Nucleosynthesis of Mo and Ru isotopes in ν-driven winds

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HELMHOLTZ GEMEINSCHAFT

GSI

HIC for FAIR
Helmholtz International Center

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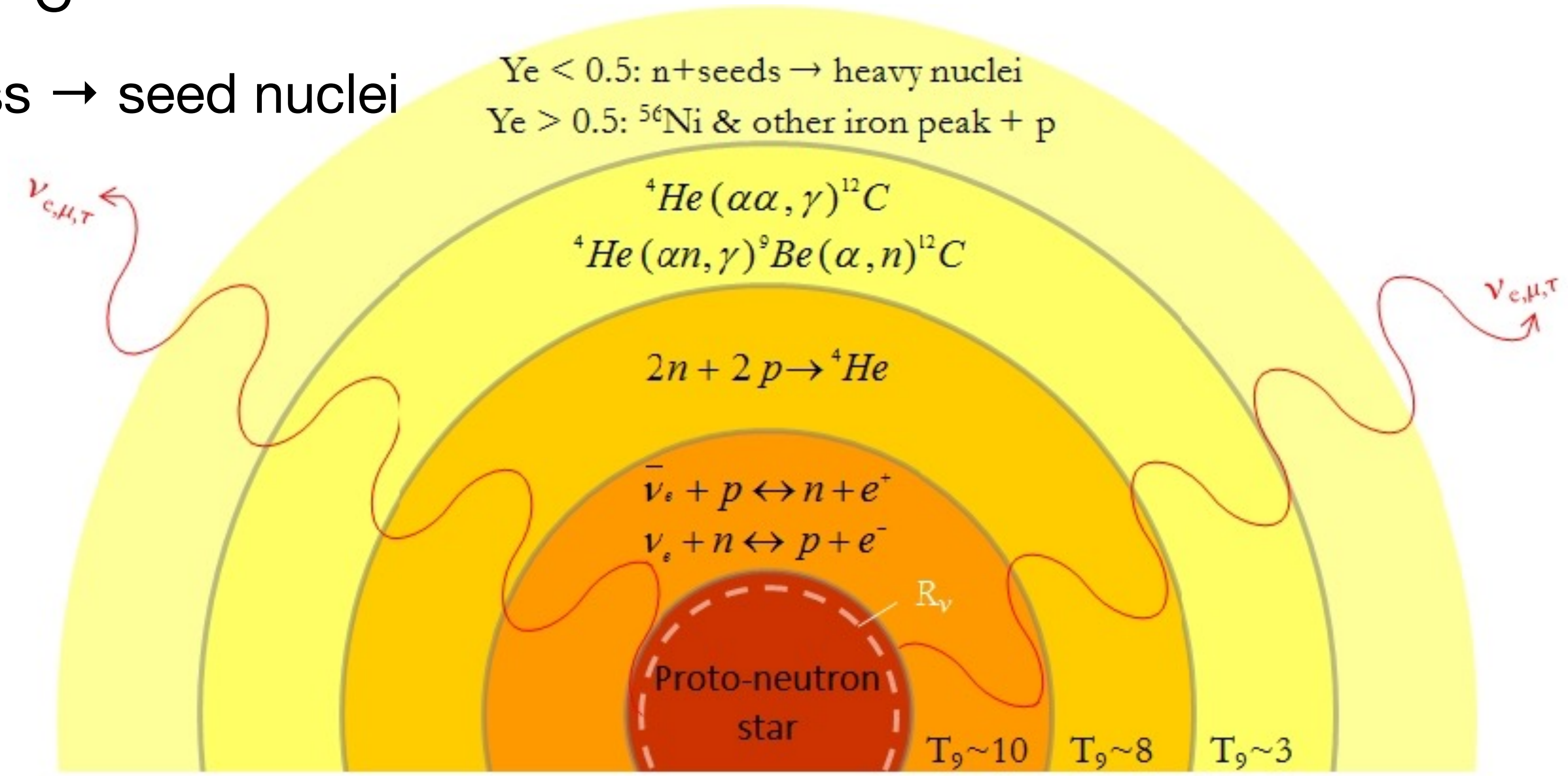
Helmholtz Graduate School for Hadron and Ion Research

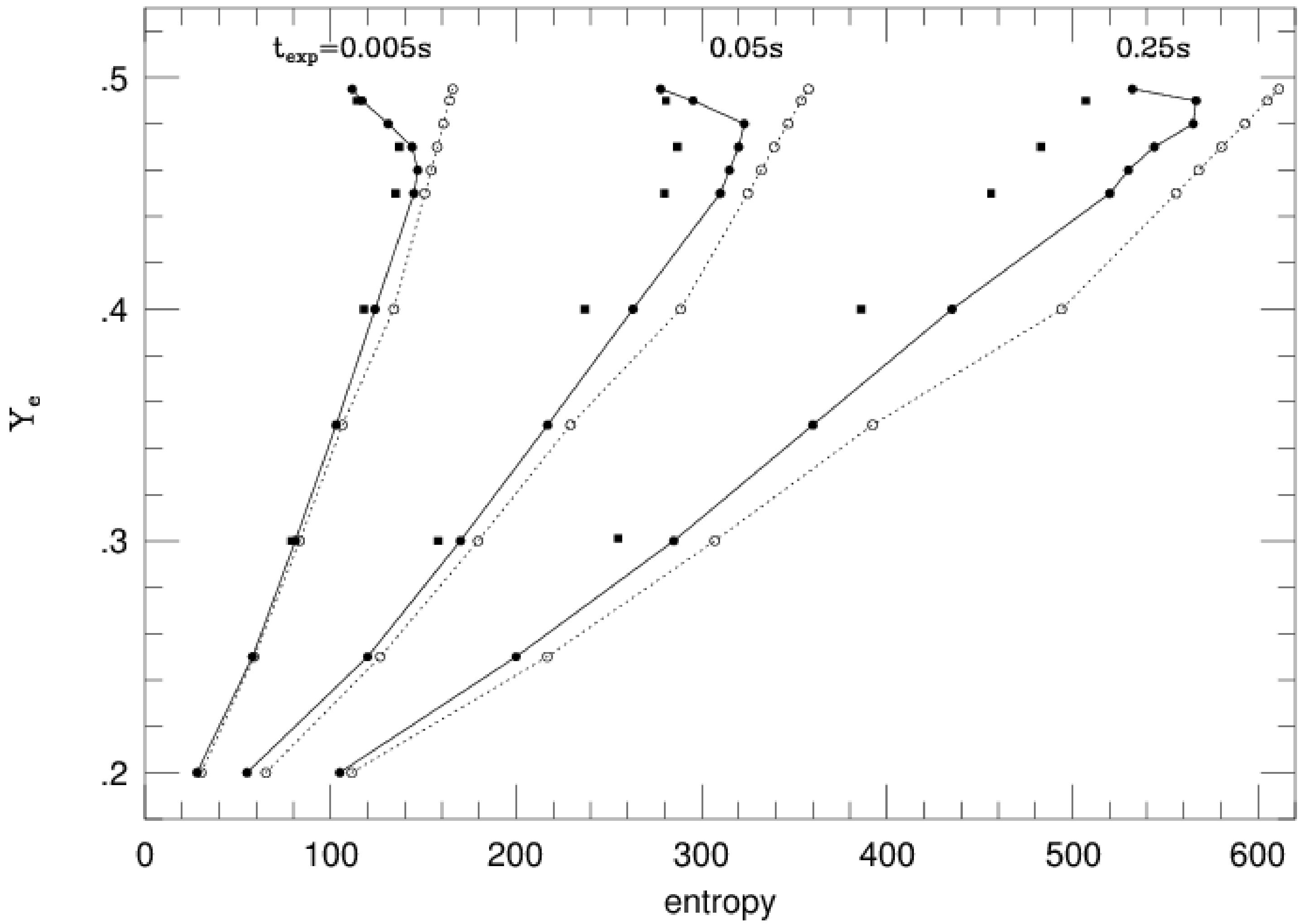
Neutrino-driven winds

- neutrino-driven winds follow core-collapse supernovae
- nuclear statistical equilibrium **(NSE)** at the beginning
- **alpha-rich freeze out**
- formation of ^{12}C
- alpha-process → seed nuclei



Nucleosynthesis in neutrino-driven winds

wind parameters: entropy, expansion timescale, electron fraction
[Hoffman et al. 1996, Meyer et al. 1994, Qian & Woosley 1996, Freiburghaus et. al 1999]



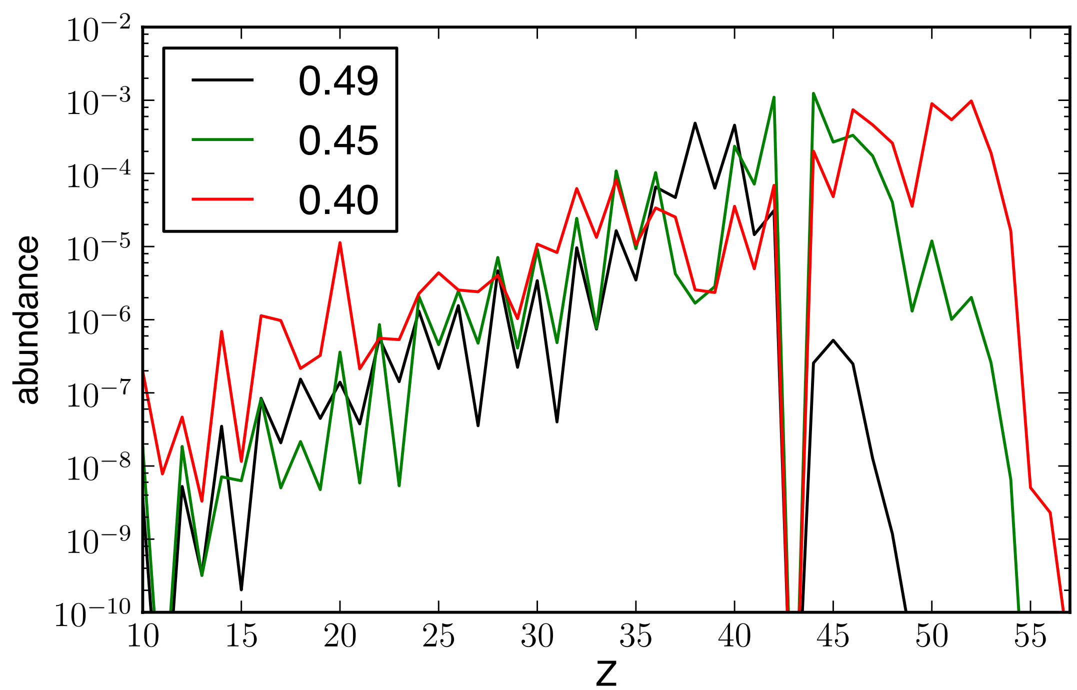
Hoffman et al. 1996

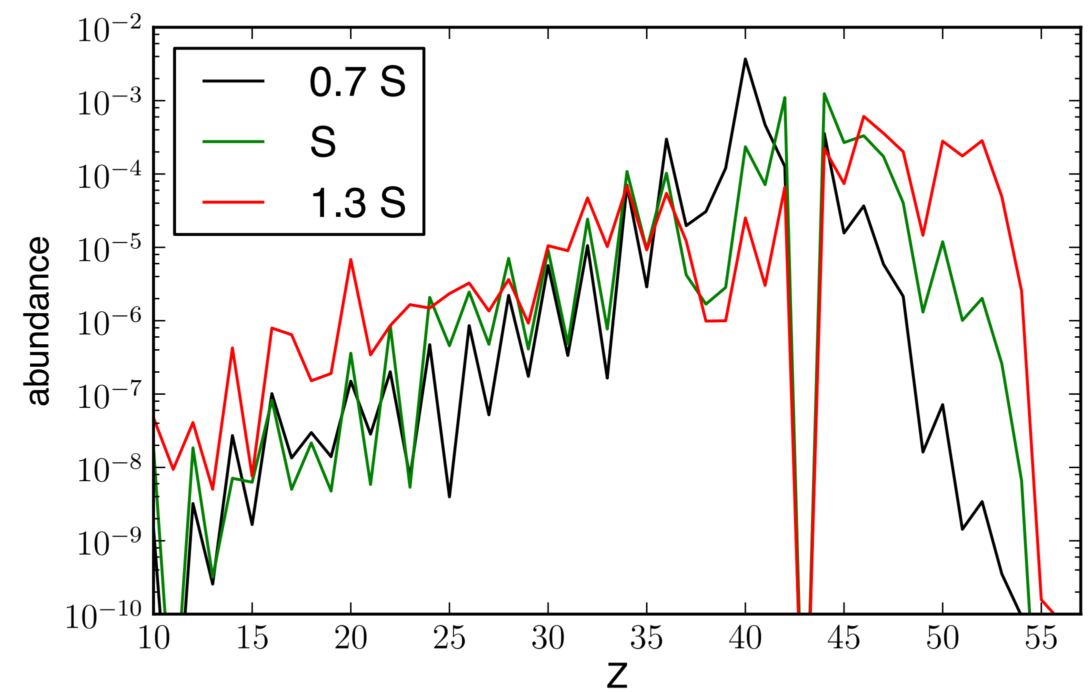
- $Y_e < 0.5$
  - $Y_n/Y_{seed} \gtrsim 100$ → **r-process**
  - $Y_n/Y_{seed} \lesssim 1$ → **weak r-process**
- $Y_e > 0.5$
  - $Y_p > Y_n$, Y_n/Y_{seed} very small → **νp-process** [Pruet et al. 2006, Fröhlich et al. 2006, Wanajo 2006]

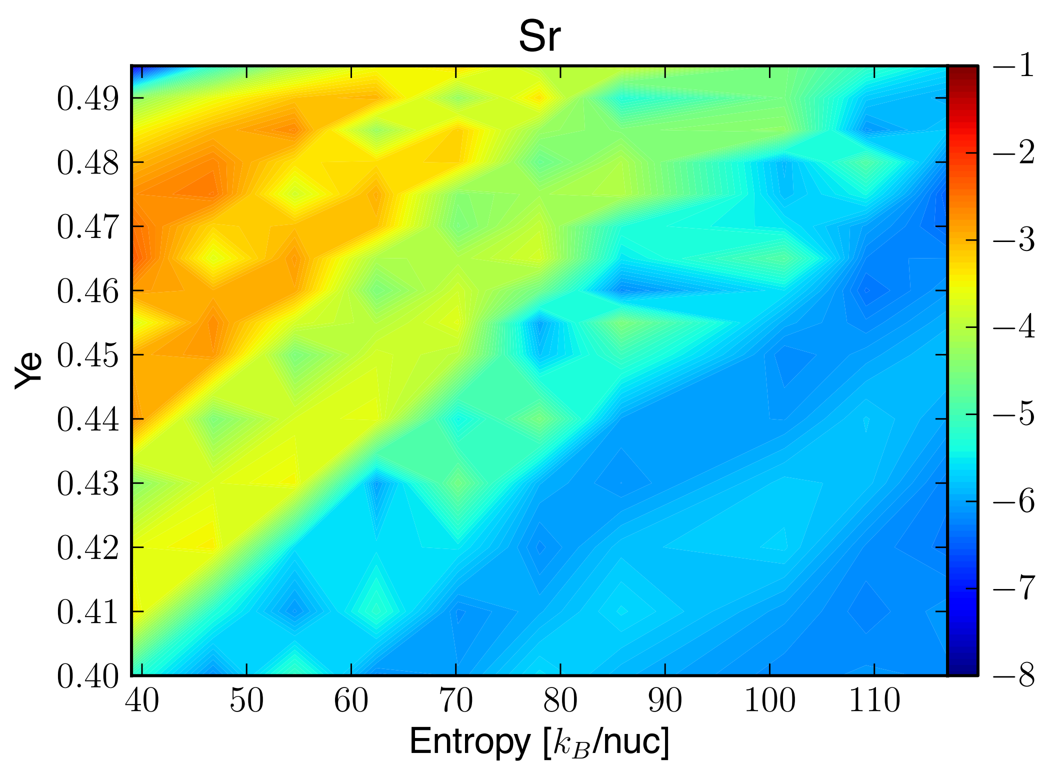
Nucleosynthesis in neutrino-driven winds

reference case

Arcones & Bliss 2014







Lighter Element Primary Process
[Travaglio et al. 2004, Montes et al. 2007, Arcones & Montes 2011]

Sr, Y, Zr

Molybdenum and ruthenium isotopes

Ru	94	95	96 p	97	98 p	99 s,r	100 s	101 s,r	102 s,r	103	104 r
Tc	93	94	95	96	97	98	99	100	101	102	103
Mo	92 p	93	94 p	95 s,r	96 s	97 s,r	98 s,r	99	100 r		
Nb	91	92 p	93 s	94	95	96	97	98	99		
Zr	90 s	91 s	92 s	93 s	94 s	95	96 r	97			
Y	89 s	90	91	92							
Sr	88 s,r	89	90	91							

- largest number of stable isotopes among lighter heavy elements
- similar structures:
  - **p-only:** ^{92,94}Mo and ^{96,98}Ru
  - **s-, r-mixed:** ^{95,97,98}Mo, ^{99,101,102}Ru
  - **s-only:** ^{96}Mo and ^{100}Ru
  - **r-only:** ^{100}Mo and ^{104}Ru

- several astrophysical sites failed to produce solar system ratios of ^{92,94}Mo and ^{96,98}Ru
  → see e.g. O/Ne layers in type II SNe (Prantzos et al. 1990, Rayet et al. 1995), slightly neutron-rich winds (Hoffman et al. 1996, Wanajo 2006), proton-rich winds (Fisker et al. 2008, Wanajo 2006)
- SiC X grains exhibit different isotopic ratios of ^{95,97}Mo than in the solar system
  → see Pellin et al. 1999

Nucleosynthesis of p-isotopes: ^{92,94}Mo

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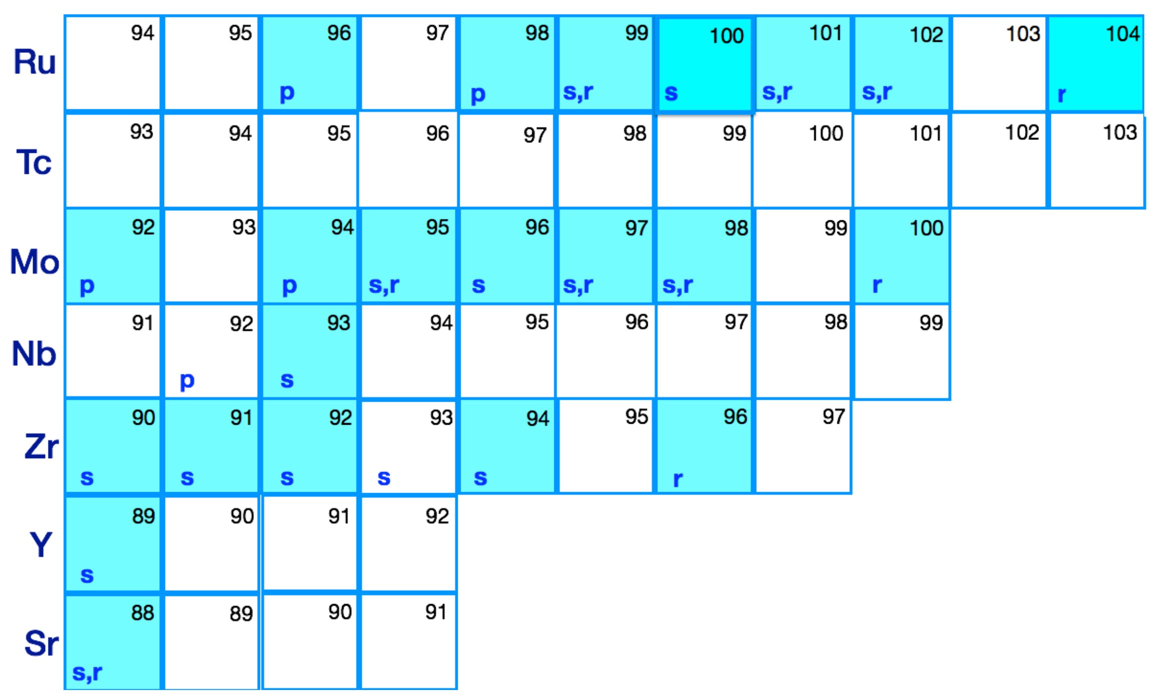
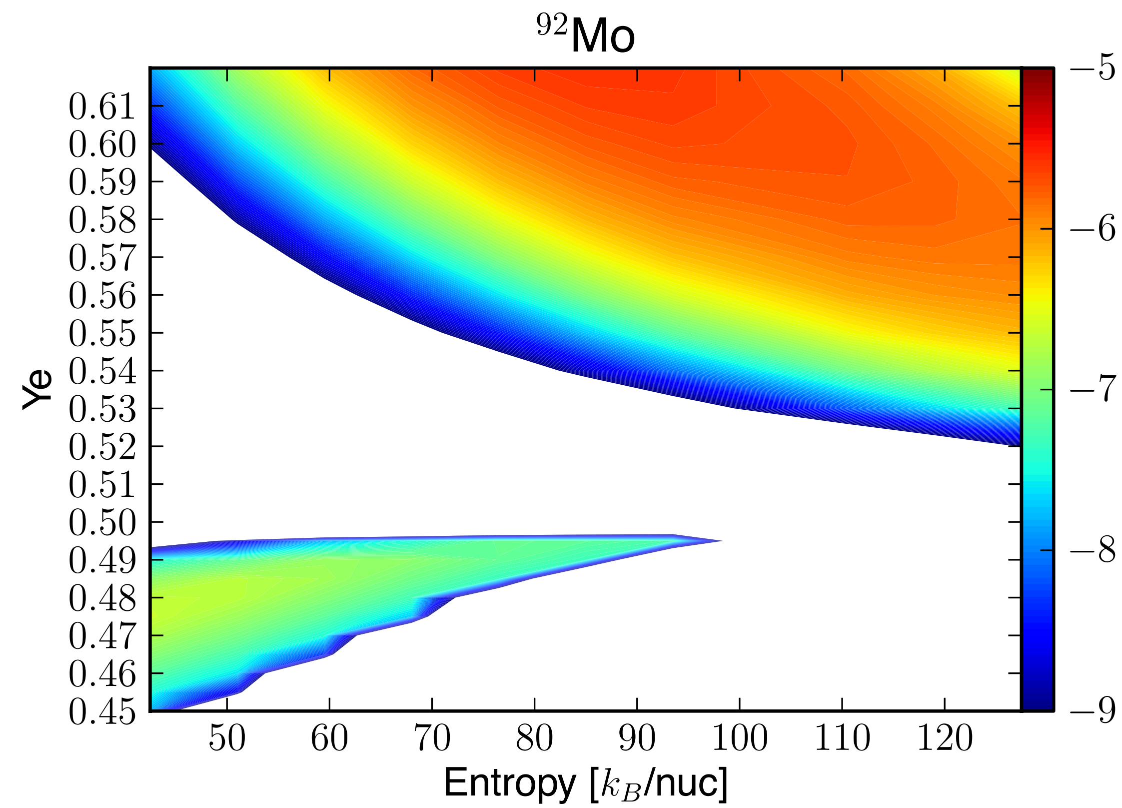
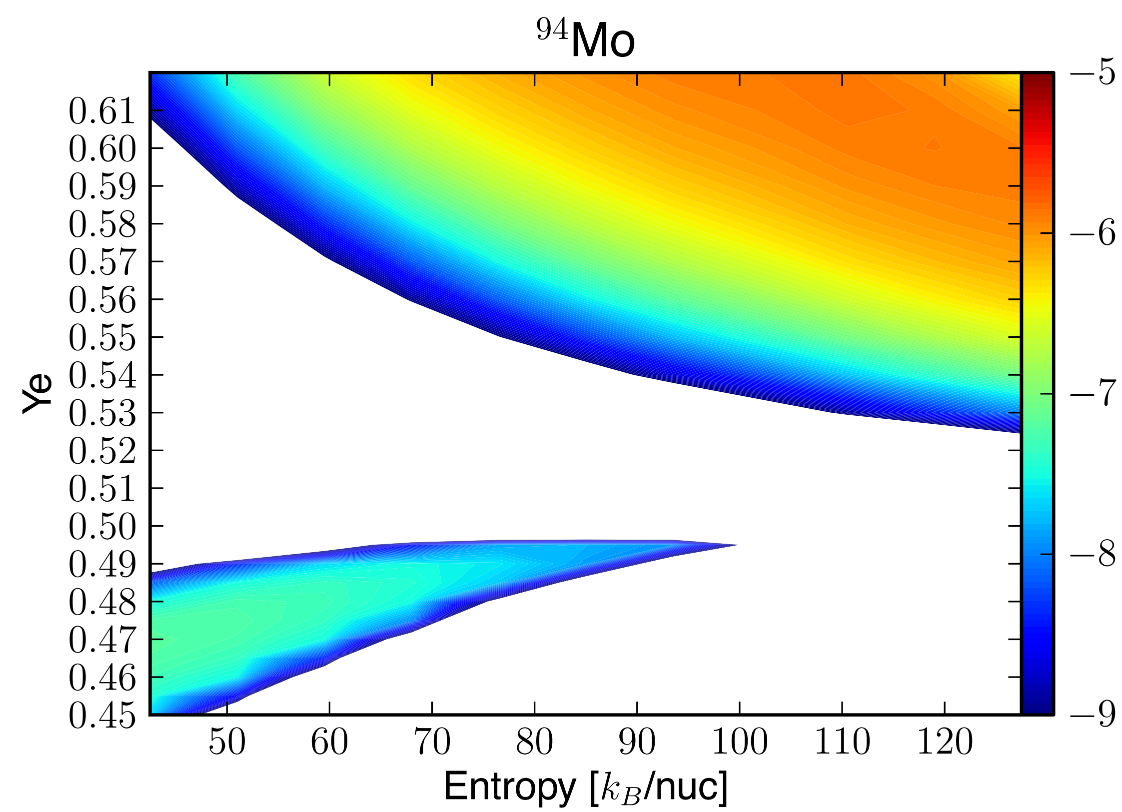
  - **charged-particle reactions**
- **proton-rich winds:**
  - **νp-process**







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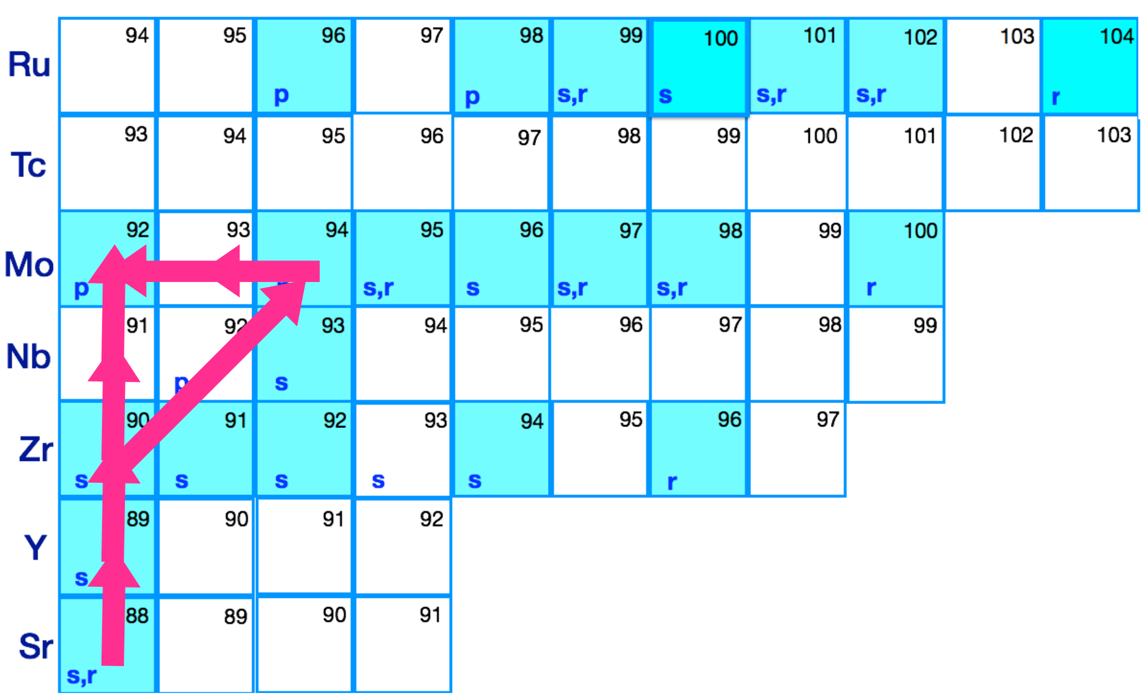

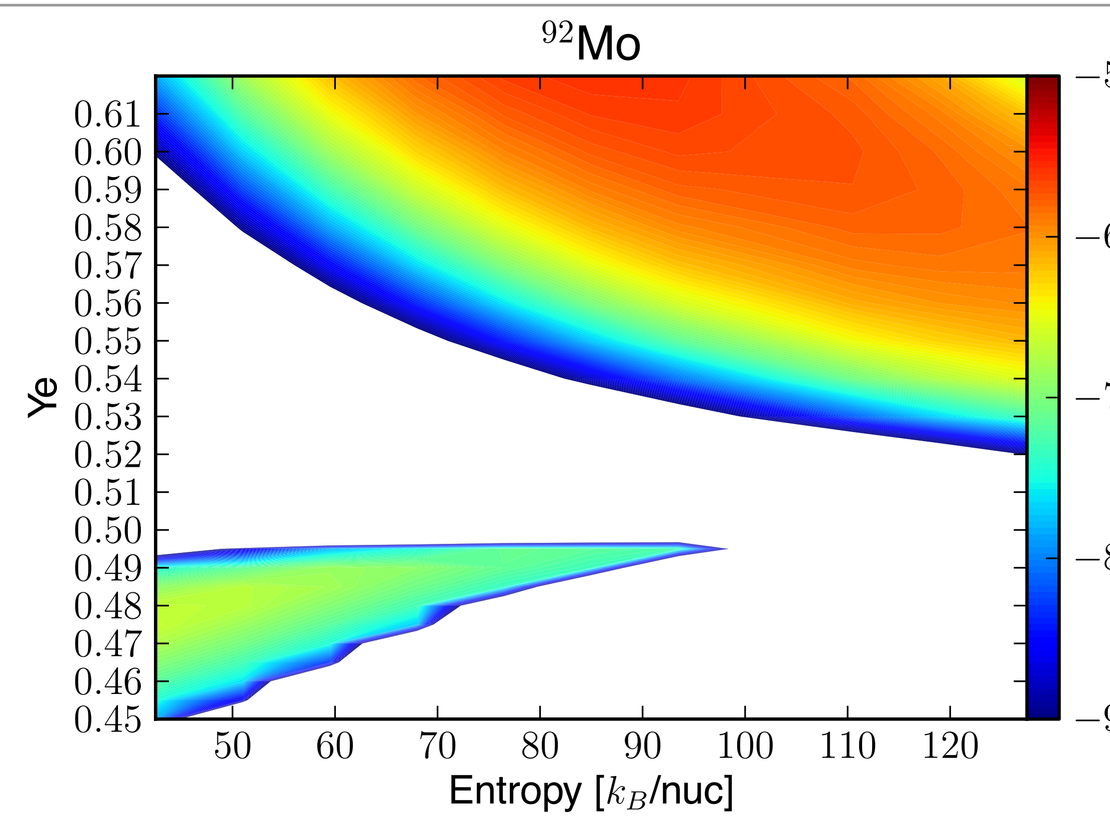

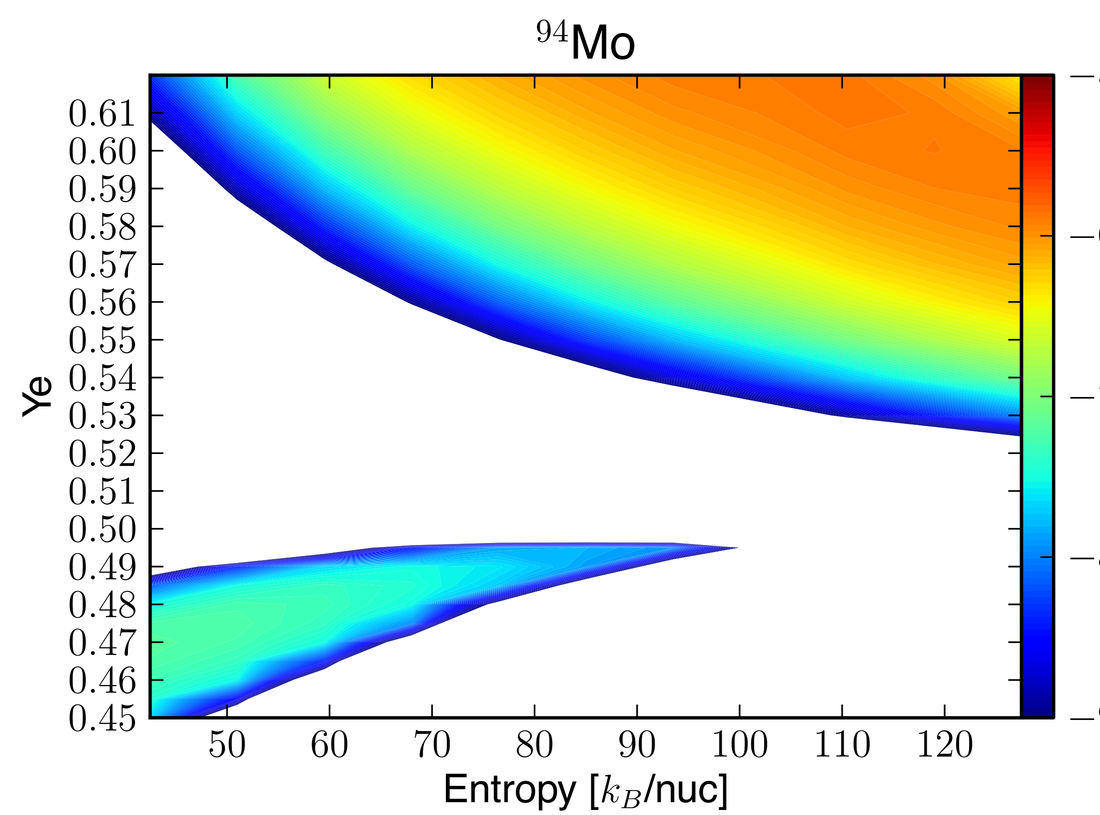

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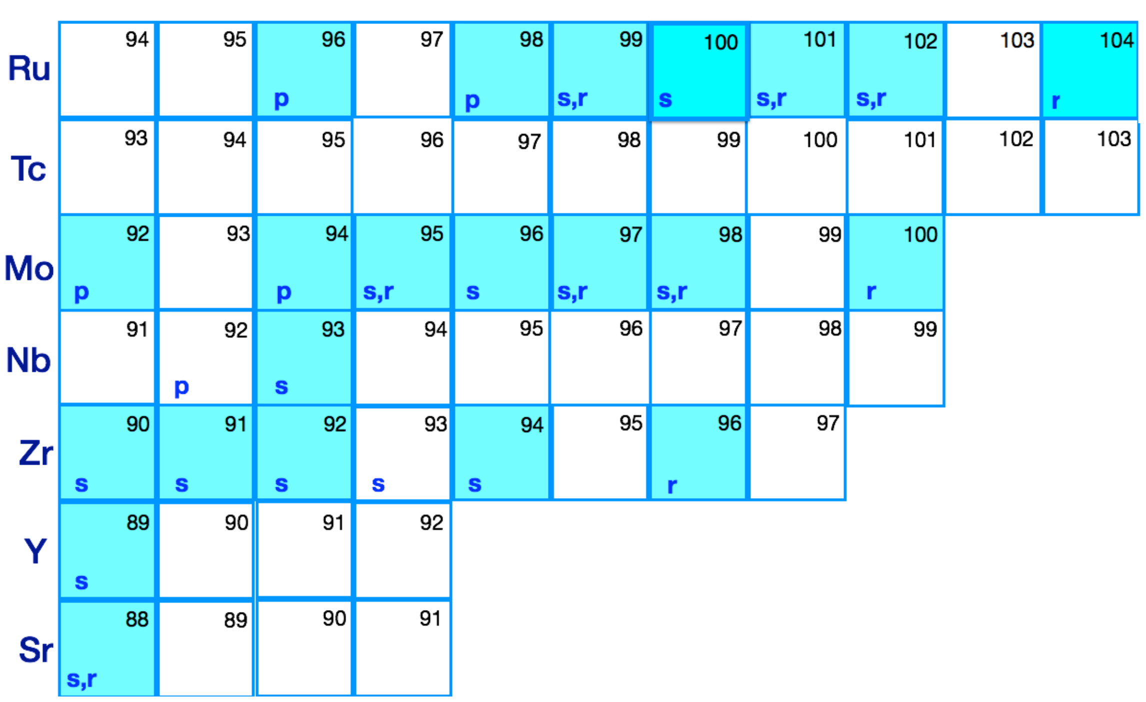

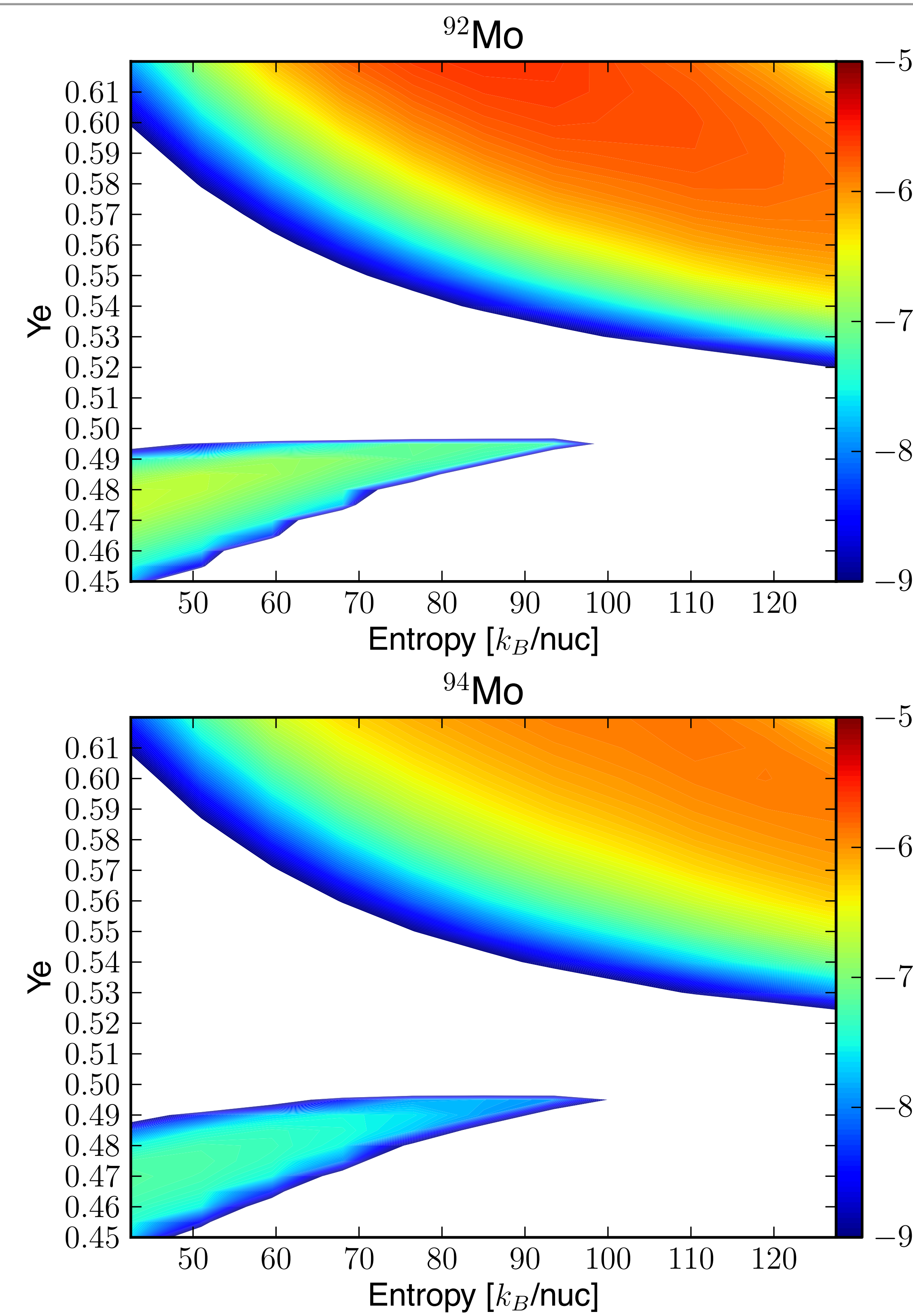

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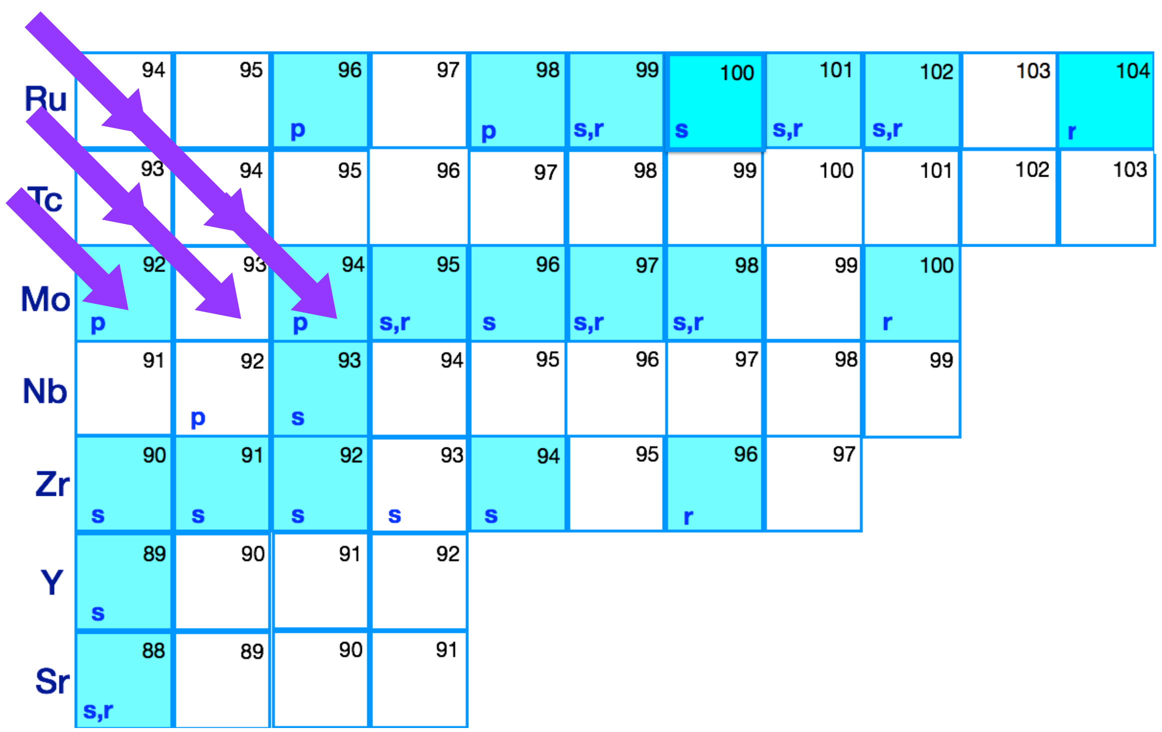
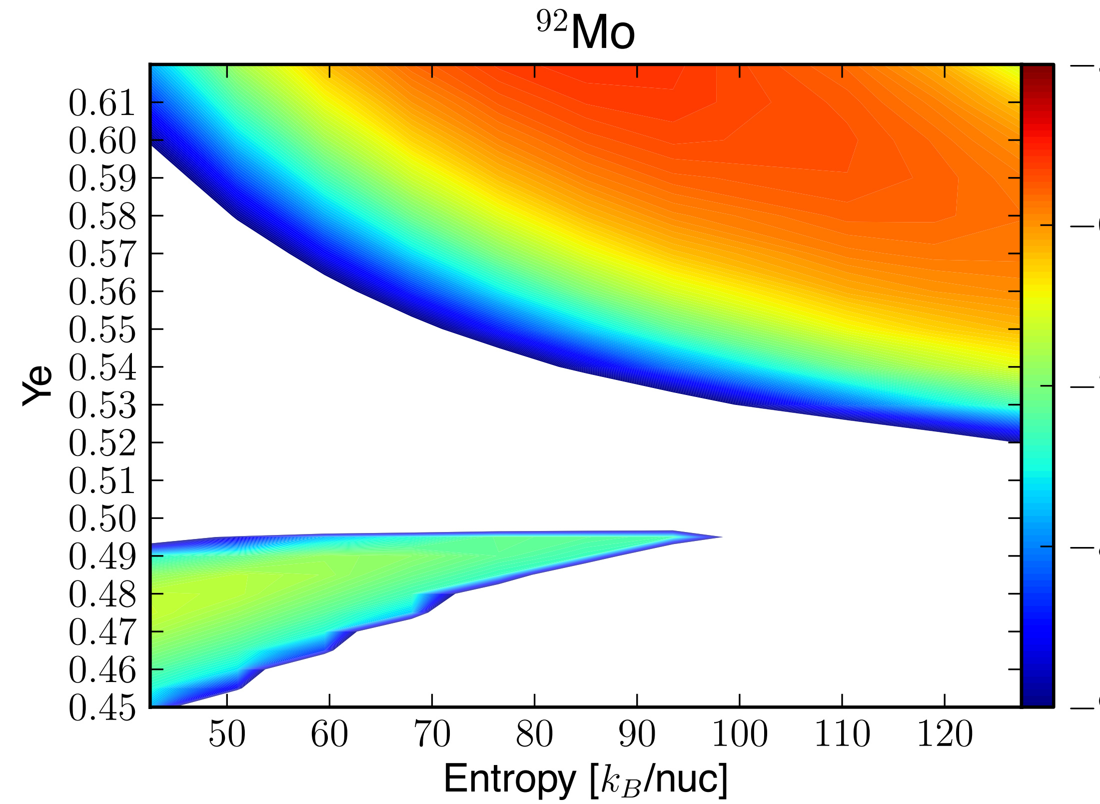
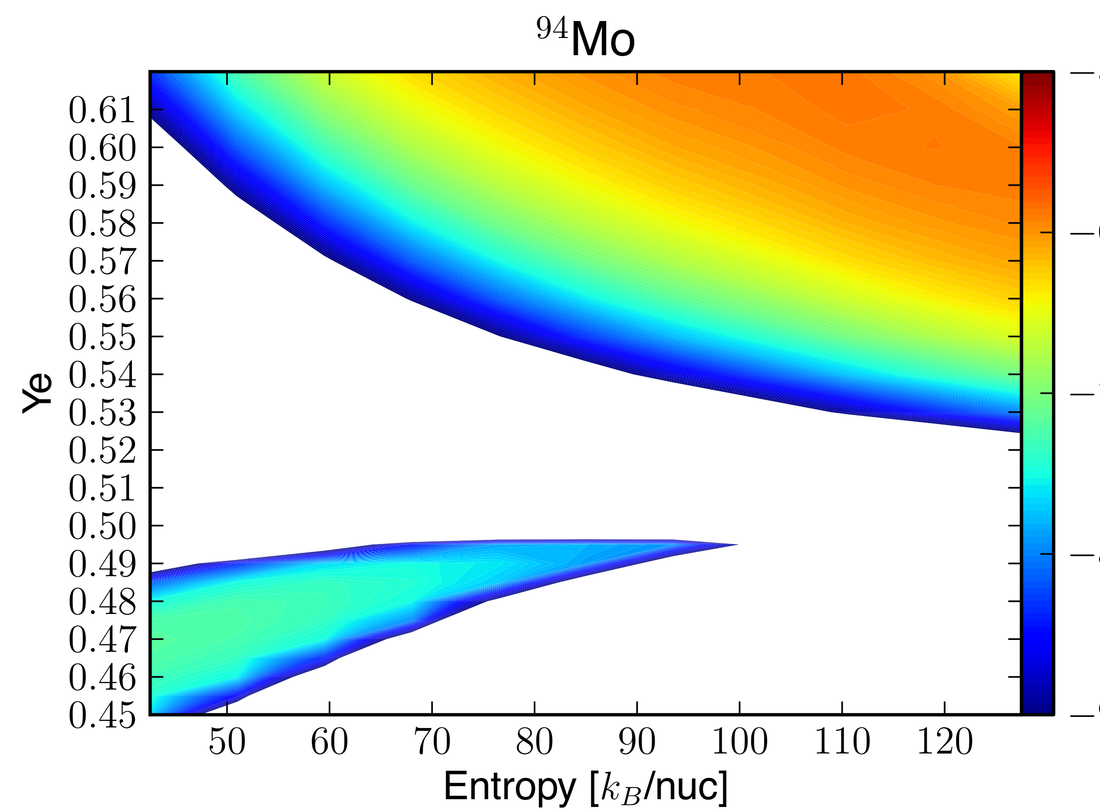
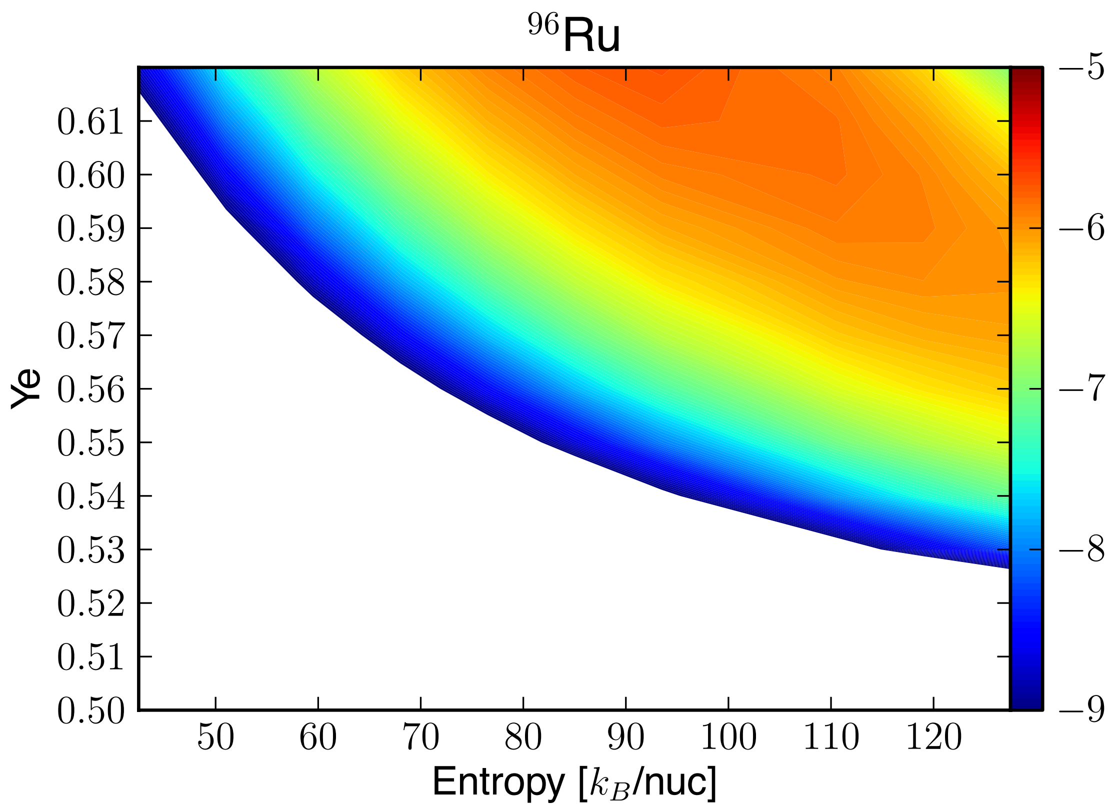
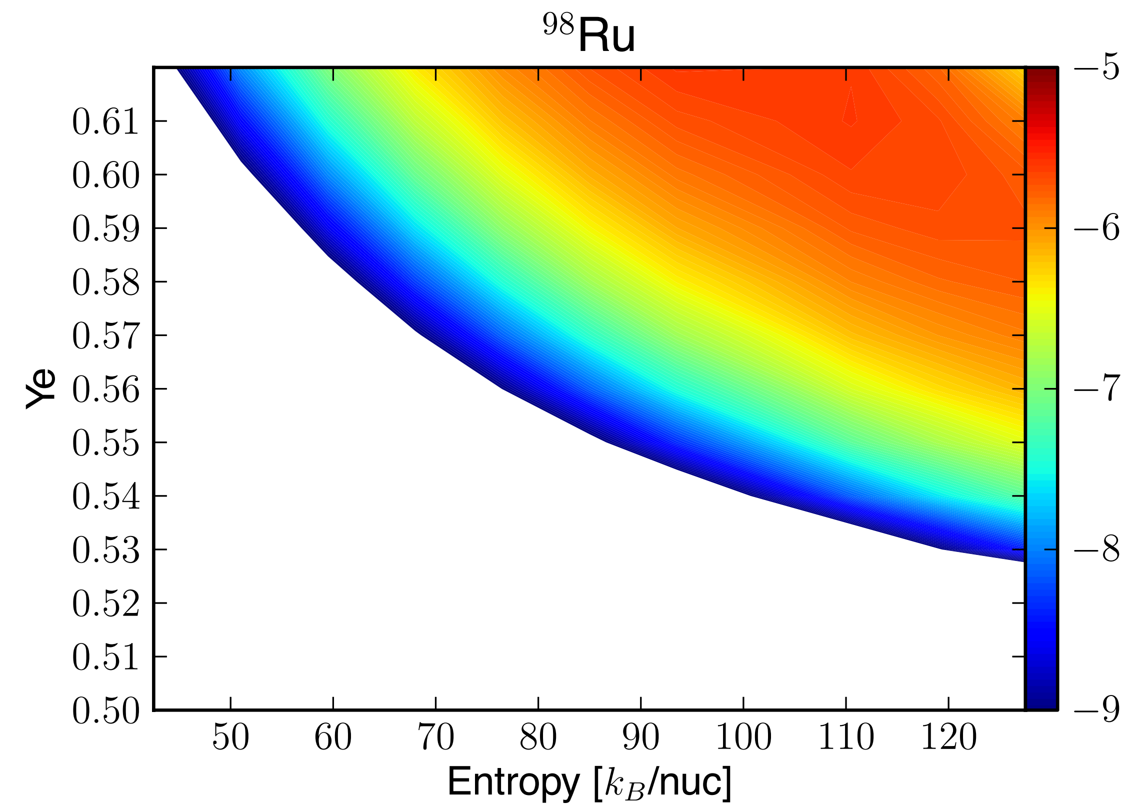






Nucleosynthesis of p-isotopes: ^{96,98}Ru





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- synthesis in proton-rich winds similar to ^{92,94}Mo
- abundances are very sensitive to trajectory timescale

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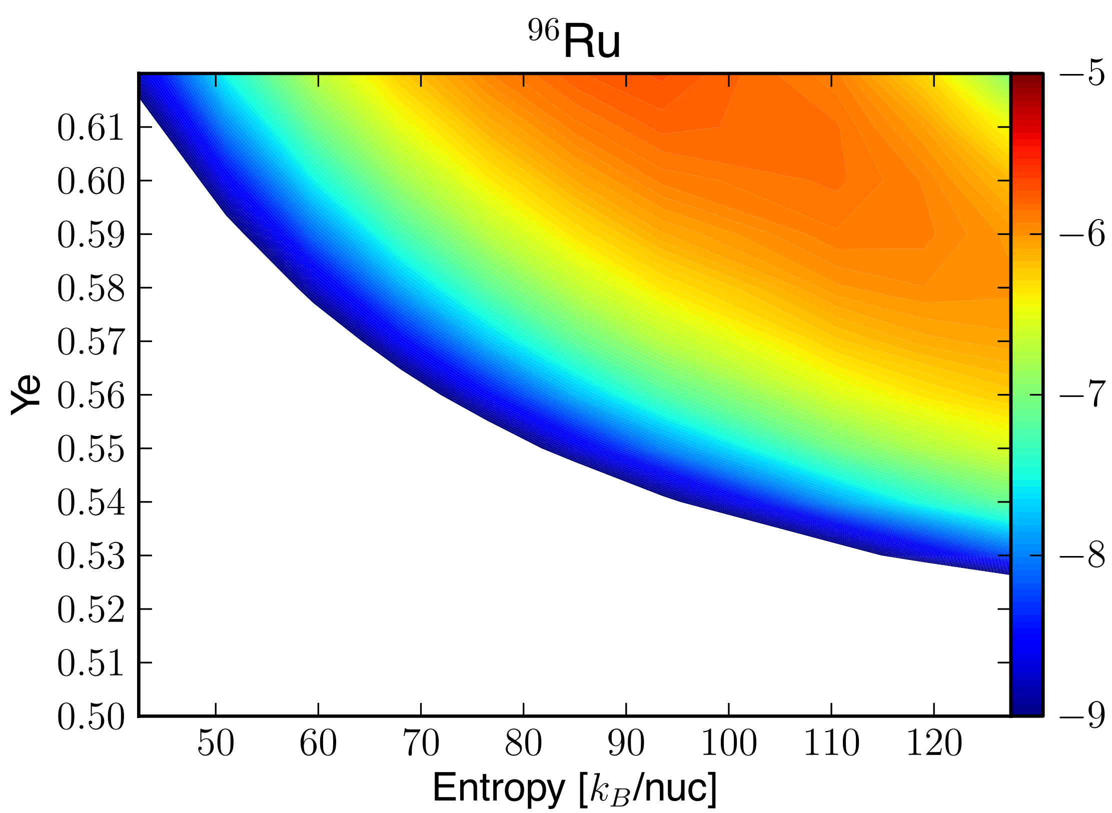

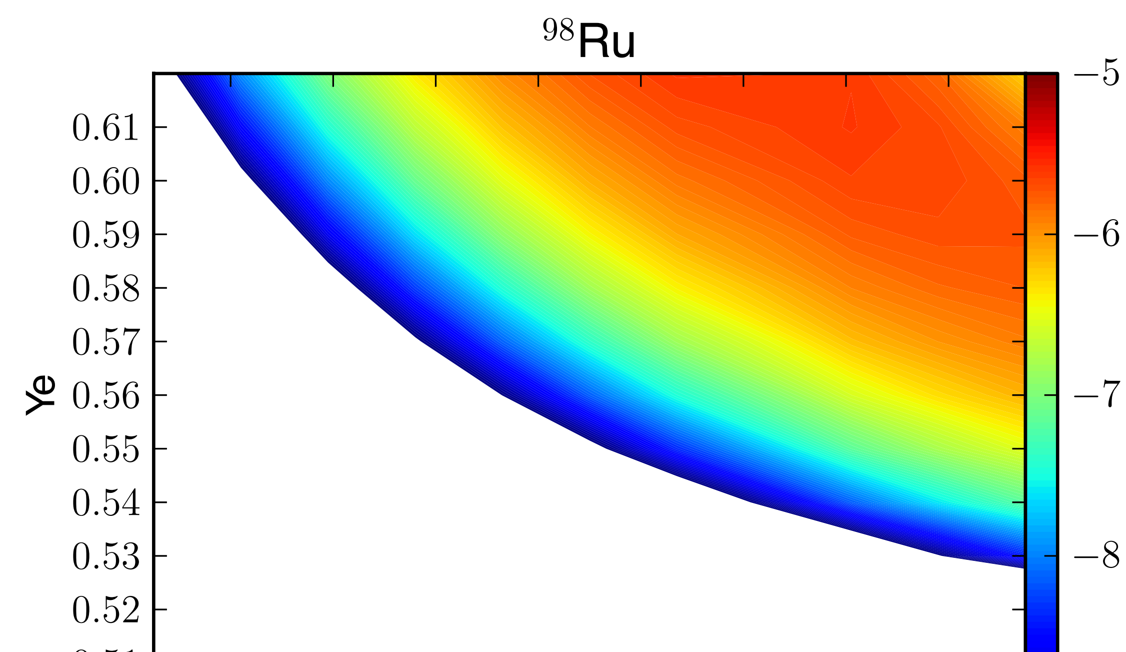

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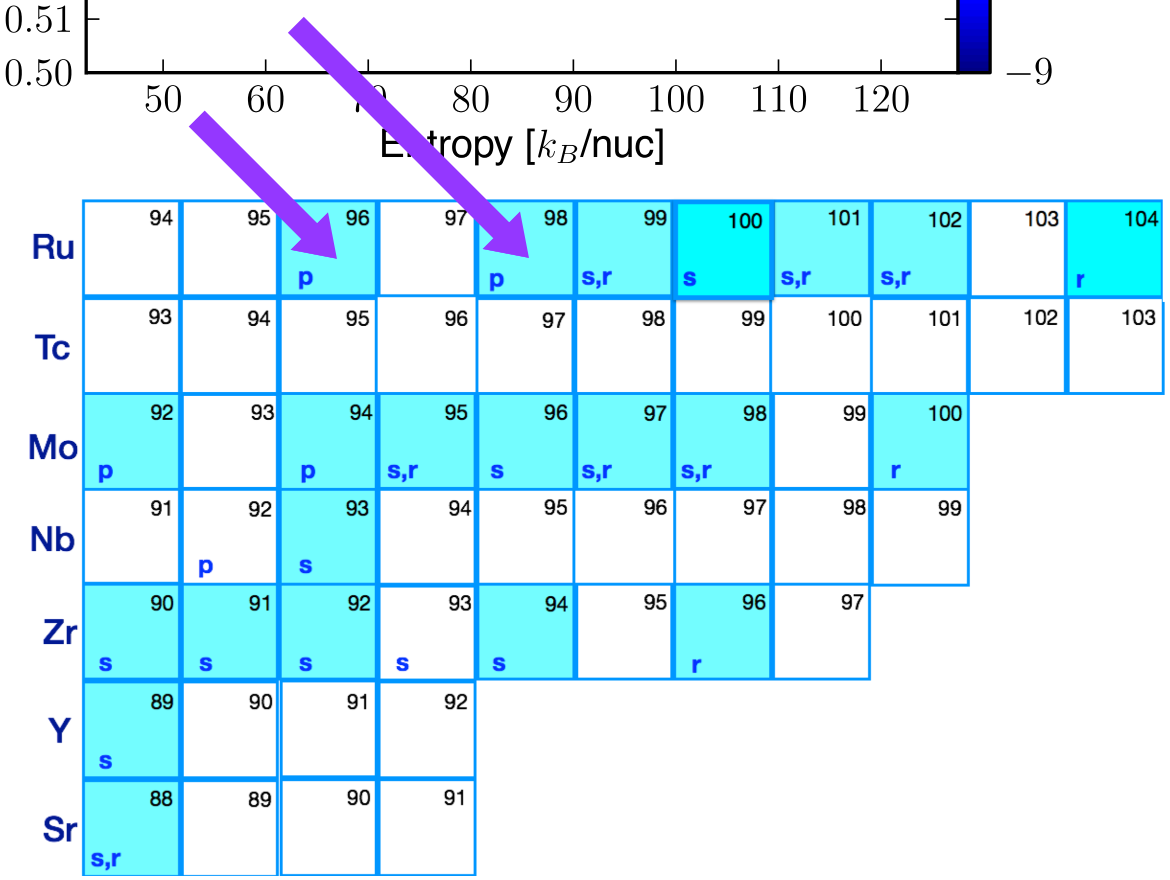
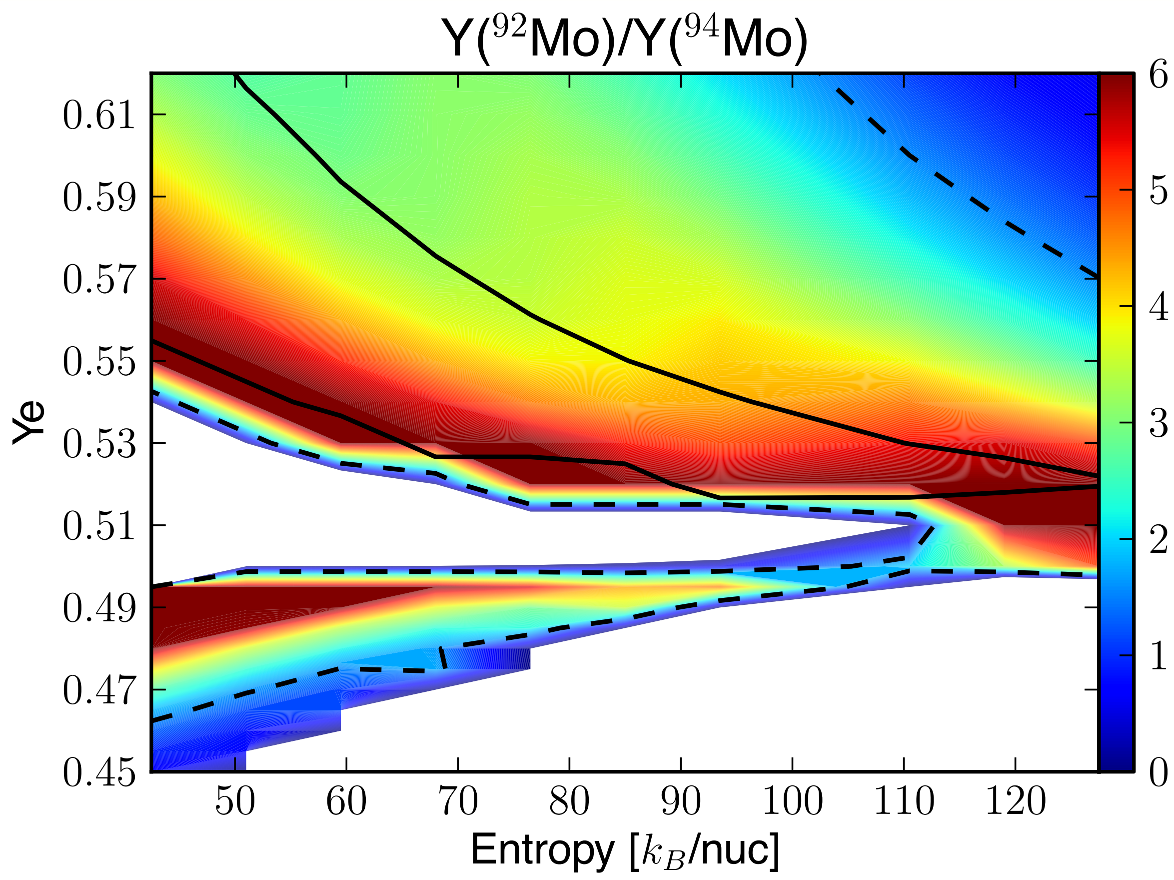
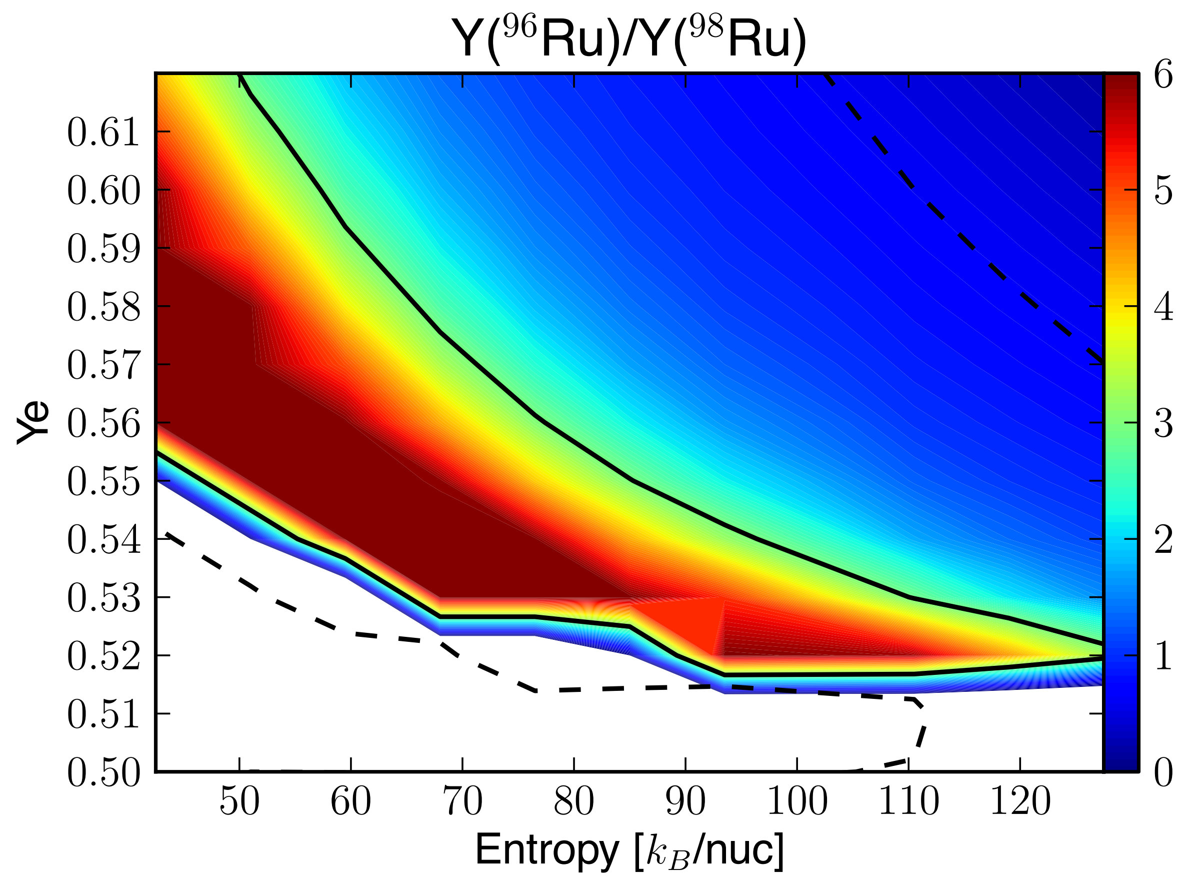


Solar system abundances of p-isotopes: ^{92,94}Mo and ^{96,98}Ru

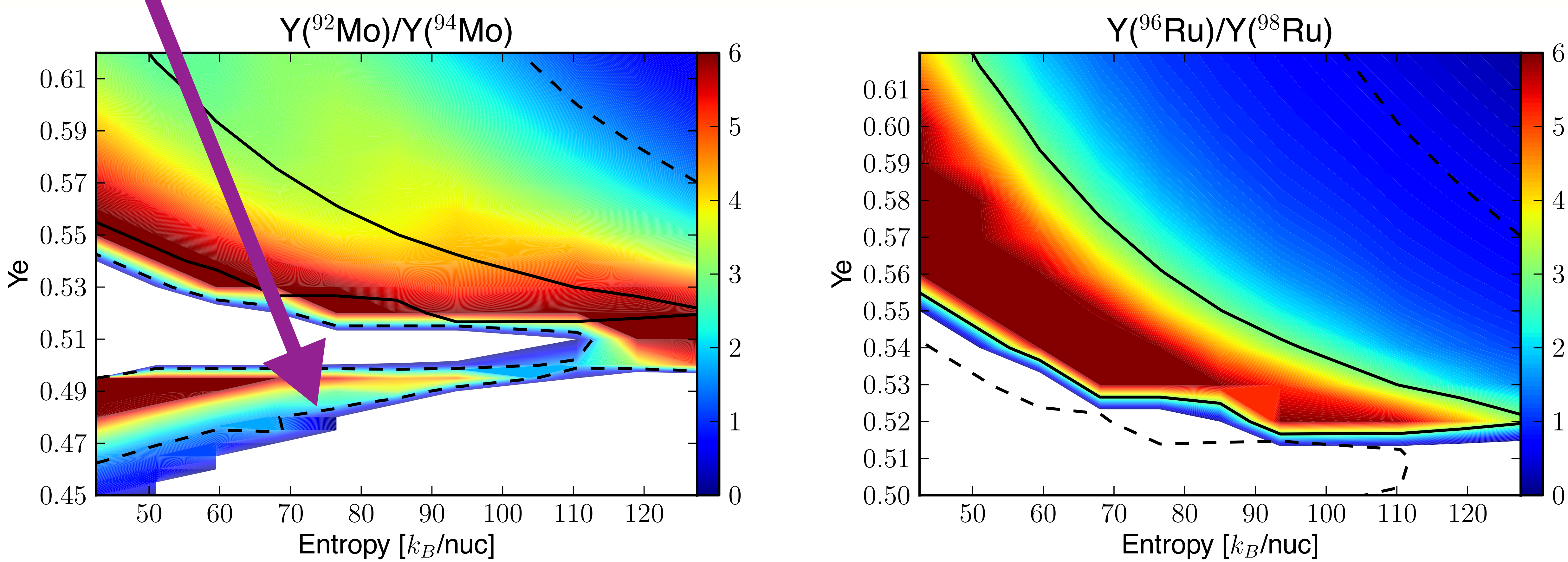




- no set of wind parameters produces simultaneously both solar system ratios:
  - ➡ combination of wind parameters is required to explain ratios based on winds
  - ➡ contributions of other sites, e.g. type Ia supernovae

Solar system abundances of p-isotopes: ^{92,94}Mo and ^{96,98}Ru

$Y_\odot(^{92}\mathrm{Mo})/Y_\odot(^{94}\mathrm{Mo}) = 1.57$ [Lodders 2003]



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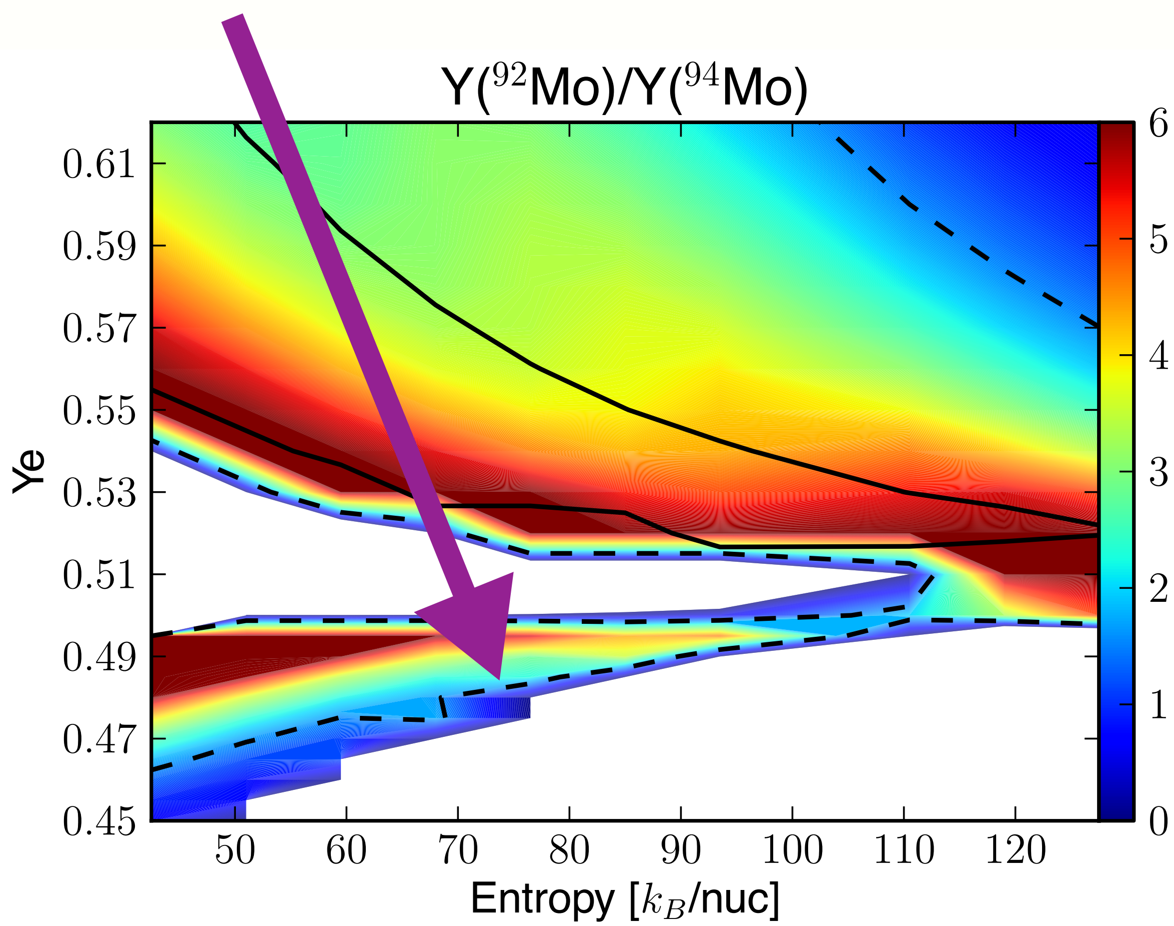
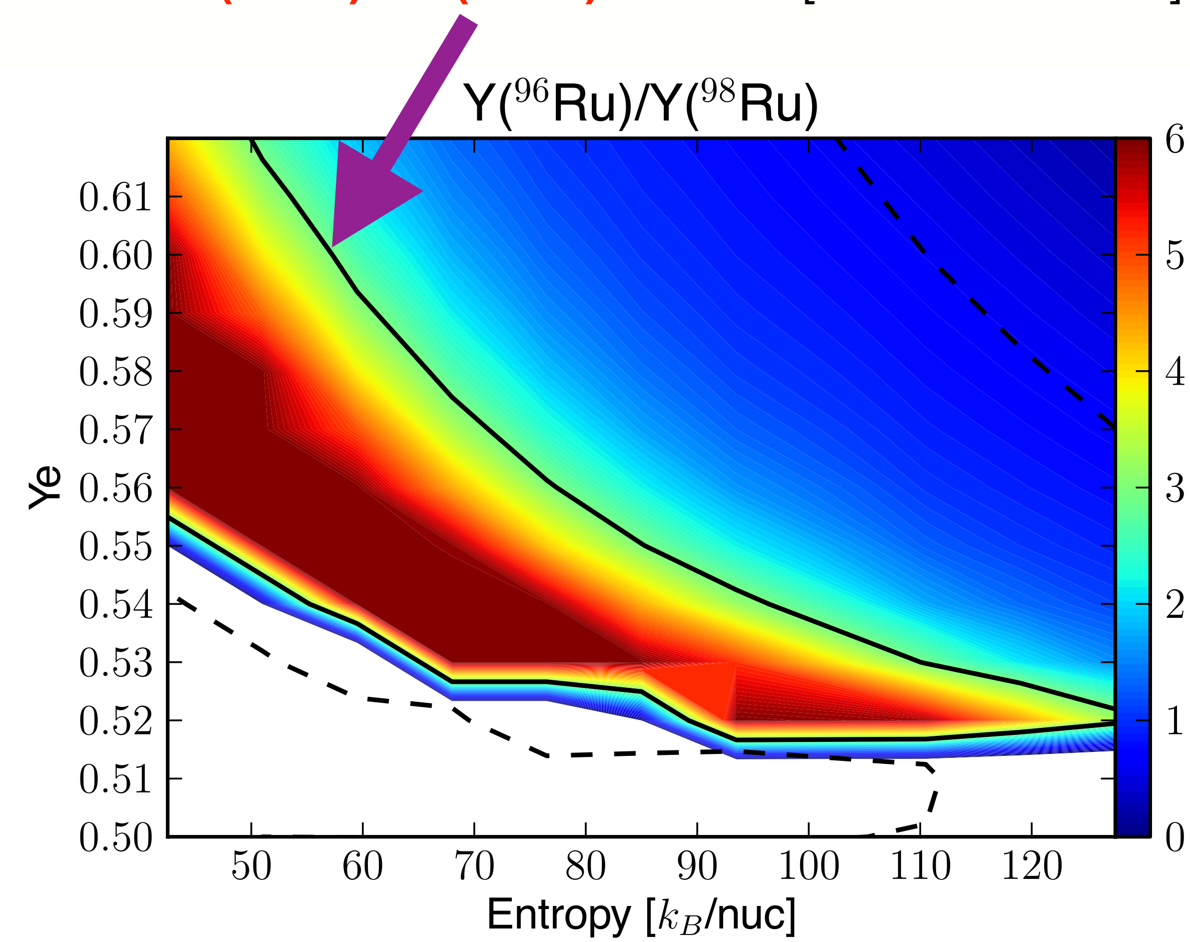


$Y_\odot(^{92}\mathrm{Ru})/Y_\odot(^{94}\mathrm{Ru}) = 2.97$ [Lodders 2003]



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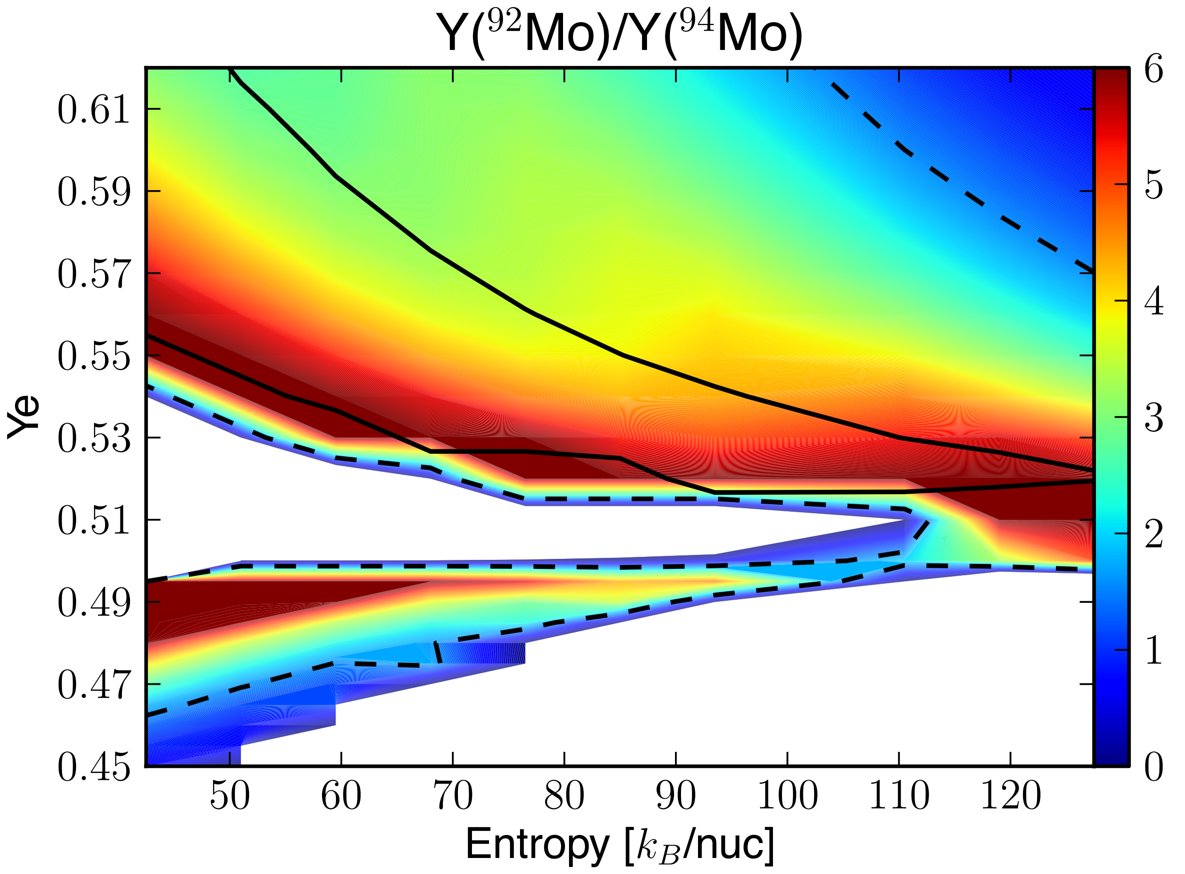

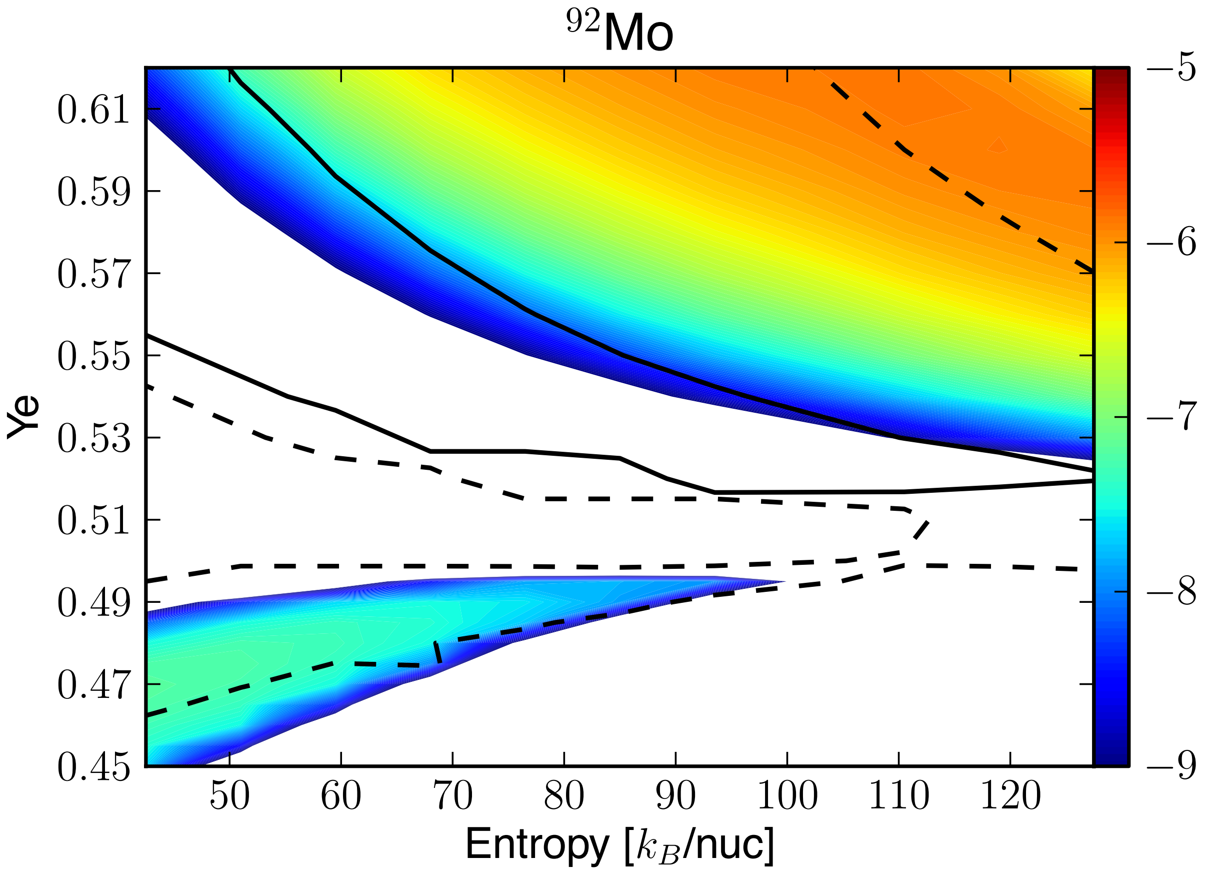

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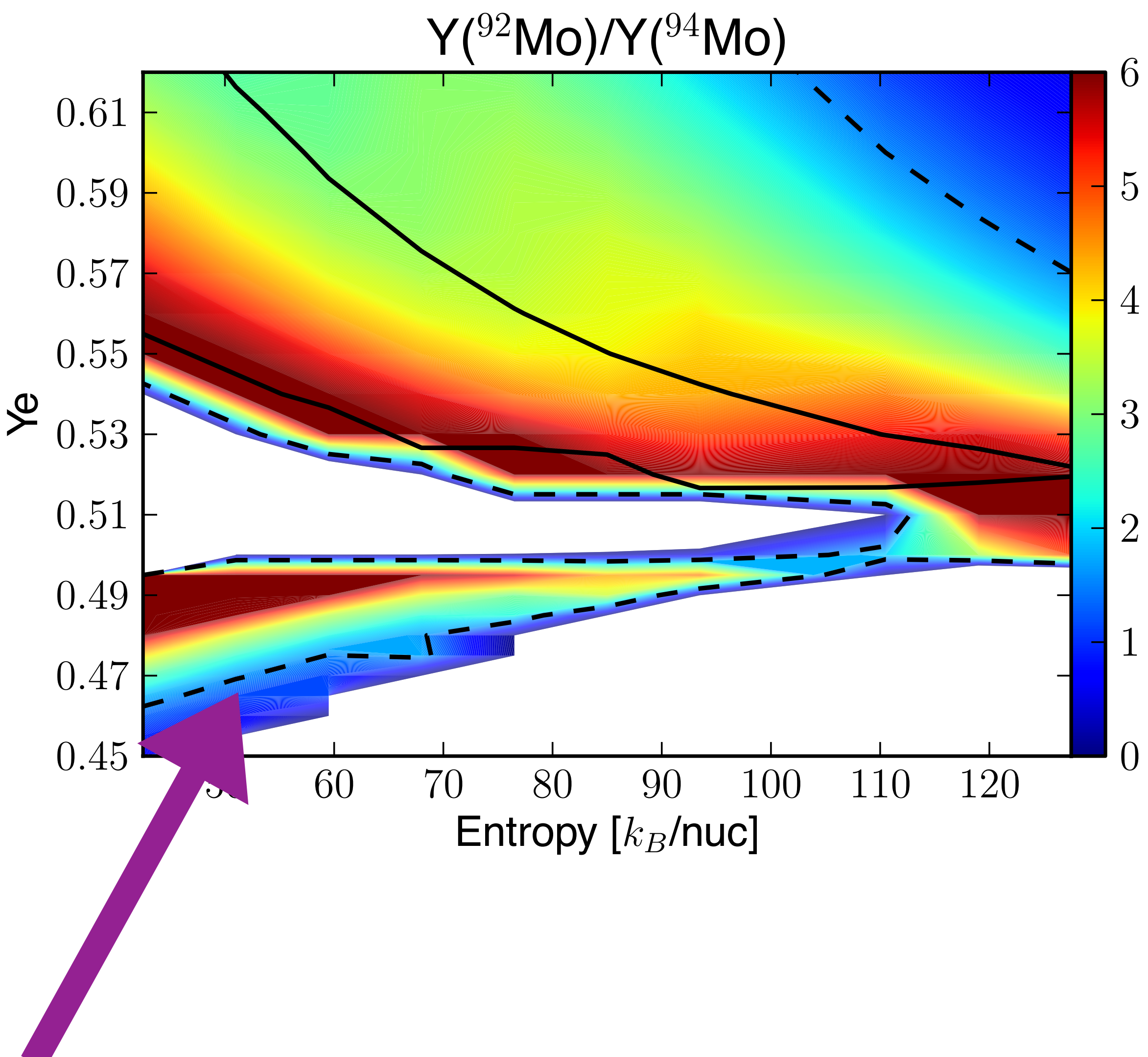

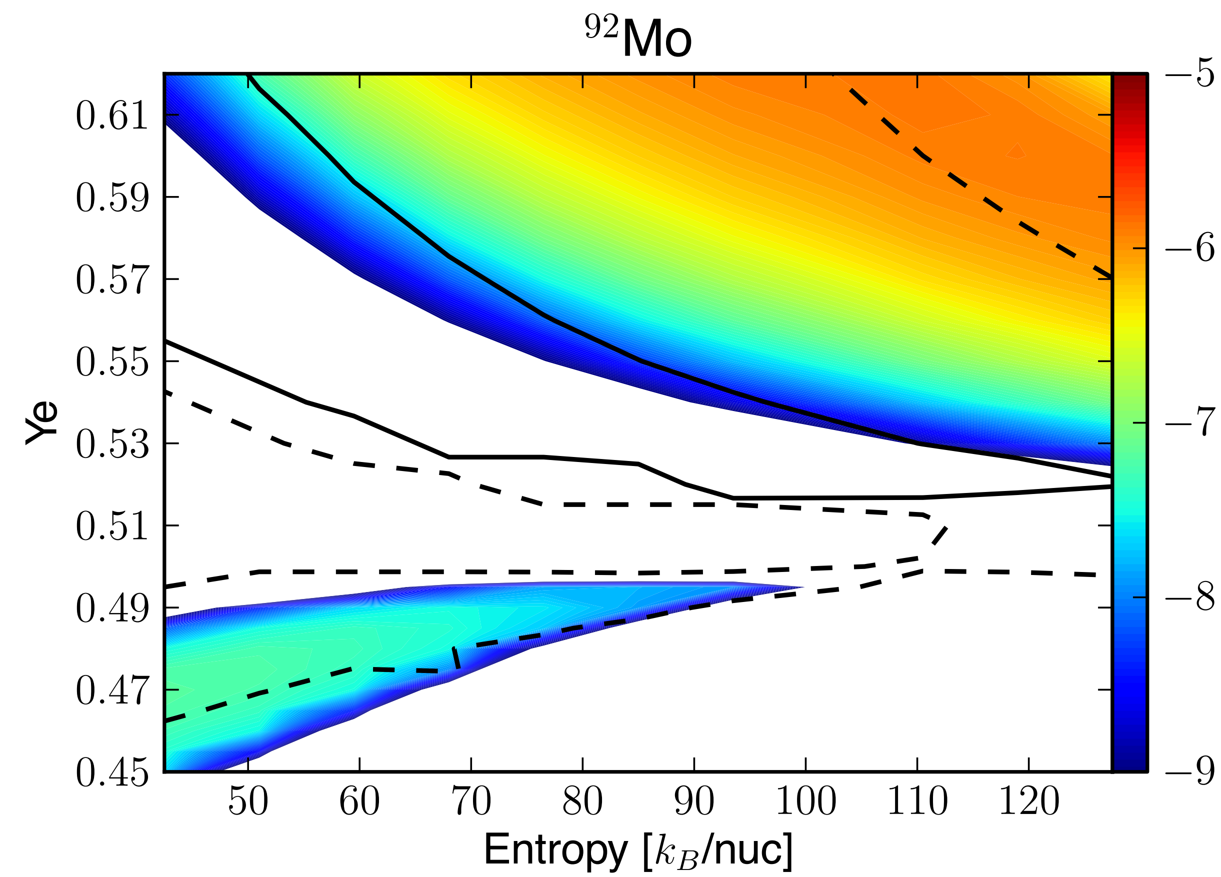

agreement with Farouqi et al. 2009

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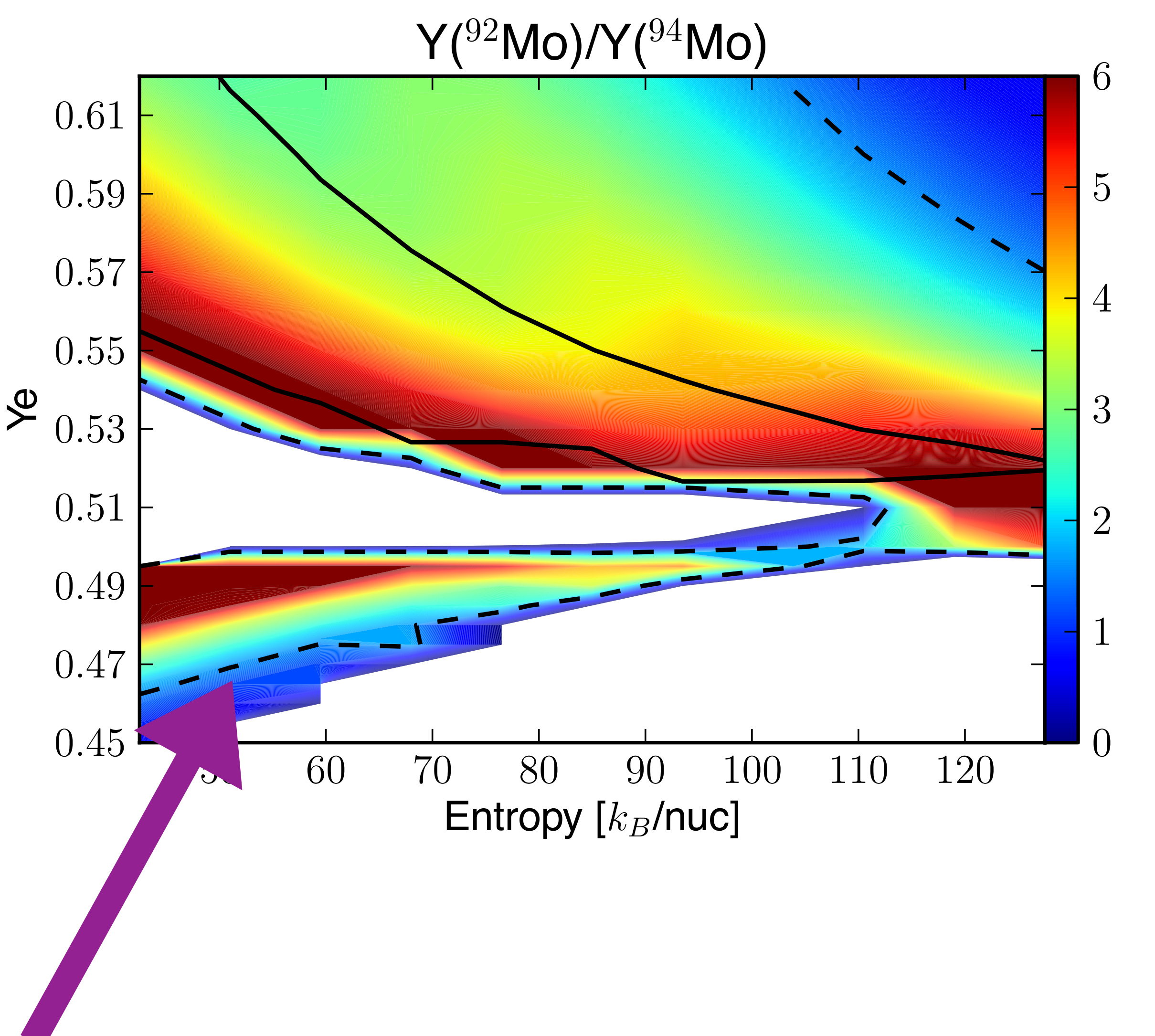

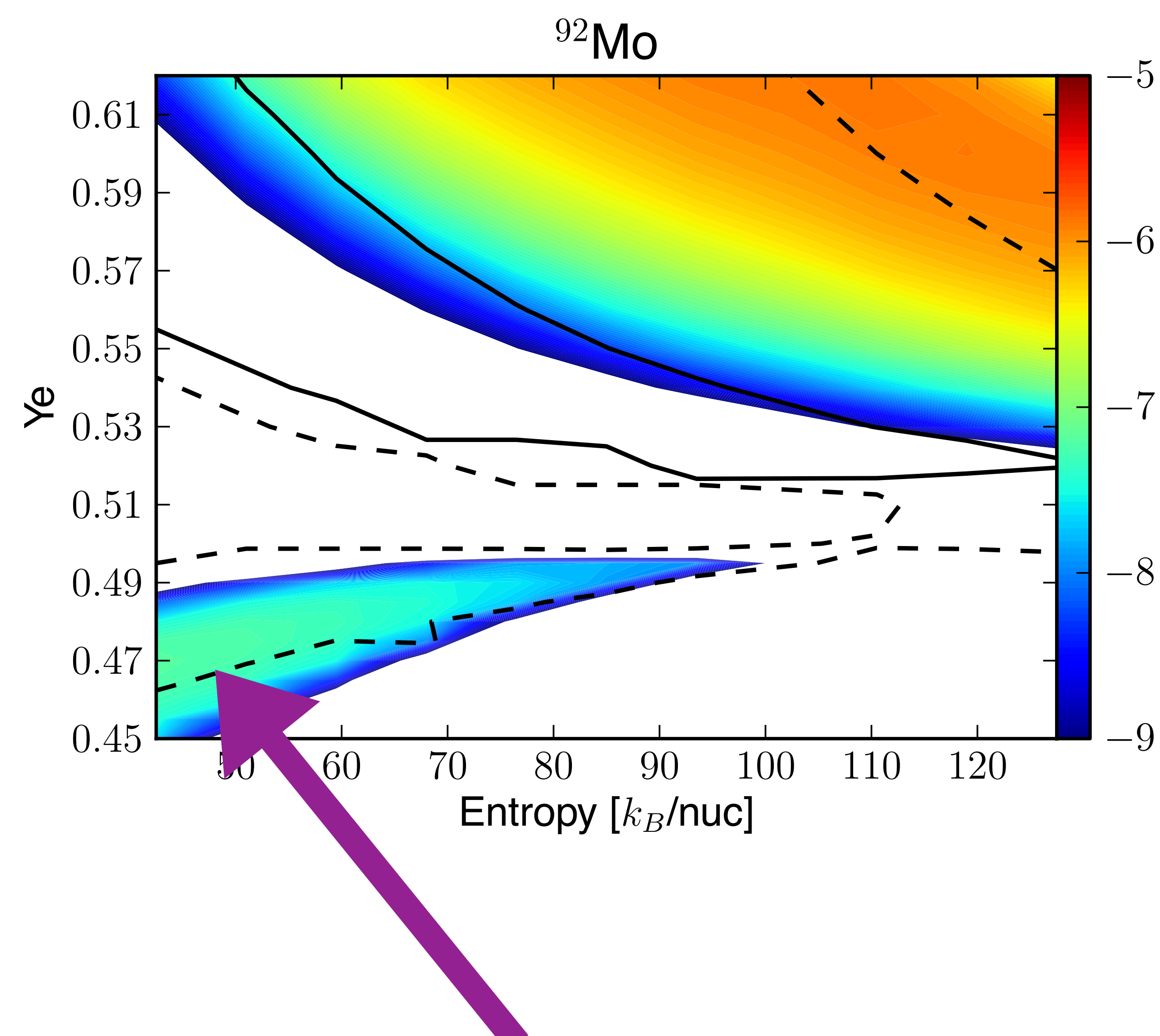

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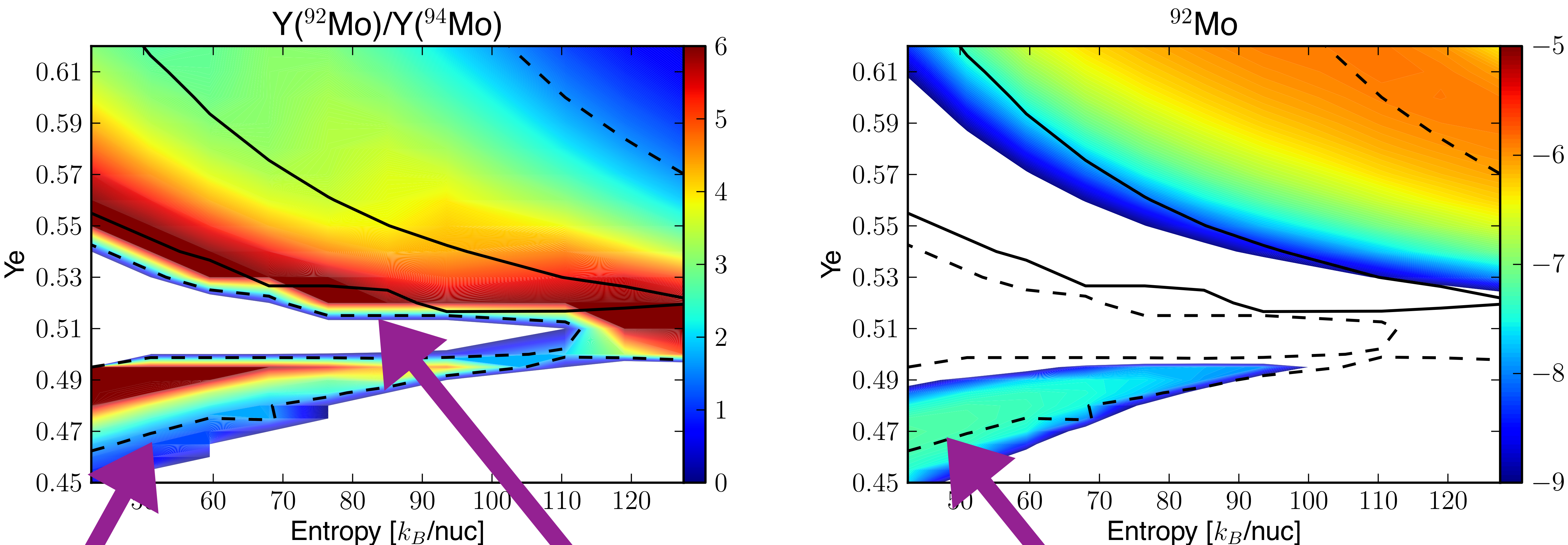

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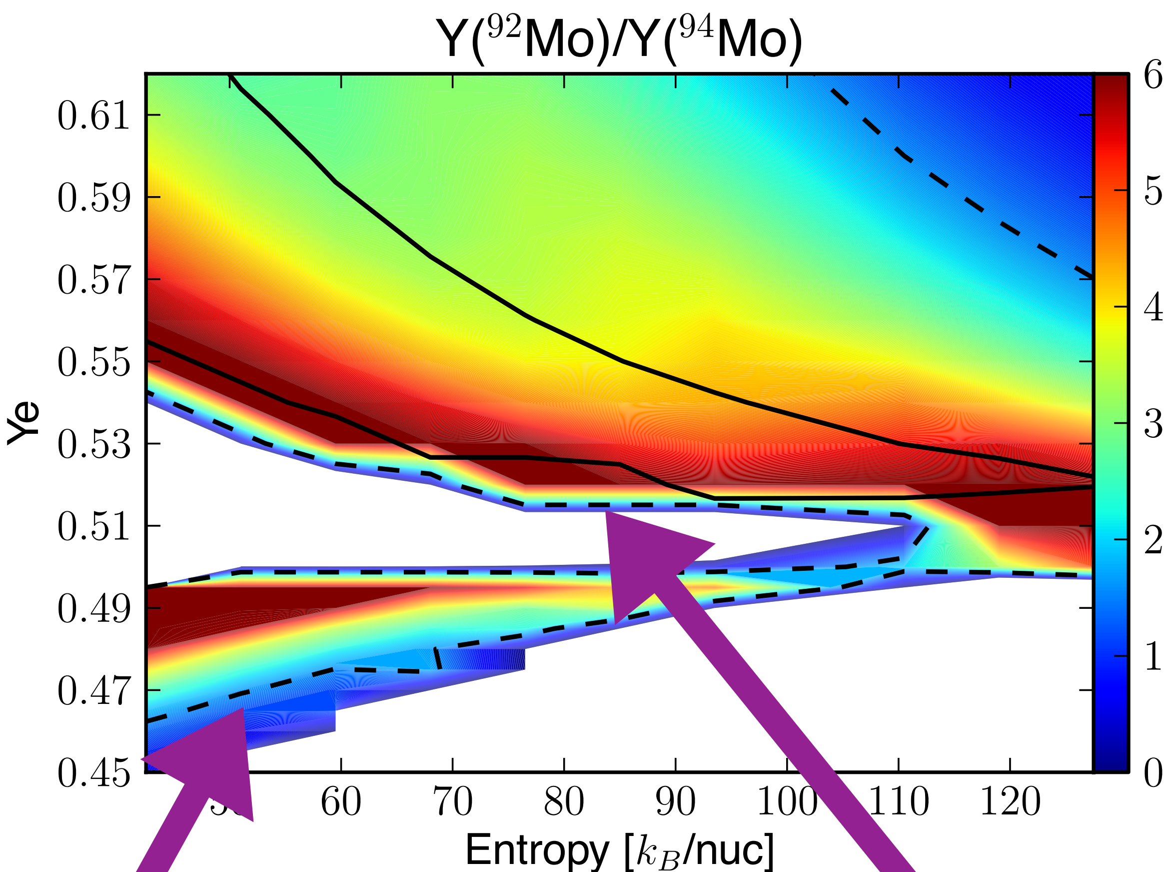

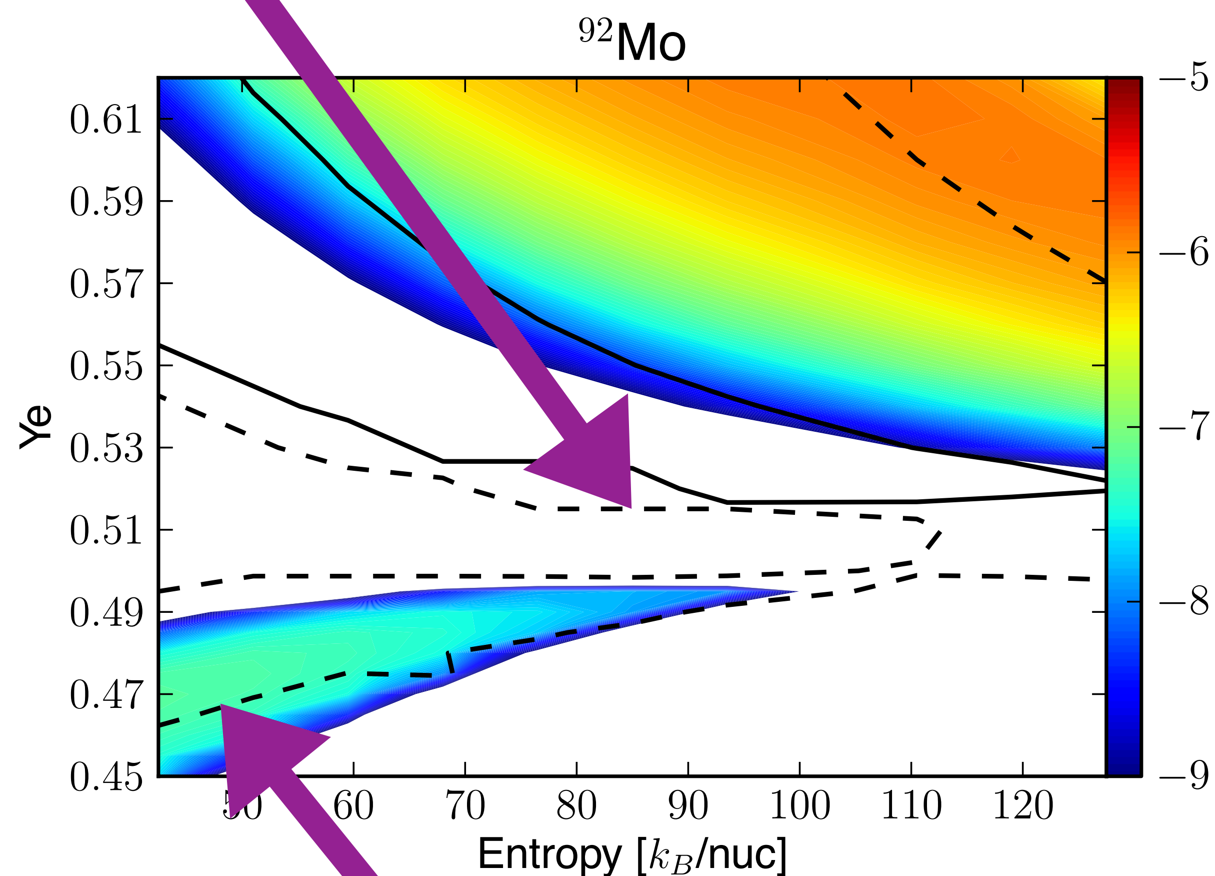

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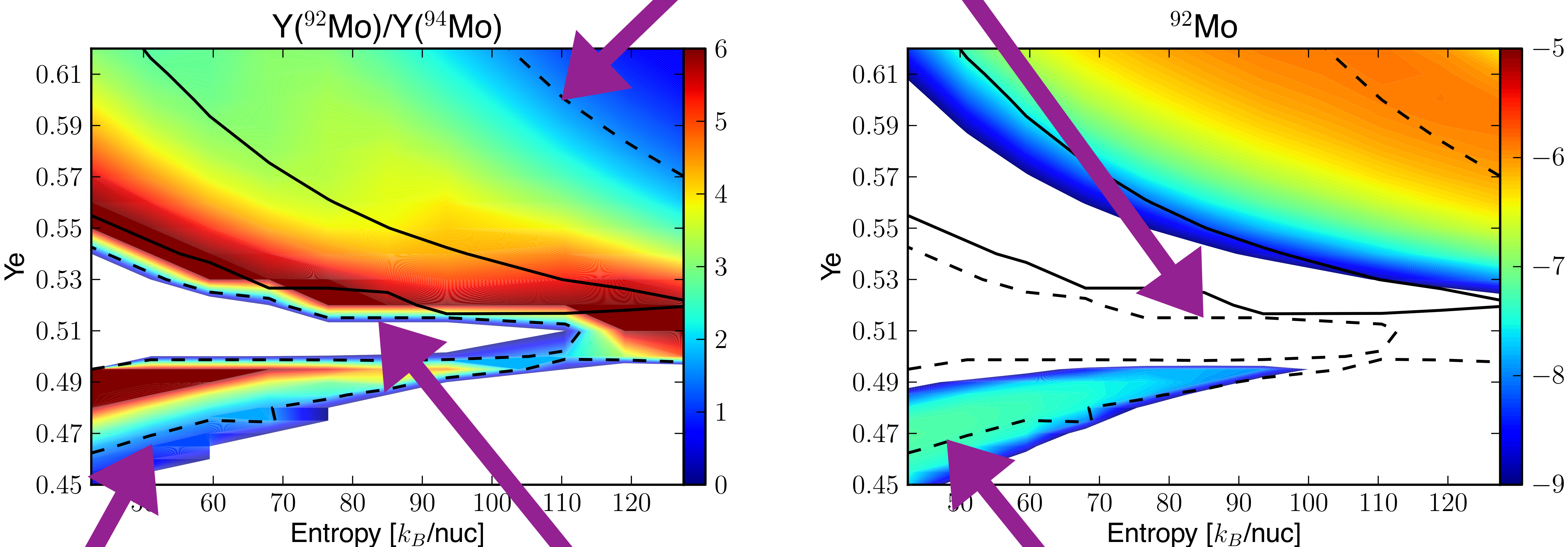

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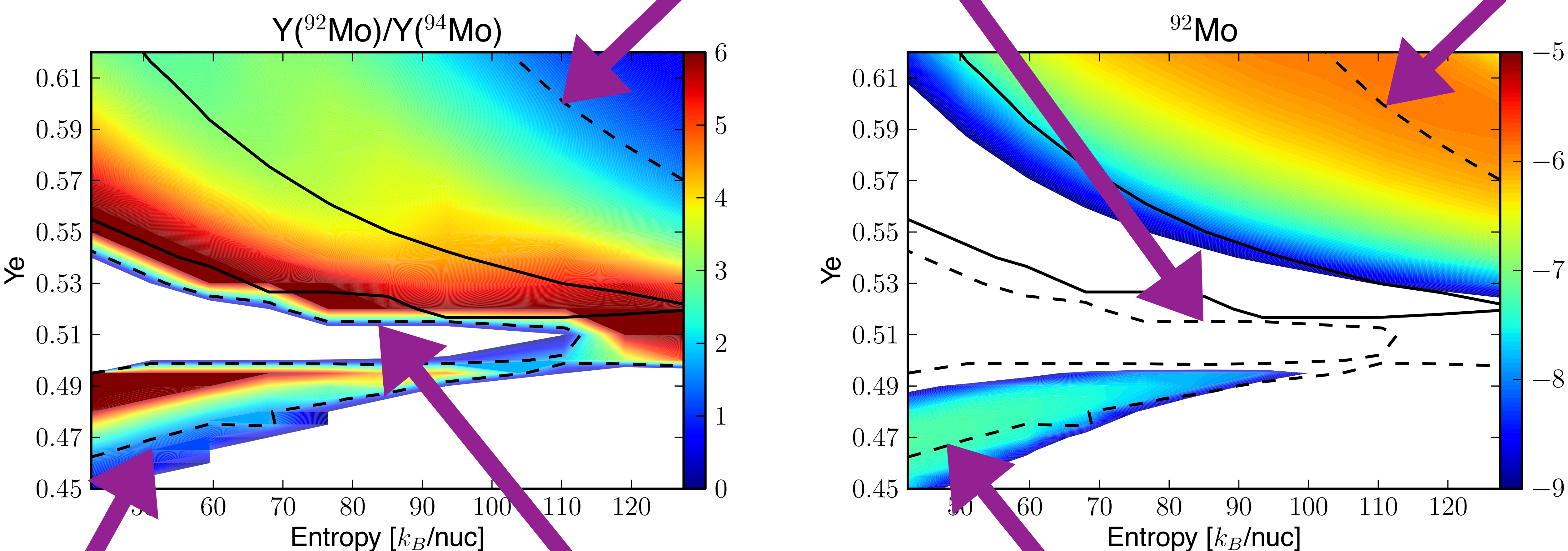

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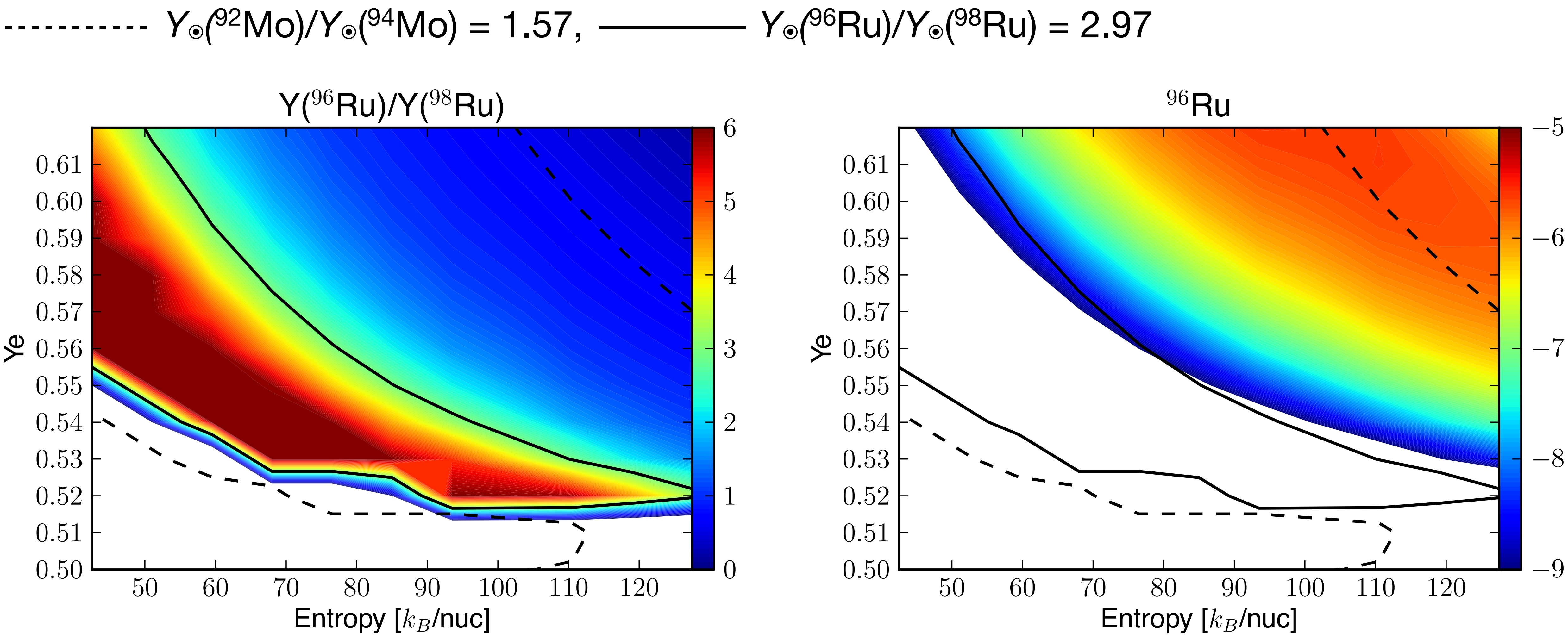

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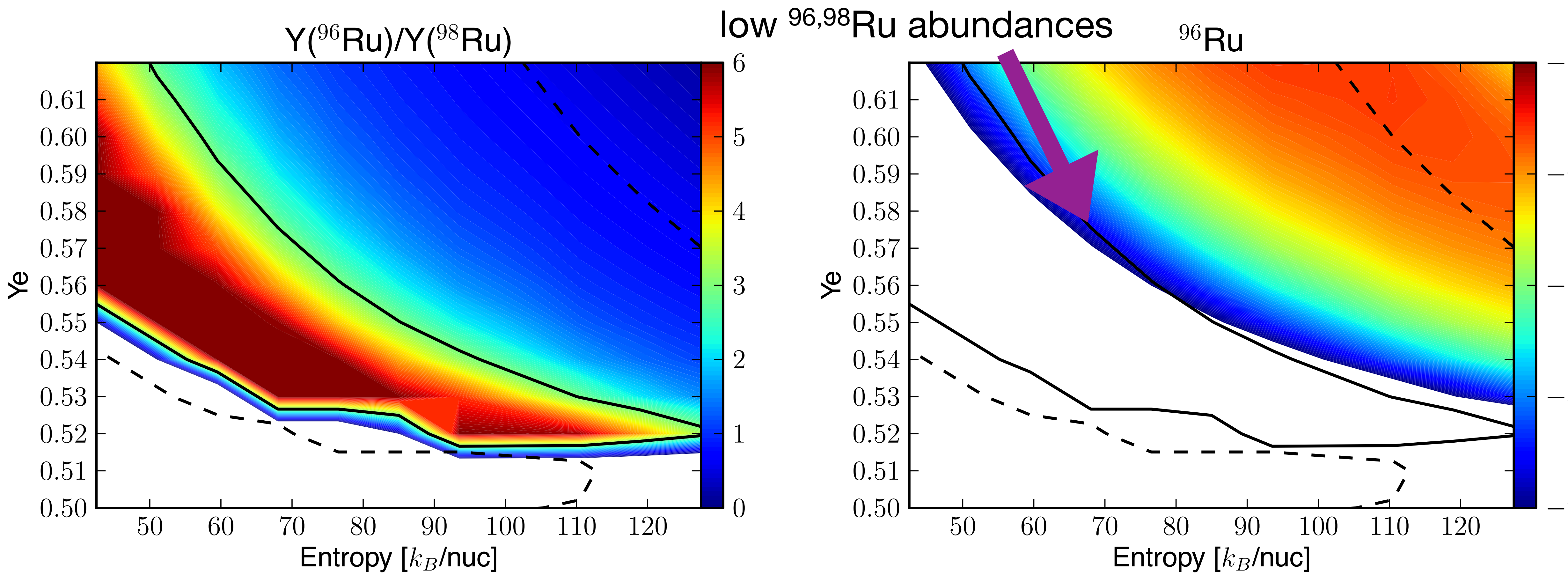

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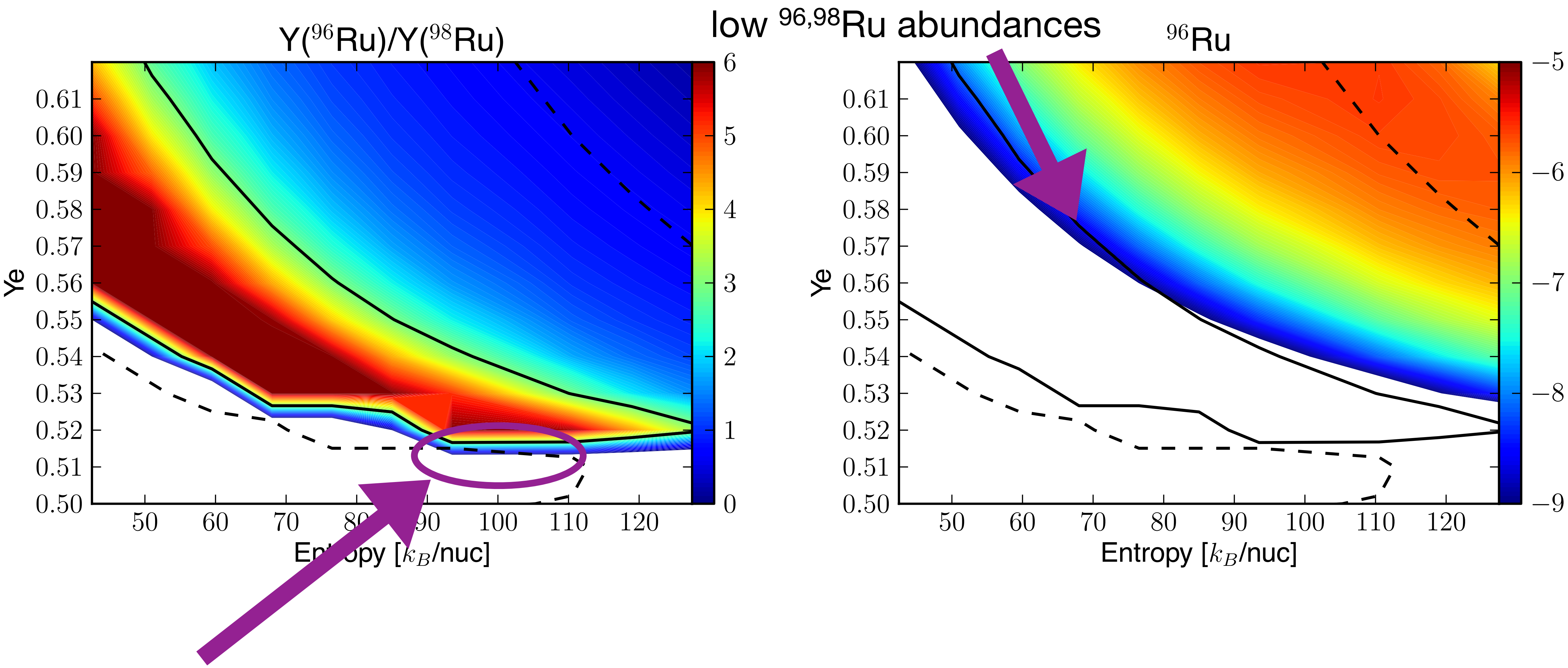

similar wind conditions lead to SoS ratio for Mo and Ru p-isotopes

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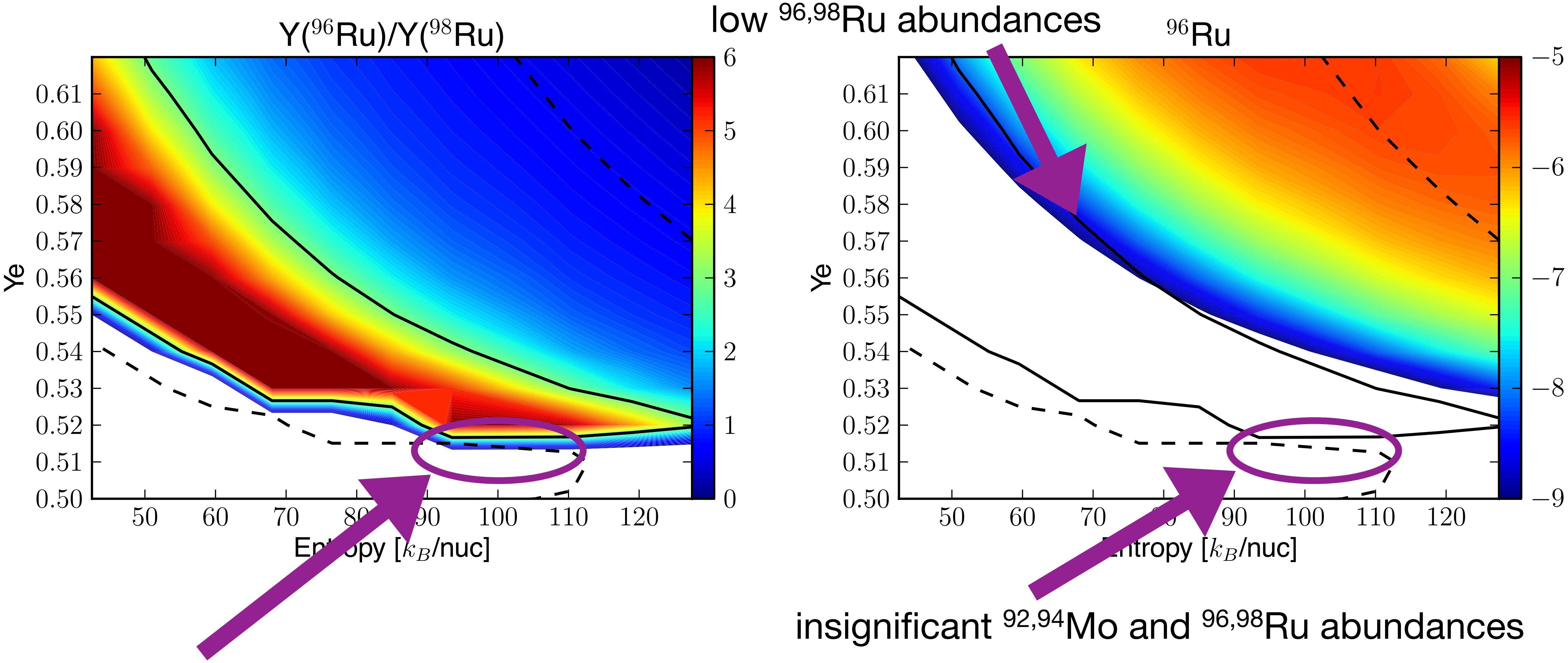

low ^{96,98}Ru abundances

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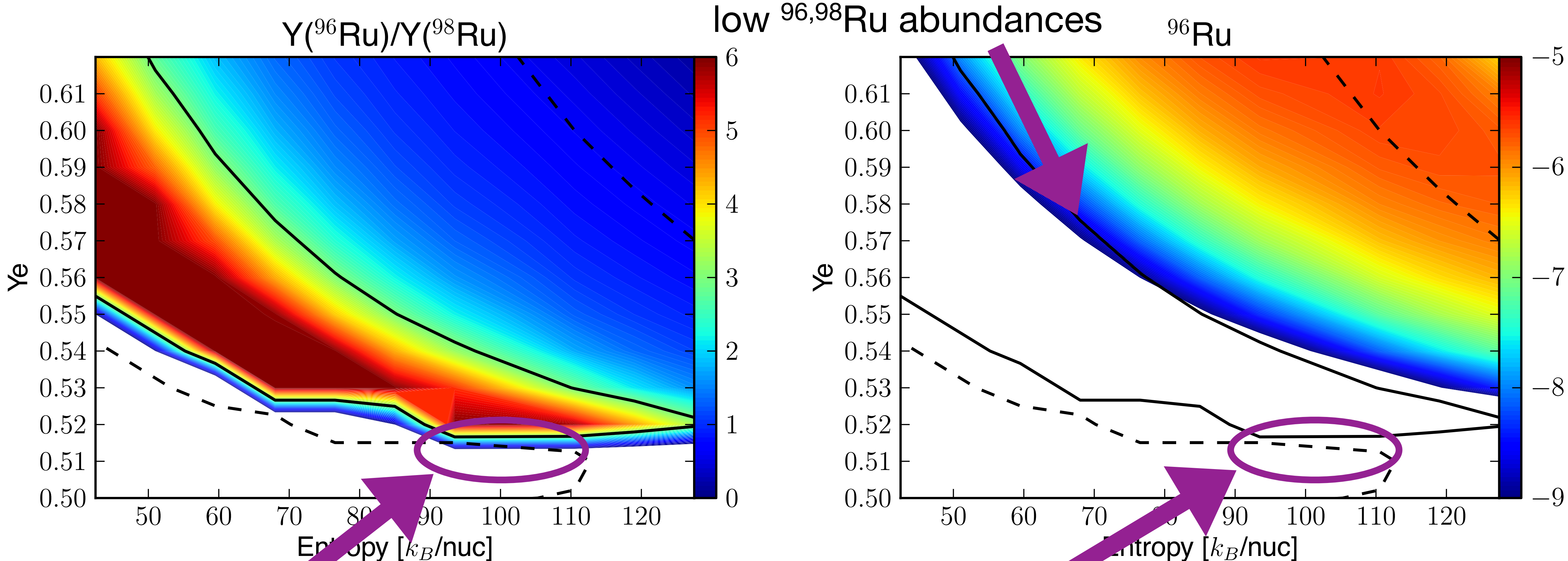

insignificant ^{92,94}Mo and ^{96,98}Ru abundances

similar wind conditions lead to SoS ratio for Mo and Ru p-isotopes

challenge: trajectory that leads to the ^{92,94}Mo solar system ratio but does not produce too much ^{96,98}Ru and vice versa

Nucleosynthesis of ^{92,94}Mo and ^{96,98}Ru: production factor

production factor: $$P(i) = \frac{X_i}{X_{i,\odot}} \cdot \frac{M_{\rm ej}^{\rm traj}}{M_{\rm ej}^{\rm tot}}$$

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~ 10^{-7}-10^{-4}

[Timmes et al. 1995, Woosley et al. 1995]

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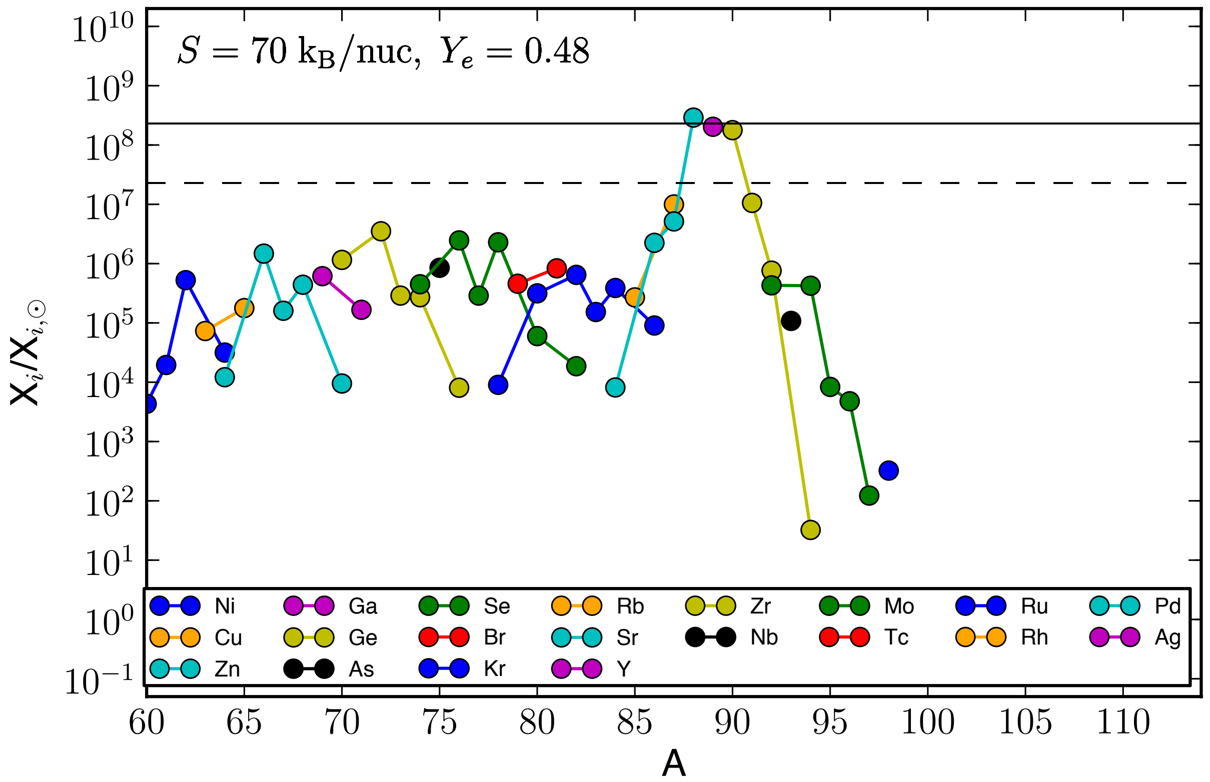

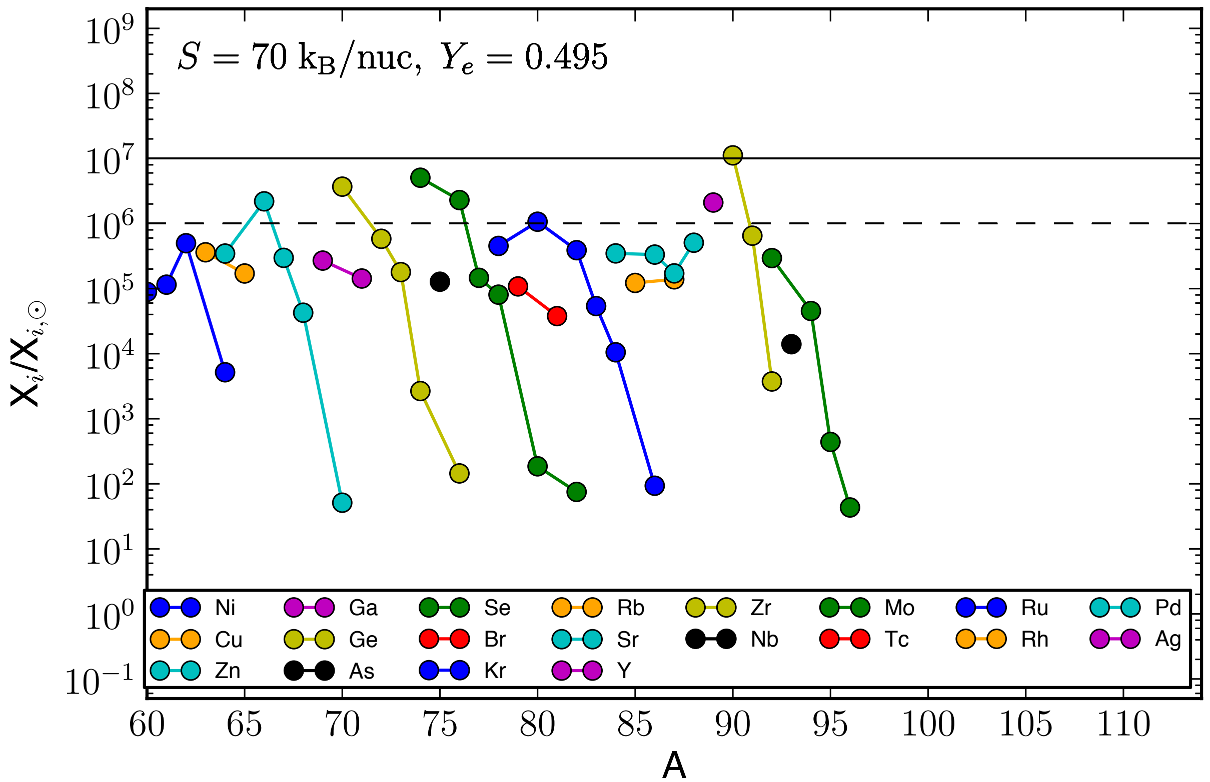

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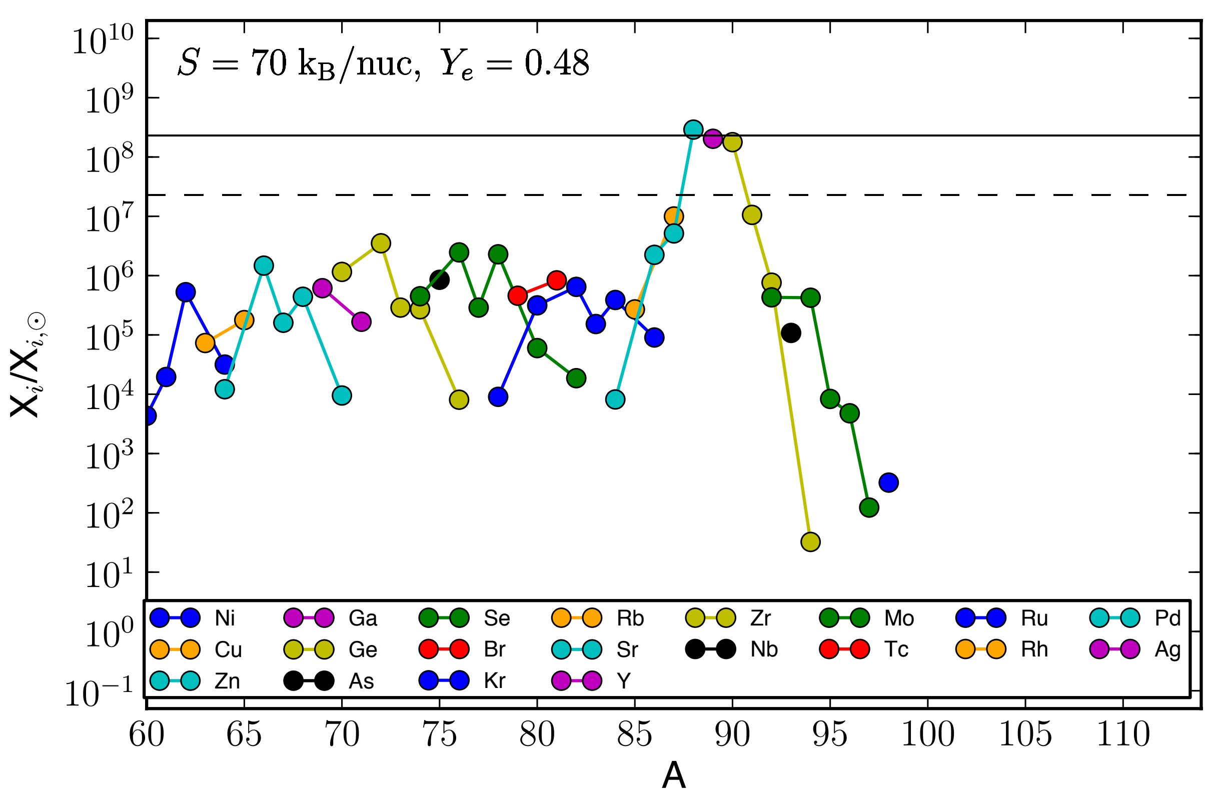

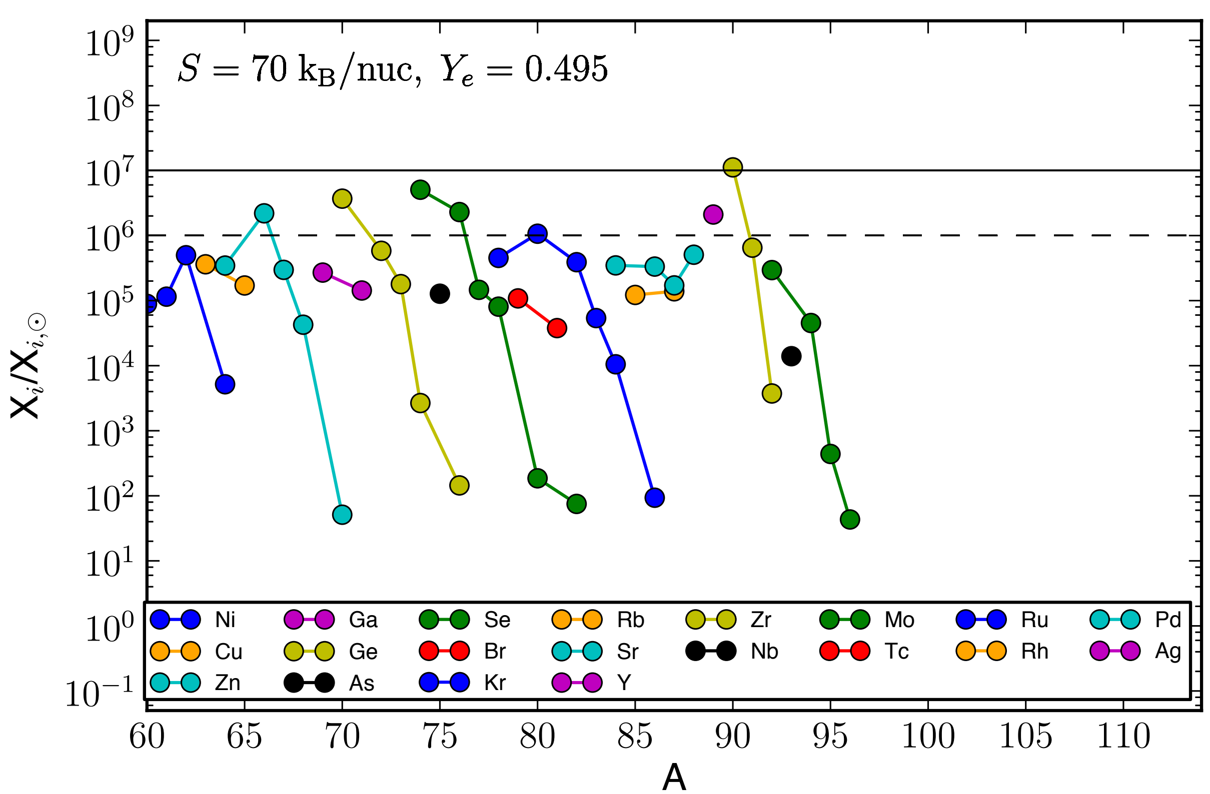

$Y_\odot(^{92}\mathrm{Mo})/Y_\odot(^{94}\mathrm{Mo}) = 1.57$ is fulfilled

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production factor: $$P(i) = \frac{X_i}{X_{i,\odot}} \cdot \frac{M_{\rm ej}^{\rm traj}}{M_{\rm ej}^{\rm tot}} \approx 10$$

$\sim 10^{-7}$-10^{-4}

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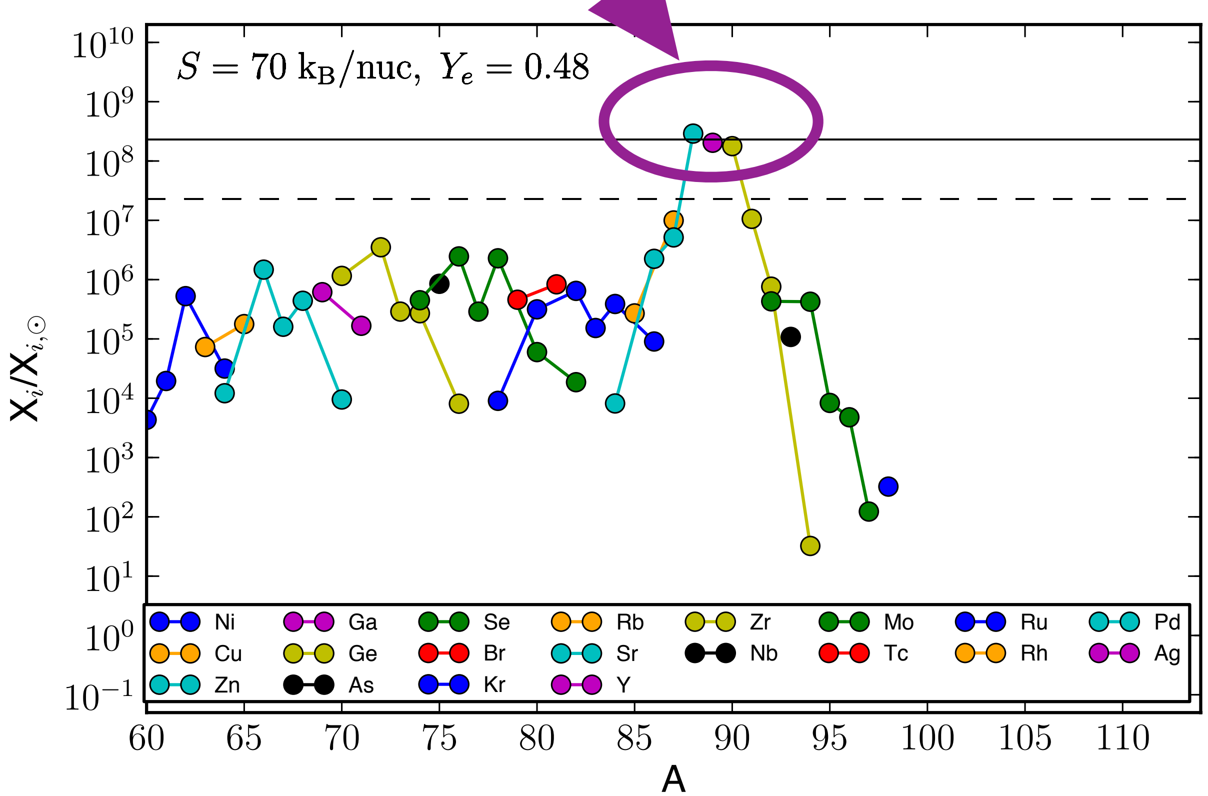
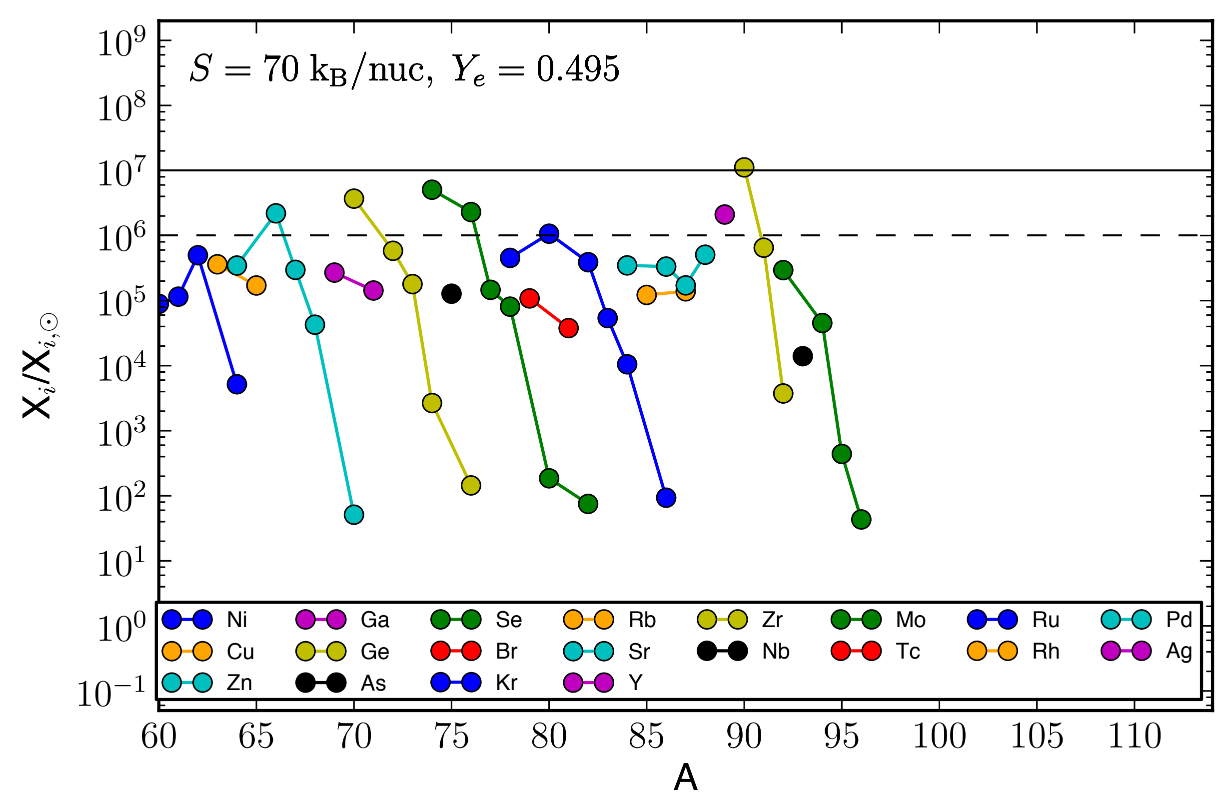
overproduction of ^{88}Sr, ^{89}Y, ^{90}Zr
[Hoffman et al. 1996, Hoffmann et al. 1997]





$Y_\odot(^{92}\mathrm{Mo})/Y_\odot(^{94}\mathrm{Mo}) = 1.57$ is fulfilled

Nucleosynthesis of ^{92,94}Mo and ^{96,98}Ru: production factor

production factor: $$P(i) = \frac{X_i}{X_{i,\odot}} \cdot \frac{M_{\rm ej}^{\rm traj}}{M_{\rm ej}^{\rm tot}}$$ **≈10**

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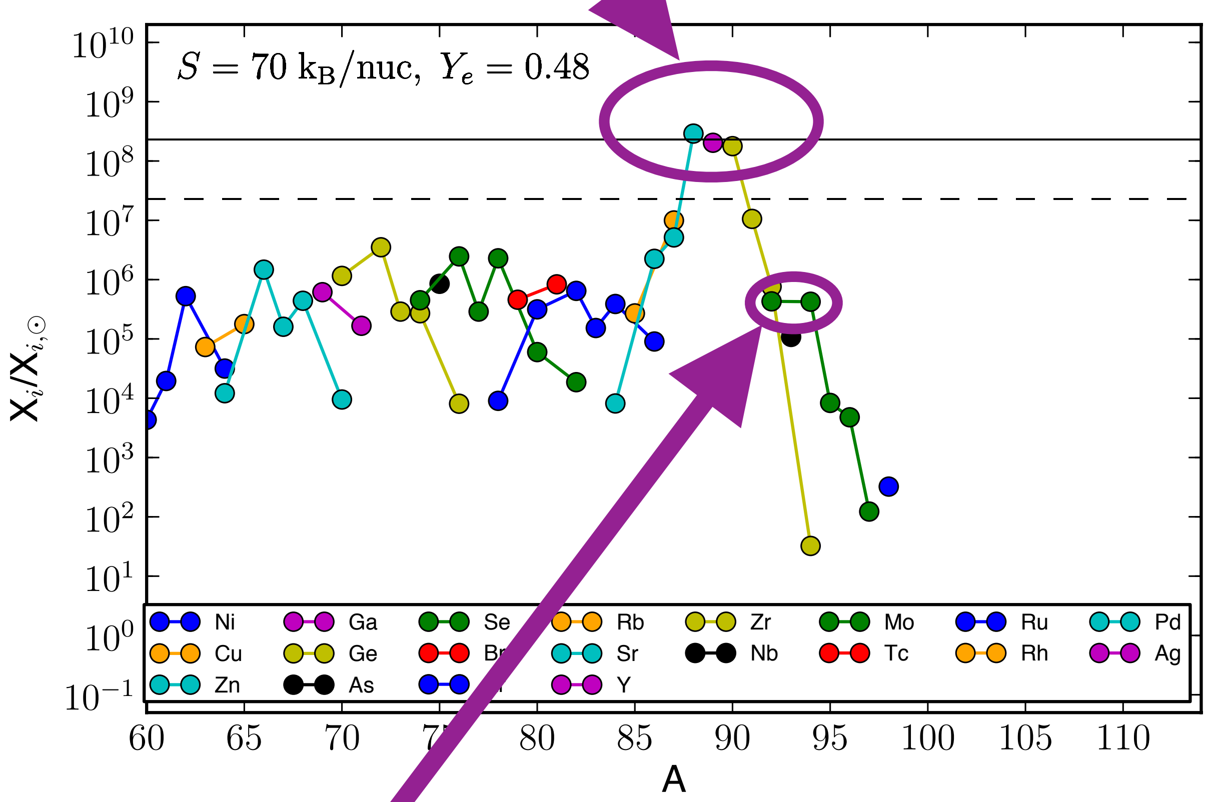

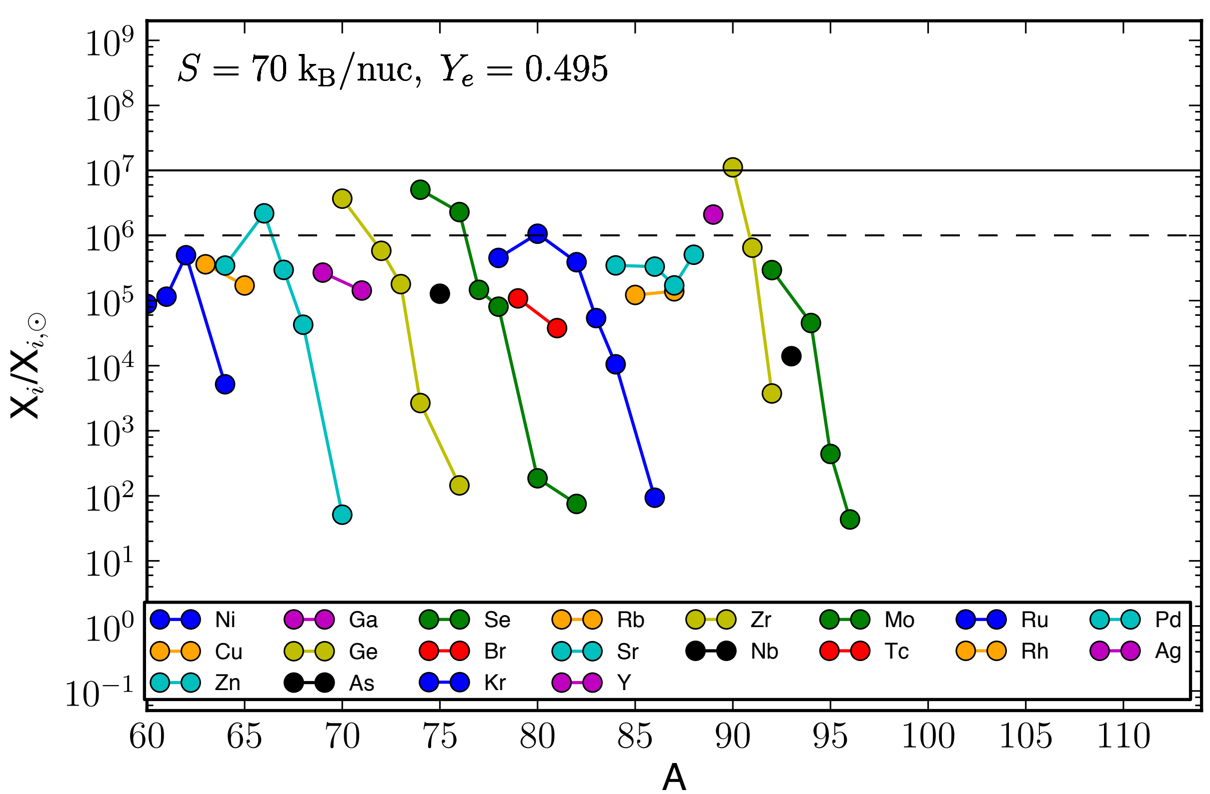

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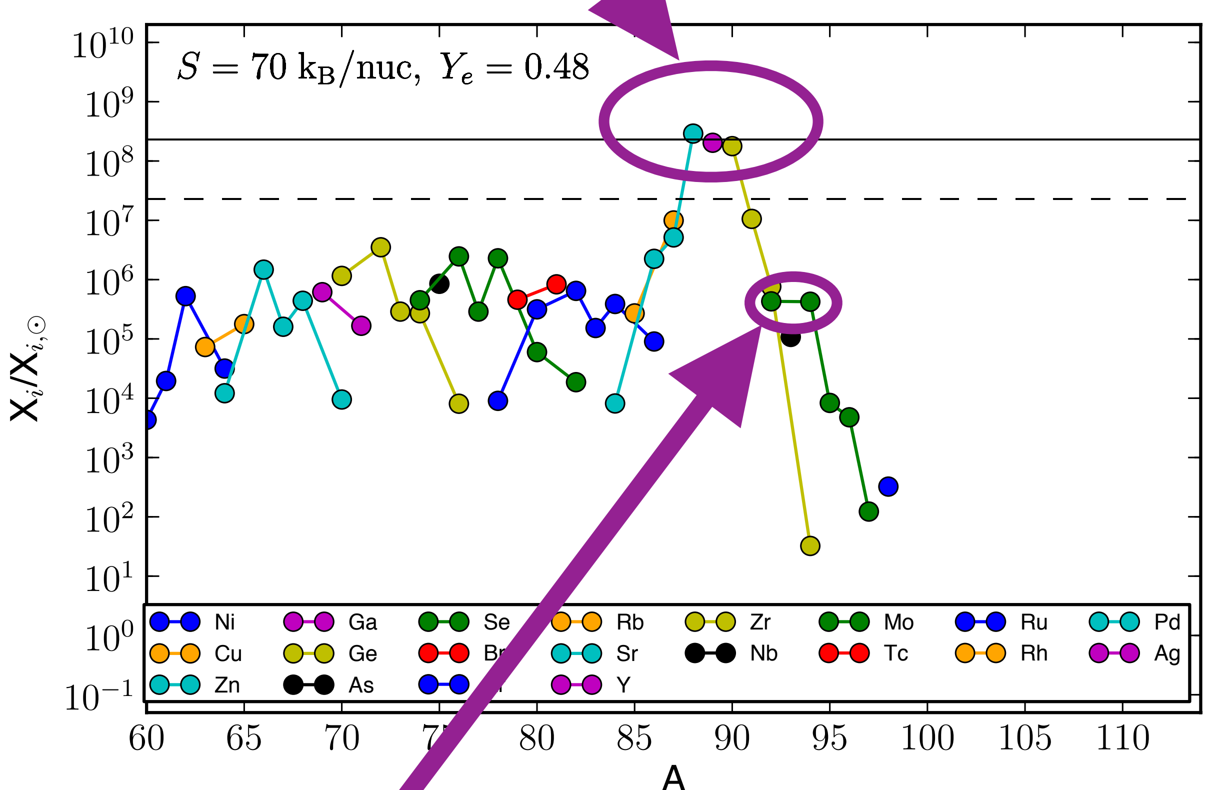

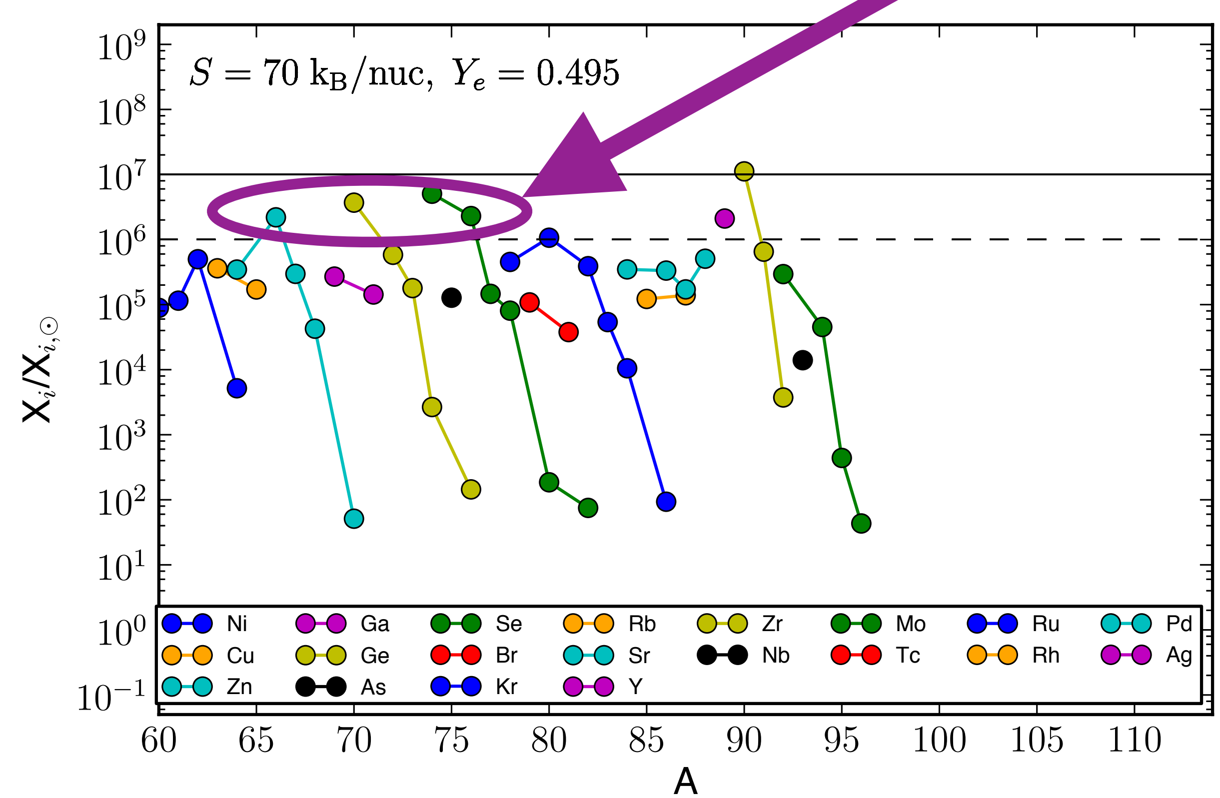

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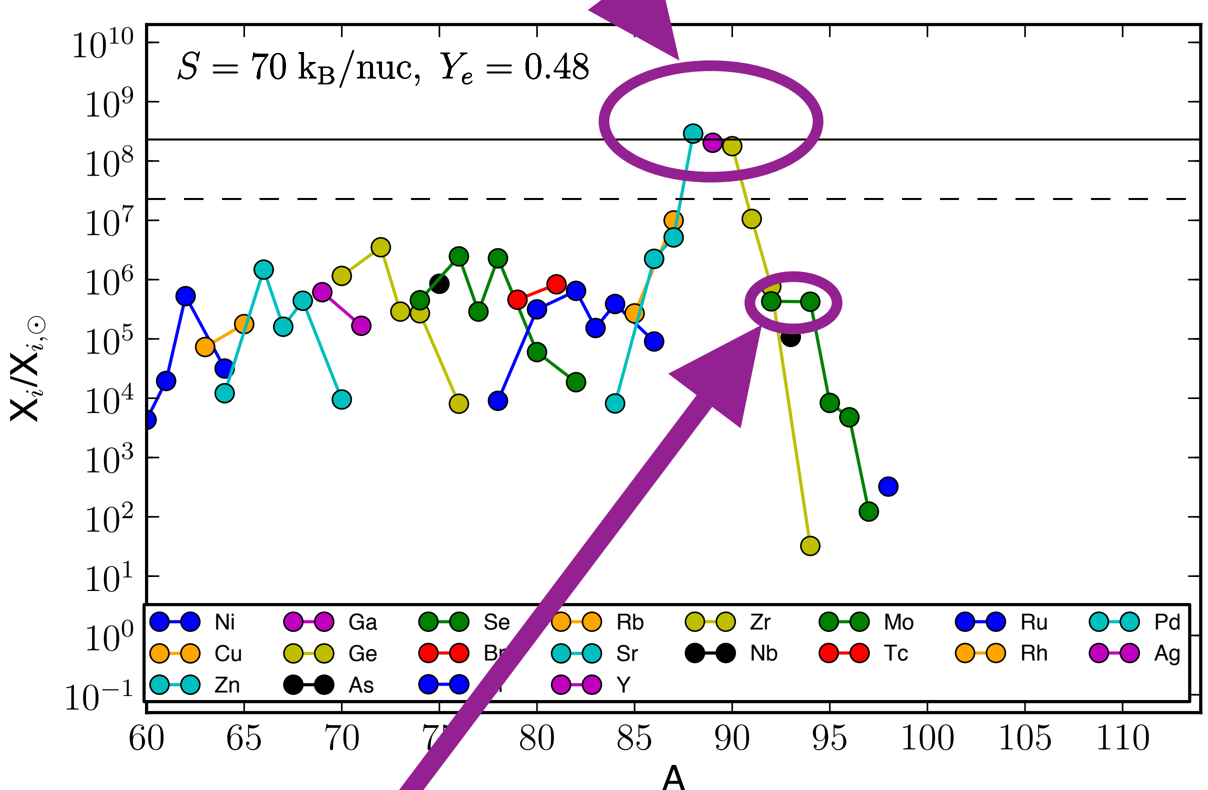

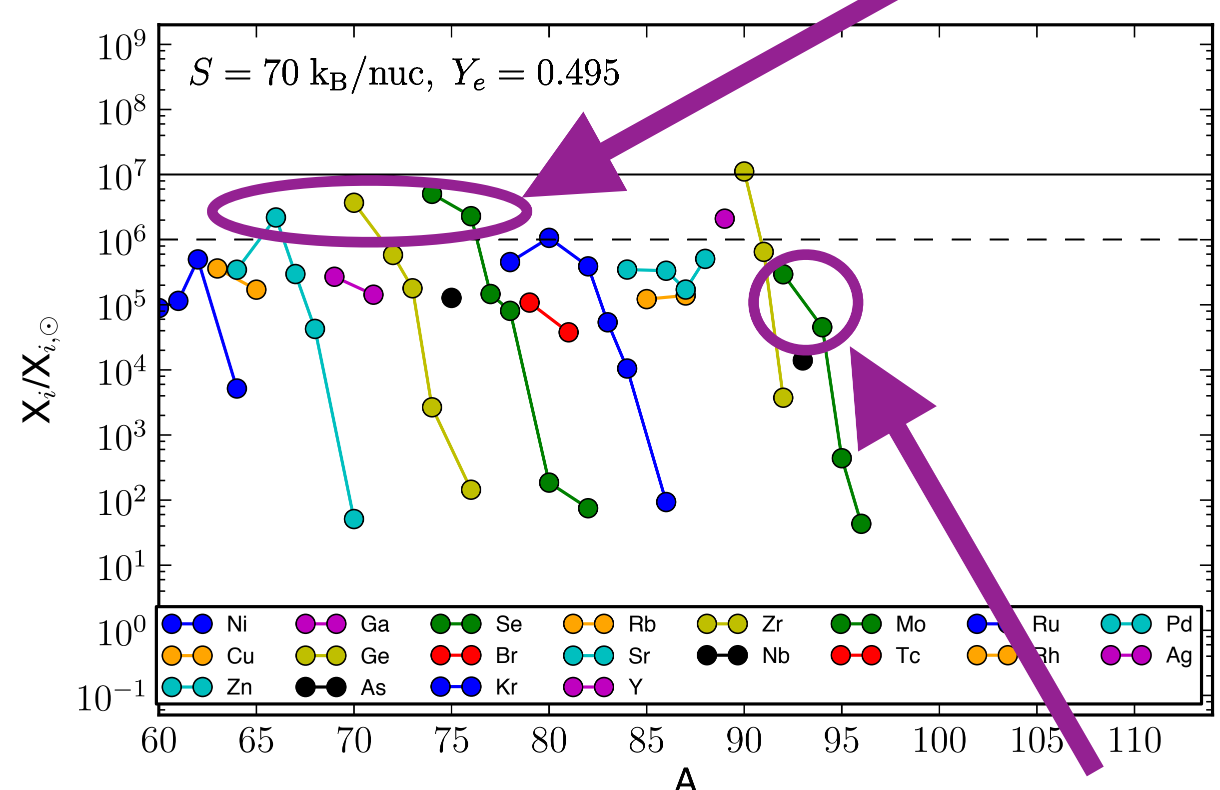

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insignificant ^{92,94}Mo abundances

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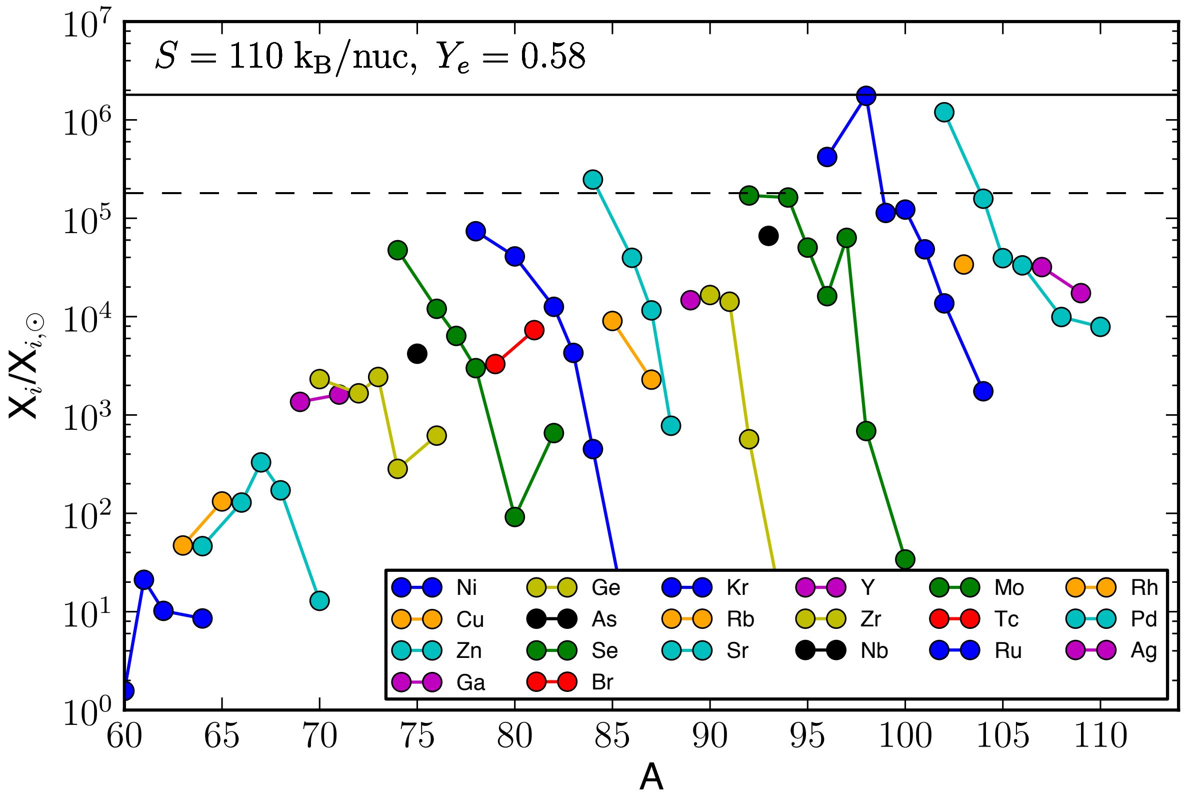

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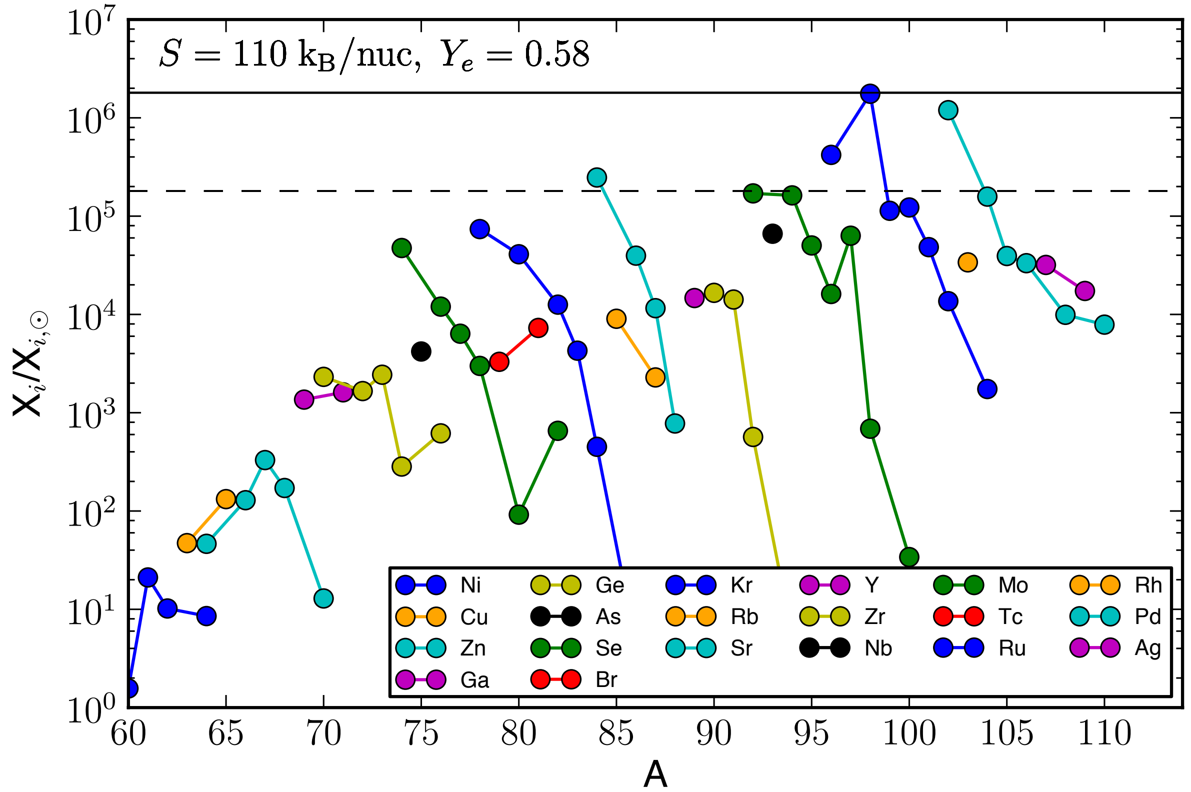

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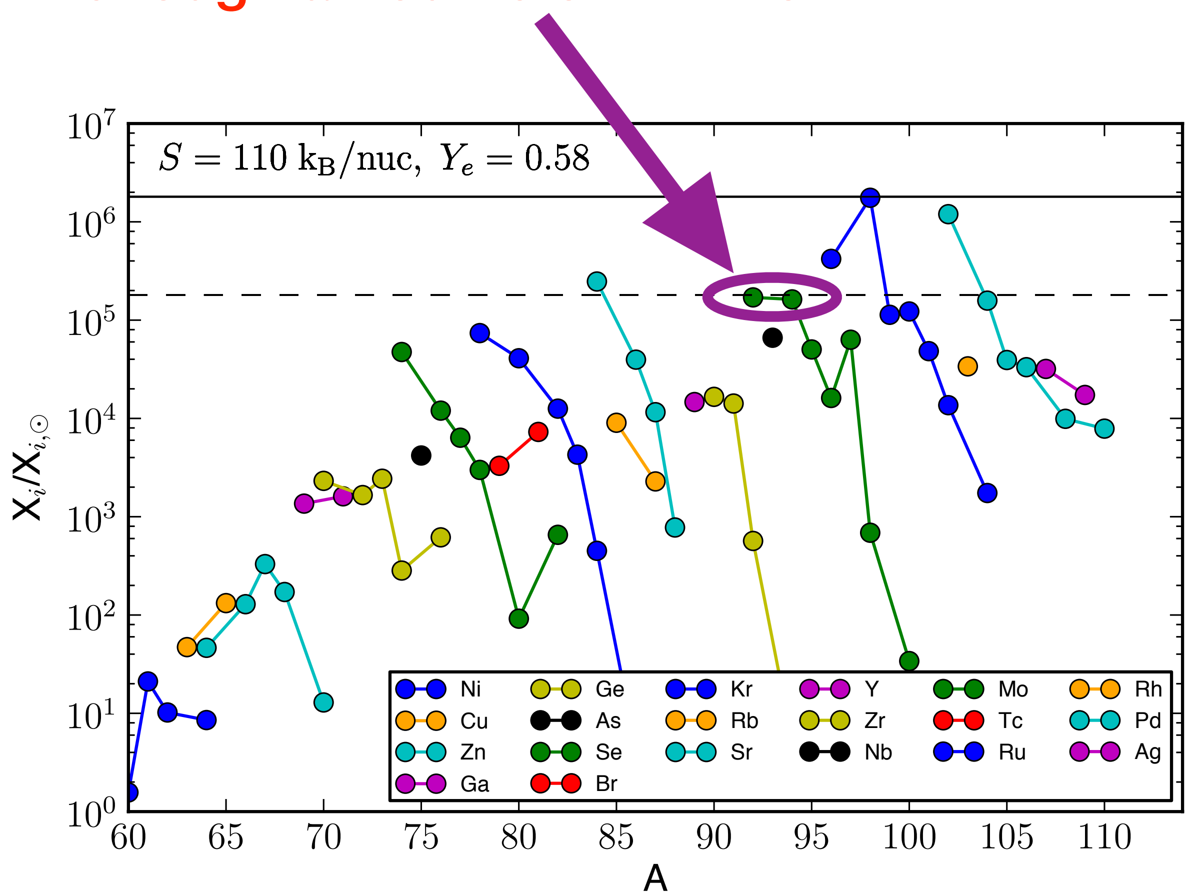
Nucleosynthesis of ^{92,94}Mo and ^{96,98}Ru: production factor

enough amounts of ^{92,94}Mo



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Nucleosynthesis of ^{92,94}Mo and ^{96,98}Ru: production factor

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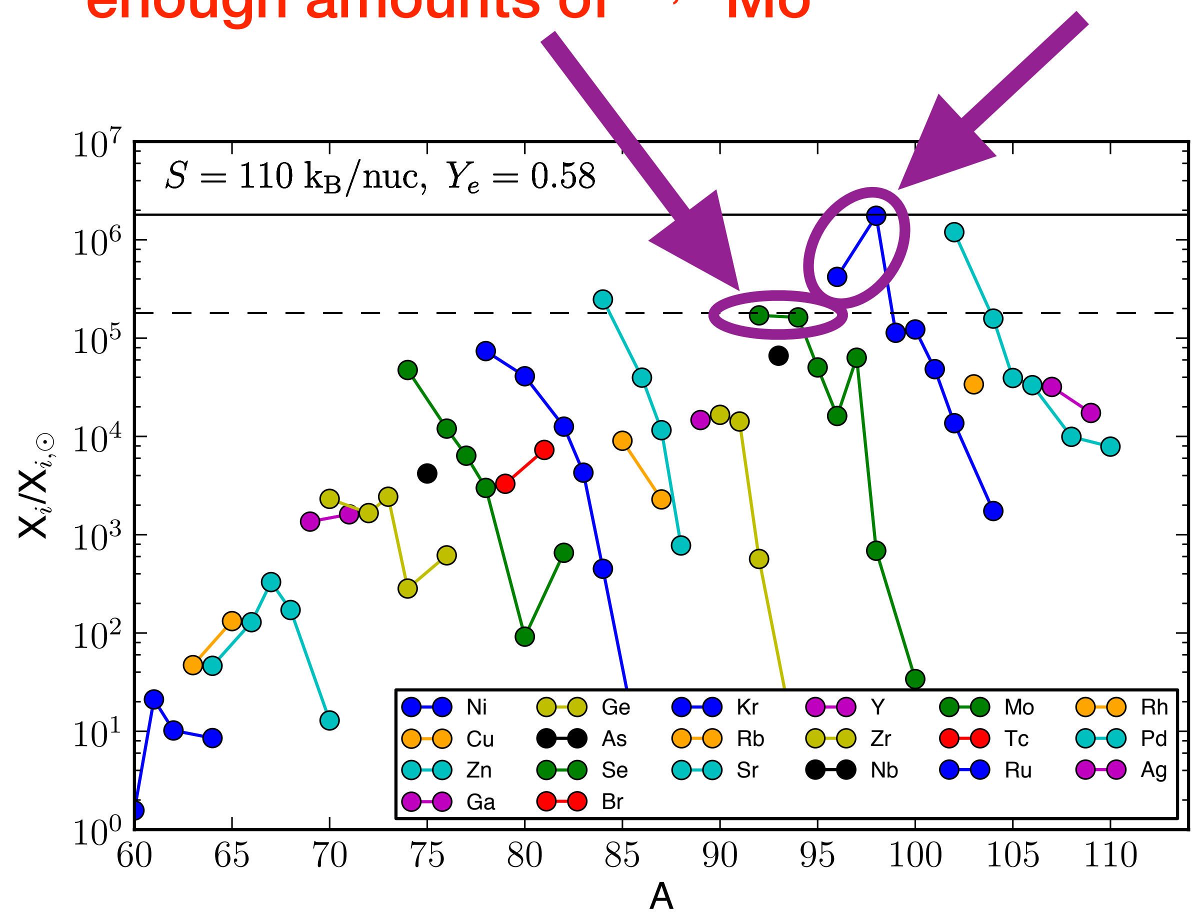
^{96,98}Ru not in SoS ratio



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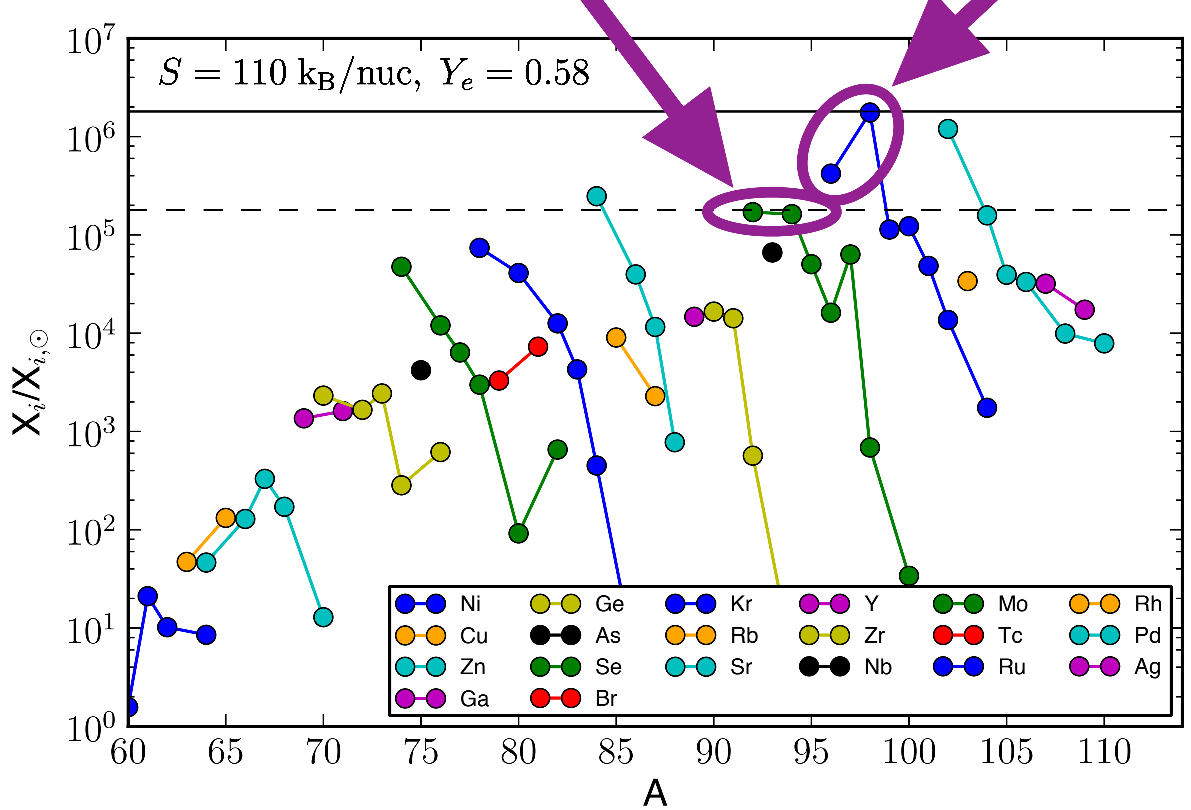

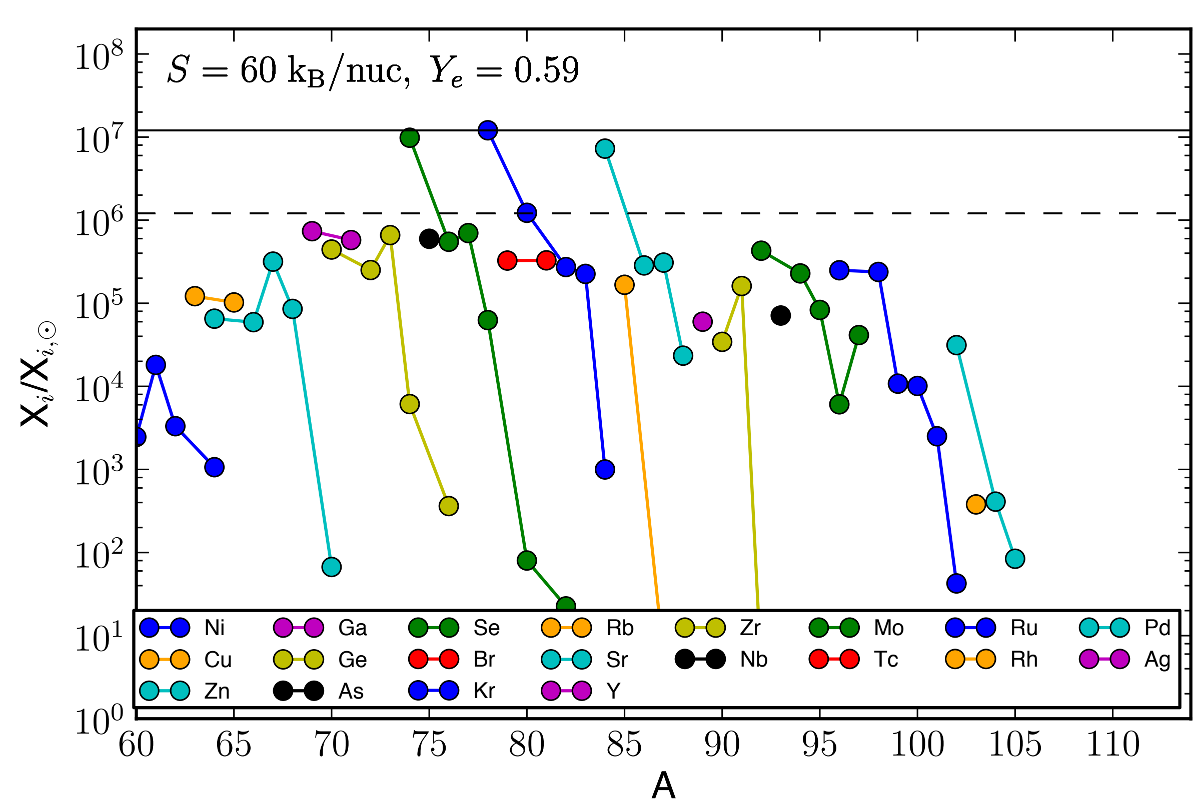

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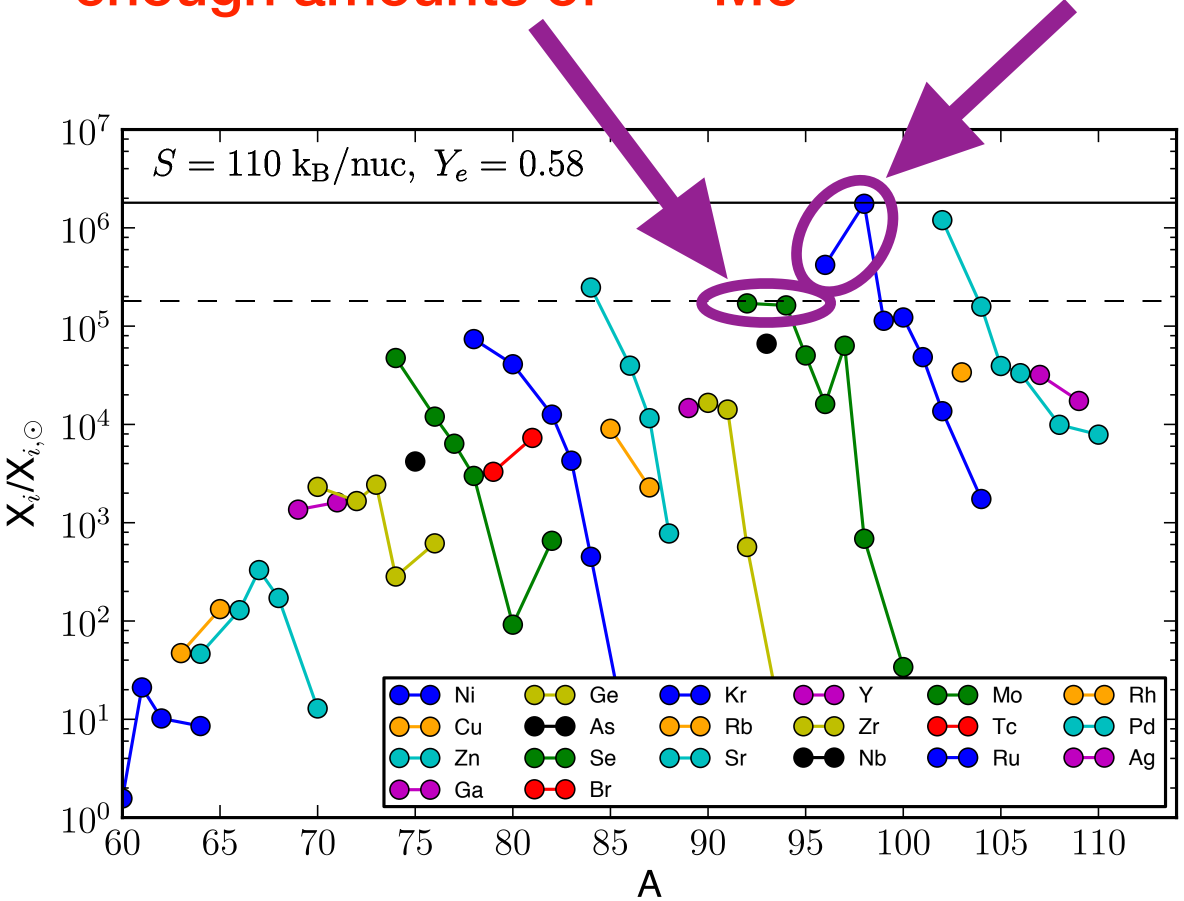
Nucleosynthesis of ^{92,94}Mo and ^{96,98}Ru: production factor

enough amounts of ^{92,94}Mo **^{96,98}Ru not in SoS ratio**



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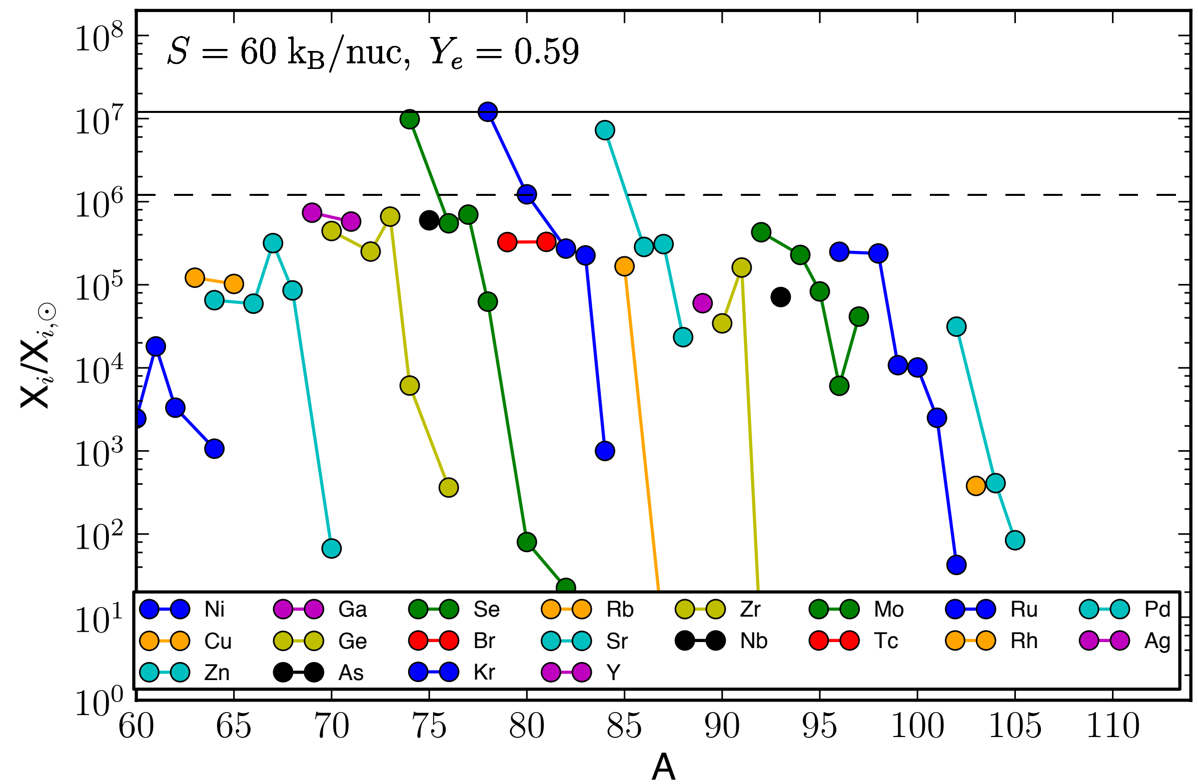

$Y_\odot(^{96}\mathrm{Ru})/Y_\odot(^{98}\mathrm{Ru}) = 2.97$ is fulfilled

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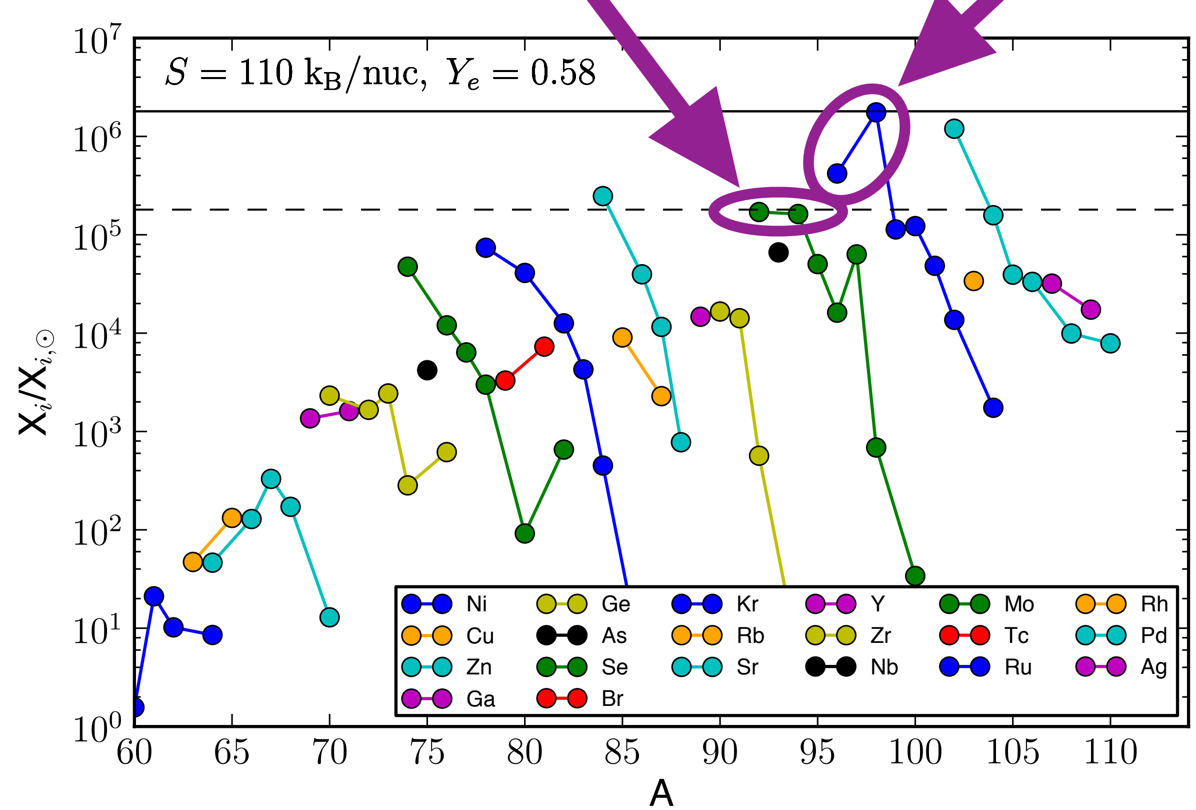
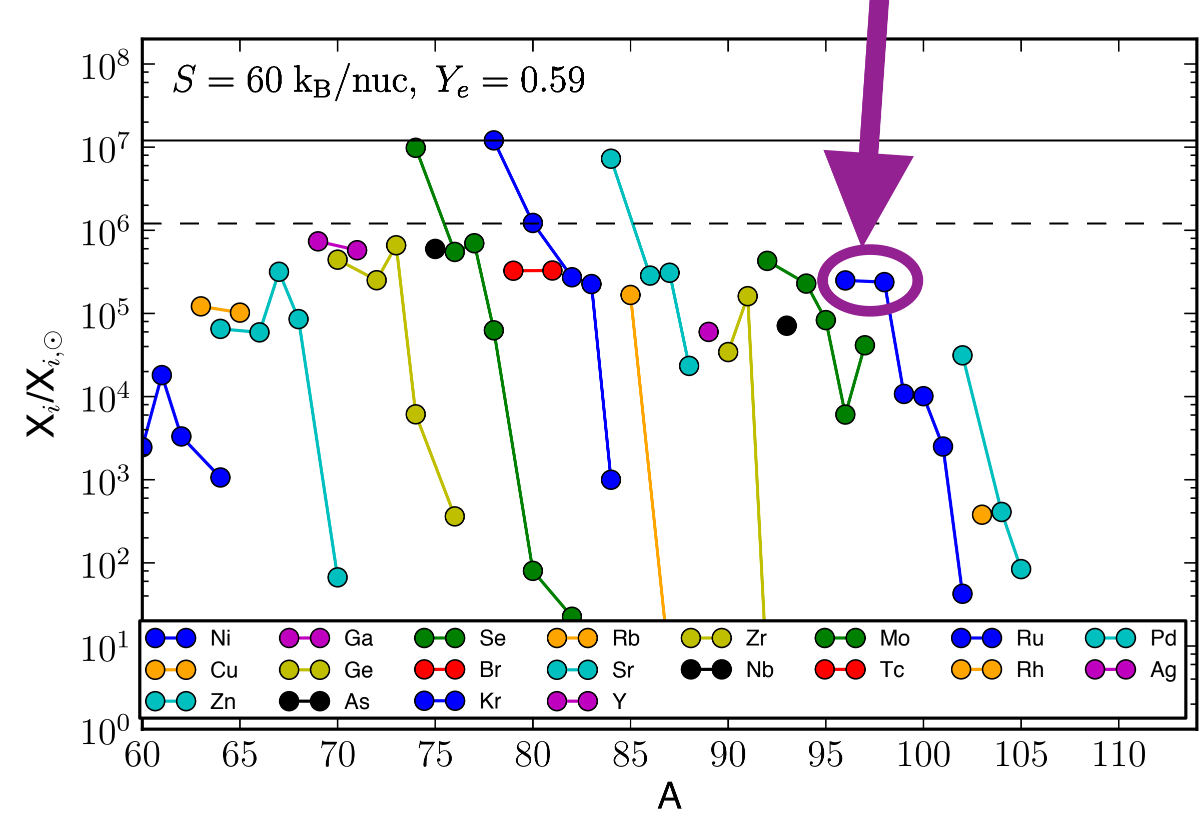
^{96,98}Ru not in SoS ratio

underproduction of ^{96,98}Ru





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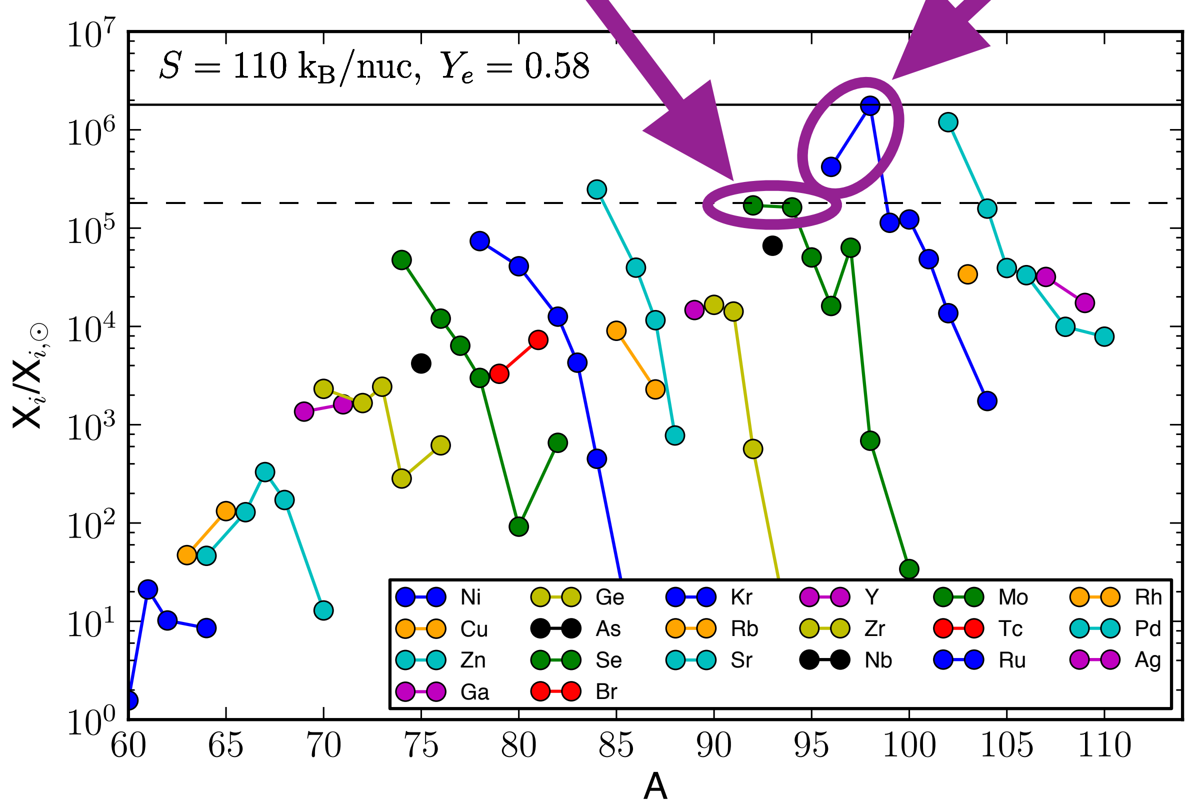
Nucleosynthesis of ^{92,94}Mo and ^{96,98}Ru: production factor

$Y(^{92}\mathrm{Mo})/Y(^{94}\mathrm{Mo})$ differs from SoS ratio

enough amounts of ^{92,94}Mo

^{96,98}Ru not in SoS ratio

underproduction of ^{96,98}Ru



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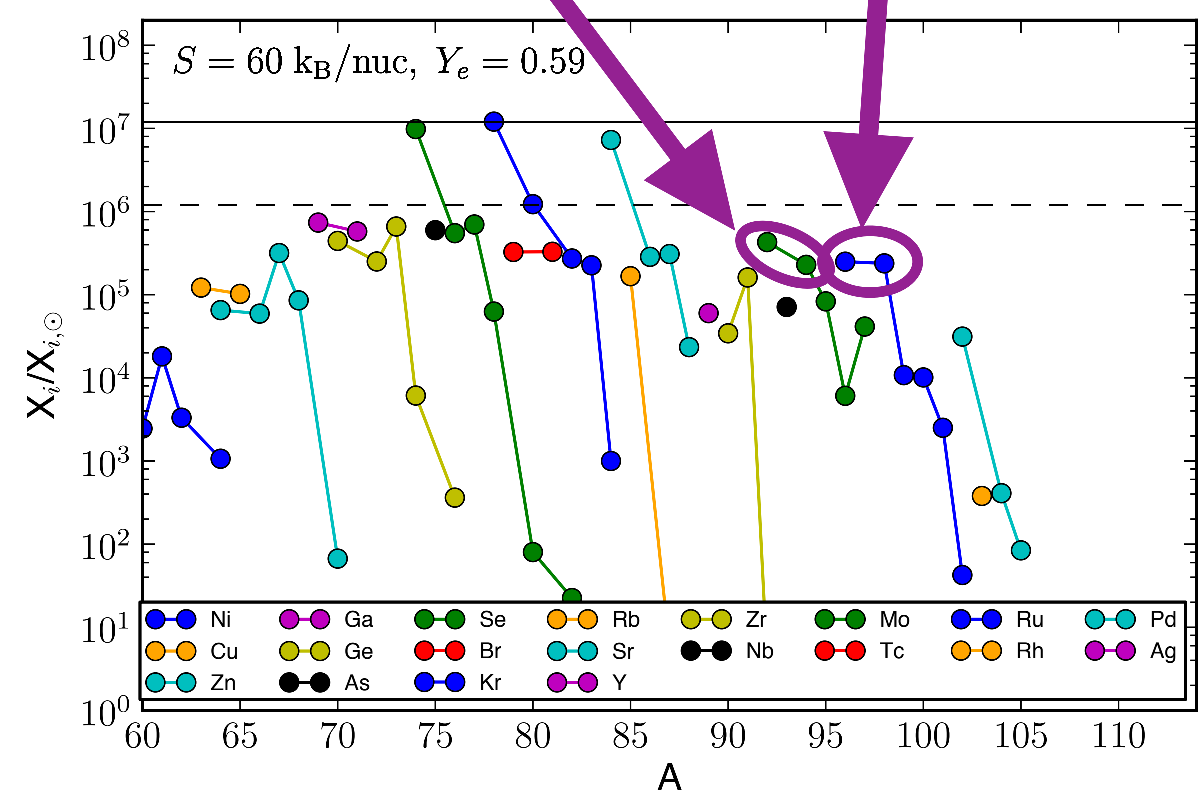

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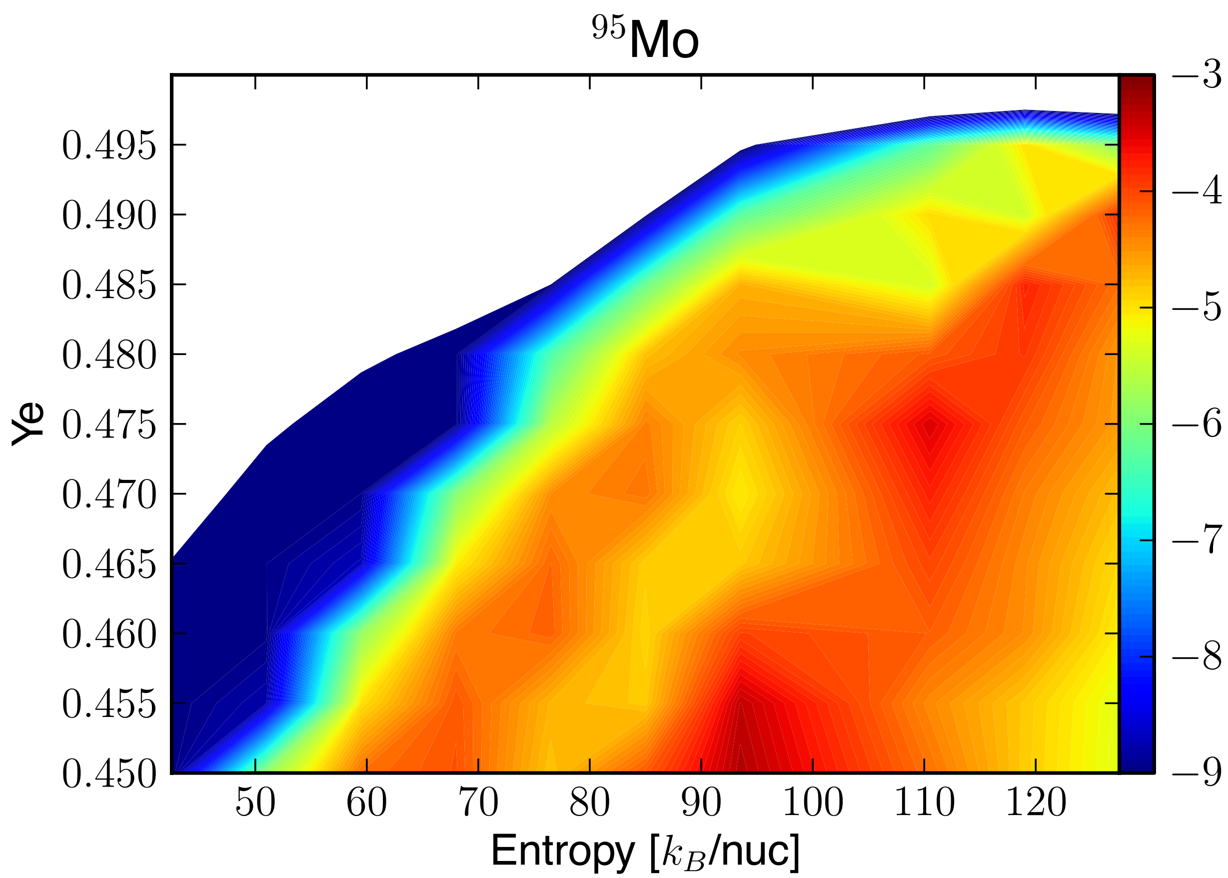
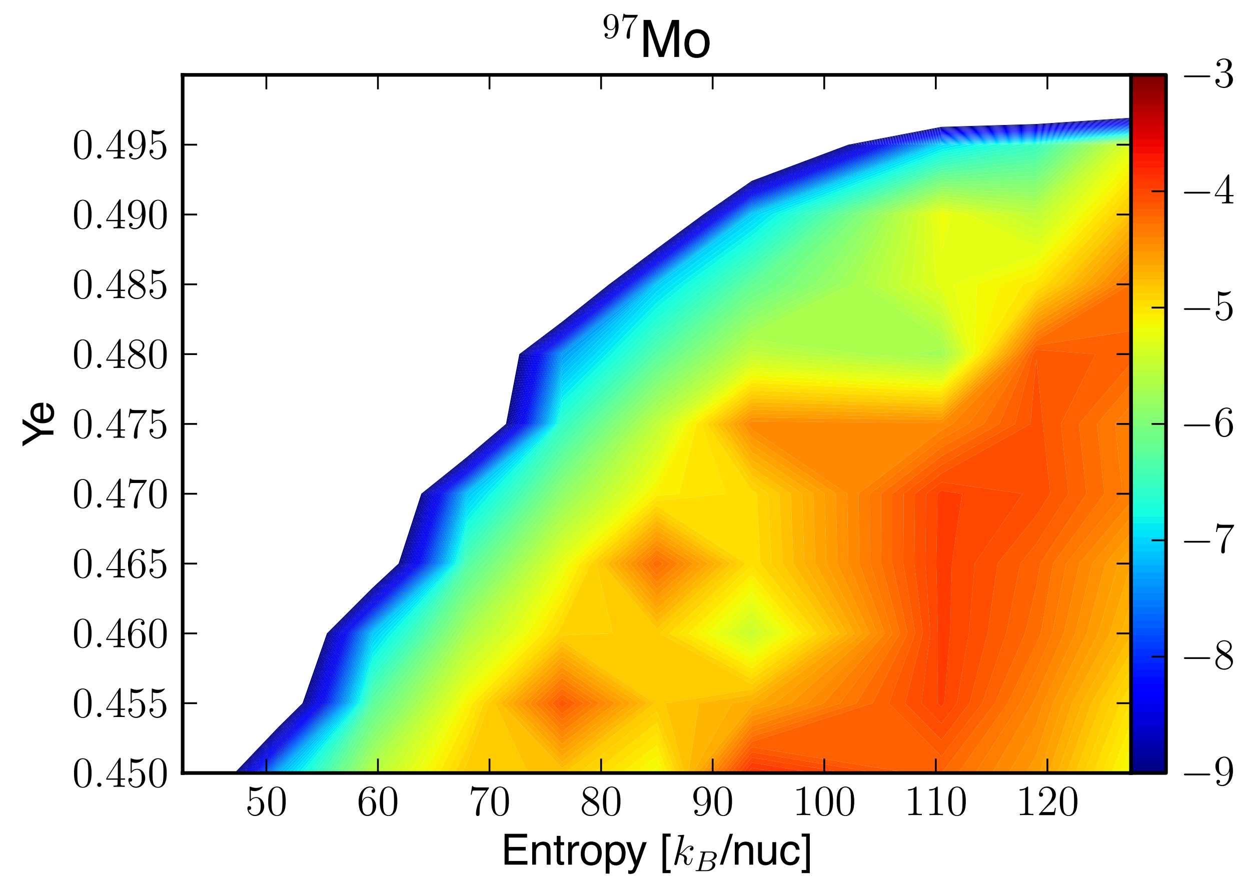
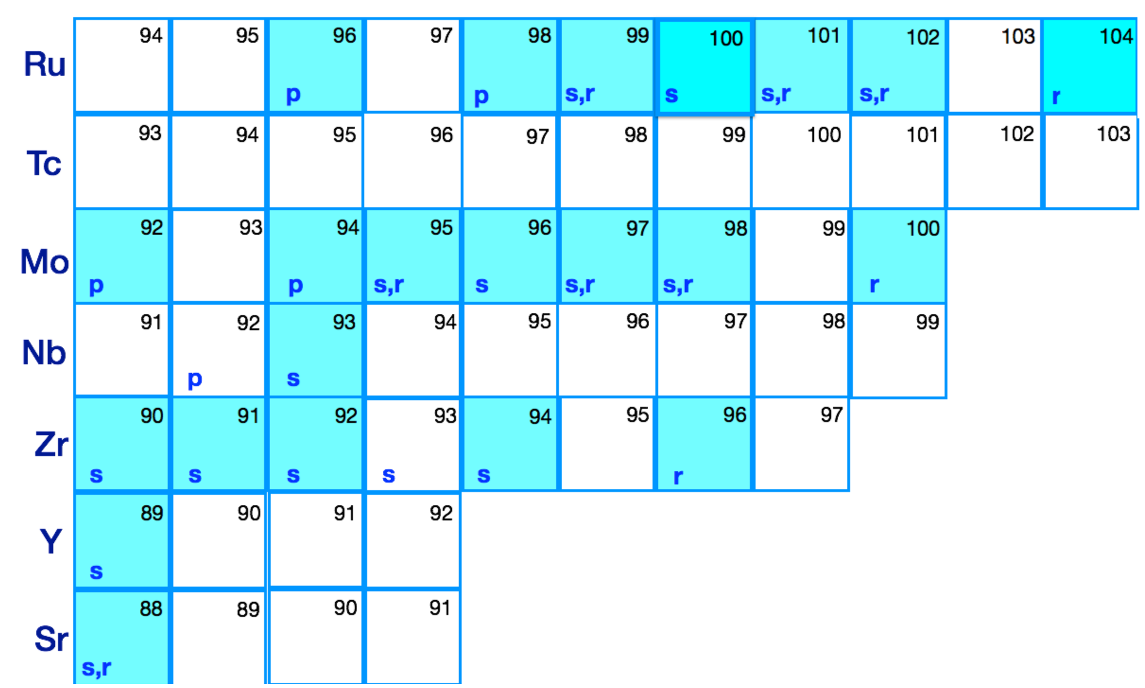
Nucleosynthesis of s-, r-isotopes: ^{95,97}Mo





- formation in neutron-rich winds
- **neutron-capture processes** close to stability
- similar abundance pattern for ^{98,100}Mo and ^{99,101,102,104}Ru



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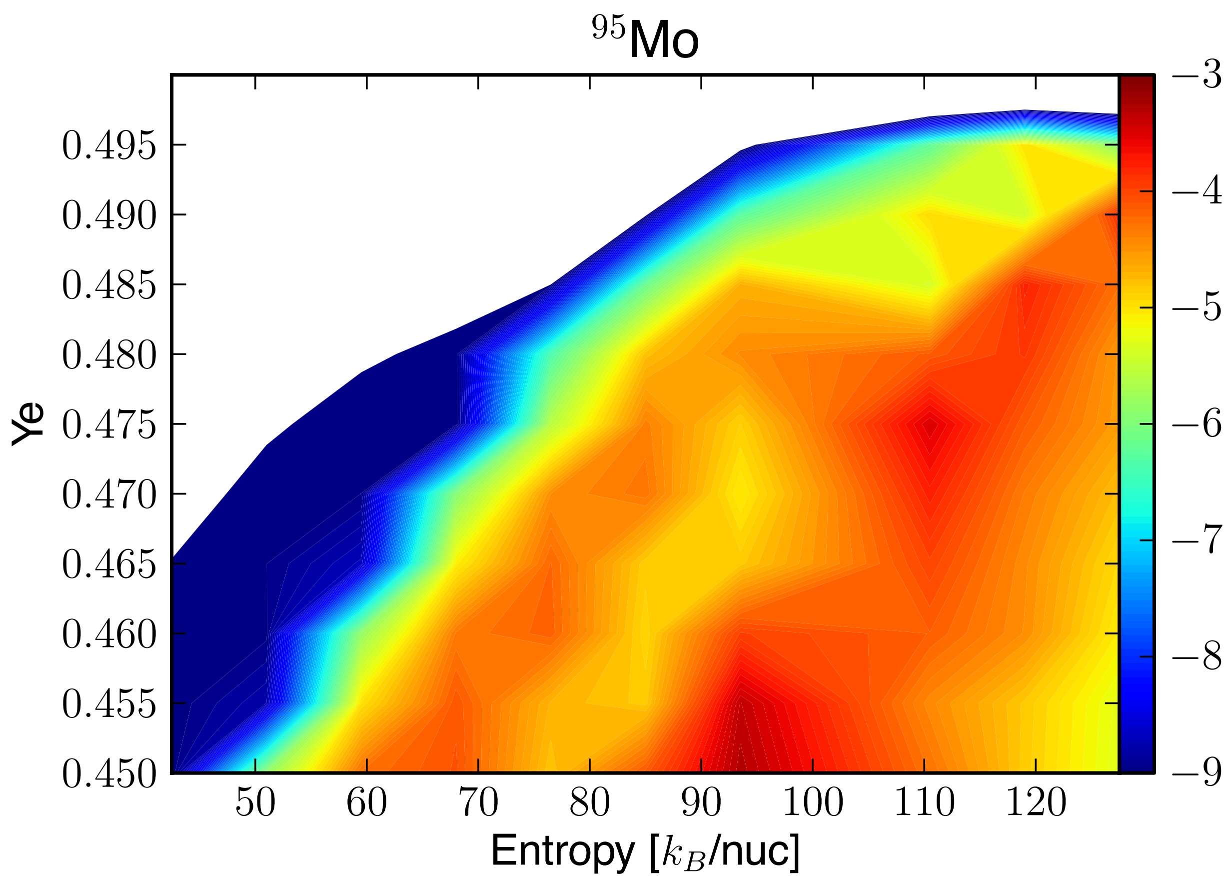

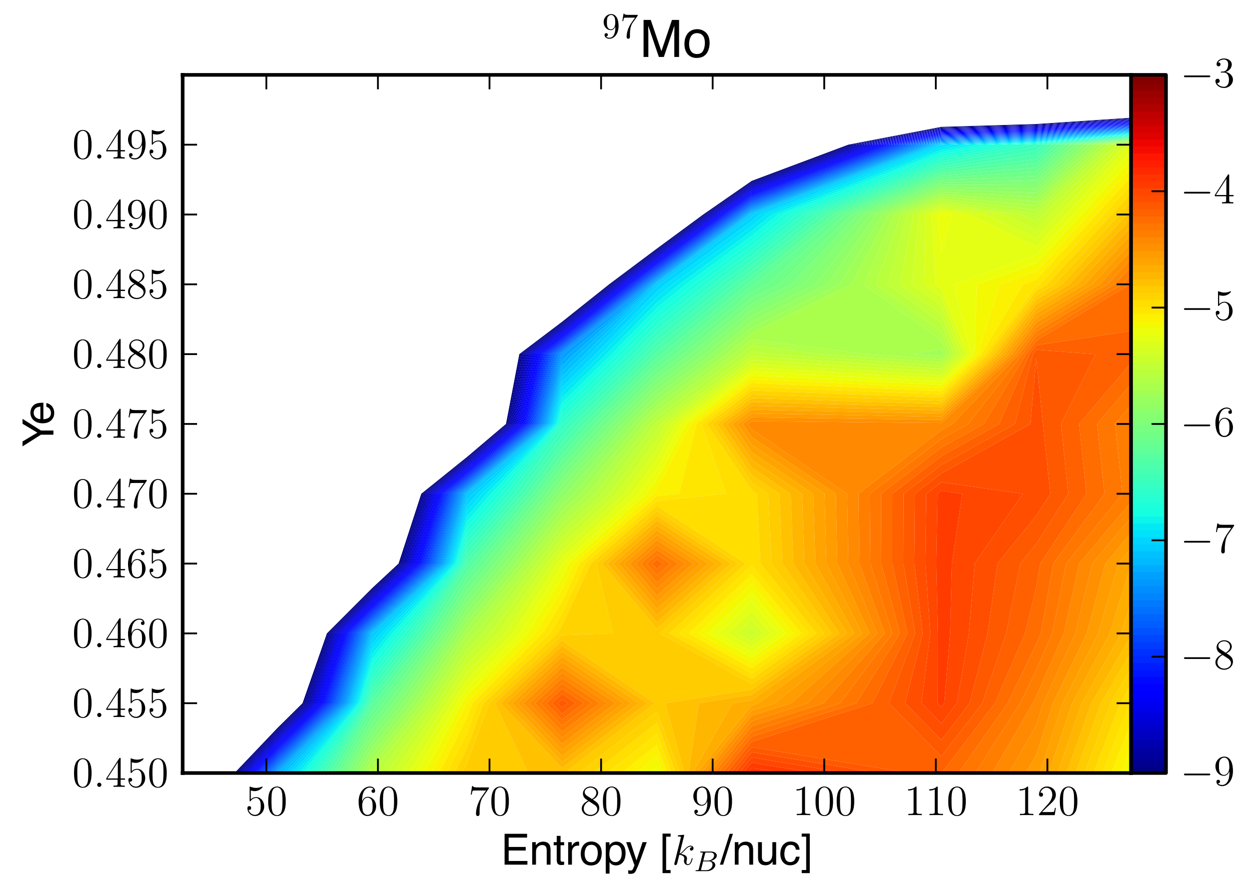

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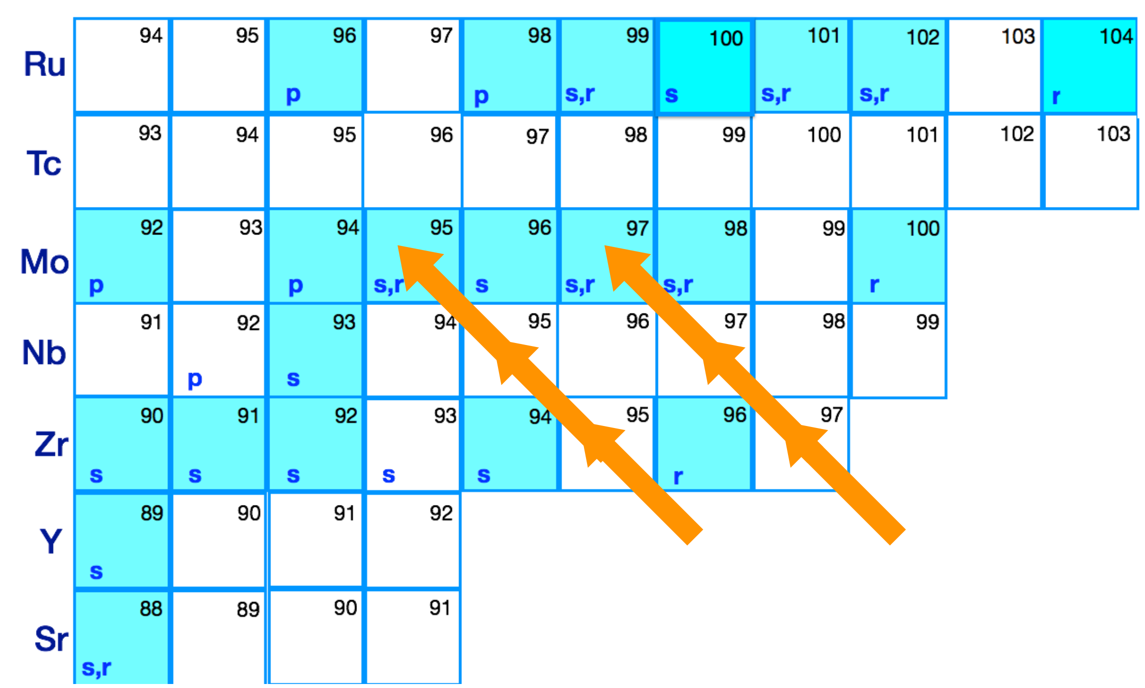

Solar system and SiC X abundances of ^{95,97}Mo

- SiC X → **silicon carbide grains of type X**
  - presolar grains recovered from meteorites
  - condensation within type Ia or II SNe
- ^{95,97}Mo are enhanced in SiC X:

  $Y_{SiC\,X}(^{95}Mo)/Y_{SiC\,X}(^{97}Mo)=1.83$ [Pellin et al. 1999]

  $Y_{\odot}(^{95}Mo)/Y_{\odot}(^{97}Mo)=1.67$ [Lodders 2003]
- no similar enhancement in ^{96,98,100}Mo

  → **differs from pure r- or s-process**
- **possible origin:**
  - neutron burst in supernova zones (see Meyer et al. 2000)
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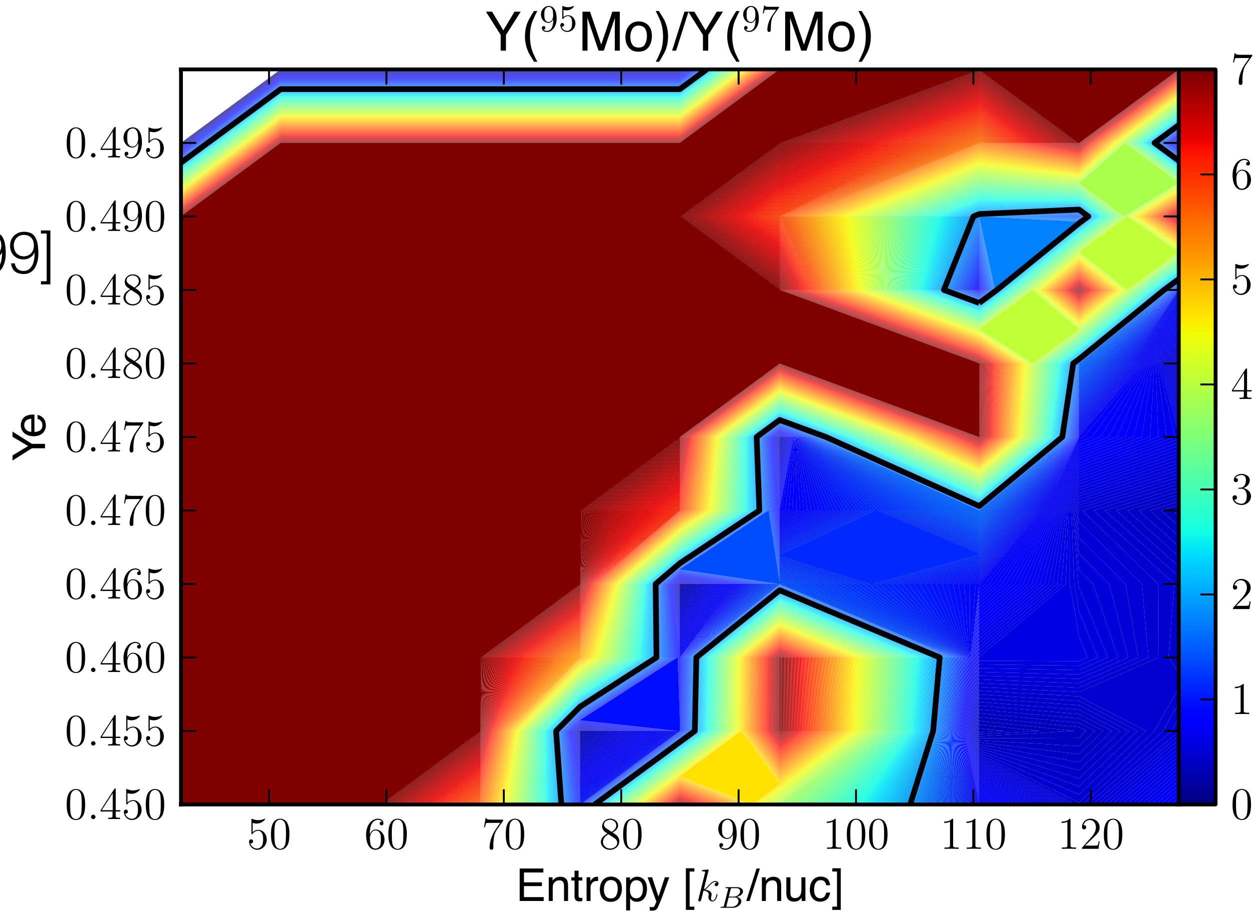
    → but **$Y_{\odot\text{-}s}(^{95}Mo)/Y_{\odot\text{-}s}(^{97}Mo)=1.88$**



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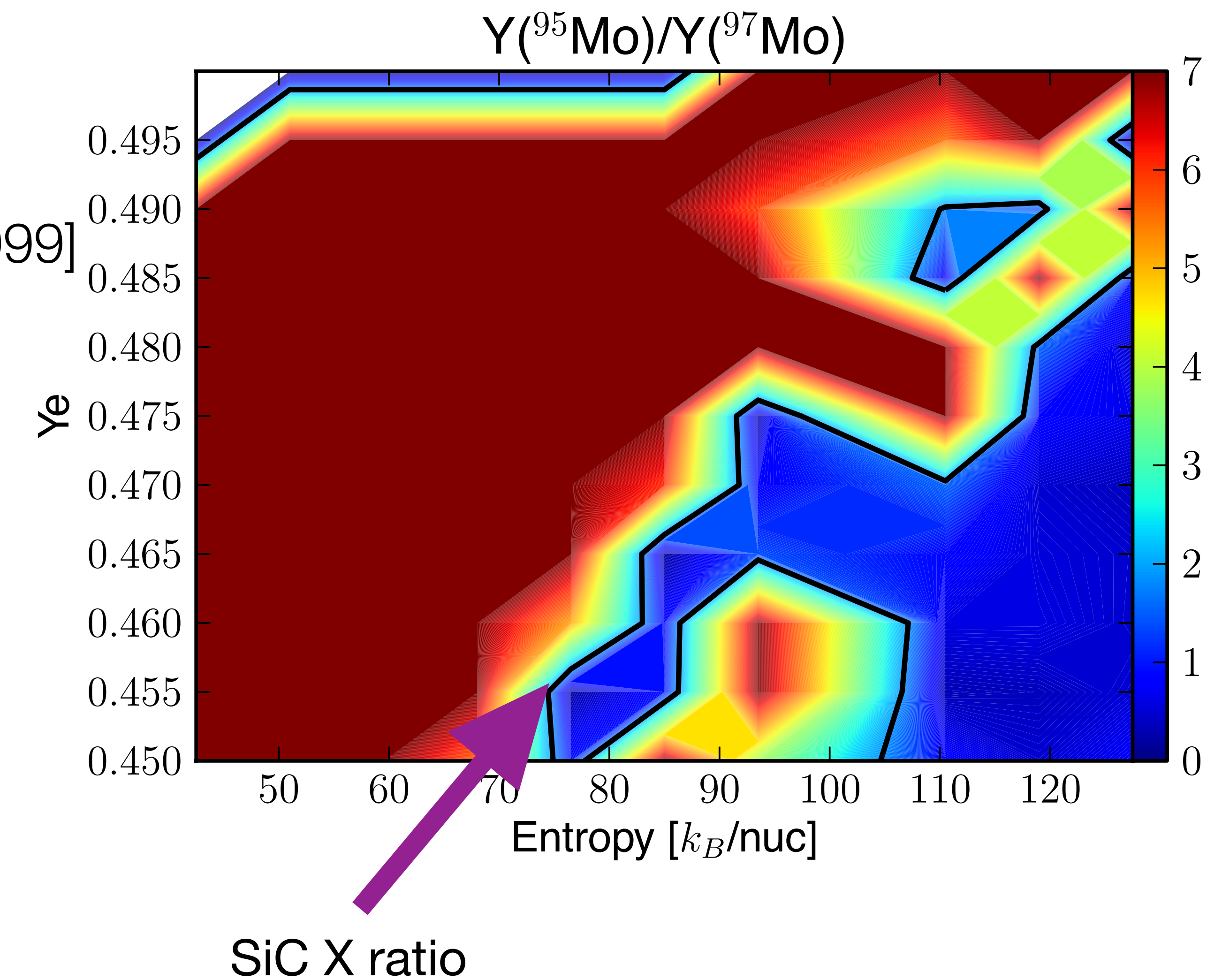

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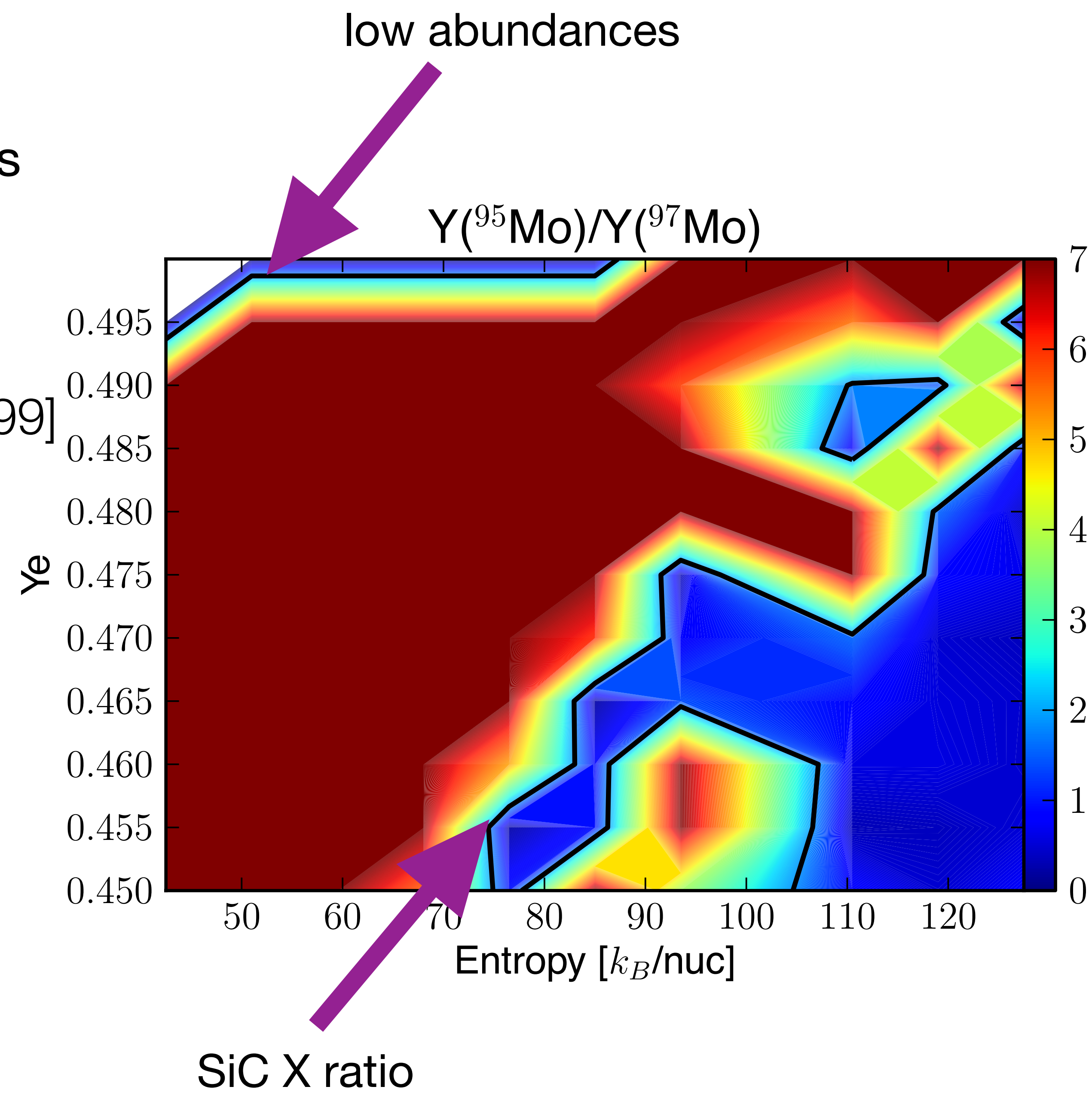
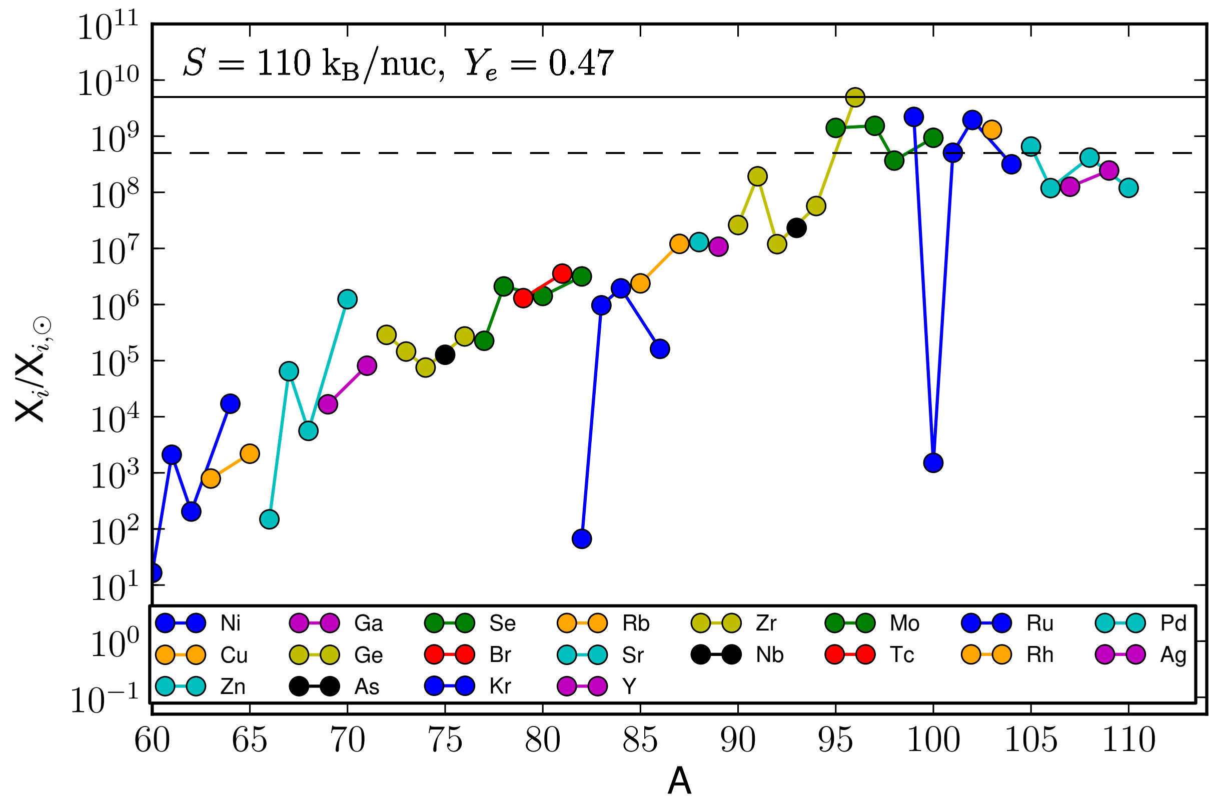


^{95,97}Mo in solar system and SiC X: production factor



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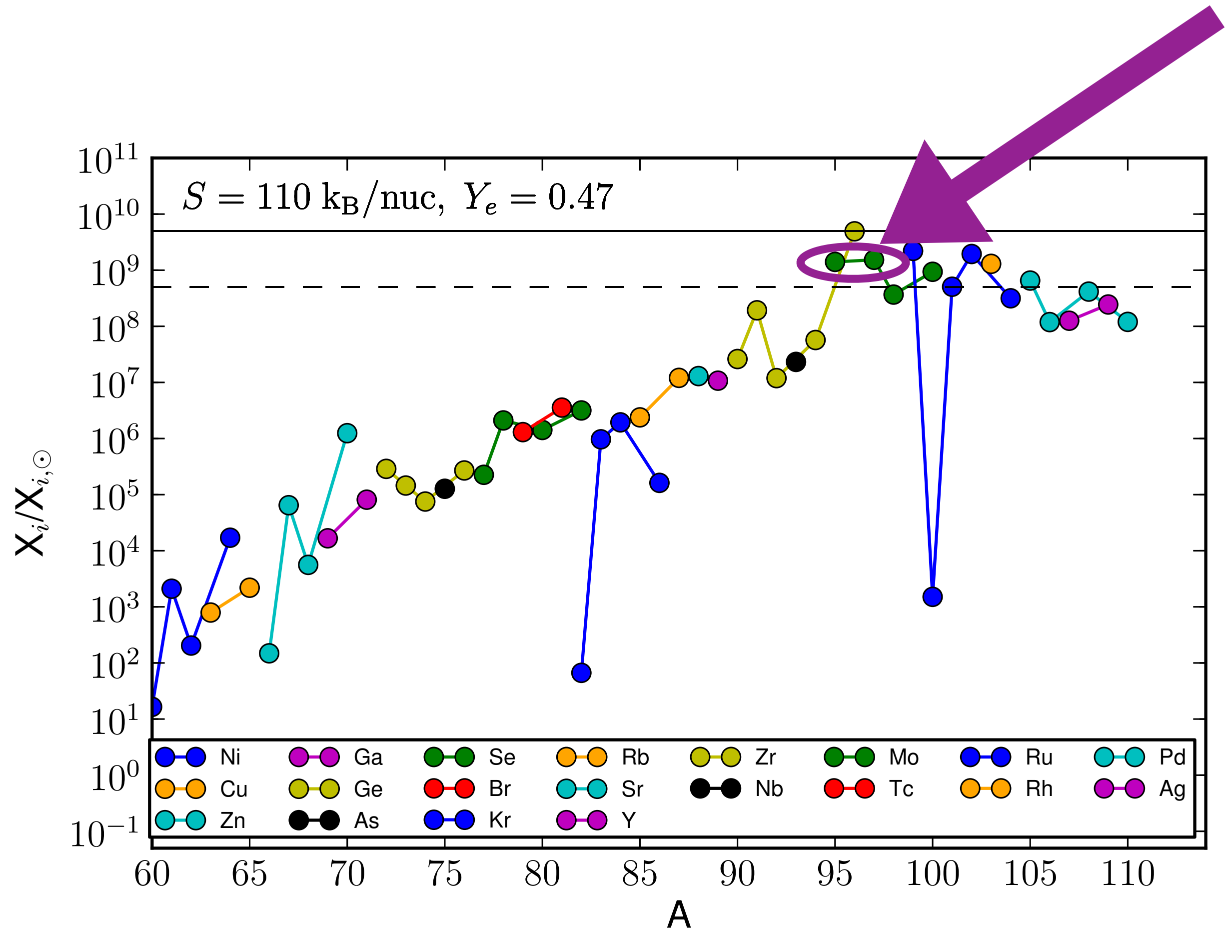
^{95,97}Mo in solar system and SiC X: production factor

production of ^{95,97}Mo



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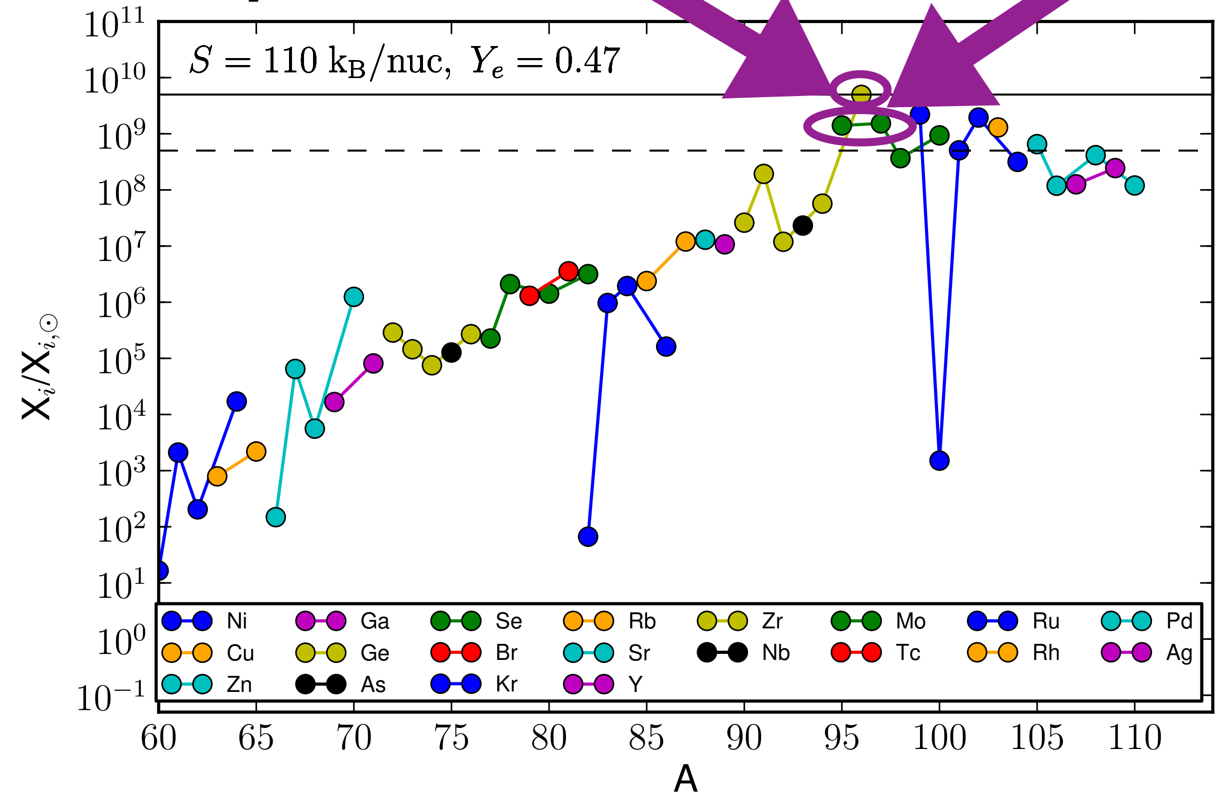

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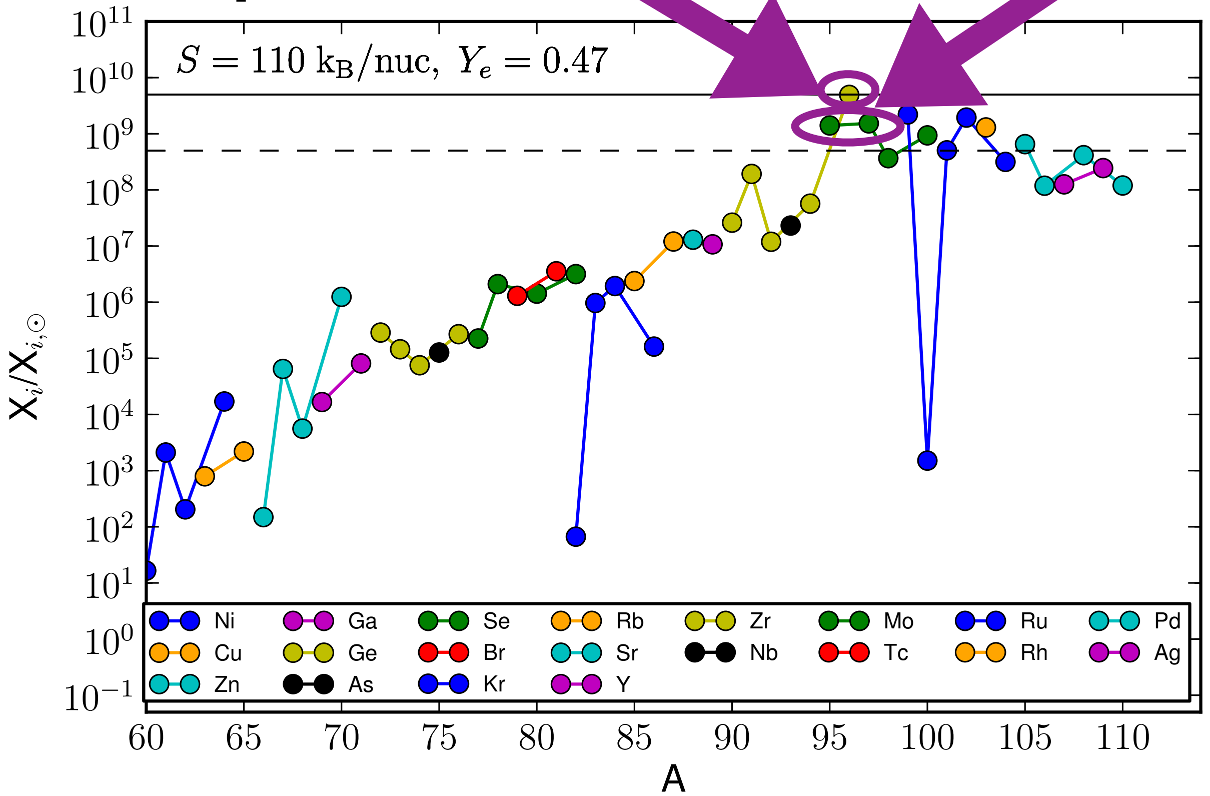
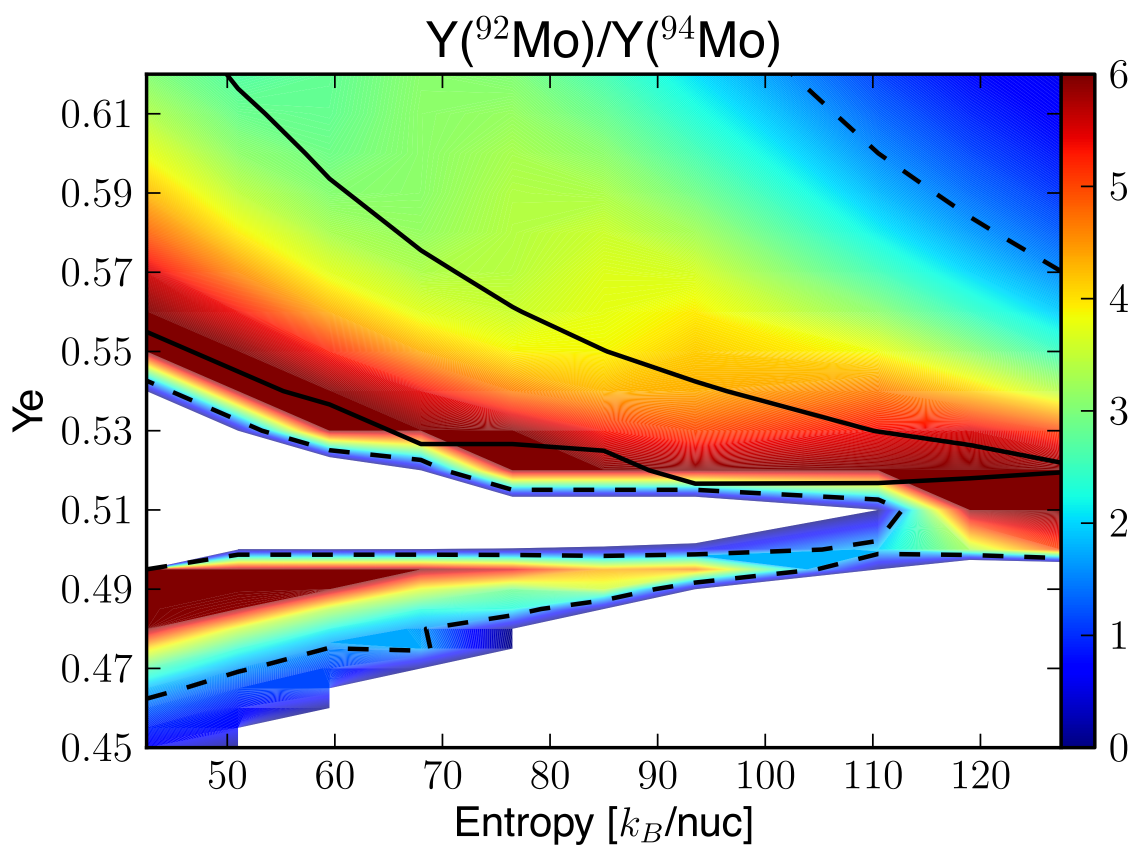


$Y_{SiC\ X}(^{95}Mo)/Y_{SiC\ X}(^{97}Mo) = 1.83$ is fulfilled

- not all neutrino-driven winds can have such wind parameters
  → **overproduction**

Summary

- neutrino-driven winds produce solar ***Y*(^{92}Mo)/*Y*(^{94}Mo)** in **neutron- and proton-rich conditions**
- synthesis of solar ***Y*(^{96}Ru)/*Y*(^{98}Ru)** in **proton-rich winds**
  - ➡ neutrino-driven winds important: origin of solar system ^{92,94}Mo and ^{96,98}Ru
  - ➡ **BUT** other sites (e.g., type Ia supernovae, (Travaglio et al. 2014))
- solar and SiC X ***Y*(^{95}Mo)/*Y*(^{97}Mo) in neutron-rich winds**



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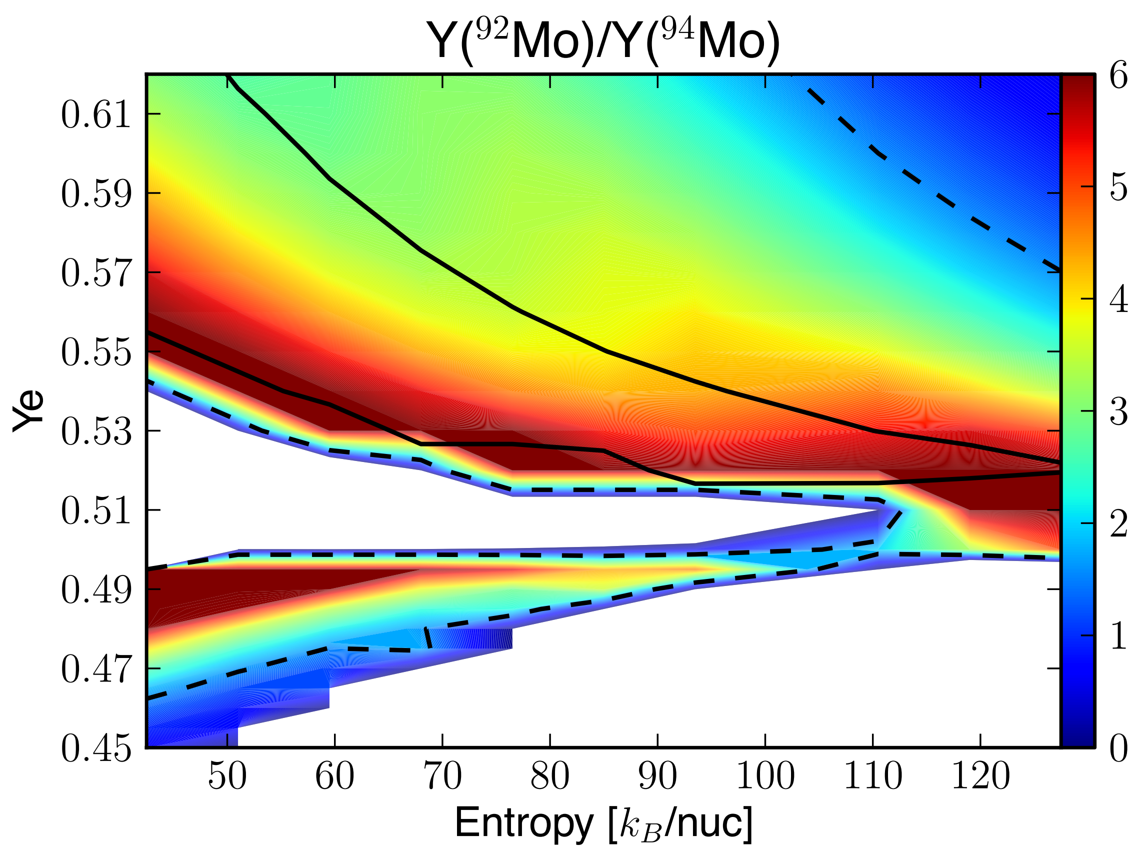

Thank you very much for your attention