Astro 596/496 NPA
Lecture 37
April 29, 2019

Announcements:

- **Take-Home Final Problem Set** out Wednesday
  due Monday May 6, 10:00 pm as pdf post on Compass
- Astro colloquium Tomorrow, 3:45pm, NCSA
  Charles Gammie, "First Event Horizon Telescope Results"
- Astros Seminar tomorrow noon: Michael Coughlin, CalTech
  "Before and after merger"

Last time: the *r*-process.

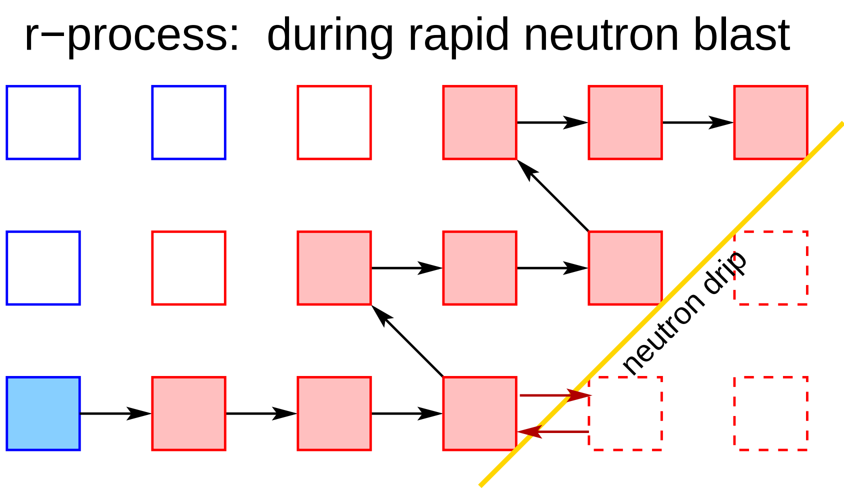
Q: similarities to s-process? differences?

Q: path in chart of nuclides?

Q: peaks in solar abundances: where? why?

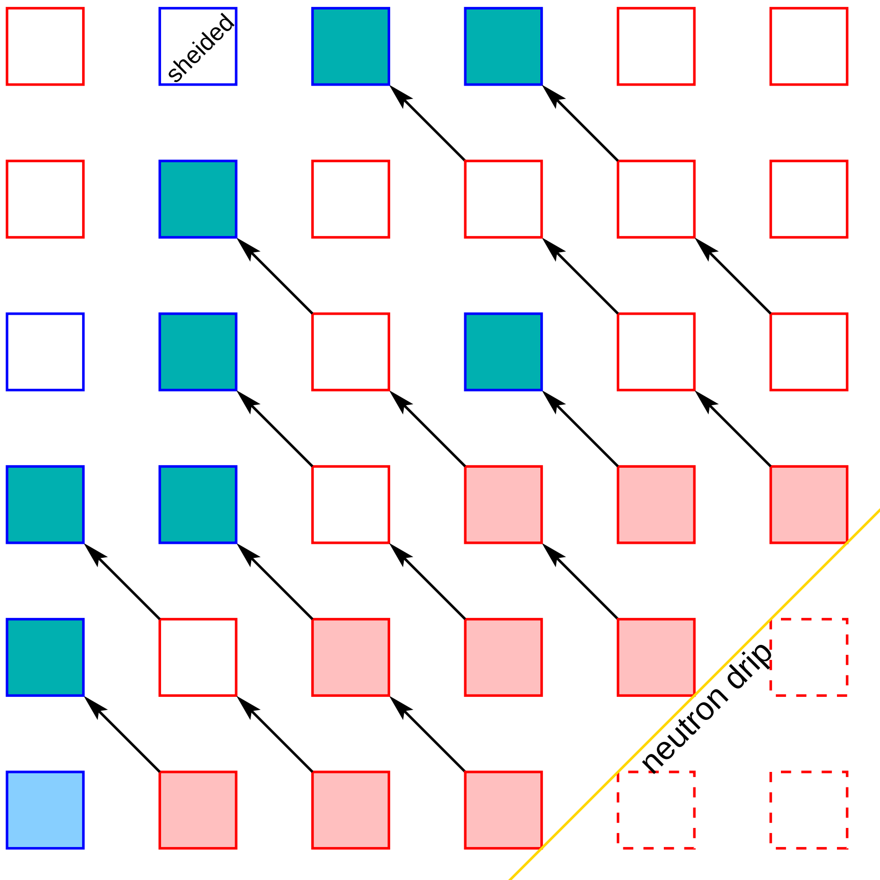
The r-Process: Basic Physics

- Rapidly add n to seeds (e.g., ^{56}Fe)
- populate n-rich nuclei far from β-stability



after blast: return to stability via repeated β decays

r−process: after neutron exposure



Candidate Astrophysical Sites for the r-Process

Core Collapse Supernovae

old ideas: outer layers of NS (near mass cut)?
helium-burning shell: n from $\neq 22(\alpha, n)^{25}$Mg
seeds are pre-existing ^{56}Fe

new ideas:

- in hot propto-NS, νs drive baryonic "wind" near mass cut
  rich in n, α
  "high-entropy bubble" high n/seed $\rightarrow$ can get *r*-process
- in *collapsar*, accretion disk also drives ν wind
  which could produce n and *r*-process
  ejected in GRB and/or accompanying Type Ic explosion?
  if true: *r*-process origin in long/soft GRB

Neutron Star – Neutron Star Mergers

neutrons are abundant! it's right there in the name!

if neutron star matter ejected:
cold NS matter expands, heats $\rightarrow$ *r*-process

mergers occur much less frequently than supernovae:
need larger *r*-production per event

if true: *r*-process origin in short/hard GRB

test: observe central engine in a short GRB

NS Mergers, Kilonovae, and the *r*-process

Early Theory: Black Hole–Neutron Star Mergers

Lattimer, Schramm, et al. (1974, 1977):
neutron star + black hole binaries

- inspiral due to gravitational radiation
- neutron star tidally disrupted
- some neutron star matter ejected

Q: what happens to ejecta material?

fate of ejected neutron star matter

- initial composition almost entirely neutrons
- expand and cools

- β decays create protons and release energy
  which is trapped in still-dense matter
  maintains high temperature, drives further expansion

Q: how will nucleosynthesis proceed in this system?

BH/NS Megers: Nucleosynthesis

1977 studies: NS/BH merge $\rightarrow$ decompressing cold NS matter

initially: nuclear density, nearly all neutrons

beta decays

expansion lowers density, allows beta decays: proton appear
protons and neutrons combine: first ^{4}He, but continues

r-process occurs in first seconds of expansion

can build to actinides!
ejected mass prediction: $0.05 \pm 0.05 M_{\odot}$ (!)

results intriguing but received little attention for $\gtrsim 10$ years
also: rates of NS/NS mergers should be higher
detailed models only arose in the late 1990s

Neutron Star Megers: Overview

based in part on Brian Metzger overview: arXiv:1710.05931

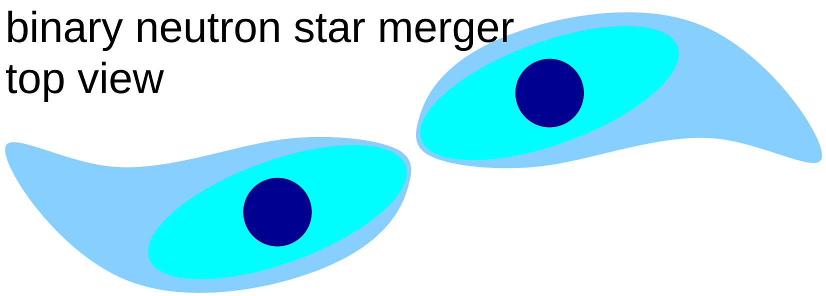
production: two scenarios (at least)

- binary massive stars, neutron stars survive explosions
- in star cluster, single neutron stars gravitationally settle to center, then become bound

evolution:

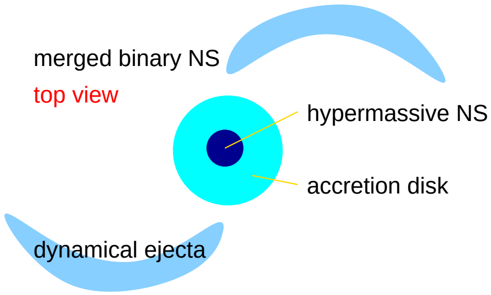
orbit inspiral - decay via gravity wave emission

near merger: tidal disruption of neutron stars `www: UIUC movie`



After The Merge

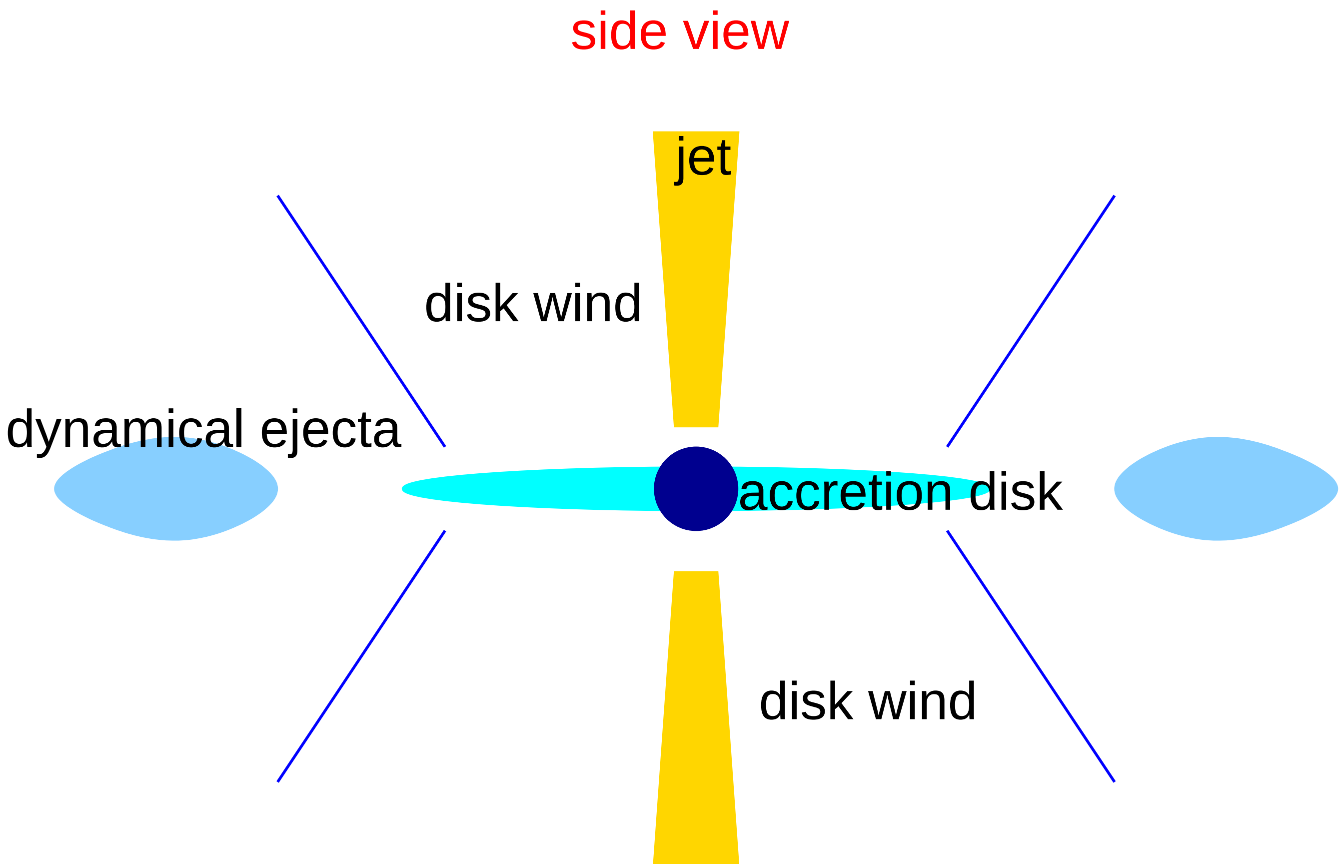
merger matter sorted by angular momentum



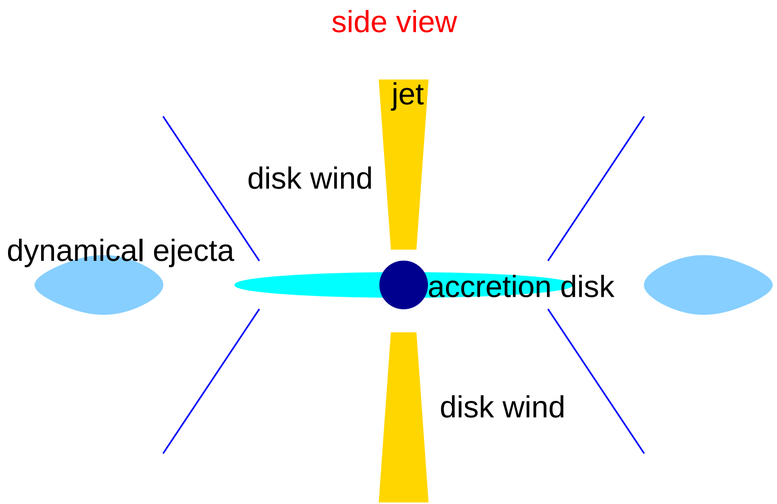
- **central object:** lowest angular momentum matter
- **black hole**, or
  rotationally supported **hypermassive neutron star**
- magnetized, spinning $\rightarrow$ **relativistic magnetized jet**

- **accretion disk:** drives hot, low-density wind
  of expanding neutron star matter: expected EM signal!

- **dynamically ejected matter**: $v \sim 0.10 - 0.3c$
  expanding neutron star matter: expected EM signal!


side view
jet
disk wind
dynamical ejecta
accretion disk
disk wind

Neutron Star Megers: Nucleosynthesis



neutron star matter ejected

- in **polar wind**
  neutrino-driven from accretion disk
- in **dynamical ejecta**
  from tidal tails

both ejected with speeds $v_{\rm ej} \sim 0.1 - 0.3c \sim v_{\rm esc,NS}$
density higher in dynamical ejecta

Q: fate of ejected material?
Q: nucleosynthesis comparison between the polar and dynamical ejecta?

Neutron Star Megers: Nucleosynthesis

merger ejecta initially *dense and neutron-rich*
in vacuum, expands → β decays → *r*-process!

• dynamical ejecta: higher density
more neutrons: can make more seeds, can capture more
r-process in all three peaks, up to actinides

• disk wind: lower density
fewer seeds, less capture
still *r*-process but only first peak
no $A \gtrsim 130$ → no *lanthanides or actinides*

radioactive β decays → e^- and γs trapped in ejecta
energy release is heat sources

Kilonova Light Curves

dense, expanding, ionized material: energy thermalized
photons trapped in interior
only emitted from surface (*optically thick*)
expect: blackbody radiation with T dropping

as you showed in PS6: rapid expansion $\rightarrow$ rapid adiabatic cooling
if initial energy only: soon invisible in the optical!
$\rightarrow$ another energy source demanded: radioactive heating!

Q: rate of heating if one species? two? many?
Q: expectations for kilonova light curve?

Radioactive Heating from One Species

if one radioactive species: heating $\propto$ decay rate
as in supernova ^{56}Ni decay
species i with mean life $\tau_i = 1/\lambda_i$ has decay rate (activity)

$$\mathcal{A}_i = |\dot{N}_i| = \lambda_i N_i = \lambda_i N_{i,0} e^{-\lambda_i t}$$

and so if energy release per decay is Q_i
then radioactive luminosity is

$$L_i = Q_i \mathcal{A}_i = Q_i \lambda_i N_{i,0} e^{-\lambda_i t}$$

an exponential decay with time constant $\tau_i = 1/\lambda_i$

Radioactive Power from Many Species

in kilonova, *r*-process generates many radioactive species with a wide range of lifetimes/decay rates

simple example: *uniform* distribution of decay rates
treat as smooth distribution of λ with $p(\lambda) = const$

net radioactive power:

$$L_{\rm rad} = \langle Q_\lambda \ \lambda \ e^{-\lambda t} \rangle = \frac{\int Q_\lambda \ \lambda \ e^{-\lambda t} \ p(\lambda) \ d\lambda}{\int p(\lambda) \ d\lambda} \quad (1)$$

$$= \langle Q \rangle \frac{\int \lambda e^{-\lambda t} d\lambda}{\int d\lambda} = \frac{\langle Q \rangle}{t} \ \propto \ t^{-1} \quad (2)$$

a power law in time!

Summary: Kilonova/Macronova Predictions

⋆ decompressing neutron star matter generates EM signal
powered by *r*-process decays

⋆ **polar wind ejecta**: lower density, lower-mass elements
not as many atomic lines $\longrightarrow$ less opacity
light diffuses out sooner, when hotter
expect **early-time UV/blue emission**

⋆ **dynamical/equatorial ejecta**:
higher density, heaviest elements
dense lanthanide lines $\longrightarrow$ huge opacity
light diffuses out later, when cooler
expect **late-time red/IR emission**

GW/GRB 170817: Electromagnetic Followup

EM counterpart discovered ~ 11 hours
after gravity waves and gamma rays

early broadband emission includes *Swift* UV detection
and discovery in blue as well as red and IR

later emission red and IR: color reddening over time

spectrum: roughly thermal, with broad features
consistent with predictions of line-blanketed kilonova

GW/GRB 170817: Results

light curve consistent with kilonova models
time profile $\sim t^{-1.3}$, not consistent with supernova

evidence for blue kilonova: polar emission?
best fit by lanthanide-free material

evidence for red kilonova: dynamical ejecta?
best fit by lanthanide-rich material

late-time X-ray: decelerating jet, reduced beaming
emission comes into our sightline

late-time radio: ejecta interaction with ISM
expansion seen!

GW/GRB 170817 and the r-process

light curve suggestive of *r*-process production
consistent with model predictions prior to discovery

ejected r-process mass $M_{\mathrm{ej},r} \sim 0.01 - 0.1\ M_{\odot}$

kilonova rate estimated from:

- one observed event
- LIGO sensitivity
- expected beaming

Combine: gives **r-process production rate from kilonovae**
broadly consistent with needed Galactic inventory!

NS/NS mergers are significant r-process source

An Exciting Multimessenger Future

GW/GRB 170817 opened a new era in astrophysics

- multimessenger astronomy with gravitational radiation
- confirmation that short GRBs are NS mergers
- confirmation that NS mergers are important *r*-process site

but we have only seen one event so far!

wish list for future:

- more kilonovae needed!
  i.e., NS-NS gravity waves with EM kilonovae observed
  will show if the first event typical
- more GW-only NS-NS mergers also useful
  events of past days not seen in EM but suggest high rates!
- detect neutron-star / black hole mergers: none seen yet
  comparison with NS/NS case will be invaluable
- futuristically: neutrinos and MeV gamma-ray lines faint
  but directly probe engine and nucleosynthesis