ACCRETION ON COMPACT OBJECTS

- Compactness allows for extraction of significant fraction of the gravitational energy (up to 40% of $\dot{M}c^2$ for a BH!)

(c) Jake Lutz, https://youtu.be/Dg_ukl_QWOw
ACCretion on Black Holes

BH accretion is involved in some of most energetic phenomena:

- X-ray binaries
- Active galactic nuclei
- Tidal disruptions of stars
- Gamma ray-bursts
- NS+BH mergers
- **Ultraluminous X-ray Sources** (NASA)
OPTICAL IMAGE OF M51 (+NGC 5195)

(c) KPNO
M51 IN X-RAYS

(c) Chandra
OPTICAL IMAGE OF M51 (+NGC 5195)
ULTRALUMINOUS X-RAY SOURCES

- Brighter than the Eddington luminosity for 10 Msun BH:
  \[ L > L_{\text{Edd}}(10M_\odot) \approx 10^{39}\text{erg/s} \]
- Non-nuclear
- Either sub-Eddington hosting intermediate mass BH or super-critical hosting BH or NS
MODES OF ACCRETION

MODES OF ACCRETION

adapted from Yuan (2003)
The standard model of a thin disk (Shakura & Sunyaev 73, Novikov & Thorne 73) provides an analytic solution of a \textit{geometrically thin, optically thick, radiatively efficient disk}.

- (Thermally unstable in the radiation pressure dominated regime)
- Radiative efficiency and emission profile uniquely determined - independent of viscosity

\[ \dot{M} \lesssim \dot{M}_{\text{Edd}} = \frac{L_{\text{Edd}}}{\eta c^2} \]
SUPER-EDDINGTON DISKS

- Geometrically thick
- Non-trivial, two-dimensional (turbulent) radiative transport
- Large optical depths - photon trapping
- Radiatively driven outflows
- Sub-Keplerian

Require numerical solutions!

\[ \dot{M} \gtrsim \dot{M}_{\text{Edd}} \]
SIMULATING BH ACCRETION

Essential components:
- stationary space-time: (GR, Kerr-Schild metric)
- magnetized gas: MHD (ideal)
- photons: radiation transfer (simplified)
- electrons: thermal & non-thermal
- radiative postprocessing: spectra, images
- multidimensional fluid dynamics solver
SIMULATING ACCRETION

KORAL
radiative MHD code
(Sadowski+13, ...)

HEROIC
GR RTE solver
(Zhu+15, Narayan+15)

other groups performing
(GR) radiative MHD:

Ohsuga+
Jiang+, Fragile+, McKinney+, Gammie+, ...
KORAL

• GR ideal MHD + div B=0
• Radiation evolved simultaneously providing cooling and pressure
• Radiative transfer under M1 approximation
• Conservation of number of photons (allows for tracking the radiation temperature)
• Comptonization
• Independent evolution of thermal electrons and ions providing self-consistent temperatures
• Synchrotron and bremsstrahlung Planck and Rosseland opacities dependent on both gas and radiation temperature
• Coulomb coupling
• Self-consistent (depending on electron and ion temperatures) adiabatic index

Sufficient set to study accretion flows at any accretion rate, including the intermediate regime
MODES OF ACCRETION

adapted from Yuan (2003)
HIGHLIGHTS OF SUPER-CRITICAL ACCRETION

- super-Eddington accretion feasible
- geometrically and optically thick
- photosphere far from the equatorial plane
- radiatively driven outflows
- significant photon trapping (affecting both radial and vertical radiation transport)
- moderate beaming
- observables strongly inclination dependent!
HEROIC
3D GR RADIATIVE POSTPROCESSOR WITH COMPTONIZATION

- General relativistic, grid base radiation transfer equation solver
- Frequency resolved radiation
- Short- and long-characteristics
- Comptonization via Kompaneets equation
- Takes density, velocities and heating rate as input
- Works efficiently for any optical depth

Aleksander Sadowski, MIT
Simulations of radiative accretion in GR

(Narayan+15)
SUPER-CRITICAL ACCRETION

- high-inclination
- moderate beaming
  - super-Eddington
- hard spectrum
- ULXs?

- low-inclination
- ~Eddington
- soft spectrum

ULSs?
(ultraluminous supersoft)
10 DEG

(bolometric flux)
20 DEG

(bolometric flux)
30 DEG

(bolometric flux)
40 DEG

(bolometric flux)

Simulations of radiative accretion in GR
SPECTRA
vs inclination angle for $10\dot{M}_{\text{Edd}}, a=0$
**RADIATIVE & KINETIC EFFICIENCY**

- Anisotropic radiation field
- Up to \( \sim 10 \) times Eddington apparent flux for near-axis observers and 10 times Eddington accretion rate
- But only \( \sim \)Eddington apparent luminosity at larger inclinations
- Low total radiative efficiency!

- But the total energy extracted efficiently (total efficiency \( \sim 3\% \dot{M}c^2 \))
- The excess must go into the kinetic component (outflows)
- The higher the accretion rate, the higher the fraction of energy output going into kinetic energy of the outflow!

\[
\dot{M}_{BH} = 10\dot{M}_{Edd}
\]

Aleksander Sadowski, MIT

Simulations of radiative accretion in GR (Narayan+15)
SPECTRA
vs accretion rate for $i=30\text{deg}, a=0$

Spectrum is getting softer with Mdot because of increasing photosphere height.
Two distinct spectral states: softer/harder
Funnel opening angle (photosphere height) varies with accretion rate - strongly modifies obscuration for a given observer
SUPER-EDDINGTON ACCRETION

- Super-critical accretion disks are geometrically and optically thick
- Total radiative efficiency drops down with increasing transfer rate
- Kinetic output balances the missing radiation
- Radiation field anisotropic - along axis observers see super-Eddington fluxes when observers at large inclinations - just Eddington
- Increasing transfer rate and the photosphere height may lead to obscuration and softer emission
- However, simulations limited to the innermost region (R<100Rg)
MOVING TO LARGER SCALES - ULX BUBBLES

- Up to 25% ULX show ISM bubbles
- Shock-ionized nebulae
- Expansion velocity ~100 km/s
- Radius ~ 100-200pc
- Lifetime ~ 1 Myrs
- Often together with jet-related hot spots

- Most likely inflated by long-lasting kinetic outflow from ULX with luminosity ~1e39 - 1e40 erg/s
EVOLUTION OF ULX BUBBLES
Project led by Magdalena Menz, Univ. of Glasgow
EVOLUTION OF ULX BUBBLES

- Outflows from the accretion flow push out and shock ISM
- Front / rear shocks form
- Shocked wind hot but low density
- ISM swept into a shell which collapses once cooling starts to be efficient
- Expected opt/UV emission from the shocked ISM and X-rays from the shocked wind
- Simulations performed with KORAL adopting free-free and bound-free opacities
EVOLUTION OF ULX BUBBLES

Diagram showing a grid with labels for 'cooling (log)' and 'density (log)', with a dimension of 100 pc.
EVOLUTION OF ULX BUBBLES
Luminosity dominated by optical/UV from shocked ISM
X-rays produced by the shocked wind
But the properties of the shocked wind depend on the properties of the outflow, e.g., the mass outflow rate, not only on the kinetic power!

We may learn a lot about the outflow if we look how they interact with ISM!
SUPER-EDD ACCRETION - SUMMARY

- Numerical simulations are a powerful and often required tool to understand supercritical accretion flows.
- More work is required to implement better physics (double Compton, frequency dependent radiative transfer...).
- Properties of the flow not unique and depend strongly on a number of parameters: accretion rate, BH spin, magnetic field properties, history of accretion?
- Simulations limited to the inner region and short.
- Constraints from the other (large scale) end may be very helpful.
- Need for innovative numerical methods.