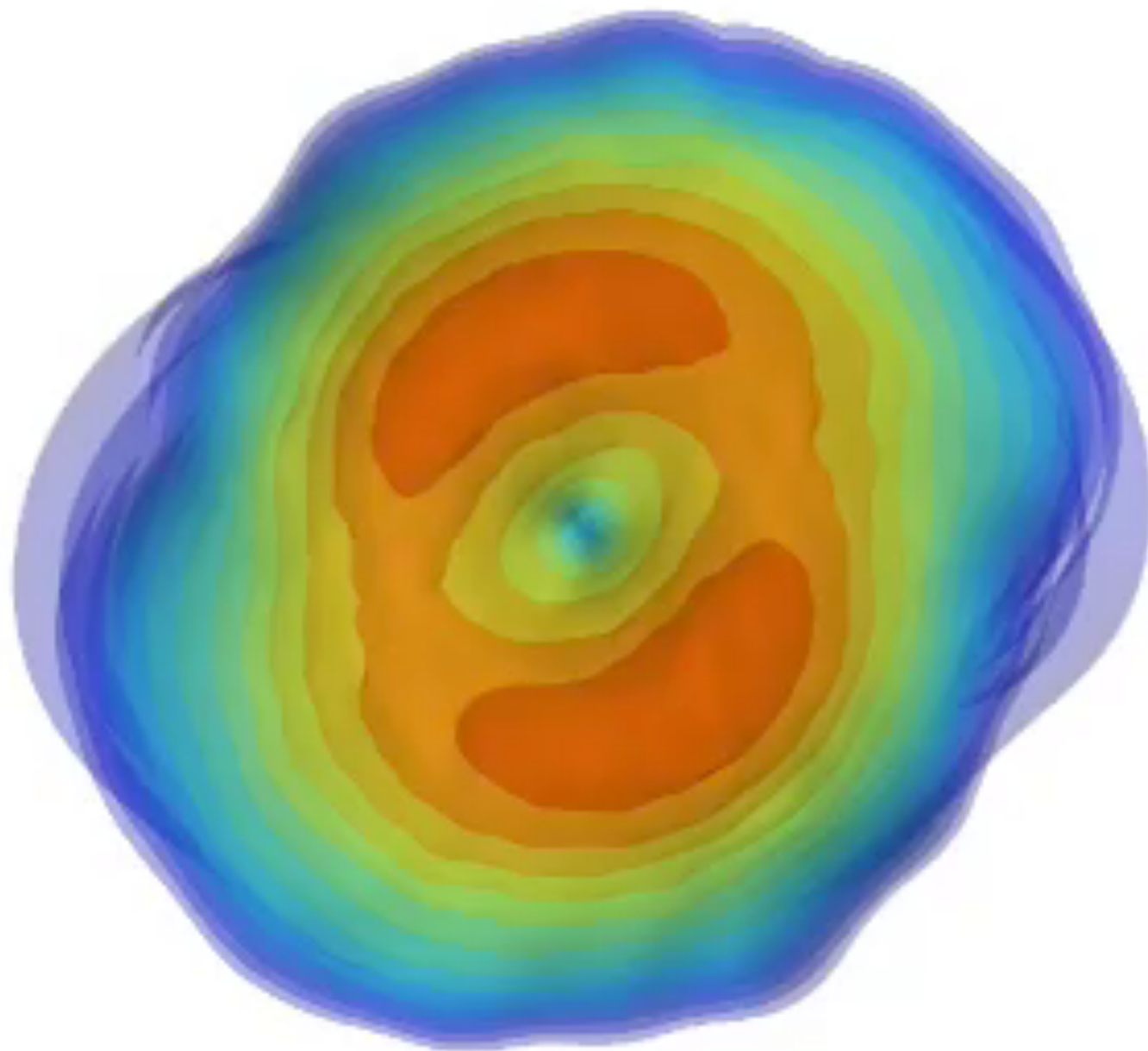


Explosive Nuclear Astrophysics and the origin of the heavy elements



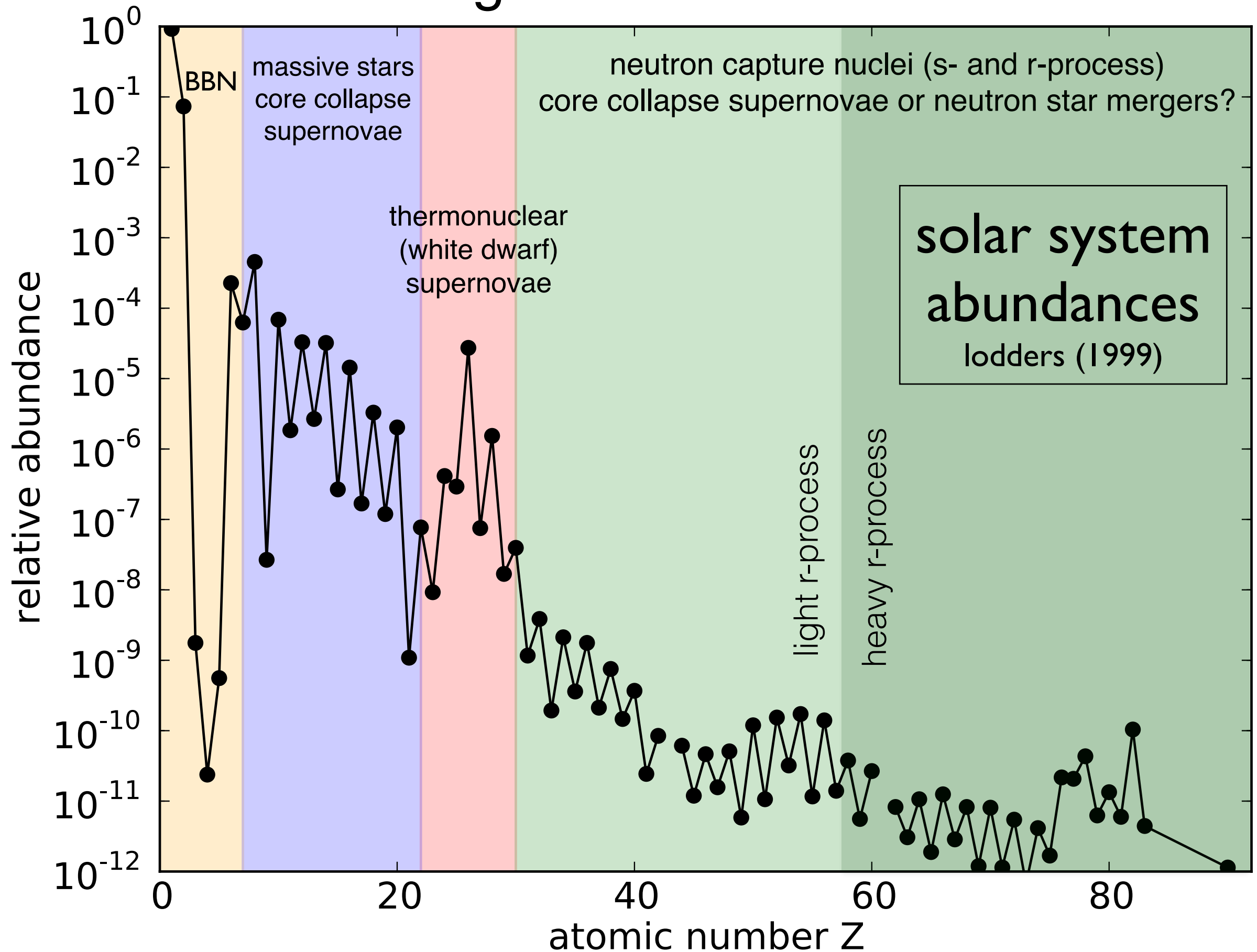
daniel kasen

UC Berkeley/LBNL

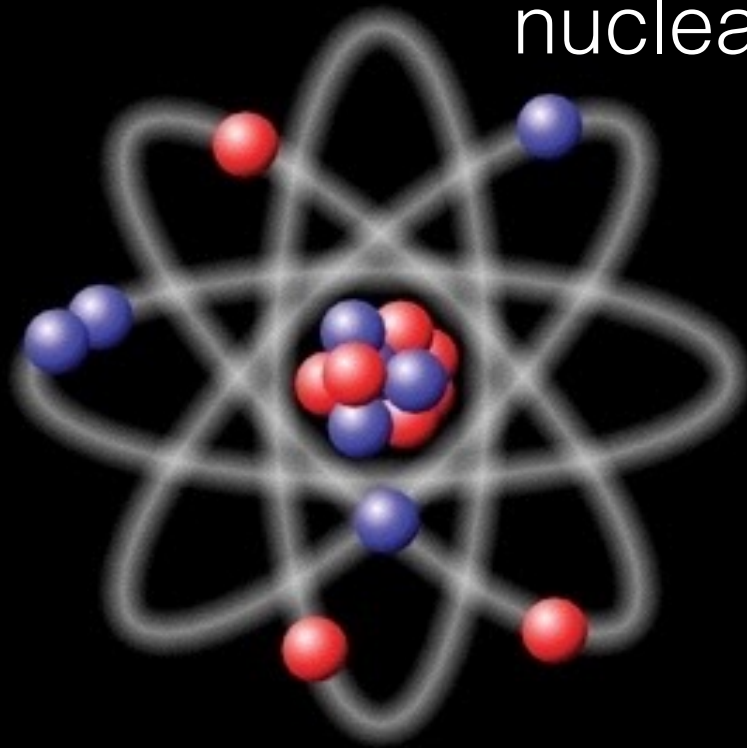
r. fernandez, b. metzger,
j. barnes, n. badnell,
s. rosswog, l. roberts,
e. ramirez-ruiz

*low energy community meeting
MSU, 8/21/2015*

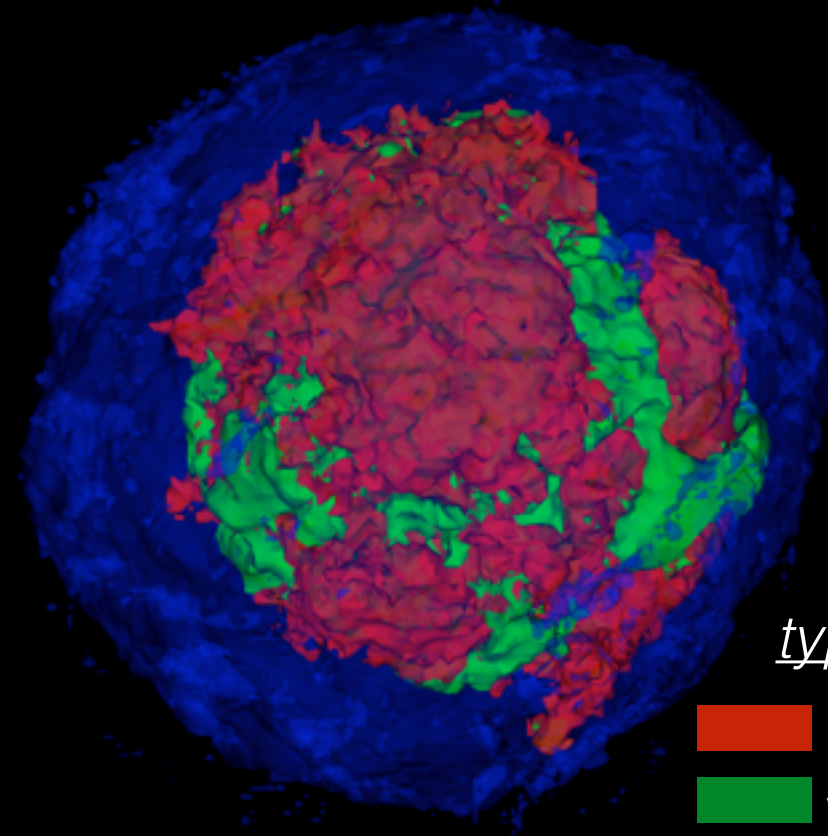
origin of the elements



nuclear physics



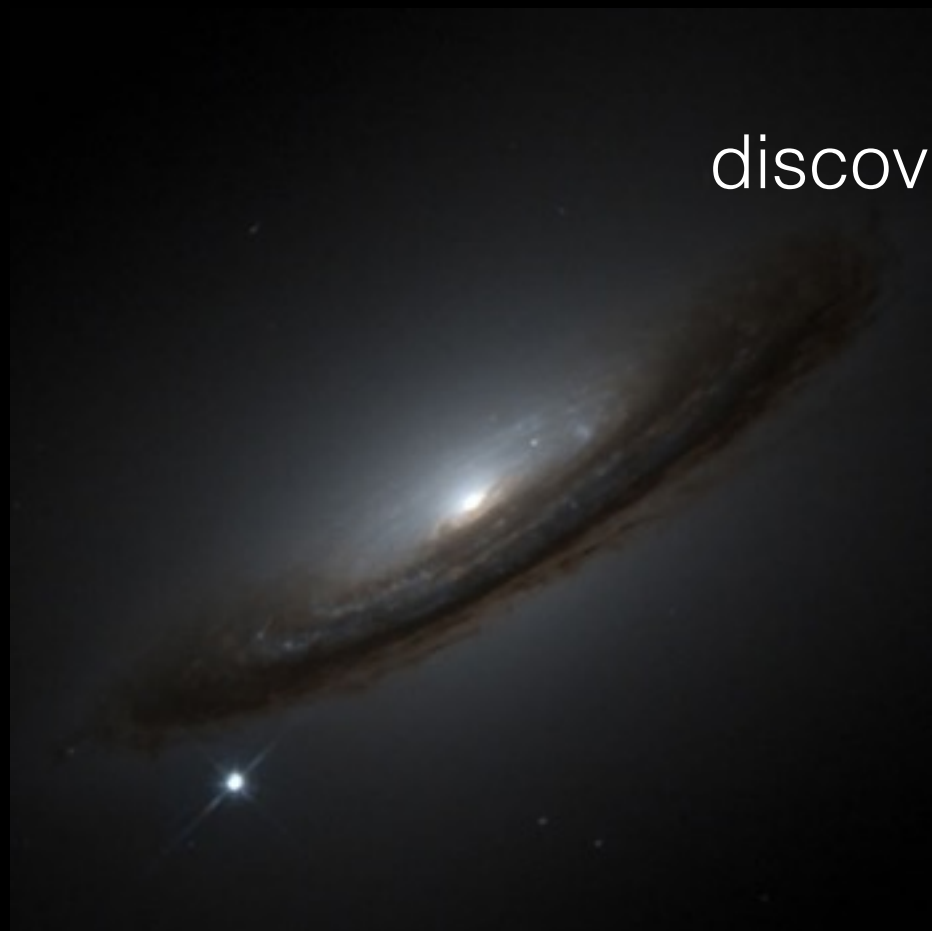
astrophysics
simulation



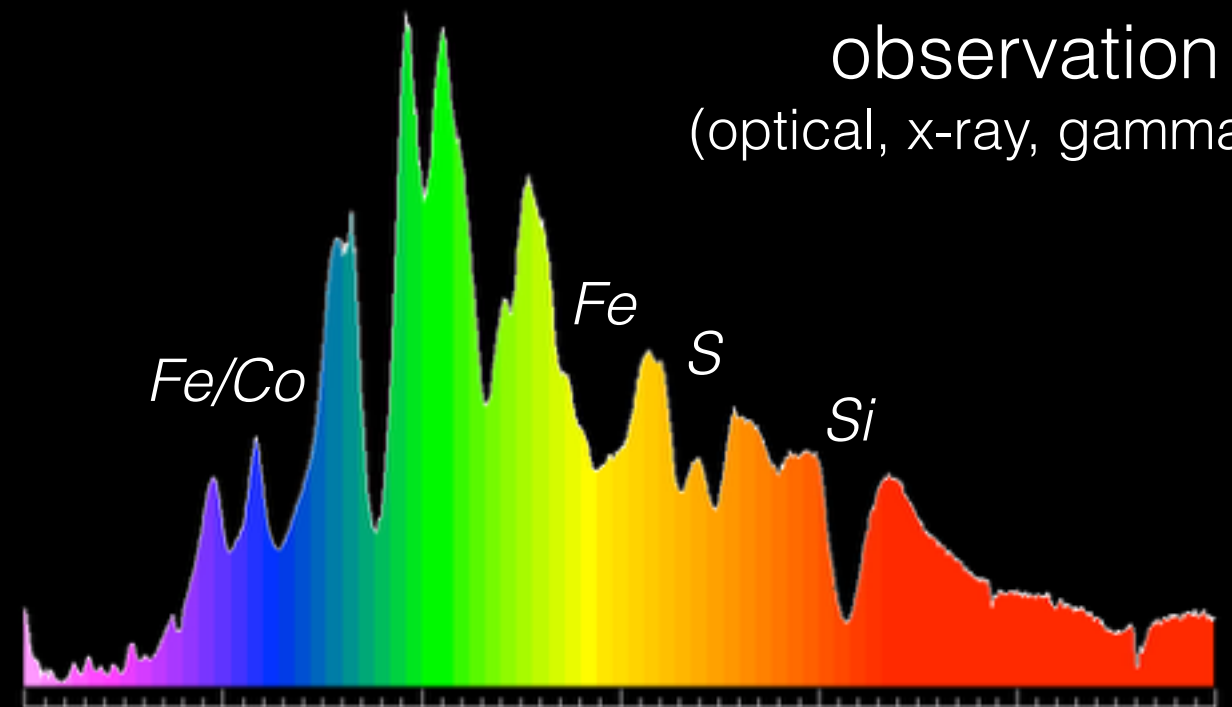
typela supernova



discovery



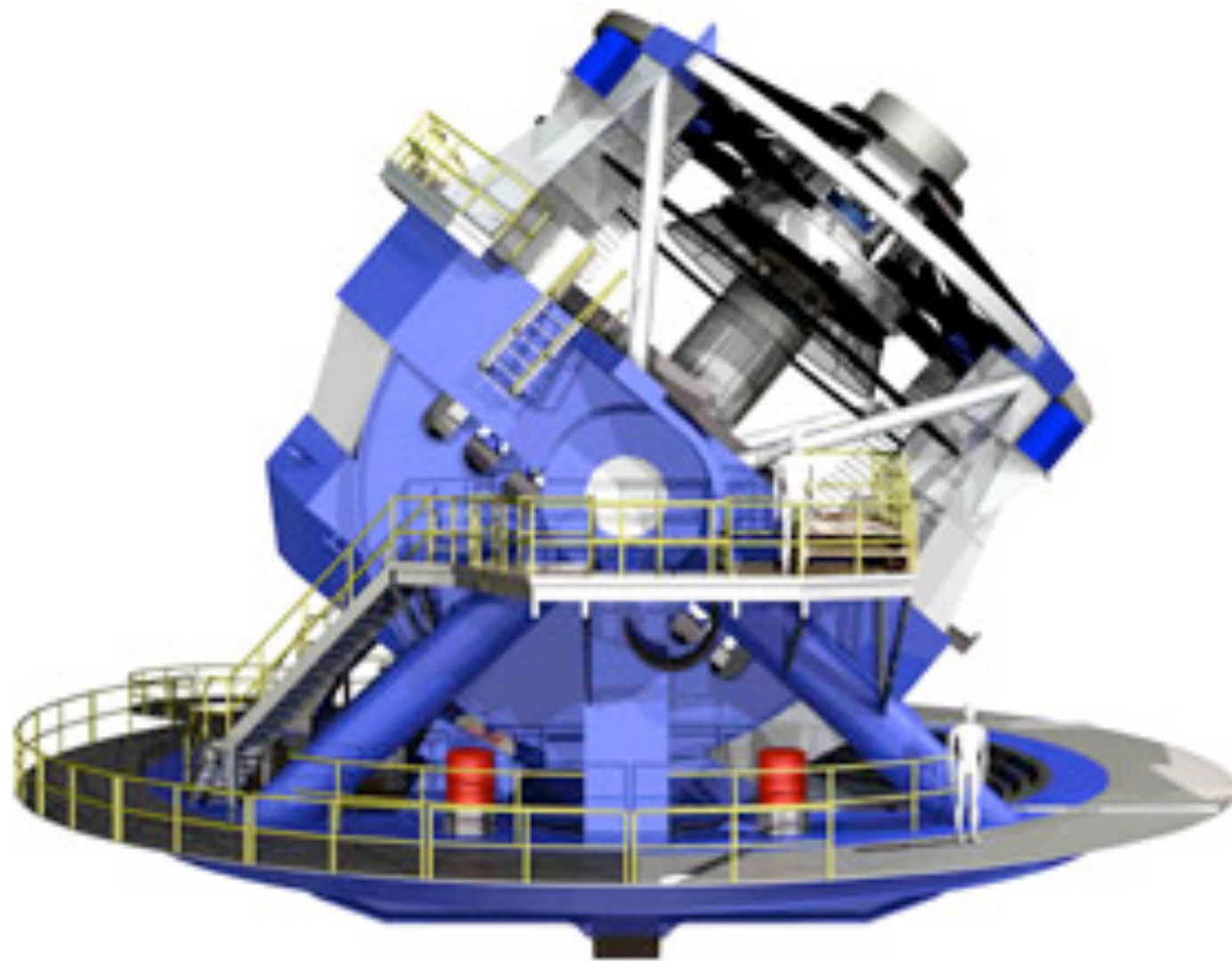
observation
(optical, x-ray, gamma-ray)



photon spectrum at visible wavelengths

the era of time domain astronomy

multiple wide-field transients optical surveys



LSST

**1000's of transients
discovered each year,
probing:**

core collapse supernovae

type Ia supernovae

jet driven supernovae

pair instability supernovae

helium shell thermonuclear detonations

failed carbon/oxygen deflagrations

magnetar powered supernovae

calcium-rich transients

neutron star merger kilonovae

white dwarf collapse

tidal disruption by black holes

end-to-end simulation of astrophysical explosions

stellar evolution ($> 10^6$ years)



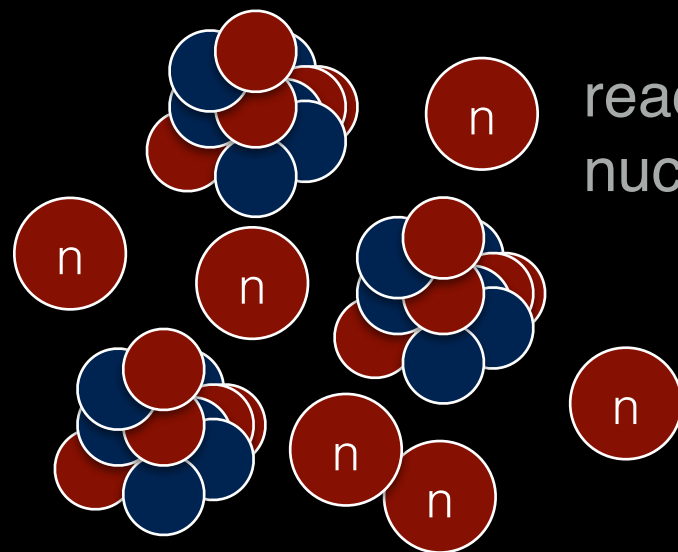
*stellar evolution
stable nuclear
reactions*

explosive dynamics (milliseconds-hours)



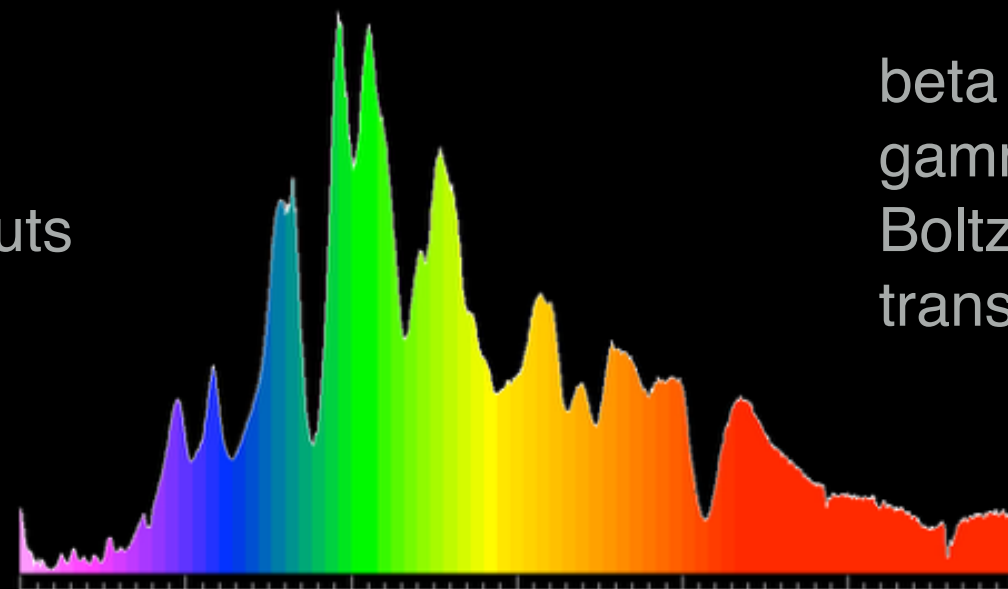
*hydrodynamics,
gravity, nuclear
equation of state,
neutrino transport,
nuclear reactions*

nucleosynthesis (seconds)



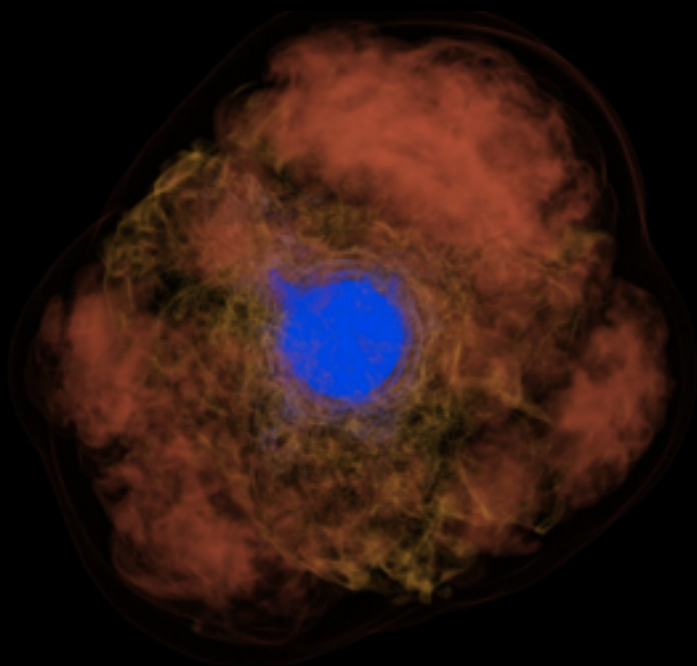
reaction networks
nuclear physics inputs

radioactive transient (days/months)



photon spectrum at visible

beta decay/fission
gamma heating
Boltzmann photon
transport

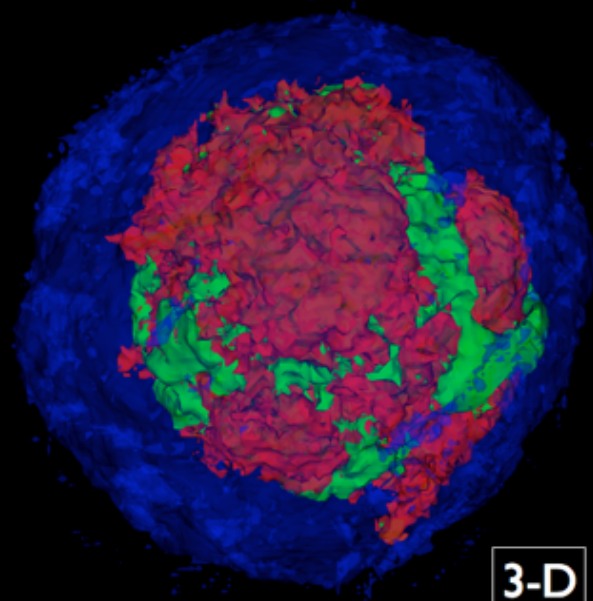


core collapse supernovae

explosion of massive stars

How do they explode (neutrino mediated)?

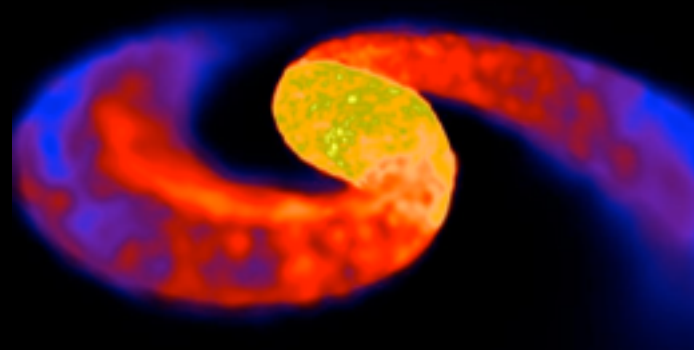
How do nuclear/neutrino physics influence energetics and the isotopes produced?



thermonuclear supernovae

explosion of white dwarfs

How does thermonuclear carbon burning ignite and propagate? What are the progenitors (one white dwarf or two)?



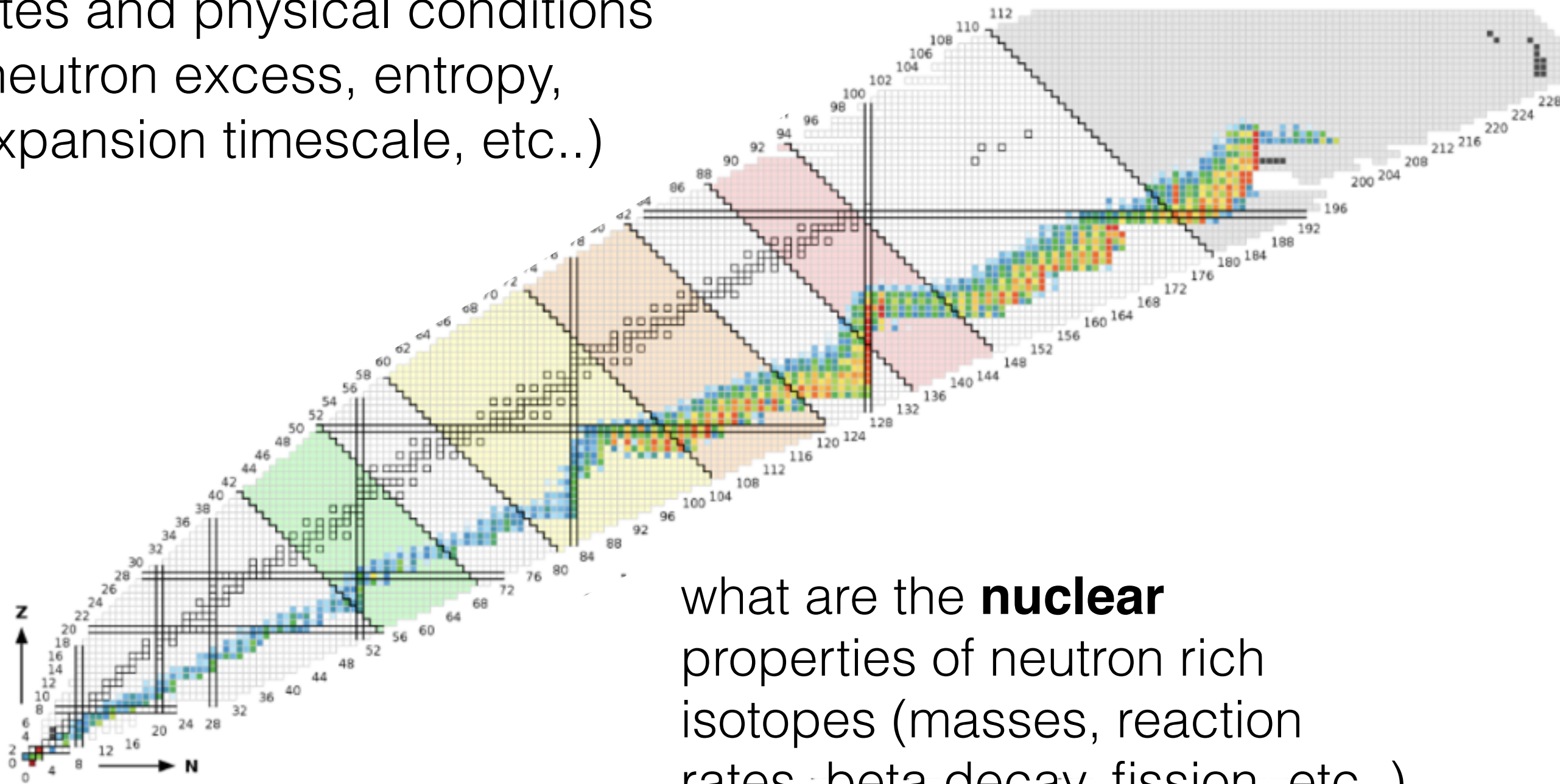
neutron star mergers

inspiral and coalescence of two neutron stars

What is their contribution to r-process nuclei production? What are the effects on the nuclear equation of state?

origin of the r-process elements

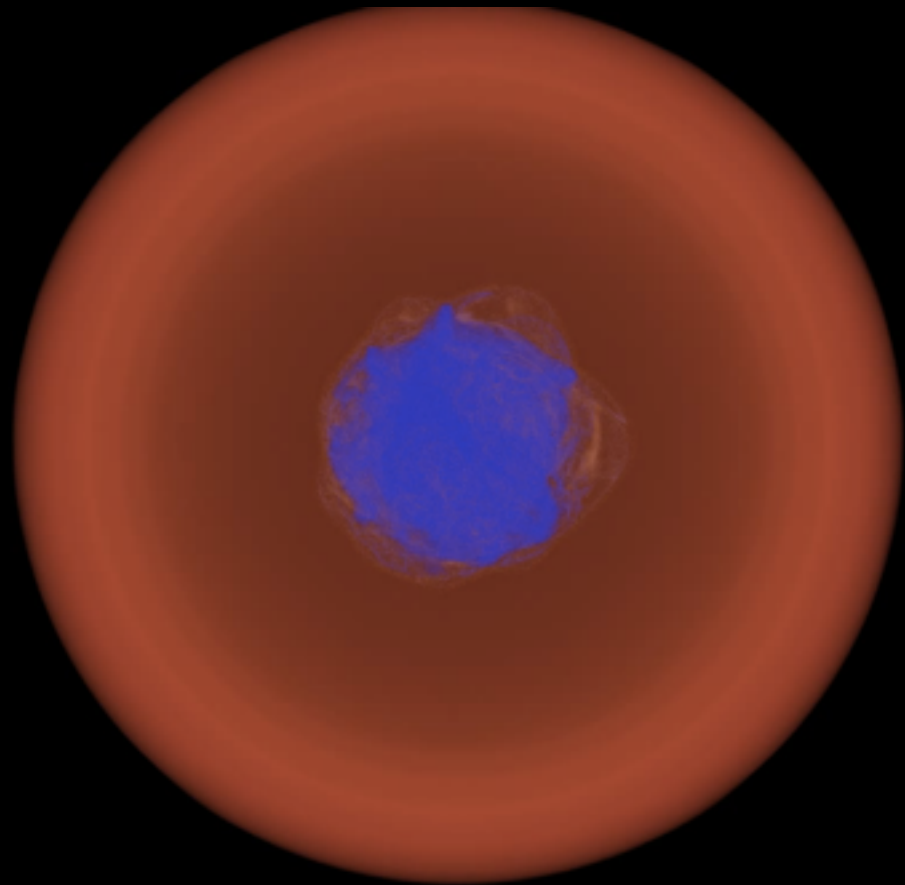
what are the **astrophysical** sites and physical conditions (neutron excess, entropy, expansion timescale, etc..)



possible r-process sites

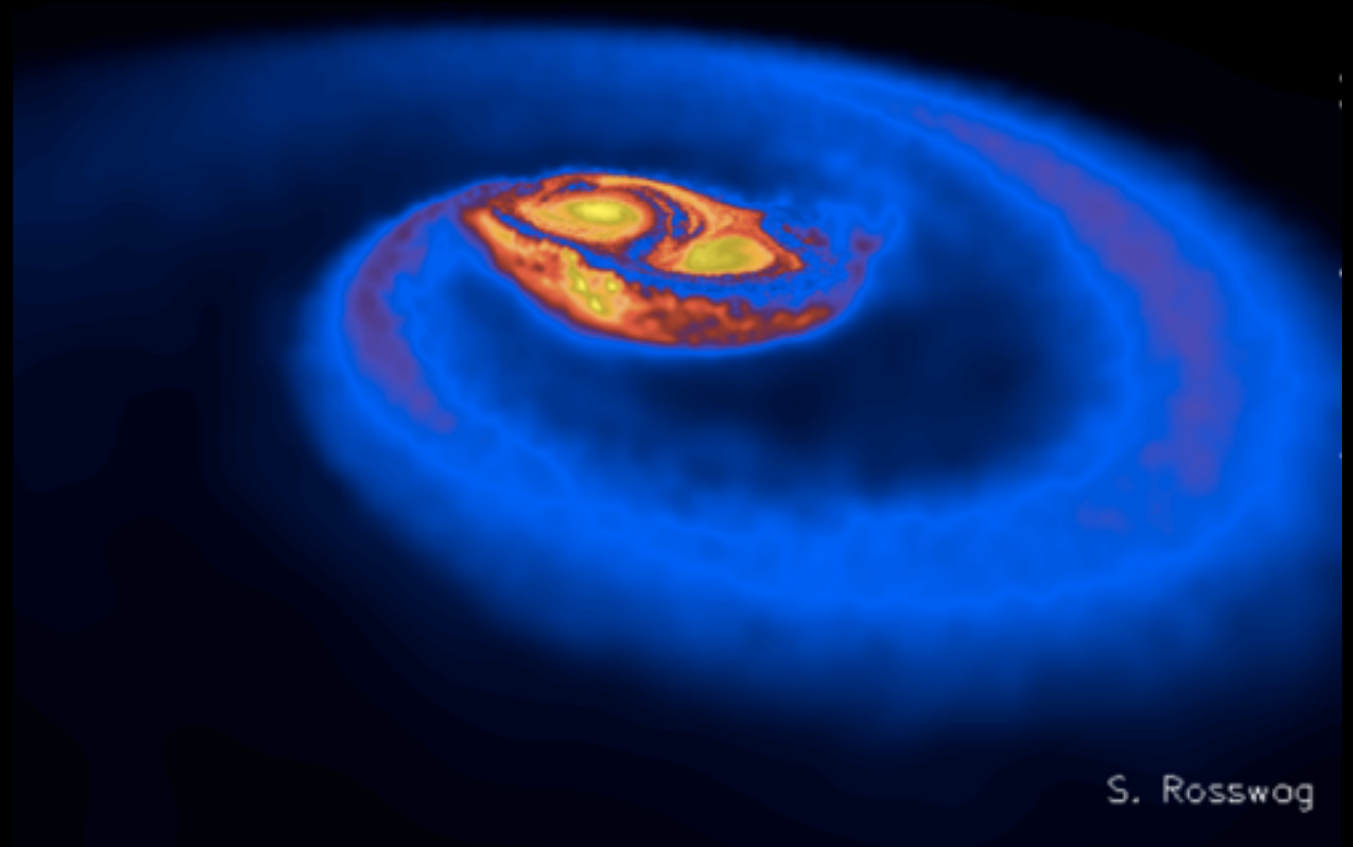
need neutron rich ejecta: $Y_e = n_p/(n_n + n_p) < 0.5$

core-collapse supernovae

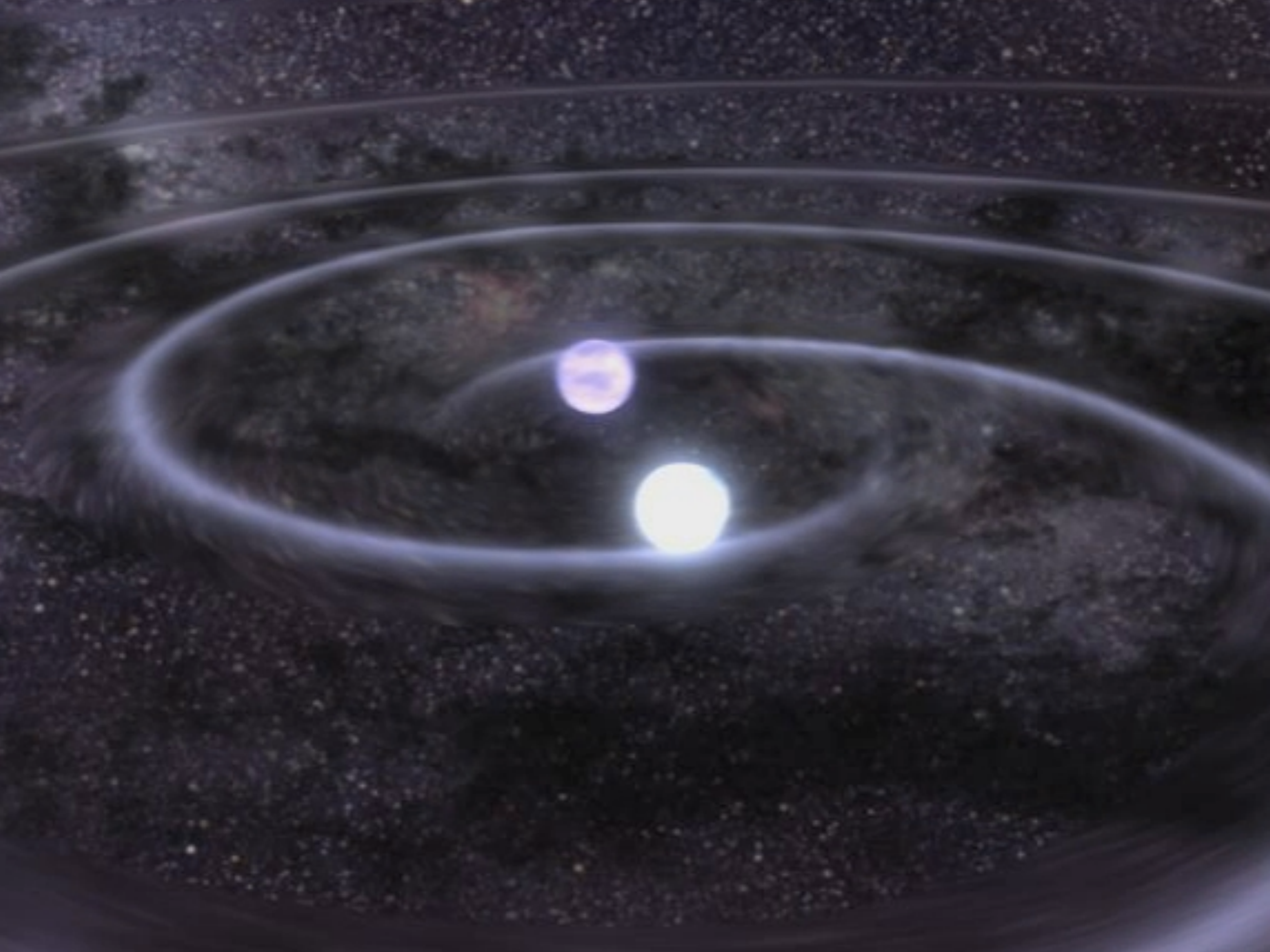


neutrino driven wind from
a proto-neutron star
common event, low yield (if any)

neutron star merger

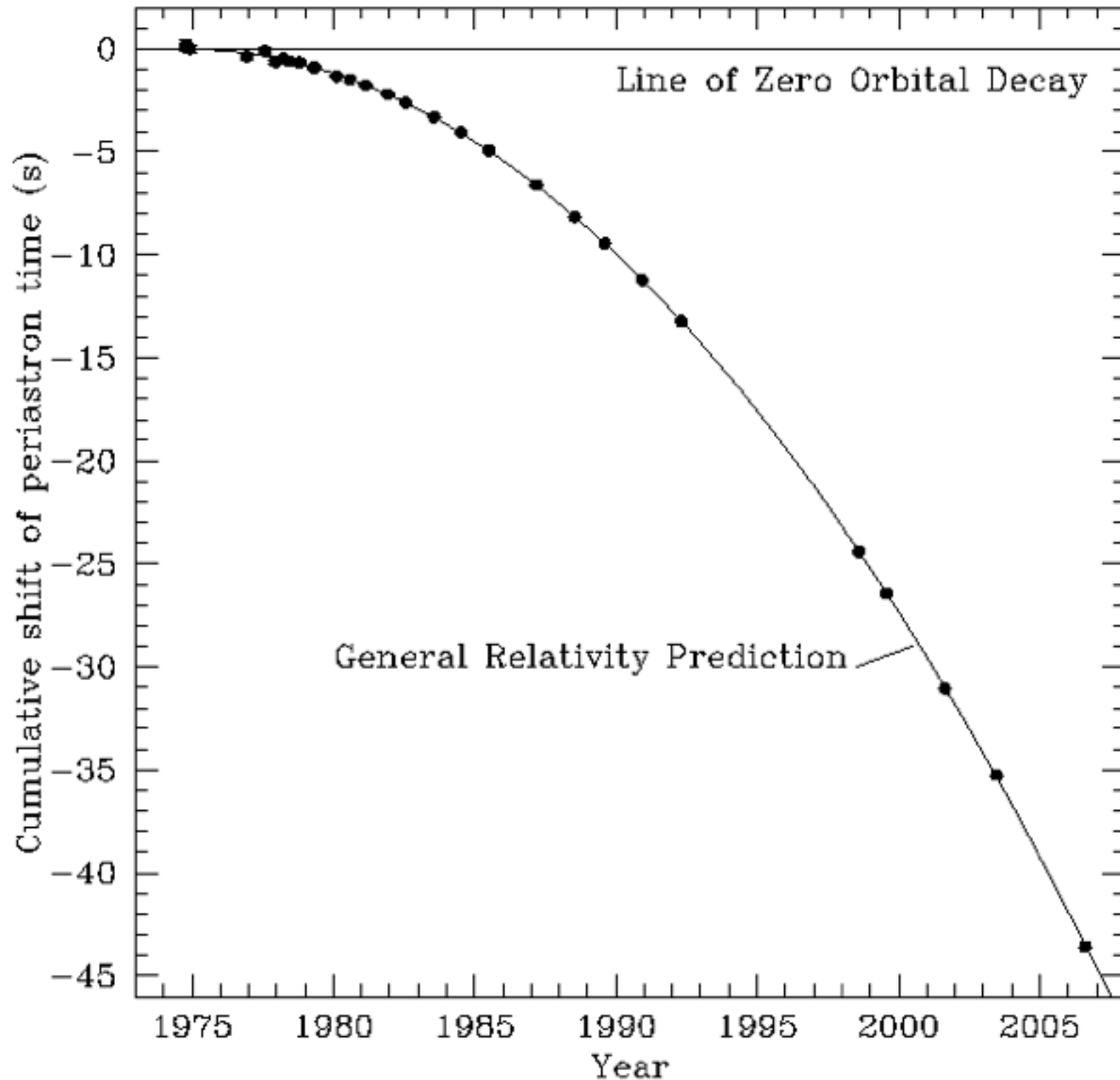


dynamical ejecta
or post-merger disk winds
rare event, high yield



Inspiral of neutron star binary

PSR B1913+16 hulse-taylor binary pulsar

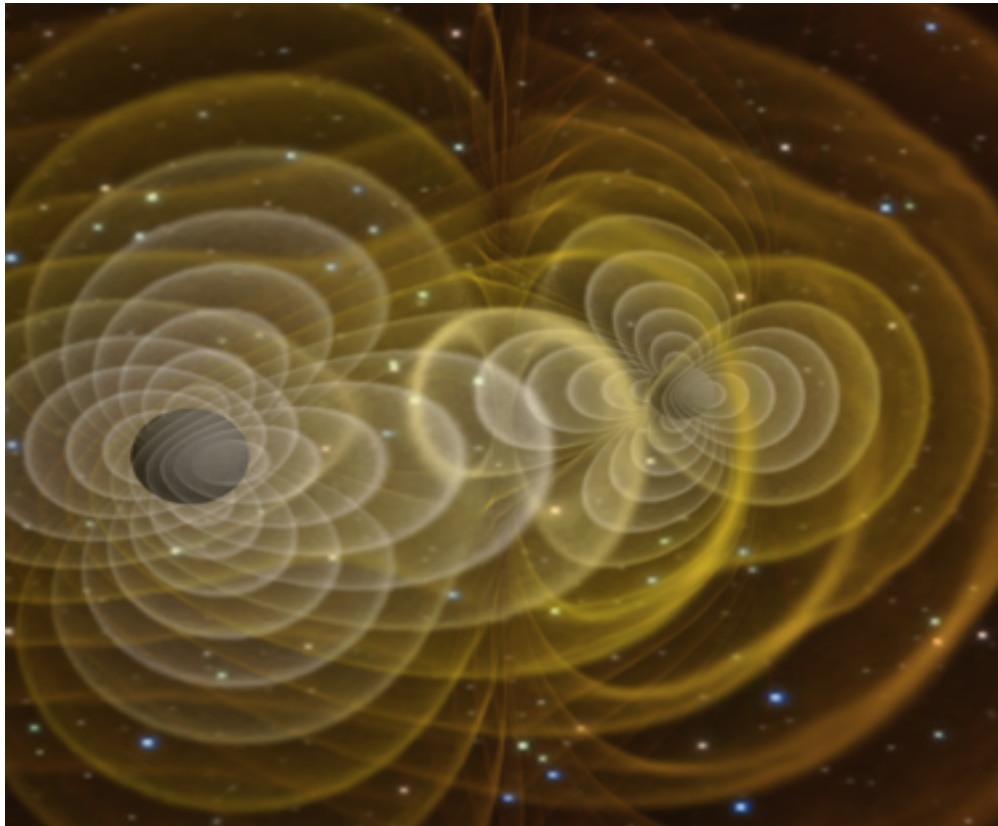


separation: $\sim 1 R_{\text{sun}}$
period: ~ 8 hours
lifetime: ~ 300 million yrs

estimated rate:
 $10^{-5} - 10^{-4}$ mergers
per galaxy per year
(but very uncertain)

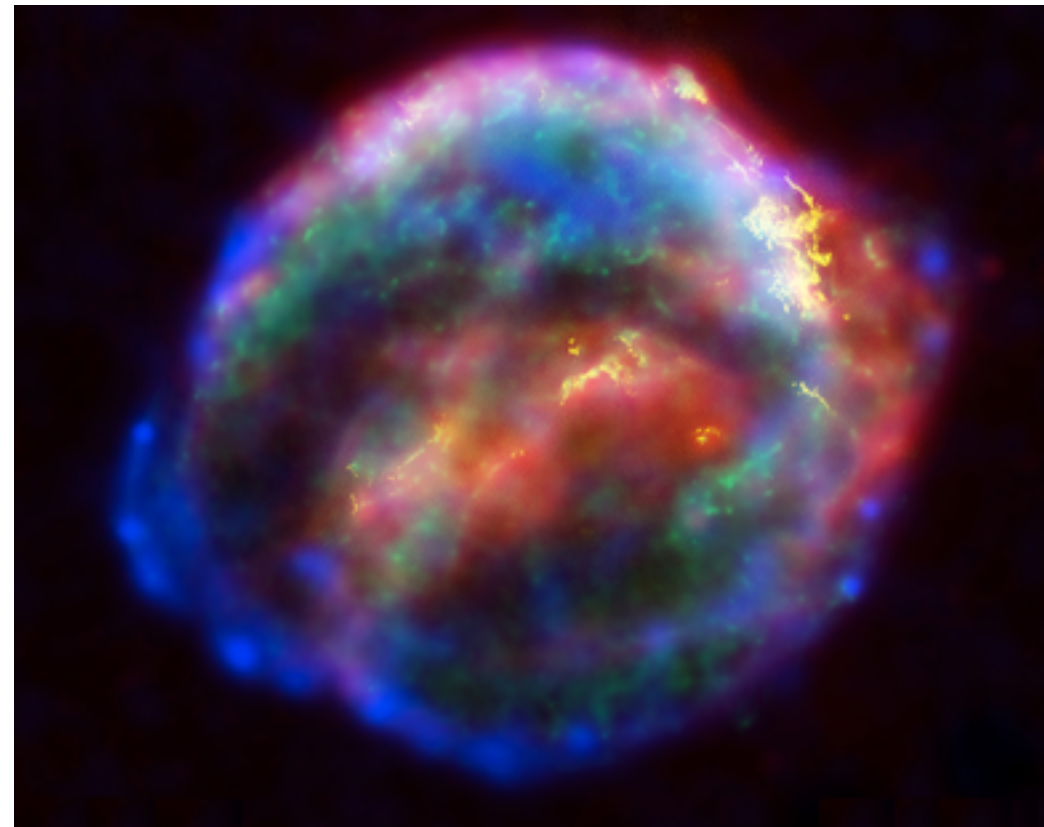
How high is the true rate?
How much r-process is produced?

upcoming **new probes** of neutron star merger physics



gravitational waves

“chirp” signal expected
to be seen by
advanced LIGO in
coming years



radioactive “kilonova”

thermal supernova-like glow from
radioactive r-process
debris ejected in the merger

neutron star merger simulation

hydrodynamics + EOS + gravity

dynamical ejecta
< 1%

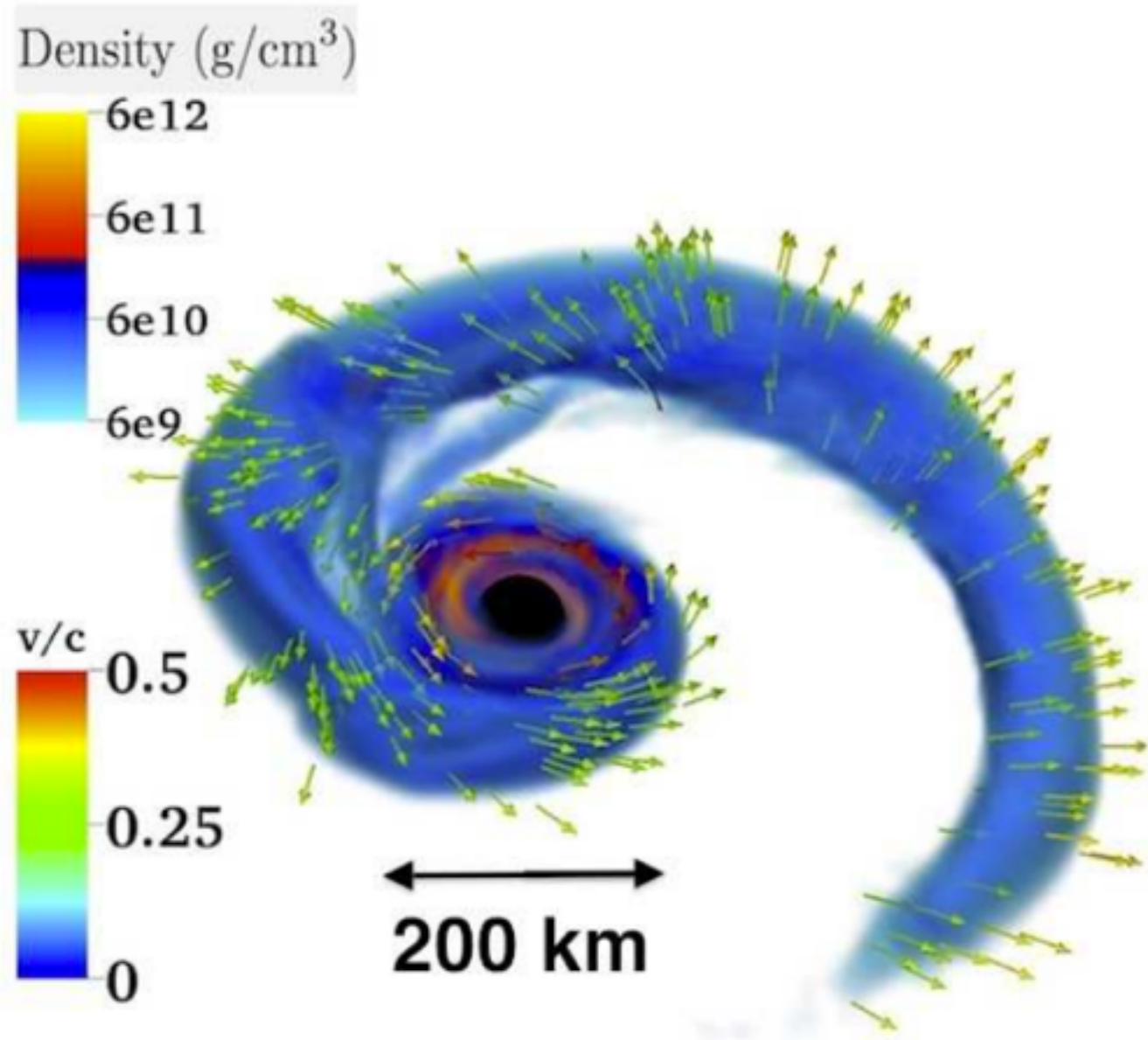
remnant: black hole or
massive neutron star
~99%

accretion disk
~1%

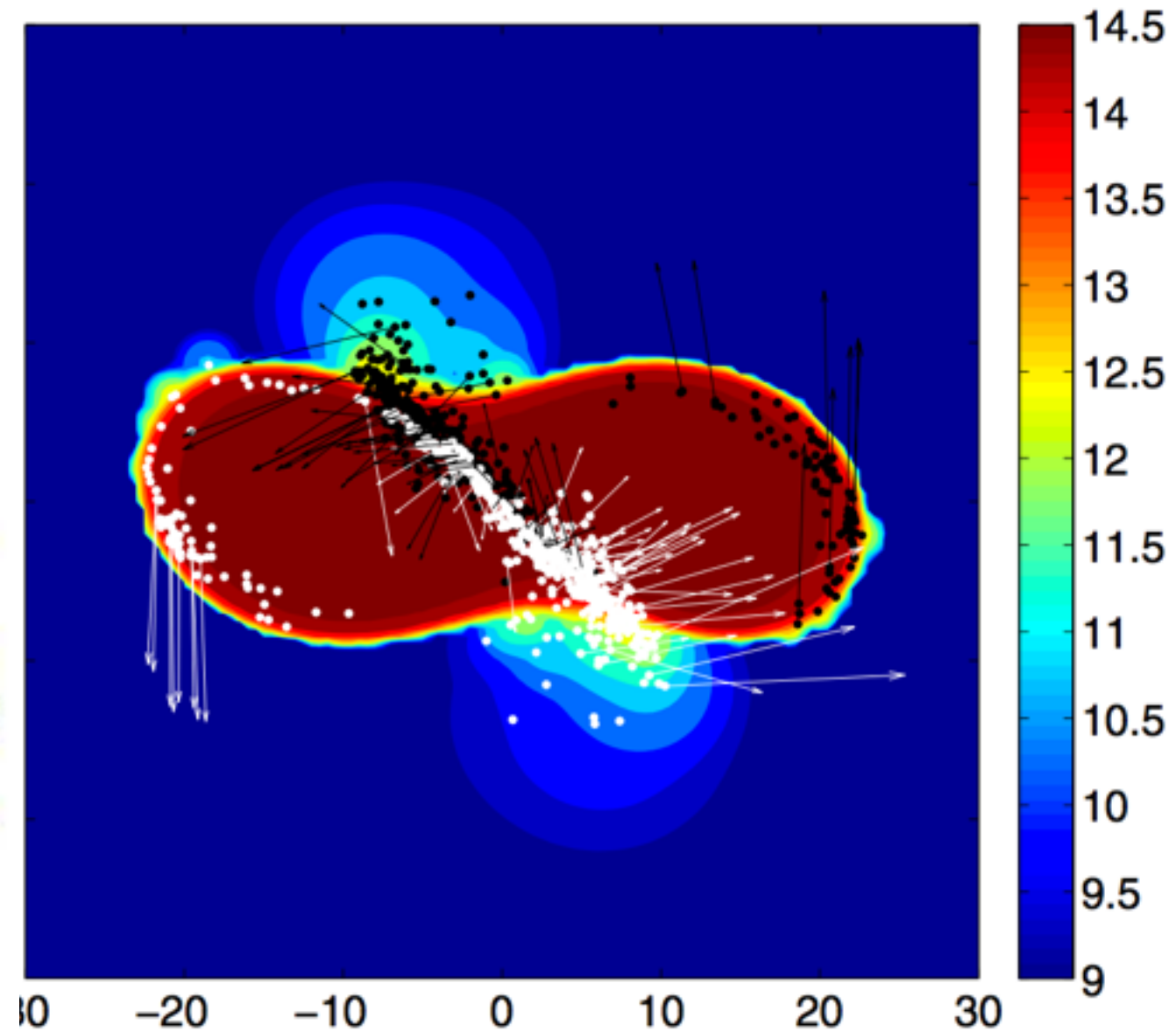
S. Rosswog

dynamical ejecta from mergers

$\sim 10^{-4} - 10^{-2} M_{\text{sun}}$ ejected on timescales of $\sim$ milliseconds
very low $Y_e < 0.1$

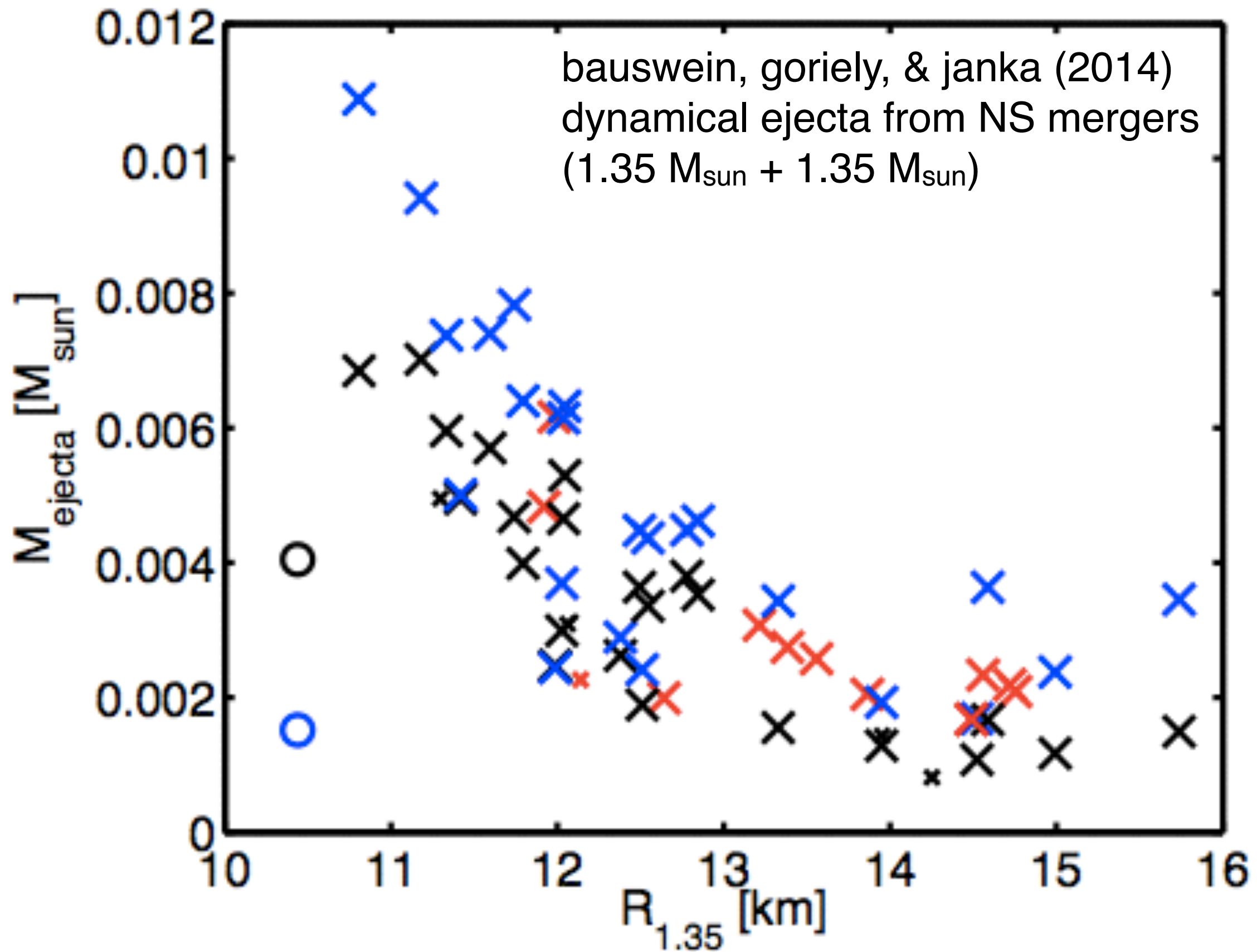


neutron star + black hole
foucart+ 2014



neutron star + neutron star
bauswein+ 2013

dependence on nuclear equation of state

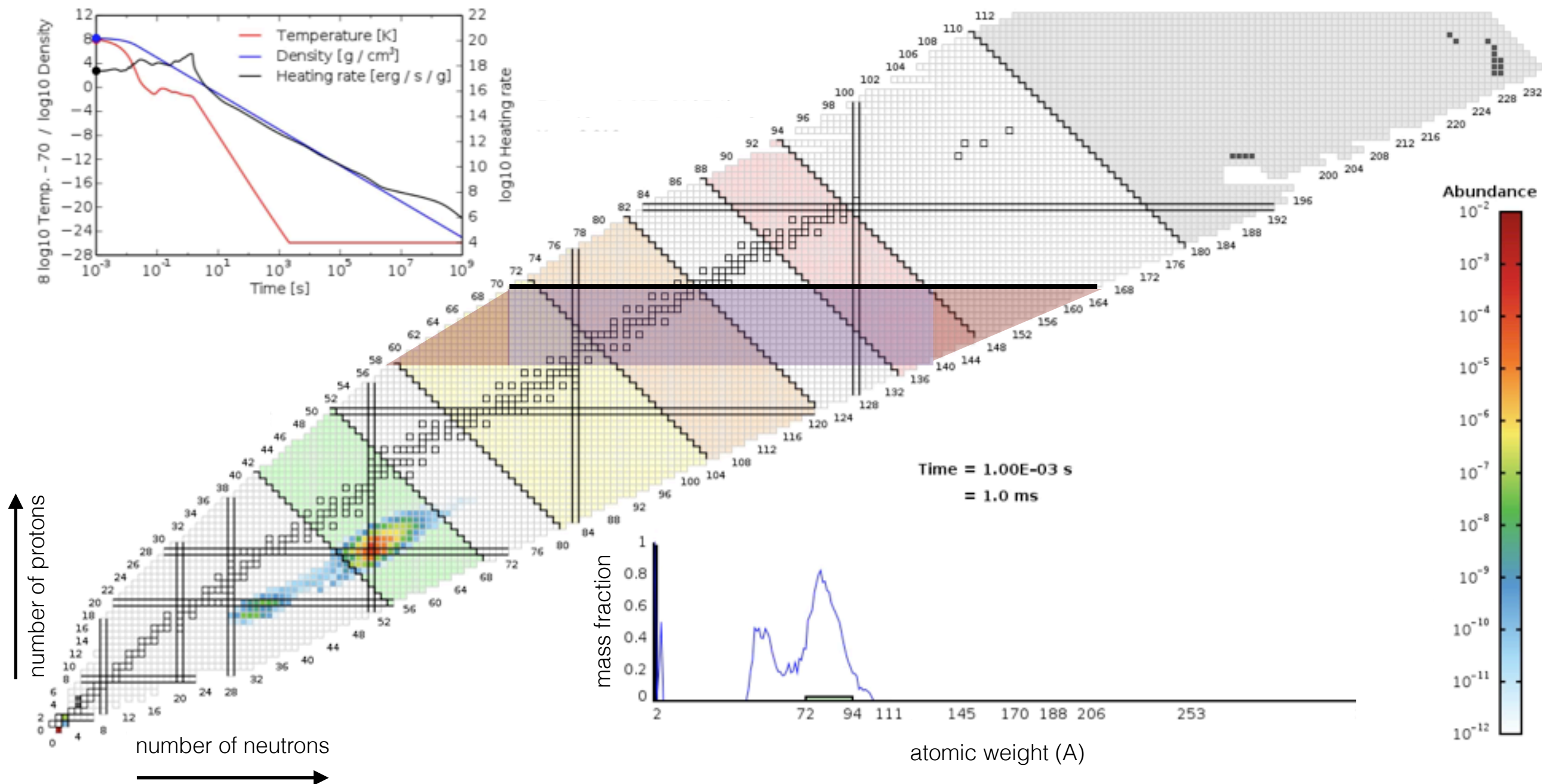


r-process nucleosynthesis

jonas lippuner, *SkyNet* nuclear reaction network code

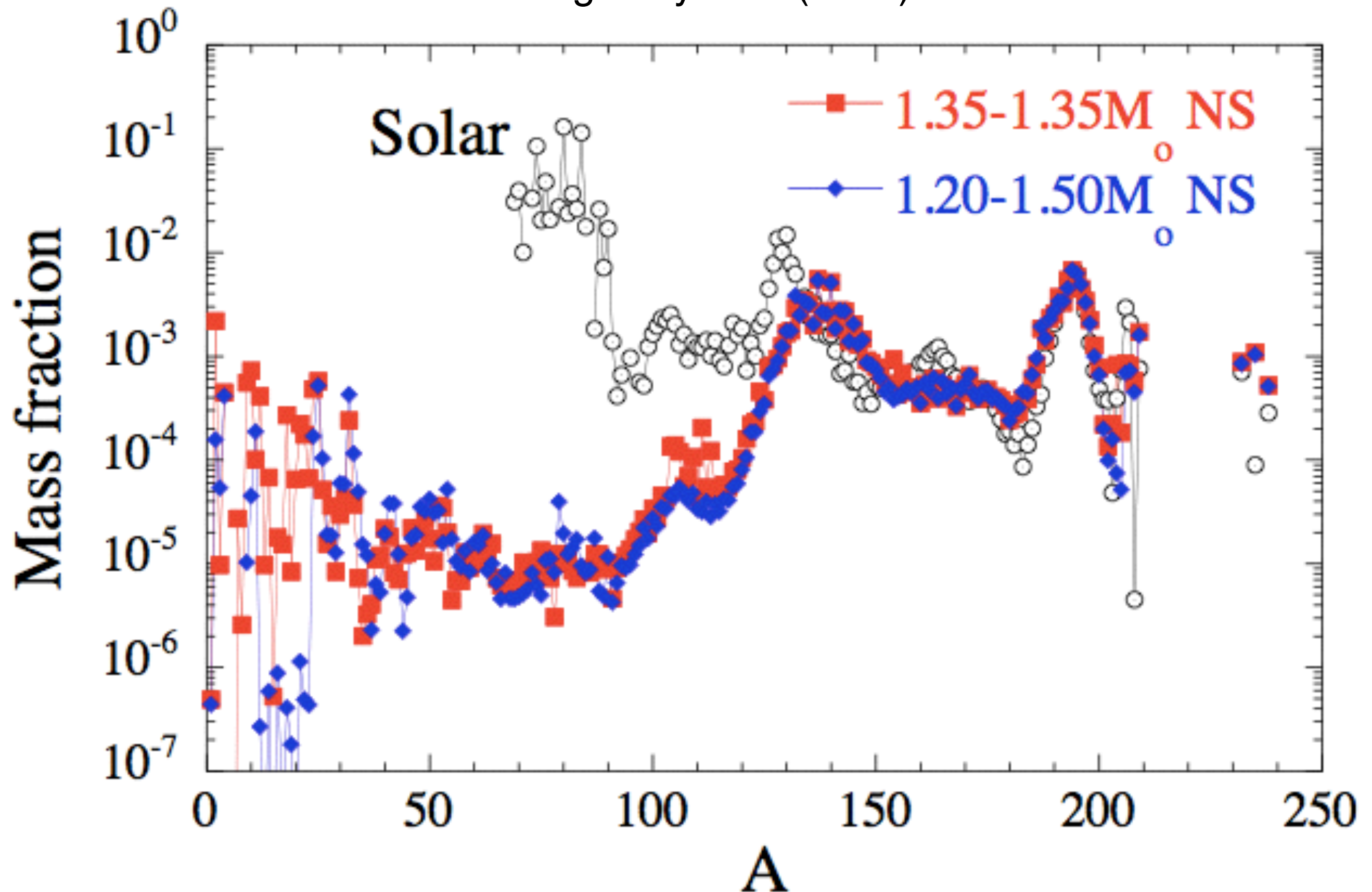


$$Y_e = 0.01$$

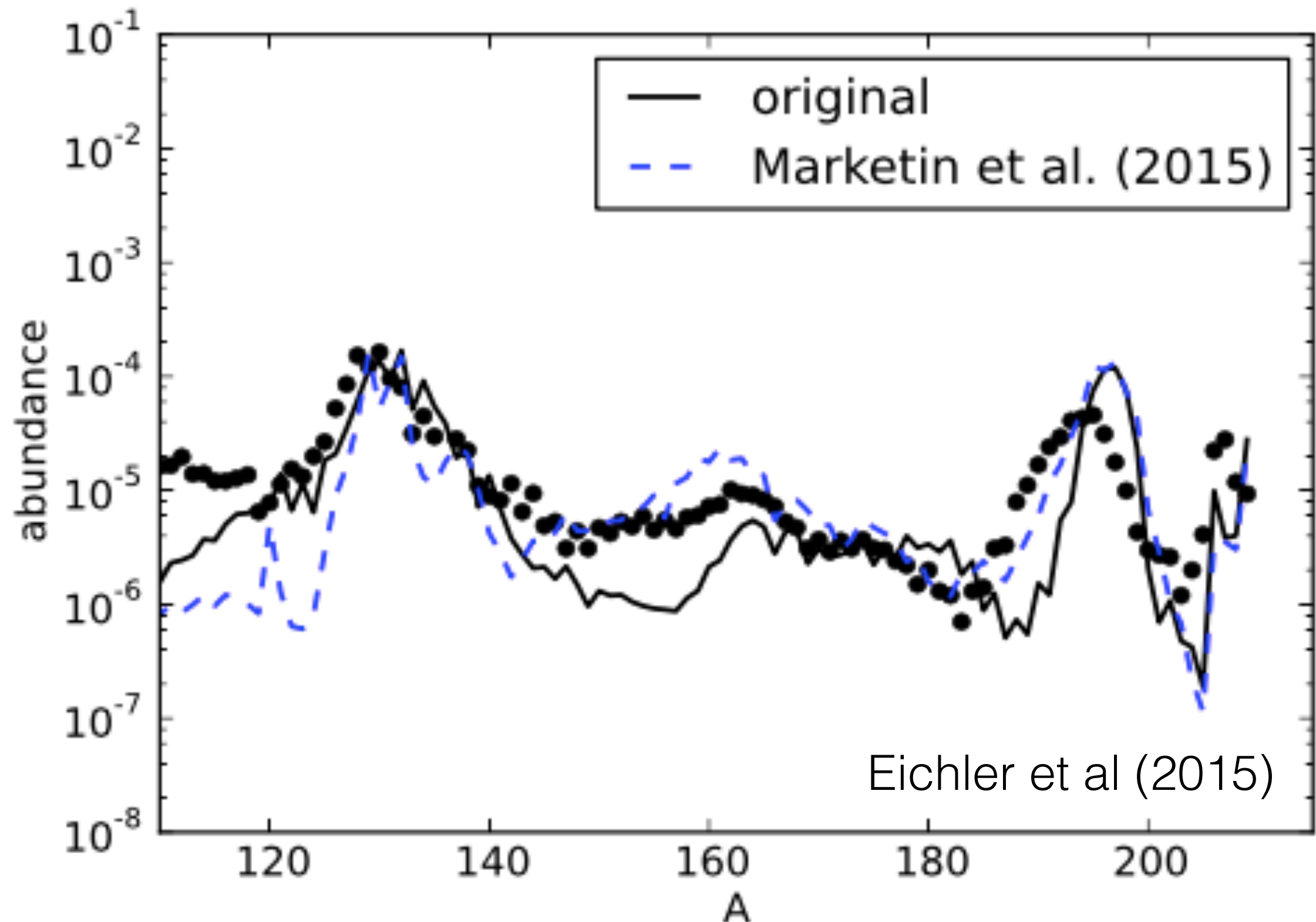


r process nucleosynthesis in low Y_e ejecta

goriely et al (2011)



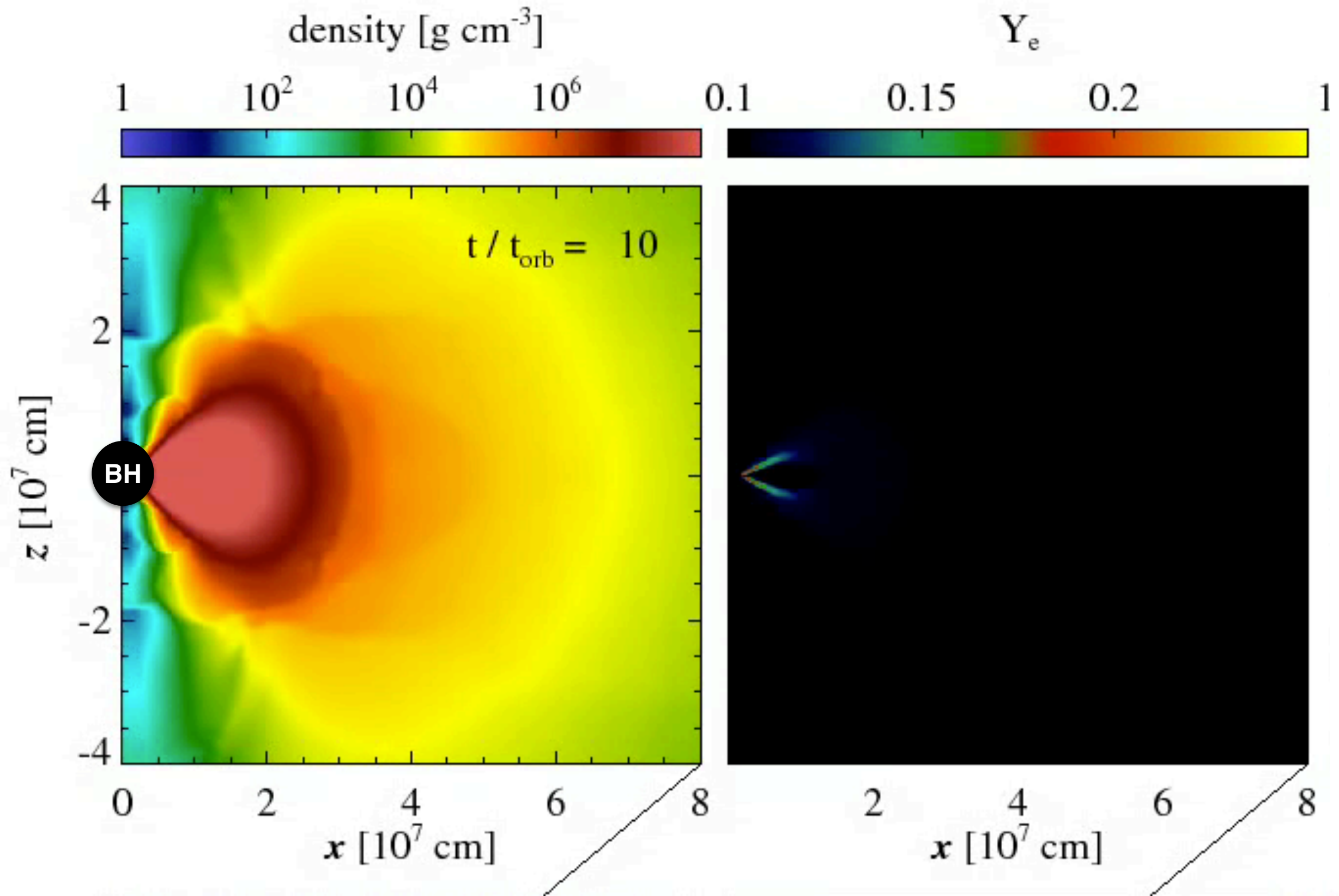
importance on nuclear physics inputs
dependence on fission rates



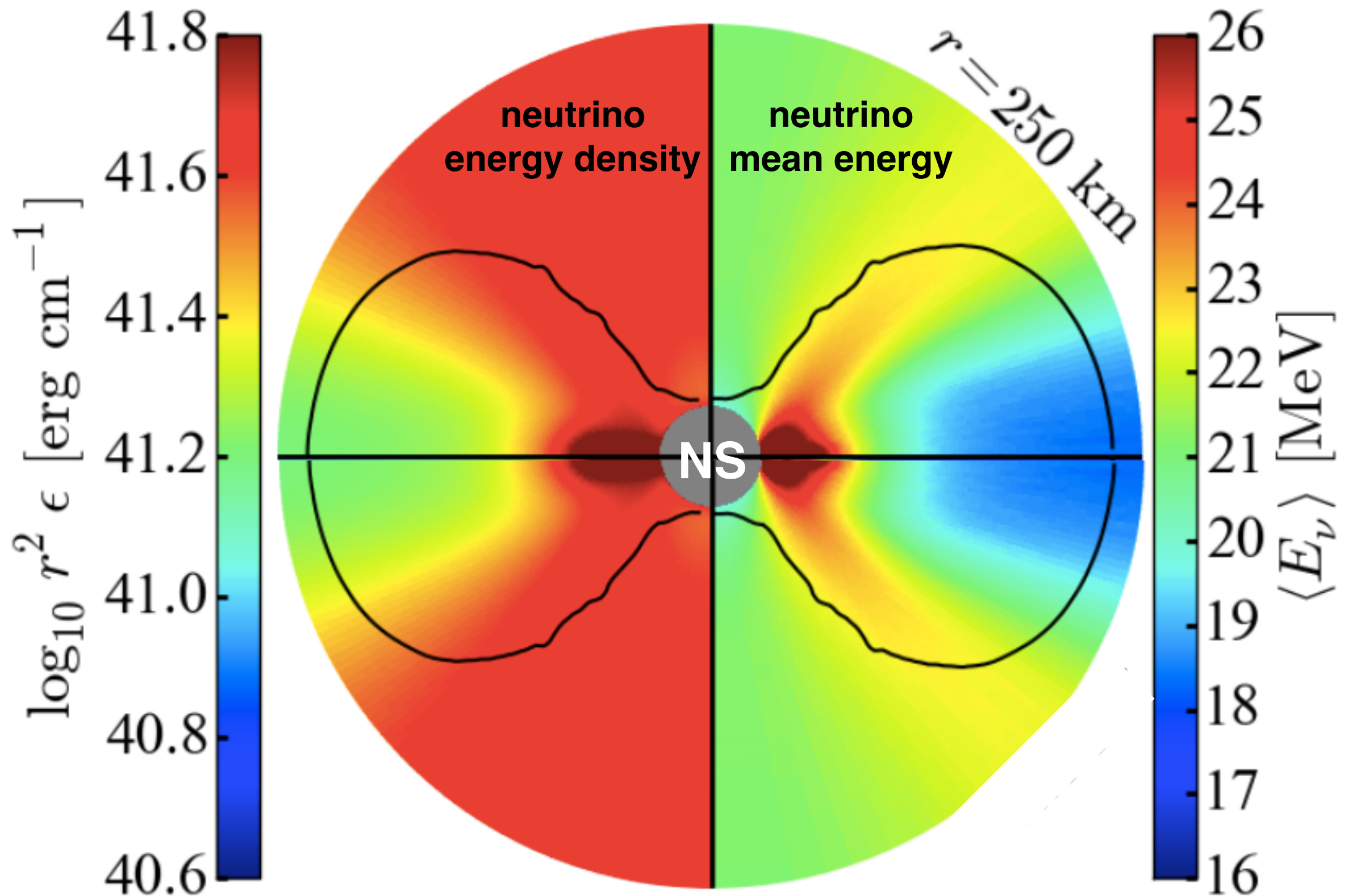
post-merger ejection in disk winds

viscous neutrino driven outflows

fernandez & metzger (2013, 2014), kasen, fernandez & metzger (2015)



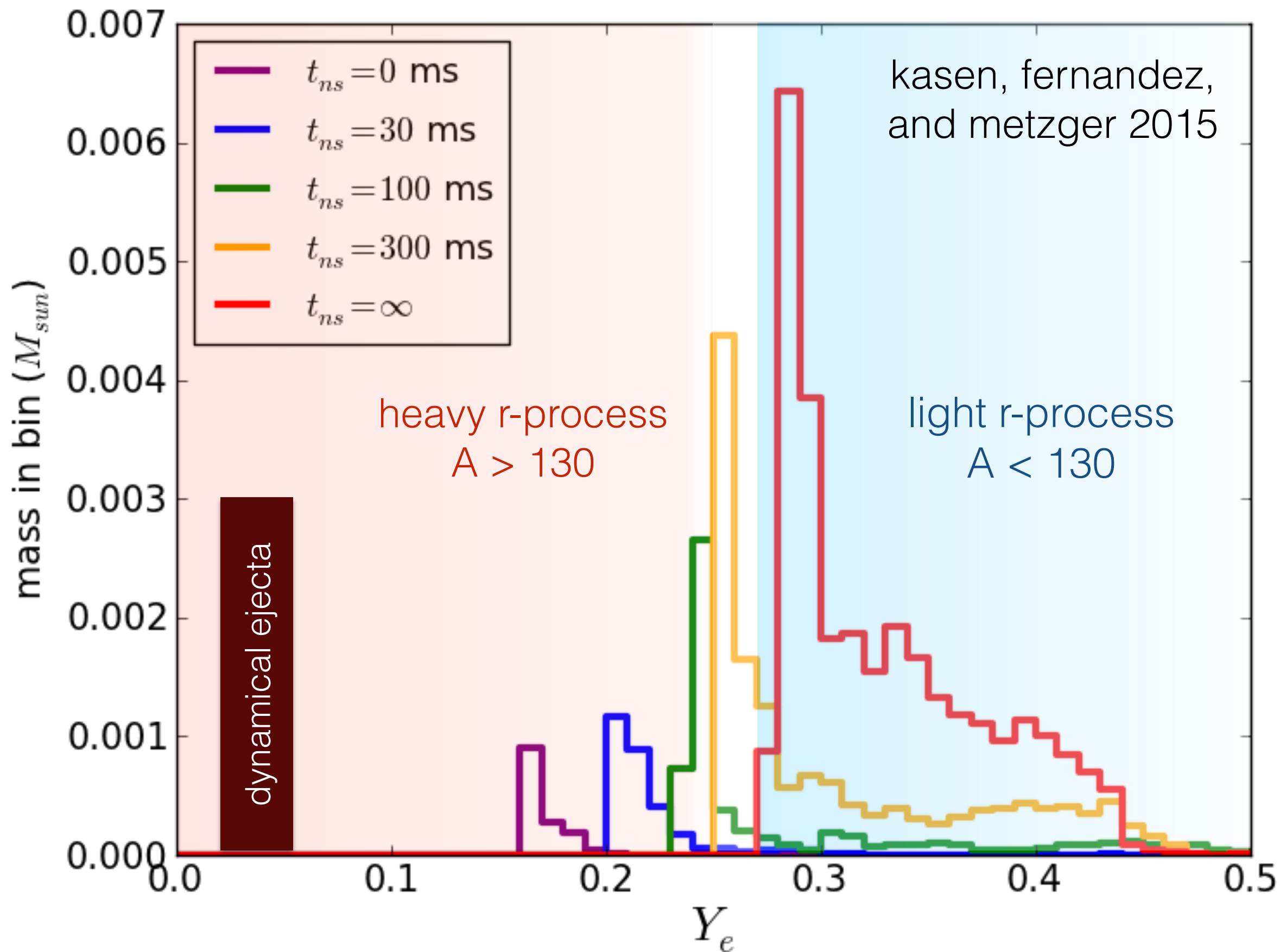
neutrino irradiation of disks

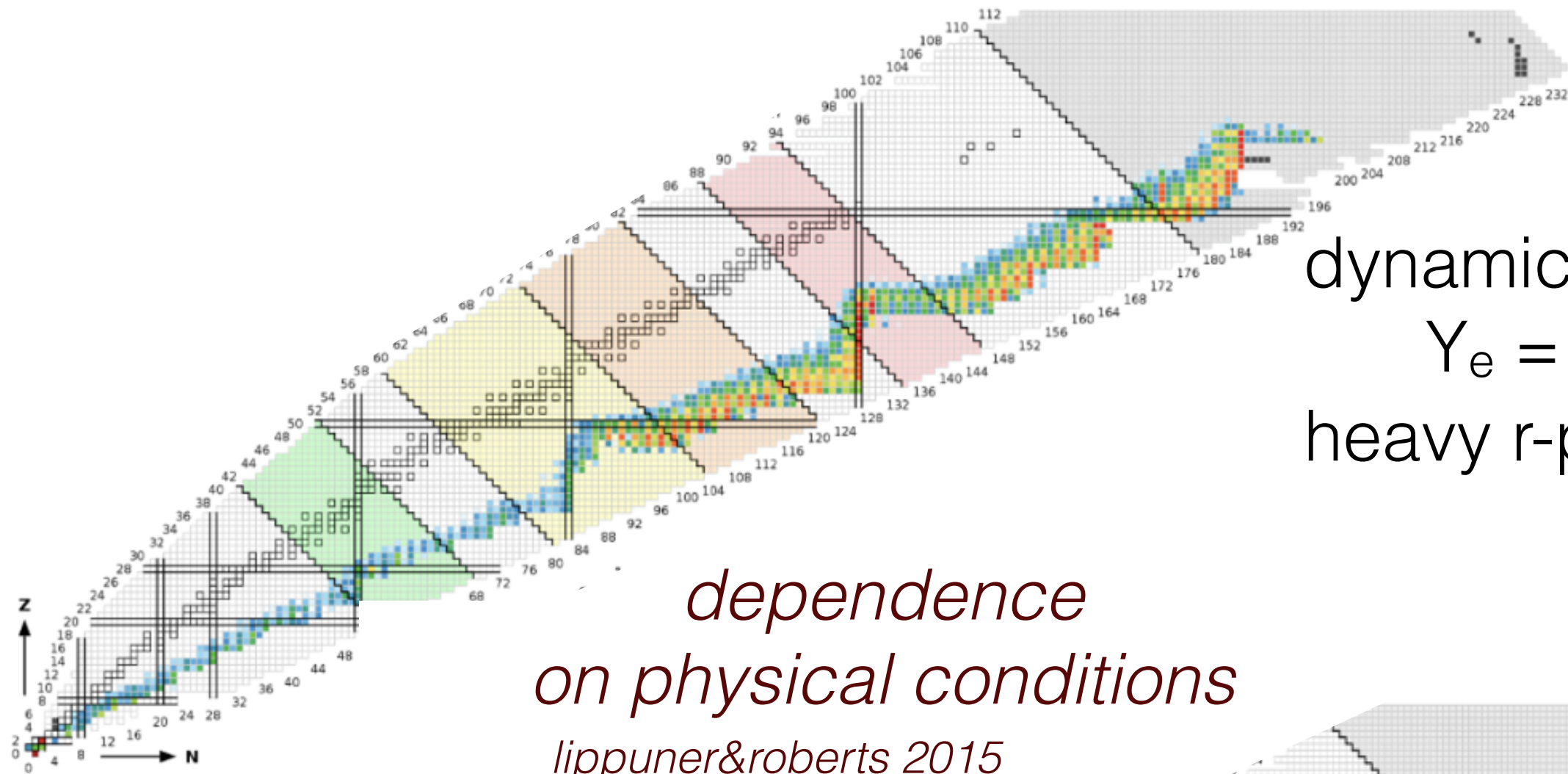


richers, kasen, et al 2015

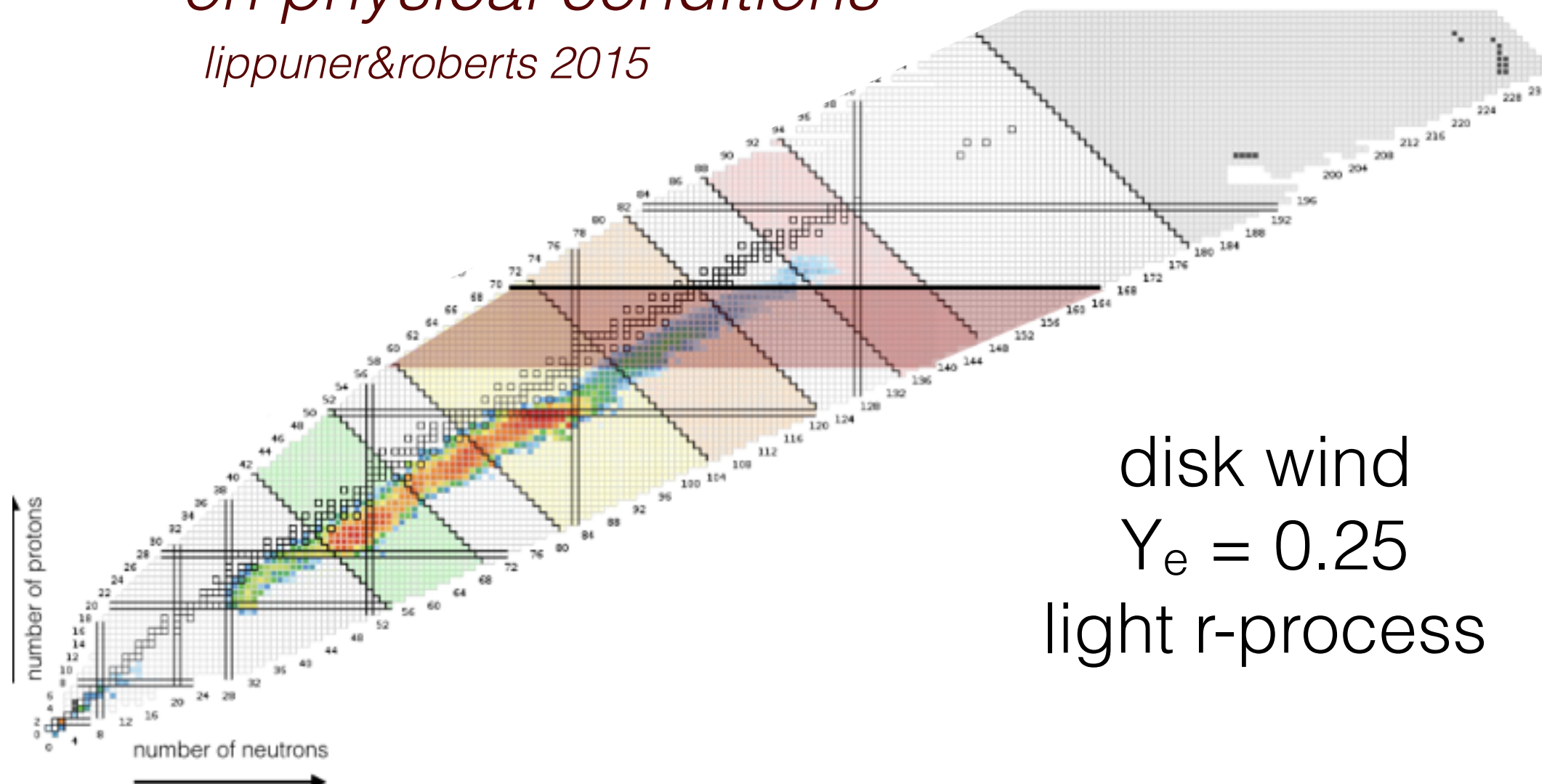
physical conditions in wind ejecta

neutron richness depends on lifetime on remnant neutron star



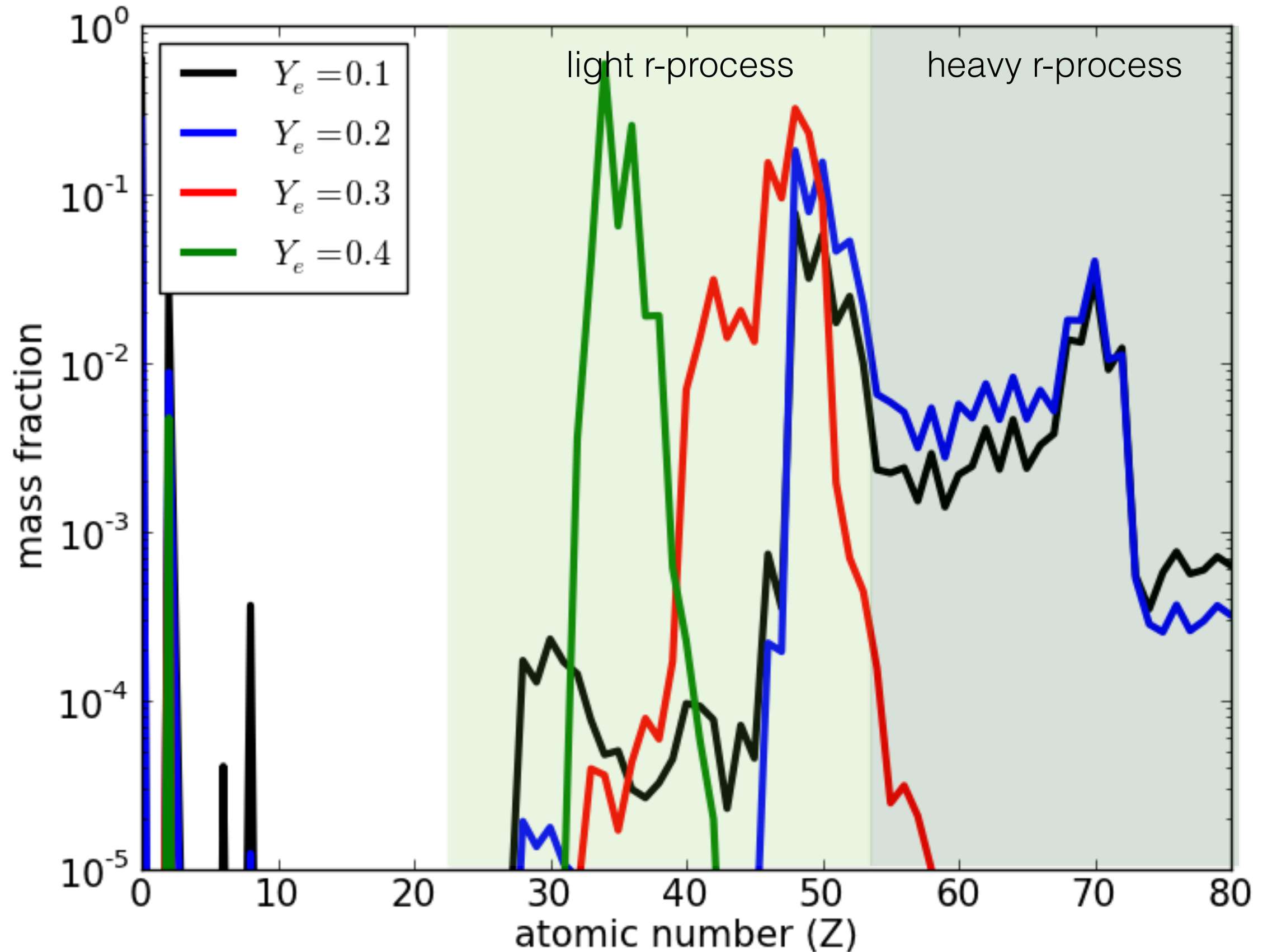


dynamical ejecta
 $Y_e = 0.01$
 heavy r-process



estimated final abundances of disk winds

kasen et al 2015



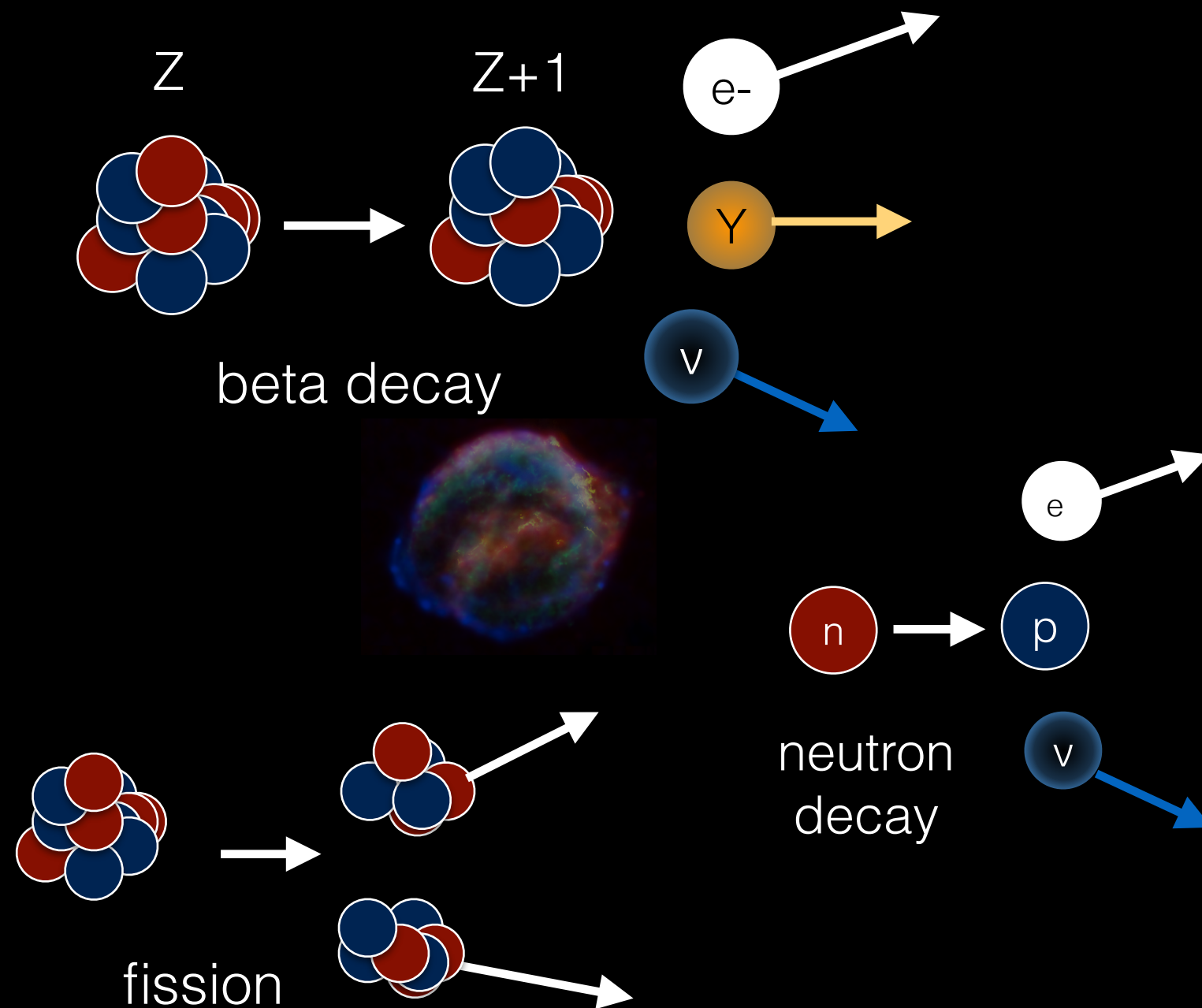
kilonova: cloud of radioactive r-process isotopes
ejected from merger at $v \sim 0.1c$

at $t \sim 1$ day

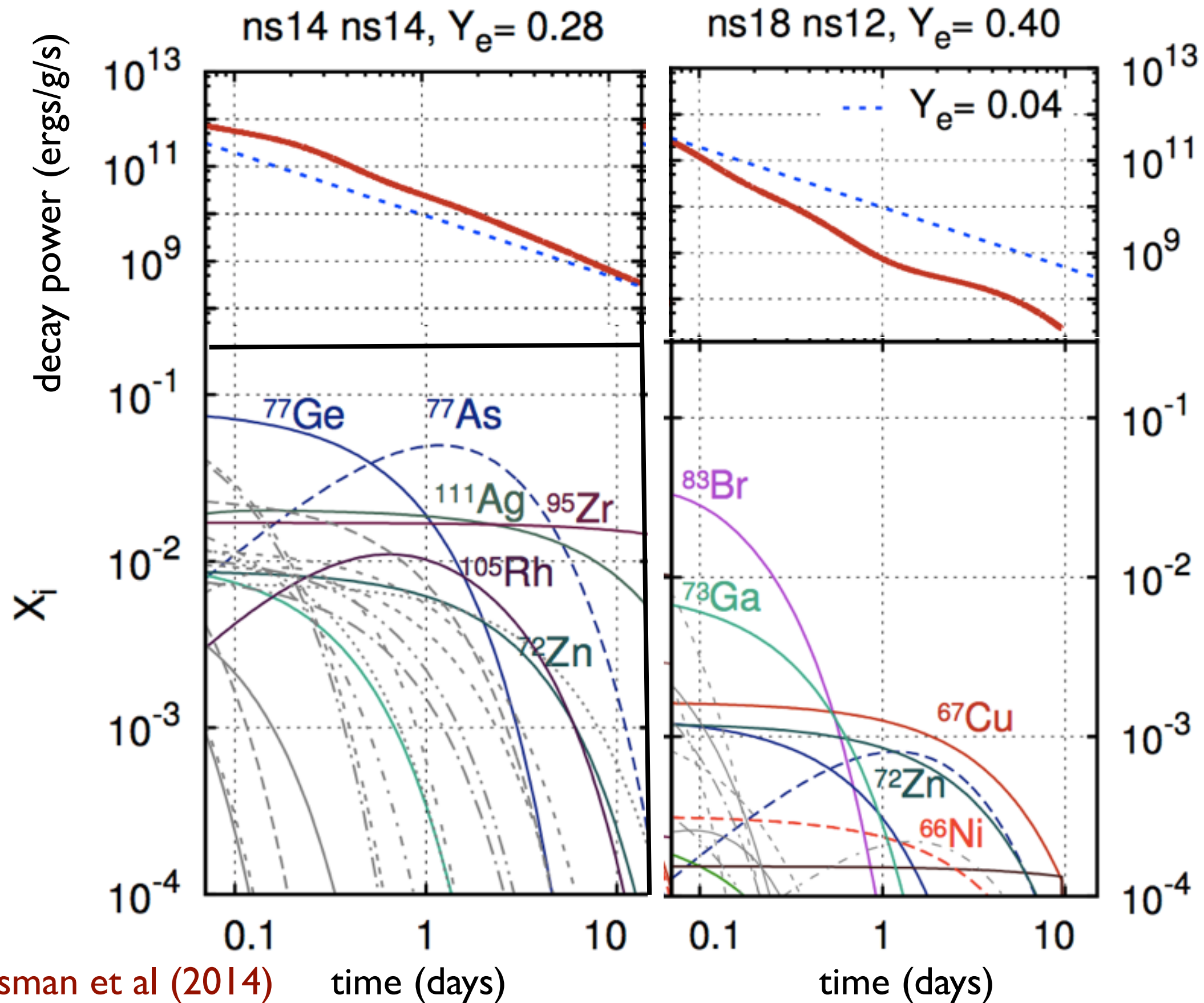
$r \sim 10^{15}$ cm

$\rho \sim 10^{-13}$ g cm $^{-3}$

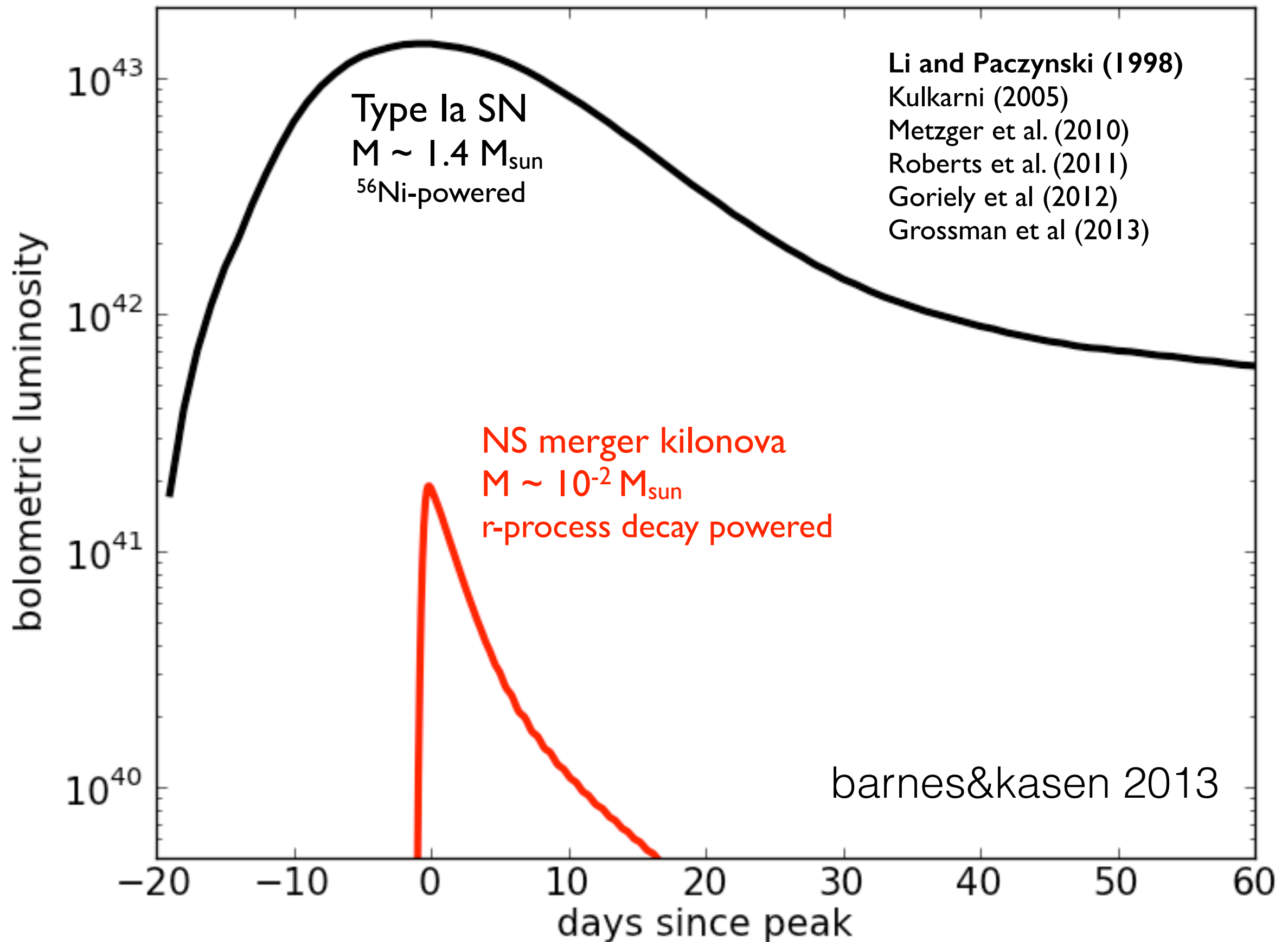
$T \sim 5000$ K



radioactive heating from r-process isotopes

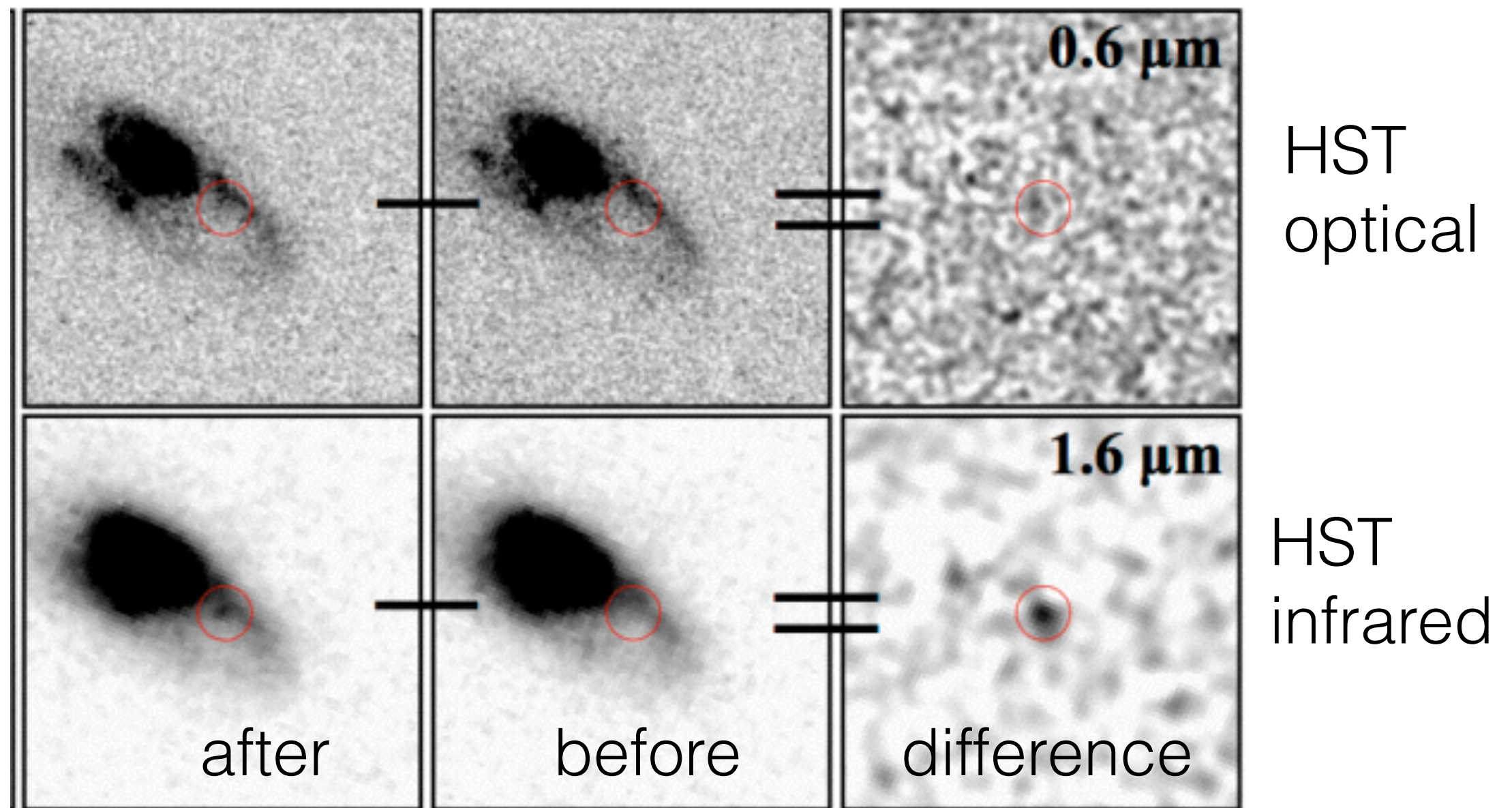


simulated r-process (kilonova) light curves



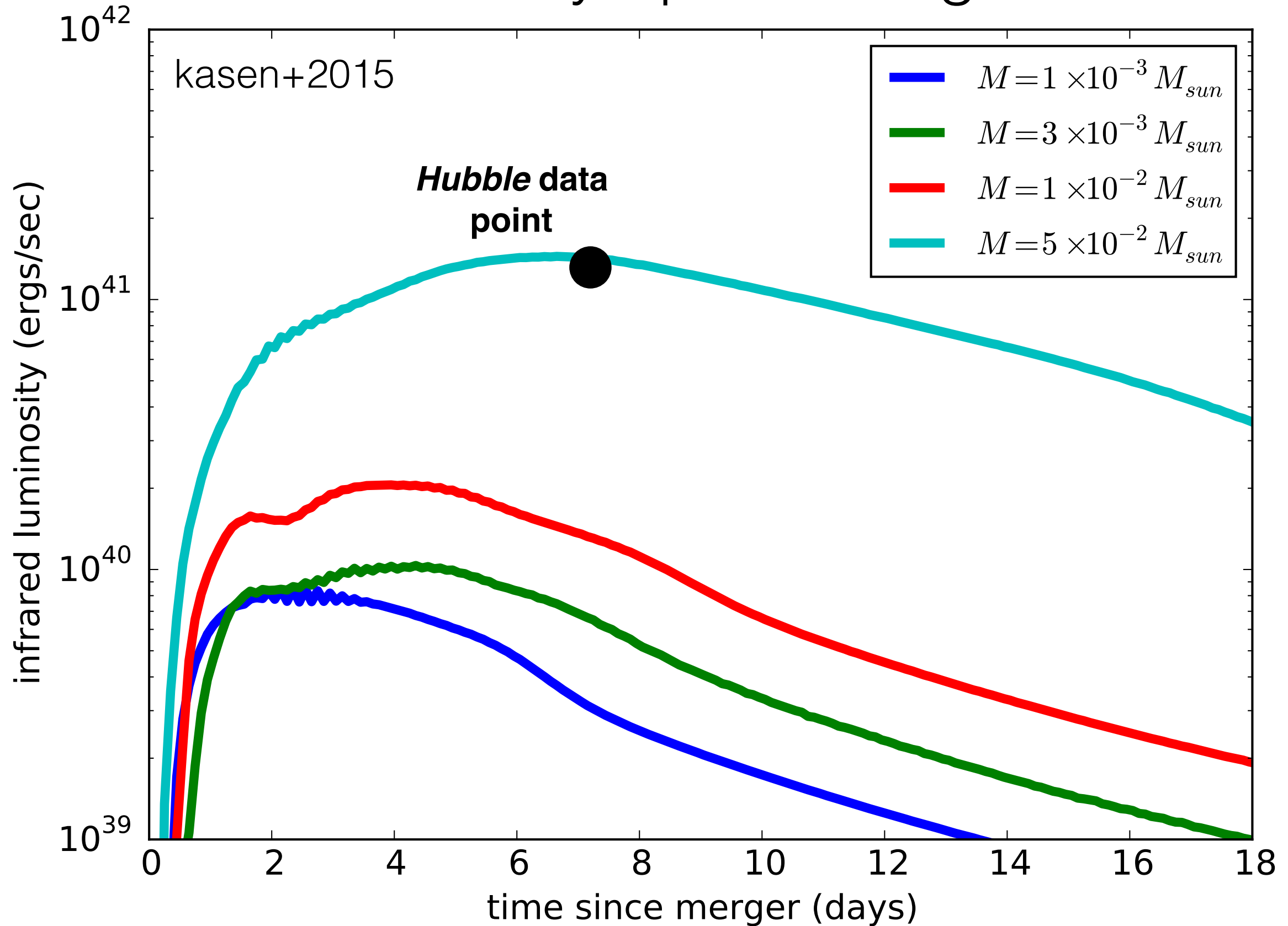
GRB130603B

relatively nearby short GRB ($z = 0.356$)

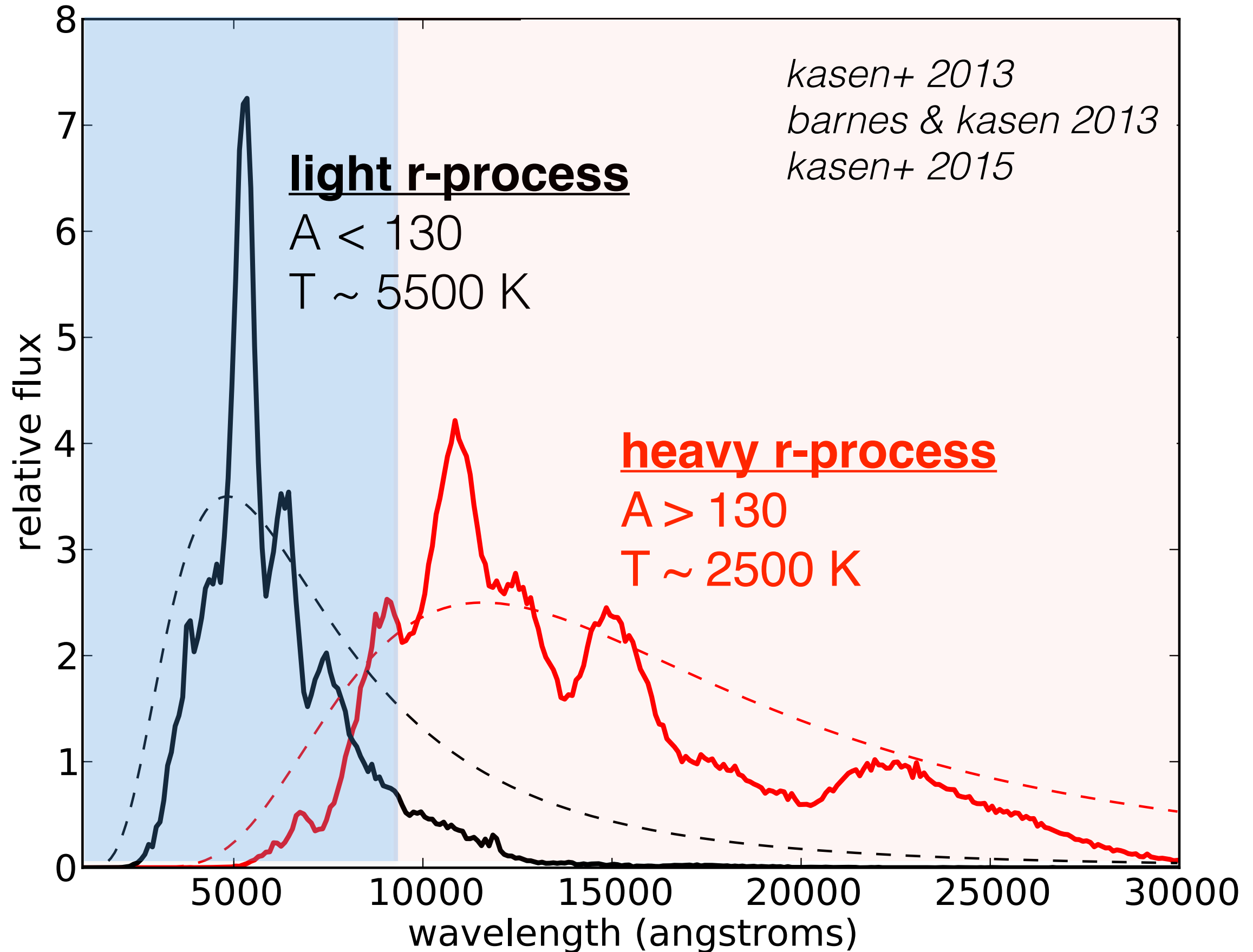


Tanvir+ 2013, Berger 2013

simulated heavy r-process light curves

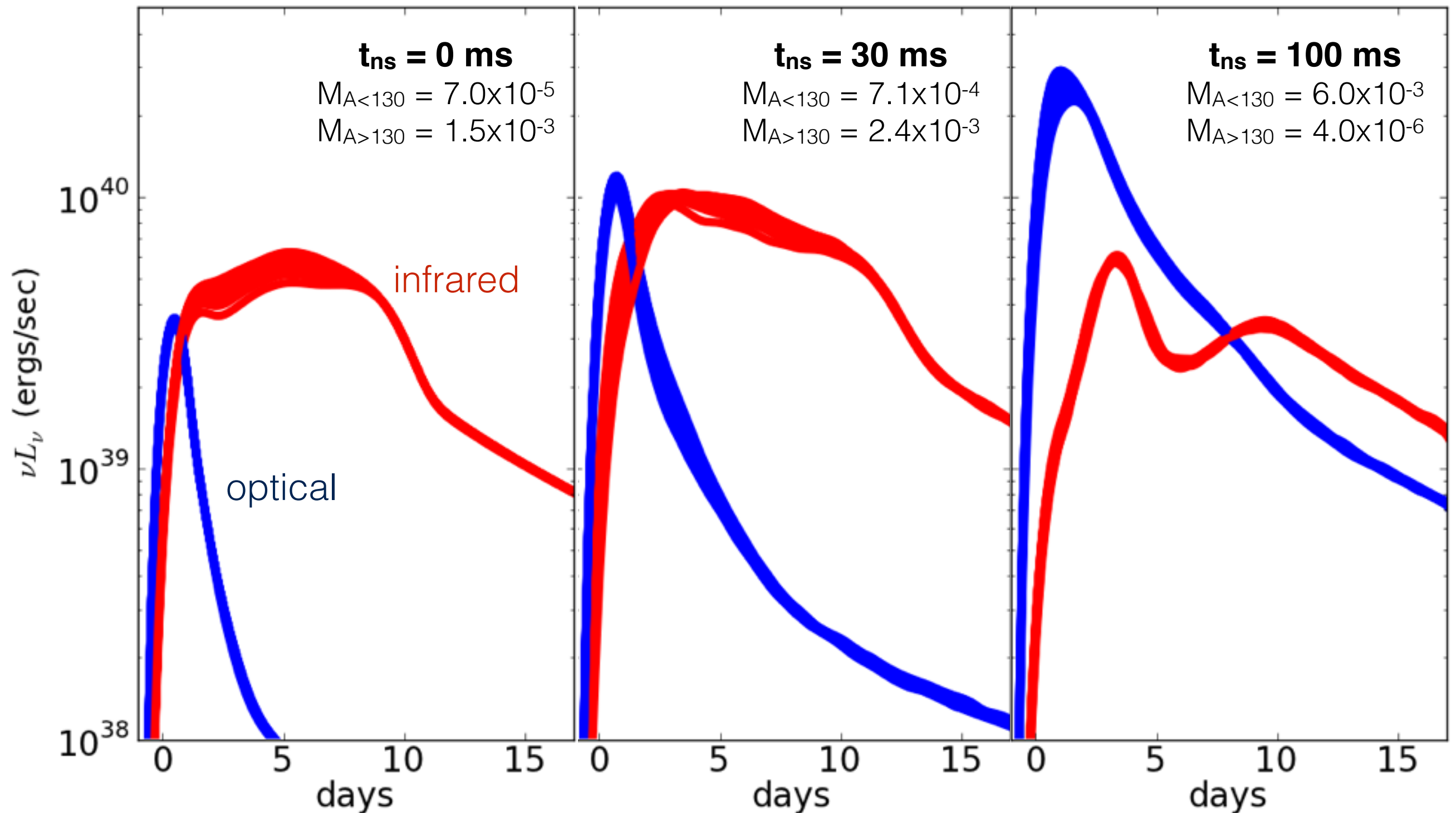


kilonova color reveals composition

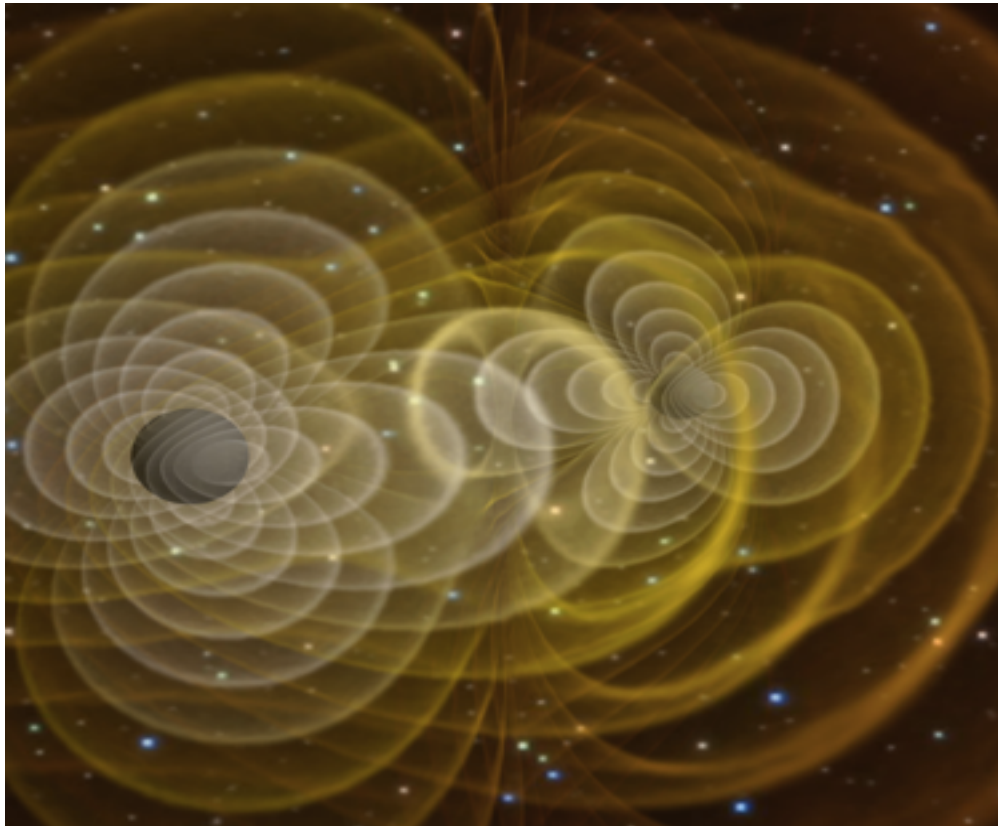


simulated light curves of merger winds

blue light probes light r-process, red heavy r-process



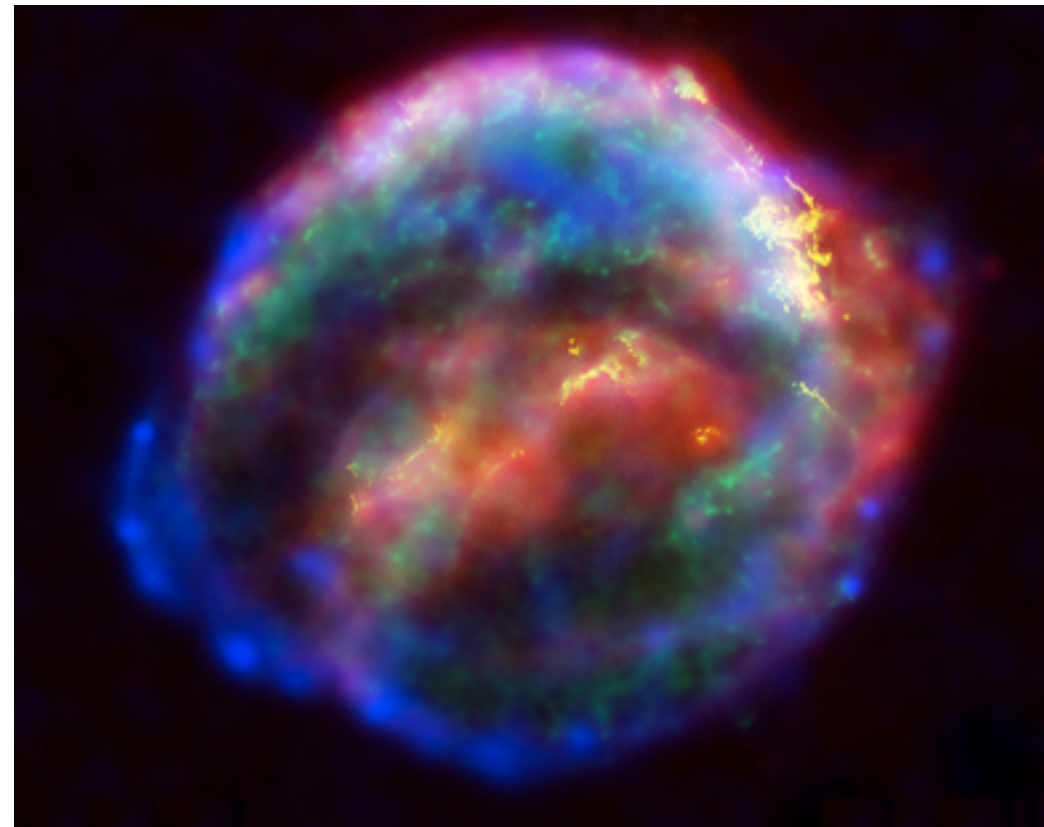
addressing the origin of r-process nuclei



gravitational waves

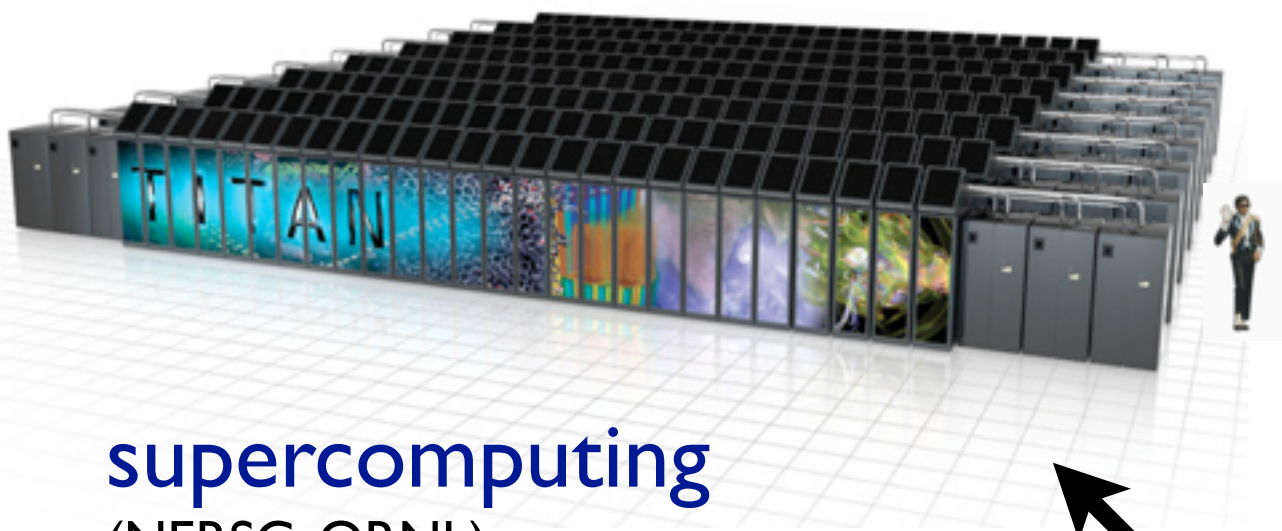
advanced LIGO

determines rates of mergers
and probes EOS



radioactive “kilonova”

optical/IR astronomical surveys
determines mass and
composition of r-process ejecta

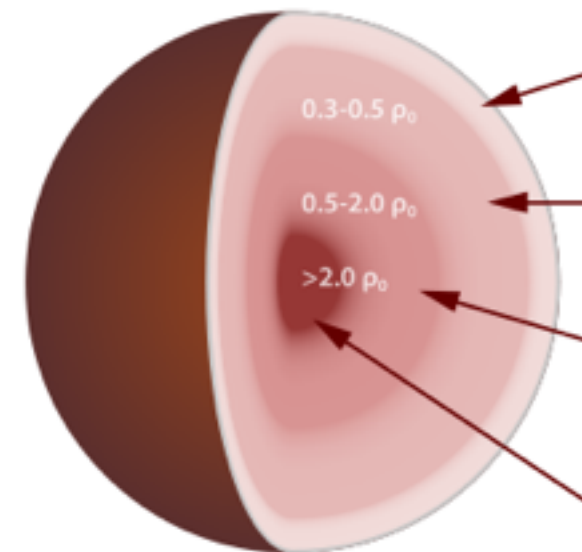
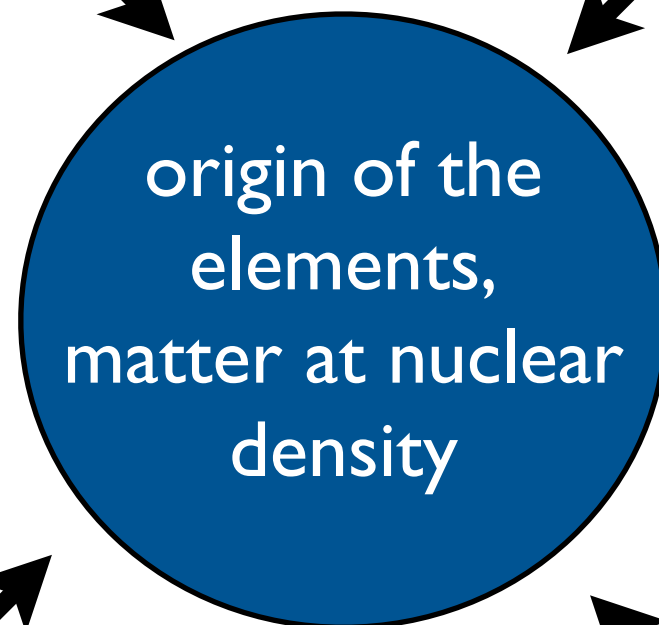
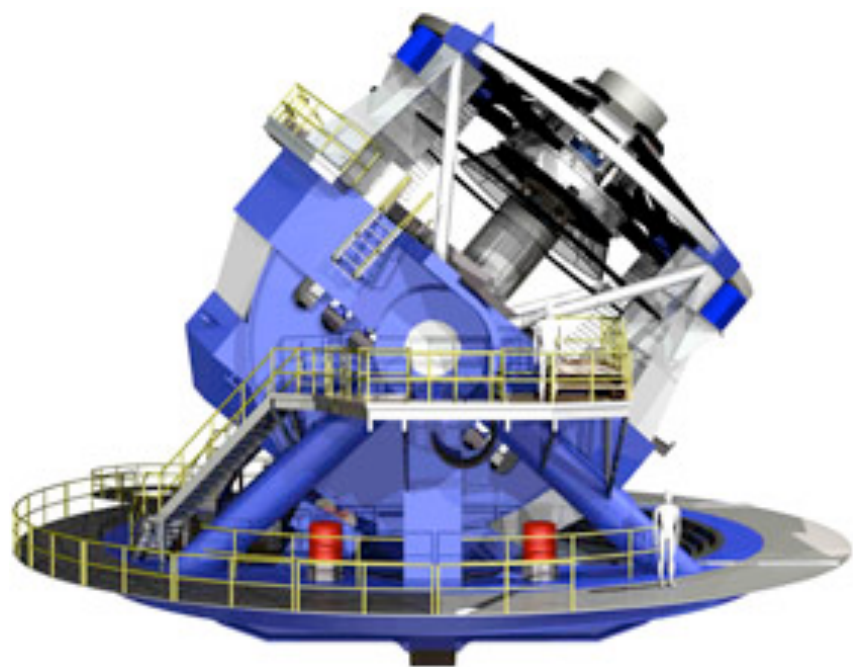


supercomputing

(NERSC, ORNL)

astro experiment

optical/IR/gamma/x-ray telescopes
neutrino detectors
gravitational waves (LIGO)



nuclear/astro theory

nuclear EOS, nuclear structure,
simulation of stellar explosions

nuclear experiment

(FRIB)

properties of isotopes,
reaction rates,
fission, decay properties

A Superconducting Linear Accelerator → B In-flight target fragment separator

