Timescale up to 25000 fm/c (10^{-20} s).

Hyper - Heavy elements in a Neutron Star environment



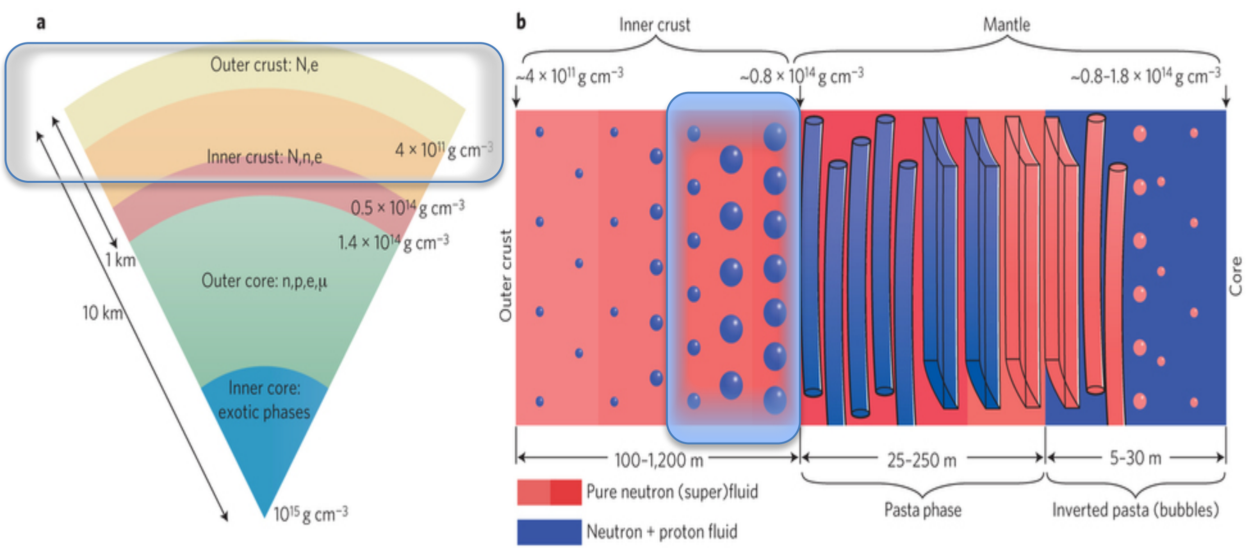
Evolution of the system $^{140}Ni+^{460}U$ in the nucleon bath with 10% proton concentration calculated using the CoMD code at beam energy 0.01 MeV/nucleon and **Coulomb interaction cutoff at 3, 2 fm** (from left to right), corresponding to nucleon bath densities **$\rho_0/10$, $\rho_0/5$**, respectively. Incompressibility is K_0 = 254 MeV and a **stiff density dependence of symmetry energy** were used. The initial distance is 25 fm. Timescale up to 25000 fm/c (10^{-20} s).

The resulting nucleus appears to dissolve in the nucleon bath with density above $\rho_0/30$, even sooner with increasing density. At lowest density the fission appears to take over, thus suggesting a maximum of lifetime between densities $\rho_0/50$ and $\rho_0/30$.

Hyper - Heavy elements in a Neutron Star environment

We suggest that this possible existence of hyper-heavy nuclei in a neutron star environment could provide observable signals.

- Extra coherent neutrino scattering could be considered as another crucial process, adding new information to the suggested models on neutron star cooling rate.
- Local events of fusion cascade leading to the production of hyper-heavy nuclei can lead to energy release due to minimization of surface energy, that, in turn may lead to an additional mechanism of **X-ray bursts**.
- Due to the local density profile modification deeper within the neutron star, **gravitational wave signals** may result from a violation of rotational symmetry.



Summary (Scenario 1)

- The properties of a non-rotating neutron star are simulated using a nuclear EoS and constructing a Universal EoS based on assumption that nuclear force is being mediated by a 17 MeV boson or and admixture of 30% - 40% of it.

- Our investigation indicates an upper limit of M_{TOV} = 2.5 Solar masses neutron star with span in radius between 11.5 km to 13 km for normal neutron matter and moderate reduction of radii for the admixture with 10% of protons.

- The value of radius is in agreement with the recent measurement by NICER.

- The maximum mass is also in agreement with the mass of remnant of the gravitational wave event GW190814.

- It appears that these EoS satisfy all the existing experimental constraints and can be considered as universal nuclear EoS.

Summary (Scenario 2)

- In a nucleonic background of surrounding nuclei, fusion becomes possible down to temperatures 10^8 K and synthesis of extremely heavy and n-rich nuclei appears feasible.
- For a stiff density dependence of symmetry energy and at lowest density, the fission appears to take over, thus suggesting a maximum of lifetime between densities $\rho_0/50$ and $\rho_0/30$, sufficient to support a fusion cascade.
- We suggest that this possible existence of hyper-heavy nuclei in a neutron star environment, could provide an extra coherent neutrino scattering affecting the neutron stars cooling rate.
- Local events of fusion cascade, leading to the production of hyper-heavy nuclei can lead to energy release due to minimization of surface energy, that, in turn may lead to an additional mechanism of X-ray bursts.
- Alternatively, due to the local density profile modification deeper within the neutron star, gravitational wave signals may result from a violation of rotational symmetry.

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Thank you