Dark Matter, Nuclear Physics, Gravitation . . . and *Murder*:

the r-process as a probe of primordial black hole capture-induced neutron star implosion

Simons Program: Current Themes in High Energy Physics and Cosmology –
Physics and Astrophysics in the Era of Gravitational Wave Detection

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Network for Neutrinos, Nuclear Astrophysics, and Symmetries (N3AS)

Dark Matter – new ideas motivated by many developments

The non-relativistic closure fraction may have many components.

A putative dark sector may have its own rich physics, with little or no connection with standard model physics, other than gravitation.
e.g., M. Buckley, A. DiFranzo, PRL **120**, 051102 (2018); S.D. McDermott, H.-B. Yu, K. Zurek, PRD **85**, 02359 (2012)

Gravitational wave and multi-messenger astrophysics may provide a window into the dark sector

because of their extreme density, **Neutron Stars** can serve as "catch basins" for various dark matter candidates, with sometimes dramatic consequences. Some examples . . .

"Dark Matter-Induced Collapse of Neutron Stars: A Possible Link Between Fast Radio Bursts and the Missing Pulsar Problem",
Jim Fuller & C. D. Ott , MNRAS Lett. **450**, L71 (2015)

"On the r-process enrichment of dwarf spheroidal galaxies",
J. Bramante & T. Linden, Astrophys. J. **826,** 57 (2016)

"Searching for Dark Matter with Neutron Star Mergers and Quiet Kilonovae",
J. Bramante, T. Linden, **Yu-Dai Tsai**, Phys. Rev. D **97,** 055016 (2018)

partners in crime . . .

Alex Kusenko (UCLA; IPMU)
Volodymyr Takhistov (UCLA)
David Radice (Princeton; IAS. --- Penn State)

"Primordial Black Holes and r-Process Nucleosynthesis",
GMF, A. Kusenko, V. Takhistov, *Phys. Rev. Lett.*, **119**, 061101 (2017)

"Positrons and 511 keV radiation as tracers of recent binary neutron star mergers",
GMF, A. Kusenko, D. Radice, V. Takhistov, *Phys. Rev. Lett.*, **122**, 121101 (2019)

"Transmuted gravity wave signals from primordial black holes",
V. Takhistov, *Phys. Lett. B*, **782**, 77 (2018)

Primordial Black Holes -- *a dark matter component?*

Radiation-dominated early universe –

-***any horizon volume is poised on the verge of instability and collapse***

Zeldovich & Novikov 67; Hawking 71; Carr, Hawking 74

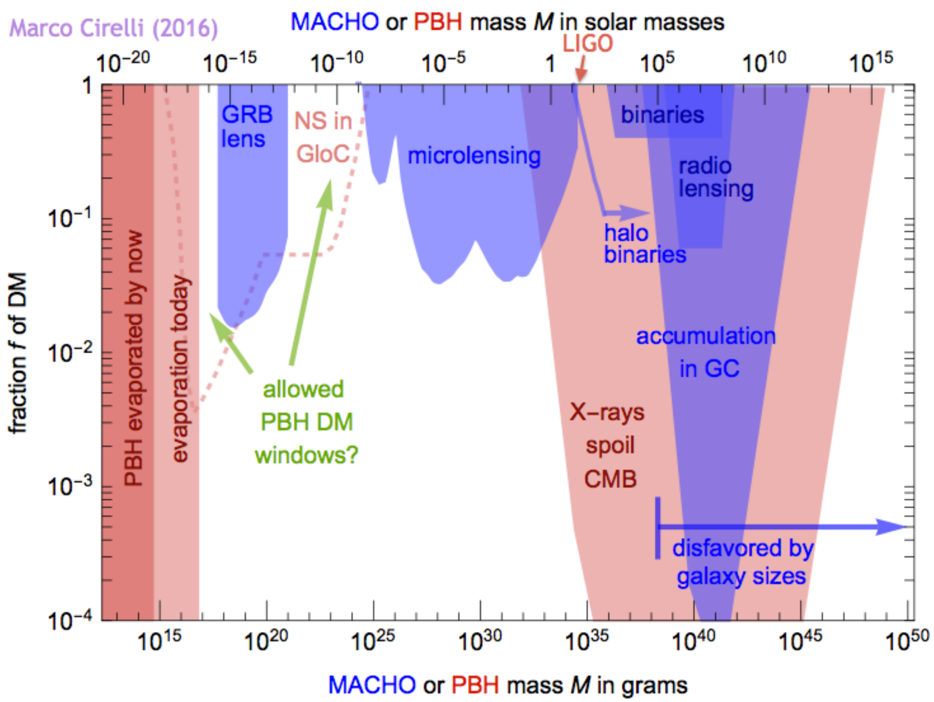
-***fluctuations can evolve to trapped surface formation***

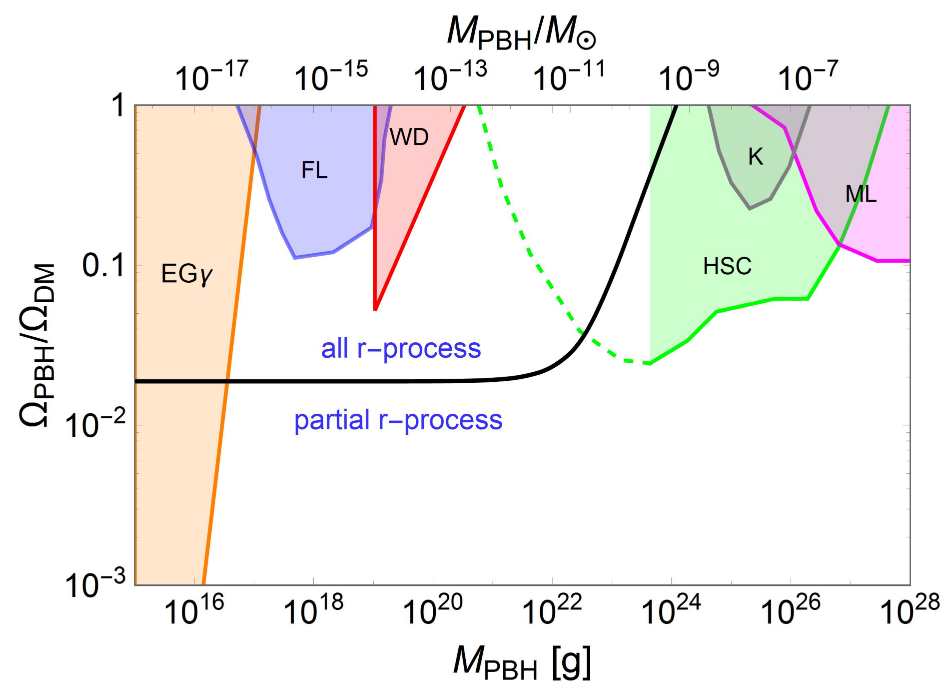
-Inflation (Carr; Garci-Bellido; Linde et al.; Kawasaki et al; . . .) may produce non-scale invariant fluctuations with extra power on some scales – can collapse to holes when they re-enter the horizon

-Vacuum phase transitions

- baryon isocurvature fluctuations (Dolgov; Silk)

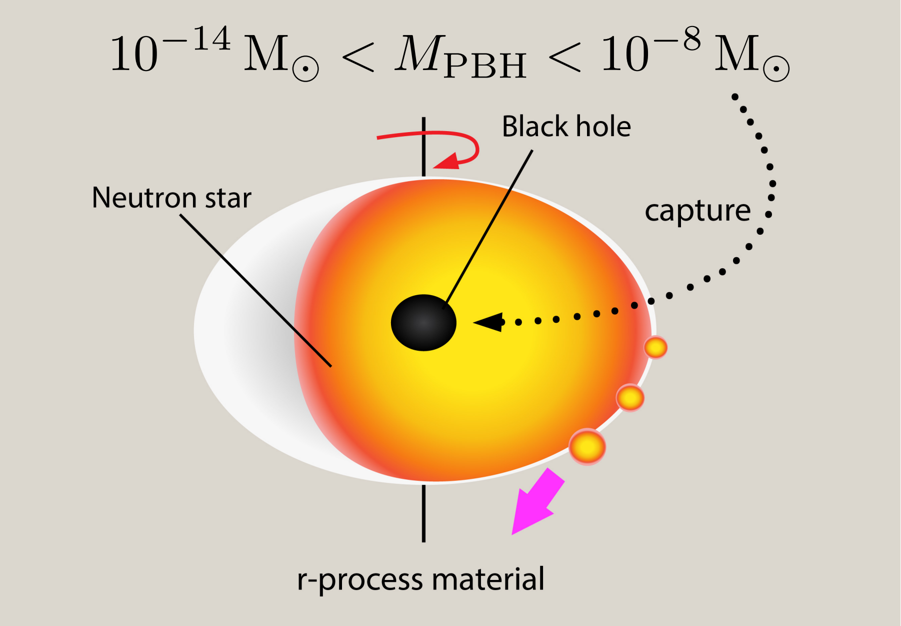
-Scalar field fragmentation, e.g., Cotner & A. Kusenko PRL **119**, 031103 (2017)





Small primordial black holes captured by neutron stars consume them from the inside.

If this happens in a *millisecond period pulsar* (MSP):cold neutron matter could be (centrifugally) ejected, decompress and make a very neutron-rich *r*-process (similar to the "tidal tails" in BNS merger scenarios); orphaned kilonova; FRB; positrons



GMF, A. Kusenko, V. Takhistov, PRL, **119**, 061101 (2017)

Capture Physics: F. Capela, M. Pshirkov, P. Tinyakov PRD **87**, 123524 (2013)

Capture rate per neutron star: $F = (\Omega_{\mathrm{PBH}}/\Omega_{\mathrm{DM}}) \cdot F_0$, where
$F_0 \approx 1.5 \times 10^{-11}\,\mathrm{yr}^{-1}$ for the Milky Way;
$F_0 \approx 6.0 \times 10^{-10}\,\mathrm{yr}^{-1}$ for Ultra Faint Dwarfs (UFDs).

Pulsar lifetimes against PBH capture-induced destruction
$\langle t_{\mathrm{NS}} \rangle = 1/F + t_{\mathrm{loss}} + t_{\mathrm{con}}$
$t_{\mathrm{loss}} \sim 10^4\,\mathrm{yr}\,\left(M_{\mathrm{PBH}}/10^{-11}\,\mathrm{M}_\odot\right)^{-3/2}$ BH settling time
$t_{\mathrm{con}} \sim 1\,\mathrm{day}\,\left(10^{-11}\,\mathrm{M}_\odot/M_{\mathrm{PBH}}\right)$ NS consumption time

MSP with a BH inside
spinning near mass shedding limit:

Bondi accretion onto PBH maintained by *rigid rotation*: viscosity sufficient even without magnetic fields [Kouvaris, Tinyakov];
more so if magnetic field flux tubes are considered

very little heating and ***scant neutrino emission*** will accompany the consumption process (so long as material is *not* quark gluon plasma -- quark nova? -- Keranen et al arXiv:0406448)

PBH-NS implosion produced r-process scenario consistent for MW and UFDs

- Abundance calculation:

Milky Way

$$\frac{\Omega_{\rm PBH}}{\Omega_{DM}} = \frac{M_{\rm tot}^{r,\rm MW}}{(F_0^{\rm MW} \cdot t_G) N_p^{\rm GC} \langle M_{\rm ej} \rangle}$$

UFD

$$\frac{\Omega_{\rm PBH}}{\Omega_{DM}} = \frac{1}{(F_0^{\rm UFD} \cdot t_{\rm UFD}) N_p^{\rm UFD}}$$

- Equal abundance *(i.e. rate for MW r-process abundance consistent with 1 event in UFD)*

$$F_0^{\rm UFD} = \boxed{\left(\frac{t_g N_p^{\rm GC} \langle M_{\rm ej} \rangle}{t_{\rm UFD} N_p^{\rm UFD} M_{\rm tot}^{r,\rm MW}}\right)} F_0^{\rm MW}$$

12

$t_g = 10^{10}{\rm yrs}$

$t_{\rm UFD} = 5 \times 10^8 {\rm yrs}$

$N_p^{\rm GC} = 1.5 \times 10^7$

$N_p^{\rm UFD} = 250$

$\langle M_{\rm ej} \rangle = 0.1 M_\odot$

$M_{\rm tot}^{\rm r,MW} = 10^4 M_\odot$

CONSEQUENCES:

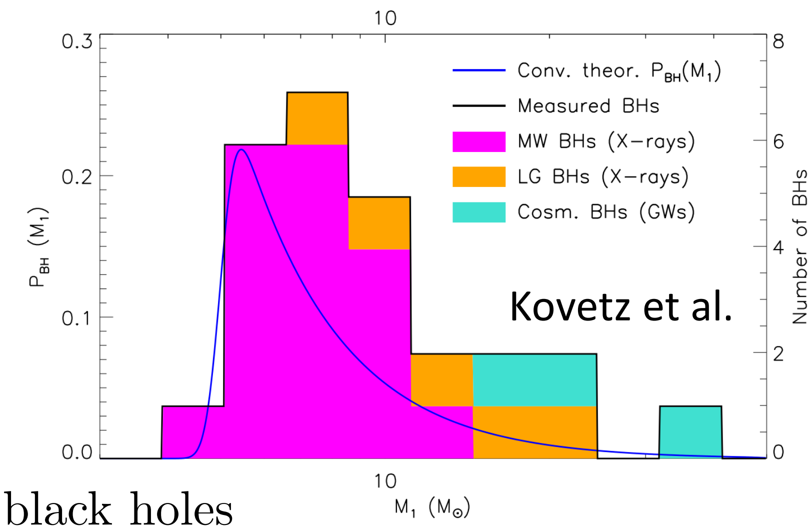
NS destruction will be most significant where the dark matter and MSP densities both high

$$\text{Destruction rate} \propto \rho_{\rm DM} \cdot \rho_{\rm NS}$$

In the age of the Galaxy expect $\mathcal{O}(1-10)\%$ of NS destroyed

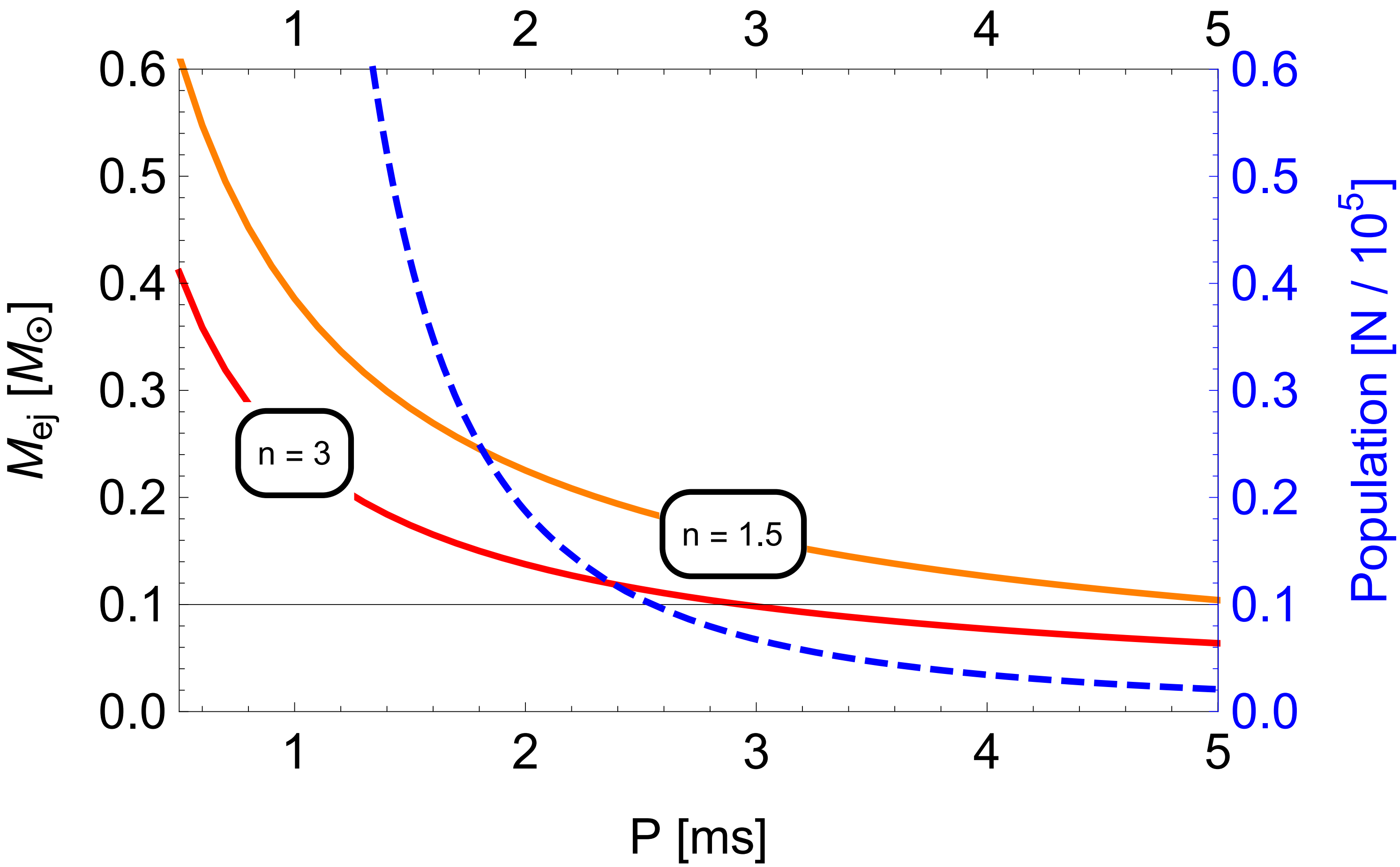
This is consistent with the observed under-abundance of pulsars in the Galactic Center (GC) [Dexter, O'Leary, 14]

Production of low mass black holes unexpected from conventional stellar evolution



PBH-NS implosion + ejected mass = $1\,M_\odot$ to $2\,M_\odot$ black holes

If this happens in a binary system,
Will GW detectors find these holes in a binary in-spiral signal?



Total ejected mass M_{ej} from an MSP with initial rotation period P shown for different density runs, polytropes with indices 3 and 1.5 as labeled.

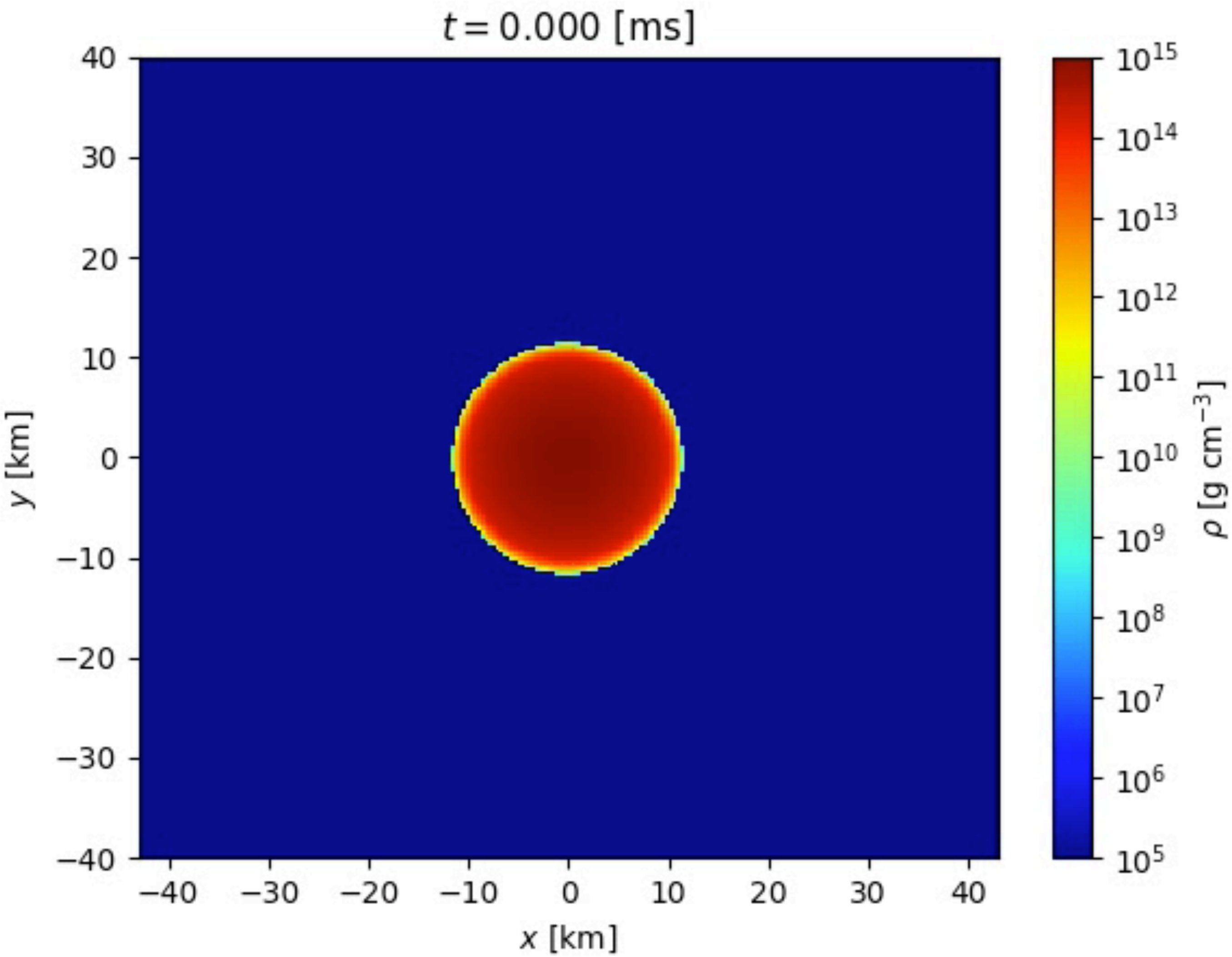
Not clear how much mass is actually ejected . . . need full GR calculation

pulsar population-period relation shown as dashed blue line

J. M. Cordes & D. F. Chernoff Astrophys. J. **482**, 971 (1997)

Full GR simulation.
preliminary result from David Radice (Princeton)

this simulation employed an initial black hole mass $= 0.03\,\mathrm{M}_\odot$



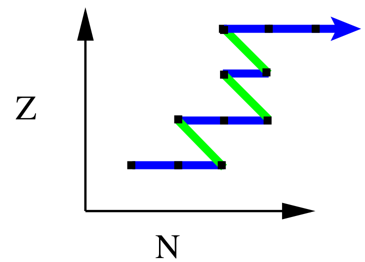
the classic r-Process Burbidge, Burbidge, Fowler, Hoyle 1957
(rapid neutron capture process of nucleosynthesis)

r-process

e. g. Uranium-238 Z=92, N=146 $\rightarrow$ need lots of neutrons

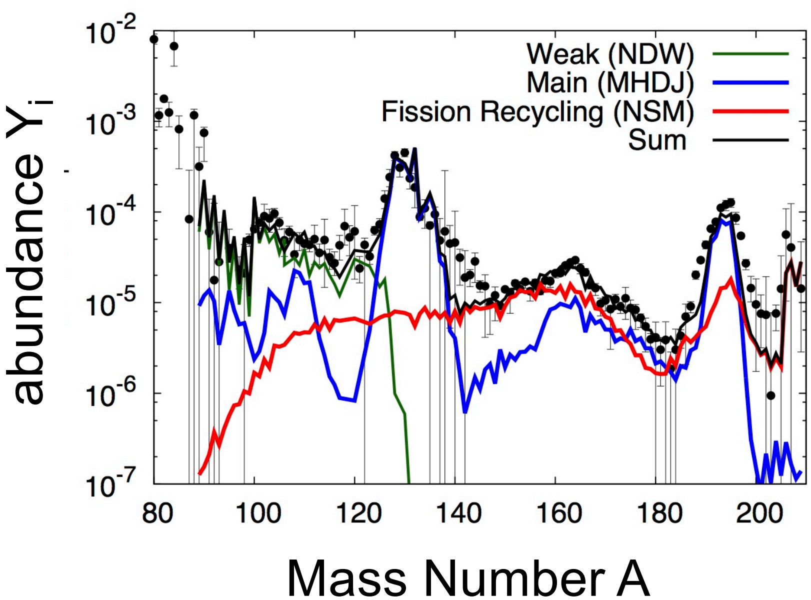
$$A(Z,N) + n \leftrightarrow A+1(Z,N+1) + \gamma$$

$$A(Z,N) \rightarrow A(Z+1,N-1) + e^- + \bar{\nu}_e$$

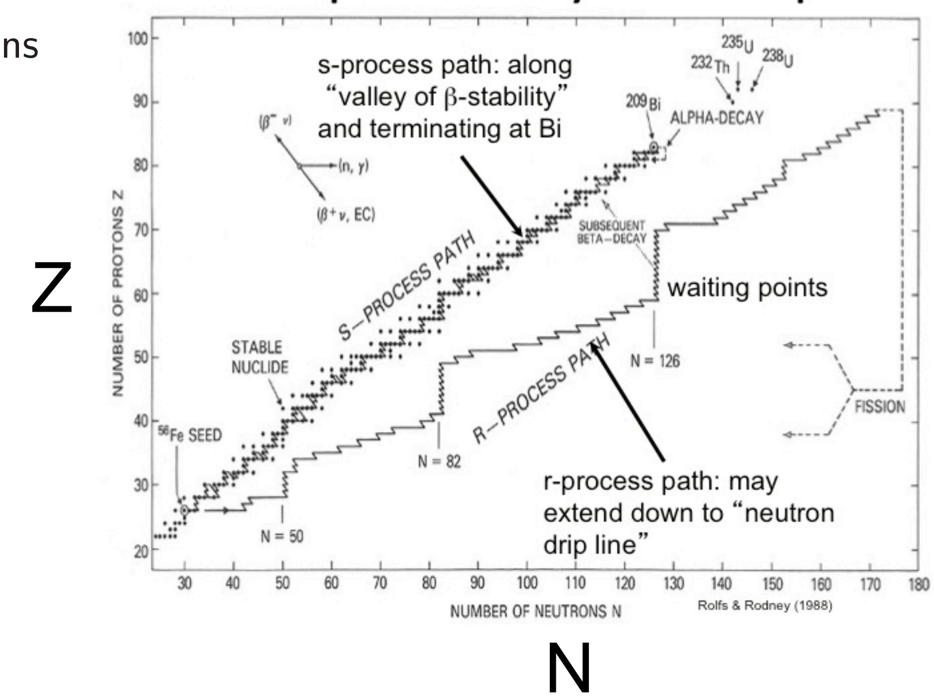


rapid neutron capture as compared with beta decay

in order to get the r-process nuclei, prefer a lot of neutrons



r- and *s*-process synthesis paths



need lots of neutrons !!

require neutron-to-"seed nucleus" ratio > 100

But neutrons are unstable. We can get them three ways:

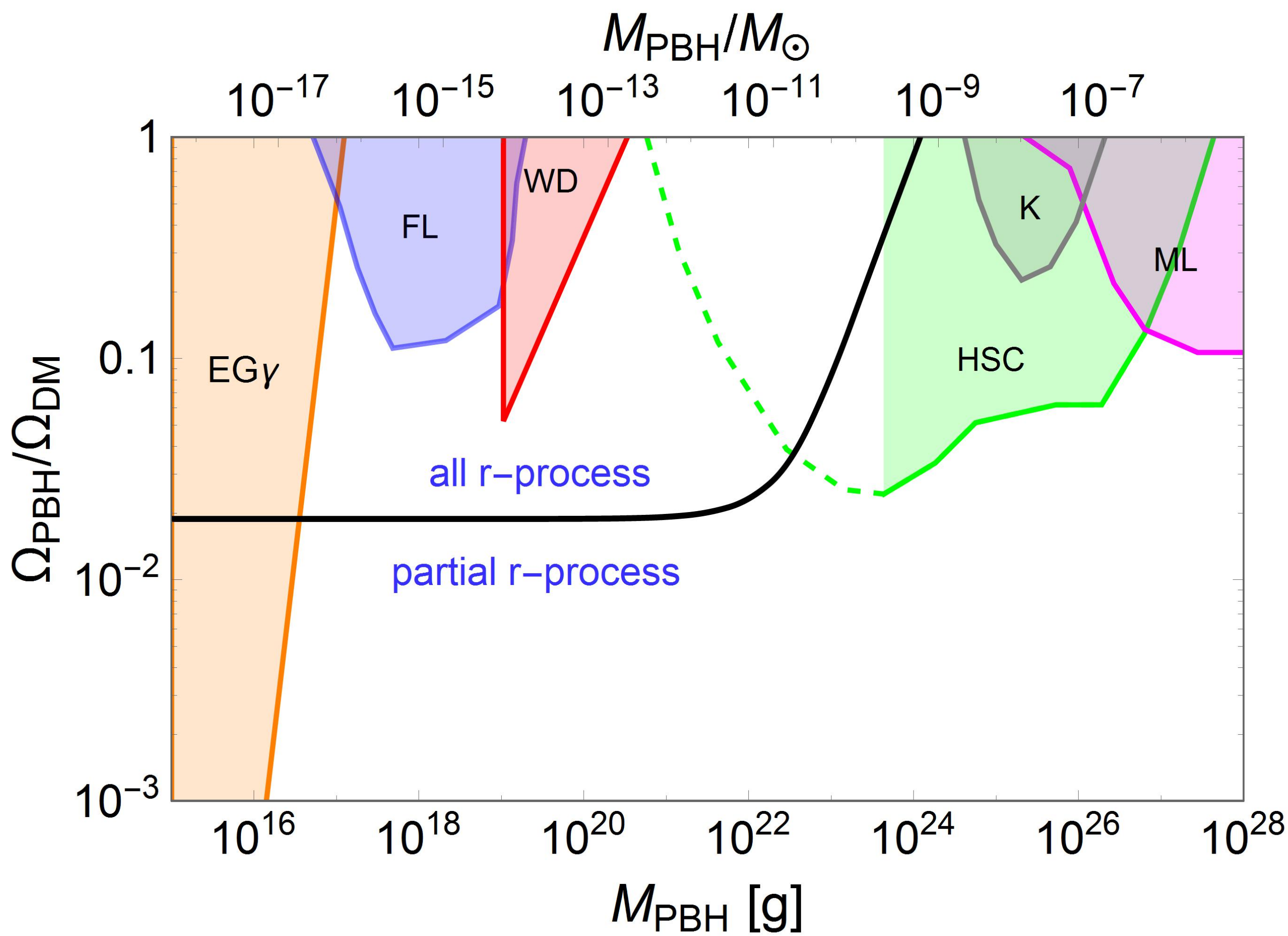
"manufacture" them directly via
$\bar{\nu}_e + p \to n + e^+$ and/or $e^- + p \to n + \nu_e$

"mine" them from nuclei where they are stabilized (by the strong interaction)

"mine" them from neutron stars where they are stabilized by high electron Fermi energy in a deep gravitational potential well

PBH-NS implosion

This model could account for *all* the $10^4\,M_\odot$ of r-Process in the Milky Way if > 2% of the Dark Matter is composed of PBHs in the indicated mass range



GMF, A. Kusenko, V. Takhistov, PRL, **119**, 061101 (2017)

Ultra Faint Dwarf (UFD) galaxies have lots of dark matter,
and they may have a fair number of NS (baryonic feedback?)

However, in a spectroscopic survey of the stars in 11 UFDs only one showed an appreciable r-Process excess, **Reticulum II**
"R-process Enrichment from a Single Event in an Ancient Dwarf Galaxy"
A.P. Ji, A. Frebel, A. Chiti, J. D. Simon, Nature **531**, 610 (2016)

The r-process is a ***rare event***, consistent with BNS mergers

. . . or with PBH-NS implosion

in stellar core collapse and neutron star mergers
most of the gravitational binding energy released
(~ 10% rest mass)
goes into ***neutrinos of all kinds***

Neutrino Poison

$$\nu_e + n \to p + e^-$$

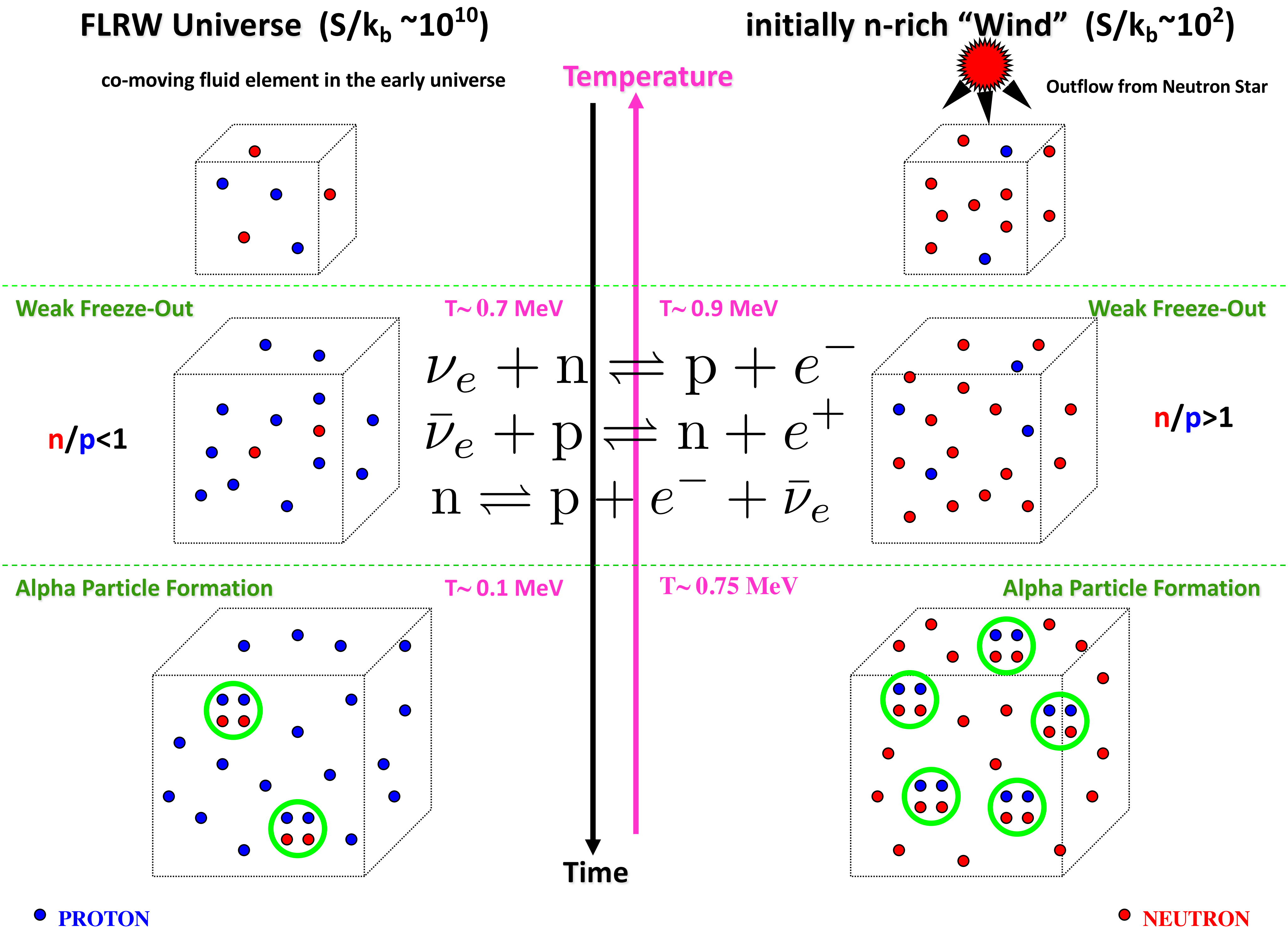
hot nuclear matter radiates nearly equal fluxes of ν_e's and $\bar{\nu}_e$'s

$$\left\{\begin{array}{l} \bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+ \\ \nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^- \end{array}\right.$$

Can drive n/p to ~ 1 BAD!

Neutrino flavor transformation, $\nu_{\mu\tau} \leftrightharpoons \nu_e$, can make this worse because mu and tau neutrinos may be more energetic

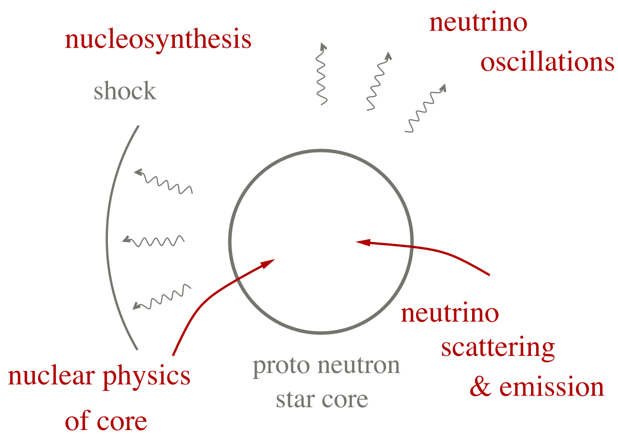
But result is nuclear EOS/neutrino spectrum dependent! (J. Tian, A. Patwardhan, GMF 2017)

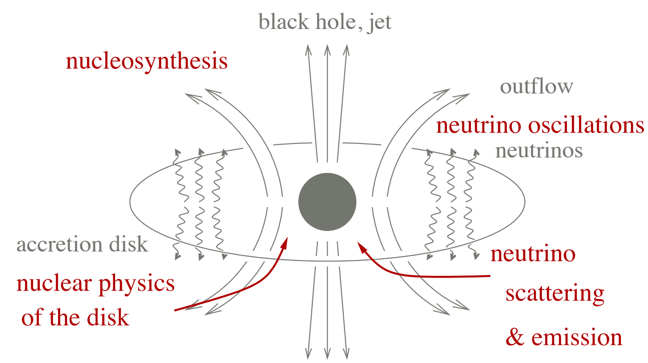


FLRW Universe (S/k_b ~10^10)
initially n-rich "Wind" (S/k_b~10^2)
co-moving fluid element in the early universe
Temperature
Outflow from Neutron Star
Weak Freeze-Out
T~ 0.7 MeV
T~ 0.9 MeV
Weak Freeze-Out
n/p<1
n/p>1
$\nu_e + n \rightleftharpoons p + e^-$
$\bar{\nu}_e + p \rightleftharpoons n + e^+$
$n \rightleftharpoons p + e^- + \bar{\nu}_e$
Alpha Particle Formation
T~ 0.1 MeV
T~ 0.75 MeV
Alpha Particle Formation
Time
PROTON
NEUTRON

Compact Object Neutrino & Nuclear Physics

to understand these environments:
we need the nuclear-neutrino physics





standard core core collapse SN

compact object merger

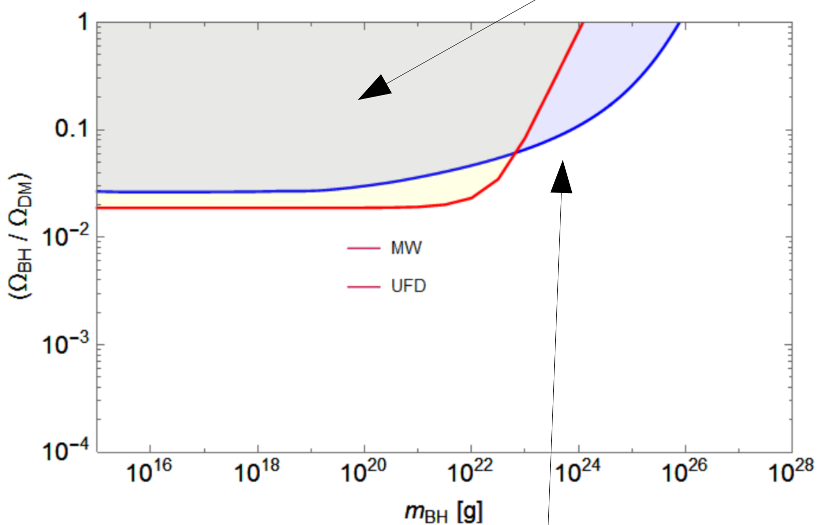
Single Core Collapse to *Hot* Neutron Star

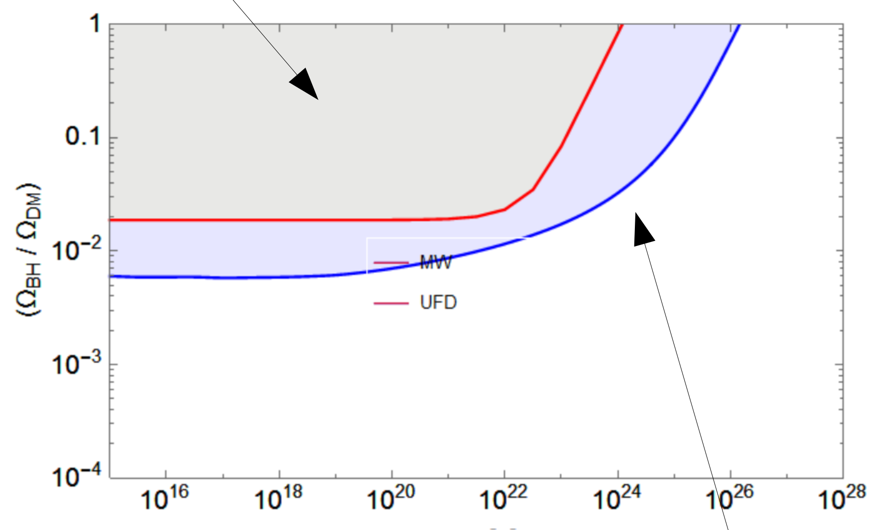
Modest Initial Neutron Excess –
evolving toward . . . ??

Merging *Cold* Neutron Stars

***Very* Neutron-rich initially**
– heating and evolving toward
lower n-richness in ejecta ? ?

UFD





MW, velocity dispersion v = 105 km/s

MW, velocity dispersion v = 50 km/s

- recall, in F_0 capture rate the velocity dispersion dependence can go as v^3

r-Process arithmetic

r-Process mass fraction $= 10^{-7} \Rightarrow 10^4\,\mathrm{M}_\odot$ of r-process in the Galaxy

age of Galaxy is $\sim 10^{10}$ years

core collapse supernova rate: $10^{-2}\,\mathrm{yr}^{-1}\,\mathrm{MWEG}^{-1} \Rightarrow 10^8$ SN

$\Rightarrow$ need $10^{-4}\,\mathrm{M}_\odot$ of r-process per SN

NS-NS merger rate rate: $10^{-3} - 10^{-6}\,\mathrm{yr}^{-1}\,\mathrm{MWEG}^{-1} \Rightarrow 10^7 - 10^4$ mergers

$\Rightarrow$ need $10^{-3}\,\mathrm{M}_\odot$ to $1\,\mathrm{M}_\odot$ (!!) of r-process per merger

For NS-NS merger rate rate: $10^{-5}\,\mathrm{yr}^{-1}\,\mathrm{MWEG}^{-1} \Rightarrow 10^5$ mergers

$\Rightarrow$ need $0.1\,\mathrm{M}_\odot$ (!!) of r-process per merger

The Problem: Deep gravitational potential wells (nucleon gravitational binding energies $\sim 10\%$ of rest mass $\sim 100\,\mathrm{MeV}$); intense neutrino fluxes which can re-set n/p ratio:

$$\left.\begin{aligned} \nu_e + n &\rightleftharpoons p + e^- \\ \bar{\nu}_e + p &\rightleftharpoons n + e^+ \end{aligned}\right\}$$

To preserve neutron excess must move baryons out of the potential well faster than the weak interaction can get a purchase on them!

Binary Neutron Star Mergers

B. Cote et al. "The Origin of the r-Process Elements in the Milky Way" arXiv:1710.05875

GW170817 ***kilonova*** –

if this event is representative of all binary neutron star (BNS) mergers then the bulk of the r-process material in the Galaxy could have been made in these events.

Certainly Lanthanides (A = 130 peak) were produced.

Not as clear for the actinides (e.g., uranium)
average $Y_e \sim 0.27$, not large, not small either : some neutrino exposure?

-***Tidal tails great*** (cold ultra neutron-rich, no appreciable neutrino exposure)

-***Disk***? likely neutrino exposure

-"***Wind***" could have considerable neutrino exposure *unless very rapid outflow*

did GW170817 produce the actinides?

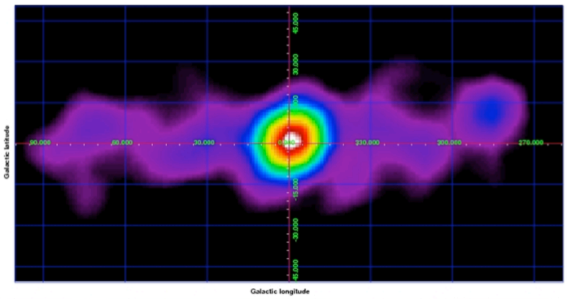
Was at least some of the ejecta neutron-rich enough to give fission cycling? If so, late energy injection from fission could be important in the spectral signature of the kilonova. J. Barnes et al. Astrophys. J. **829** 110 (2016)

signature of actinide production?

A "bump" in the light curve at $\sim$ 100 days from energy injection via spontaneous fission of ^{254}Cf
Y. Zhu et al. arXiv:1806.0972

But see N. Vassh et al. arXiv:1810.08133,
need high fission barriers (uncertain nuclear physics) to get n-capture flow out to ^{254}Cf

positron production in BNS mergers
and possibly
this PBH-NS implosion scenario

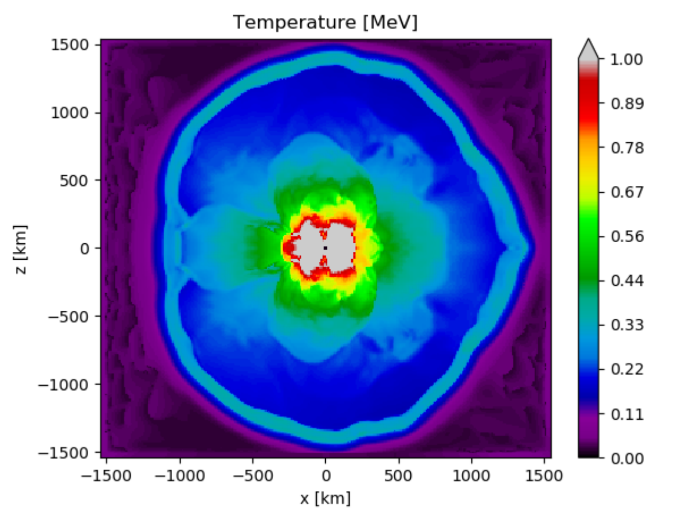


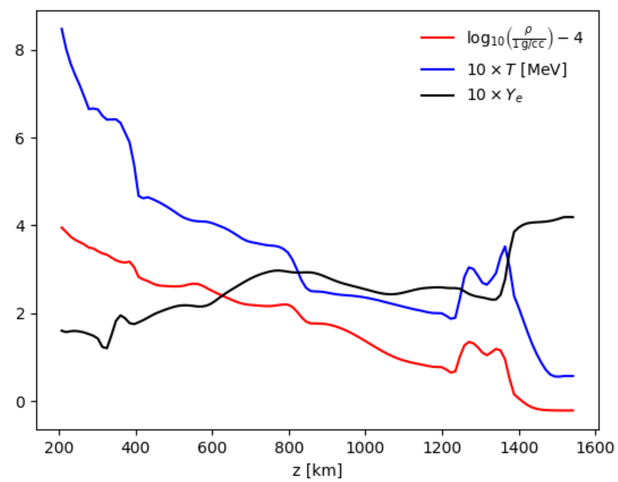
GC 511 keV gammas
ESA/
Bouche et al

Origin of positrons unknown. Need to produce 10^{50} positrons per year. $\Gamma(e^+e^- \to \gamma\gamma) \sim 10^{50}\mathrm{yr}^{-1}$
Positrons must be produced with energies below 3 MeV to annihilate at rest. [Beacom,Yuksel '08]

"Positrons and 511 keV radiation as tracers of recent binary neutron star mergers",
GMF, A. Kusenko, D. Radice, V. Takhistov, arXiv:1811.00133 [astro-ph.HE]

Cold, n-rich material ejected in BNS mergers & PBH-NS events is heated by β-decay and fission to T~0.1 MeV
→ **generates > 10^{50} e^+/yr** for the rates needed to explain r-process nucleosynthesis.





BNS merger simulations
WhiskyTHC code

"**smoking gun" coincidence?** In a survey using INTEGRAL, T. Siegert et al. Astron. Astrophys. **595**, A25 (2016), the *only* dwarf galaxy to show a significant 511 keV flux was **Reticulum II**
Concordance of r-process and gamma-ray observations points to a BNS merger origin of both.

Summary

Toward using GW and multi-messenger astrophysics to probe the Dark Sector

The PBH-NS implosion scenario could consistently account for r-Process nucleosynthesis in the MW and in UFDs (Reticulum II) if PBHs in the mass range $10^{-14}\,\mathrm{M}_\odot < M_{\mathrm{PBH}} < 10^{-8}\,\mathrm{M}_\odot$ comprise more than a few percent of the Dark Matter

signatures of this process:

- kilonova-like display **without** the classic GW in-spiral signal or a weak/unusual GW signal

- An unexpected population of low mass BHs

- Galactic and UFD positrons, FRBs, etc.

Remarkable concordance between **r-Process content** and **511 keV flux** in UFDs (Reticulum II) points to origin of r-Process and positrons in BNS mergers and/or NS implosion events