Nucleosynthesis with Quark Nugget

LUO, Yudong
Department of Astronomy
Peking Univ.

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Motivation I

• Confirm or exclude them observationally ?

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- Stellar properties: mass-radius relation, moment of inertia, tidal deformability, Kepler limit…
  (More measurements are needed, as well as more precise measurements.)

- In this talk, I focus on the ejecta from BQS or QS-BH mergers

  $T \gtrsim 1$ MeV: nugget evaporation

  $T \lesssim 1$ MeV: Nucleosynthesis ——> next talk by Yudong Luo

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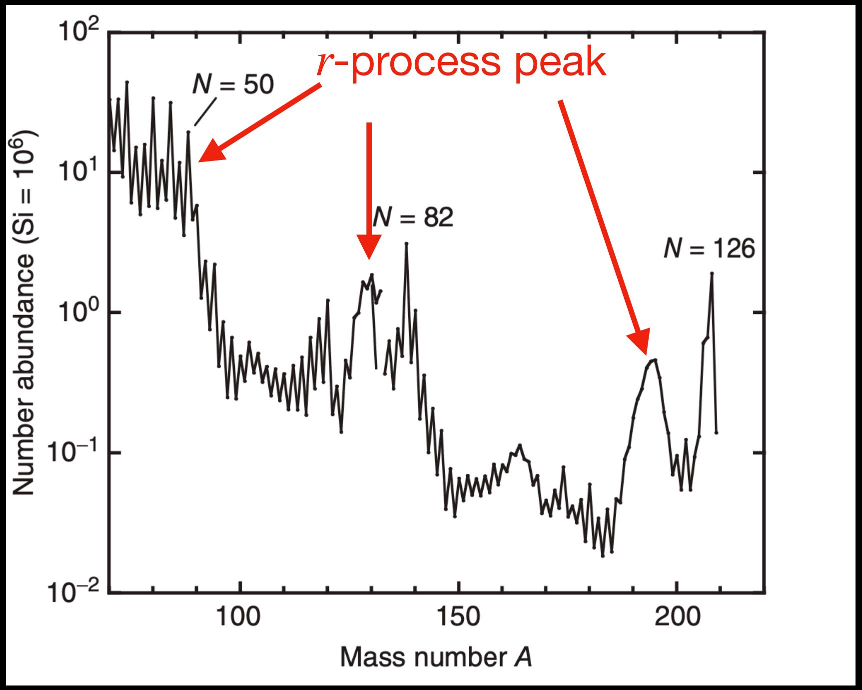
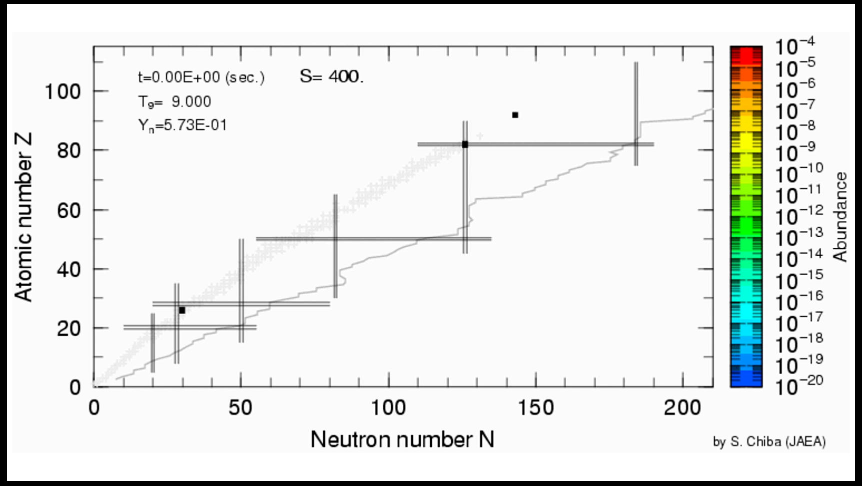
From Zhiqiang's talk

- Constrain the nuggets model

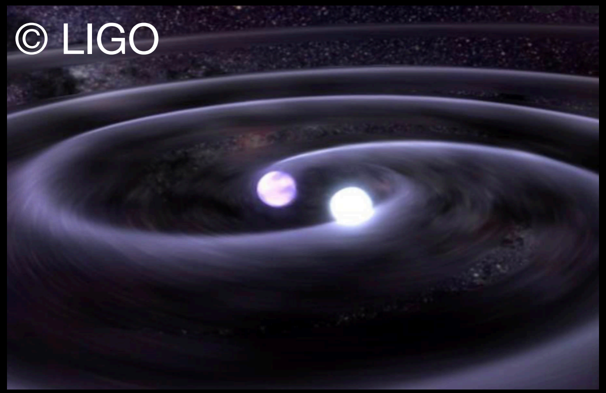
Nucleosynthesis in Binary Quark Stars

Motivation

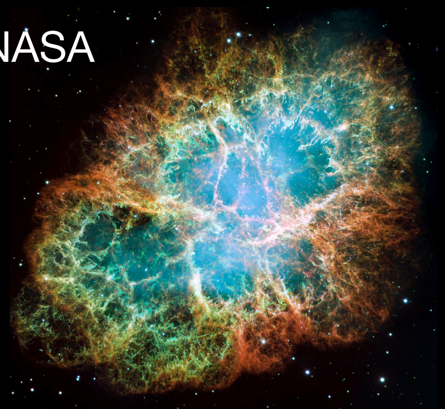




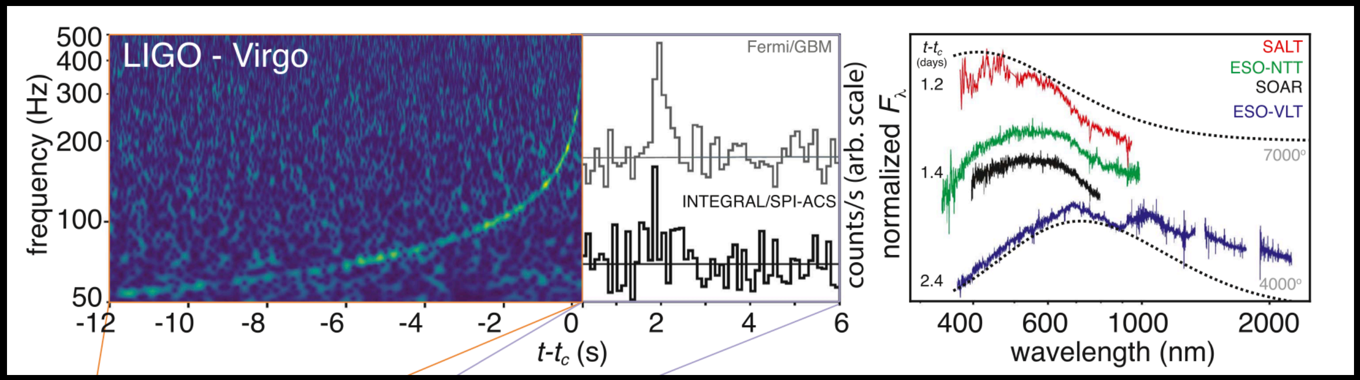
- Main sites of r-process nucleosynthesis
  - Binary neutron star merger



  - Supernovae



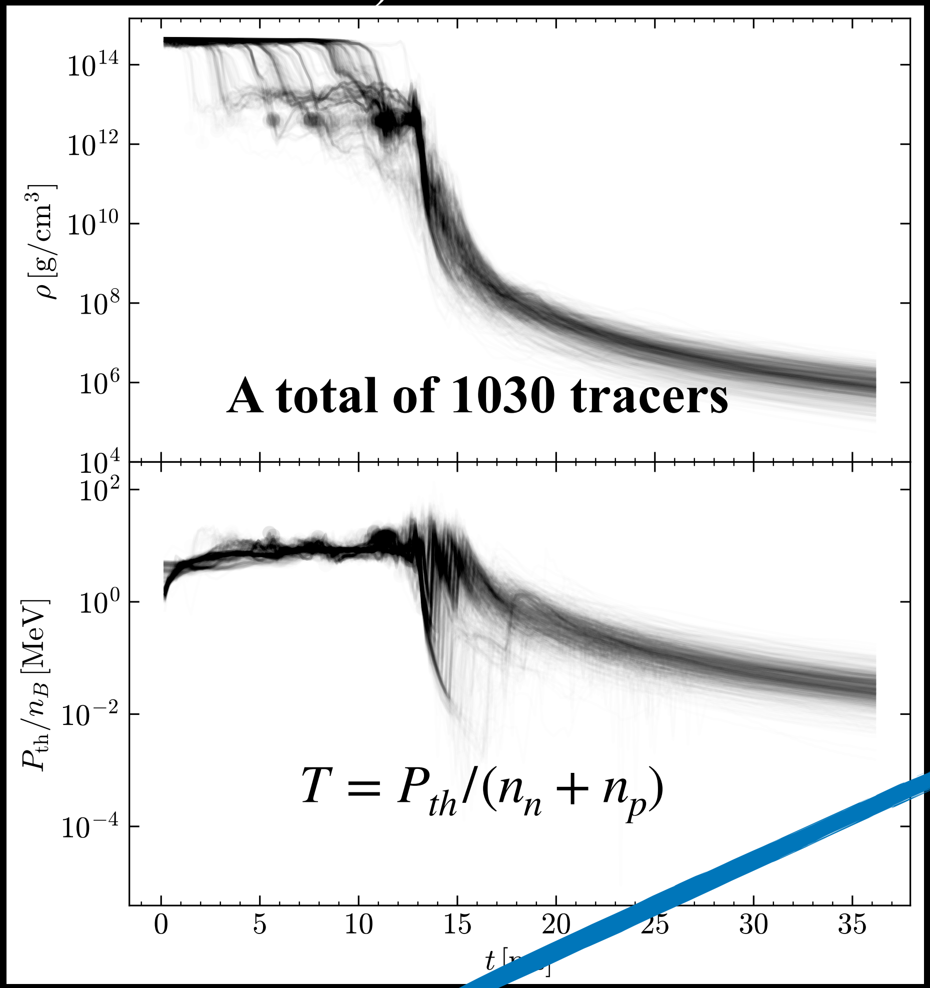
GW detection + GRB observation

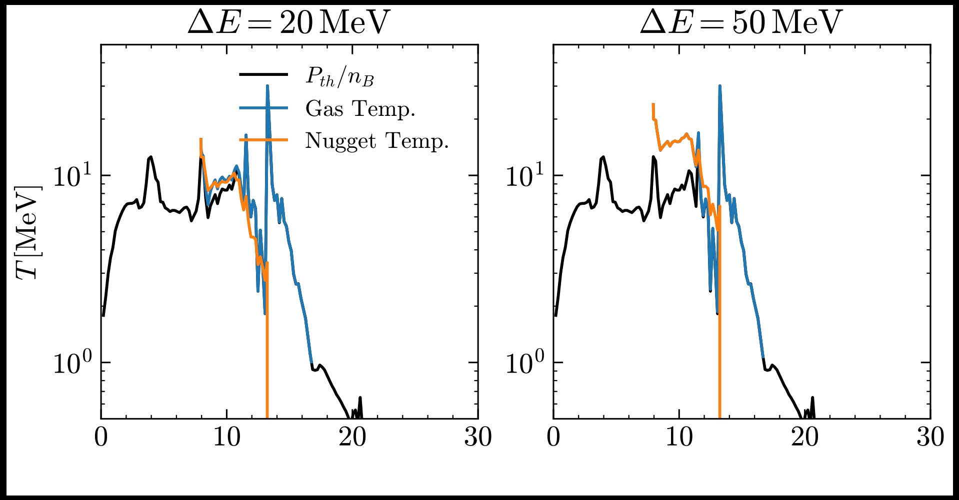


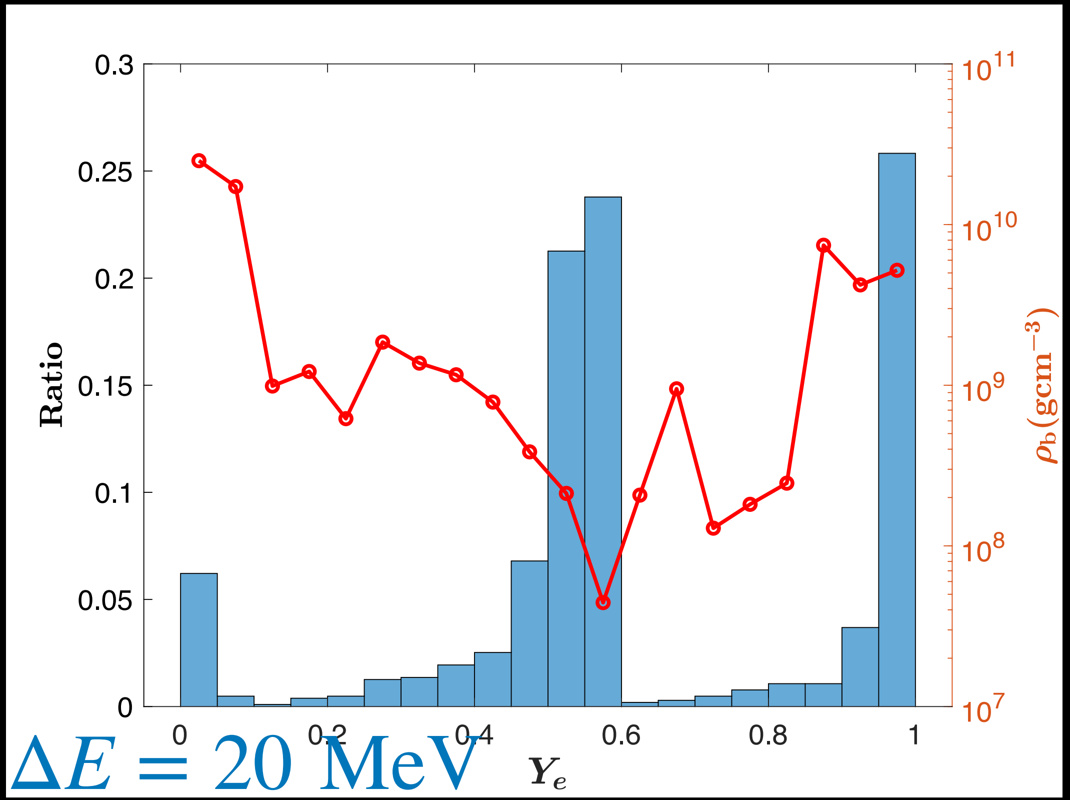
(Abbott et al 2017)

Initial Condition

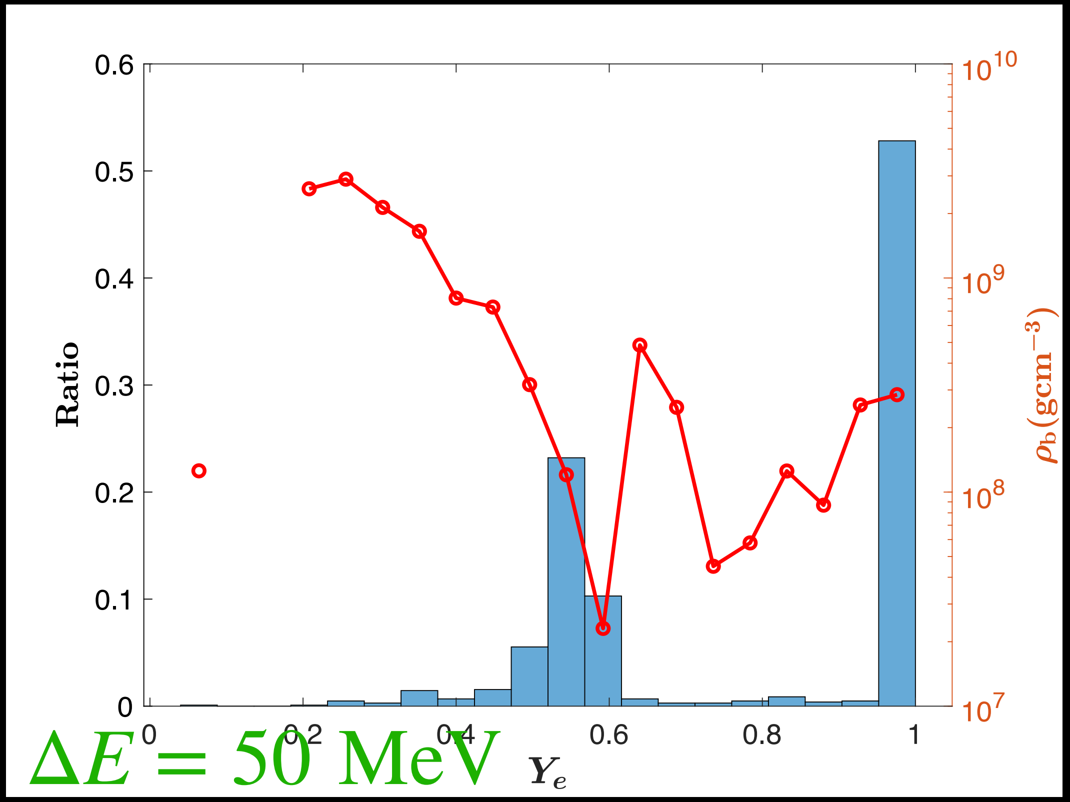
- Fully general-relativistic simulations of binary quark stars, equal mass $1.35M_\odot - 1.35M_\odot$ (Zhu & Rezzolla 2021)



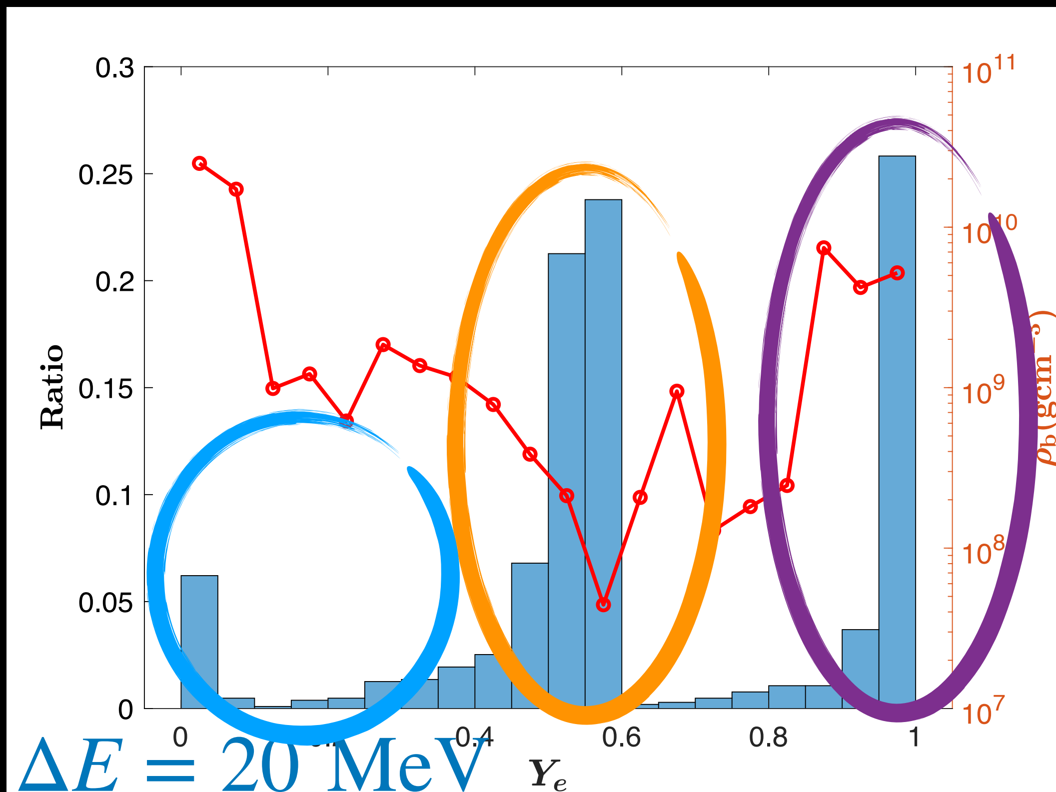




@T =1 MeV



Nucleosynthesis Yields (Preliminary)



1. Low Y_e component corresponding to strong r-process (less then 10%)

2. Some p-nuclei around A~100 could be produced?

Light Curve?

3. Very High Y_e components could produce much more iron group nuclei

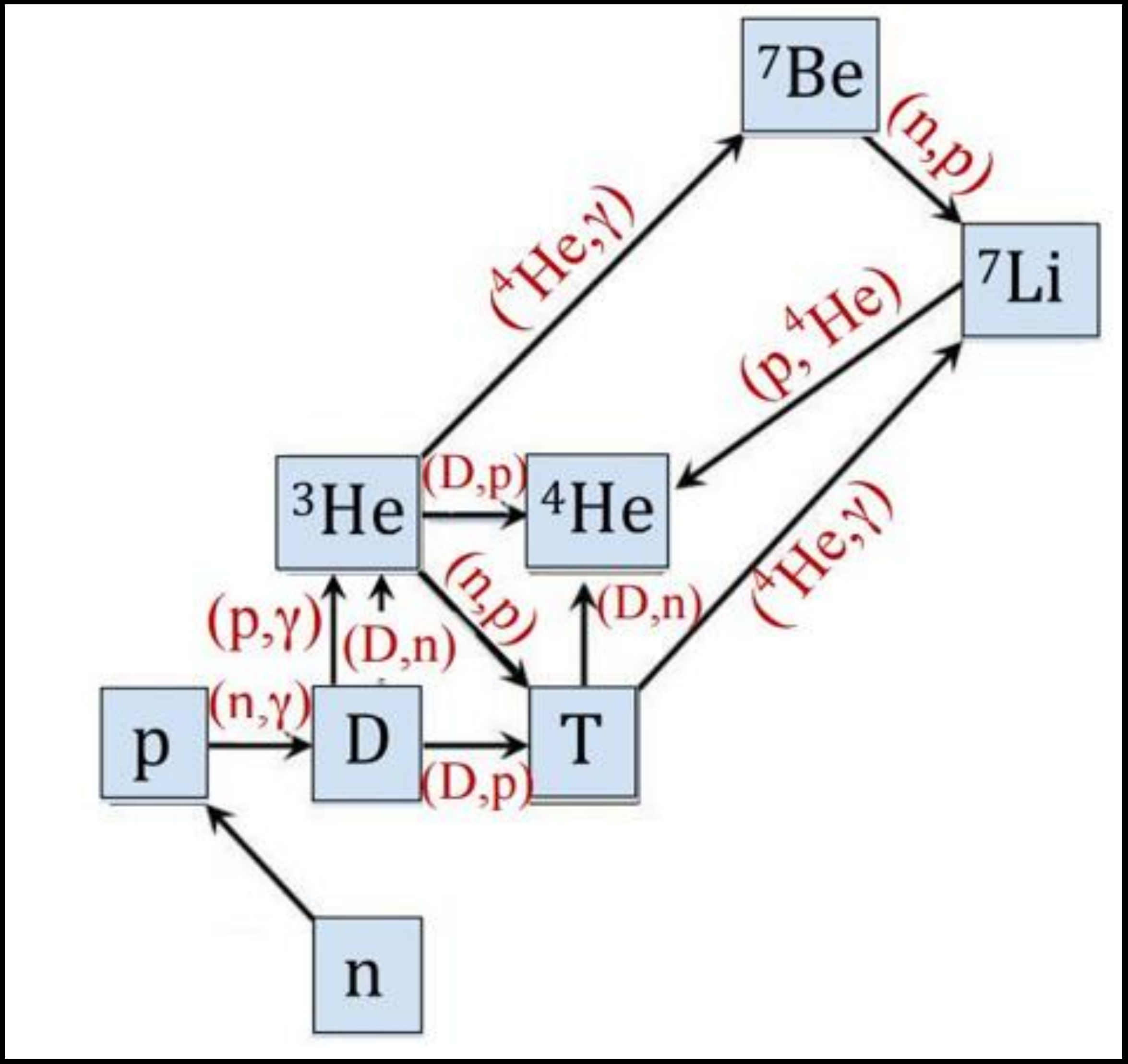
Big Bang Nucleosynthesis with Quark Nuggets

BBN reaction network

After weak interaction decoupling

$t \sim 0.1 \text{ sec} - 3 \text{ min}$

$T \sim$0.3 MeV to 0.01 MeV



Main Production:
^{4}He + small amount of ^{2}H, ^{3}He, ^{3}H + *tiny amount of* ^{7}Li

Friedmann Equations

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi G}{3}\rho_{\text{tot}}$$

$$\frac{d\rho}{dt} = -3H\left(\rho + p\right)$$

Number density evolution

Reaction rate $$r_{ij} = \frac{n_i n_j}{1+\delta_{ij}}\langle \sigma v \rangle_{ij}$$

Network Chain $$\left(\frac{\partial n_i}{\partial t}\right)_\rho = \sum_j N^i_j r_j + \sum_{j,k} N^i_{j,k} r_{j,k} + \sum_{j,k,l} N^i_{j,k,l} r_{j,k,l}$$

BBN recalling

Theoretical yields $@\eta_{10} = 6.10$

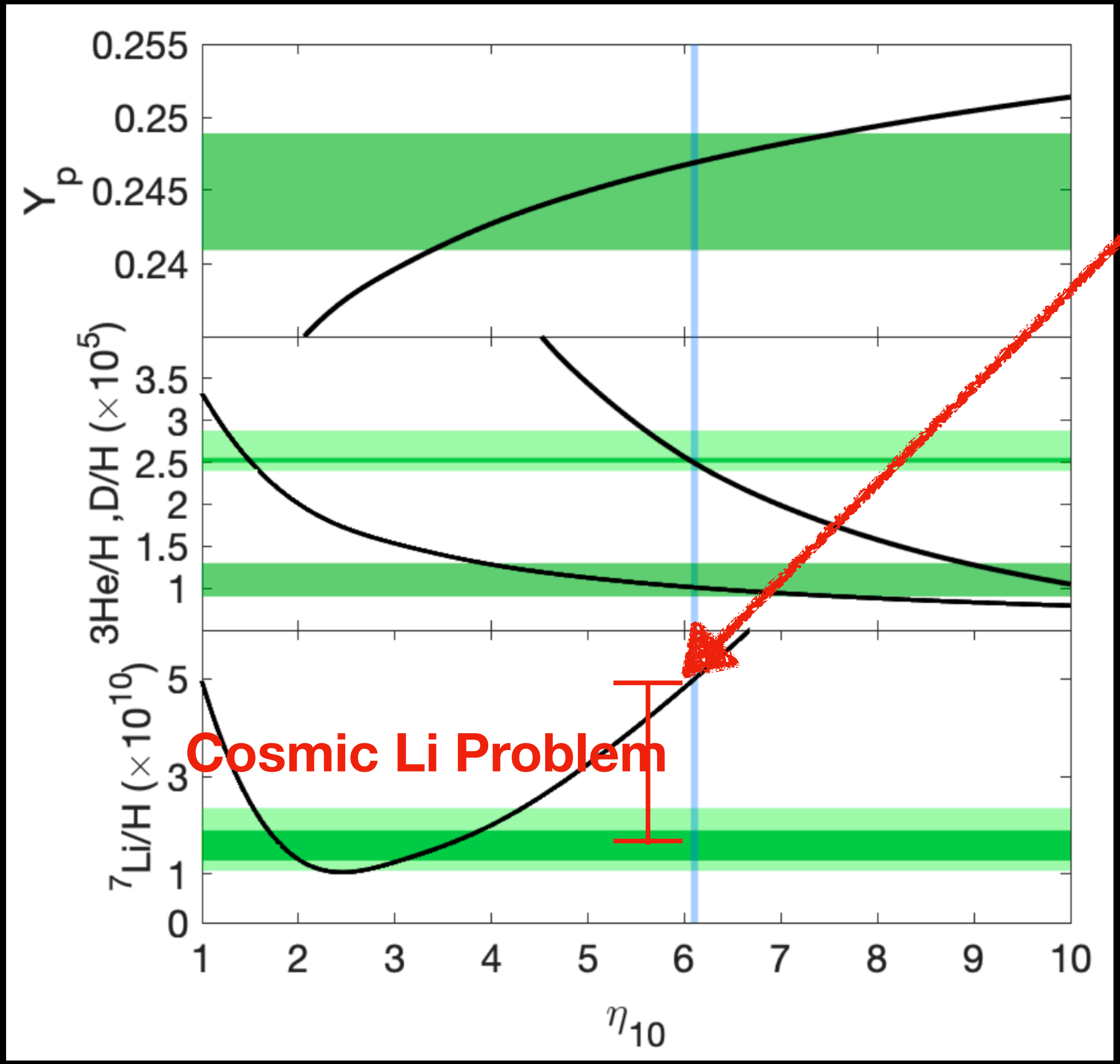
Y_p *(mass fraction of* ^{4}He) : 0.2466

D/H : 2.46×10^{-5}

^{3}He/H : 1.041×10^{-5}

^{7}Li/H : 5.188×10^{-10}

Abundance vs η_{10}



Observations

η_{10} : Ade et al., 2016 (Planck satellite)

$\eta_{10} := n_{baryon}/n_{photon} \times 10^{10}$

Baryon-to-photon ratio

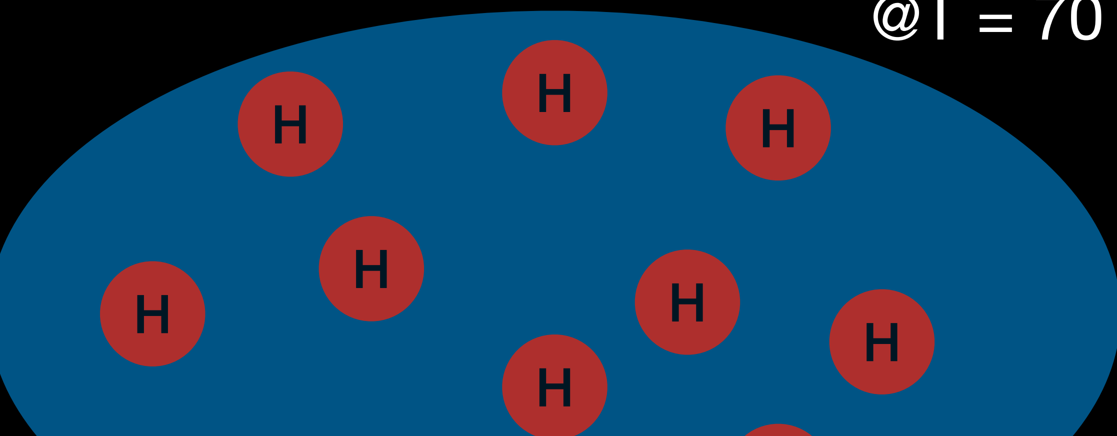
Y_p: Aver et al., 2015

D/H: Cooke et al., 2018

^{7}Li/H: Sbordone et al., 2010

New Inhomogeneous BBN

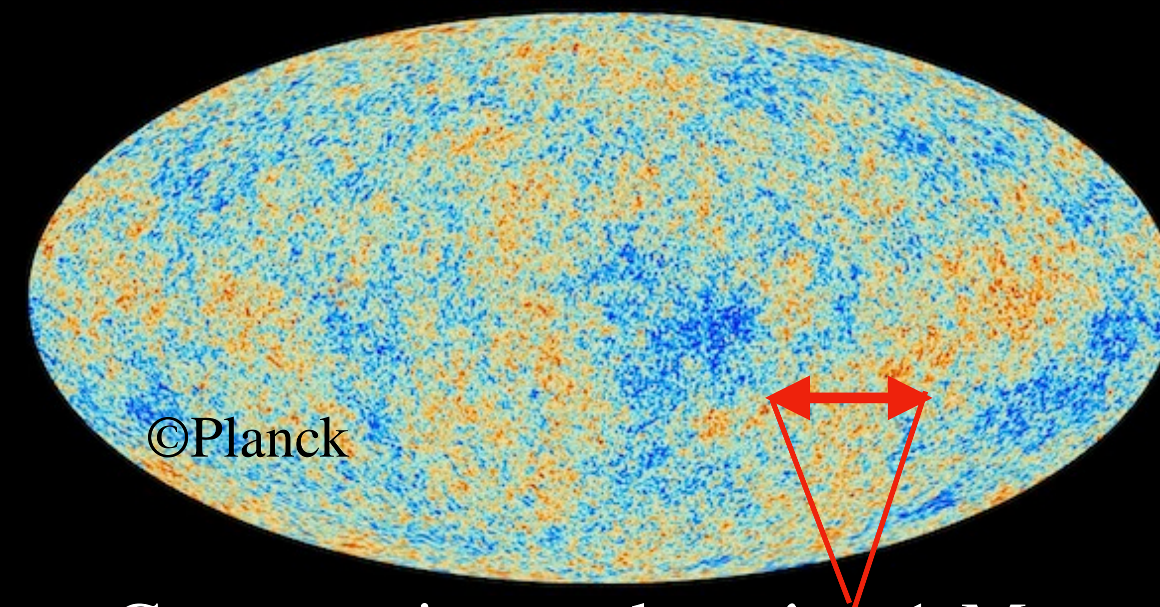
@T = 70 MeV ~ 1E-6 s



$$\bar{\rho}_b = 10^6 \mathrm{g} \cdot \mathrm{cm}^{-3}$$

$$\rho_H = 10^6 \rho_b \rightarrow R_H = 10^{-2} R_{cosmic}$$

@T = 2.73 K



$$\mathrm{Co-moving\ scale}: \ \lambda = 1\ \mathrm{Mpc}$$

Friedmann Equations

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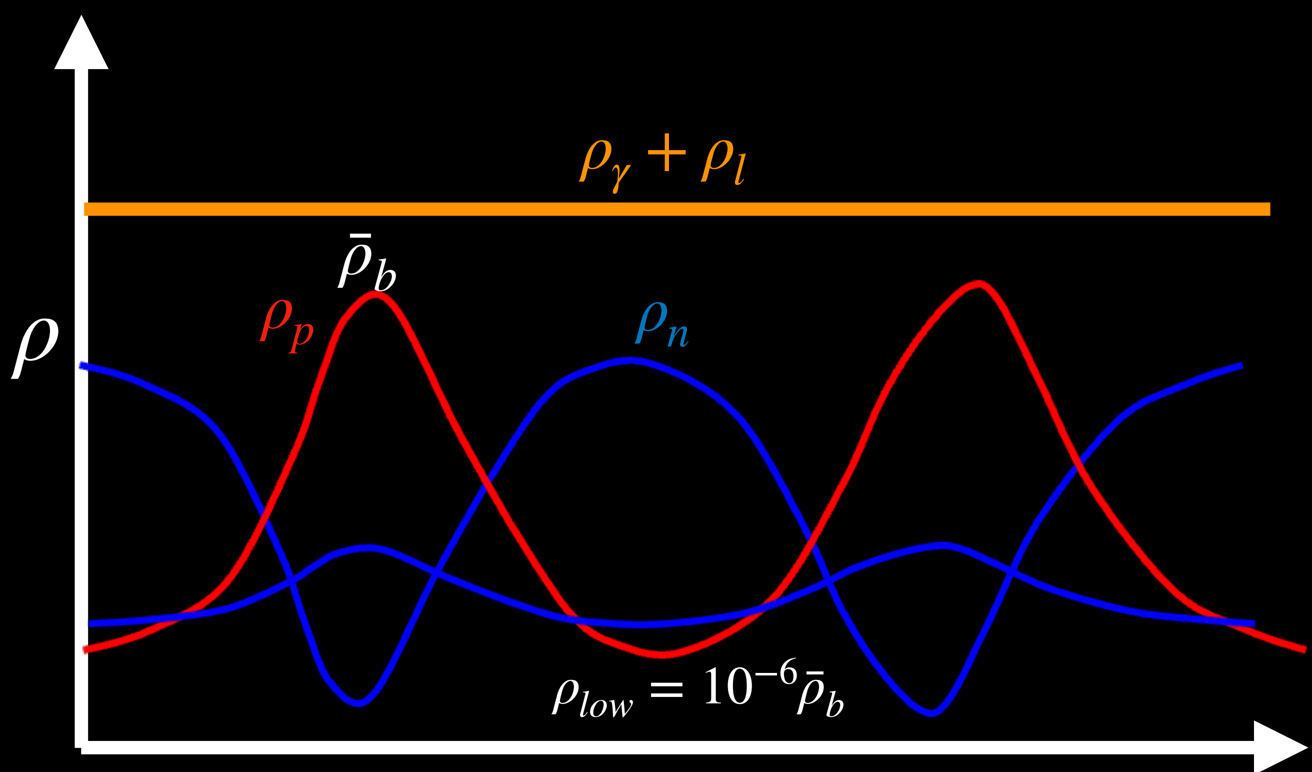
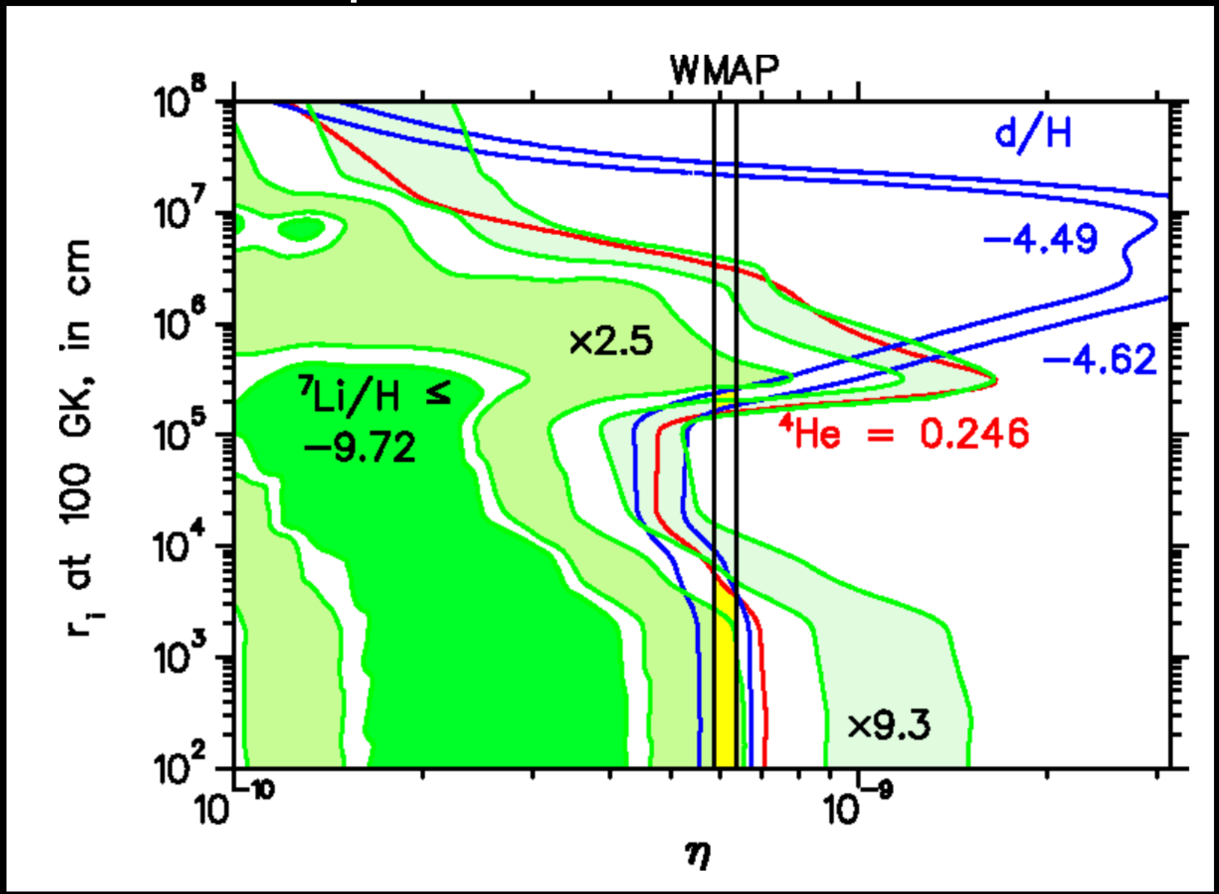
$$\frac{dA}{dt} = -\frac{dN_n}{dt} - \frac{dN_p}{dt}$$

$$\frac{dN_{n,p}}{dt} = \left[\frac{dN_{n,p}}{dt}\right]_{A\rightarrow(A-1)+n,p} + \left[\frac{dN_{n,p}}{dt}\right]_{n\rightarrow p}$$

Inhomogeneous BBN in 1990's



Space Coordinate



Lara et al (2006)

Comparison

- **High-density regions are 10^6 than the $\bar{\rho}_b$, they are proton-rich**

Three cases (depending on ΔE)

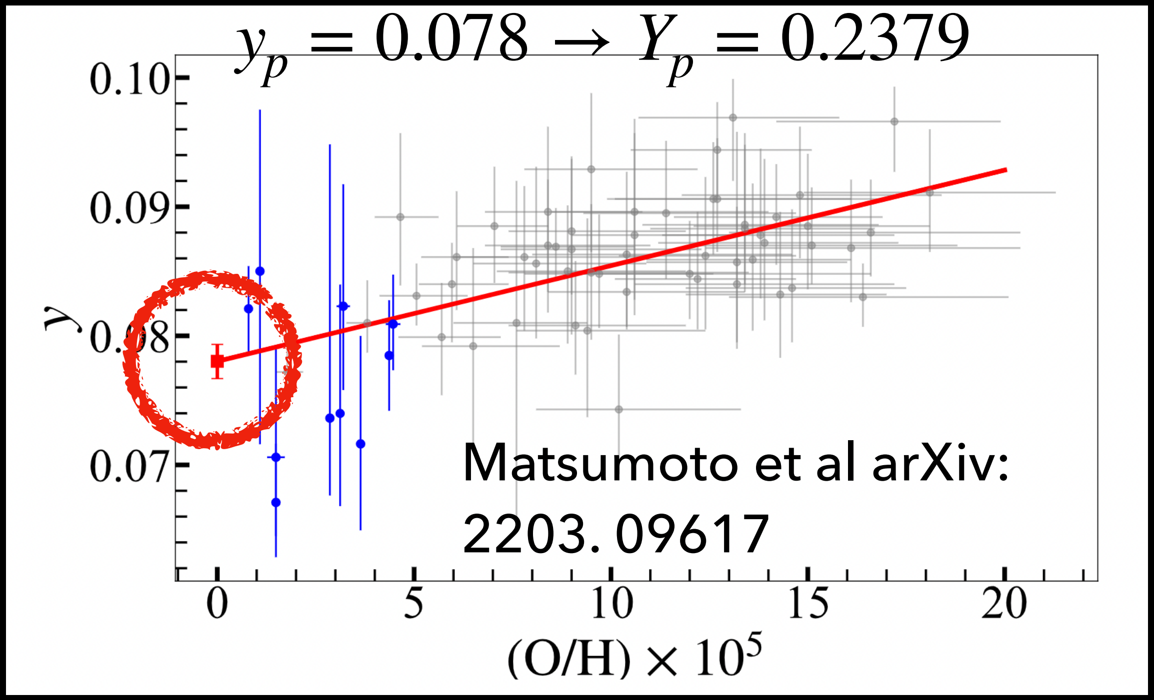
1. All QN evaporated at T>>1 MeV, then the dense region will recover to the n-p equilibrium. Then when the temperature drops to about 1 MeV, we will have a similar scenario as IBBN.
2. QN could survive after T<1 MeV. Then, the dense regions are pure proton gas, barely proceed any nucleosynthesis. The dilute regions are the standard BBN.
3. All QN evaporated at T~1 MeV, then the weak interaction rates are not efficient, so we will have some neutrons inside the proton-rich region.

Conclusion

- In Binary Quark Stars, our preliminary calculation shows the distinguishing results from BNSM

Thank You !

- In Big Bang Nucleosynthesis, we hope we can constrain the nuggets model from primordial abundances



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3. All QN evaporated at T~1 MeV, then the weak interaction rates are not efficient, so we will have some neutrons inside the proton-rich region.