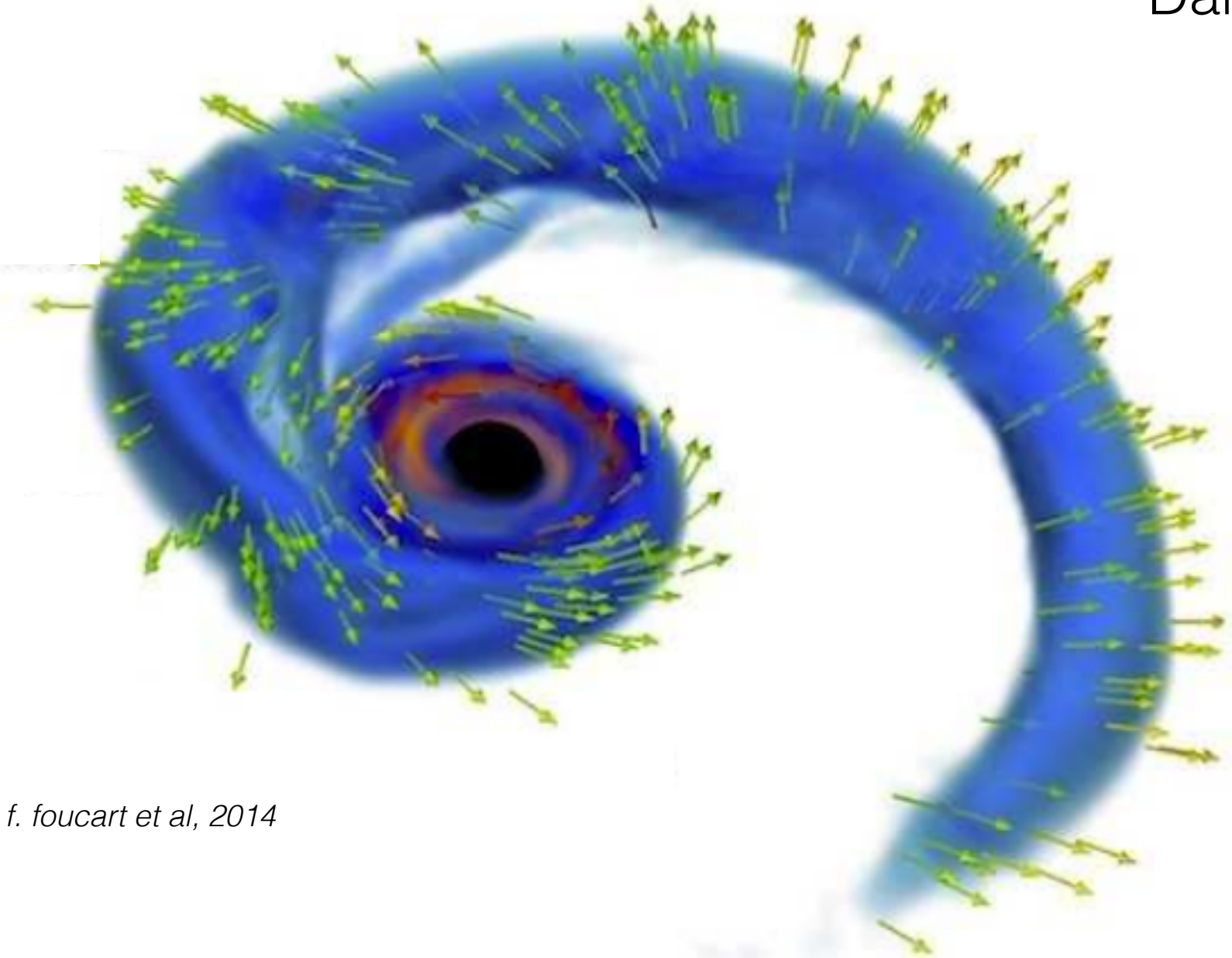
Nuclear Astrophysics at LBNL

Daniel Kasen



f. foucart et al, 2014

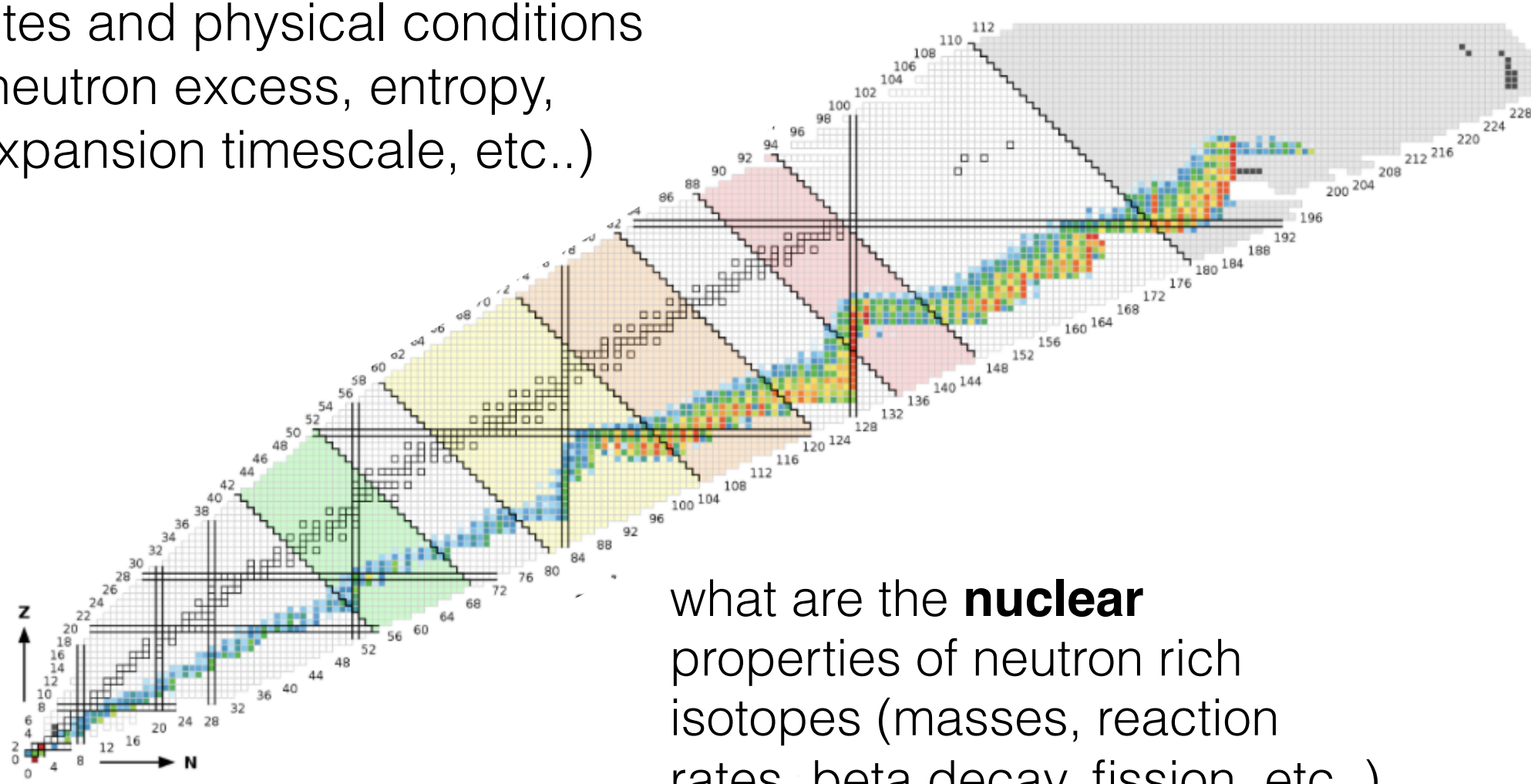
Core Questions in Nuclear Astrophysics

- What is the origin of the elements?
  nucleosynthesis in stars/stellar explosions

- What physics is realized under extreme astrophysical conditions?
  equation of state of dense matter
  neutrino interactions and oscillations

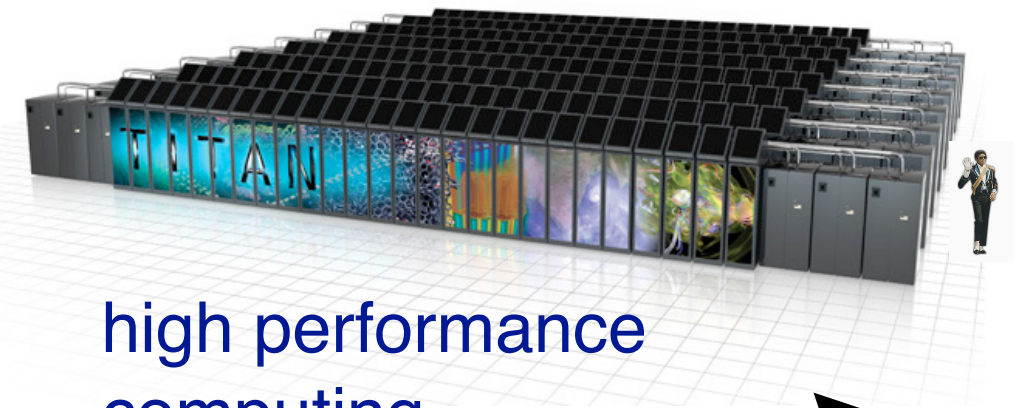
Origin of the heavy (r-process) elements

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



what are the **nuclear** properties of neutron rich isotopes (masses, reaction rates, beta decay, fission, etc..)

SkyNet reaction network
jonaslippuner.com/research/skynet/



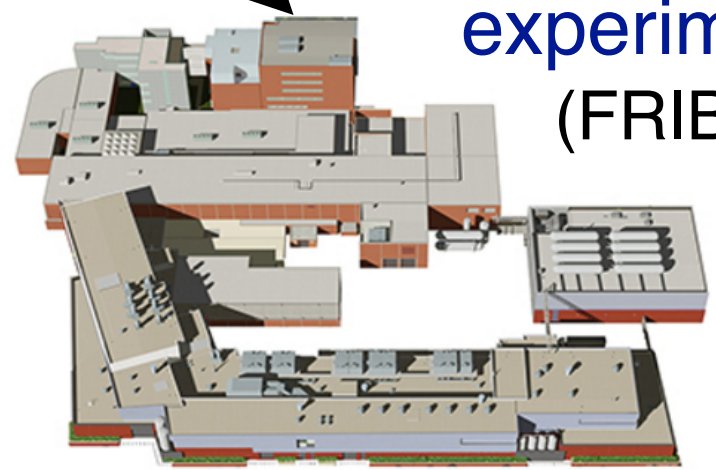
high performance computing
(NERSC, OLCF, ALCF)

Origin of the elements
Matter at nuclear density
Neutrino physics

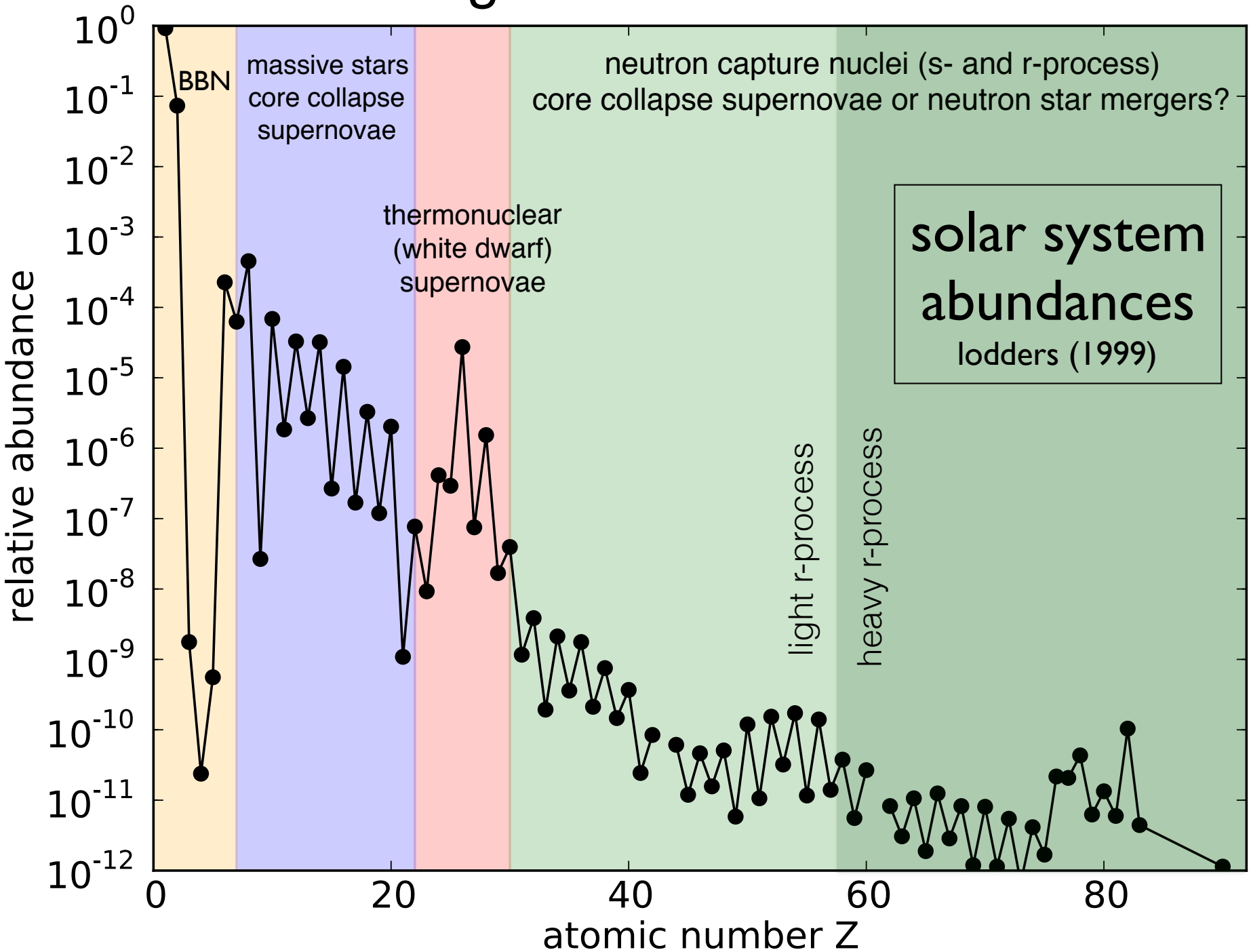
theoretical/ computational nuclear astrophysics

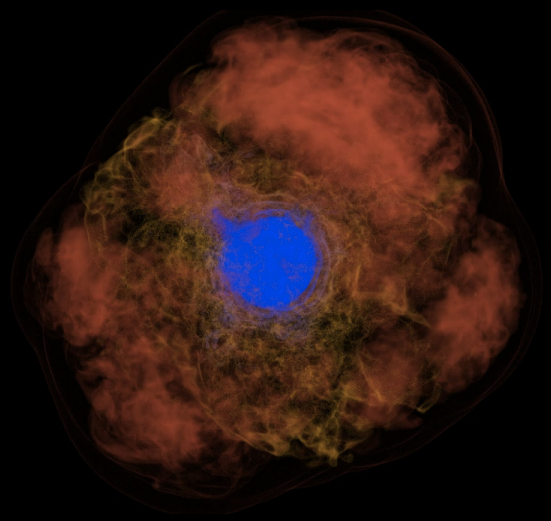
astro experiment
optical telescopes (ZTF, DES, LSST)
x-ray, gamma-ray satellites (nuStar)
neutrino detectors (DUNE)
gravitational wave exp. (LIGO)

nuclear experiment
(FRIB)



origin of the elements

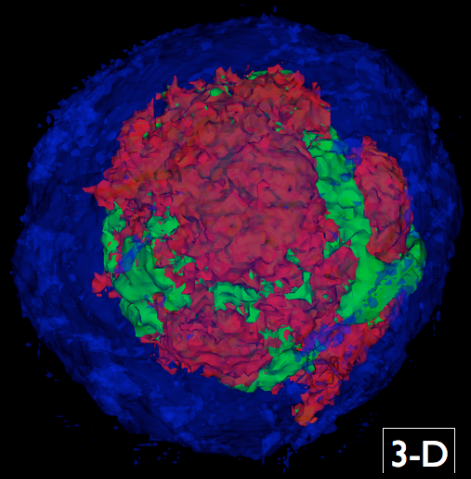




core collapse supernovae

explosion of massive stars

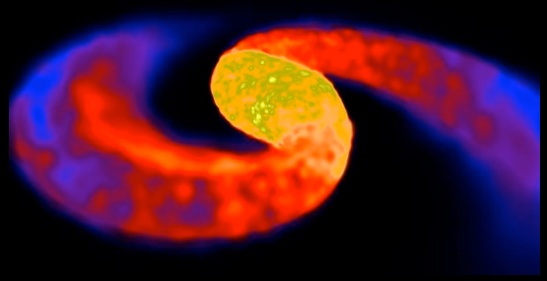
How do they explode and what neutrino signals and isotopes are produced?



thermonuclear supernovae

explosion of white dwarfs

What are the progenitors and how does thermonuclear burning ignite and propagate?



neutron star mergers

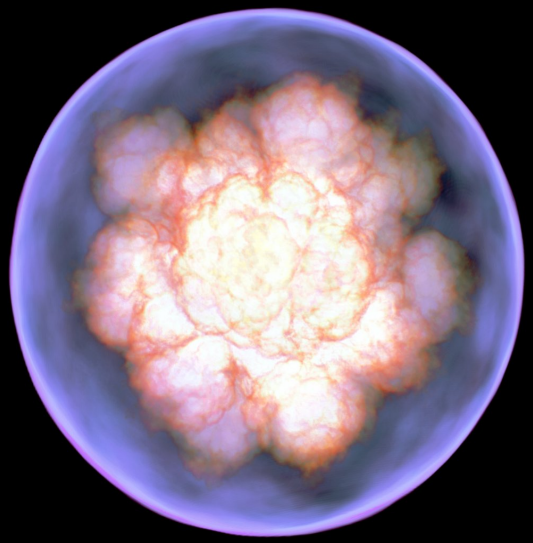
inspiral and coalescence of compact stars

What is their contribution to the r-process and can they probe the nuclear EOS?

Codes for end-to-end simulation

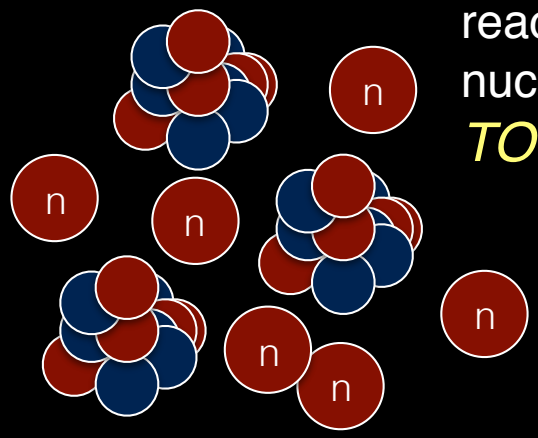
stellar evolution
stable nuclear
reactions
MESA, KEPLER

stellar evolution (> 10^6 years)



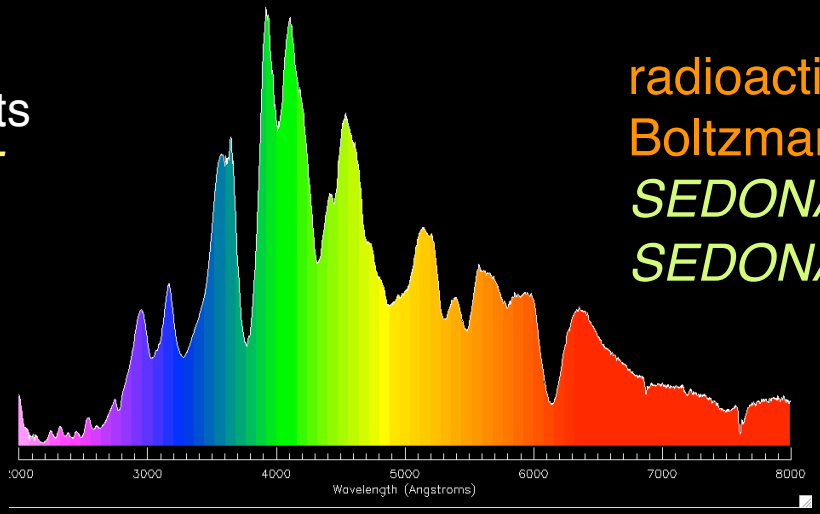
hydrodynamics,
gravity, equation
of state, neutrino
transport,
nuclear reactions
CASTRO, FLASH
CLASH

explosion (seconds-hours)



reaction networks
nuclear physics inputs
TORCH, SKYNET

nucleosynthesis (seconds)

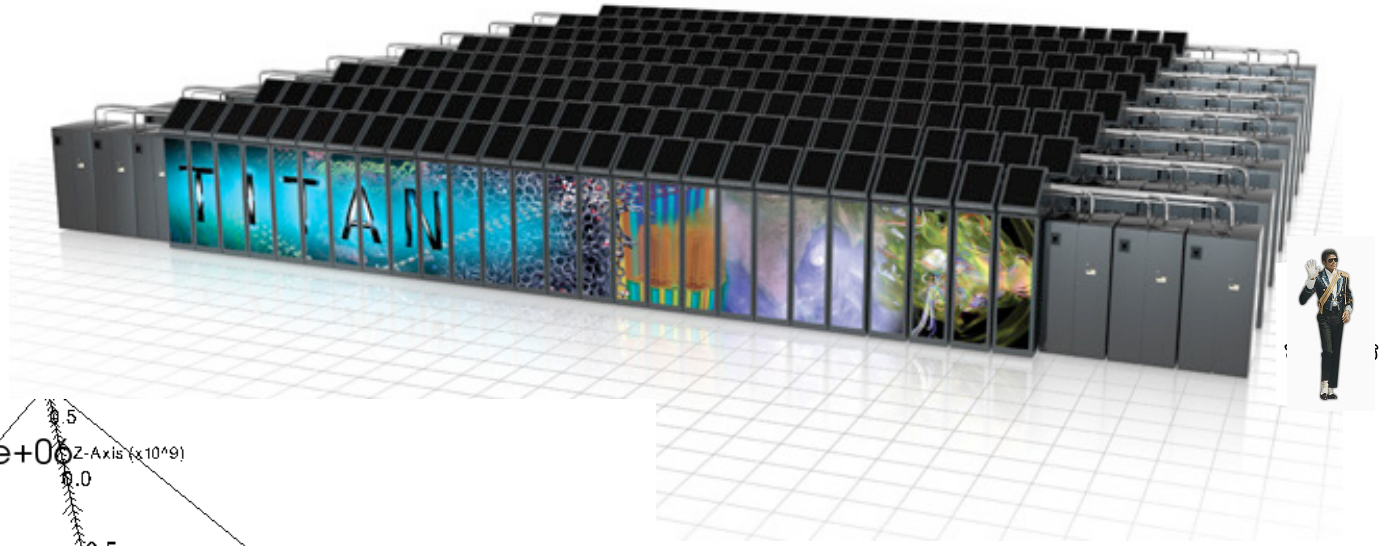


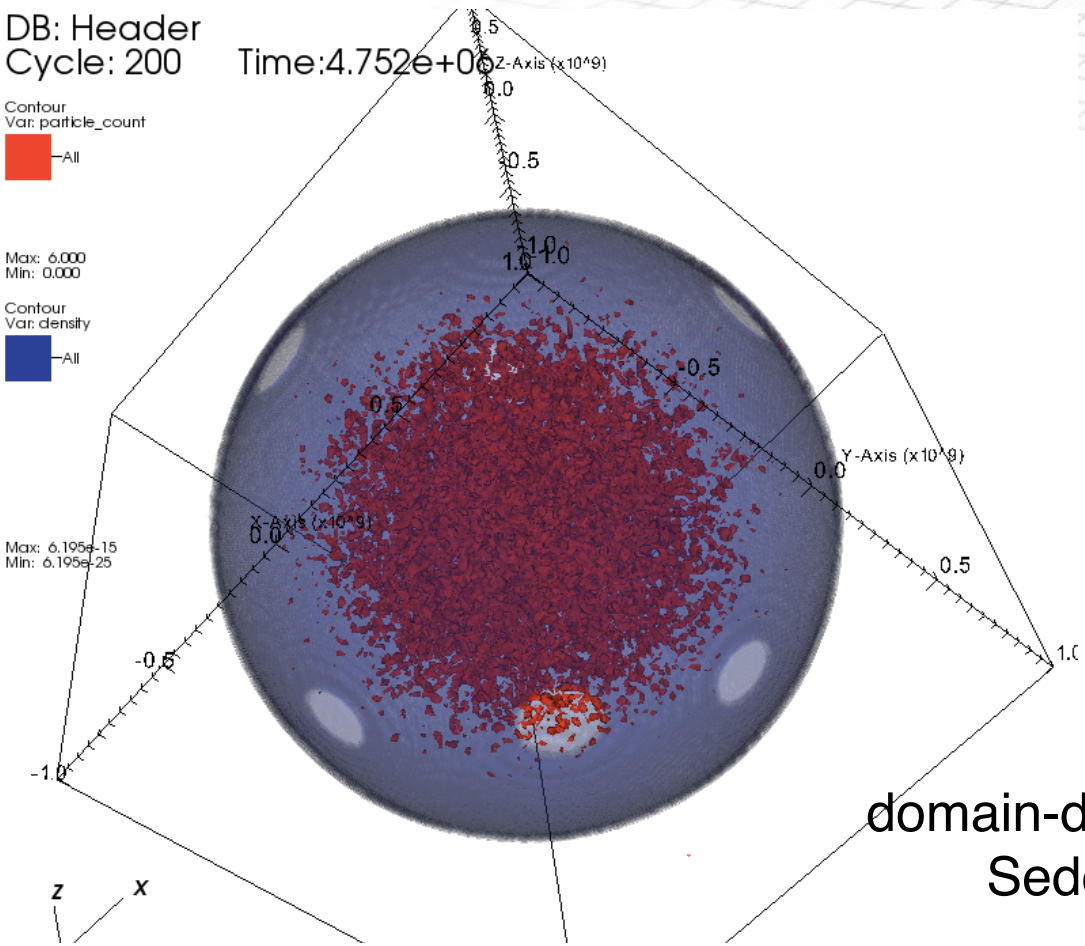
radioactive decay
Boltzmann transport
SEDONA
SEDONA-BOX

radioactive/transport (months)

High performance computing

@ leadership facilities: petascale moving to exascale





2015 INCITE award (PI: Zingale)
55 million cpu-hours on TITAN (OLCF)

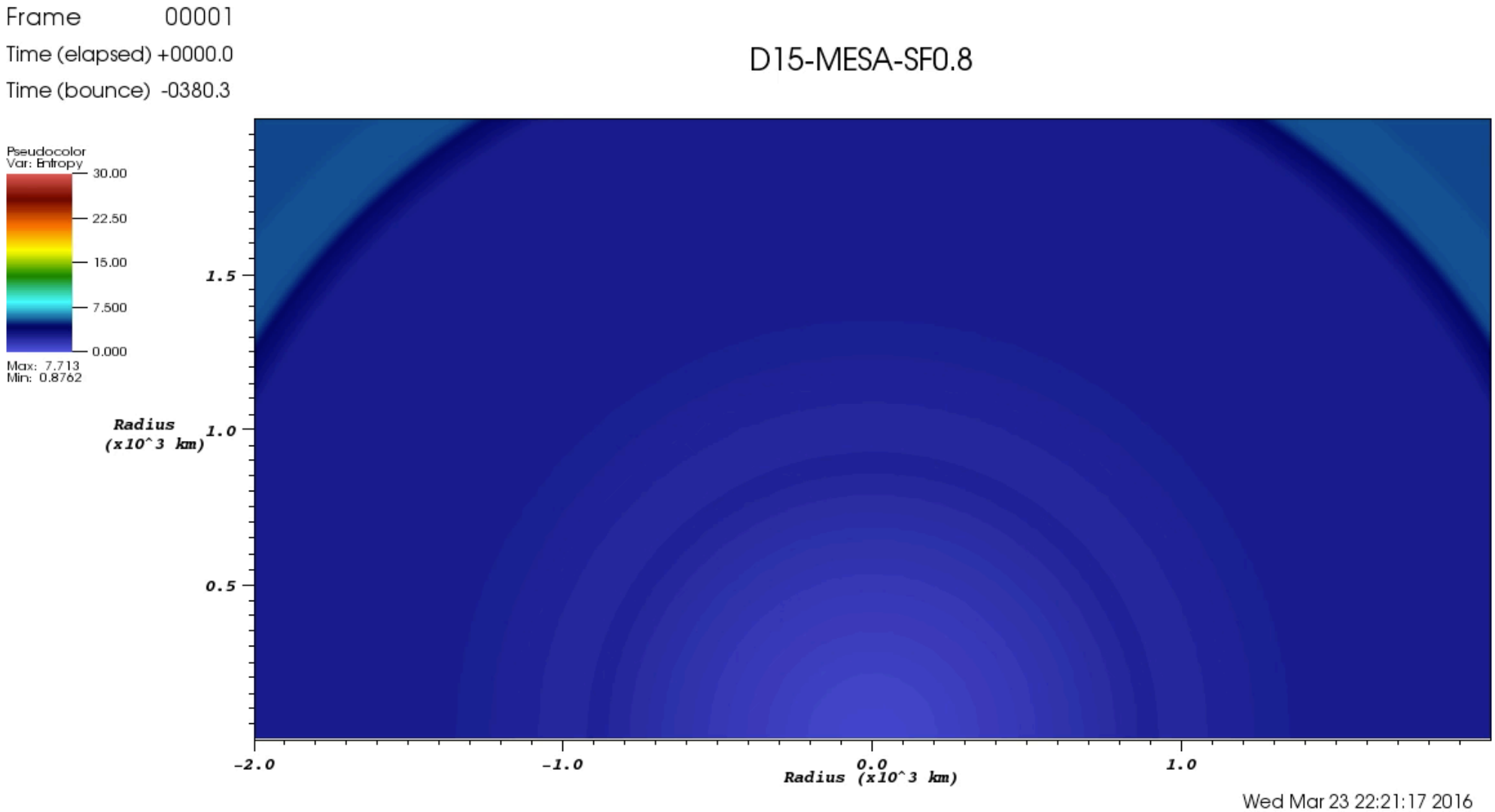
Fruitful collaborations with LBNL Computing Research Division (CRD) and NERSC

domain-decomposed AMR particle transport
Sedona + BoxLib = SEDONABOX

2D core collapse supernova simulation

hydrodynamics+gravity+neutrino transport+EOS+reactions

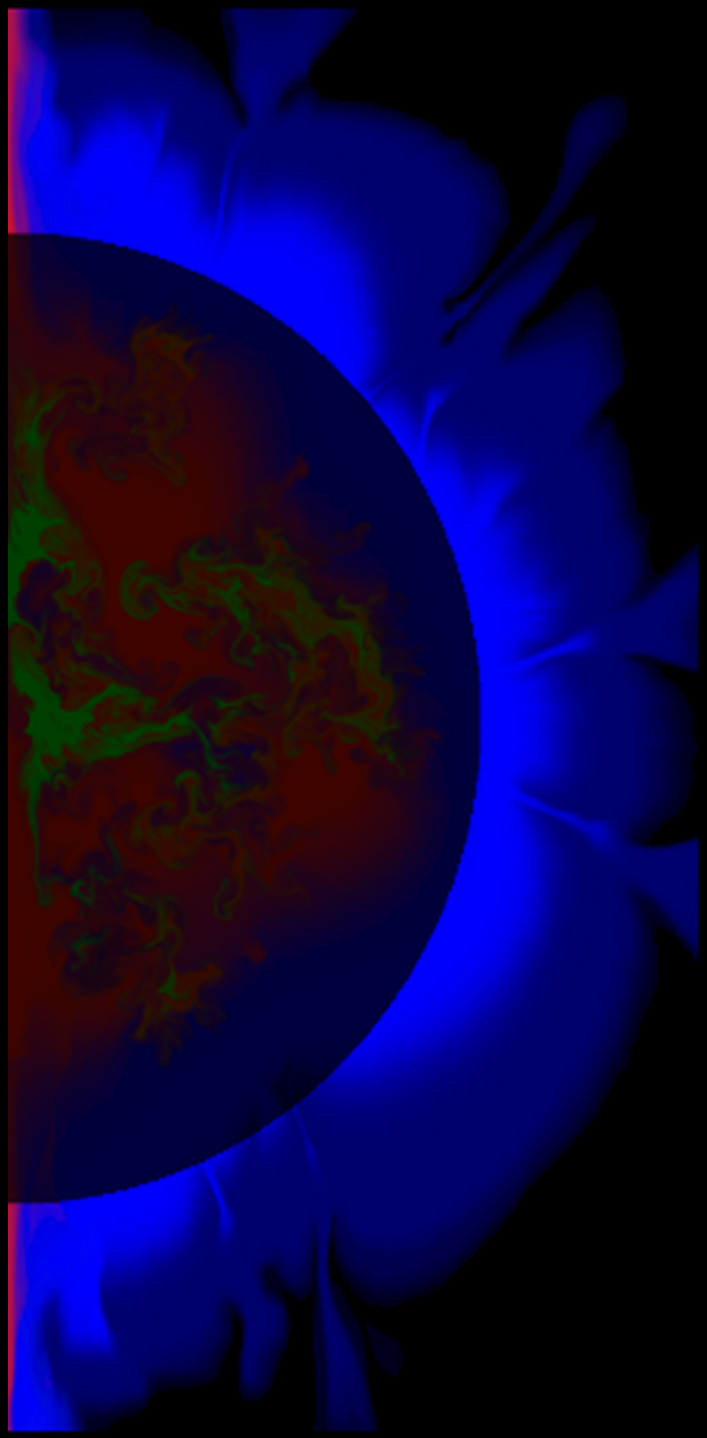
Austin Harris (LBNL postdoc), chimera code

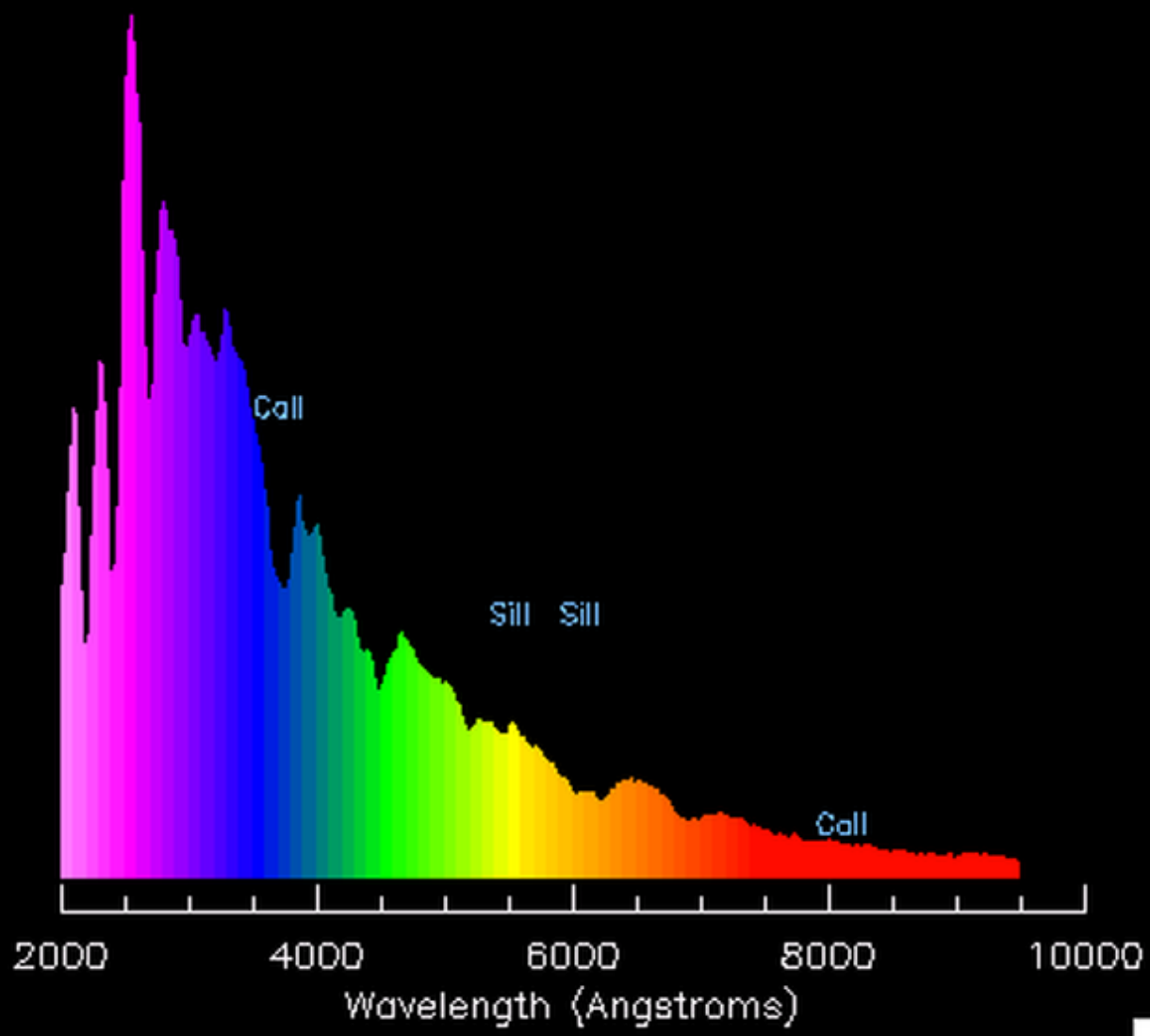


model (Type Ia SN) spectral evolution

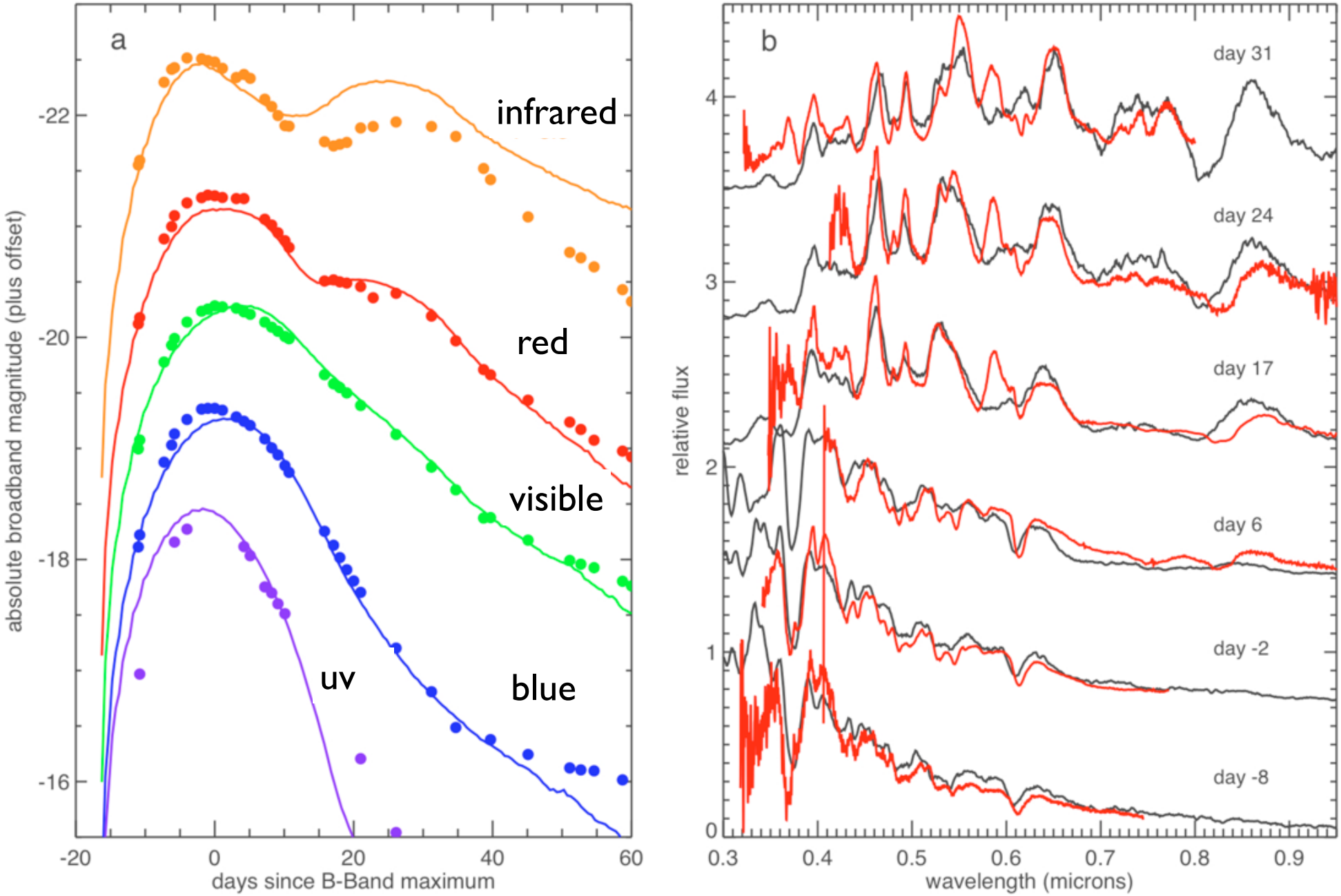
t = 6.0 days

sedona radiation transport calculation



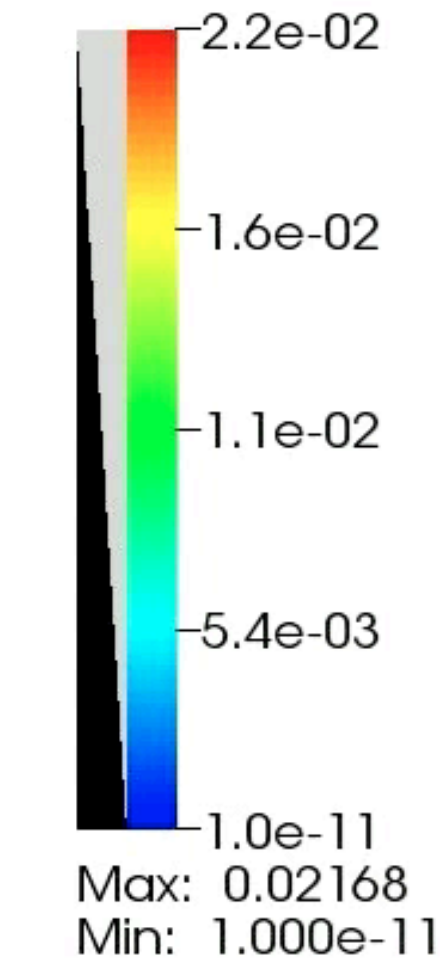


Comparing model predictions to observations



Neutron Star Mergers

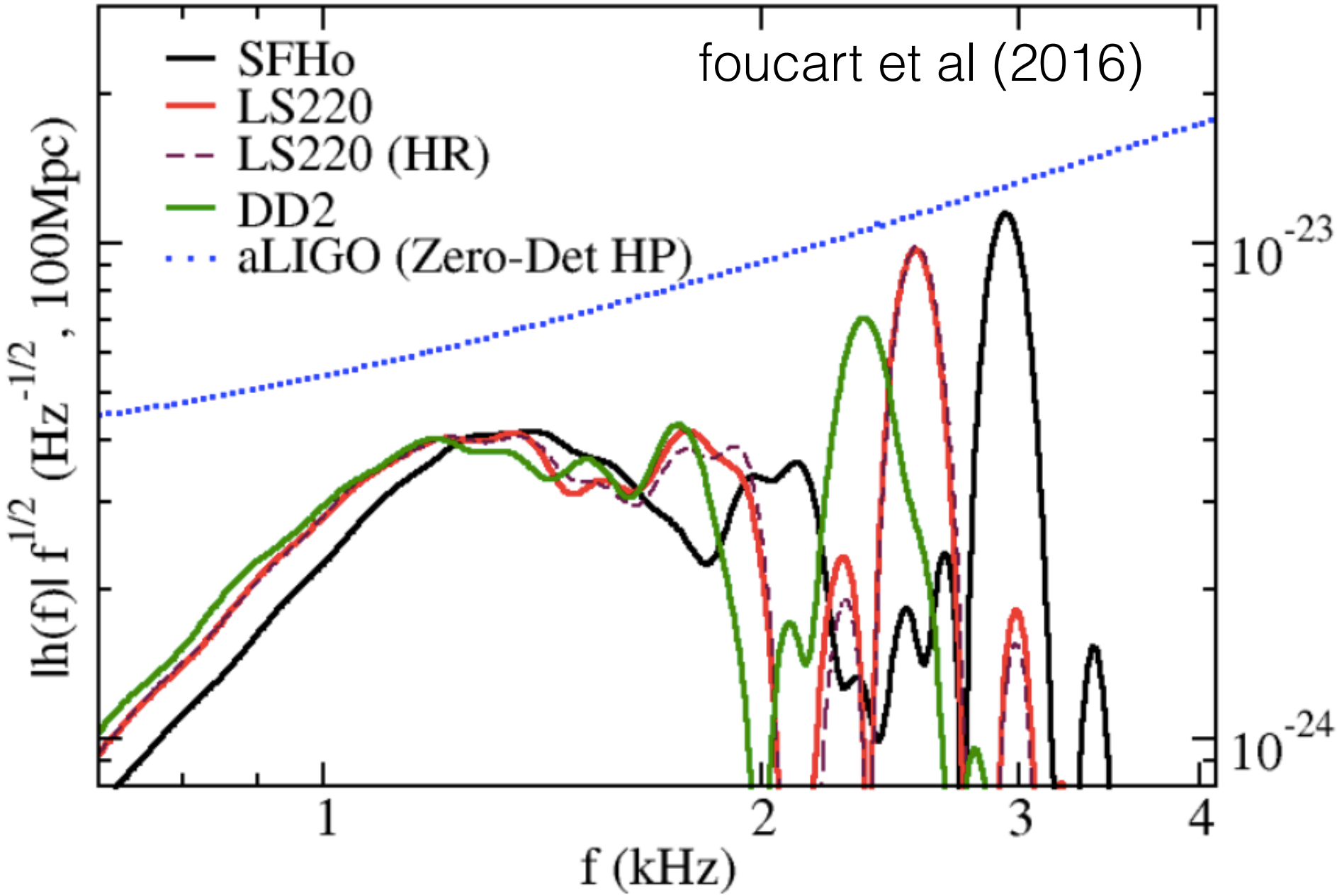
4 M_{sun} black hole + 1.4 M_{sun} neutron star
general relativistic merger simulation
Francois Foucart (LBNL)



foucart et al 2015

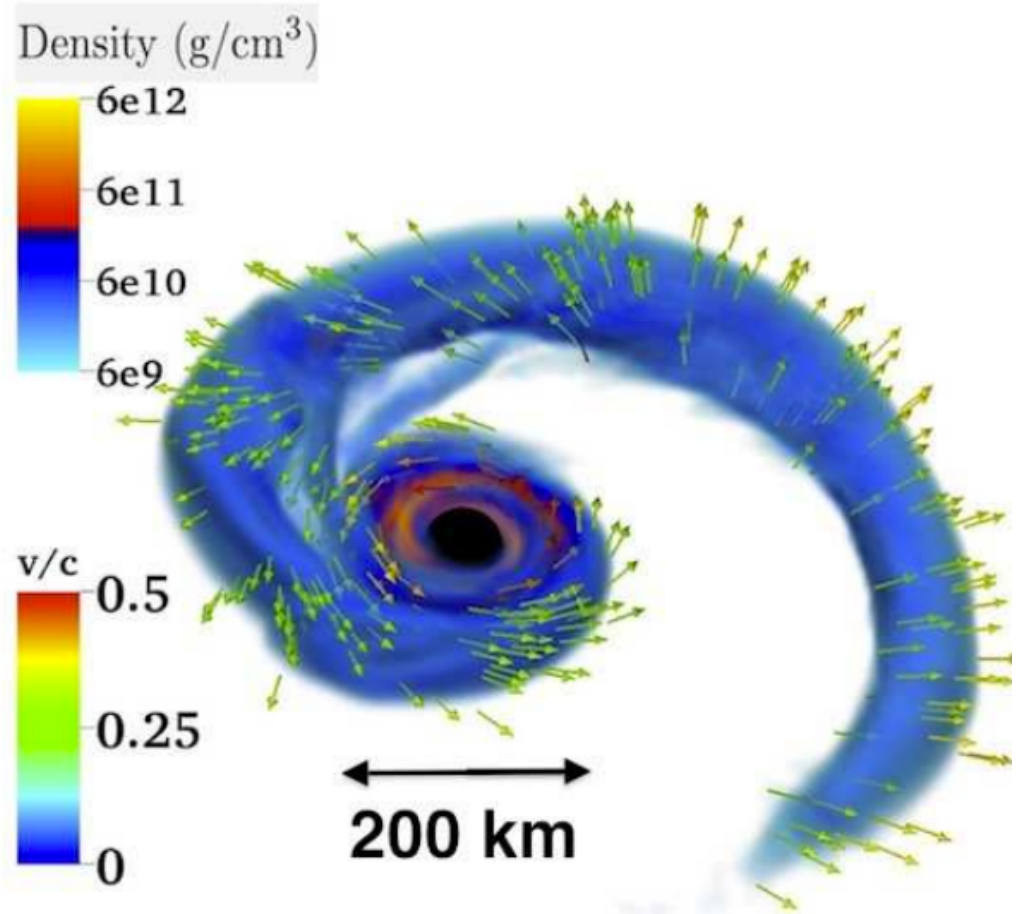
Neutron star + neutron star mergers

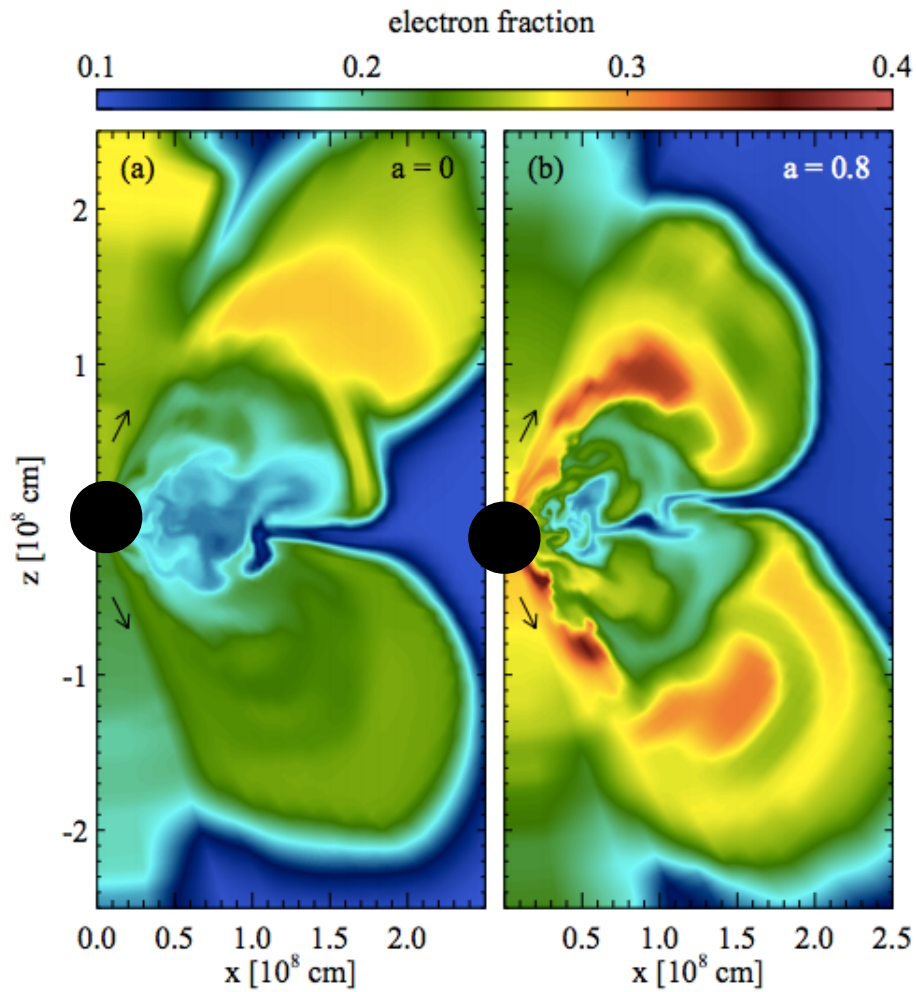
gravitational wave spectrum probing nuclear EOS



Heavy element production in merger ejecta

both short and long time scale contributions





merger prompt ejecta (miliseconds)

cold, very neutron rich

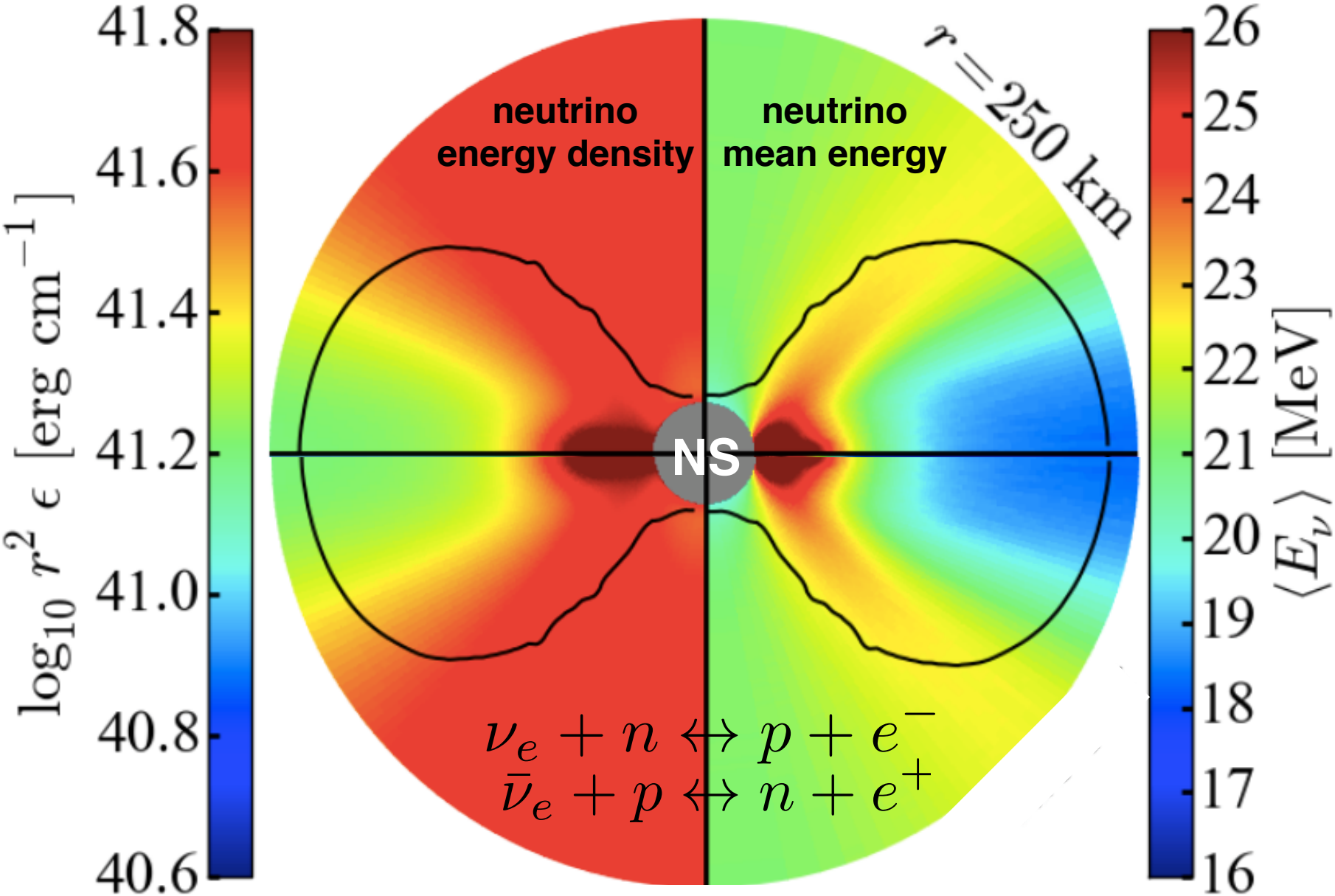
e.g., foucart+ 2014, 2015

post-merger winds (seconds)

hot, less neutron rich

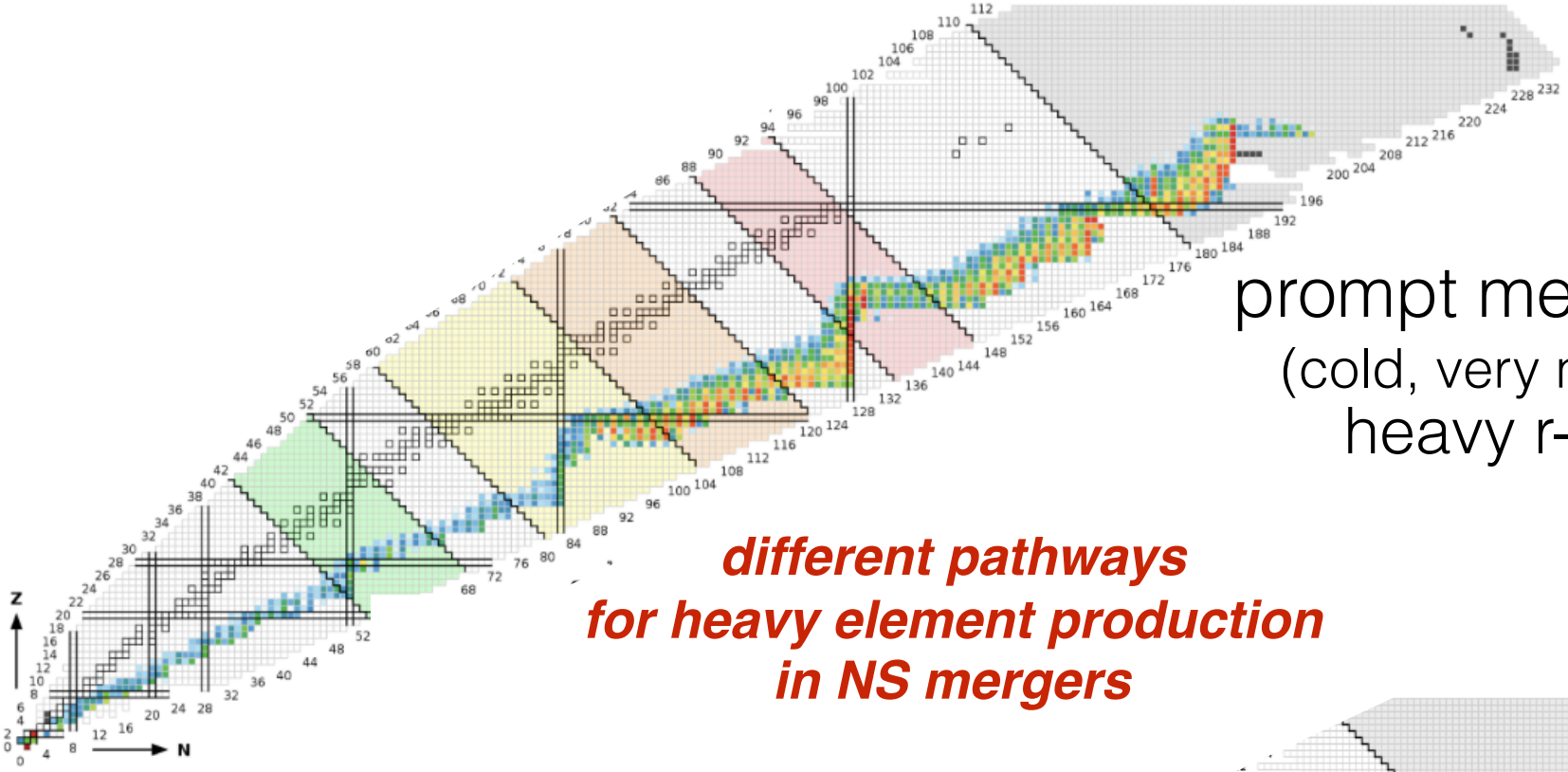
e.g., fernandez, kasen+ 2015, kasen+2015

neutrino irradiation of NS merger remnants



define leptonization of disk, conditions for flavor oscillations

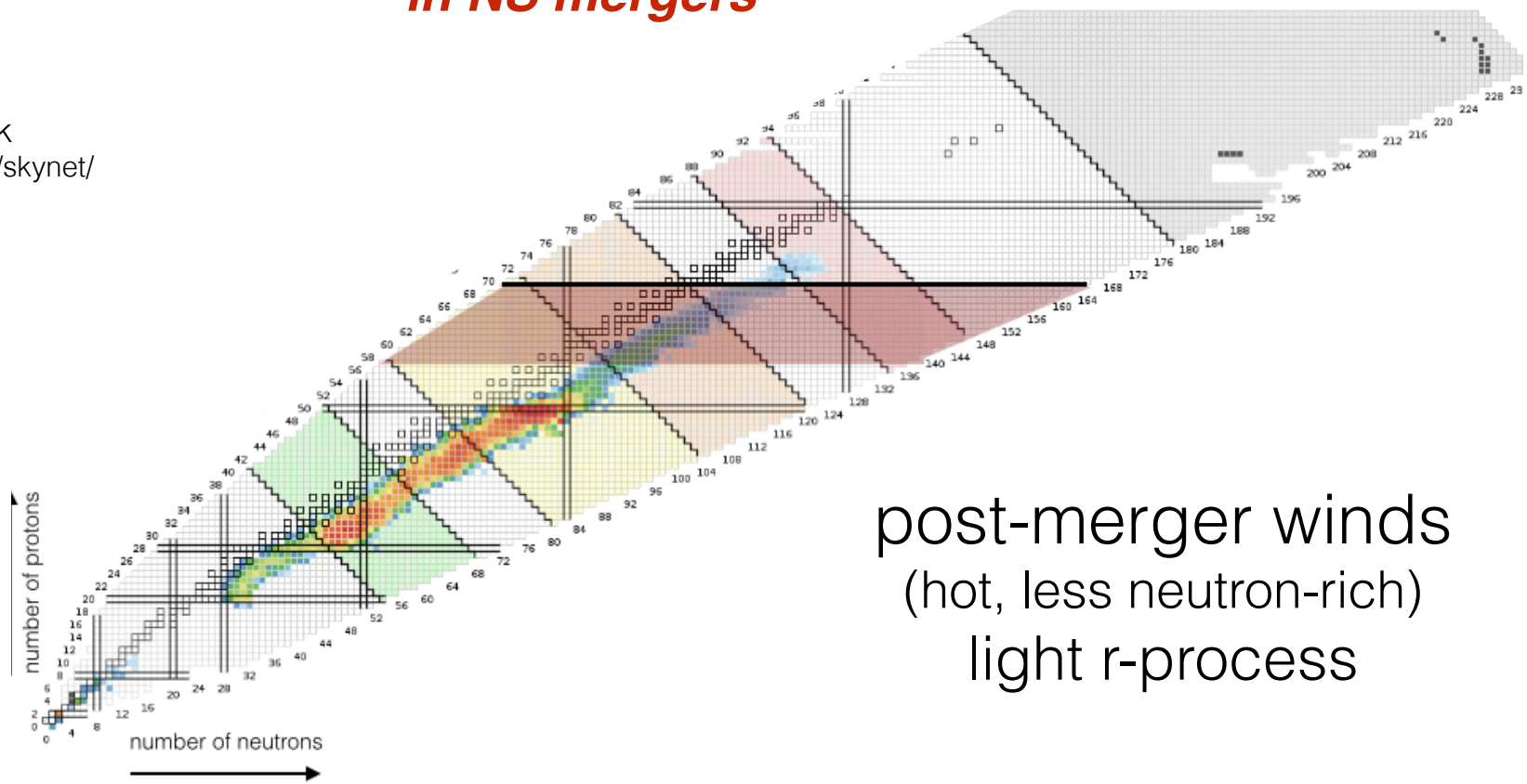
richers, kasen, et al 2015



prompt merger ejecta
(cold, very neutron-rich)
heavy r-process

different pathways
for heavy element production
in NS mergers

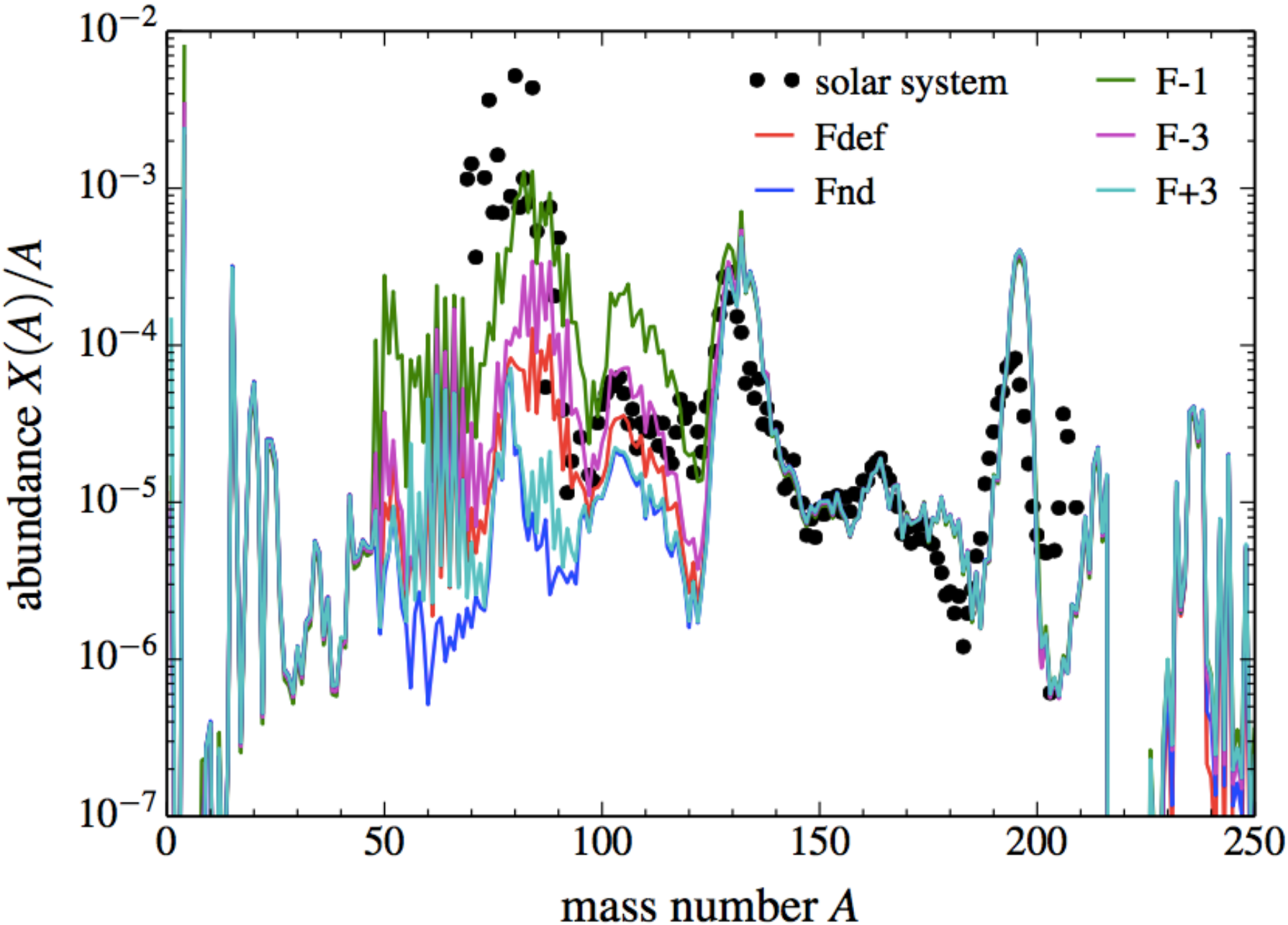
SkyNet reaction network
jonaslippuner.com/research/skynet/



post-merger winds
(hot, less neutron-rich)
light r-process

Modeled nuclear abundances

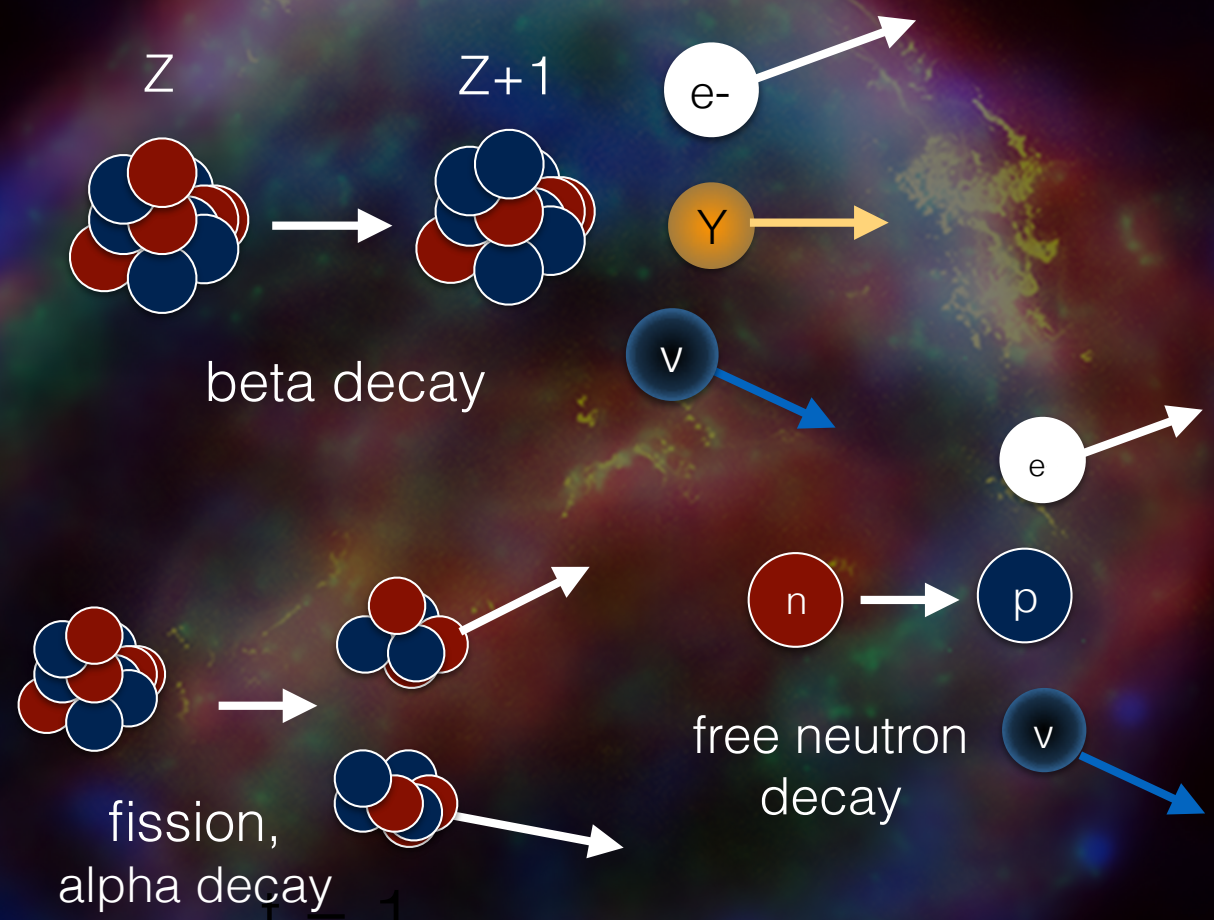
fernandez, foucart, kasen+ (2016 in prep)



kilonova: direct emission from r-process isotopes

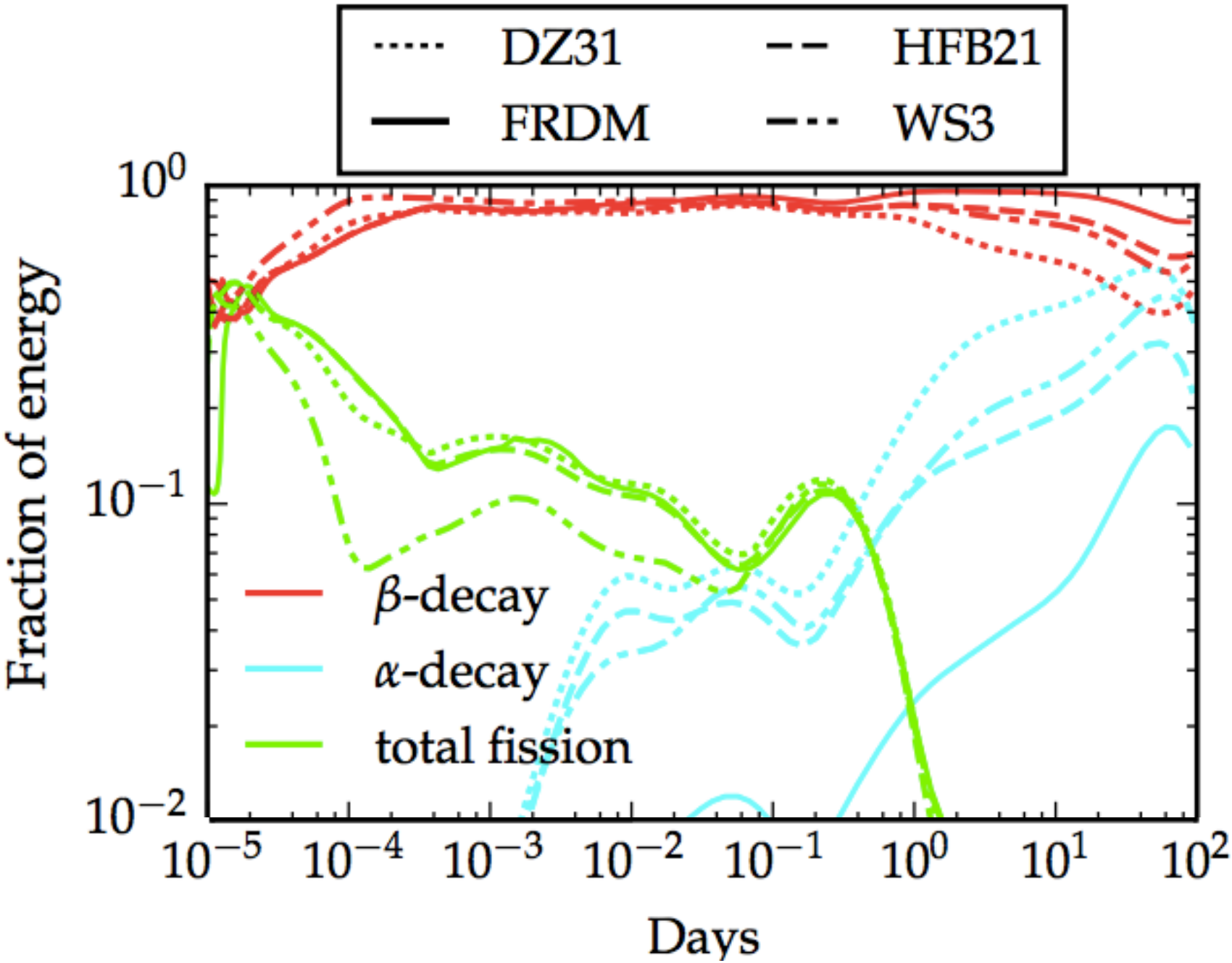
at t ~ 1 day

r ~ 100 AU
L ~ 10^7 L_{sun}
T ~ 5000 K

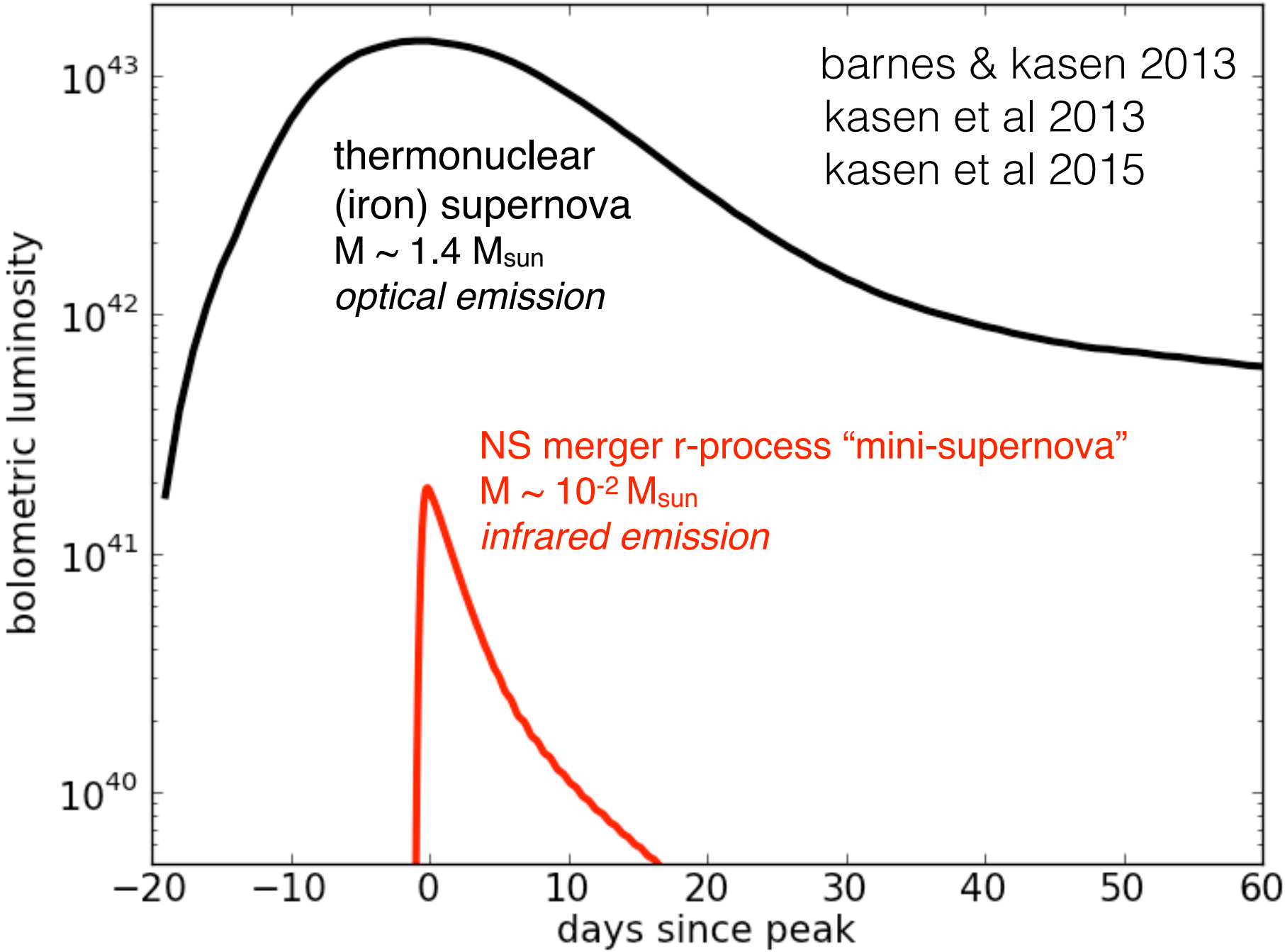


Radioactive decay — nuclear mass models

barnes, kasen, wu, martinez-pinedo (2016)

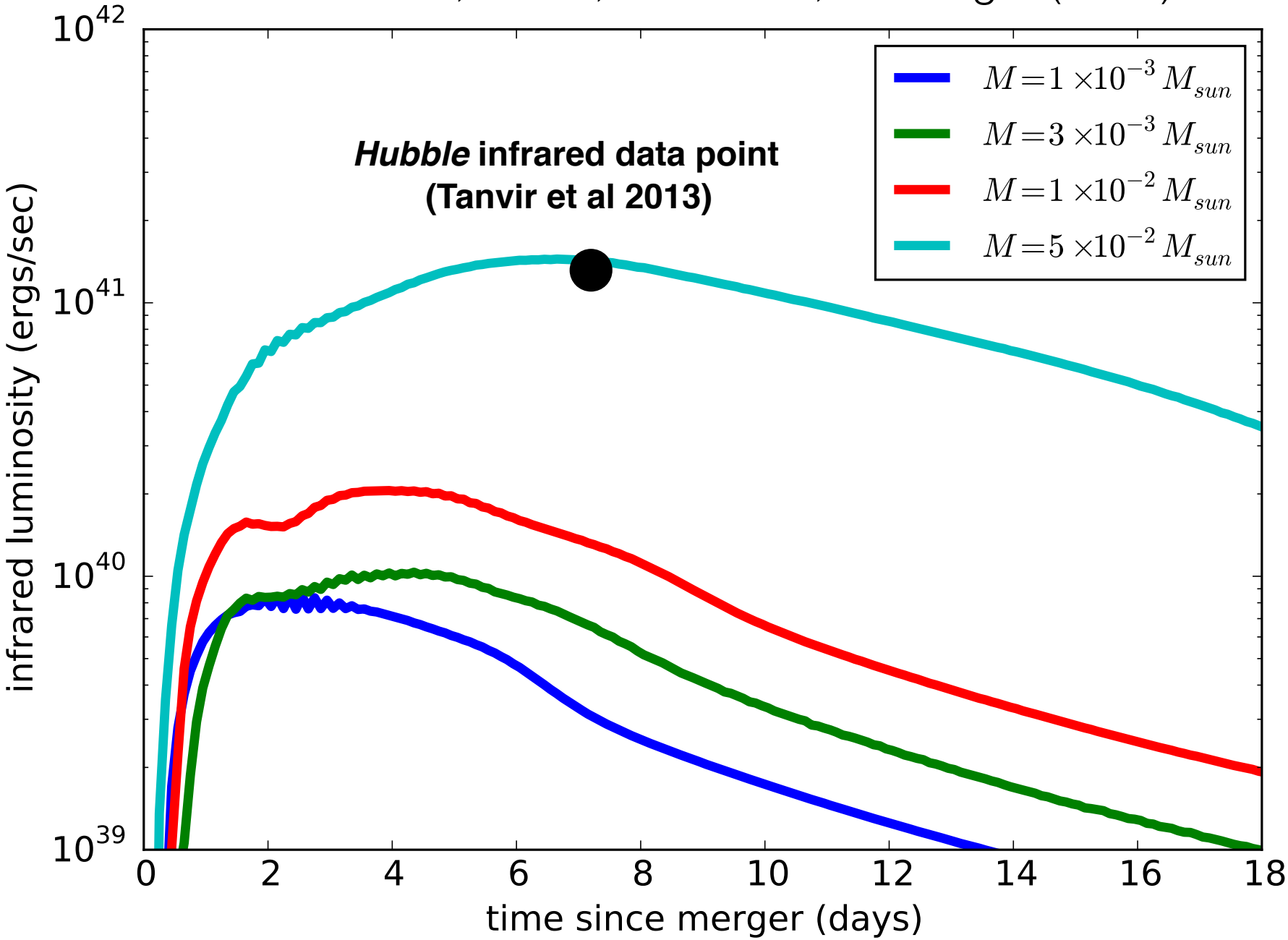


Simulated r-process "mini-supernova" light curves

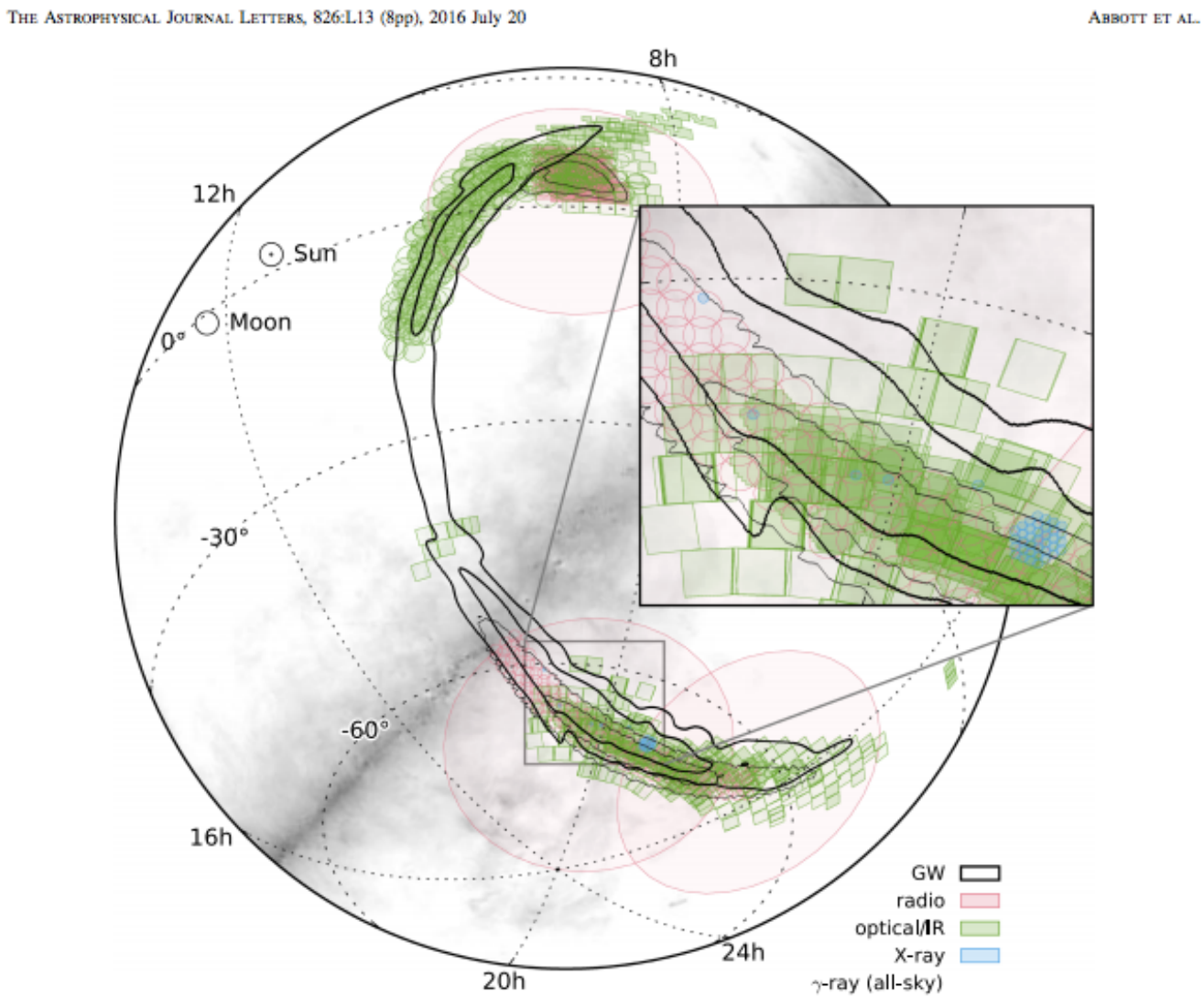


first hint of an r-process "mini-supernova"?

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



Electromagnetic followup of LIGO sources



Kasen a member of DES and LCOGT collaborations for LIGO follow-up

e.g., Abbot et al (2016), Santos-Soares et al (2016), Cowperthwaite et al (2016)

Exascale Computing Project

nuclear astrophysics application

"Exascale Models of Stellar Explosions: Quintessencial multi-physics simulations"

LBL lead: Kasen (PI), Haxton, Almgren, Zhang (CRD)
Partners: ORNL, ANL, Stonybrook

Seed funding started10/2016
Plan to ramp up to full support ($2.5M/yr) by 2018
Also upcoming: SciDAC collaboration

EXASCALE COMPUTING PROJECT