X-ray Bursts: Thermonuclear Reactions on the Surface of Neutron Star

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Outline

- Introduction to X-ray Bursts
  - Observation and Theory
- Numerical Models with Stellar Evolution Code
- Nuclear Physics for XRBs
  - Reaction Network of Rapid Proton Process
  - Experiment with Rare Isotope Beam
- Summary

LMXBs vs HMXBs

Properties	LMXBs	HMXBs
Accreting object	Low B-field NS or BH	High B-field NS or BH
Companion	Low-mass main sequence	High-mass (O or B type) main sequence
	$(L_{opt}/L_x \ll 0.1)$	$(L_{opt}/L_x > 1)$
Stellar population	Old$(> 10^9$ yr$)$	Young$(< 10^7$ yr$)$
Mechanism	Roche-lobe overflow	Stellar wind
Accretion timescale	$10^7 - 10^9$ yr	10^5 yr
Variability	X-ray bursts, Transient behavior	Regular X-ray pulsation
X-ray spectra	Soft (≤ 10 keV)	Hard (≥ 15 keV)

Table 1: Summary of LMXBs and HMXBs (Rosswog et al. 2011)

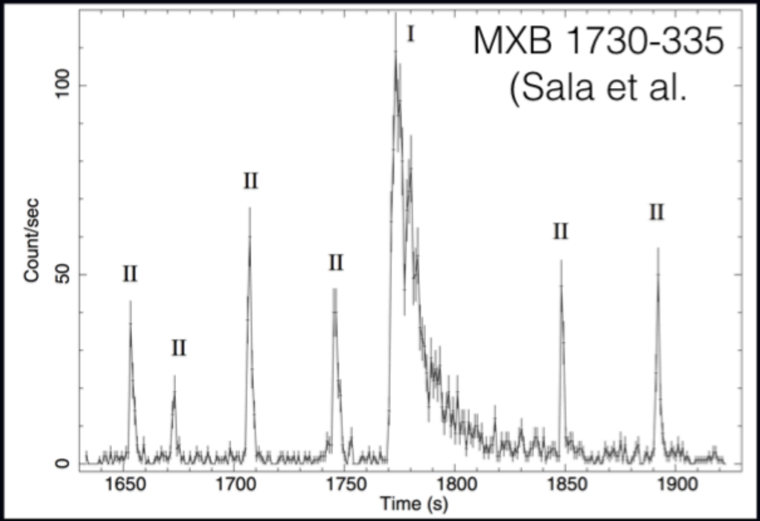
Where do we find them and what is the mechanism of X-ray Bursts?

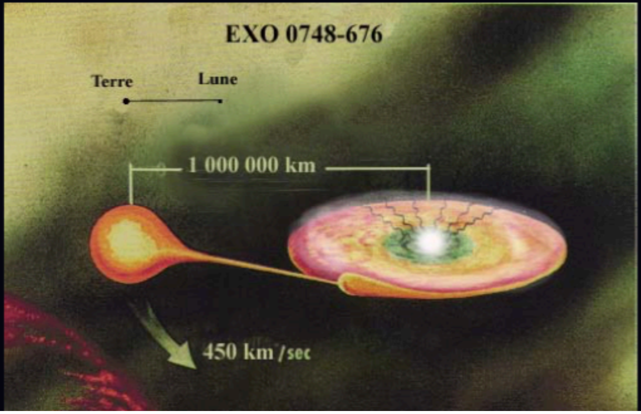
- **Low-Mass X-ray Binaries(LMXBs)**

Accreting H and/or He from companion stars

Thermonuclear explosion (X-ray)

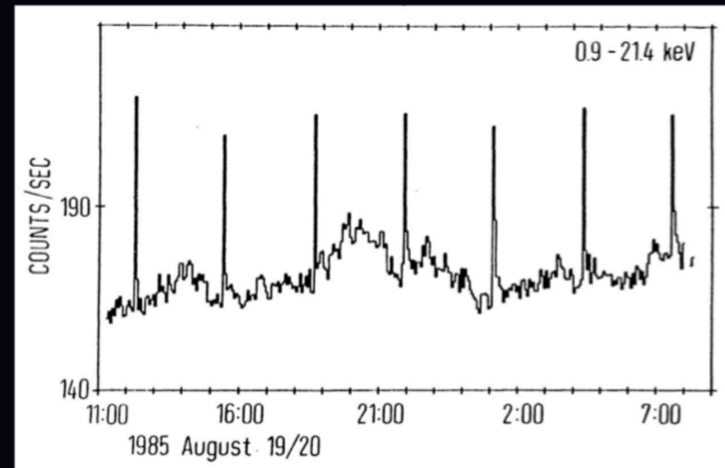
Can be observable near the neutron star surface





What are the characteristic of Type I X-ray bursts?

- Occurs on the neutron star surface in LMXBs by nuclear ignition (unstable H or He)
- Energy range ~ 10keV (soft X-ray)
- Maximum luminosity ~ 10^{38} erg/s (Eddington limit)
- recurrence time ~ hours to days
- X-ray softening during decay
- regular or irregular bursts recurrence



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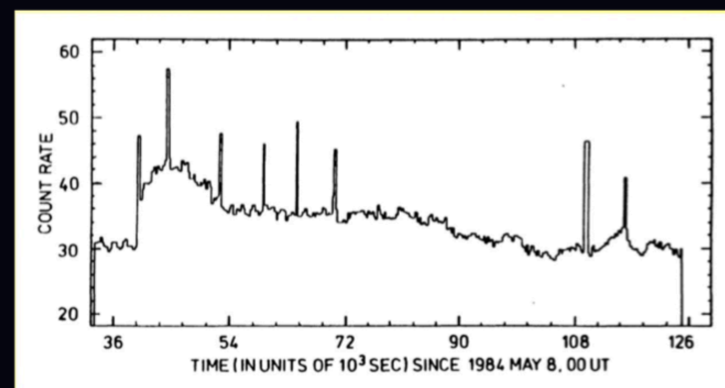

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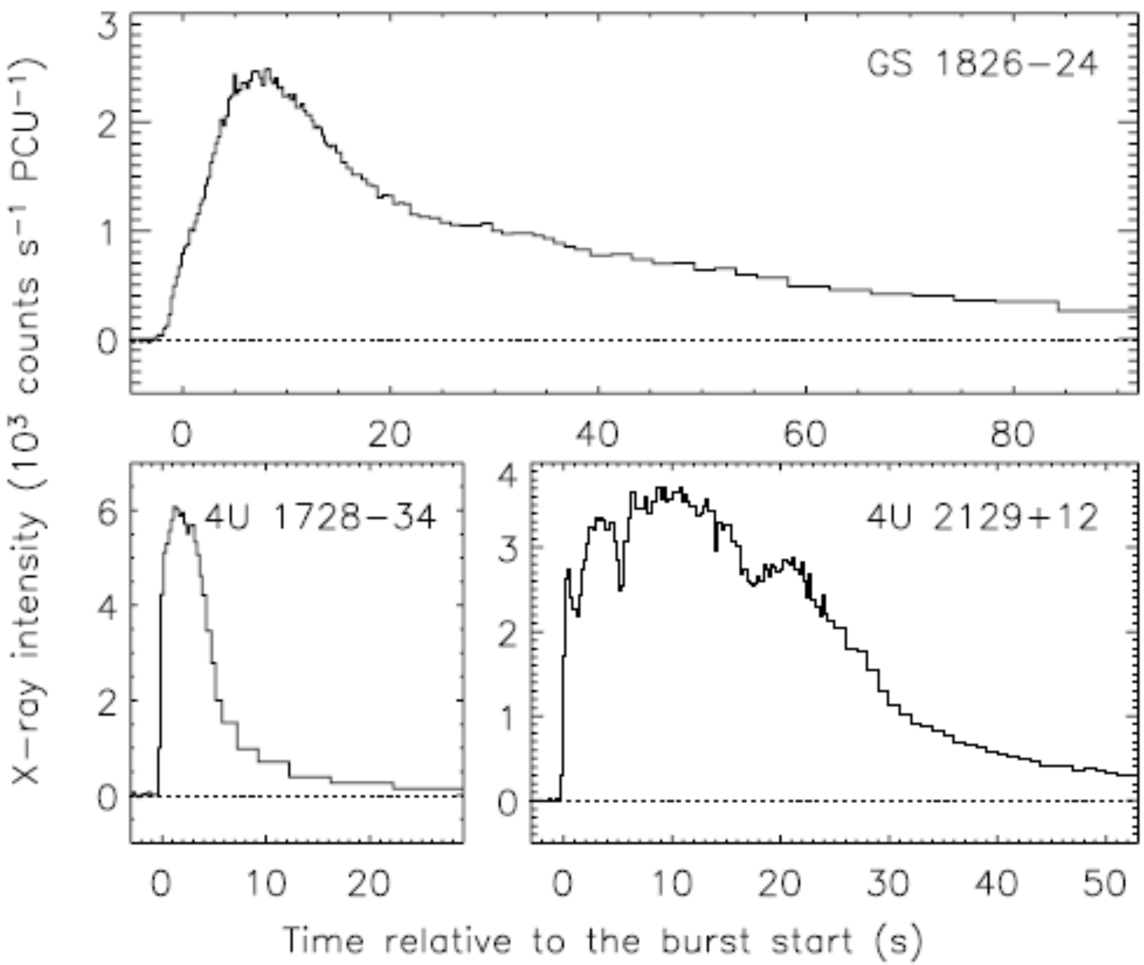
number of Type I X-ray bursters ~ 84(2007)
(of ~160 LMXBs), 2/3 located in the Galactic Bulge

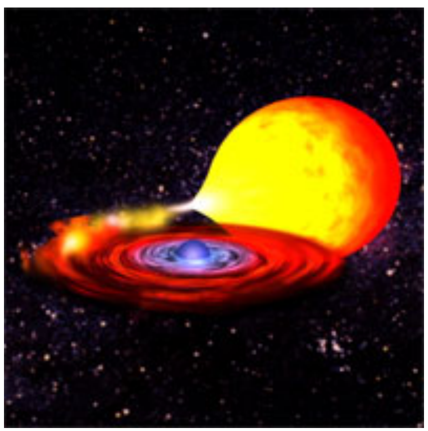
Lightcurve of XRBs



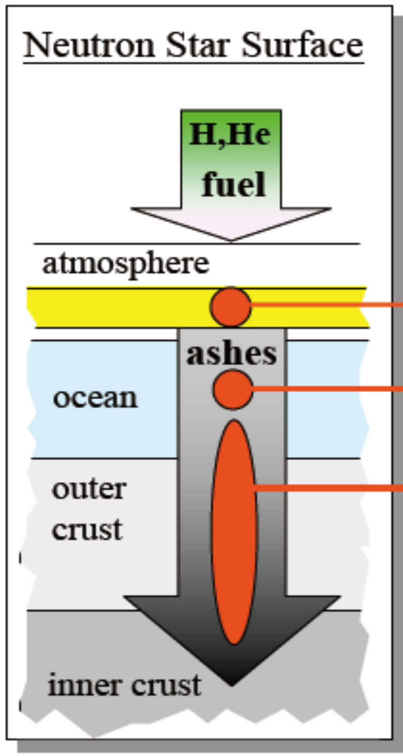
Galloway et al. 2008, ApJS

X-ray Bursts

- Accretion onto the surface of neutron star: high or low mass X-ray binaries



Nuclear reactions on accreting neutron stars



H and He burning (rp-process)

- X-ray bursts lightcurves (10s – min's)
- Radius expansion
- Nucleosynthesis (p-nuclei ?)
- Start composition for deeper processes

Deep burning: H-EC/ C-fusion
Photodisintegration of heavy ashes

- Superbursts

Electron captures
Pycnonuclear fusion reactions

- Cooling / off state observations
- Heat feeds back on burst properties
- Gravitational wave emission
- Magnetic fields

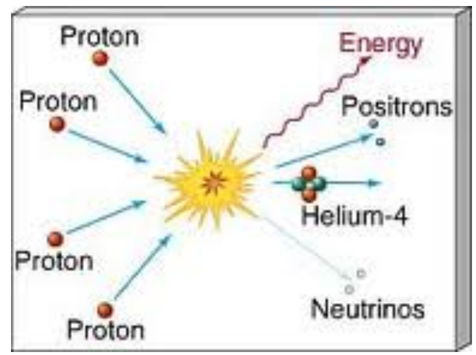
From Schatz's Presentation

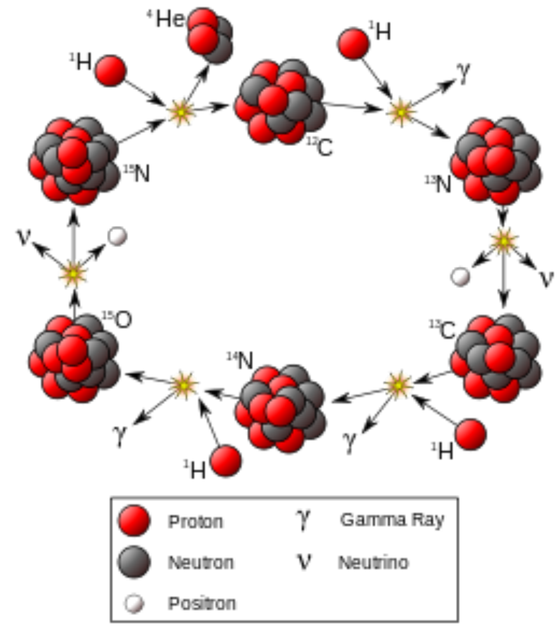
Nuclear Reactions for Type I X-ray Bursts

- Hydrogen burning by CNO-cycle
- 3-alpha reaction
- alpha-p reaction
- p-gamma reaction
- weak interactions

$$e^- + {}^A Z \rightarrow {}^A(Z-1) + \nu_e,$$

$${}^A Z \rightarrow {}^A(Z-1) + e^+ + \nu_e,$$

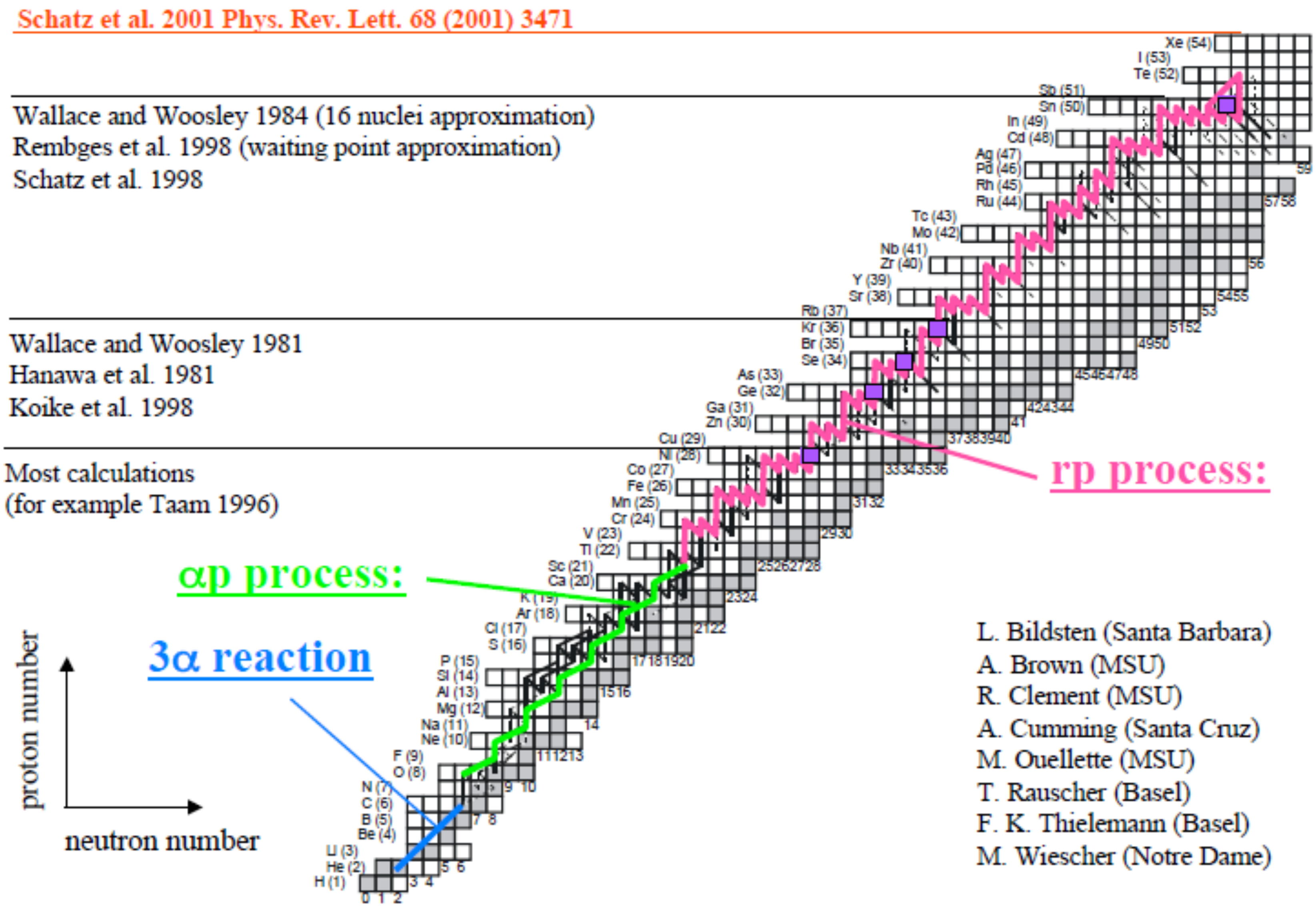




CNO-I Cycle

$$3\alpha \rightarrow {}^{12}\mathrm{C}\ (p,\gamma)\ {}^{13}\mathrm{N}\ (p,\gamma)\ {}^{14}\mathrm{O}\ (\alpha,p)\ {}^{17}\mathrm{F}(p,\gamma)$$
$${}^{18}\mathrm{Ne}\ (\alpha,p)\ {}^{21}\mathrm{Na}\ (p,\gamma)\ {}^{22}\mathrm{Mg}\ (\alpha,p)\ {}^{25}\mathrm{Al}\ldots$$

Thermonuclear burning during X-ray burst – STEP 1: one zone model



From Schatz's Presentation

Waiting Points Nuclei

TABLE 1

PROTON SEPARATION ENERGIES OF ISOTONES NEAR THE LONG-LIVED WAITING POINT NUCLEI ^{64}Ge, ^{68}Se, ^{72}Kr, AND ^{76}Sr

Nucleus	S_p[a] (MeV)	Uncertainty (keV)
^{65}As	−0.43	290
^{66}Se	2.43	180
^{69}Br	−0.73	320
^{70}Kr	2.14	190
^{73}Rb	−0.55	320
^{74}Sr	1.69	210
^{77}Y	−0.23	Unknown
^{78}Zr	1.28	Unknown

[a] Taken from the compilation of Brown et al. 2002, except for the proton separation energies of ^{77}Y and ^{78}Zr, which were taken from the unpublished calculations of A. Brown 2002 (private communication).

Woosley et al., 2004, ApJS

Numerical Simulations of XRBs

- 1D model with spherical coordinates
- Modify 1D stellar evolution code
  - Hydro-dynamic/static conditions with nuclear reactions and energy transport via radiation and convection
  - Model parameters: accretion rates and composition of accreted material
  - Envelope of neutron star surface, e.g., crust and pycno-reaction at crust

Equations for Stellar Evolution

Basic equations to calculate stellar structure(Using Lagrangian coordinates)

1. $\frac{dP(M)}{dM} = -\frac{GM}{4\pi r^4(M)}$ Hydrostatic equilibrium equation

2. $\frac{dL(M)}{dM} = \varepsilon - T\frac{dS}{dt}$ Thermal energy conservation equation

3. $\frac{dT}{dM} = -\frac{3kL}{4acT^3 16\pi^2 r^4}$ Energy transfer equation for radiative equilibrium condition

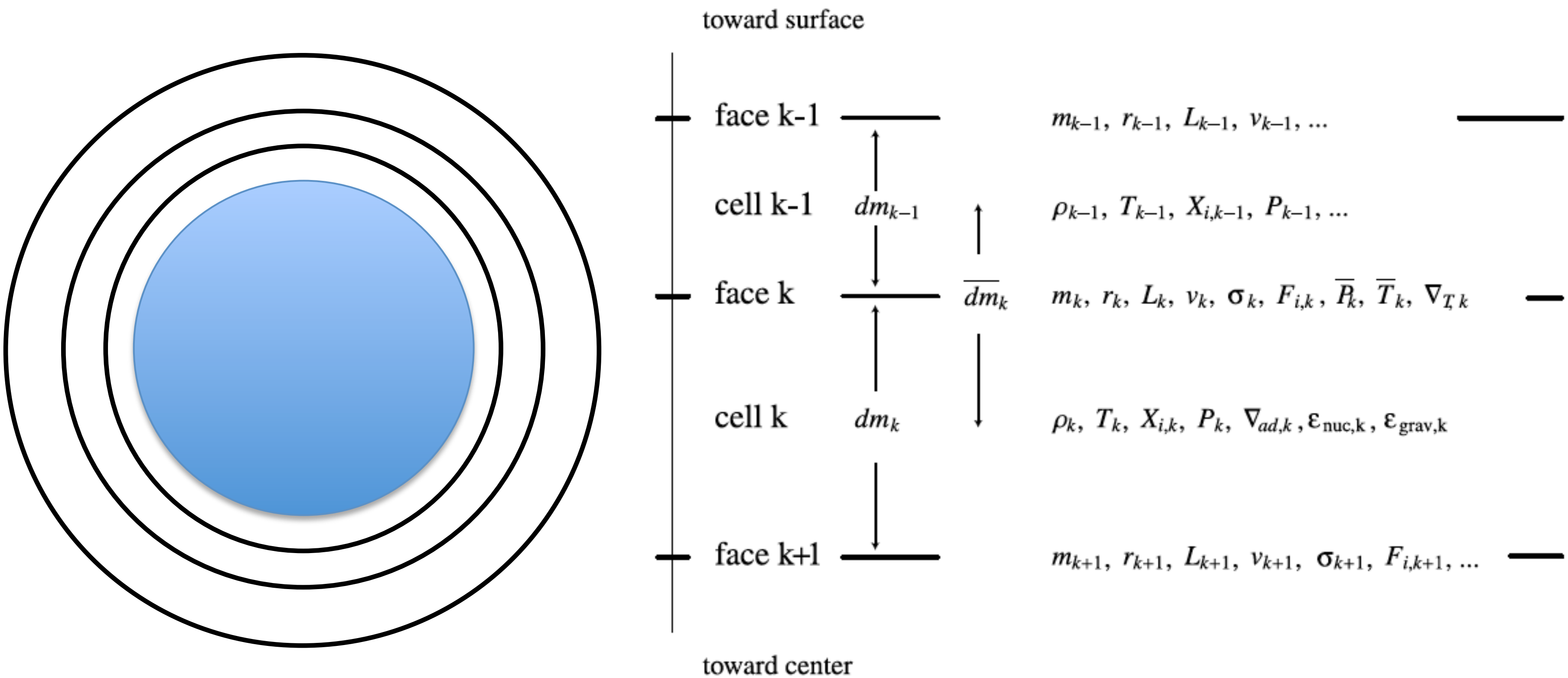
4 . $\frac{dT}{dM} = \frac{\Gamma_2 - 1}{\Gamma_2}\frac{T}{P}\frac{dP}{dM}$ Energy transfer equation for convective condition

To calculate the composition of a star, we need to solve general composition change equation

5 . $\left[\frac{\partial N(A,Z)}{\partial t}\right]_{nuclear\ reaction} = r_{generation}(A,Z) - r_{annihilation}(A,Z)$

This equation should include all related isotopes. So it is generally represented by a matrix form.

Numerical Simulations of XRBs



Network of Nuclear Reactions

- Various websites linked from ‘nucastrodata.org’ (e.g., JINA REACLIB)
- Experiments and Theoretical Calculations
- Which reaction network to use?
- Any opportunity to improve the current reaction rates?
- If so, how does a new reaction rate affect the astrophysical phenomena?

Nuclear Reactions for Type I X-ray Bursts

- Rates are available from experiments, shell-model calculations, and statistical model (e.g., Hauser-Feshbach calculations such as NON-SMOKER)
- Little experimental information for the proton-rich nuclei
- Shell-model calculations can provide experimentally undetermined p-gamma rates for A=44-63

1D Multi-Zone Model

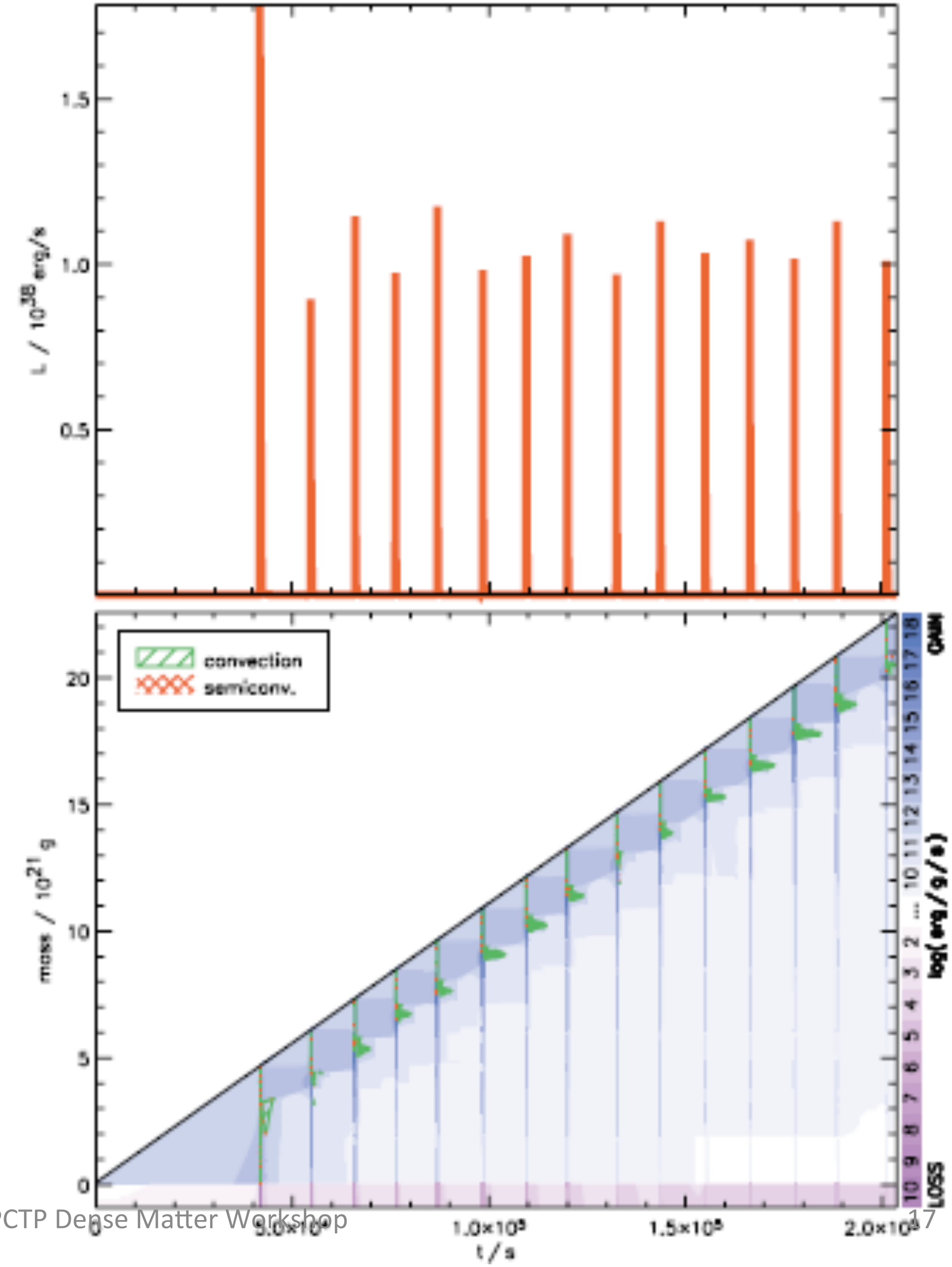
- Woosley et al., 2004, ApJS
  - Nuclear reaction networks of ~1300 isotopes

TABLE 2

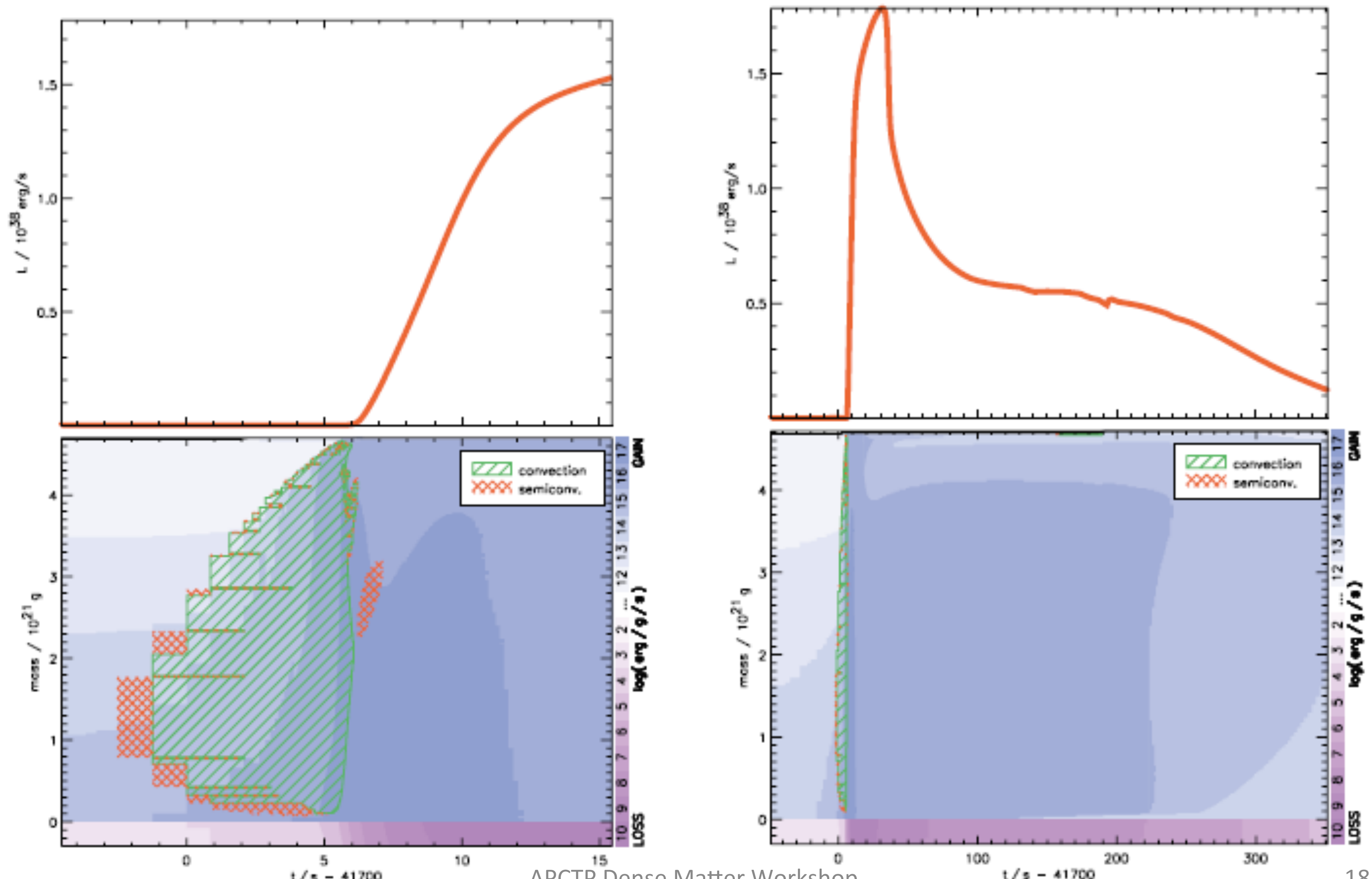
SUMMARY OF MODEL PROPERTIES

Model	Z $(Z_\odot)$	Acc. Rate $(10^{-10}\ M_\odot\ \mathrm{yr})$	Number of Bursts
zm	0.05	3.5	4
zM	0.05	17.5	15
Zm	1	3.5	7
ZM	1	17.5	12

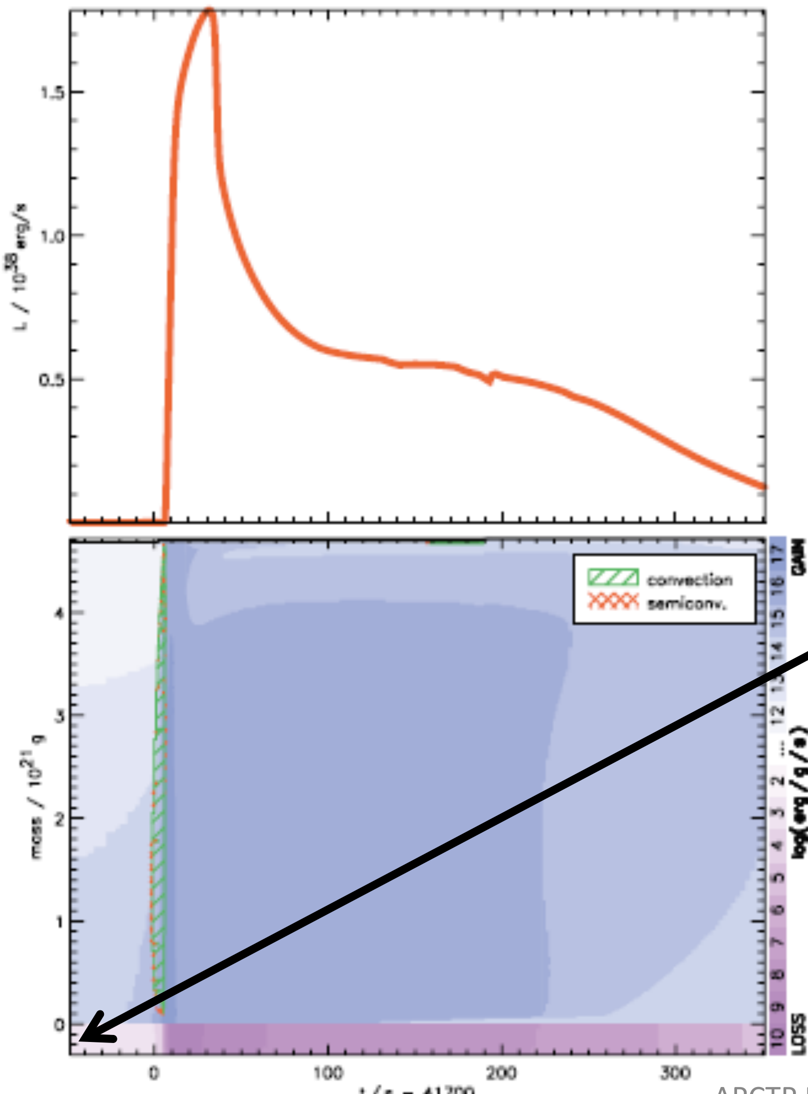
Evolution of zM

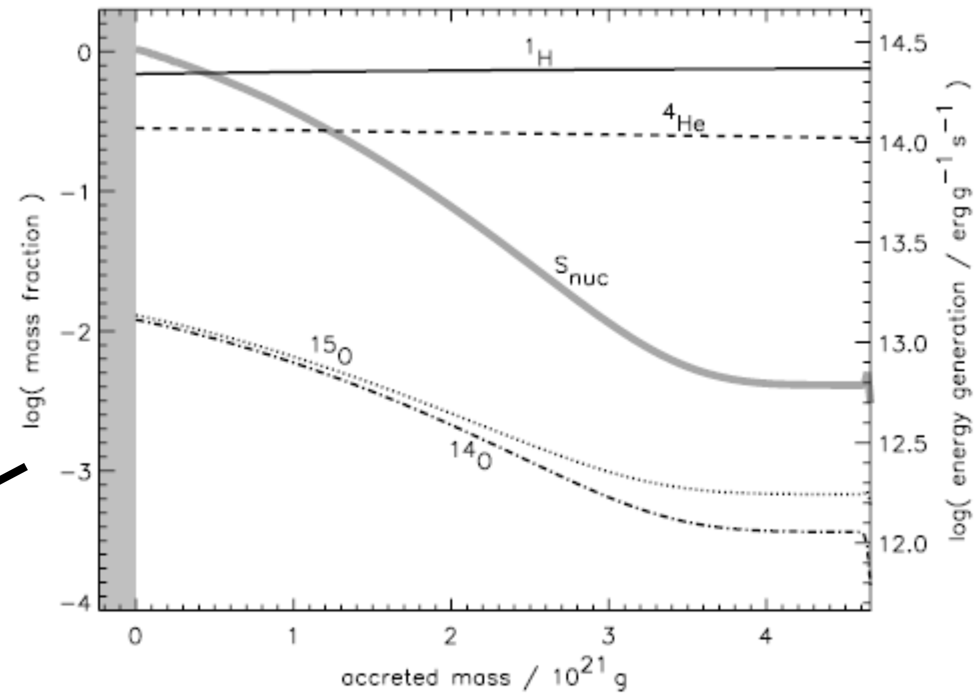


1st Burst of zM

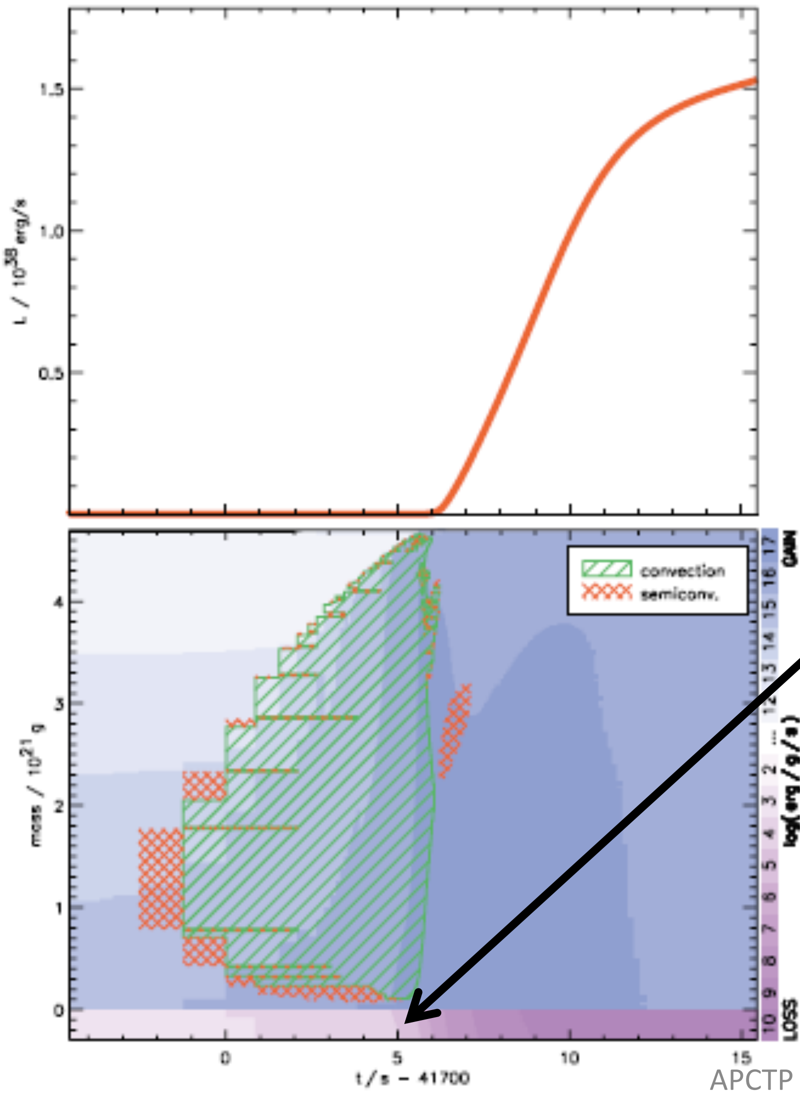


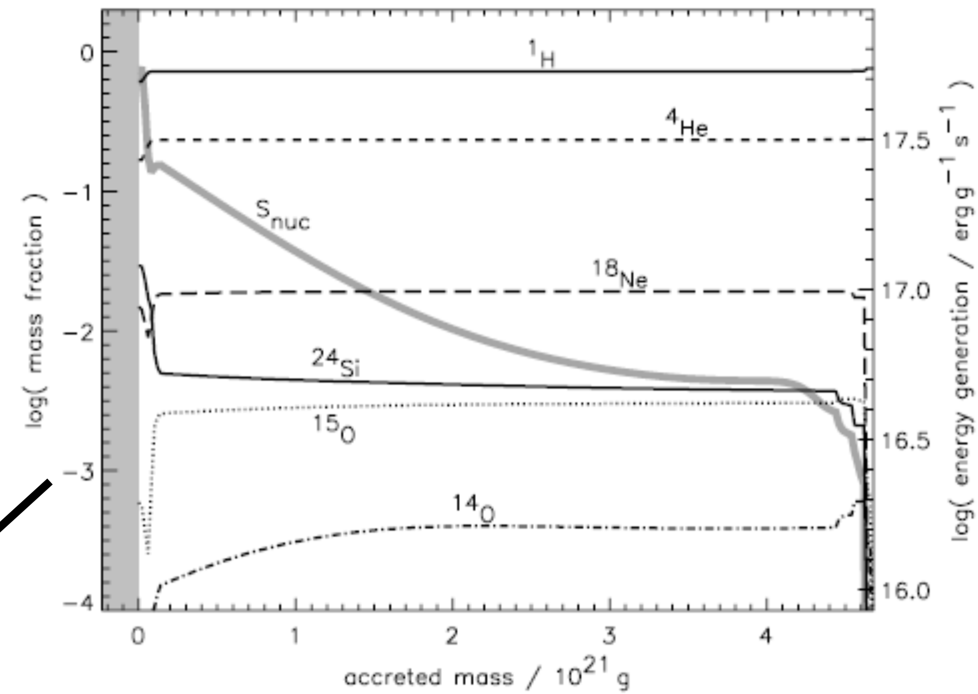
Composition of 1st Burst of zM



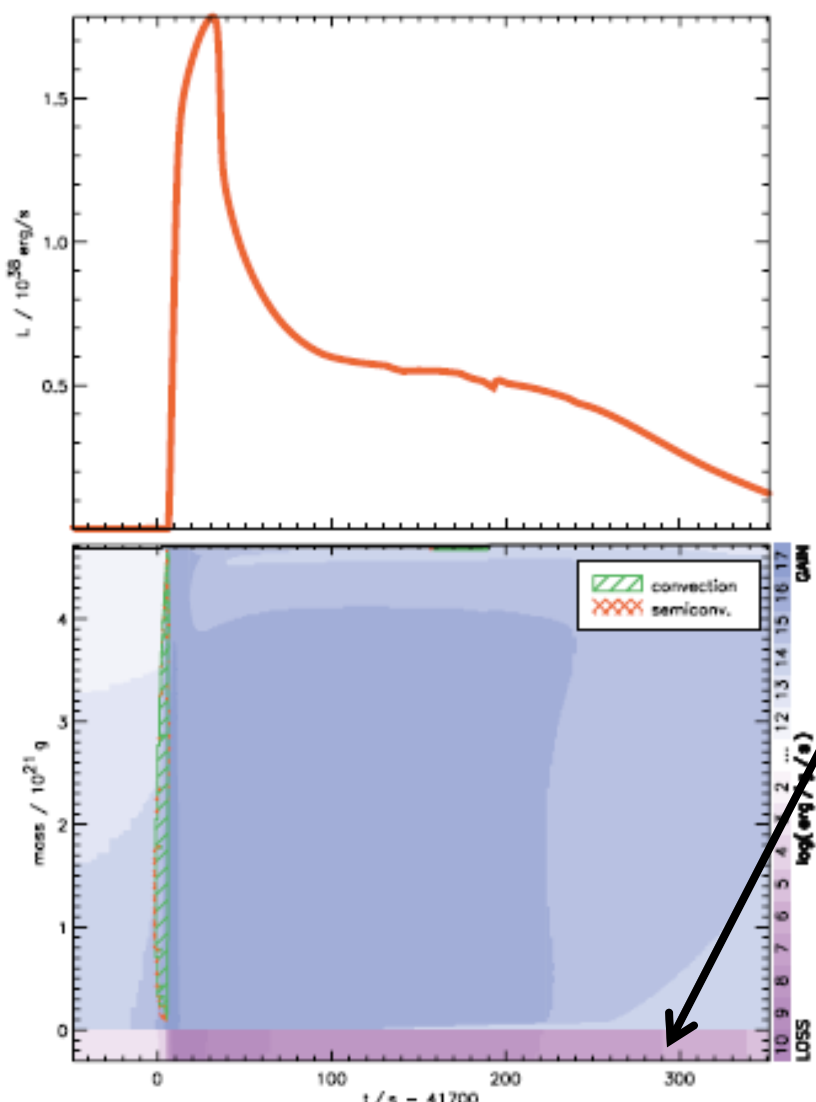


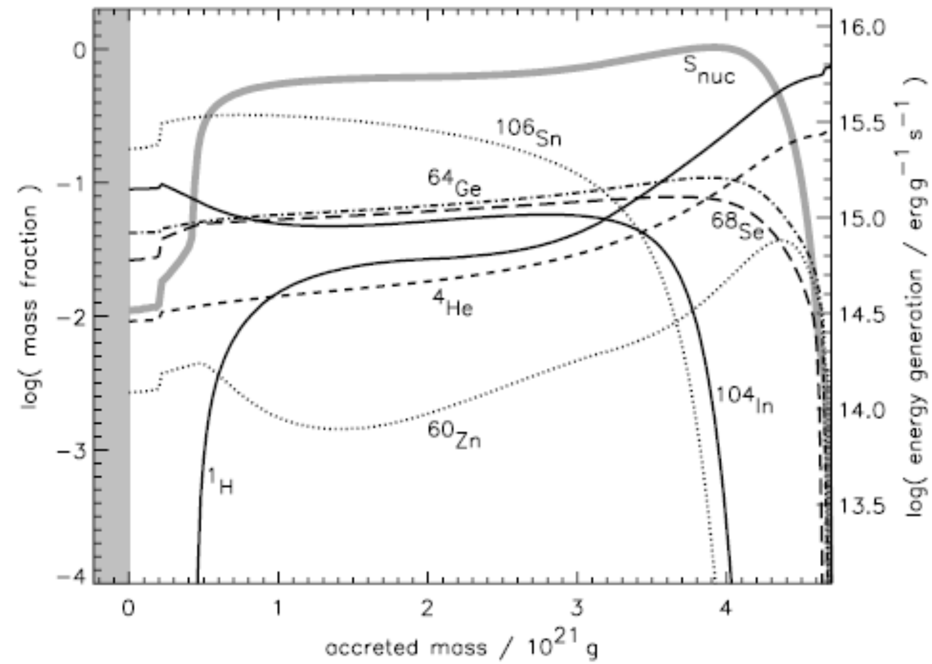
Composition of 1st Burst of zM

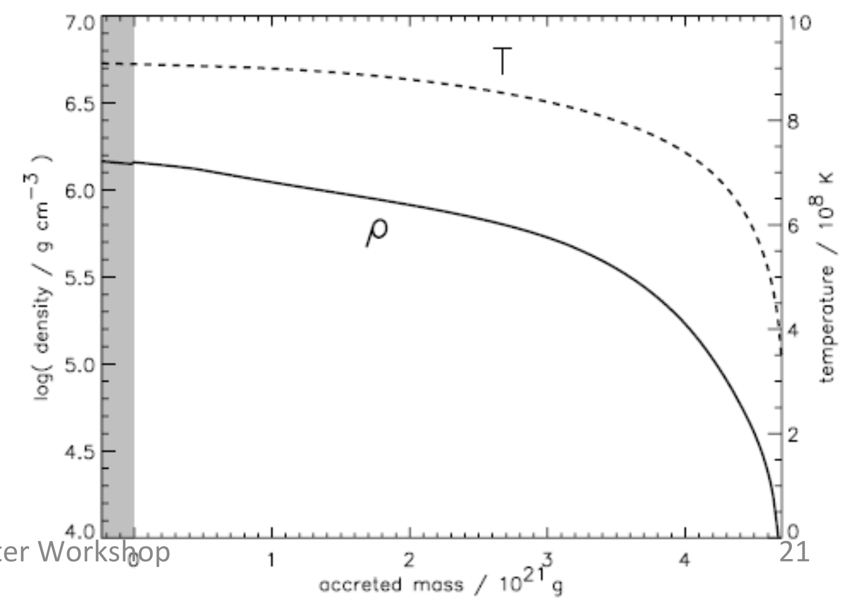




Composition of 1st Burst of zM







Effects of Reaction Rates on the Shape of the Light Curve

- Triple alpha
- Two reactions for HCNO break-out

$$^{18}\mathrm{Ne}(\alpha, p)^{21}\mathrm{Na}$$

$$^{15}\mathrm{O}(\alpha, \gamma)^{19}\mathrm{Ne}$$

HCNO Cycle

CNO-I

$^{12}_{6}C + ^{1}_{1}H \rightarrow ^{13}_{7}N + \gamma + 1.95\ \mathrm{MeV}$

$\boxed{^{13}_{7}N} \rightarrow ^{13}_{6}C + e^{+} + \nu_e + 1.20\ \mathrm{MeV}$ (half-life of 9.965 minutes[7])

$^{13}_{6}C + ^{1}_{1}H \rightarrow ^{14}_{7}N + \gamma + 7.54\ \mathrm{MeV}$

$^{14}_{7}N + ^{1}_{1}H \rightarrow ^{15}_{8}O + \gamma + 7.35\ \mathrm{MeV}$

$\boxed{^{15}_{8}O} \rightarrow ^{15}_{7}N + e^{+} + \nu_e + 1.73\ \mathrm{MeV}$ (half-life of 122.24 seconds[7])

$^{15}_{7}N + ^{1}_{1}H \rightarrow ^{12}_{6}C + ^{4}_{2}He + 4.96\ \mathrm{MeV}$

HCNO-I

$^{12}_{6}C + ^{1}_{1}H \rightarrow ^{13}_{7}N + \gamma + 1.95\ \mathrm{MeV}$

$^{13}_{7}N + ^{1}_{1}H \rightarrow ^{14}_{8}O + \gamma + 4.63\ \mathrm{MeV}$

$\boxed{^{14}_{8}O} \rightarrow ^{14}_{7}N + e^{+} + \nu_e + 5.14\ \mathrm{MeV}$ (half-life of 70.641 seconds)

$^{14}_{7}N + ^{1}_{1}H \rightarrow ^{15}_{8}O + \gamma + 7.35\ \mathrm{MeV}$

$^{15}_{8}O \rightarrow ^{15}_{7}N + e^{+} + \nu_e + 2.75\ \mathrm{MeV}$ (half-life of 122.24 seconds)

$^{15}_{7}N + ^{1}_{1}H \rightarrow ^{12}_{6}C + ^{4}_{2}He + 4.96\ \mathrm{MeV}$

CNO-II

$${}^{15}_{7}N + {}^{1}_{1}H \rightarrow {}^{16}_{8}O + \gamma + 12.13\ \text{MeV}$$

$${}^{16}_{8}O + {}^{1}_{1}H \rightarrow {}^{17}_{9}F + \gamma + 0.60\ \text{MeV}$$

$$\boxed{{}^{17}_{9}F} \rightarrow {}^{17}_{8}O + e^{+} + \nu_e + 2.76\ \text{MeV} \quad \text{(half-life of 64.49 seconds)}$$

$${}^{17}_{8}O + {}^{1}_{1}H \rightarrow {}^{14}_{7}N + {}^{4}_{2}He + 1.19\ \text{MeV}$$

$${}^{14}_{7}N + {}^{1}_{1}H \rightarrow {}^{15}_{8}O + \gamma + 7.35\ \text{MeV}$$

$$\boxed{{}^{15}_{8}O} \rightarrow {}^{15}_{7}N + e^{+} + \nu_e + 2.75\ \text{MeV} \quad \text{(half-life of 122.24 seconds)}$$

HCNO-II

$${}^{15}_{7}N + {}^{1}_{1}H \rightarrow {}^{16}_{8}O + \gamma + 12.13\ \text{MeV}$$

$${}^{16}_{8}O + {}^{1}_{1}H \rightarrow {}^{17}_{9}F + \gamma + 0.60\ \text{MeV}$$

$${}^{17}_{9}F + {}^{1}_{1}H \rightarrow {}^{18}_{10}Ne + \gamma + 3.92\ \text{MeV}$$

$$\boxed{{}^{18}_{10}Ne} \rightarrow {}^{18}_{9}F + e^{+} + \nu_e + 4.44\ \text{MeV} \quad \text{(half-life of 1.672 seconds)}$$

$${}^{18}_{9}F + {}^{1}_{1}H \rightarrow {}^{15}_{8}O + {}^{4}_{2}He + 2.88\ \text{MeV}$$

$$\boxed{{}^{15}_{8}O} \rightarrow {}^{15}_{7}N + e^{+} + \nu_e + 2.75\ \text{MeV} \quad \text{(half-life of 122.24 seconds)}$$

HCNO-III

$$ {}^{18}_{9}\mathrm{F} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{19}_{10}\mathrm{Ne} + \gamma + 6.41\ \mathrm{MeV} $$

$$ \boxed{{}^{19}_{10}\mathrm{Ne}} \rightarrow {}^{19}_{9}\mathrm{F} + e^{+} + \nu_e + 3.32\ \mathrm{MeV}\ \text{(half-life of 17.22 seconds)} $$

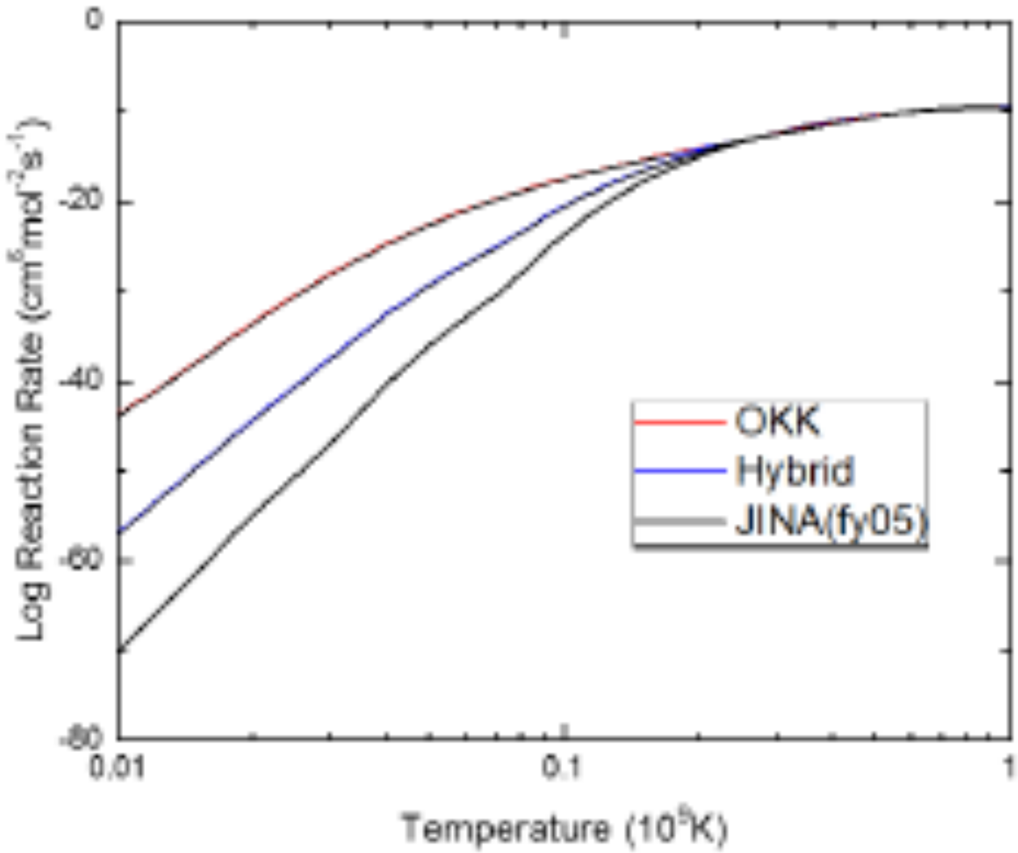
$$ {}^{19}_{9}\mathrm{F} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{16}_{8}\mathrm{O} + {}^{4}_{2}\mathrm{He} + 8.11\ \mathrm{MeV} $$

$$ {}^{16}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{17}_{9}\mathrm{F} + \gamma + 0.60\ \mathrm{MeV} $$

$$ {}^{17}_{9}\mathrm{F} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{18}_{10}\mathrm{Ne} + \gamma + 3.92\ \mathrm{MeV} $$

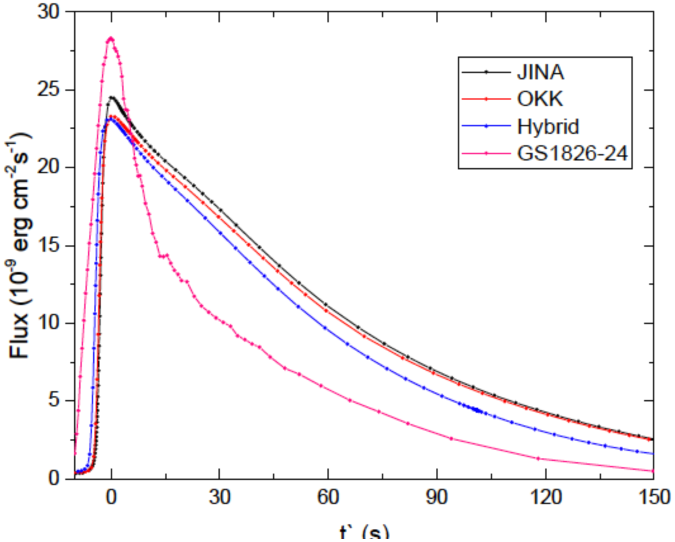
$$ \boxed{{}^{18}_{10}\mathrm{Ne}} \rightarrow {}^{18}_{9}\mathrm{F} + e^{+} + \nu_e + 4.44\ \mathrm{MeV}\ \text{(half-life of 1.672 seconds)} $$

Triple Alpha I

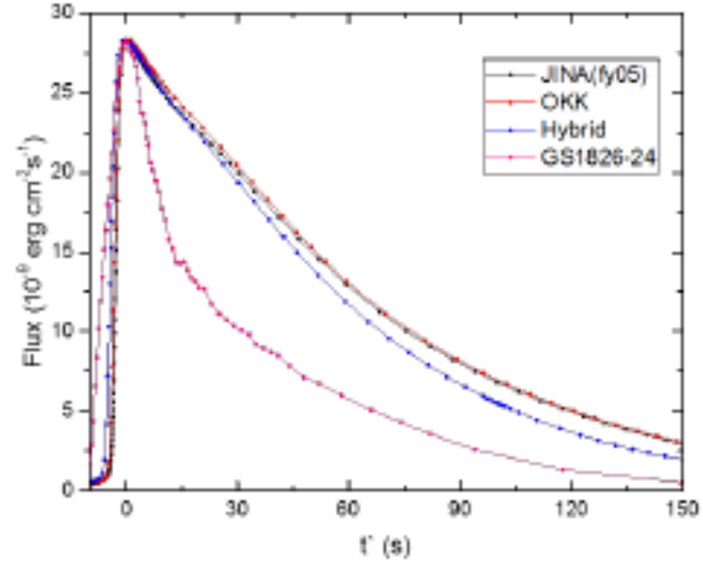


Triple Alpha II

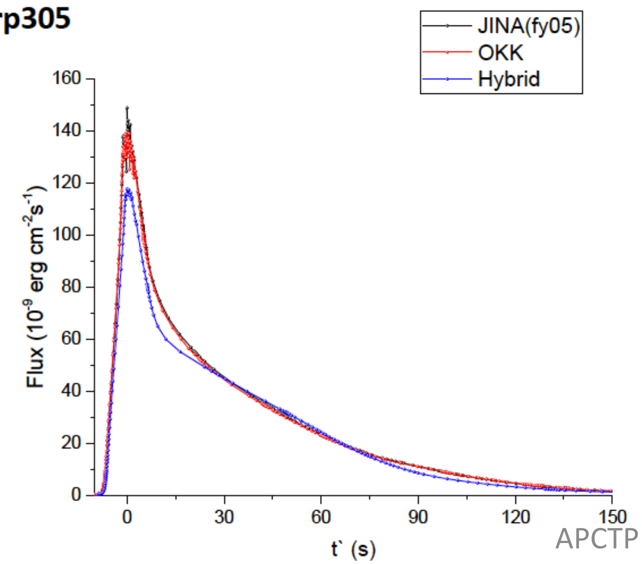
Peak Matched



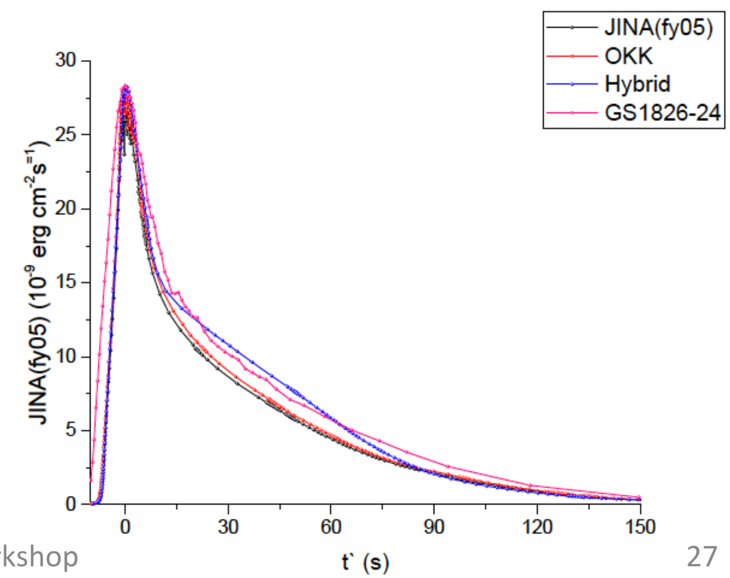
53 isotopes



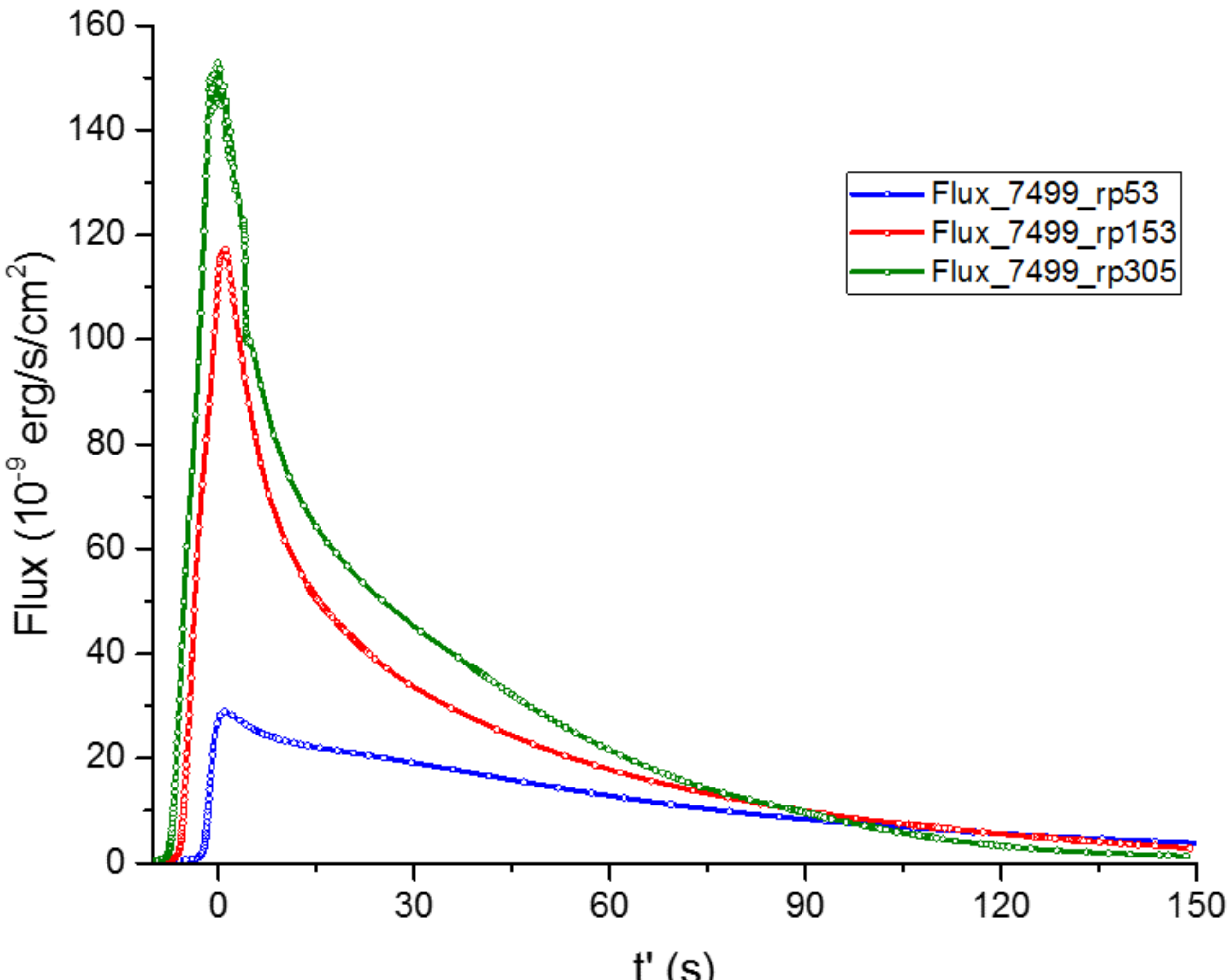
Triple Alpha Reaction_rp305



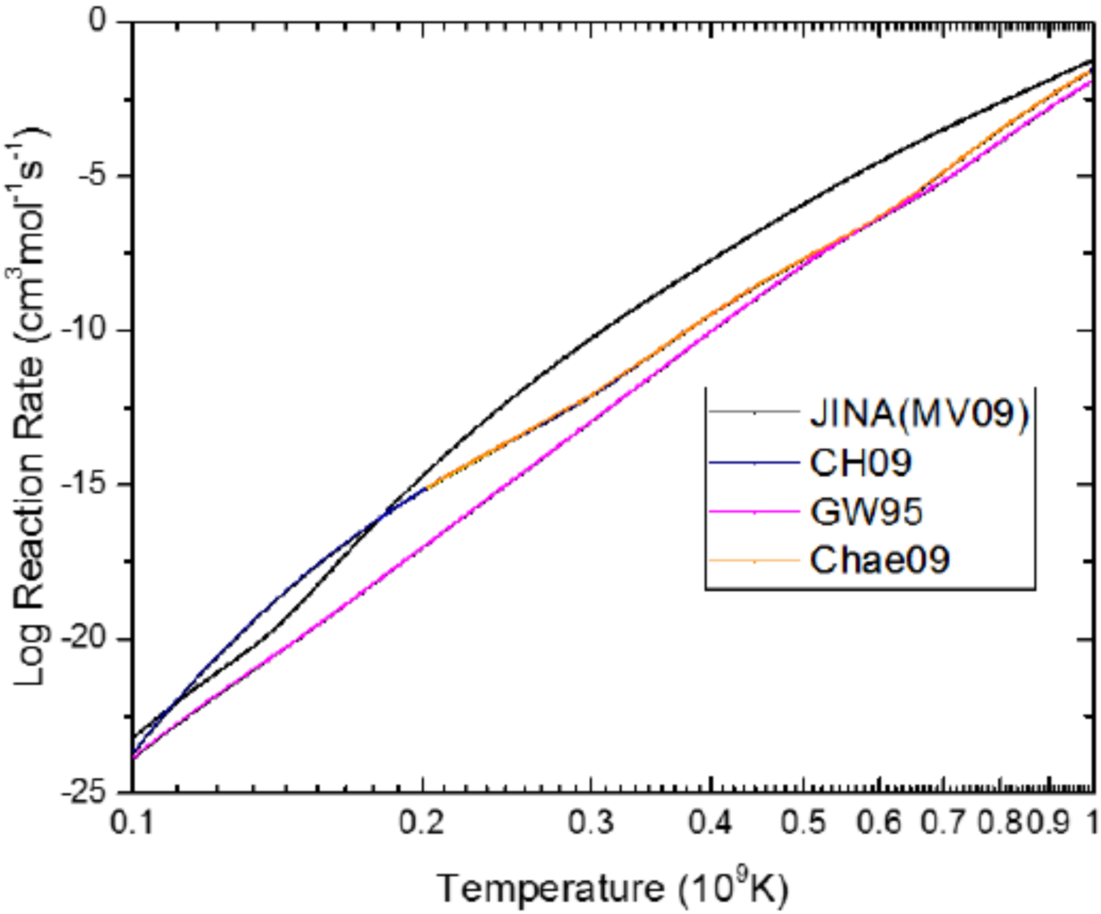
305 isotopes

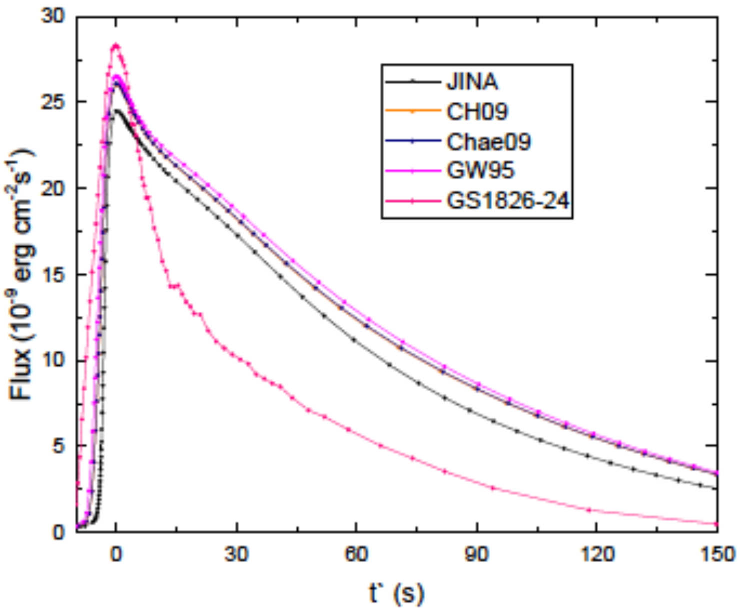


Effect of Number of Isotopes



$$^{18}\mathrm{Ne}(\alpha, p)^{21}\mathrm{Na}$$





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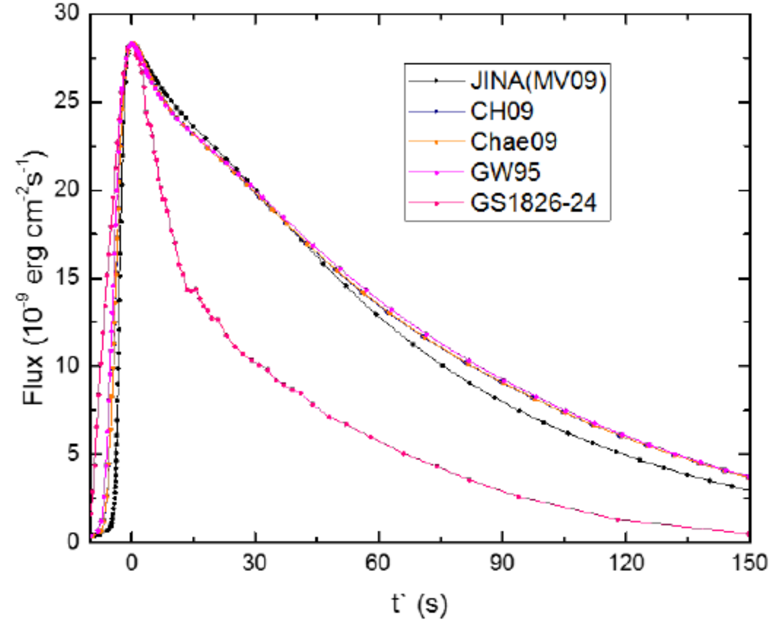
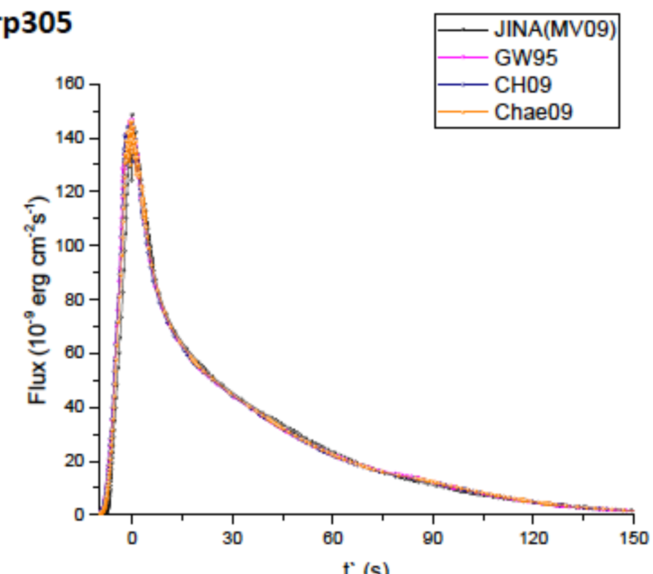
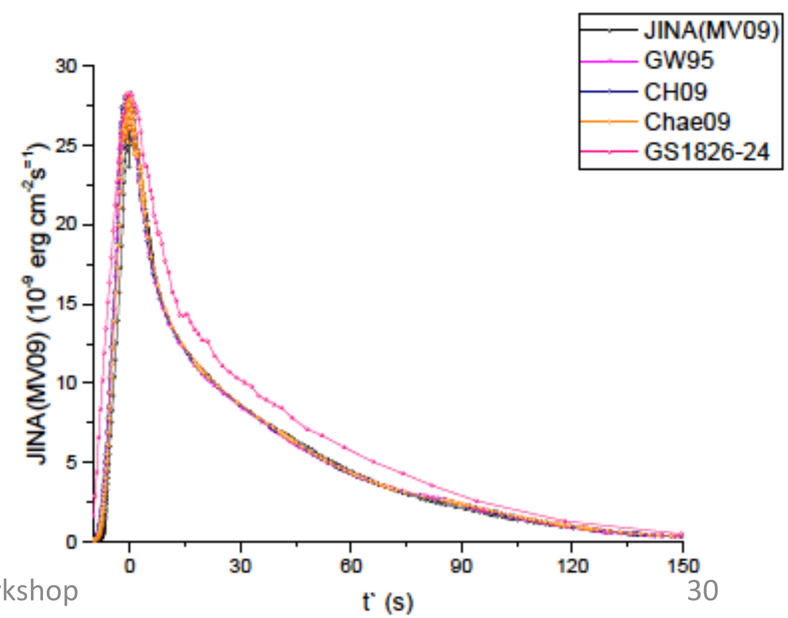


53 isotopes

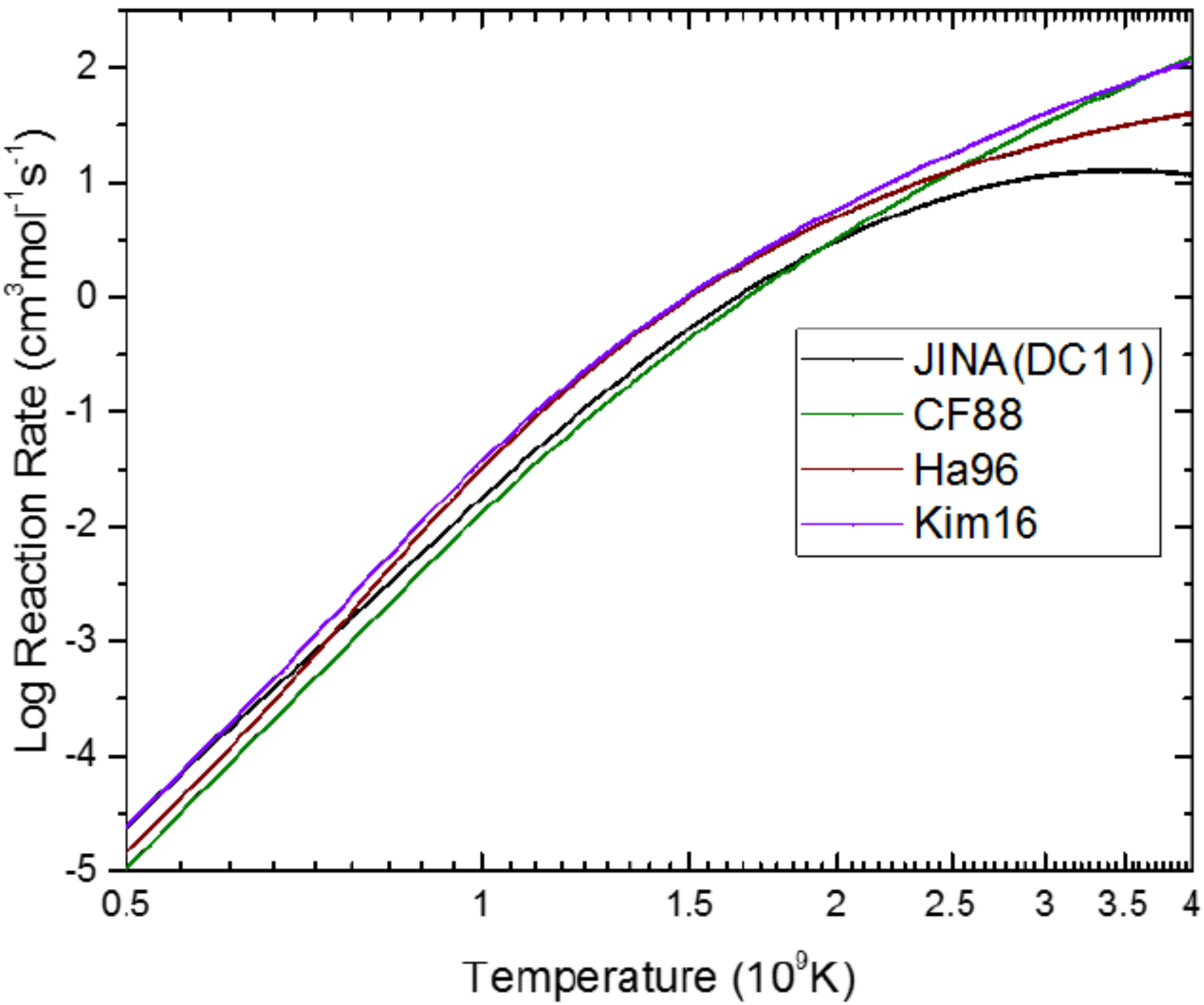
Ne18(α,p)Na21
Reaction_rp305

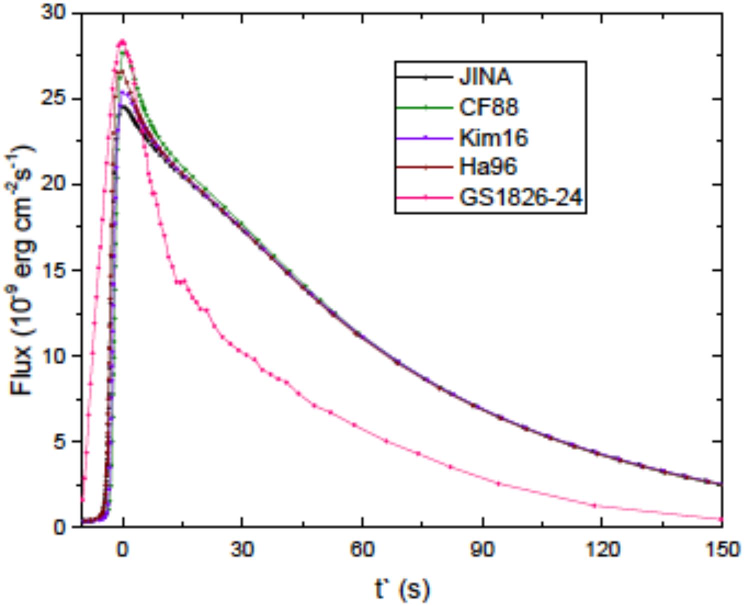


305 isotopes

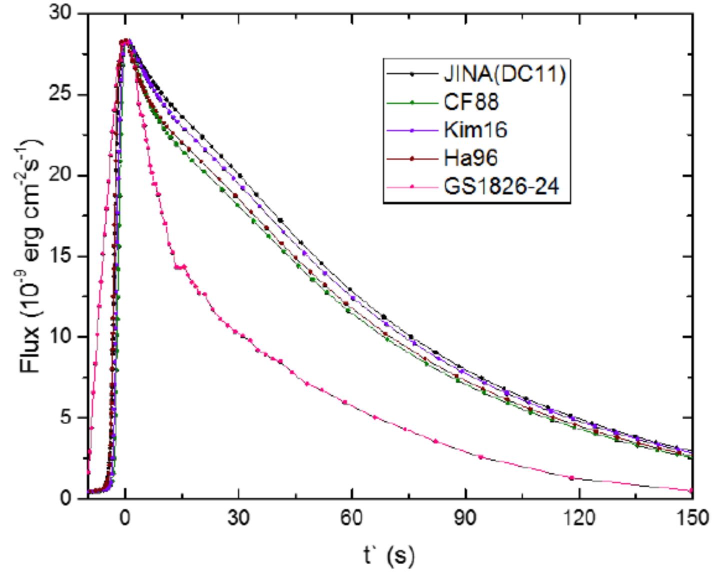


$^{15}O(\alpha,\gamma)^{19}Ne$



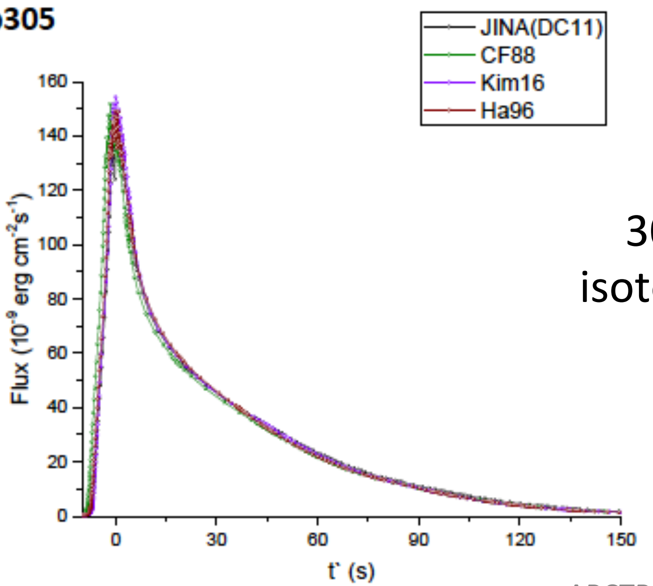


Peak Matched

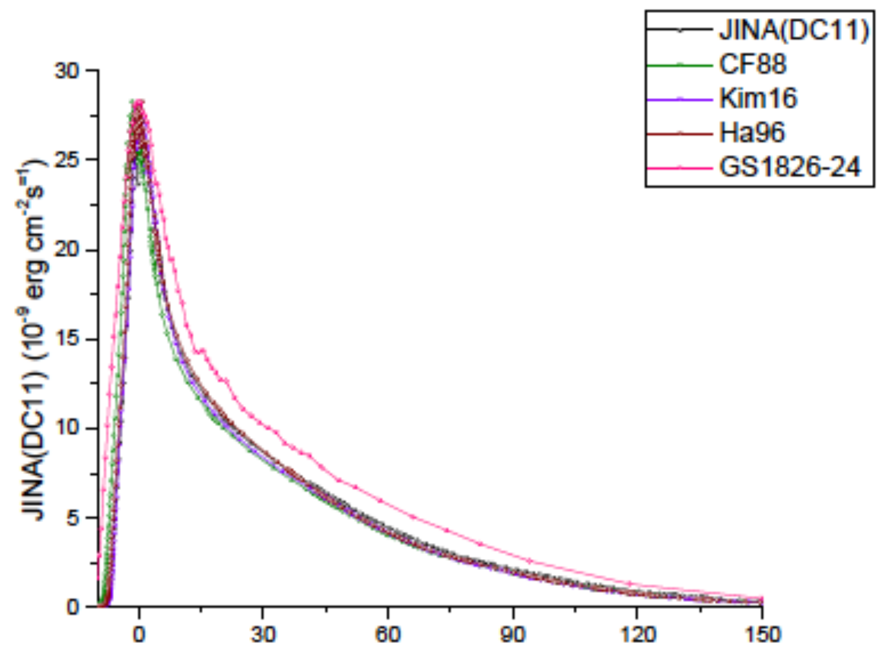


53
isotopes

O15(α,γ)Ne19
Reaction_rp305

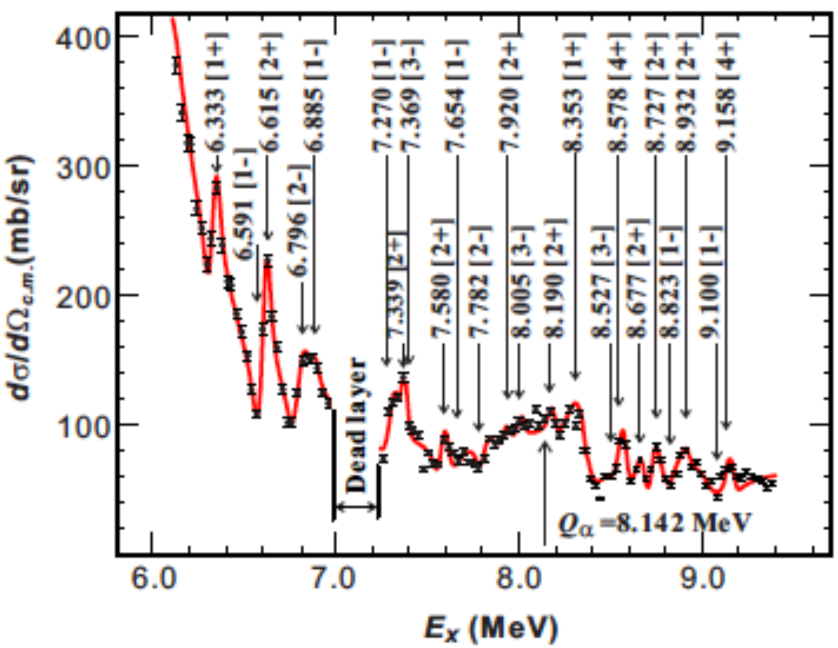


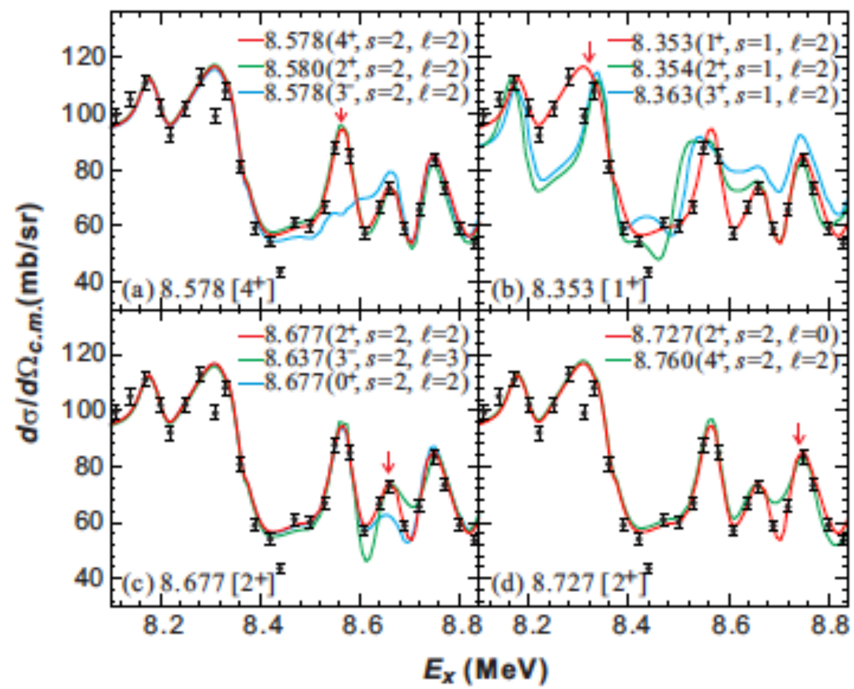
305
isotopes



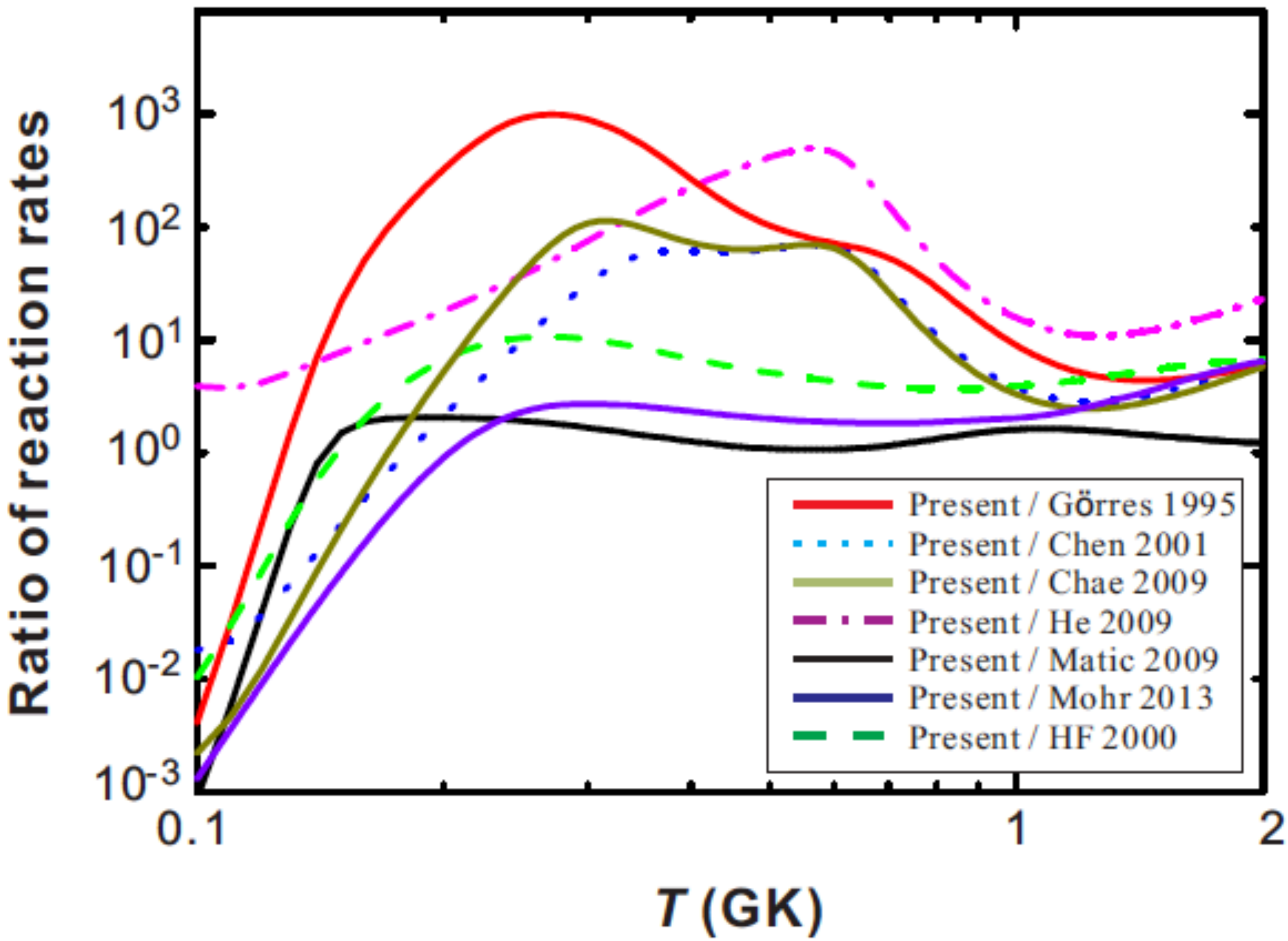
Experiments

- Example: resonant elastic scattering of ^{21}Na+p to obtain the ^{22}Mg structure, which is related to ^{18}Ne(α,p)^{21}Na and ^{18}Ne(α,γ)^{22}Mg (He + 2013, PRC)

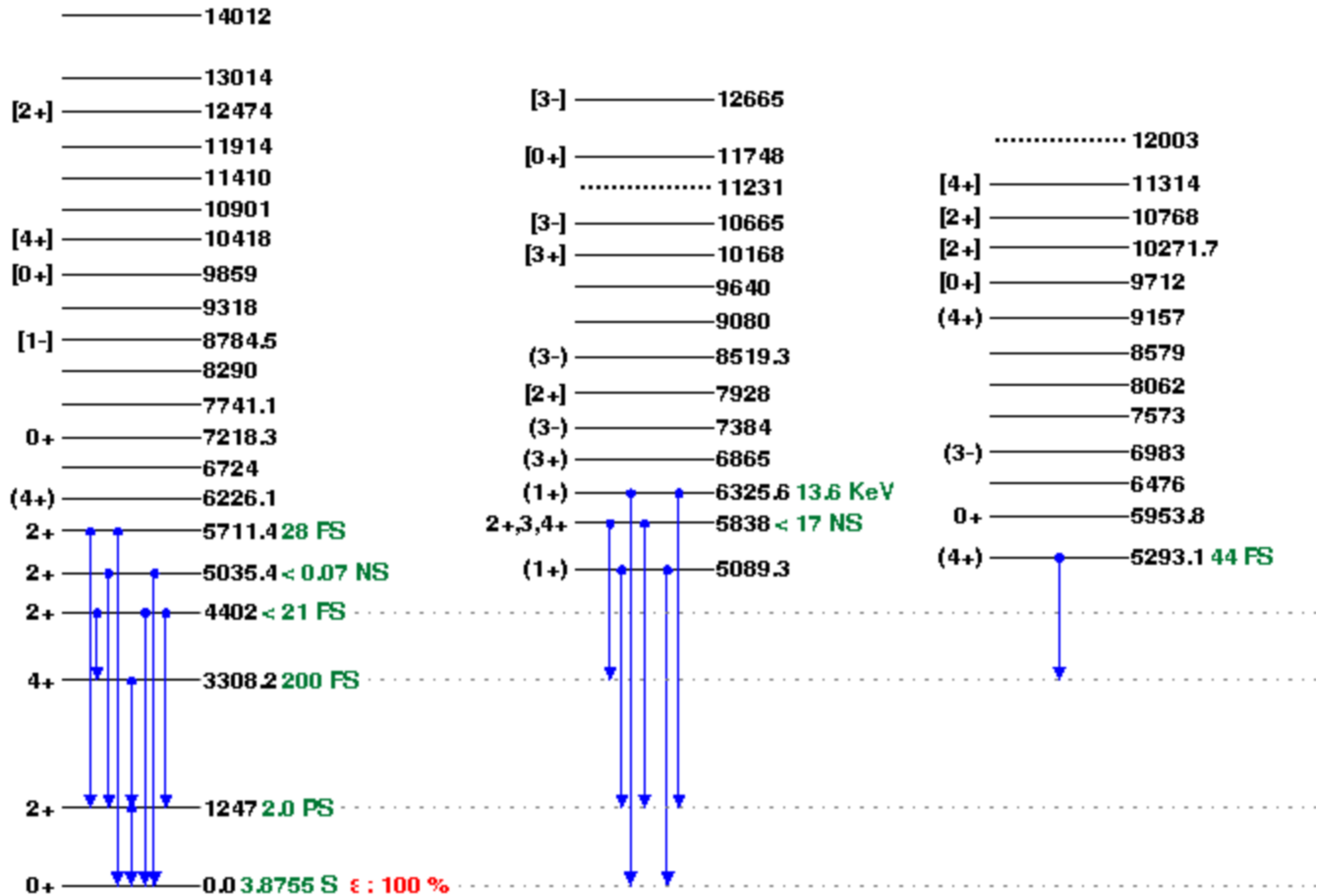




Astrophysical Inputs



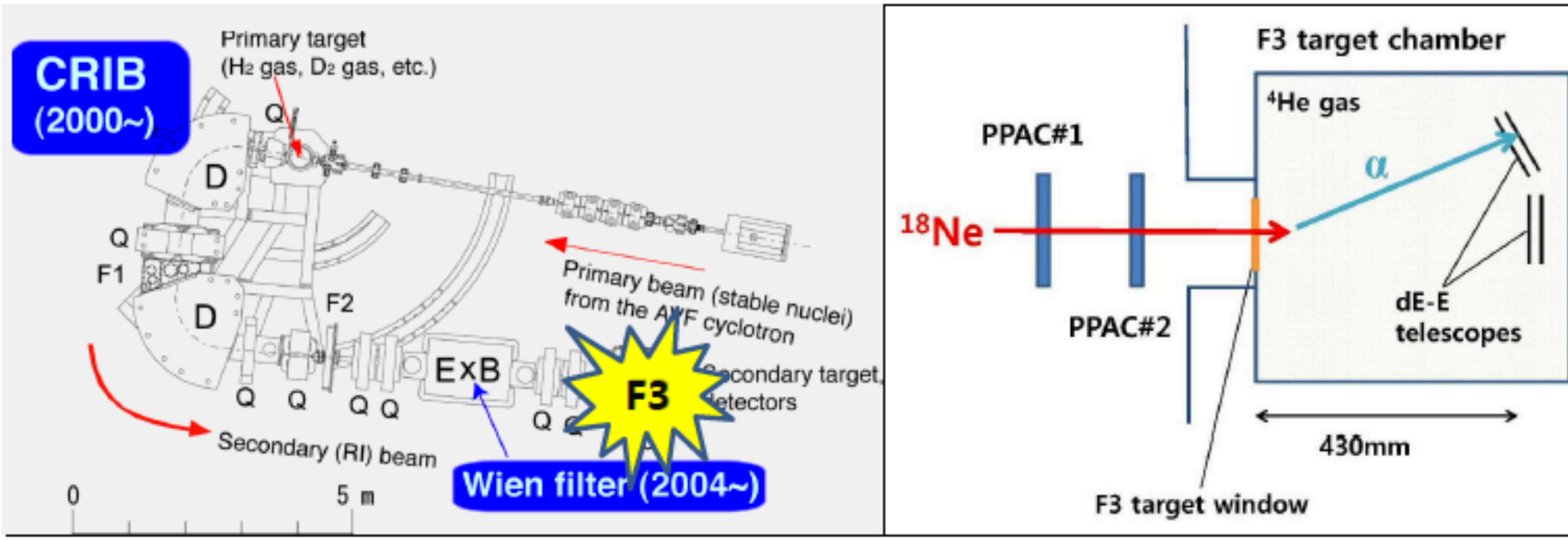
Structure of ^{22}Mg



From National Nuclear Data Center

Current Experiments @CRIB/CNS, RIKEN

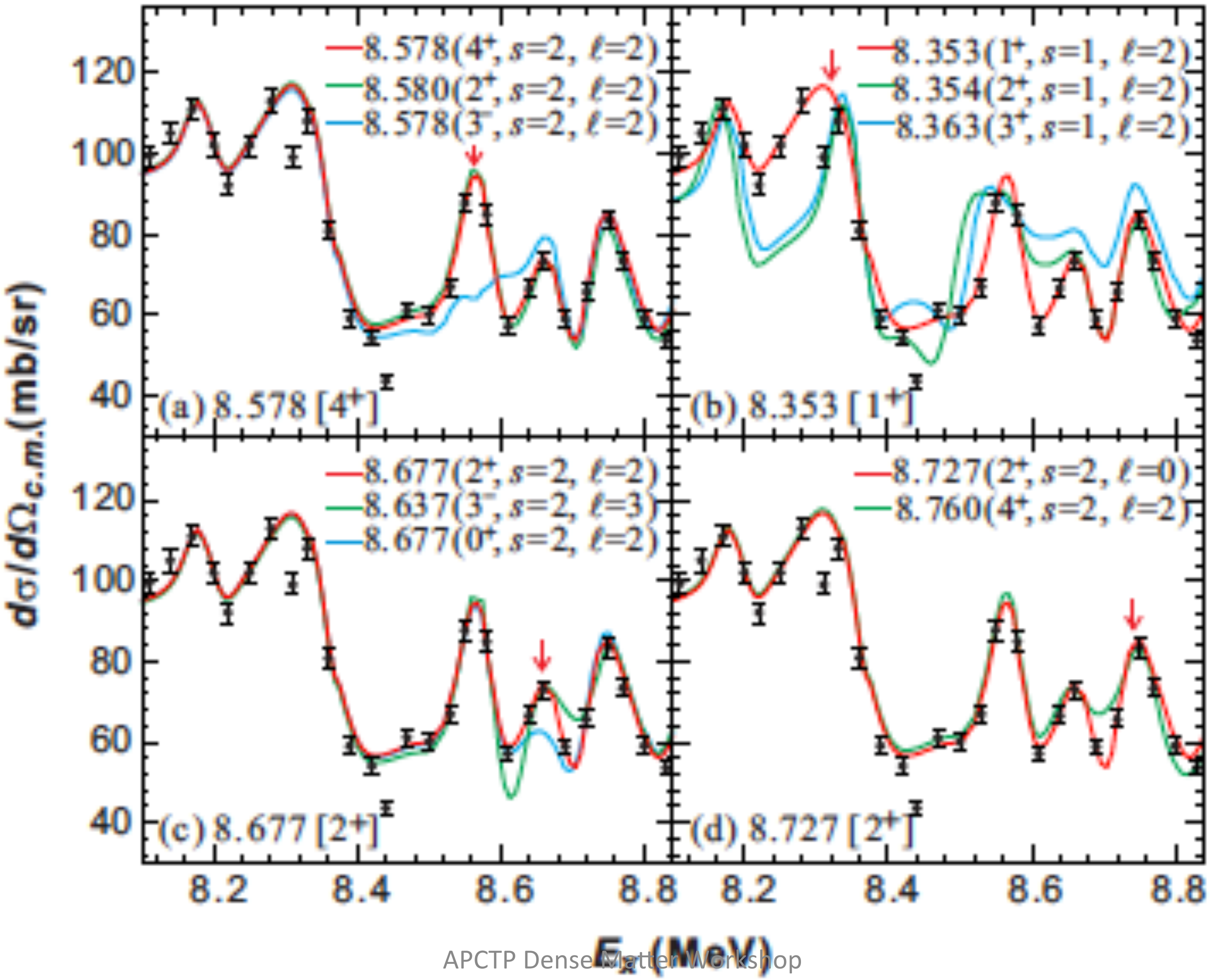
Experimental Setup



- two dipoles and a Wien filter for beam selection
- a pair of PPACs for beam particle tracking
- large reaction target chamber filled with ~470 Torr of ^{4}He gas (thick target)
- two ΔE-E telescopes to identify scattered α particles

Courtesy of Prof. Chae @SKKU

R-matrix Calculation with Nuclear Structure



HCNO Cycle

CNO-I

$$^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{13}_{7}N + \gamma \quad + 1.95\ \text{MeV}$$

$$\boxed{^{13}_{7}N} \rightarrow {}^{13}_{6}C + e^{+} + \nu_e + 1.20\ \text{MeV}$$ (half-life of 9.965 minutes[7])

$$^{13}_{6}C + {}^{1}_{1}H \rightarrow {}^{14}_{7}N + \gamma \quad + 7.54\ \text{MeV}$$

$$^{14}_{7}N + {}^{1}_{1}H \rightarrow {}^{15}_{8}O + \gamma \quad + 7.35\ \text{MeV}$$

$$\boxed{^{15}_{8}O} \rightarrow {}^{15}_{7}N + e^{+} + \nu_e + 1.73\ \text{MeV}$$ (half-life of 122.24 seconds[7])

$$^{15}_{7}N + {}^{1}_{1}H \rightarrow {}^{12}_{6}C + {}^{4}_{2}He \quad + 4.96\ \text{MeV}$$

HCNO-I

$$^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{13}_{7}N + \gamma \quad + 1.95\ \text{MeV}$$

$$^{13}_{7}N + {}^{1}_{1}H \rightarrow {}^{14}_{8}O + \gamma \quad + 4.63\ \text{MeV}$$

$$\boxed{^{14}_{8}O} \rightarrow {}^{14}_{7}N + e^{+} + \nu_e + 5.14\ \text{MeV}$$ (half-life of 70.641 seconds)

$$^{14}_{7}N + {}^{1}_{1}H \rightarrow {}^{15}_{8}O + \gamma \quad + 7.35\ \text{MeV}$$

$$^{15}_{8}O \rightarrow {}^{15}_{7}N + e^{+} + \nu_e + 2.75\ \text{MeV}$$ (half-life of 122.24 seconds)

$$^{15}_{7}N + {}^{1}_{1}H \rightarrow {}^{12}_{6}C + {}^{4}_{2}He \quad + 4.96\ \text{MeV}$$

CNO-II

$$^{15}_{7}N + ^{1}_{1}H \rightarrow ^{16}_{8}O + \gamma + 12.13\text{ MeV}$$

$$^{16}_{8}O + ^{1}_{1}H \rightarrow ^{17}_{9}F + \gamma + 0.60\text{ MeV}$$

$$\boxed{^{17}_{9}F} \rightarrow ^{17}_{8}O + e^{+} + \nu_e + 2.76\text{ MeV} \quad \text{(half-life of 64.49 seconds)}$$

$$^{17}_{8}O + ^{1}_{1}H \rightarrow ^{14}_{7}N + ^{4}_{2}He + 1.19\text{ MeV}$$

$$^{14}_{7}N + ^{1}_{1}H \rightarrow ^{15}_{8}O + \gamma + 7.35\text{ MeV}$$

$$\boxed{^{15}_{8}O} \rightarrow ^{15}_{7}N + e^{+} + \nu_e + 2.75\text{ MeV} \quad \text{(half-life of 122.24 seconds)}$$

HCNO-II

$$^{15}_{7}N + ^{1}_{1}H \rightarrow ^{16}_{8}O + \gamma + 12.13\text{ MeV}$$

$$^{16}_{8}O + ^{1}_{1}H \rightarrow ^{17}_{9}F + \gamma + 0.60\text{ MeV}$$

$$^{17}_{9}F + ^{1}_{1}H \rightarrow ^{18}_{10}Ne + \gamma + 3.92\text{ MeV}$$

$$\boxed{^{18}_{10}Ne} \rightarrow ^{18}_{9}F + e^{+} + \nu_e + 4.44\text{ MeV} \quad \text{(half-life of 1.672 seconds)}$$

$$^{18}_{9}F + ^{1}_{1}H \rightarrow ^{15}_{8}O + ^{4}_{2}He + 2.88\text{ MeV}$$

$$\boxed{^{15}_{8}O} \rightarrow ^{15}_{7}N + e^{+} + \nu_e + 2.75\text{ MeV} \quad \text{(half-life of 122.24 seconds)}$$

HCNO-III

$$^{18}_{9}F + ^{1}_{1}H \rightarrow ^{19}_{10}Ne + \gamma + 6.41\ \text{MeV}$$

$$\boxed{^{19}_{10}Ne} \rightarrow ^{19}_{9}F + e^{+} + \nu_e + 3.32\ \text{MeV (half-life of 17.22 seconds)}$$

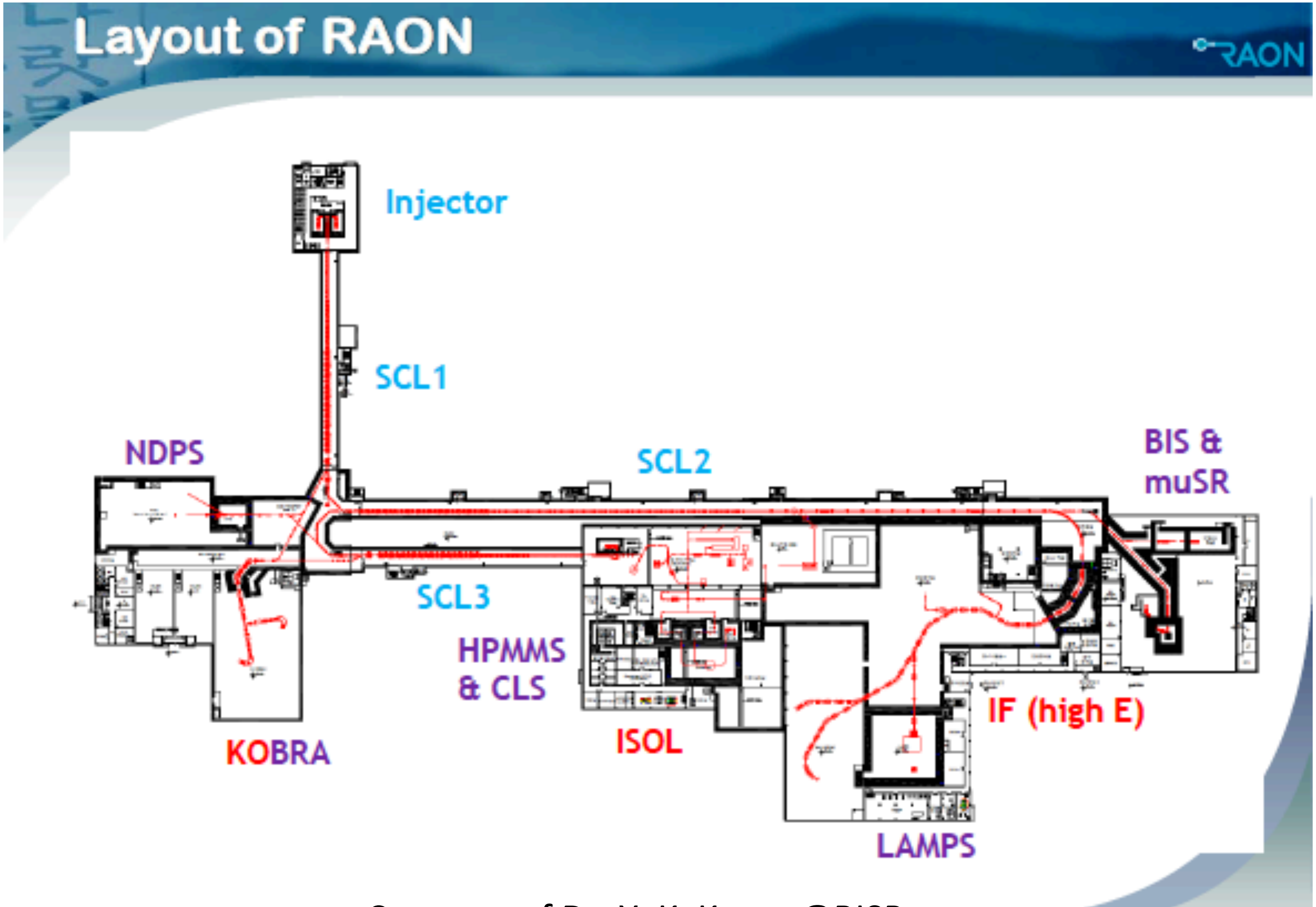
$$^{19}_{9}F + ^{1}_{1}H \rightarrow ^{16}_{8}O + ^{4}_{2}He + 8.11\ \text{MeV}$$

$$^{16}_{8}O + ^{1}_{1}H \rightarrow ^{17}_{9}F + \gamma + 0.60\ \text{MeV}$$

$$^{17}_{9}F + ^{1}_{1}H \rightarrow ^{18}_{10}Ne + \gamma + 3.92\ \text{MeV}$$

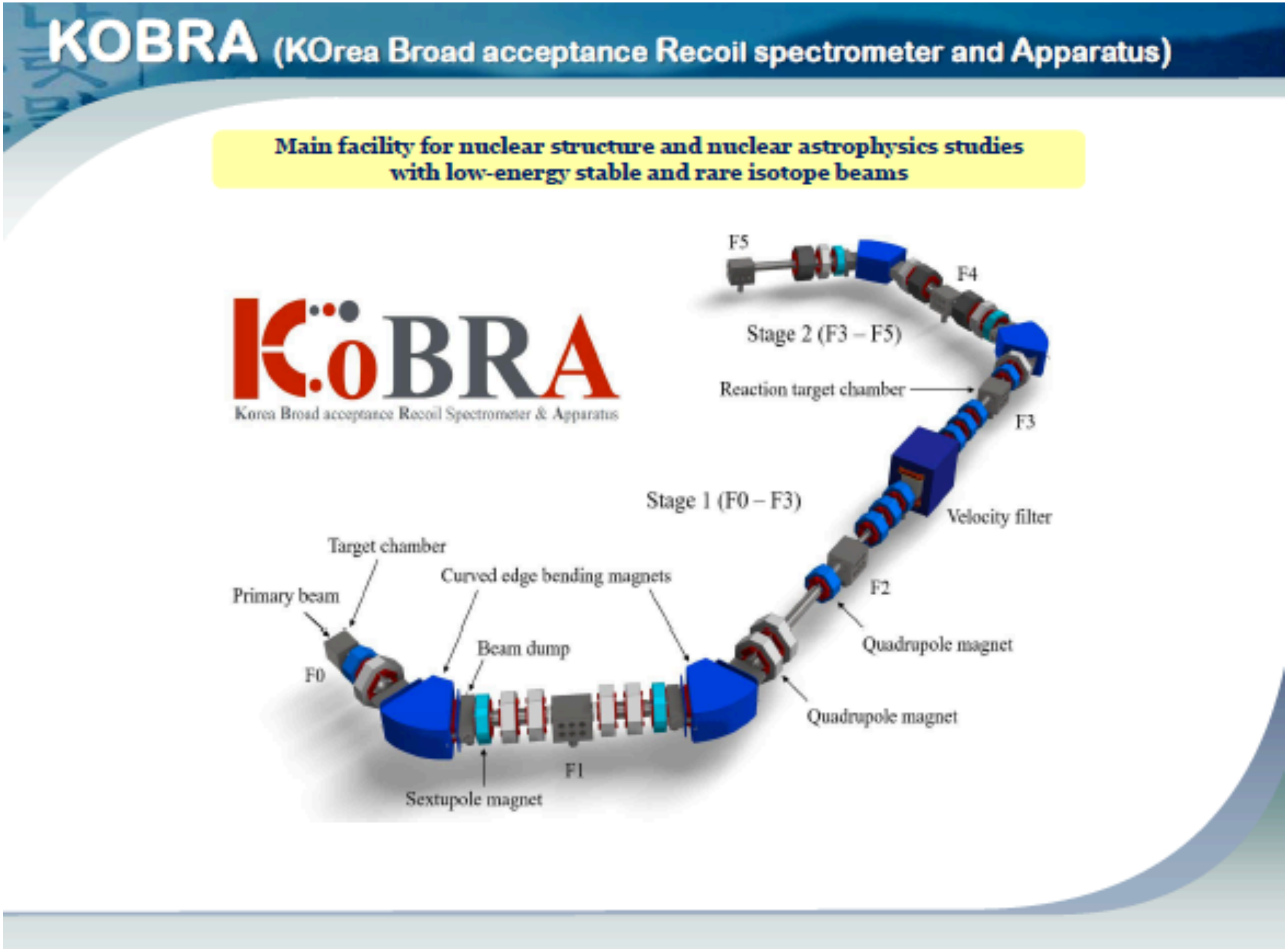
$$\boxed{^{18}_{10}Ne} \rightarrow ^{18}_{9}F + e^{+} + \nu_e + 4.44\ \text{MeV (half-life of 1.672 seconds)}$$

RAON



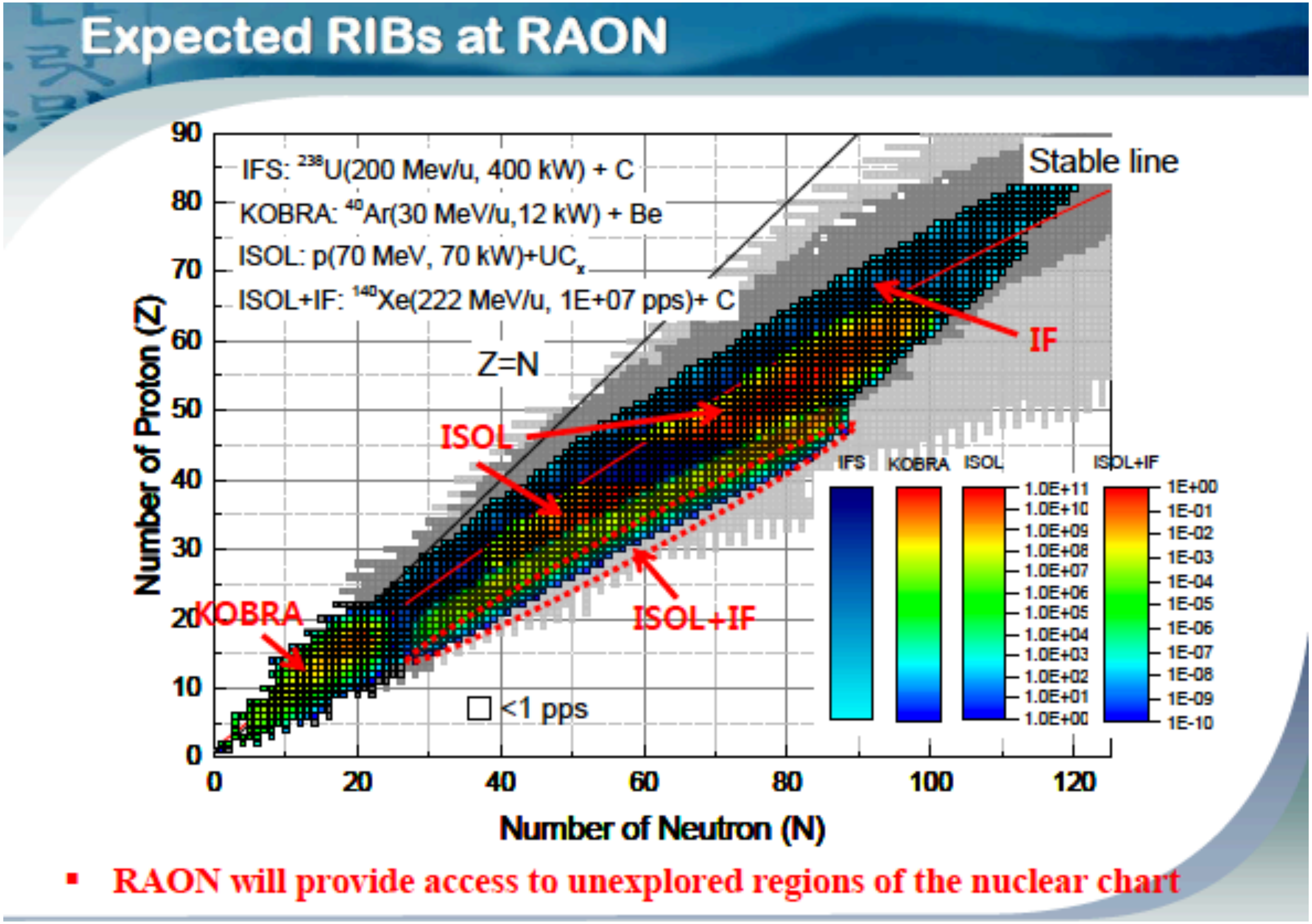
Courtesy of Dr. Y. K. Kwon @RISP

KOBRA @RAON



Courtesy of Dr. Y. K. Kwon @RISP

Experiments @KOBRA/RAON



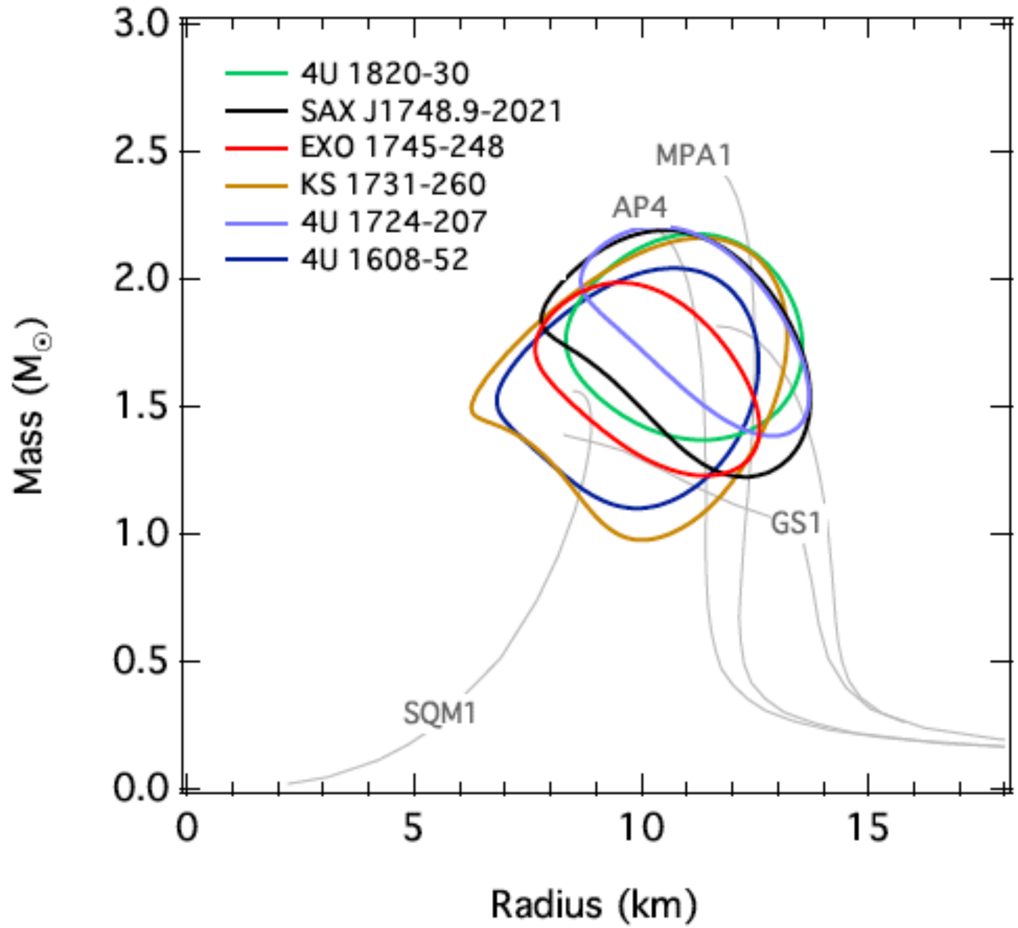
Courtesy of Dr. Y. K. Kwon @RISP

Collaborative Efforts in Korea

- Effects of two reaction rates, 18Ne(a,p)21Na and 15O(a,g)18Ne, on the light curve of XRB are currently under investigation.
- These two are break-out reactions of hot CNO cycle.
- They are now being measured experimentally by Korean group @SKKU and EWU.
- Experimental simulations are being prepared now by theory group at RISP.

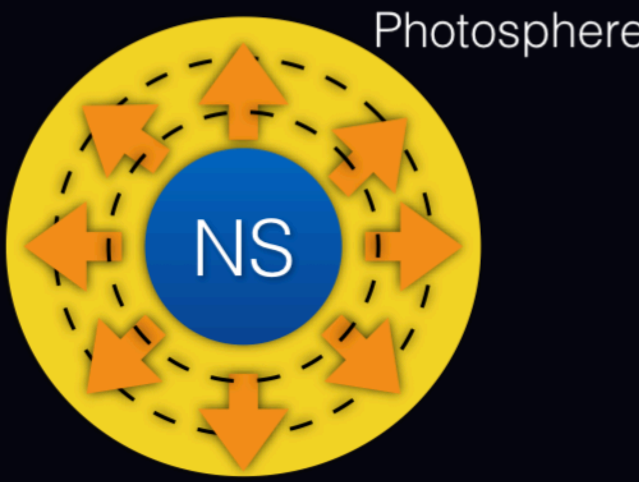
Photospheric Radial Expansion (PRE) XRBs

M-R Relations of NS



Photospheric Radius Expansion

- In bright bursts, the luminosity L can reach the Eddington limit L_{Edd}
  - *$P_{radiation} >> P_{gravitation}$*
  - *Photospheric layers are lifted off*
- During PRE the luminosity is nearly constant(near L_{Edd})
- About 20% shows the evidence of PRE bursts (Galloway et al. 2008)

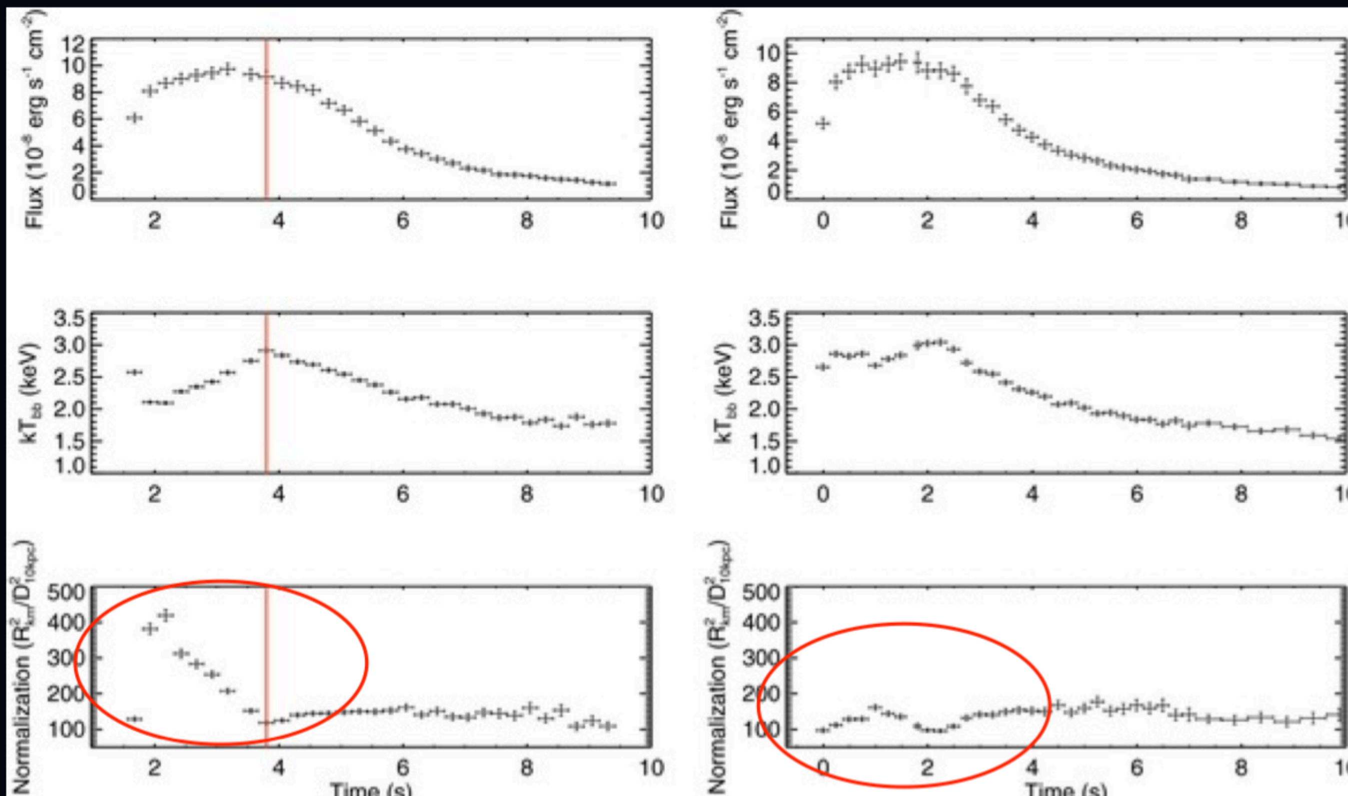


Expansion stage

'touchdown' stage

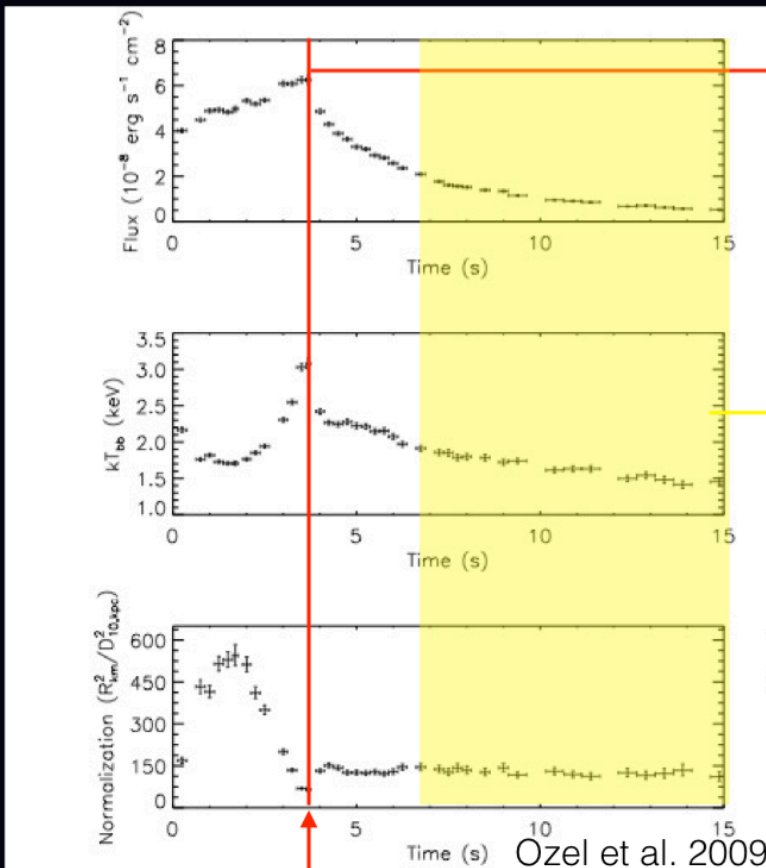
PRE or non PRE X-ray burst in 4U 1728-34

PRE (burst ID:86) non-PRE (burst ID:104)



Guver et al, 2012

Method to determine Mass and Radius I



Özel et al. 2009

'touchdown' point

$$F_{\mathrm{TD},\infty} = \frac{GMc}{\kappa D^2}\sqrt{1-2\beta(r_{\mathrm{ph}})}$$

$$\beta(r) = GM/(rc^2)$$

$$\kappa = 0.2(1+x)\mathrm{cm}^2/\mathrm{g}$$

$$A \equiv \frac{F_\infty}{\sigma T^4_{\mathrm{bb},\infty}} = f_c^{-4}\left(\frac{R}{D}\right)^2(1-2\beta)^{-1}$$

$$\alpha \equiv \frac{F_{\mathrm{TD},\infty}}{\sqrt{A}}\frac{\kappa D}{c^3 f_c^2} \qquad \alpha = \beta\sqrt{1-2\beta}$$

$$\gamma \equiv \frac{Ac^3 f_c^4}{F_{\mathrm{TD},\infty}\kappa} \qquad \gamma = \frac{R}{\beta(1-2\beta)}$$

$$\boxed{R = \alpha\gamma\sqrt{(1-2\beta_{1,2})} \quad M = c^2\alpha^2\gamma/G}$$

Method to determine Mass and Radius II

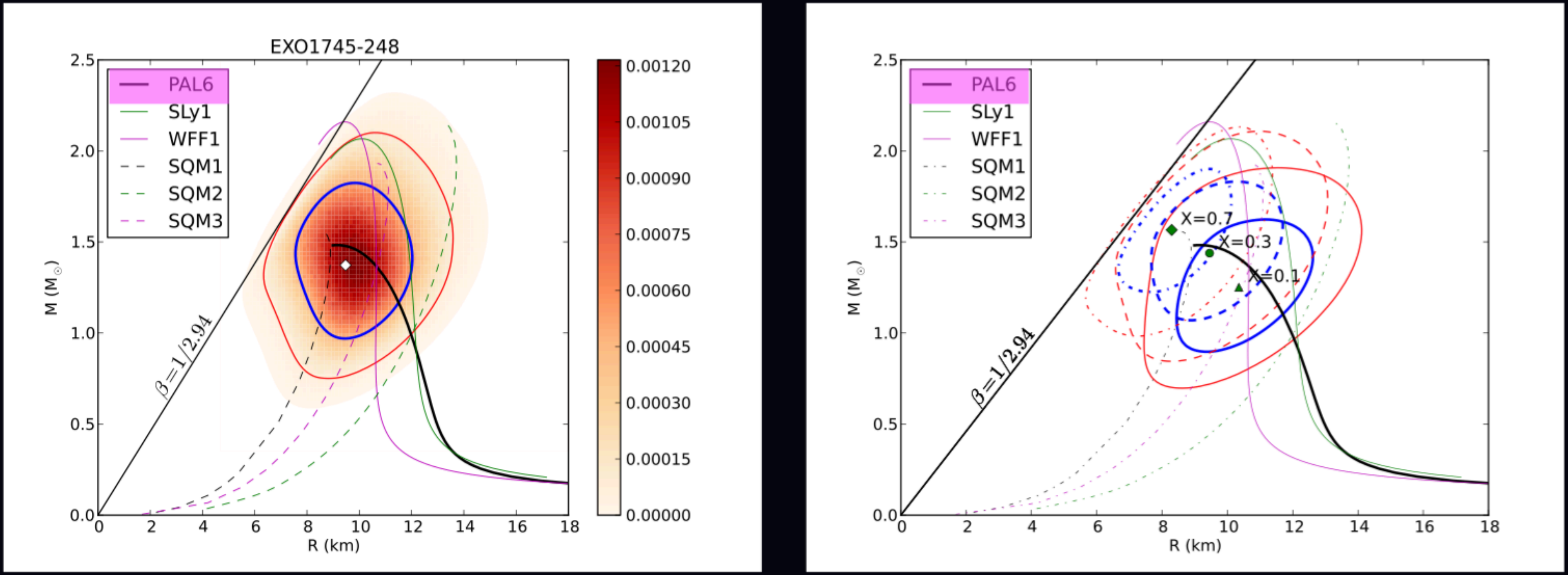
Quantities	EXO 1756–248	4U 1608–522	4U 1820–30	4U 1746–37	EXO 0748-676
D	6.3 ± 0.6	5.8± 2.0	8.2± 0.7	11.05± 0.85	7.1± 1.2
A	1.17± 0.13	3.246± 0.024	0.9198± 0.0186	0.109± 0.044	1.14± 0.10
$F_{\mathrm{TD},\infty}$	6.25± 0.2	15.41± 0.65	5.39± 0.12	0.269± 0.057	2.25± 0.23

D (kpc): distance
A (km^2 kpc^{-2}): normalised surface area
F_{TD} (10^{-8} erg cm^{-2} s^{-1}): touchdown flux

- Previous - Gaussian distribution of F_{TD}, A, and D (observation)
  uniform distribution of f_c and x *(theoritical)*
  $f_c(=T_{bb}/T_{eff})$: 1.3 -1.4,
  x : 0.0 - 0.7
- Our work - x dependence (0.1, 0.3, 0.7)

M-R probability distribution I

uniform distribution fixed distribution



- mass increases and radius decreases as x increases
- mass (M/M⊙) : 1.24 - 1.57
  radius (km) : 8.29 - 10.38

1D Radiation Hydrodynamic Simulations with SNEC

Summary

- XRB is a good example of nuclear astrophysics that requires all of observation, theory, and experiment.
- Both theoretical and experimental efforts from nuclear physics are essential.
- RAON and other rare isotope accelerators play an important role in understanding XRBs.
- Close collaboration across many interdisciplinary fields is also essential.

Physics Dept. @UNIST since 2014

Plasma Physics
Beam Physics

- Fusion and astrophysical plasmas
- Beam physics
- Advanced accelerators

Soft Matter Physics
Biological Physics

- Soft matter Physics
- Complex systems
- Biological physics

Condensed Matter Physics
Quantum Physics

- Condensed matter physics
- Quantum materials & devices
- Quantum optics & information

고에너지 천체물리 연구센터

Center for High Energy Astrophysics (CHEA)

❑ 센터소개

고에너지 천체물리학은 열적(thermal)·비열적(nonthermal) 고에너지 입자들이 방출하는 전파, X-선, 감마선 등 전자기파와 중성미자, 중력파 등의 관측에 기반을 두어, 이와 관련된 천문학 현상의 물리 기작을 연구하는 분야이다. 본 센터에는 이론·시뮬레이션을 중심으로 하는 천체물리를 천문 관측 및 실험 천체물리(laboratory astrophysics)와 결합하여, 은하단(clusters of galaxies)과 밀집천체(compact objects)에서 고에너지 천체물리 현상에 대한 연구를 수행한다. 이를 통해 고에너지 천체물리 연구의 국내 거점을 마련하고, 세계 선도 연구 그룹으로 발전할 기반을 구축하는 한편, 이 분야에서 세계적 수준의 미래 핵심 인력을 양성한다.

❑ 센터목표

PAL-XFEL: 4세대 방사광 가속기
RAON: 한국형 중이온 가속기

주관: 울산과학기술원 (UNIST)
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