Title: Numerical simulations at the frontier of relativistic astrophysics

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Abstract: <p>In the coming years, astrophysical observations of strongly gravitating systems will provide us with exciting new data to study extremely compact objects and Einsteinâ€™s theory of general relativity. In particular, gravitational wave observatories will soon reach the sensitivity required to detect merging black holes and neutron stars, while the Event Horizon Telescope is about to observe accretion flows around two supermassive black holes with sub-horizon resolution. Accurate modeling of these systems require complex simulations including general relativistic magnetohydrodynamics, radiation transport, and, for the Event Horizon Telescope, heat conduction and viscosity in a nearly collisionless plasma. In this talk, I will discuss recent results from global general relativistic simulations of these systems. I will mainly focus on our understanding of the gravitational wave and electromagnetic signals powered by binary mergers, and what they may tell us about the properties of neutron-rich nuclear matter and the origin of many heavy elements observed in the Universe today. I will also discuss how to model non-ideal fluids in general relativistic magnetohydrodynamics simulations of accretion disks, and how non-ideal effects may modify the properties of accretion flows around slowly accreting supermassive black holes â€” including the two targets of the Event Horizon Telescope.</p>

- **Part I : Compact binary mergers**
    - Gravitational wave astrophysics
    - Electromagnetic signals and nucleosynthesis
    - Numerical relativity: BH-NS and NS-NS mergers
- **Part II : Accretion disks around supermassive black holes**
    - Slowly accreting supermassive black holes
    - Modeling accretion flows as weakly collisional plasmas

Gravitational waves

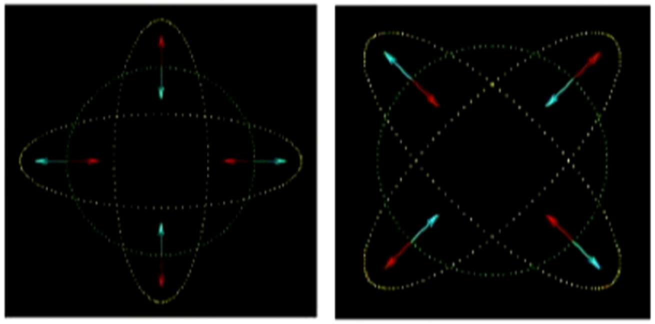


Image: Cardiff University

Advanced LIGO / VIRGO

Image: LIGO Livingston (LA)

Indirect observation: Hulse-Taylor binary

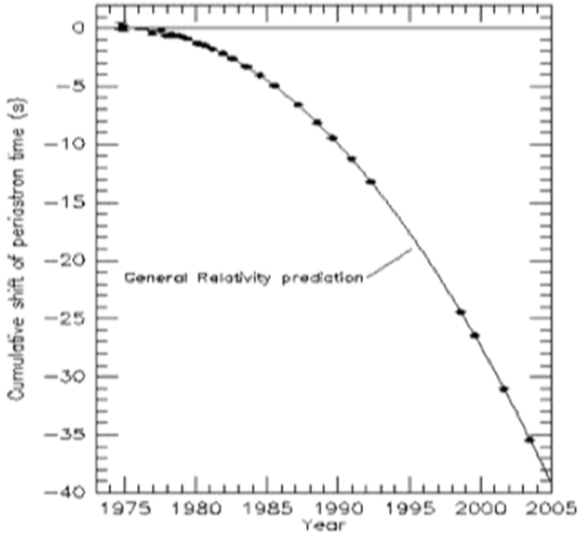


Image: Weisberg & Taylor 2004

Promising sources: Merging BHs and NSs

Event rate ~ 40/yr
(very uncertain)

Short Gamma-Ray Bursts

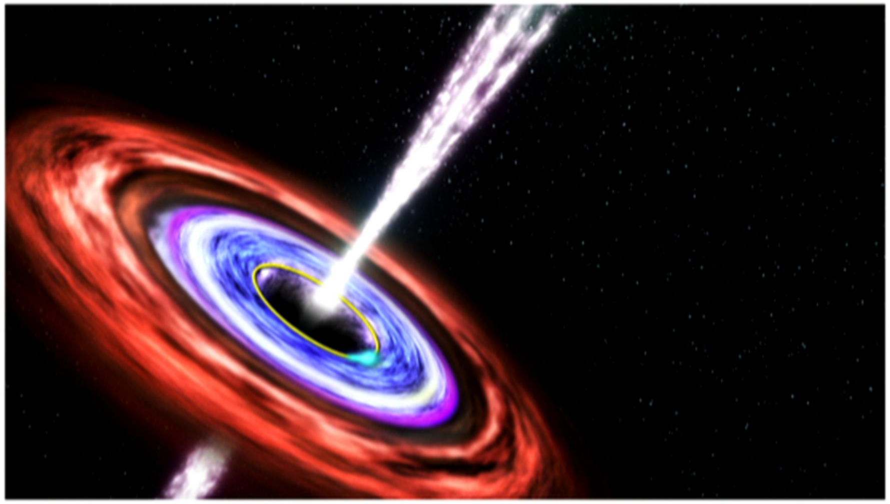


Image: NASA [Artist's rendition]

- Short GRBs probably result from binary mergers
- How often? Which binaries? By what mechanism?
- Can provide improved localization!
- Problem: probably strongly beamed!

Radioactively Powered Transients

- (Optical)/IR transient from radioactive decay of neutron rich ejecta
- Fainter, but (more) isotropic!!
- Carries information on unbound mass and its composition

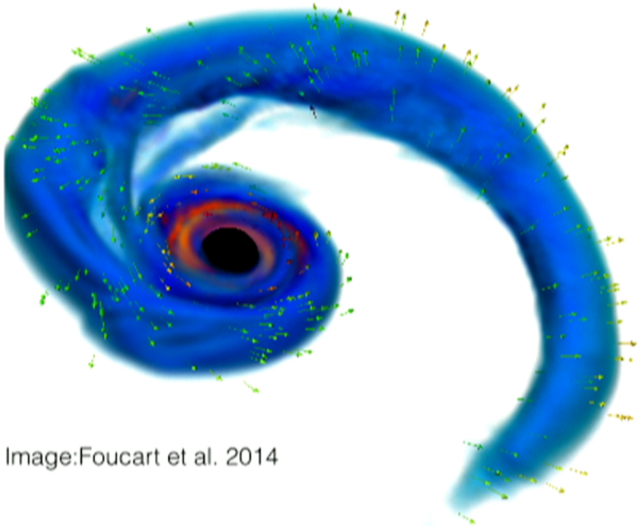


Image:Foucart et al. 2014

A first detection?

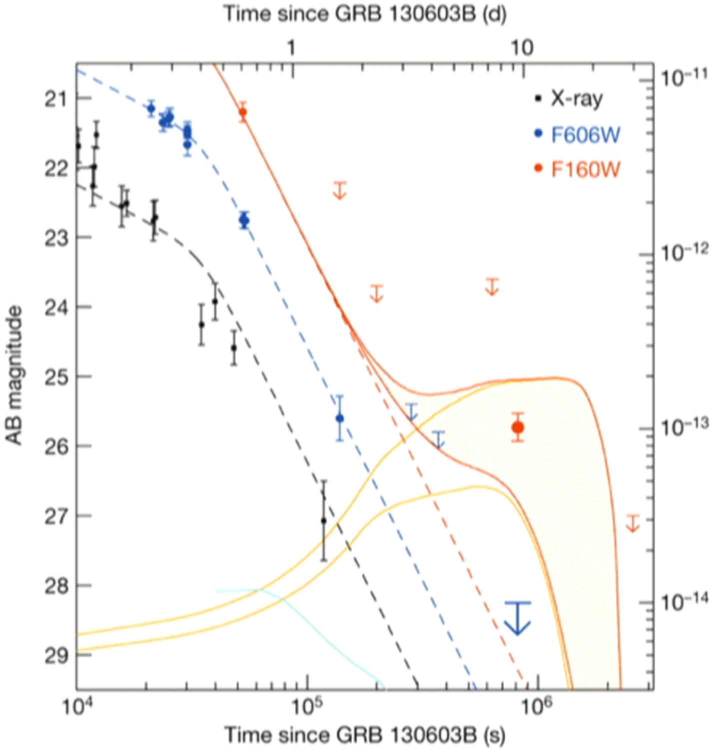
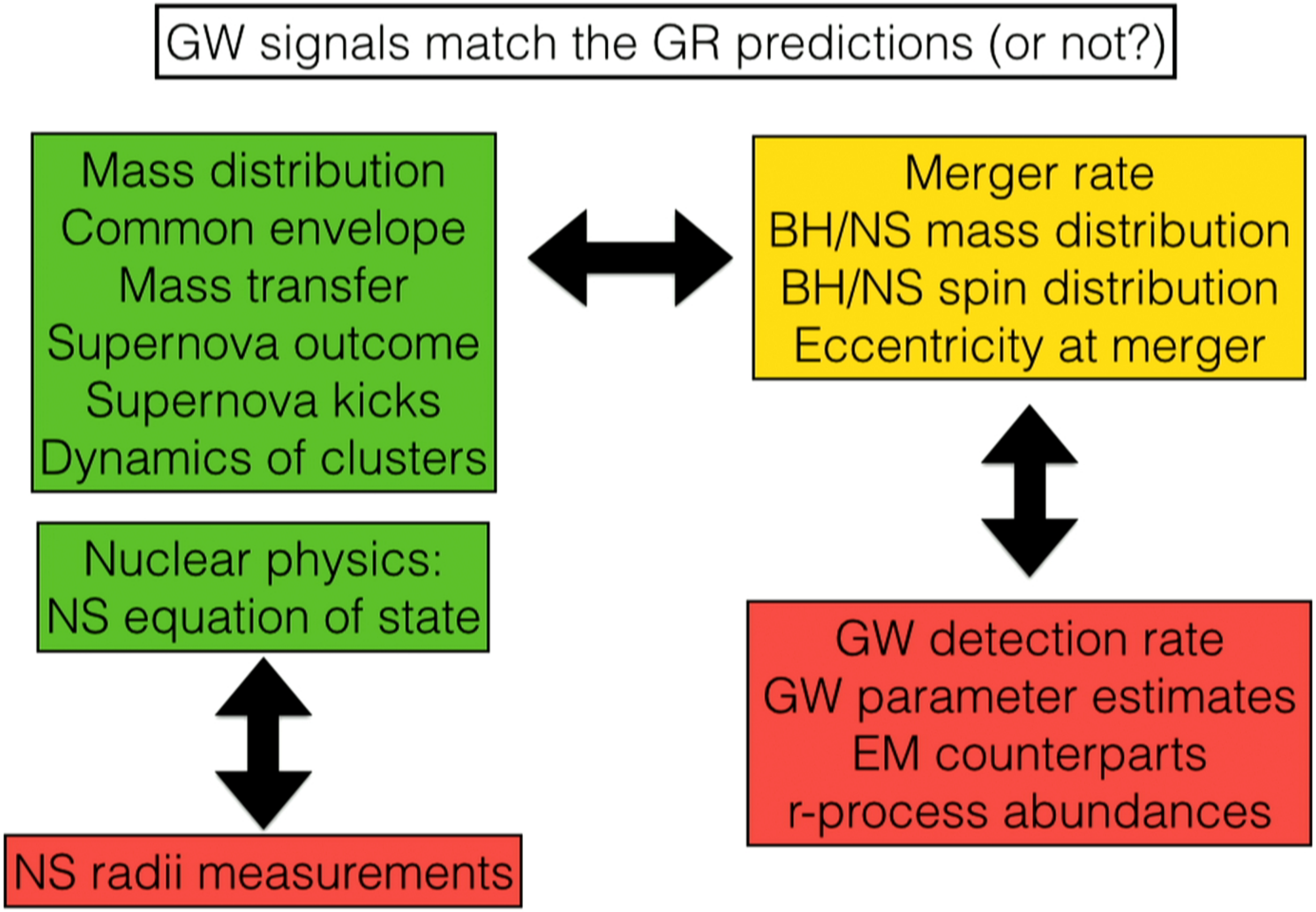


Image: Tanvir et al. 2013

What can we learn from GW detections?



GW signals match the GR predictions (or not?)

Mass distribution
Common envelope
Mass transfer
Supernova outcome
Supernova kicks
Dynamics of clusters

Merger rate
BH/NS mass distribution
BH/NS spin distribution
Eccentricity at merger

Nuclear physics:
NS equation of state

GW detection rate
GW parameter estimates
EM counterparts
r-process abundances

NS radii measurements

Nuclear physics and the neutron star equation of state

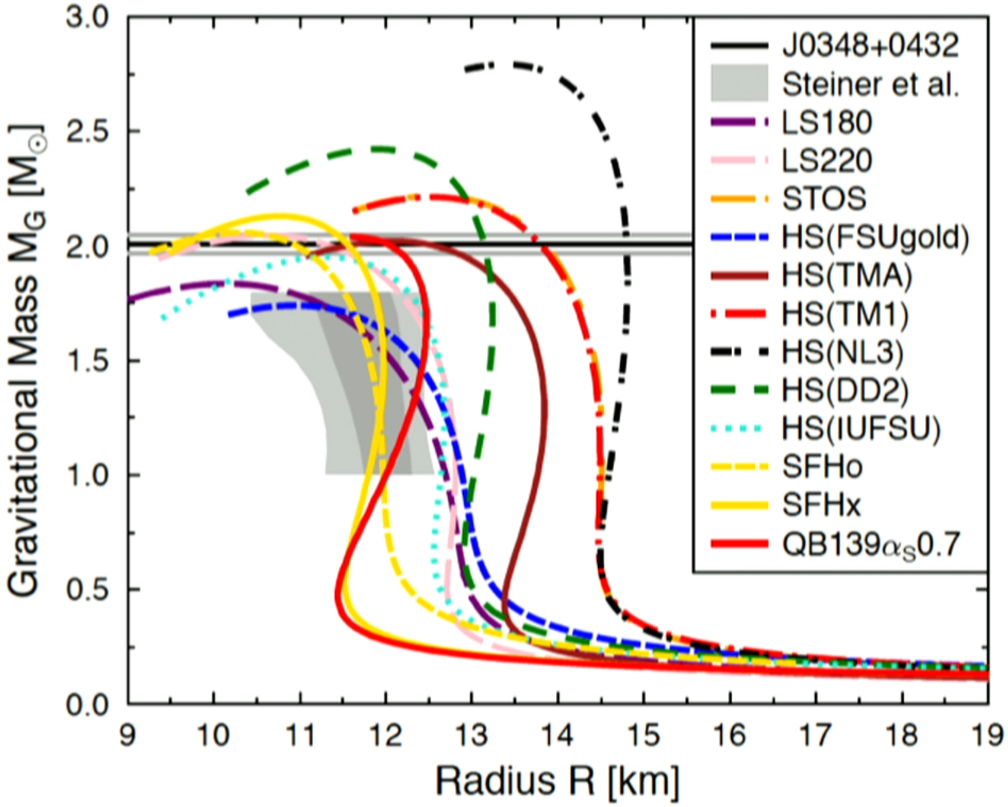


Image: Fischer et al 2014

Astrophysics:
NS radii
NS max. mass

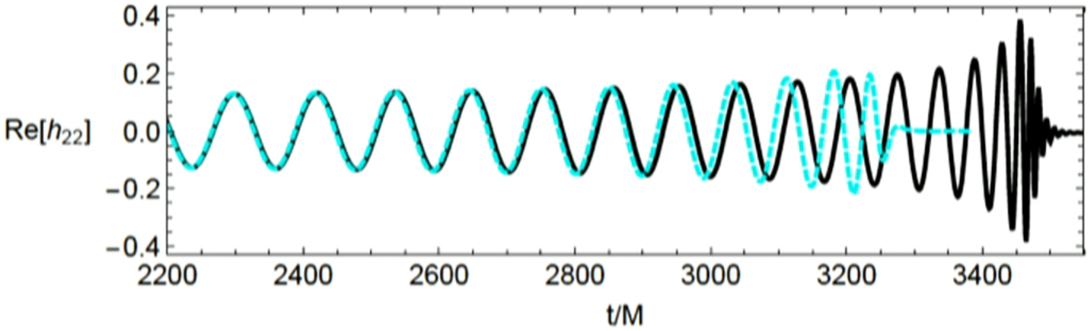
Experimental nuclear physics:
Low-density /
High Energy
constraints

Theoretical nuclear physics:
EoS models

GWs : Independent mass and radius measurements?

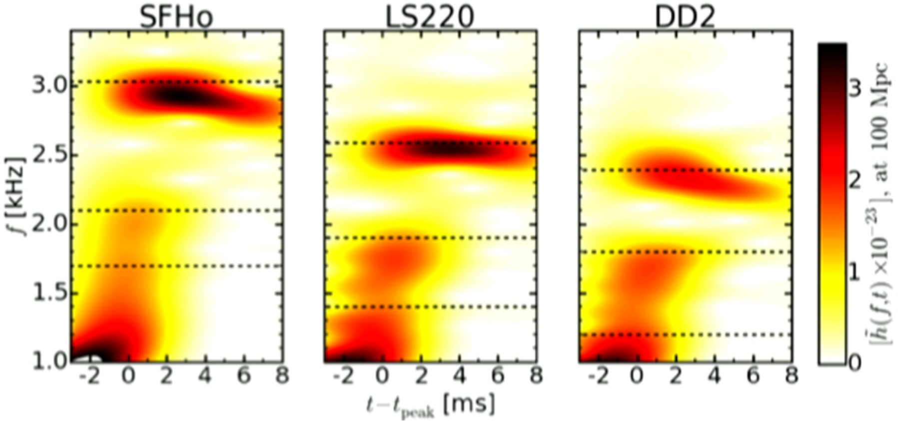
Finite size effects on GWs

Pre-merger signal: Faster inspiral for larger NSs



Small effect for asymmetric systems (e.g. realistic BH-NS)

Merger and Post-merger signal :



BH-NS : NS disruption

NS-NS : Merger, excited NS remnant, collapse to BH

Image: Foucart et al., subm.

R-process nucleosynthesis:
Neutron Star Mergers or Supernovae?

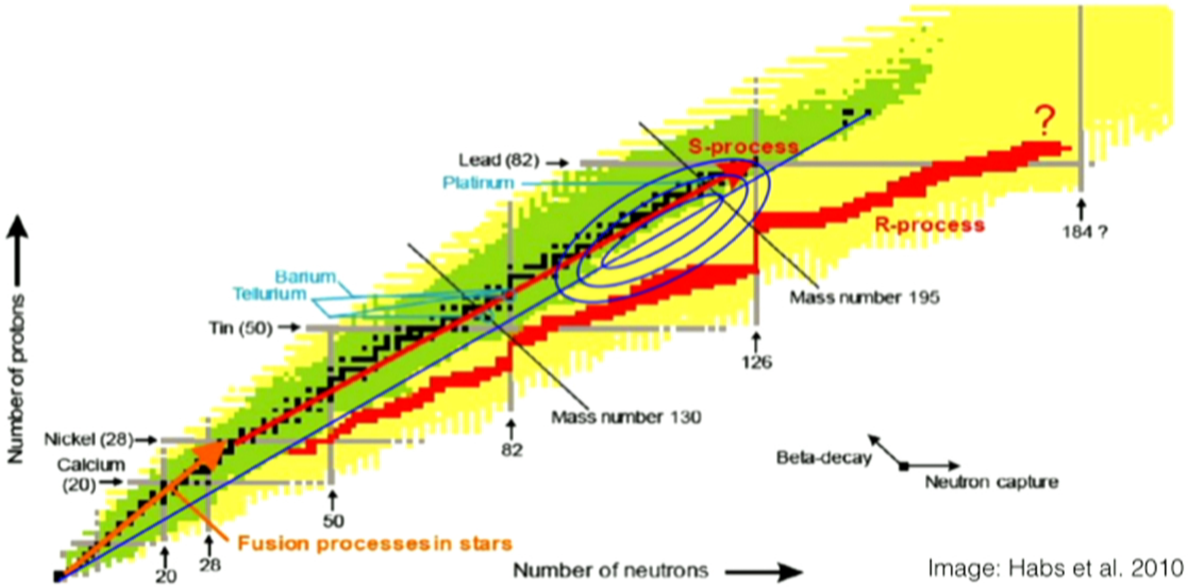
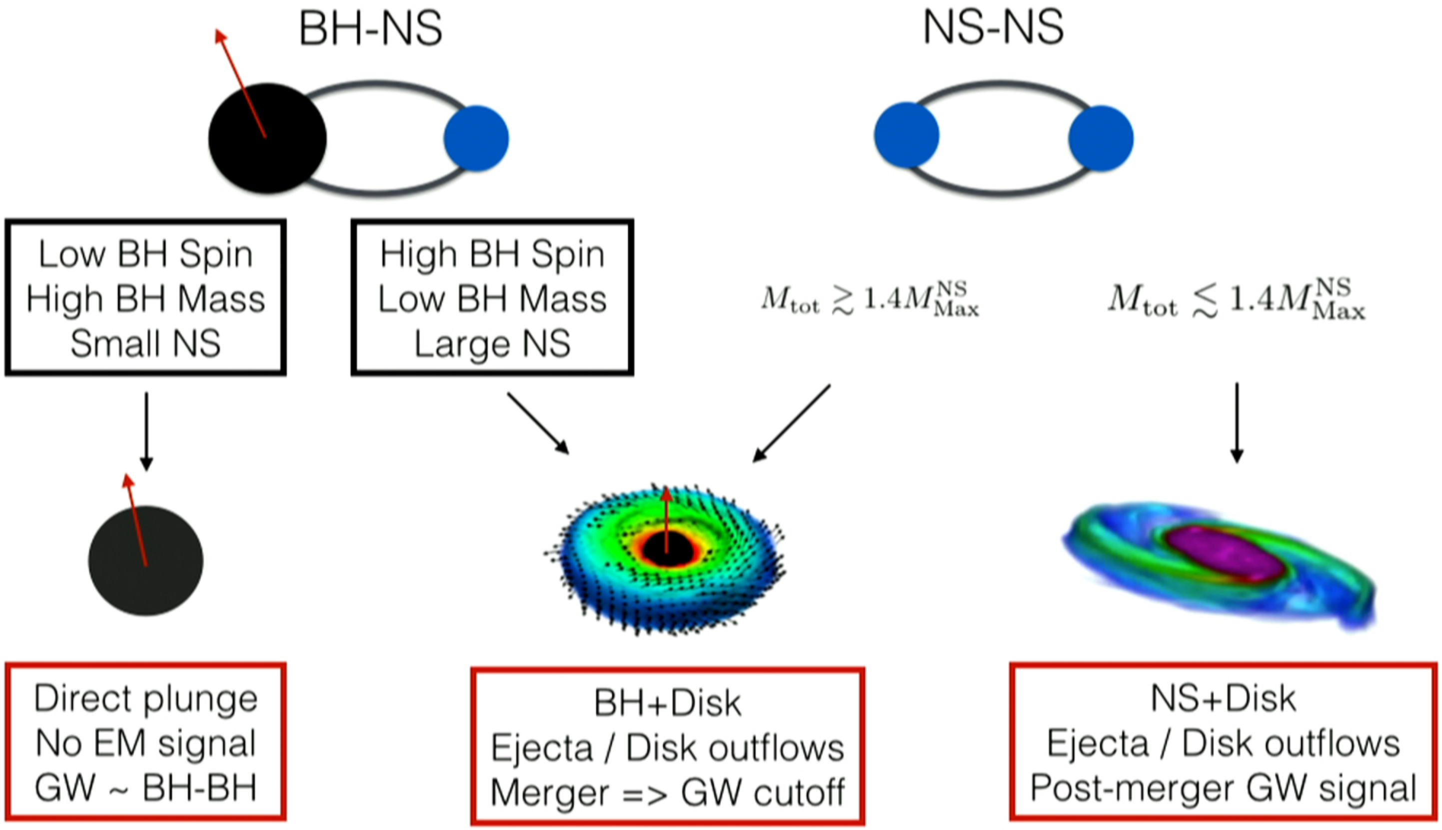


Image: Habs et al. 2010

- Where are r-process elements produced?
- Robust r-process occurs in NS mergers. What about supernovae?
- How much r-process do NS mergers produce?
- Need to explain total abundances, abundance variations in low metallicity stars, deep sea measurements of Pu244

Neutron Star Mergers



BH-NS

NS-NS

Low BH Spin
High BH Mass
Small NS

High BH Spin
Low BH Mass
Large NS

$M_{\mathrm{tot}} \gtrsim 1.4 M^{\mathrm{NS}}_{\mathrm{Max}}$

$M_{\mathrm{tot}} \lesssim 1.4 M^{\mathrm{NS}}_{\mathrm{Max}}$

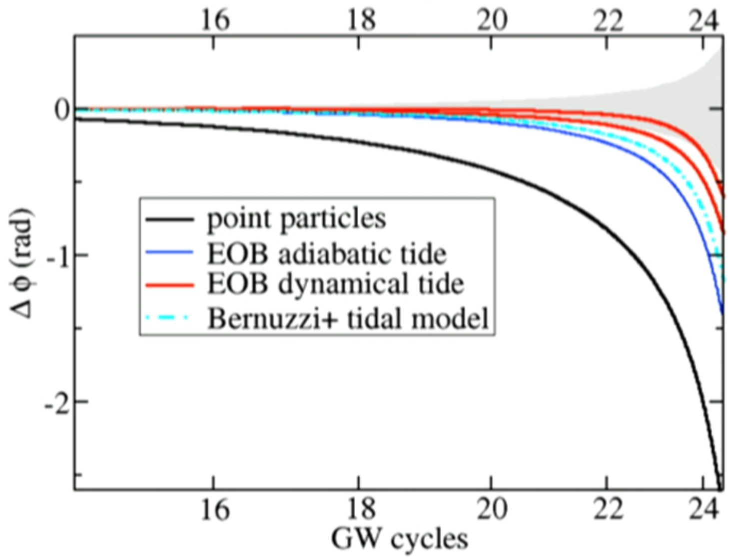
Direct plunge
No EM signal
GW ~ BH-BH

BH+Disk
Ejecta / Disk outflows
Merger => GW cutoff

NS+Disk
Ejecta / Disk outflows
Post-merger GW signal

Gravitational wave modeling : Inspiral

Image credit: T. Hinderer



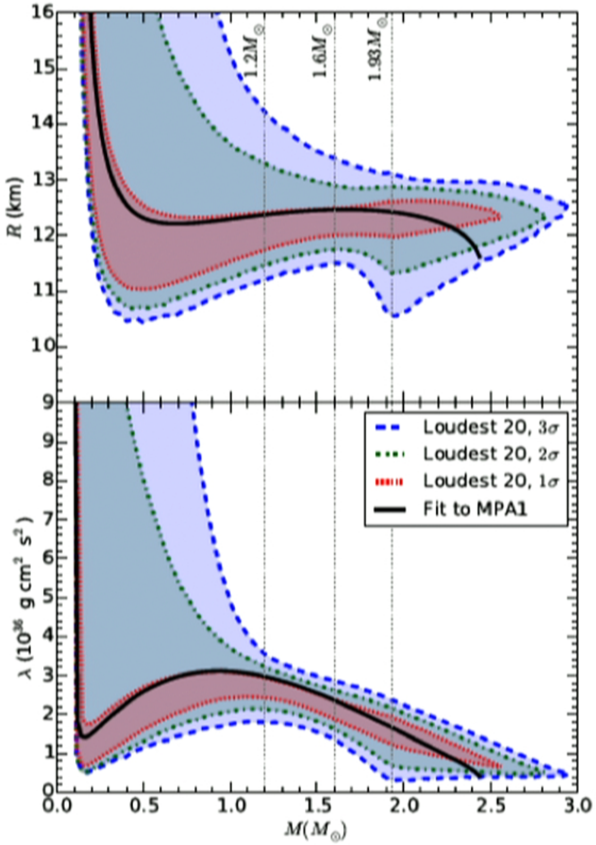


Image: Lackey & Wade 2015

Could measure radii to ~1km

Need very accurate templates

Construction of model work in progress

Numerical simulations still need to improve!

Gravitational waves : Merger and Post-Merger

BH-NS : Disruption at
EoS-dependent frequency
NS-NS : Clear peaks
in post-merger spectrum

Very difficult to detect
with aLIGO!

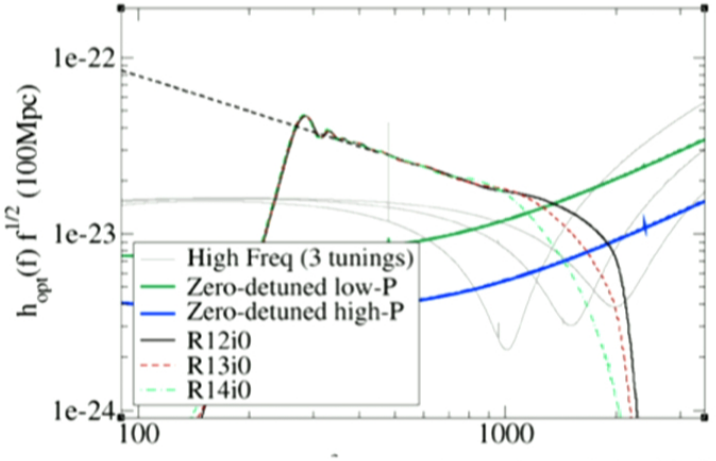


Image: Foucart et al. 2013

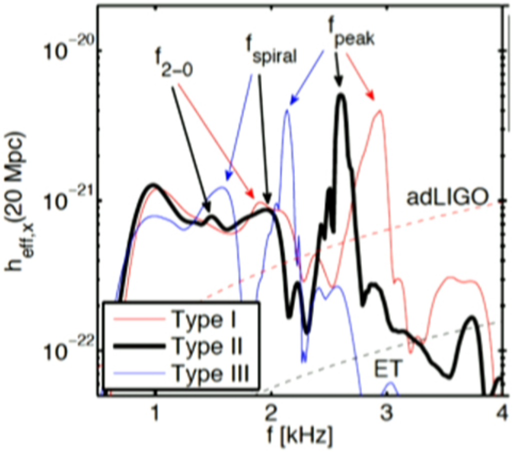


Image: Bauswein & Stergioulas 2015

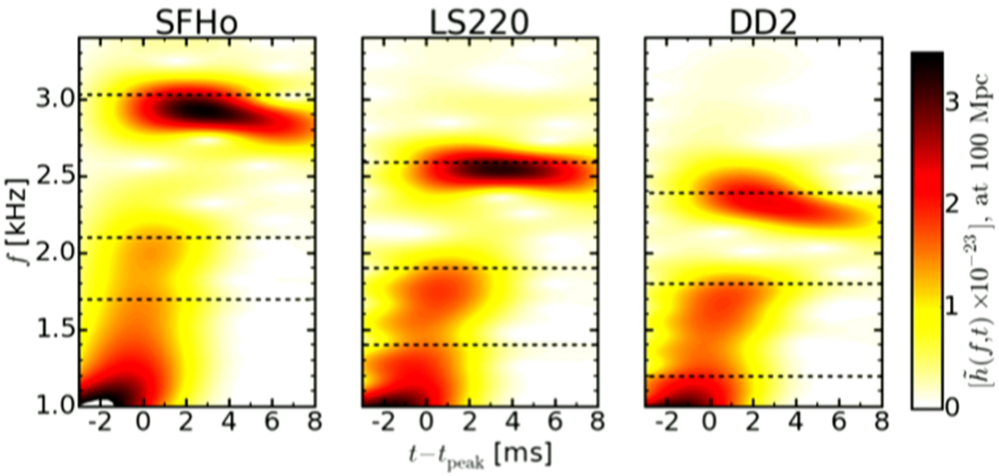


Image: Foucart et al., subm.

Outflows : r-process nucleosynthesis

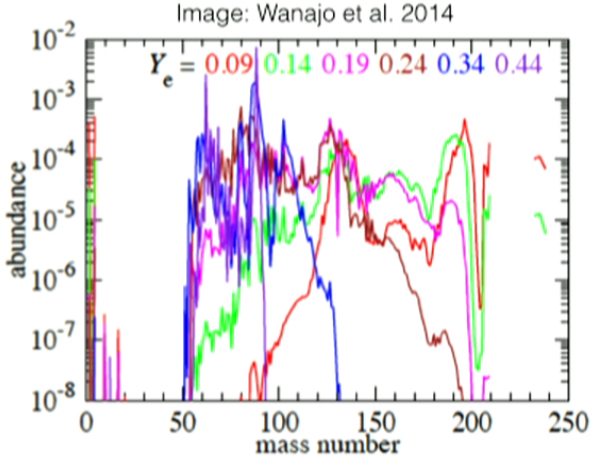


Image: Wanajo et al. 2014

Nucleosynthesis outcome determined by:
Outflow electron fraction
Outflow entropy
Outflow velocity

Neutron rich ejecta → Strong r-process
Produce 2nd/3rd peak
Outcome robust to IC

Ye > 0.2-0.3 → Weak r-process
Produce lighter nuclei

Outflows : radioactively powered transients

Strong r-process creates high-opacity lanthanides

↓

EM signal significantly affected by nucleosynthesis output

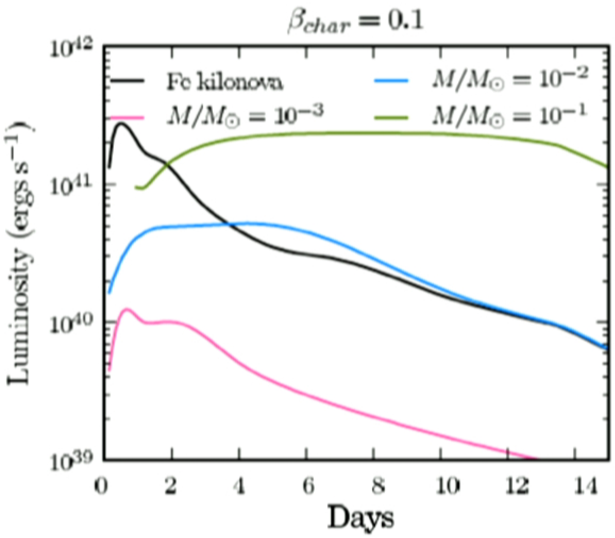
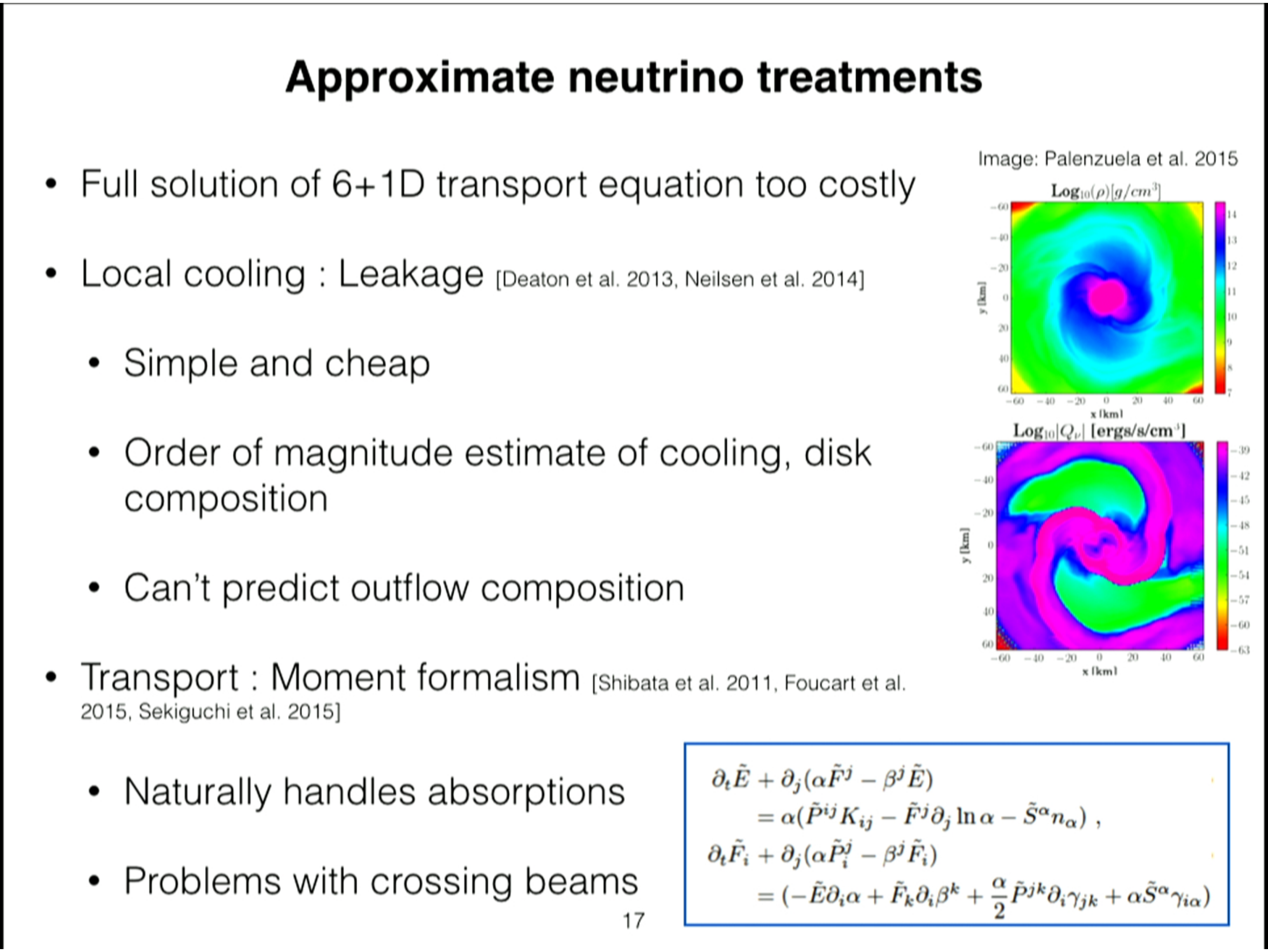


Image: Barnes & Kasen 2013

Weak r-process:
Day-long transient
Optical wavelength

Strong r-process:
Week-long transient
Infrared wavelength



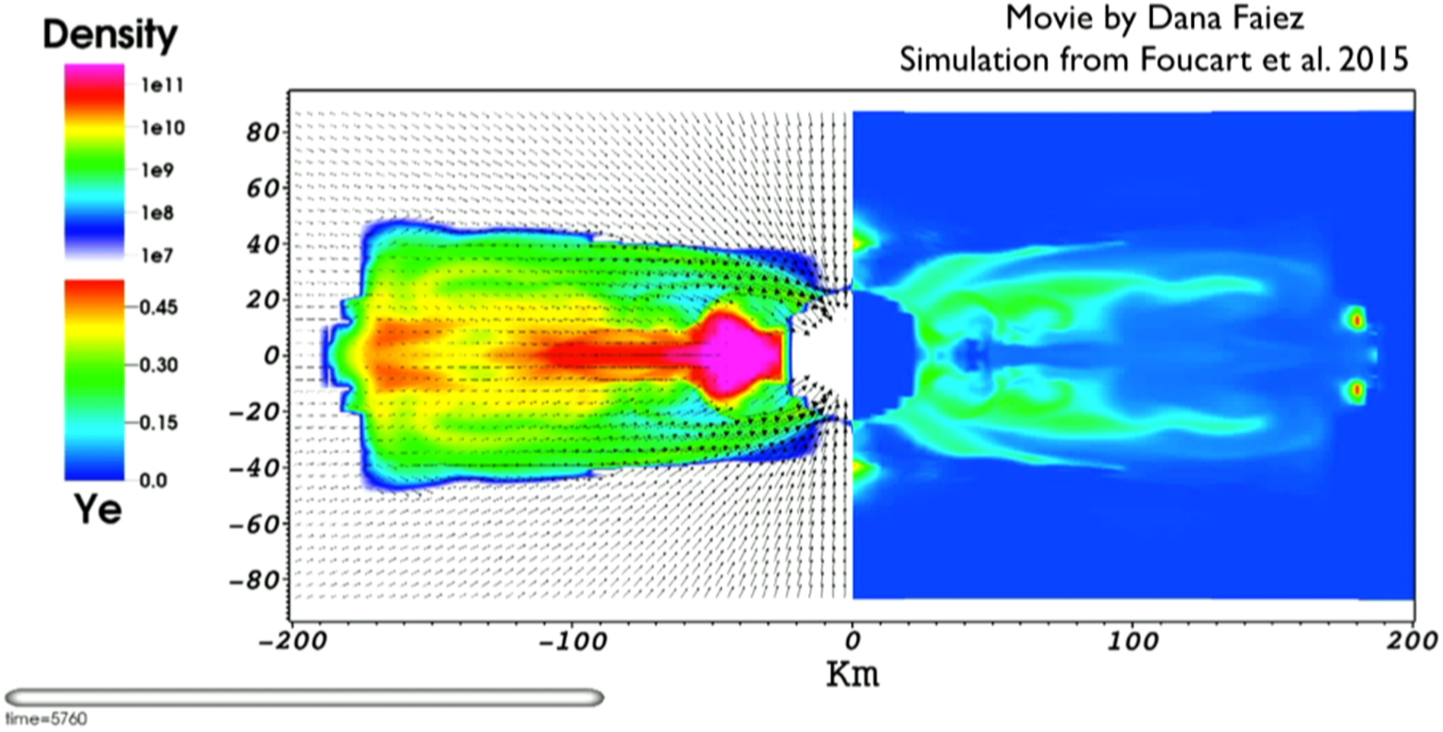
Approximate neutrino treatments

- Full solution of 6+1D transport equation too costly
- Local cooling : Leakage [Deaton et al. 2013, Neilsen et al. 2014]
  - Simple and cheap
  - Order of magnitude estimate of cooling, disk composition
  - Can't predict outflow composition
- Transport : Moment formalism [Shibata et al. 2011, Foucart et al. 2015, Sekiguchi et al. 2015]
  - Naturally handles absorptions
  - Problems with crossing beams

Image: Palenzuela et al. 2015

$$\begin{aligned}
&\partial_t \tilde{E} + \partial_j(\alpha \tilde{F}^j - \beta^j \tilde{E}) \\
&\qquad = \alpha(\tilde{P}^{ij} K_{ij} - \tilde{F}^j \partial_j \ln \alpha - \tilde{S}^\alpha n_\alpha) \ , \\
&\partial_t \tilde{F}_i + \partial_j(\alpha \tilde{P}_i^j - \beta^j \tilde{F}_i) \\
&\qquad = (-\tilde{E}\partial_i \alpha + \tilde{F}_k \partial_i \beta^k + \frac{\alpha}{2} \tilde{P}^{jk} \partial_i \gamma_{jk} + \alpha \tilde{S}^\alpha \gamma_{i\alpha})
\end{aligned}$$

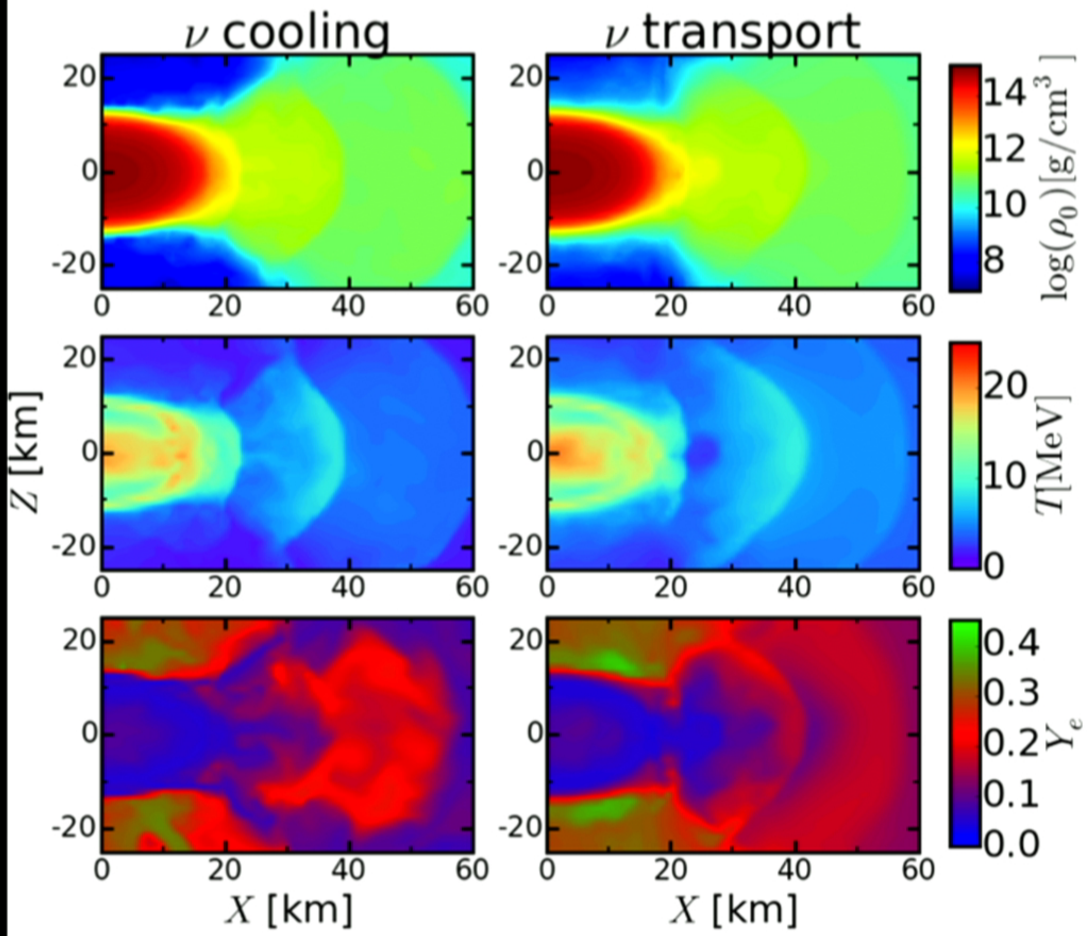
Neutrino transport



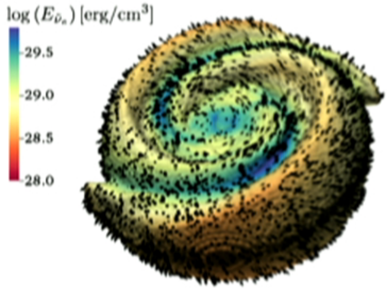
Movie by Dana Faiez
Simulation from Foucart et al. 2015

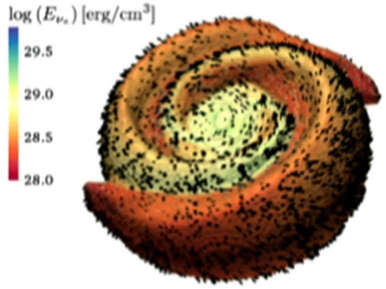
Rapid variations in electron fraction after merger
Noticeable impact of choice of neutrino treatment!

Neutrino transport



Images: Foucart et al., subm.





Outflows

BH-NS (dyn.)	NS-NS (dyn.)	Disk outflows
Tidal disruption	Tides + Shocks	Wind (neutrinos, B-fields) Viscosity/Recombination
$M \sim 10^{-2}$-10^{-1} M_{sun}	$M \sim 10^{-4}$-10^{-2} M_{sun}	$M \sim 10^{-2}$ M_{sun}
Cold, $Y_e<0.1$	Large range of T, Y_e	Large range of T, Y_e
Equatorial, Asymmetric	Isotropic	Isotropic
$v > 0.2c$	$\langle v \rangle \sim 0.2c$ - $0.3c$	$\langle v \rangle \sim 0.1c$-$0.2c$

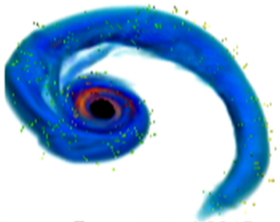


Image: Foucart et al 2015

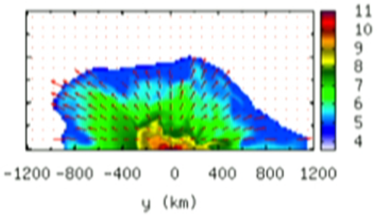


Image: Hotokezaka et al 2013

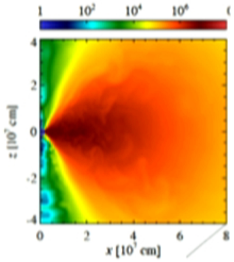
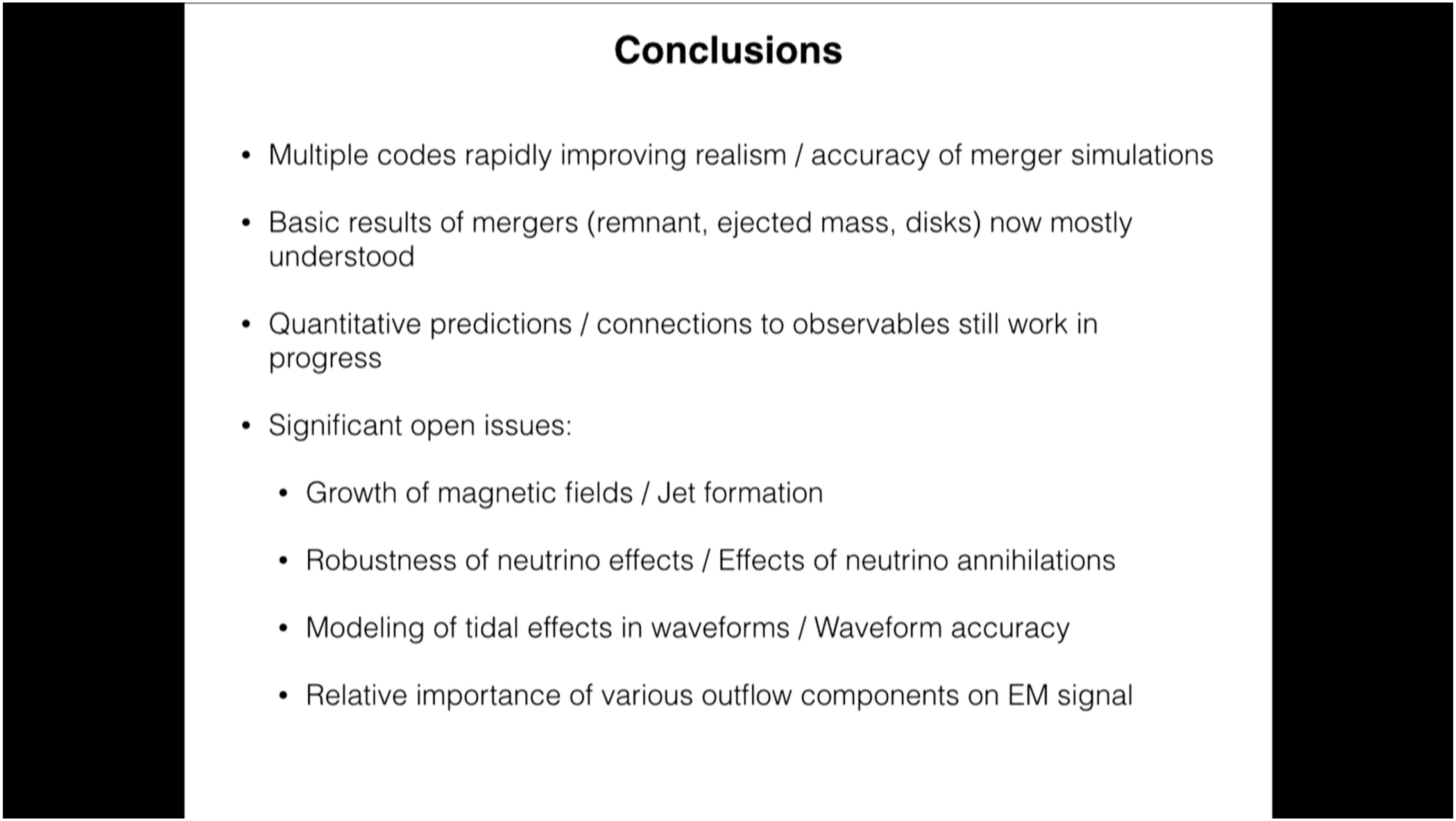


Image: Fernandez & Metzger 2013



Conclusions

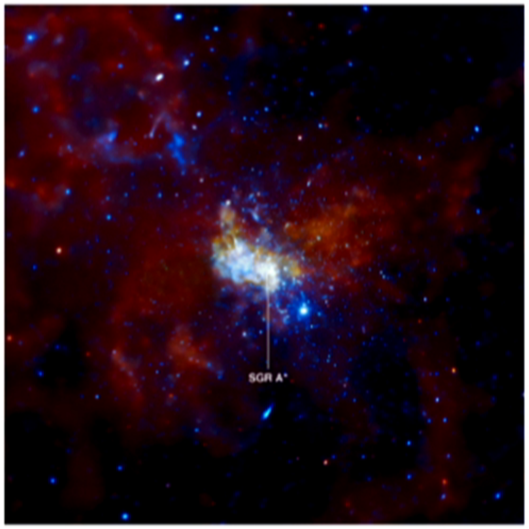
- Multiple codes rapidly improving realism / accuracy of merger simulations
- Basic results of mergers (remnant, ejected mass, disks) now mostly understood
- Quantitative predictions / connections to observables still work in progress
- Significant open issues:
    - Growth of magnetic fields / Jet formation
    - Robustness of neutrino effects / Effects of neutrino annihilations
    - Modeling of tidal effects in waveforms / Waveform accuracy
    - Relative importance of various outflow components on EM signal

Part II : Accretion disks around supermassive black holes

Slowly accreting disks around Supermassive BHs

- Most disks around SMBH accrete well below the Eddington rate. Disk plasma is then *collisionless.*
- Easiest BHs to resolve are slowly accreting, e.g. Event Horizon Telescope targets

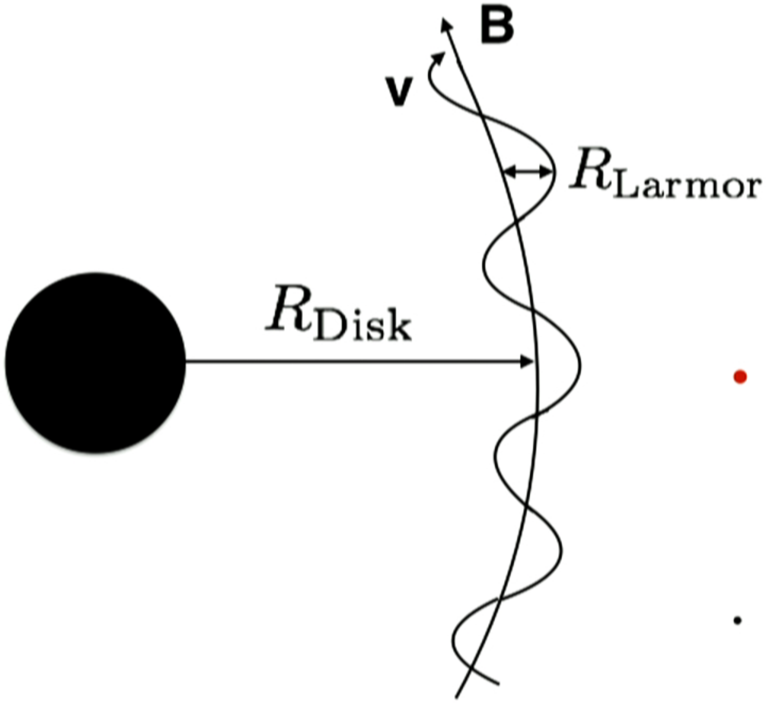
Images: NASA/CXC



SgrA* $M \sim 4 \times 10^6 M_\odot$ $\dot{M} \sim 10^{-8} \dot{M}_{\rm Edd}$

M87 $M \sim (3-7) \times 10^9 M_\odot$ $\dot{M} \sim 10^{-4} - 10^{-5} \dot{M}_{\rm Edd}$

Weakly collisional accretion disks



- For slowly accreting black holes:

$$R_{\mathrm{Larmor}} \ll R_{\mathrm{Disk}} \ll \lambda_{\mathrm{mfp}}$$

- Efficient transport of energy/ momentum along magnetic field lines!

- **Not an ideal fluid!!**

Anisotropic distribution function of charged particles: $f(x^\mu, p^\mu) \rightarrow f(x, t, p_\perp, p_\parallel)$

Effective collision rate (wave-particle interactions): $\lambda_{\mathrm{eff}} \sim R_{\mathrm{disk}}$

Modeling weakly collisional plasmas

see M. Chandra et al, ApJ 810,162

(1) Modified stress-energy tensor $T^{\mu\nu} = T^{\mu\nu}_{\text{ideal}} + q^\mu u^\nu + q^\nu u^\mu + \Pi^{\mu\nu}$

(2) Evolved heat flux along B $q^\mu = q\hat{b}^\mu$

(3) Evolved pressure anisotropy $\Pi^{\mu\nu} = -\Delta P\left(\hat{b}^\mu\hat{b}^\nu - \frac{1}{3}h^{\mu\nu}\right)$

$$P_\parallel = P - \tfrac{2}{3}\Delta P \quad P_\perp = P + \tfrac{1}{3}\Delta P$$

(4) Equations for non-ideal pieces (causality, 2nd law)

$$\nabla_\mu(\tilde{q}u^\mu) = -\frac{\tilde{q}-\tilde{q}_0}{\tau_R} + \frac{\tilde{q}}{2}\nabla_\mu u^\mu, \qquad \tilde{q} = q\left(\frac{\tau_R}{\chi\rho\Theta^2}\right)^{1/2}$$

$$\nabla_\mu(\Delta\tilde{P}u^\mu) = -\frac{\Delta\tilde{P}-\Delta\tilde{P}_0}{\tau_R} + \frac{\Delta\tilde{P}}{2}\nabla_\mu u^\mu \qquad \Delta\tilde{P} = \Delta P\left(\frac{\tau_R}{\nu\rho\Theta}\right)^{1/2}$$

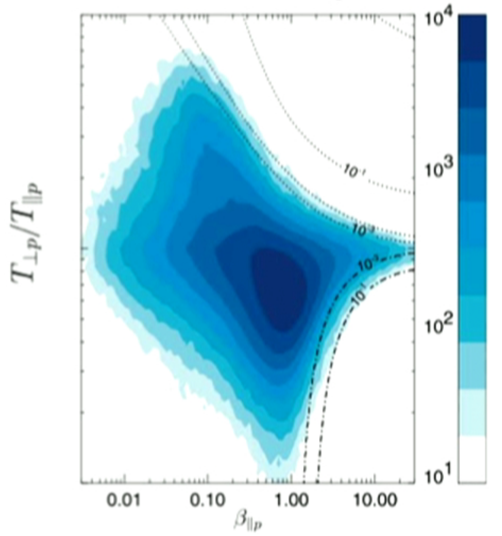
(5) Equilibrium values (2nd law, Braginskii)

$$q_0 = -\rho\chi\hat{b}^\mu(\nabla_\mu\Theta + \Theta u^\nu\nabla_\nu u_\mu) \qquad \Delta P_0 = 3\rho\nu(\hat{b}^\mu\hat{b}^\nu\nabla_\mu u_\nu - \frac{1}{3}\nabla_\mu u^\mu)$$

Closure relations

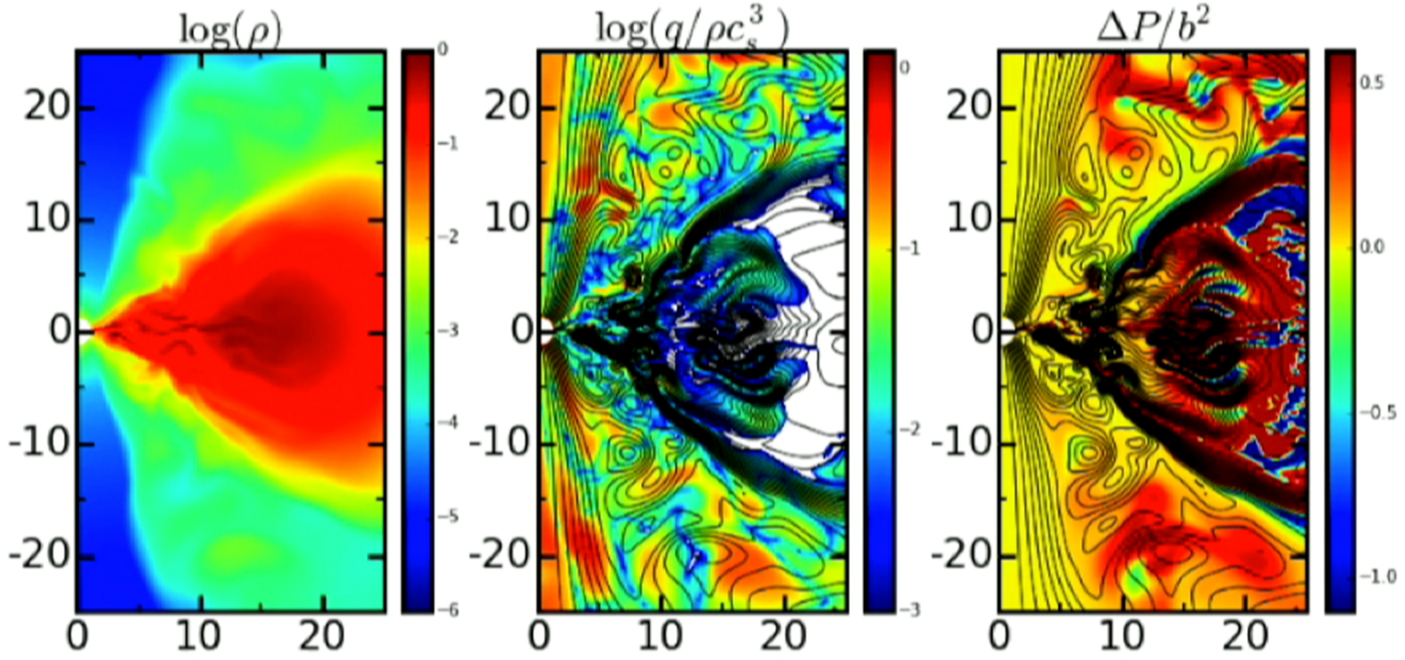
- Model has 3 free parameters.
    - Damping timescale ~ collision timescale τ_R
    - Kinematic viscosity (kinetic theory) : $\nu = \psi c_s^2 \tau_R$
    - Conductive diffusivity (kinetic theory) : $\chi = \phi c_s^2 \tau_R$
- What is the collision timescale?
    - Estimate: ~ orbital timescale
    - BUT: ion pressure anisotropy may saturate due to velocity-space instabilities (mirror, firehose, ion cyclotron), for $|\Delta P| \sim b^2$
    - At saturation, effective collision rate increases / non-ideal effects saturate

Solar Wind Hellinger et al 2006



Disk evolution - 2D simulations

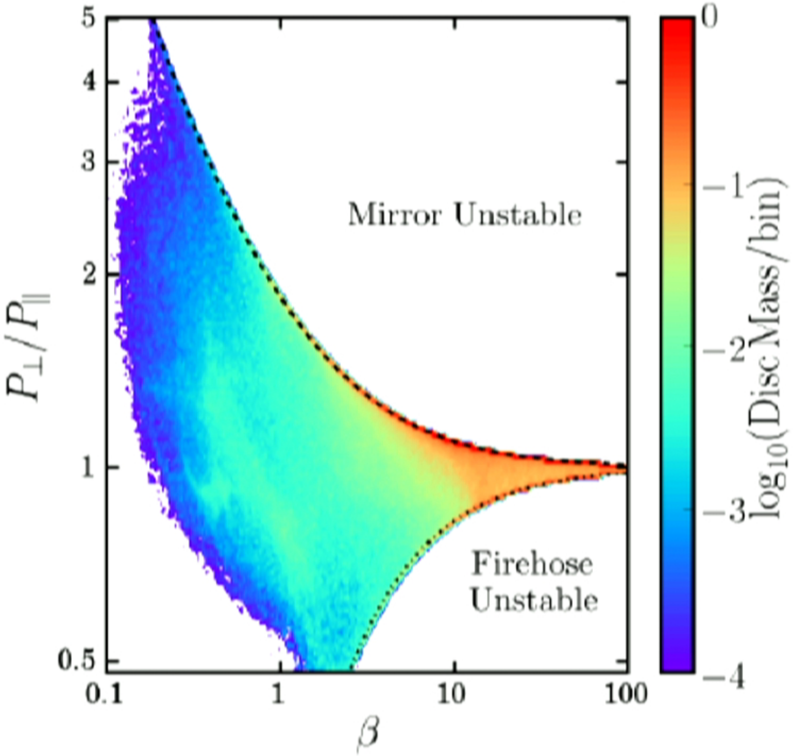
Foucart et al, MNRAS (accepted)



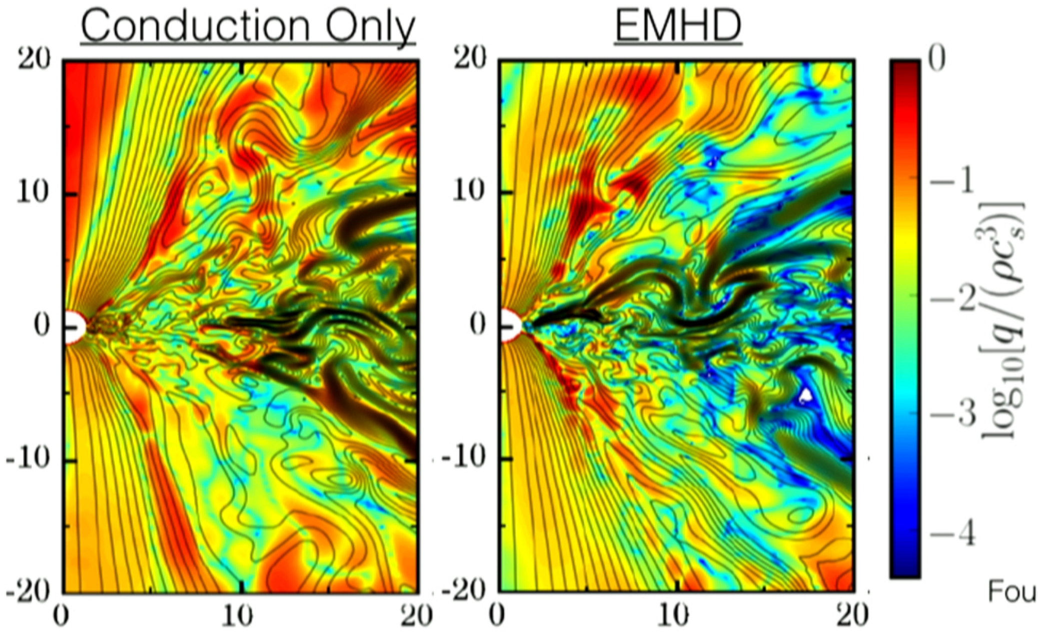
Pressure anisotropy

- ~50% of the mass at mirror saturation
- Agrees with theoretical expectation for Keplerian shear flow, outflows
- Shows importance of saturation limit
- In corona: what about the ion cyclotron instability?
- **Causes O(1) changes in inflow/outflows/coronal temperatures!!**

Foucart et al, MNRAS (accepted)



Heat Flux


Conduction Only

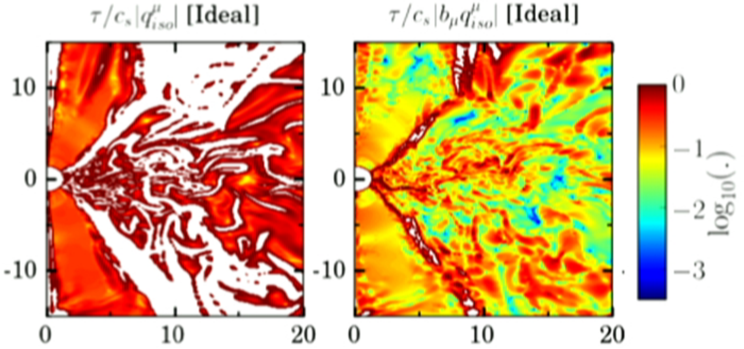
EMHD

Heat flux
<< Saturation

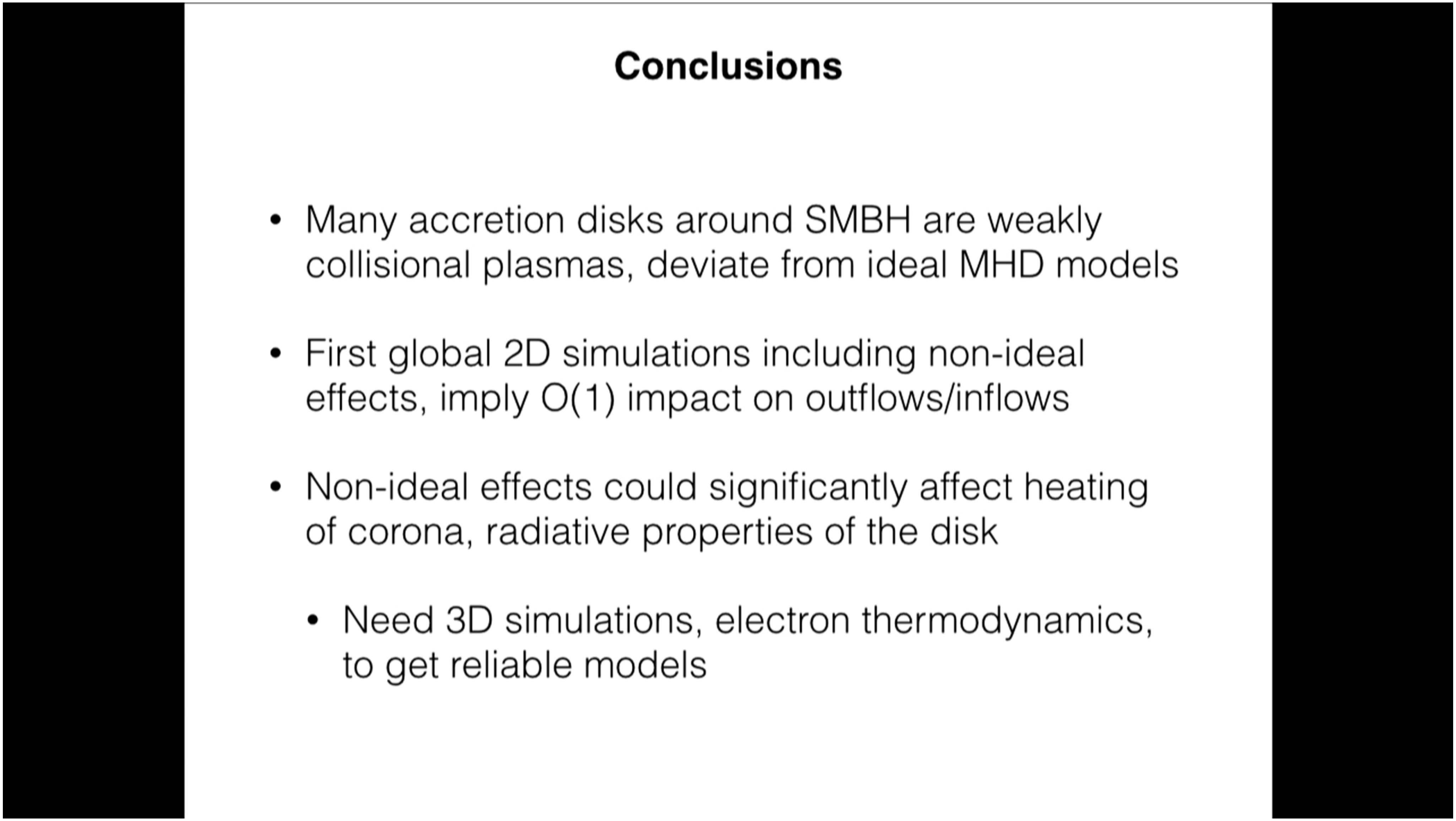
Foucart et al, MNRAS (accepted)

(1) Temperature gradients are not along **B**

(2) Mirror instability increases collisionality, decreases q


$\tau/c_s|q^\mu_{iso}|$ **[Ideal]**

$\tau/c_s|b_\mu q^\mu_{iso}|$ **[Ideal]**



Conclusions

- Many accretion disks around SMBH are weakly collisional plasmas, deviate from ideal MHD models
- First global 2D simulations including non-ideal effects, imply O(1) impact on outflows/inflows
- Non-ideal effects could significantly affect heating of corona, radiative properties of the disk
    - Need 3D simulations, electron thermodynamics, to get reliable models