Origin of the Heavy Elements in a Neutron Star Merger

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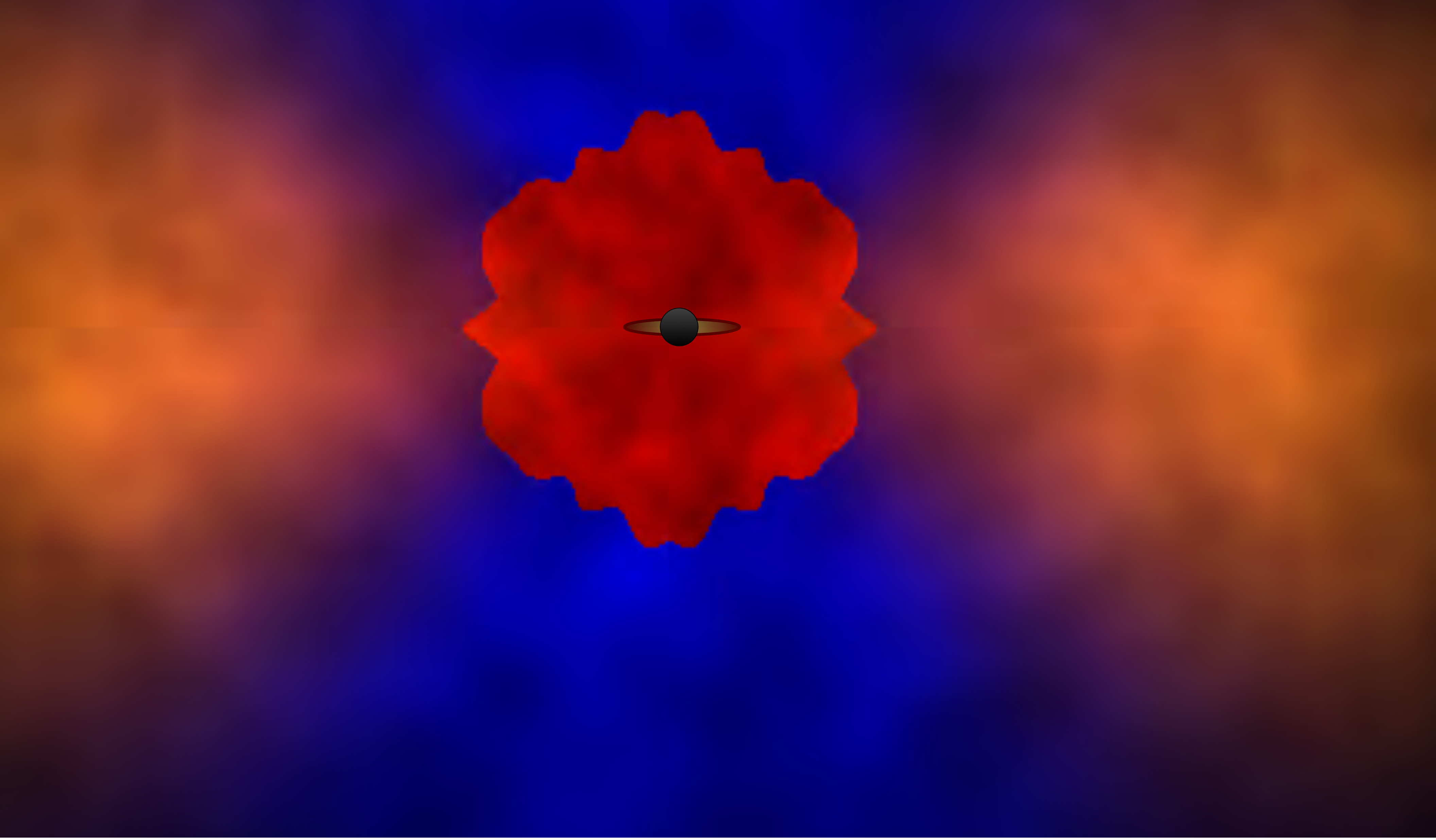
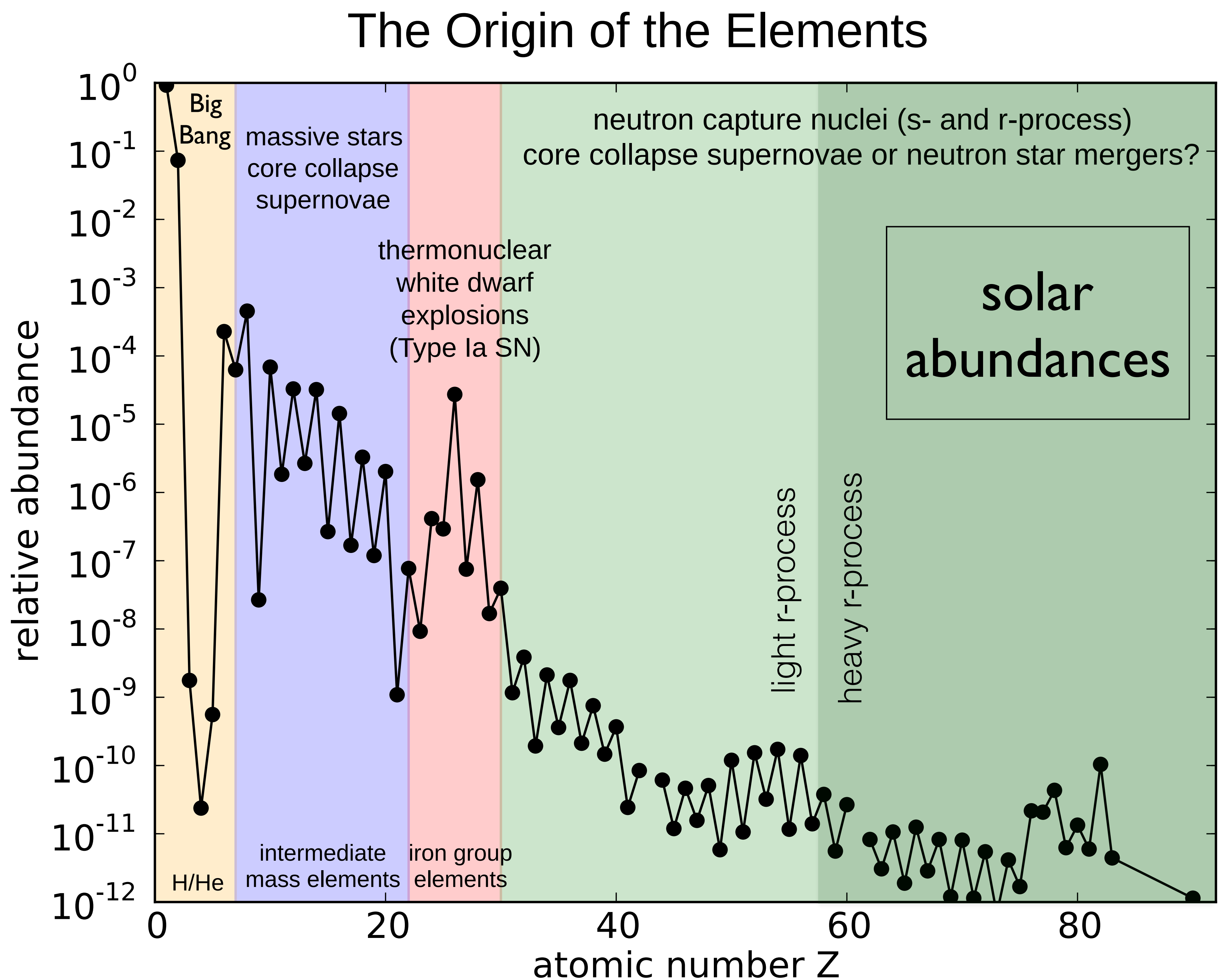


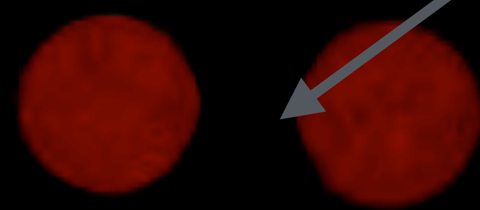


The Origin of the Elements
Big Bang
massive stars core collapse supernovae
thermonuclear white dwarf explosions (Type Ia SN)
neutron capture nuclei (s- and r-process) core collapse supernovae or neutron star mergers?
solar abundances
light r-process
heavy r-process
H/He
intermediate mass elements
iron group elements
relative abundance
atomic number Z
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
0
20
40
60
80

neutron star mergers and mass ejection

dynamical ejecta
~ 1%

remnant: black hole or
massive neutron star
> 90%

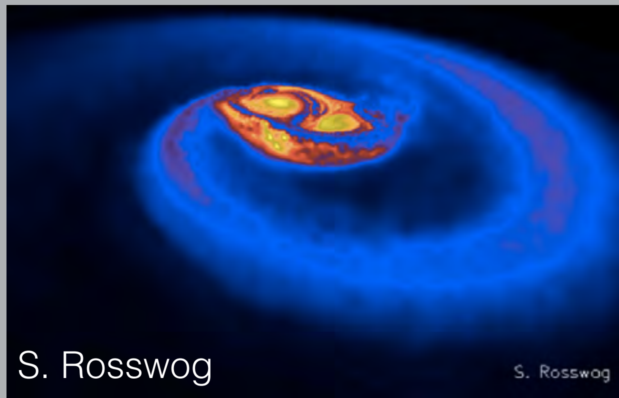


accretion disk
~1-10%

S. Rosswog

simulation of merger dynamics ideally include:
hydrodynamics + nuclear EOS + gravity + neutrinos + nuclear reactions

dynamical (during merger)
t ~ milliseconds

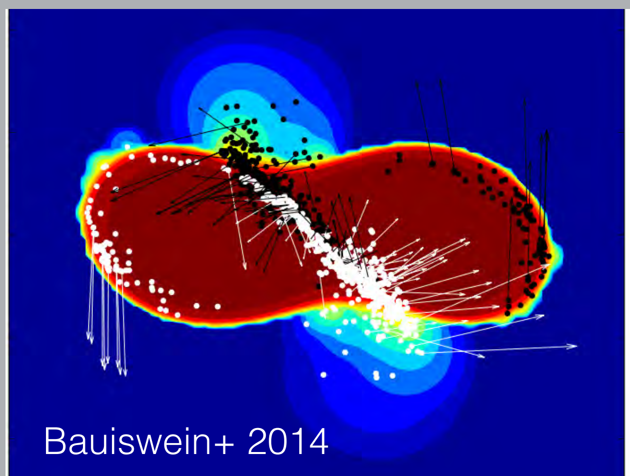


tidal tail ejecta

M ~ 10^{-4} - 10^{-2} M_{sun}

v ~ 0.2c - 0.3c

cold, very neutron rich (n_n/n_p ~ 10)



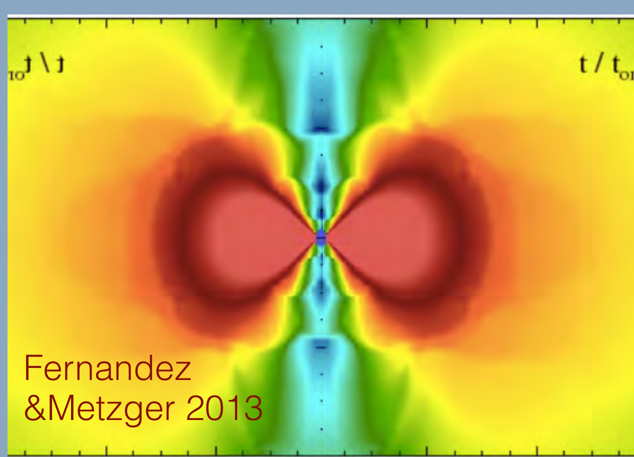
“squeezed” polar ejecta

M ~ 10^{-4} - 10^{-2} M_{sun}

v ~ 0.2c - 0.3c

hotter, less neutron rich (n_n/n_p ~ 3)

after-merger
t ~ seconds



disk wind ejecta

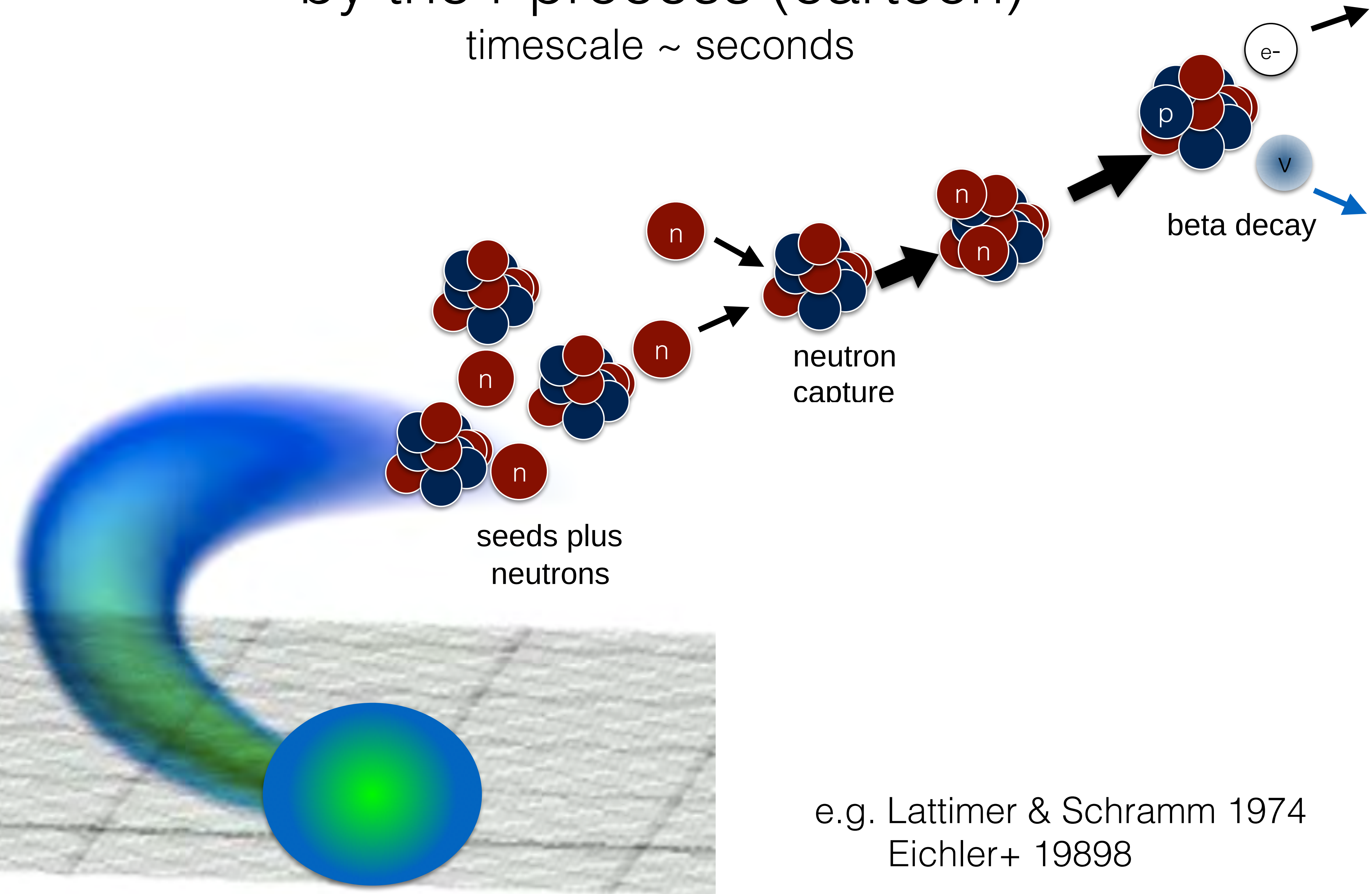
M ~ 10^{-2} - 10^{-1} M_{sun}

v ~ 0.05c - 0.1c

hotter, range of neutron richness

Production of the heavy elements by the r-process (cartoon)

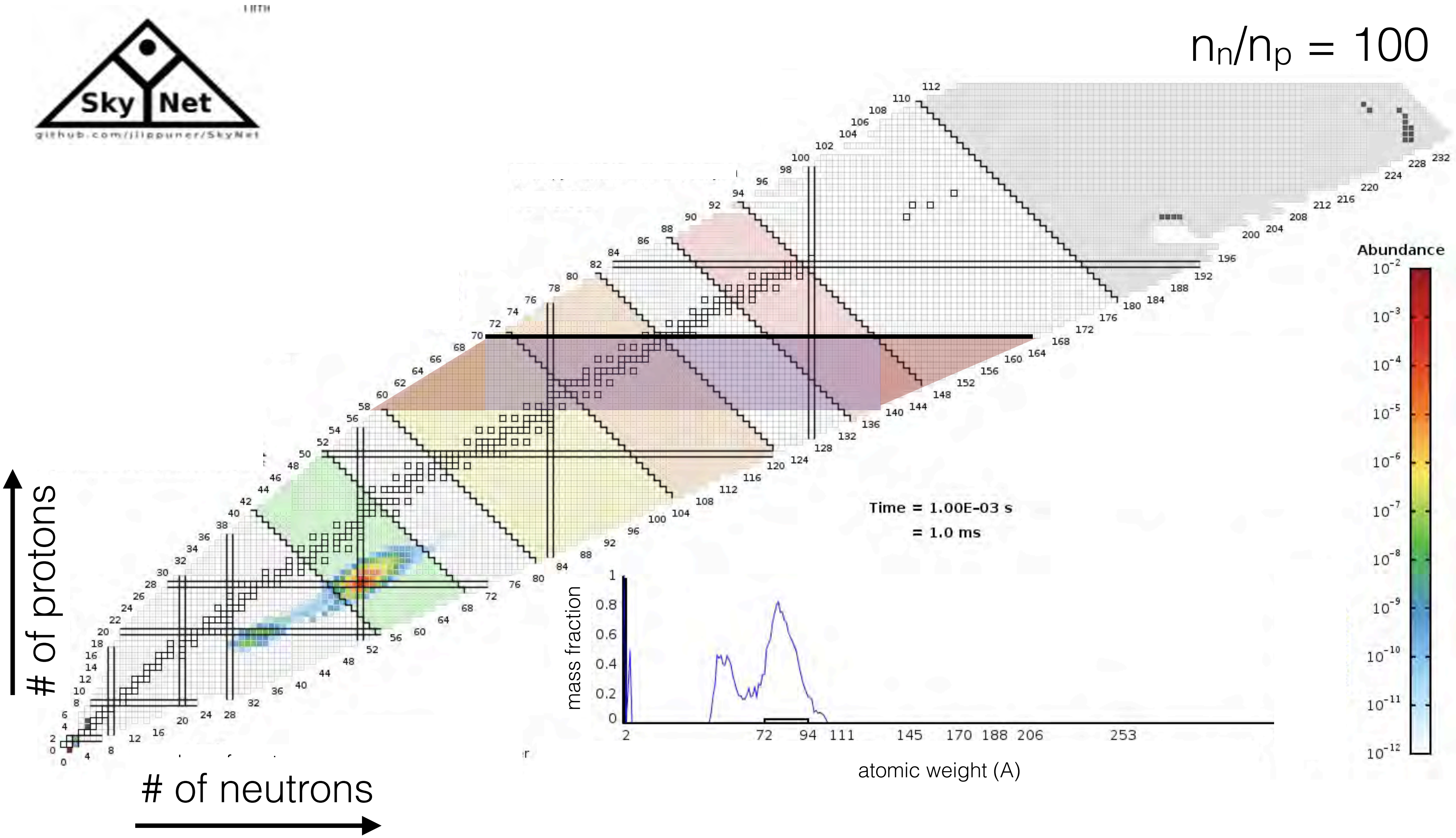
timescale ~ seconds



e.g. Lattimer & Schramm 1974
Eichler+ 19898

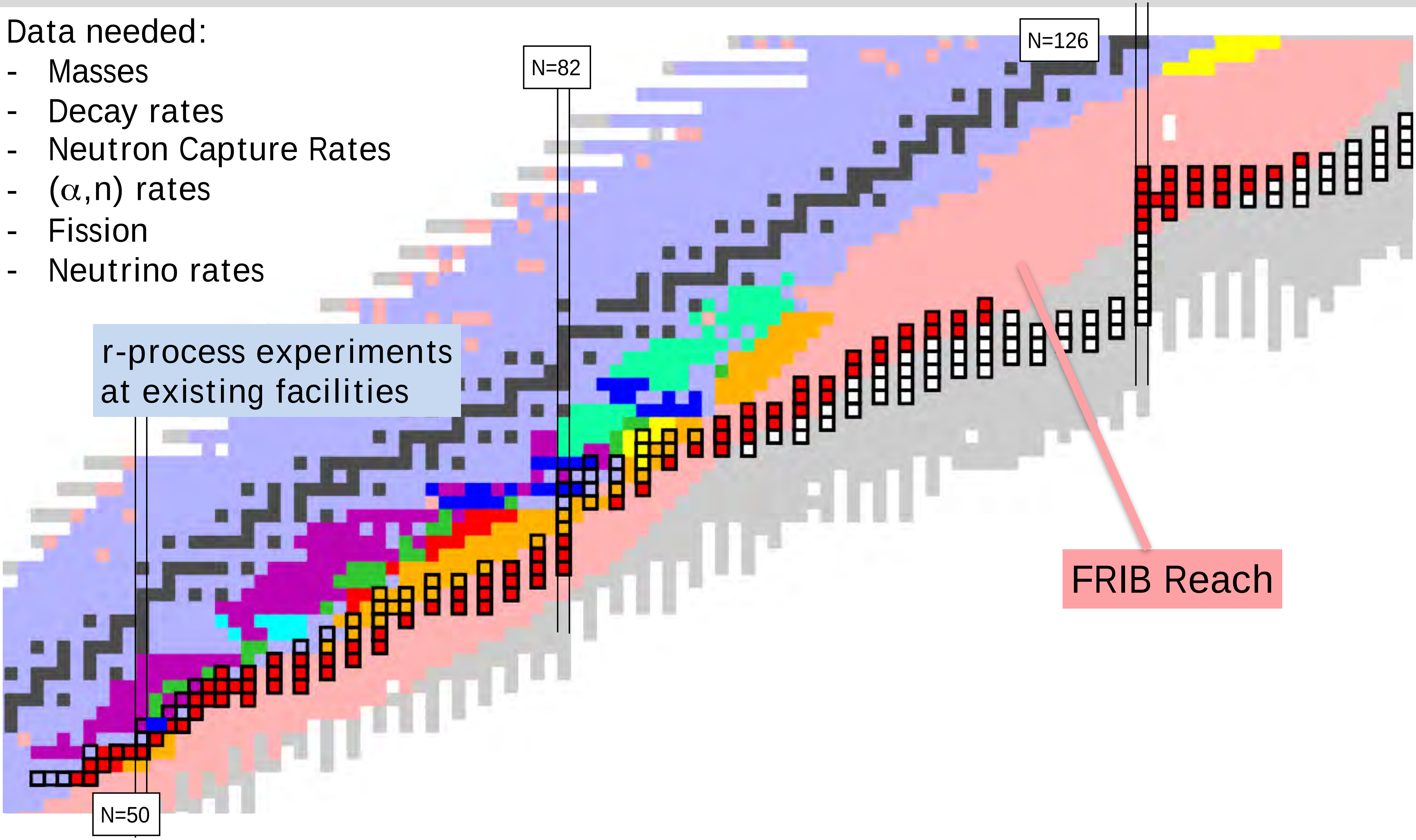
r-process nucleosynthesis

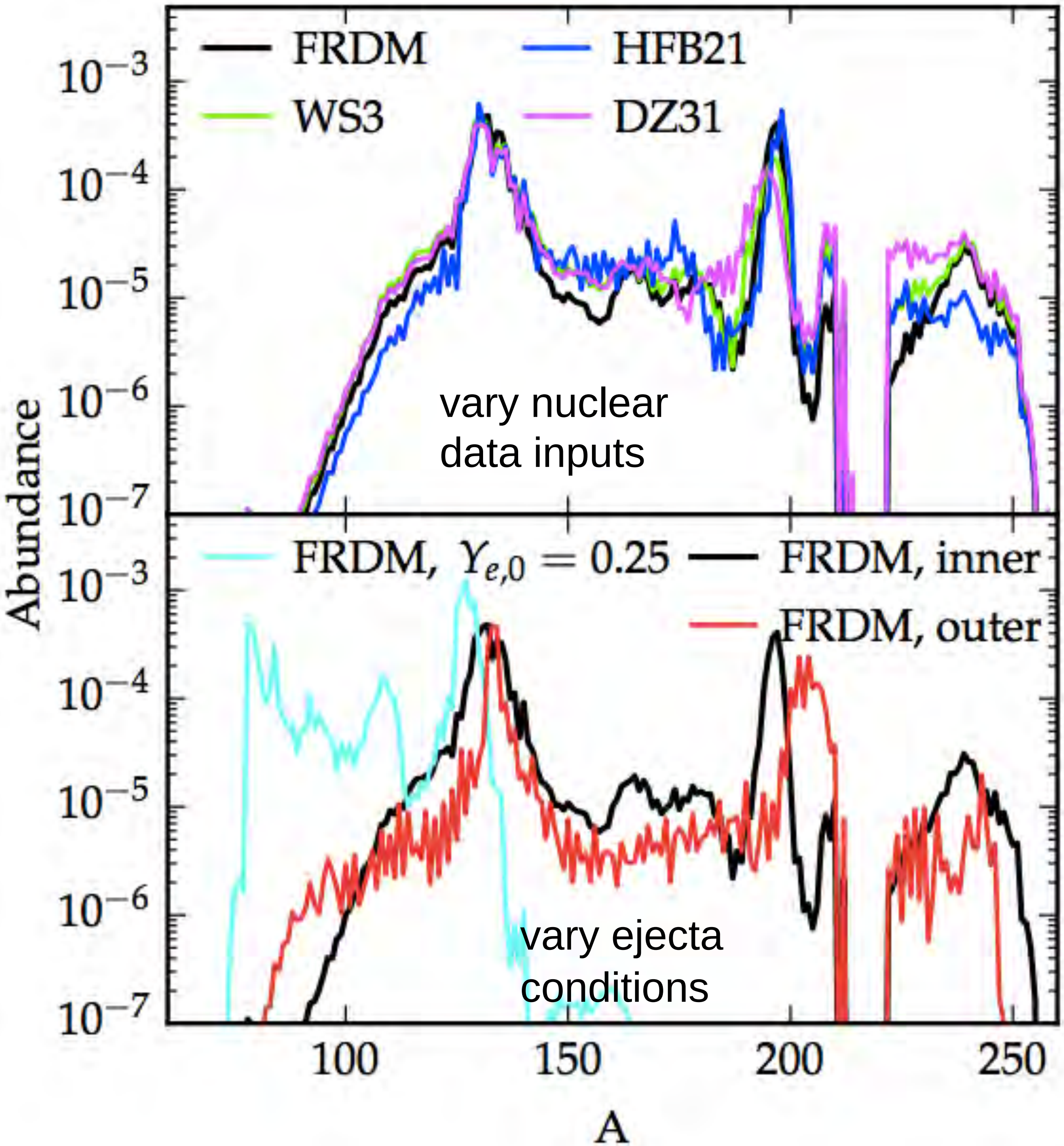
, Lippuner & Roberts (2015) *SkyNet* nuclear reaction network code



New Generation of Facilities Will Enable Measurements of r-Process Nuclei

Data needed:
- Masses
- Decay rates
- Neutron Capture Rates
- (α,n) rates
- Fission
- Neutrino rates



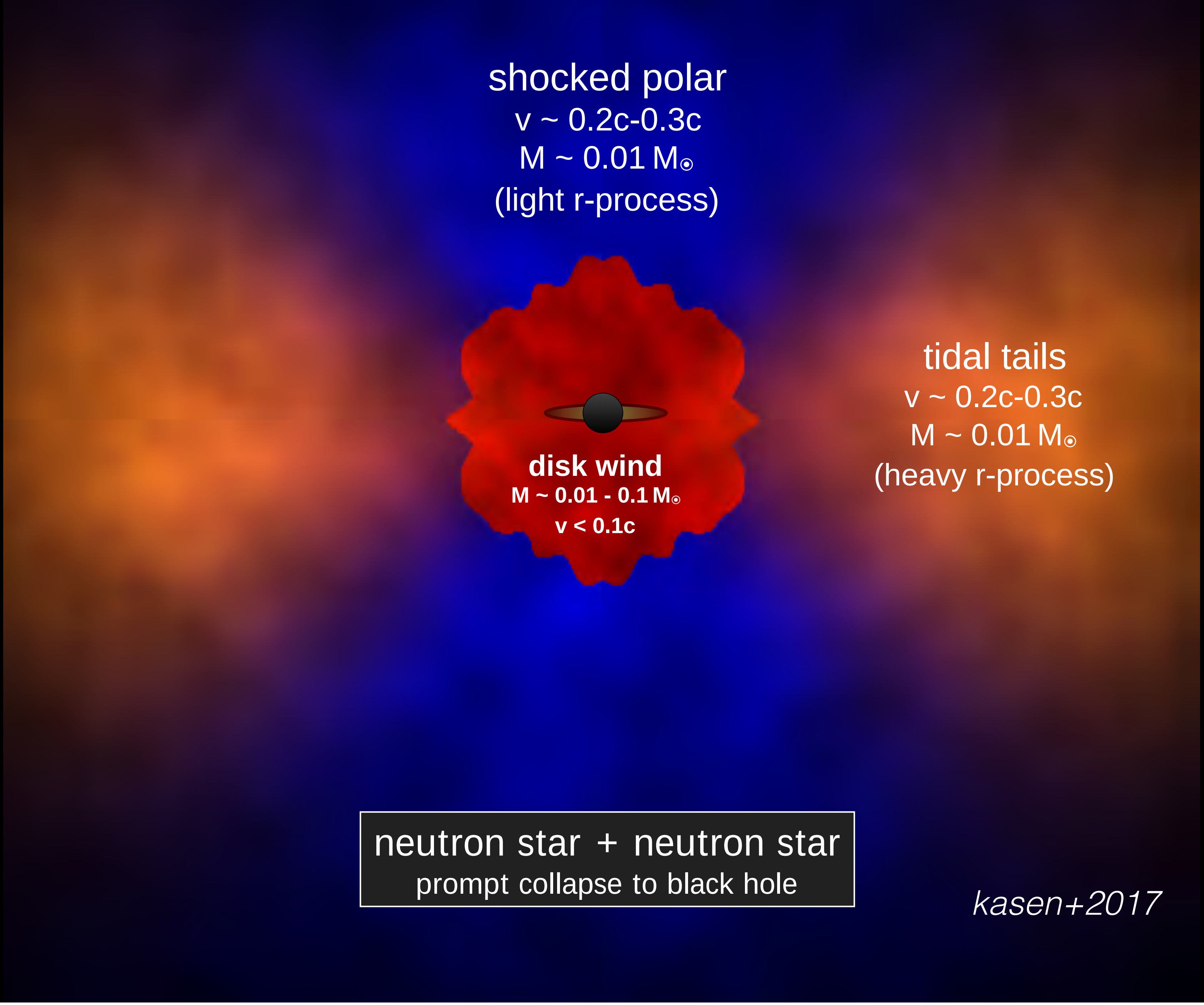


r-process abundances from neutron star merger ejecta

elements produced both nuclear data inputs and astrophysical conditions

Barnes, Kasen,Wu, Martinez-Pinedo 2016

Schematic view of NS merger ejecta



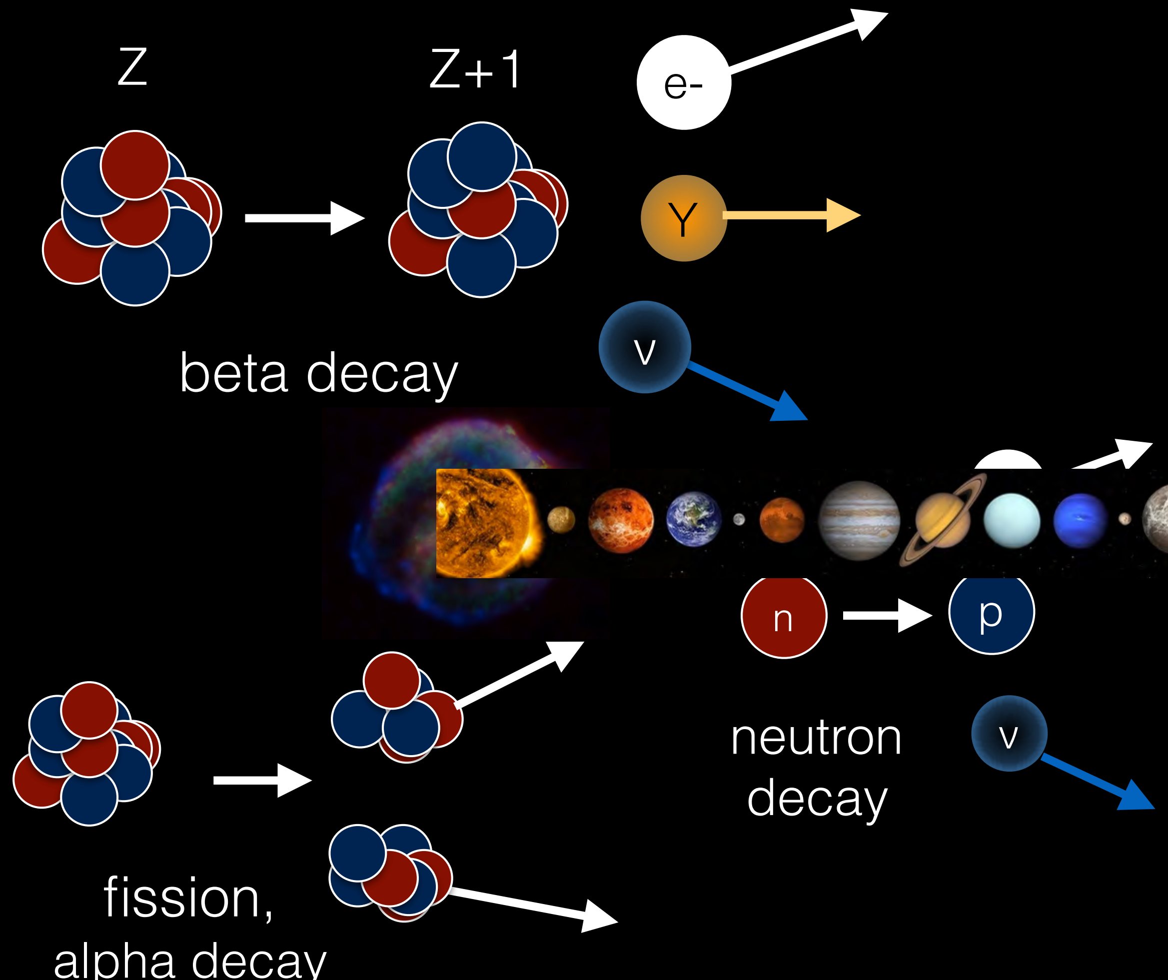
kilonova: emission from a cloud of radioactive ejecta

(Li & Paczynski 1999, Metzger et al. 2010, Roberts et al 2011)

at t ~ 1 day

L ~ 10^7 L_{sun}

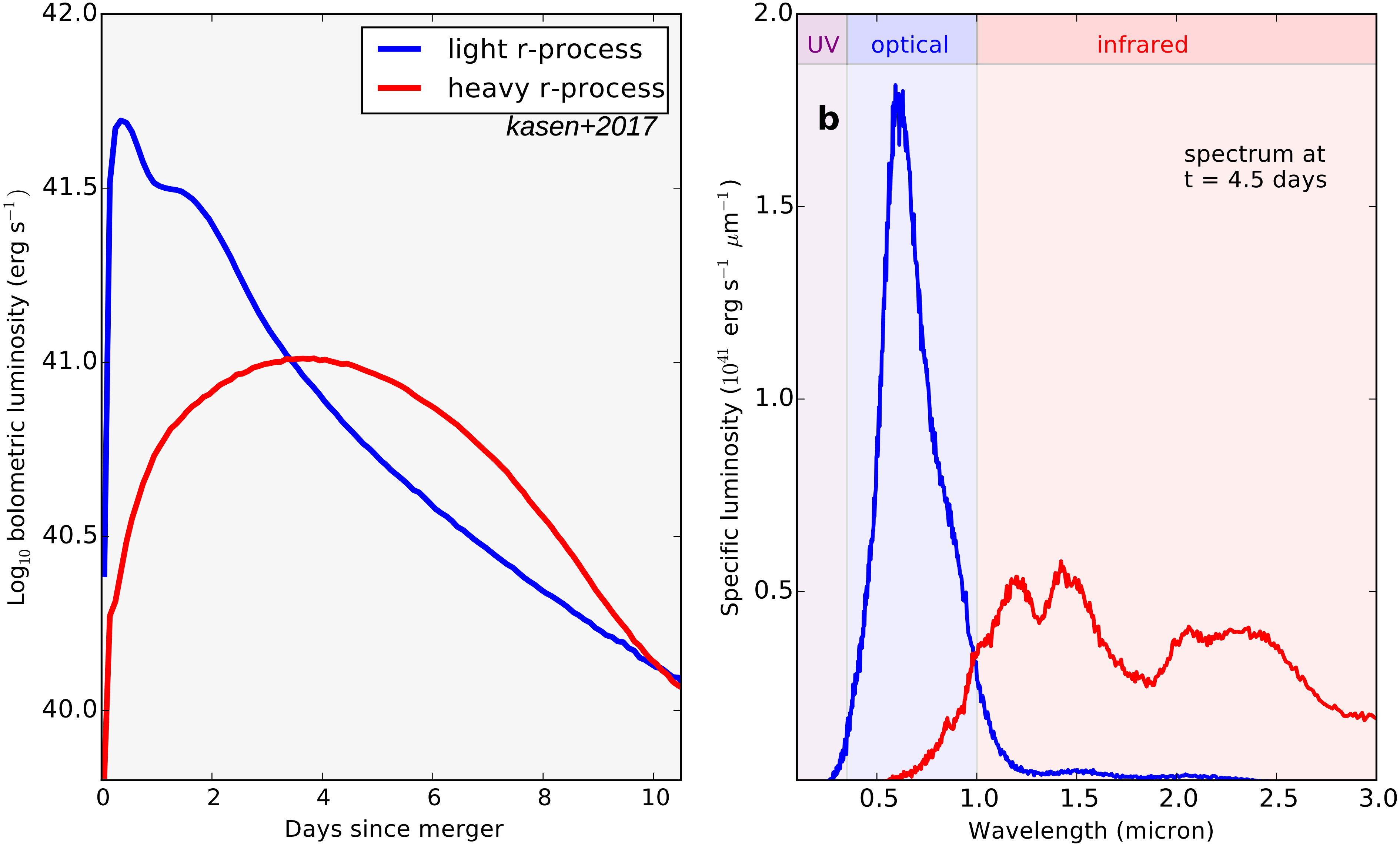
T ~ 5000 K



Kilonova Model Spectra and Light Curves

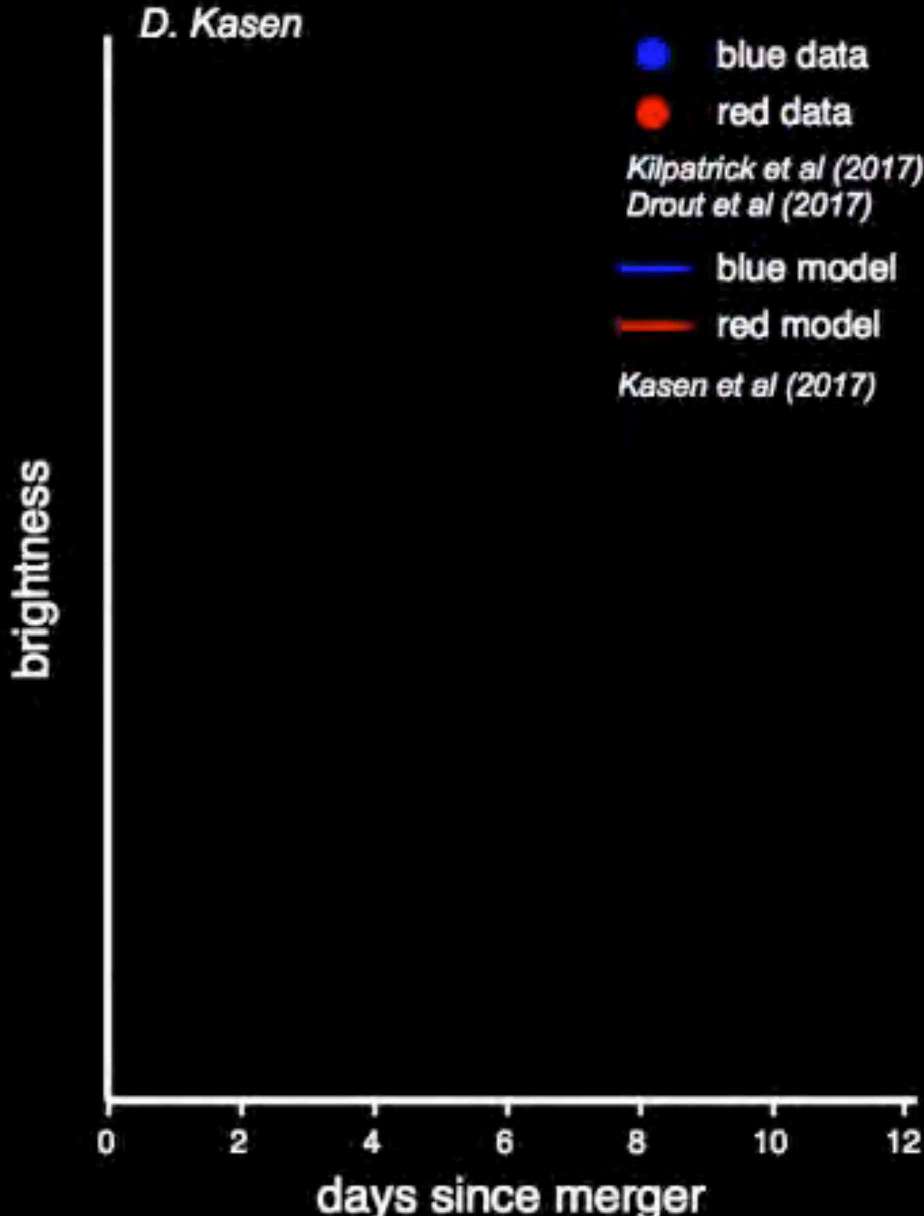
kasen, badnell and barnes 2013, barnes & kasen 2013

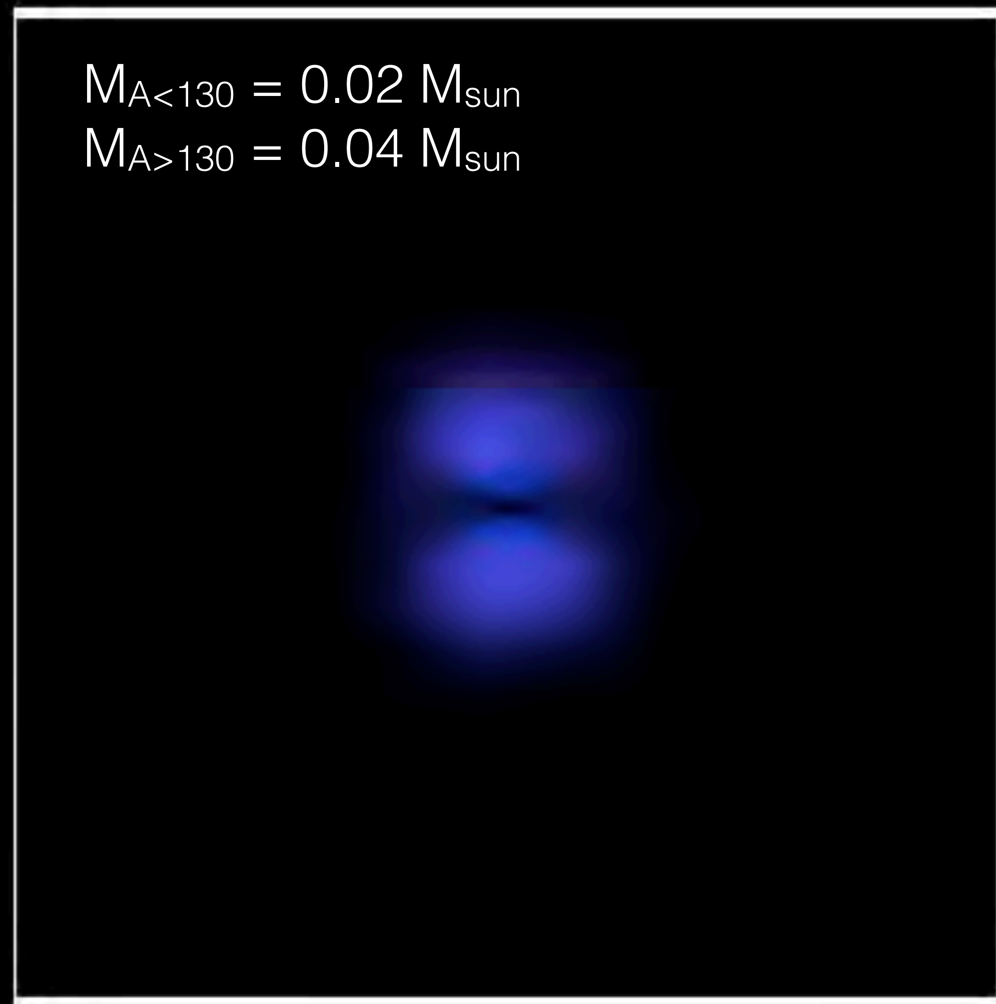
heavy (A > 130) r-process elements are more opaque than light (A < 130) r-process elements leading to longer lasting, redder emission



Observing heavy elements *at their production site*

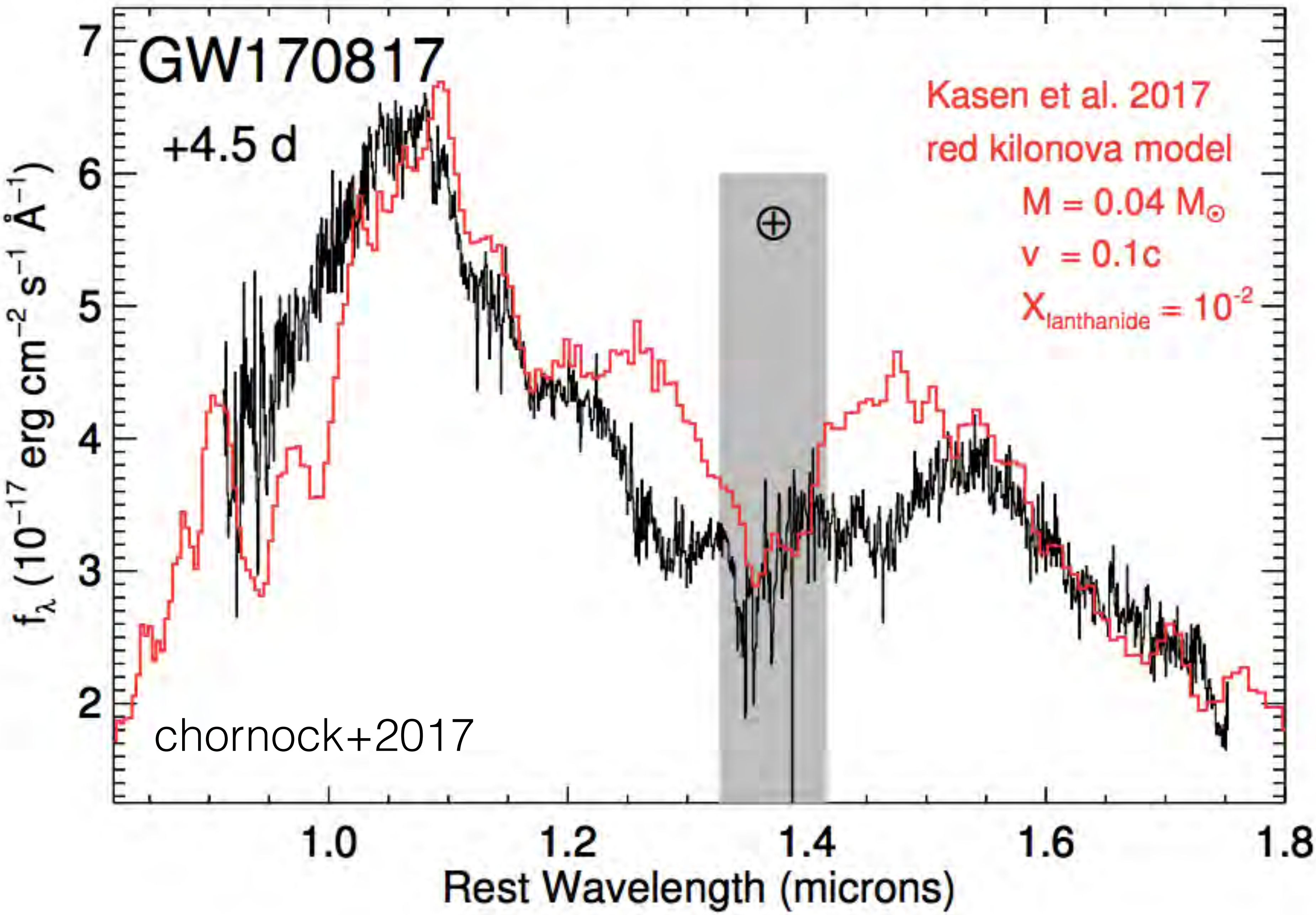
radioactive emission ("kilonova") provide a direct measure of mass and abundance

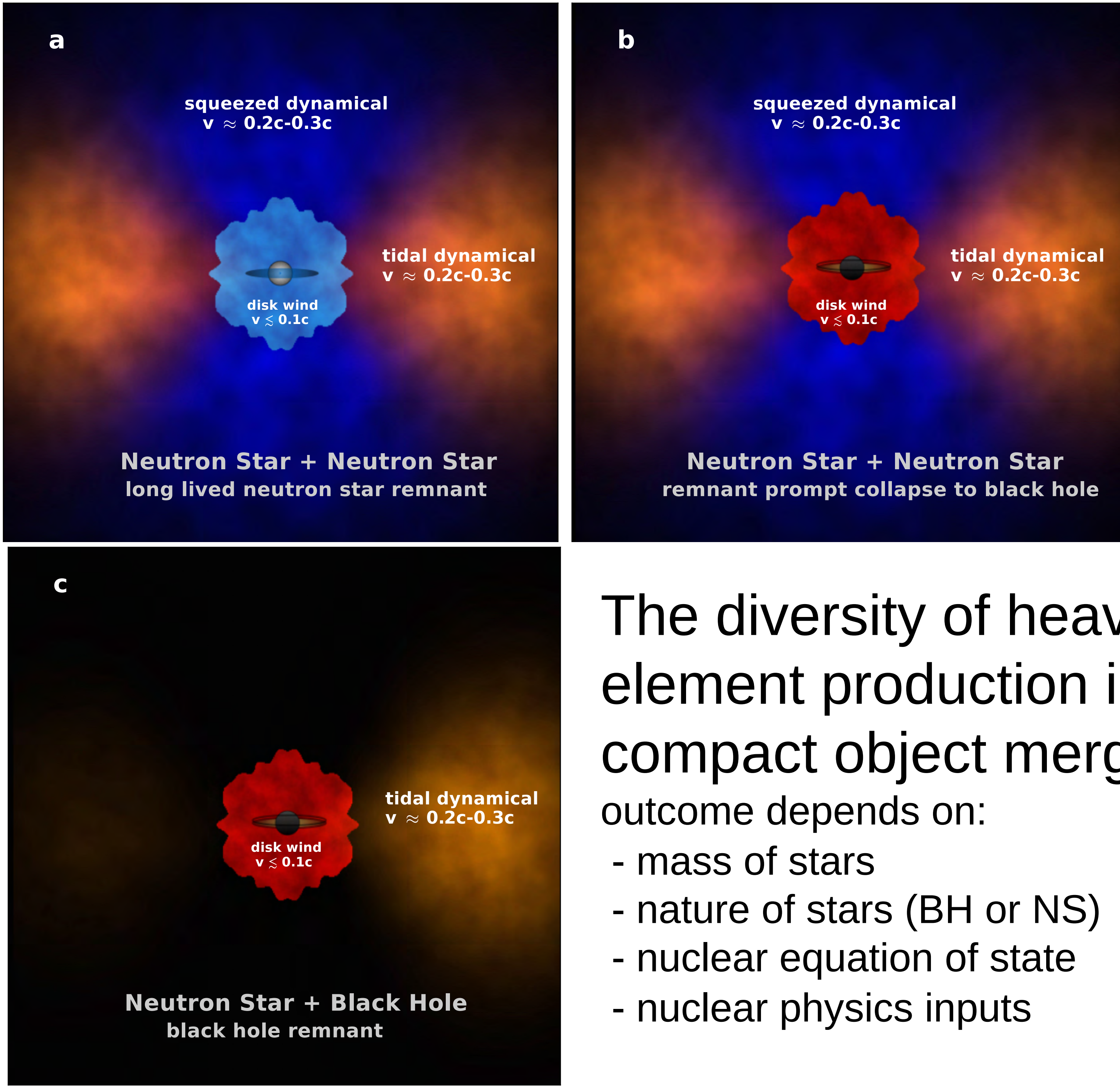




radioactive debris cloud

near-infrared spectrum of kilonova



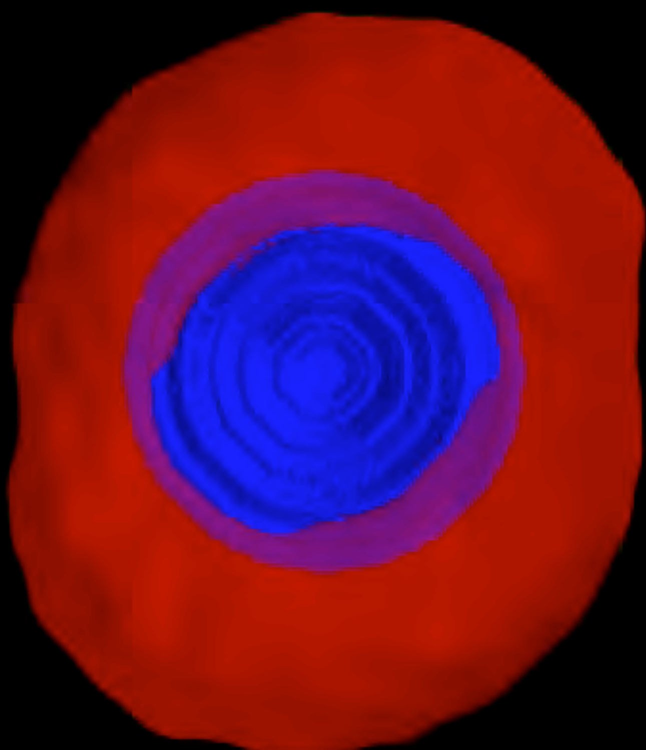


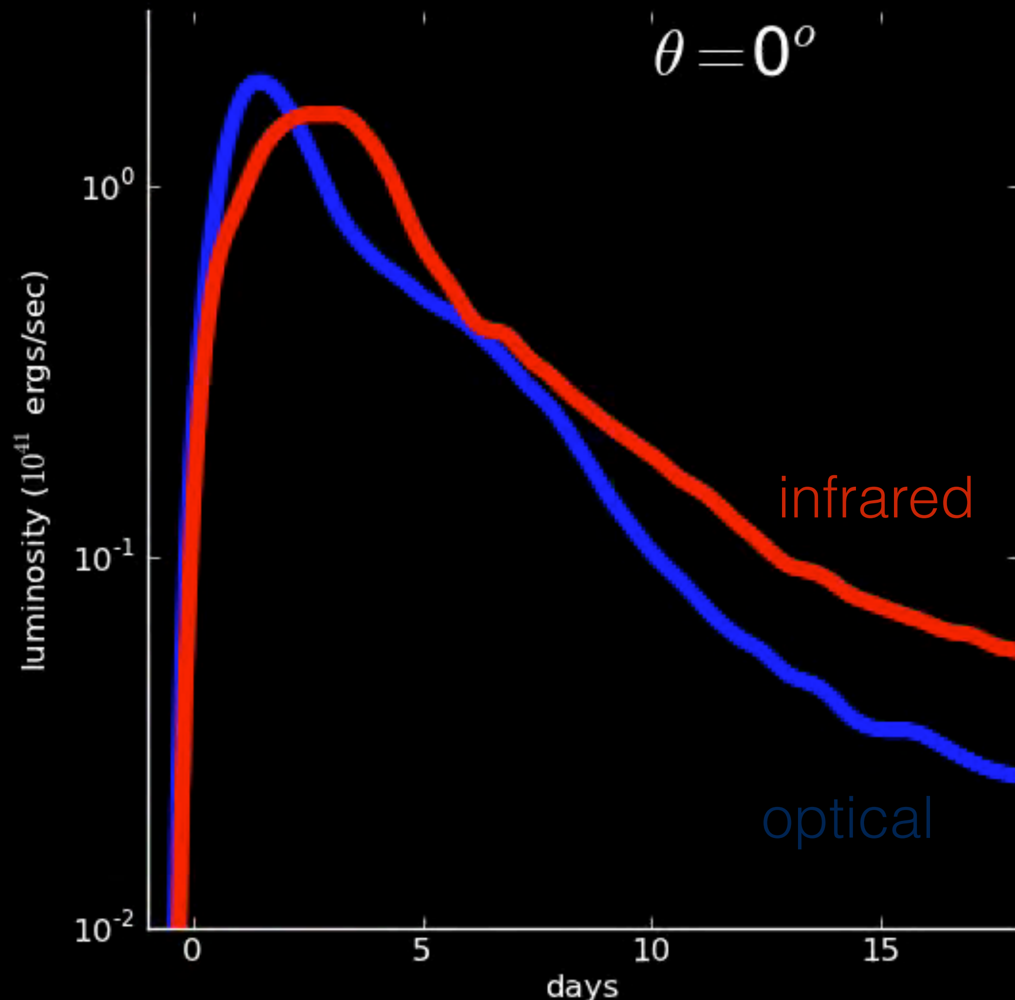
The diversity of heavy element production in compact object mergers

outcome depends on:

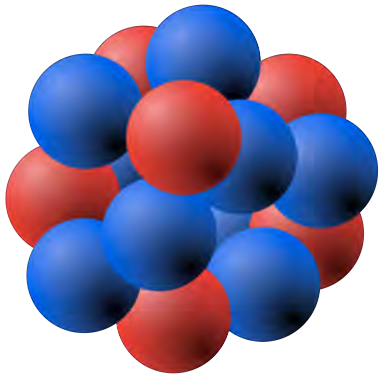
- mass of stars
- nature of stars (BH or NS)
- nuclear equation of state
- nuclear physics inputs

multi-D model - dependence on orientation “blue” kilonova embedded in “red” tidal tails

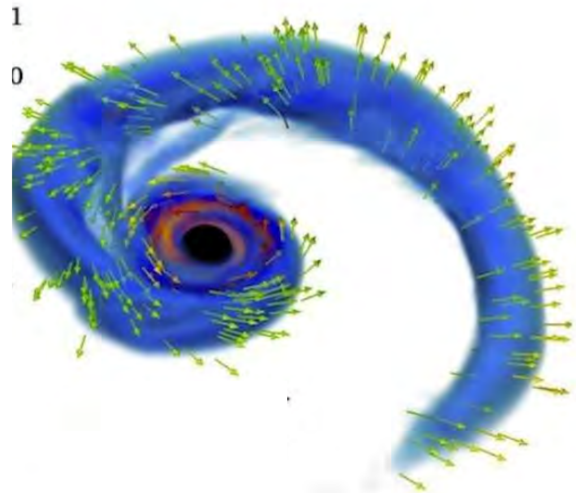




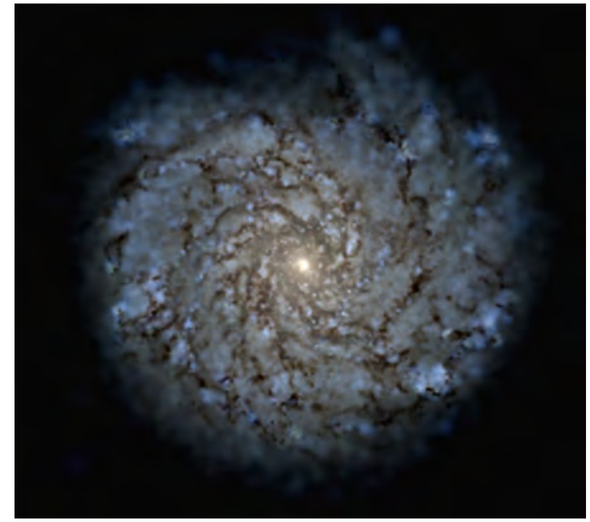
kasen+2015



nuclear theory
atomic theory
general relativity

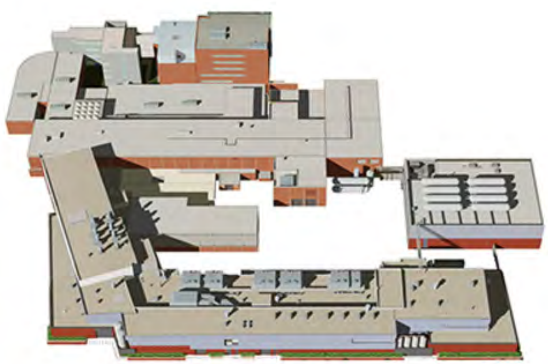


stellar scale
simulation



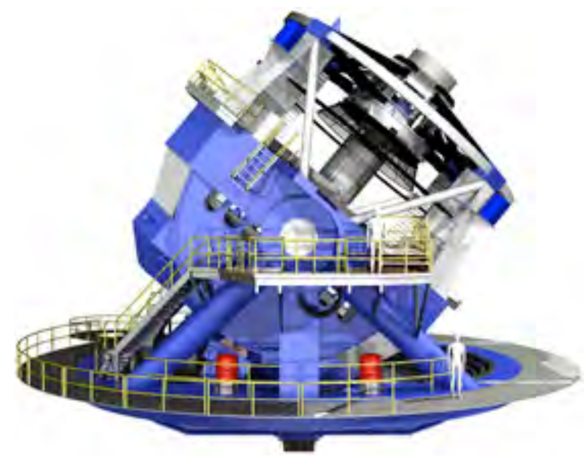
origin of the heavy
elements in the galaxy

our multi-messenger, multi-scale future



nuclear experiment
(FRIB)

gravitational
wave experiment



astronomical
surveys