

$10^{4-5} M_{\odot}$ 程度の Supermassive Star の進化と爆発

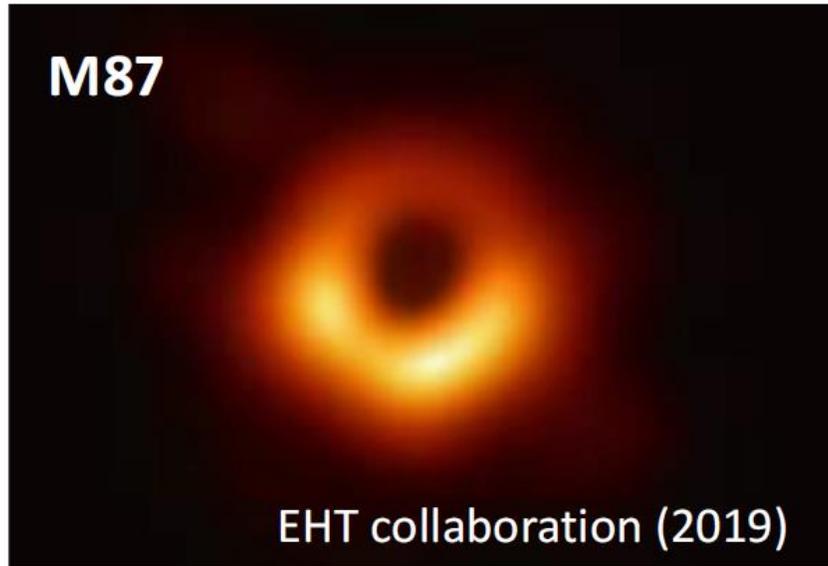
梅田 秀之 (H. Umeda), Univ of Tokyo

初代星・初代銀河研究会2024

信州大学 長野(工学)キャンパス 太田国際記念館 2024年11月11日(月)-11月13日(水)

Supermassive star は SMBHの種

Quasars & AGNs host supermassive black holes



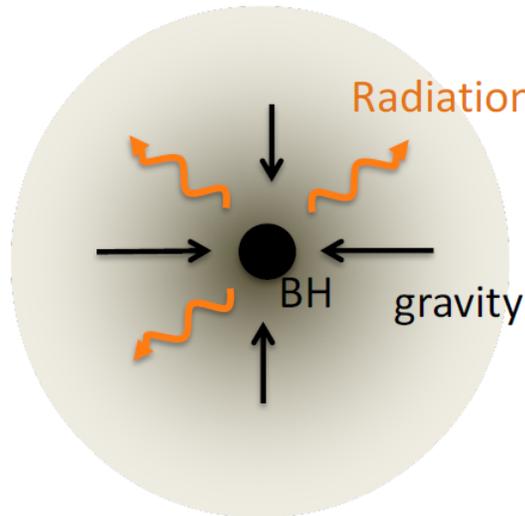
相当遠方(宇宙初期)にもある、例えば

@ $z=7.5$, J1342+0928 (Banados et al. 2018,
BH mass $\sim 7.8 \times 10^8 M_{\odot}$)

@ $z=7.64$, J0313-1806 (Wang et al. 2021,
BH mass $\sim 1.6 \times 10^9 M_{\odot}$)

Seed BH and growth

*Eddington Accretion



By S. Chon (Tohoku Univ.)

When the radiation pressure balances with the gravity,

$$\sigma_{\text{Th}} P_{\text{rad}} = \frac{GM_{\text{BH}}m_{\text{p}}}{R^2} :$$

Then, we can define the critical luminosity

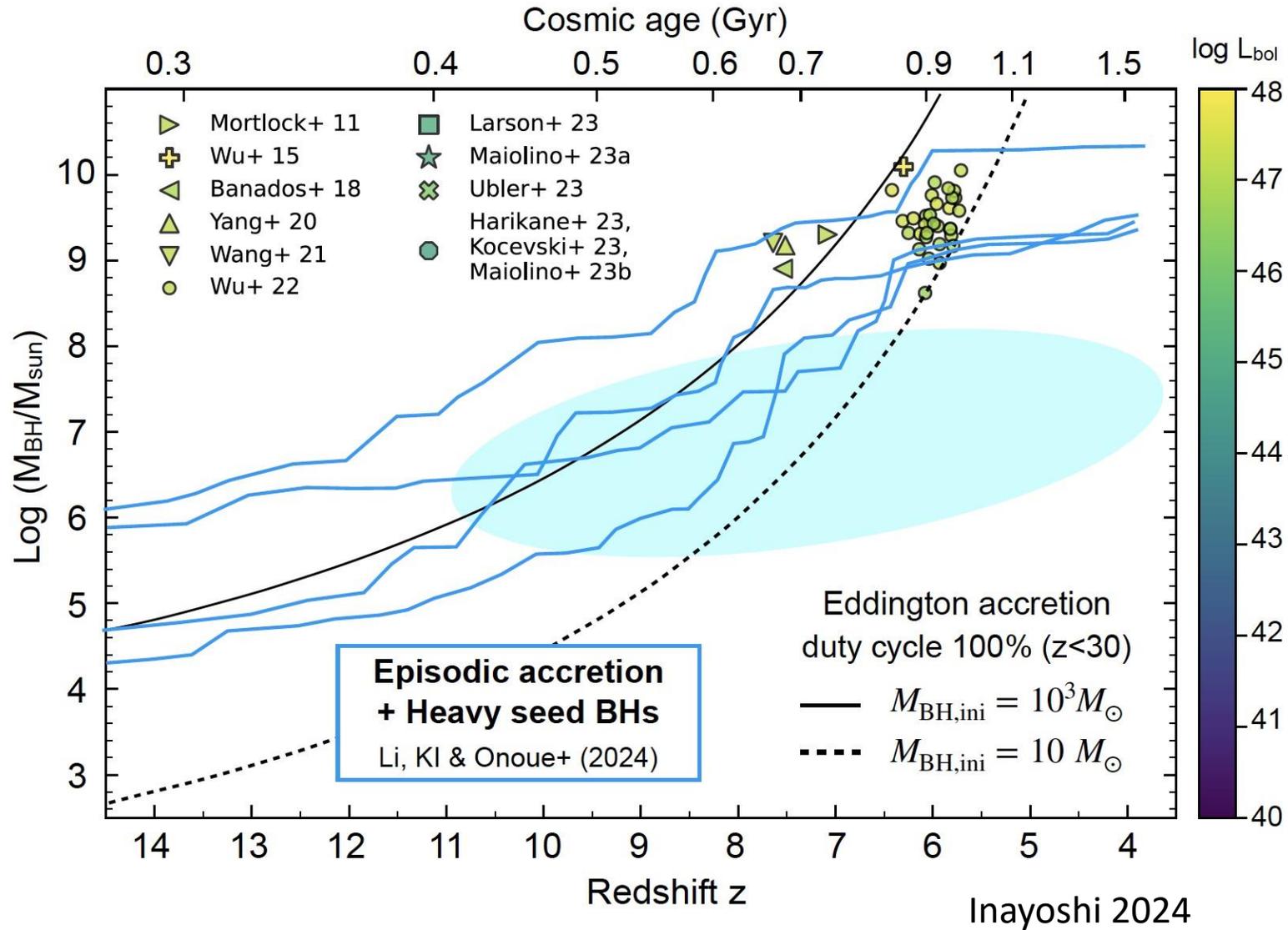
$$L_{\text{Edd}} = \frac{4\pi cGM_{\text{BH}}m_{\text{p}}}{\sigma_{\text{Th}}}$$

Assuming fraction ϵ of the energy of the accreting matter is liberated ($L = \epsilon \dot{M} c^2$),

$$\dot{M}_{\text{Edd}} = \frac{1 - \epsilon}{\epsilon} \frac{4\pi GM_{\text{BH}}m_{\text{p}}}{\sigma_{\text{Th}}c} \propto M_{\text{BH}}$$

$$\therefore M_{\text{BH}} = M_{\text{ini}} \exp(t / t_{\text{E}}), \quad t_{\text{E}} \sim 50 \text{ Myr}$$

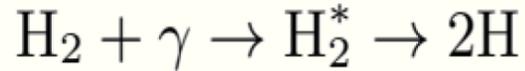
Seed BH and growth



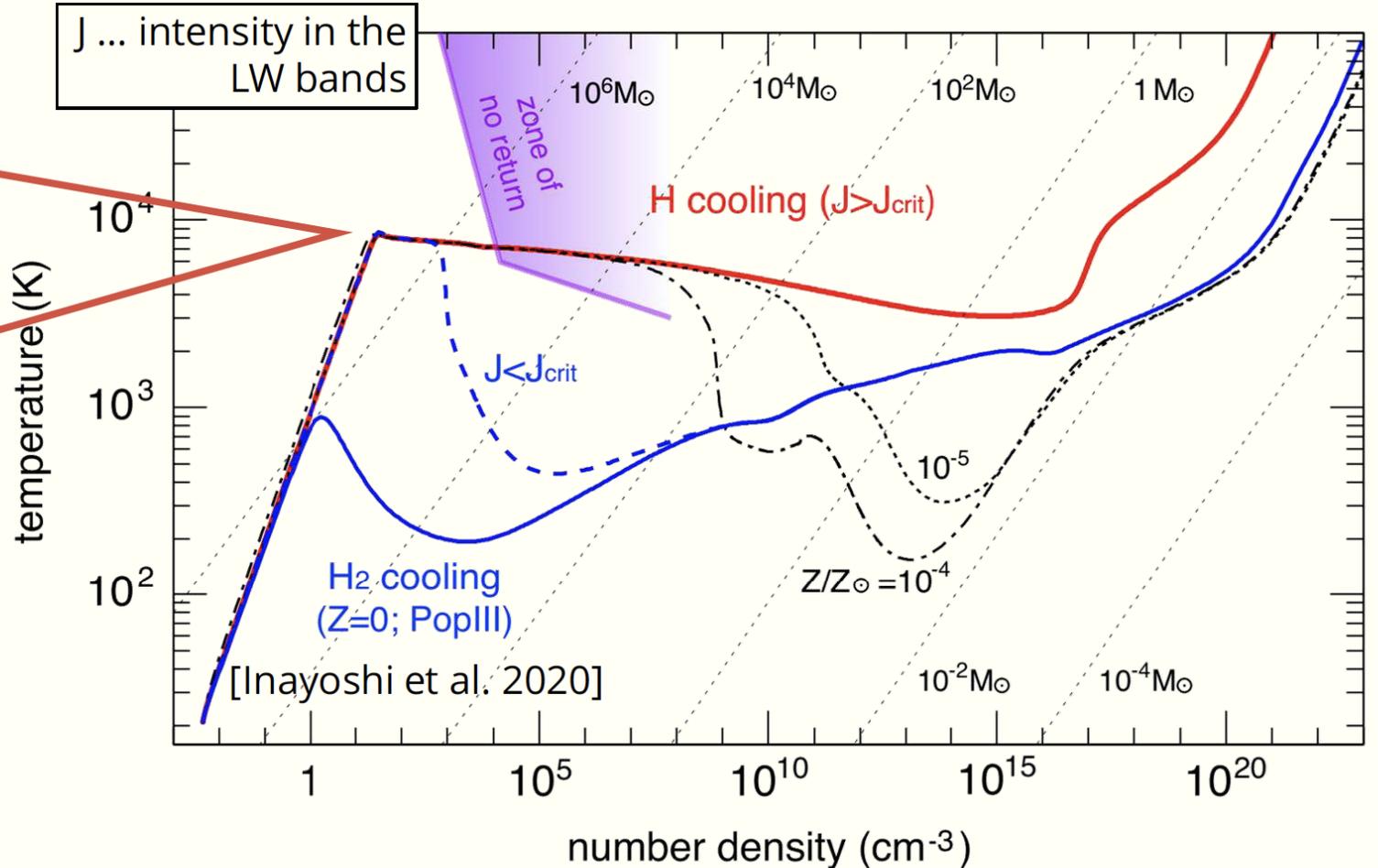
SMSを形成する場合の熱的進化

(e.g.) H_2 photo-dissociation by FUV photons with $11.2 < h\nu/\text{eV} < 13.6$ in the Lyman-Werner (LW) bands

Solomon process



Atomic H cooling halo, with massive $M_{\text{cloud}} = 10^5 [M_{\odot}]$, appears with $J > J_{\text{crit}}$.



質量降着を考慮した恒星進化計算の結果

➤ Final Mass

各グループの結果は概ね一致しているが、微妙には異なる。

最終的にGR不安定で星が崩壊する時点の決定に困難さがあることが一因

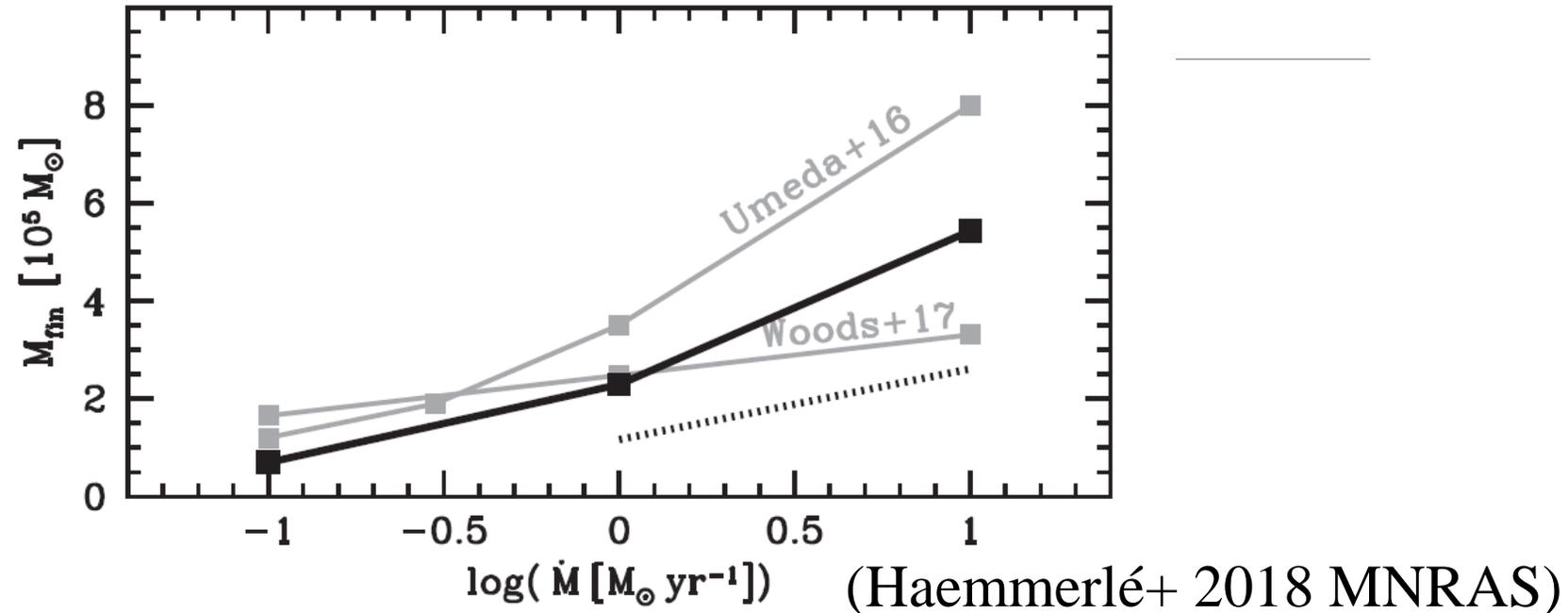


Figure 13. Final masses as a function of the accretion rate. The black curves show the results of the present work: the solid line corresponds to the final mass of our runs, and the dotted line to the mass at which the polytropic criterion indicates instability for $n = 3$. The grey curves are the final masses according to previous studies (Umeda et al. 2016; Woods et al. 2017).

(Nagele, Umeda + 2020-2023 の3つの Pop III SMS 論文)

1. Nagele, Umeda +2020, MNRAS 496, 1224

The final fate of supermassive $M \sim 5 \times 10^4 M_{\odot}$ Pop III stars: explosion or collapse?

2. Nagele, Umeda +2022, MNRAS 517, 1584

Stability analysis of supermassive primordial stars: a new mass range for general relativistic instability supernovae

3. Nagele, Umeda +2023, MNRAS 520, L72

Pulsations of primordial supermassive stars induced by a general relativistic instability;

visible to JWST at $z > 12$

Nagele, Umeda +2020, MNRAS 496 (論文1)

The final fate of supermassive $M \sim 5 \times 10^4 M_{\odot}$ Pop III stars: explosion or collapse?

主目的: Chen +2014, 5.55万 M_{\odot} の星(極めて狭い質量範囲、多分1例)が爆発(He燃焼時、GR不安定性、巨大エネルギー爆発)の検証

結果: Chen+を概ね追認。ほぼ全てのモデルが爆発(に近いが)しない。
非回転モデルは全滅。極めて低速自転のもの1例で爆発

* 従来の我々の手法を踏襲: 星のコードから、崩壊時は一般相対論的流体コードへ切り替え。結果が切り替えの微妙なタイミングに依存するので、すこし(かなり)もやもや感が残る。

一般相対論 (GR) 的不安定爆発とはどういうことか

- ・星は状態方程式のべき $d \ln P / d \ln \rho = \gamma < 4/3$ であると崩壊する
- ・ Supermassive star は Radiation dominant であるため、もともと γ がほぼ $4/3$
- ・星が非常に重い ($\sim 10^6 M_{\odot}$) と γ はますます $4/3$ に近くなり、GR効果で微妙に重力が強くなる効果で崩壊する
- ・星が水素でできている段階で崩壊するのでCNOサイクルで爆発するのではないかと考えられたが(1960年代)、1986 Fuller + ぐらいで、こういう**初代星**は爆発しないことは確定した。
- ・今回のものはより低い質量でHe燃焼時のGR不安定での崩壊、爆発を考えていることが新しい。

Nagele, HU +2022, MNRAS 517 (論文2)

Stability analysis of supermassive primordial stars: a new mass range for general relativistic instability supernovae.

Chris Nagele,¹★ Hideyuki Umeda,¹ Koh Takahashi,^{2,3} Takashi Yoshida,⁴ Kohsuke Sumiyoshi⁵

¹*Department of Astronomy, Graduate School of Science, the University of Tokyo, Tokyo, 113-0033, Japan*

²*Astronomical Institute, Graduate School of Science, Tohoku University, Sendai, 980-8578, Japan*

³*Max Plank Institute for Gravitational Physics (Albert Einstein Institute), D-14476 Potsdam, Germany*

⁴*Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502 Japan*

⁵*National Institute of Technology, Numazu College, Ooka 3600, Numazu, Shizuoka 410-8501, Japan*

Consider an infinitesimal, radial, Lagrangian perturbation which varies in time (t) as $\xi \propto e^{i\omega t}$ for $\omega^2 \in \mathbb{R}$. In Newtonian gravity, this perturbation obeys the equation (Shapiro & Teukolsky 1983)

$$\frac{d}{dr} \left[\Gamma_1 \frac{P}{r^2} \frac{d}{dr} (r^2 \xi) \right] - \frac{4}{r} \frac{dP}{dr} \xi + \omega^2 \rho_0 \xi = 0 \quad (2)$$

be exponential. Sturm–Liouville equations have the property that a sequence of solutions exist

$$\omega_0^2 < \omega_1^2 < \omega_2^2 < \dots \quad (4)$$

corresponding to ξ_i s where i is the number of nodes in the perturbation. Because of the above property, a necessary condition for instability is

$$\omega_0^2 < 0. \quad (5)$$

The corresponding equation in GR is ([Chandrasekhar 1964](#))

$$e^{-2a-b} \frac{d}{dr} \left[e^{3a+b} \Gamma_1 \frac{P}{r^2} \frac{d}{dr} (e^{-a} r^2 \xi) \right] - \frac{4}{r} \frac{dP}{dr} \xi + e^{-2a-2b} \omega^2 (P + \rho c^2) \xi - \frac{8\pi G}{c^4} e^{2b} P (P + \rho c^2) \xi - \frac{1}{P + \rho c^2} \left(\frac{dP}{dr} \right)^2 \xi = 0 \quad (6)$$

where a, b are the metric coefficients as in [Haemmerlé \(2021\)](#) and the density is defined in Eq. 1.

$$\rho = \rho_0 \left(1 + \frac{\epsilon}{c^2} \right)$$

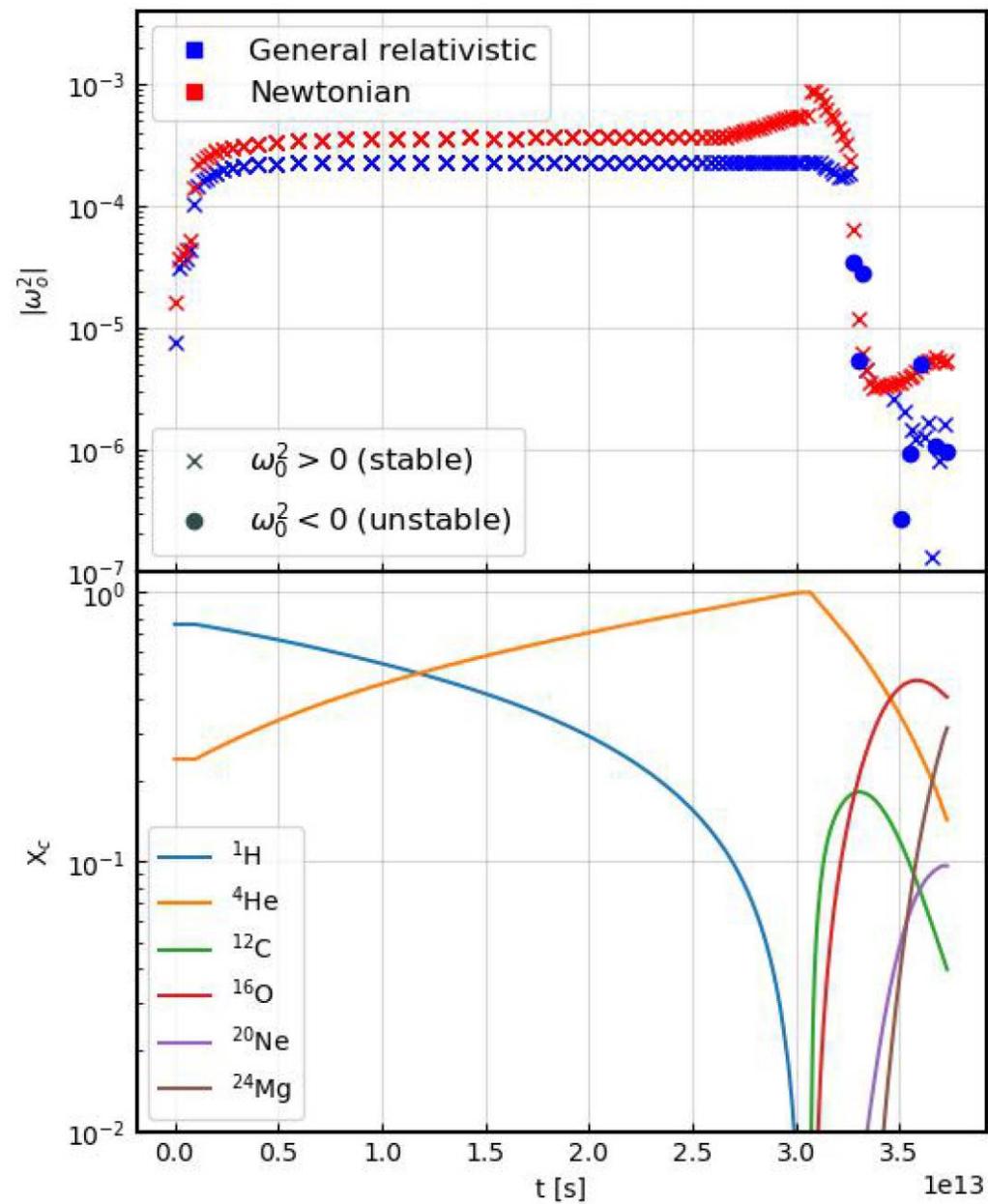


Figure 4. GR stability analysis (Sec. 2.2) applied to the results of the $3 \times 10^4 M_\odot$ model in HOSHI. Upper panel — amplitude of the fundamental

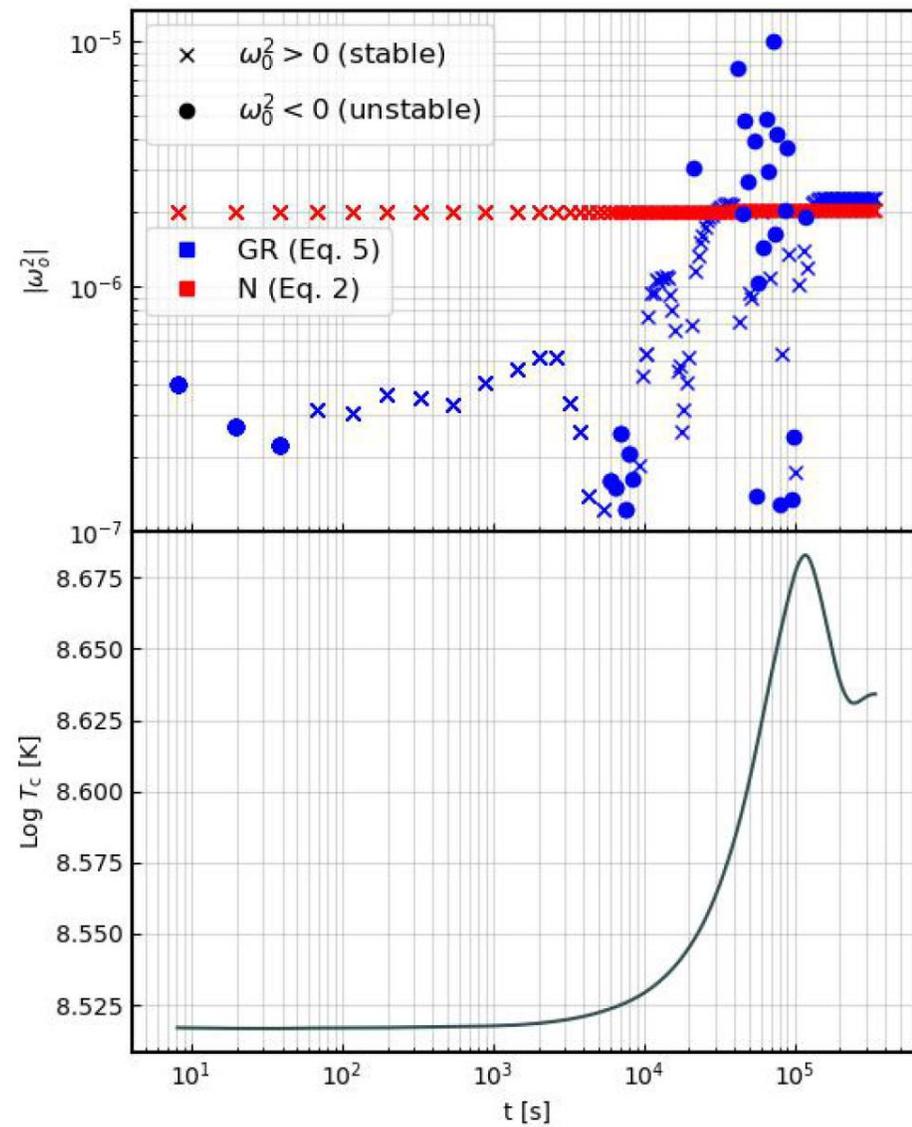


Figure 5. Stability analysis performed on the results of the HYDnuc calculation for the first unstable model of $2 \times 10^4 M_{\odot}$. Upper panel — stability analysis. Lower panel — central temperature.

Table 1. Summary table for all models. The columns are total mass, outcome of HYDnuc, mass of the isentropic core, central helium mass fraction at the start of HYDnuc, change in helium mass fraction, explosion energy, maximum central temperature, and maximum velocity of the outermost mesh point, denoted v_R .

	M [$10^4 M_\odot$]	Outcome	M_{core} [M_\odot]	$X_c(^4\text{He})$	$\Delta X_c(^4\text{He})$	E_{exp} [ergs]	max T_c [K]	max v_R/c
	2	Collapse	10926	1.37e-3	—	—	—	—
	2.1	Collapse	11368	2.23e-4	—	—	—	—
	2.2	Collapse	11729	1.22e-4	—	—	—	—
	2.3	Collapse	12595	3.17e-2	—	—	—	—
	2.4	Collapse	13180	3.44e-18	—	—	—	—
	2.5	Collapse	13798	2.69e-3	—	—	—	—
	2.6	Pulsation	14772	0.104	0.104	4.32e53	7.58e8	0.032
	2.7	Pulsation	14964	0.222	0.147	4.70e52	6.62e8	0.021
	2.8	Collapse	15596	0.713	—	—	—	—
	2.9	Pulsation	16183	0.589	0.153	7.56e53	7.33e8	0.041
	2.95	Explosion	16504	0.599	0.168	1.23e54	7.69e8	0.046
	3	Explosion	16817	0.652	0.152	1.43e54	8.06e8	0.048
	3.05	Collapse	17144	0.734	—	—	—	—
	3.1	Collapse	17516	0.794	—	—	—	—
	3.15	Collapse	17793	0.815	—	—	—	—
	3.2	Collapse	18091	0.815	—	—	—	—
	3.3	Collapse	18888	1.000	—	—	—	—
	3.4	Collapse	19460	1.000	—	—	—	—
	3.5	Collapse	19933	0.950	—	—	—	—
	4	Collapse	23891	0.960	—	—	—	—

初期質量
／ $10^4 M_\odot$

これらは
一定質量のモデル

爆発
エネルギー

Table 2. Mass ejecta by isotope for the explosions and the pulsations. Except for the first column which is consistent with Table 1, values are recorded in units of M_\odot . Yield tables for the explosions are available online.

M [$10^4 M_\odot$]	M_{ej}	$M(^1\text{H})$	$M(^4\text{He})$	$M(^{12}\text{C})$	$M(^{16}\text{O})$	$M(^{20}\text{Ne})$	$M(^{24}\text{Mg})$	$M(^{28}\text{Si})$	$M(^{32}\text{S})$
2.6	2808	1877	974	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
2.7	2299	1584	759	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
2.9	2078	1465	651	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
2.95	29500	5441	16946	3006	2505	481	812	306	1.2
3	30000	5537	18077	2986	1829	367	702	497	5.1

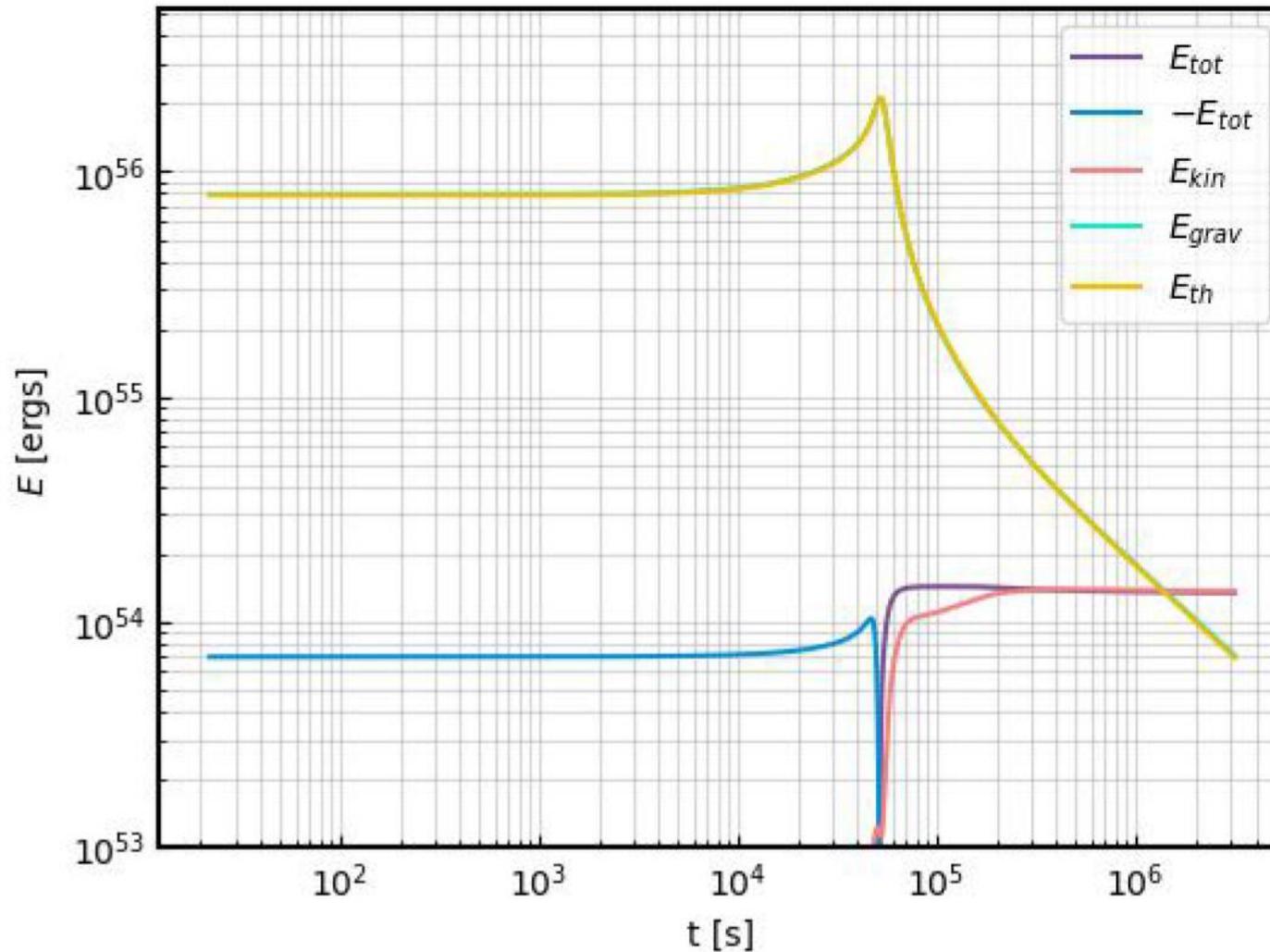
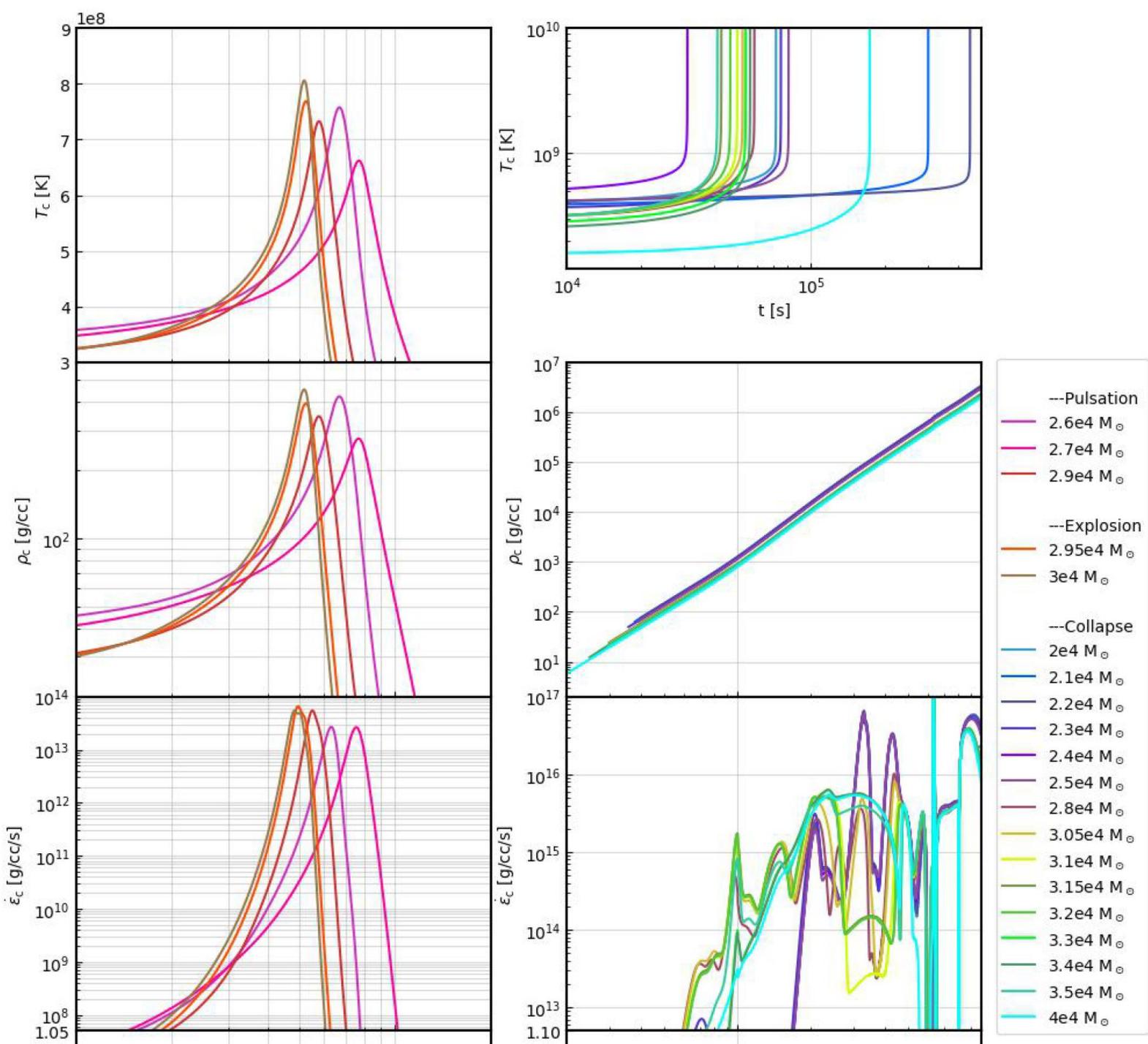


Figure 12. Total energy, kinetic energy, gravitational energy, and thermal energy (as defined in [Nagele et al. \(2020\)](#)) in HYDnuc as a function of time for the explosion of the $3 \times 10^4 M_{\odot}$ model. Unless otherwise specified, subsequent figure will show the $3 \times 10^4 M_{\odot}$ model.



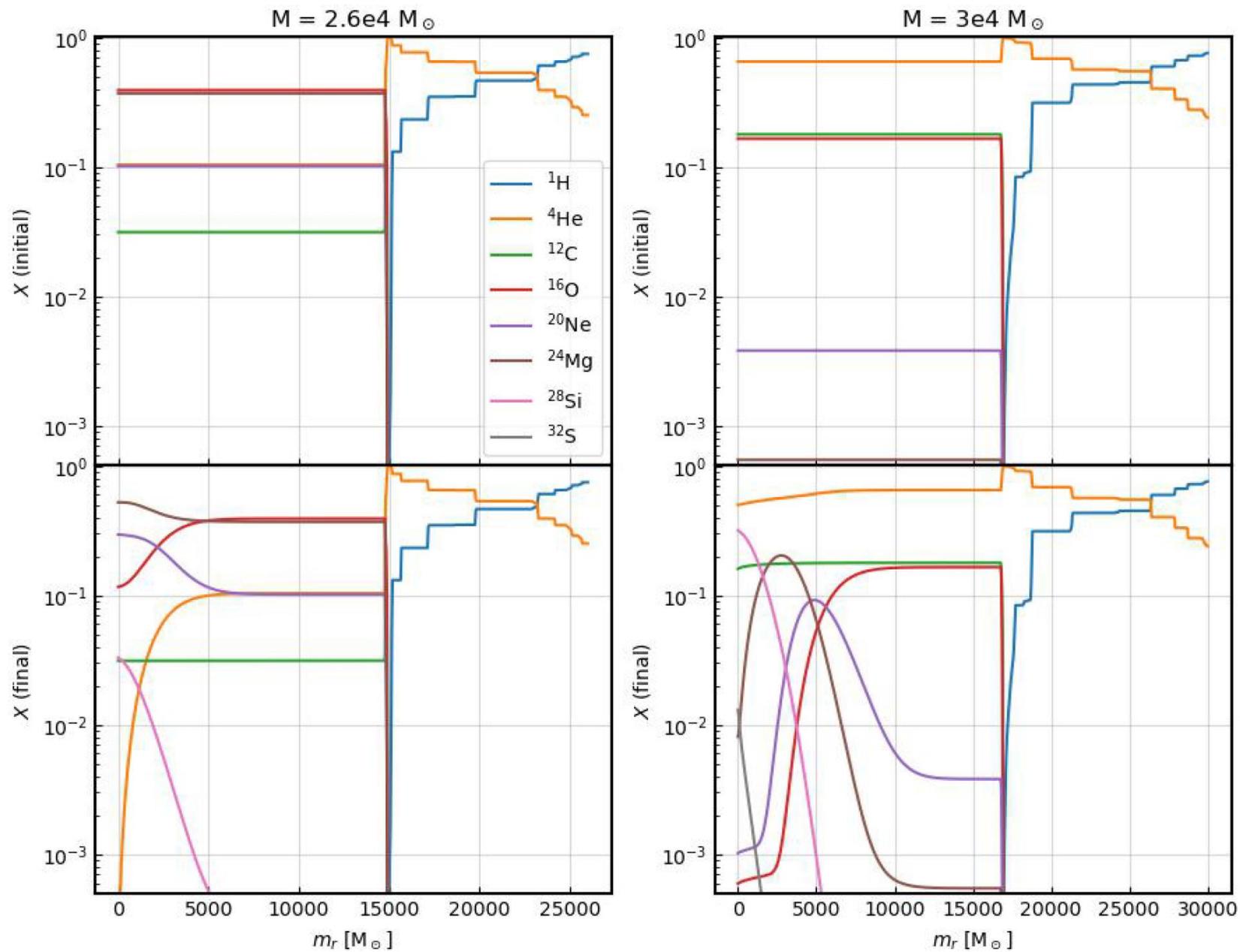
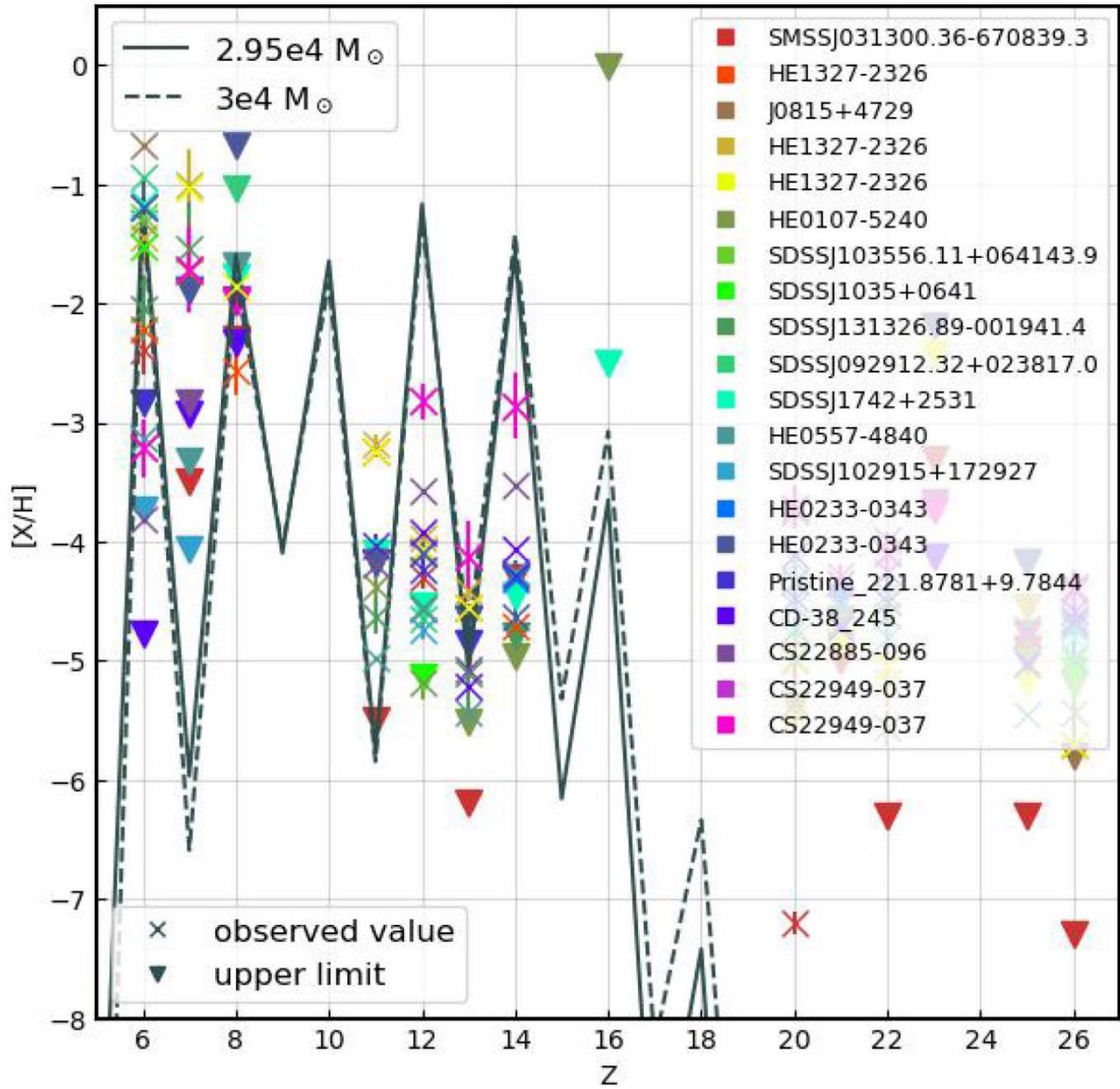


Figure 13. Initial (upper panel) and final (lower panel) isotope mass fractions as a function of the mass coordinate for the pulsation, $M = 2.6 \times 10^4 M_{\odot}$ (left) and the explosion, $M = 3 \times 10^4 M_{\odot}$ (right).



このような爆発
 をした元素組成を
 持ったEMP星は
 これまでに
 見つかっていない

さきほどのモデルの光度曲線とJWSTによる観測可能性の論文

Nagele, Umeda +2023, MNRAS 520, L72 (論文3)

Pulsations of primordial supermassive stars induced by a general relativistic instability; visible to JWST at $z > 12$.

[arXiv:2210.08662](https://arxiv.org/abs/2210.08662)

Chris Nagele,¹★ Hideyuki Umeda,¹ Koh Takahashi,² Keiichi Maeda³

¹*Department of Astronomy, Graduate School of Science, the University of Tokyo, Tokyo, 113-0033, Japan*

²*Astronomical Institute, Graduate School of Science, Tohoku University, Sendai, 980-8578, Japan*

³*Department of Astronomy, Kyoto University, Kitashirakawa-Oiwake-cho, Sakyo-ku, Kyoto 606- 8502*

用いたモデル

Table 1. Summary table for all models. The columns are total mass, outcome of HYDnuc, explosion energy, energy produced by nuclear reactions, ejecta mass, initial helium and oxygen fractions in the core, total (units of M_{\odot}) and percentage changes of helium and oxygen in the core.

$M [10^4 M_{\odot}]$	Outcome	E_{exp} [ergs]	E_{nuc} [ergs]	M_{ej} [M_{\odot}]	$X_{\text{c}}(^4\text{He})$	$X_{\text{c}}(^4\text{O})$	$\Delta M(^4\text{He})$	$\% M(^4\text{He})$	$\Delta M(^{16}\text{O})$	$\% M(^{16}\text{O})$
2.60	Pulsation #1	4.32e53	6.95e53	2808	0.104	0.392	244.3	15.9	697.7	12.0
	Pulsation #2	2.32e53	5.27e53	1175	0.090	0.345	180.4	12.3	489.5	10.7
2.70	Pulsation #1	4.70e52	4.20e53	2299	0.222	0.479	149.1	4.5	443.3	6.2
	Pulsation #2	-2.42e53	1.23e53	0	0.215	0.448	43.5	1.4	129.0	2.1
2.90	Pulsation #1	7.56e53	1.12e54	2078	0.589	0.221	360.2	3.8	806.6	22.5
	Collapse	—	—	—	0.566	0.172	—	—	—	—
2.95	Explosion	1.23e54	1.49e54	29500	0.599	0.211	478.4	4.8	985.2	28.3
3.00	Explosion	1.43e54	1.62e54	30000	0.652	0.165	519.0	4.7	955.5	34.4

光度曲線

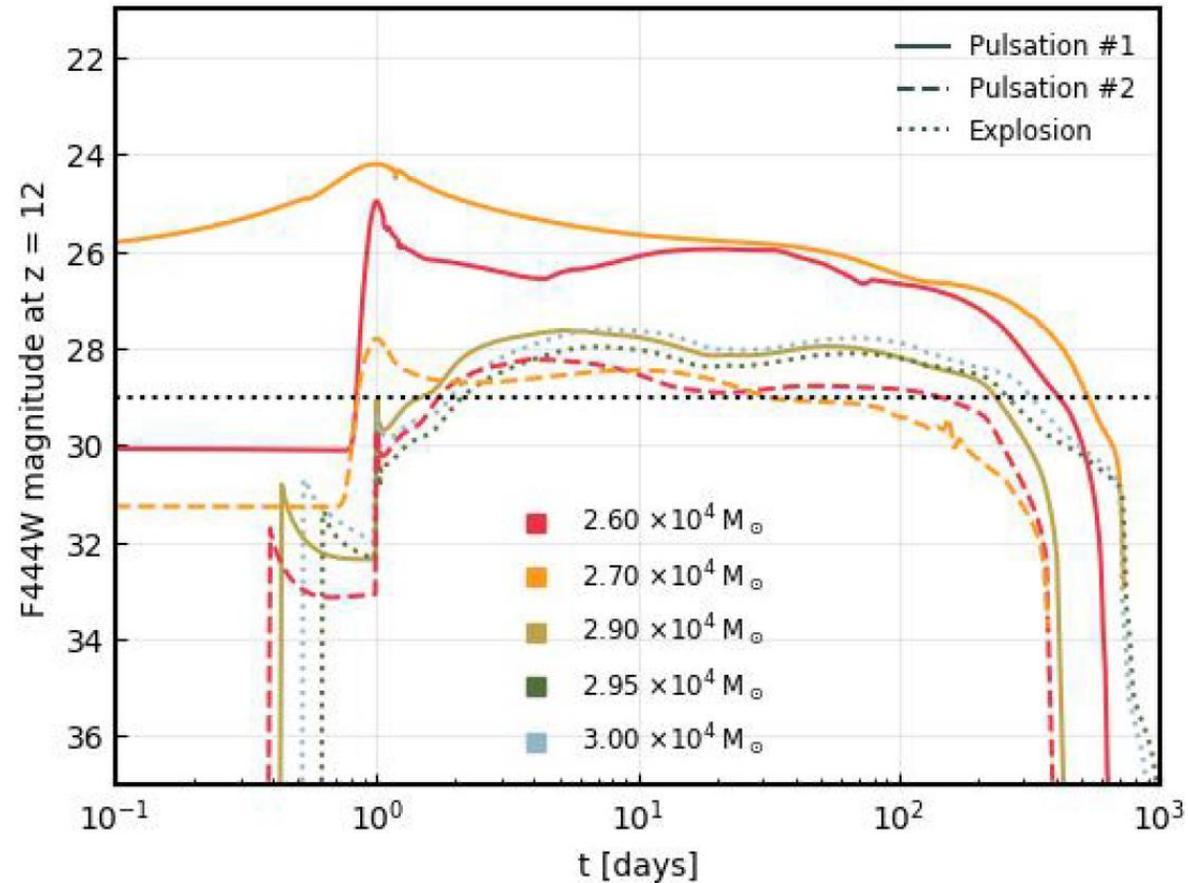


Figure 3. JWST AB magnitudes (F444W band) at $z = 12$ for pulsation #1 (solid lines) pulsation #2 (dashed lines) and the explosions from [Nagele et al. \(2022\)](#) (dotted lines). For convenience, the time is normalized so that maximum luminosity occurs at 1 day. For some models, the beginning of the SNEC calculation occurs less than 1 day before maximum luminosity. The horizontal black dotted line shows a typical limiting magnitude (29) for JWST and other near infrared instruments.

Cosmic Reionization

COSMIC MICROWAVE BACKGROUND

About 13.7 billion years ago
(370,000 years after the big bang)

BIG BANG

13.8 billion years ago

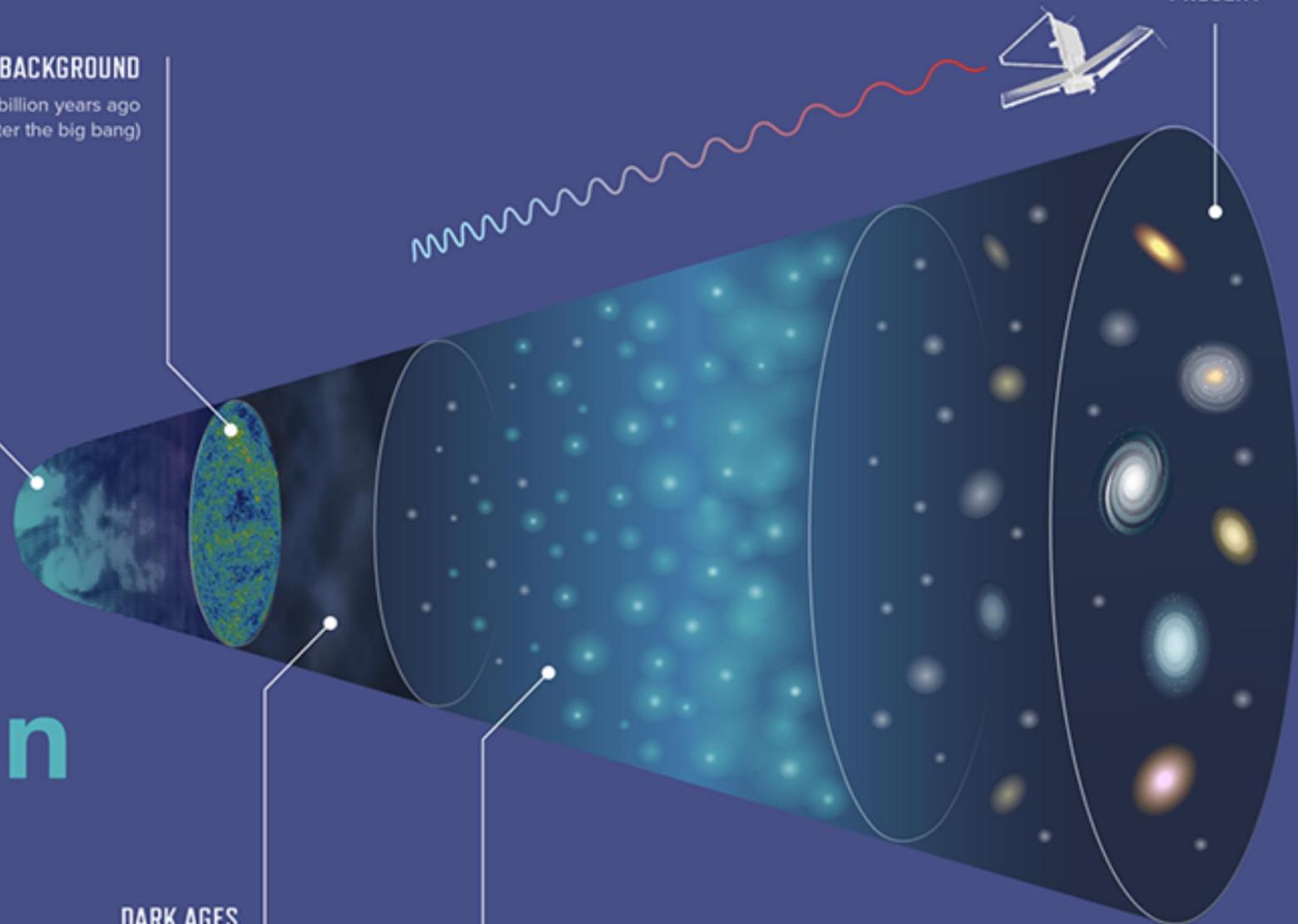
DARK AGES

Ended 13.6 billion years ago

ERA OF REIONIZATION

Ended 12.8 billion years ago

PRESENT



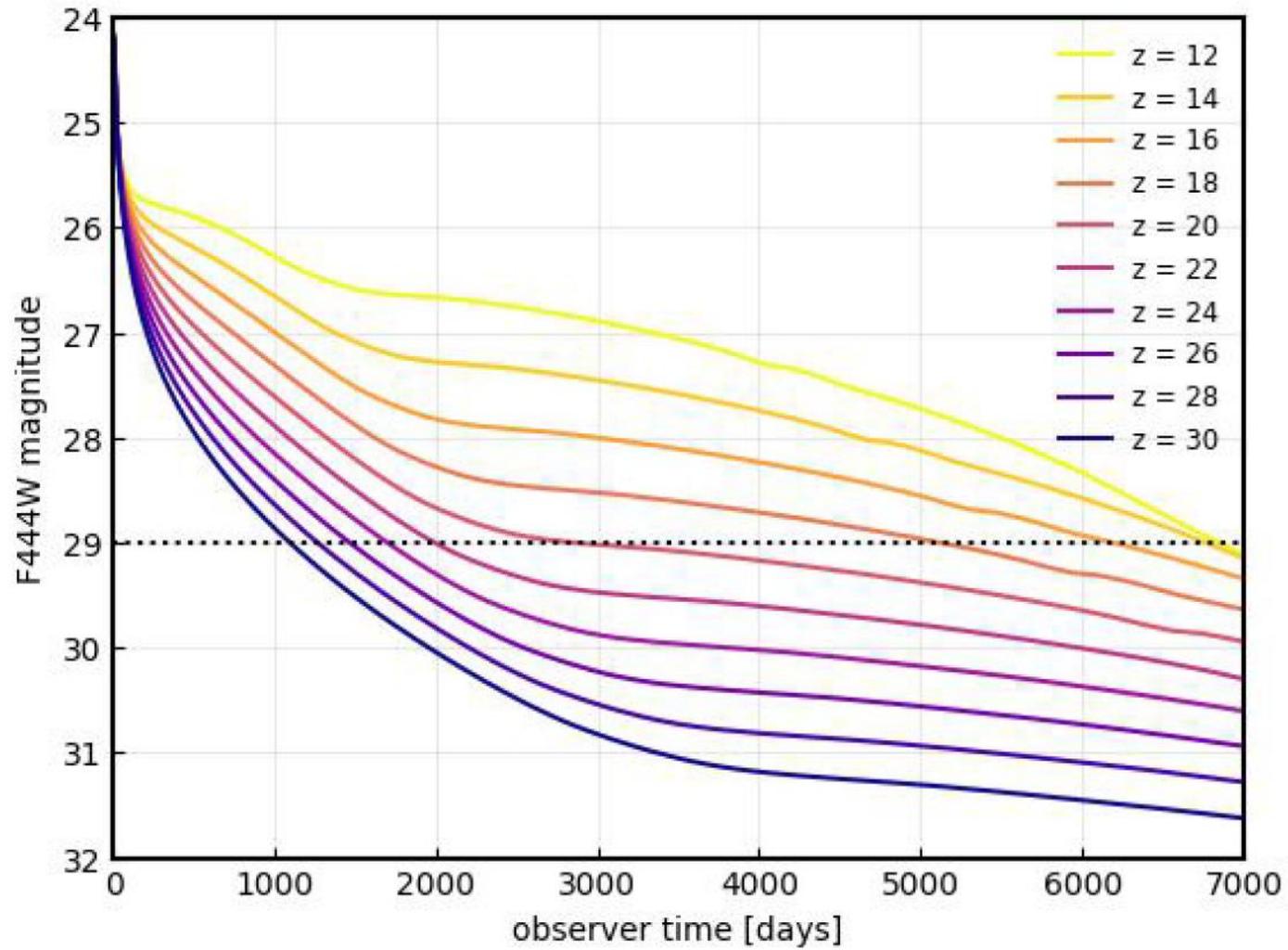


Figure 5. Redshift dependence of the F444W magnitude for our most luminous model, 27000 first pulsation. The x axis is shown in the observer frame.

ここまで(PopIII SMS)のまとめ

この質量範囲（2~3万太陽質量程度）でHe燃焼中のGR不安定性により初代星が（巨大エネルギーで）爆発できることを示したのは初である。

Chen+で見つけたものは、より大きい質量で、極めて狭い質量範囲（おそらく1例のみ発見）、それが観測される確率はほぼ無い

Chen+と（我々以前の結果とも）異なるのは、GR不安定性をより厳密に調べた結果であり、これを星の進化コードでのみで判定するのは極めて困難であったため。

この質量程度のSMSは初代星形成シナリオから比較的達成しやすい

実在すれば、JWSTで見える可能性がある

金属の多い SMS (Metal-enriched SMS)

(Nagele, Umeda + 2020-2023 の3つの論文: Pop II (& Pop III) SMS)

4. Nagele, Umeda +2023, MNRAS 523, 1629

Evolution and explosions of metal-enriched supermassive stars: proton rich general relativistic instability supernovae

5. Nagele & Umeda 2023, ApJ 949, L16

Multiple Channels for Nitrogen Pollution by Metal-enriched Supermassive Stars and Implications for GN-z11

6. Nagele & Umeda 2024, PhRvD 110, 1301

The formation of black holes from rapidly accreting supermassive stars is not trivial: Simulations of thermonuclear pulsations and explosions

金属の多い SMS の形成

Pop III SMS と同様な形成方法では 金属量に上限 $Z < 10^{-3} Z_{\odot}$ (Chon & Omukai 2020)

もっと Metal-rich なものの可能性は、

1. formed by runaway collisions (?)

2. merger of two gas-rich massive galaxies (Mayer et al. 2010, 2015; Mayer & Bonoli 2019)

これらの計算では 太陽組成 (を超える) SMS の形成が示されている

形成過程としては中心の原始星にハイパー-Eddington Accretion (降着率 $10^{2-4} M_{\odot}/\text{yr}$ など) をして形成 (と仮定)

こういうものが実在した場合にどうなるかを考えるため、このような Metal-enriched SMS の進化と元素合成 (一定質量、論文4)、その応用 (論文5) ハイパー Eddington Accretion を仮定した恒星進化計算 (論文6) を行った。

4. Nagele, Umeda +2023, MNRAS 523, 1629

Evolution and explosions of metal-enriched supermassive stars: proton rich GR instability SNe

These stars contain both hydrogen and metals and thus may **explode** due to **the CNO cycle** (carbon–nitrogen–oxygen) and the **rp process** (rapid proton capture).

These explosions are characterized by enhanced nitrogen and intermediate mass elements ($16 \geq A \geq 25$), and suppressed light elements ($8 \geq A \geq 14$)

爆発するモデルと
しないモデル

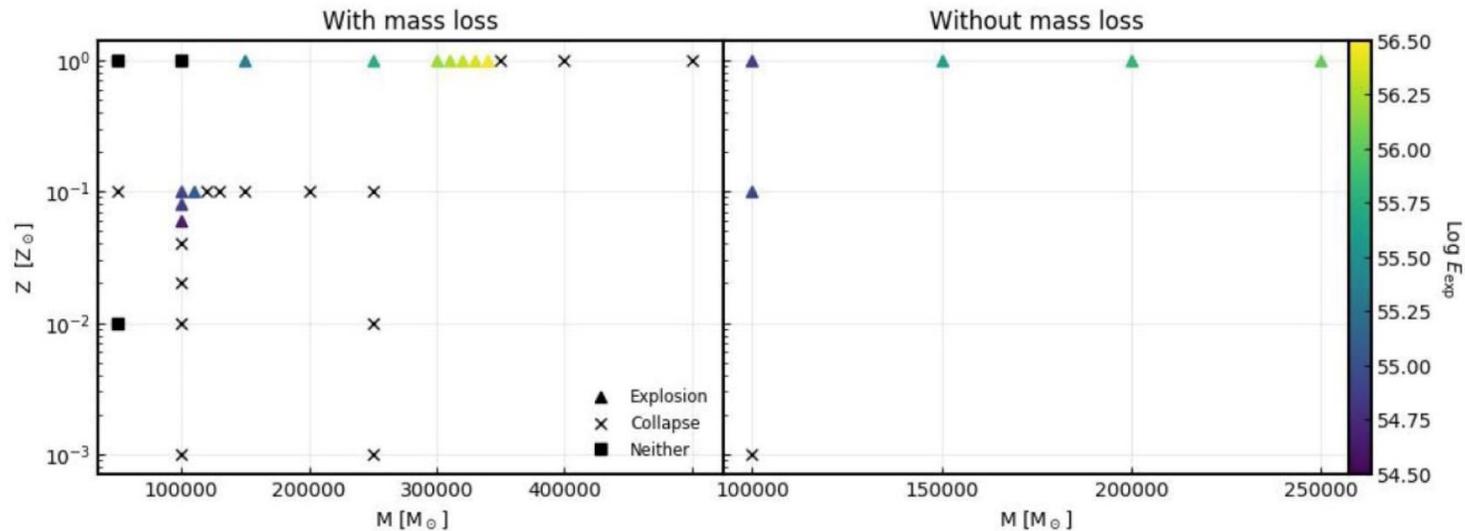


Figure 4. Dependence of explosion energy (colour) for the exploding models (triangles) on mass and metallicity. The black crosses are models which failed to explode and black squares either do not reach the GR instability (because of large mass-loss) or are stable. The left-hand panel shows models with mass-loss while the right-hand panel shows those without.

元素合成に関する応用例 1例: Nagele & Umeda 2023, ApJ 949, L16 (論文5)

Multiple Channels for Nitrogen Pollution by Metal-enriched Supermassive Stars and Implications for GN-z11

•Nagele, Chris & Umeda, Hideyuki

GN-z11 の組成観測
の範囲と

金属の多いSMS
による放出元素
組成比との比較

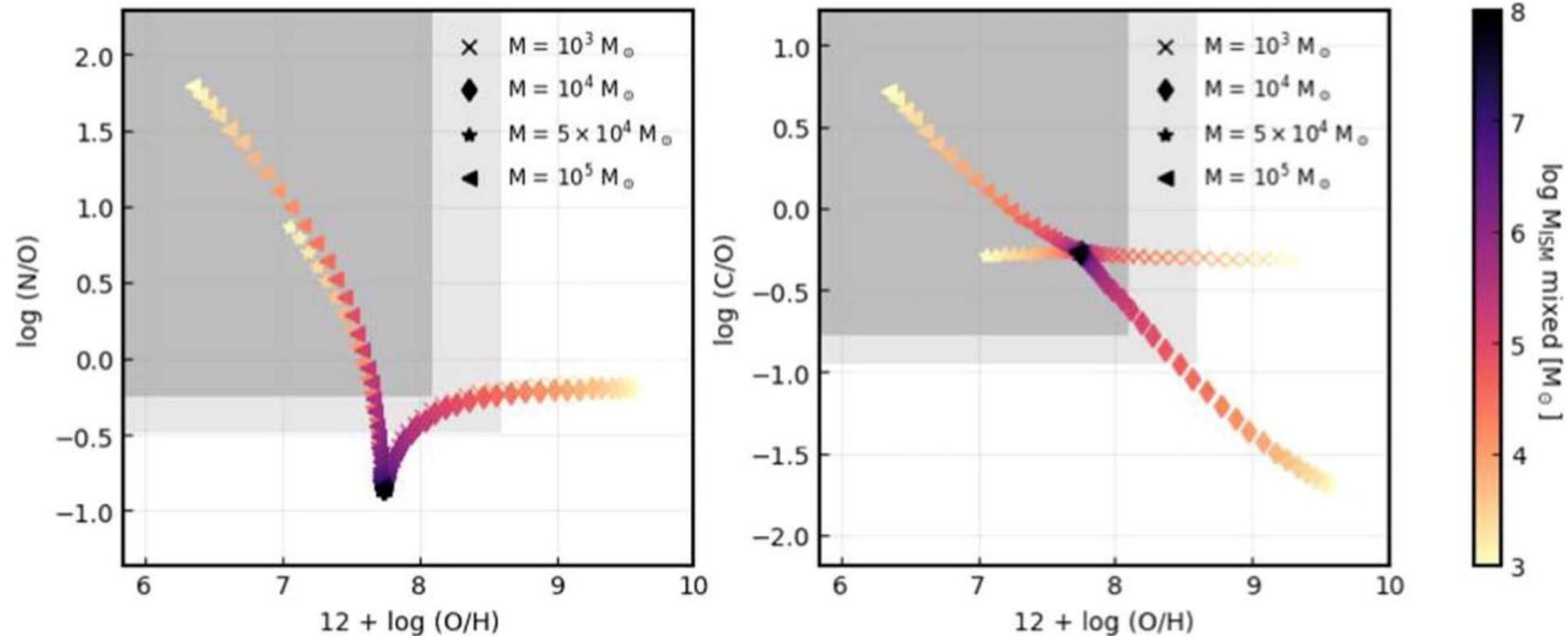


Figure 3. Abundance ratios of nitrogen to oxygen, carbon to oxygen, and oxygen to hydrogen. The symbols denote each of the four models, while the color shows how much $Z = 0.1 Z_{\odot}$ ISM the yields from each model have mixed with. The gray regions show the conservative (lighter) and fiducial (darker) constraints on GN-z11 from the model of Cameron et al. (2023).

Metal-rich なものが含まれています

6. Nagele & Umeda 2024, PhRvD 110, 1301

**The formation of black holes from rapidly accreting supermassive stars is not trivial:
Simulations of thermonuclear pulsations and explosions**

We present the first ever general relativistic hydrodynamical simulations of the collapse of **rapidly accreting supermassive stars**.

We find that **black hole formation is in many cases prevented by nuclear burning** due to the long timescales of the collapse of these stars (106 s).

Consequently, this is **a novel astrophysical site for hot CNO burning and hydrogen burning via proton captures**.

For Pop III accreting supermassive stars, we find that **only stars with very high (100 M_{\odot}/yr) or low (0.1 M_{\odot}/yr) accretion rates can form black holes**
(Pulsation で質量を飛ばすという意味で、その後BHになる可能性はかなりある)

For metal rich accreting supermassive stars ($Z \geq 0.1Z_{\odot}$), we do not find any black hole formation, with some models undergoing extremely energetic explosions (1055 ergs).

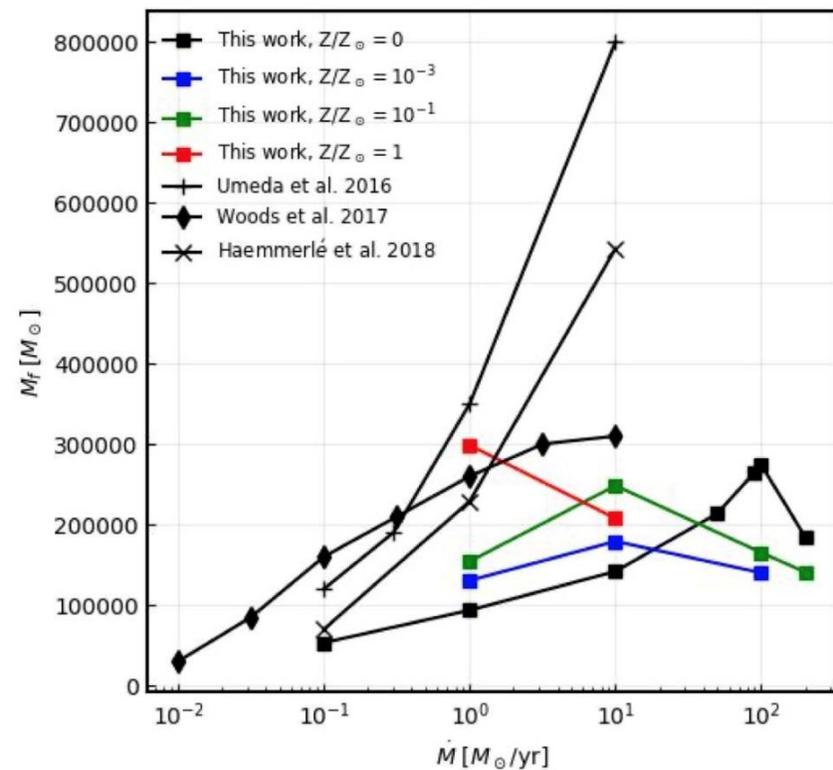
論文6

パルス放出モデル 爆発したモデル

降着率 金属量

爆発の有無

放出質量



\dot{M} [M_{\odot}/yr]	Z [Z_{\odot}]	Log $T_{c,GRI}$	M_{GRI} [M_{\odot}]	$M_{core,GRI}$ [M_{\odot}]	Outcome	Log $T_{c,max}$	E_{nuc} [10^{54} ergs]	$M_{ejected}$ [M_{\odot}]	E_{kin} [10^{54} ergs]
0.1	0	8.184	5.325e4	2.375e4	Collapse	—	—	—	—
1	0	8.202	9.356e4	1.756e4	Pulsation	8.709	1.059	3051	0.1312
10	0	8.199	1.418e5	9349	Pulsation	8.471	0.6154	0	0
50	0	8.226	2.138e5	5881	Pulsation	8.519	1.138	1046	0.01036
90	0	8.239	2.648e5	1.02e4	Collapse	—	—	—	—
100	0	8.253	2.742e5	7148	Collapse	—	—	—	—
200	0	8.254	1.846e5	6954	Pulsation	8.649	1.792	3878	0.1255
1	10^{-3}	8.012	1.305e5	3.411e4	Collapse	—	—	—	—
10	10^{-3}	8.055	1.791e5	2.204e4	Pulsation	8.343	0.88	0	0
100	10^{-3}	8.124	1.4e5	7364	Pulsation	8.47	0.8506	0	0
1	10^{-1}	7.868	1.542e5	4.886e4	Pulsation	8.236	1.27	4312	0.1733
10	10^{-1}	7.886	2.484e5	2.25e4	Pulsation	8.176	0.9747	0	0
100	10^{-1}	8.032	1.651e5	1.35e4	Explosion	8.297	4.725	1.651e5	1.043
200	10^{-1}	8.013	1.409e5	1.013e4	Explosion	8.28	3.196	1.409e5	0.3221
1	1	7.808	2.986e5	1.188e5	Explosion	8.274	17.26	2.986e5	10.3
10	1	7.805	2.076e5	4.294e4	Pulsation	8.069	0.8976	0	0

全質量 コア質量

爆発時
最高温度

爆発
エネルギー

現在行っている計算

平野(神奈川大学)他((2017)の宇宙論的シミュレーションで Streaming velocity の大きな領域で SMS 形成が期待されているモデル、の降着率データを用いて、どの様な SMS が形成されるか、またそれらは爆発するのかどうかを調べている。

また、その計算の降着物質に角運動量を与えて、SMSがどの程度まで速く回転できるのか、今後調べていく予定である

(slow rotation の計算は半年以上かかって、ようやく先週終わった、爆発しないでGR崩壊へ(より高速回転の計算は始めたばかり。time step 非常に小さくしないとすぐ破綻するので、かなり時間がかかるかもしれない。)