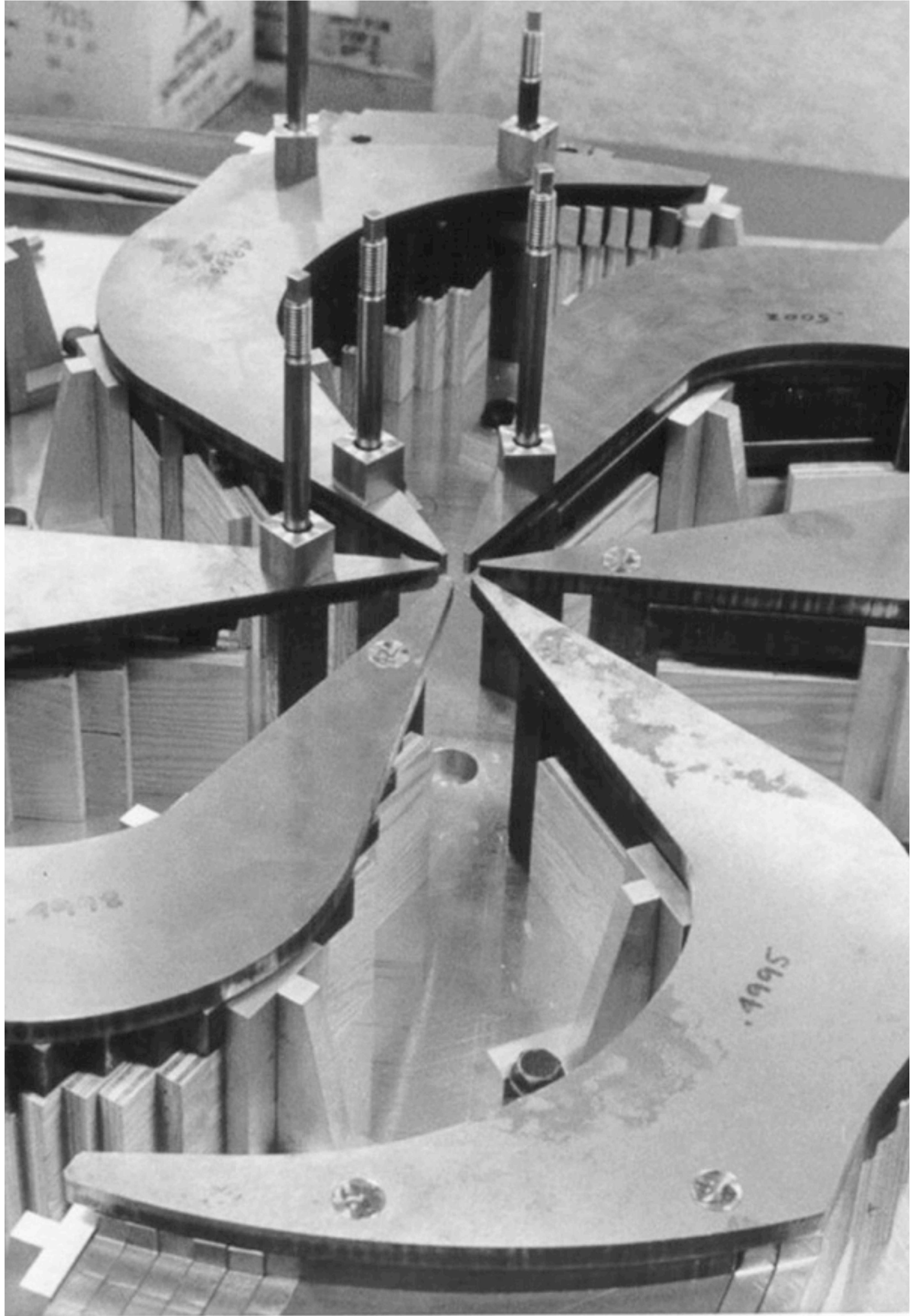
# Nucleosynthesis for the lightest and the heaviest elements

Tsung-Han Yeh (葉宗翰)
TRIUMF theory department

2026 CAP Congress
(DNP) T2-6 Nuclear Theory

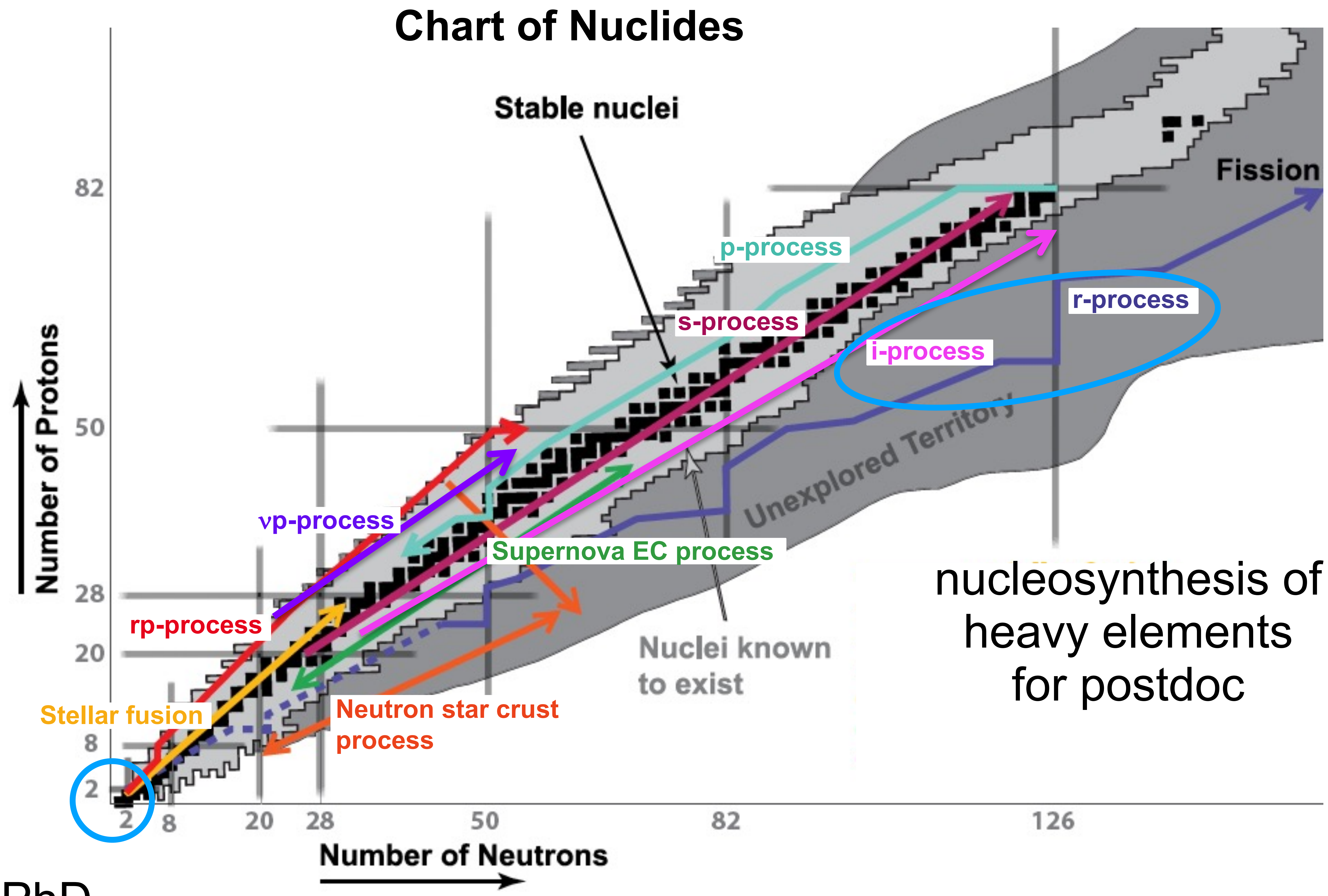
June 23, 2026



Discovery, accelerated

# About my research interests

Prof. Brian Fields
at UIUC



BBN for PhD

nucleosynthesis of
heavy elements
for postdoc

Fig 2 of arXiv: 2205.07996

Dr. Nicole Vassh
at TRIUMF

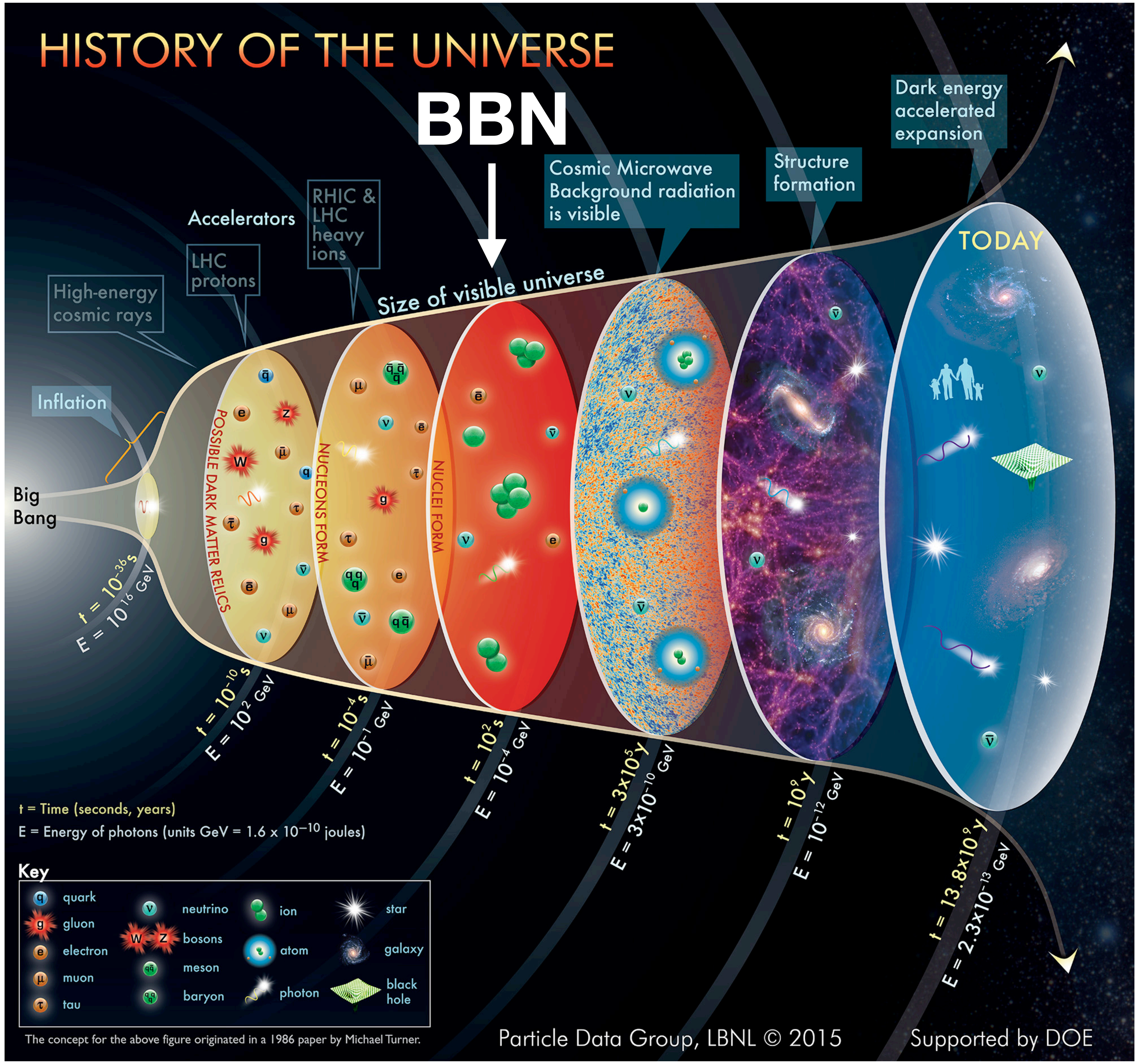
# Outline

1. brief BBN introduction & new BBN constraint on effective cosmic neutrinos

2. brief introduction of neutron capture processes
    - motivation of our work & some interesting findings

# Big Bang Nucleosynthesis

- the very first nucleosynthesis
  - lasting from ~1 sec to ~10 mins after the big bang
- the cosmic origin of light elements
  - almost all neutrons → $^4$He
  - trace amounts of d, $^3$He, and $^7$Li
- BBN predictions v.s. astro observations
  - probing the early universe physics

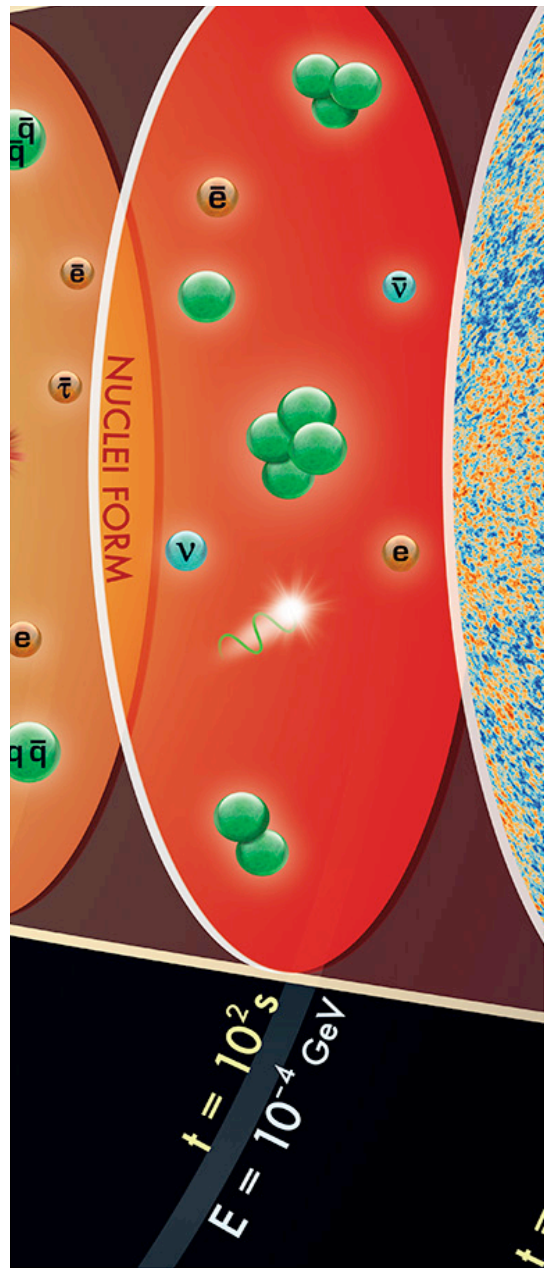


The concept for the above figure originated in a 1986 paper by Michael Turner.

Particle Data Group, LBNL © 2015

Supported by DOE

# Standard BBN (SBBN)



PDG, LBNL @ 2015

ΛCDM cosmology + Standard Model of particle/nuclear physics

- radiation-dominated universe by $\gamma,\ e^{\pm},\ \nu_i$ and $\bar{\nu}_i$ , where $i = e,\ \mu,\ \tau$
- homogeneous and isotropic universe within the context of general relativity

⇒ cosmic expansion rate (Hubble parameter) by Friedmann equation:

$$H^2 = \frac{8\pi G_N}{3}\rho_{\rm rad}$$

SBBN + precise nuclear inputs measured from experiments

*e.g.*,* neutron mean lifetime, recent updates for $d(p,\gamma)^3\mathrm{He}$, $d(d,n)^3\mathrm{He}$ & $d(d,p)^3\mathrm{t}$

***Yeh+** (2021,2022,2023)

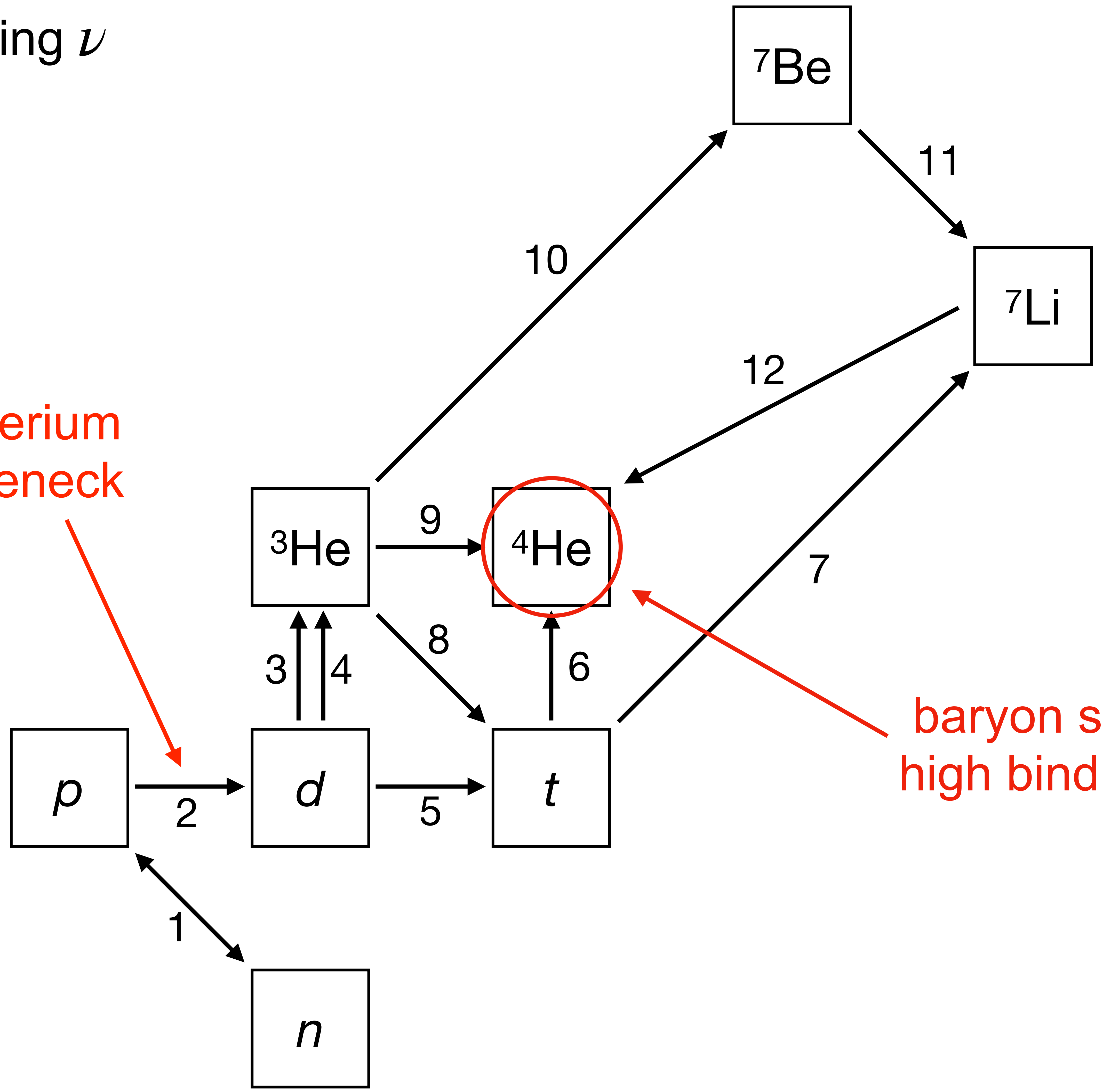
⇒ single parameter: baryon-to-photon ratio $\eta = \dfrac{n_b}{n_\gamma}$ . (or $\eta_{10} = \eta \times 10^{10}$ for convenience)

$\eta$ can be constrained via convolving SBBN theory likelihood functions with abundance observations

# SBBN Core Network of 12 Dominant reactions

**1.** $n \leftrightarrow p$ Weak reactions involving $\nu$

| | Q (MeV) |
|---|---|
| **2.** $p(n,\gamma)d$ | 2.225 |
| **3.** $d(p,\gamma)^3\mathrm{He}$ | 5.493 |
| **4.** $d(d,n)^3\mathrm{He}$ | 3.269 |
| **5.** $d(d,p)t$ | 4.033 |
| **6.** $t(d,n)^4\mathrm{He}$ | 17.589 |
| **7.** $t(\alpha,\gamma)^7\mathrm{Li}$ | 2.467 |
| **8.** $^3\mathrm{He}(n,p)t$ | 0.764 |
| **9.** $^3\mathrm{He}(d,p)^4\mathrm{He}$ | 18.353 |
| **10.** $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ | 1.586 |
| **11.** $^7\mathrm{Be}(n,p)^7\mathrm{Li}$ | 1.644 |
| **12.** $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$ | 17.347 |

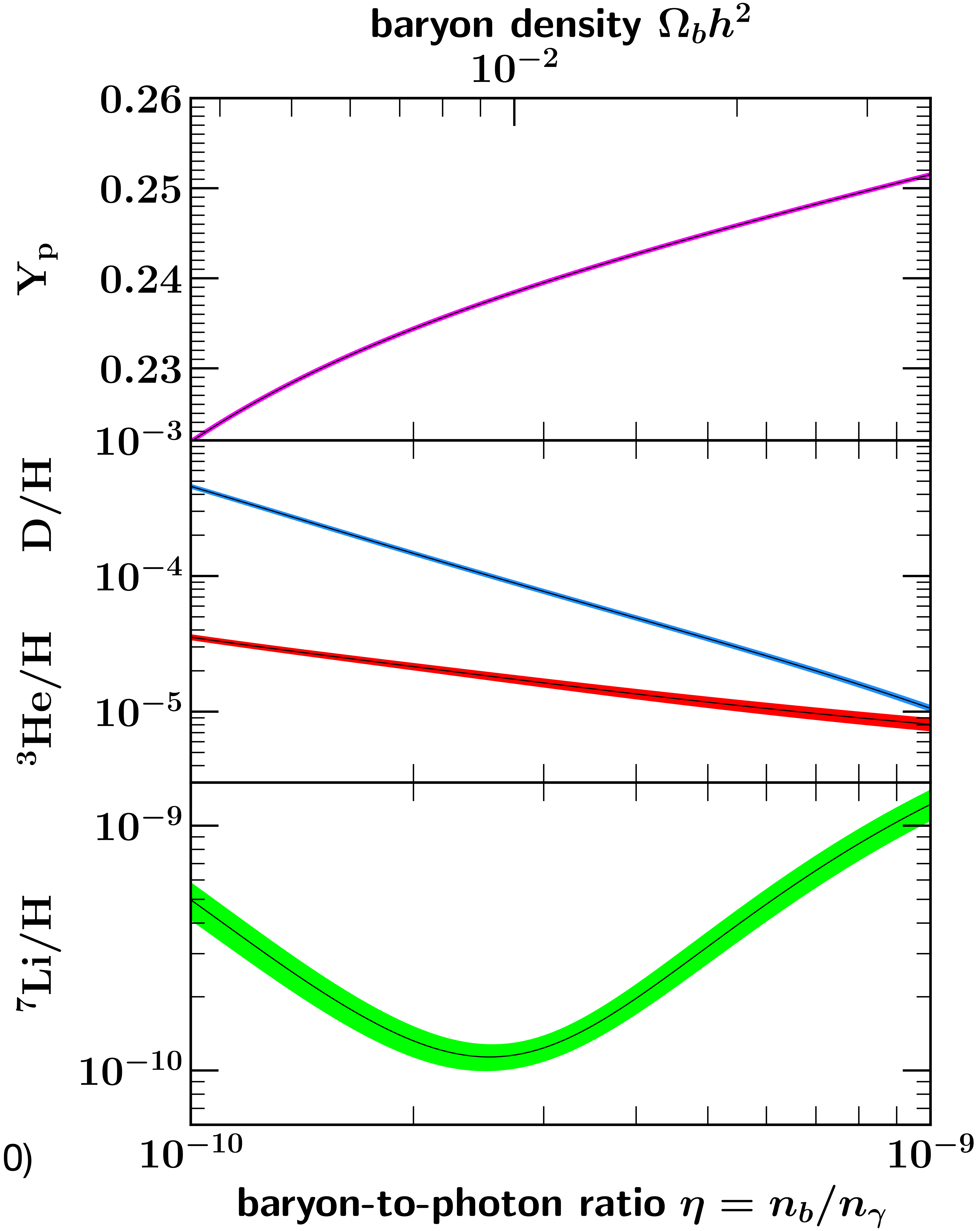


deuterium bottleneck

baryon sink due to high binding energy

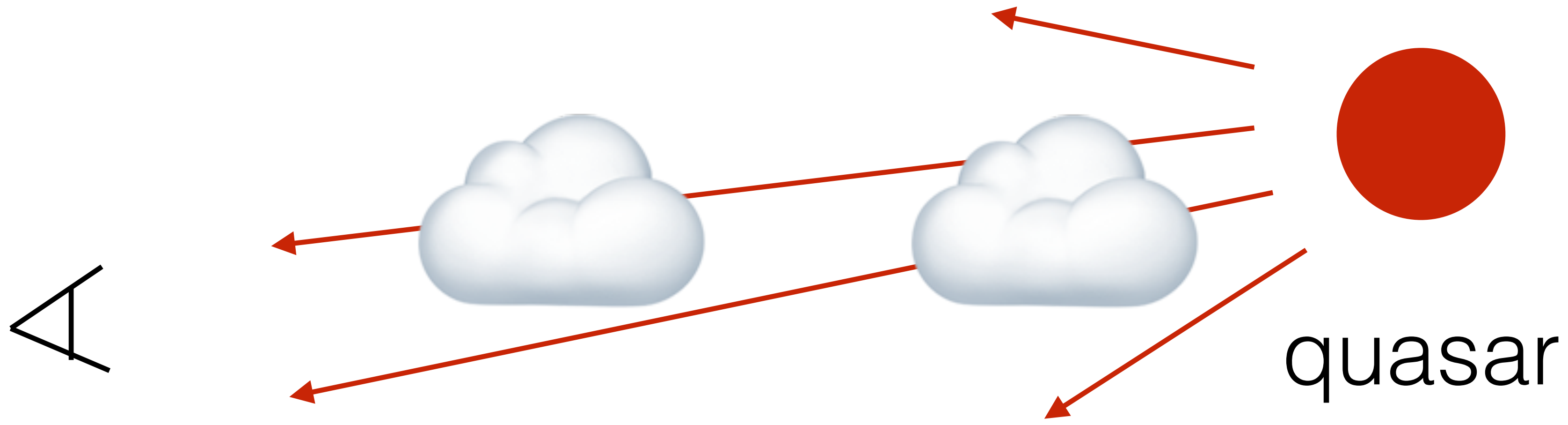
# Schramm Plot

- classic tool to show abundances as functions of baryon-to-photon ratio $\eta$
- mass fraction $Y_p$ for $^4\mathrm{He}$; abundance ratio to H for other elements
- widths determined from Monte Carlo runs on nuclear rates



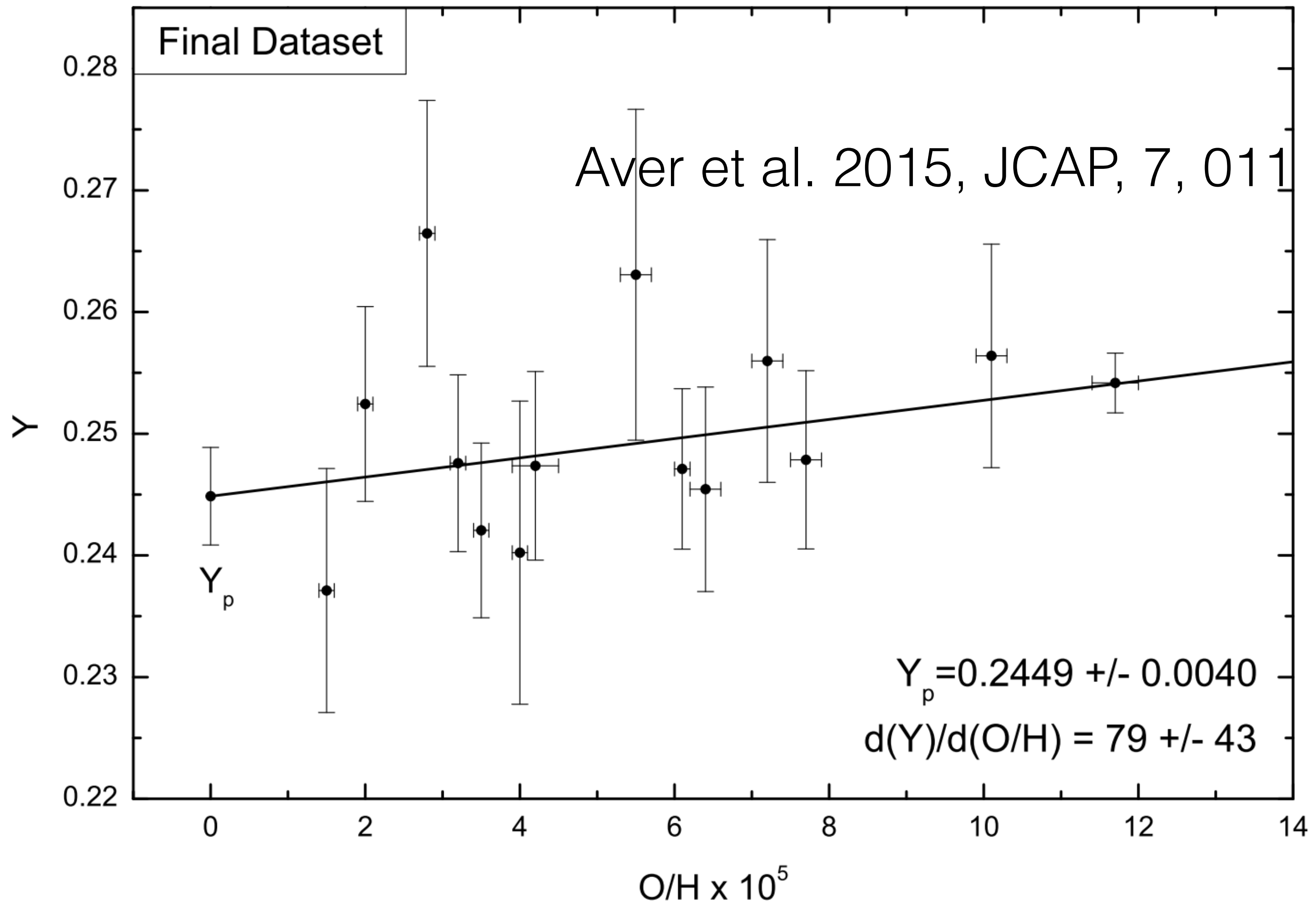
Fields, Olive, **Yeh**, & Young (2020)

# Astronomical Systems for Light Element Observations

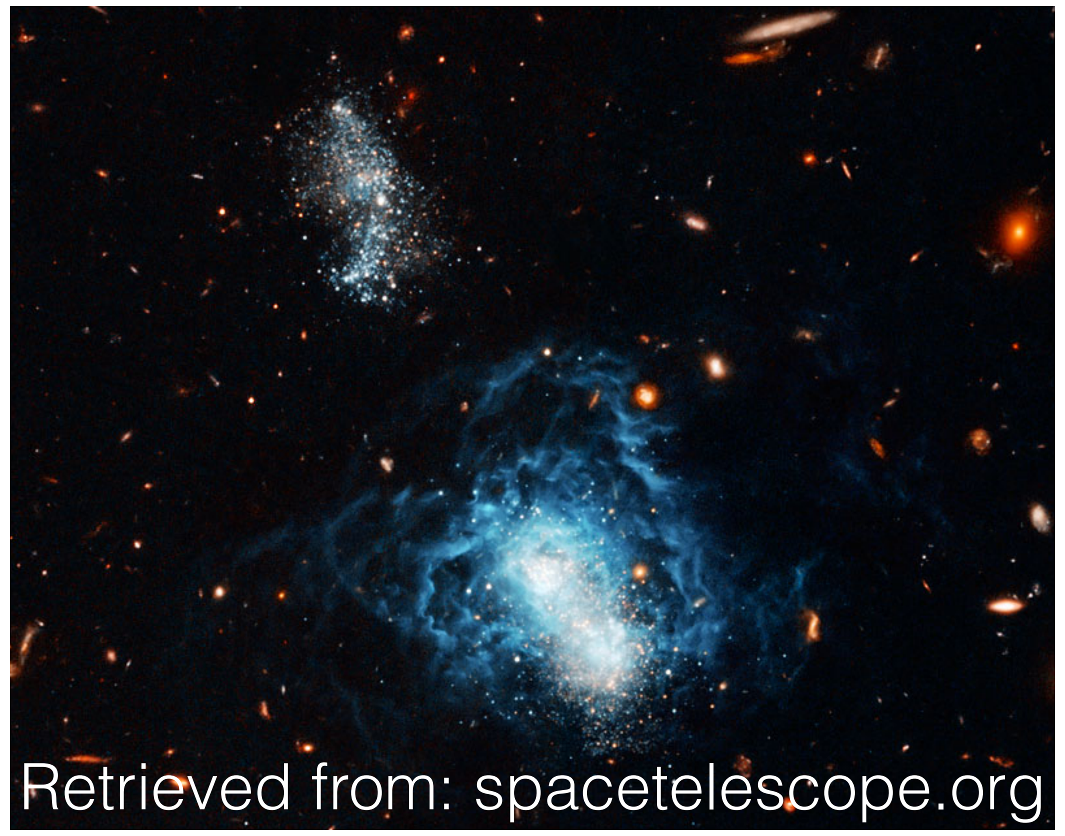


D: quasar absorption systems at high redshift (distant, old)

$Y_p$: helium emission lines in extragalactic H II regions
and determined by regression to zero metallicity

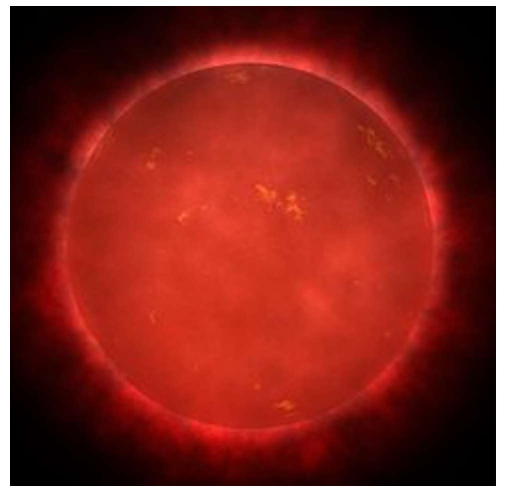


Aver et al. 2015, JCAP, 7, 011



Retrieved from: spacetelescope.org

$^7$Li: absorption lines from metal-poor halo stars in our Galaxy



$^3$He: controversial, only galactic observations at high metallicity (polluted)

# Schramm Plot + Observations

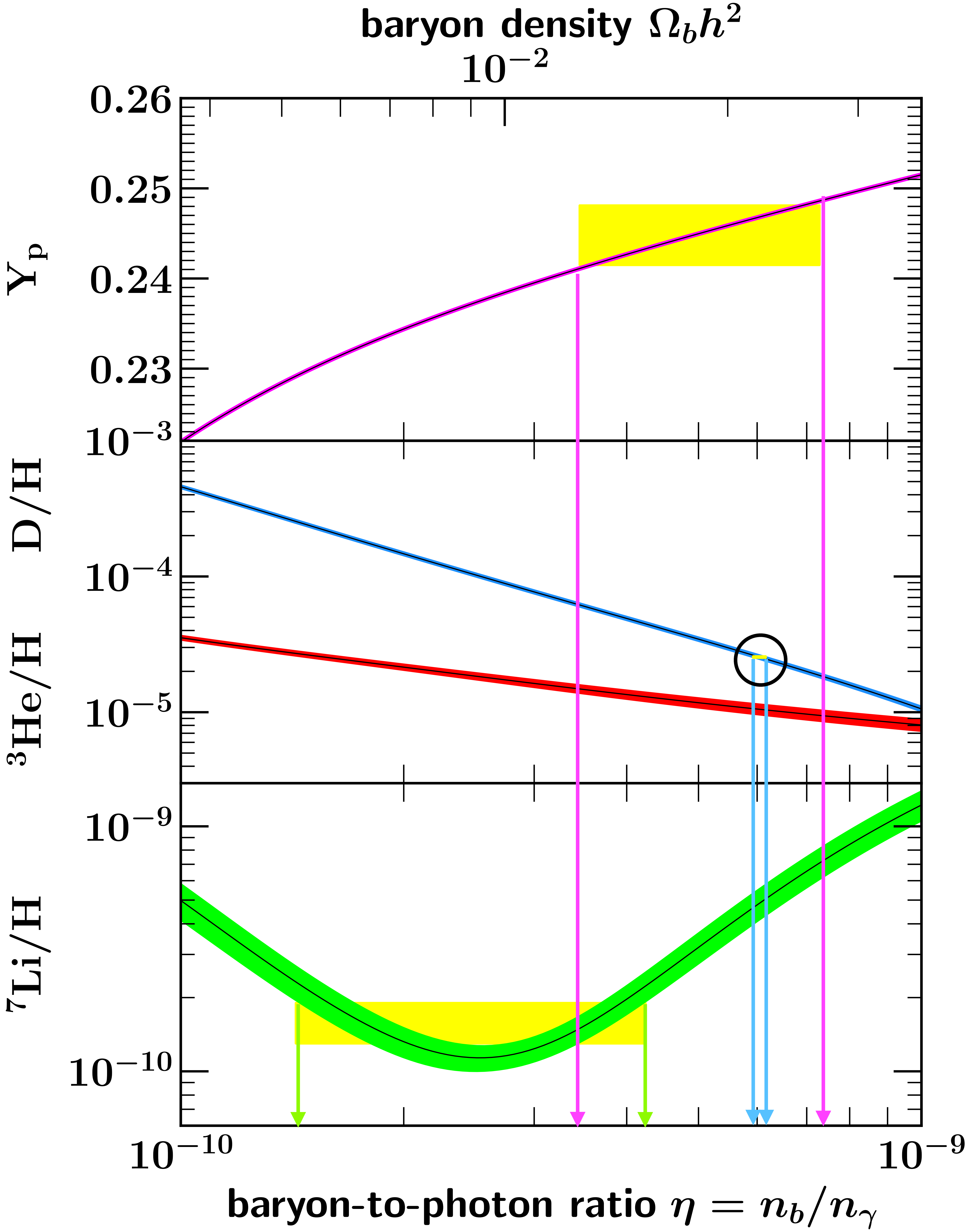
- $^4$He, D, $^7$Li observations for primordial values

|  | mean | σ | source |
|---|---|---|---|
| $Y_p$ ($^4$He) | 0.2448 | 0.0033 | Aver+ (2022) |
| D/H x $10^5$ | 2.527 | 0.030 | Cooke+ (2018) |
| $^7$Li/H x $10^{10}$ | 1.6 | 0.3 | Sbordone+ (2010) |

- each one selects a range of $\eta$:
  Over-constrained! — nontrivial test!

- SBBN+D is an excellent baryometer!

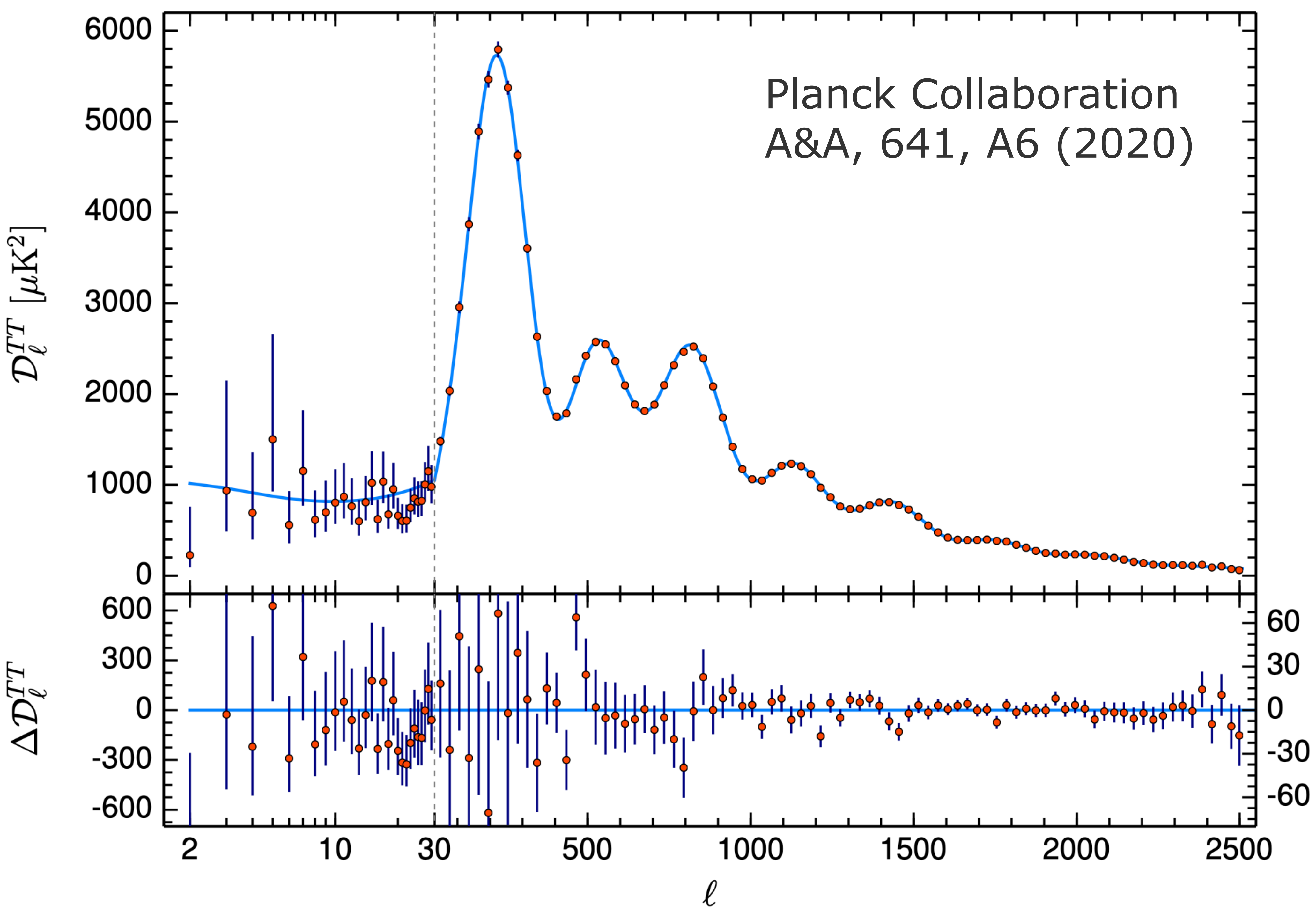
- D and $^7$Li disagree?!



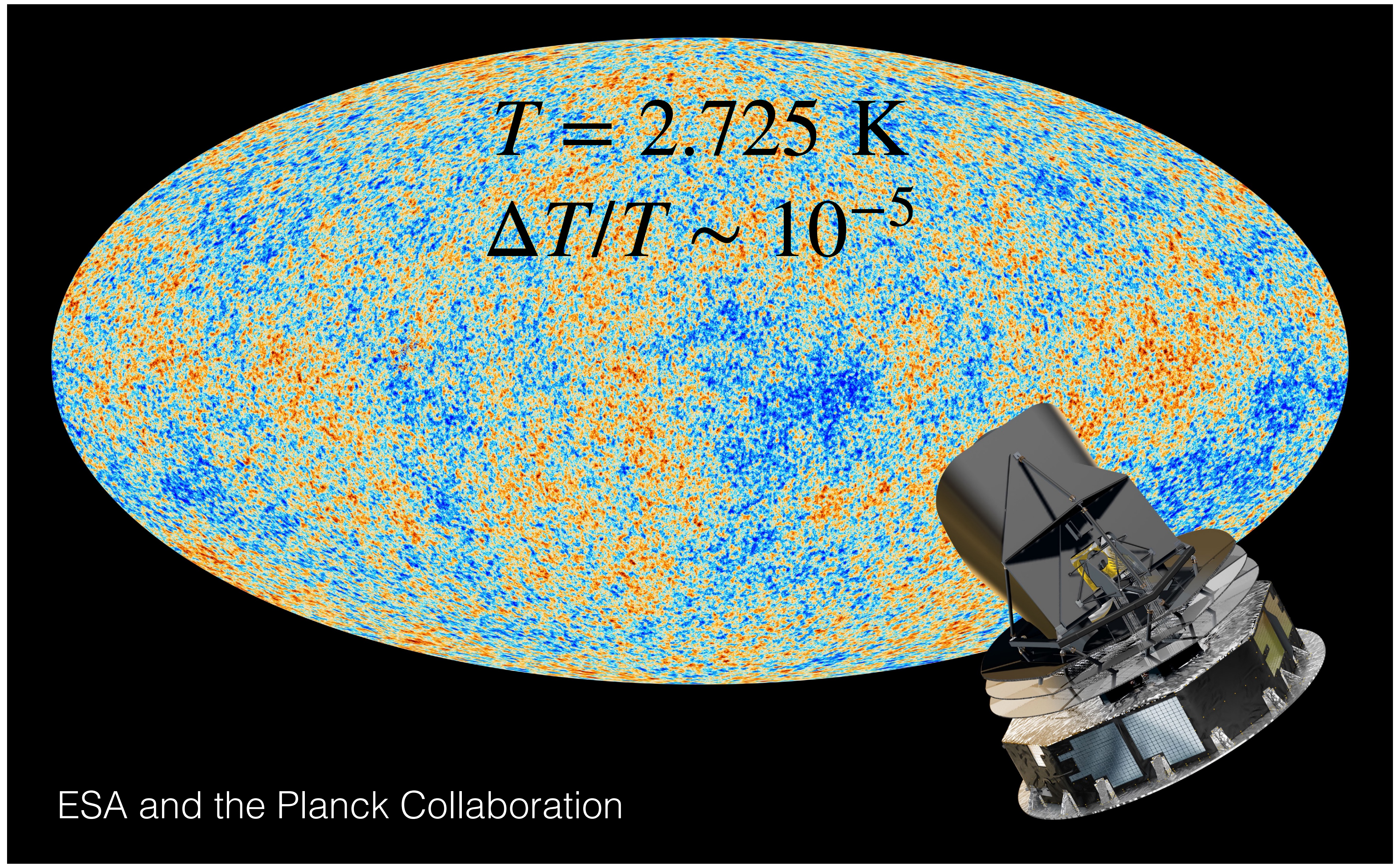
# $\eta$ from the Cosmic Microwave Background

- CMB: a snapshot of the baby Universe
- $\eta$ parametrizes CMB anisotropy power spectra

*Planck* 2018 temperature power spectrum


Planck Collaboration A&A, 641, A6 (2020)

All-Sky CMB Map from the *Planck* mission


$T = 2.725$ K

$\Delta T/T \sim 10^{-5}$

ESA and the Planck Collaboration

- precise cosmic baryometer

$$\eta_{CMB} = (6.104 \pm \underline{0.055}) \times 10^{-10}$$

*i.e.* $\Omega_b h^2 = 0.02230 \pm \underline{0.0002}$

< 1%

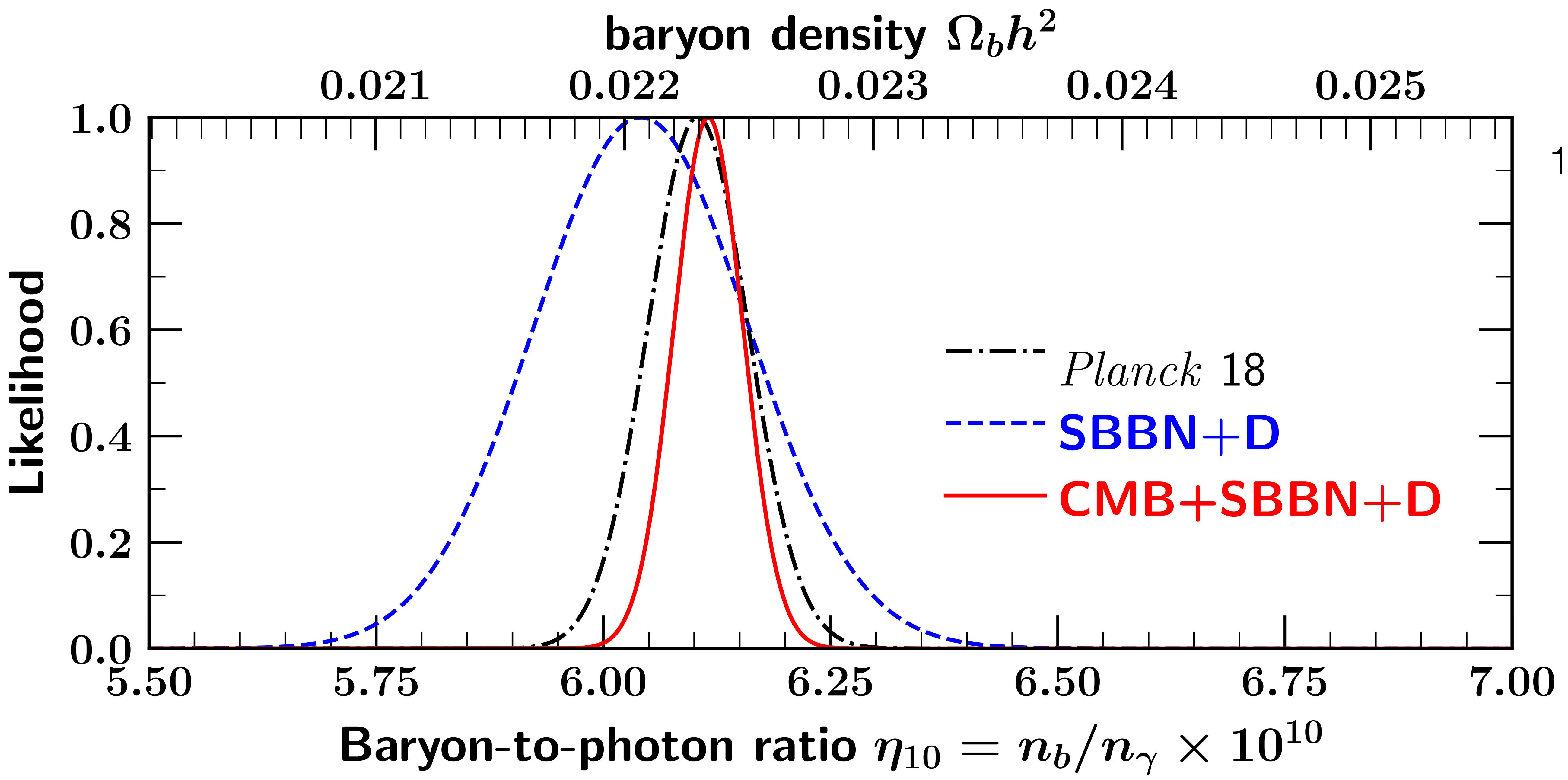
# CMB v.s. SBBN Baryometers

summary statistics in $\eta_{10} = \eta \times 10^{10}$

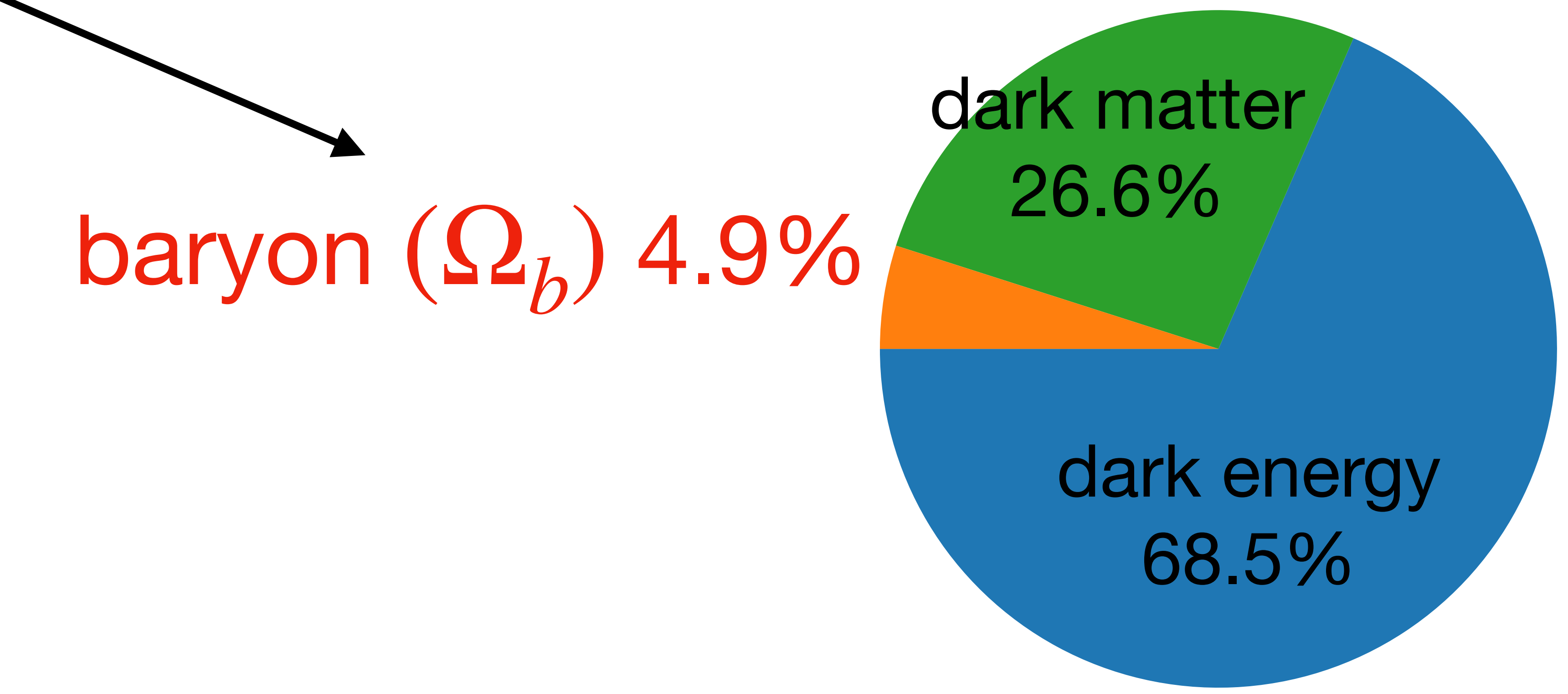
| | mean | σ |
|---|---|---|
| Planck 18 | 6.104 | 0.055 |
| BBN+D<sub>obs</sub> | 6.042 | 0.118 |
| combined | 6.115 | 0.038 |

in $\Omega_b h^2$

| | mean | σ |
|---|---|---|
| Planck 18 | 0.02230 | 0.00020 |
| BBN+D<sub>obs</sub> | 0.02207 | 0.00043 |
| combined | 0.02233 | 0.00014 |



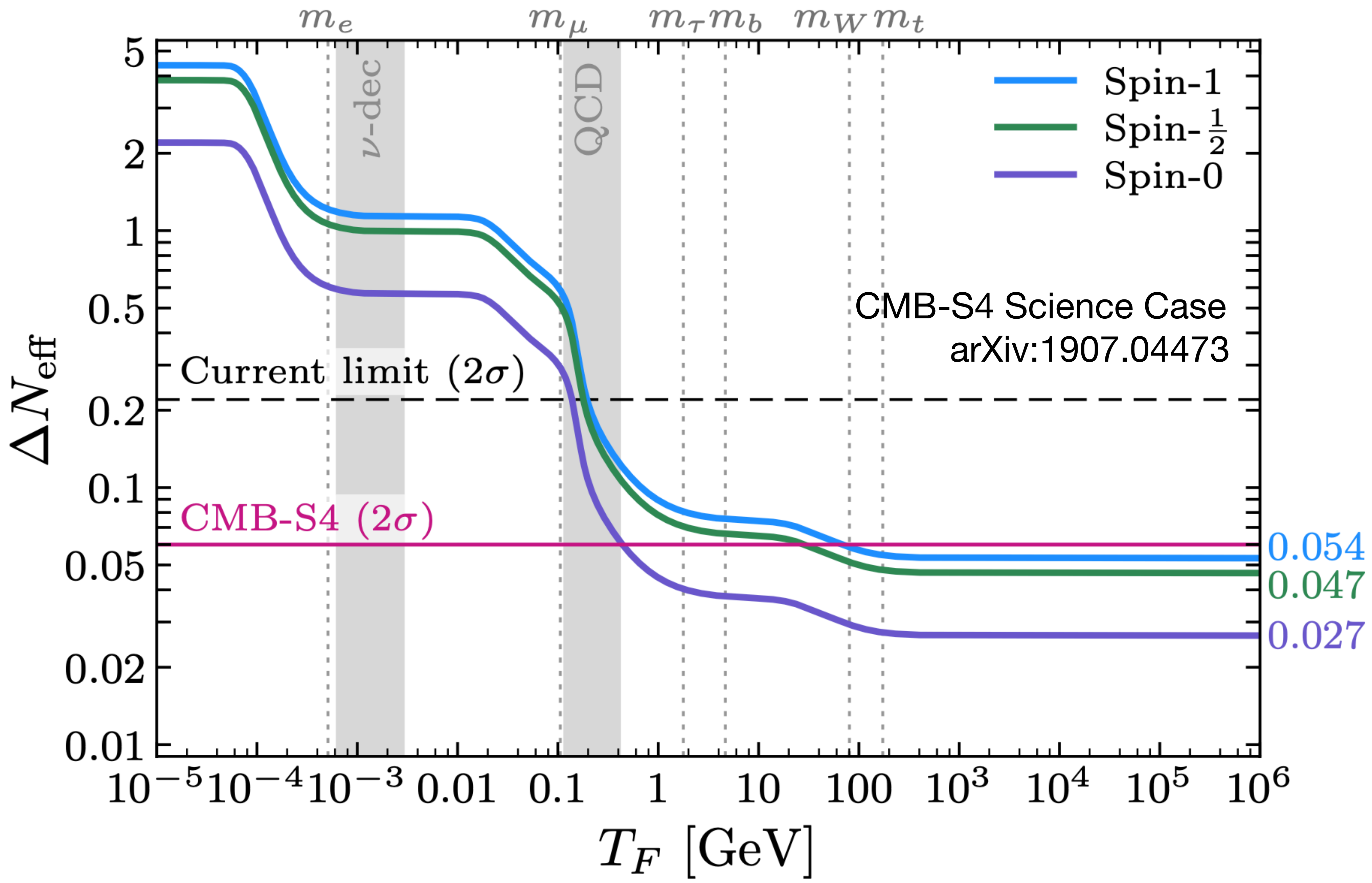
**Yeh+** (2022)



- SBBN agrees the baryon measurement from the CMB within percent-level uncertainties!

  - nontrivial success of the hot big bang model

# Probing Big Bang Light Relics



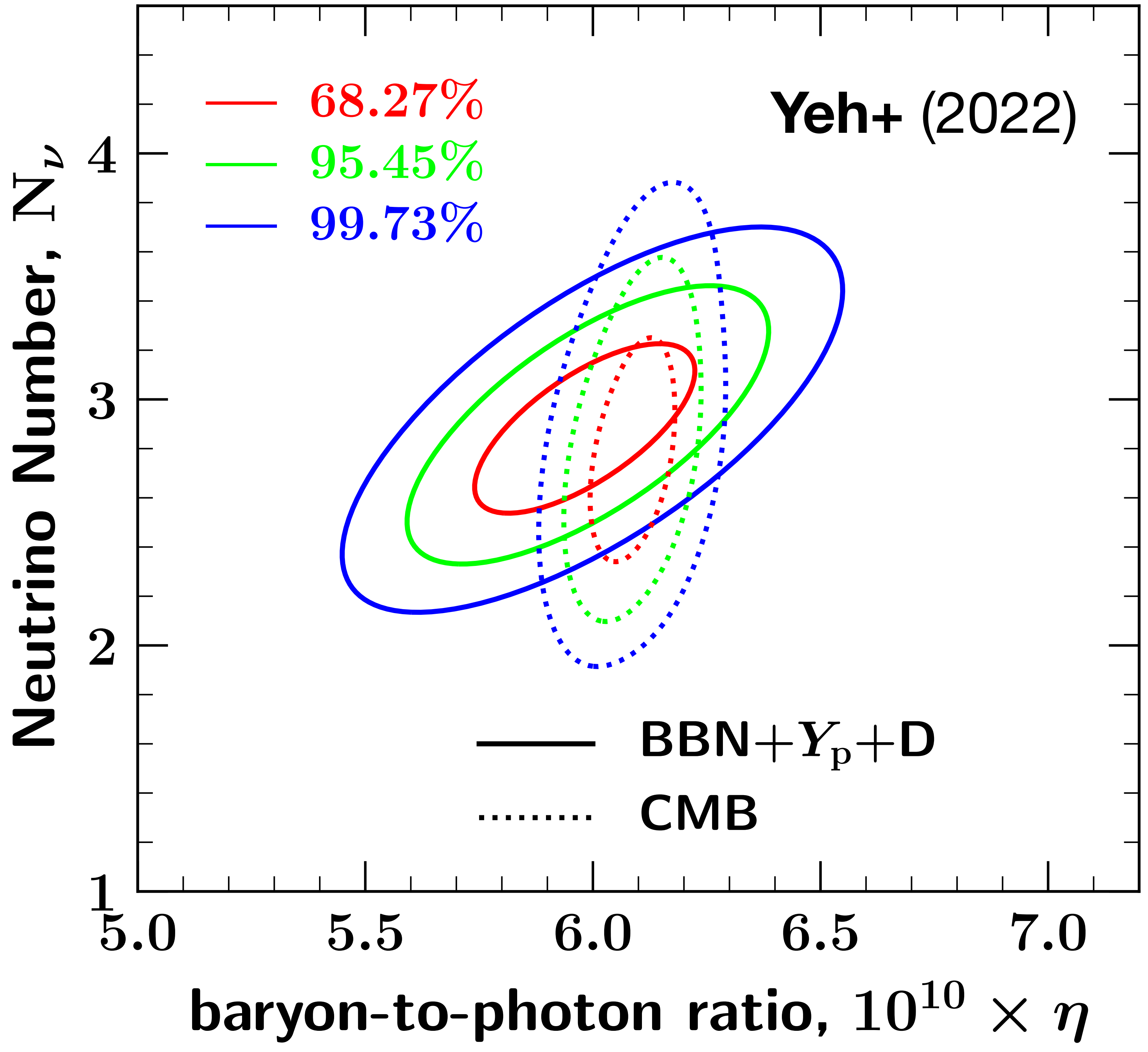
- many BSM models predict extra radiation:

$$H^2 = \frac{8\pi G}{3}(\rho_{\rm rad}^{\rm SM} + \rho_{\rm rad}^{\rm BSM})$$

- parameterize effects of light relics in terms of effective # of neutrinos $\Delta N_{\rm eff} = N_{\rm eff} - N_{\rm eff}^{\rm SM}$
( $N_\nu^{\rm SM} = 3 \leftrightarrow N_{\rm eff}^{\rm SM} = 3.044$ by heating effect from $e^\pm$ annihilation )

- Non-Standard BBN: allow neutrino flavor $N_\nu \neq 3$
  -> 2 parameters $(\eta, N_\nu)$ v.s. 2 observables $({}^4{\rm He}, {\rm D})$

- NBBN and CMB in good agreement



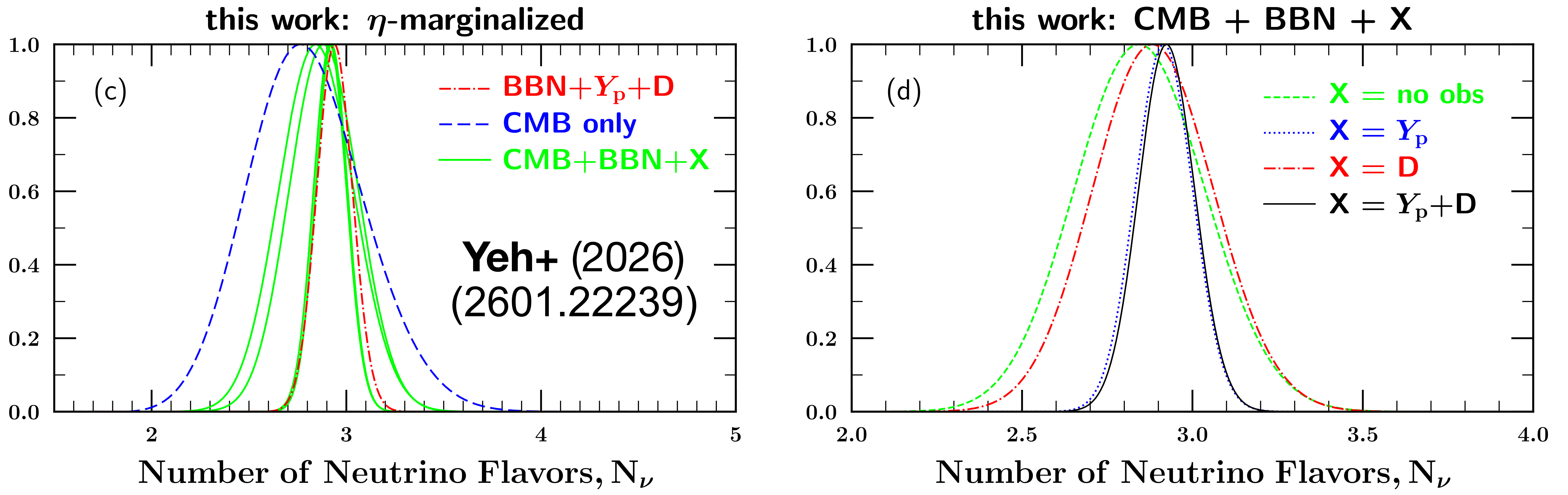
# New Limits on Neutrino Flavors $N_\nu$ using new $\mathrm{Y_p}$ measurement

summary statistics for $N_\nu$

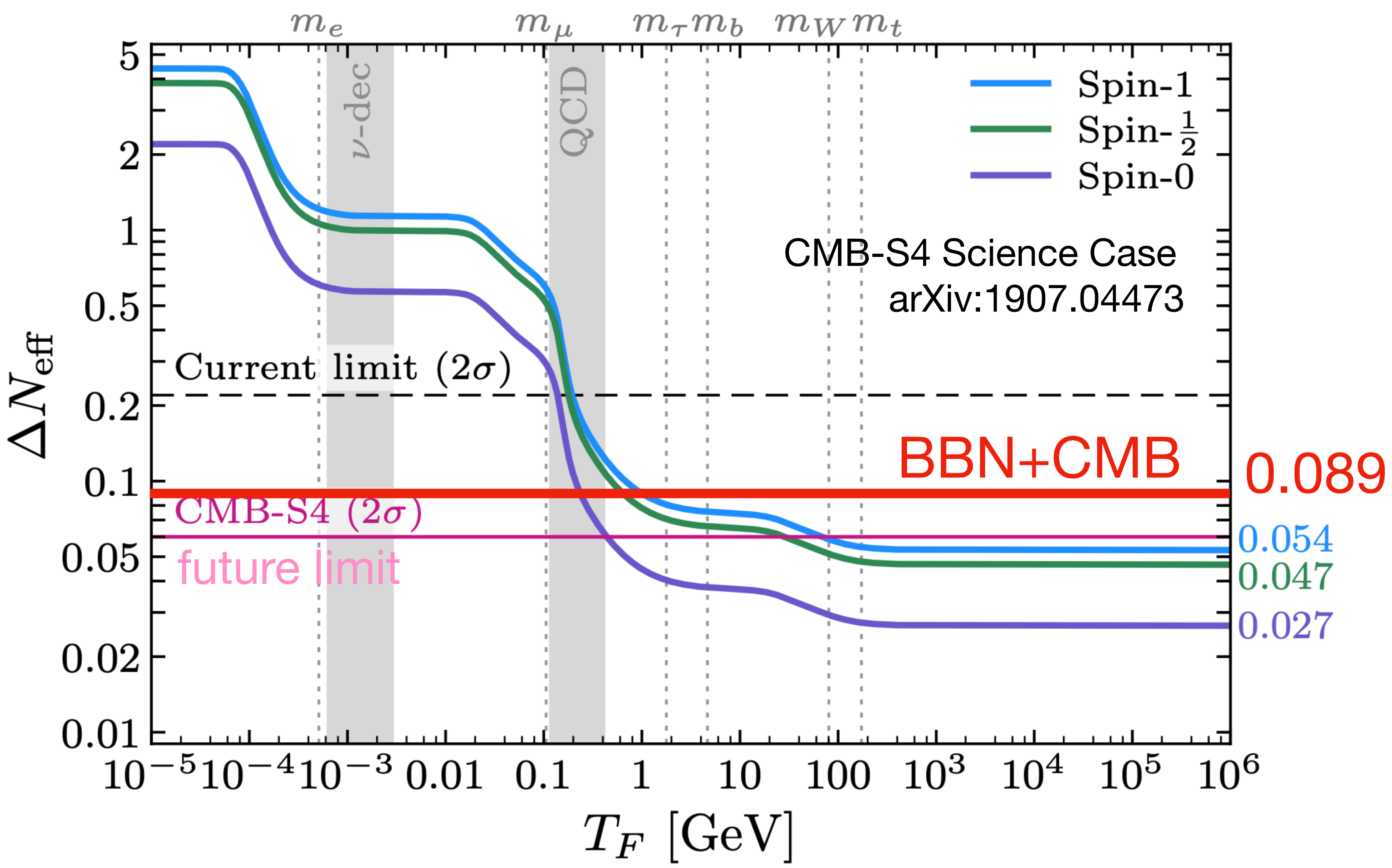
| | mean | $\sigma$ |
|---|---|---|
| CMB | 2.800 | 0.294 |
| BBN+Obs | 2.941 | 0.092 |
| combined | 2.925 | 0.082 |

=> 95% upper limit: $N_\nu < 3.089$

=> $\Delta N_{\mathrm{eff}} \simeq \Delta N_\nu = N_\nu - 3 < 0.089$



**Yeh+** (2026)
(2601.22239)



- new precise primordial helium $\mathrm{Y_p}$ was determined with observations from the Large Binocular Telescope: $Y_p = 0.2458 \pm 0.0013$ (2601.22238)
- Uncertainty significantly reduced from $Y_p = 0.2448 \pm 0.0033$ (Aver et al. 2021)

=> new species must be:

1. thermally decoupled before the end of QCD transition
2. produced with non-thermal distribution

# Outline

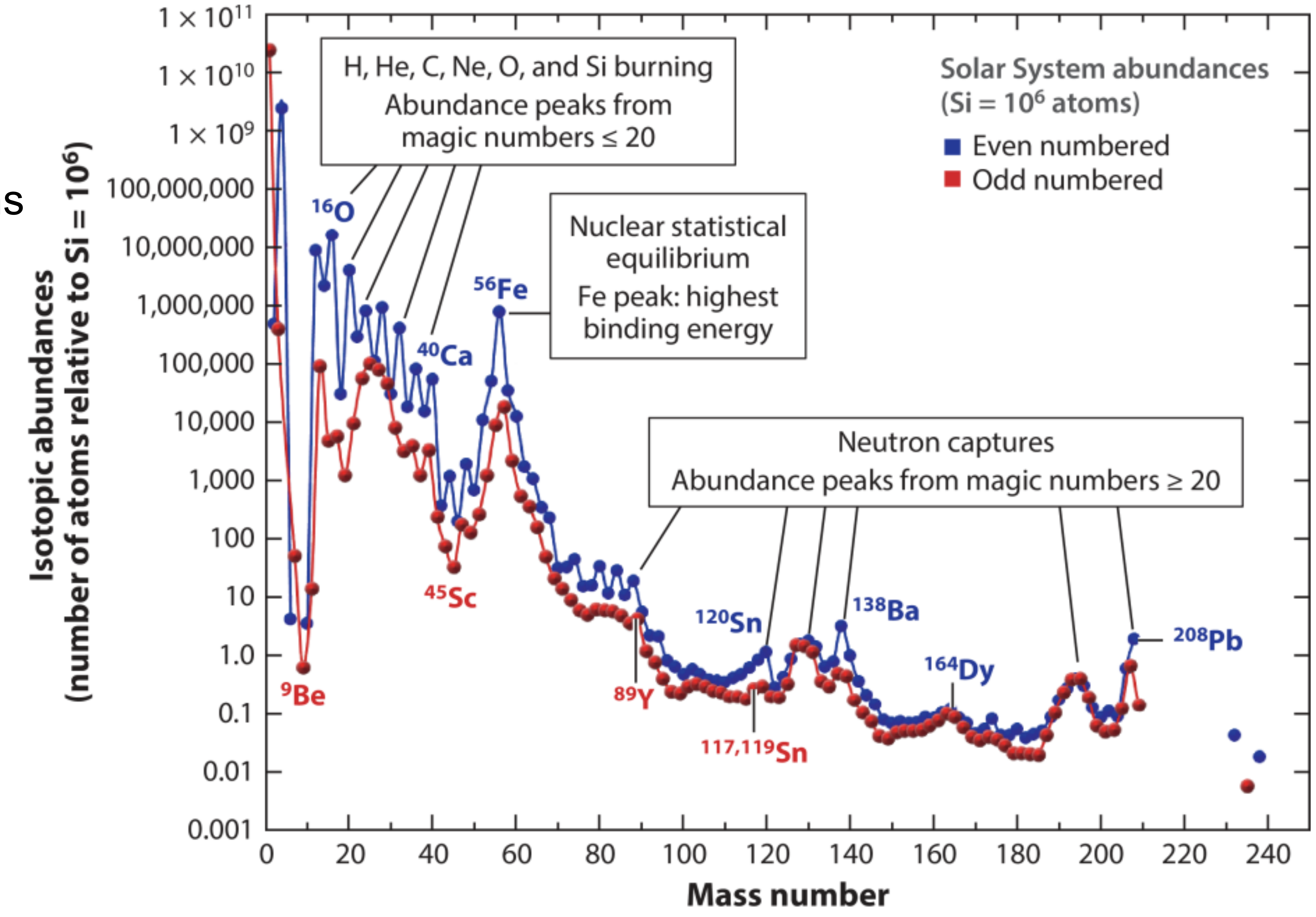
1. brief BBN introduction & new BBN constraint on effective cosmic neutrinos

2. brief introduction of neutron capture processes

    - motivation of our work & some interesting findings

# How the elements are made?

- H, most He, some Li from BBN
- stellar burning powered by fusion
  - Coulomb Barrier suppress charged-particle reactions
  - alpha elements (even-even nuclei) with relative higher abundances built by sequentially adding $^4$He
- iron peak from NSE conditions
  - elements around iron have the highest binding energy per nucleon
  - e.g. SNe Ia, explosive silicon burning
- trans-iron elements mainly synthesized via neutron captures (s-, i-, r-processes)
- p-process ($\gamma$-process), $\nu$p-process for neutron deficient isotopes



Lugaro M, et al. 2023
*Annu. Rev. Nucl. Part. Sci.* 73:315–40

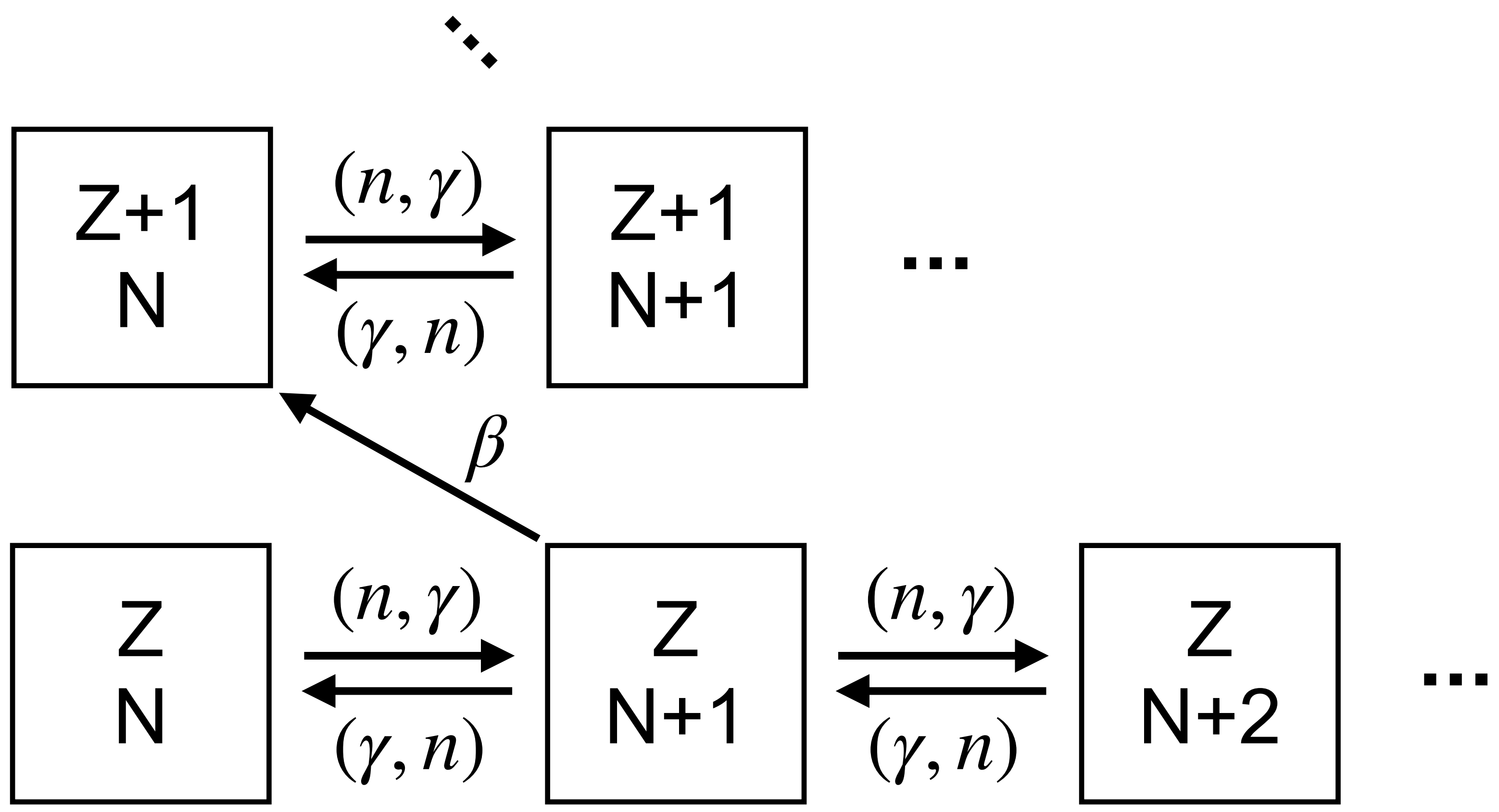
# neutron capture processes

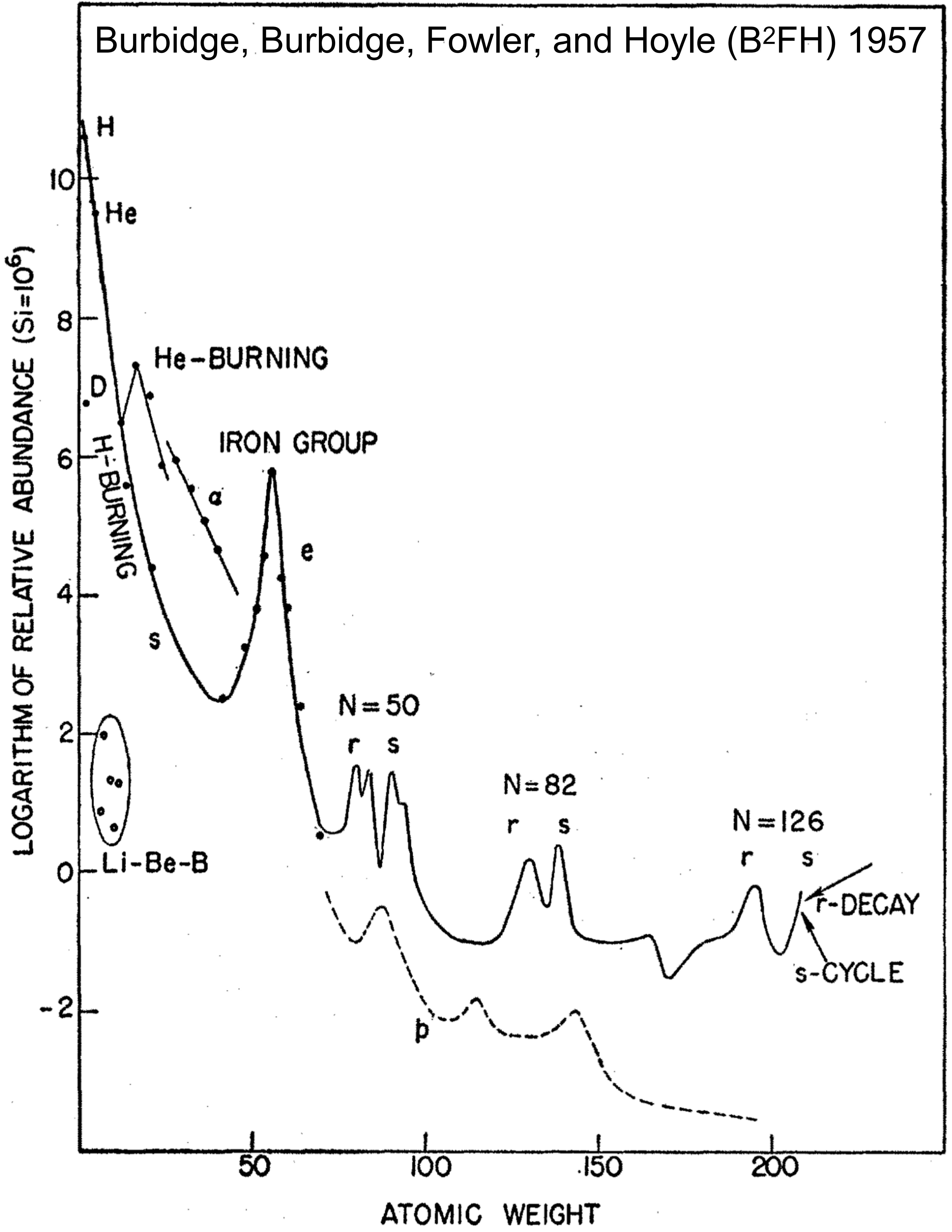
- Already in B²FH, s and r processes identified
- slow neutron capture process (s-process)

$$\tau_{ncap} >> \tau_\beta$$

- rapid neutron capture process (r-process)

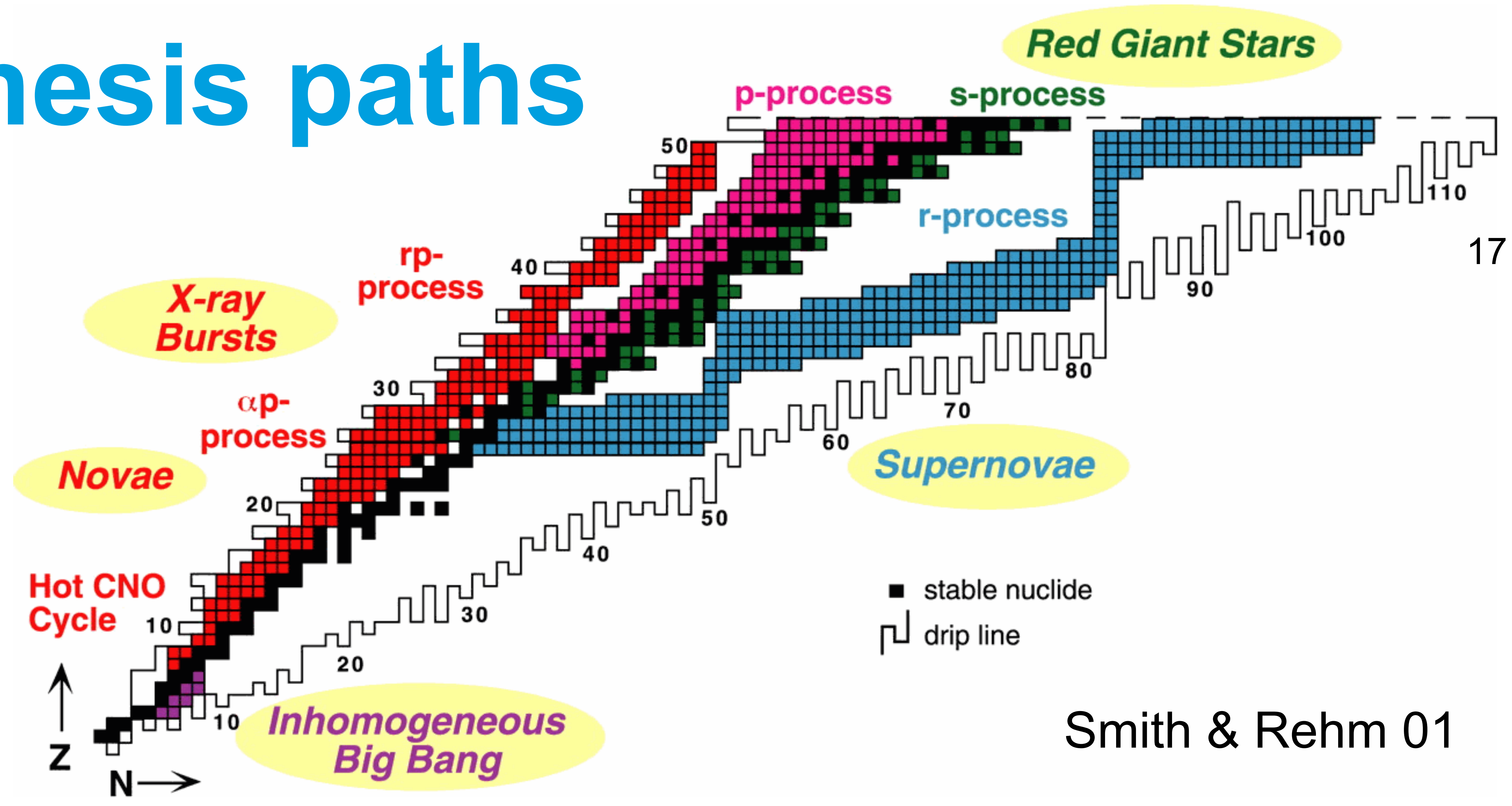
$$\tau_{ncap} << \tau_\beta$$



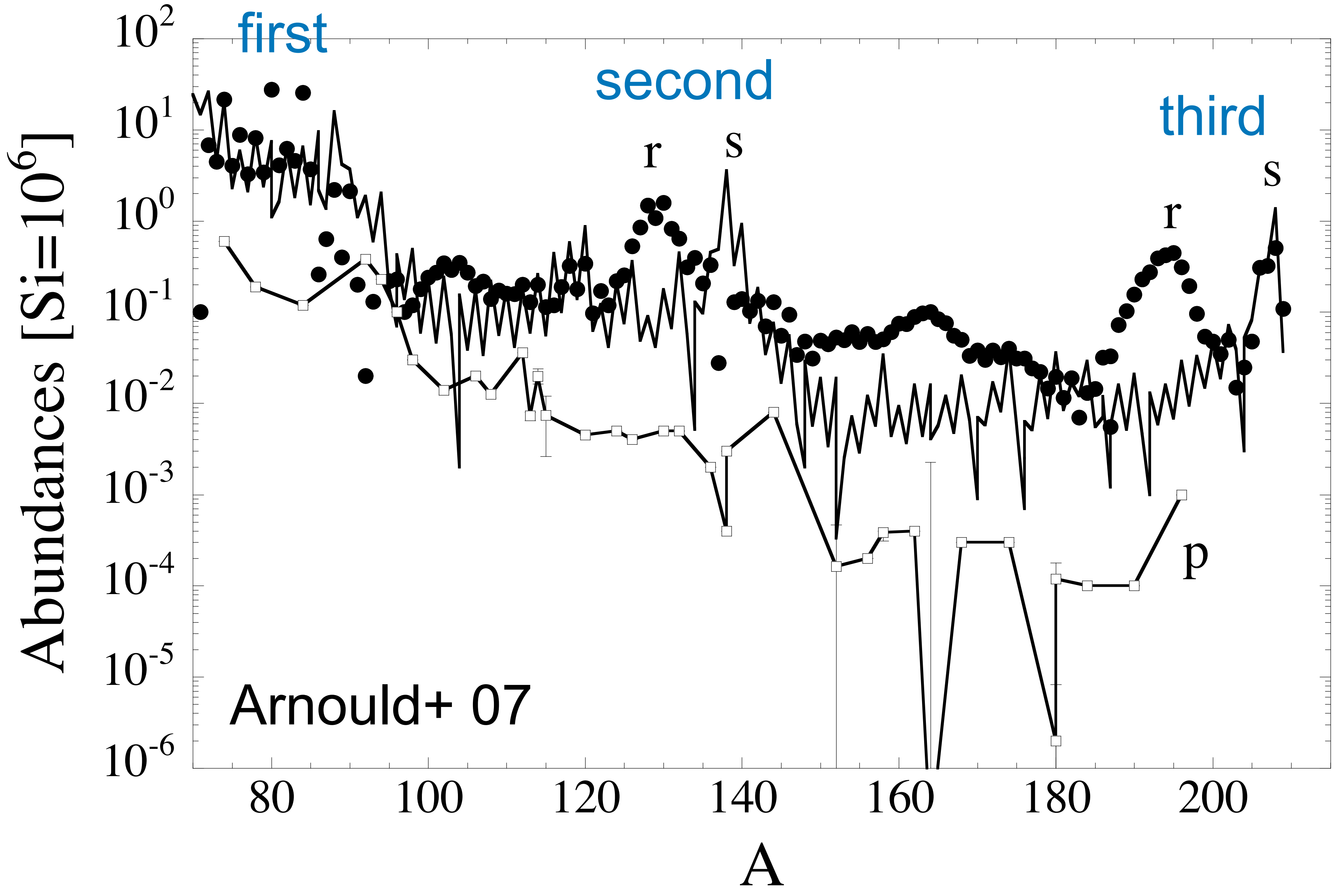

Burbidge, Burbidge, Fowler, and Hoyle (B²FH) 1957

# s- & r-process nucleosynthesis paths

- s-process $N_n \simeq 10^6 - 10^{11}\ \mathrm{cm}^{-3}$, $t_{\mathrm{scale}}$ ~ $10^4$ yrs (example site: AGB stars); path runs close to the valley of stability
- r-process $N_n > 10^{20}\ \mathrm{cm}^{-3}$, $t_{\mathrm{scale}}$ ~ 1s (example site: neutron star mergers); path roceeds into very neutron rich region
- shell closure at N = 50, 82,126 (magic #)
- ncap $\sigma$ much smaller -> bottlenecks -> abundance pile up
- three double-peaks seen in solar abundances



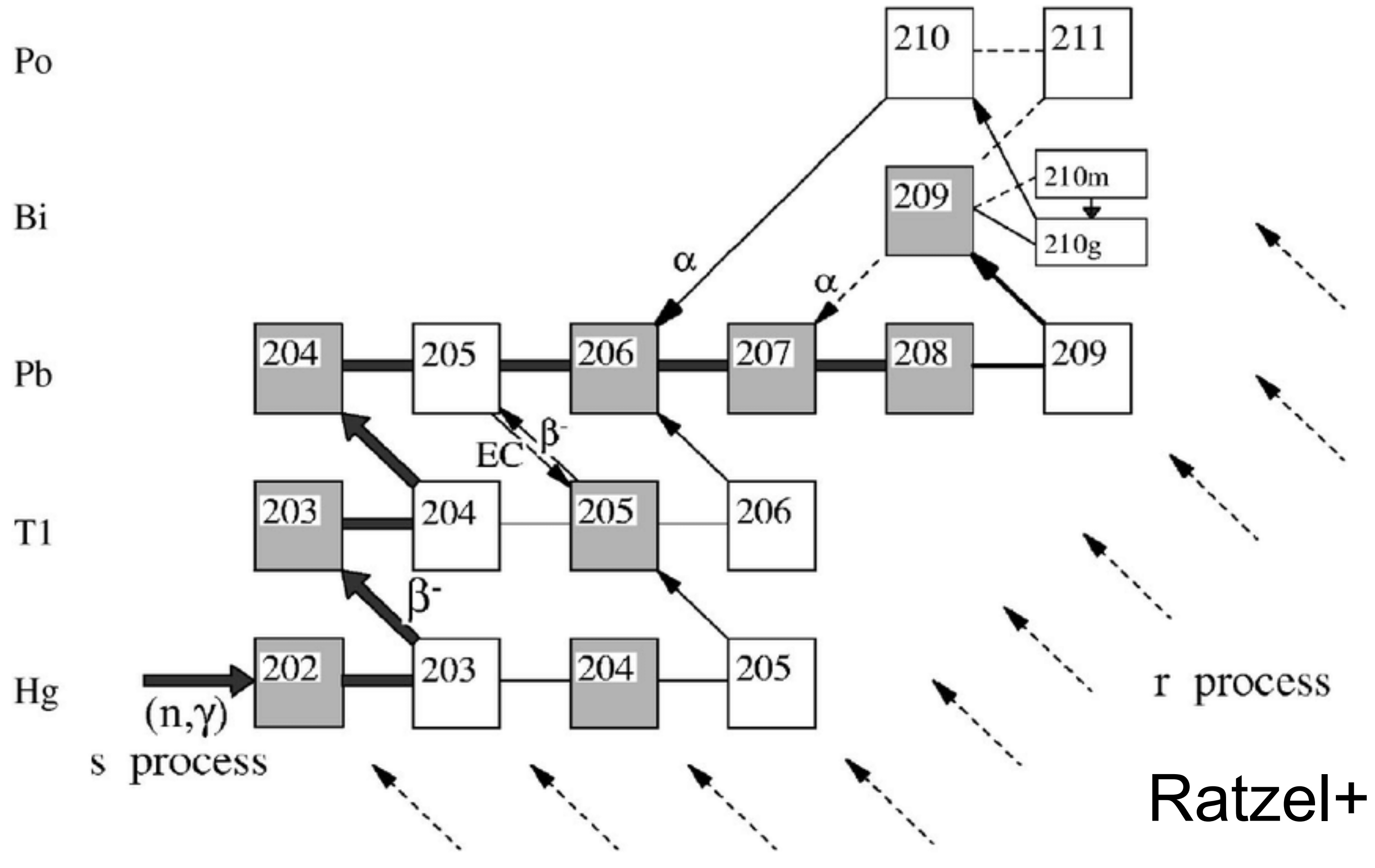
Smith & Rehm 01



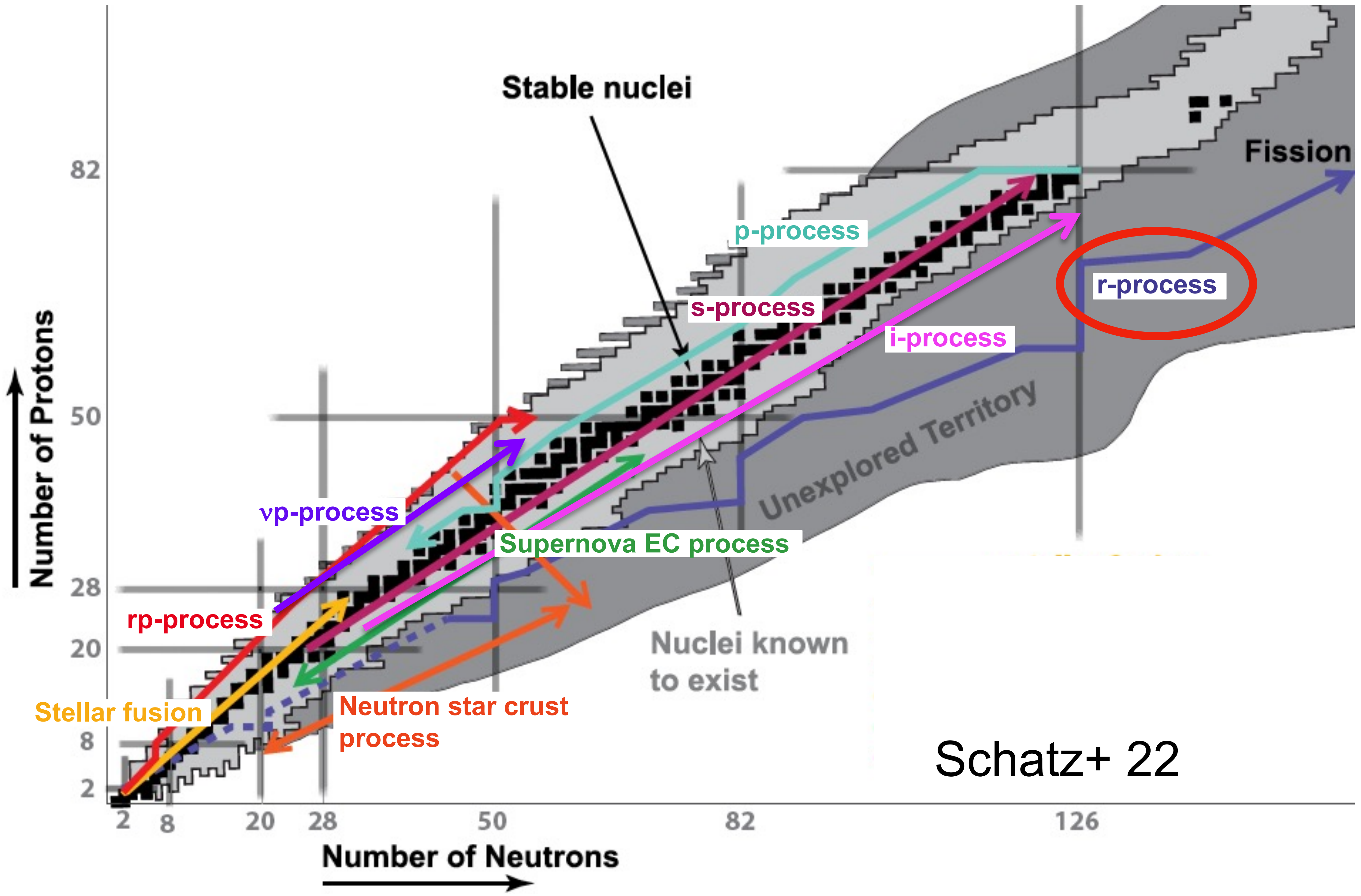
Arnould+ 07

# s-process termination

- reaction flow trapped at $^{208}$Pb and $^{209}$Bi due to low n cap cross-section at N = 126
- $\alpha$-decay terminate the production of heavier isotopes and cycling the flow to $^{206}$Pb, $^{207}$Pb
- s-process can't reach actinides, but actinide isotopes been found on Earth (such as Th and U ores, $^{244}$Pu in deep-sea sediments), observed in meteorites, in stars, etc.
- r-process can make heavy elements beyond Pb with extremely high neutron-rich conditions



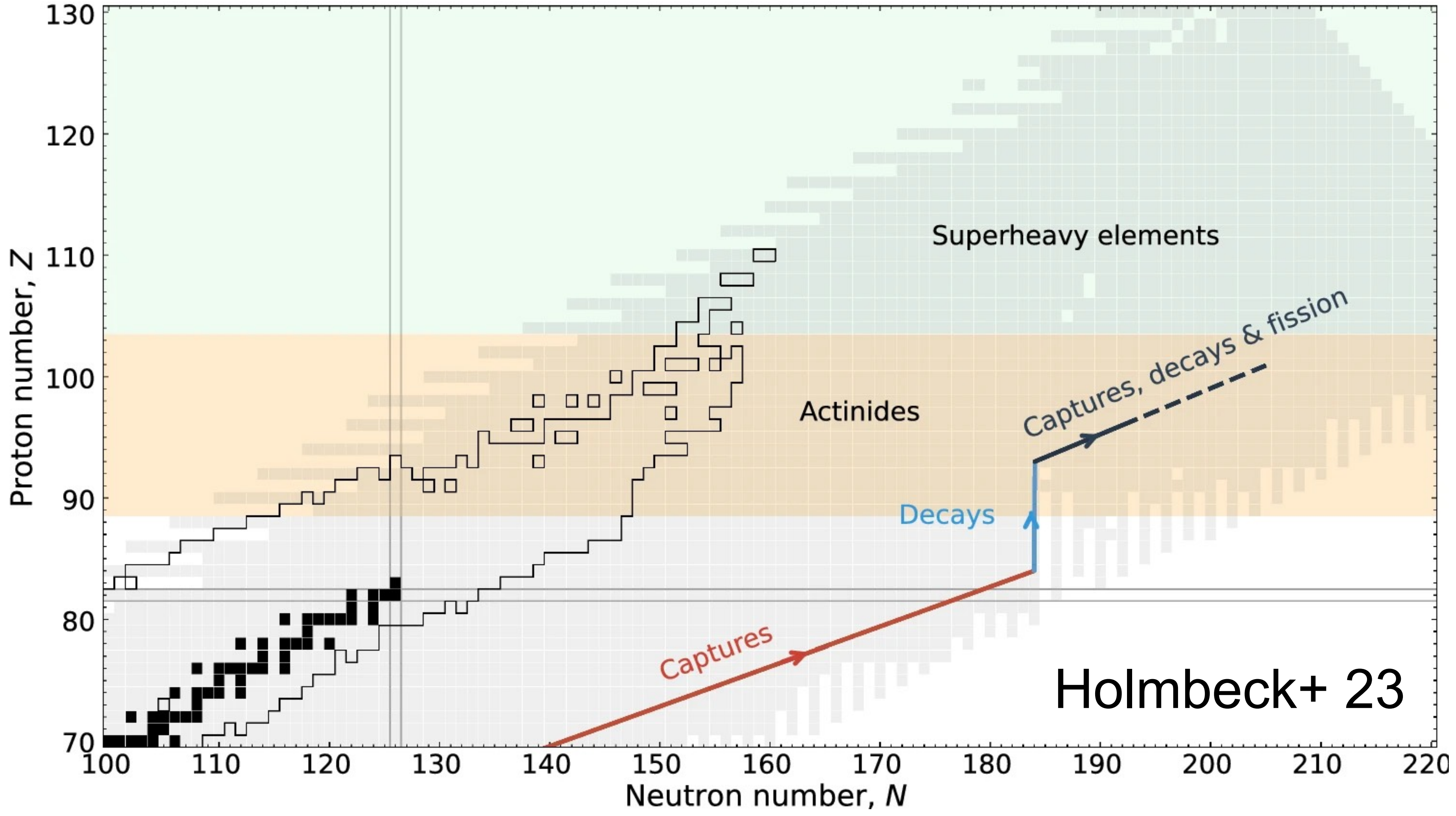
Ratzel+ 04



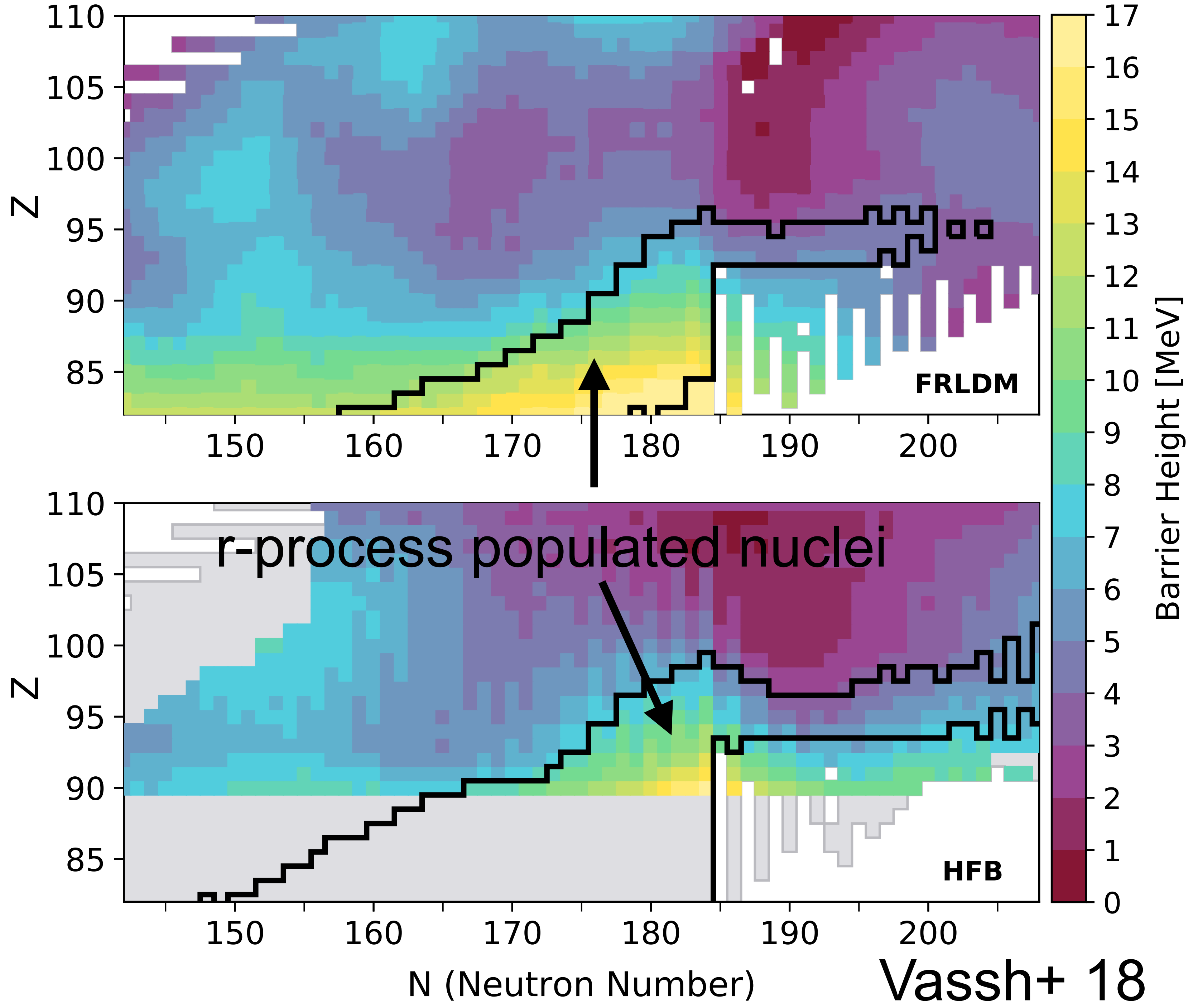
Schatz+ 22

# r-process termination

- can’t infinitely synthesize neutron-rich superheavy elements through r-process; terminated by fission between A ~ 270 to 300
- deep into regions having no exp data; rely on theory fission rates (model dependent)
- e.g. fission barrier heights vs. termination of r-path
- once Nn drops and ncap slows down, radioactive heavy isotopes undergo $\beta$-decay (to higher z), fissions (to lighter daughter nuclei)



Holmbeck+ 23



Vassh+ 18

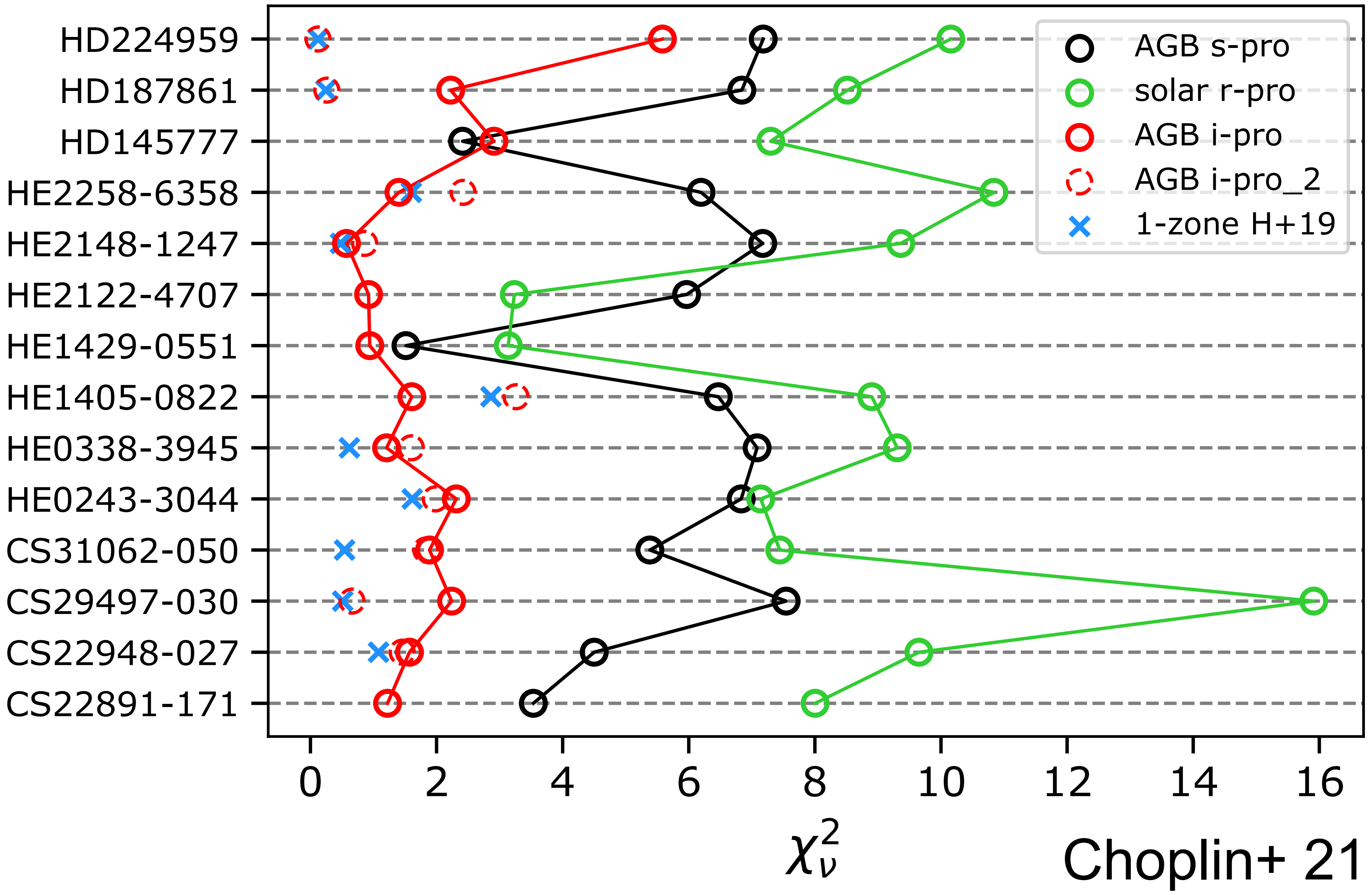
# intermediate neutron capture process

- i-process was first introduced by Cowan & Rose 1977 in theoretical red giant calculations: a neutron flux found many orders of magnitude above the flux required for s-process

- gained more attention with the observation of stellar abundances difficult to explain with s-process, r-process or their combination: e.g. carbon-enhanced metal-poor r/s stars (CEMP-r/s) showing both Ba and Eu enhancement

- could be explained by i-process
  $N_n \simeq 10^{12} - 10^{15}\ \mathrm{cm}^{-3}$, $t_{\mathrm{scale}} \sim 10^5$ s (example site: AGB stars with proton ingestion event)

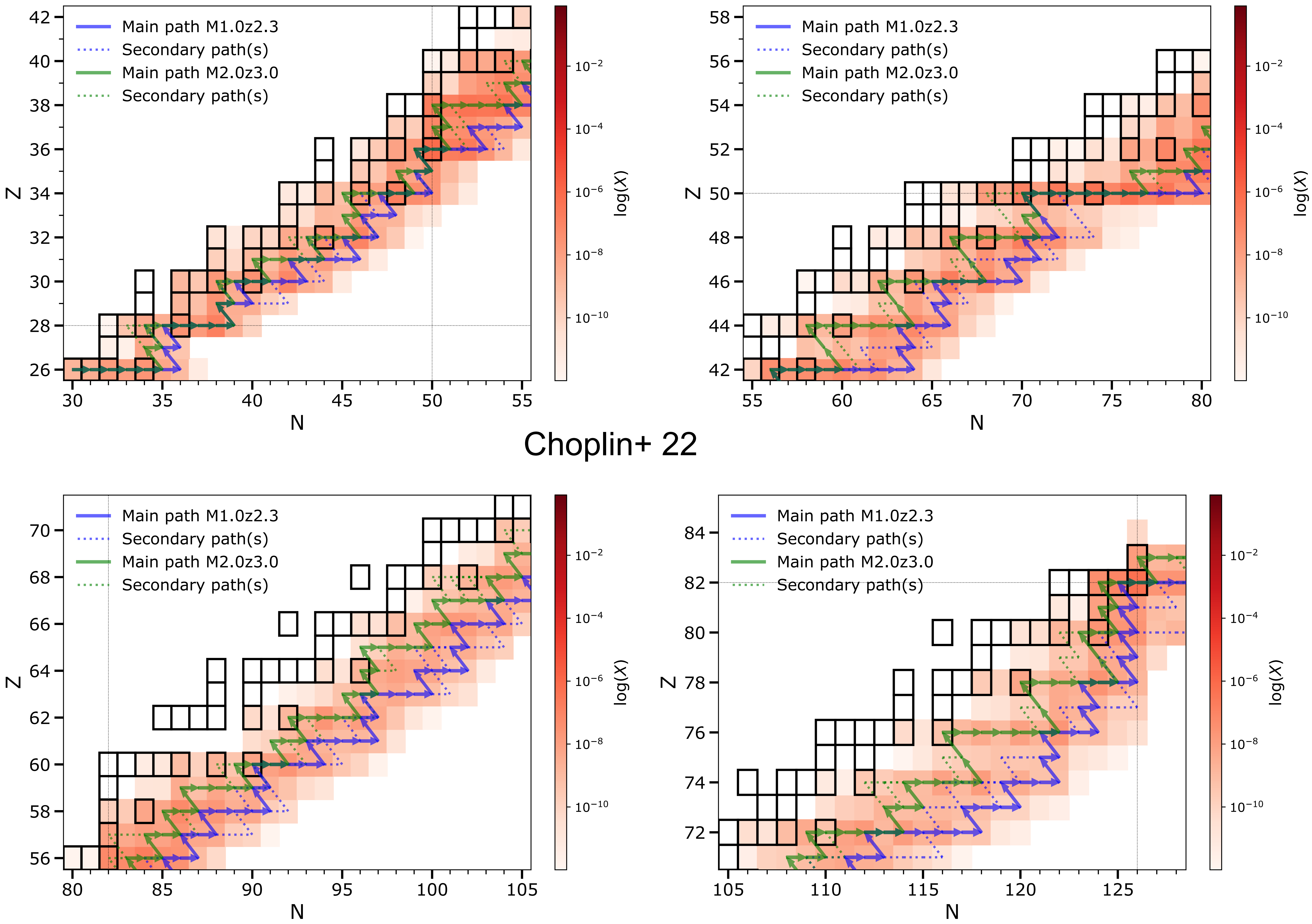
- selected r/s-stars better fitted by i-process models than s-process and scaled solar r-distribution



Choplin+ 21

# i-process path

- path several steps away from stability
- blue case:
  $N_{n,max} = 2.19 \times 10^{15}\ \mathrm{cm}^{-3}$
- green case:
  $N_{n,max} = 6.76 \times 10^{13}\ \mathrm{cm}^{-3}$
- path-dependent final isotopic ratios



Choplin+ 22

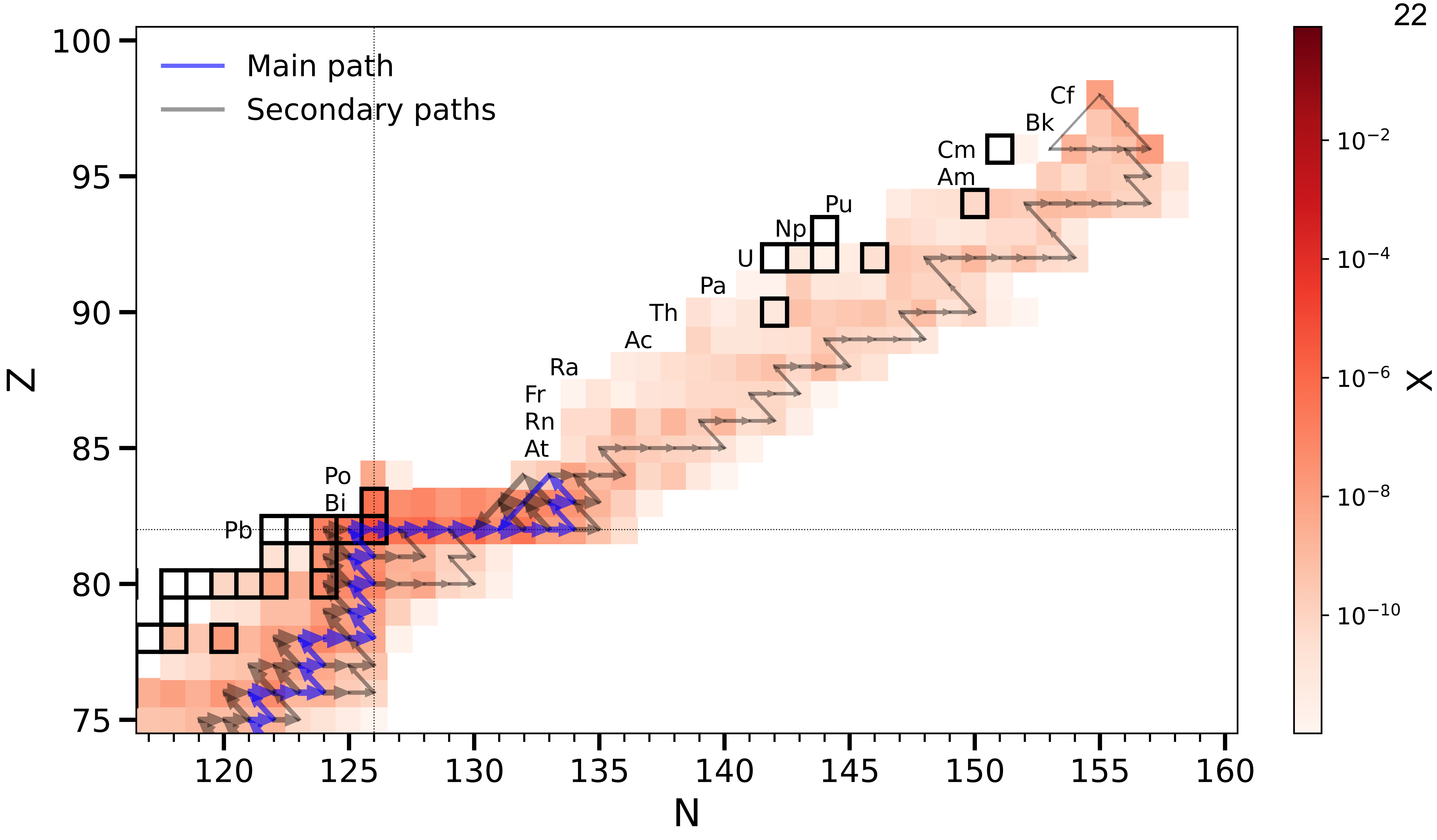
# i-process termination

- 1 M⊙ AGB at [Fe/H] = −2.5,
  at t of $N_{n,max} = 2.17 \times 10^{15}\ \mathrm{cm}^{-3}$

- main path loop at
  $^{216}\mathrm{Pb}(\beta^-)^{216}\mathrm{Bi}(n,\gamma)^{217}\mathrm{Bi}(\beta^-)^{217}\mathrm{Po}(\gamma,\alpha)^{213}\mathrm{Pb}$

- secondary path (30%+ of total flux)
  due to $(n,\gamma)$ compete with $\beta$ decays
  at $^{216}$Pb, $^{217}$Bi and $^{217}$Po at $N_n \simeq 10^{15}\ \mathrm{cm}^{-3}$

- i-process may produce actinides!



Choplin+ 25

# Outline

1. brief BBN introduction & new BBN constraint on effective cosmic neutrinos

2. brief introduction of neutron capture processes

   - motivation of our neutron capture studies

   - sweeping across the chart of nuclides with different free neutron conditions

   - i-process like case w/ & w/o actinides

# motivation of our neutron injection model

- (original) study i-process abundance pattern and its potential actinide production in one zone with constant T and $\rho$ using the PRISM code (version 1.6.0 by Sprouse and Mumpower)

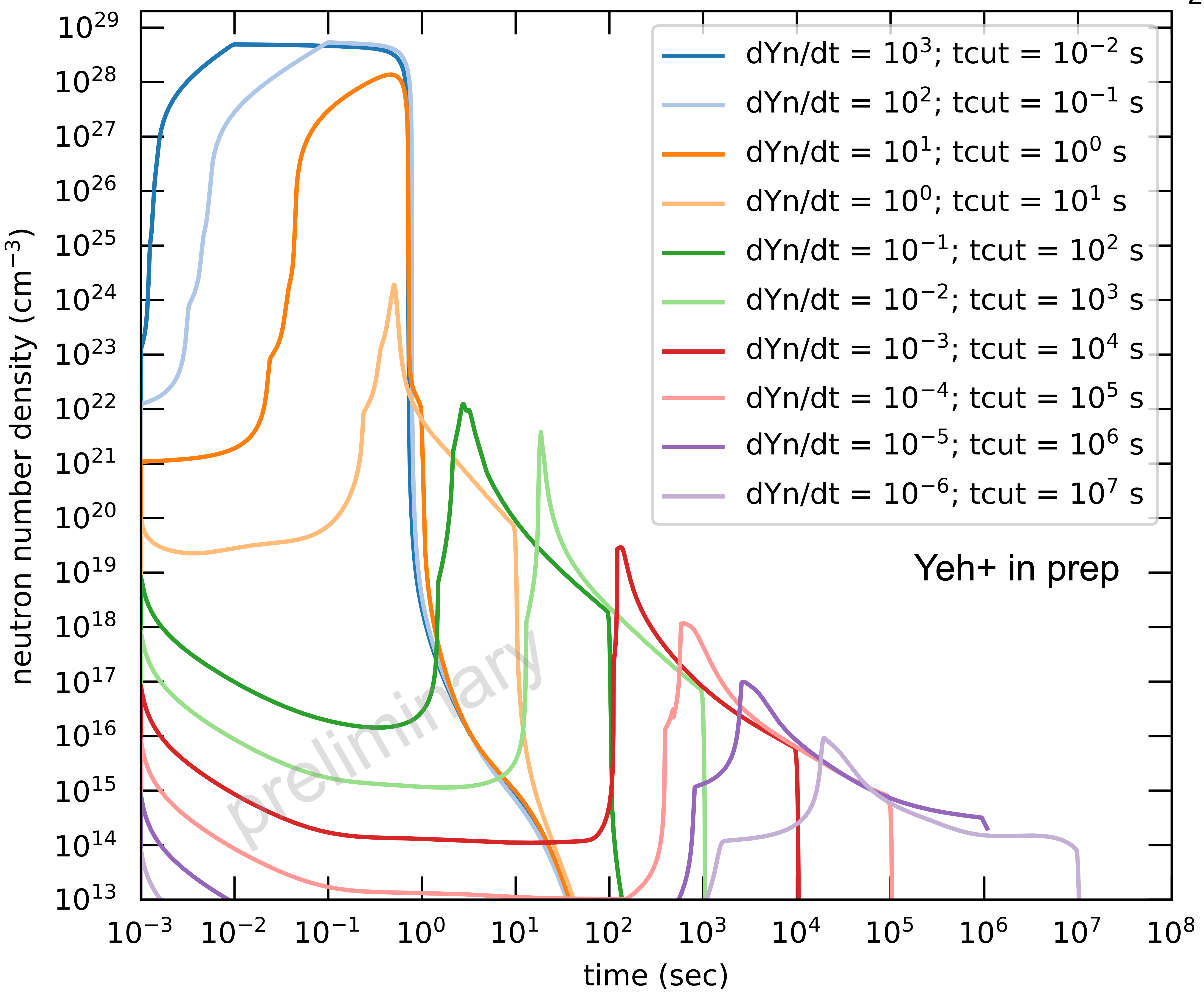
- not all calculations get final actinides; ncap processes depend on densities and timescales of free neutrons that determine nucleosynthesis paths and hence final yields

- (now) study such dependences without complex details of astrophysics: we model an external source injecting neutrons into the “one-zone box” of simulation with constant T

- goal: to explore conditions of paths from near stability to neutron dripline and identify their termination points and compare their final abundances

# nucleosynthesis sweeping across chart of nuclides

- do multi-D grid calculations; then set constraints for easy comparison
- simple case: same # of injected n $\mathrm{rate} \times \mathrm{t_{cutoff}} = 10$ times the initial baryon # why? try to cover r-like and i-like densities at both ends
- 10 examples with even log spacing
- for short injection timescales (≲ 1 s), density almost reaches its final value before significant actinide isotopes production at t~1 s; look like r-process at constant T



# nucleosynthesis sweeping across chart of nuclides

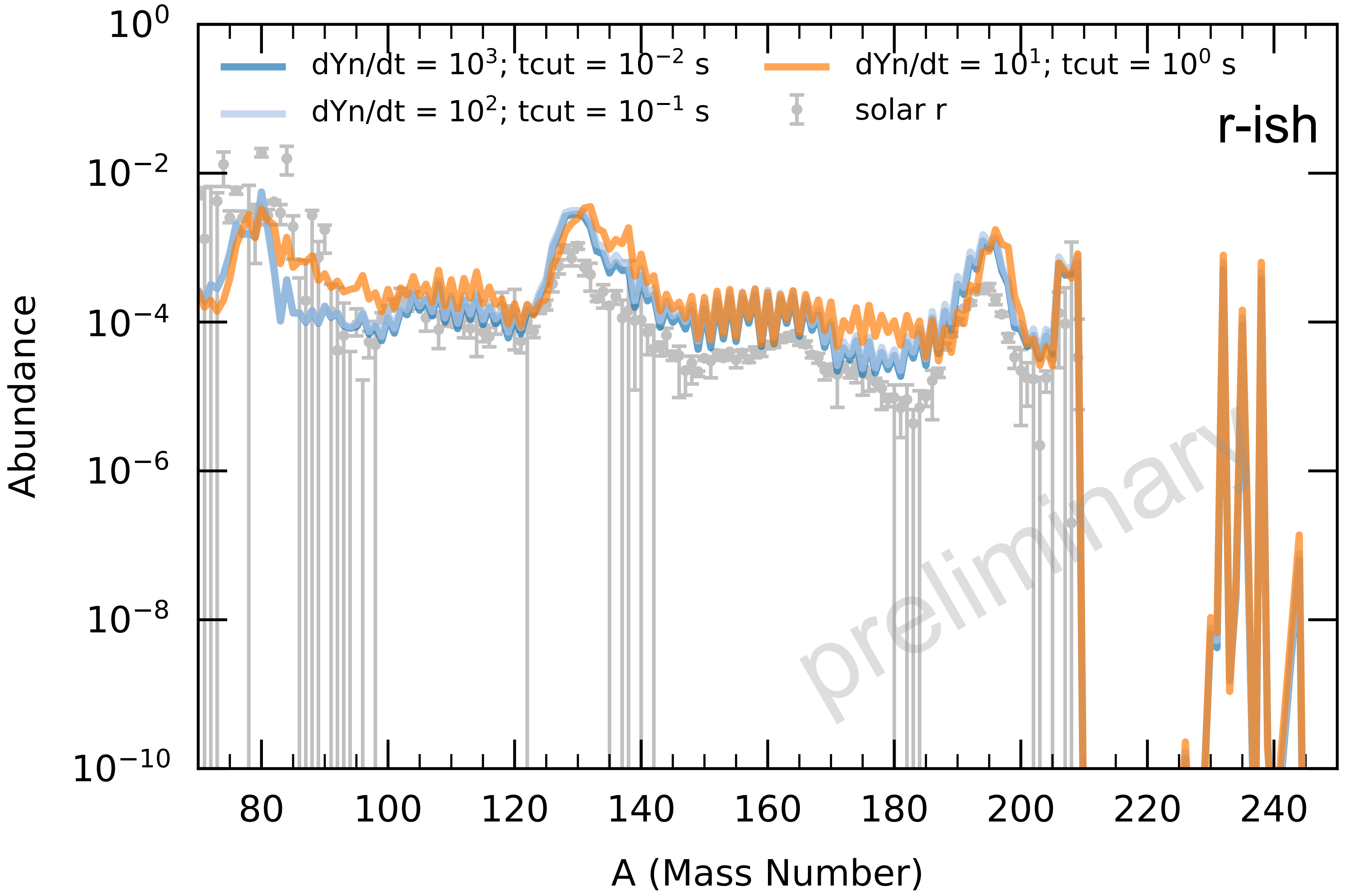
- path is defined when <A> abundance weighted average mass for A ≥ 212 (no s-process nuclei) reaches its farthest endpoint at early times

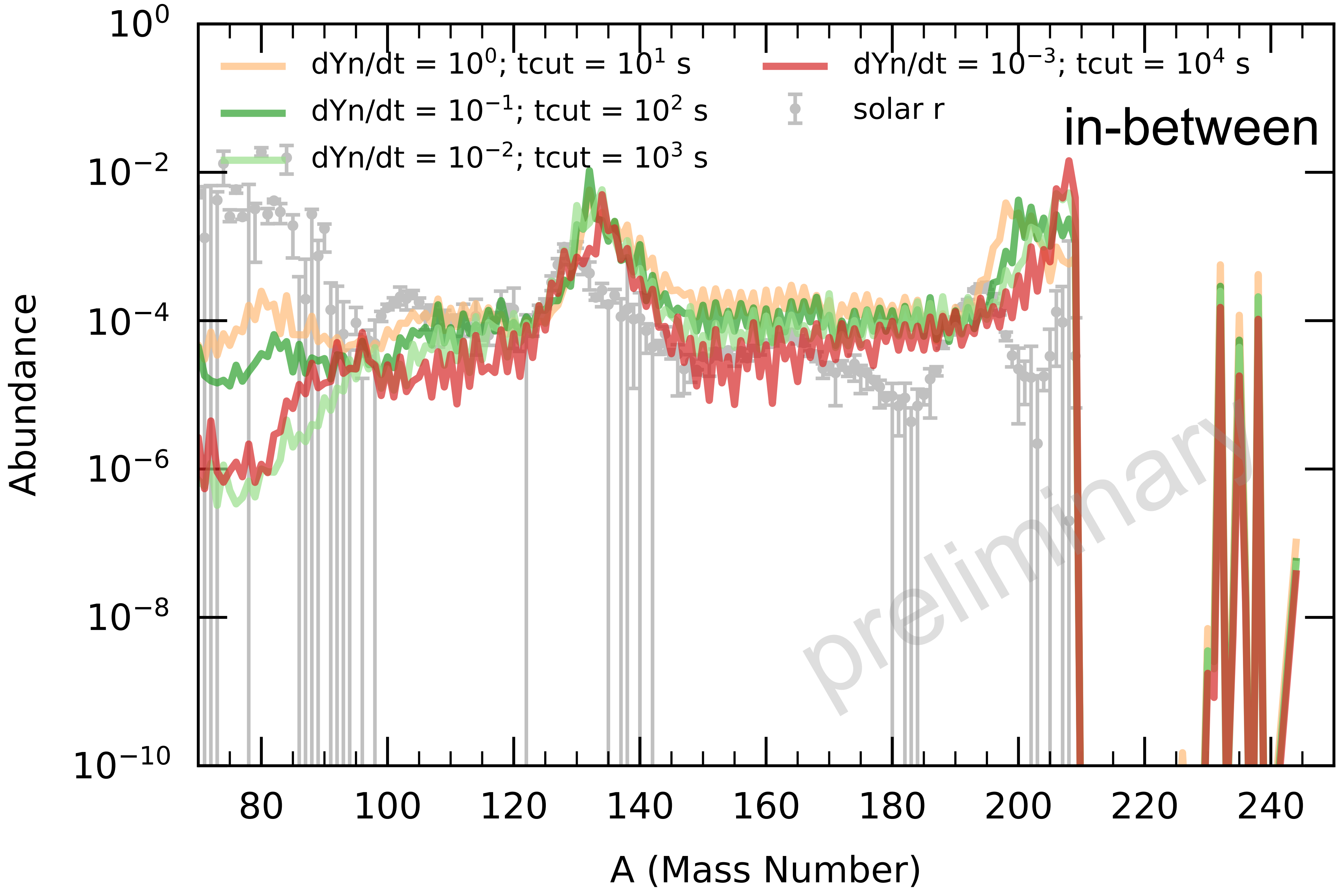
- $t_{path}$ occurs just soon after Nn passes its peak; path terminated by fissions

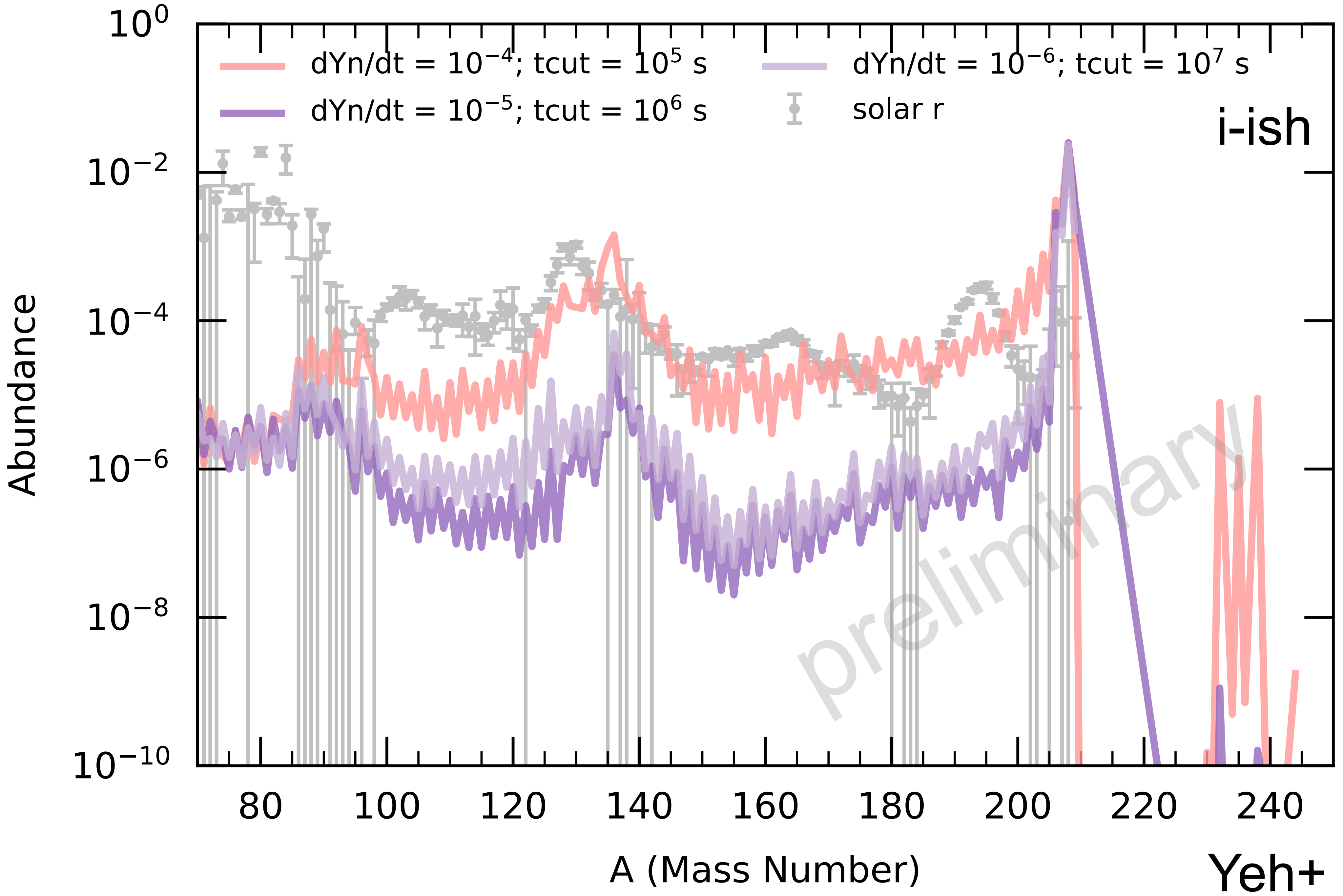
- for long timescales, density not change much at $t_{path}$, late time free n mainly participate in fission cycling when path moves back to stability

# final yields at 1 Gyr

- put into groups based on features
- in-between cases (in particular the greens): peaks lie between r and s peaks, rare earth peak not obvious, and make actinides



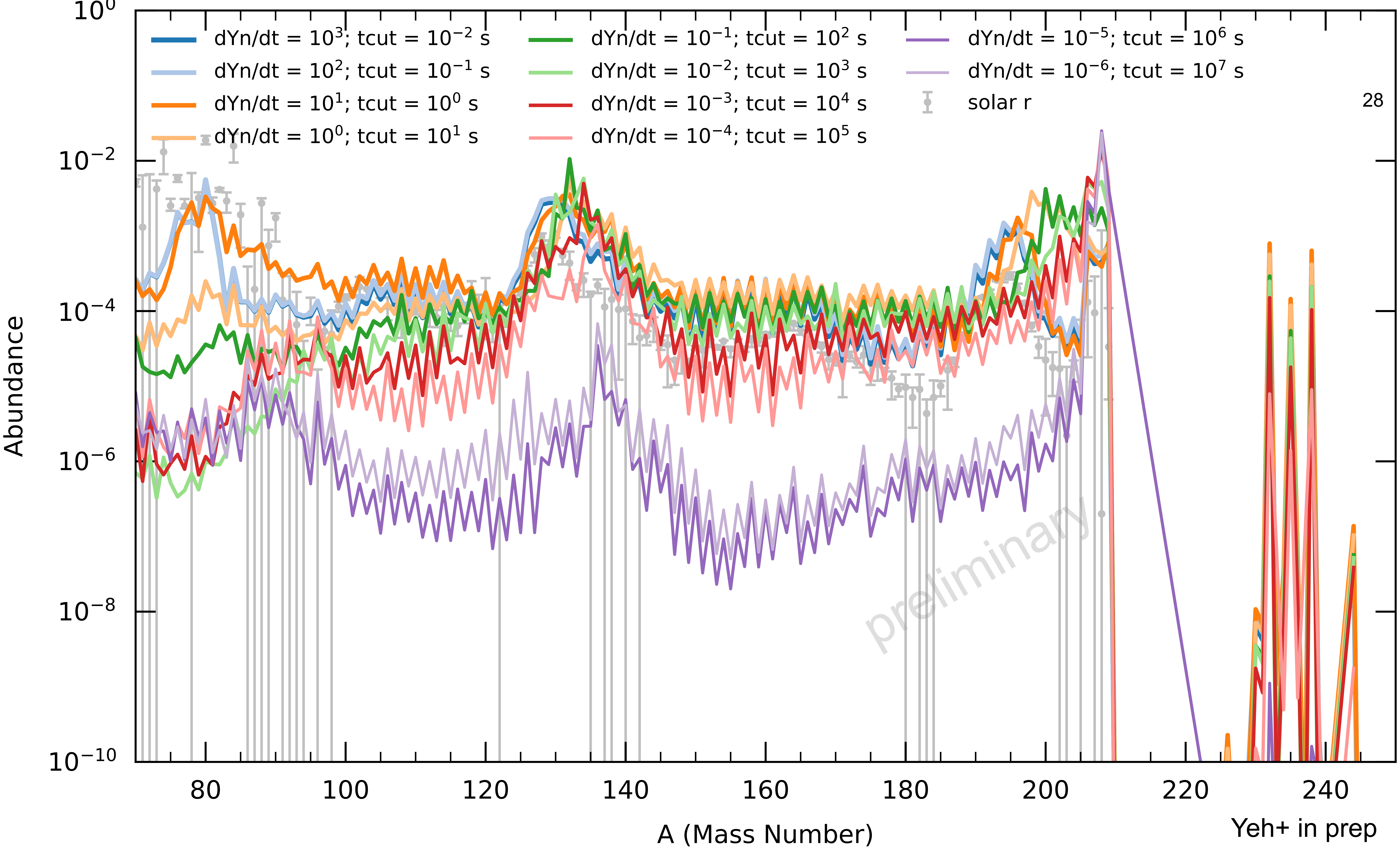




Yeh+ in prep

# final yields at 1 Gyr (all distributions in one plot)

- transition from r-ish to i-ish yields



Yeh+ in prep

# Outline

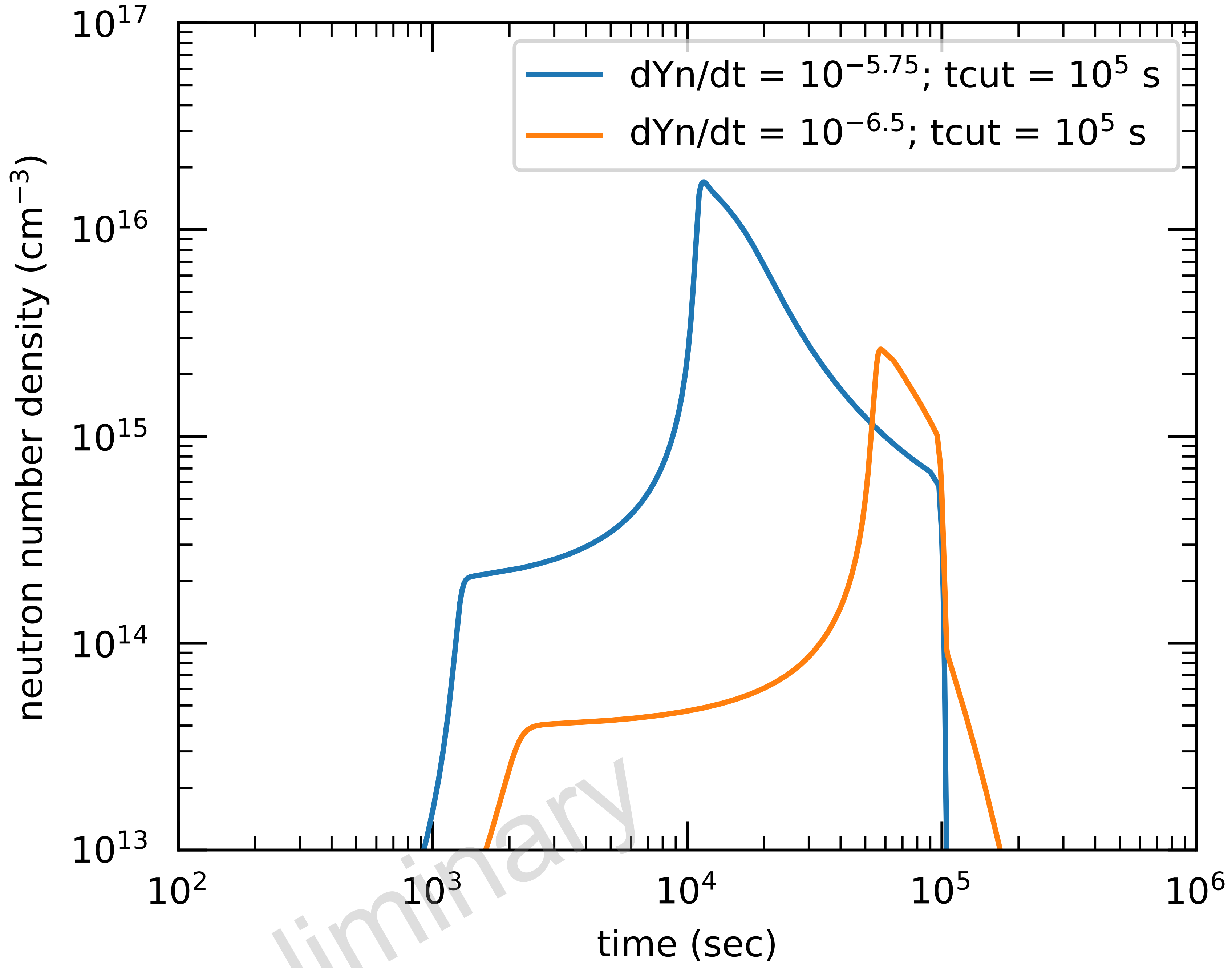
1. brief BBN introduction & new BBN constraint on effective cosmic neutrinos

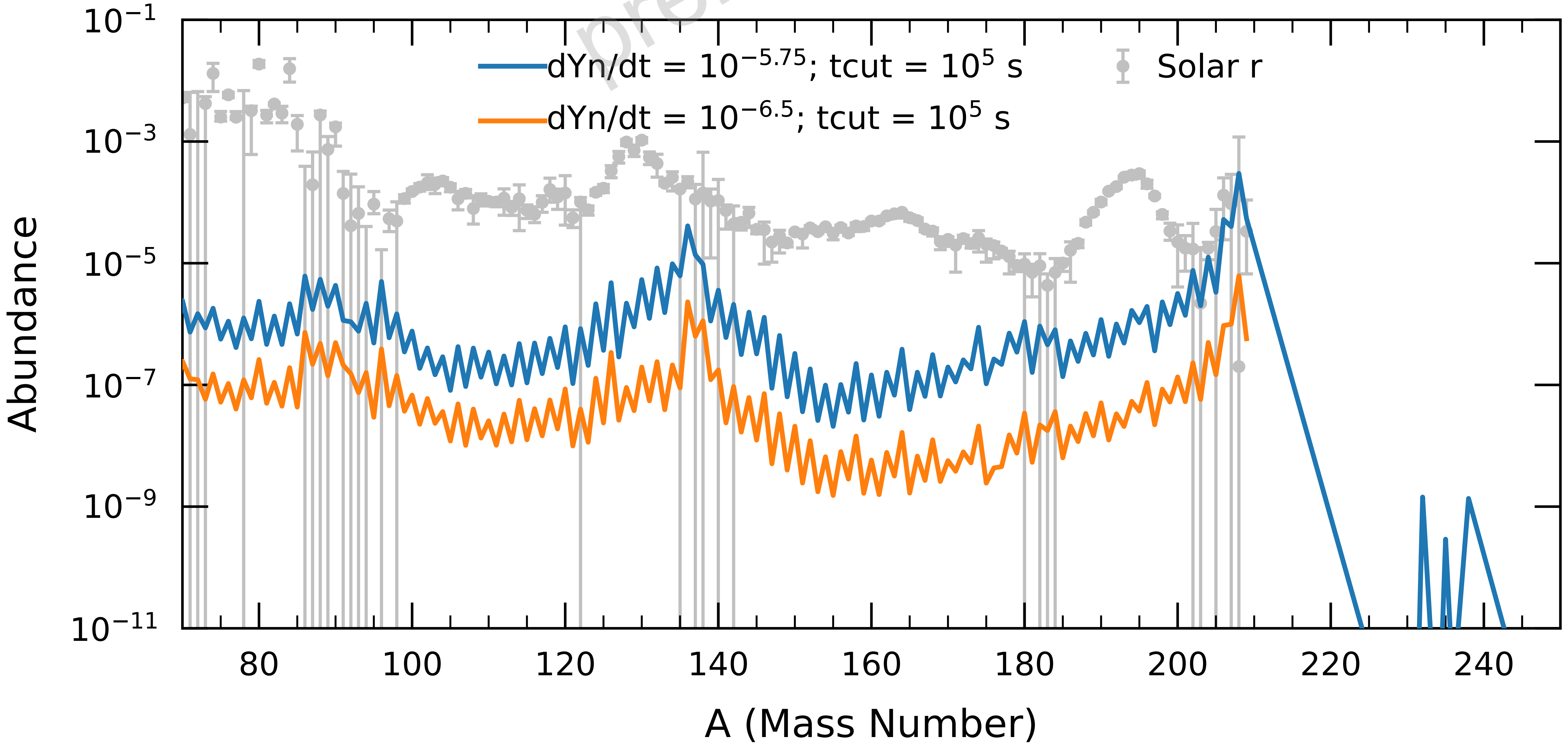
2. brief introduction of neutron capture processes

   - motivation of our neutron capture studies
   - sweeping across the chart of nuclides with different free neutron conditions
   - i-process like case w/ & w/o actinides

# i-process w/ & w/o actinides

- adjust injection strength and timescale to produce typical i-process neutron densities ($N_n \sim 10^{15}$ cm$^{-3}$)
- initial density $10^4$ g cm$^{-3}$ and constant $T_9$ = 0.2
- after injection, increasing density by 17.8 % and 3.2% respectively
- typical i-process neutron exposure ( $\tau = \int N_n v_T dt$ = 10 ~ 50 mbarn$^{-1}$ ) about 47 and 18 in total respectively
- similar final abundance except actinides

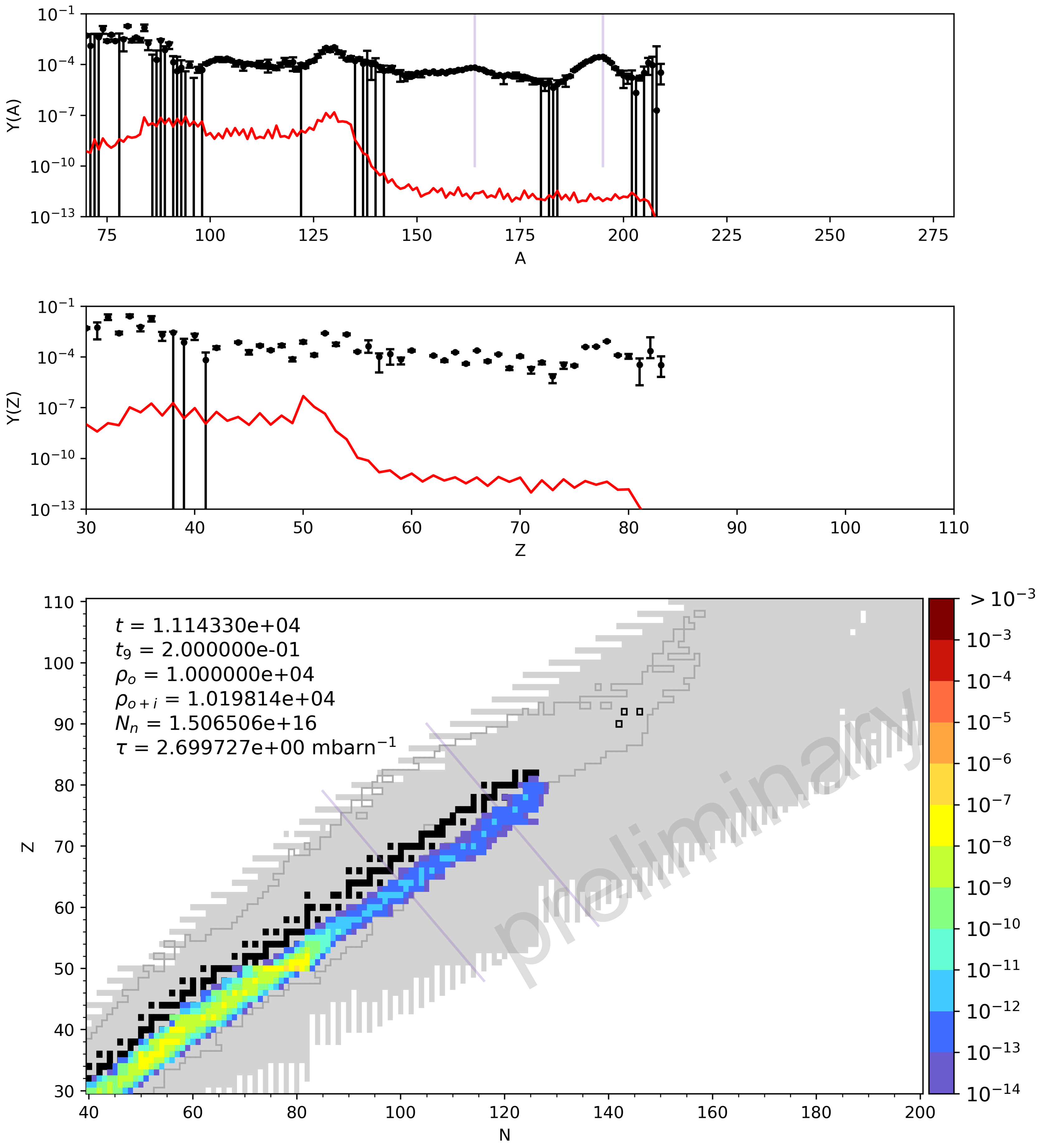




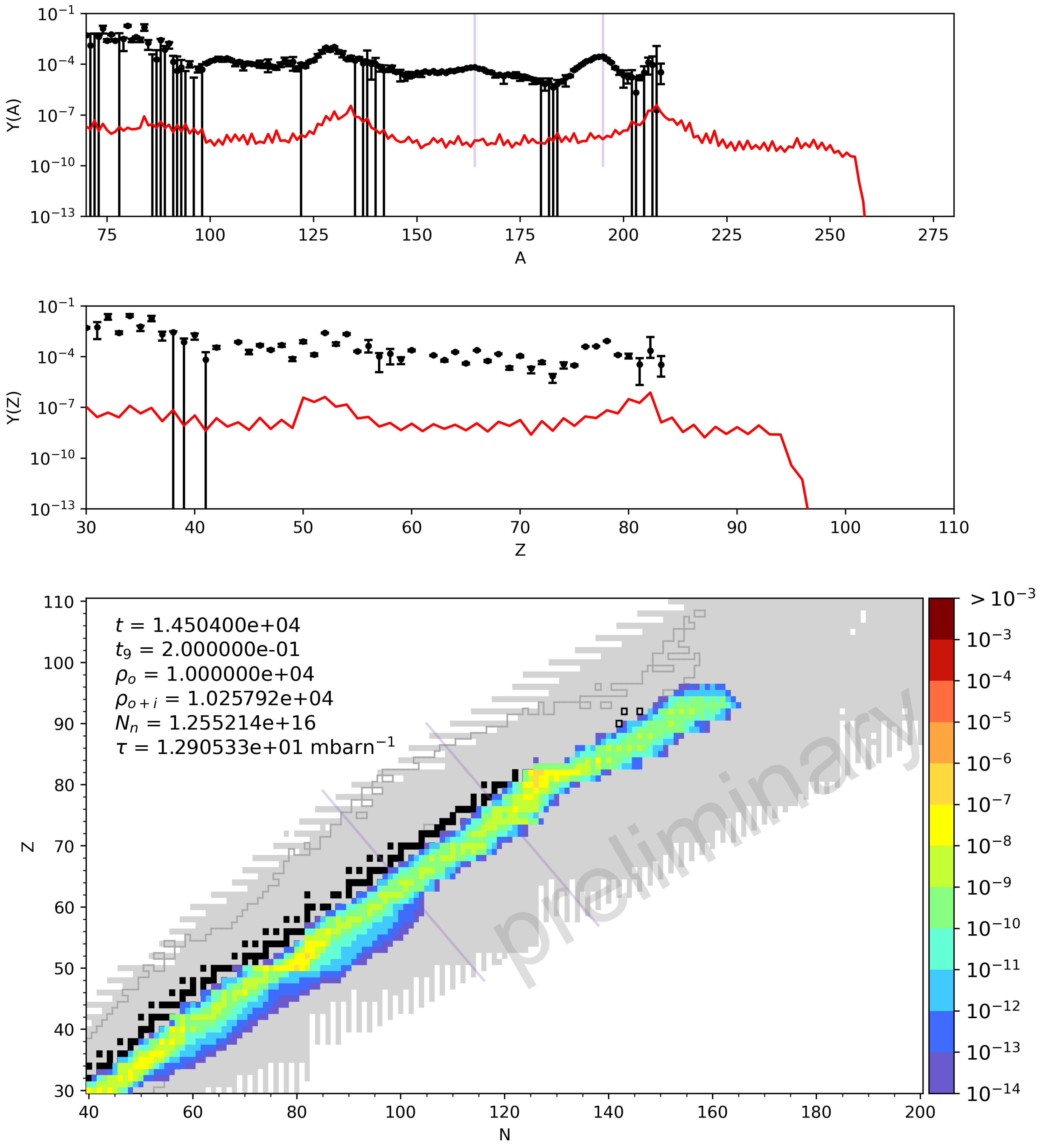
Yeh+ in prep

# snapshots for i-ish case with final actinides

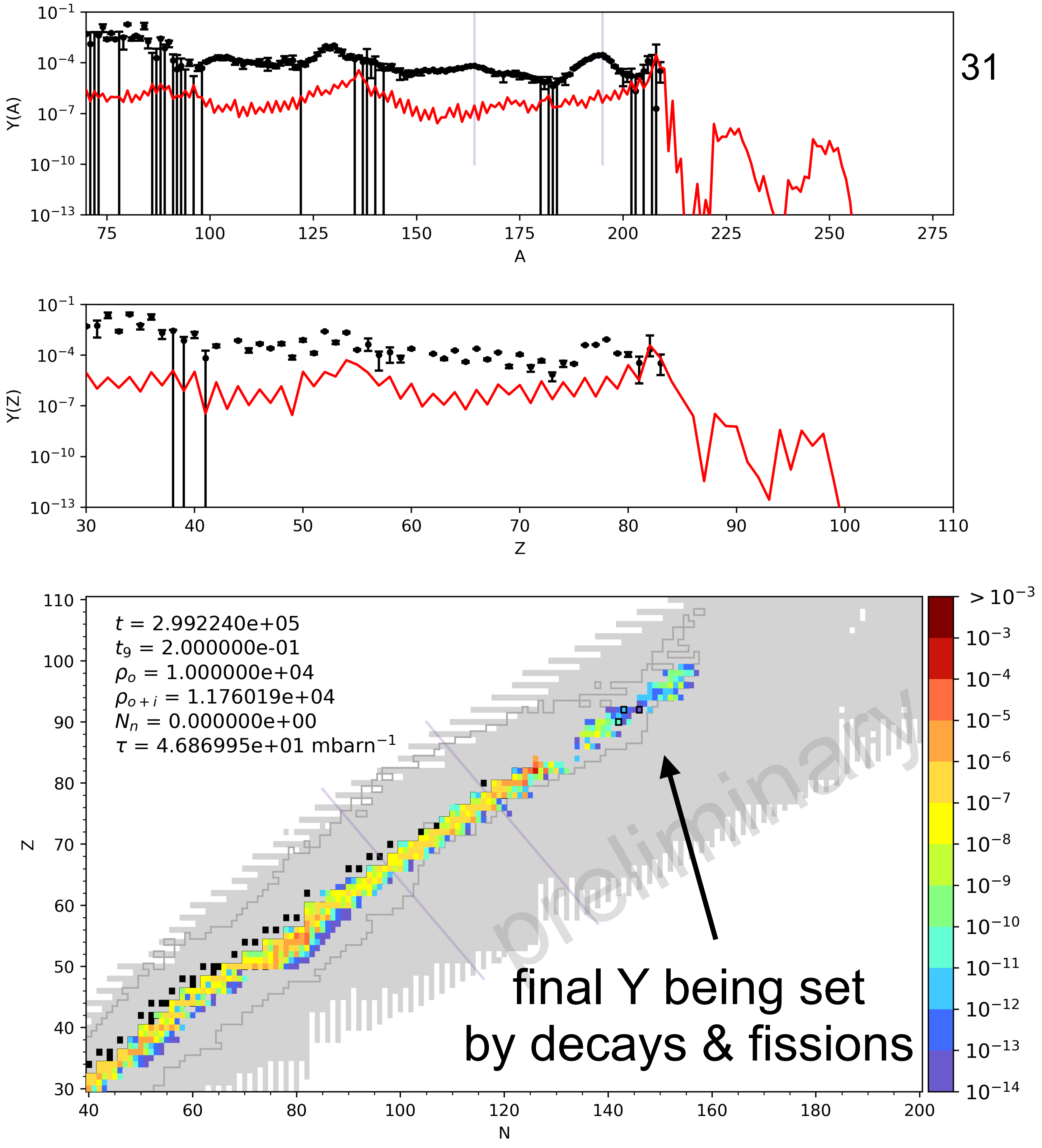
$dY_n/dt = 10^{-5.75}$
$t_{cut} = 10^5$ s



when reach A ~ 208
t = 1.1 x $10^4$ s
Nn ~ 1.5 x $10^{16}$ cm$^{-3}$
$\tau$ ~ 3



when path is defined by <a>$_{max}$
t = 1.5 x $10^4$ s
Nn ~ 1.25 x $10^{16}$ cm$^{-3}$
$\tau$ ~ 13



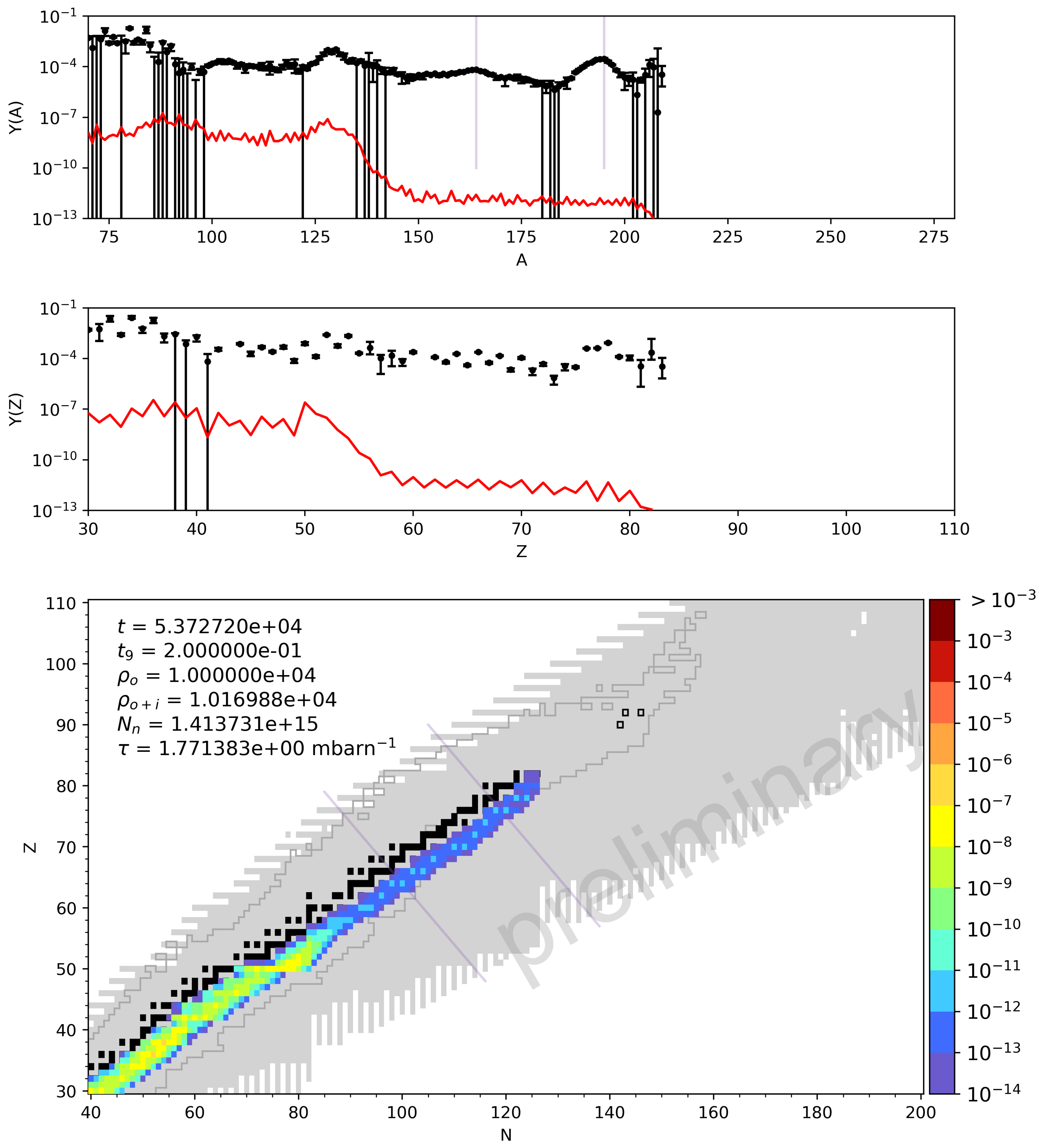
final Y being set
by decays & fissions

when Nn -> 0
t = 3 x $10^5$ s
$\tau$ ~ 47

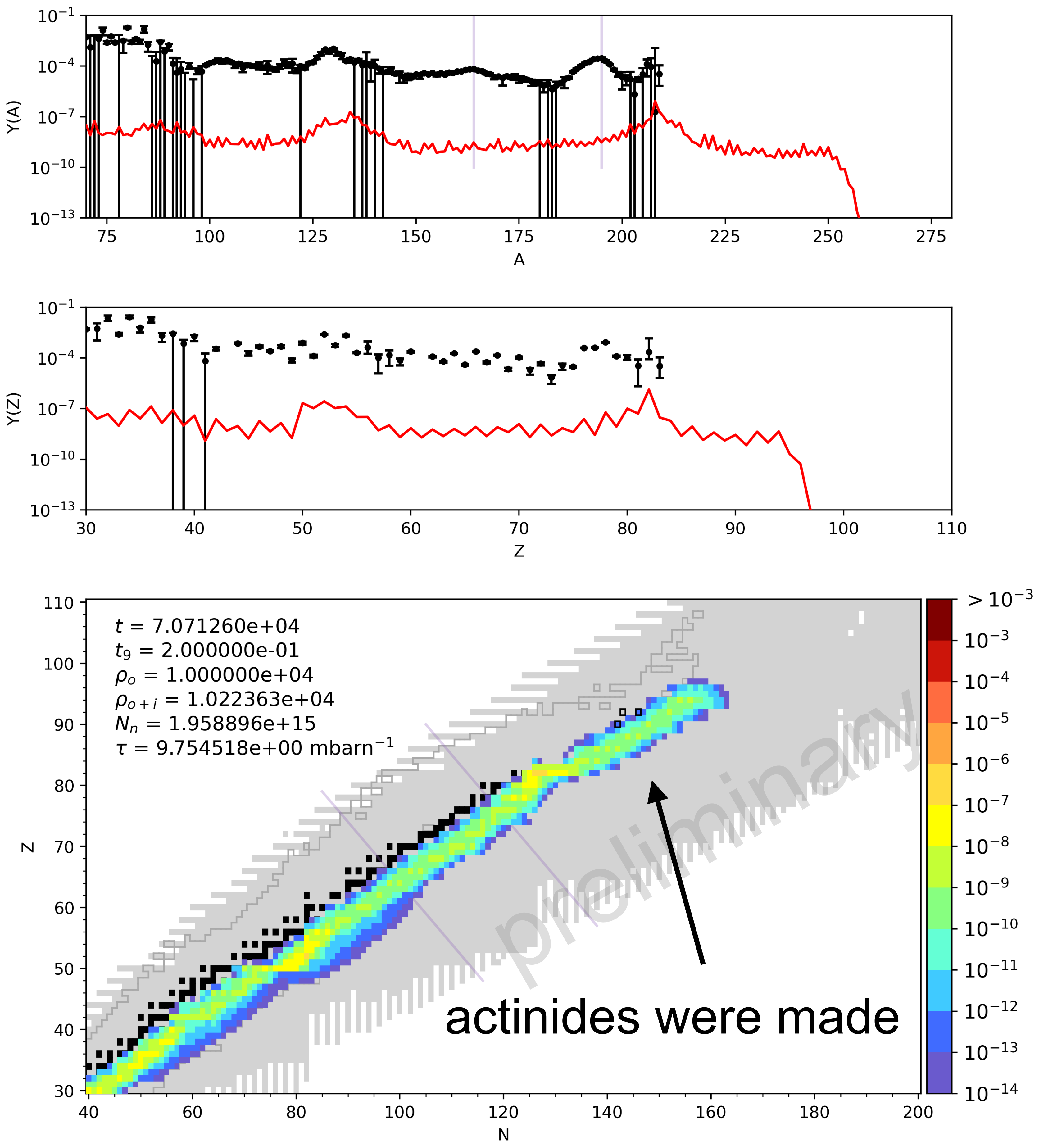
Yeh+ in prep

# snapshots for i-ish case w/o final actinides

$dYn/dt = 10^{-6.5}$
$t_{cut} = 10^5$ s

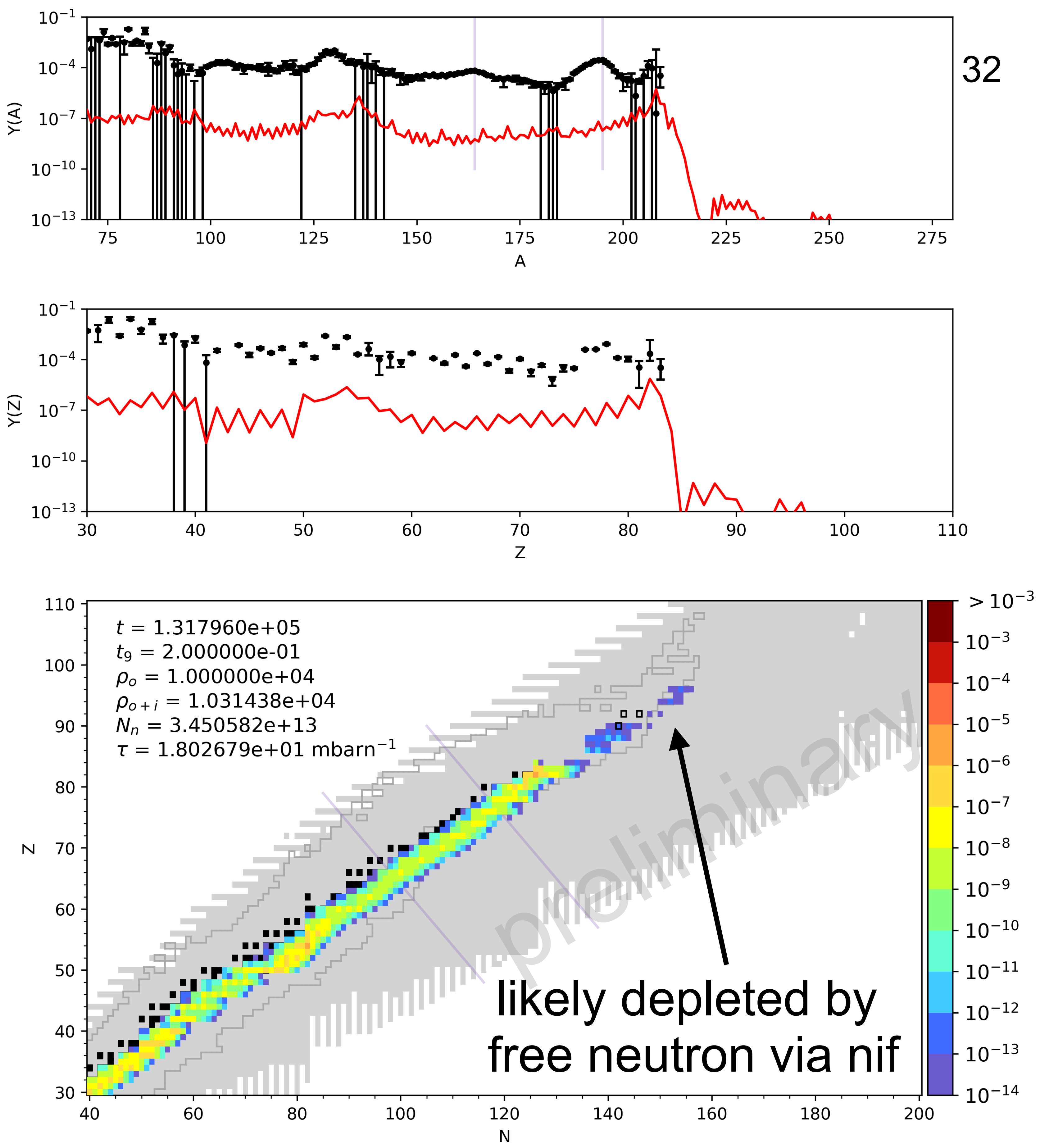


when reach A ~ 208
$t = 5.4 \times 10^4$ s
$Nn \sim 1.4 \times 10^{15}$ cm$^{-3}$
$\tau \sim 2$



actinides were made

when path is defined by $<a>_{max}$
$t = 7.1 \times 10^4$ s
$Nn \sim 2.0 \times 10^{15}$ cm$^{-3}$
$\tau \sim 10$



likely depleted by free neutron via nif

when Y(actinides) -> 0
$t = 1.3 \times 10^5$ s
$Nn \sim 3.45 \times 10^{13}$ cm$^{-3}$
$\tau \sim 18$

Yeh+ in prep

# Summary

- well-understood BBN physics and precision nuclear and observational data as input
  → BBN is a reliable and powerful probe to the early universe physics in the era of precision cosmology

- SBBN+D and CMB baryon measurements in good agreement (within %-level)
  → crucial consistency test of the hot big bang model

- BBN+observations and CMB neutrino numbers are also consistent within uncertainties
  → set strong cosmological constraints on departures from SM: e.g. BBN+CMB $\Delta N_\nu = N_\nu - 3 < 0.089$

- s-, i-, r- processes operate at distinct neutron densities and timescales, having distinct paths and terminations

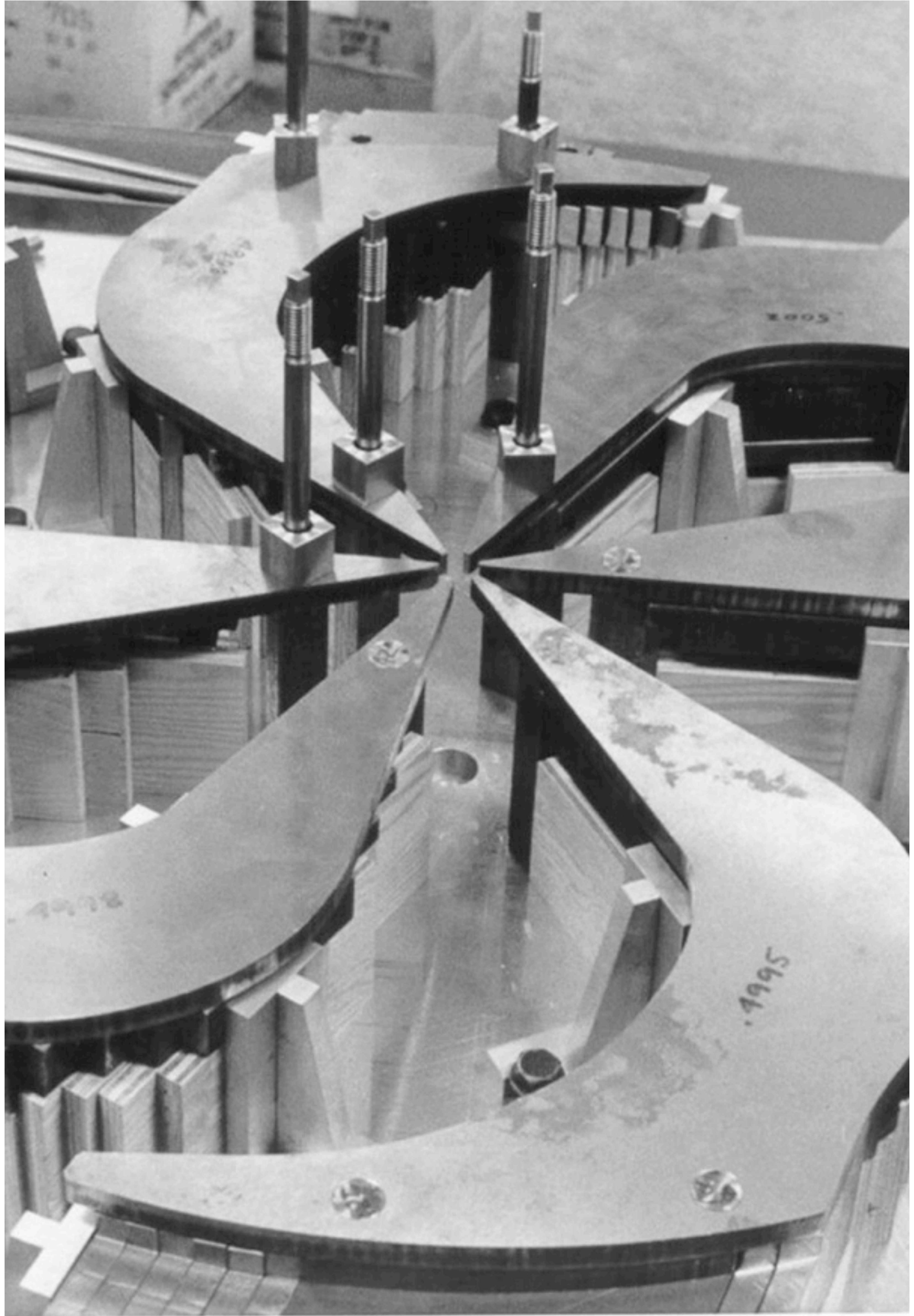
- we model external neutron source and probe the impact of n-injection strength and timescale on nucleosynthesis paths and final abundance yields
  → by varying n-injection intensity, we perform nucleosynthesis sweeping across chart of nuclides with different neutron densities; we see interesting transitions from r-like to i-like abundance patterns

- i-process can synthesize actinides given typical $N_n \simeq 10^{15}\ \mathrm{cm}^{-3}$, but $t_{\mathrm{scale}}$ of free n seems to be critical for actinides to survive

# Thank you
# Merci

www.triumf.ca

Follow us **@TRIUMFLab**



Discovery, accelerated

# Backup Slides

# a quick BBN update


https://www.lbto.org/

- the most precise primordial helium mass fraction to date was determined using a new analysis methodology and 15 new observations of extremely metal-poor HII regions from the Large Binocular Telescope:

$$Y_p = 0.2458 \pm 0.0013$$

(2601.22238)

- Uncertainty significantly reduced from $Y_p = 0.2448 \pm 0.0033$ (Aver et al. 2021)
- $^4$He is one the the primary BBN light element observables; physics beyond the Standard Model can be constrained provided with accurate abundance measurements
- We update BBN cosmological constraints using this new observational input (2601.22239)

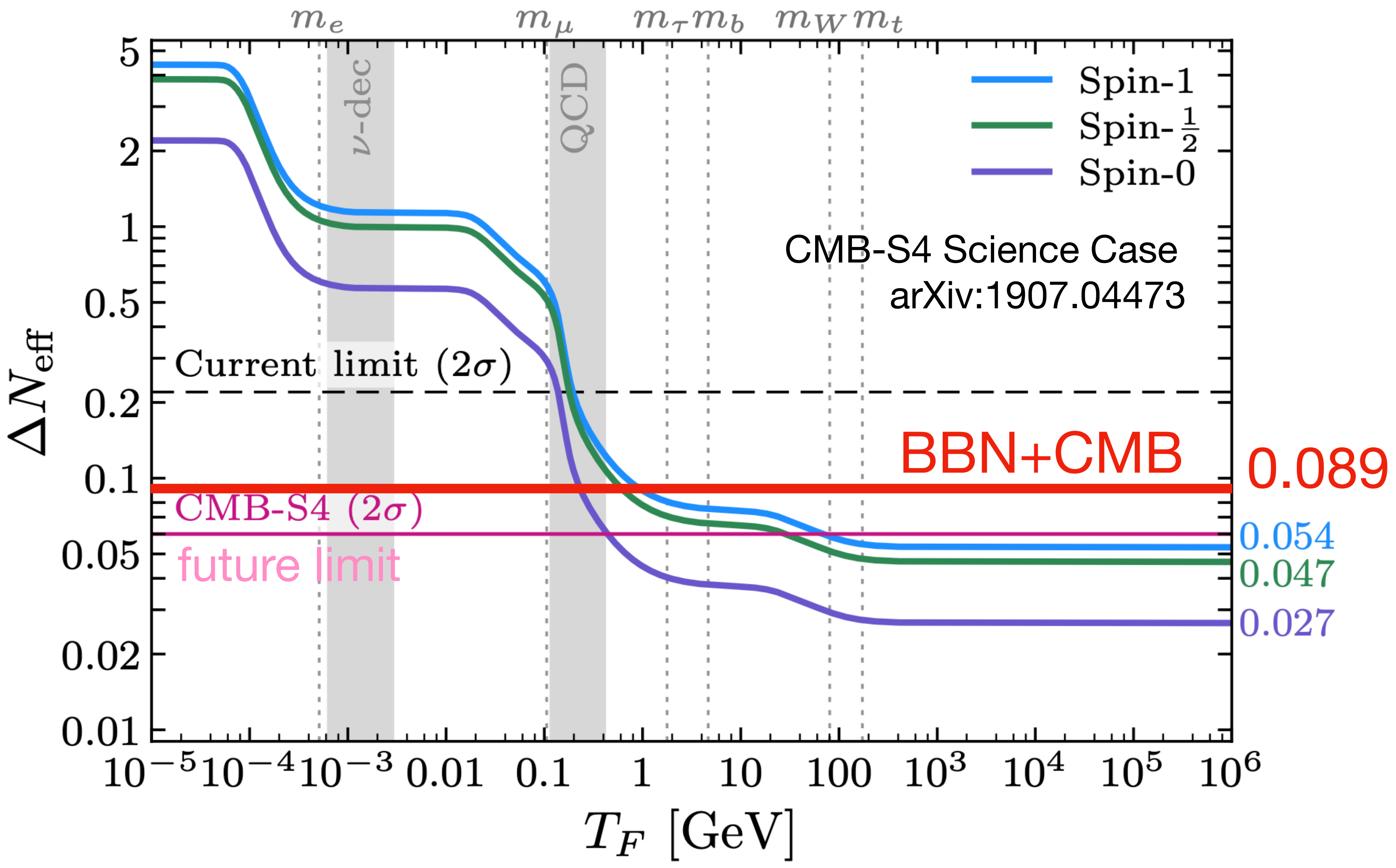
# New Limits on Neutrino Flavors $N_\nu$

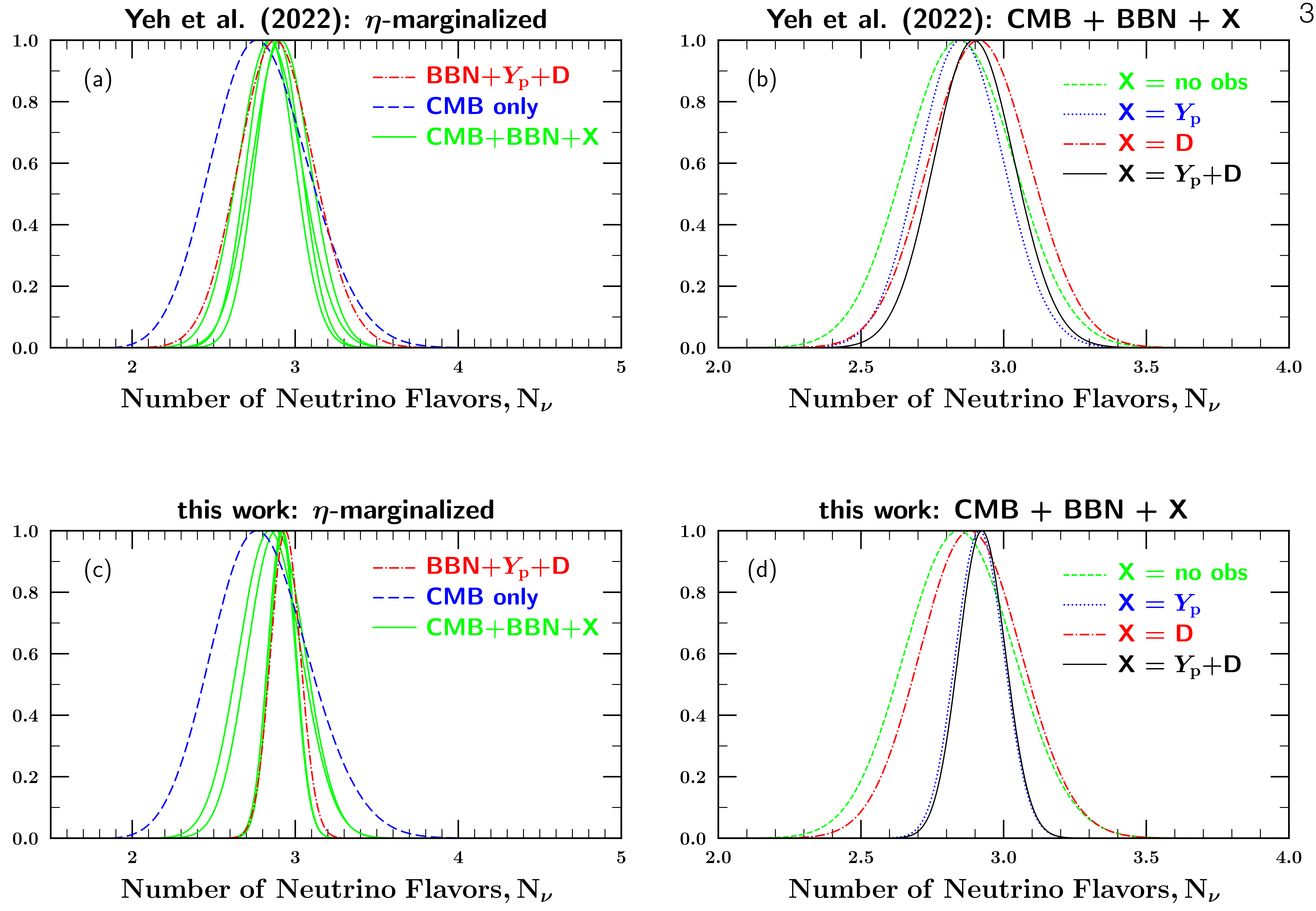
summary statistics for $N_\nu$

| | mean | σ |
|---|---|---|
| CMB | 2.800 | 0.294 |
| BBN+Obs | 2.941 | 0.092 |
| combined | 2.925 | 0.082 |

=> 95% upper limit: $N_\nu < 3.089$

=> $\Delta N_{\rm eff} \simeq \Delta N_\nu = N_\nu - 3 < 0.089$





(2601.22239)

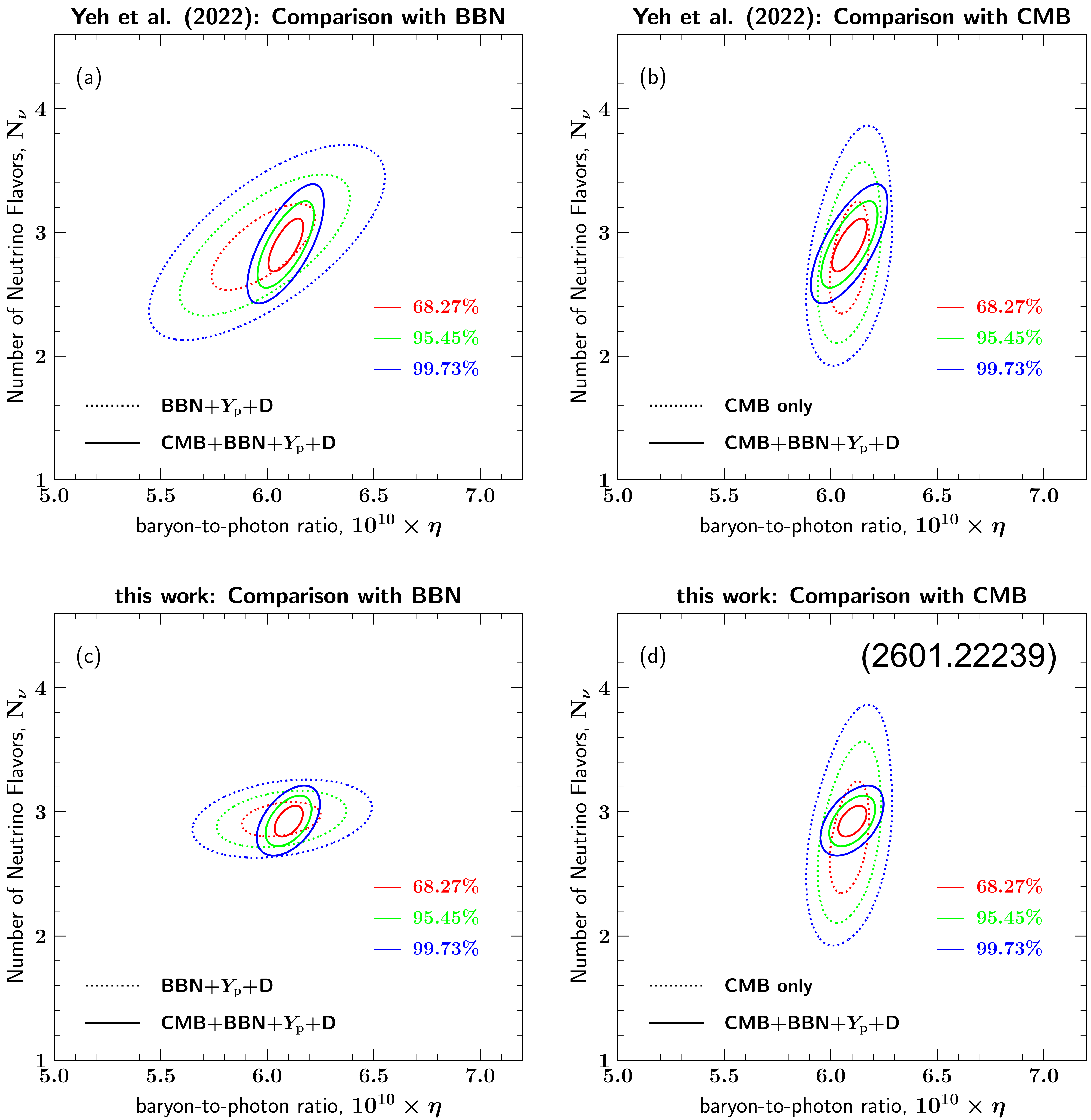
# 2D Likelihoods

previous statistics for $N_\nu$

| | mean | σ |
|---|---|---|
| Planck 18 | 2.800 | 0.294 |
| BBN+Obs | 2.889 | 0.229 |
| combined | 2.898 | 0.141 |

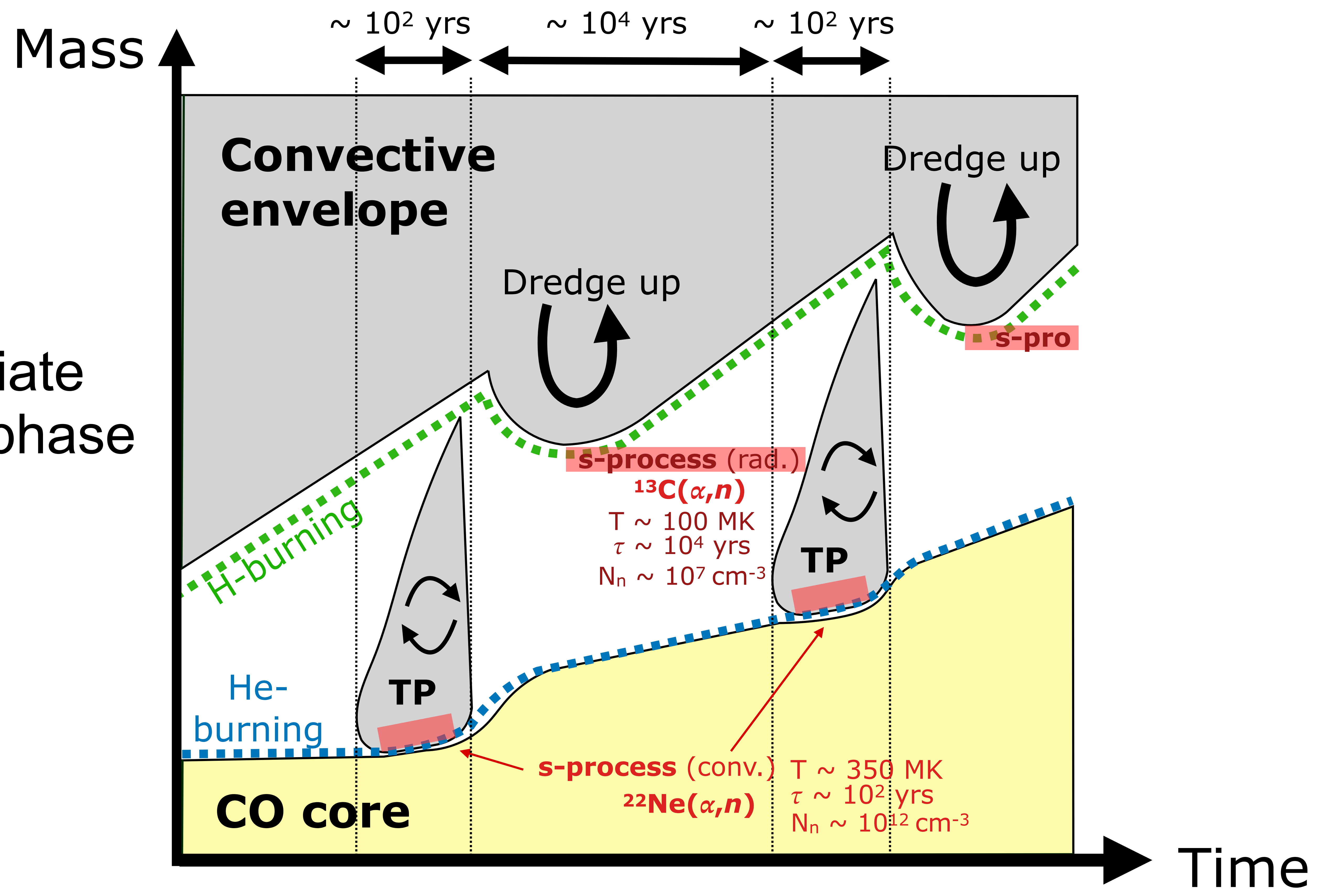
NEW statistics for $N_\nu$

| | mean | σ |
|---|---|---|
| Planck 18 | 2.800 | 0.294 |
| BBN+Obs | 2.941 | 0.092 |
| combined | 2.925 | 0.082 |



# AGB stars are the main site of s-process

- low neutron density $N_n \simeq 10^6 - 10^{10}\ \mathrm{cm}^{-3}$
- main component for A > 90 elements
- n source $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$
- formation of $^{13}$C pocket at low- and intermediate stars during asymptotic giant branch (AGB) phase
- weak component for A < 90 elements
- n source $^{22}\mathrm{Ne}(\alpha,n)$
- at low-metallicity massive AGB stars



Choplin+ 25

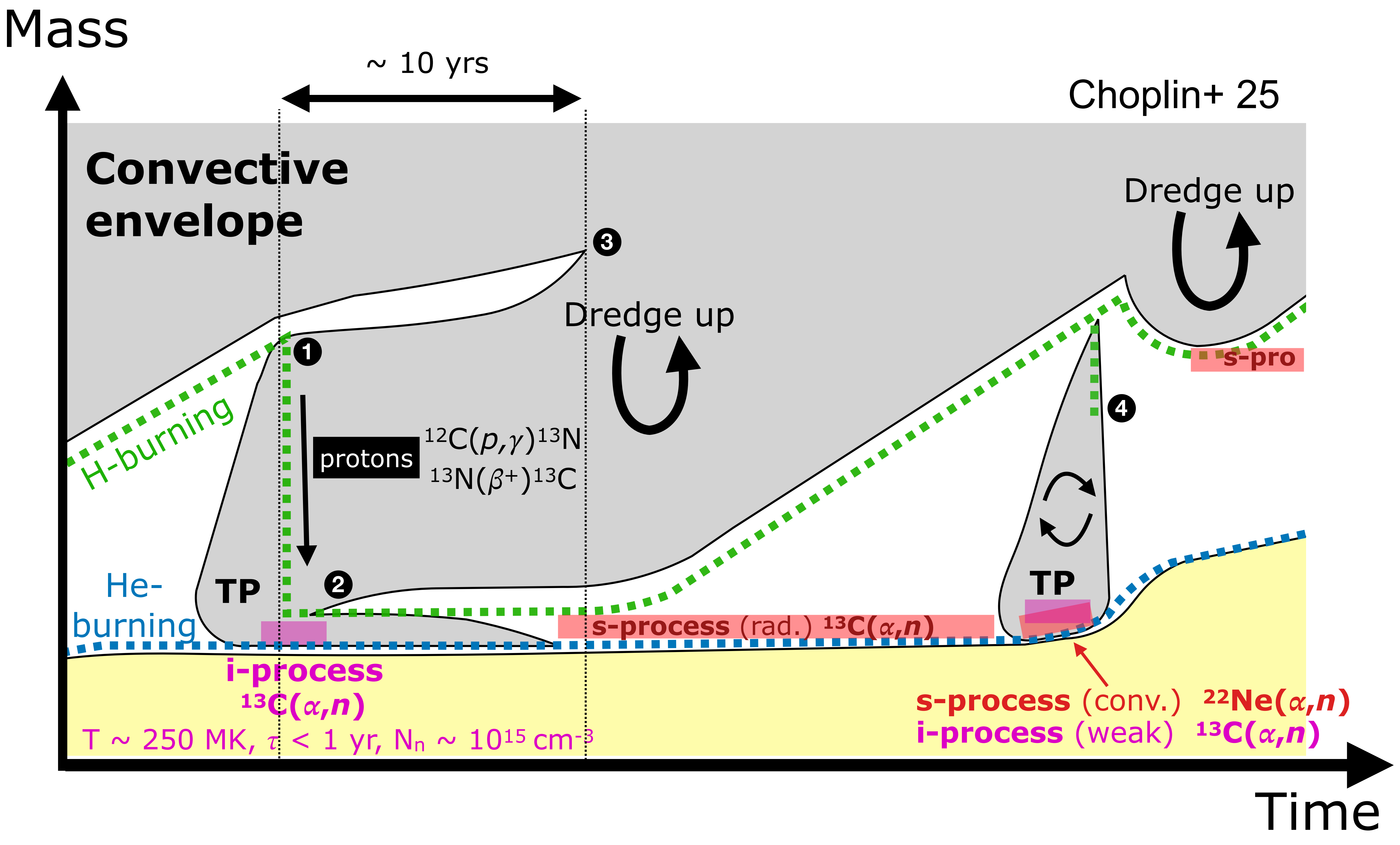
# proton ingestion episode (PIE) in low-metallicity low-mass AGB stars as a potential i-process site

- He-burning shell produces convective thermal pulse and the top of TP encroaches H-rich layer, leading to PIE

- i-process neutron source:
  $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$
  producing $N_n \simeq 10^{15}\ \mathrm{cm}^{-3}$
  → i-process

- upper part of the TP merges with the envelope, changing metallicity and opacity, mass loss rate ↑

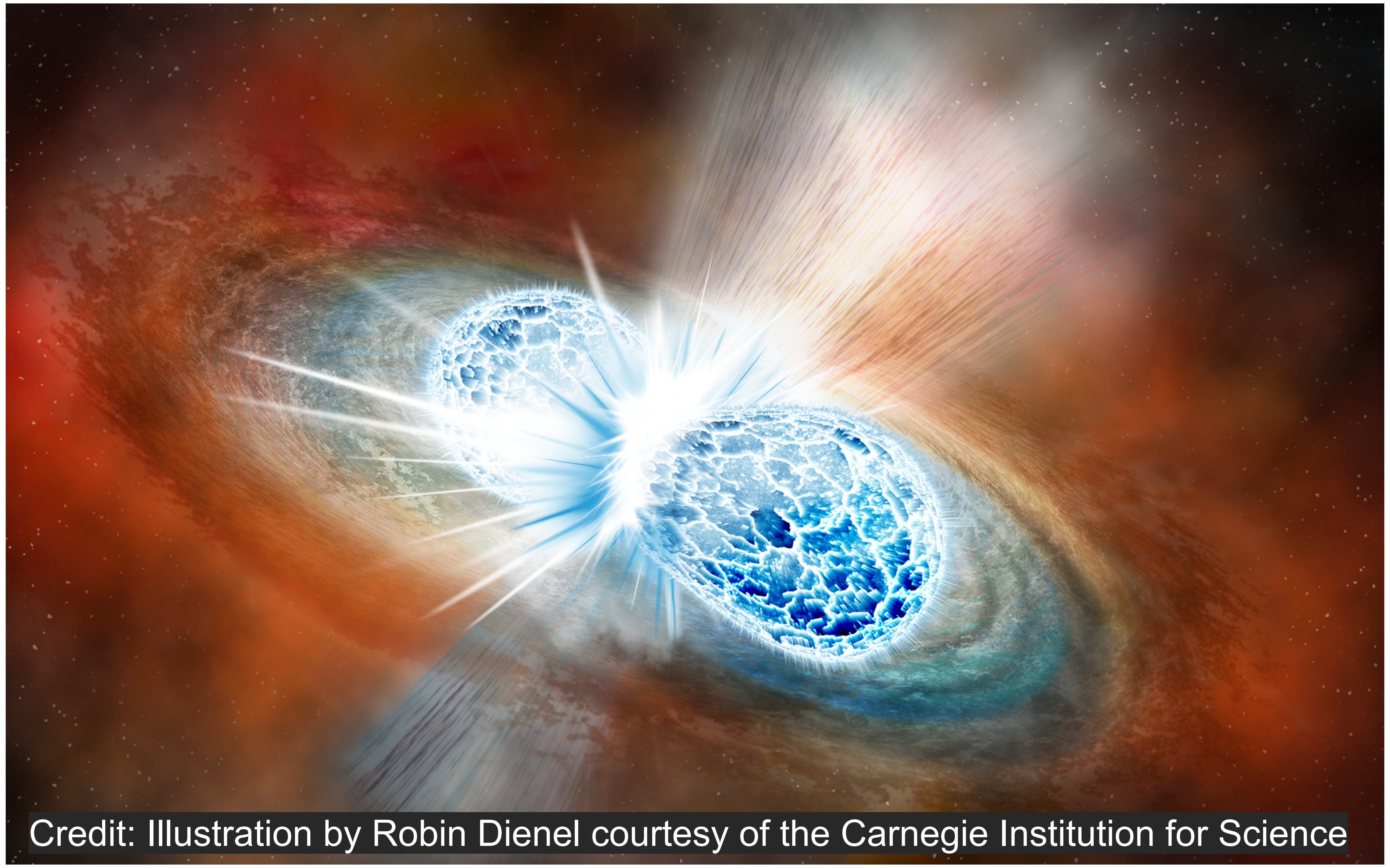
- leftover $^{13}$C pocket → s-process



Choplin+ 25

# neutron star mergers: strong r-process candidate

- $N_n > 10^{20}\ \mathrm{cm}^{-3}$
- timescale ~ O(1) s
- neutron rich ejecta and disk wind
- supported by NSM merger event: EM counterpart is compatible with lightcurve prediction powered by r nuclides
- other possible sites: collapsars, magneto-rotational supernovae…



Credit: Illustration by Robin Dienel courtesy of the Carnegie Institution for Science