# New Reaction Rates of $^{64}$Ge($p$,$\gamma$)$^{65}$As and $^{65}$As($p$,$\gamma$)$^{66}$Se and the Impact on Nucleosynthesis in Type-I X-ray Bursts


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# New Reaction Rates of $^{64}Ge(p,\gamma)^{65}As$ and $^{65}As(p,\gamma)^{66}Se$ and the Impact on Nucleosynthesis in Type-I X-ray Bursts

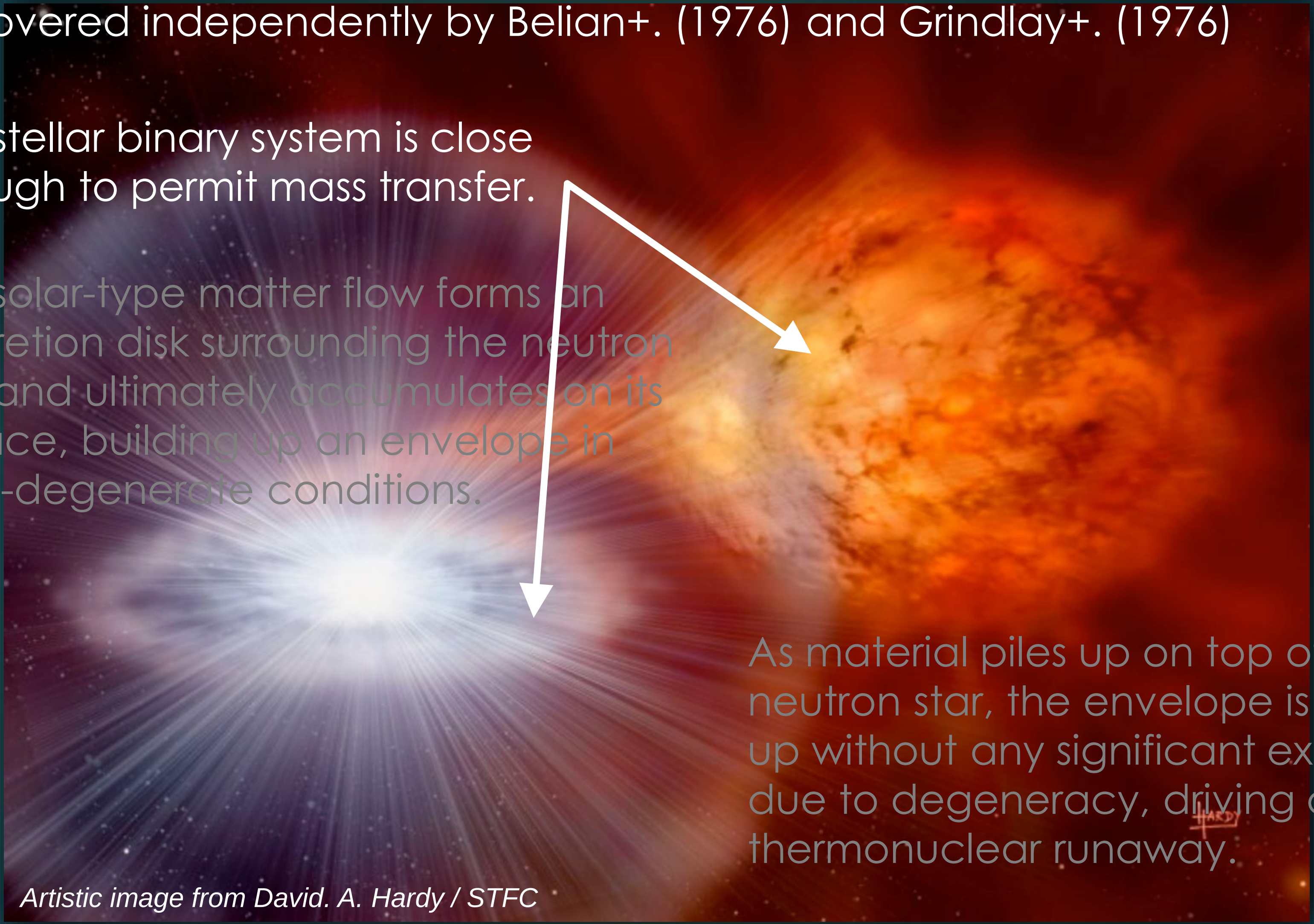
- Background
  - Type-I x-ray burst (and *models*)
  - Rapid-proton capture (*rp*) process
- New *rp*-process reaction rates of $^{64}Ge(p,\gamma)^{65}As$ and $^{65}As(p,\gamma)^{66}Se$
- The impact on end-stage abundances and light curve
- Summary and Perspectives

# Type I X-ray burst (XRB)

Discovered independently by Belian+. (1976) and Grindlay+. (1976)

The stellar binary system is close enough to permit mass transfer.

The solar-type matter flow forms an accretion disk surrounding the neutron star and ultimately accumulates on its surface, building up an envelope in semi-degenerate conditions.



As material piles up on top of the neutron star, the envelope is heated up without any significant expansion due to degeneracy, driving a violent thermonuclear runaway.

*Artistic image from David. A. Hardy / STFC*

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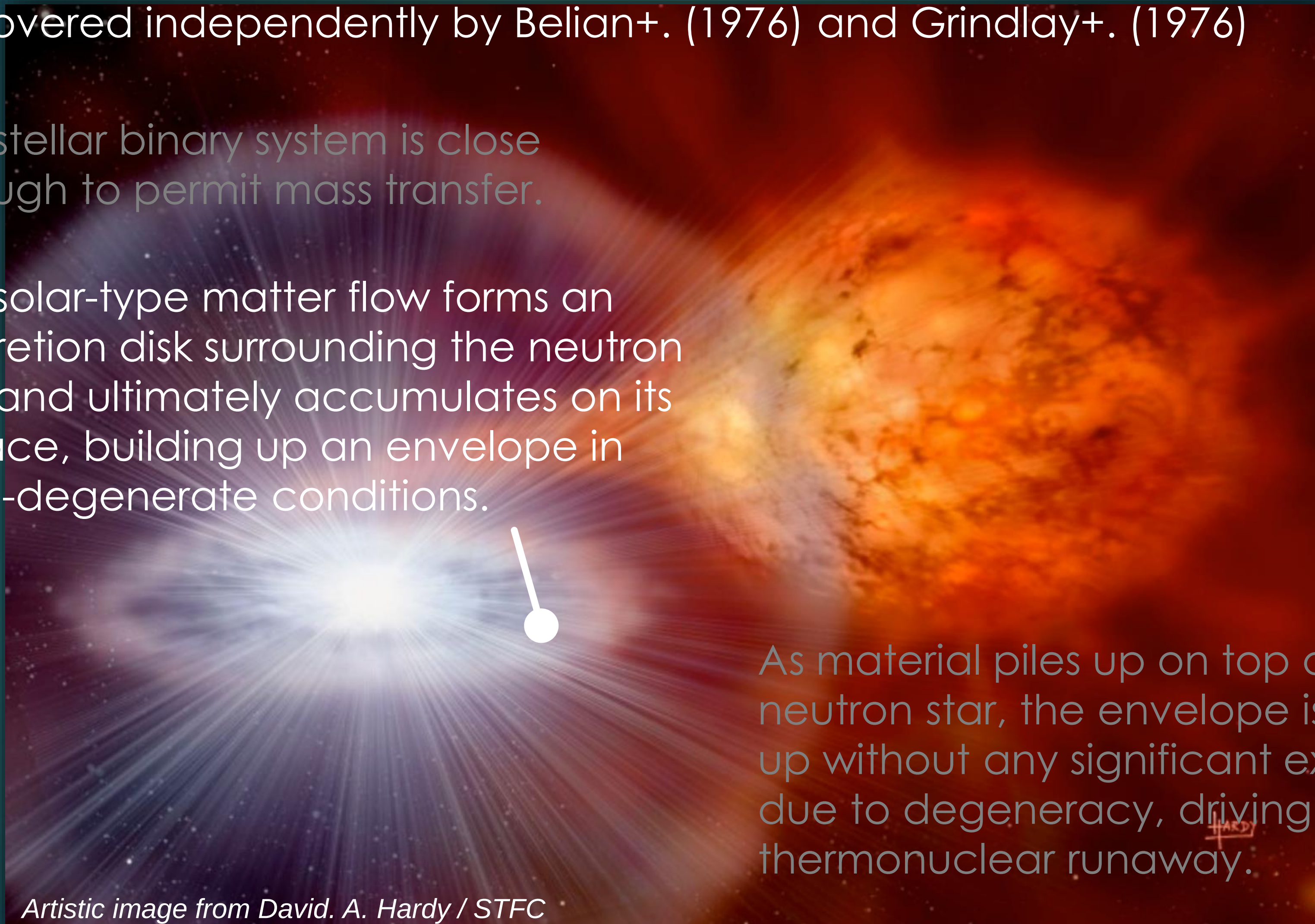

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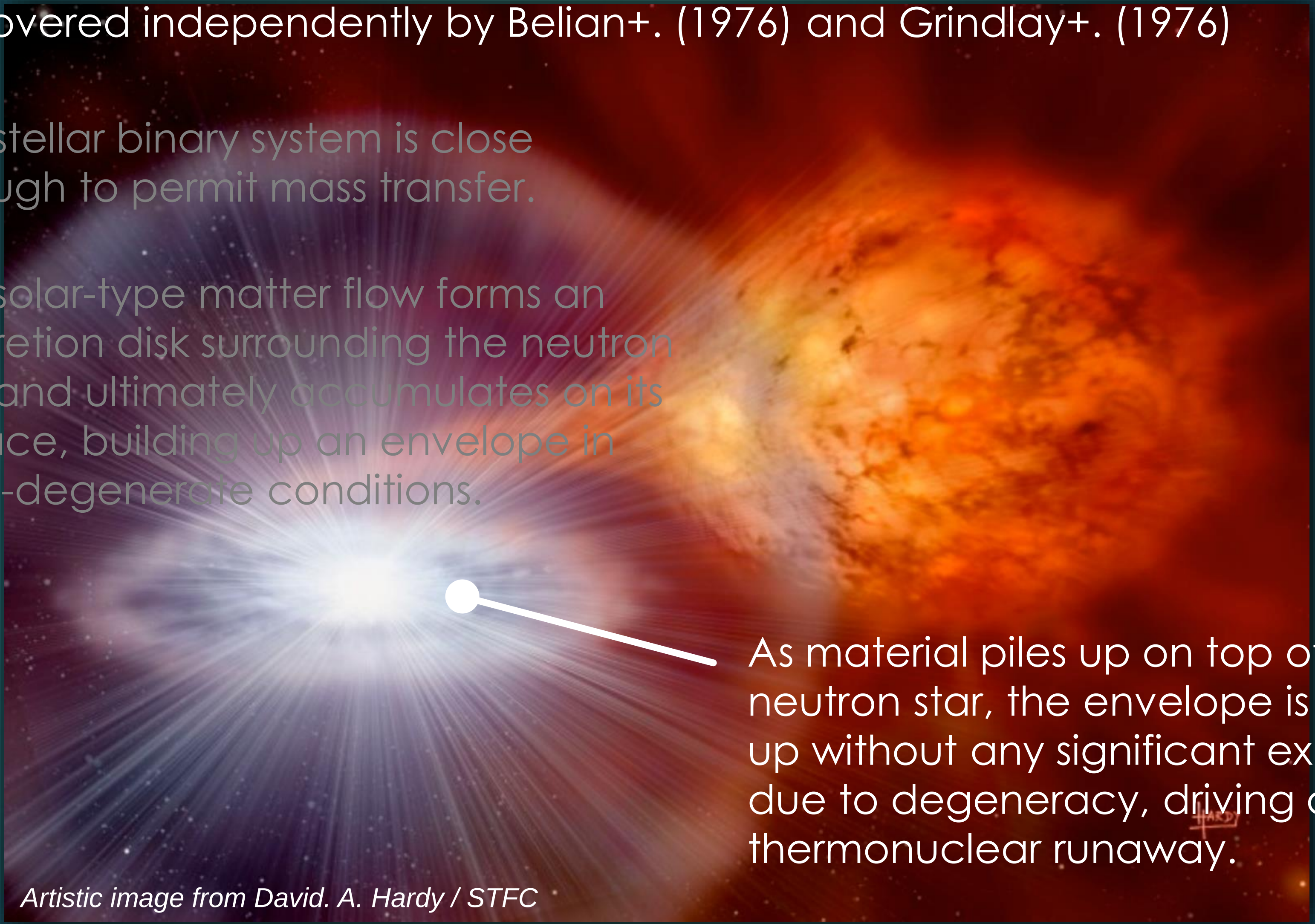

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# Type I X-ray burst (XRB)

Reaching $A$>60 and even $A$>100

Burst energies:
$10^{38} – 10^{40}$ ergs;
timescales: 10 – 100s;
recurrence times: hours – days; max.
temperatures: 1 – 2 GK;
densities: ~$10^6$ g/cm$^3$.

Drive nucleosynthesis along the proton-rich side:

- *rp* process [($p$, $\gamma$) reactions ] (**main process**)
- $\alpha p$ process [a sequence of ($\alpha$,$p$), ($p$, $\gamma$) reactions ]
- 3$\alpha$-reaction
- $\beta^+$ decay

Parikh+ (2008, 2009, 2013), Woosley+(2004), Schatz+ (1999)

# Type I X-ray burst (XRB)
# rapid proton capture (*rp*)-process

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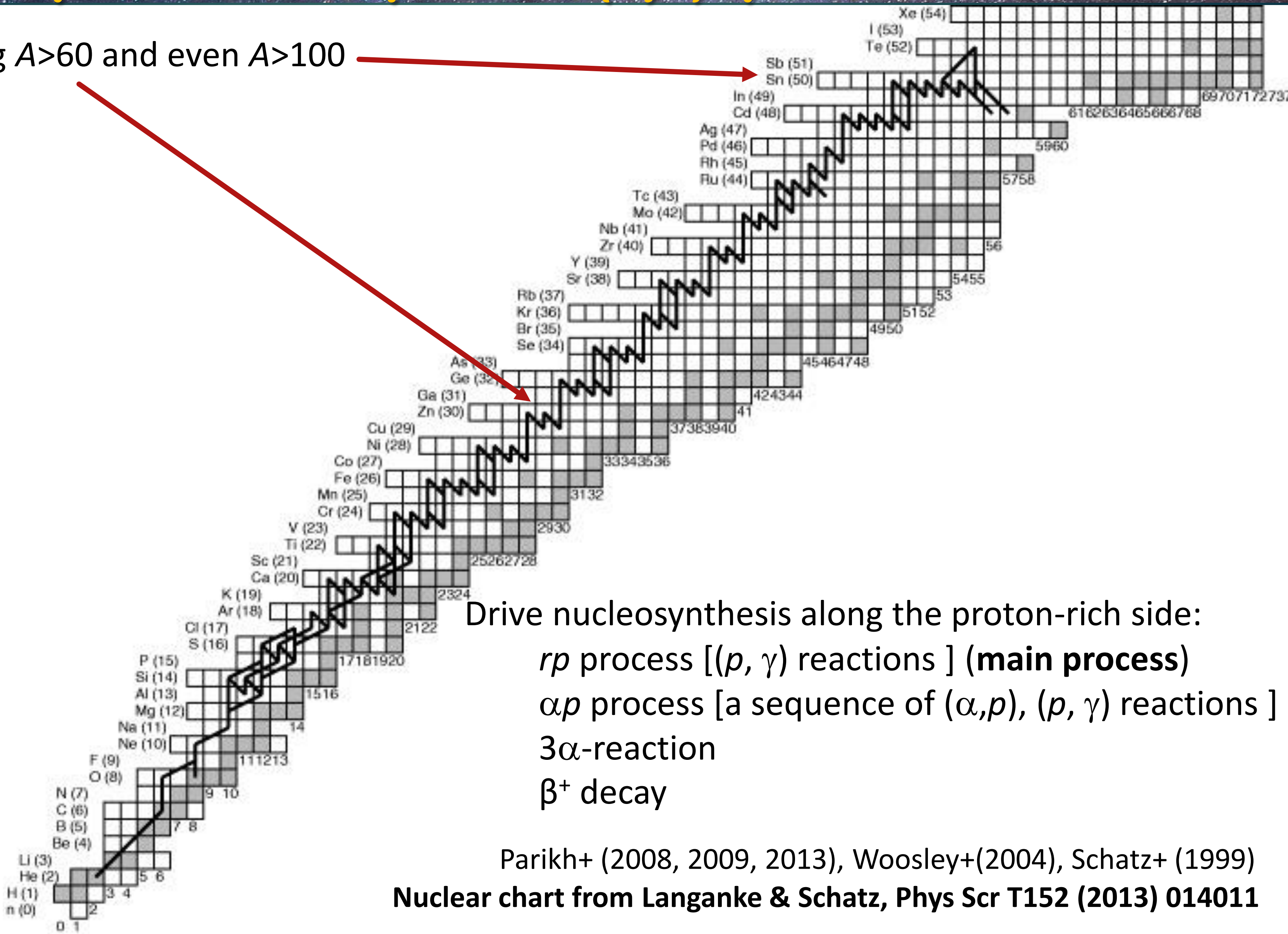


Drive nucleosynthesis along the proton-rich side:

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**Nuclear chart from Langanke & Schatz, Phys Scr T152 (2013) 014011**

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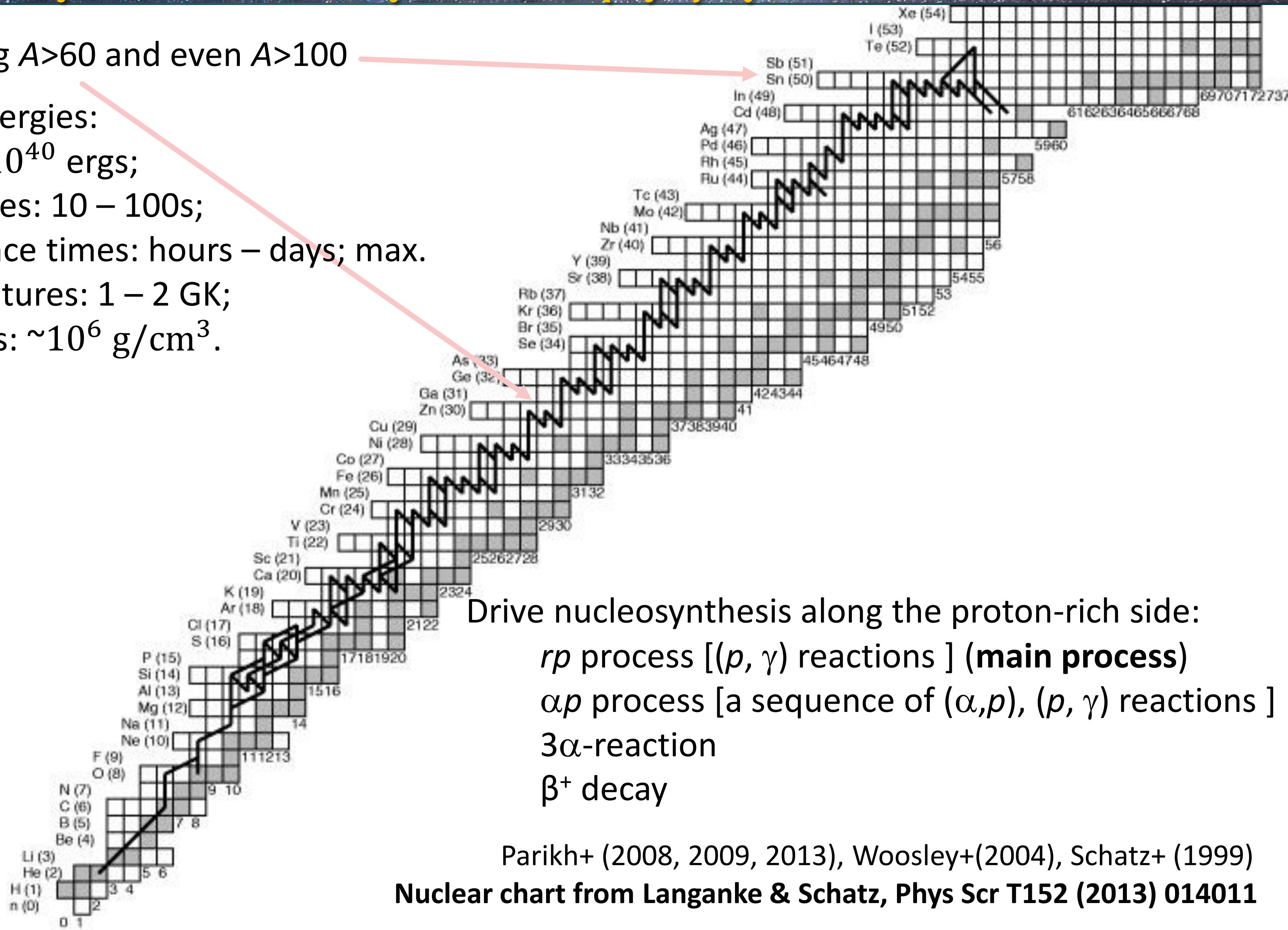


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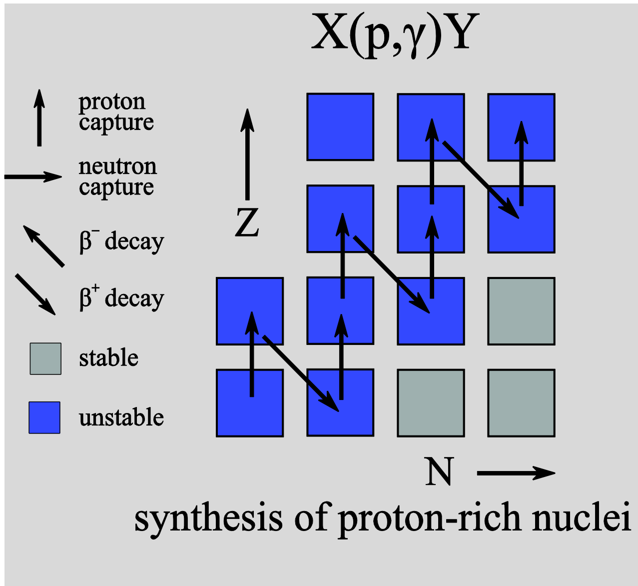


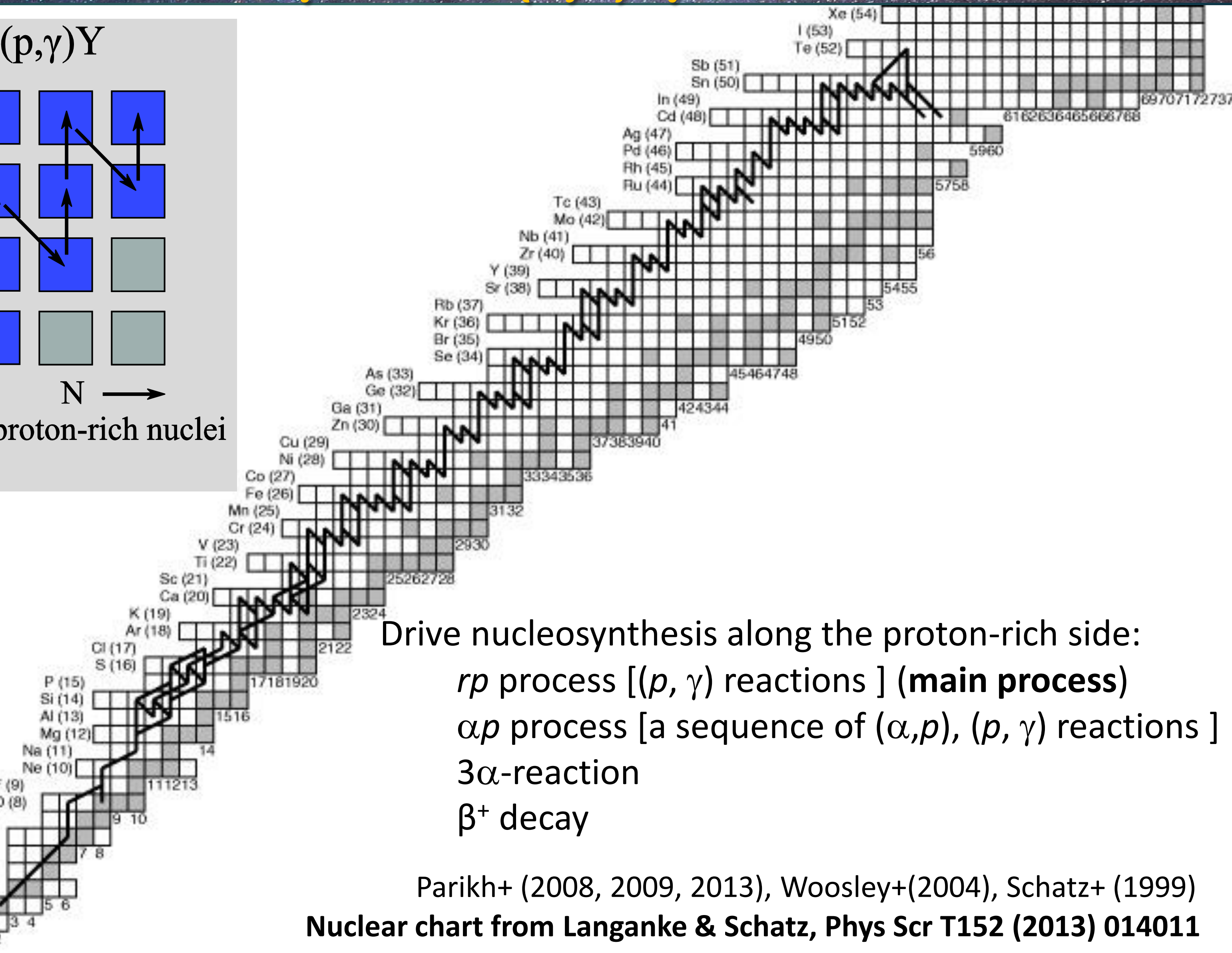


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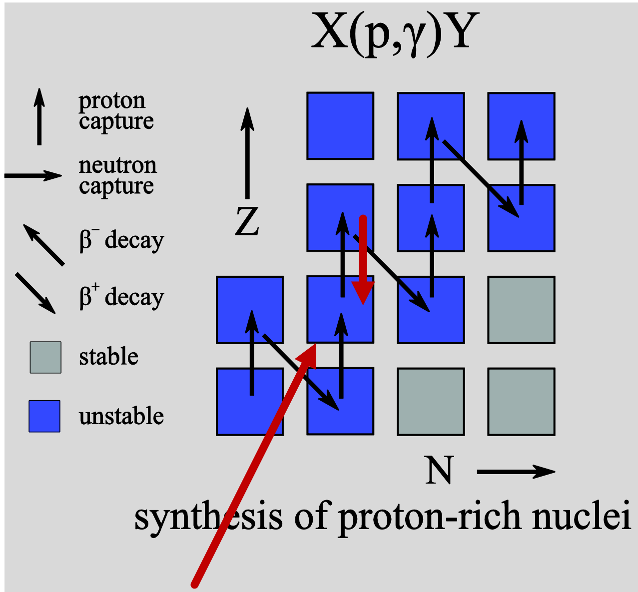
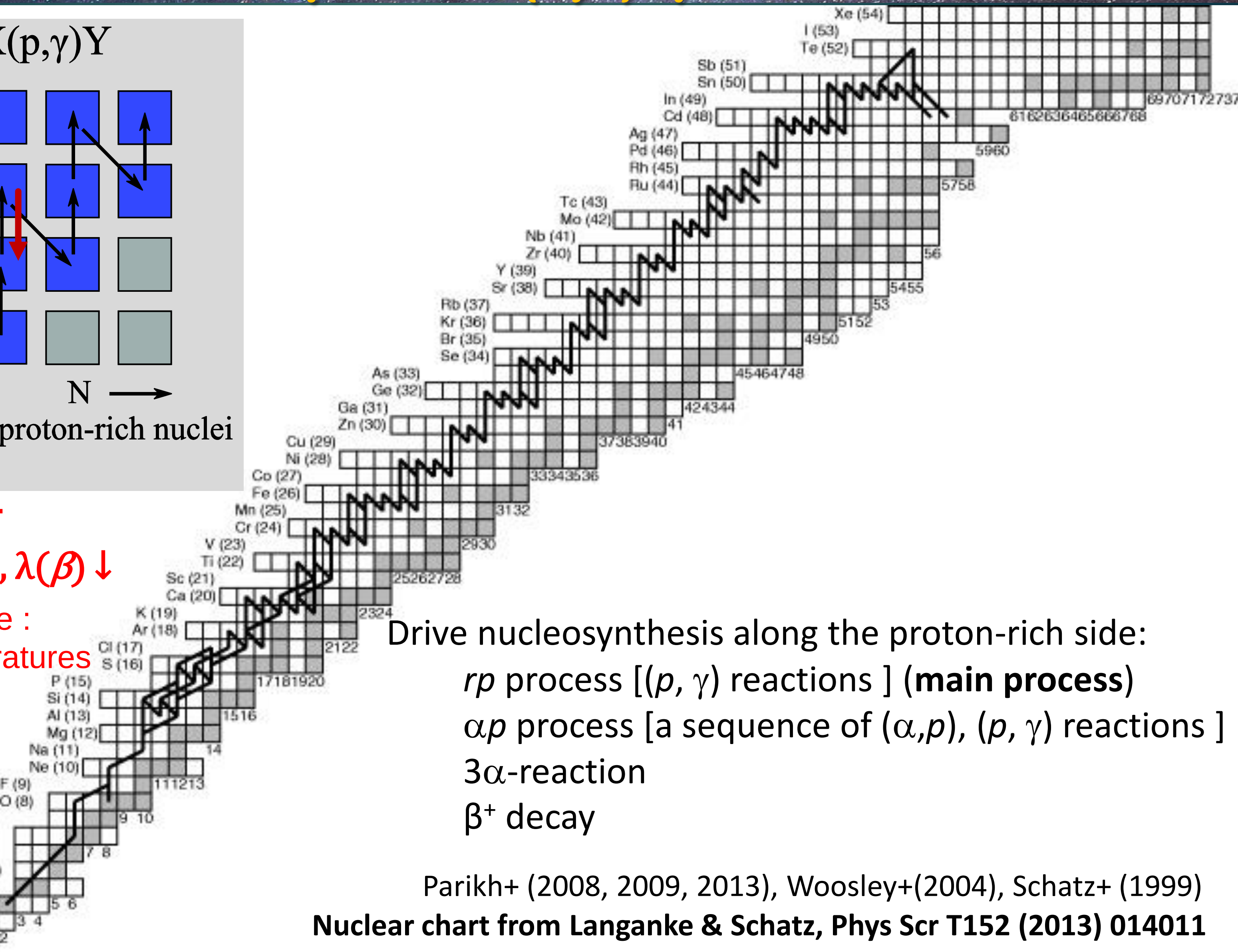
## rapid proton capture (*rp*)-process




**waiting point**

$(p,\gamma) \approx (\gamma,p), \lambda(\beta)\downarrow$

small ($p$,$\gamma$) $Q$-value :
$kT$ at XRB temperatures

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# Type I X-ray burst (XRB)
# rapid proton capture (*rp*)-process

PRL **106,** 112501 (2011) PHYSICAL REVIEW LETTERS week ending 18 MARCH 2011

## Direct Mass Measurements of Short-Lived $A = 2Z - 1$ Nuclides $^{63}$Ge, $^{65}$As, $^{67}$Se, and $^{71}$Kr and Their Impact on Nucleosynthesis in the *rp* Process

X. L. Tu,[1,2] H. S. Xu,[1,*] M. Wang,[1] Y. H. Zhang,[1] Yu. A. Litvinov,[3,4,1] Y. Sun,[5,1] H. Schatz,[6] X. H. Zhou,[1] Y. J. Yuan,[1] J. W. Xia,[1] G. Audi,[7] K. Blaum,[3] C. M. Du,[1,2] P. Geng,[1,2] Z. G. Hu,[1] W. X. Huang,[1] S. L. Jin,[1,2] L. X. Liu,[1,2] Y. Liu,[1] X. Ma,[1] R. S. Mao,[1] B. Mei,[1] P. Shuai,[8] Z. Y. Sun,[1] H. Suzuki,[9] S. W. Tang,[1,2] J. S. Wang,[1] S. T. Wang,[1,2] G. Q. Xiao,[1] X. Xu,[1,2] T. Yamaguchi,[10] Y. Yamaguchi,[11] X. L. Yan,[1,2] J. C. Yang,[1] R. P. Ye,[1,2] Y. D. Zang,[1,2] H. W. Zhao,[1] T. C. Zhao,[1] X. Y. Zhang,[1] and W. L. Zhan[1]

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[10]*Department of Physics, Saitama University, Saitama 338-8570, Japan*
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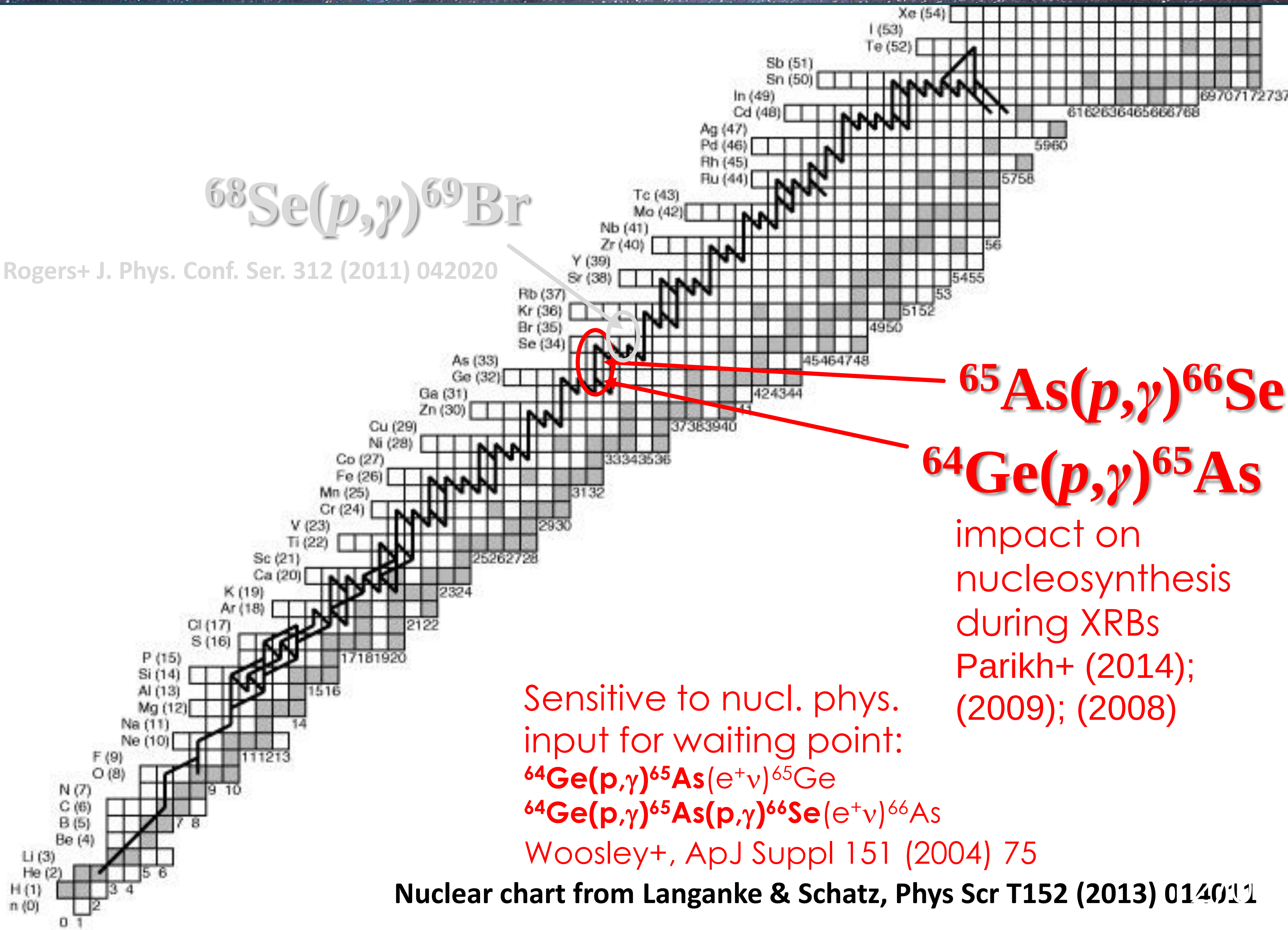
(Received 8 January 2011; published 16 March 2011)

Mass excesses of short-lived $A = 2Z - 1$ nuclei $^{63}$Ge, $^{65}$As, $^{67}$Se, and $^{71}$Kr have been directly measured to be −46 921(37), −46 937(85), −46 580(67), and −46 320(141) keV, respectively. The deduced proton separation energy of −90(85) keV for $^{65}$As shows that this nucleus is only slightly proton unbound. X-ray burst model calculations with the new mass excess of $^{65}$As suggest that the majority of the reaction flow passes through $^{64}$Ge via proton capture, indicating that $^{64}$Ge is not a significant *rp*-process waiting point.

DOI: 10.1103/PhysRevLett.106.112501 PACS numbers: 21.10.Dr, 26.30.Ca, 29.20.db

# rapid proton capture (*rp*)-process




$^{68}$Se($p$,$\gamma$)$^{69}$Br

Rogers+ J. Phys. Conf. Ser. 312 (2011) 042020

$^{65}$As($p$,$\gamma$)$^{66}$Se

$^{64}$Ge($p$,$\gamma$)$^{65}$As

impact on nucleosynthesis during XRBs
Parikh+ (2014); (2009); (2008)

Sensitive to nucl. phys. input for waiting point:
**$^{64}$Ge(p,$\gamma$)$^{65}$As**($e^+\nu$)$^{65}$Ge
**$^{64}$Ge(p,$\gamma$)$^{65}$As(p,$\gamma$)$^{66}$Se**($e^+\nu$)$^{66}$As
Woosley+, ApJ Suppl 151 (2004) 75

**Nuclear chart from Langanke & Schatz, Phys Scr T152 (2013) 014011**

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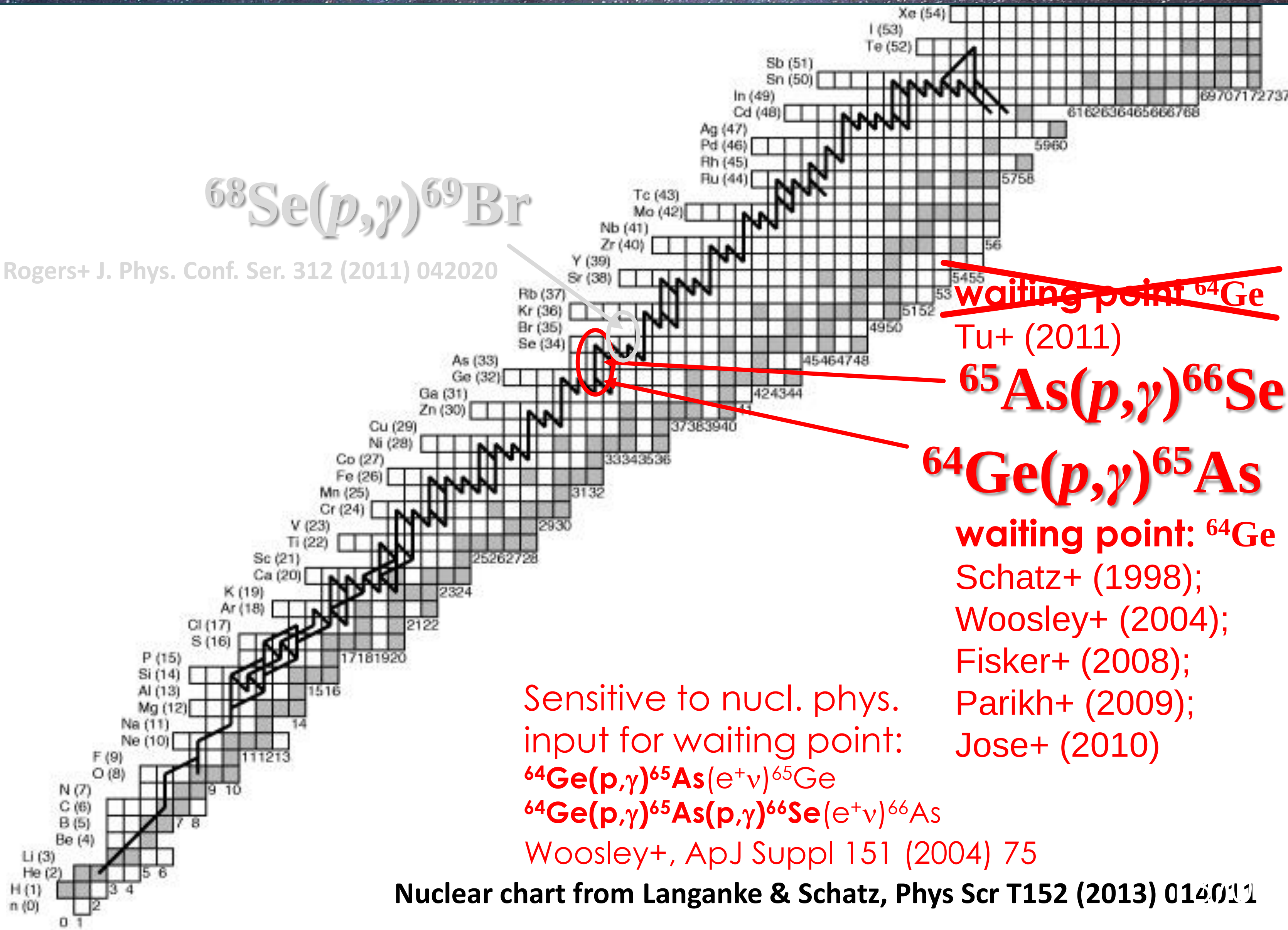


$^{68}$Se($p$,$\gamma$)$^{69}$Br

Rogers+ J. Phys. Conf. Ser. 312 (2011) 042020

~~waiting point $^{64}$Ge~~

Tu+ (2011)

$^{65}$As($p$,$\gamma$)$^{66}$Se

$^{64}$Ge($p$,$\gamma$)$^{65}$As

**waiting point: $^{64}$Ge**

Schatz+ (1998);
Woosley+ (2004);
Fisker+ (2008);
Parikh+ (2009);
Jose+ (2010)

Sensitive to nucl. phys. input for waiting point:

**$^{64}$Ge(p,$\gamma$)$^{65}$As**($e^+\nu$)$^{65}$Ge

**$^{64}$Ge(p,$\gamma$)$^{65}$As(p,$\gamma$)$^{66}$Se**($e^+\nu$)$^{66}$As

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**Nuclear chart from Langanke & Schatz, Phys Scr T152 (2013) 014011**

# Nuclear structure

## Large scale shell-model calculations + exp. data

- **Experiment:**
  Obertelli+ (2011),
  Ruotsalainen+(2013),
  NNDC
- **Theory:**
  Shell model (GXPF1a)
- **Sp:**
  AME(2012),
  Tu+ (2011)

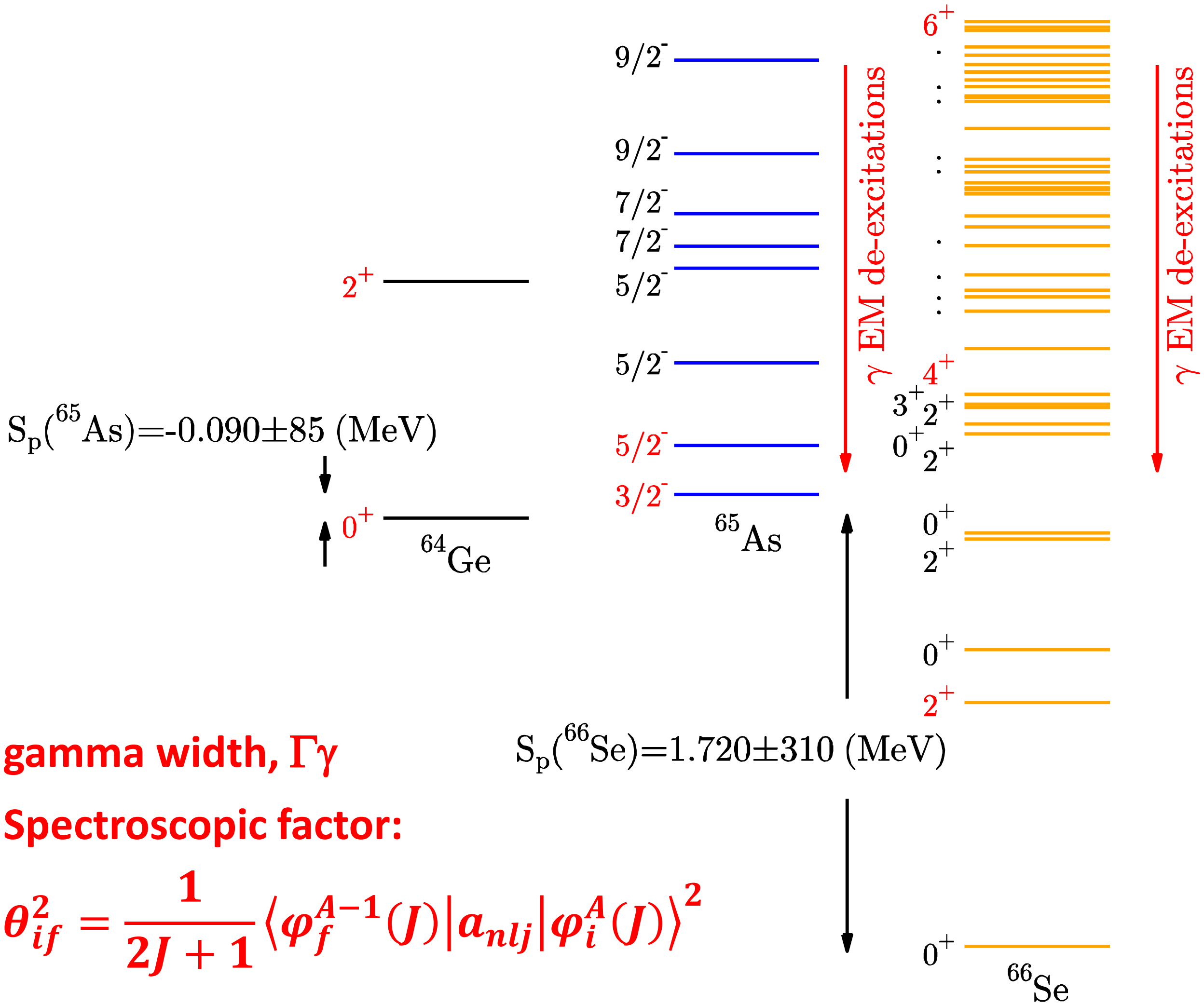
**gamma width, $\Gamma\gamma$**

**Spectroscopic factor:**

$$\theta_{if}^{2} = \frac{1}{2J+1}\left\langle \varphi_f^{A-1}(J) \middle| a_{nlj} \middle| \varphi_i^{A}(J) \right\rangle^2$$

# Nuclear structure

## Large scale shell-model calculations + exp. data

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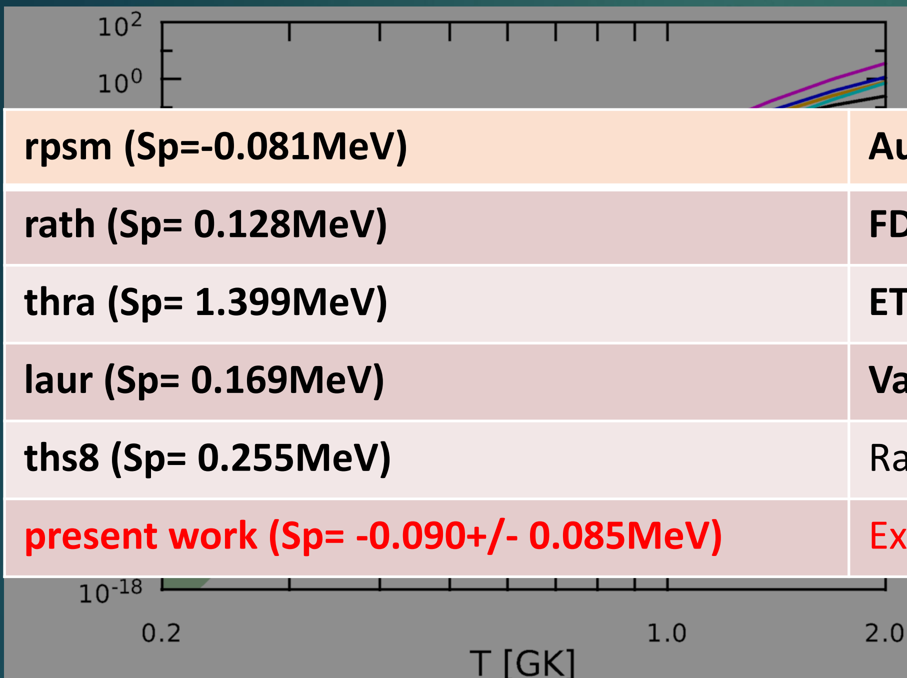
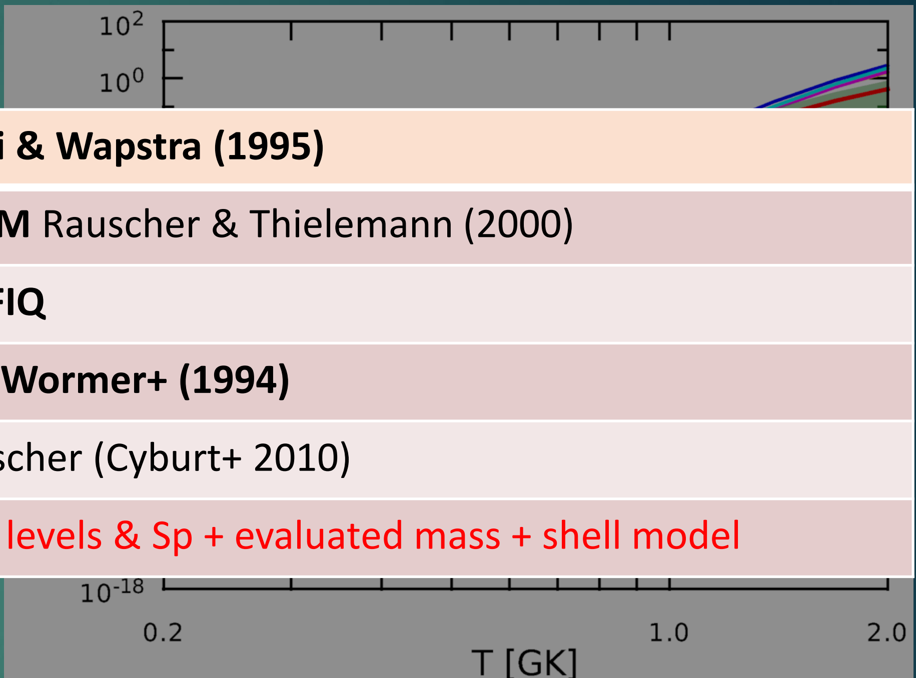
**gamma width, Γγ**

**Spectroscopic factor:**

$$\theta_{if}^2 = \frac{1}{2J+1}\langle \varphi_f^{A-1}(J)|a_{nlj}|\varphi_i^A(J)\rangle^2$$

# Comparisons of present reaction rates with JINA data (REACLIB)



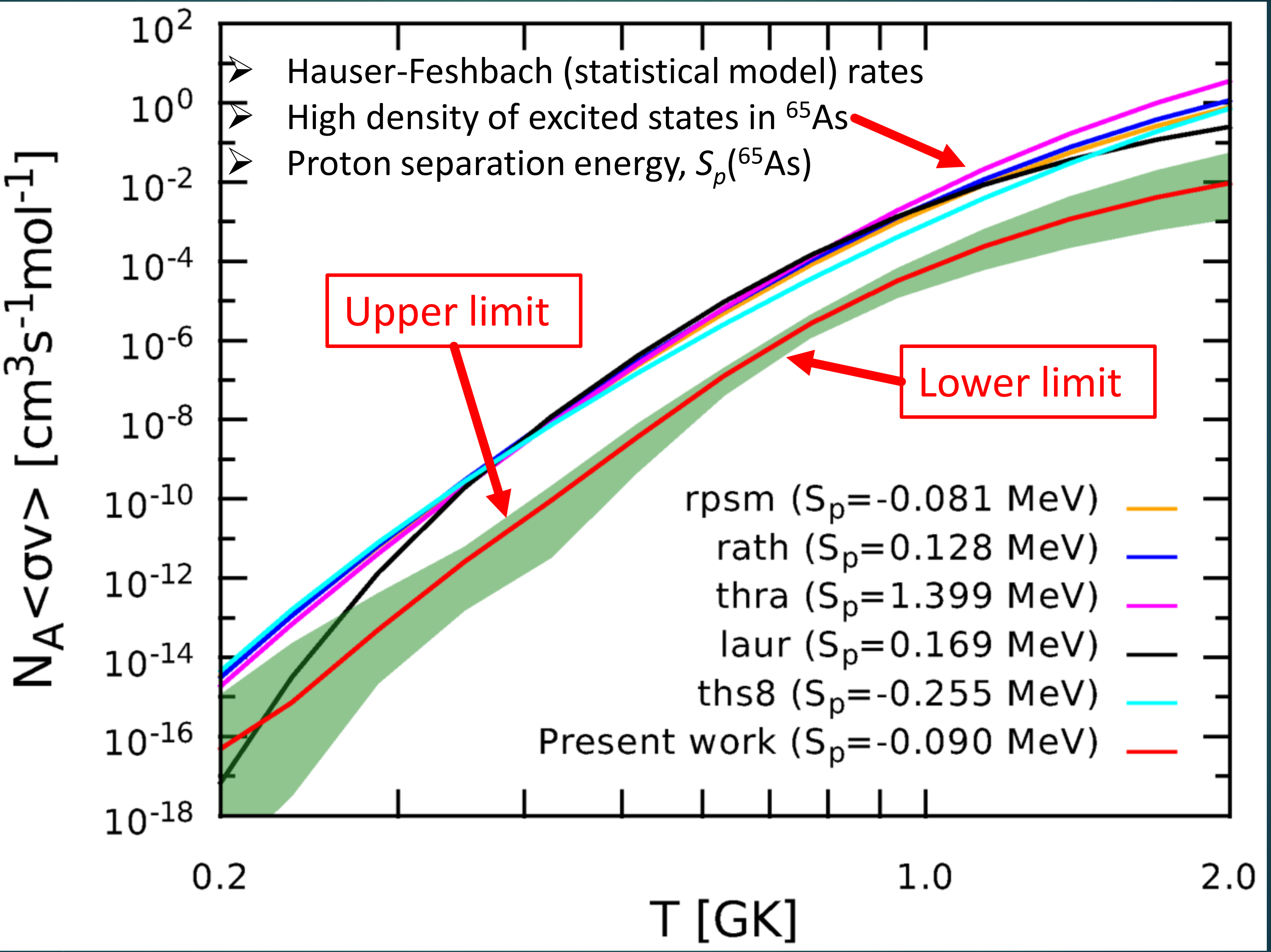

| | |
|---|---|
| **rpsm (Sp=-0.081MeV)** | **Audi & Wapstra (1995)** |
| **rath (Sp= 0.128MeV)** | **FDRM** Rauscher & Thielemann (2000) |
| **thra (Sp= 1.399MeV)** | **ETSFIQ** |
| **laur (Sp= 0.169MeV)** | **Van Wormer+ (1994)** |
| **ths8 (Sp= 0.255MeV)** | Rauscher (Cyburt+ 2010) |
| **present work (Sp= -0.090+/- 0.085MeV)** | Exp. levels & Sp + evaluated mass + shell model |

$^{64}Ge(p,\gamma)^{65}As$

$^{65}As(p,\gamma)^{66}Se$

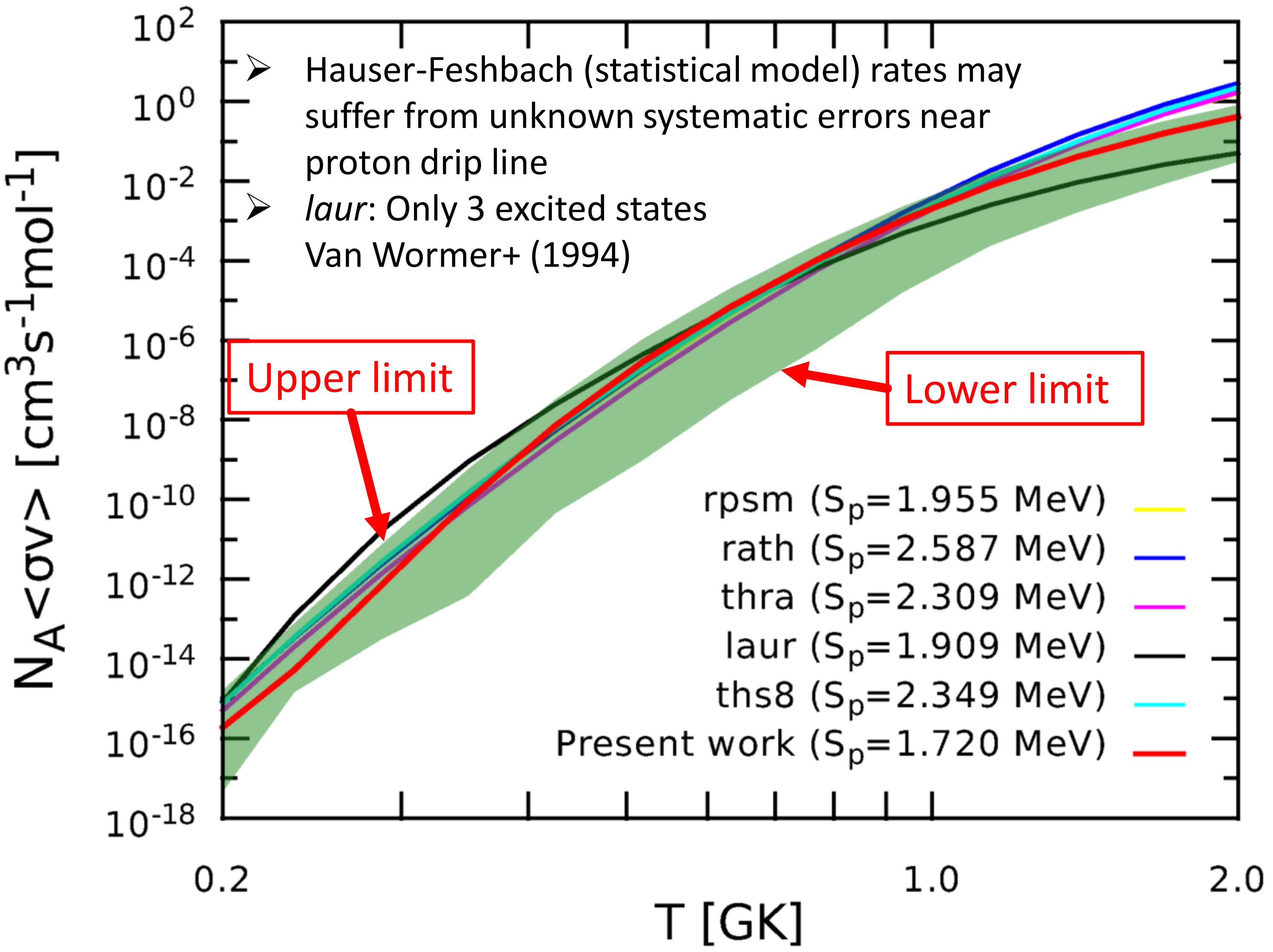
# Comparisons of reaction rates

## $^{64}Ge(p,\gamma)^{65}As$

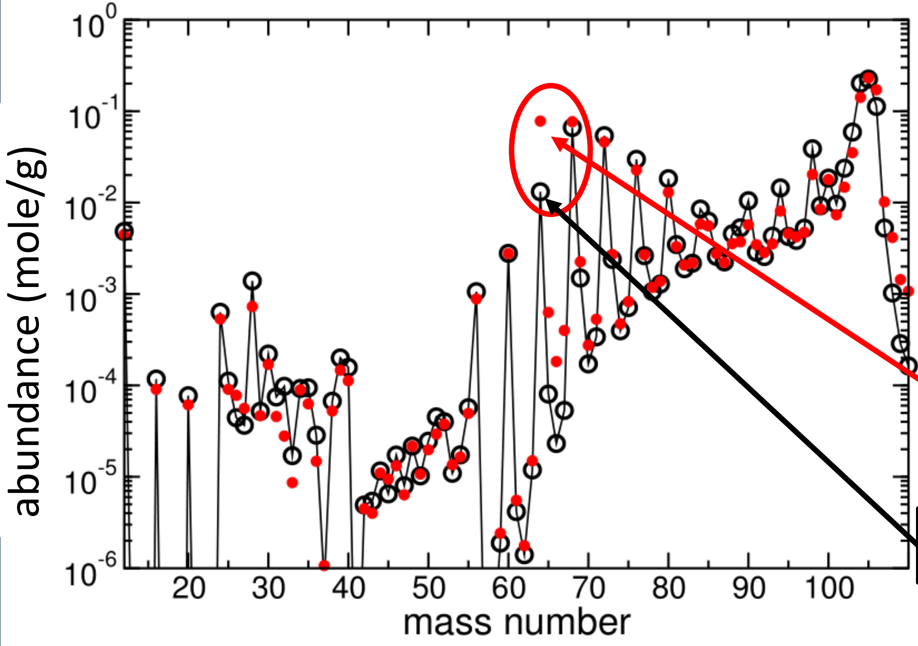


# Comparisons of reaction rates

$^{65}\mathrm{As}(p,\gamma)^{66}\mathrm{Se}$



# Abundance distribution of the XRB ashes




$$ratio = \frac{\text{Abundance of } A = 64}{\text{Abundance of } A = 68}$$

$ratio = 1.1$, $^{64}$Ge $\rightarrow$ the strongest waiting point

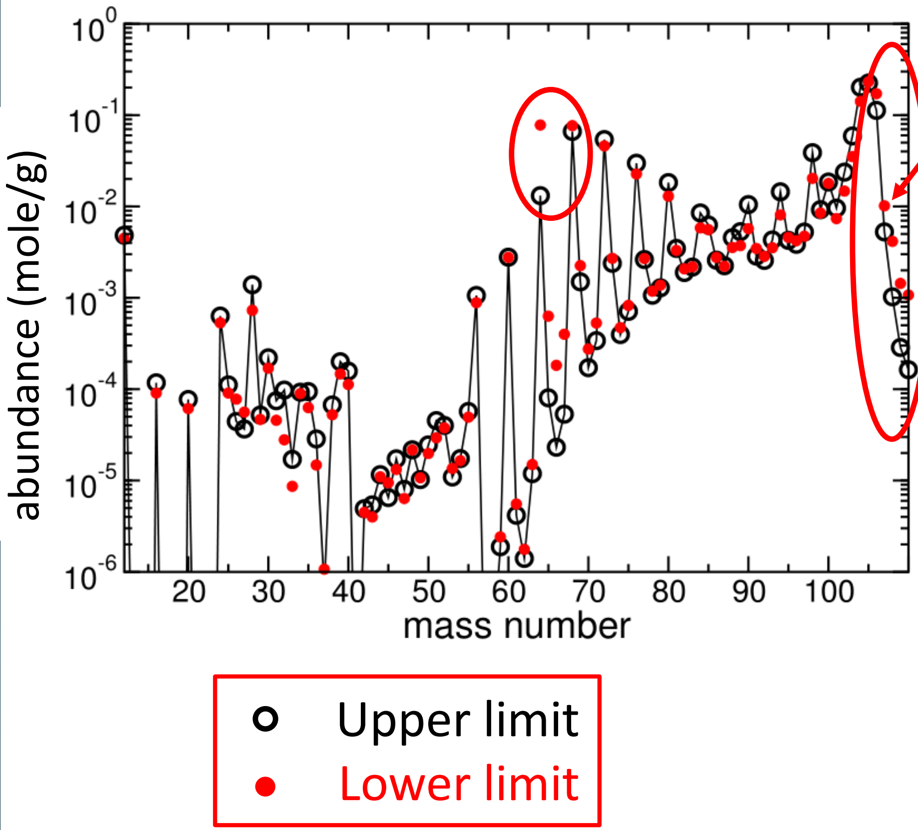
$ratio = 0.7$, $^{64}$Ge $\rightarrow$ not a significant waiting point

- ○ Upper limit
- ● Lower limit

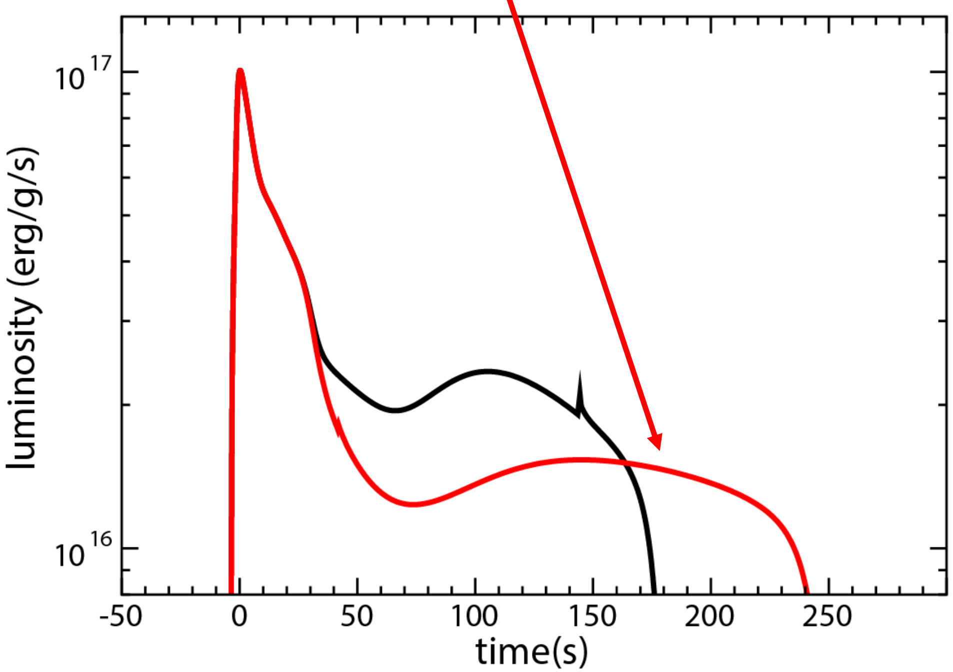
*Present* $^{64}$Ge$(p,\gamma)^{65}$As and $^{65}$As$(p,\gamma)^{66}$Se

One-zone XRB hydrodynamic model nucleosynthesis simulation (S01 model)

# Abundances and end stage light curve




$A \geq 106$, heavy-isotope production is enhanced, slower burning at high T and leading to longer burst

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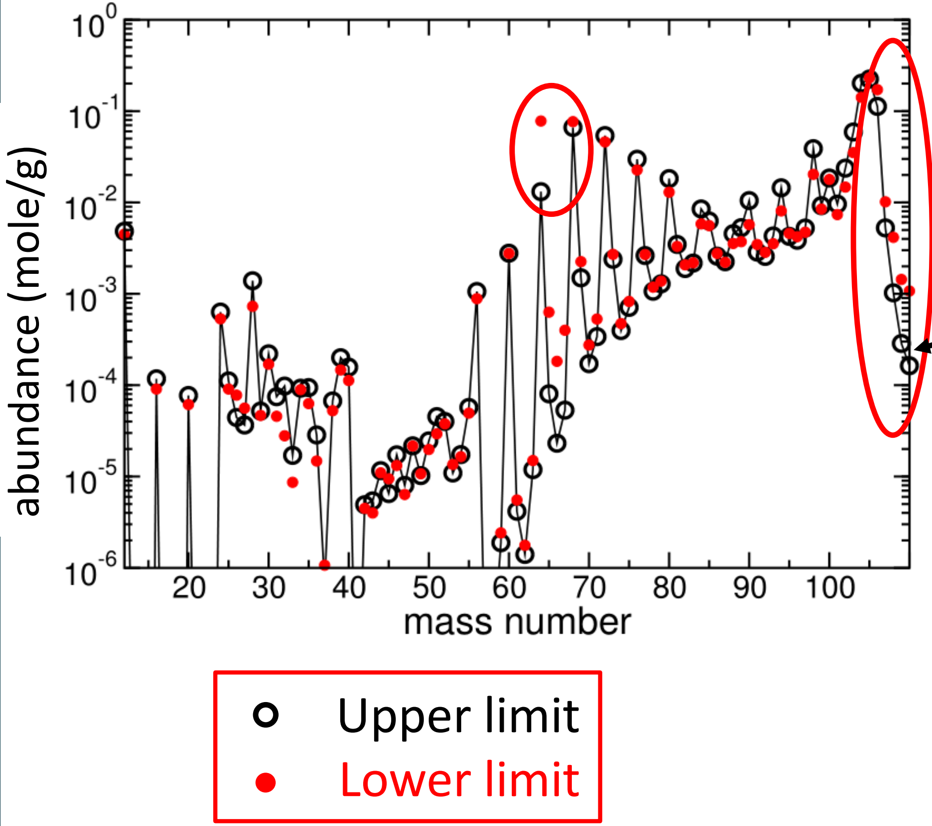
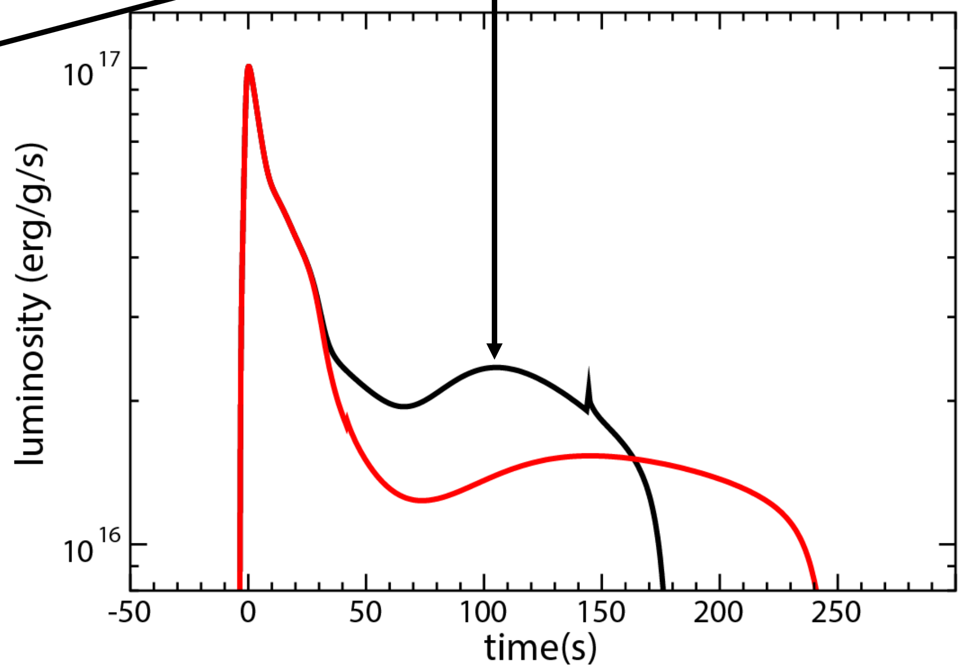



$A \geq 106$, heavy-isotope production is reduced, faster burning at high T consuming H quickly and leading to shorter burst

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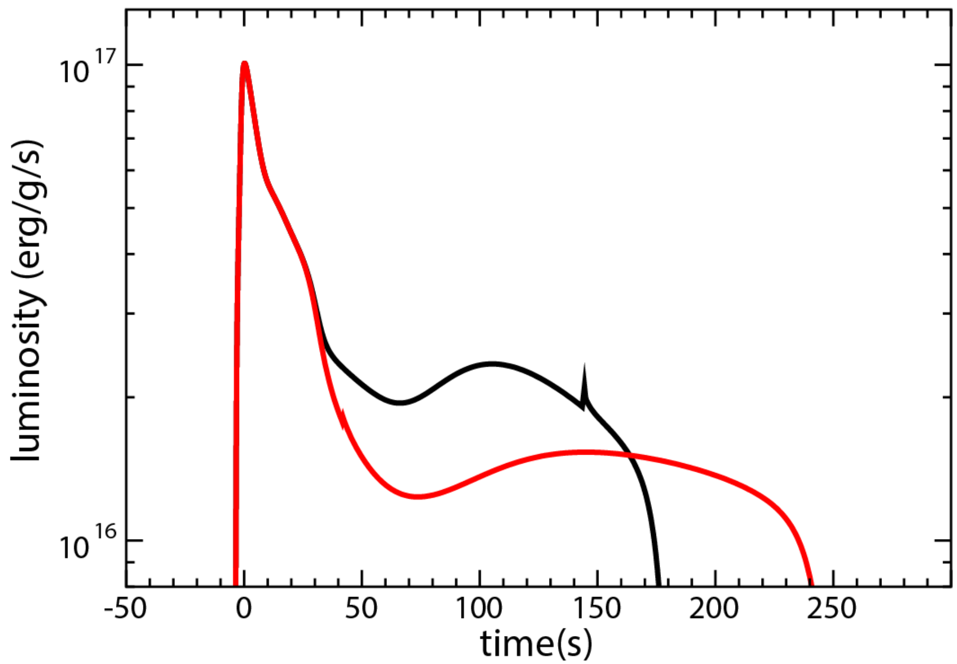
One-zone XRB hydrodynamic model nucleosynthesis simulation (S01 model)

# End stage light curve

Changing only $S_p(^{65}As)$ and/or $S_p(^{66}Se)$:

- Producing (roughly) similar light curve

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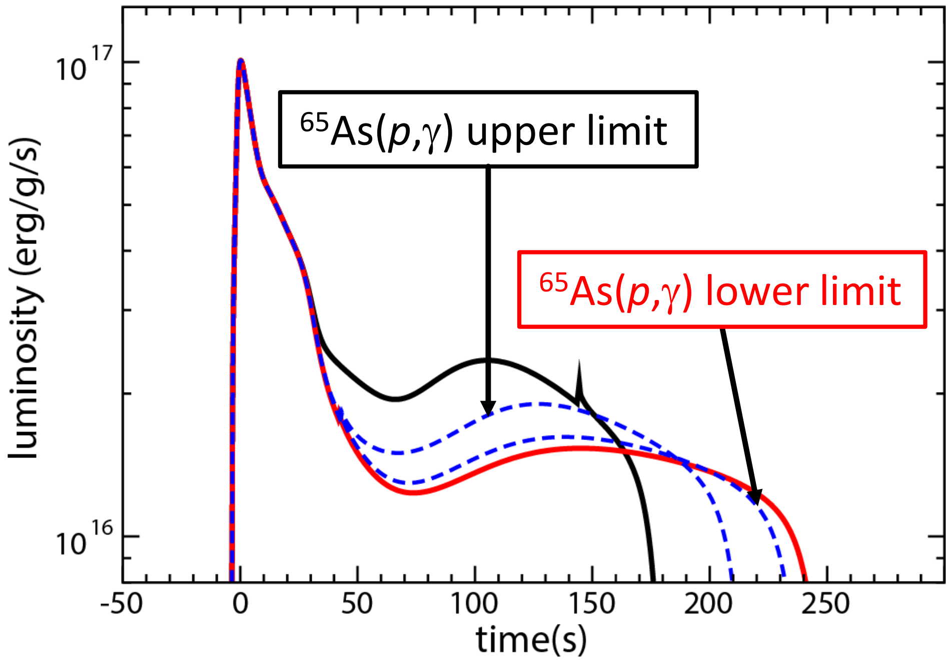
# End stage light curve

Changing only $S_p(^{65}As)$ and/or $S_p(^{66}Se)$:

- Producing (roughly) similar light curve

Using nominal values of $S_p(^{65}As)$, $S_p(^{66}Se)$, and $^{64}Ge(p,\gamma)$, vary $^{65}As(p,\gamma)$ :

- Significant change of end light curve
- $0.7 \leq ratio \left(\frac{\text{Abundance of } A=64}{\text{Abundance of } A=68}\right) \leq 1.0$
- the $^{65}As(p,\gamma)$ has significant role




*Present* $^{64}Ge(p,\gamma)^{65}As$ and $^{65}As(p,\gamma)^{66}Se$

# Summary & Perspective

- New thermonuclear rates of **$^{64}$Ge($p$,$\gamma$)$^{65}$As** and **$^{65}$As($p$,$\gamma$)$^{66}$Se** reactions have been determined based on newly measured $S_p$($^{65}$As), evaluated $S_p$($^{66}$Se), large-scale shell model calculation, and exp. levels of $^{65}$As. These new rates differ, for instance at ≈ 1 GK, a factor of ≈ 3 – 90 from others.
- The waiting point $^{64}$Ge is not completely ruled out using one-zone XRB model.
- We propose:
  - to measure the mass of $^{66}$Se,
  - to obtain higher precision of mass $^{65}$As, and
  - nuclear structure of both nuclei
  - investigation with 1D multi-zone hydrodynamic XRB model.