PARTICLE ACCELERATION & NEUTRINO PRODUCTION IN PNS OUTFLOWS

Outline

- Why study neutrino emission? Plausible astrophysical sources
- Protomagnetars as multi-energy neutrino sources
- Properties of neutrino-driven PNS winds
- Impact of stellar progenitor on EM observables
- Detectability of TeV neutrinos from magnetized PNS outflows
- Summary, model limitations & scope of future work

Mukul Bhattacharya
SCEECS Postdoc @ UW-Madison

Collaborators:

Jose Carpio (U. Nevada, Las Vegas)
Kohta Murase (Penn State)
Nick Ekanger (Virginia Tech, Tohoku)
Shunsaku Horiuchi (Virginia Tech)

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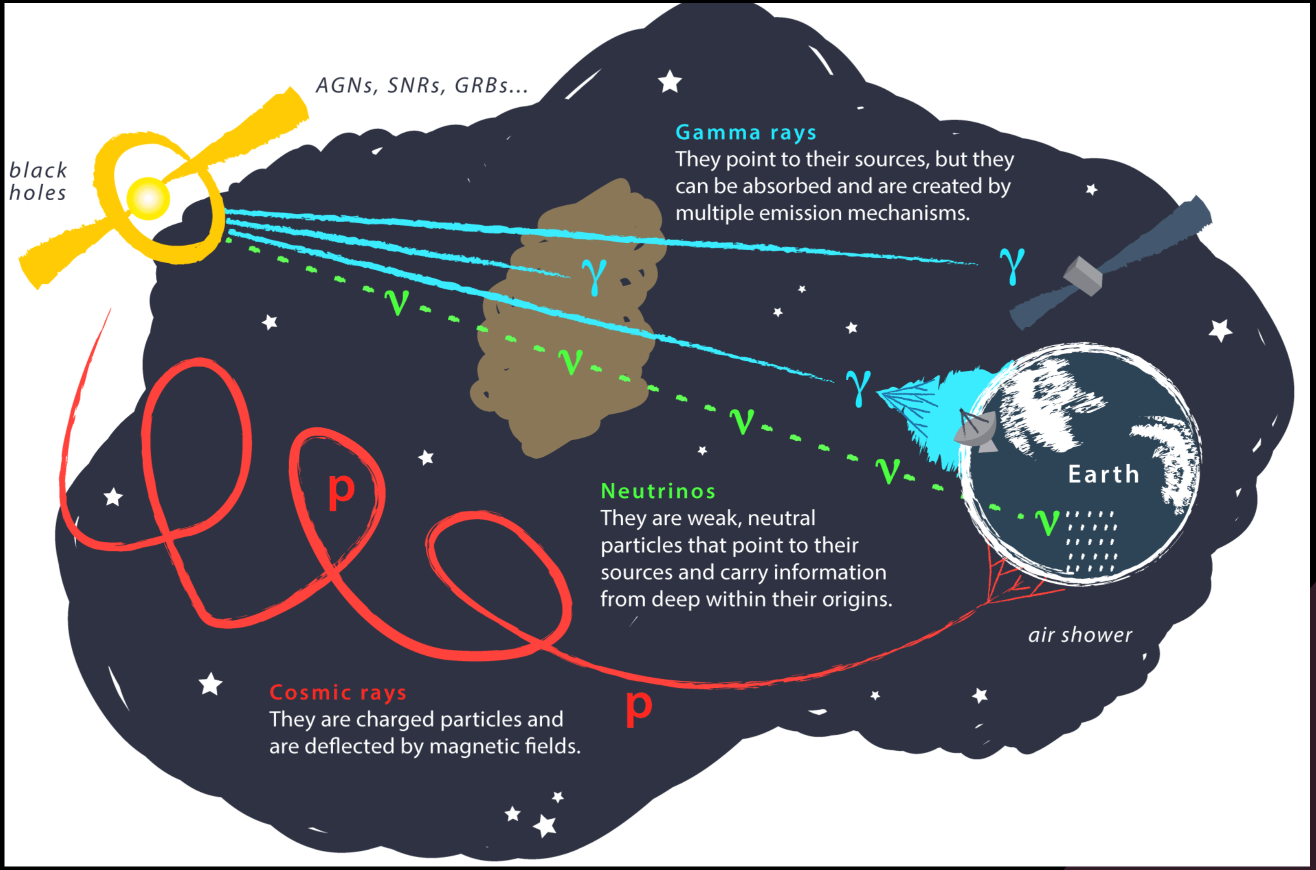
Why study neutrino emission?

Advantages:

- No charge → not deflected by magnetic fields → point back to the source
- Undergo weak interaction → escape the source unimpeded; not absorbed by dust, CMB, EBL

Challenges:

- Require huge detectors, have low statistics
- Large atmospheric background



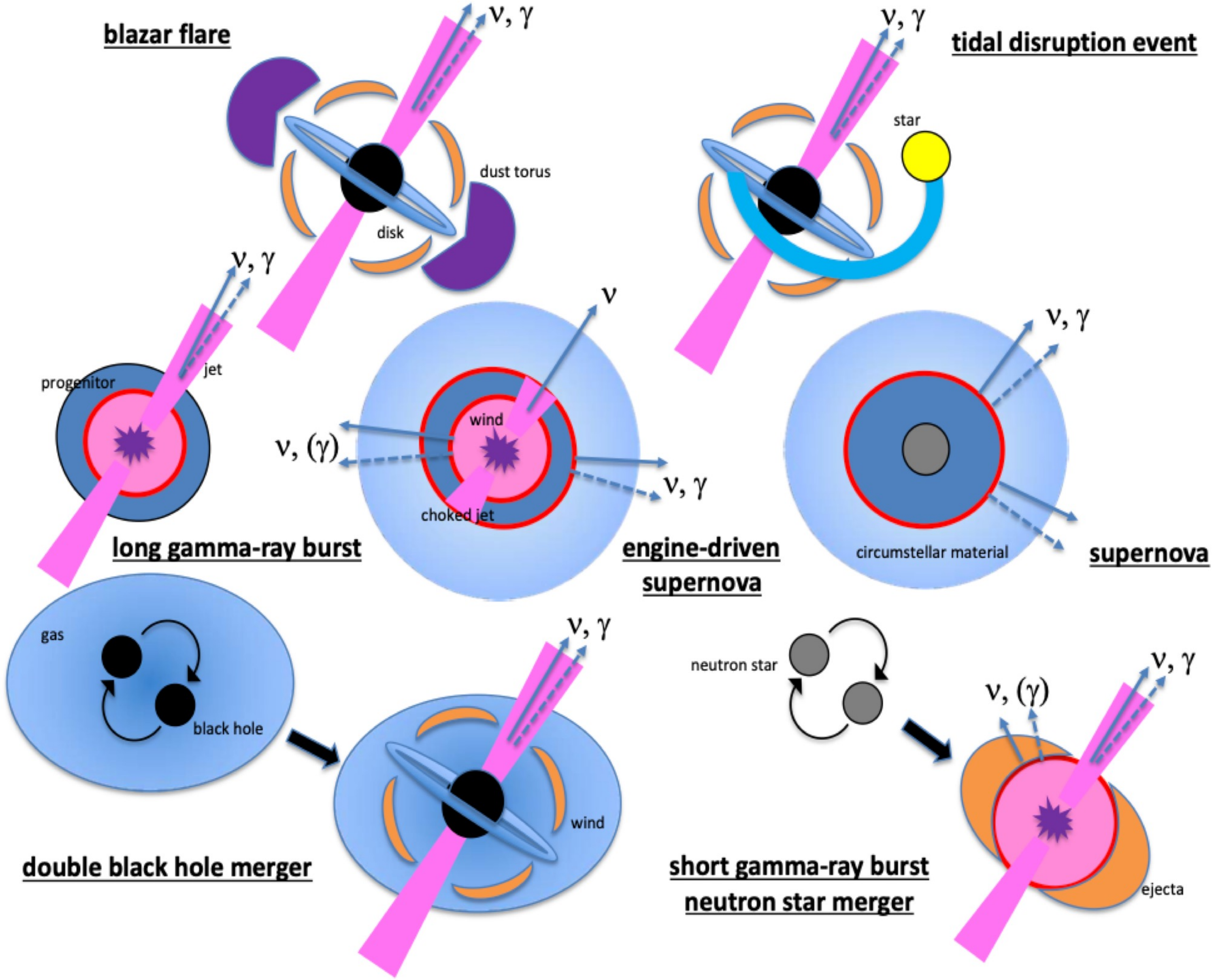
Gamma rays They point to their sources, but they can be absorbed and are created by multiple emission mechanisms.

Neutrinos They are weak, neutral particles that point to their sources and carry information from deep within their origins.

Cosmic rays They are charged particles and are deflected by magnetic fields.

Credits: Juan Antonio Aguilar & Jamie Yang. IceCube/WIPAC

Astrophysical sources

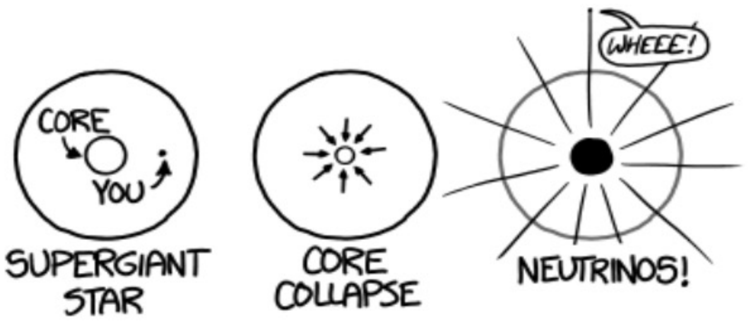


Bartos & Murase (2019)

Neutrino transient candidates can also be:

- Cosmic ray accelerators (*see talks by Abhishek, Jose, Shiqi, Luca, …*)
- Gamma-ray emitters (*see talks by Regina, Ke, Eduardo, Silvia, …*)
- Accompanied by GWs (*see talks by Justin, Maya, Mainak, …*)

PNS as multi-energy neutrino sources



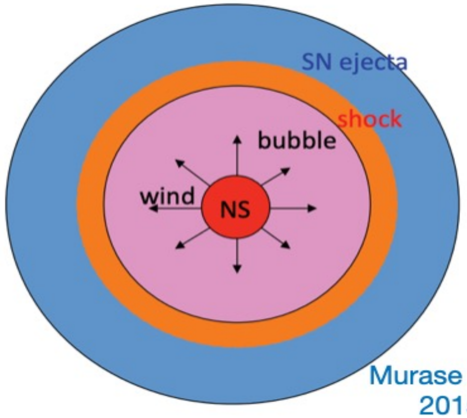
Credit: https://neutrino.physics.iastate.edu/project/dune

Supernova neutrinos

Lasts ~ 10 seconds

~ 1 MeV to ~ 50 MeV

Thermal



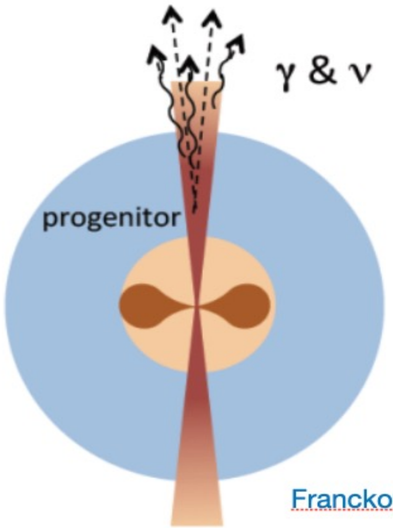
Murase et al. 2015

Produced in neutron-rich winds

Created from neutron-proton interactions

~ 0.1 GeV to ~ 10 GeV

Quasi-thermal



Franckowiak 2017

From SNe hosting relativistic jets

Result from $p\gamma$ interactions

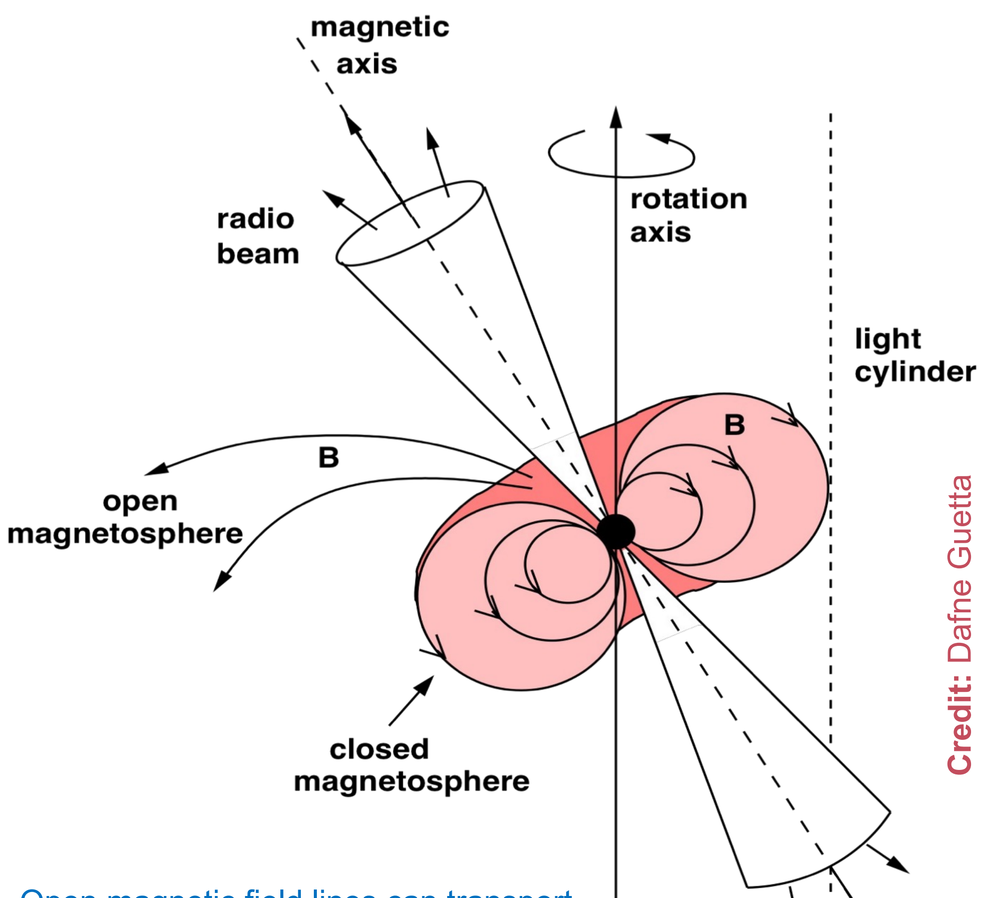
Non-thermal

MeV νs — GeV νs — TeV - PeV νs — E_ν

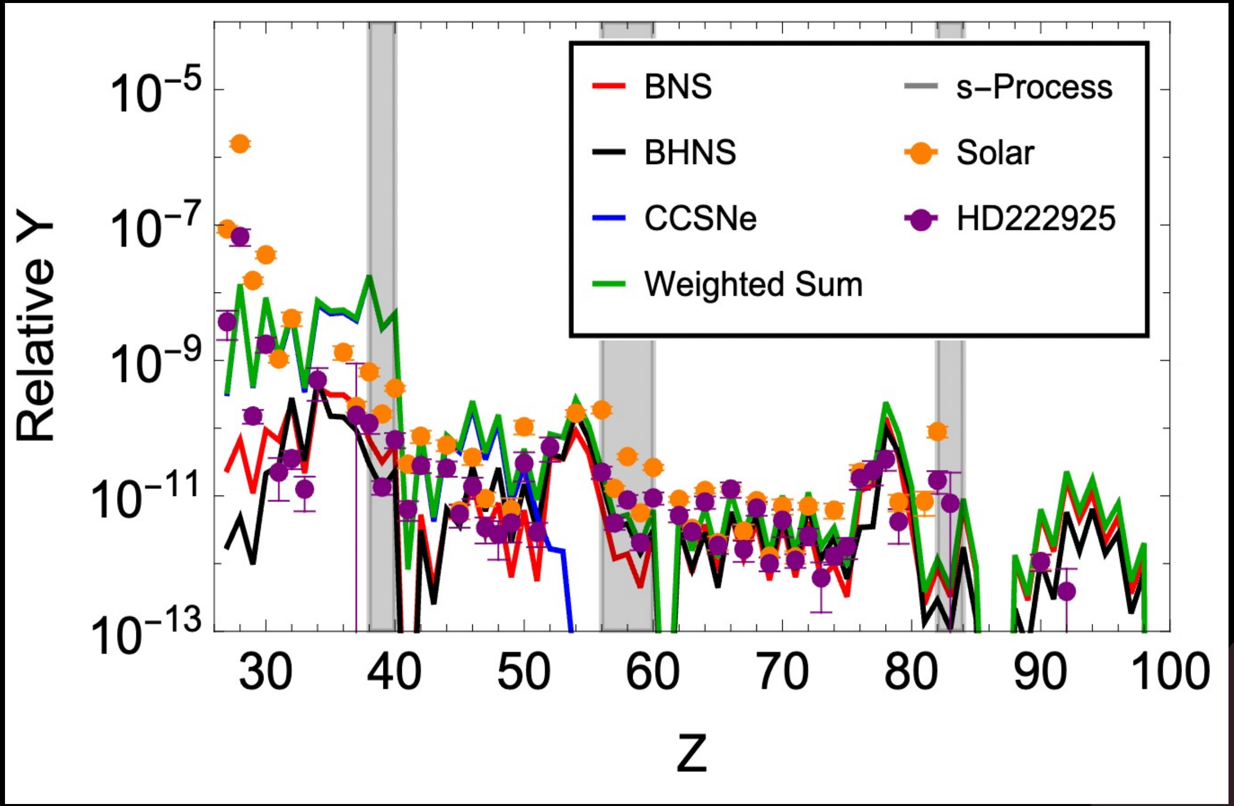
Credit: Jose Carpio

Will focus on protomagnetars as the sources of high-energy (TeV-PeV) neutrinos

Nuclei in neutrino-driven PNS winds

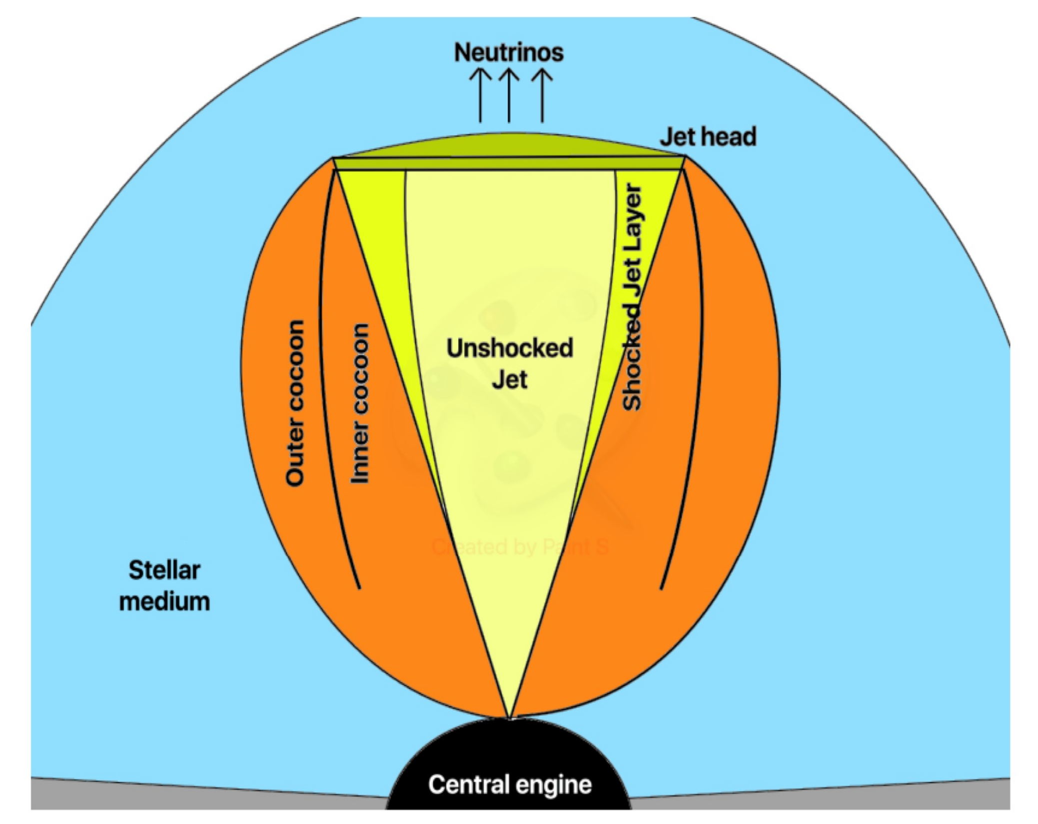


Open magnetic field lines can transport and accelerate nuclei outwards, these can eventually escape as CRs

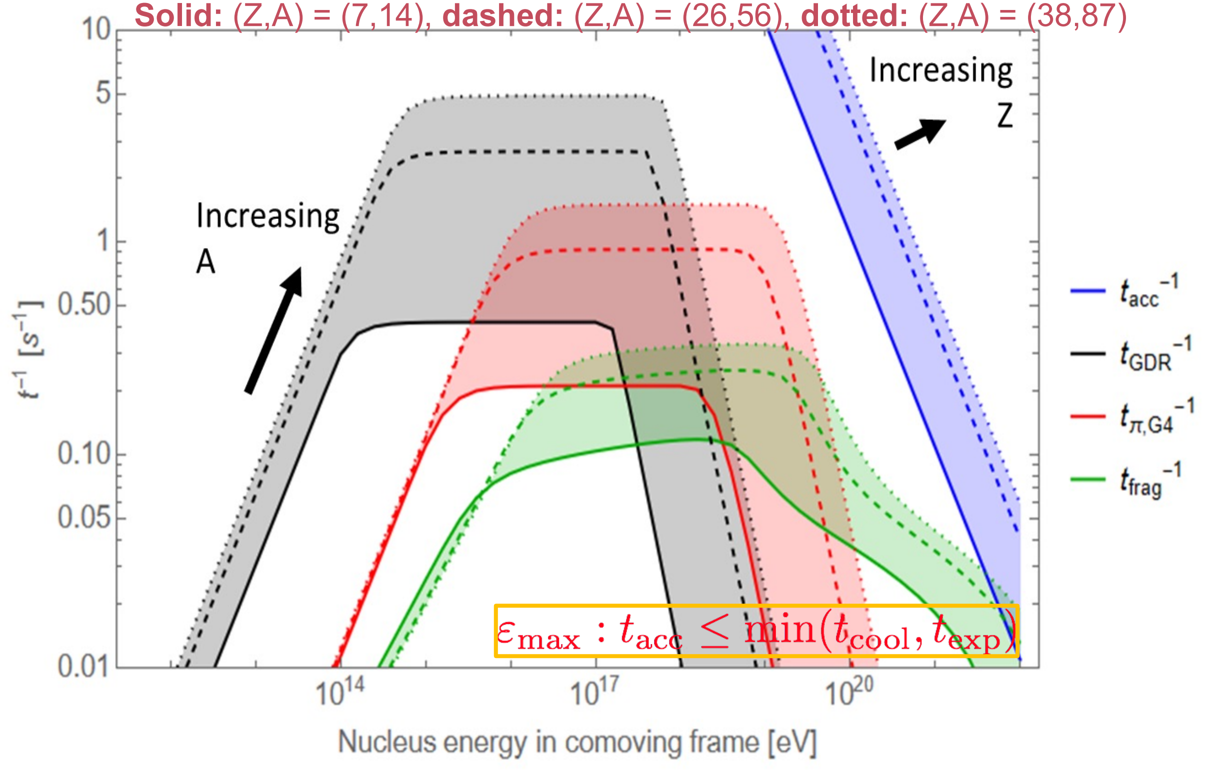


Magnetized CCSNe outflows can generate Fe-like nuclei but not heavier nuclei (likely to come from BNS/BHNS mergers)

Nuclei acceleration & survival



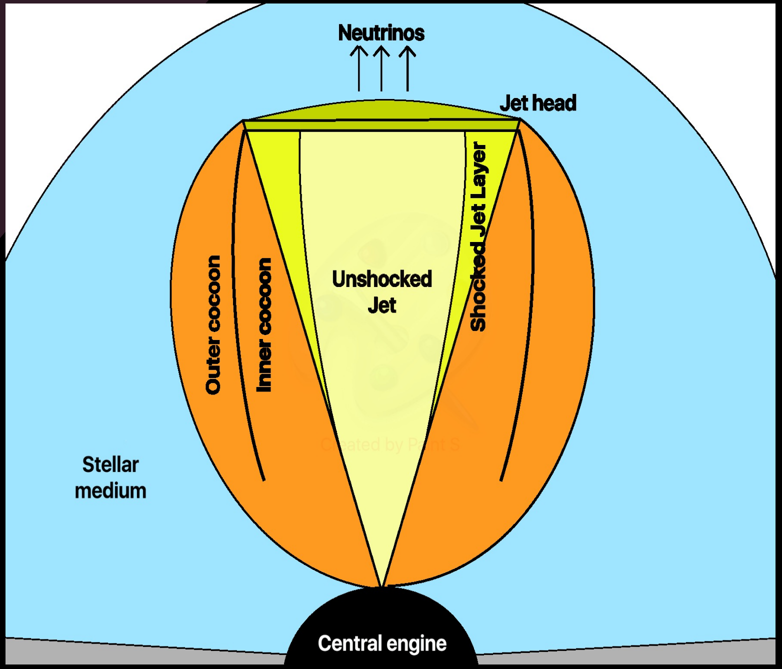
Particles in jet are accelerated via magnetic reconnection



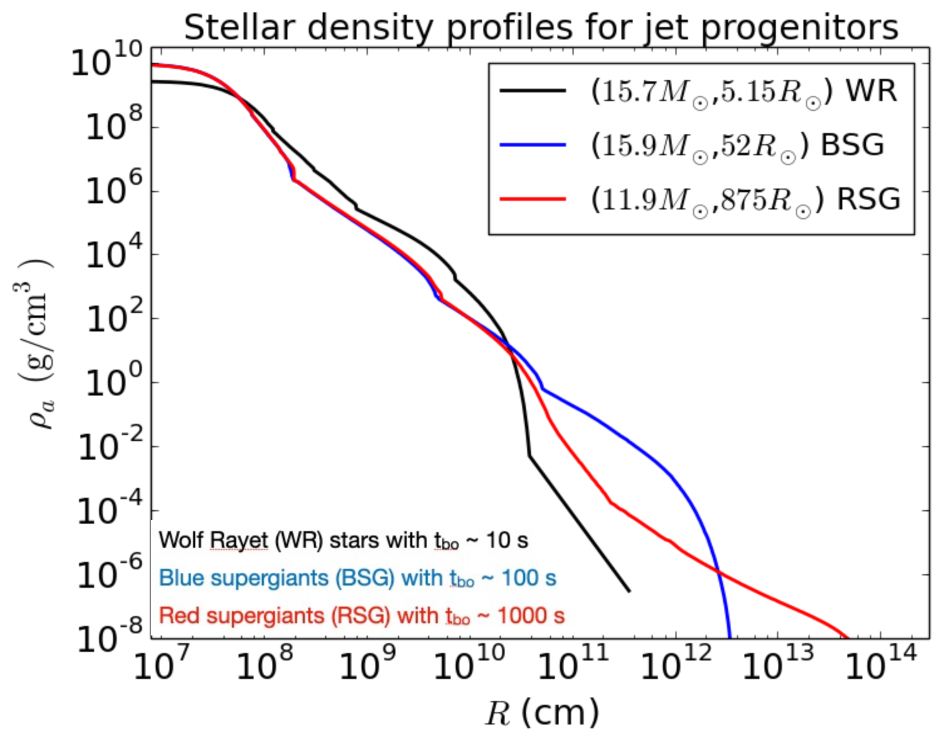
Intermediate phase (σ_0 ~ 10^2-10^3, t ~ 20-50 sec): nuclei synthesized in PNS outflow are capable of reaching $\varepsilon_{max} > 10^{20}$ eV and are not photodisintegrated by the high-energy GRB photons ($\tau_{A\gamma} < 1$)

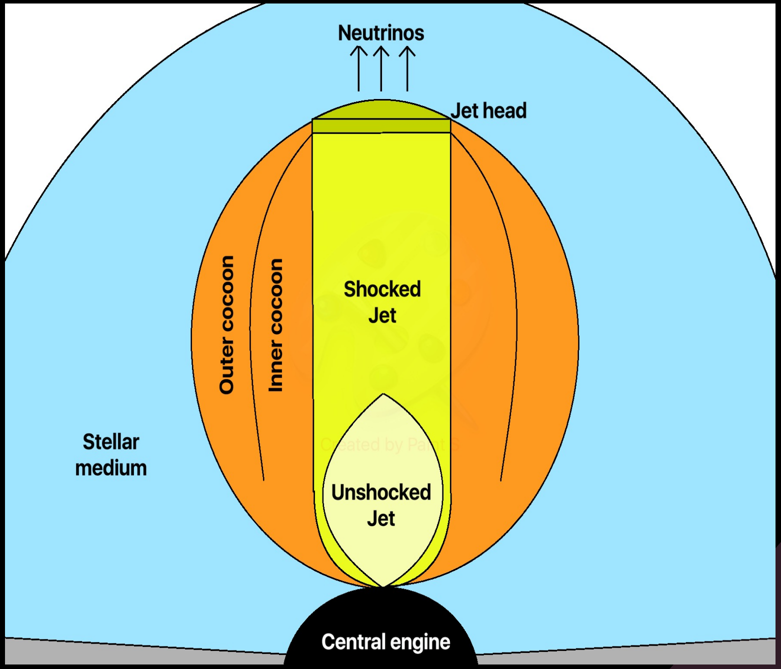
MB, Horiuchi & Murase 2022

Effect of stellar progenitor on observables



Uncollimated jet



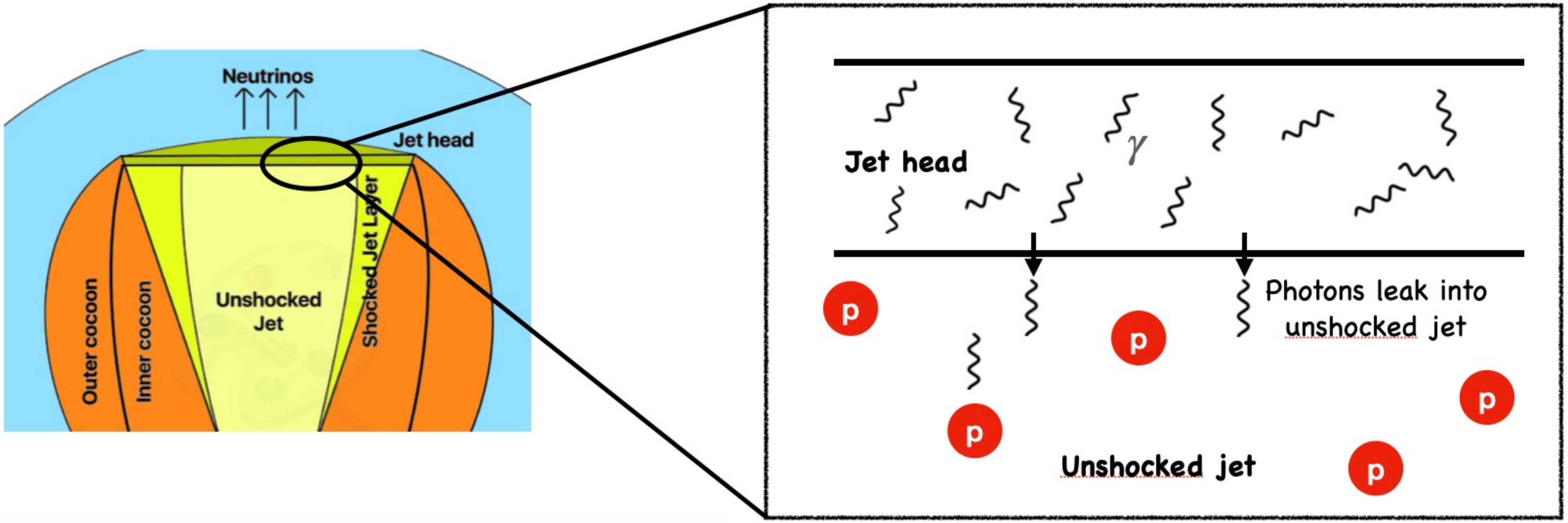


Collimated jet

- Nature of the stellar progenitor decides the outcome for jet breakout and collimation, and therefore
- also the observability of EM and neutrino signals

- More energy is deposited into the cocoon for BSG and RSG jet compared to WR progenitors, due to longer t_{bo}
- $E_{j,iso}/E_{ej} \propto 10^{-4}$: outflows from protomagnetars with $B_{dip} < 10^{15}$ G can get choked inside WR stars

CR acceleration and neutrino production



Protons

Accelerated close to the jet head

Highly magnetized jets lead to hard spectra E_p^{-s} with $1 \leq s \leq 2$ (e.g., Guo et al. 2016)

Photons

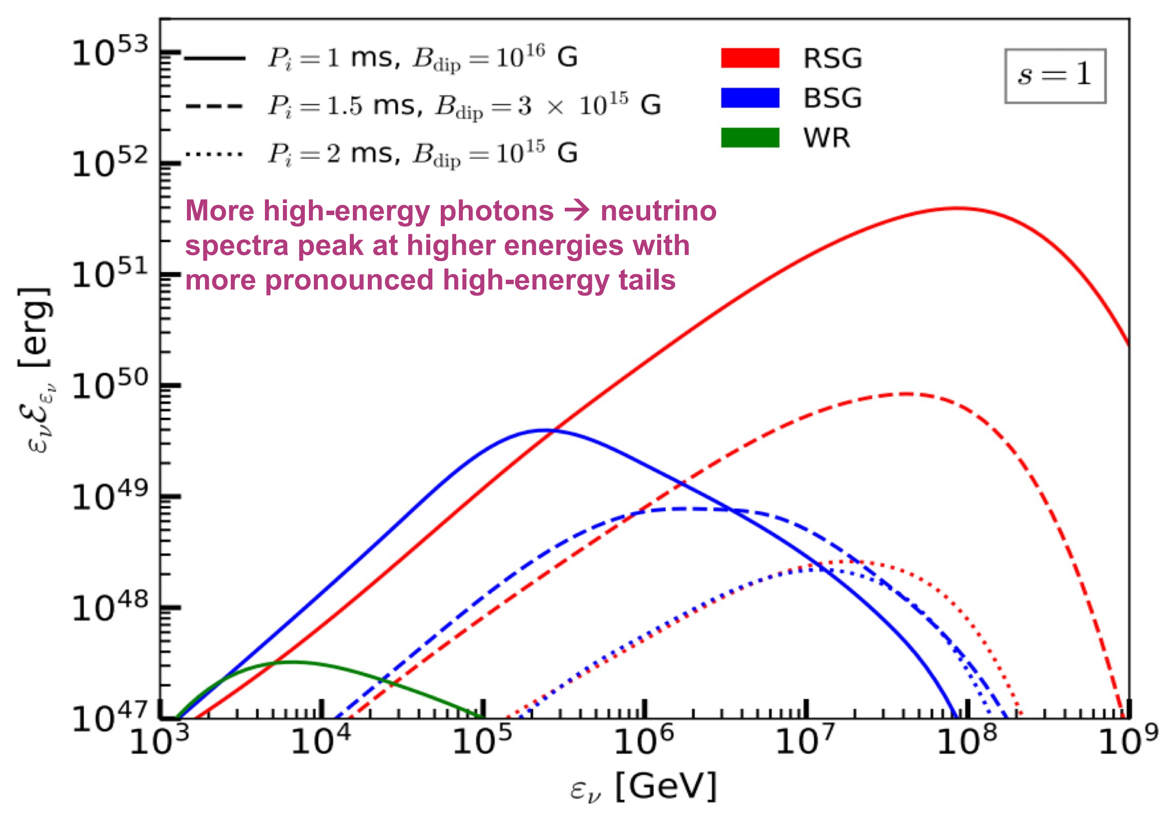
Optically thick jet head ⟶ thermal photons (small leakage fraction)

Optically thin ⟶ non-thermal (broken PL) photons

Credit: Jose Carpio

Detectability of neutrinos

High jet luminosities in RSGs and BSGs present most promising detection scenario



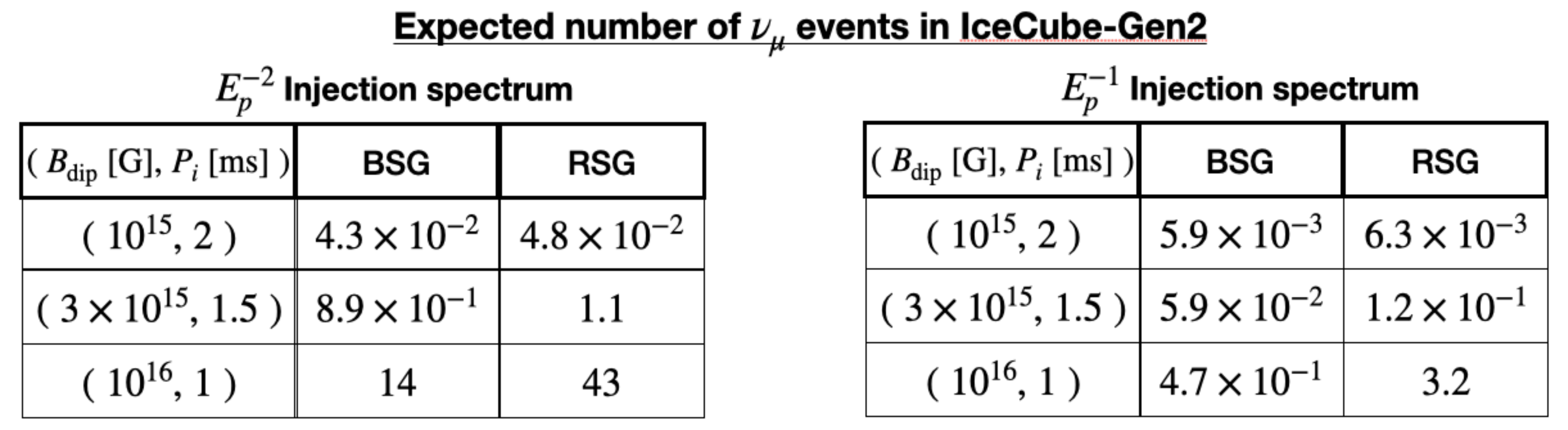
More high-energy photons → neutrino spectra peak at higher energies with more pronounced high-energy tails

- **WR**: neutrinos with $E_\nu > 1$ TeV scarce due to strong IC cooling/attenuation at breakout/earlier times. Fluence too small for detectable signal.
- **Supergiants**: neutrino spectra can reach ~0.1 PeV/~10 PeV for BSG/RSG. Larger R_* → less attenuation at late times.
  - Neutrinos detectable for optimistic BSG scenarios, RSG most promising.

MB, Carpio, Murase & Horiuchi 2023

Detectable events with IceCube-Gen2

High luminosities and large LF for magnetised jets propagating in BSGs and RSGs present most promising scenario for detection with ~few - 10 events above 1 TeV



Expected number of ν_μ events in IceCube-Gen2

E_p^{-2} Injection spectrum

($B_{\rm dip}$ [G], P_i [ms])	BSG	RSG
(10^{15}, 2)	4.3×10^{-2}	4.8×10^{-2}
(3×10^{15}, 1.5)	8.9×10^{-1}	1.1
(10^{16}, 1)	14	43

E_p^{-1} Injection spectrum

($B_{\rm dip}$ [G], P_i [ms])	BSG	RSG
(10^{15}, 2)	5.9×10^{-3}	6.3×10^{-3}
(3×10^{15}, 1.5)	5.9×10^{-2}	1.2×10^{-1}
(10^{16}, 1)	4.7×10^{-1}	3.2

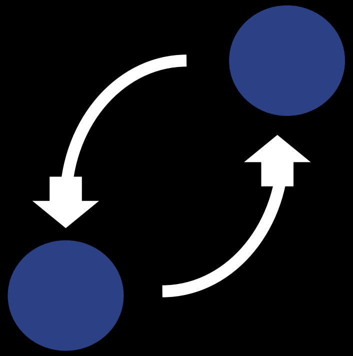
- **BSG**: neutrinos detectable only for most energetic PNS outflows
- **RSG**: most optimistic scenario with ~few-10s neutrino events detectable above 1 TeV

Summary

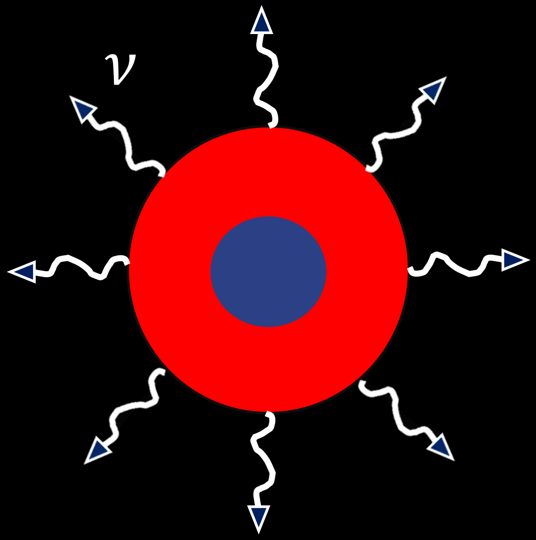
1. Nuclei in magnetized PNS outflows ($B_{dip} \sim 10^{14} - 10^{16}$ G, P ~ 1 - 10 ms) can interact with jet photons to generate TeV-PeV neutrinos.
2. Conditions during intermediate phase ($\sigma_0 \sim 10^{2-3}$, t ~ 20-50 sec) ideal for *survival of nuclei, acceleration to UHECR energies* and production of gamma-ray emission.
3. E_ν > 1TeV neutrinos produced by pγ interactions in magnetised jets: *~few-10s events can be detected with IceCube-Gen2 for BSG/RSG sources* at D ~ 100 Mpc, WR not as promising.

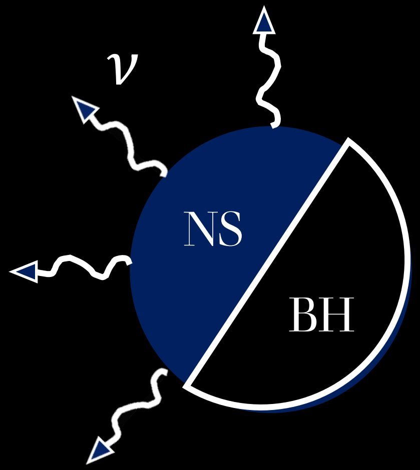
Future work

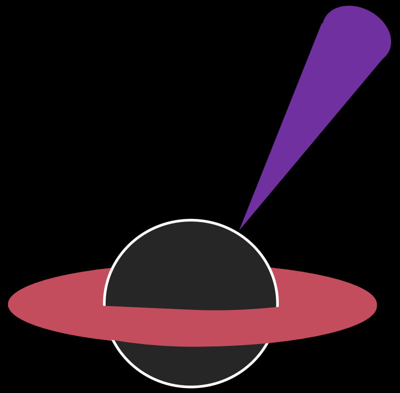
- GRMHD simulations to model: particle acceleration, jet structural stability, baryon loading/mixing, time evolution of ejecta properties *(also see Eduardo's talk later in this session)*.
- Impact of neutrinos oscillations on high-energy spectra and detectability from distant sources.
- GW-triggered multi-messenger search strategies for high-energy neutrinos as well as EM emission *(also see Mainak's talk later in this session)*.
- Role of neutrinos from PNS outflows as probes to understand GRB-SNe connection.

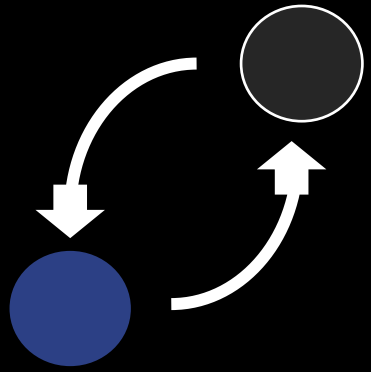


Thank you!







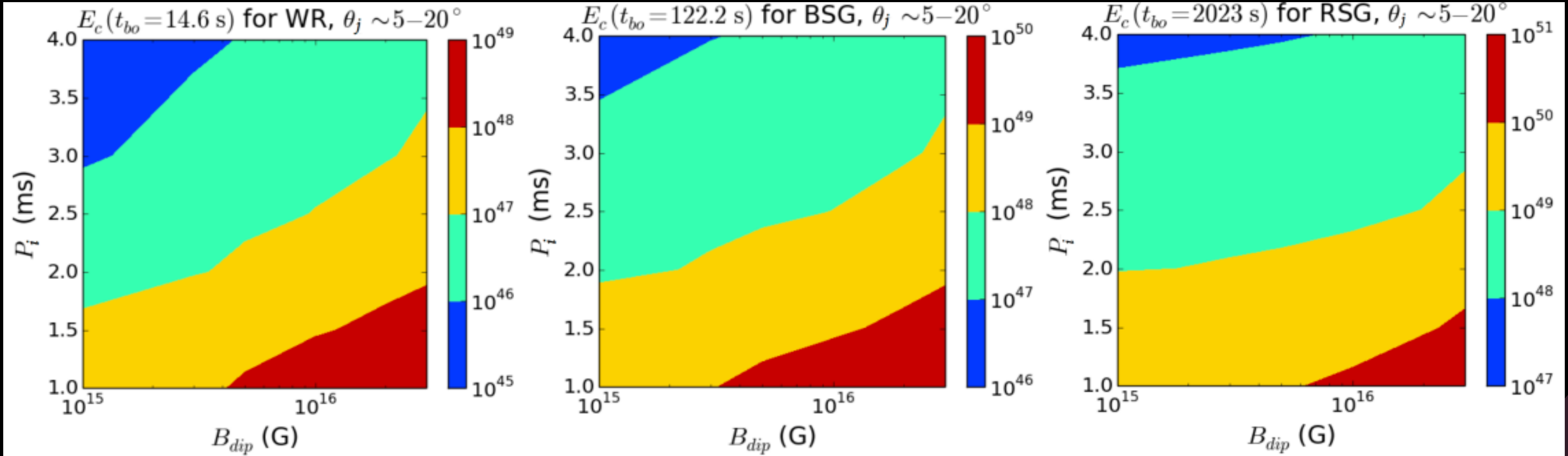


BACKUP SLIDES

Jet-cocoon interaction & breakout

- Jet cocoon interaction determines energy deposited onto cocoon and jet breakout criterion.

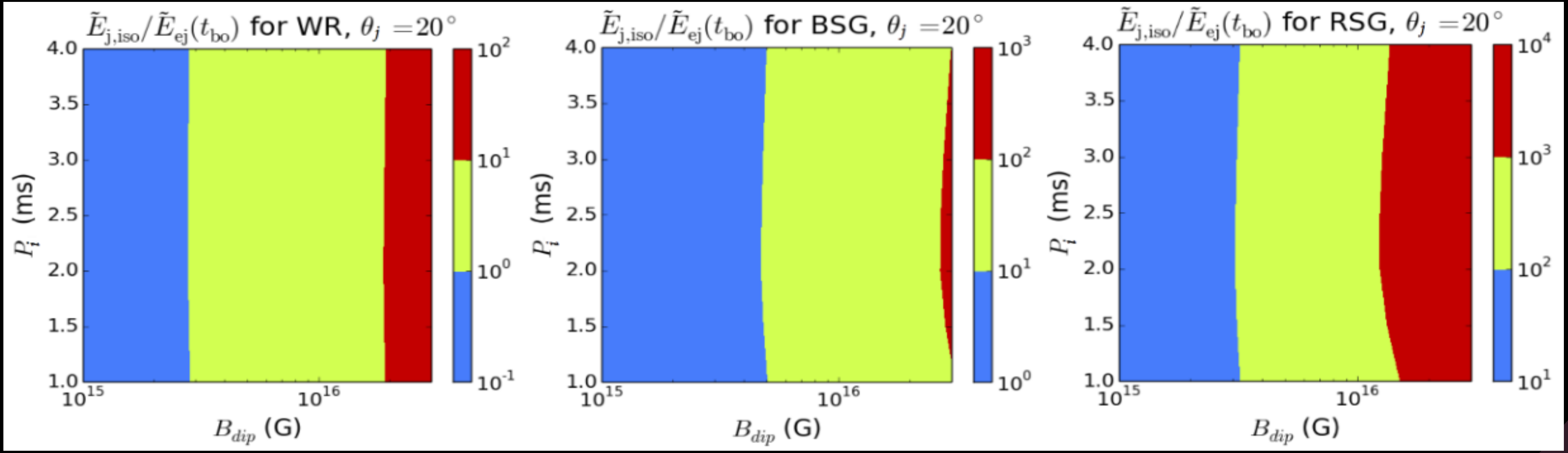
$$P_c = \frac{E_c}{3V_c} = \frac{\eta}{3}\frac{\int L_j(1-\beta_h)dt}{\pi r_c^2 z_h}, \quad \beta_c = \sqrt{\frac{P_c}{\bar{\rho}_a c^2}}$$



More energy is deposited into the cocoon for BSG and RSG compared to WR, due to longer t_{bo}

Jet choking criteria

- Central engine has to be active for at least $t_{eng} > t_{th} = t_{bo} - R_*/c$. The jet can get choked if: (a) engine stops at $t < t_{th}$ before jet exits star, OR (b) jet power is less than minimum requirement
- Gottlieb & Nakar (2021) derived jet breakout criterion: $\int_0^{t_{\rm bo}} \dot{E}_{\rm j,iso} dt \gtrsim \tilde{E}_{\rm ej} \approx 40 E_c(t_{\rm bo})\theta_j^2$



- $E_{j,iso}/E_{ej} \propto \theta_j^{-4}$, outflows from protomagnetars with $B_{dip} < 3\times10^{15}$ G can get choked inside WR stars

Heavy nuclei:
r-process

- ***Rapid*** neutron capture process
- Seed nuclei quickly capture neutrons before decays occur

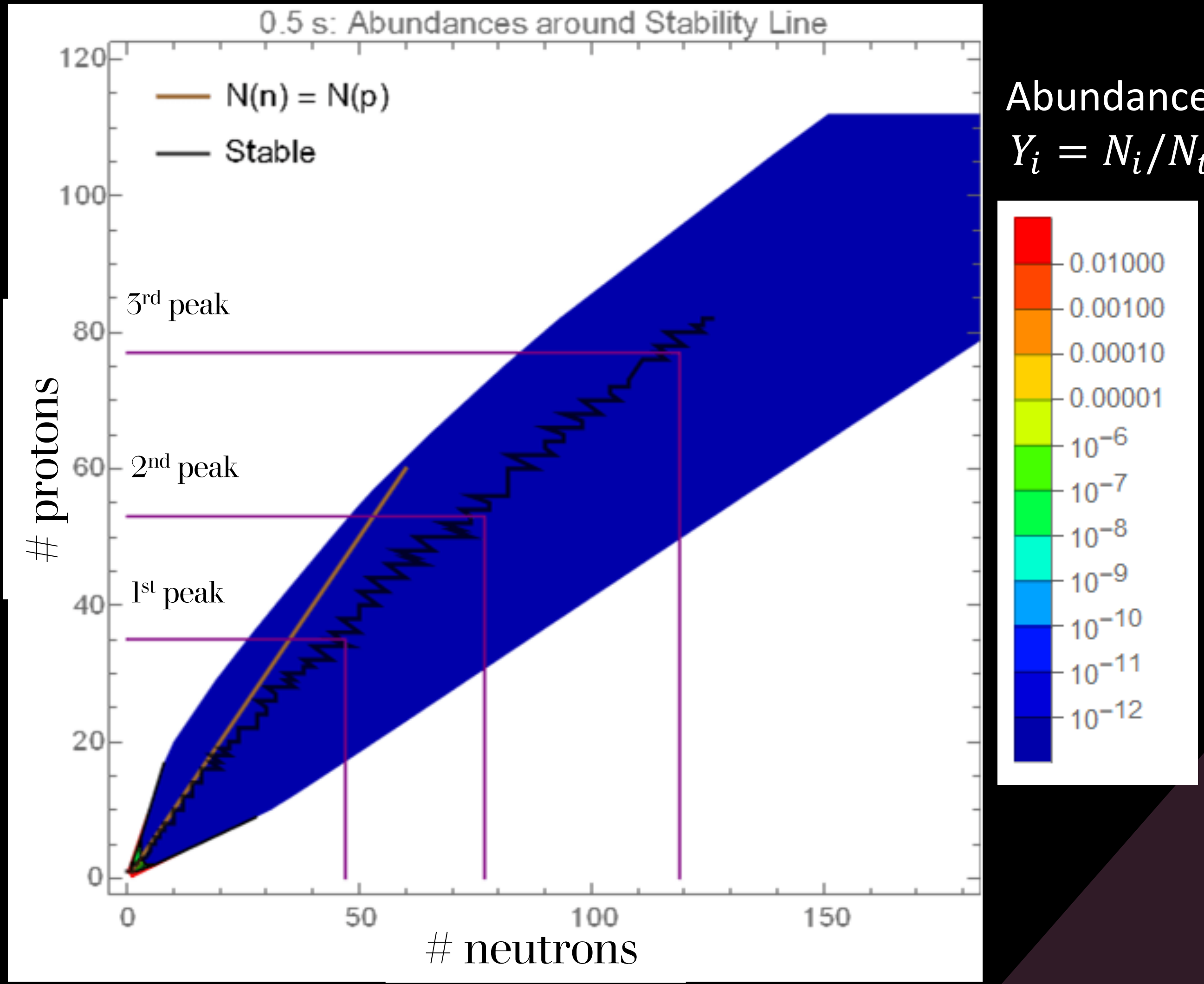
  ~100 n-captures per second (r-process)

  vs ~few per 10-100 years (s-process)

$$\boxed{Y_e = \frac{N_p}{N_n + N_p}}$$

$$\boxed{\begin{aligned} p + \bar{\nu}_e &\leftrightarrow n + e^+ \\ n + \nu_e &\leftrightarrow p + e^- \end{aligned}}$$

Abundance:
$Y_i = N_i/N_{tot}$

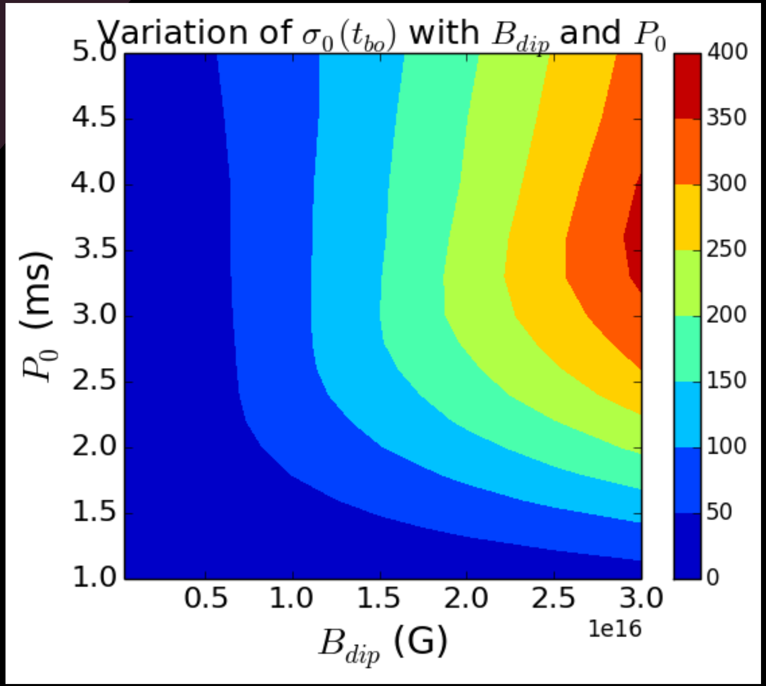


Rapid n-capture to seed nuclei, followed by n→p decay

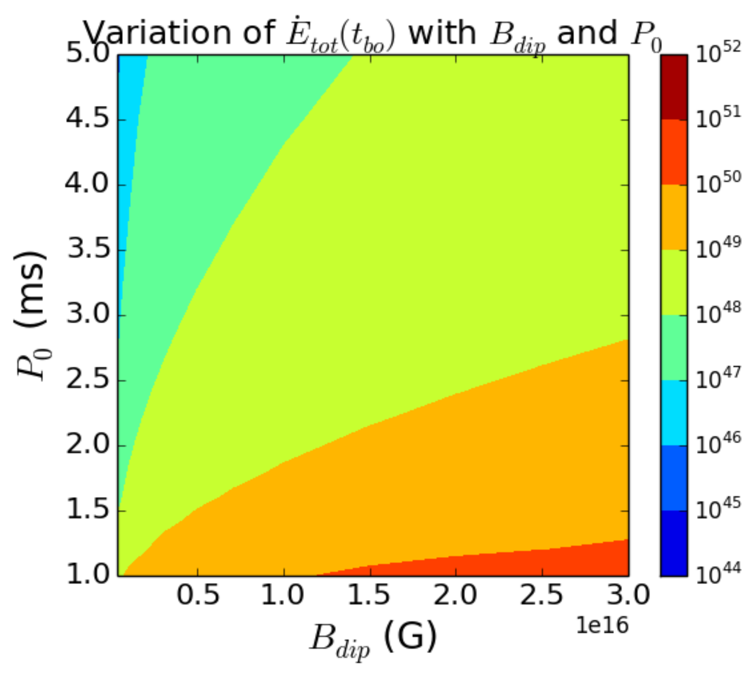
Image credit: Nick Ekanger

Protomagnetar wind properties

$$\sigma_0 = \phi_B^2\Omega^2/\dot{M}c^3, \phi_B = \frac{f_{\rm open}}{4\pi} B_{\rm dip} R_{\rm NS}^2$$

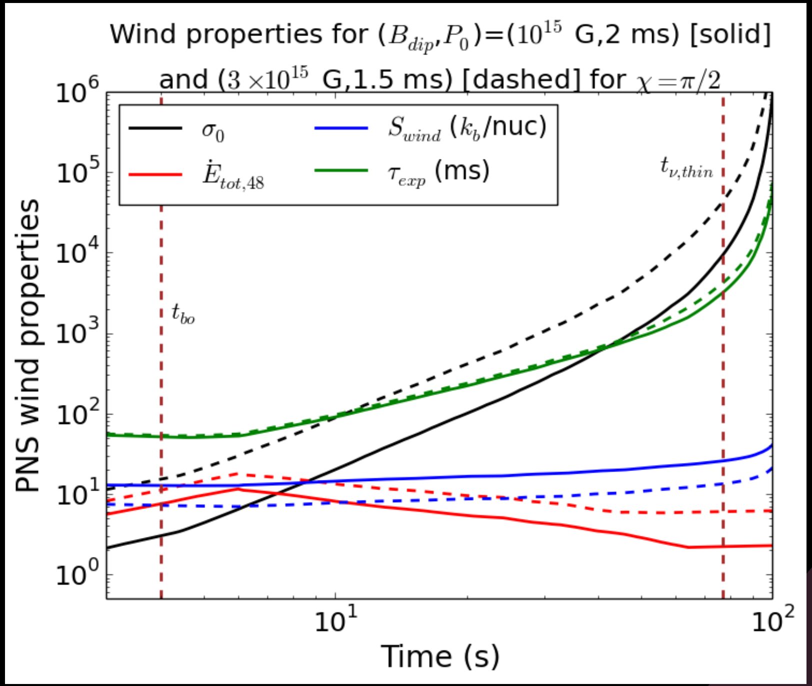


$$\dot{E}_{\rm mag} = (2/3)\dot{M}c^2\sigma_0 \quad [\sigma_0 \gg 1]$$



$$S_{\rm wind}(\Omega = 0) \propto C_{\rm es}^{-1/6} L_{\nu,52}^{-1/6} \epsilon_{\nu,10}^{-1/3} R_{10}^{-2/3} M_{1.4}$$

$$\tau_{\rm exp}|_{T=T_{\rm rec}} = r/v_r$$



σ_0 is suppressed significantly due to enhanced mass loss aided by magneto-centrifugal slinging for rapid rotation

Feasibility of successful jets turns out to be much higher in outflows with $B_{\rm dip} > 10^{16}$ G and $P_0 < 2$ ms

Synthesis of heavier nuclei through r-process is facilitated by combination of low $S_{\rm wind}$ and $\tau_{\rm exp}$ in magnetised outflows

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MB, Horiuchi & Murase 2021

SkyNet: Nuclear reaction network

- Inputs are astrophysical environment data:
  - *Density (t)*
  - *Temperature (t)*
  - *Electron fraction*

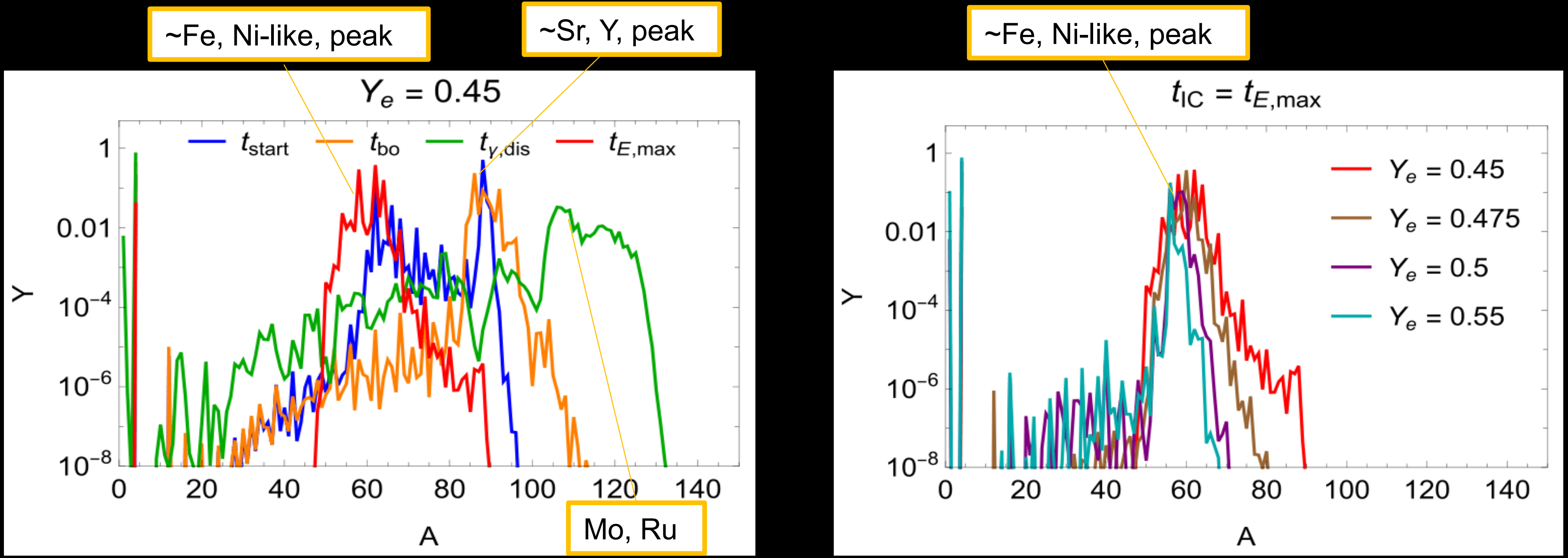
Sky Net

github.com/jlippuner/SkyNet

- Provided $\rho(t)$ and $T(t)$ are sufficiently high, nucleosynthesis yields are primarily determined by Y_e
- ~8,000 nuclei with library of ~100,000 reactions
- Can make precise predictions for elemental abundance distributions

Protomagnetar wind nucleosynthesis

- $\rho(t), T(t), Y_e$ for SkyNet are calculated from initial model conditions


~Fe, Ni-like, peak

~Sr, Y, peak

~Fe, Ni-like, peak

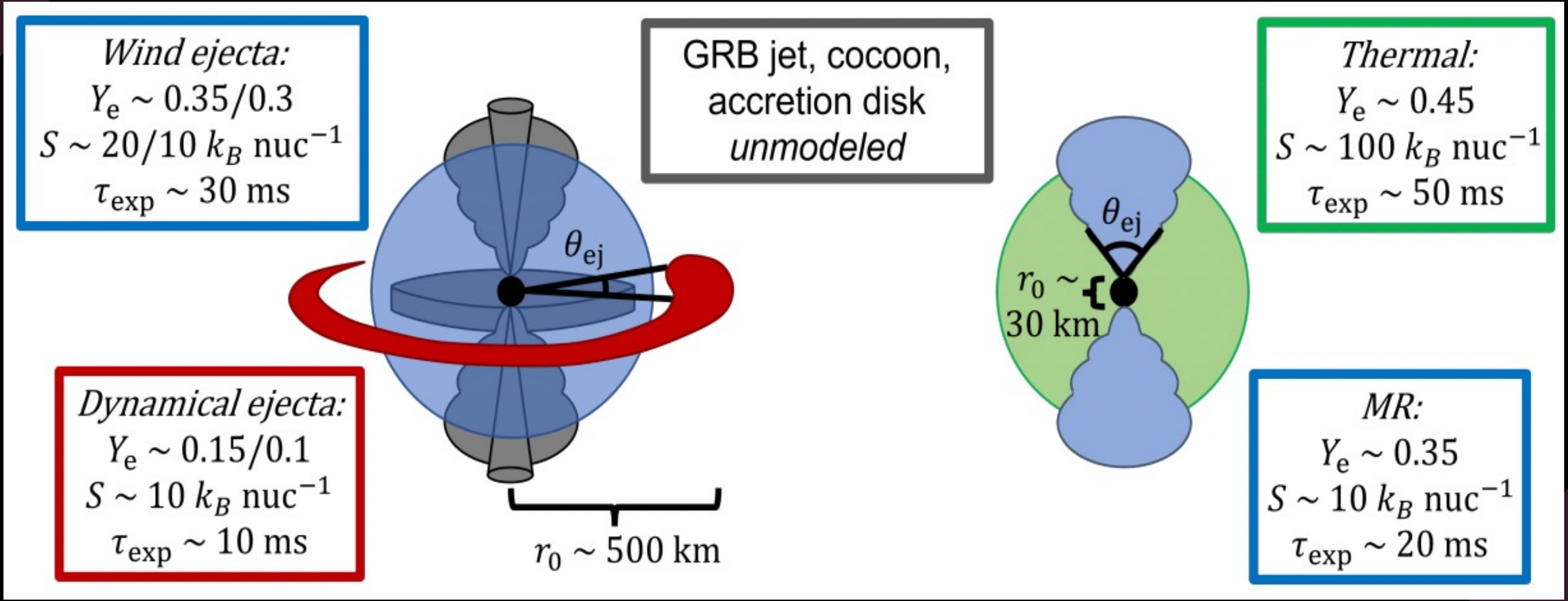
Mo, Ru

t_{start}=0.5 sec, **t_{bo}**: breakout time, **$t_{\gamma,dis}$**: time when $\tau_{A\gamma}$~1, **$t_{E,max}$**: time when nuclei attain max energy ~ $10^{21\text{-}22}$ eV

Protomagnetars can undergo some amount of heavy element nucleosynthesis or a ‘weak’ r-process (1st + 2nd peak)

Ekanger, **MB** & Horiuchi 2022

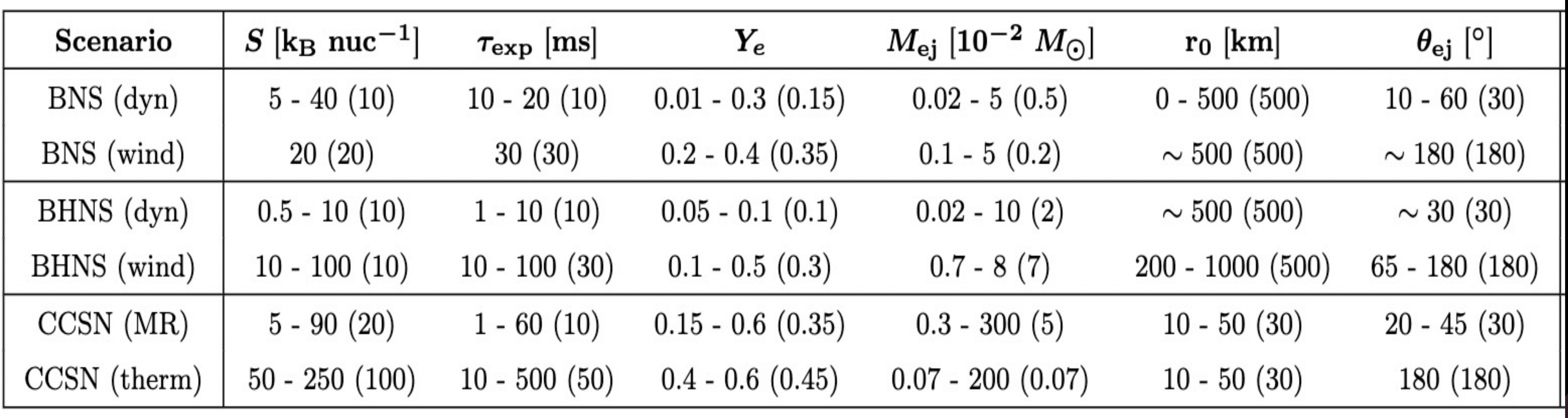
Ejecta properties from NR simulations



BNS/BHNS mergers CCSNe: thermal/MR

Ekanger, **MB**, Horiuchi 2023

Ejecta properties from NR simulations



Scenario	S [k_{B} nuc^{-1}]	τ_{exp} [ms]	Y_e	M_{ej} [10^{-2} $M_{\odot}$]	r_0 [km]	θ_{ej} [°]
BNS (dyn)	5 - 40 (10)	10 - 20 (10)	0.01 - 0.3 (0.15)	0.02 - 5 (0.5)	0 - 500 (500)	10 - 60 (30)
BNS (wind)	20 (20)	30 (30)	0.2 - 0.4 (0.35)	0.1 - 5 (0.2)	$\sim$ 500 (500)	$\sim$ 180 (180)
BHNS (dyn)	0.5 - 10 (10)	1 - 10 (10)	0.05 - 0.1 (0.1)	0.02 - 10 (2)	$\sim$ 500 (500)	$\sim$ 30 (30)
BHNS (wind)	10 - 100 (10)	10 - 100 (30)	0.1 - 0.5 (0.3)	0.7 - 8 (7)	200 - 1000 (500)	65 - 180 (180)
CCSN (MR)	5 - 90 (20)	1 - 60 (10)	0.15 - 0.6 (0.35)	0.3 - 300 (5)	10 - 50 (30)	20 - 45 (30)
CCSN (therm)	50 - 250 (100)	10 - 500 (50)	0.4 - 0.6 (0.45)	0.07 - 200 (0.07)	10 - 50 (30)	180 (180)

BNS: Just+2015, Lippuner & Roberts 2015, Radice+2018, Zhu+2021, Combi & Siegel 2023, Kiuchi+2022, …

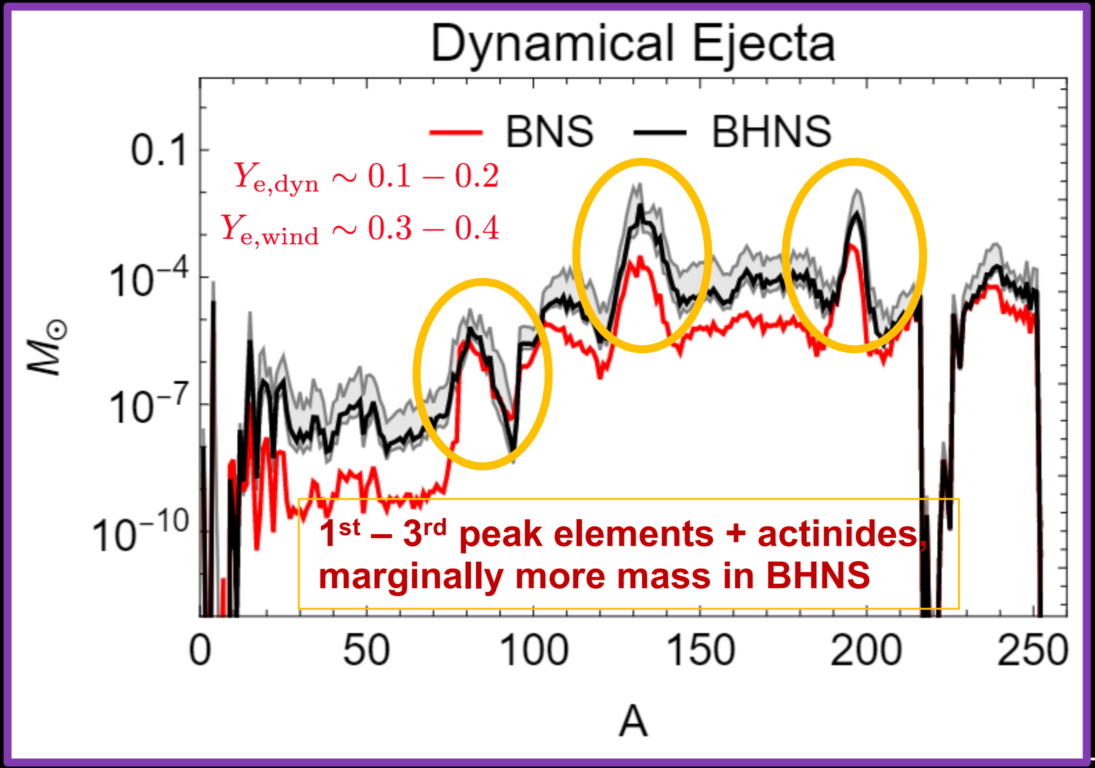
BHNS: Korobkin+2012, Roberts+2017, Bhattacharya+2019, Fujibayashi+2020, Kyutoku+2021, …

MR CCSN: Vlasov+2017, Halevi & Mosta 2018, Reichert+2021, Desai+2022, Reichert+2023, …

Thermal CCSN: Qian & Woosley 1996, Goriely & Janka 2016, Bliss+2018, Witt+2021, Psaltis+2022

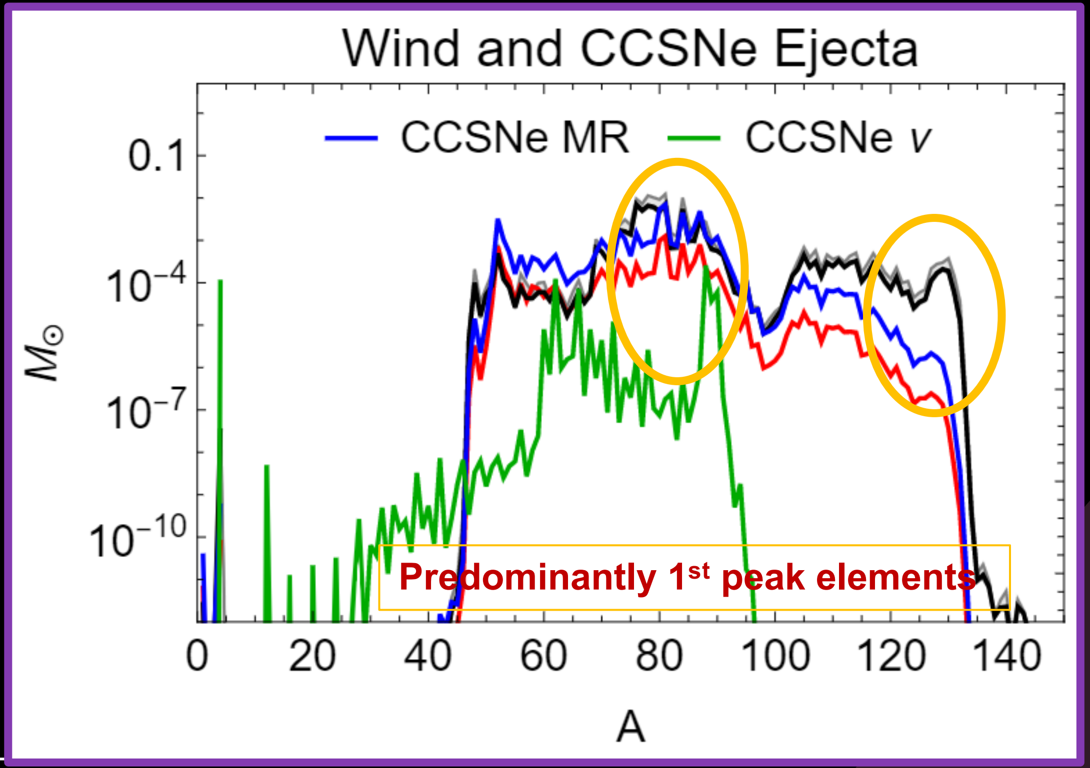
Comparing nucleosynthesis yields

Dynamical ejecta and wind in BHNS mergers tend to be slightly more neutron rich compared to BNS mergers. Both can robustly produce 1st, 2nd and 3rd r-process peak elements + actinides, whereas CCSNe primarily generate 1st peak elements.



$Y_{\mathrm{e,dyn}} \sim 0.1 - 0.2$
$Y_{\mathrm{e,wind}} \sim 0.3 - 0.4$

1st – 3rd peak elements + actinides, marginally more mass in BHNS



Predominantly 1st peak elements

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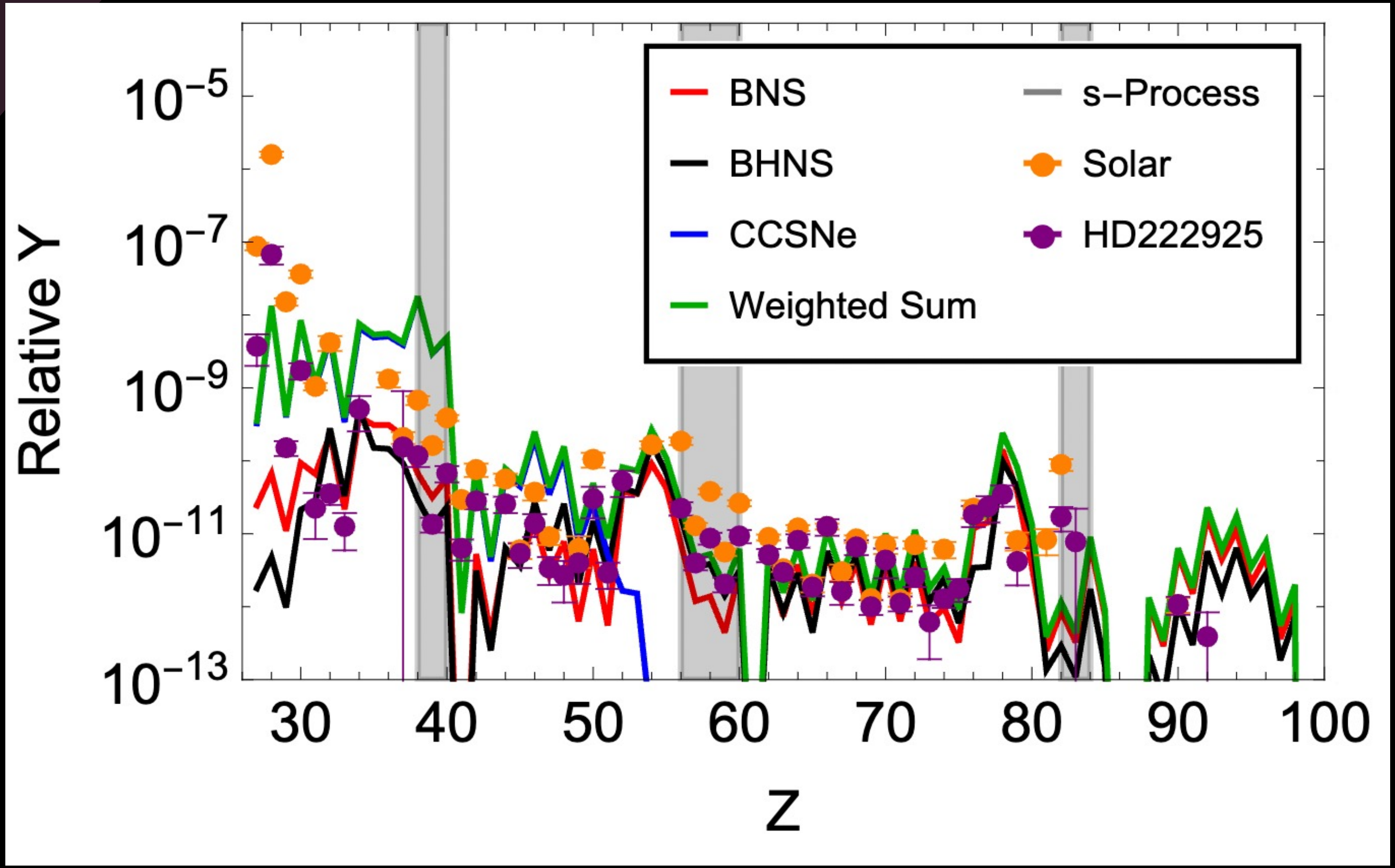
Rate-weighted abundance distributions



Comparing solar and metal-poor star HD222925 abundance data with event-rate-weighted BHNS+BNS nucleosynthesis yields.

Yields are rescaled to match solar lanthanide (dysprosium, Z=66) abundances.

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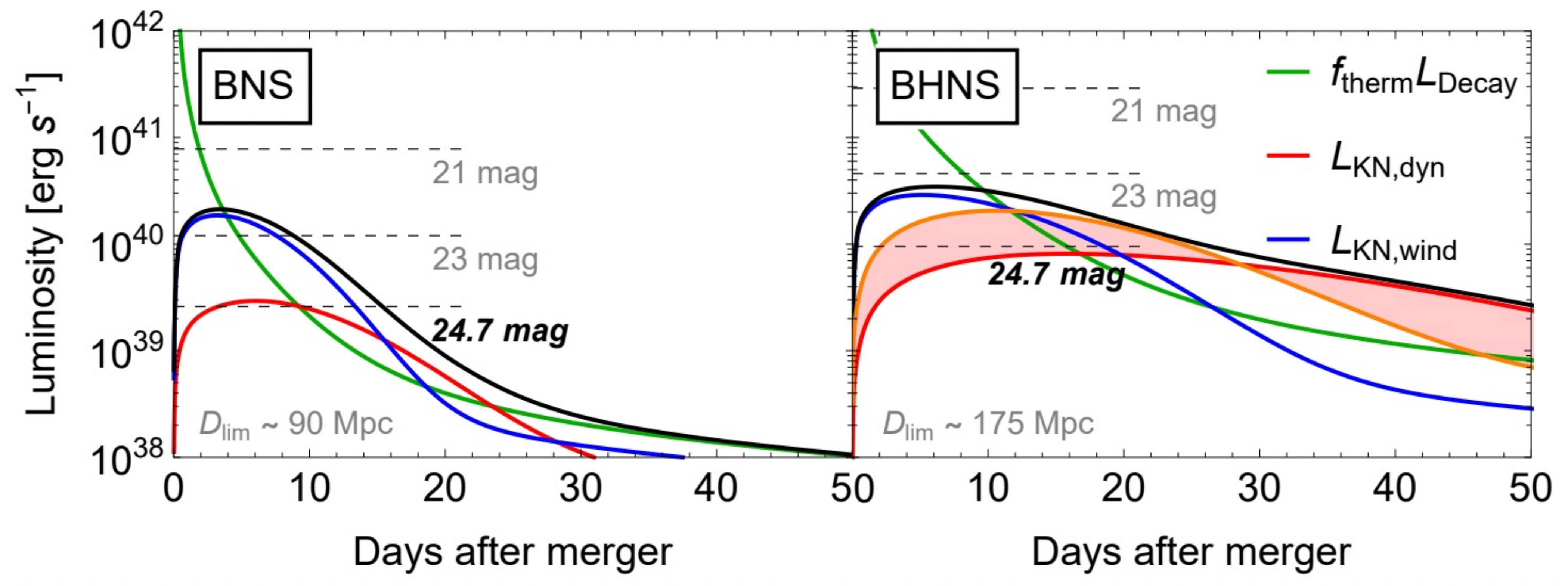
Kilonova light curves

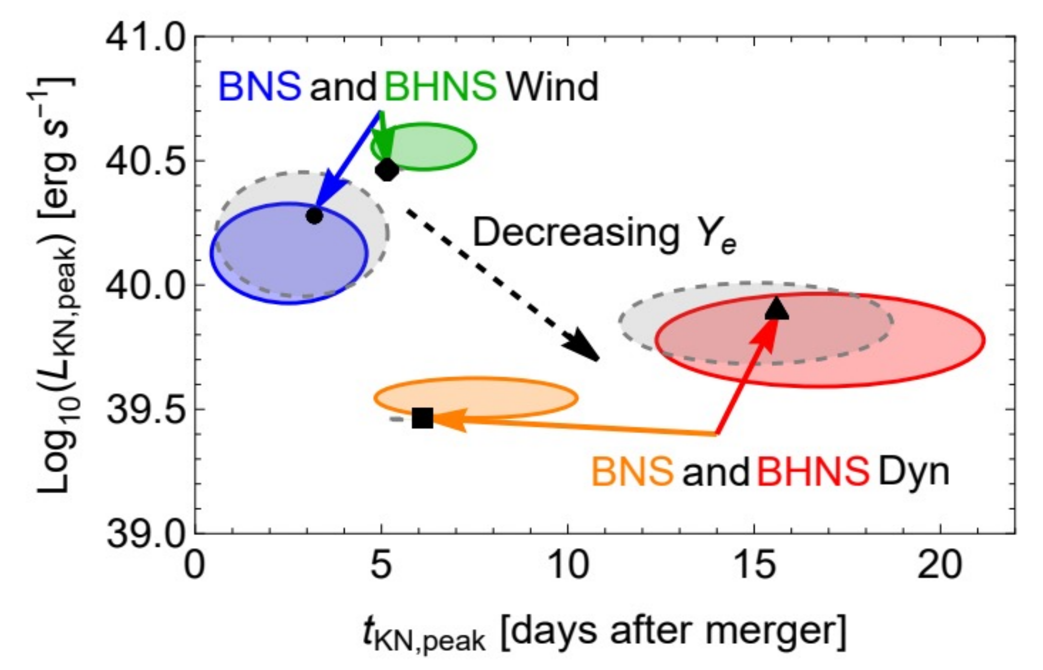
$$\frac{dE(t)}{dt} = -L_{\mathrm{KN}}(t) - L_{\mathrm{ad}}(t) + f_{\mathrm{therm}}(t)L_{\mathrm{decay}}(t),\ \ L_{\mathrm{decay}} = M_{\mathrm{ej}}\dot{\epsilon}_{\mathrm{decay}}\ \text{from SkyNet}$$



BHNS mergers show characteristically brighter and longer-lasting emission compared to BNS

Ekanger, **MB**, Horiuchi 2023

Kilonova observability with LSST



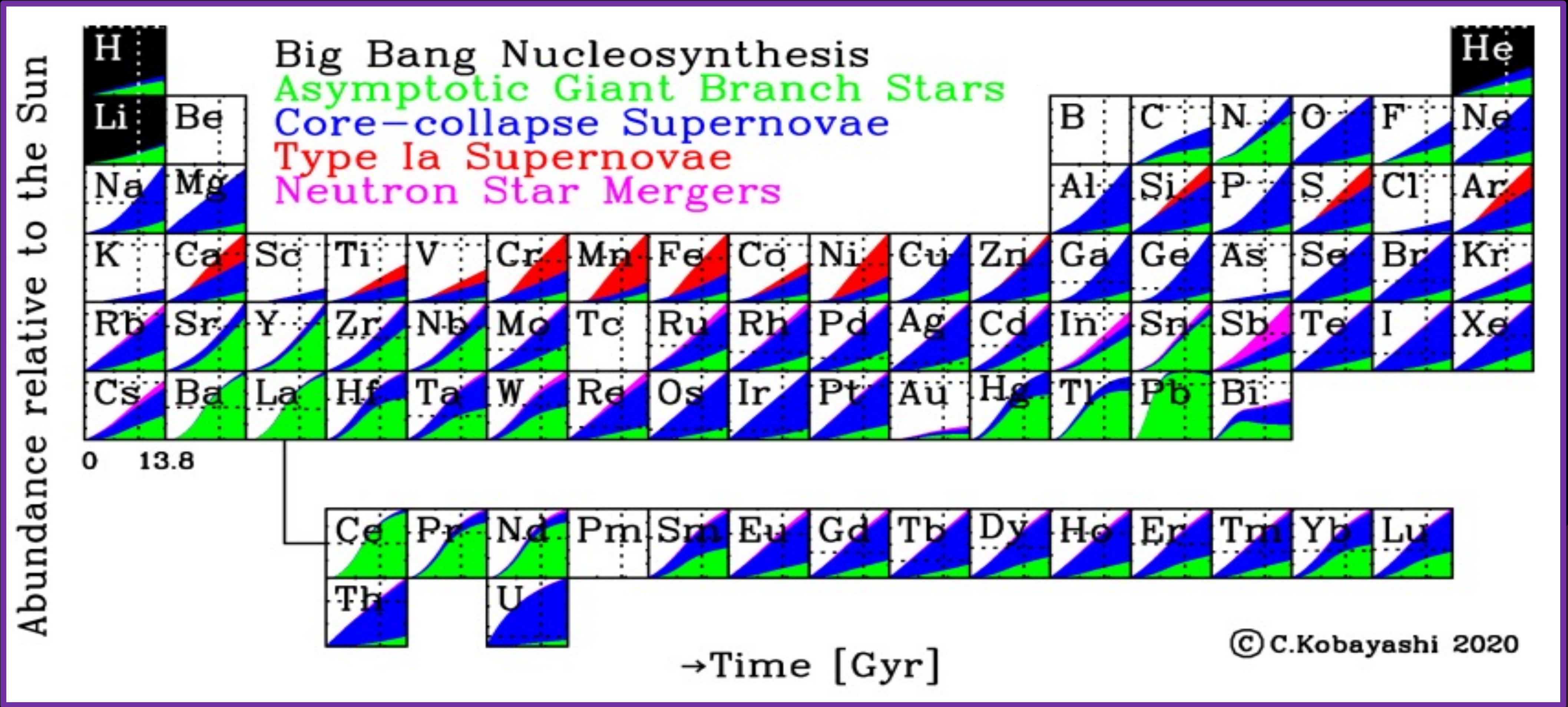
LIGO O4 (May 2023) + LSST (~mid 2024) can detect KN signatures from BHNS/BNS.

~7 BNS and ~2 BHNS events/year

Vera C. Rubin Observatory: https://noirlab.edu/public/images/iotw2207a/

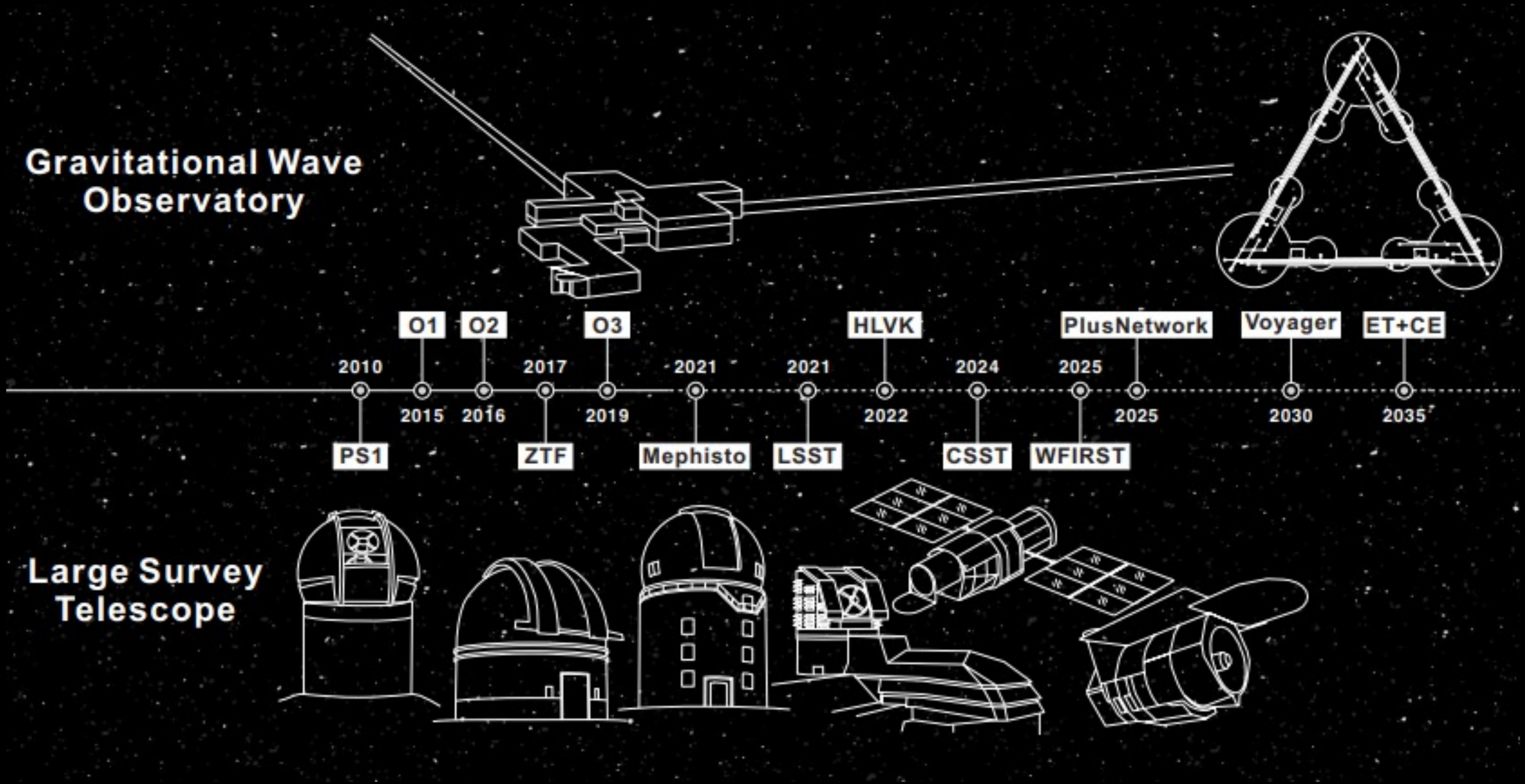
A holistic approach: Galactic chemical evolution

Accounting for nucleosynthesis yields and event rates of transient phenomena, GCE provides a holistic view of nucleosynthesis (including r-process) that has occurred over our Galaxy's evolution



[1] Zhu et al. 2021

Prospects are optimistic!

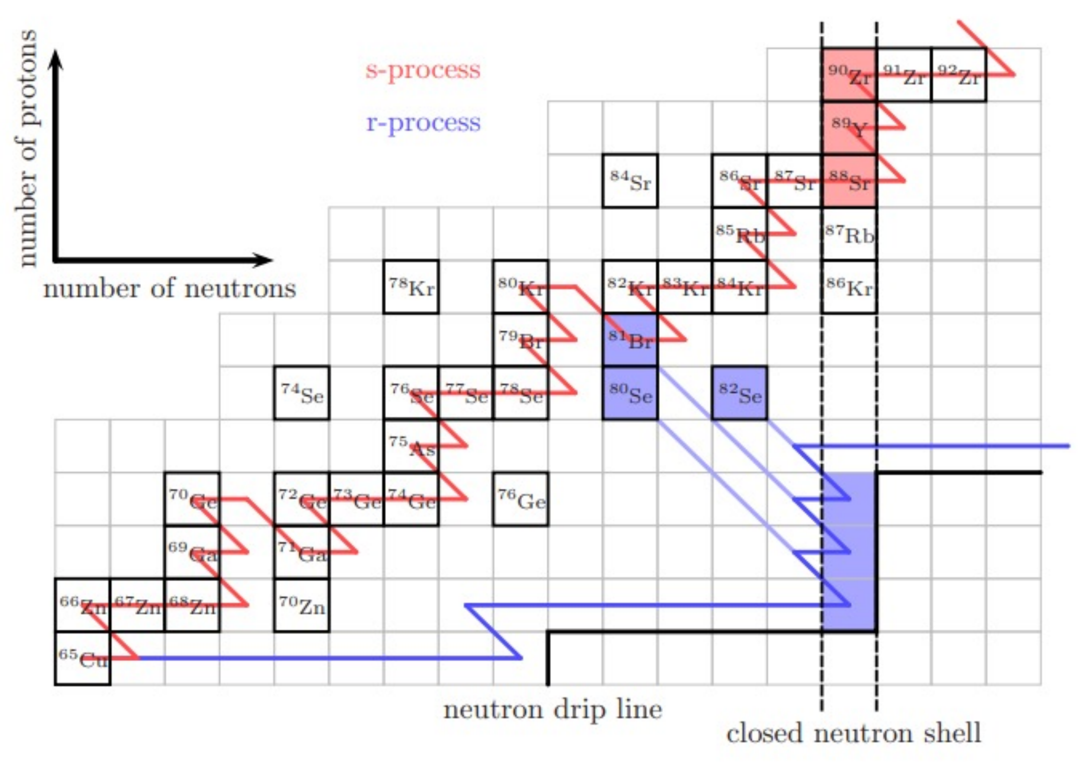


[1]

[1] J. Lippuner Thesis, 2018.

Why are r/s –process peaks where they are?

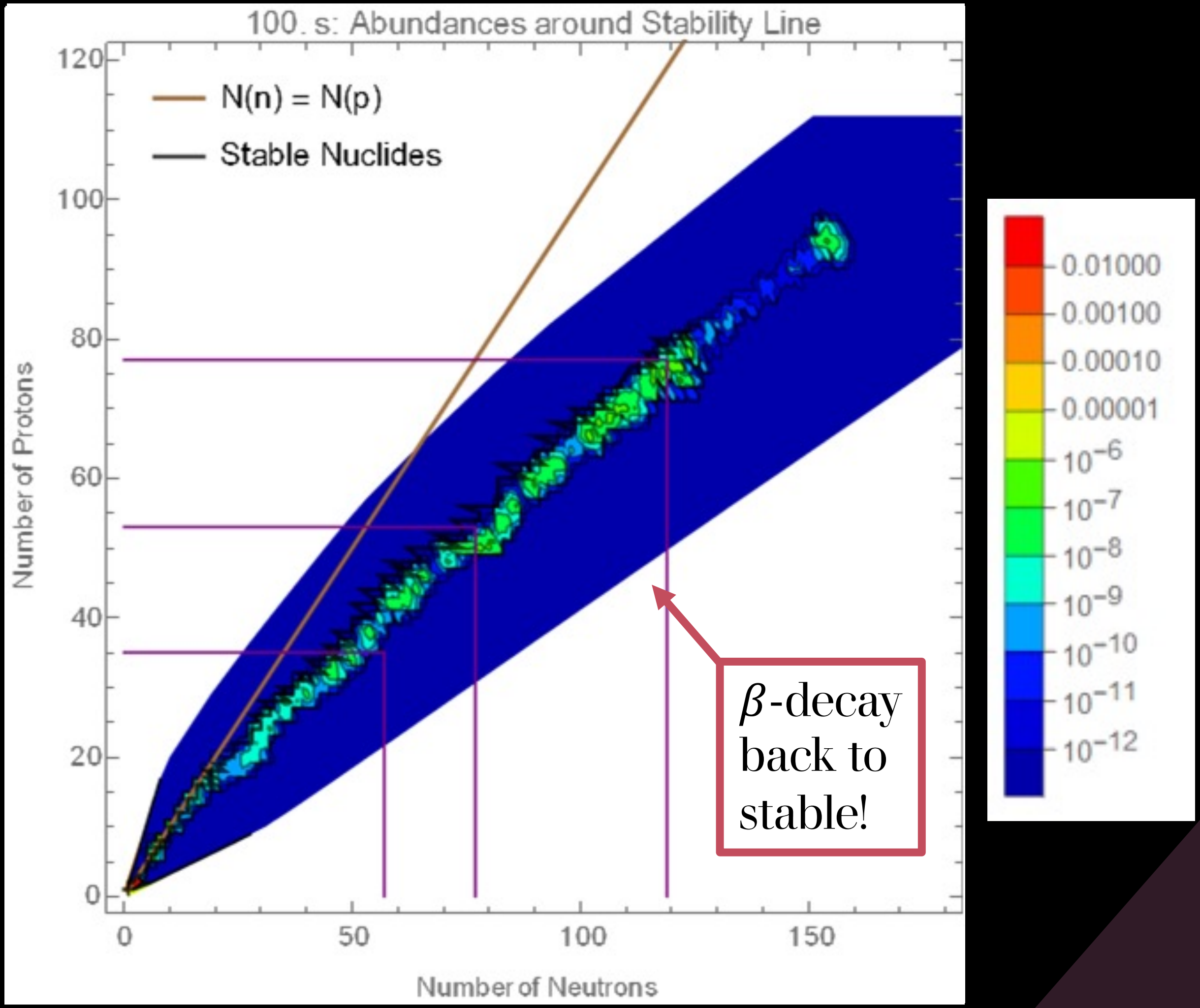
- Neutron capture cross section drops off at closed neutron shell locations (N = 50 for first peak, magic number)
- In s- these species are necessarily stable
- In r- they are unstable, and decay from N = 50 shell back to stable line
- At each peak there is this feature



[1]

Detailed r-process

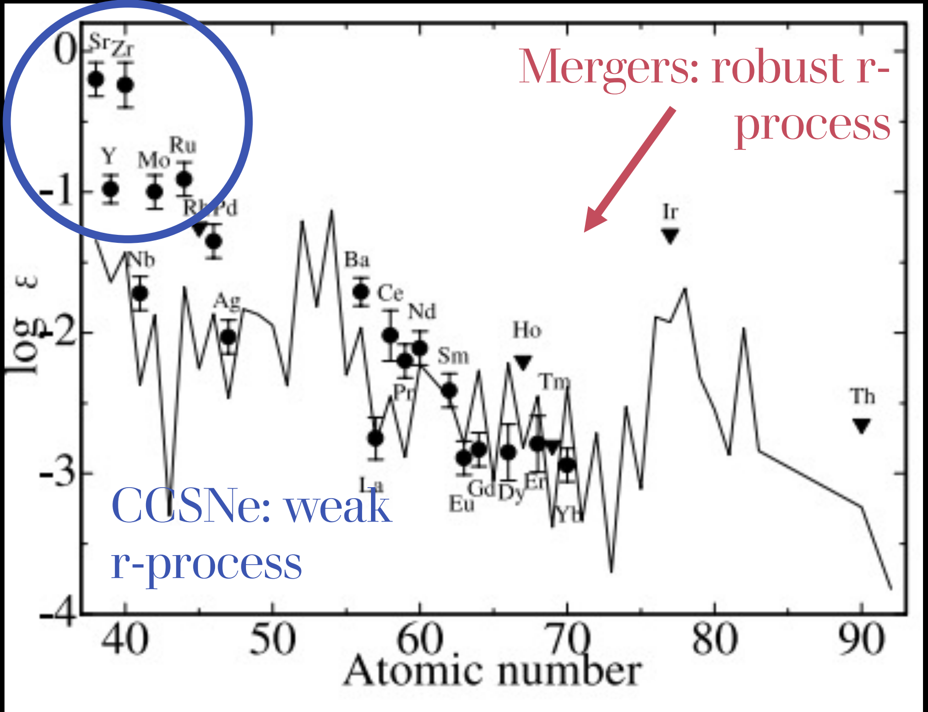
- Back-to-back α particle captures
- Seeds for heavier nuclei to capture many neutrons up to peaks
- Beta decay back to stability



β-decay back to stable!

[1] Honda et al. 2007

Two populations?



Mergers: robust r-process

CCSNe: weak r-process

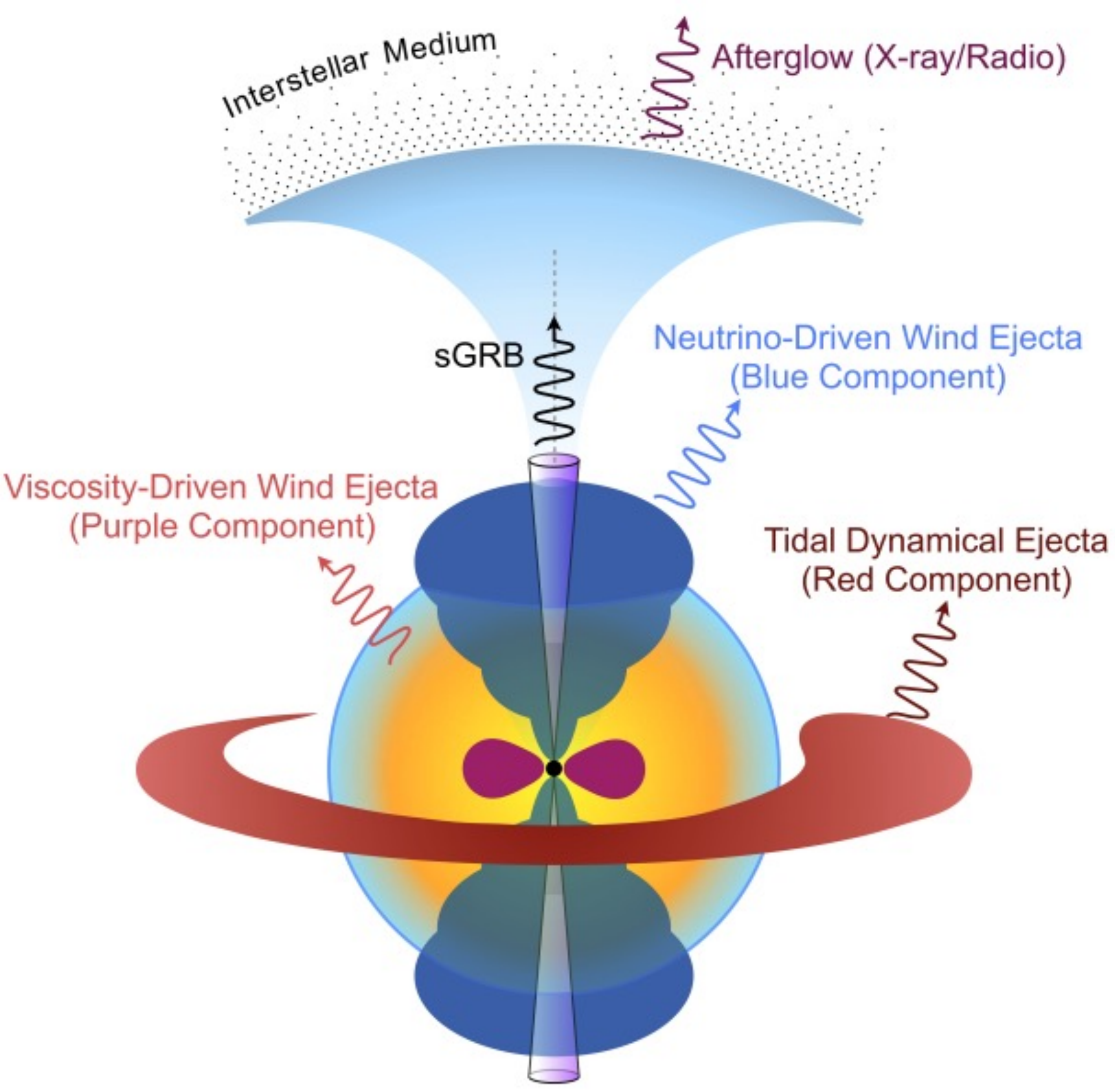
[1]

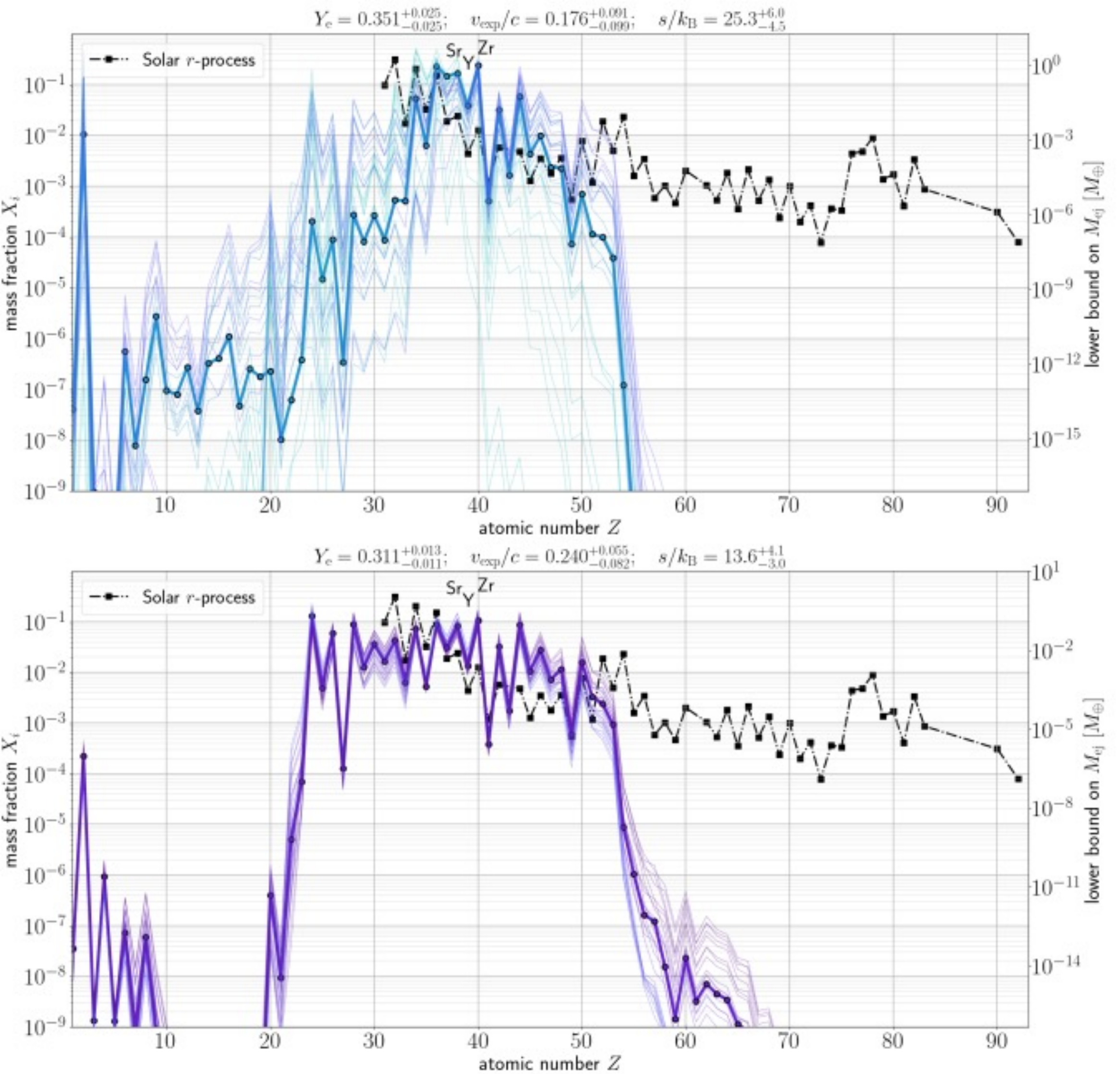
- Extra relative enrichment for the ‘weak’ r-process elements compared to solar/higher peak elements
- Two components:

1. >1st r process peak elements from mergers
2. ‘Weak’ ~1st r process peak elements from CCSNe

[1] Zhu et al. 2020
[2] Vieira et al. 2022

[1]

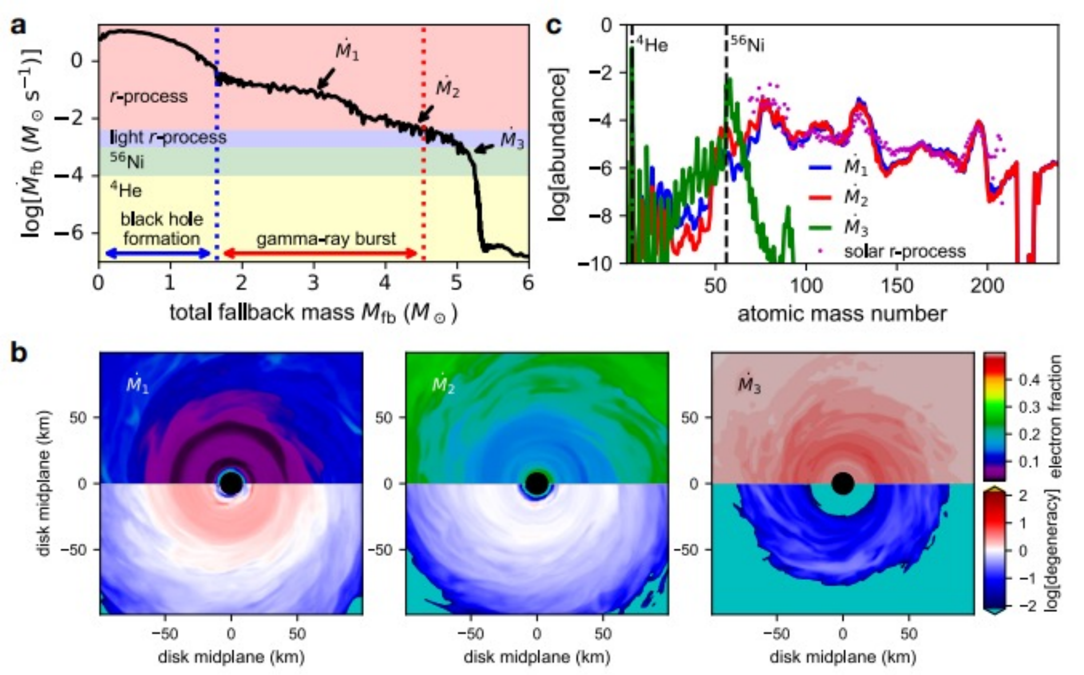




[2]

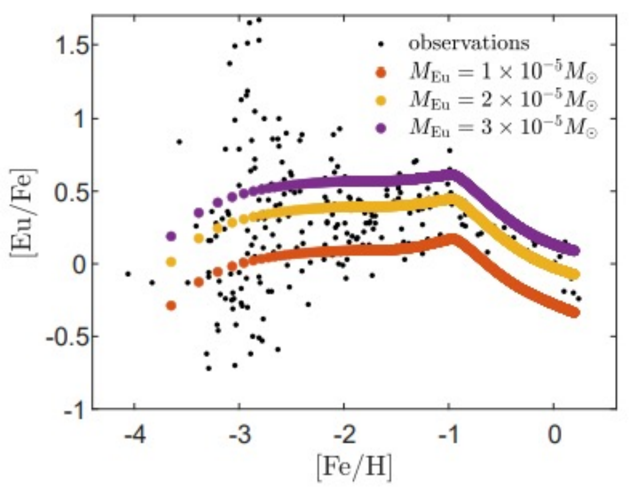
[1] Siegel et al. 2018
[2] Grichener et al. 2022
[3] Kobayashi et al. 2020 -> Kobayashi and Tominaga (in prep?)

Additional scenarios



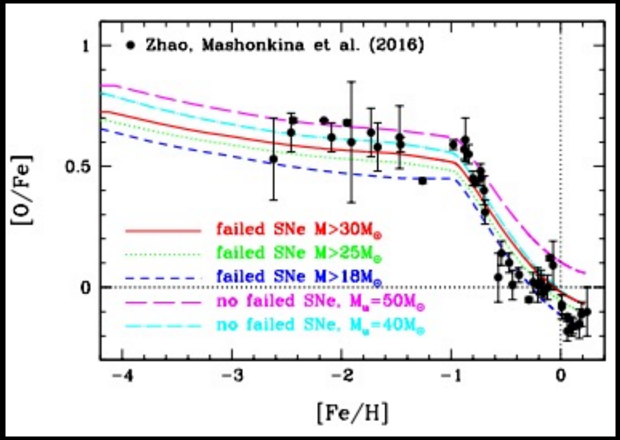
[1]

Collapsar accretion disks



[2]

Common envelope jet supernovae



[3]

Failed supernovae

Timescales

- CCSNe collapse timescale: $10\text{ Myr} \rightarrow \sim 1s$
- Merger timescale: $> \text{Gyr} \rightarrow \sim 100s$
- Rates:

  $CCSNe - 1 * 10^5\ Gpc^{-3} yr^{-1}$

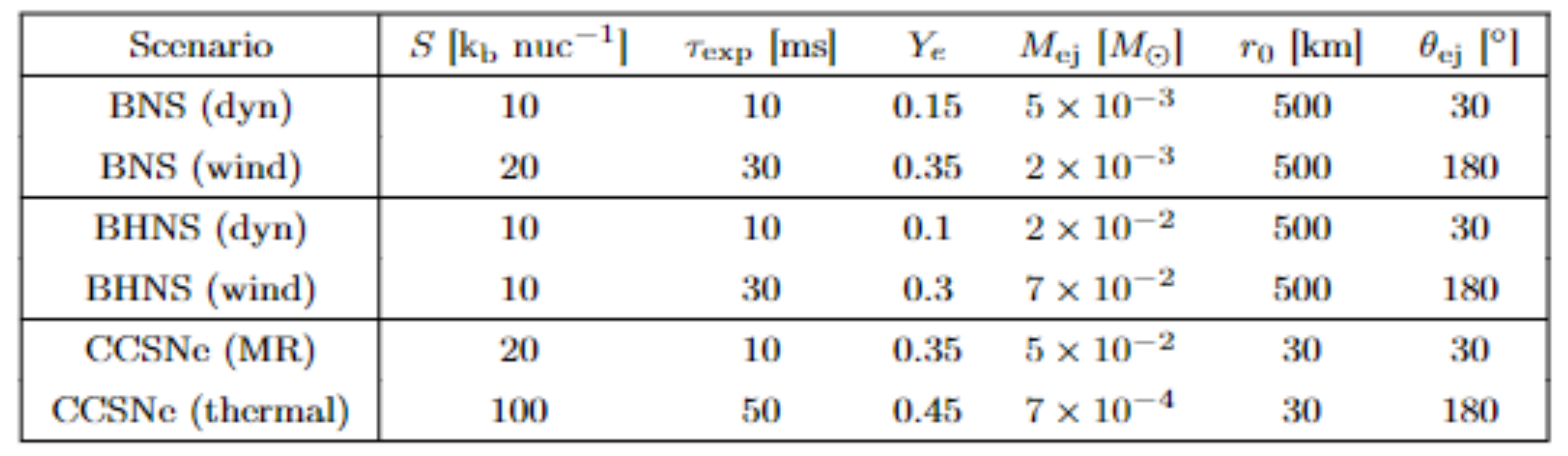
  $BNS - 10 - 1700\ Gpc^{-3} yr^{-1}$

  $BHNS - 7.8 - 140\ Gpc^{-3} yr^{-1}$

[1] Ekanger, Bhattacharya, Horiuchi (in prep)

Typical values

[1]



Scenario	S [$\mathrm{k_b}$ nuc^{-1}]	τ_{exp} [ms]	Y_e	M_{ej} [$M_\odot$]	r_0 [km]	θ_{ej} [°]
BNS (dyn)	10	10	0.15	5×10^{-3}	500	30
BNS (wind)	20	30	0.35	2×10^{-3}	500	180
BHNS (dyn)	10	10	0.1	2×10^{-2}	500	30
BHNS (wind)	10	30	0.3	7×10^{-2}	500	180
CCSNe (MR)	20	10	0.35	5×10^{-2}	30	30
CCSNe (thermal)	100	50	0.45	7×10^{-4}	30	180