Title: Detectable signatures of compact binaries involving neutron stars

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Abstract: <div>In this talk I will focus on two topics concerning compact binaries that involve a neutron star companion: a) the fate of and observable signatures from merging white dwarf-neutron star (WDNS) binaries, and b) electromagnetic signals from black hole - neutron star (BHNS) binaries.</div><div>WDNS systems - the neglected child among compact binaries - generate detectable gravitational waves (GWs) and may also generate observable electromagnetic (EM) signals. One of the most fascinating aspects about these systems is that they are known to exist, but the final fate of massive, merged WDNSs remnants is currently work in progress. Determining the fate of WDNS remnants will be important for interpreting observations from future transient surveys. I will review recent work that provides insight into the physics of WDNSs remnants. </div><div>Black hole - neutron star systems are among the most promising sources for gravitational waves, and at the same time also possible sources of detectable precursor and aftermath EM signals. I will present recent the results from general relativistic force-free simulations of binary BHNSs and a type of EM precursor signatures expected from these systems.</div>

Detectable signatures of compact binaries involving neutron stars

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Seminar, Perimeter Institute
for Theoretical Physics, May 16, 2013

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Brian Farris, Roman Gold,
Yuk Tung Liu, Stuart Shapiro

Outline

1st Part: White dwarf – neutron star (WDNS) binaries

- Why are they interesting?

- Late evolution of a WDNS binary
  - Stable mass transfer (SMT) regime: "out-spiral"
  - Unstable mass transfer (UMT) regime => merger
  - Disk models (Nuclear dominated accretion flows)

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<u>1st Part: White dwarf – neutron star (WDNS) binaries</u>

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  - Unstable mass transfer (UMT) regime => merger
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Why are WDNS binaries interesting?

- Like NSNS binaries, WDNS exist!

VP et al. (2009)

TABLE I: WDNS binaries with well-determined masses. From left to right the columns give the name of the object, the orbital period, the corresponding quadrupole GW frequency, the WD mass, the NS mass, the total mass, the mass ratio $q = M_{\rm WD}/M_{\rm NS}$ and the stability of mass transfer after its onset.

PSR	T (days)	$f_{\rm GW} = \frac{2}{T}$ (10^{-4}Hz)	$M_{\rm WD}(M_\odot)$	$M_{\rm NS}(M_\odot)$	$M_{\rm T}(M_\odot)$	q	Stable?
B2303+46[a]	12.34	0.0187	1.3	1.34	2.64	0.97	No
J0621+1002[b]	8.32	0.0278	0.67	1.70	2.37	0.394	?
J1141−6545[c,d]	0.198	1.169	1.02	1.27	2.29	0.803	No
B1516+02B[e]	6.858	0.0337	0.13	2.08	2.21	0.0625	Yes
J1713+0747[a]	67.8	0.0034	0.33	1.60	1.93	0.206	?
B1855+09[a]	12.3	0.0188	0.267	1.58	1.847	0.169	Yes
J0437−4715[a]	5.74	0.0403	0.236	1.58	1.816	0.149	Yes
J1012+5307[a]	0.605	0.382	0.16	1.64	1.80	0.097	Yes
J0751+1807[a]	0.263	0.88	0.125	1.26	1.385	0.099	Yes
J1757−5322[b]	0.453	0.511	0.55	1.35	1.90	0.407	?

- There exist 2×10^6 WDNS in our Galaxy (Nelemans et al. 2000) and they have a merger rate of $\sim10^{-5}$/yr (Nelemans et al. 2000, Cooray 2004)
- LISA-like detectors should be able to detect between 1-10 pre-mergers per year (Nelemans et al. 2000, Cooray 2004)

Why are WDNS binaries interesting?

- They are promising sources of gravitational waves detectable by LISA-like detectors and possibly also LIGO.

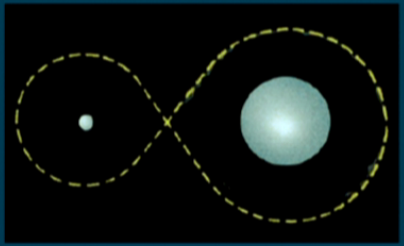
$$h = \frac{4M_{\rm NS}M_{\rm WD}}{rA} \simeq 1\times 10^{-21}\left(\frac{M_{\rm NS}}{1.5M_\odot}\right)\left(\frac{M_{\rm WD}}{0.5M_\odot}\right)\left(\frac{30000{\rm Km}}{A}\right)\left(\frac{8{\rm Kpc}}{r}\right)$$

$$f_{\rm GW} = \frac{\Omega_{Kepler}}{\pi} = \frac{1}{\pi}\sqrt{\frac{M_{\rm NS}+M_{\rm WD}}{A^3}} \simeq 3\times 10^{-2}\left(\frac{M_{\rm T}}{2M_\odot}\right)^{1/2}\left(\frac{30000{\rm Km}}{A}\right)^{3/2} Hz$$

- eLISA 's predicted strain sensitivity at $\mathbf{10^{-2}}$ Hz is h ~ $\mathbf{10^{-23}}$

- WDNS merger may lead to catastrophic phenomena:
  - WD tidal disruption
  - NS collapse to BH
  - Nuclear burning and detonations → Observable EM singatures

Late evolution of a WDNS binary



Gravitational waves => inspiral

↓ A

WD Roche-lobe (R_r) shrinks

$$R_{\rm r} = A f(q), \quad f(q) \simeq 0.44 q^{1/3}$$
$$q = M_{\rm WD}/M_{\rm NS}$$

Late evolution of a WDNS binary

Gravitational waves => inspiral

$\Downarrow$ A $\downarrow$

$R_\mathrm{r} = Af(q), \quad f(q) \simeq 0.44 q^{1/3}$

$q = M_\mathrm{WD}/M_\mathrm{NS}$

WD Roche-lobe (R_r) shrinks

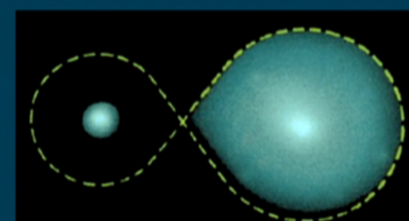
$\Downarrow$

Critical A_r: The WD fills R_r

$$J = \left(\frac{G M_\mathrm{WD}^2 M_\mathrm{NS}^2 A}{M_\mathrm{WD} + M_\mathrm{NS}} \right)^{1/2} \Rightarrow$$

$$A \sim M_\mathrm{WD}^{-2} M_\mathrm{NS}^{-2} \Rightarrow (\dot{M}_\mathrm{NS} = -\dot{M}_\mathrm{WD})$$

$$\frac{\dot{A}}{A} = \frac{2\dot{M}_\mathrm{WD}(M_\mathrm{WD} - M_\mathrm{NS})}{M_\mathrm{NS} M_\mathrm{WD}}$$



$M_\mathrm{WD} \downarrow \;=>\; R_\mathrm{WD} \uparrow$

Late evolution of a WDNS binary

Gravitational waves => inspiral

⇓ A ↓

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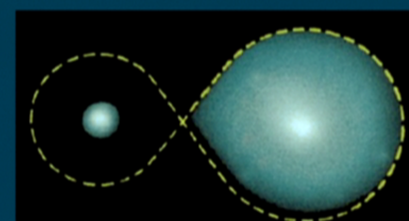
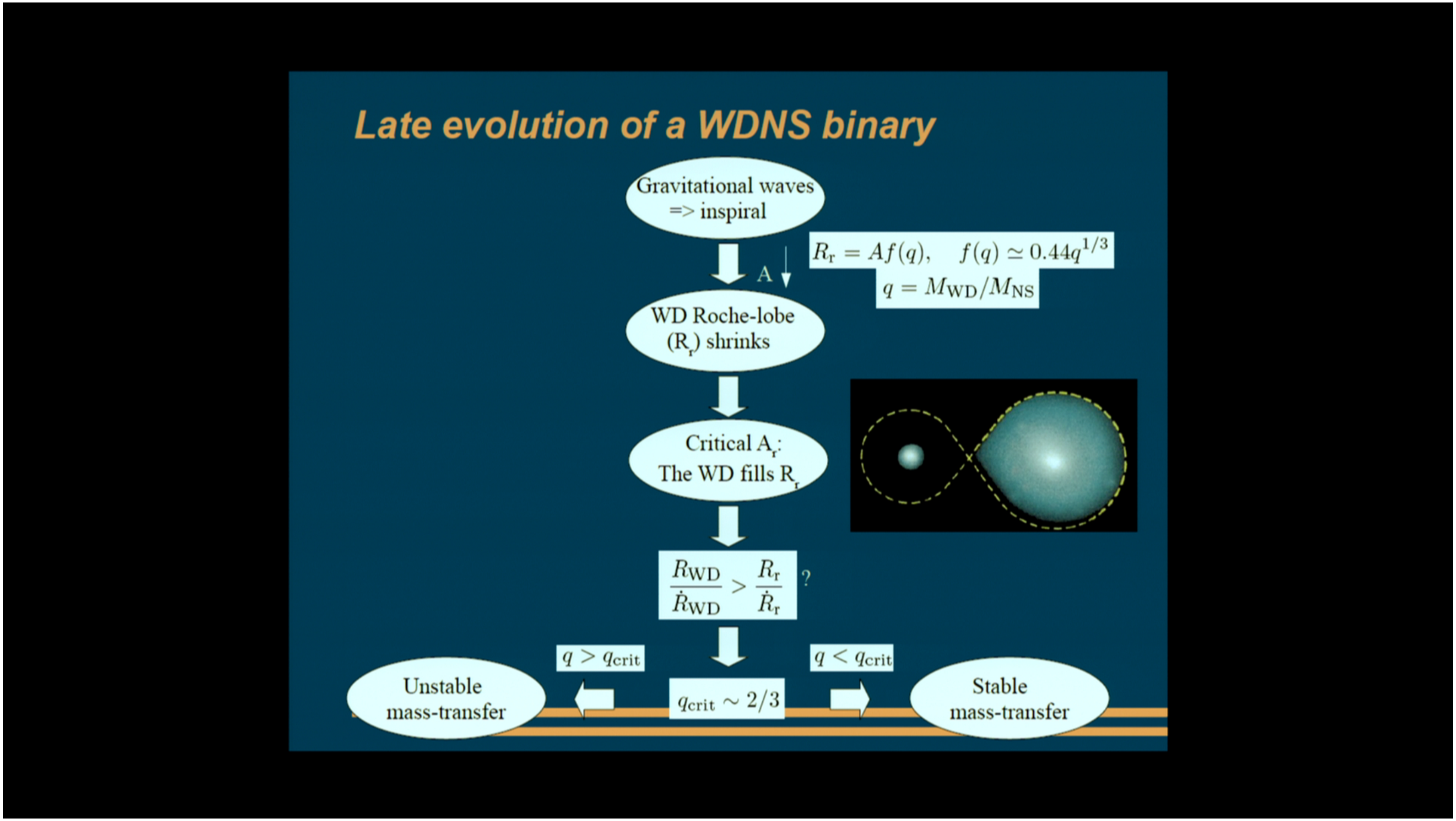


M_{WD} ↓ => R_{WD} ↑


Late evolution of a WDNS binary
Gravitational waves => inspiral
A
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$q = M_{WD}/M_{NS}$
WD Roche-lobe (R_r) shrinks
Critical A_r: The WD fills R_r
$\frac{R_{WD}}{\dot{R}_{WD}} > \frac{R_r}{\dot{R}_r}$?
$q > q_{crit}$
$q < q_{crit}$
Unstable mass-transfer
$q_{crit} \sim 2/3$
Stable mass-transfer

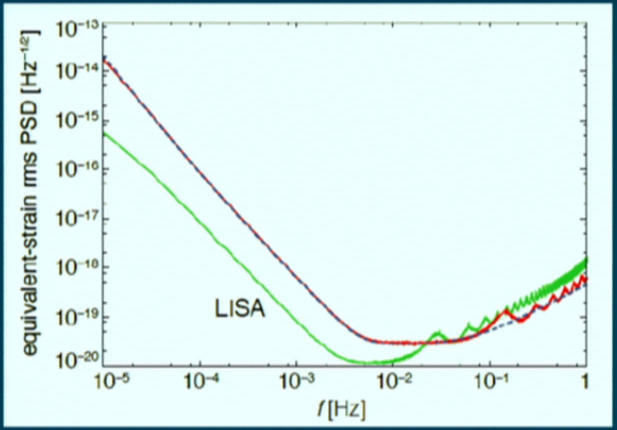
GW frequency at the Roche separation

- The GW frequencies at the onset of SMT fall right at the sweet spot of LISA-like detectors!

$$R_r = Af(q), \quad f(q) \simeq 0.44q^{1/3}$$

PSR	f_{GW} (10^{-2}Hz)
B1516+02B	0.57
B1855+09	1.21
J0437−4715	1.06
J1012+5307	0.70
J0751+1807	0.55
J1232−6501	0.77

VP et al. (2009)



Amaro-Seoane et al. 2012

Evolution in the SMT regime

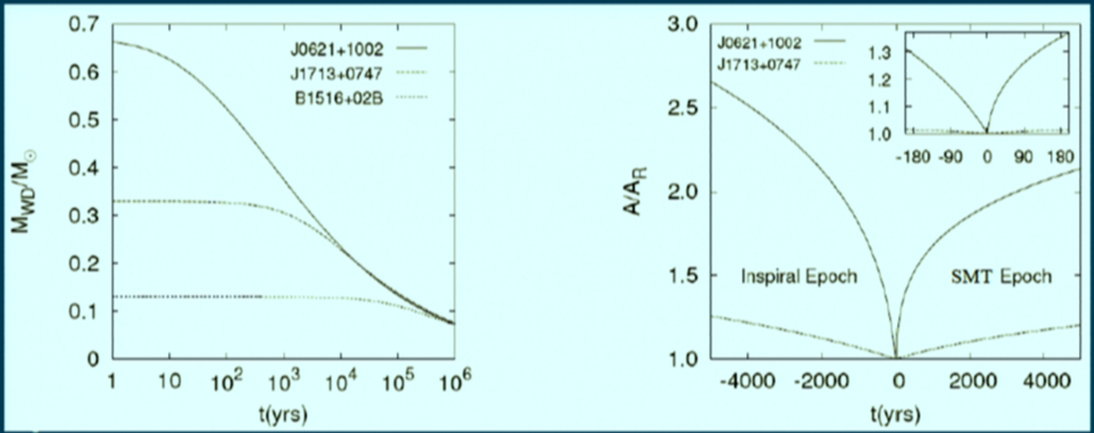
- Approach of Clark & Eardley (1977) for NSNS, and Faber et al. (2006) (Illinois group) for BHNS (mass and angular momentum conservation)

$$\frac{\dot{J}}{J_{\rm orb}} = \frac{\dot{J}_{\rm GW}}{J_{\rm orb}}.$$

Assuming the quadrupole approximation for J_{GW} and corotation we eventually derive a simple system of uncoupled ODEs for the evolution of mass and orbital separation, which we solve numerically.

$$\dot{M}_{\rm WD} = -\frac{64}{5}\left[\frac{d\ln R_{\rm WD}}{d\ln M_{\rm WD}} + 2\,(1-q) - \frac{d\ln f}{d\ln q}(1+q)\right]^{-1}\frac{(1+q)f(q)^4}{q^2}\frac{M_{\rm WD}^4}{R_{\rm WD}^4}.$$

Mass and Separation plots (SMT)



- J0621+1002: $M_{WD} = 0.67\ M_\odot$, $q = 0.394$
- J1713+0747: $M_{WD} = 0.33\ M_\odot$, $q = 0.206$
- B1516+02B: $M_{WD} = 0.13\ M_\odot$, $q = 0.0625$

So far we have assumed conservative mass transfer and corotation

- NS is not a point mass and will not be tidally locked in corotation
- Accretion will transfer angular momentum to the NS → Spin-up
- Allowing for NS spin-up → Different waveforms in the SMT regime
- GW measurements will be able to place constraints on the physics of SMT

Plausible outcomes of unstable mass transfer?

- If the total mass of the WDNS remnant exceeds the NS maximum mass:
  - Prompt collapse to a black hole (Disk? GRBs?)
    Possible sweep of both the eLISA and LIGO bands
  - OR formation of a differentially rotating, hypermassive NS
    => delayed collapse to a BH
- OR formation of a Thorne-Zytkow-like object
- OR ejection of appreciable WD debris leaving a rotating NS remnant
- NS + disk => if the disk lives long enough +fragmentation =>
  WDNS mergers may offer a plausible channel to planet formation around isolated NS's.

Computational Challenge

- Lengthscales

For $M_{\rm WD} = 1 M_\odot$ => $R_{\rm WD} \approx 5000{\rm km}$

For $M_{\rm NS} = 1.5 M_\odot$ => $R_{\rm NS} \approx 10{\rm km}$

$$\frac{R_{\rm WD}}{R_{\rm NS}} \approx 500$$

Separation at the Roche limit is A ~ 2-5 R_{WD}

Wave zone (outer grid boundary) is $\gtrsim$ 2A ~ 5000 R_{NS}

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  Separation at the Roche limit is A ~ 2-5 R_{WD}
  Wave zone (outer grid boundary) is $\gtrsim$ 2A ~ 5000 R_{NS}

- Time scales

  NS dyn. timescale

  $$t_{\rm d,NS} = \sqrt{\frac{R_{\rm NS}^3}{M_{\rm NS}}} \approx 5.75 M$$

  WD dyn. timescale

  $$t_{\rm d,WD} = \sqrt{\frac{R_{\rm WD}^3}{M_{\rm WD}}} \approx 7.8 \times 10^4 M$$

  Orbital period

  $$T = 2\pi \sqrt{\frac{A^3}{M}} \approx 1.4 \times 10^6 M$$

- Benchmark runs utilizing 256 cores on Ranger at TACC;
  Using 192^3 grid points in the innermost refinement level, the Illinois GR Hydro AMR code advances 6M/hour => 132 years of pure computing time for 5 orbits!!!

- Full GR Hydro simulations of realistic binary WDNS mergers are currently not practical!

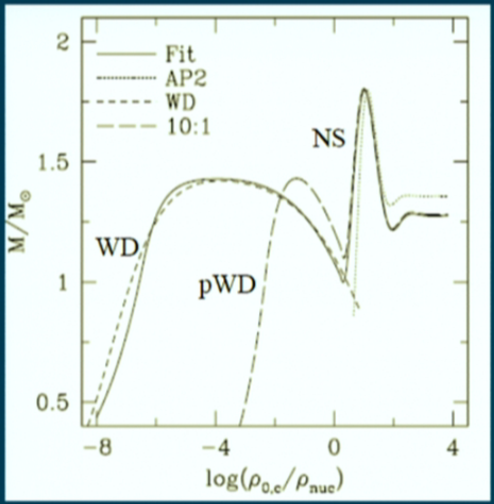
Pseudo white dwarfs (pWDs)

- Equation of state (EOS)

$$\frac{P}{\rho_0} = \begin{cases} \kappa_1 \rho_0^{1/n_1}, & \rho_0 \leqslant \rho_1 \\ \kappa_2 \rho_0^{1/n_2}, & \rho_1 < \rho_0 \leqslant \rho_2 \\ \kappa_3 \rho_0^{1/n_3}, & \rho_0 > \rho_2 \end{cases}$$

$$\kappa_1 = \kappa_2 \rho_1^{1/n_2 - 1/n_1}, \quad \kappa_2 = \kappa_3 \rho_2^{1/n_3 - 1/n_2}$$

$M_{NS,max}=1.8M_\odot$, $M_{WD,max}=1.43M_\odot$



VP et al. (2011)

- Using pWDs a of study binary WDNSs becomes possible

Justification of the pWD approach; scalability

- Pre-shocked WD sound speed: $c_s \sim (M/R_{WD})^{1/2}$
- Collision velocity: $v_c \sim (M/R_{WD})^{1/2}$

The Mach number = v_c/c_s is invariant under R_{WD}

- Thermal energy: $E_{th} \sim M^2/R_{WD}$
- Kinetic energy: $T \sim M^2/R_{WD}$
- Gravitational potential energy: $|W| \sim M^2/R_{WD}$

$E_{th}/|W|$, $T/|W|$ are invariant under R_{WD}

=> **pWDNS mergers are scalable to WDNS mergers of identical masses**

- **Test scalability using head-on collisions**

Head-on collision initial data

- Assumptions
  - Model the stars assuming a perfect fluid stress-energy tensor
  - Assume the stars to be temporarily at rest (in the center of mass frame) at large separation; moment of time symmetry $K_{ij} = 0$
  - TOV rest-mass density profile for the stars

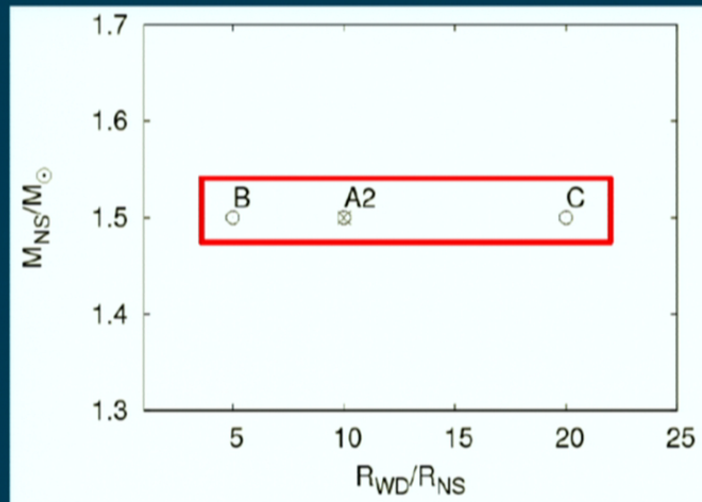
- Solve the Hamiltonian constraint: $\gamma_{ij} = \Psi^4 f_{ij}$ => $\nabla^2 \Psi = -2\pi \Psi^5 \rho$

  using the FMR FD elliptic code we developed and validated.

- Momentum constraint; automatically satisfied

Cases and evolution methods

- Cases studied
  M_{WD}=0.98$M_{\odot}$



- Evolution
  - Employ the Illinois GR Hydrodynamics AMR code (BSSN, HRSC, equatorial symmetry)
  - EOS: $P = P_{\rm th} + P_{\rm cold}$, where $P_{\rm th} = (\Gamma_{th} - 1)\rho_0(\epsilon - \epsilon_{\rm cold})$ and $\Gamma_{\rm th} = 1.66\ (\simeq 5/3)$

Initial data

- We prepare binary pWDNS initial data in circular orbit that

  a) are corotational

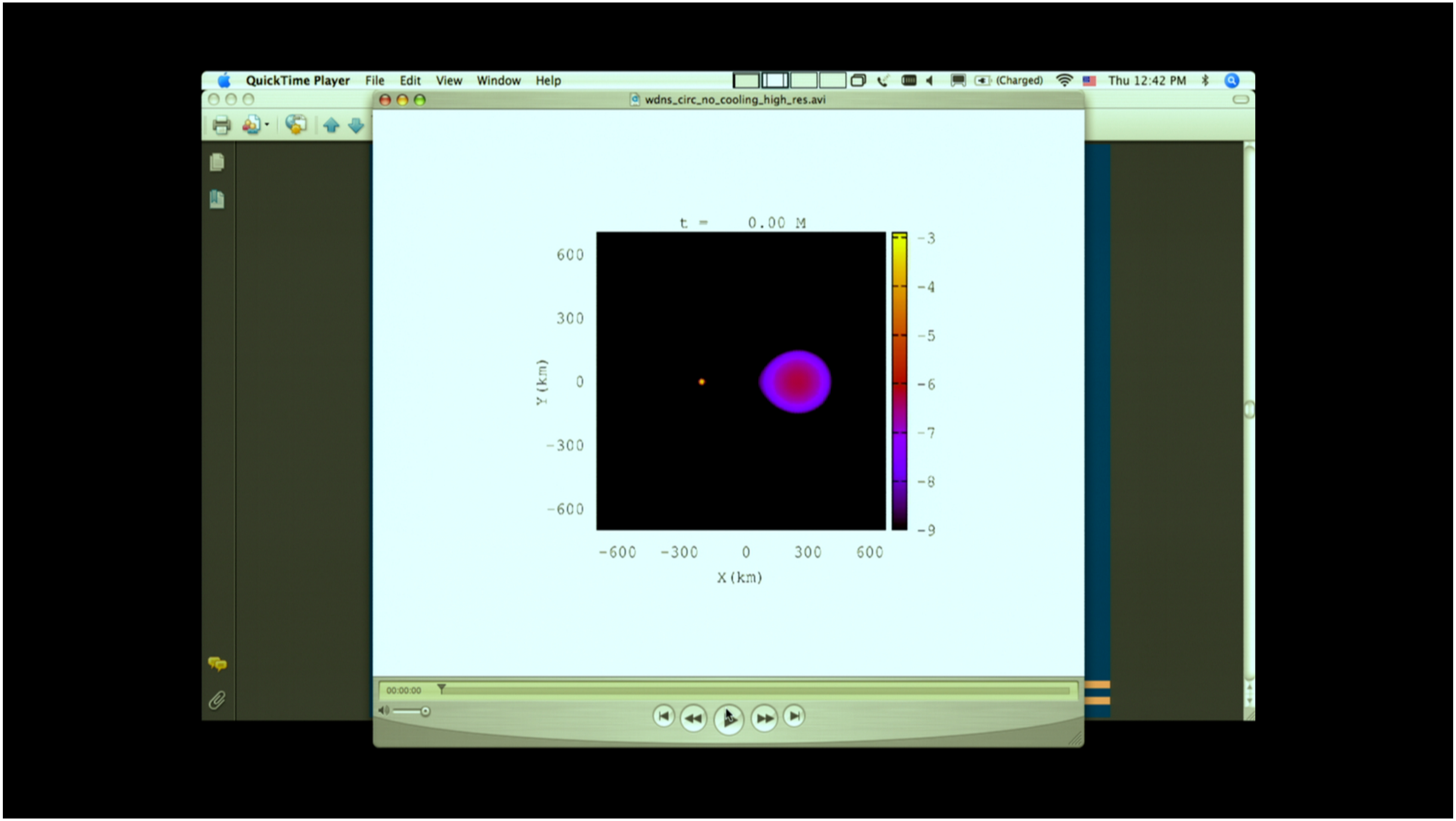
  b) are quasiequilibrium

  c) satisfy the conformal-thin-sandwich equations

Case and evolution methods: Movie

- $M_{NS} = 1.4M_\odot$, $M_{WD} = 1.0M_\odot$,
- $q \simeq 0.7 > 0.66 \Rightarrow$ WD tidal disruption
- $M = 2.4\ M_\odot > M_{max,\ rot} \simeq 2.1\ M_\odot$; **Remnant collapse to a BH?**
- <u>Evolution</u>
  - Illinois GR Hydro AMR code (BSSN, HRSC, equatorial symmetry)
  - EOS: $P = P_{\rm th} + P_{\rm cold}$, where $P_{\rm th} = (\Gamma_{\rm th} - 1)\rho_0(\epsilon - \epsilon_{\rm cold})$

    and $\Gamma_{\rm th} = 5/3$



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Thermally or centrifugally supported?

- Prompt collapse to a BH does not occur; remnants are hot and differentially rotating
- Introduce parametric, optically thin covariant cooling (neutrinos)
- Choose cooling timescale much longer than remnant dynamical timescale
- Evolve with and without cooling and compare

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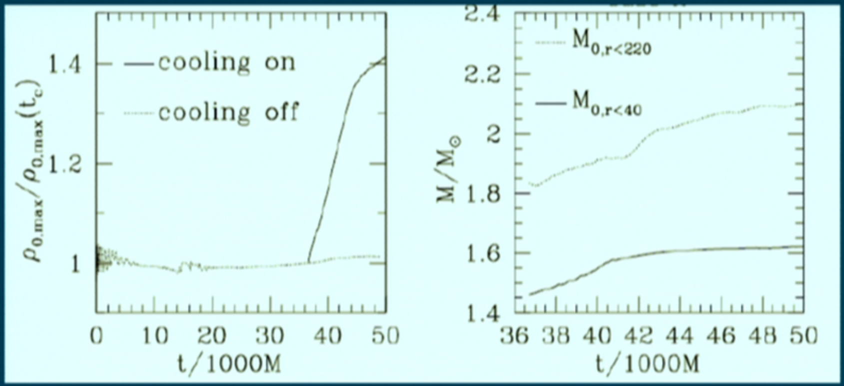
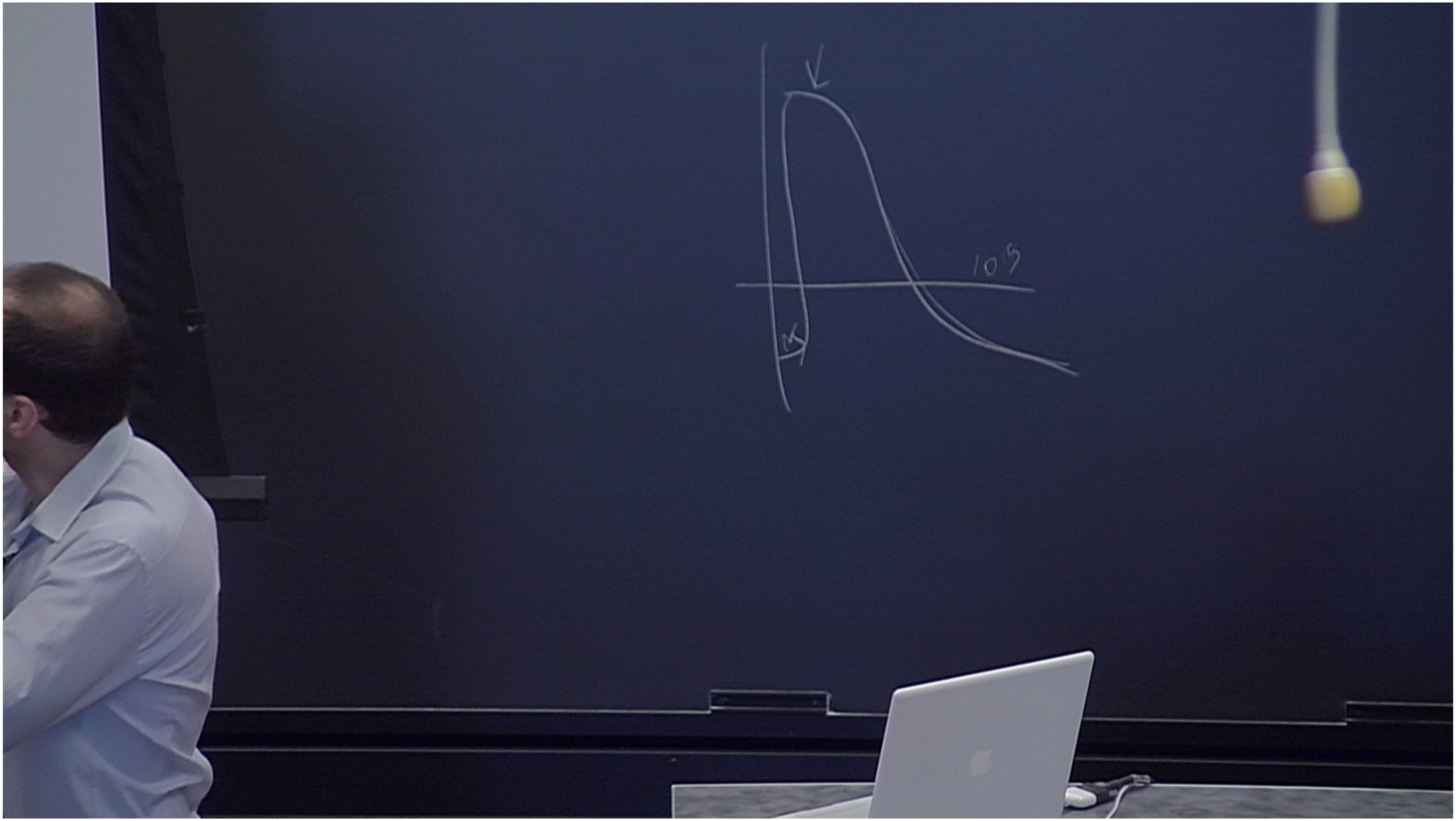
Results of simulations



VP et al. (2012)



Temperature: nuclear reactions

- Typical temperatures are: $E_{\rm th} \sim \frac{M_{\rm WD}}{m_{\rm n}} k{\rm T} \sim \frac{M_{\rm NS} M_{\rm WD}}{R_{\rm WD}}$ $\rightarrow$ ${\rm T} \sim \frac{C_{\rm WD} m_{\rm n}}{qk}$ $\rightarrow$

$$T \sim 1.5 \times 10^9 \left(\frac{C_{\rm WD}}{10^{-4}}\right)\left(\frac{q}{0.7}\right)^{-1} {\rm K}$$

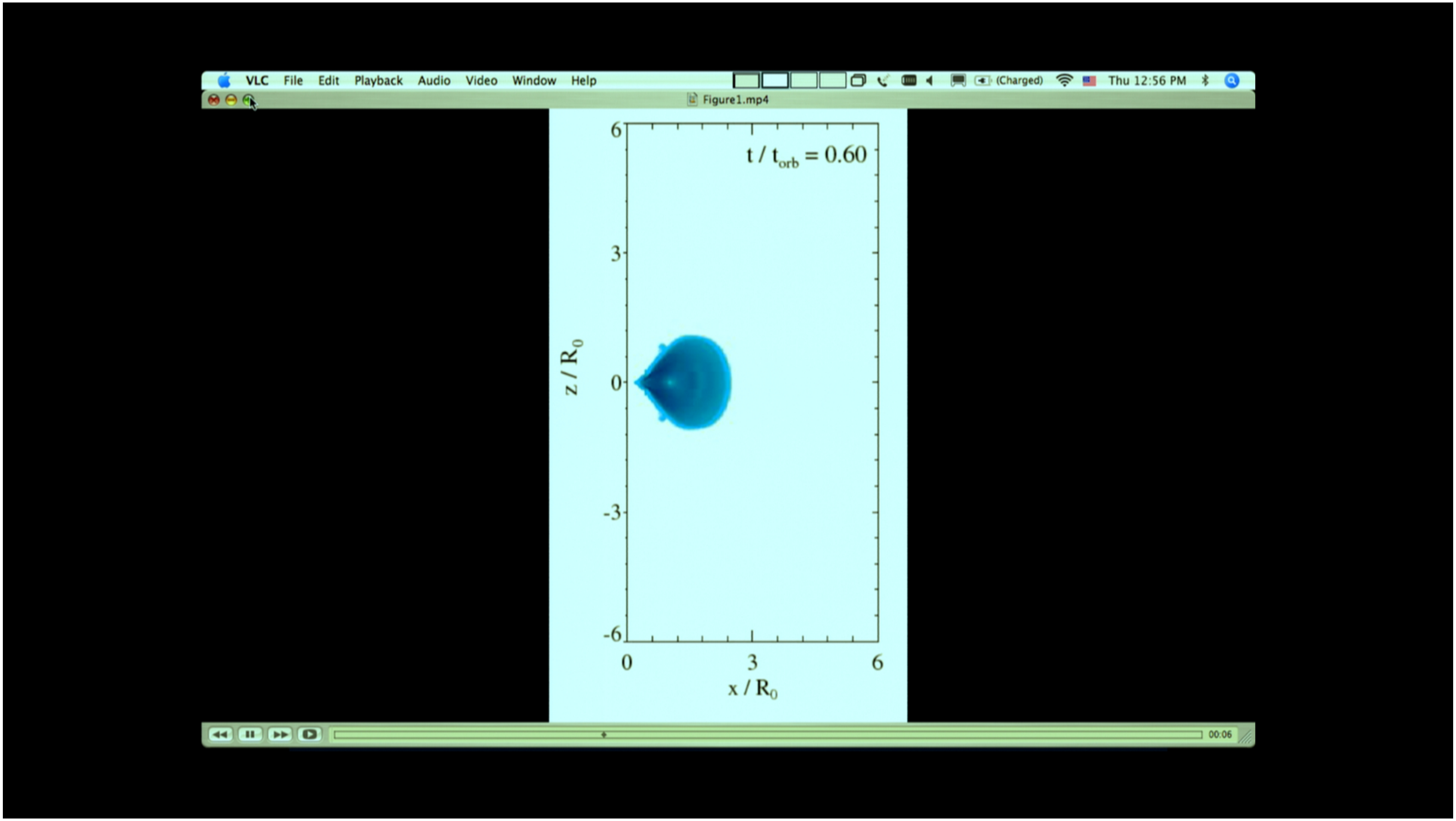
- Typical WD densities are 10^6 gr/cm^3
- At these densities and temperatures C can be ignited but not O.
- Recently Metzger (2011) & Fernandez and Metzger (2012) considered Newtonian accretion flows including nuclear burning (for $M_{disk} < 0.6\ M_{sun}$)
  - 1D (height-integrated, nuclear reaction networks)
  - 2D (axisymmetric, parametric nuclear burning)

  A Shakura-Sunyaev alpha parametrization was chosen to model viscosity

NuDAFs – Results – Possible EM signals

- Whether detonation or quiescent burning occurs depends on $\Psi = \frac{\varepsilon_{\rm nuc}}{w(r_{\rm nuc})}$

$\Psi > 1 \rightarrow$ Detonation $\rightarrow$ Disk is unbound (movie)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NuDAFs – Results – Possible EM signals

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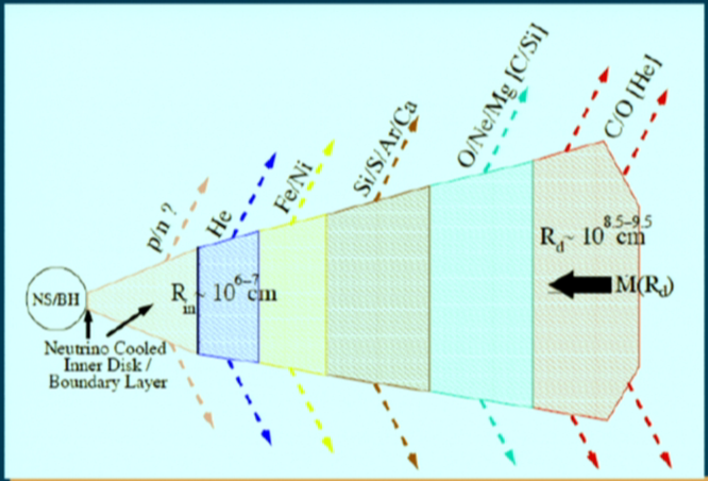
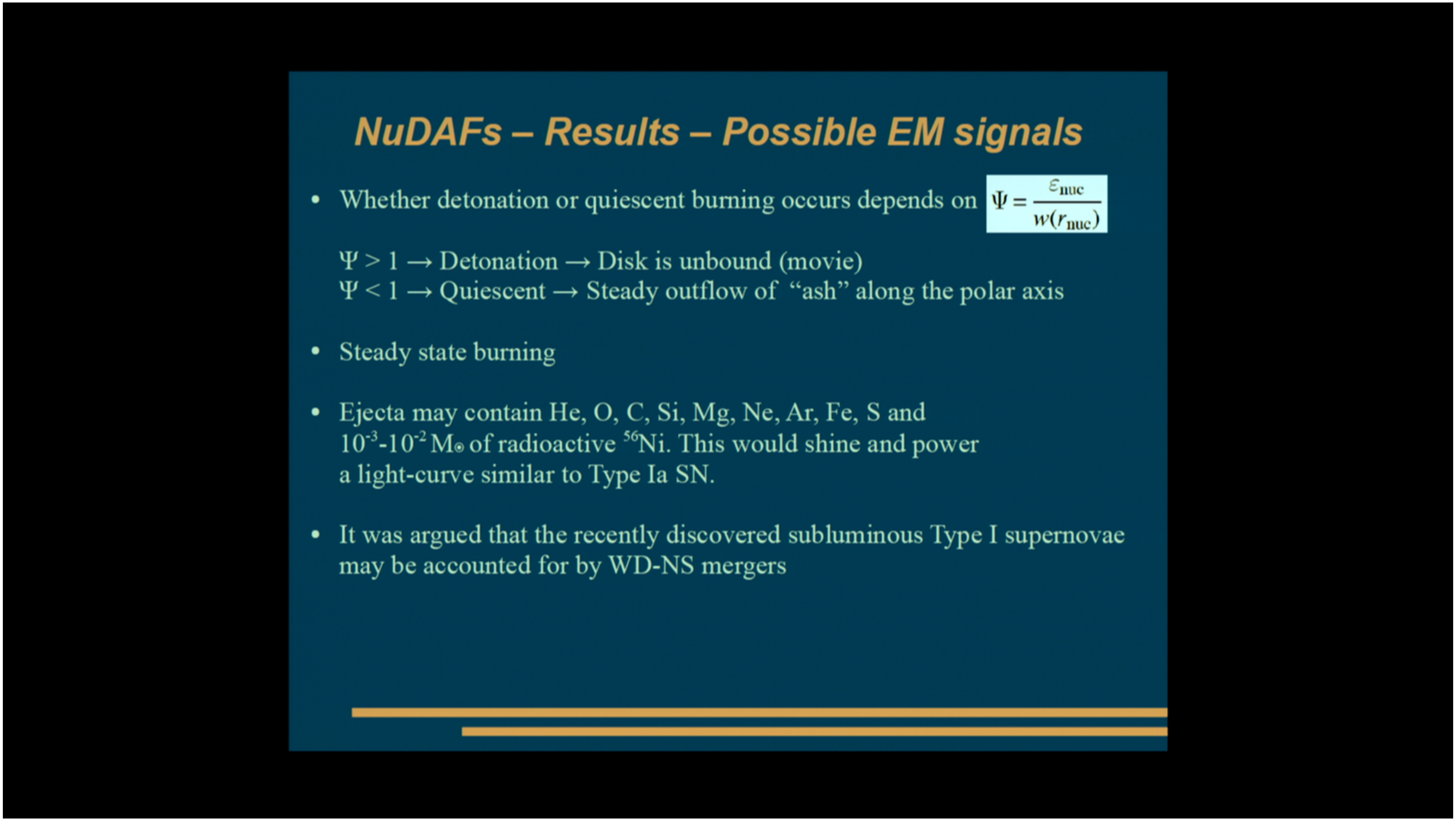
  $\Psi < 1 \rightarrow$ Quiescent $\rightarrow$ Steady outflow of "ash" along the polar axis

- Steady state burning picture



B. D. Metzger 2011


NuDAFs – Results – Possible EM signals
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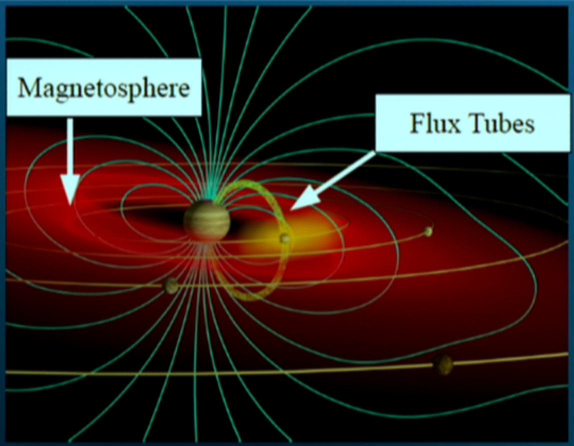
$\Psi > 1 \rightarrow$ Detonation $\rightarrow$ Disk is unbound (movie)
$\Psi < 1 \rightarrow$ Quiescent $\rightarrow$ Steady outflow of "ash" along the polar axis
• Steady state burning
• Ejecta may contain He, O, C, Si, Mg, Ne, Ar, Fe, S and 10^{-3}-10^{-2} $M_\odot$ of radioactive ^{56}Ni. This would shine and power a light-curve similar to Type Ia SN.
• It was argued that the recently discovered subluminous Type I supernovae may be accounted for by WD-NS mergers

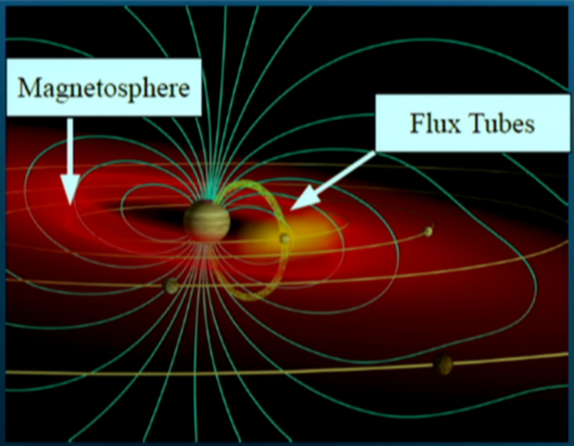
Black hole – neutron star binaries: Pre-merger EM signals

Unipolar inductor: The Jupiter – Io system



- Io is volcanically very active
- Volcanic eruptions eject ionized material high in Io's atmosphere
- Jupiter's strong magnetic field captures significant amounts of this ionized matter
- Establising a (conducting) magnetosphere and flux tubes connecting with Io → Decameter radiation?

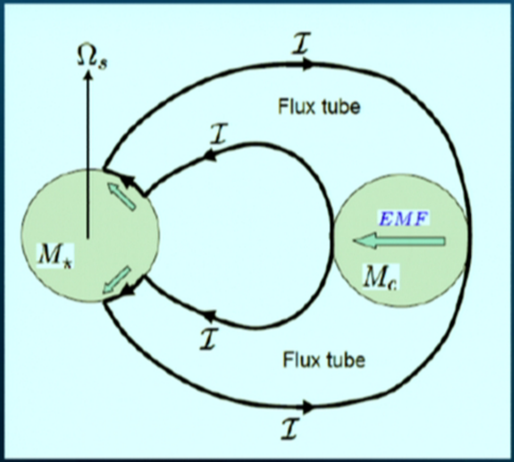
Unipolar inductor: The Jupiter – Io system



- Io is volcanically very active
- Volcanic eruptions eject ionized material high in Io's atmosphere
- Jupiter's strong magnetic field captures significant amounts of this ionized matter
- Establishing a (conducting) magnetosphere and flux tubes connecting with Io → Decameter radiation?
- Io 's surface is a conductor that is moving through Jupiter's magnetic field → EMF → Currents → Dissipation on Io, Jupiter and in the flux tubes.
- Goldreich & Lynden Bell (1969) conceived the UI: predicted Decameter radiation

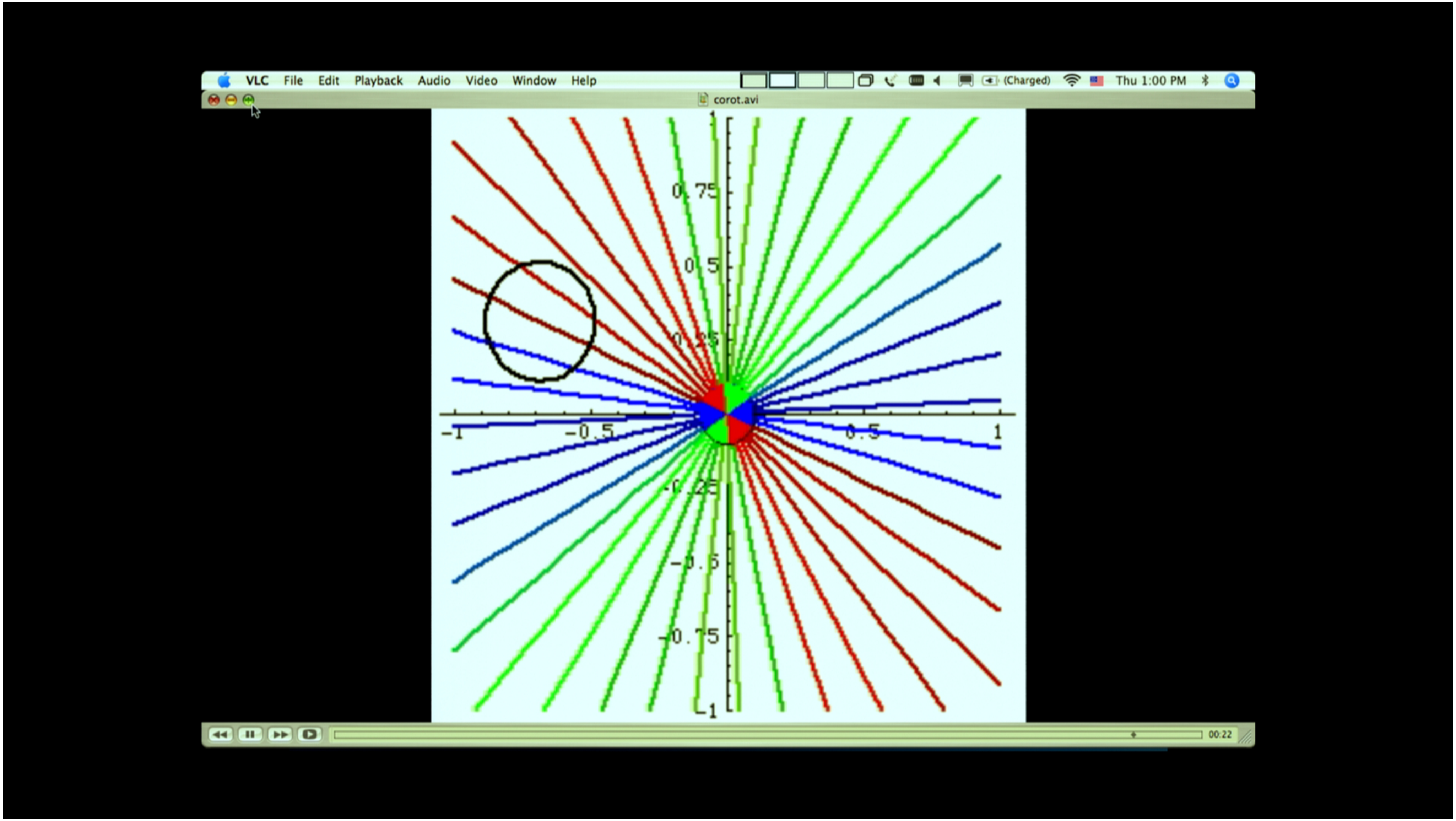
The Unipolar Inductor: Qualitative analysis

- Setting: The magnetosphere of a magnetized body corotates with the body sweeping the companion



Dong Lai 2012

- As long as the magnetic body is not locked into corotation, the magnetic field will be sweeping the (conducting) non-magnetized companion → an EMF will be induced.



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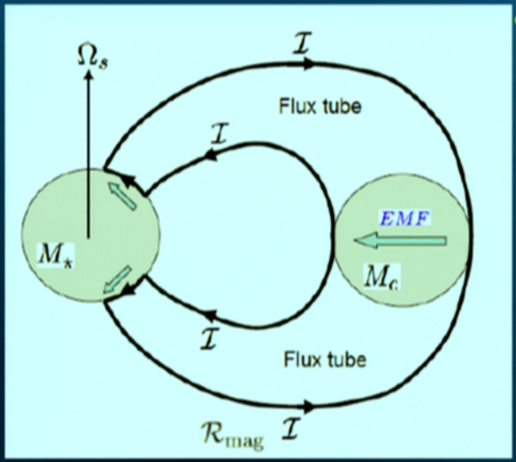
The Unipolar Inductor: Equations

- Assume the magnetized body has spin Ω_s and a dipole B-field with moment μ, the orbital ang. freq. is Ω and the separation a.



Dong Lai 2012

- In the north hemisphere: the E-field induced by charge separ. on the companion is $\mathbf{E} = \mathbf{v}_{\rm rel} \times \mathbf{B}/c$, where $\mathbf{v}_{\rm rel} = (\Omega - \Omega_s) a\,\hat{\phi}$, $\mathbf{B} = (-\mu/a^3)\hat{\mathbf{z}}$

Applications: BHNS binaries

- McWilliams and Levin (2011) applied the UI model to BHNS binaries.
- The NS is the magnetic object, the BH is the "conducting" body.
- In the membrane paradigm of a BH, the BH can be considered as a sphere of radius $R_H=2GM/c^2$ and resistance $\mathbb{R}=4\pi/c$.
- The energy dissipation rate becomes

$$\dot{E}_{\rm diss} = 5.7 \times 10^{42} \left(\frac{B_*}{10^{13}{\rm G}}\right)^2 \left(\frac{M_{\rm H}}{10 M_\odot}\right)^4 \left(\frac{a}{3R_H}\right)^{-7} {\rm erg/s}$$

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- We performed simulations of the BHNS UI to check the viability of the mechanism

- Evolve Poynting vector and Magnetic Field: enforcing the “frozen-in” condition in the interior, solving the GR force-free equations in the exterior

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- a) a/M = -0.5, b) a/M = 0, c) a/M = 0.75 ($q = M_{BH}/M_{NS} = 3$, $r = 6.6R_{NS}$)
- After an initial transient phase, the fields relax

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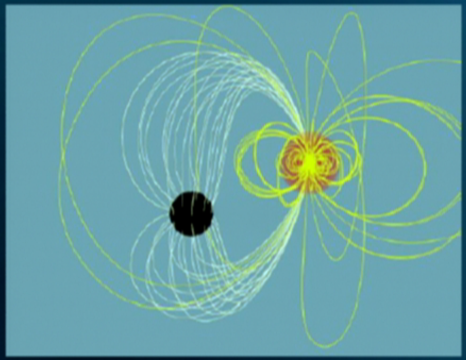

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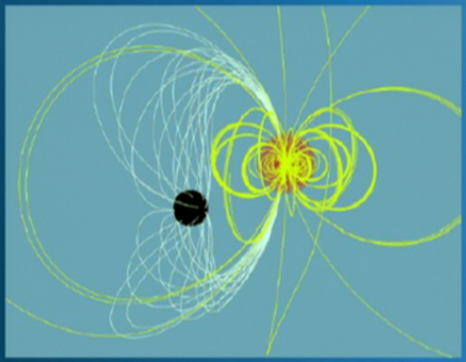

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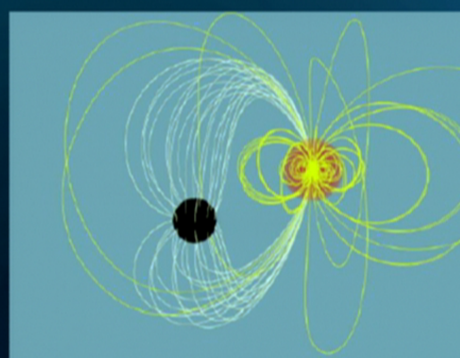

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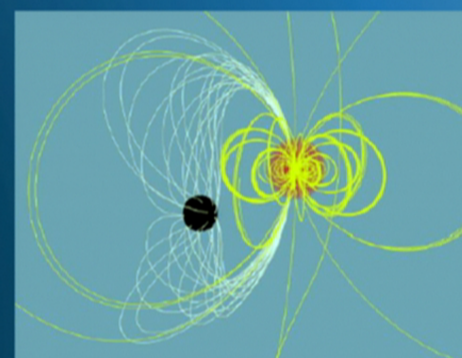

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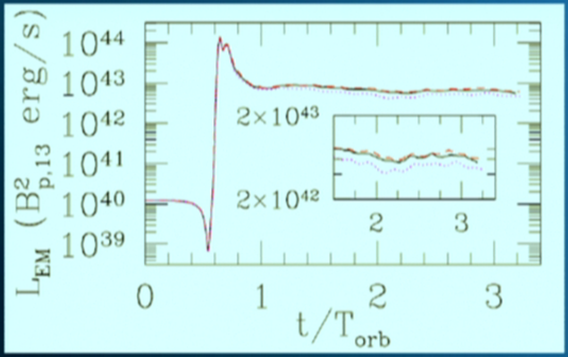

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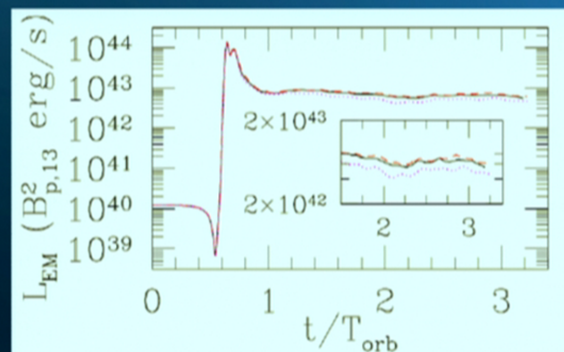

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