Title: Simulations of Binary Neutron Star Mergers

Date: May 07, 2014 04:35 PM

URL: http://pirsa.org/14050053

Abstract: By numerically solving Einstein equations we are able to study the strong regime of gravity. In many astrophysical scenarios strong gravity plays a fundamental role such as compact binary systems: e.g. Black Hole binaries binary Neutron Stars and Black Hole-Neutron Star systems. In this talk I will discuss the simulations our group has been conducting in binary Neutron Star system where we can study the dynamics and gravitational radiation of the systems but also establish important connections with electromagnetic counterparts and even testing alternatives theories of gravity (i.e. Scalar-Tensor theories).

Neutron-Star Mergers
Gravitational & Electromagnetic Radiation

Compute Ontario Research Day
May, 2014 -- Waterloo, ON

Marcelo Ponce
University of Guelph

OUTLINE

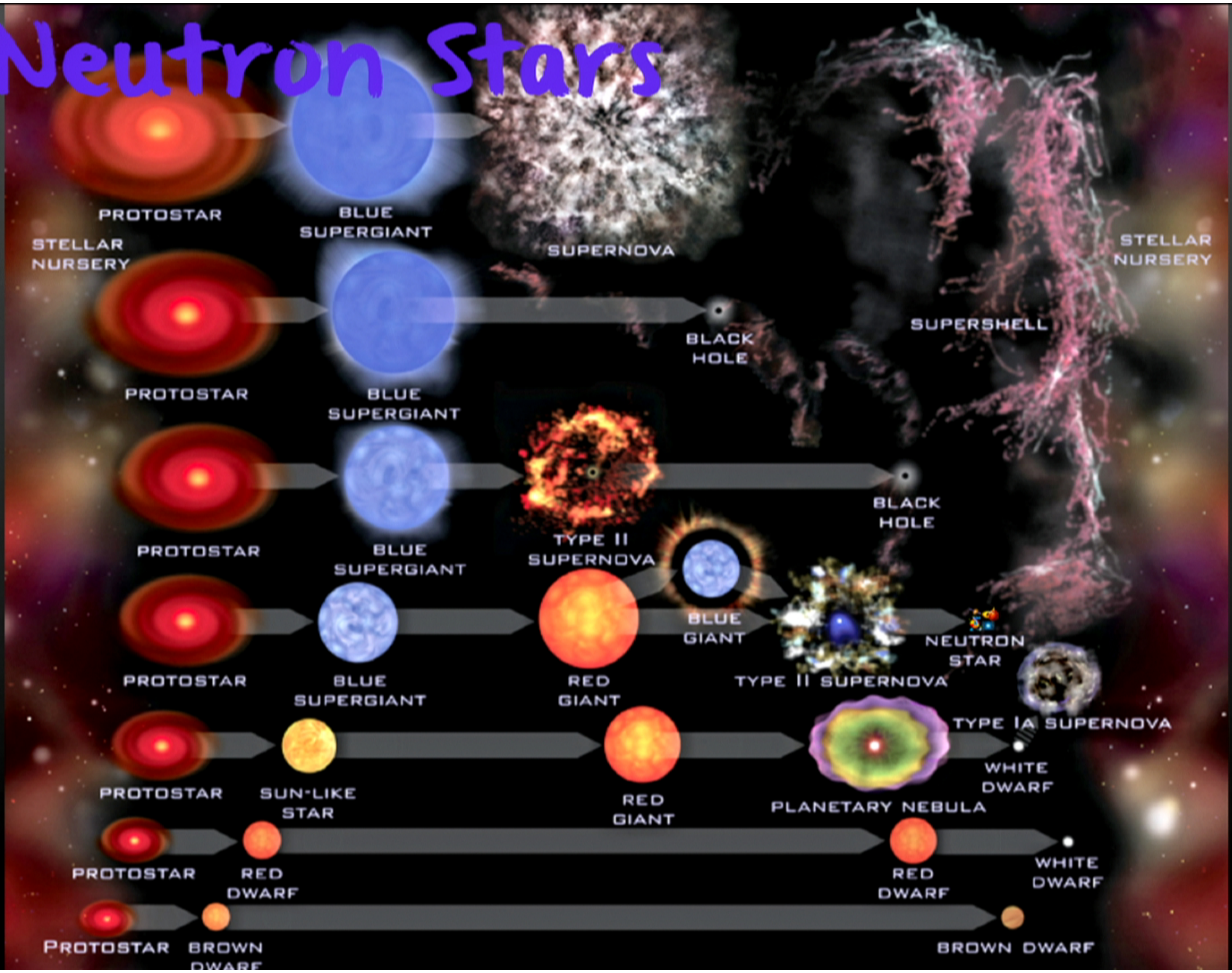
1) Introduction/Motivation

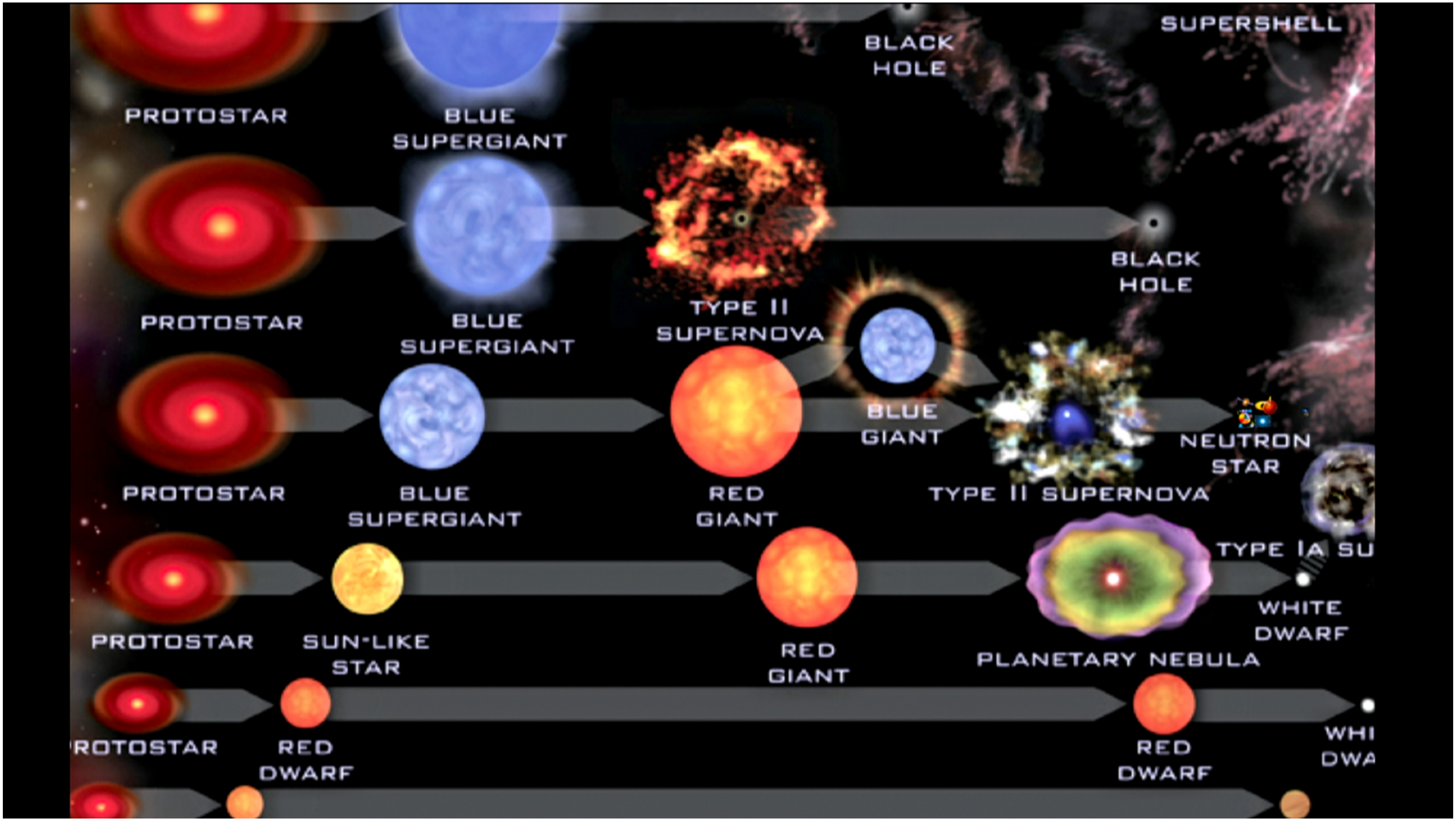
* Neutron Stars
* Binary Neutron Stars
* Gravitational/Electromagnetic Radiation

2) Simulations & Results

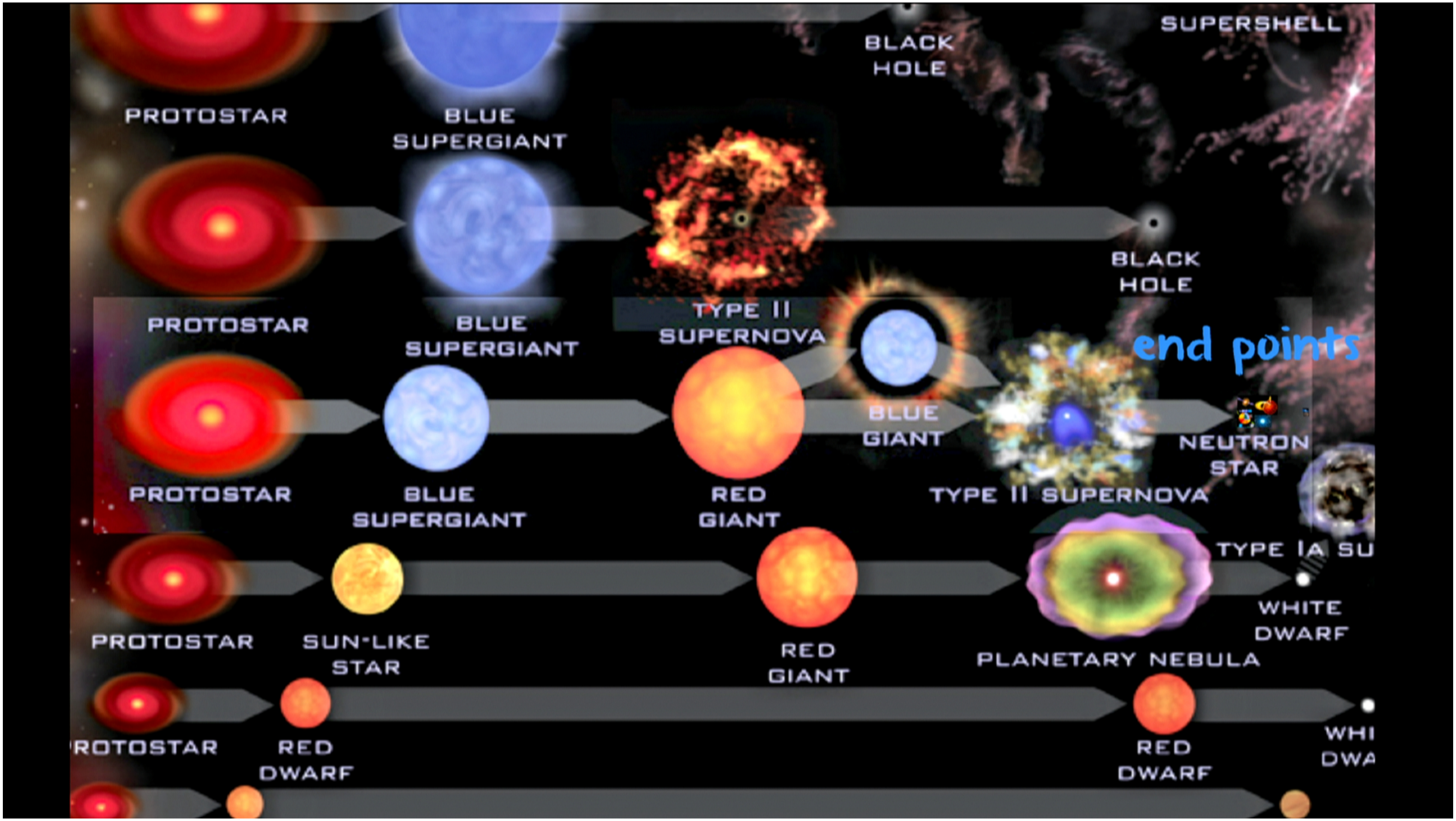
3) Conclusions

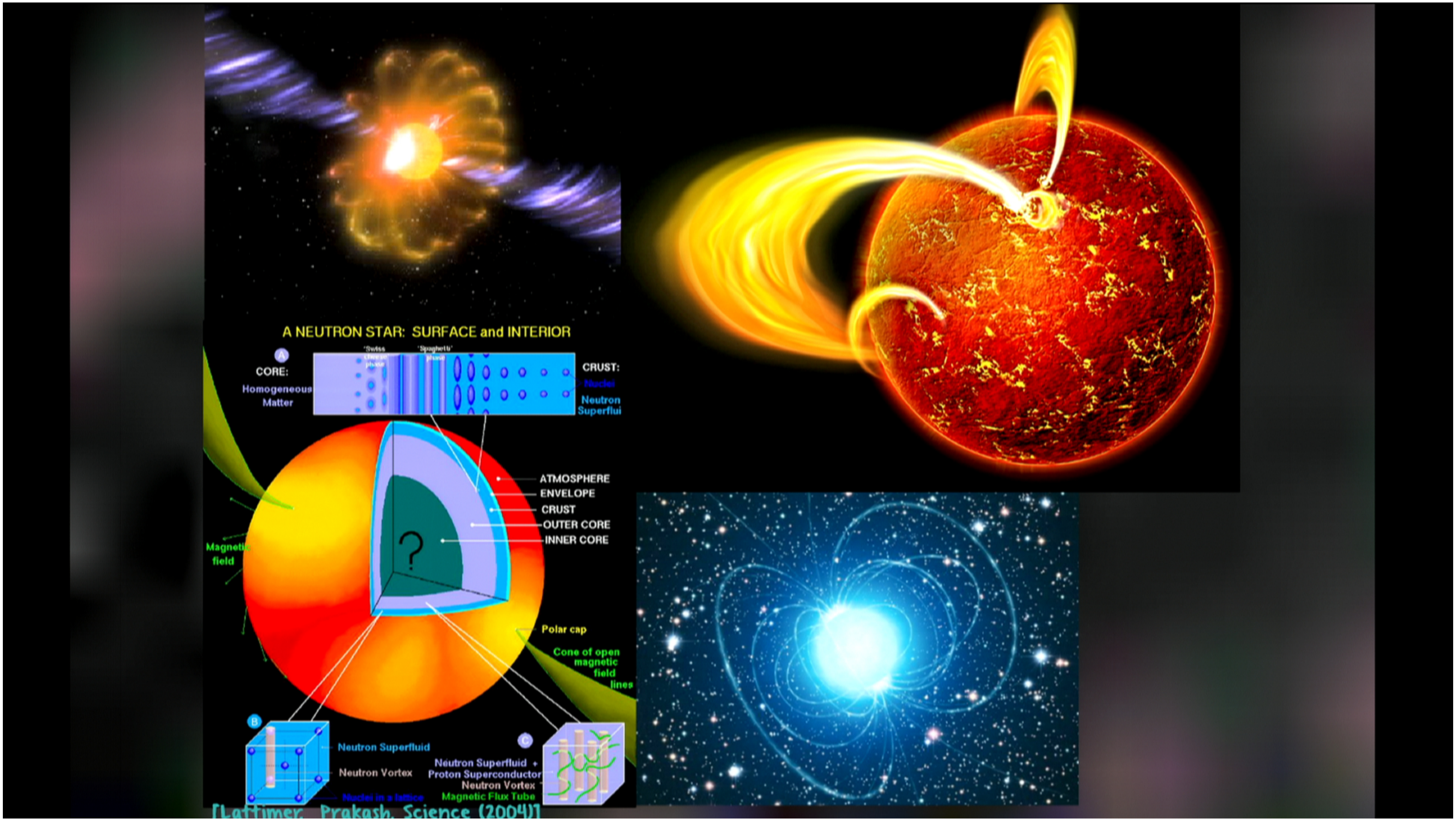
Neutron Stars



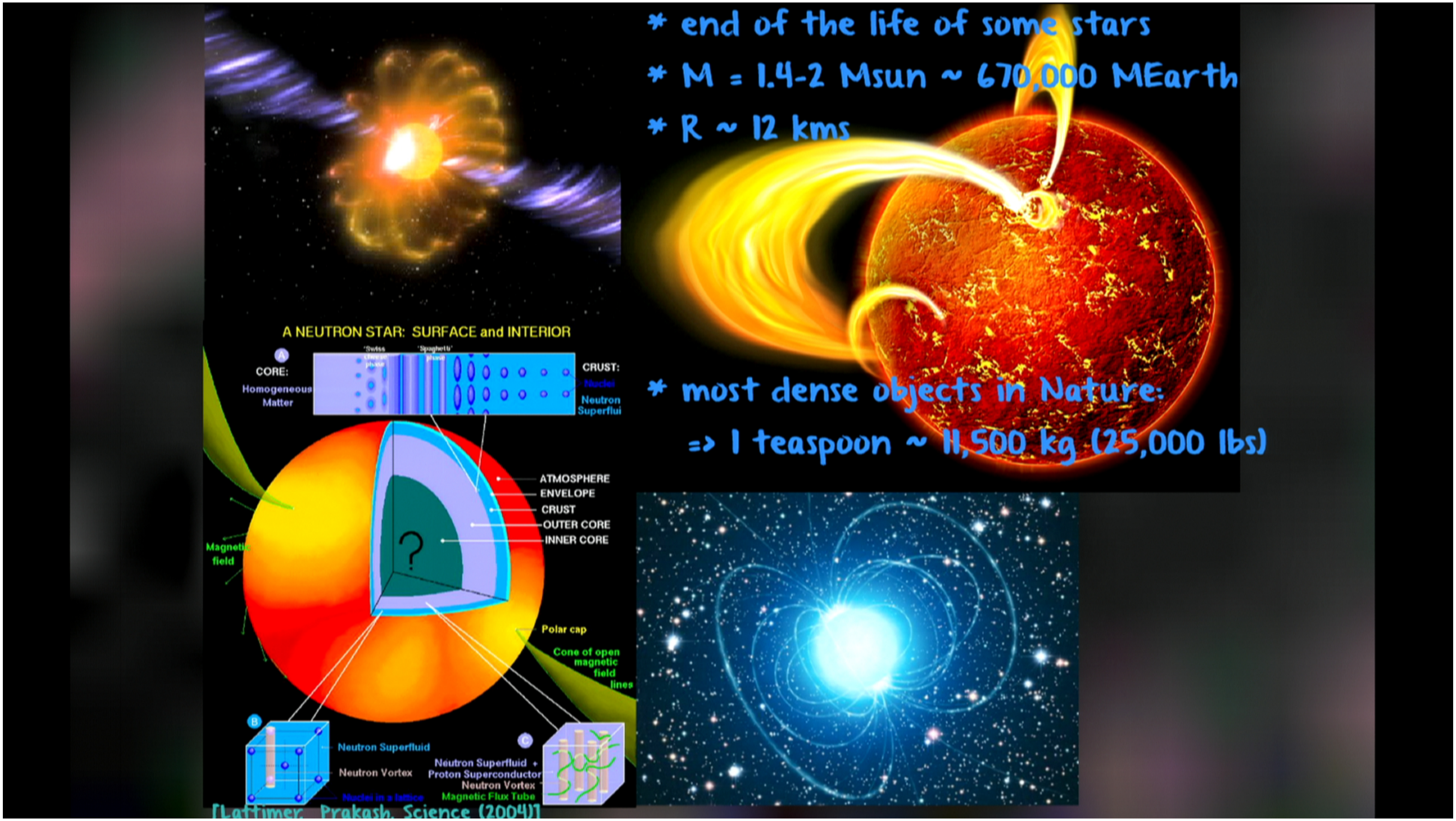


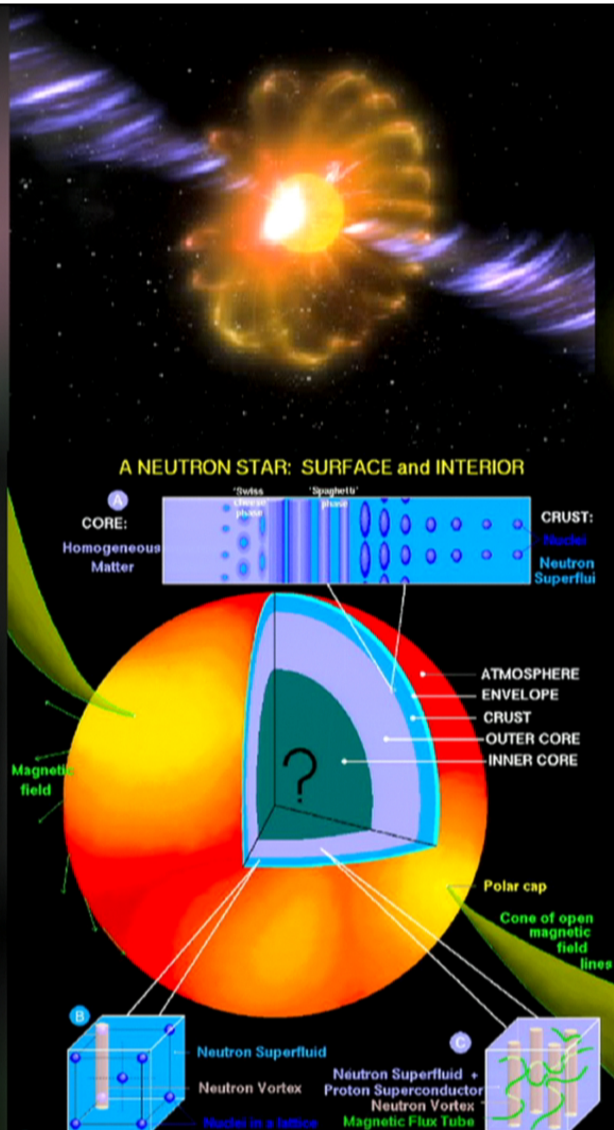
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
SUPERSHELL
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
TYPE II SUPERNOVA
NEUTRON STAR
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
TYPE IA SU
WHITE DWARF
ROTOSTAR
RED DWARF
RED DWARF
WHI DWA


SUPERSHELL
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
end points
BLUE GIANT
NEUTRON STAR
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
TYPE II SUPERNOVA
TYPE IA SU
WHITE DWARF
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
ROTOSTAR
RED DWARF
RED DWARF
WHI DWA



A NEUTRON STAR: SURFACE and INTERIOR
CORE:
Homogeneous Matter
CRUST:
Neutron Superflui
ATMOSPHERE
ENVELOPE
CRUST
OUTER CORE
INNER CORE
?
Magnetic field
Polar cap
Cone of open magnetic field lines
Neutron Superfluid
Neutron Vortex
Neutron Superfluid + Proton Superconductor
Neutron Vortex
Magnetic Flux Tube
[Lattimer, Prakash, Science (2004)]


* end of the life of some stars
* M = 1.4-2 Msun ~ 670,000 MEarth
* R ~ 12 kms
* most dense objects in Nature:
=> 1 teaspoon ~ 11,500 kg (25,000 lbs)
A NEUTRON STAR: SURFACE and INTERIOR
CORE:
Homogeneous Matter
'Swiss cheese' phase
'Spaghetti' phase
CRUST:
Nuclei
Neutron Superflui
ATMOSPHERE
ENVELOPE
CRUST
OUTER CORE
INNER CORE
?
Magnetic field
Polar cap
Cone of open magnetic field lines
Neutron Superfluid
Neutron Vortex
Nuclei in a lattice
Neutron Superfluid + Proton Superconductor
Neutron Vortex
Magnetic Flux Tube
[Lattimer, Prakash, Science (2004)]



[Lattimer, Prakash, Science (2004)]

* end of the life of some stars
* M = 1.4-2 Msun ~ 670,000 MEarth
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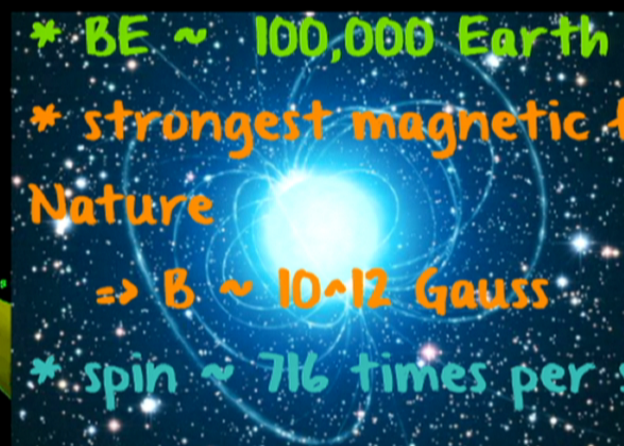
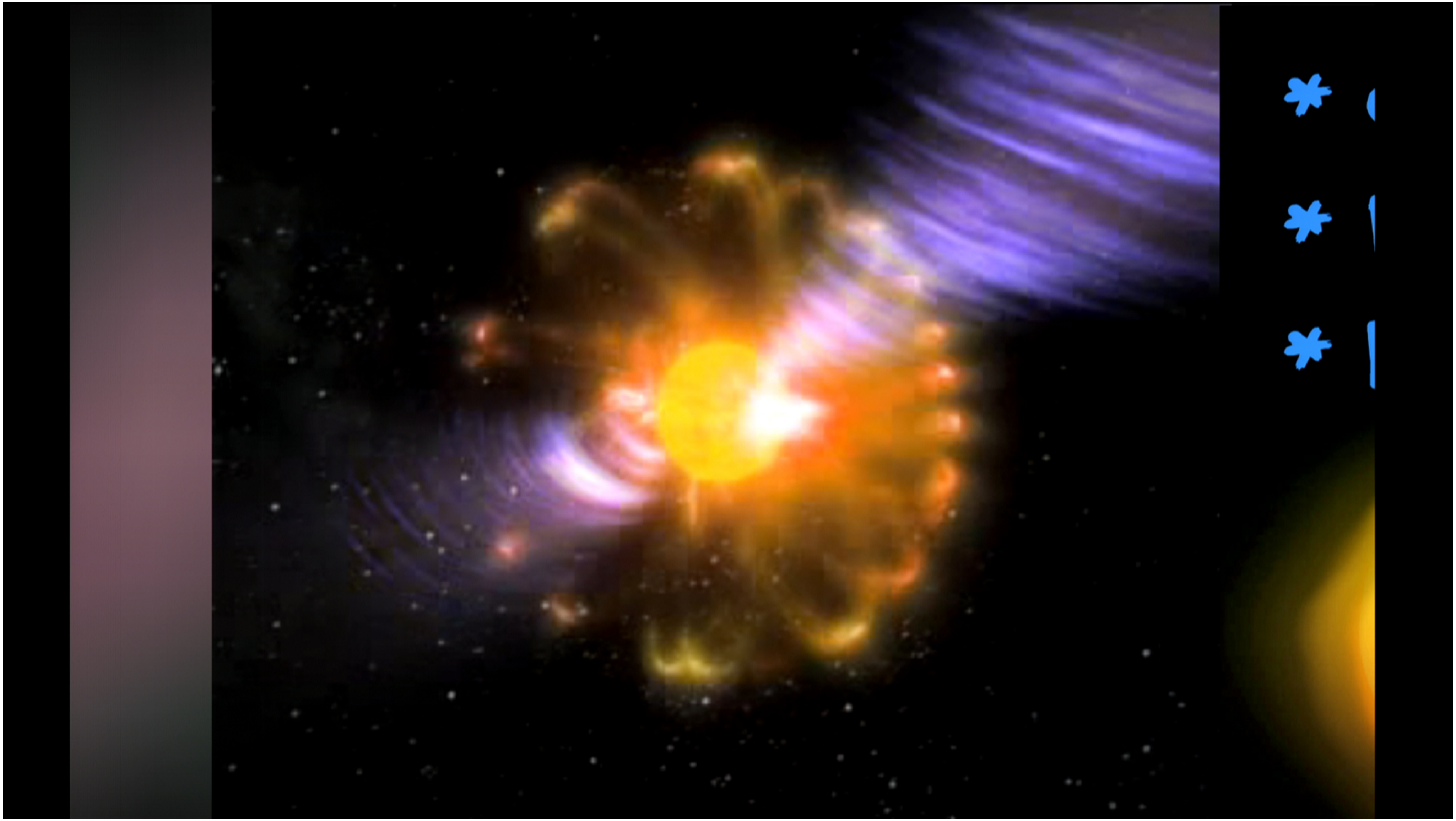
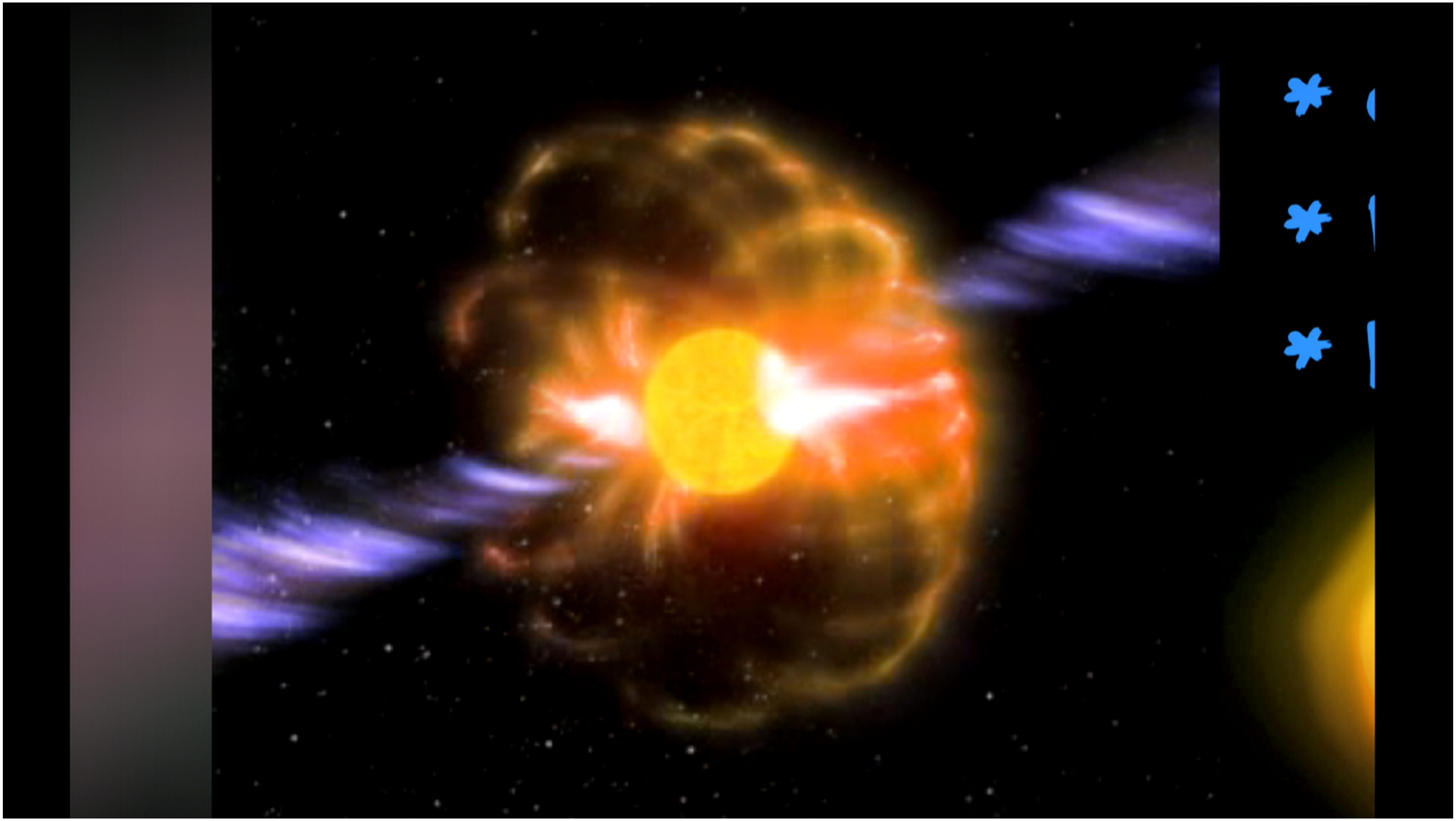
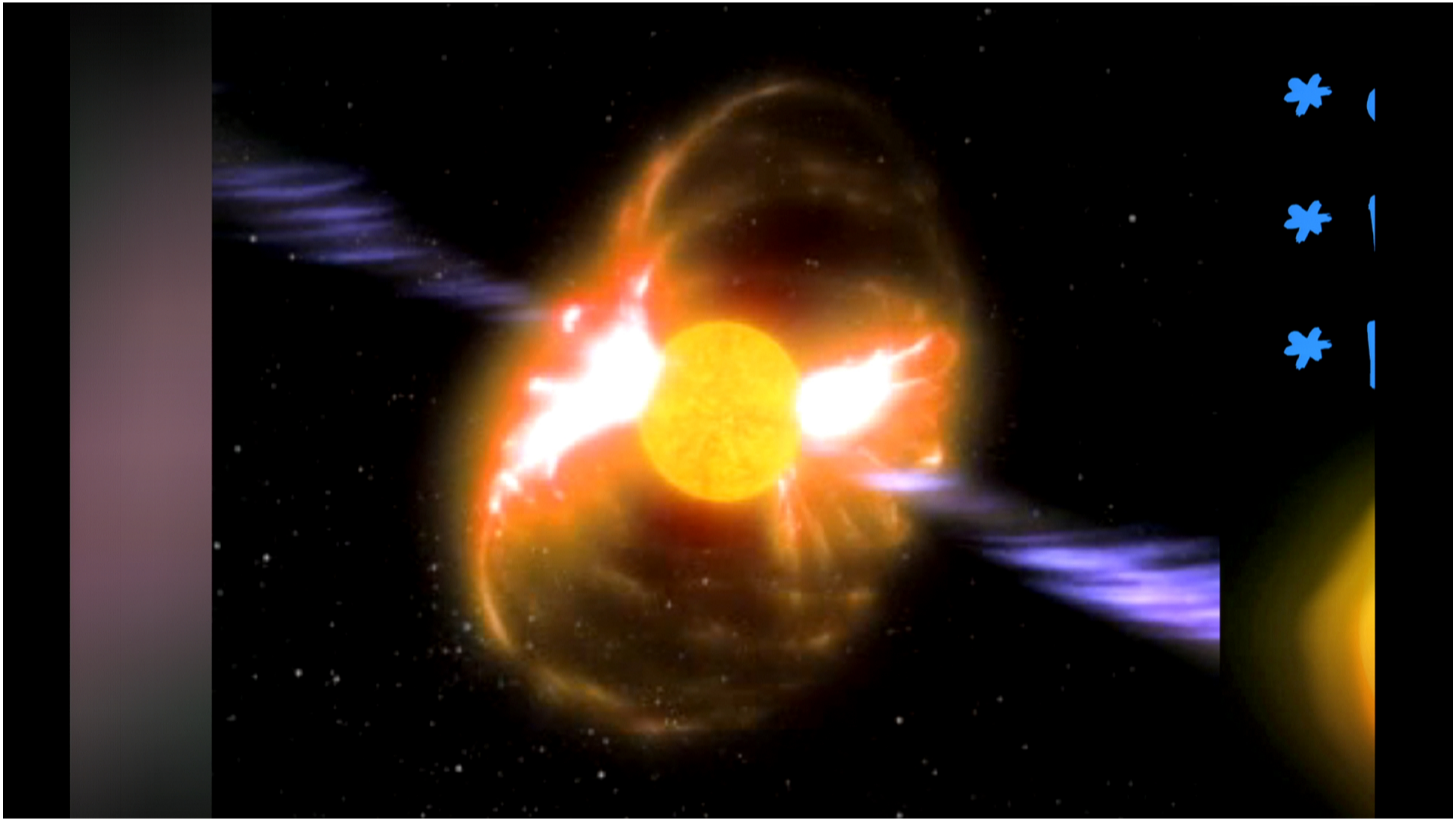
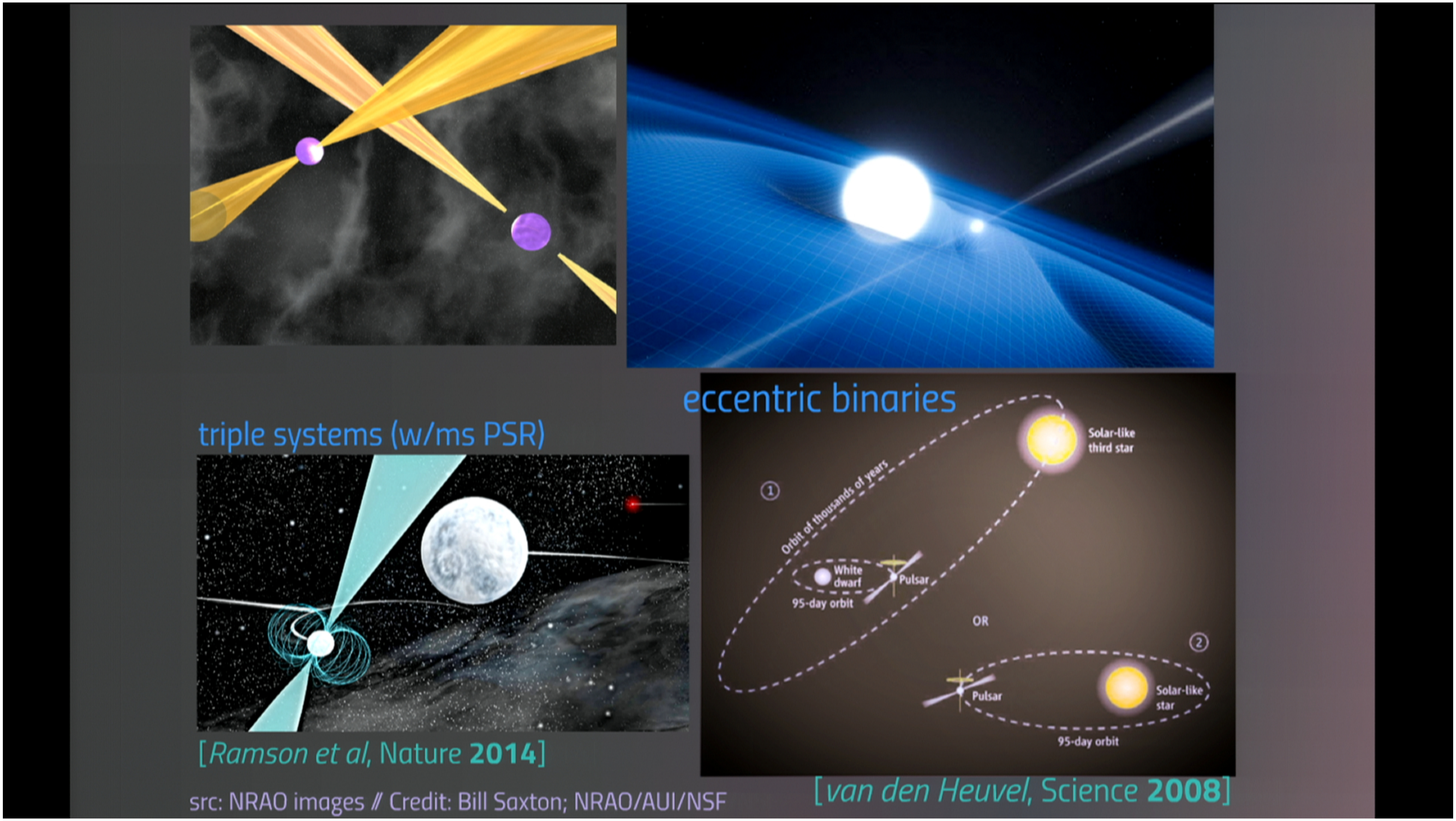


* BE ~ 100,000 Earth mass (/c^2)
* strongest magnetic fields in Nature
  => B ~ 10^12 Gauss
* spin ~ 716 times per second

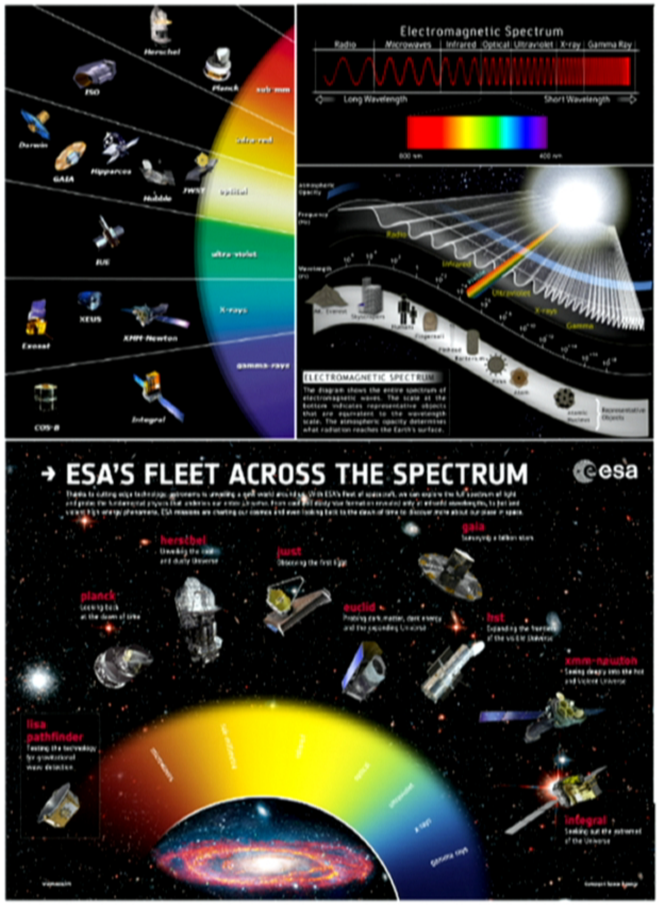


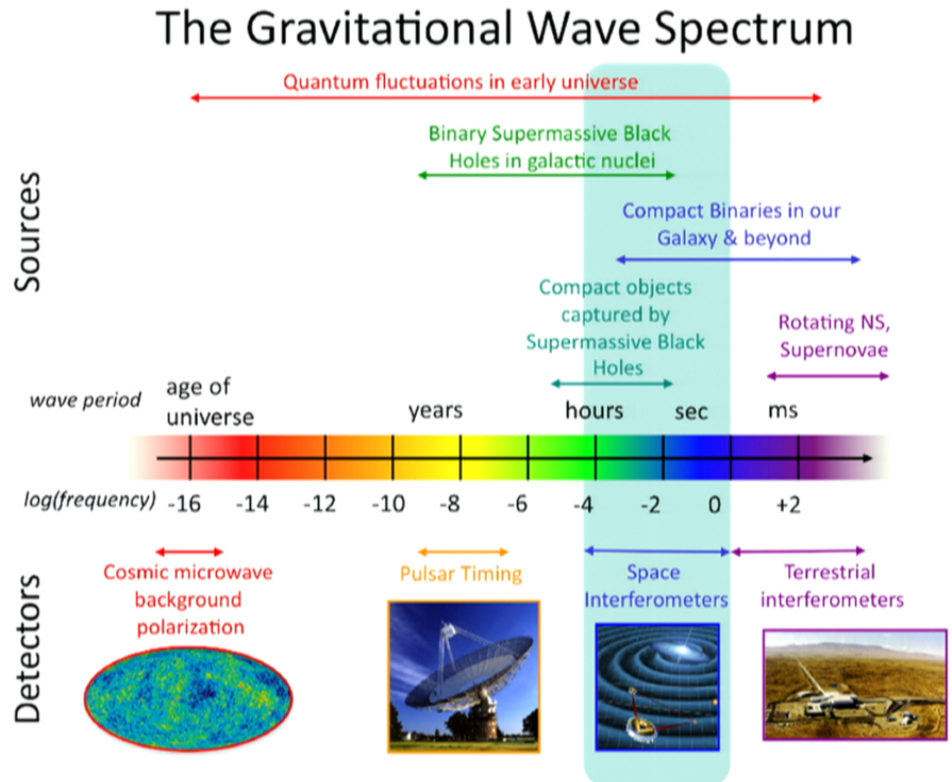


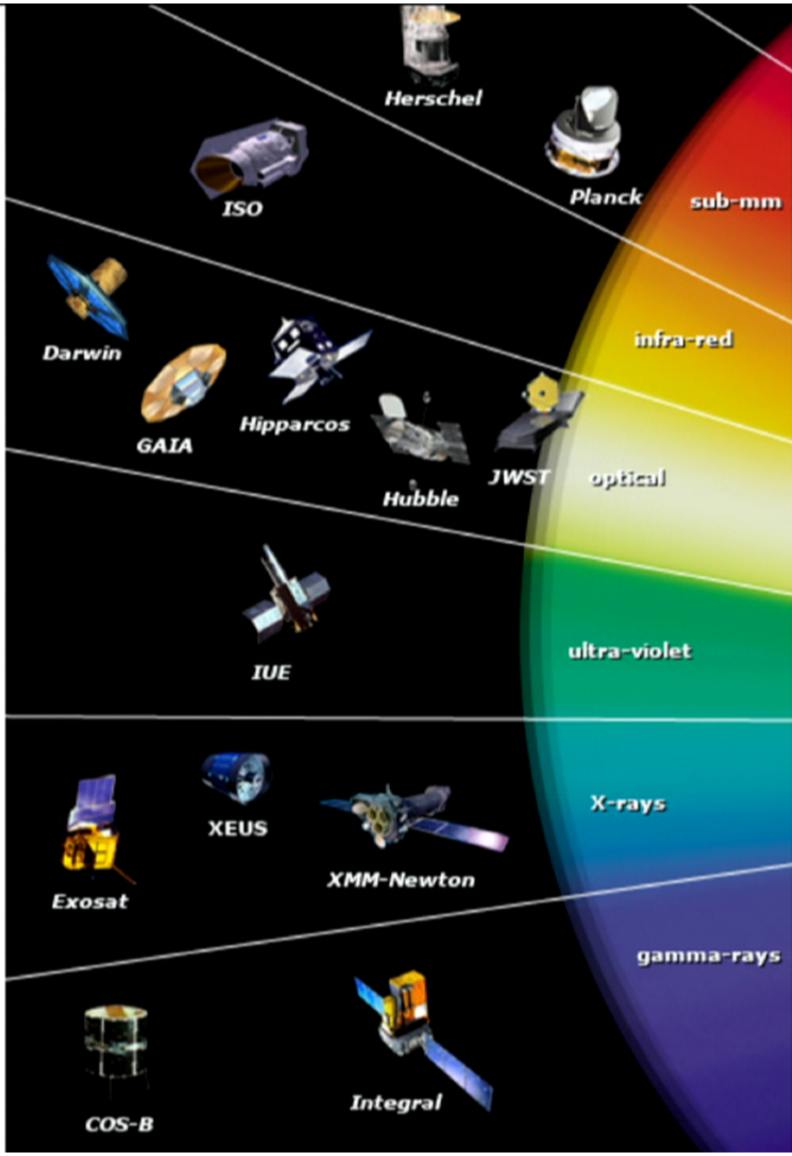


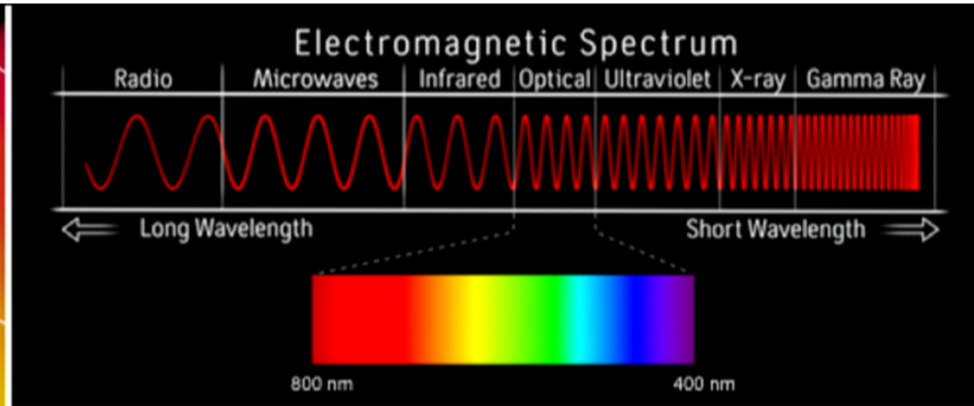

eccentric binaries
triple systems (w/ms PSR)
Solar-like third star
Orbit of thousands of years
①
White dwarf
Pulsar
95-day orbit
OR
②
Pulsar
Solar-like star
95-day orbit
[Ramson et al, Nature 2014]
src: NRAO images // Credit: Bill Saxton; NRAO/AUI/NSF
[van den Heuvel, Science 2008]

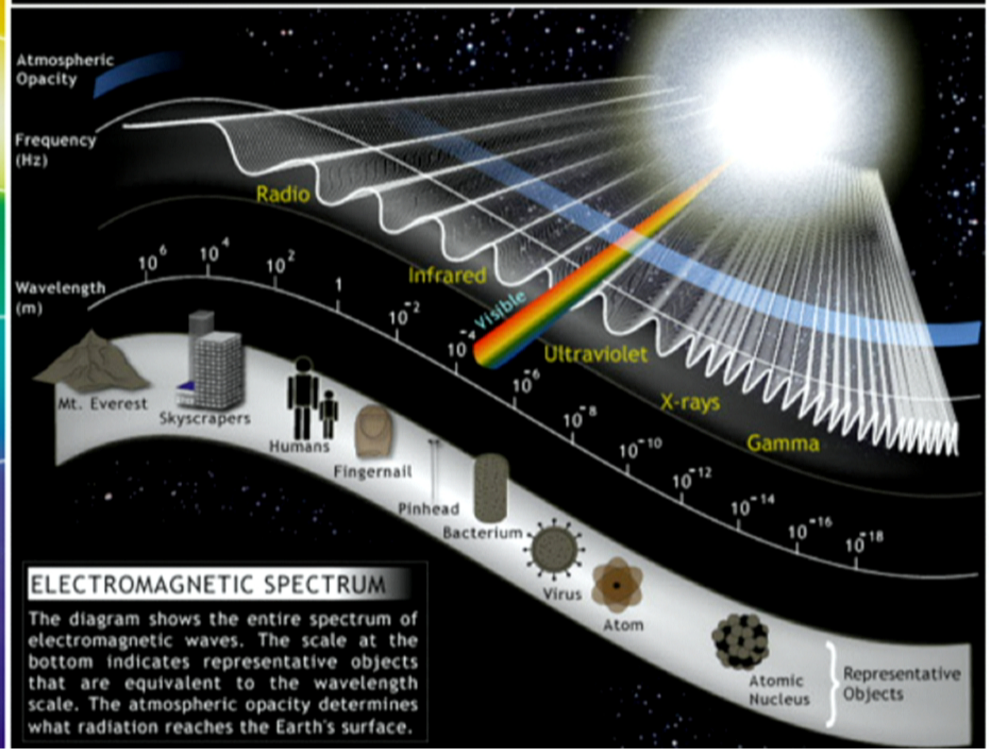
Electromagnetic & Gravitational Spectra

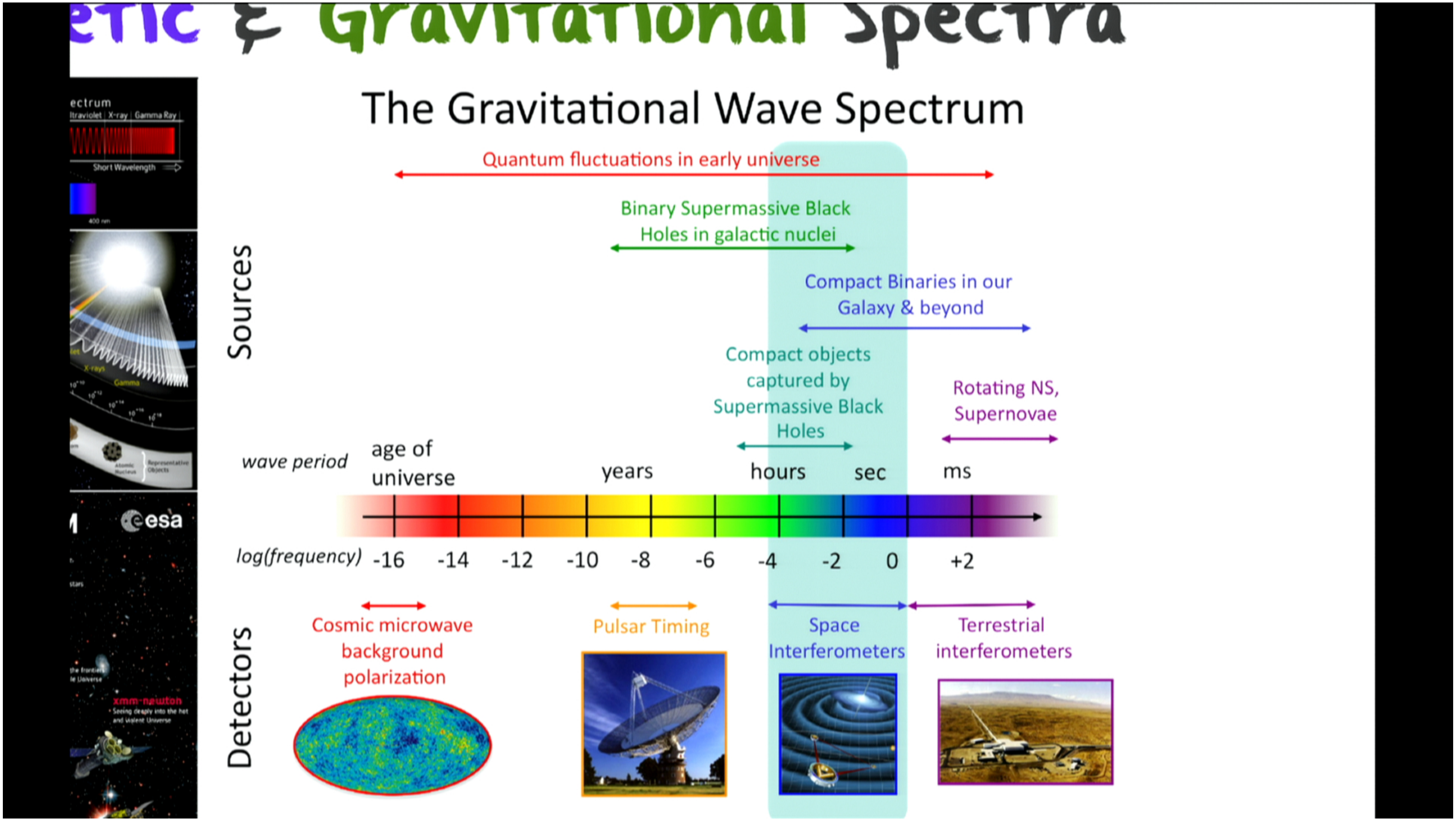





Herschel
ISO
Planck
sub-mm
Darwin
infra-red
GAIA
Hipparcos
Hubble
JWST
optical
IUE
ultra-violet
Exosat
XEUS
XMM-Newton
X-rays
gamma-rays
COS-B
Integral


Electromagnetic Spectrum
Radio
Microwaves
Infrared
Optical
Ultraviolet
X-ray
Gamma Ray
Long Wavelength
Short Wavelength
800 nm
400 nm


Atmospheric Opacity
Frequency (Hz)
Wavelength (m)
Radio
Infrared
Visible
Ultraviolet
X-rays
Gamma
10^6
10^4
10^2
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
Mt. Everest
Skyscrapers
Humans
Fingernail
Pinhead
Bacterium
Virus
Atom
Atomic Nucleus
Representative Objects
ELECTROMAGNETIC SPECTRUM
The diagram shows the entire spectrum of electromagnetic waves. The scale at the bottom indicates representative objects that are equivalent to the wavelength scale. The atmospheric opacity determines what radiation reaches the Earth's surface.


etic & Gravitational Spectra
The Gravitational Wave Spectrum
Quantum fluctuations in early universe
Binary Supermassive Black Holes in galactic nuclei
Compact Binaries in our Galaxy & beyond
Compact objects captured by Supermassive Black Holes
Rotating NS, Supernovae
Sources
wave period
age of universe
years
hours
sec
ms
log(frequency)
-16
-14
-12
-10
-8
-6
-4
-2
0
+2
Detectors
Cosmic microwave background polarization
Pulsar Timing
Space Interferometers
Terrestrial interferometers
esa

Simulations

Images: MPA, GSFC

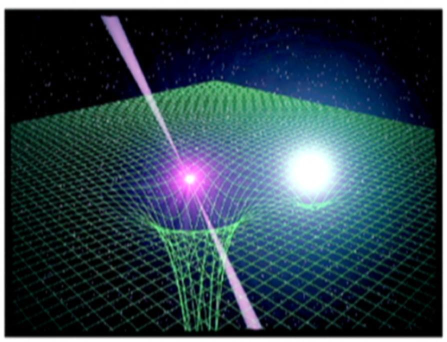
 Simulations 

* Einsteins eqns of General Relativity (GR)

Images: MPA, GSFC

Simulations

* Einsteins eqns of General Relativity (GR)

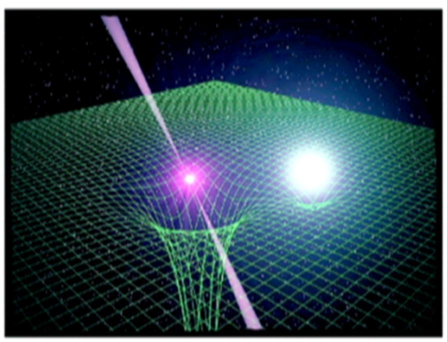


Images: MPA, GSFC

Simulations

* Einsteins eqns of General Relativity (GR)

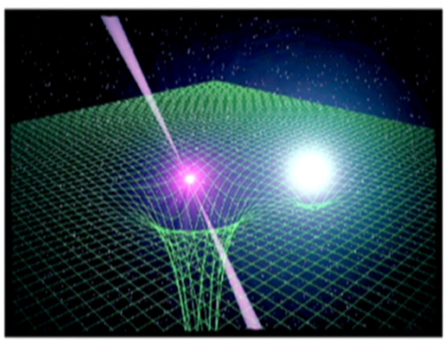
* hydro. eqns. ("fluid")



Images: MPA, GSFC

Simulations

* Einsteins eqns of General Relativity (GR)
* hydro. eqns. ("fluid")
* electromagnetic (Maxwell) eqns.



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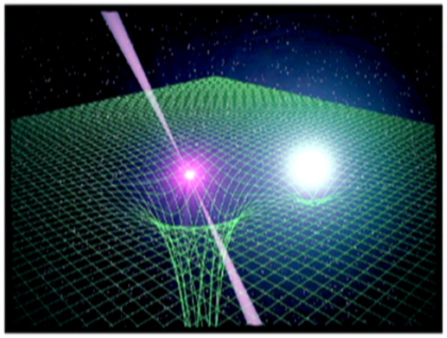

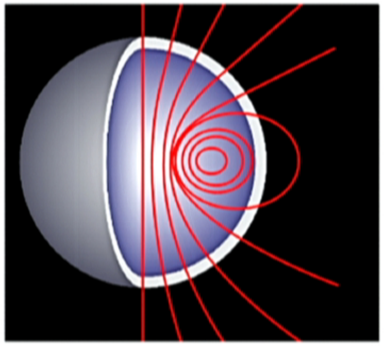

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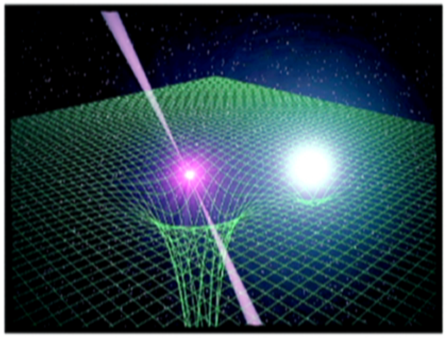

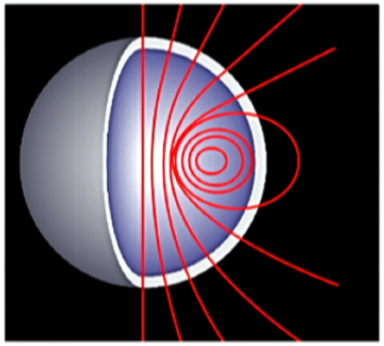

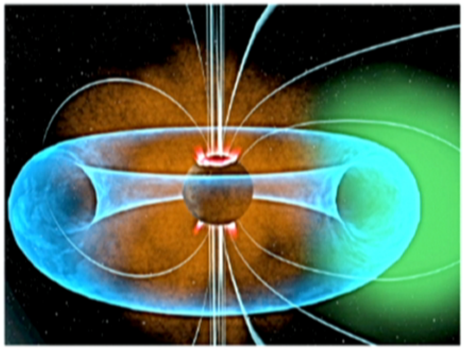

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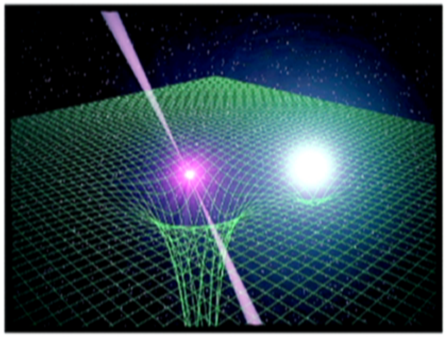
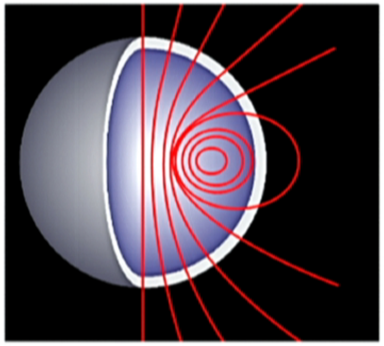
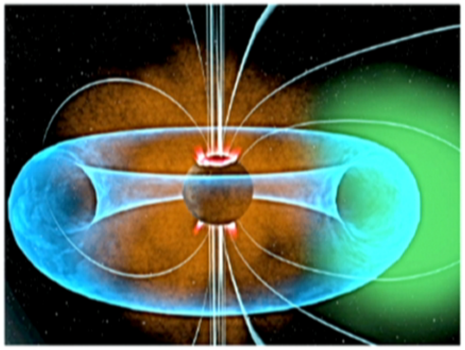
==> GR+MHD ----> GRrMHD







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 Simulations 

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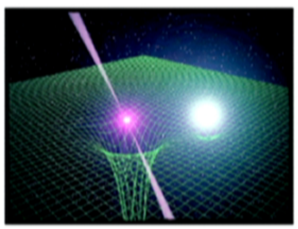
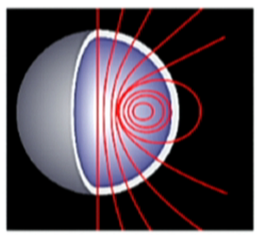
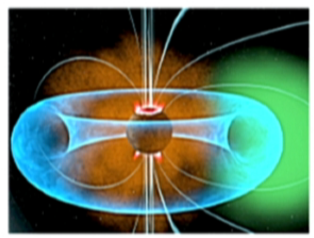
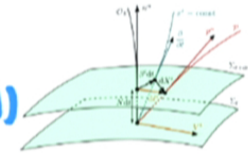
  

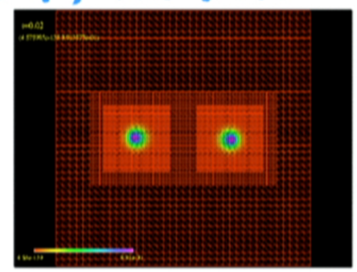
Images: MPA, GSFC.

> 3+1 (BSSN)



> 4th order finite diff.

> AMR, via HAD

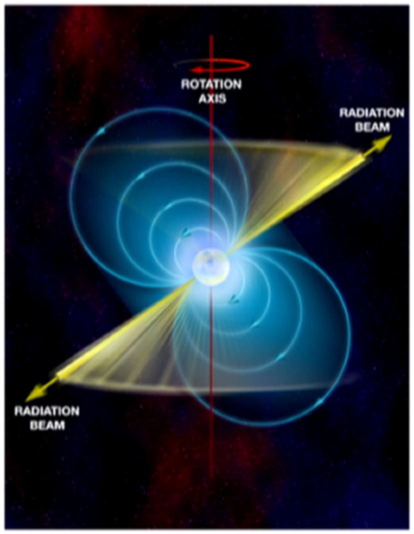


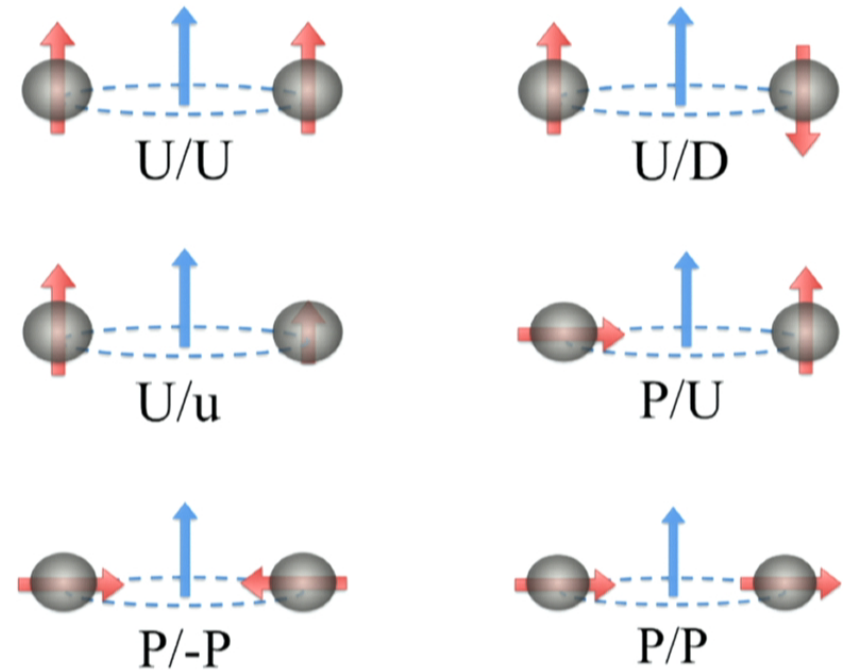
> HRSC (fluid)

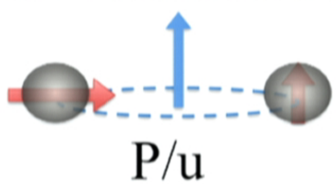
> IMEX: 3rd order R-K time integ.

~ 30 batches x 48 hs x 200 nodes = 300,000 SUs [~ 2 months] (on gpc@Scinet)

>>> configurations studied

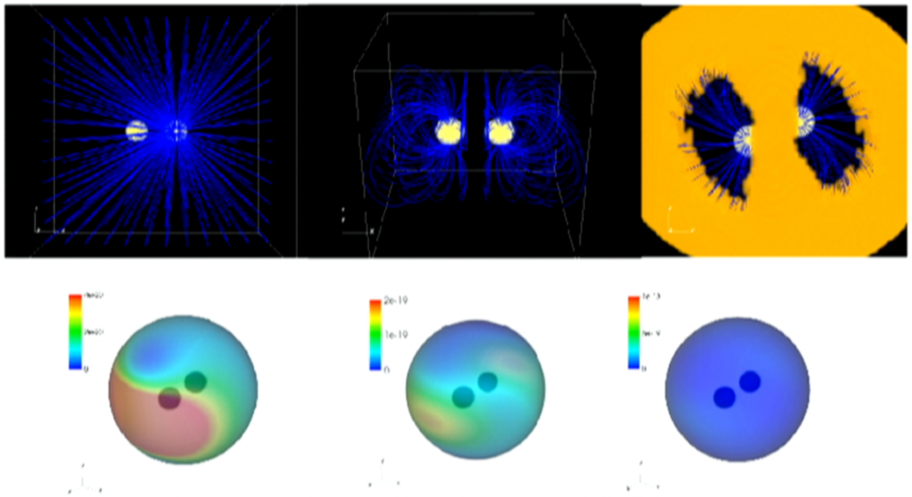






[Palenzuela, Lehner, MP et al., **PRL (2013)**; **PRD (2013)**;
MP, Palenzuela, Lehner, Liebling (**2014**)]

///*** Results ***///



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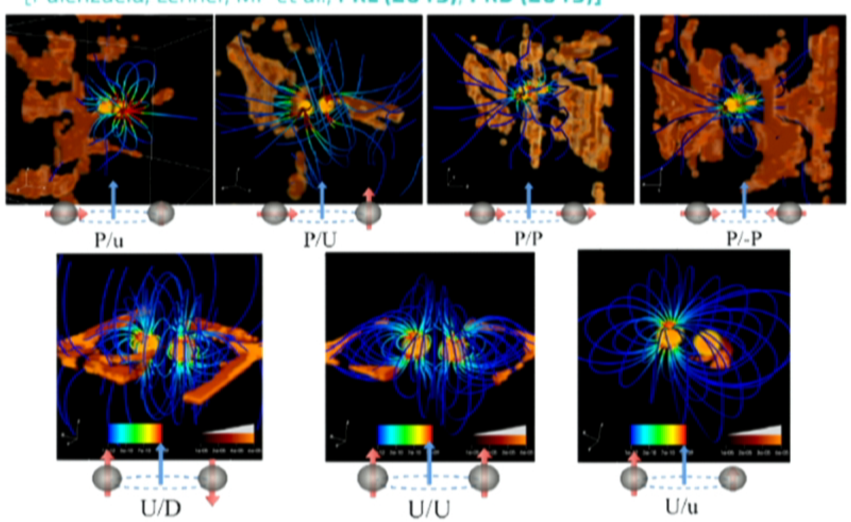
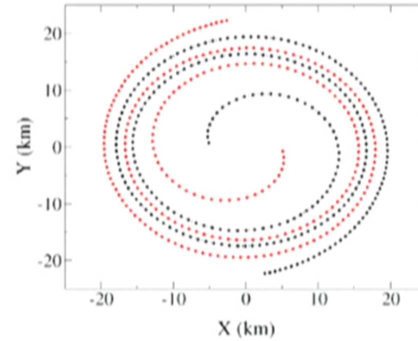
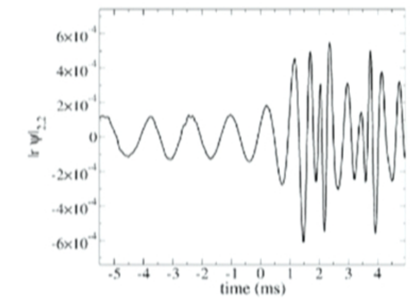
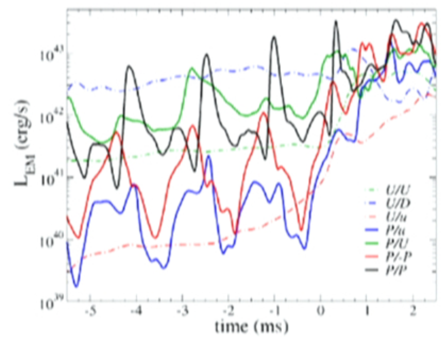
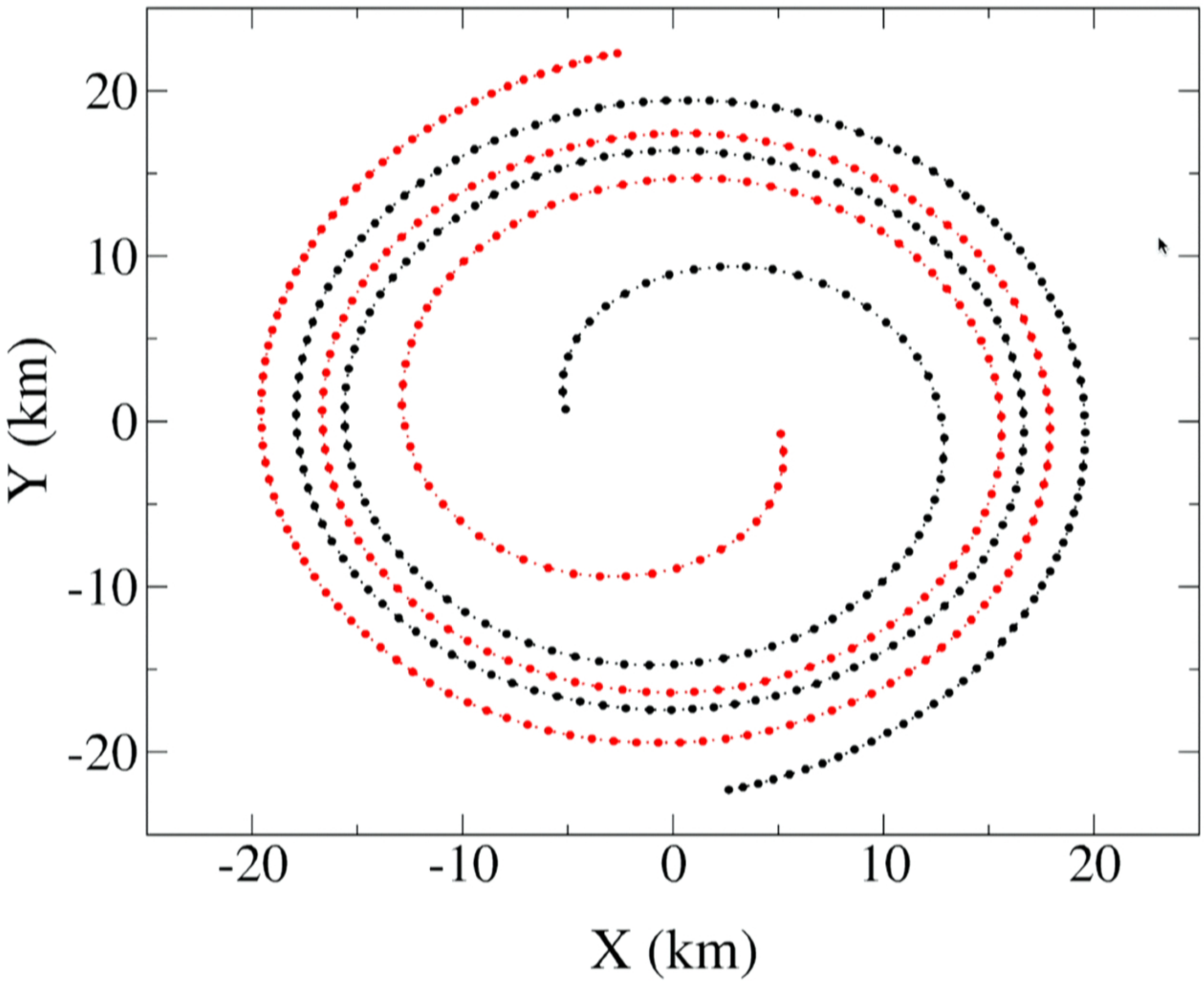


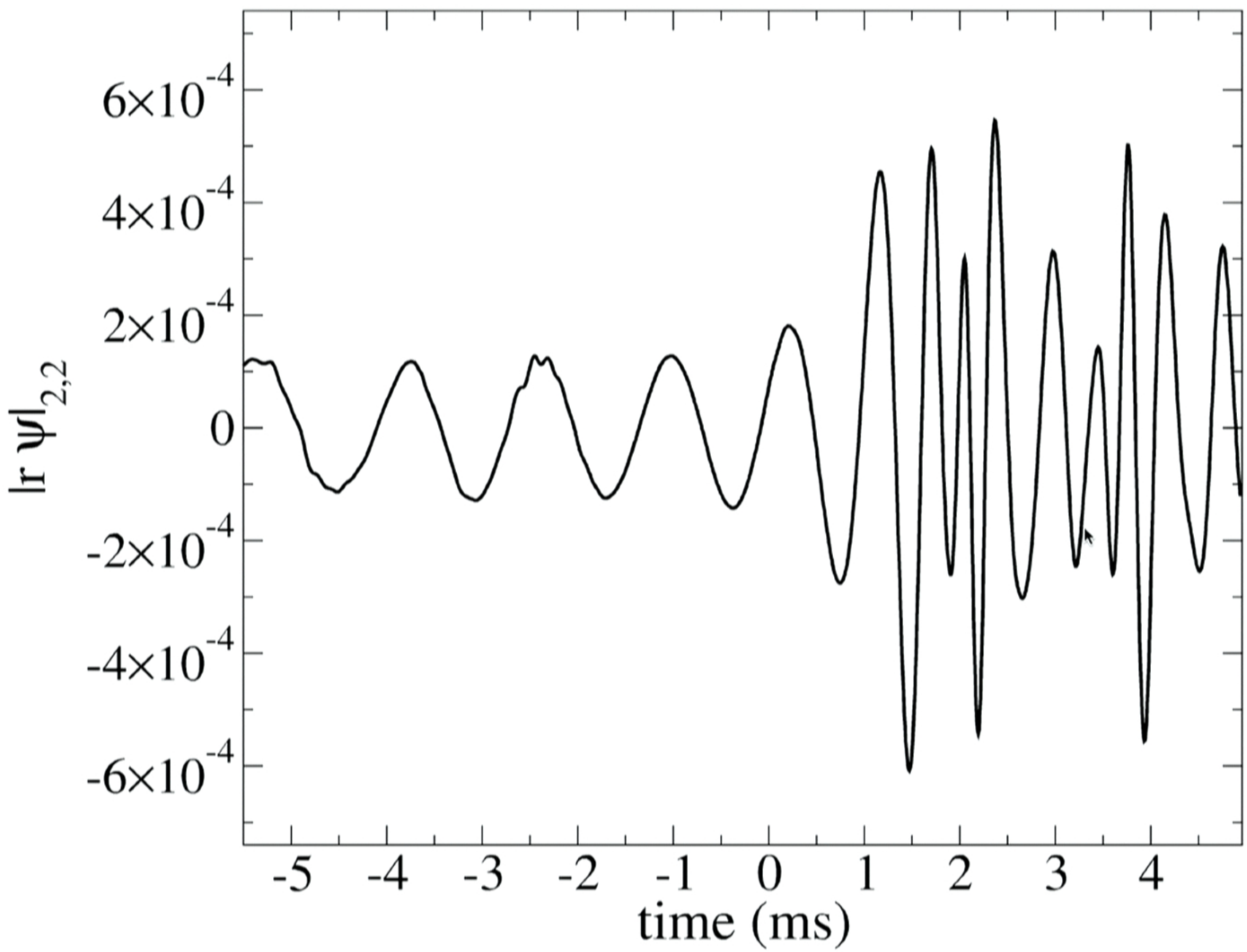




[MP, Palenzuela, Lehner, Liebling (**2014**)]

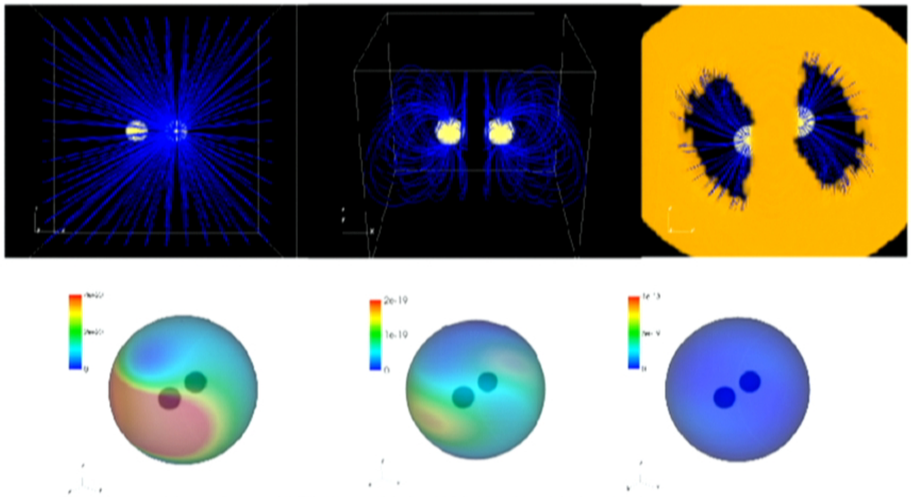



20
10
0
-10
-20
Y (km)
-20
-10
0
10
20
X (km)

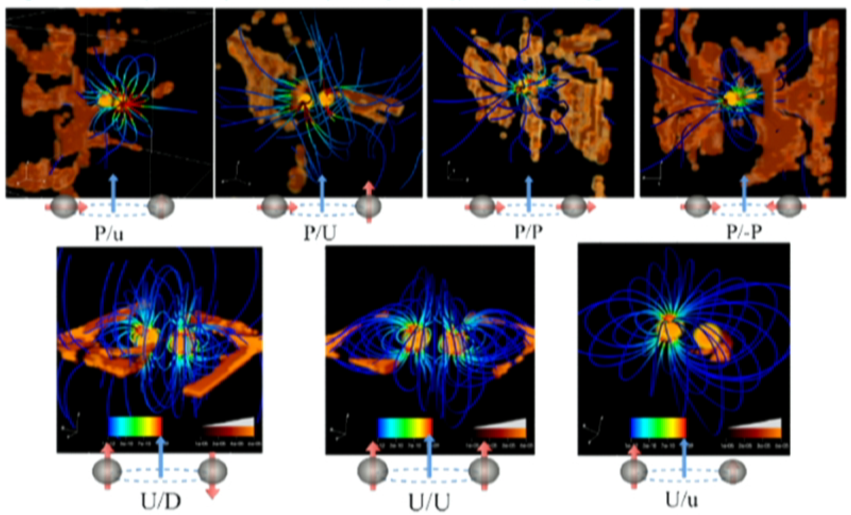


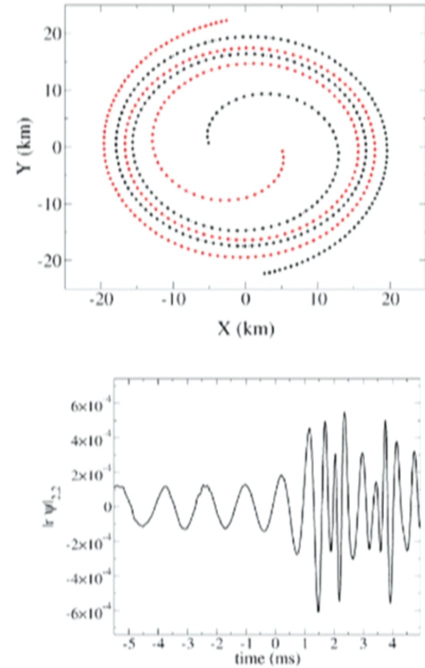
6×10^{-4}
4×10^{-4}
2×10^{-4}
0
-2×10^{-4}
-4×10^{-4}
-6×10^{-4}
$|r\,\psi|_{2,2}$
-5 -4 -3 -2 -1 0 1 2 3 4
time (ms)

///*** Results ***///



[Palenzuela, Lehner, MP et al., **PRL (2013)**; **PRD (2013)**]





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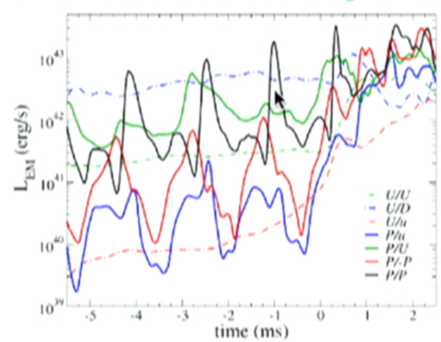
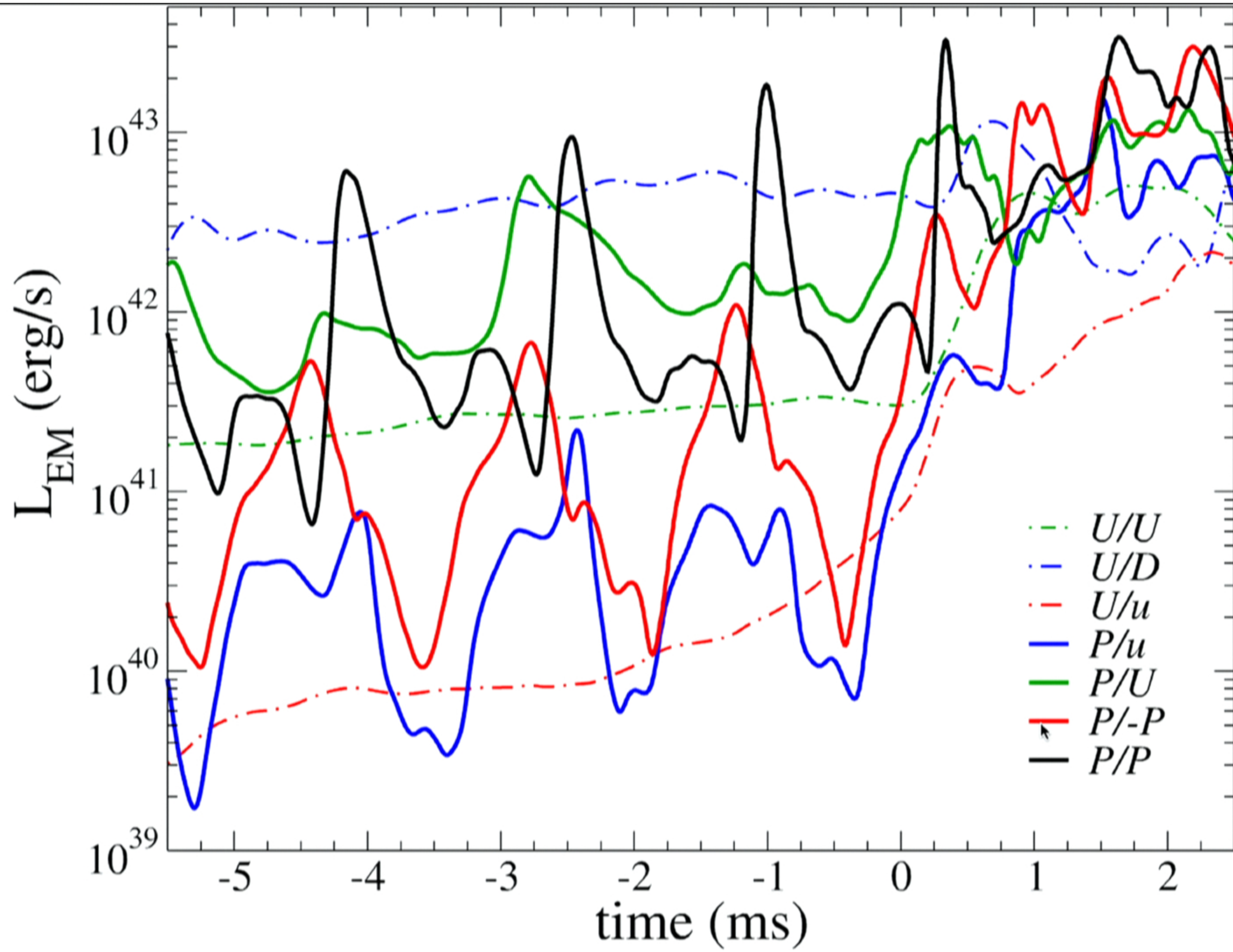
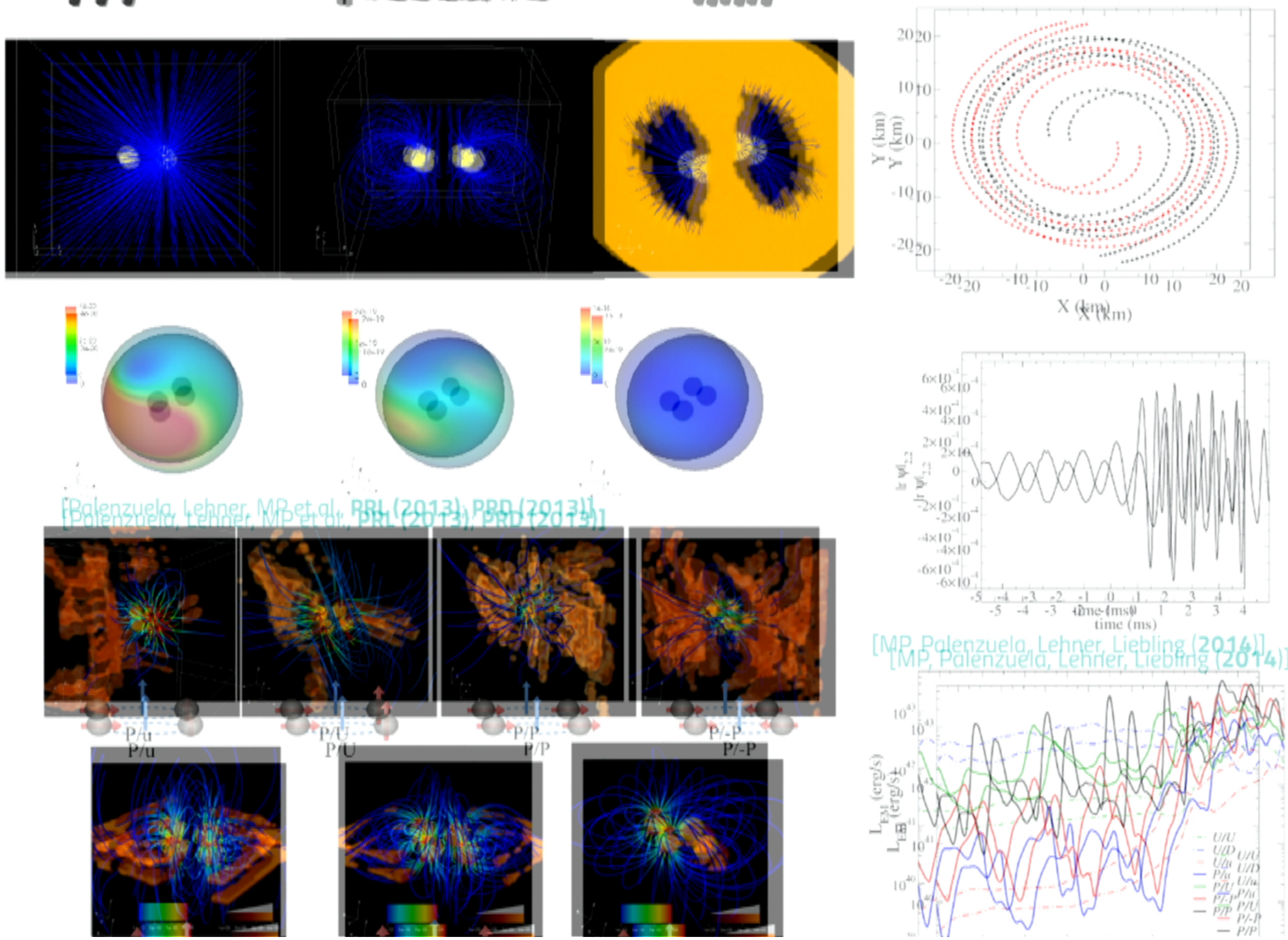




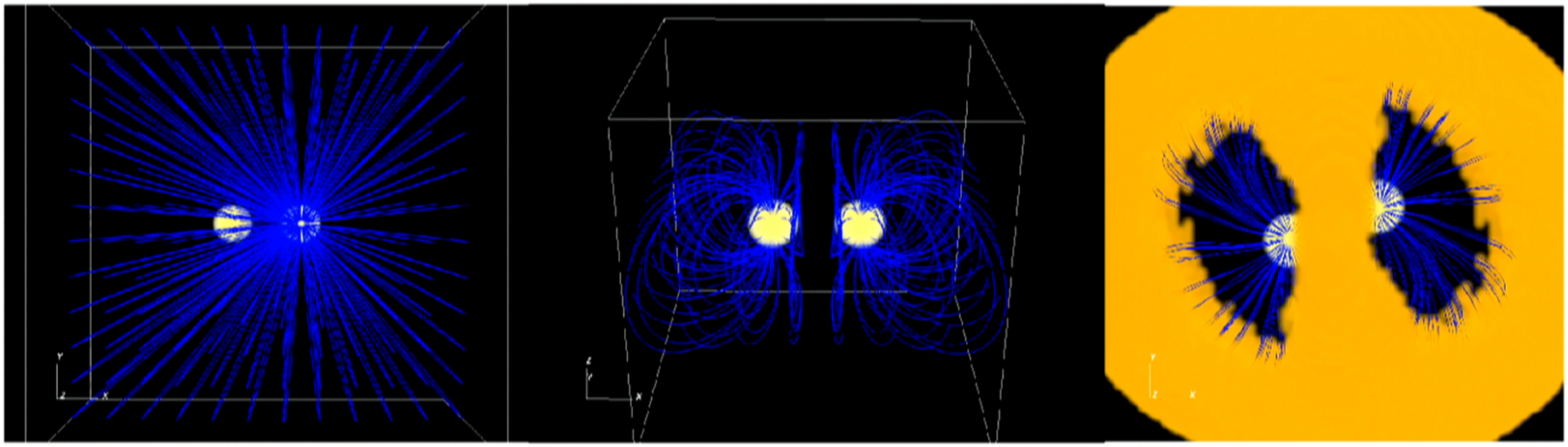
L_{EM} (erg/s)
10^{43}
10^{42}
10^{41}
10^{40}
10^{39}
-5
-4
-3
-2
-1
0
1
2
time (ms)
U/U
U/D
U/u
P/u
P/U
P/-P
P/P

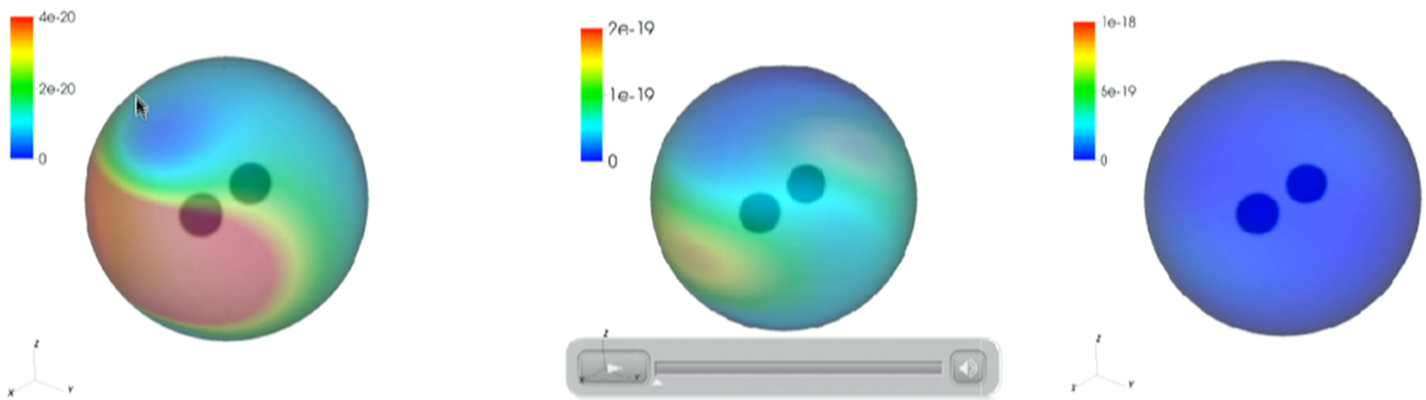
///### Results ###//////



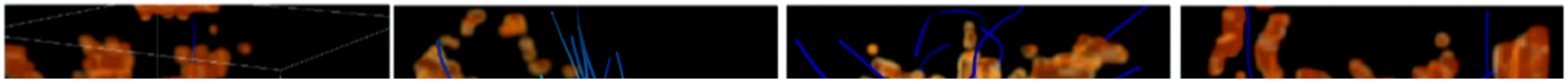
[Palenzuela, Lehner, MP et al. PRL (2013), PRD (2013)]

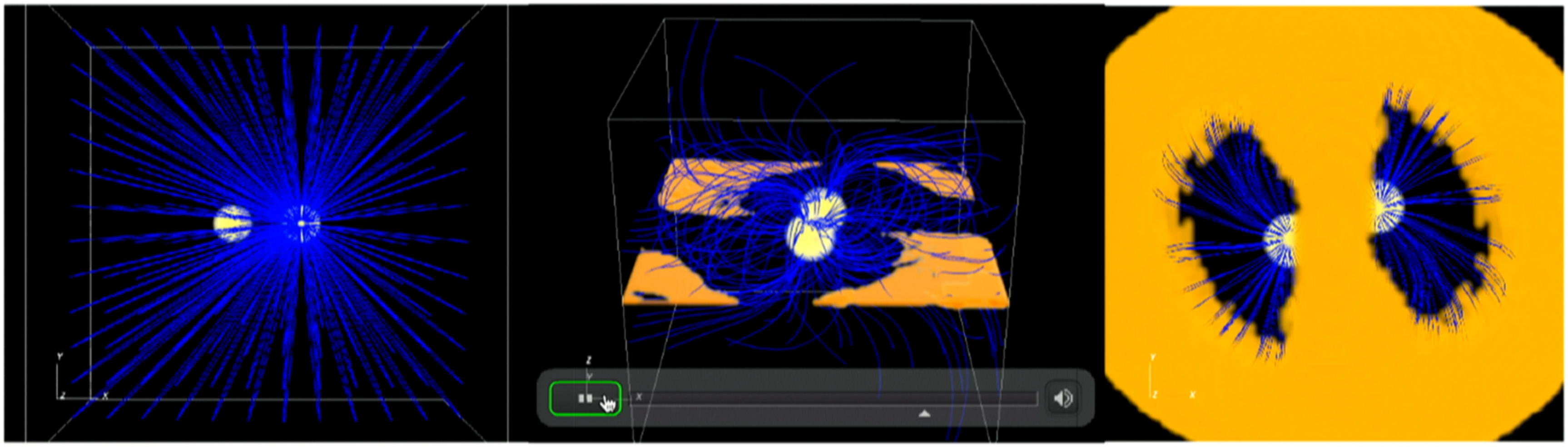
[MP, Palenzuela, Lehner, Liebling (2014)]

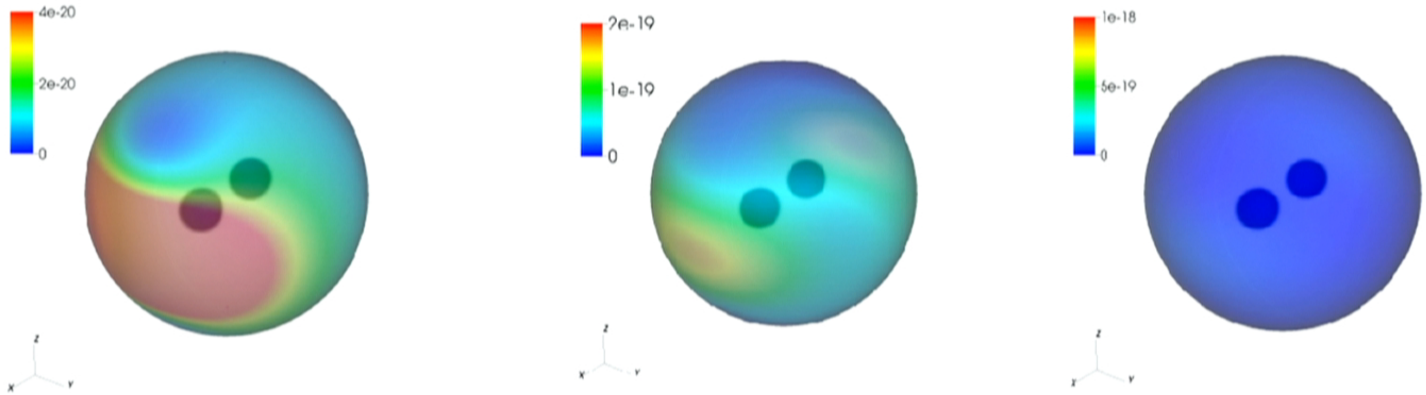




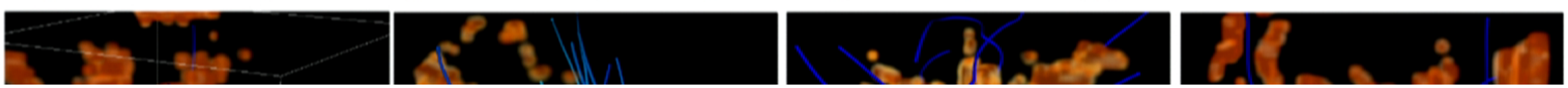
[Palenzuela, Lehner, MP et al., **PRL (2013)**; **PRD (2013)**]







[Palenzuela, Lehner, MP et al., **PRL (2013)**; **PRD (2013)**]



Conclusions

* Simulate dynamics & magnethosperic interactions in BNS, by solving GR-rMHD eqns
* magnetospheric interactions extract kinetic energy, powering a strong Poynting flux
* pre-merger counterparts EM/GW
* test alternative theories of gravity

Collaborators

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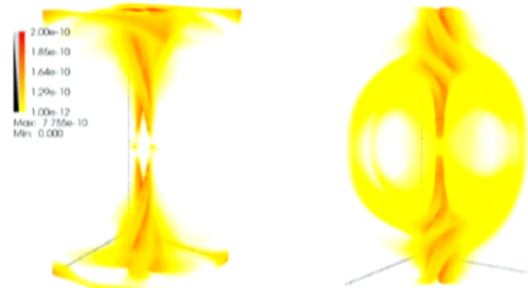
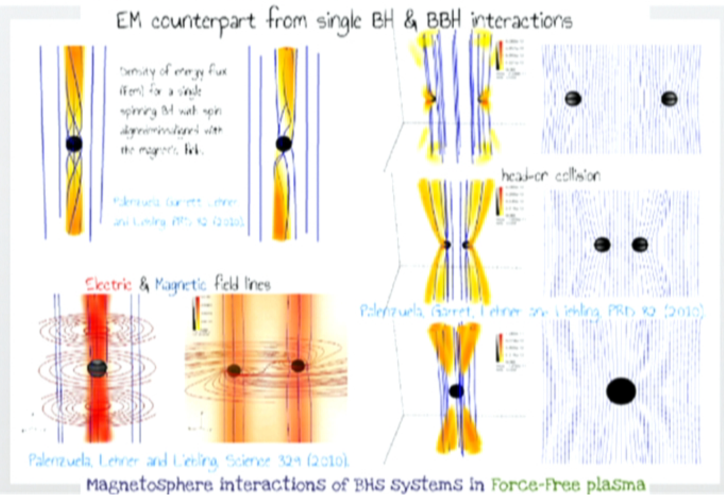
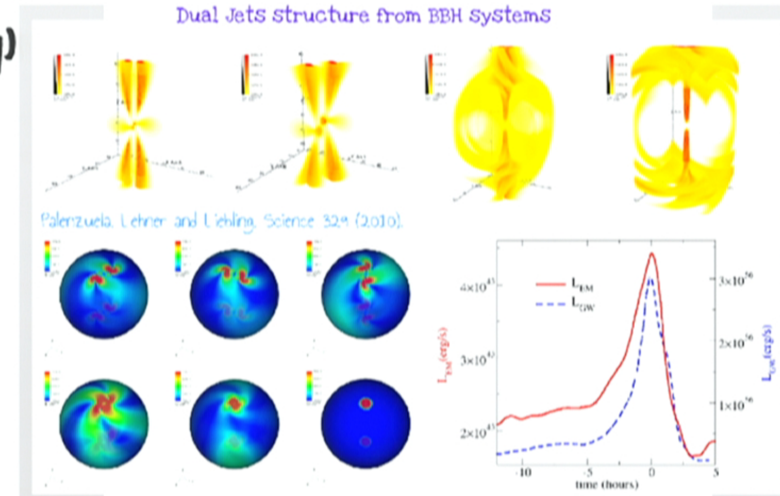


Palenzuela, Garret, Lehner and Liebling
PRD 82 (2010)





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