Theoretical Nuclear Astrophysics and Gravitational Waves

Nicole Vassh

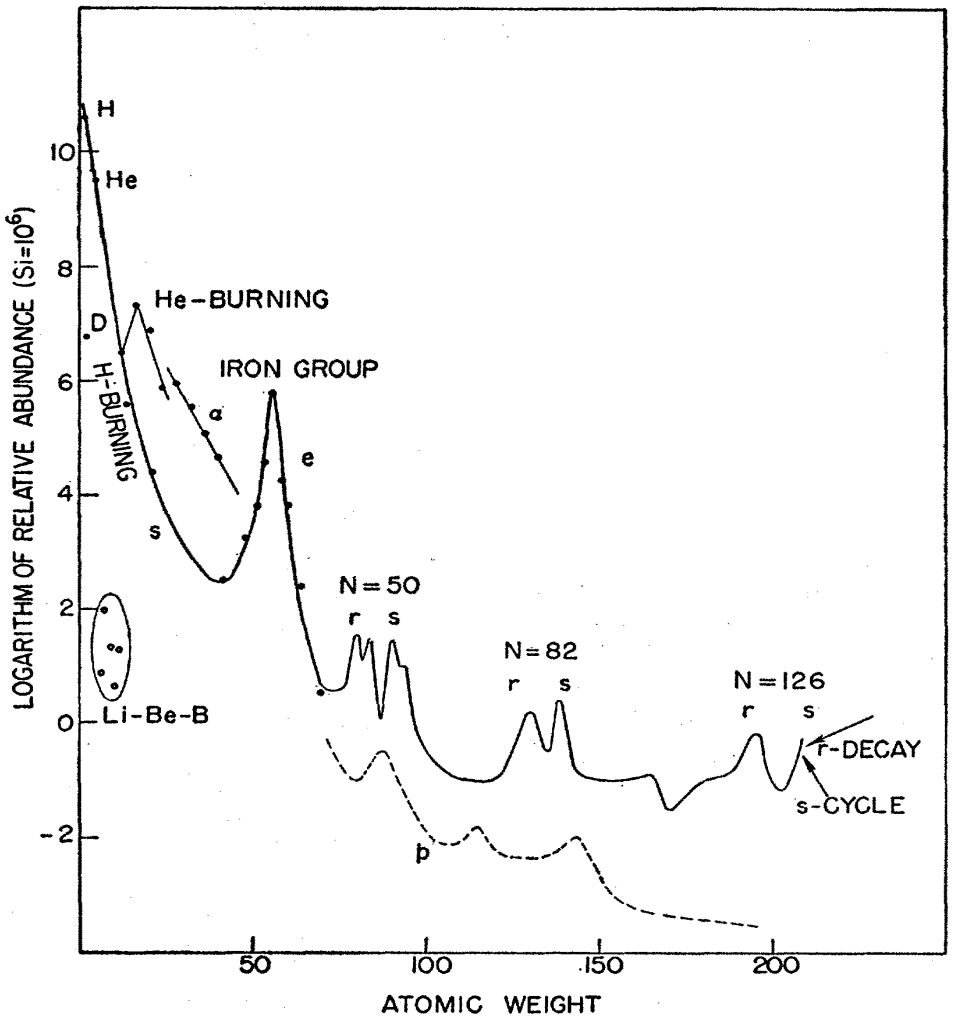
TRIUMF Theory Group

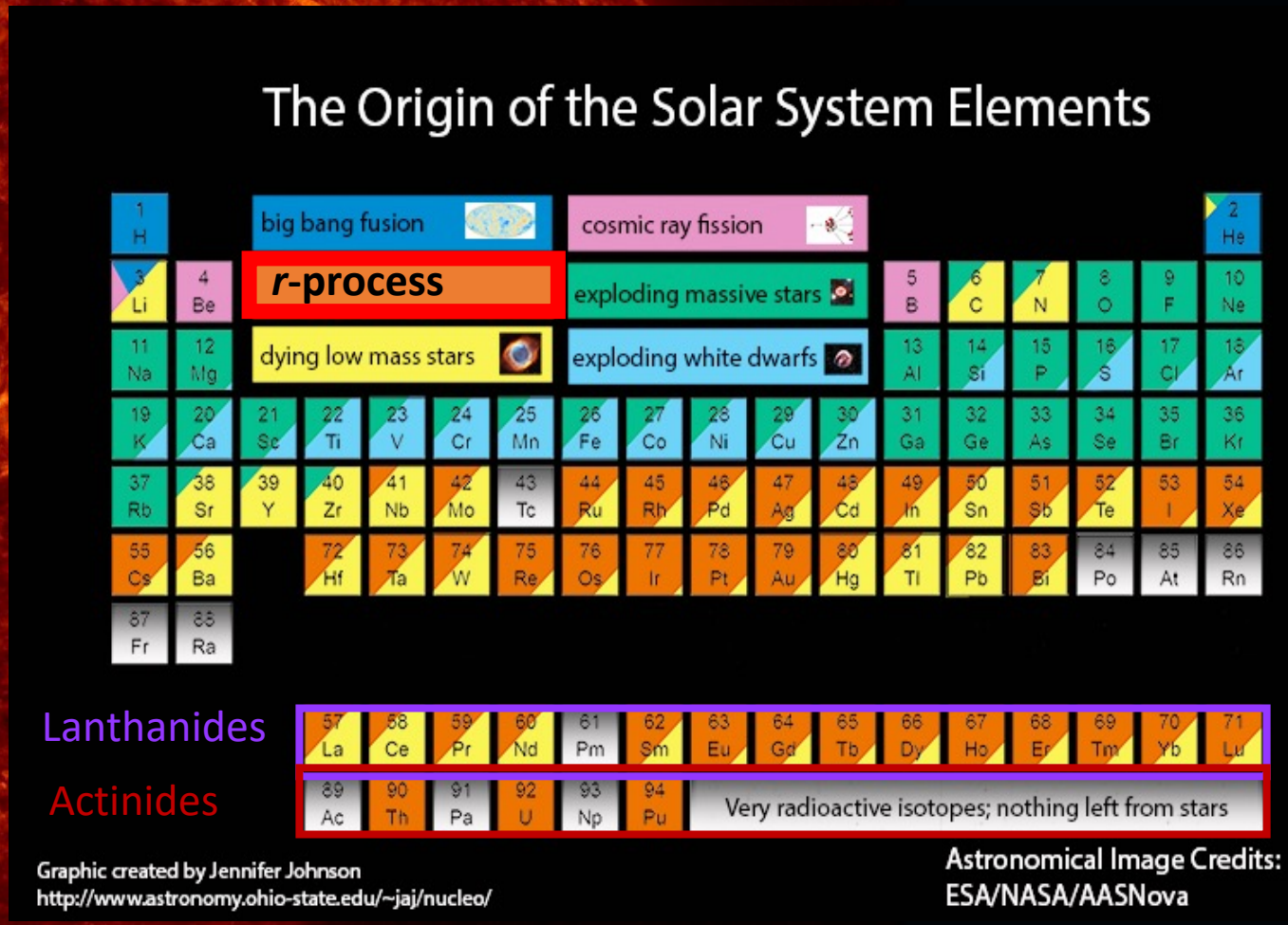
LISA Canada Workshop,

August 25, 2022

65 years of Nuclear Astrophysics: Multiple nucleosynthesis sites enriched the solar system

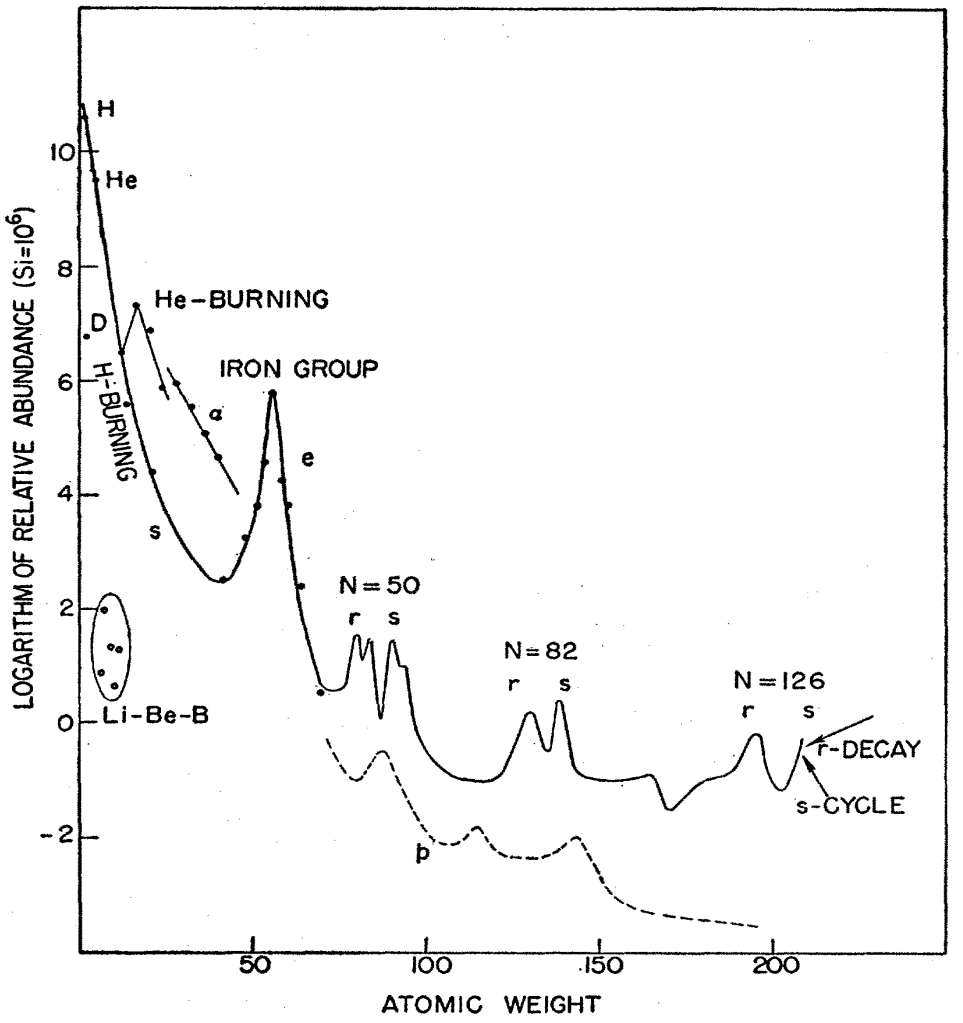
Burbidge, Burbidge, Fowler, and Hoyle (B^2FH) (1957)

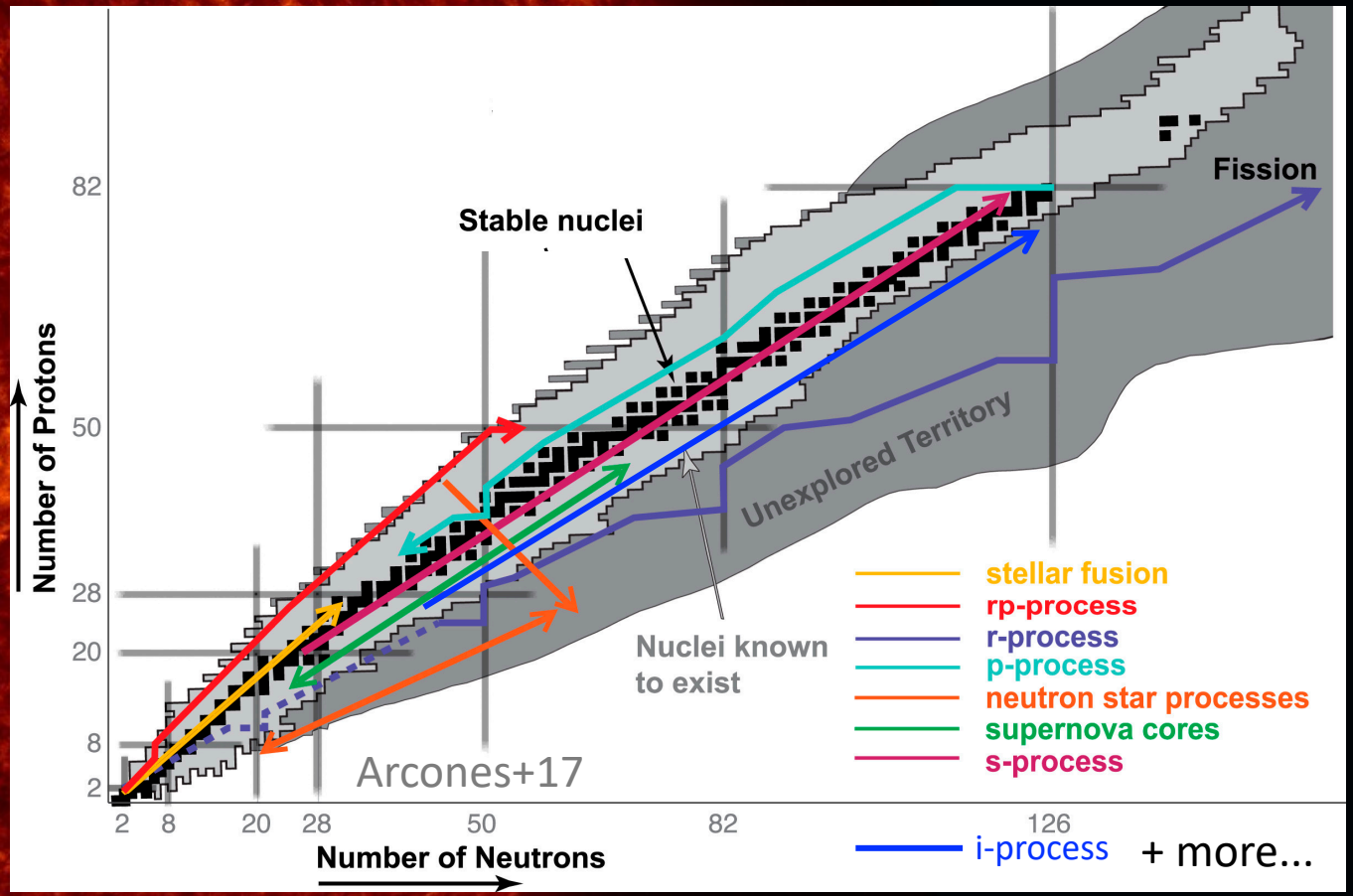




65 years of Nuclear Astrophysics:
How many processes? What are their astrophysical sites?

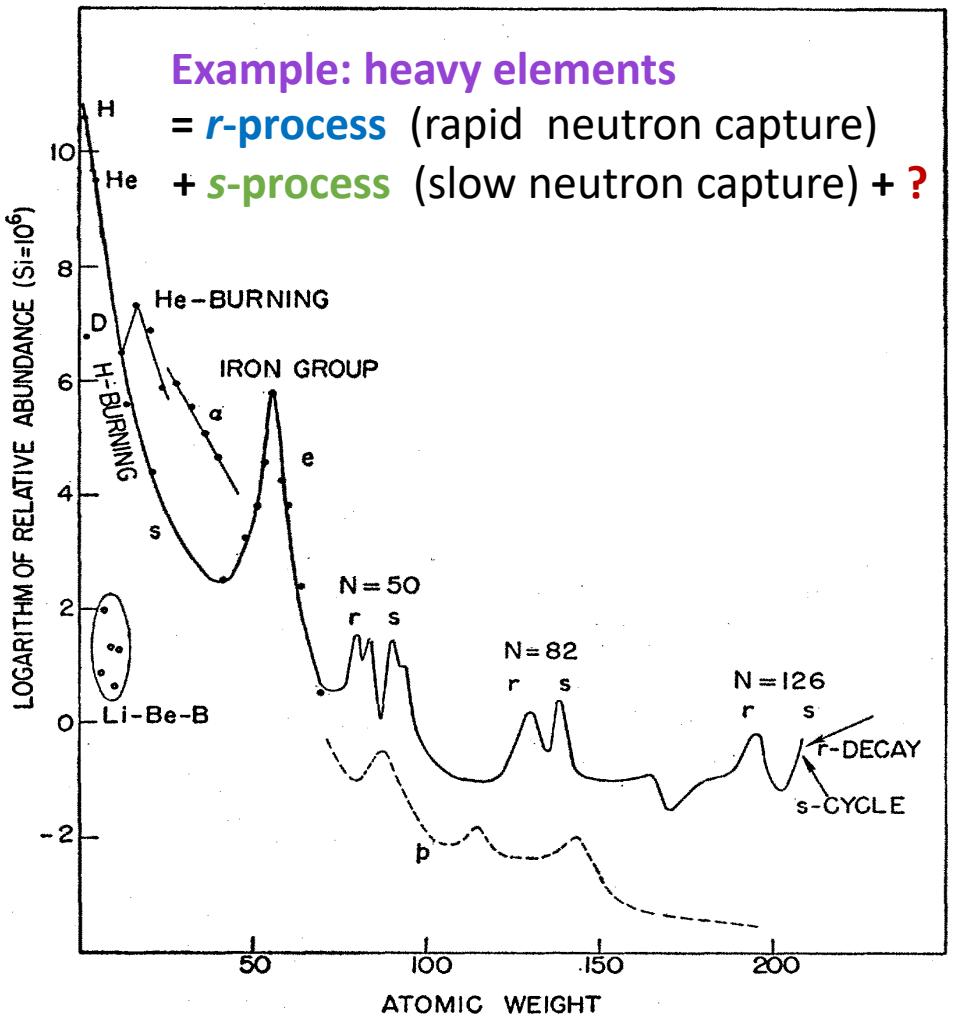
Burbidge, Burbidge, Fowler, and Hoyle (B^2FH) (1957)

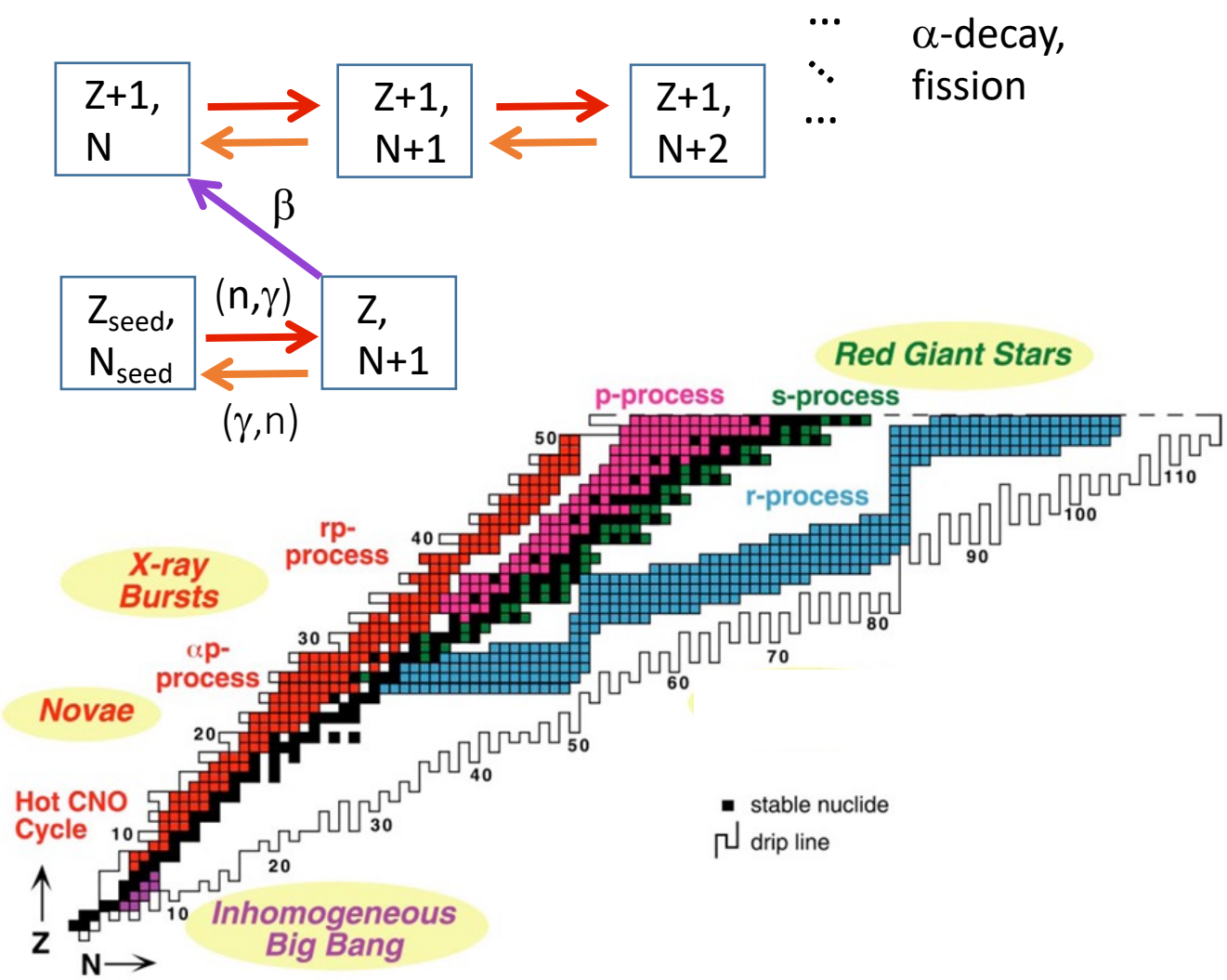




65 years of Nuclear Astrophysics:
Observables depend on the properties of exotic nuclei

Burbidge, Burbidge, Fowler, and Hoyle (B^2FH) (1957)

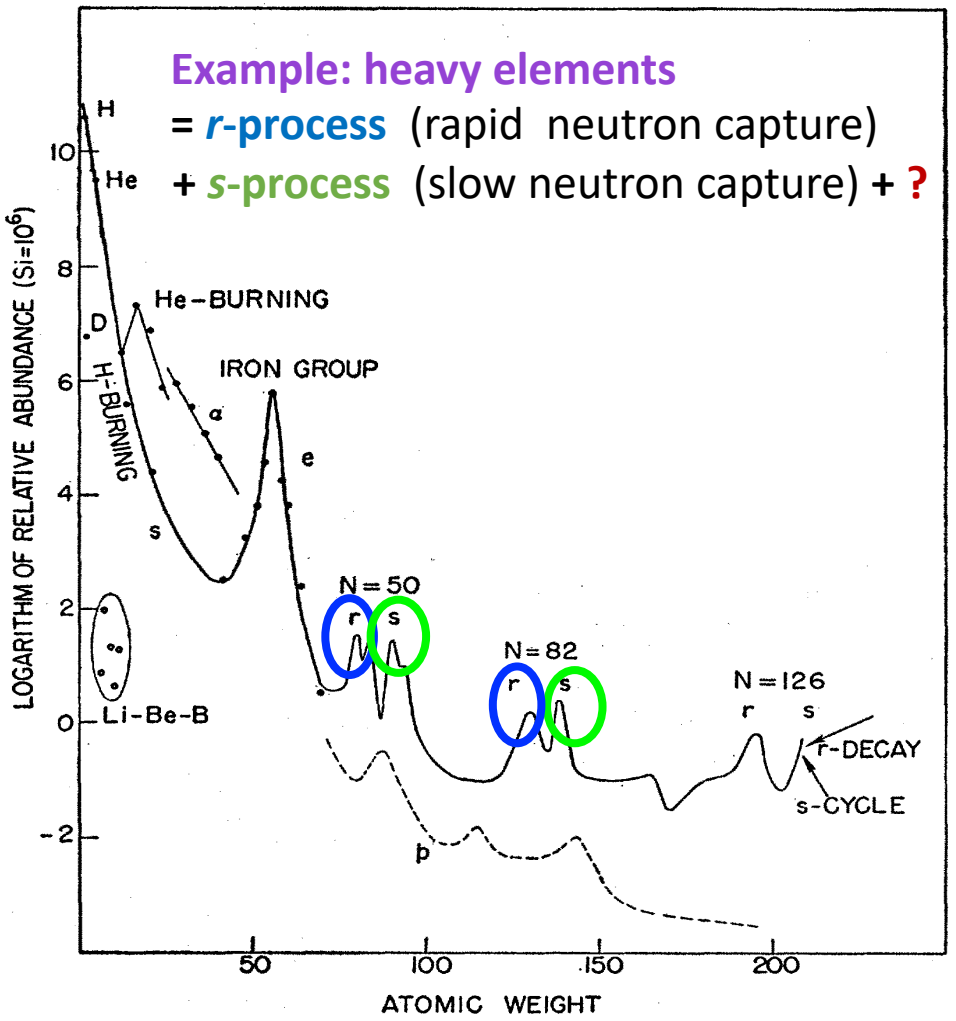


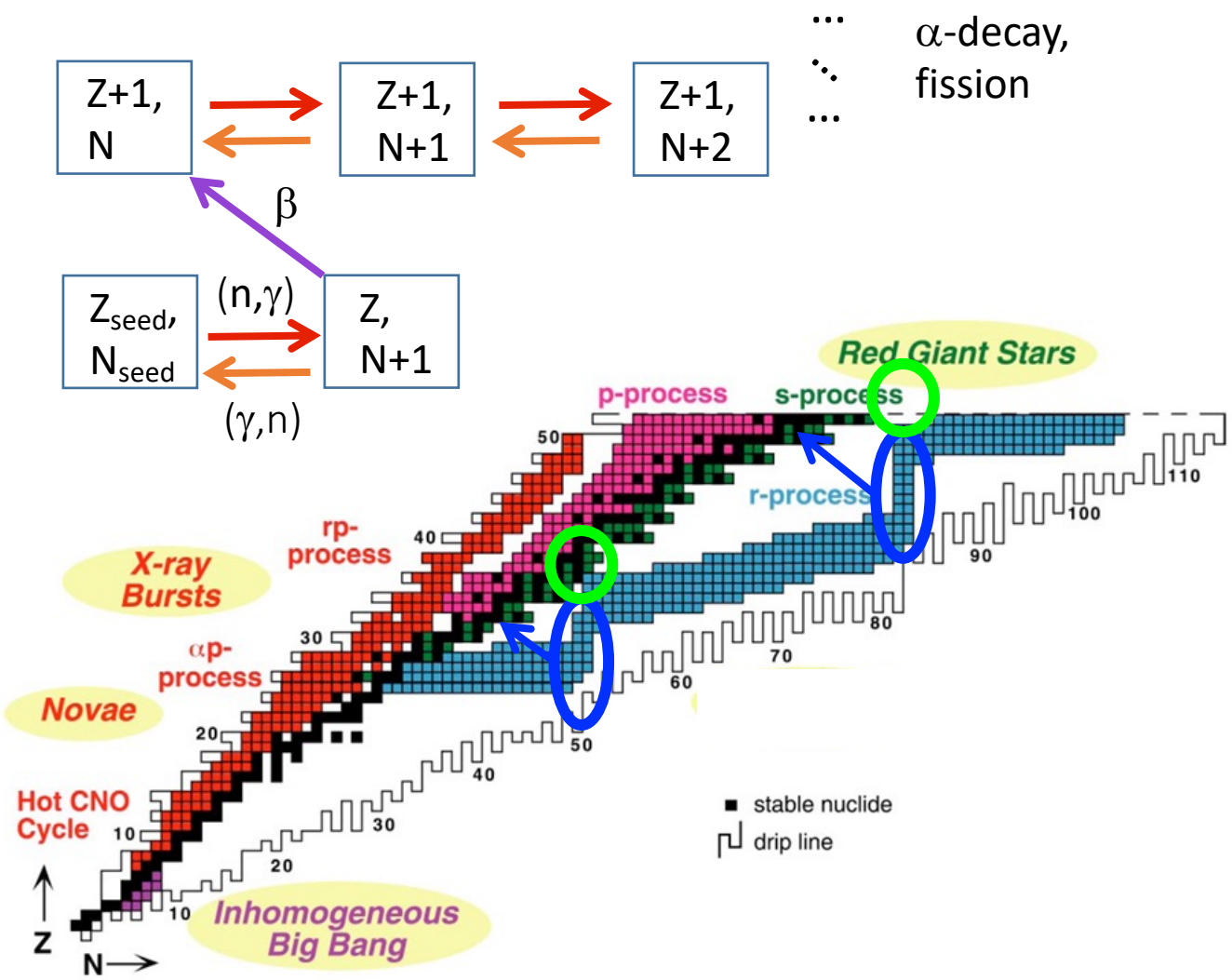


Smith&Rehm 01

65 years of Nuclear Astrophysics:
Observables depend on the properties of exotic nuclei

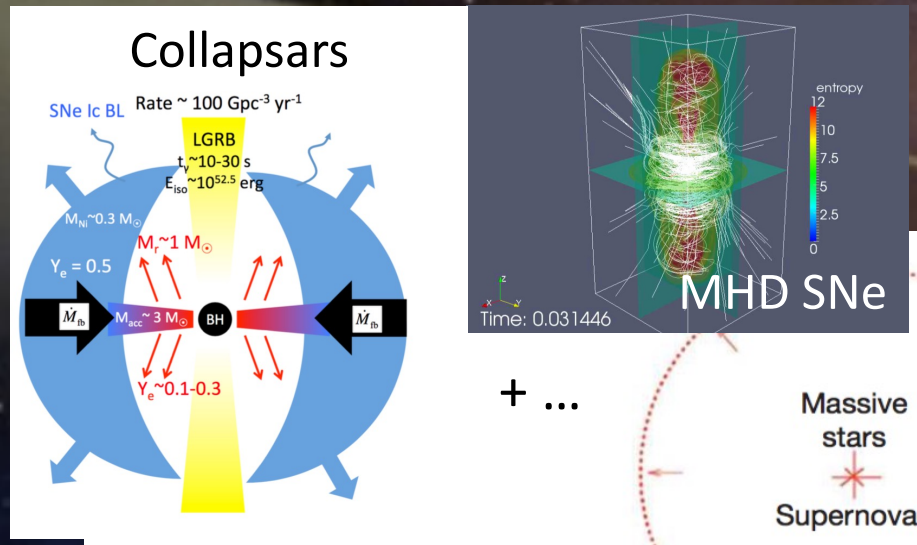
Burbidge, Burbidge, Fowler, and Hoyle (B^2FH) (1957)





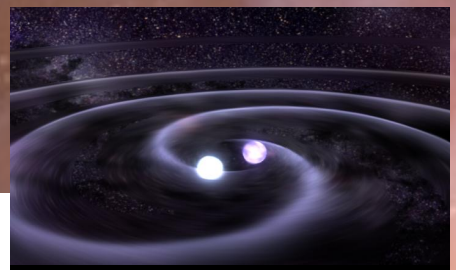
Smith&Rehm 01

Where *and when* were the elements we see in stars produced?

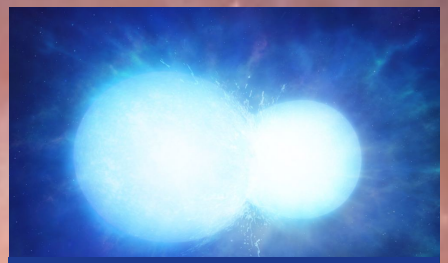


+ …

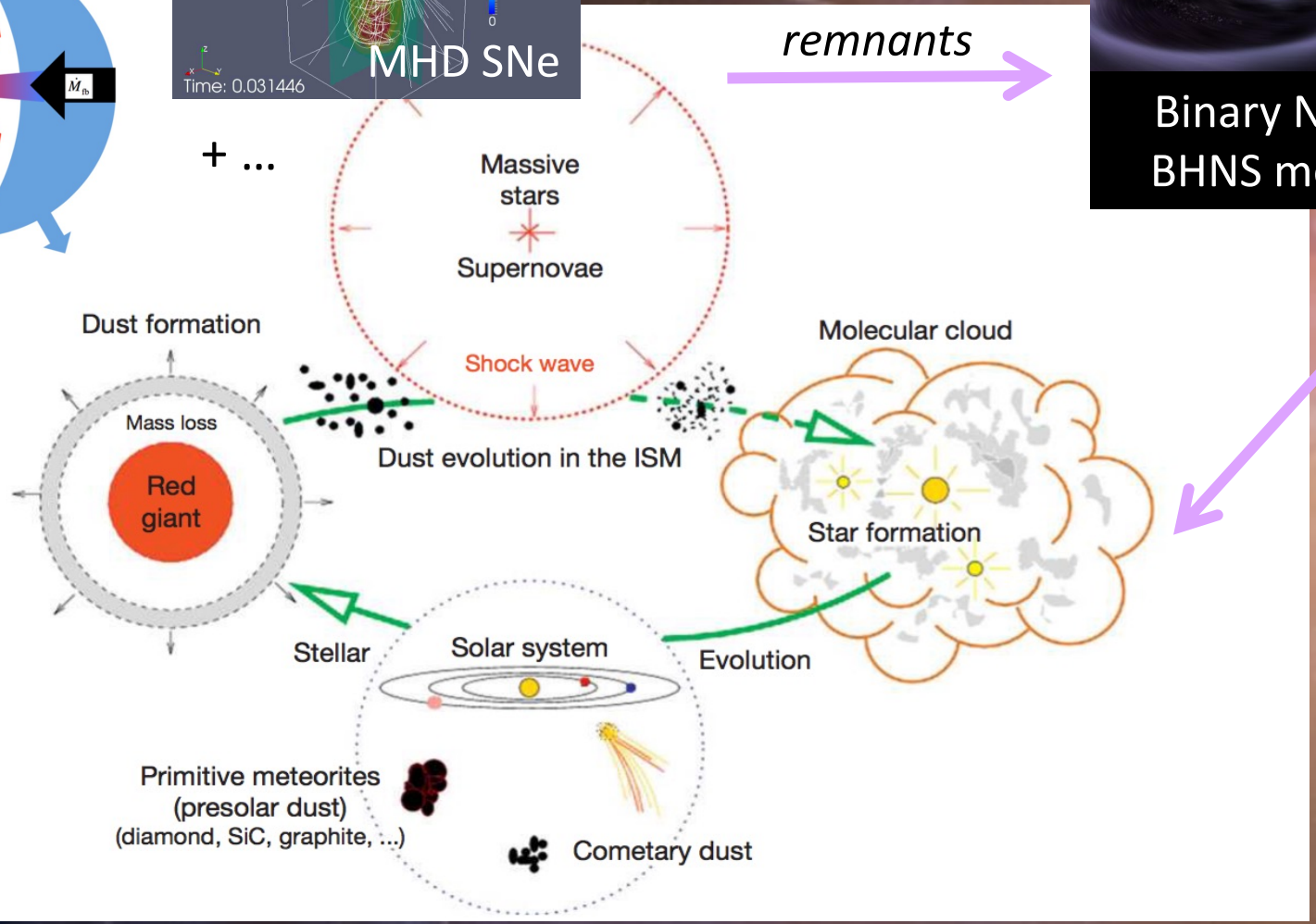
remnants



Binary NS and BHNS mergers



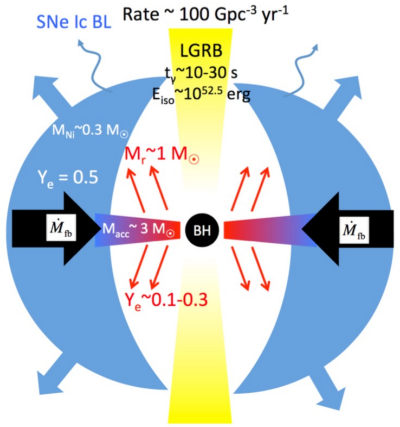
Accreting WD and WD mergers

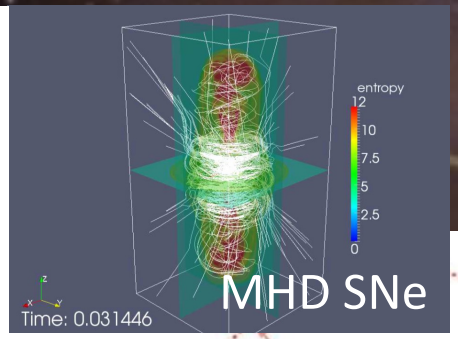


Palm+14

Where *and when* were the elements we see in stars produced?

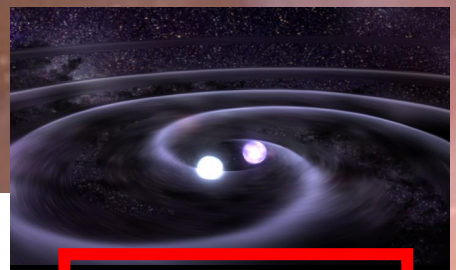
Collapsars



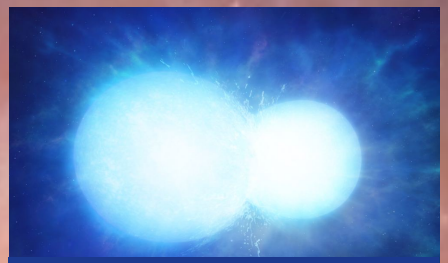


+ …

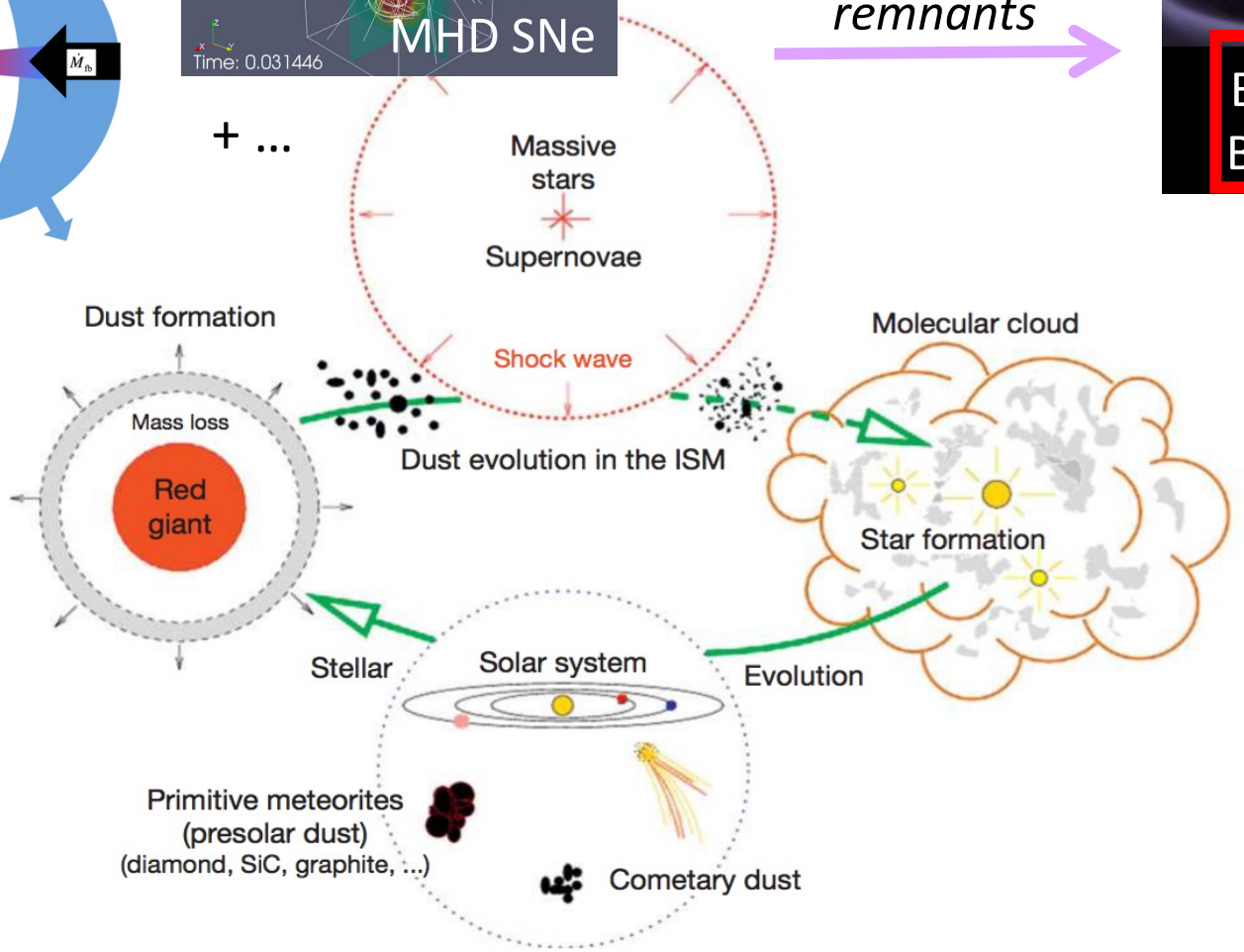
remnants



Binary NS and BHNS mergers



Accreting WD and WD mergers



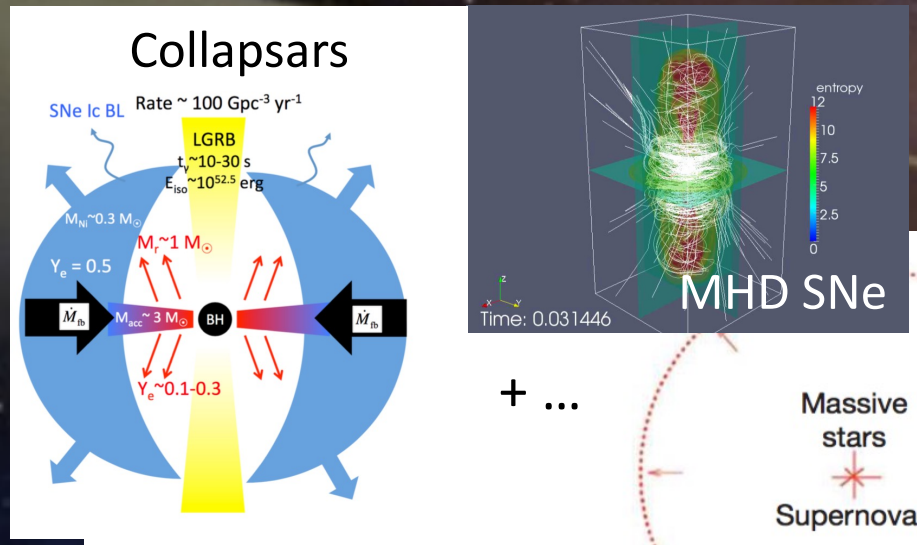
Palm+14

How do current gravitational wave detections inform this picture?

BNS example:

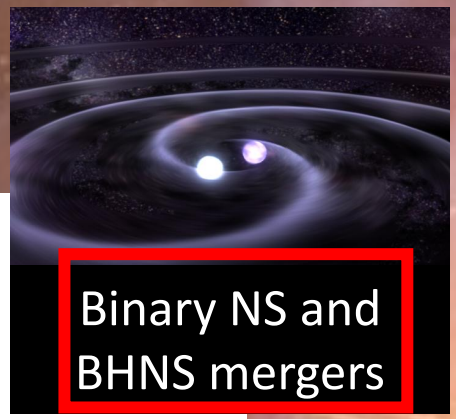
1. Event identification + EM follow-up
2. NS EOS
3. NS merger rate in the local universe

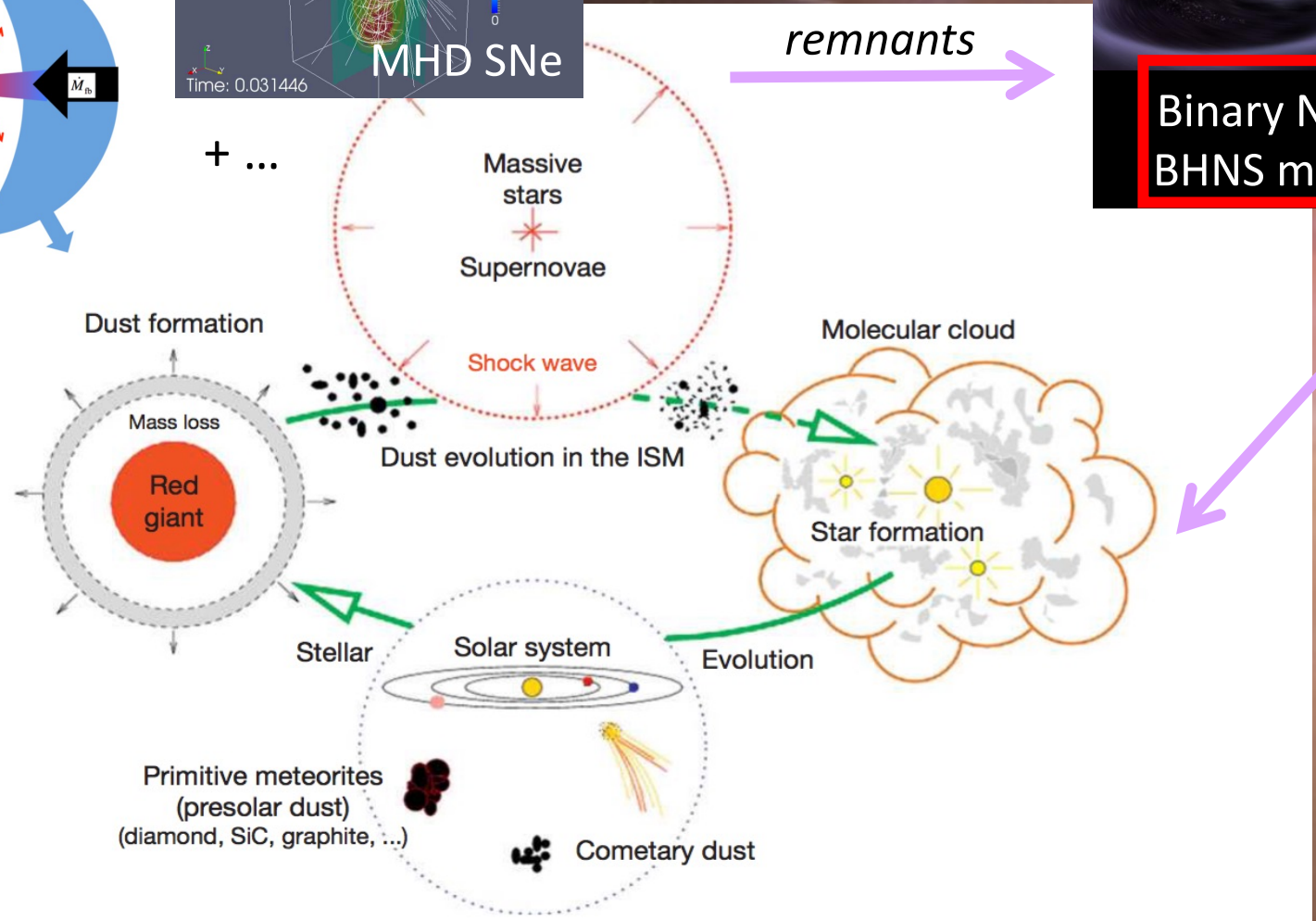
Where *and when* were the elements we see in stars produced?



+ …

remnants





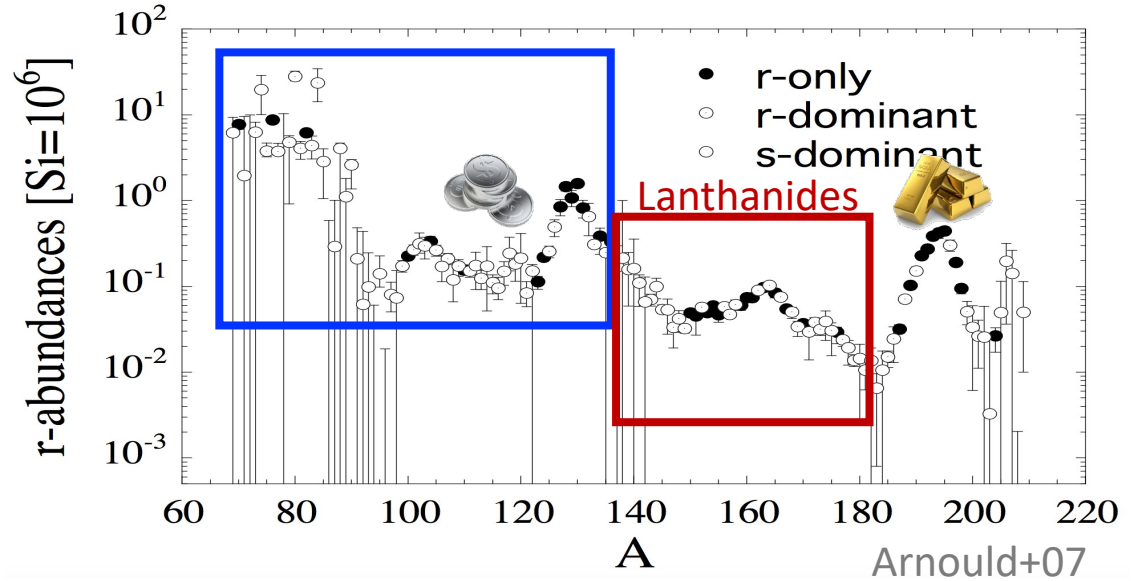
Palm+14

How do current gravitational wave detections inform this picture?

BNS example:

1. Event identification + EM follow-up
2. NS EOS
3. NS merger rate in the local universe

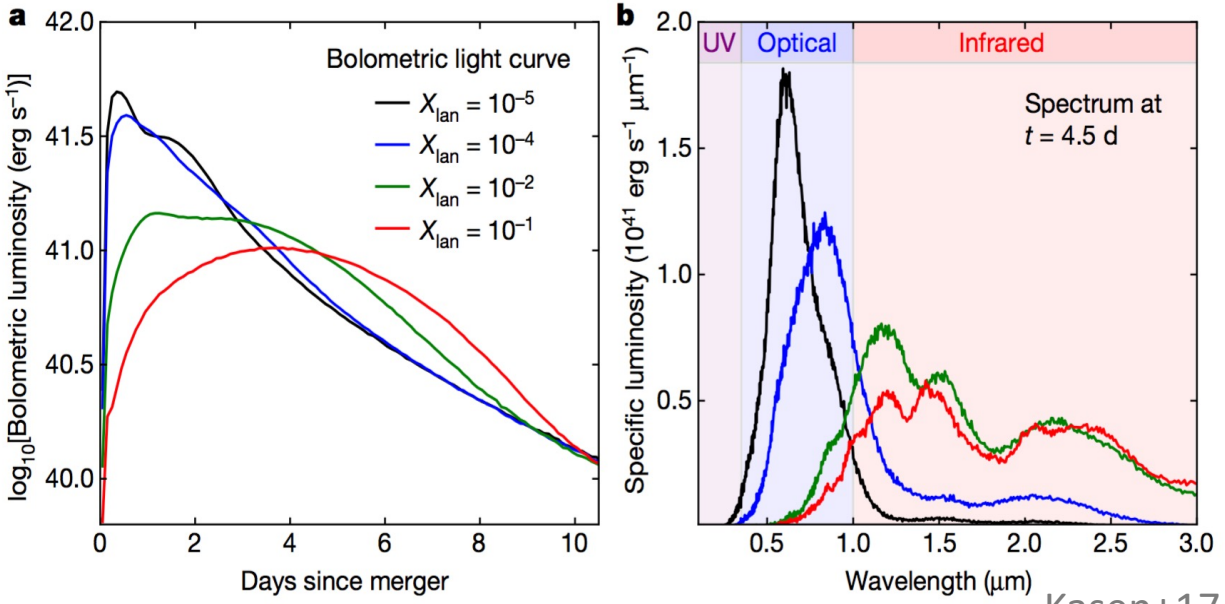
Binary neutron star merger GW170817 & “red” / “blue” kilonovae



Arnould+07

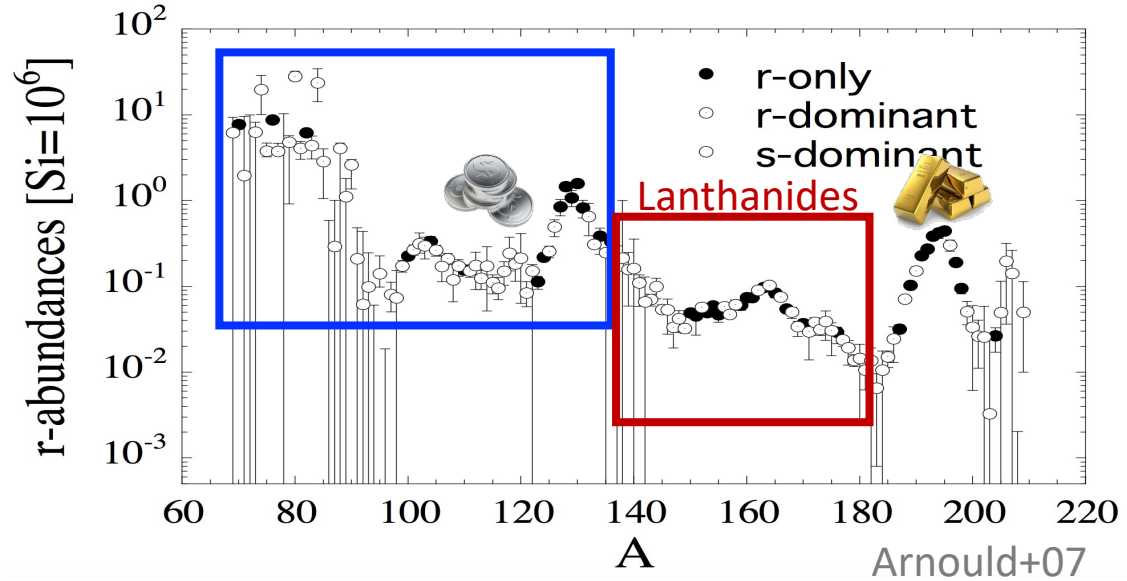
Spectra and light curves depend on the species present; Lanthanide and/or actinide mass fraction ↑, opacity ↑, longer duration light curve shifted toward infrared

Model



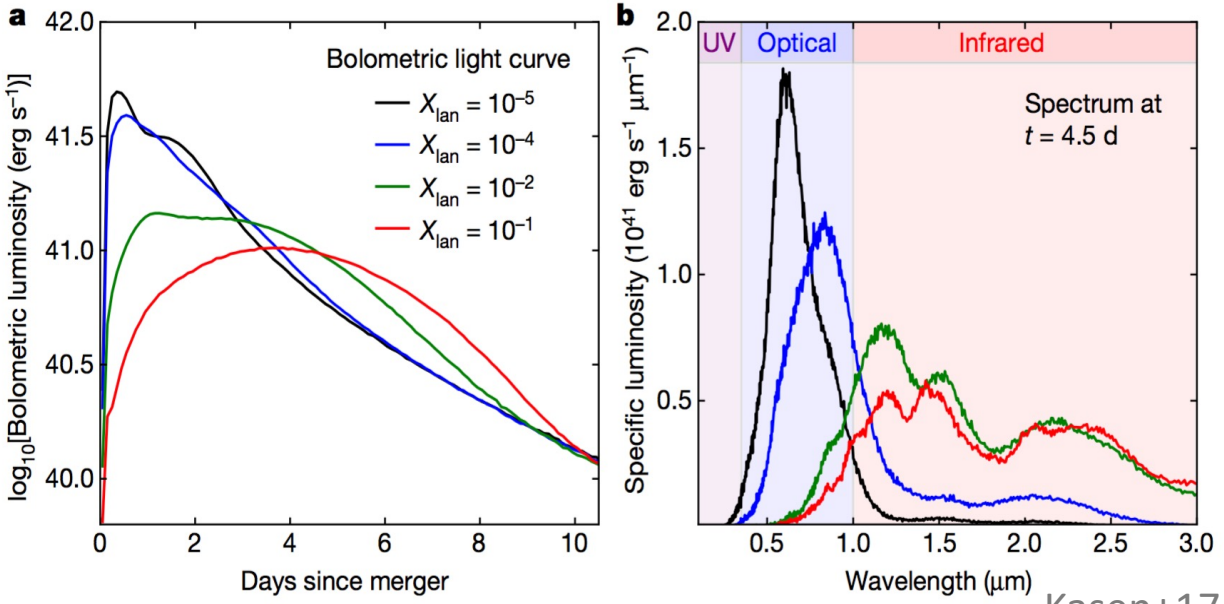
Kasen+17

Binary neutron star merger GW170817 & “red” / “blue” kilonovae

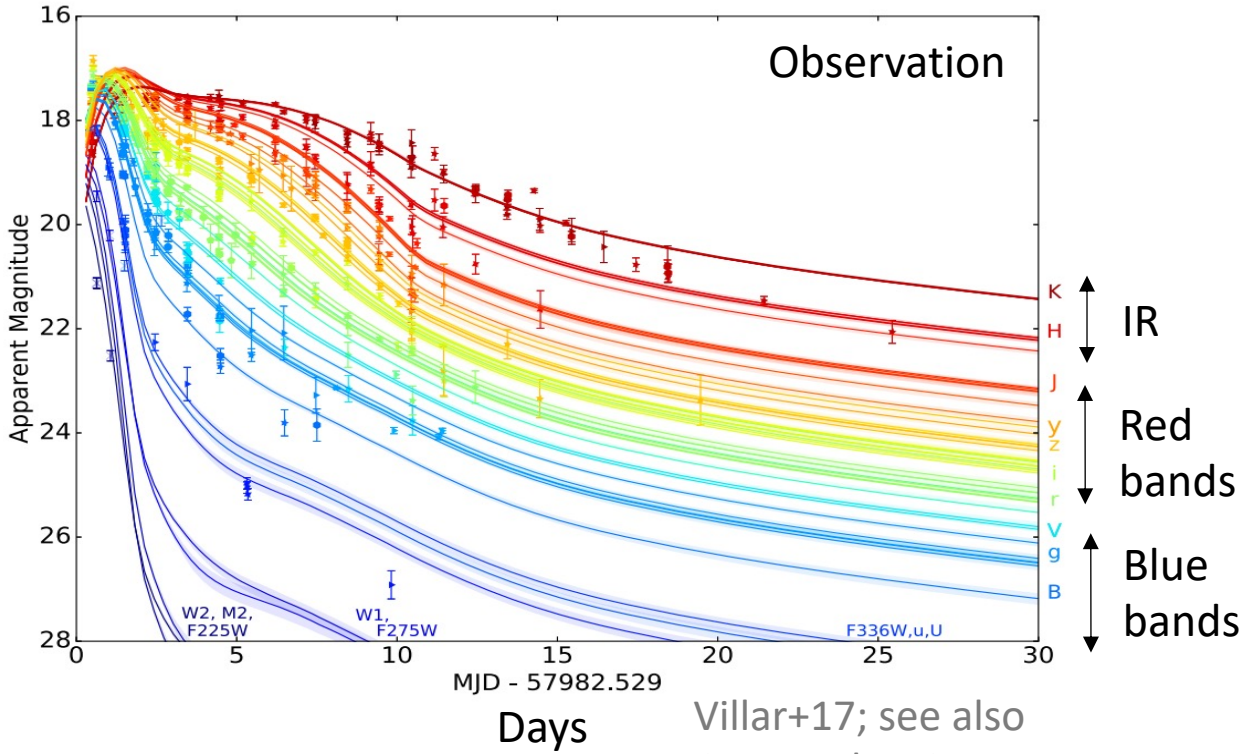


Spectra and light curves depend on the species present; Lanthanide and/or actinide mass fraction ↑, opacity ↑, longer duration light curve shifted toward infrared

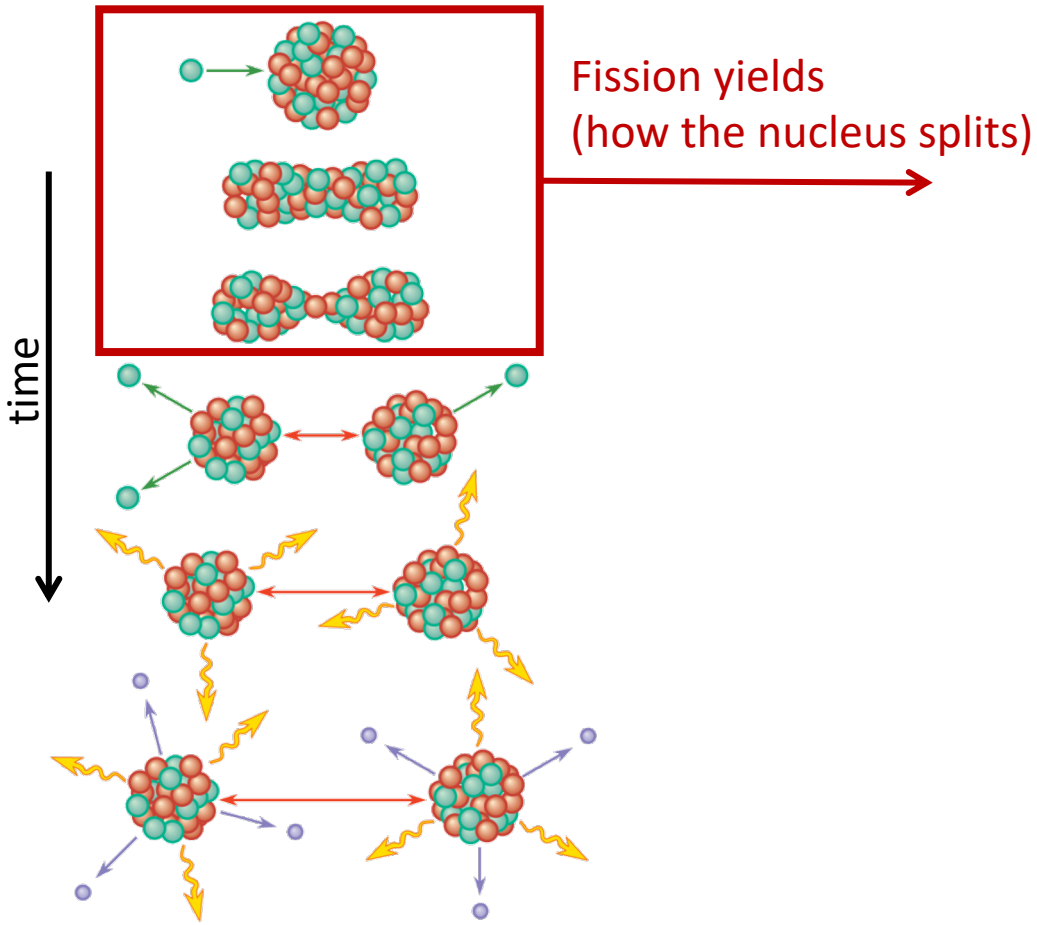
Model



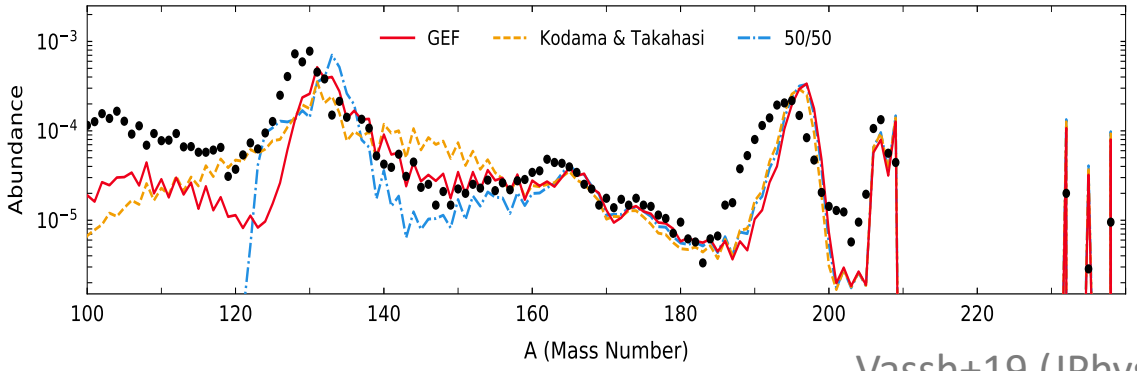
Observation



Actinides in mergers? Spotlight on nuclear fission in astrophysics

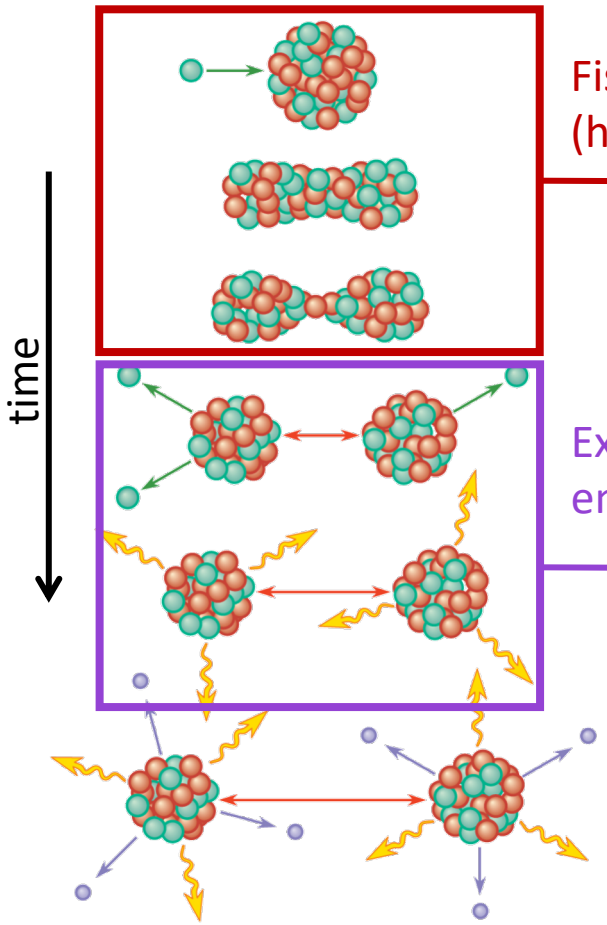


Fission yields
(how the nucleus splits)



Vassh+19 (JPhysG)

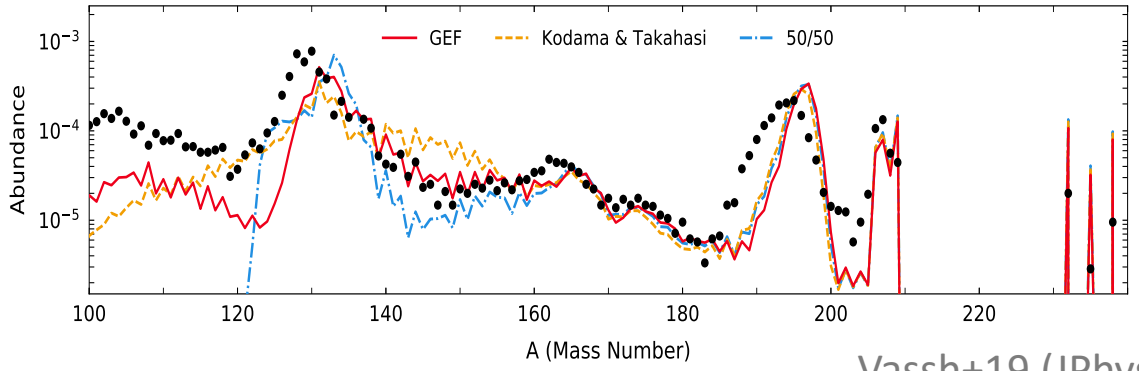
Actinides in mergers? Spotlight on nuclear fission in astrophysics



Fission yields
(how the nucleus splits)

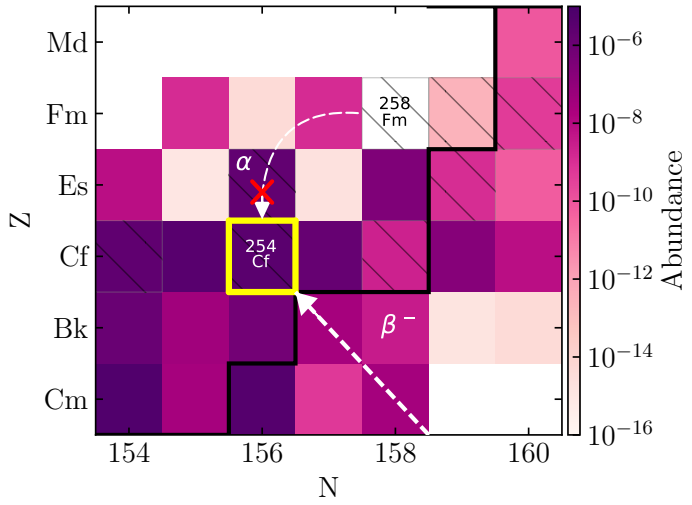
Excited fragment kinetic energy and emission

Q~200 MeV

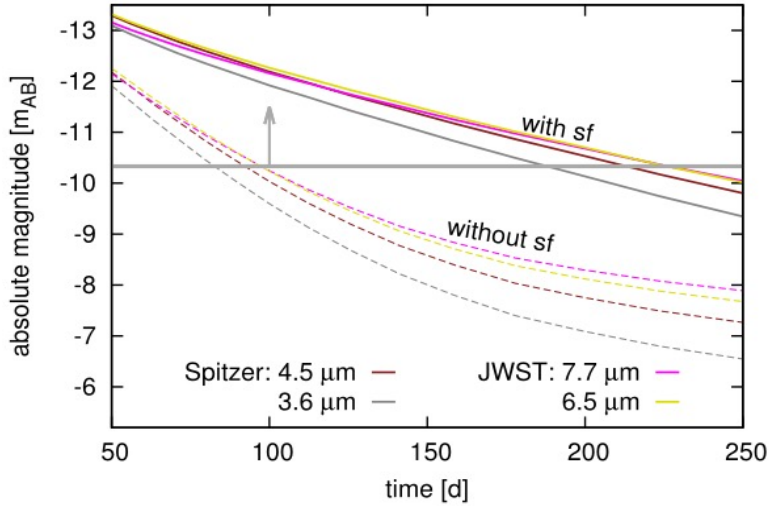


Vassh+19 (JPhysG)

Cf-254 has measured half-life ~60 days

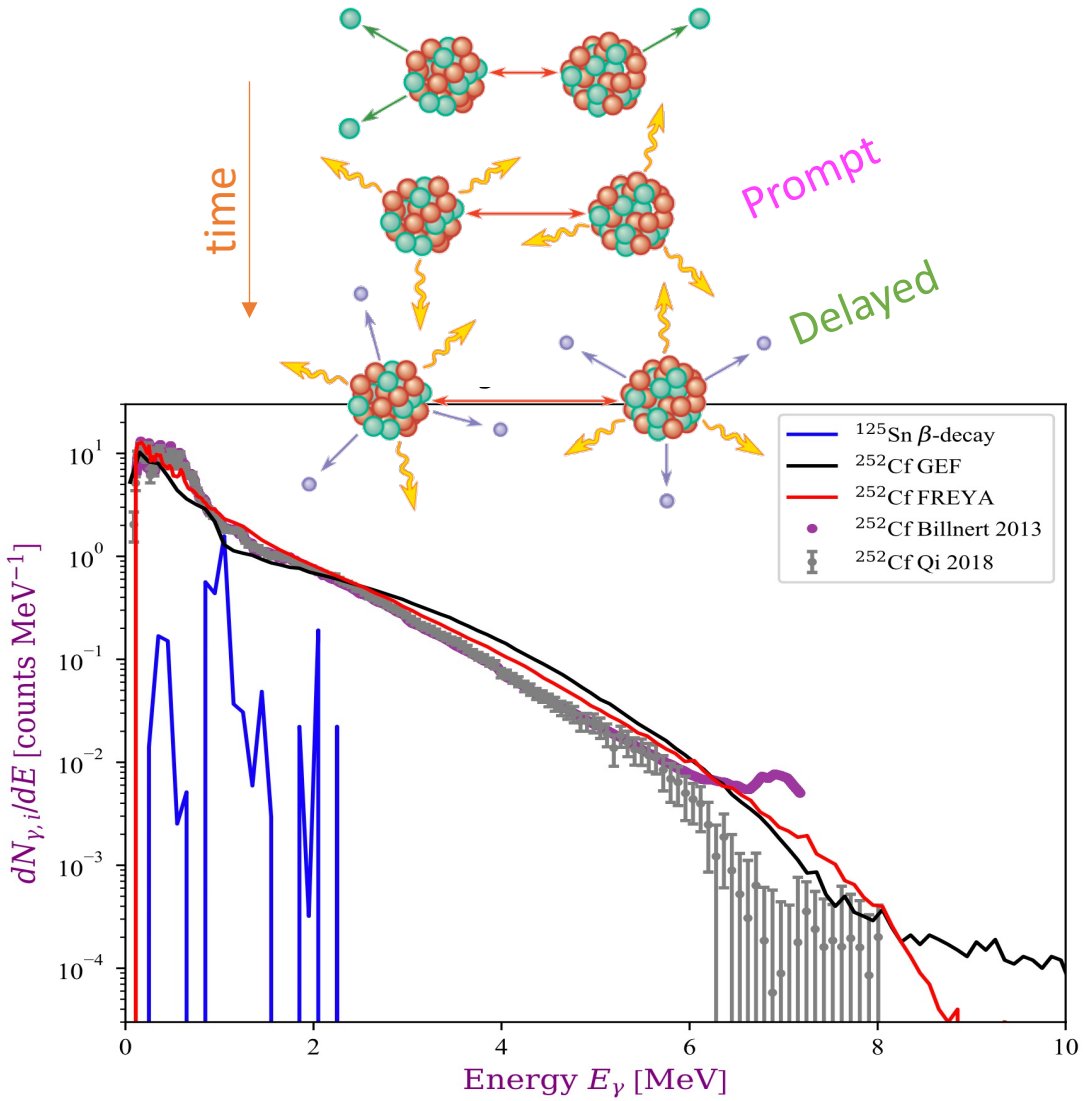


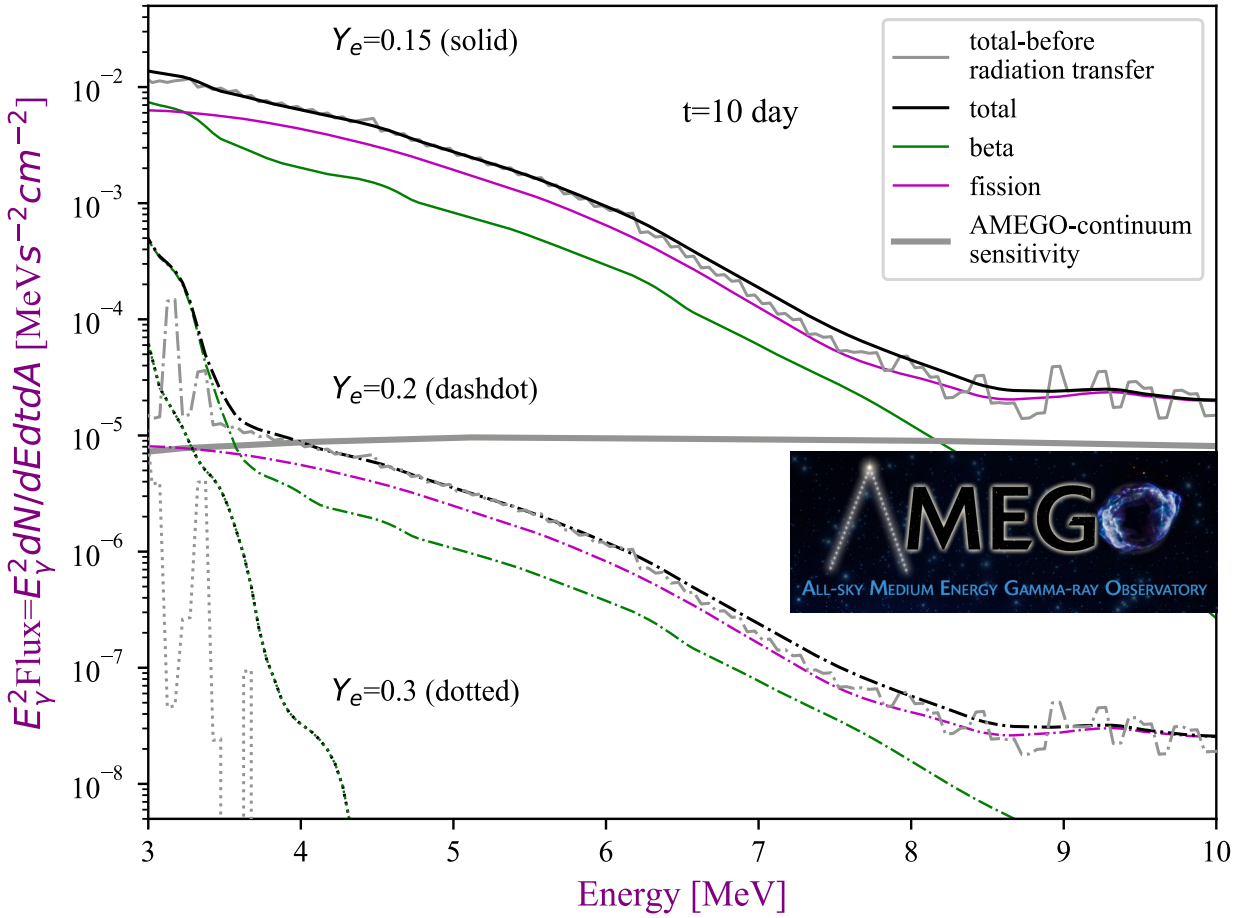
Predicted kilonova light curve with and without late time Cf heating



Zhu+18 (including Vassh)(ApJ Letters)

Another messenger from NSMs: MeV gamma rays from fission

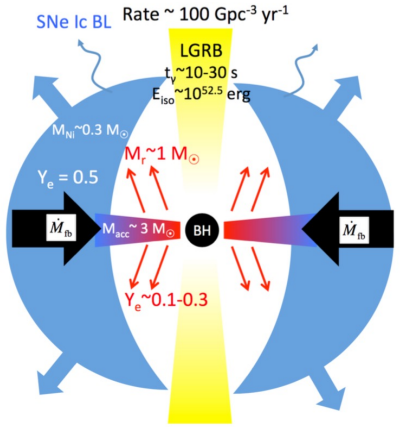


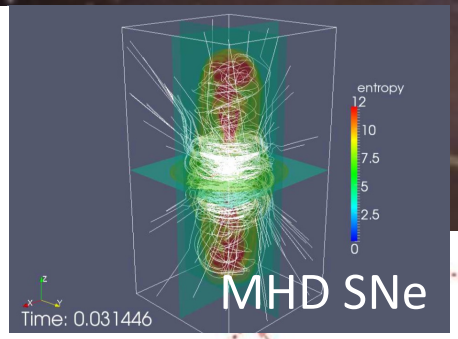


Wang, Vassh+20 (ApJ Letters 903, L3)
using GEF inputs from Vassh+19 (J. Phys. G 46, 065202)

Where *and when* were the elements we see in stars produced?

Collapsars

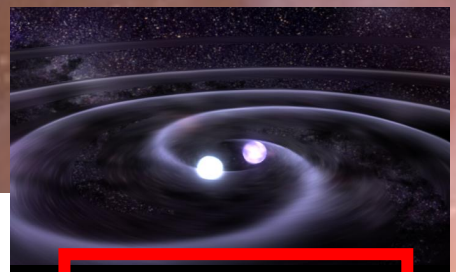




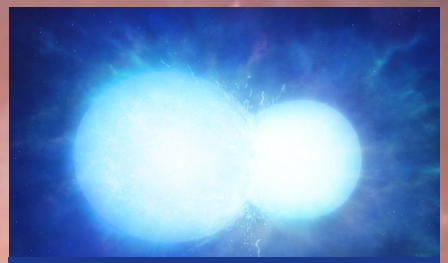
MHD SNe

+ …

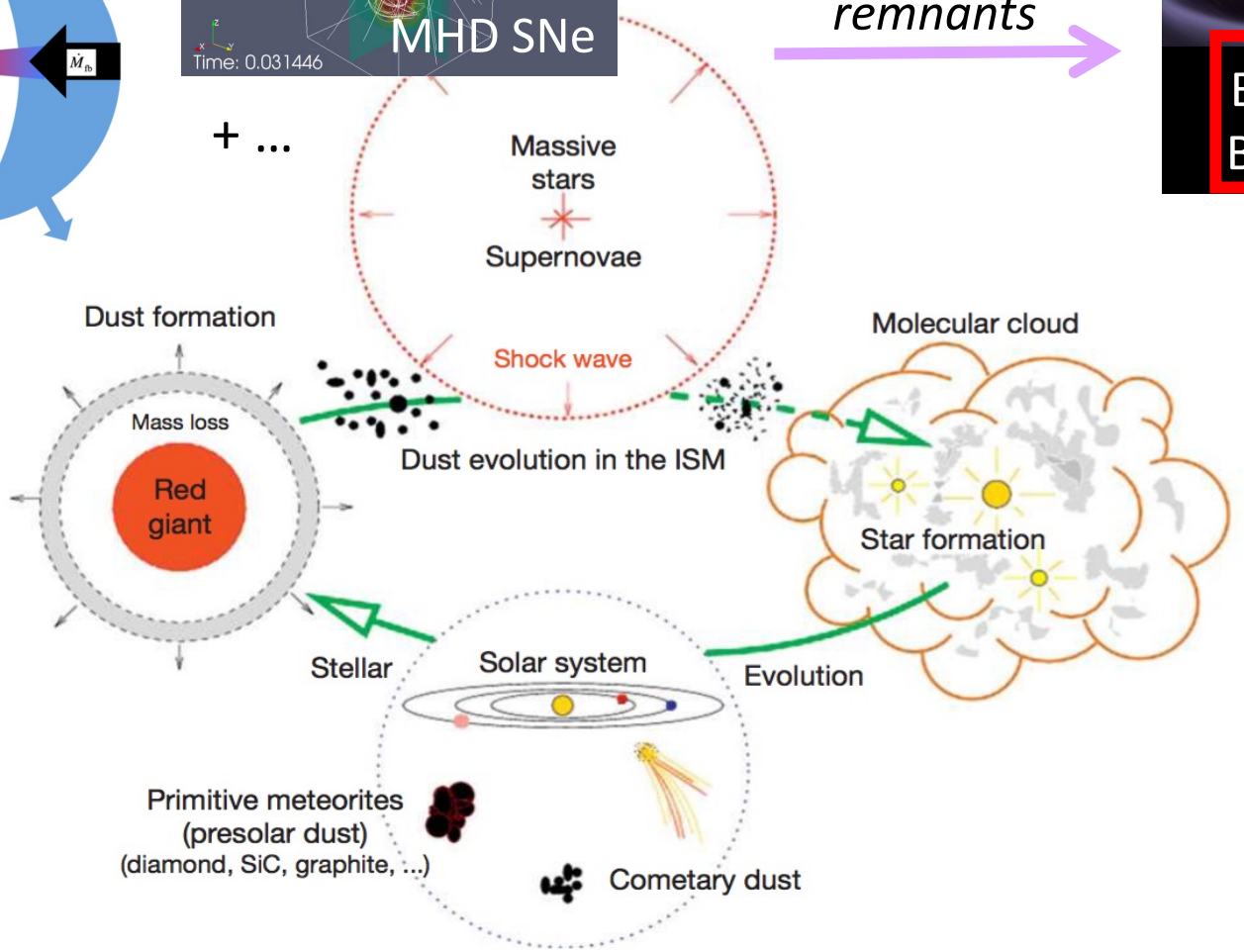
remnants



Binary NS and BHNS mergers



Accreting WD and WD mergers



Palm+14

How do current gravitational wave detections inform this picture?

BNS example:

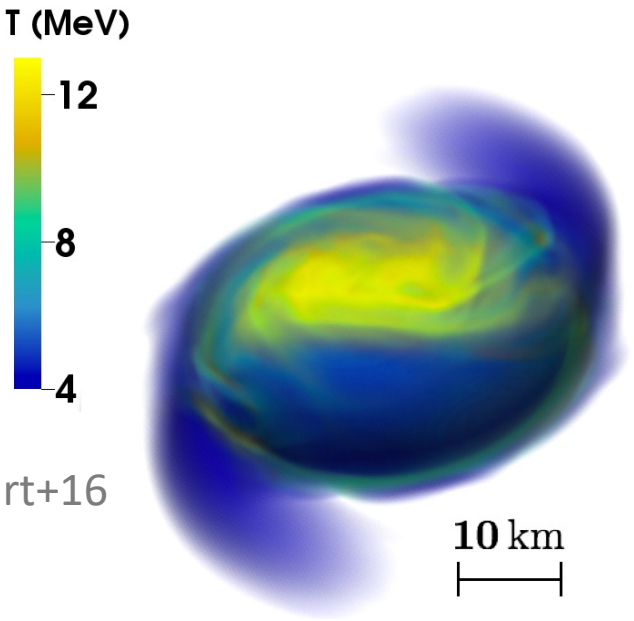
1. Event identification + EM follow-up
2. NS EOS
3. NS merger rate in the local universe

NS merger dynamical ejecta: dependence on the NS EOS

Dynamical ejecta

Hot, shocked ejecta

Very neutron-rich cold, tidal ejecta

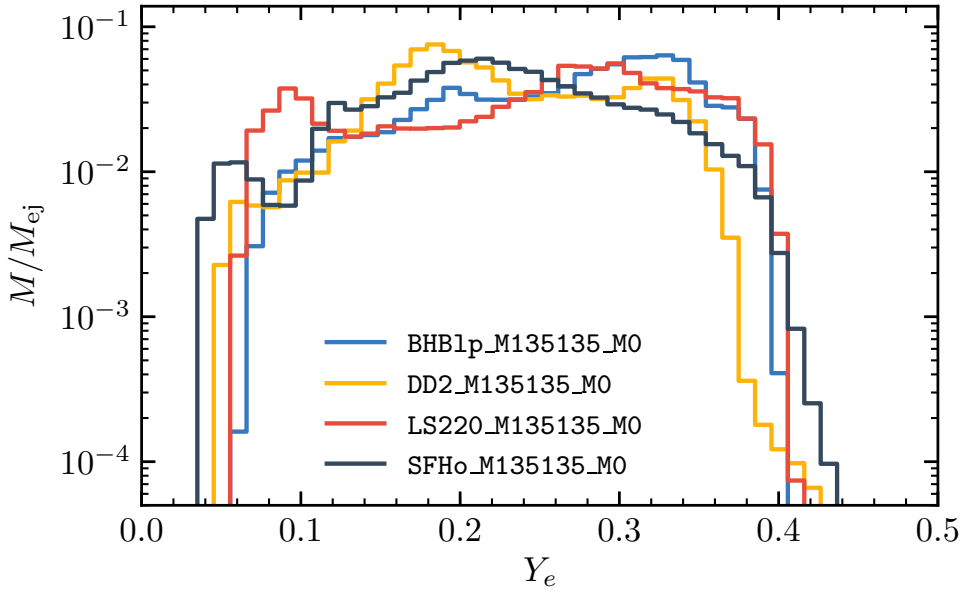


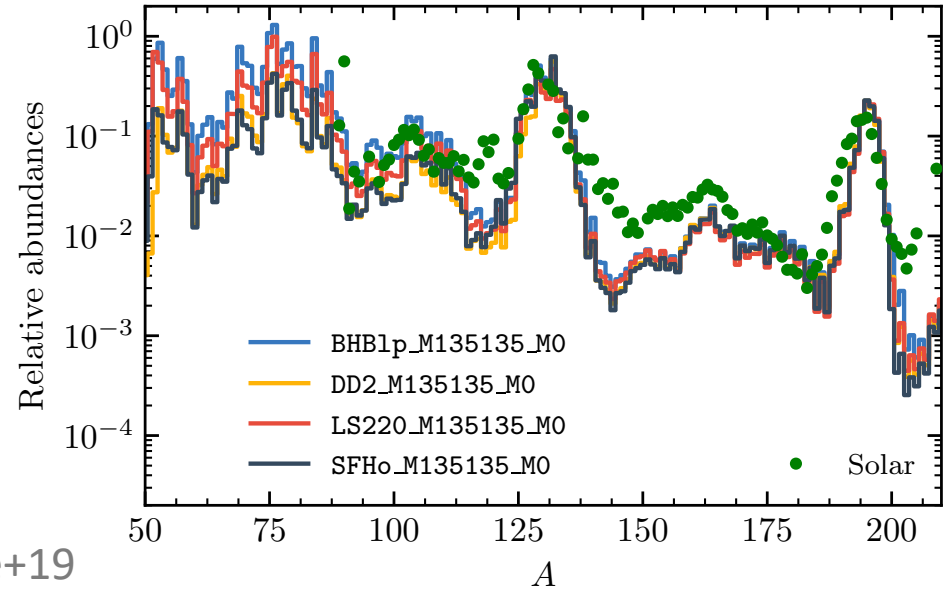
Foucart+16

NSM simulations with EOS variations by Radice+19 found:

* Stiff EOSs such as BHB$\Lambda\phi$ and DD2 typically have less tidally dominated ejecta than softer EOSs such as LS220 and SFHo

* Softer EOSs eject more mass overall

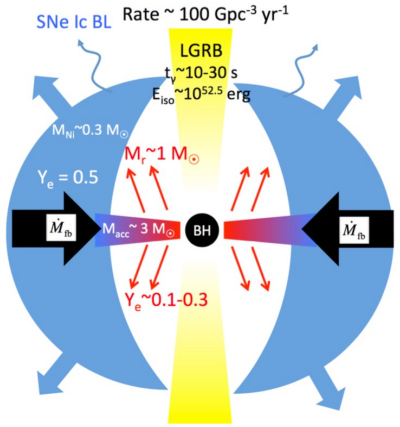


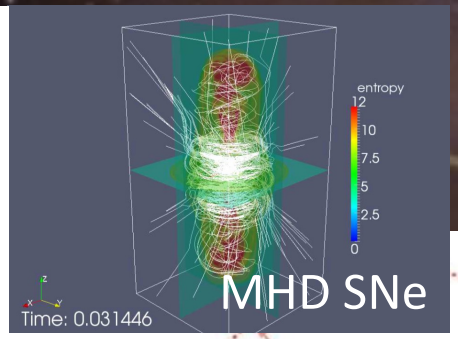


Radice+19

Where *and when* were the elements we see in stars produced?

Collapsars

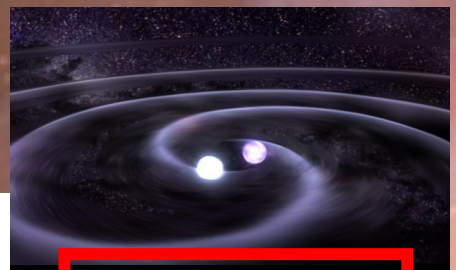




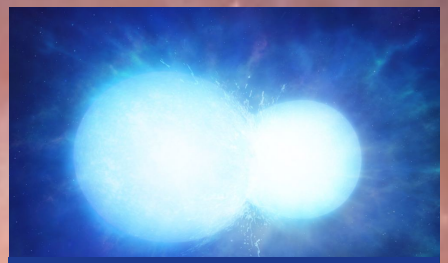
MHD SNe

+ …

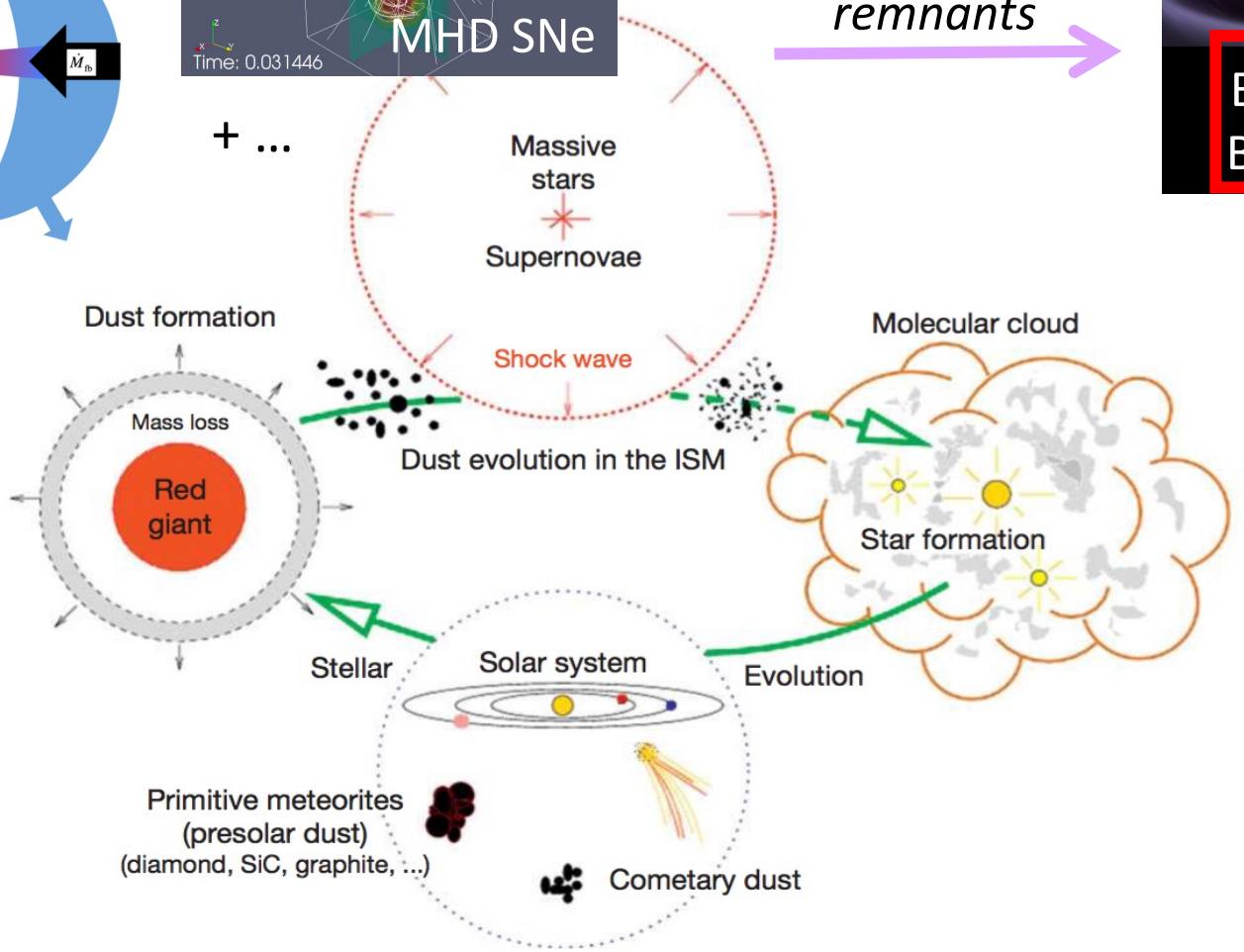
remnants



Binary NS and BHNS mergers



Accreting WD and WD mergers



Palm+14

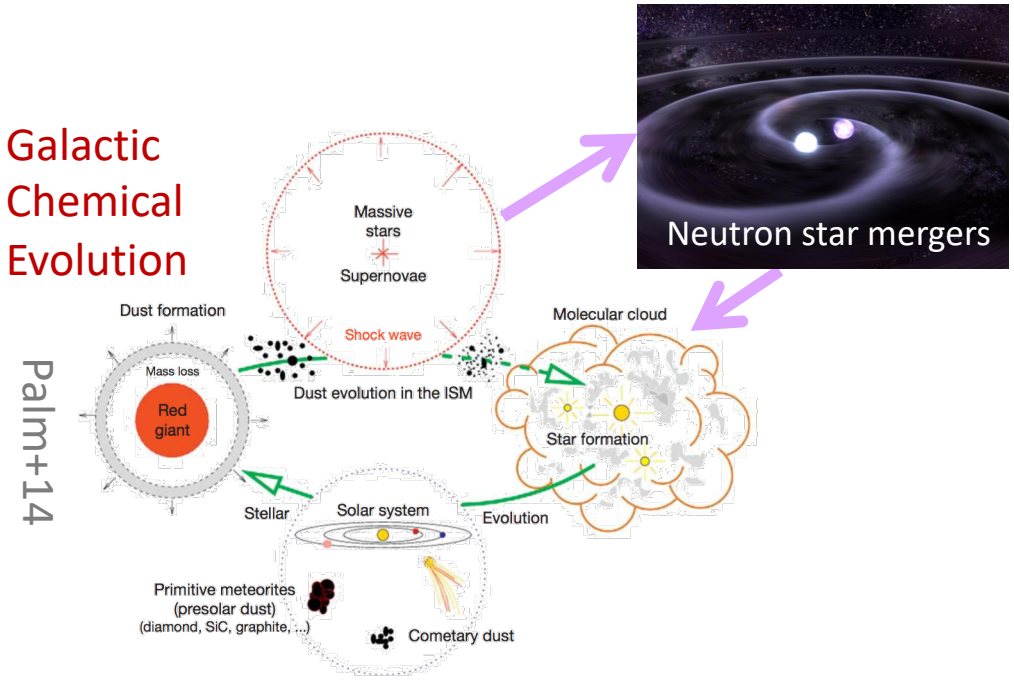
How do current gravitational wave detections inform this picture?

BNS example:

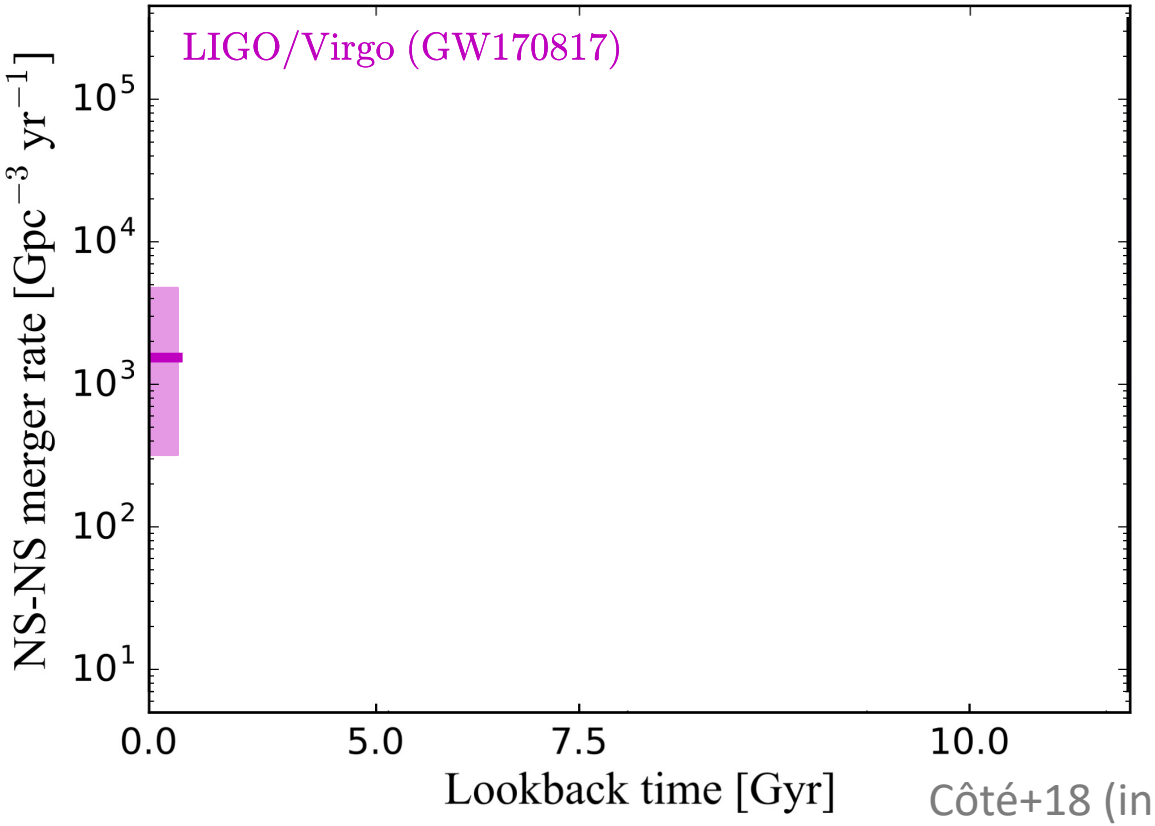
1. Event identification + EM follow-up
2. NS EOS
3. NS merger rate in the local universe

Do binary NSMs make enough heavy elements?

Galactic Chemical Evolution



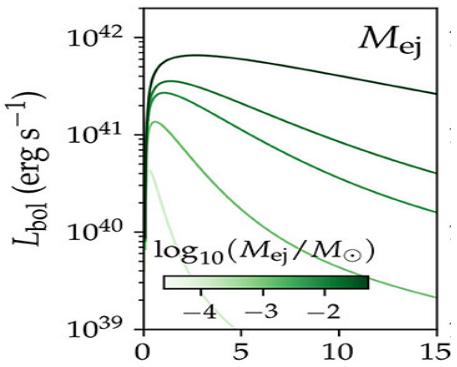
Palm+14



Côté+18 (including Vassh) (ApJ 855, 2)

Do binary NSMs make enough heavy elements?

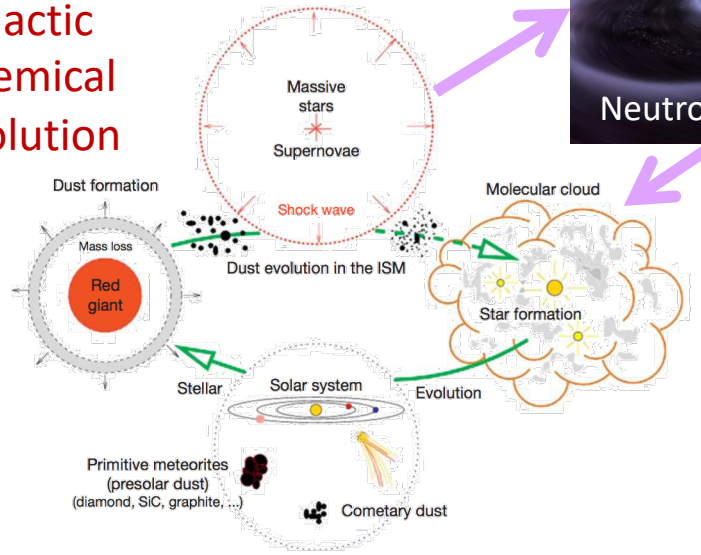
Barnes 20



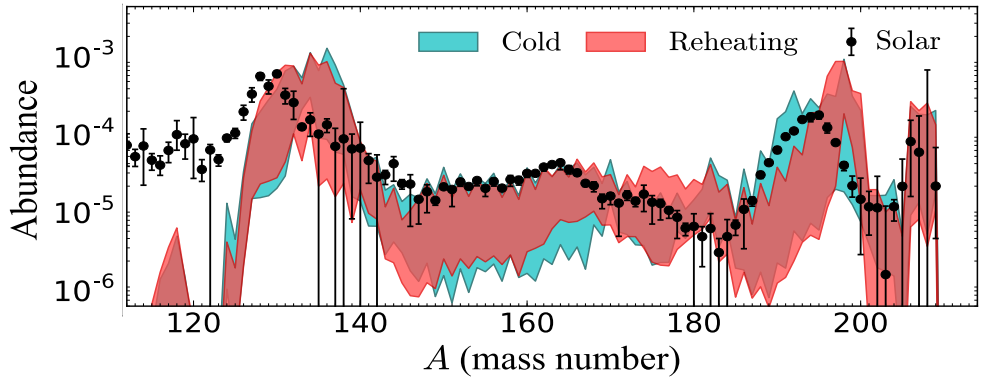
Light Curves

Take estimates for GW170817 mass ejection range from literature

Galactic Chemical Evolution

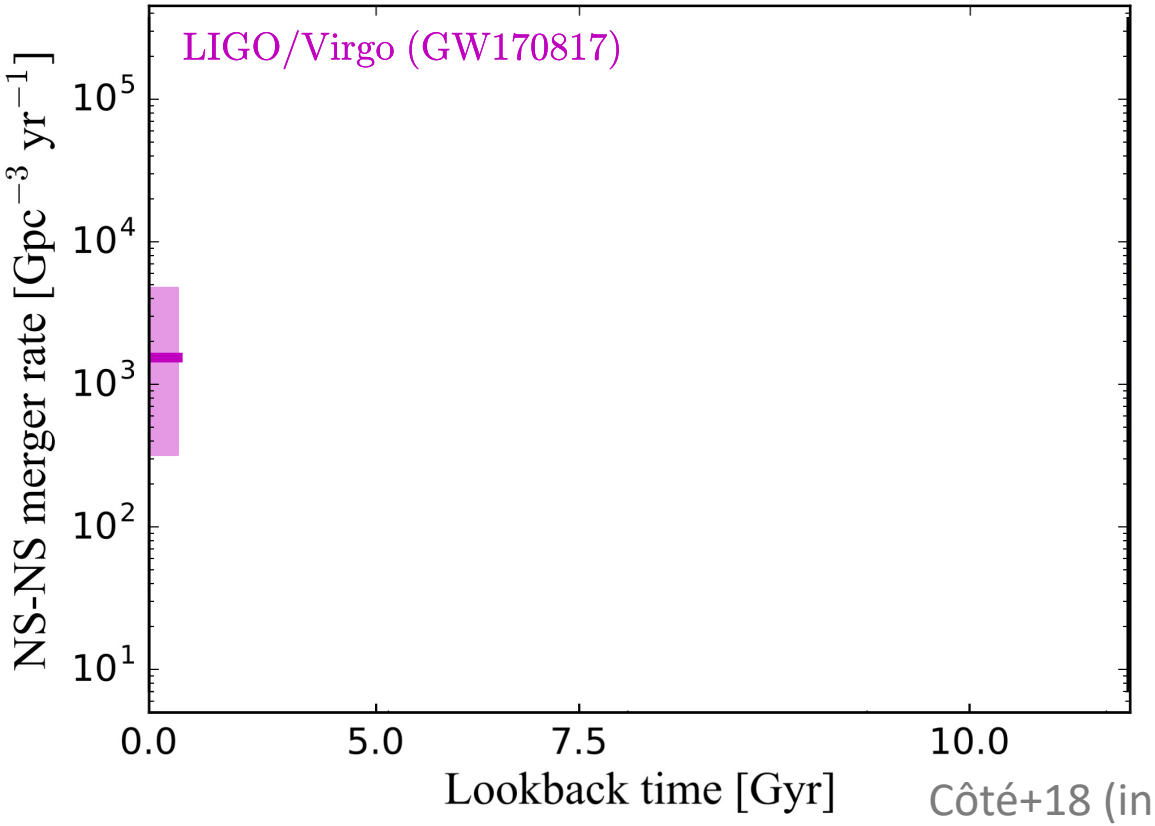


Palm+14



Nucleosynthesis Predictions

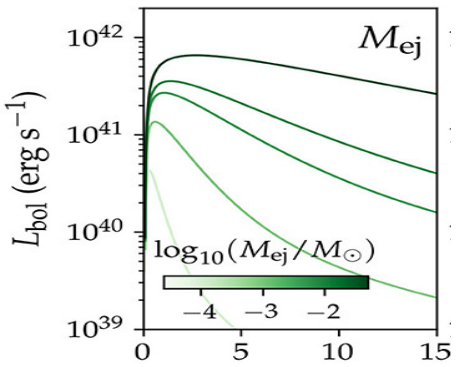
Abundance range of dynamical ejecta from 10 mass models



Côté+18 (including Vassh) (ApJ 855, 2)

Do binary NSMs make enough heavy elements?

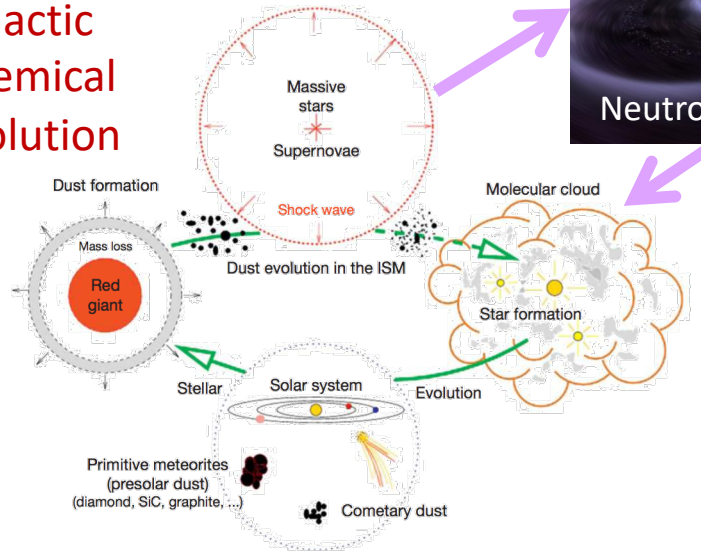
Barnes 20



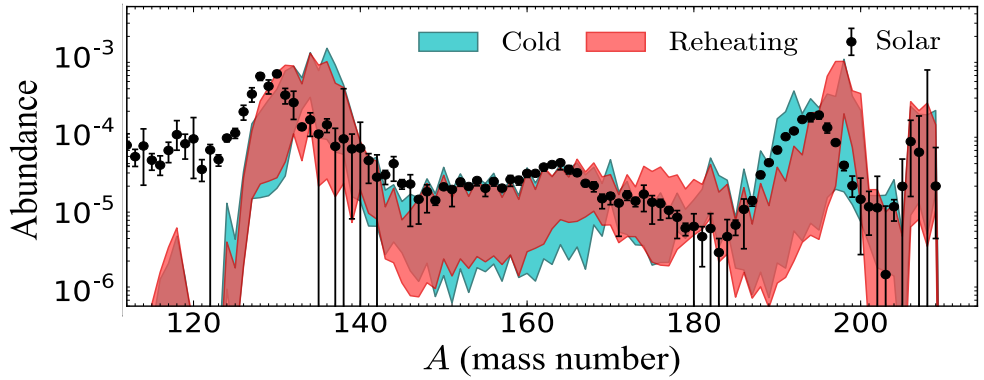
Light Curves

Take estimates for GW170817 mass ejection range from literature

Galactic Chemical Evolution

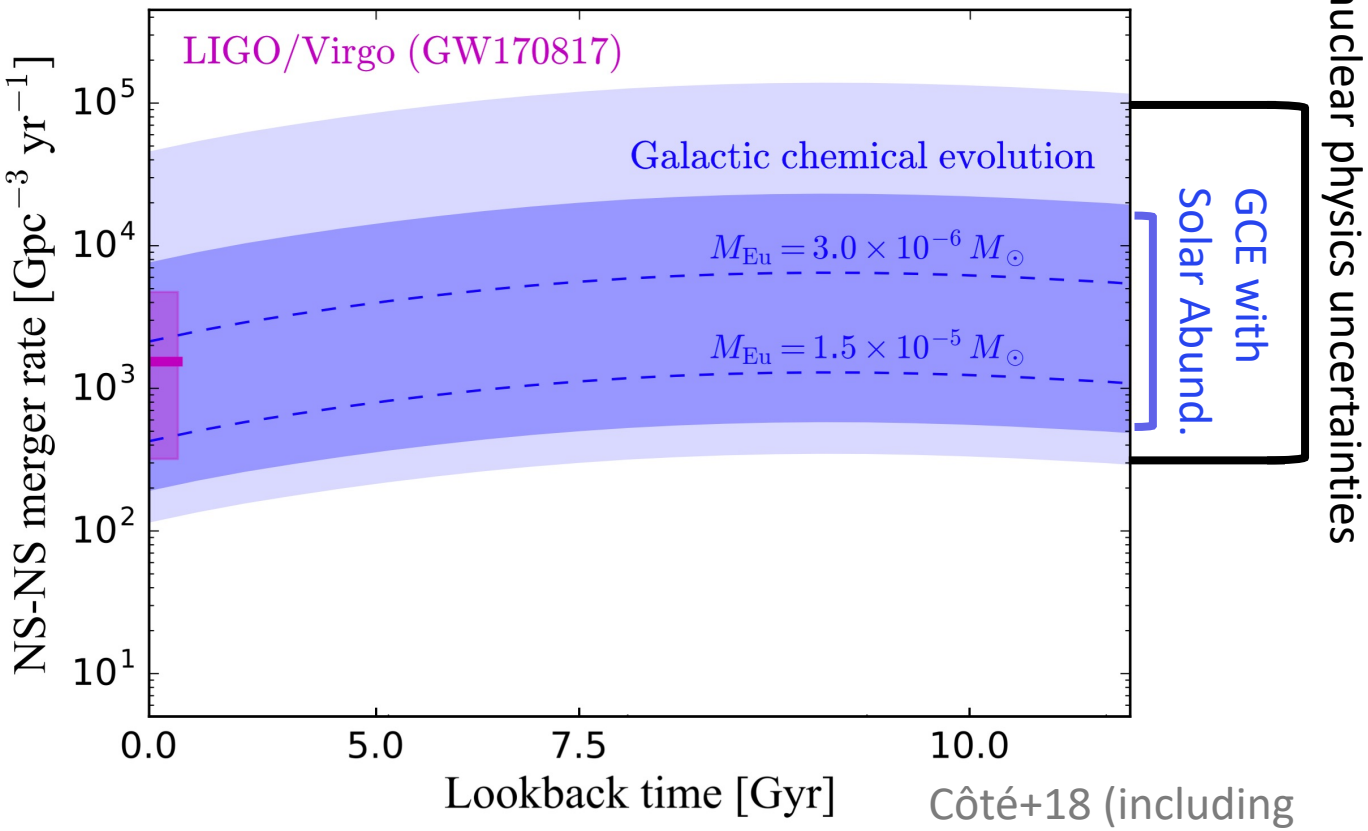


Palm+14



Nucleosynthesis Predictions

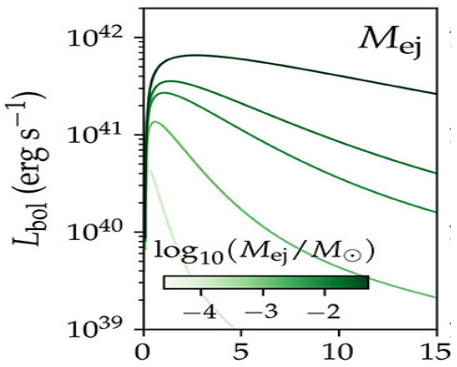
Abundance range of dynamical ejecta from 10 mass models



Côté+18 (including Vassh) (ApJ 855, 2)

Do binary NSMs make enough heavy elements?

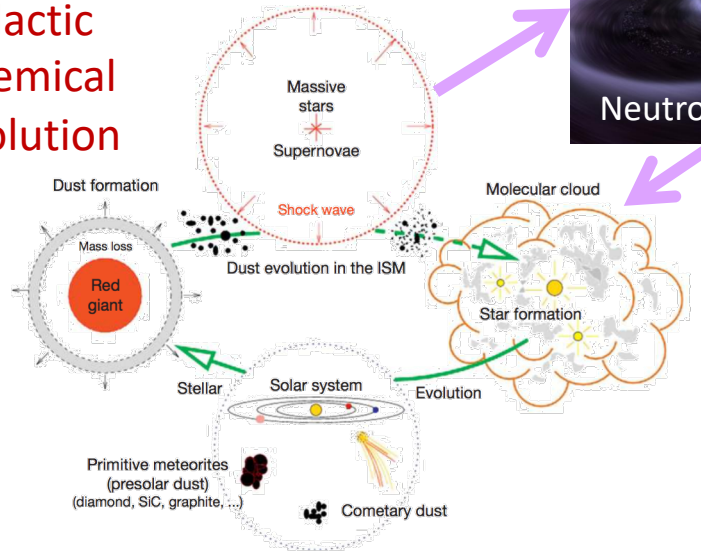
Barnes 20



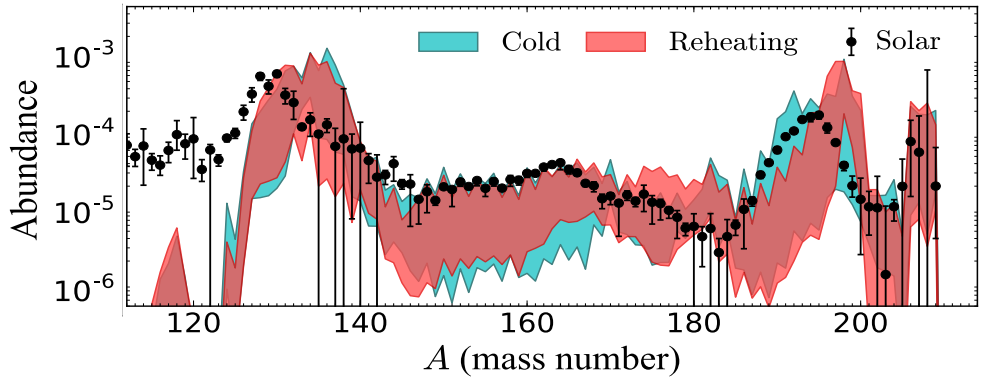
Light Curves

Take estimates for GW170817 mass ejection range from literature

Galactic Chemical Evolution

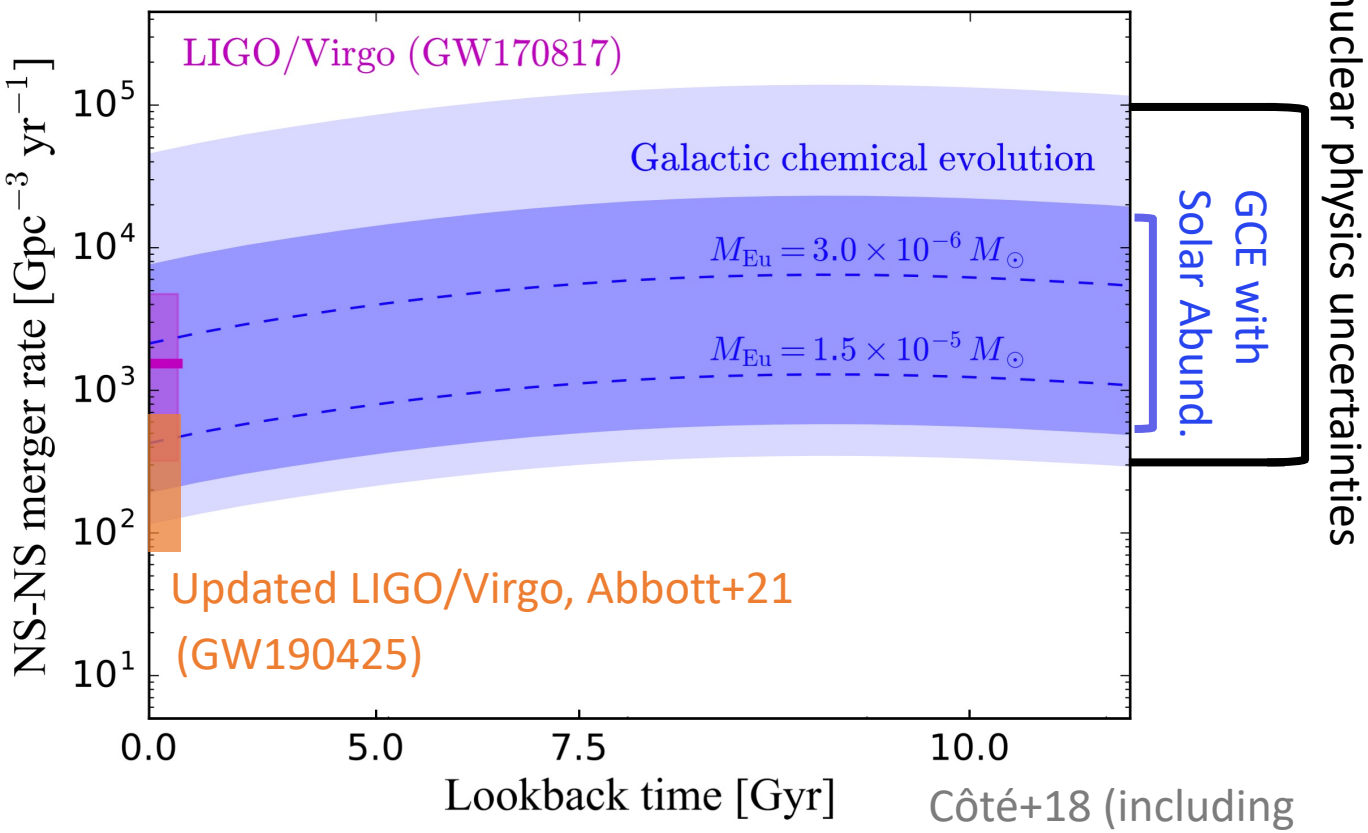


Palm+14



Nucleosynthesis Predictions

Abundance range of dynamical ejecta from 10 mass models



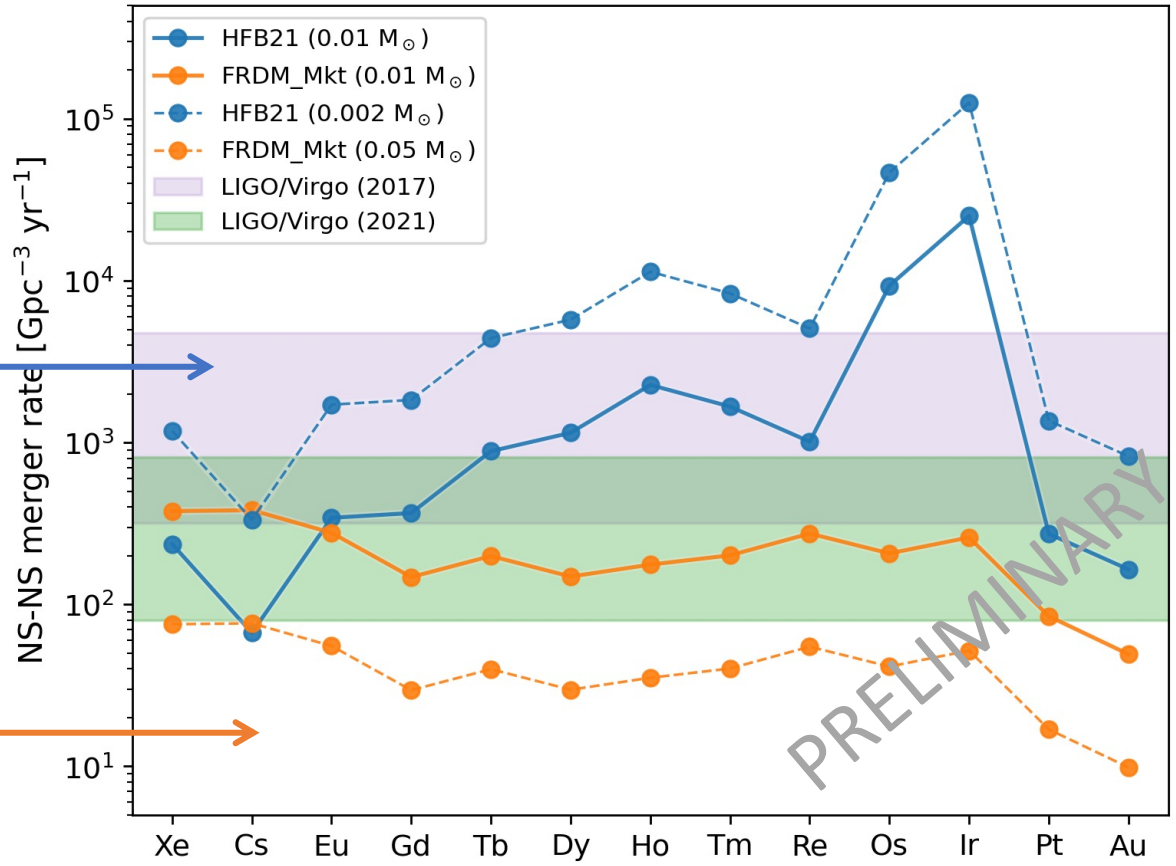
Côté+18 (including Vassh) (ApJ 855, 2)

Do binary NSMs make enough heavy elements?

Previous analysis considered Eu only, now extended to all *r*-process dominated elements

Models / mass ejection combos that require a higher LIGO rate implies the need for additional astrophysical sources

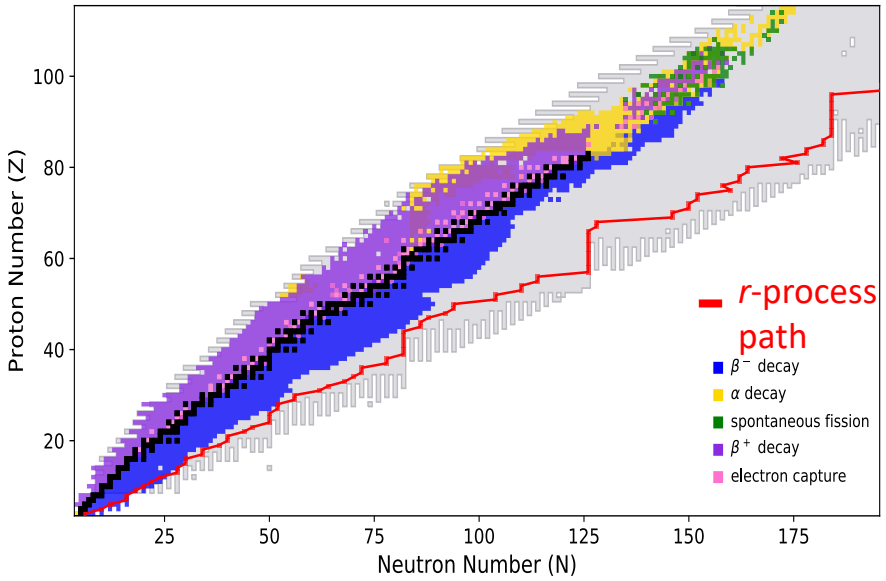
Models / mass ejection combos that require a lower LIGO rate can be ruled out



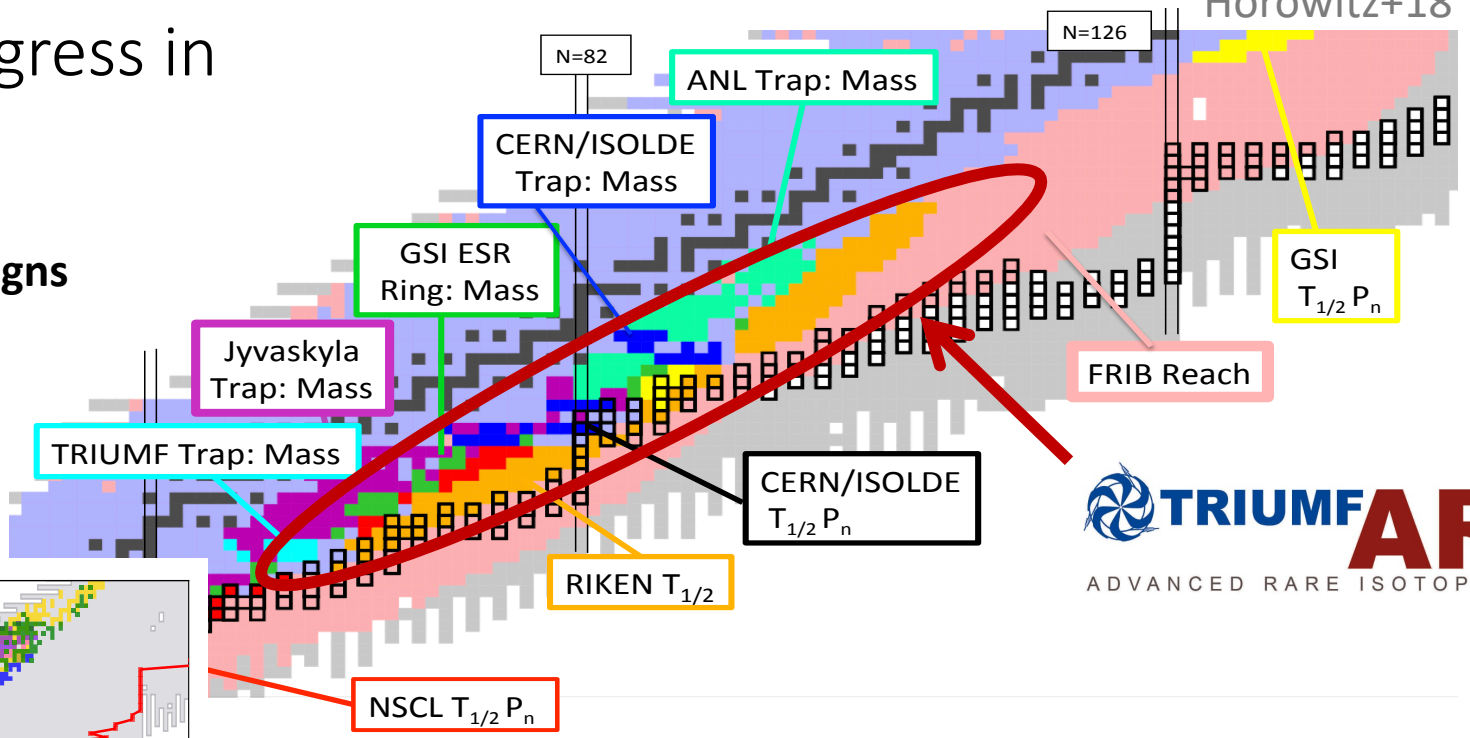
Côté, Vassh+22 (in prep)

Opportunities for progress in nuclear astrophysics

Worldwide experimental campaigns to measure the properties of neutron-rich nuclei:
masses, half-lives,
reaction rates…



Horowitz+18

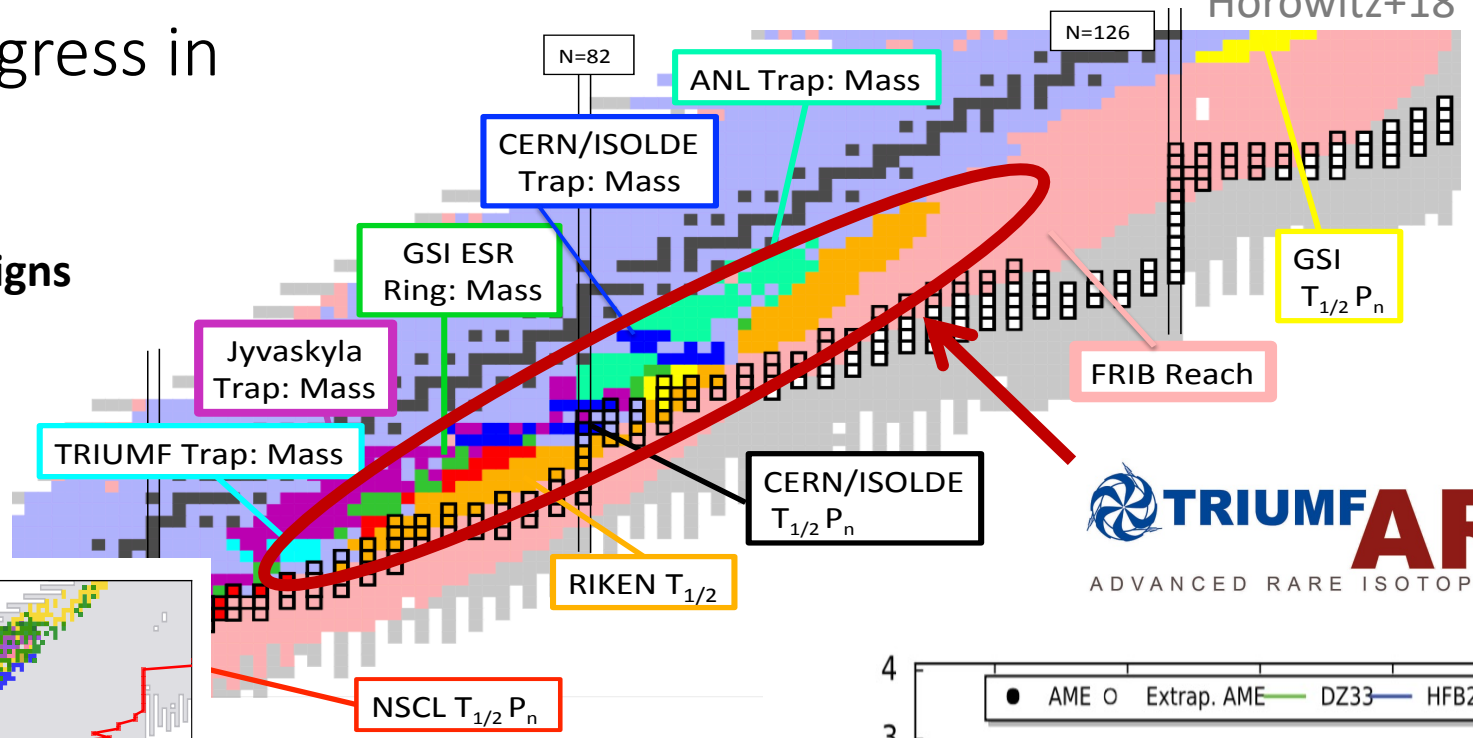


TRIUMF ARIEL
ADVANCED RARE ISOTOPE LABORATORY

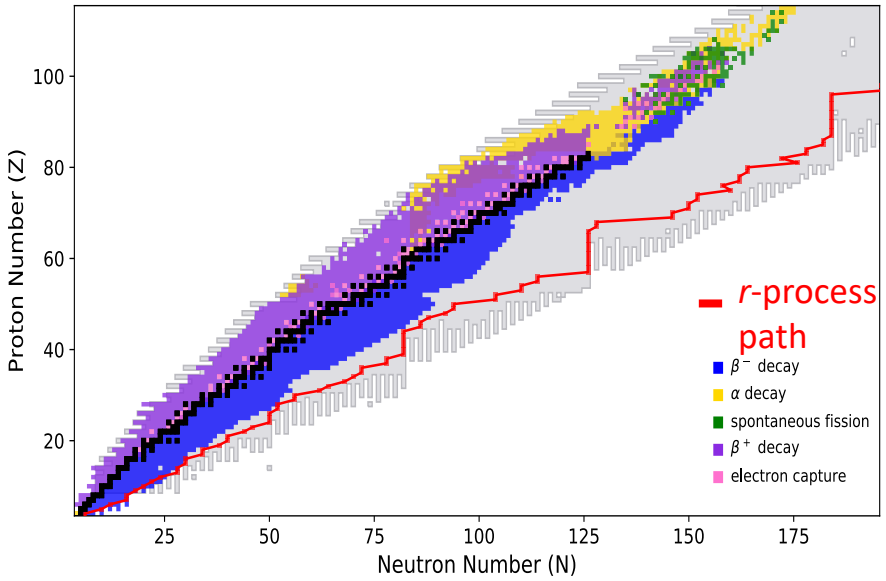
Opportunities for progress in nuclear astrophysics

Worldwide experimental campaigns to measure the properties of neutron-rich nuclei:
masses, half-lives,
reaction rates…

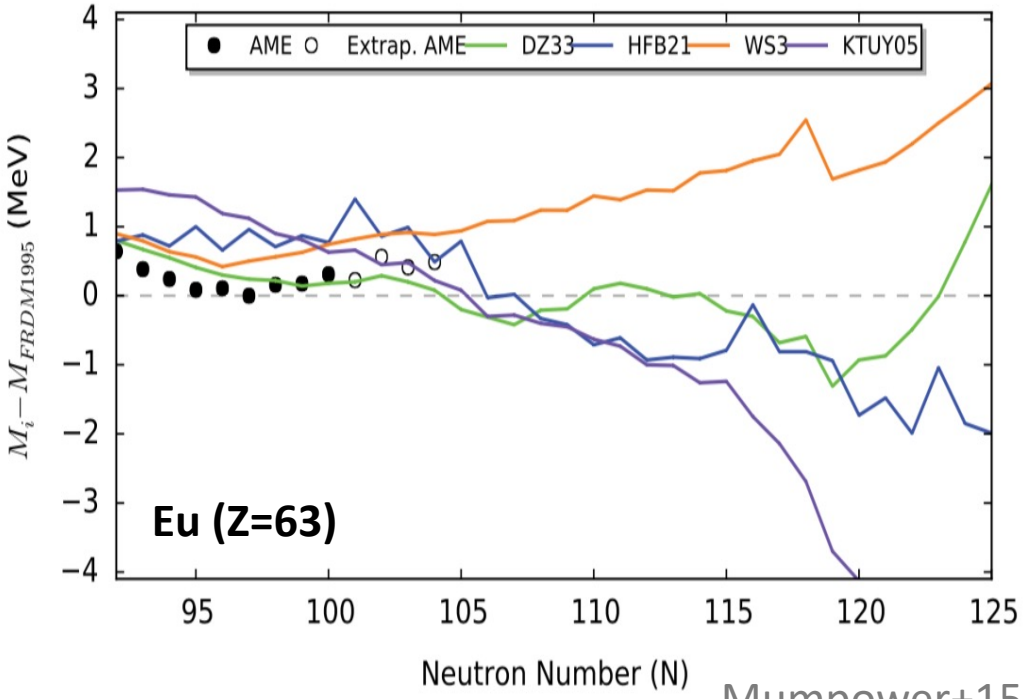
Horowitz+18



TRIUMF ARIEL
ADVANCED RARE ISOTOPE LABORATORY



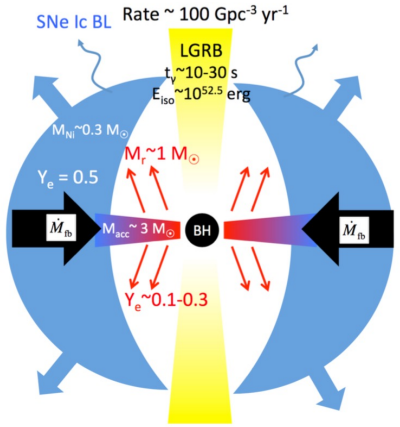
Developments in nuclear theory:
Structure theory (masses, deformation…), reaction theory (capture cross sections…), fission yields and rates, and β-decay rates….

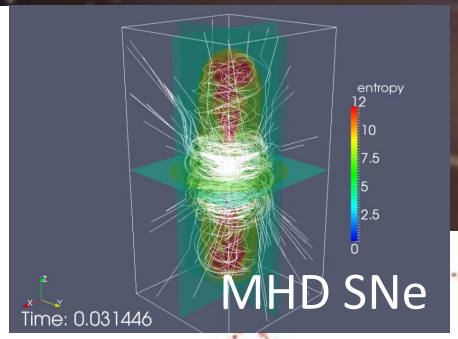


Mumpower+15

Where *and when* were the elements we see in stars produced?

Collapsars

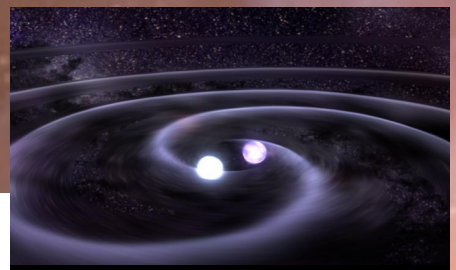




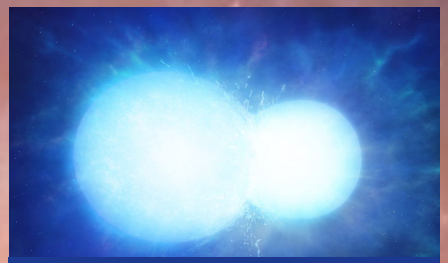
MHD SNe

+ ...

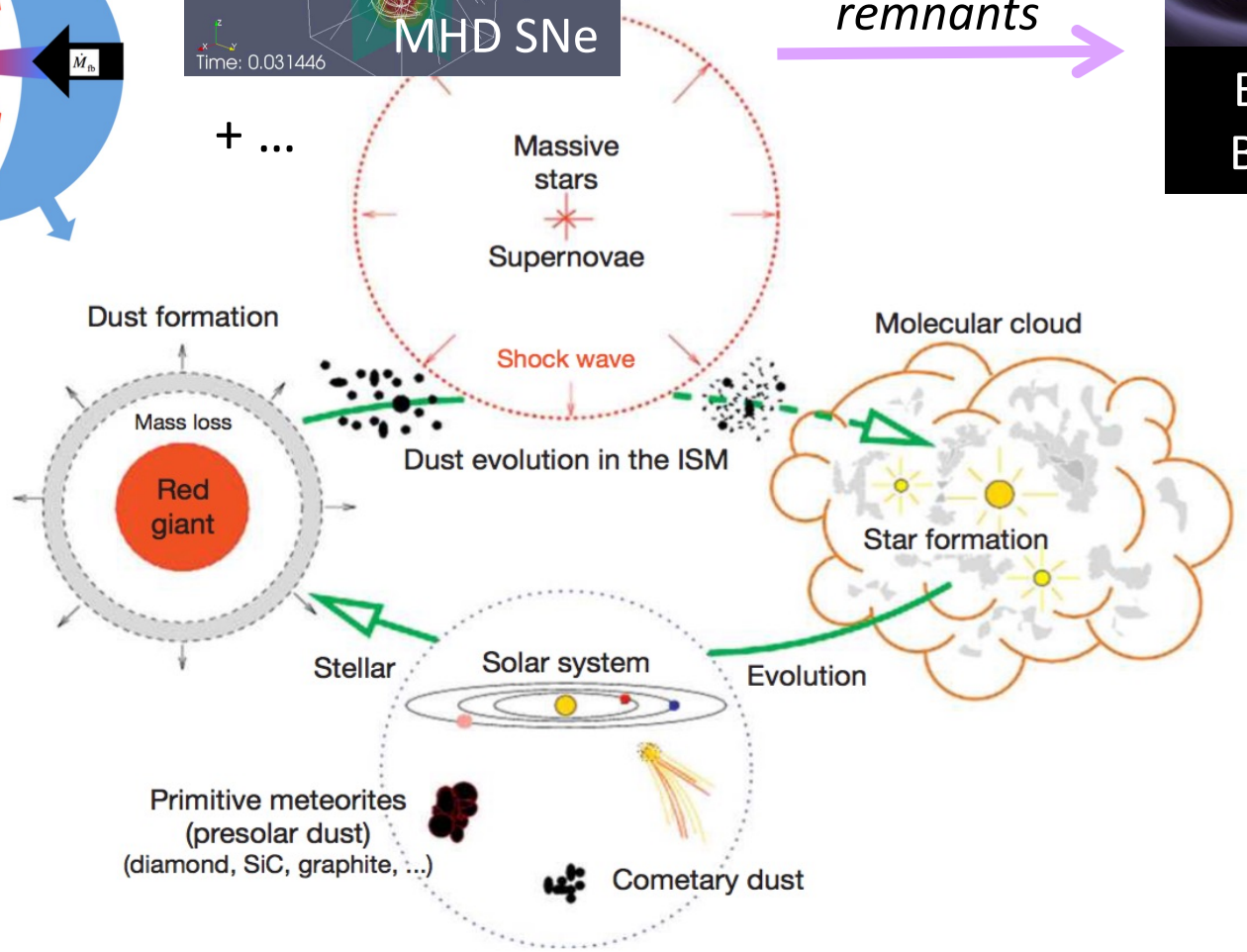
remnants



Binary NS and BHNS mergers



Accreting WD and WD mergers



Palm+14

future

How do ~~current~~ gravitational wave detections inform this picture?

Some thoughts:

1. NS merger rates as a function of cosmic time with advanced ground-based detectors (Cosmic Explorer)
2. Supermassive BH merger rates inform galaxy evolution sims (insights on star formation) (LISA)
3. Insights on WDWD merger rate (LISA) (WD+WD = SN1a progenitor? Informs Fe production in GCE sims)

Thank you! Merci!

TRIUMF

FRIB Theory Alliance

NSERC CRSNG

Nicole Vassh

TRIUMF Theory Group

LISA Canada Workshop,

August 25, 2022