Variety of disk wind-driven explosions in massive rotating stars

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Introduction

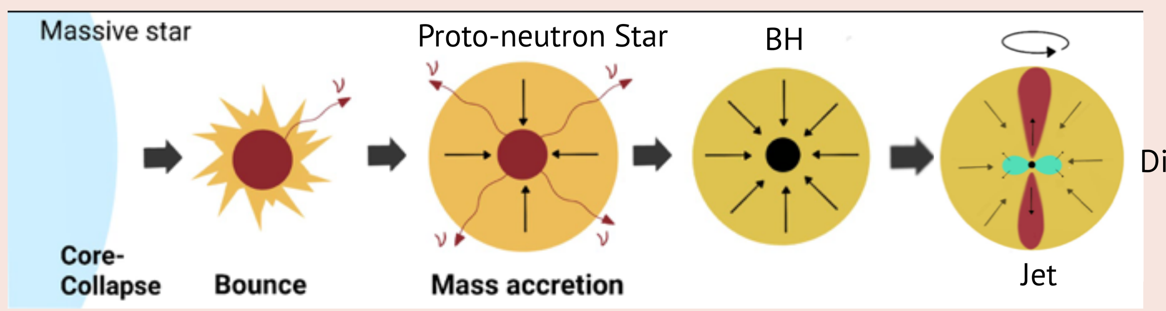
Massive stellar core collapse is a promising scenario (collapsar scenario) to explain energetic supernovae such as broad-lined type Ic SNe (Type Ic-BL SNe) or hypernovae and their associated GRBs [1], [2]. Very massive stars ($M_{\rm ZAMS} > 16\,M_\odot$) are prone to fail the explosion during the PNS phase undergoing a failed CCSN in which the core collapses into a black hole (BH). In the presence of an appreciable rotation, the BH should be surrounded by an accreting disk [3]. In failed supernova the wind created by the viscous heating inside the accretion disk may be a natural source of the SN energy with an explosion energy $E_{\rm expl} > 10^{52}$ erg [4], [5] and it has been found rich in ^{56}Ni [6], [7].The interaction between the newly-born BH and the accreting stellar material can then also be the engine for the relativistic jets that account for gamma-ray bursts (GRBs).

This led us to explore the properties of sub-relativistic outflow in the collapsar scenario, with the explosion fueled by a BH-accretion disk system. This study is based on se axisymmetric hydrodynamics simulations for modeling the ejecta produced by the collapse of a massive, rotating star.

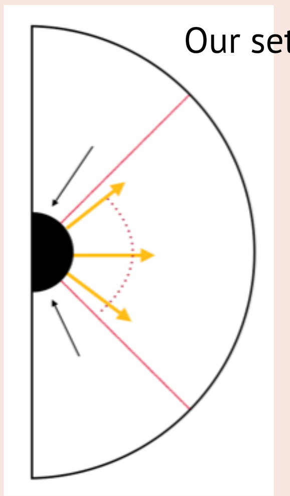
Method

Studying the explosion properties and ^{56}Ni production as a function of the wind injection and the progenitor in massive stars

$$M \gtrsim 16 - 20\,M_\odot$$
$$\xi_{2.5} > 0.45$$



- $2D$ axis symmetric non-relativistic simulations with **Athena++**
- New feature to compute the self-gravity with the gravitational potential Φ
- Oxygen based equation of state
- Rapidly rotating progenitors from Aguilera-Dena et al. (2020)
- Central engine cut at $r_{\rm in} = 1000$ km



WIND INJECTION

- $\theta_{\rm w} = \pi/4$ along the equatorial plane
- Parabolic density profile
- Injected specific energy: $\frac{1}{2}v_{\rm w}^2 + \frac{1}{2}f_{\rm therm}v_{\rm w}^2 + \Phi = \frac{1}{2}\xi^2 v_{\rm esc}^2$

Model of the central engine

The central engine in a semi-analytical way by evolving the BH and the disk through the transfer of matter and angular momentum [8].

Their change is due to three components:

1. The rates of the mass accretion that directly infalls onto the disk and onto the BH;
2. The mass and angular momentum transfer between the disk and the BH. This is the accretion component and it is controlled by the *accretion timescale* t_{acc};
3. The contribution of the wind measured by the *wind timescale* t_w.

We evolve the masses of the disk and the BH, $M_{\rm disk}$ and $M_{\rm BH}$, and their angular momenta $J_{\rm disk}$ and $J_{\rm BH}$ as:

$$\frac{dM_{\rm disk}}{dt} = \dot{M}_{\rm fall,disk} - \dot{M}_{\rm acc} - \dot{M}_{\rm wind}$$
$$\frac{dM_{\rm BH}}{dt} = \dot{M}_{\rm fall,BH} + \dot{M}_{\rm acc}$$
$$\frac{dJ_{\rm disk}}{dt} = \dot{J}_{\rm fall,disk} - \dot{J}_{\rm acc} - \dot{J}_{\rm wind}$$
$$\frac{dJ_{\rm BH}}{dt} = \dot{J}_{\rm fall,BH} + \dot{J}_{\rm acc}$$

Accretion Term

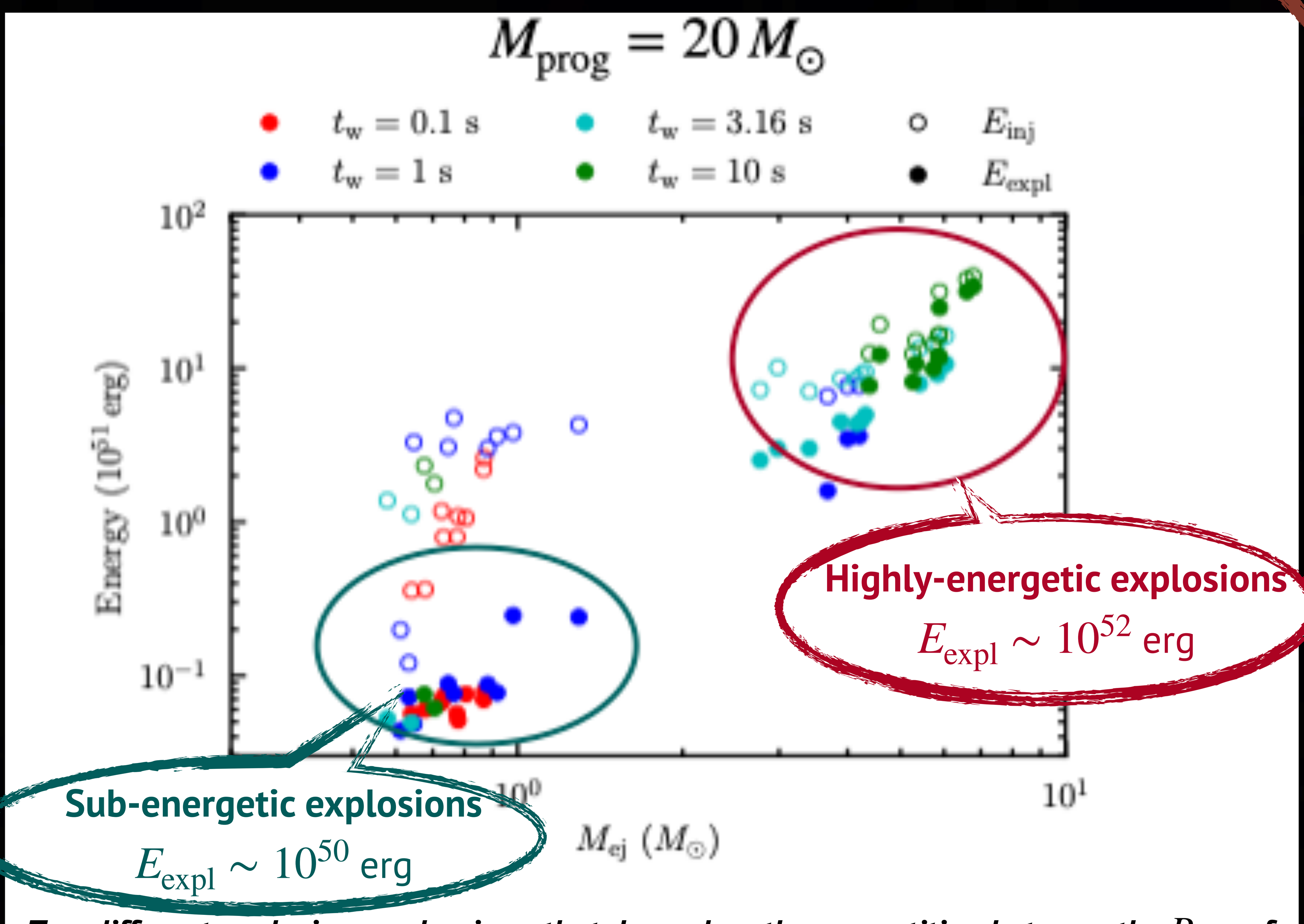
$$\begin{cases} \dot{M}_{\rm acc} = \dfrac{M_{\rm disk}}{t_{\rm acc}} \\ \dot{J}_{\rm acc} = \dfrac{M_{\rm disk}}{t_{\rm acc}} j_{\rm ISCO} \end{cases}$$

Wind Term

$$\begin{cases} \dot{M}_{\rm wind} = \dfrac{M_{\rm disk}}{t_{\rm w}} \\ \dot{J}_{\rm wind} = j_{\rm disk}\dot{M}_{\rm wind} \end{cases}$$

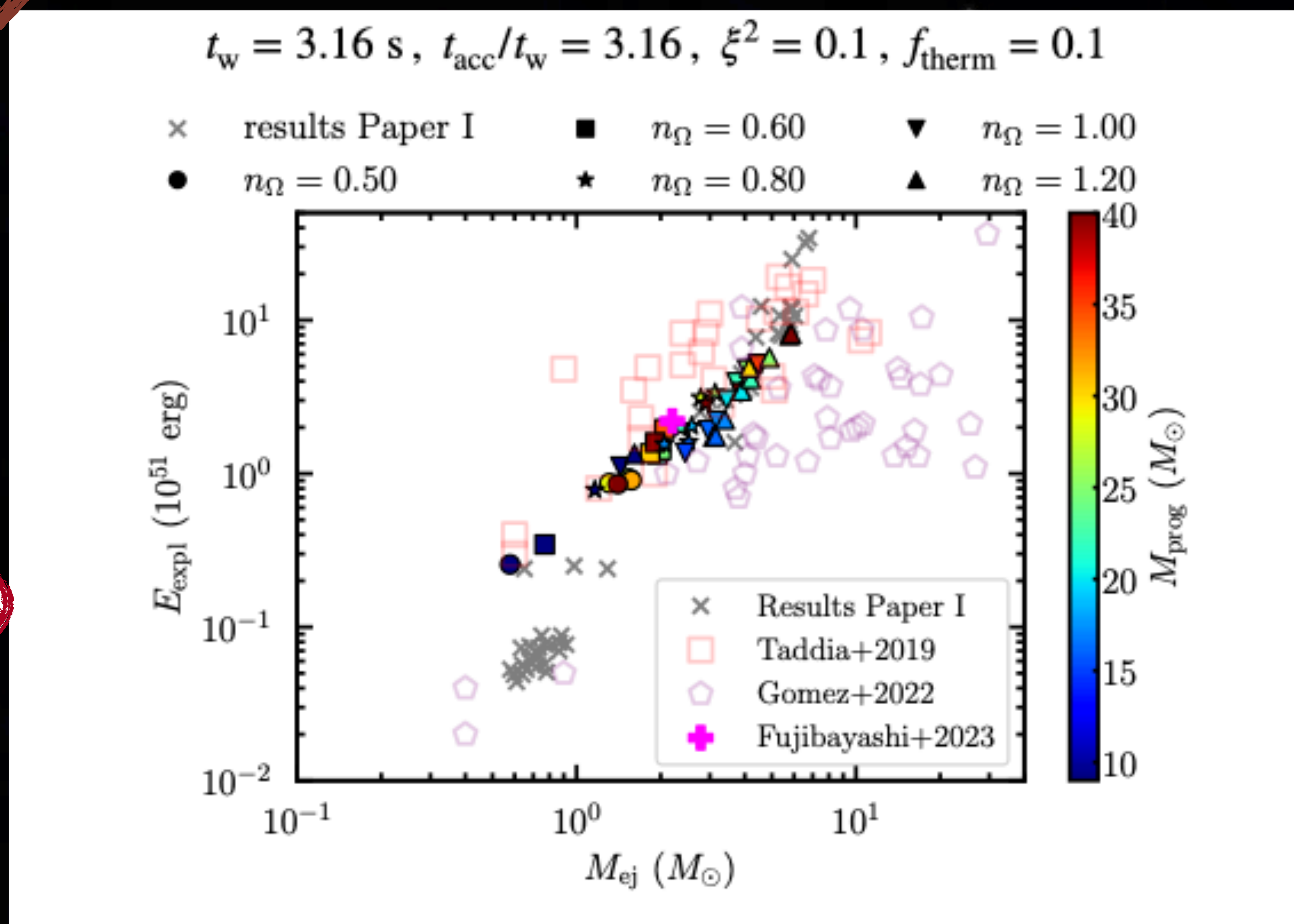
RESULTS

Two explosion mechanism for different wind injection models



Two different explosion mechanisms that depend on the competition between the $P_{\rm ram}$ of the injected and infalling matter

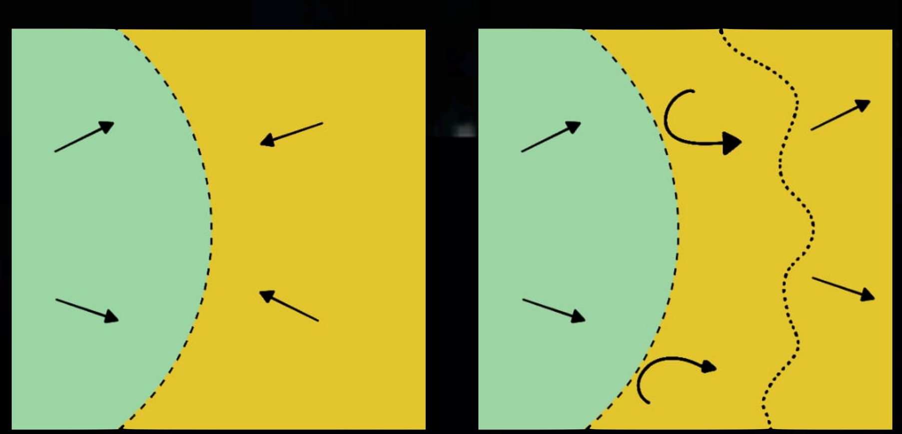
Variety of $E_{\rm expl}$ for different progenitor models



The explosion mechanisms is not affected by the progenitor model

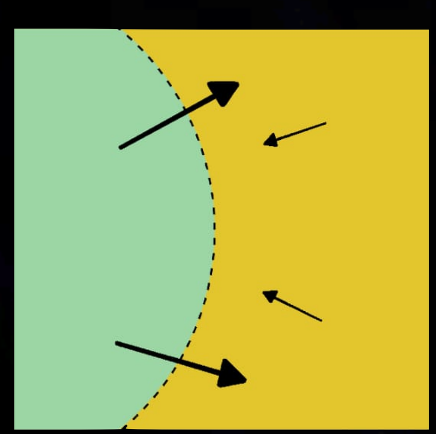
Sub-energetic explosions

$P_{\rm ram}$ of the injected matter is smaller than that of the infalling envelope, the the stellar envelope is not directly pushed ouwords, but it "bounces" on the wind shock front. Thus it is the bounce shock that, propagating outwords, determins the ejection of the matter.

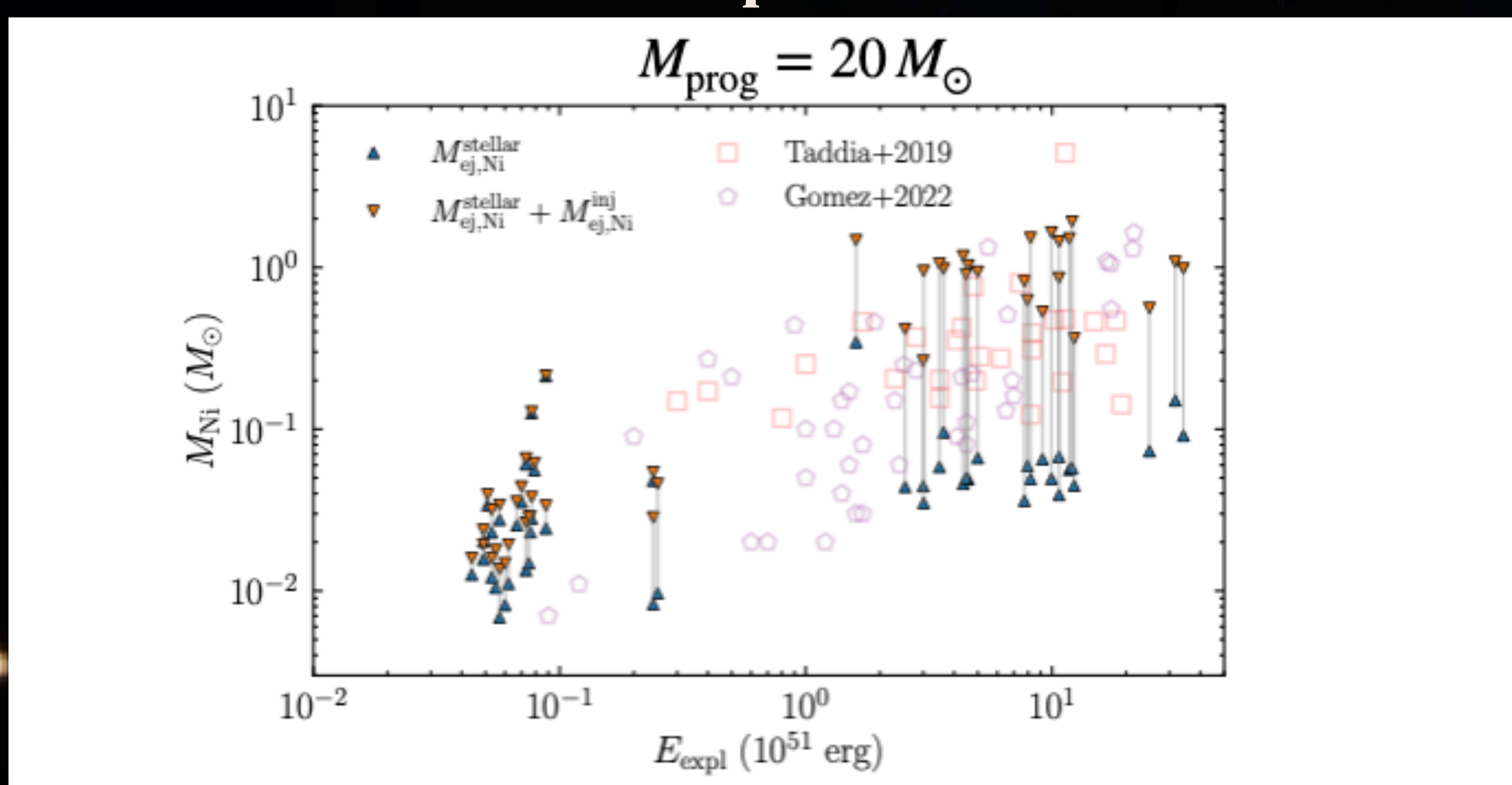


Highly-energetic explosions

The $P_{\rm ram}$ of the injected matter can overcome $P_{\rm ram}$ of the infalling envelope, then the first one can efficiently push the second one outwords preventing it from falling back.



^{56}Ni production



References:

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4] Woosley (1993)
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