From Chirps to Jets:
The extreme world of Black Holes and Neutron Stars

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Neutron Stars: $(1-2?) \, M_{\text{Sun}}$ within $R \sim (10-15) \, \text{km}$

Black Holes: $M=1 \, M_{\text{Sun}} \Rightarrow$ horizon at $(1.5-3)\, \text{km}$
Black Holes and Neutron Stars

BH & NS test extreme environments

Very compact -> Strong gravity: Test General Relativity

Unknown nuclear interactions in NS: Test nuclear physics

Black hole-Neutron star merger

SgrA* (center of the Milky Way)

Image: Foucart et al 2017

Part I
Slowly Accreting Supermassive Black Holes
Event Horizon Telescope

- Very long baseline interferometry:
  - 1.3 mm wavelength, baseline the size of the earth, aim for 12 participating telescopes (incl. soon ALMA)
  - Objective: resolve accretion flows to sub-Horizon resolution!
Plasma physics in disks

Low density + High Temperature
\Rightarrow
Very large mean free path
Not an ideal fluid!

Model the disk as a weakly collisional plasma.
Includes: heat conduction, anisotropic pressure

(see Chandra, Foucart et al 2015)
Pressure anisotropy

**Solar Wind** (1AU)  
Kasper et al. 2016

**Accretion disk**  
Foucart et al., in prep

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Plasma remains at mirror instability threshold

Pressure anisotropy $\sim$ Magnetic pressure
First global 3D simulations of a disk with $\Delta P, q$

Foucart et al., in prep

For a compact torus with small magnetic field:

Many similarities with ideal MHD disks
(With some magnetic shear replaced by viscous shear)
Current status

- First global simulations of disks capturing non-ideal effects in plasma (Foucart et al. 2016, Foucart et al. in prep)
- Saturation of pressure anisotropy at mirror instability threshold (dP~magnetic pressure)
- Practical effect on dynamics of compact, low magnetization disk is small.
- More significant effects likely for
  - Larger B-fields
  - Wider disks with resolved outflows
Part II
Merging Black Holes and Neutron Stars
Simulations in General Relativity
Density

Movie: D. Faiez
Gravitational waves and the Neutron Star equation of state
Gravitational Waves

**General relativity:**
Mass/Energy creates Spacetime curvature
Masses moving in curved space generate gravitational waves

To first order:
Quadrupole formula

\[ L_{GW} \propto \sum_{i,j} (\partial_t Q_{ij})^2 \]

For binaries:

\[ L_{GW} \propto M^2 \Omega^6 d^4 \]

\[ \propto (M/d)^5 \]

=> strong emission for very compact systems (e.g. BH, NS)
Gravitational Waves

First Detection: GW150914

Image: LIGO Collaboration, PRL

Movie: SxS Collaboration

Image: LIGO Collaboration, PRL

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UVa
Nuclear physics and the neutron star equation of state

Measurements of neutron star radii = Constraints on nuclear physics!!

Image: Fischer et al 2014
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Image: Steiner, Lattimer & Brown 2012
Equation of state effects during inspiral

Quadrupole formula: \( L_{GW} \propto \sum_{i,j} (\partial^3 Q_{ij})^2 \)

Tides in neutron stars cause large stars to merge faster!

Tidal dephasing (leading order in \( \Omega \)): \( \delta \Phi \sim R^5 \Omega^{5/3} \)

\(~40\) NS-NS mergers [NOT BH-NS]

Radii measured to \(~10\%\)

(see Del'Pozzo et al. 2013, Lackey & Wade 2015)

Important caveat:
Assumes perfect waveform model (Lackey & Wade 2015)
New simulations with high-order methods:

- **Rules out simplest static tides models**
- Allowed derivation of new model including dynamical tides (Hinderer, .., FF et al., 2016)
- Still $\sim 25\%$ numerical error in tidal dephasing!

**Numerical simulation vs Theoretical model**

Image Hinderer, ..FF et al. 2016
Post-merger emission (NS-NS mergers)

- Clear dominant frequency in post-merger signal
- Probe fundamental $l=2$, $m=2$ excitation mode of remnant
- **Reliable models** (Bauswein et al. 2012, Takami et al. 2015, Lehner et al. 2016), but hard to detect
Merger simulations with SpEC

http://www.black-holes.org/SpEC.html
Numerical Simulations with SpEC

Evolve Einstein’s equations with sources:
Pseudospectral methods, comoving grid, ~100 coupled diff. eq.

General relativistic hydrodynamics:
High-order shock capturing methods
Mesh refinement
Excised black hole interior
Modules for MHD/Neutrinos (Two-moment formalism)/Composition
Electromagnetic Transients and r-process nucleosynthesis
Short Gamma-Ray Bursts

Kilonovae + r-process!

Pre-merger Signals

Long-duration radio emission

Image: Tanvir et al. 2013

Image: Tsang et al. 2012

What can we learn from EM transients?

Demonstrate origin of SGRBs
Estimate contributions to r-process elements production
Merger environment: host galaxy, ISM density

Sky localization of GW150914 (LIGO Collaboration)

Independent constraints on NS/BH properties
1) From existence of EM counterpart in BHNS mergers
2) From IR/Optical lightcurves
Merger outcome: BH-NS binaries

Min. BH spin to disrupt a $1.4 M_\odot$ NS

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(see Foucart 2012)
r-process nucleosynthesis and kilonovae

Nucleosynthesis in **neutron rich material** (e.g. tidal ejecta from BH-NS binary)

Visualization: Jonas Lippuner (Caltech), SkyNet code
Kilonovae and r-process

**Tidal Ejecta**
- Cold, mostly neutrons
- Favored by:
  - Large stars
  - Asymmetric mergers
- IR transient

**Shocked Ejecta**
- Hot, less neutrons
- Only for NS-NS
- Favors small radii
- Optical transient (?)

**Post-Merger Disks:**
- Winds (B-fields, ν)
- Strong ν effects
- Uncertain EM counterpart

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Nucleosynthesis in kilonovae

Dynamical ejecta produces heavy elements
Disk outflows produce lighter elements
Solar system abundances if the two components have similar masses

Abundances from SkyNet (J. Lippuner, L. Roberts)
Neutron star mergers: Current status and Future work

- Wide range of physical effects can be studied through BH-NS / NS-NS mergers
- Merger dynamics and outcome can only be studied with general relativistic simulations
- Good qualitative understanding of merger dynamics
- Improving waveform models for NS, more work needed to prepare for LIGO observations
- More detailed microphysics in mergers is beginning to make EM / nucleosynthesis predictions possible