ERGOG

Gamma-ray emission from the coalescence of binary neutron stars: an electromagnetic counterpart of gravitational radiation

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PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

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PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Stephen Green

Ryan Westernacher-Schneider

Plan of the talk

1. Motivation

- The role of electromagnetic (EM) counterparts
- EM counterparts of binary systems mergers
- Short Gamma-ray Bursts afterglows

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- Light curves
- Pulsar configuration
- Magnetosphere models

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5. Summary

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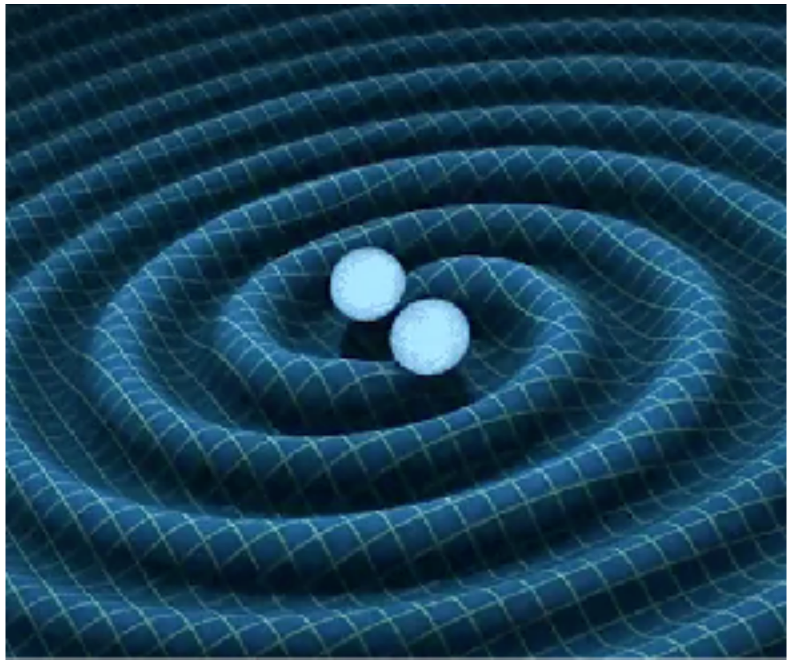
- The role of electromagnetic (EM) counterparts

Gravitational/EM radiation sources

LIGO Scientific Collaboration (LSC) started the era of gravitational wave (GW) astronomy.



Credit: LSC

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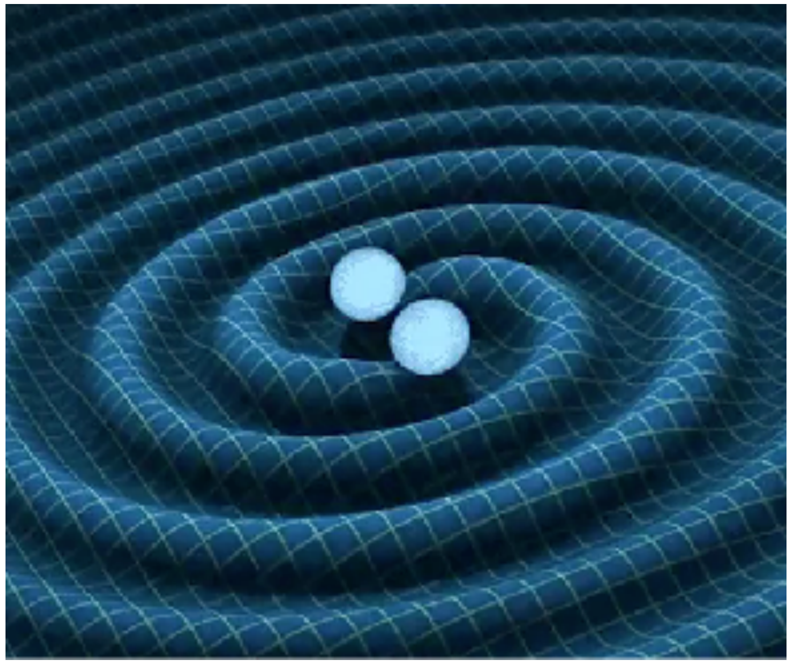

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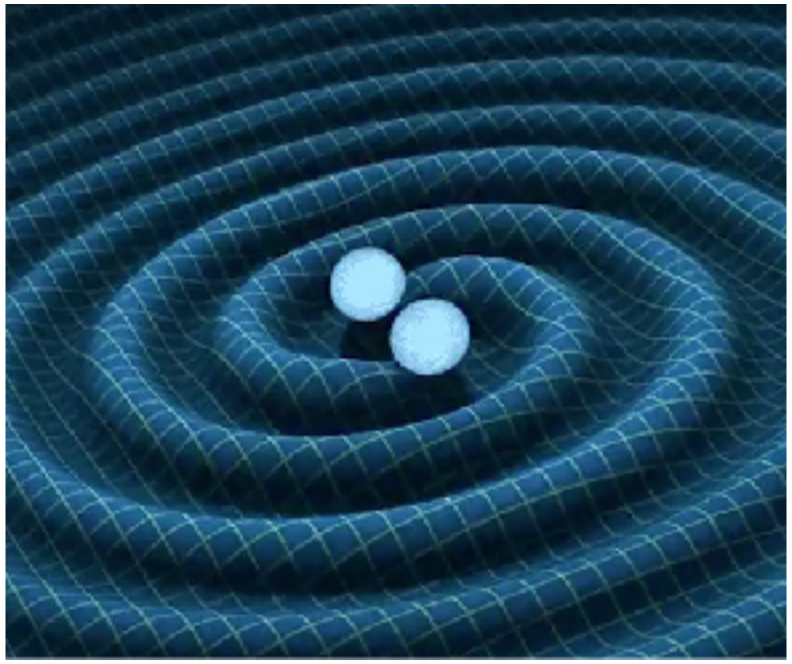

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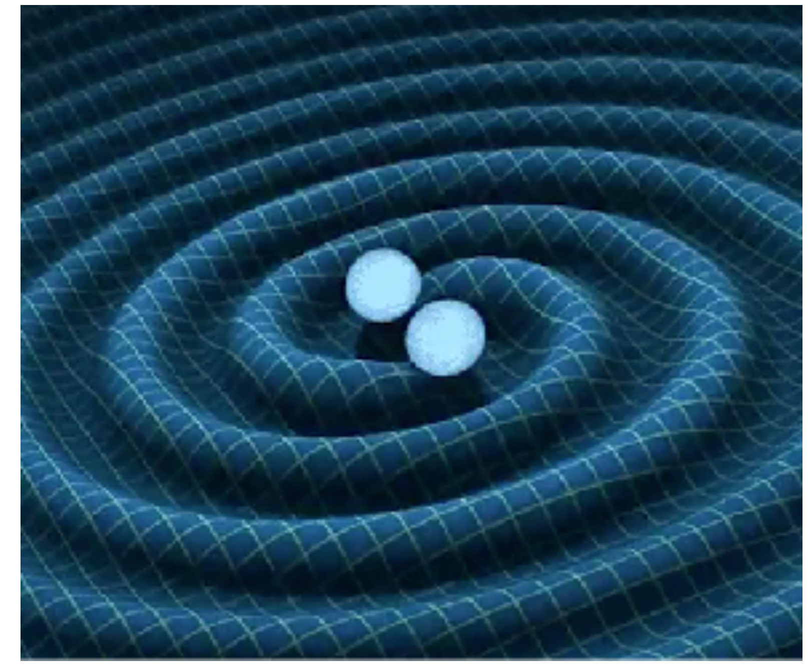

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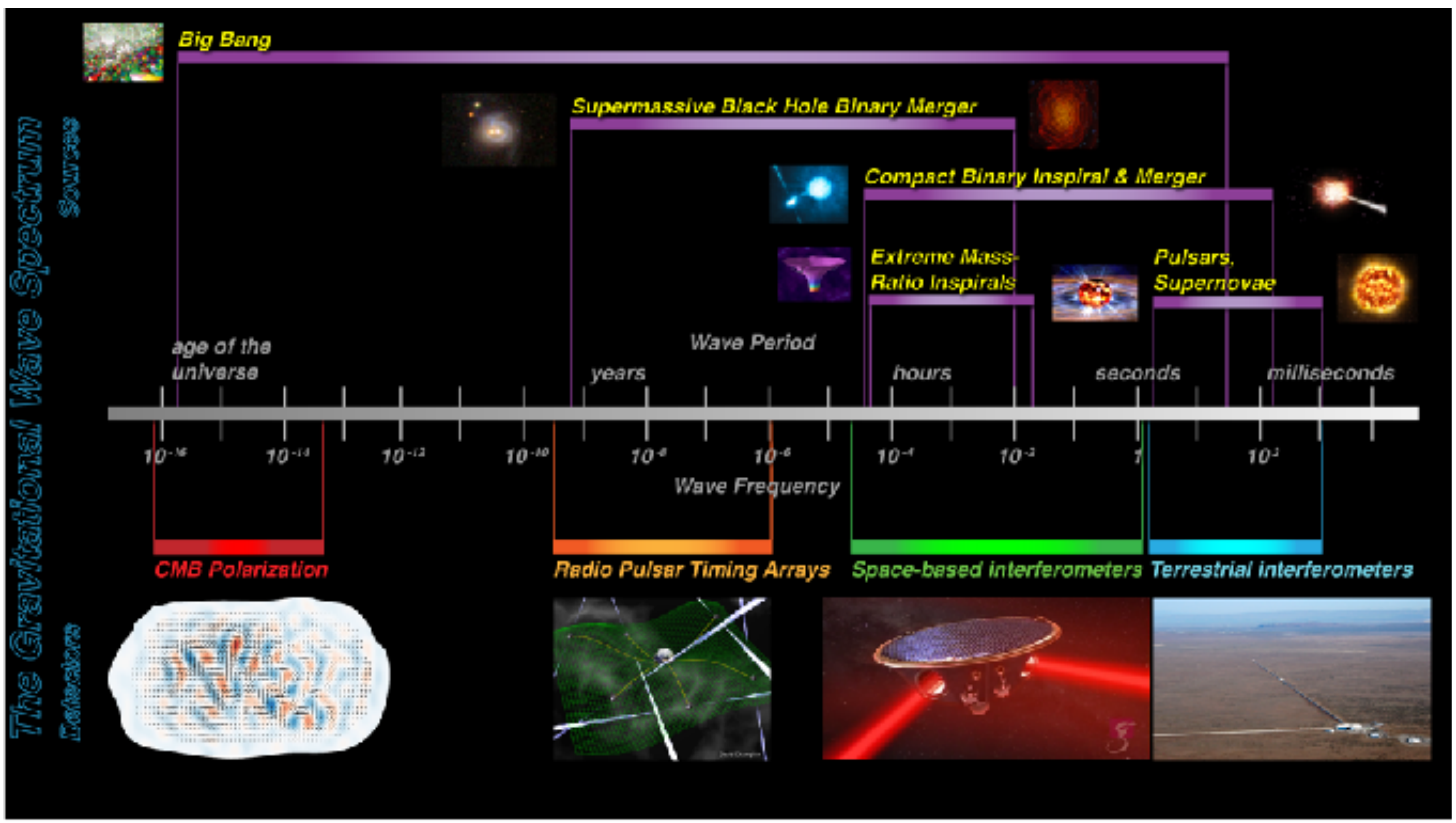

Credit: NASA/J. I.Thorpe

- The GW spectrum is wide
- More detectors needed
- Complementary data needed

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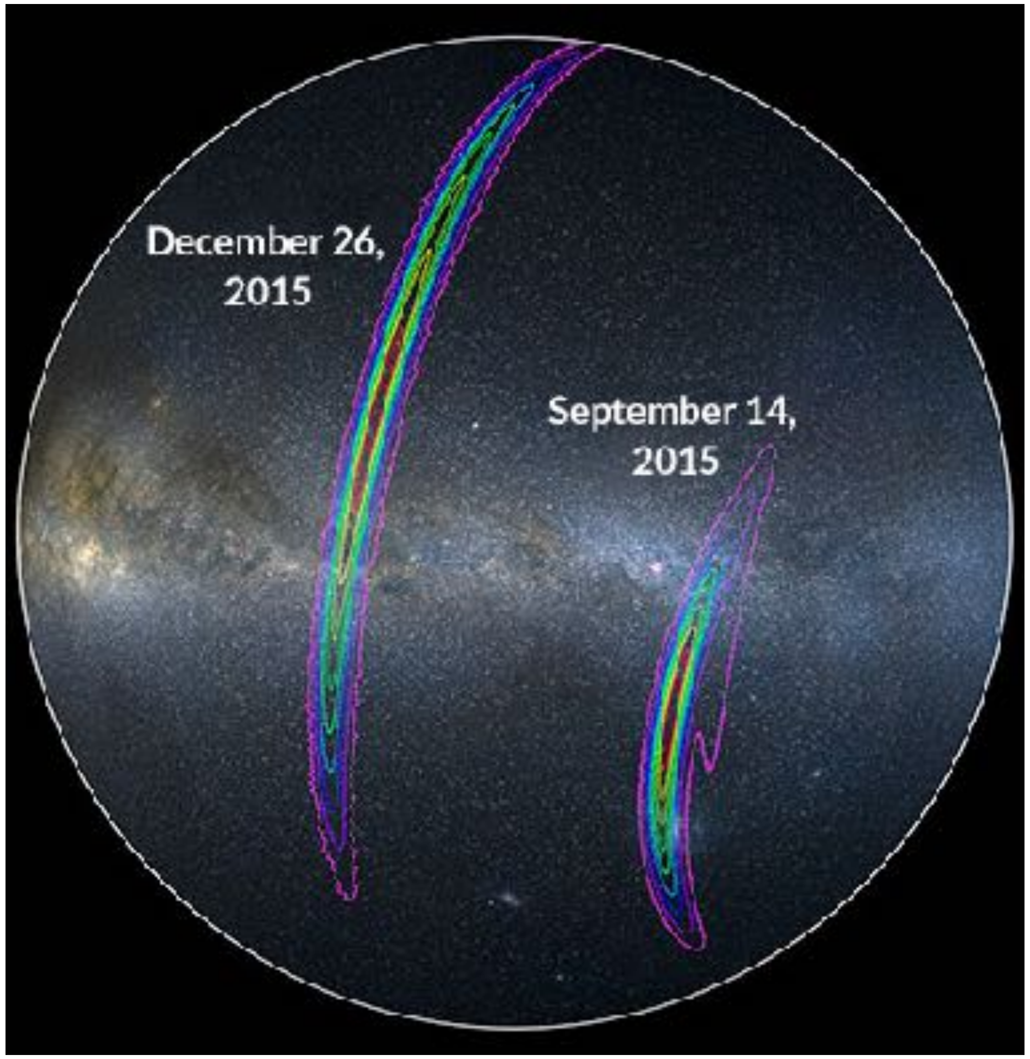
The location problem of binary systems mergers

Two interferometers are not enough to precisely locate sources



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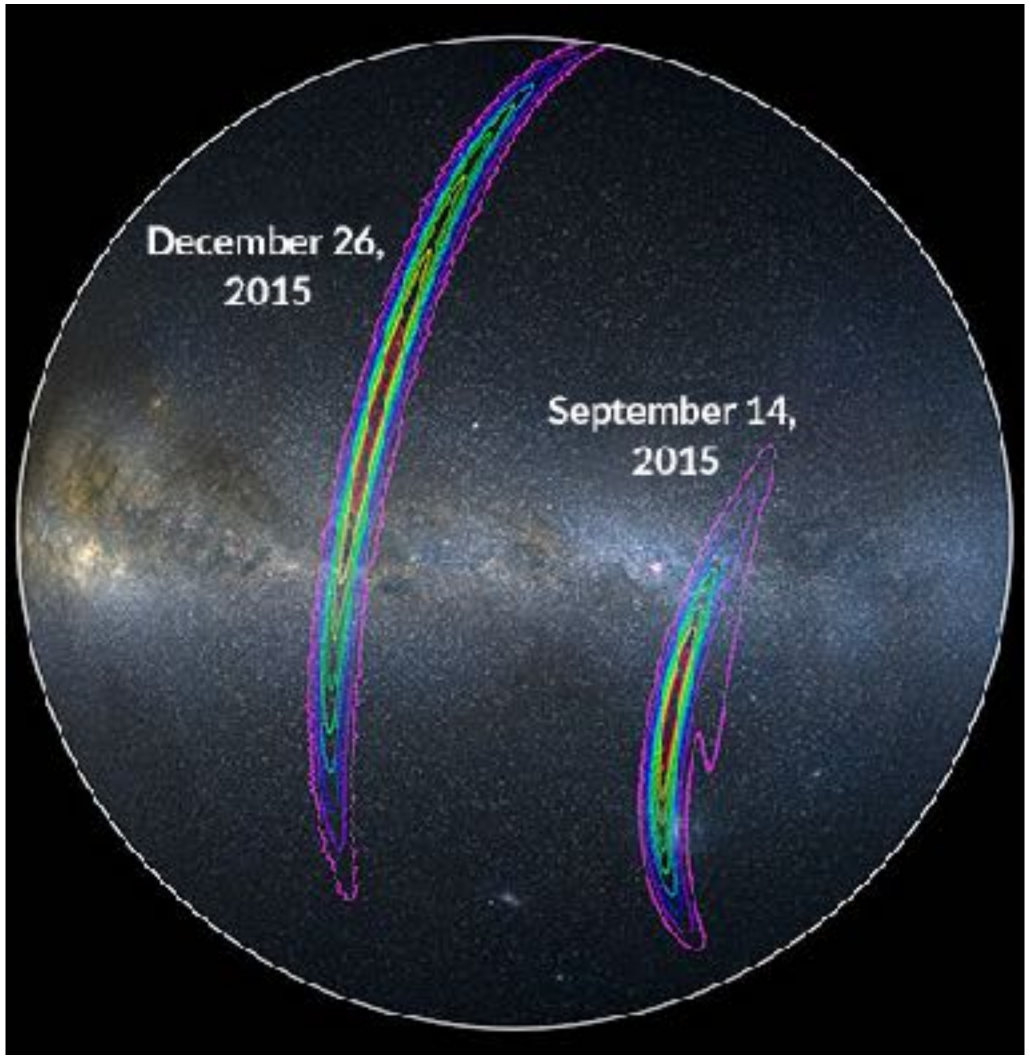

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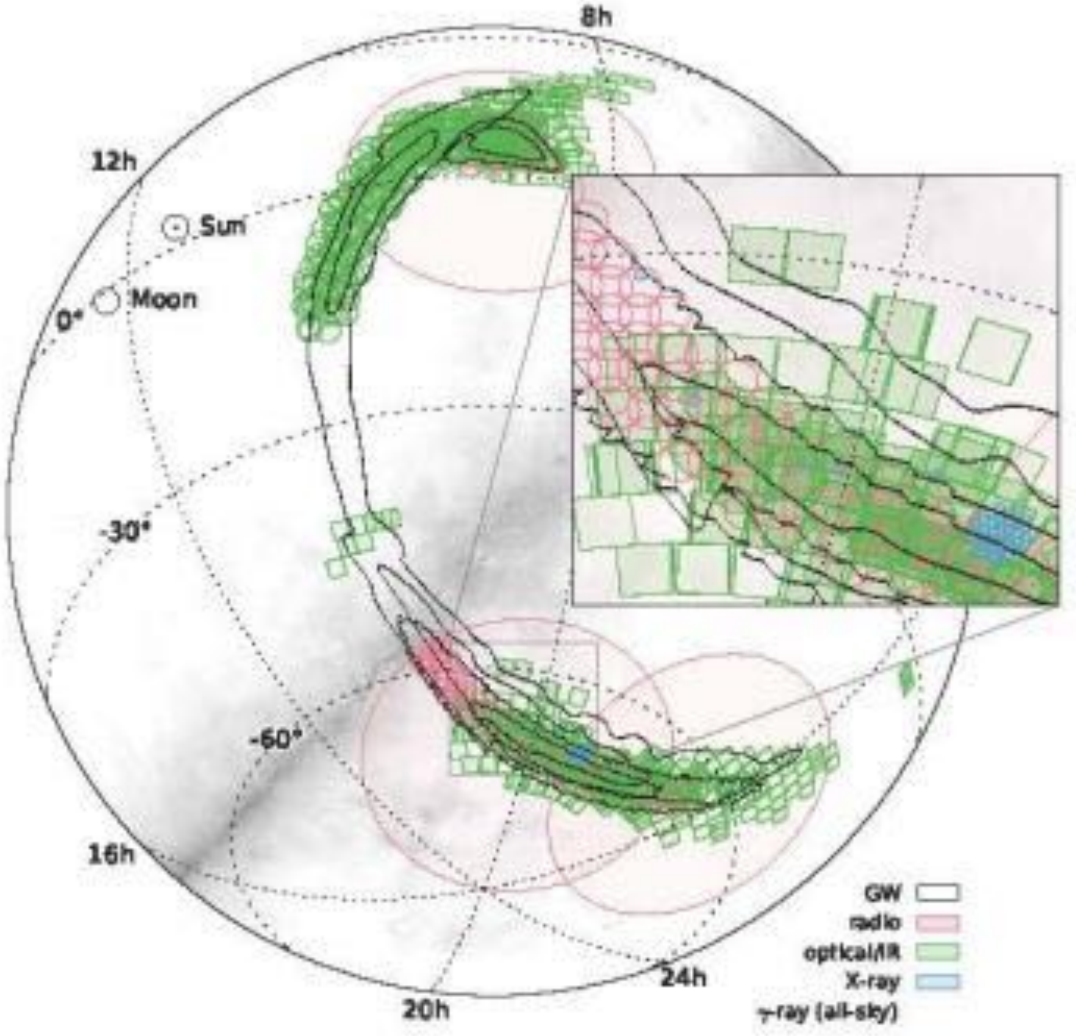

[Abbott et al, 2016]

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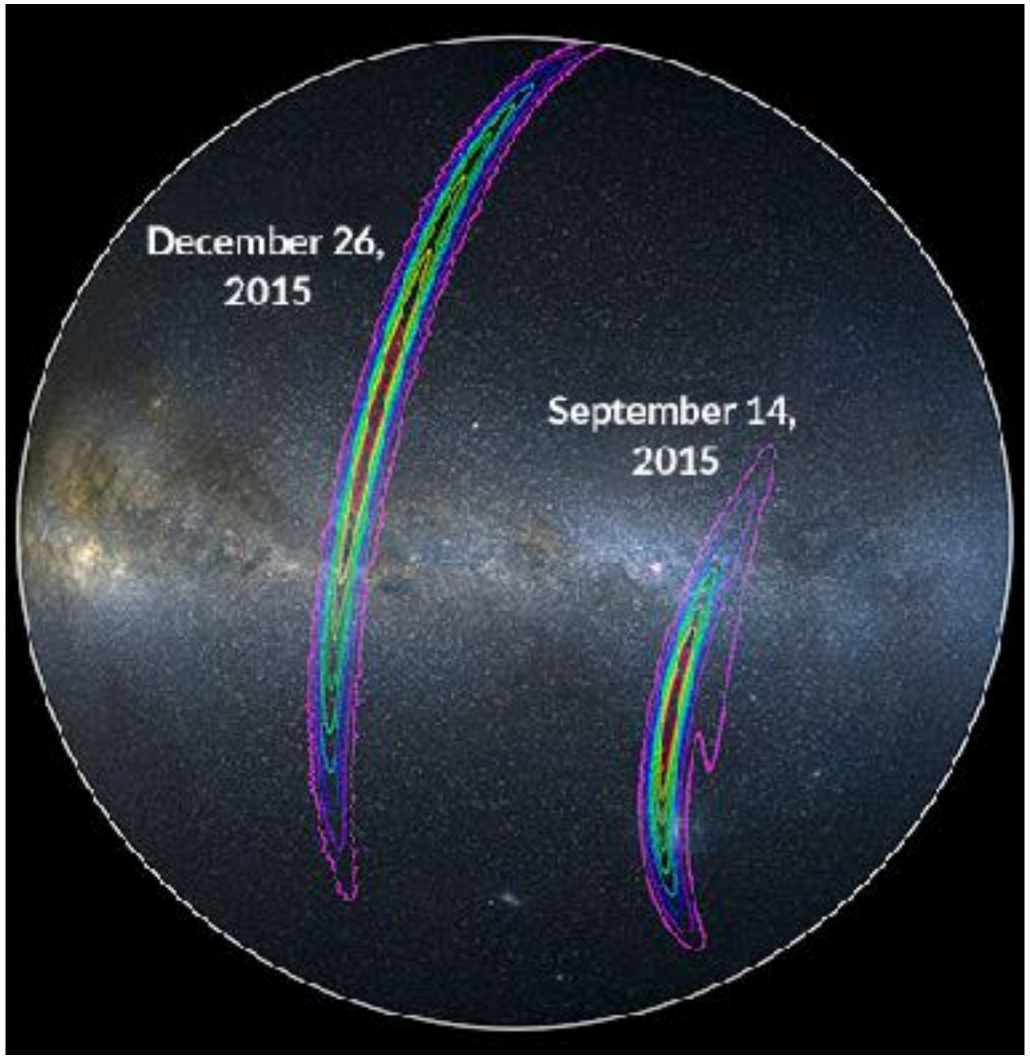

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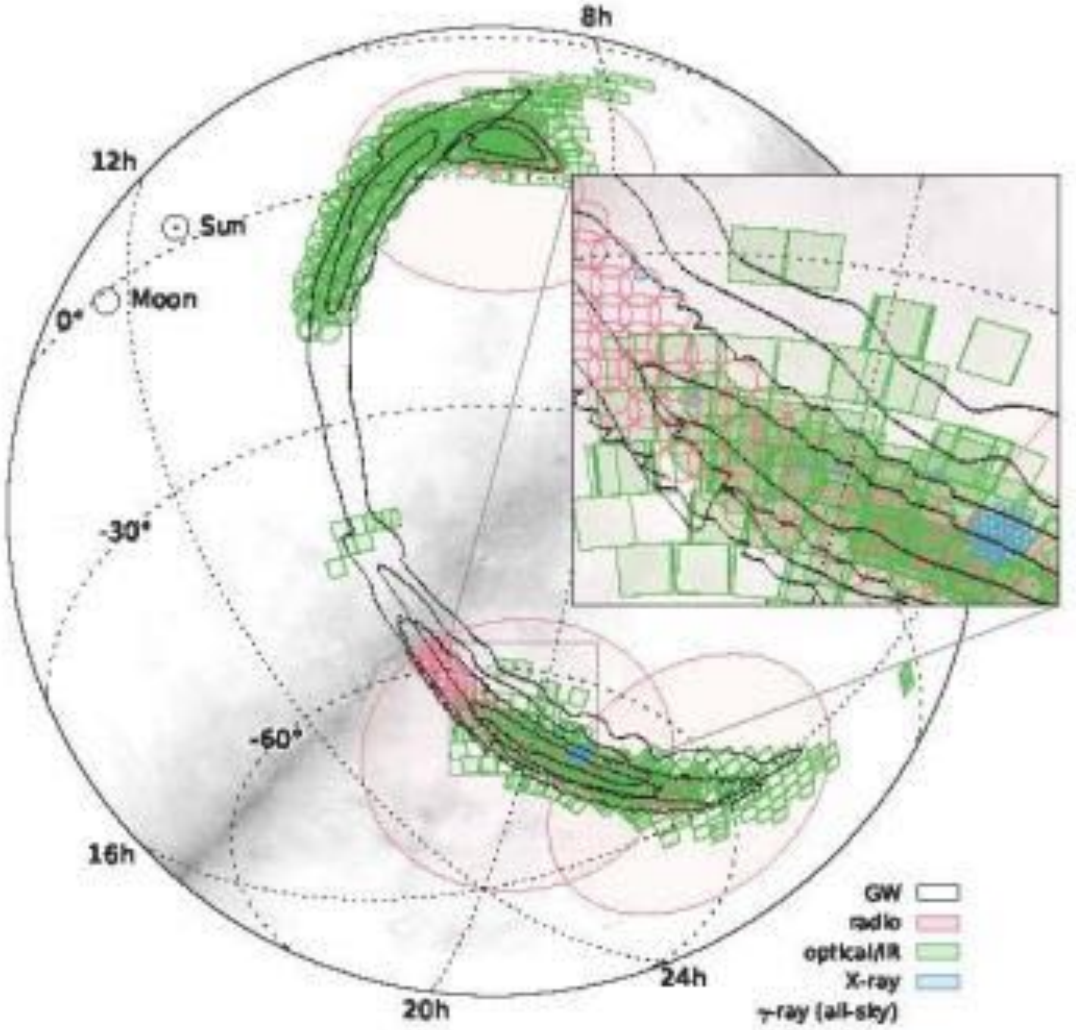

[Abbott et al, 2016]

EM counterparts to gravitational radiation will definitely help characterize/identify/locate sources

(see next talk by Ramiro Franco)

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Binary NS-NS/BH-NS mergers

In the target of aLIGO interferometers

Prime EM counterpart candidates:

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Prime EM counterpart candidates:

1. **Short Gamma-Ray Bursts (SGRBs)** → **Associated afterglows**
   - **1.1 X-Ray**
   - **1.2 Optical**
   - **1.3 Radio**
2. **Orphan afterglows in radio/optical bands**
3. **Kilonovae**

(Will discuss some pros and cons in a bit)

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Associated afterglows
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Part of the relevance:

- Astrophysical environment information
- Heavy r-process ion nucleosynthesis
- Independent constraints of system parameters
- Constraints on NS Equation of State (EoS)

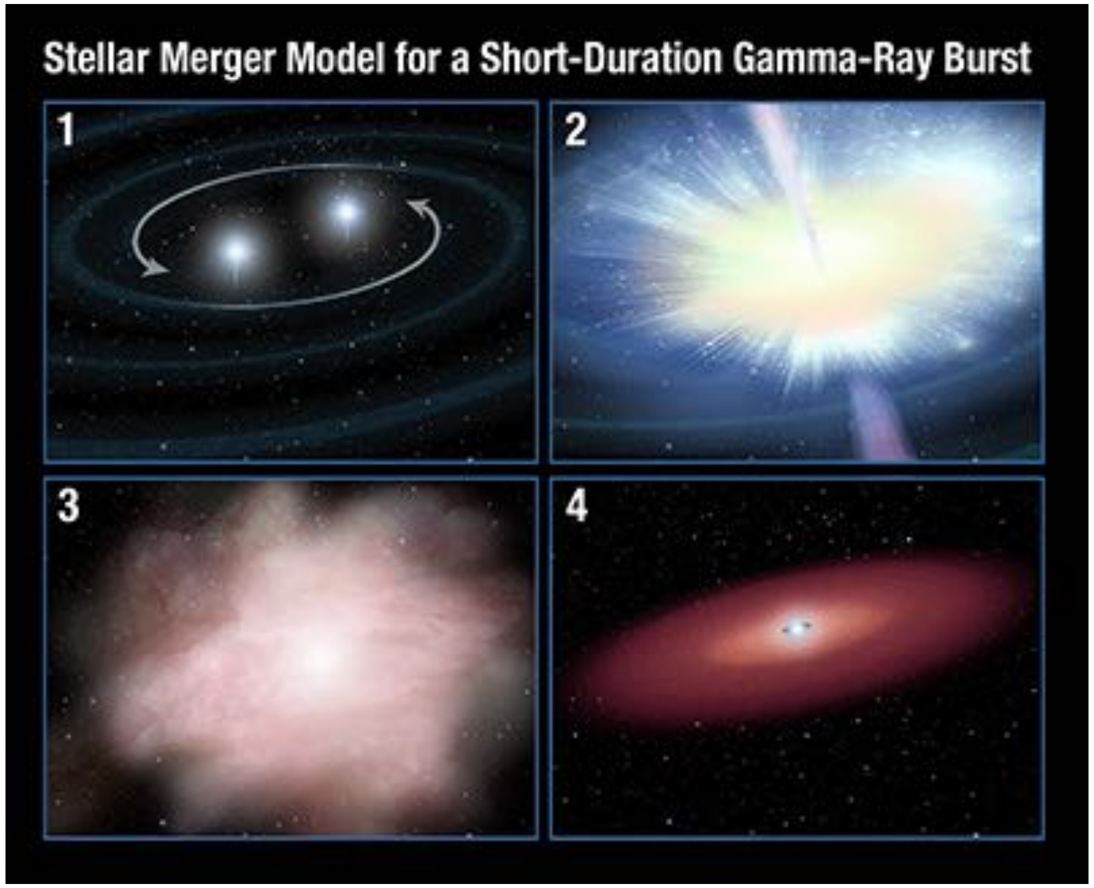
1. Motivation

- EM counterparts of binary mergers

1. Short Gamma-Ray Bursts (SGRBs)

- Relativistic ejecta along rotation axis
- Less that 2 sec duration

Leading idea: After NS-NS/BH-NS merger, accretion onto newly formed BH can lead to bright Gamma-ray emission. Possible similarity with Supernovae Ia mechanism. [Rezzolla et al 2010]



Credit: NASA

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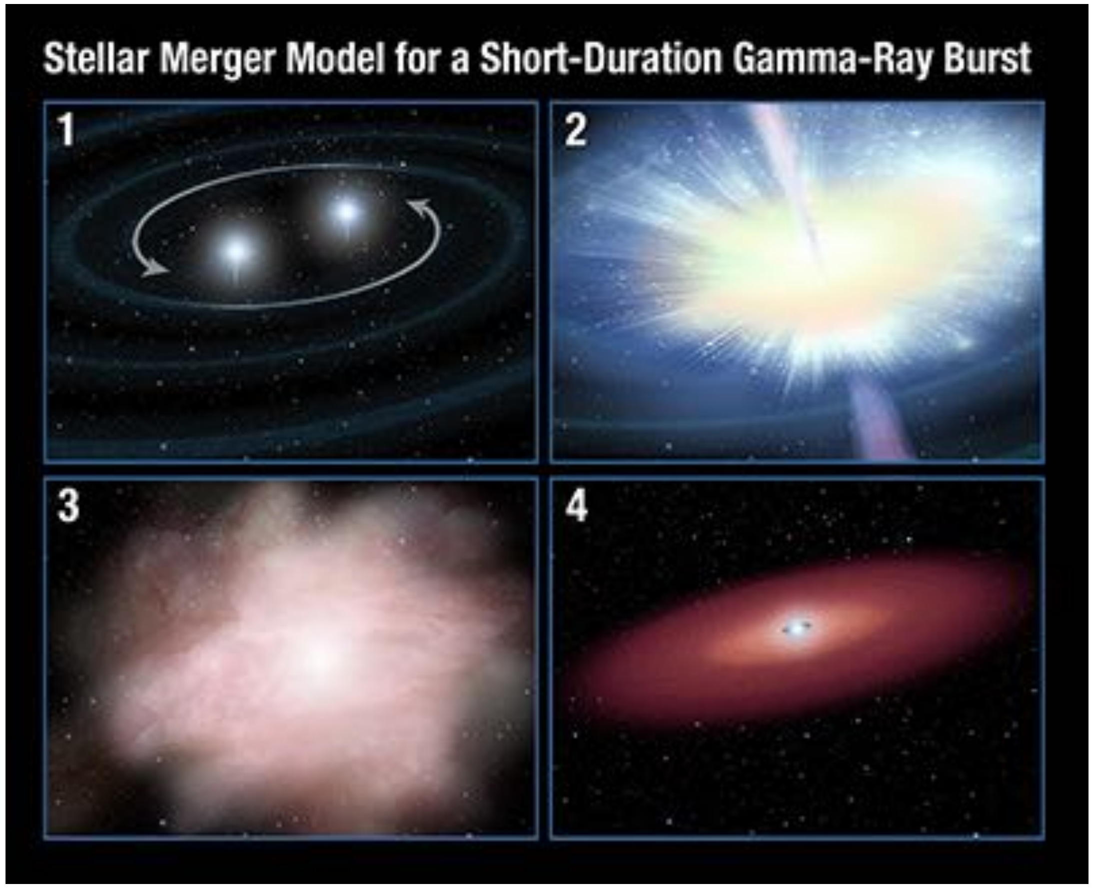

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- Extremely bright
- Well know associated afterglows

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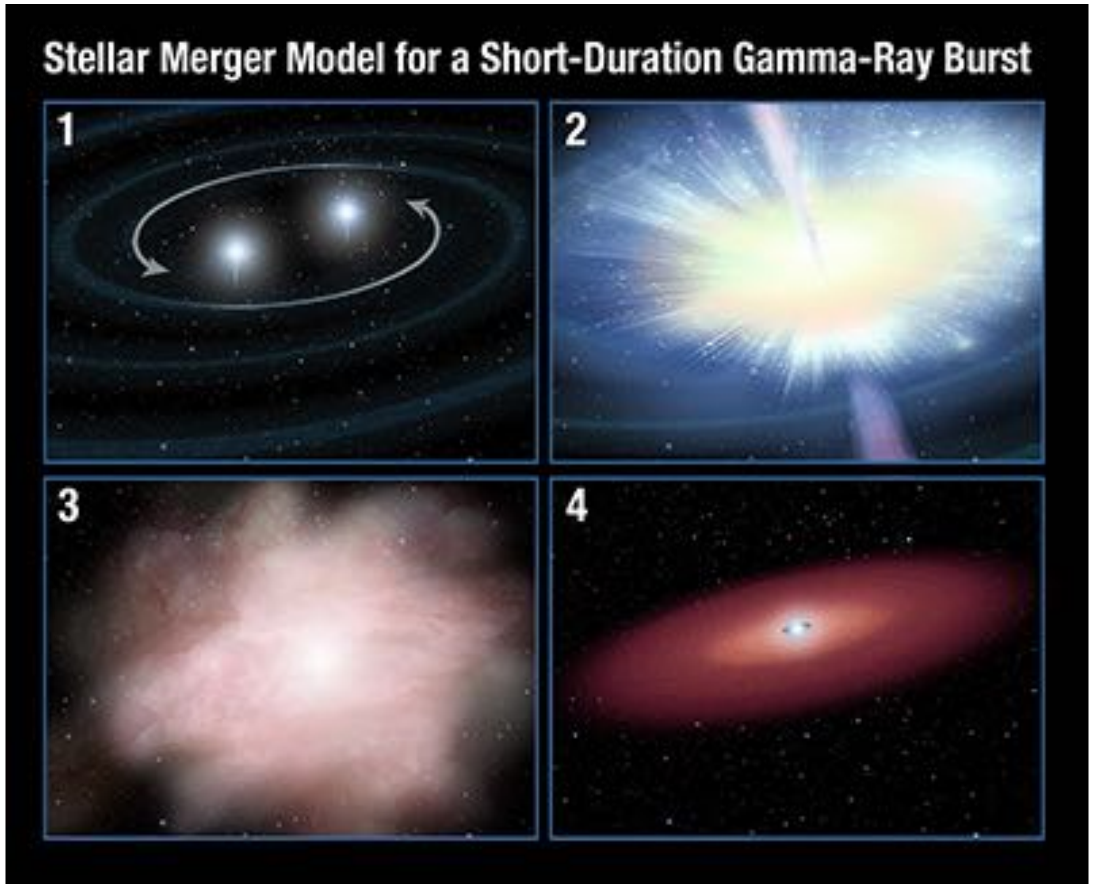

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- Models are still uncertain:

No clear link between merger and SGRBs

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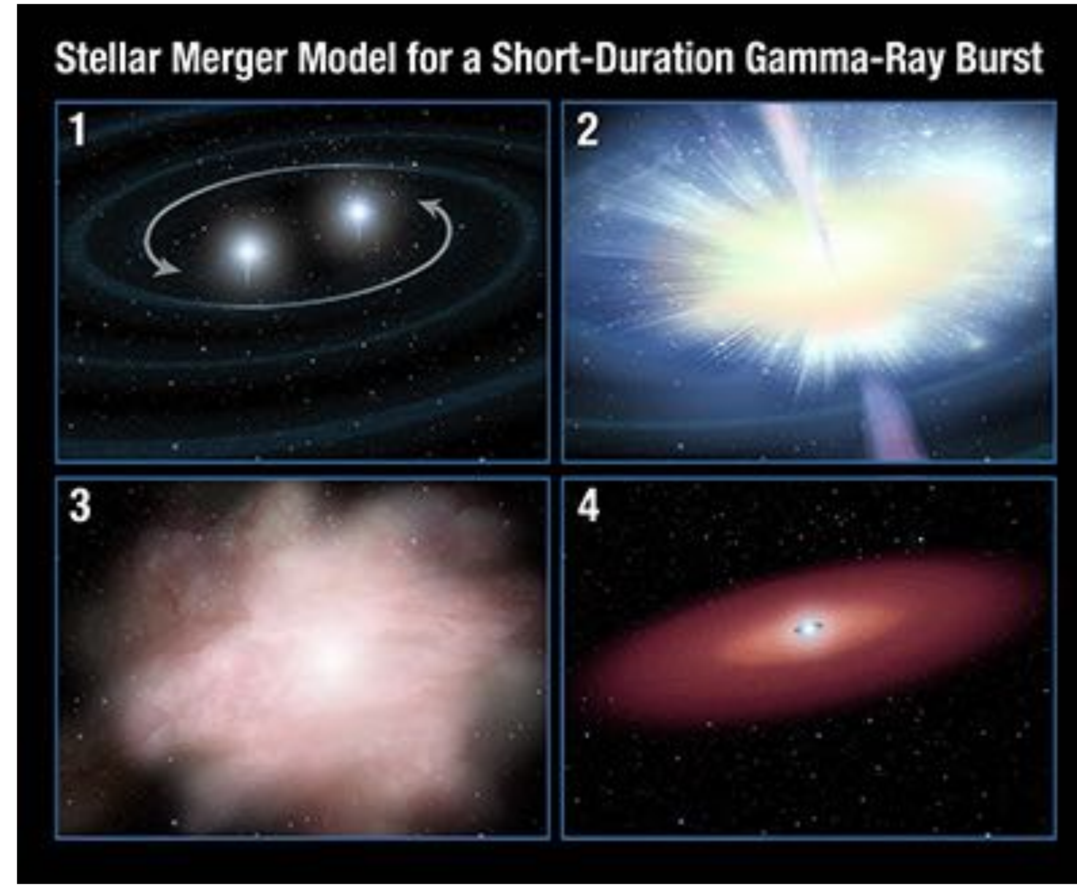

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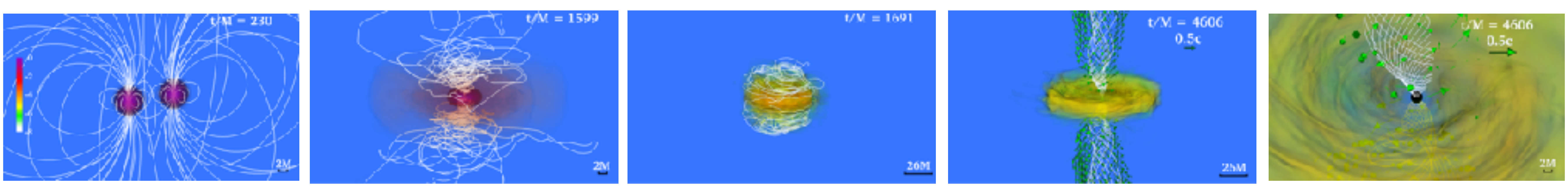
However: some promising NS-NS simulations by the Illinois Relativity Group [Ruiz et al, 2016]



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- Believed to originate from SGRBs outflow interaction with surrounding medium
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[van Eerten and MacFadyen, 2011]

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- Magnetically driven outflows prior to NS-NS merger or GW excitation of magnetized plasma post merger.
- Duration of a few minutes pre/post merger.
- Relativistic post-merger plasma could produce short, strong flare (<30 minutes).
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- Dispersion
- Low energy radiation
- Not necessarily coincident with merger
- Not always isotropic (radio signals can be isotropic but peak in months/years)

[Metzger and Berger, 2011]

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- EM counterparts of binary mergers

3. Kilonovae

Radioactive decay of heavy
r-process elements in ejecta

* Of the order 10^44 J energy release
* 5x10^4 ~ 1x10^5 times Sun luminosity
(~1000 brighter than a typical nova)

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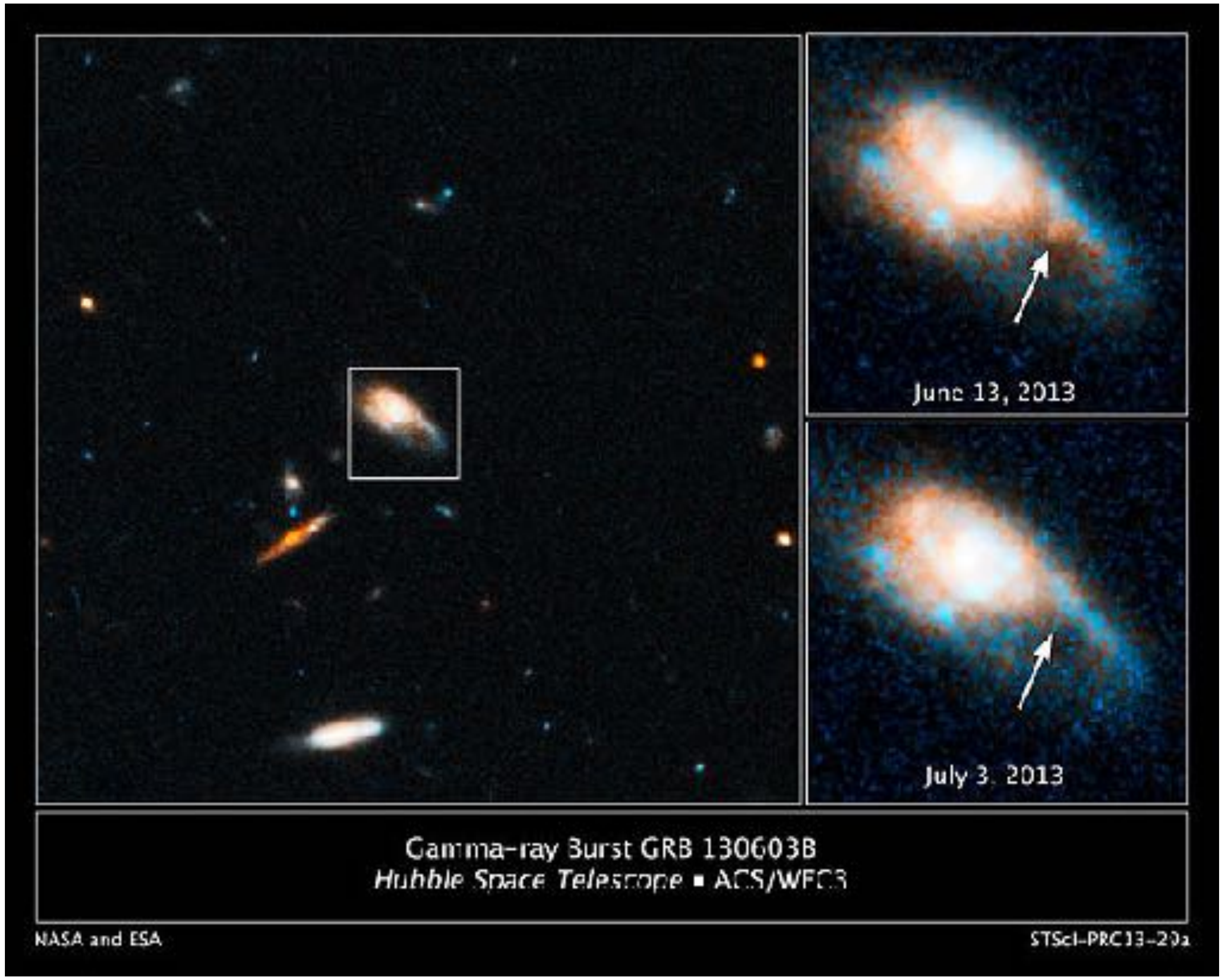
One single detected event: GRB 130603B



[Tanvir et al. 2013, Berger et al. 2013]

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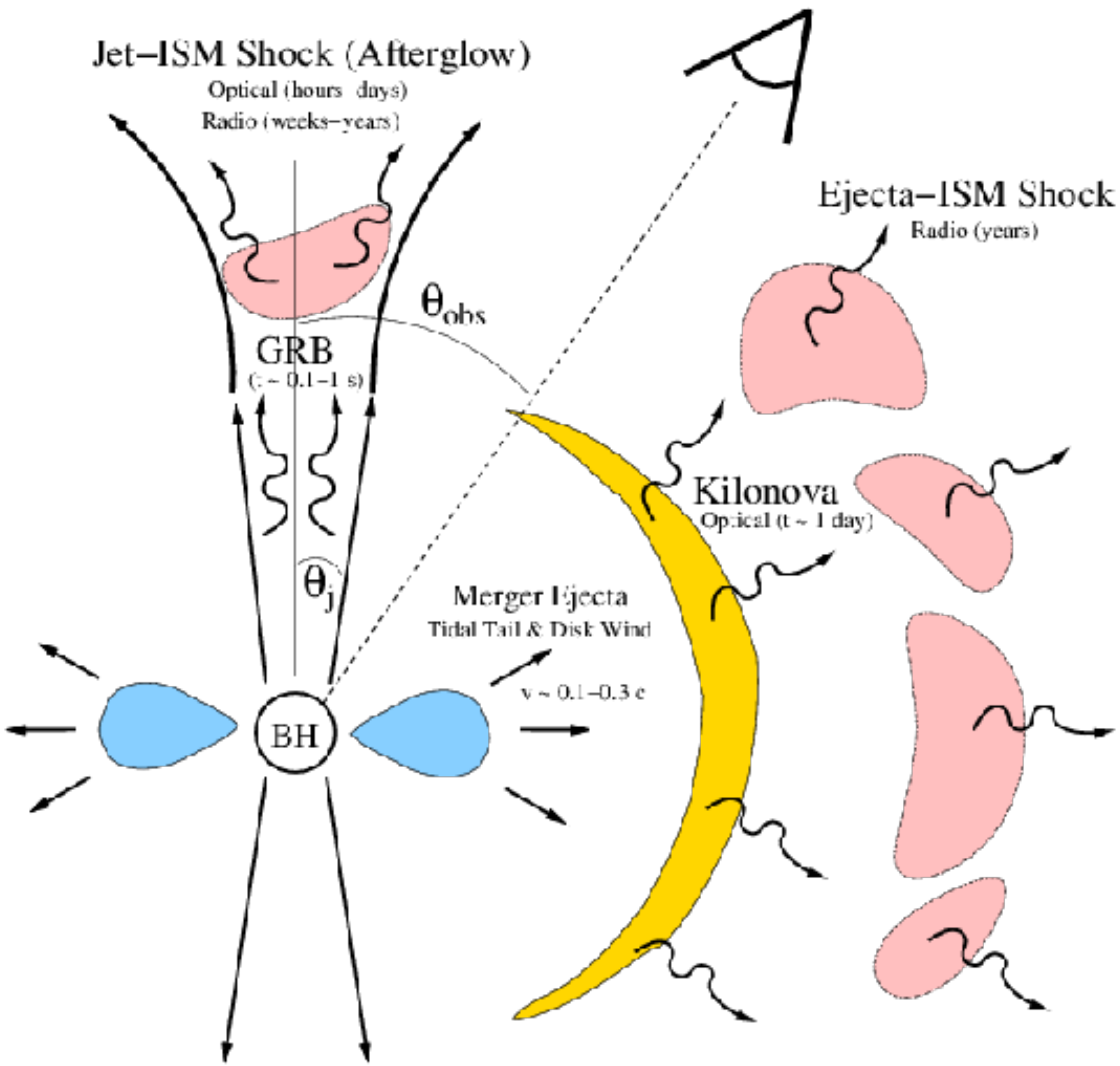
Overall picture



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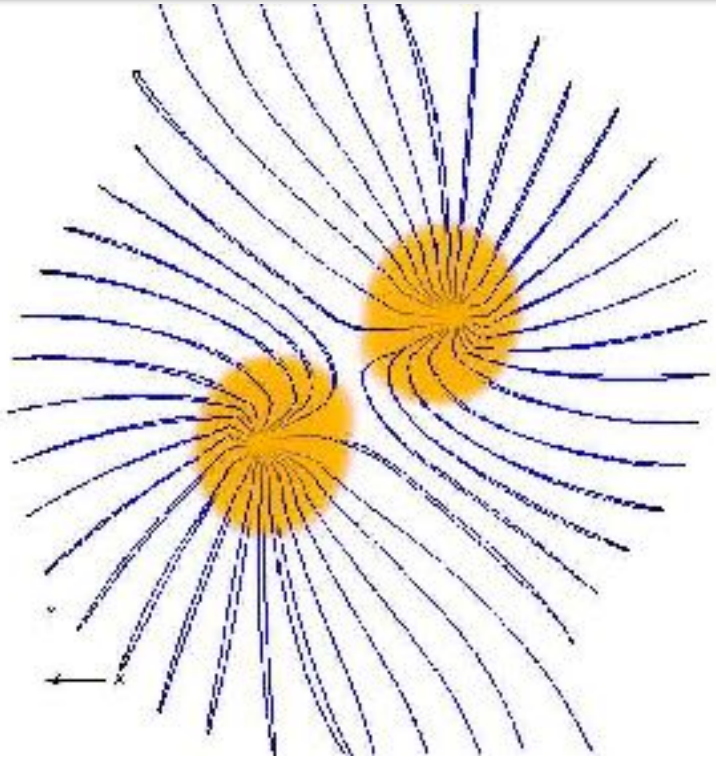

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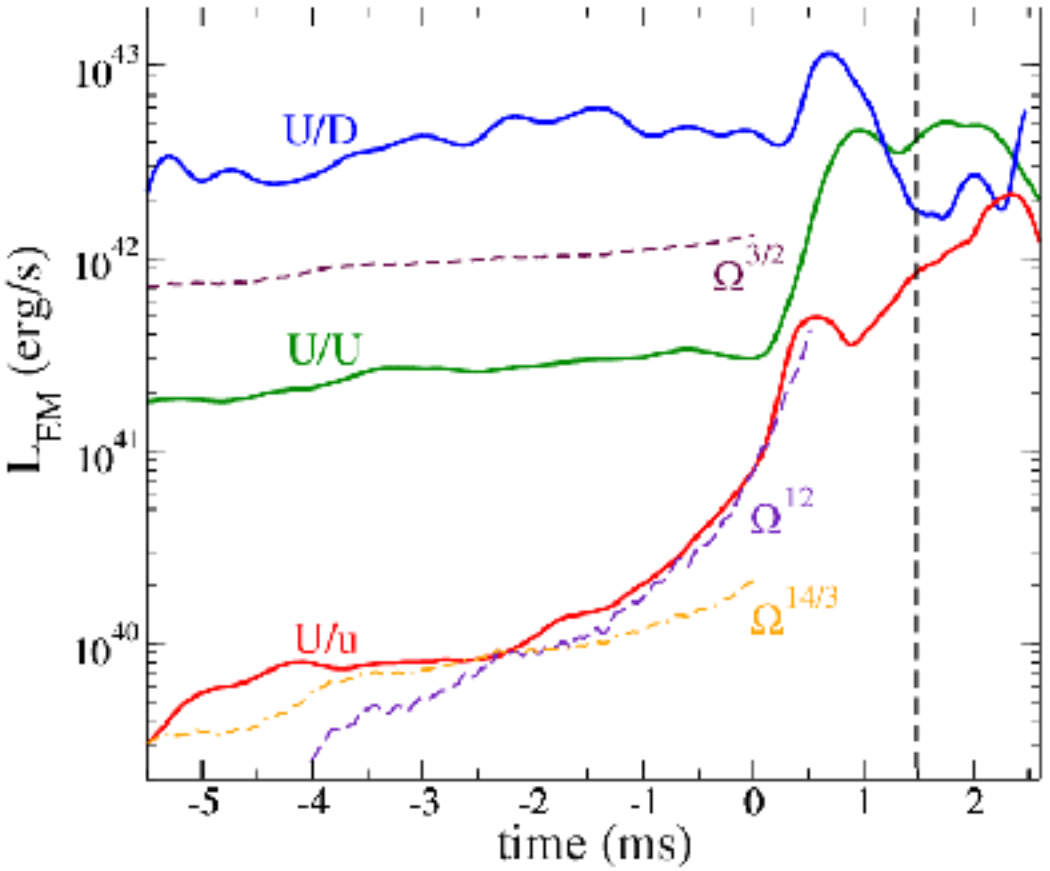

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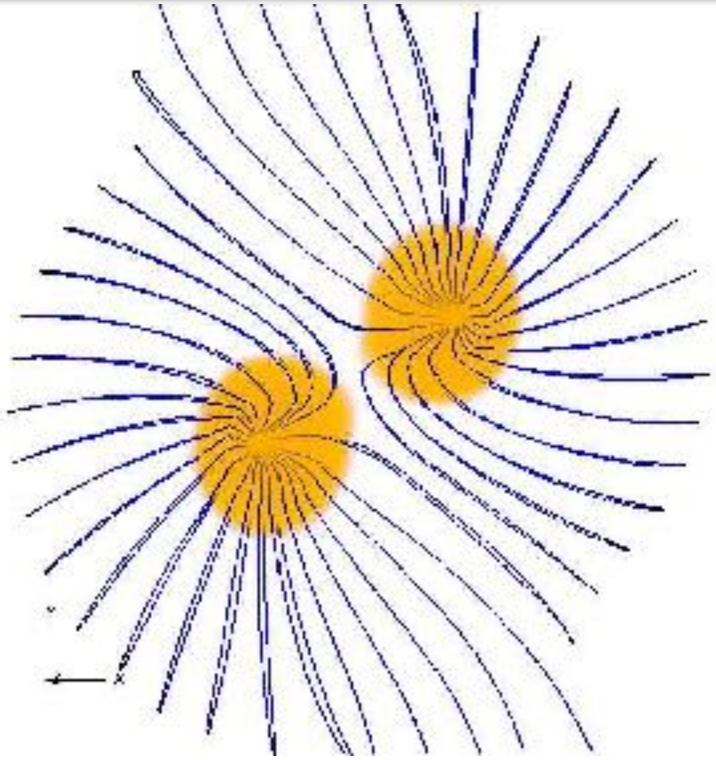

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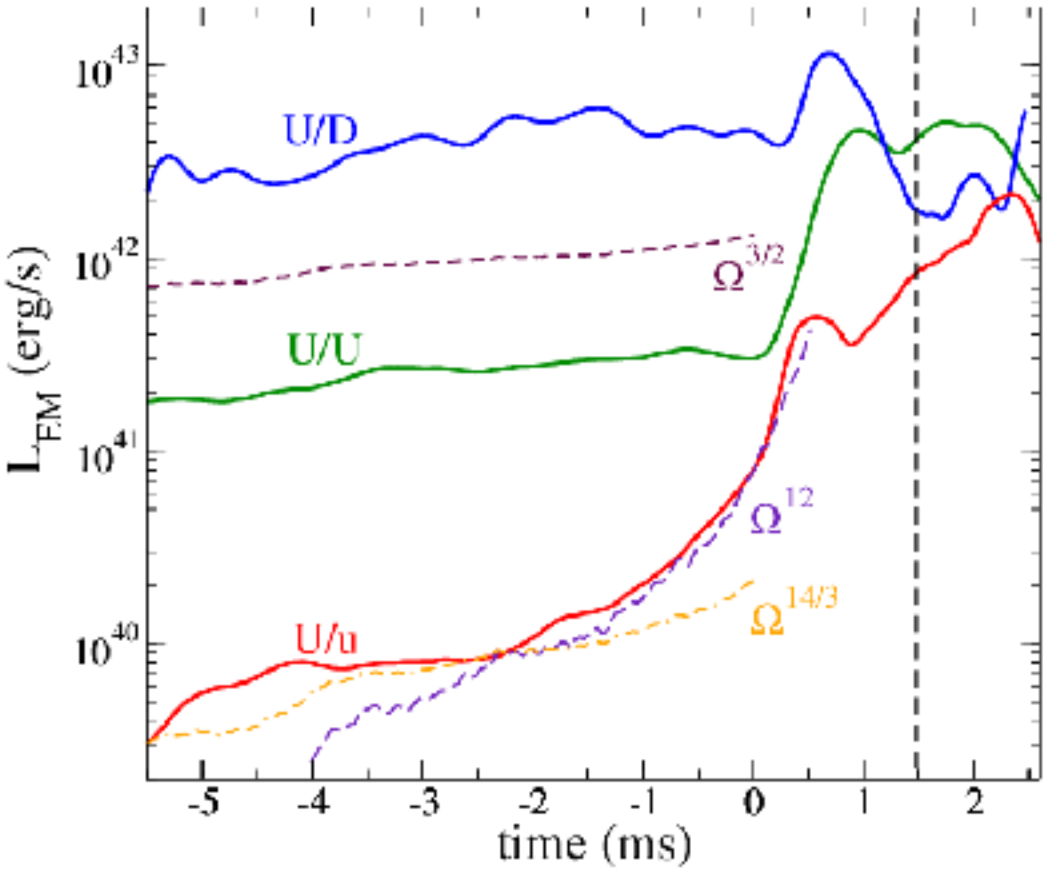
3. Characteristic light curves?



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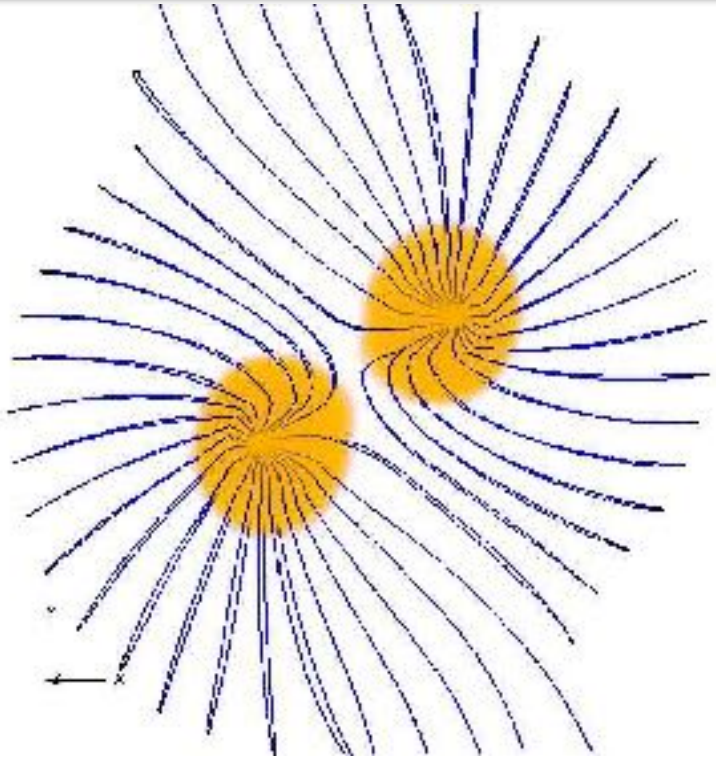

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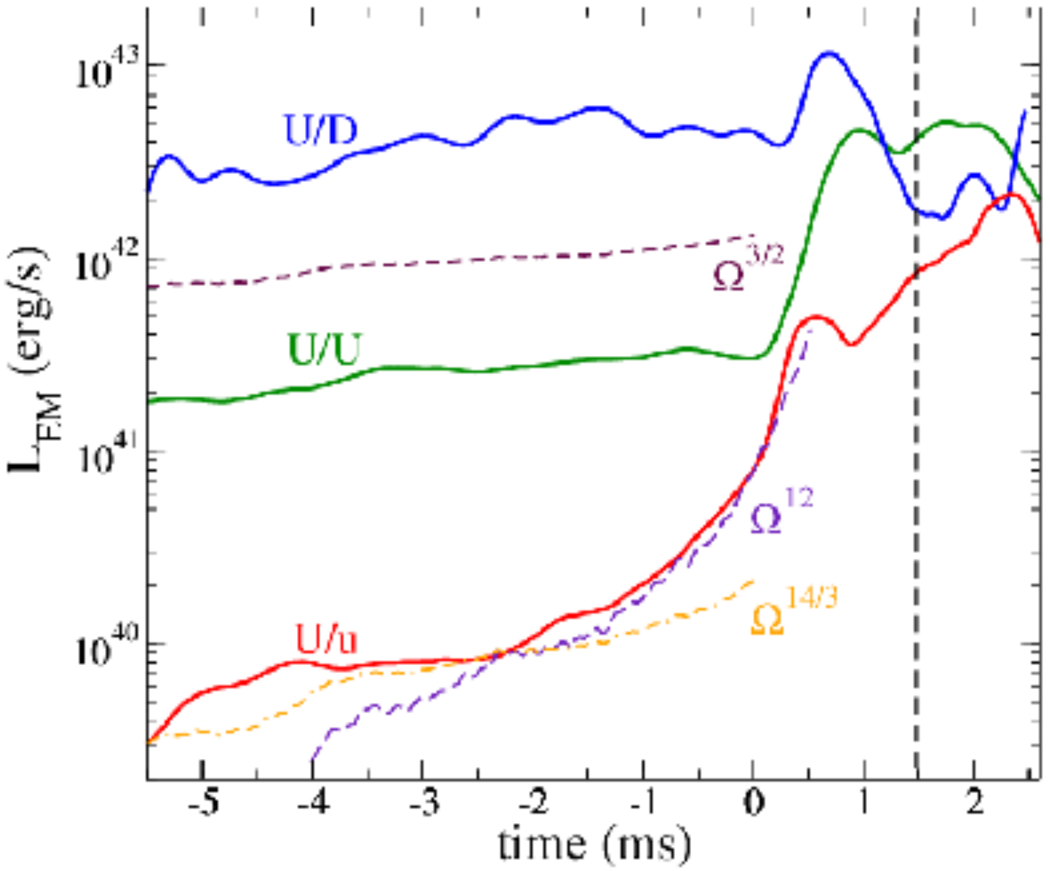
Have to figure it out …



Idea: Find all directions of gamma-ray emission, generate sky maps of radiation and light curves

Strategy: Extract magnetosphere EM fields from existing numerical simulations

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Their strong magnetic fields power
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~2,300 known pulsars
~230 millisecond pulsars

In average, ~1kPa away

Typical radius: 10~20km

Typical mass: $1.4 \sim 2M_{\odot}$

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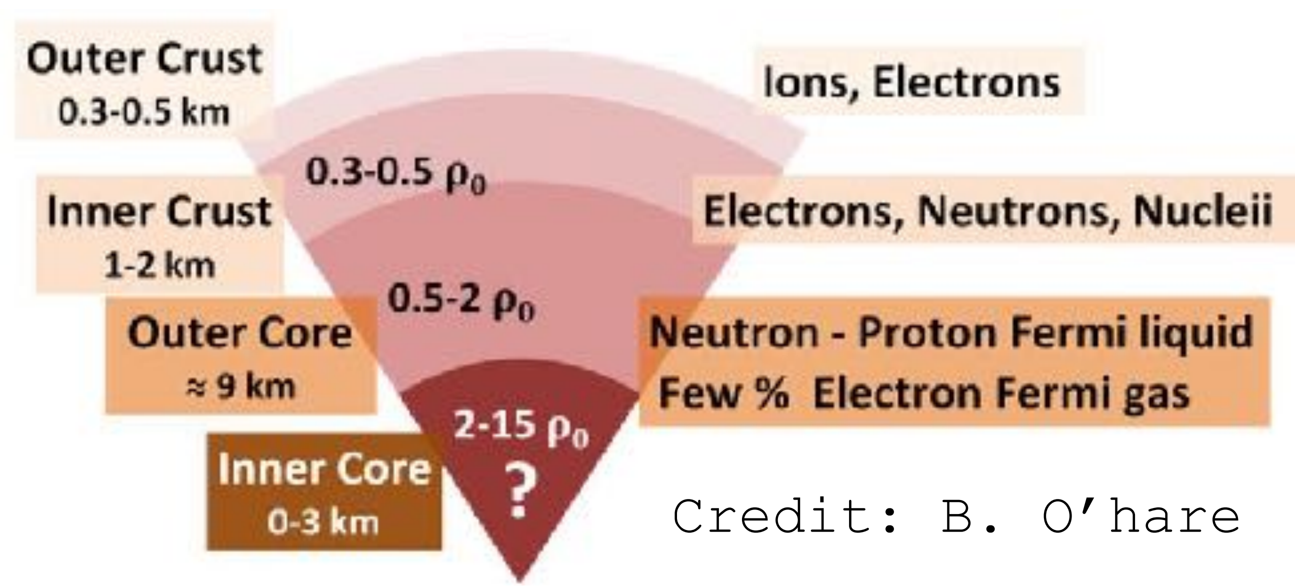

Credit: B. O'hare

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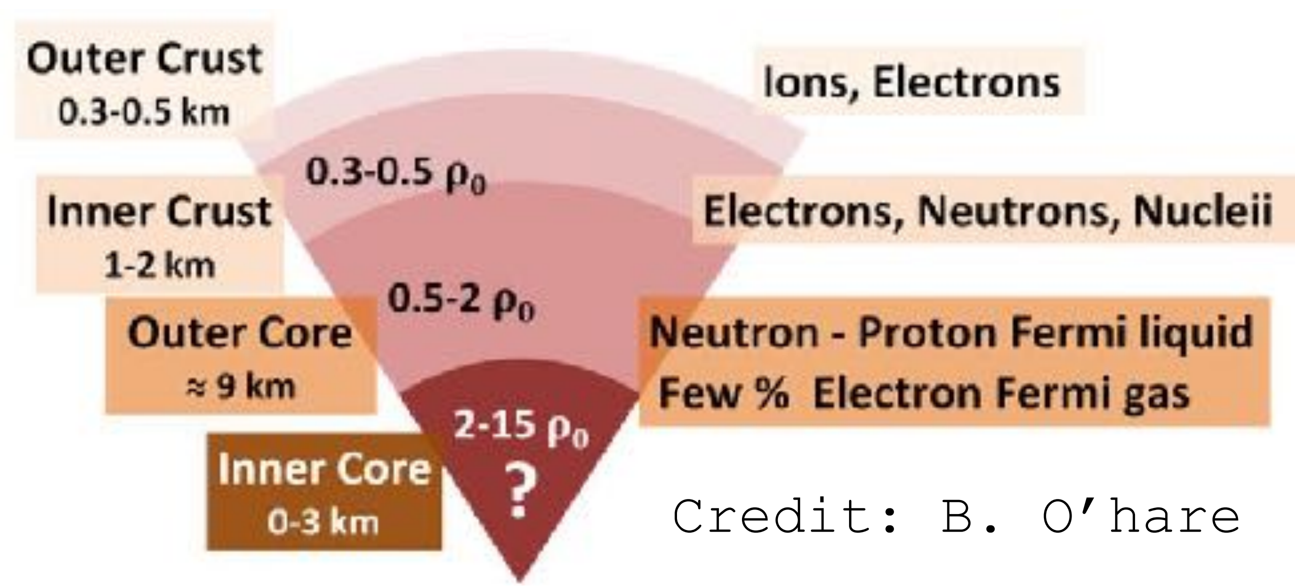

Credit: B. O'hare

The problem ~30 years ago:
Reproduce observed light curves
of Crab-like pulsars

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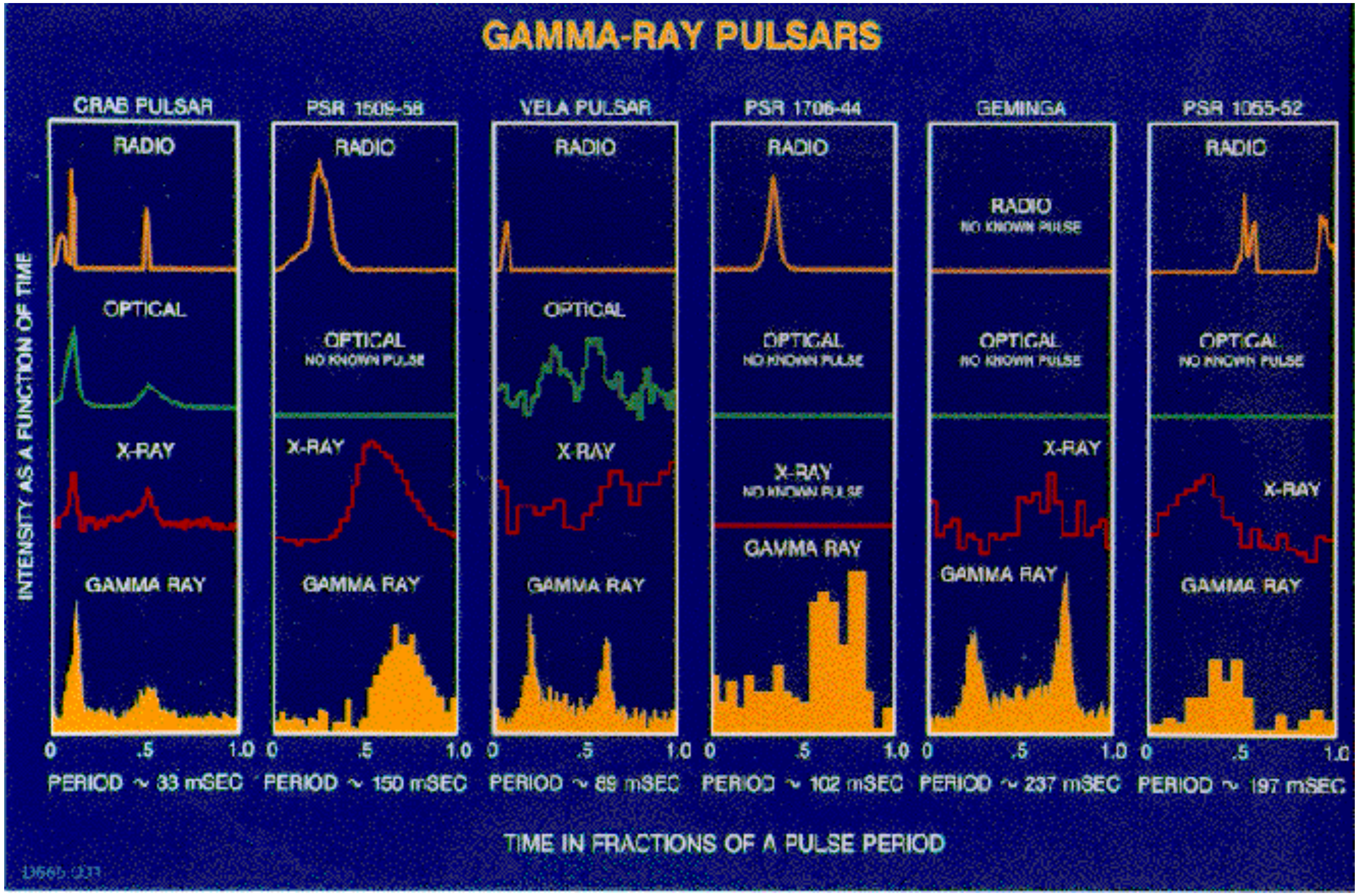
- Light curves

Some refined, light curves of observed pulsars:



Credit: Jim Napolitano

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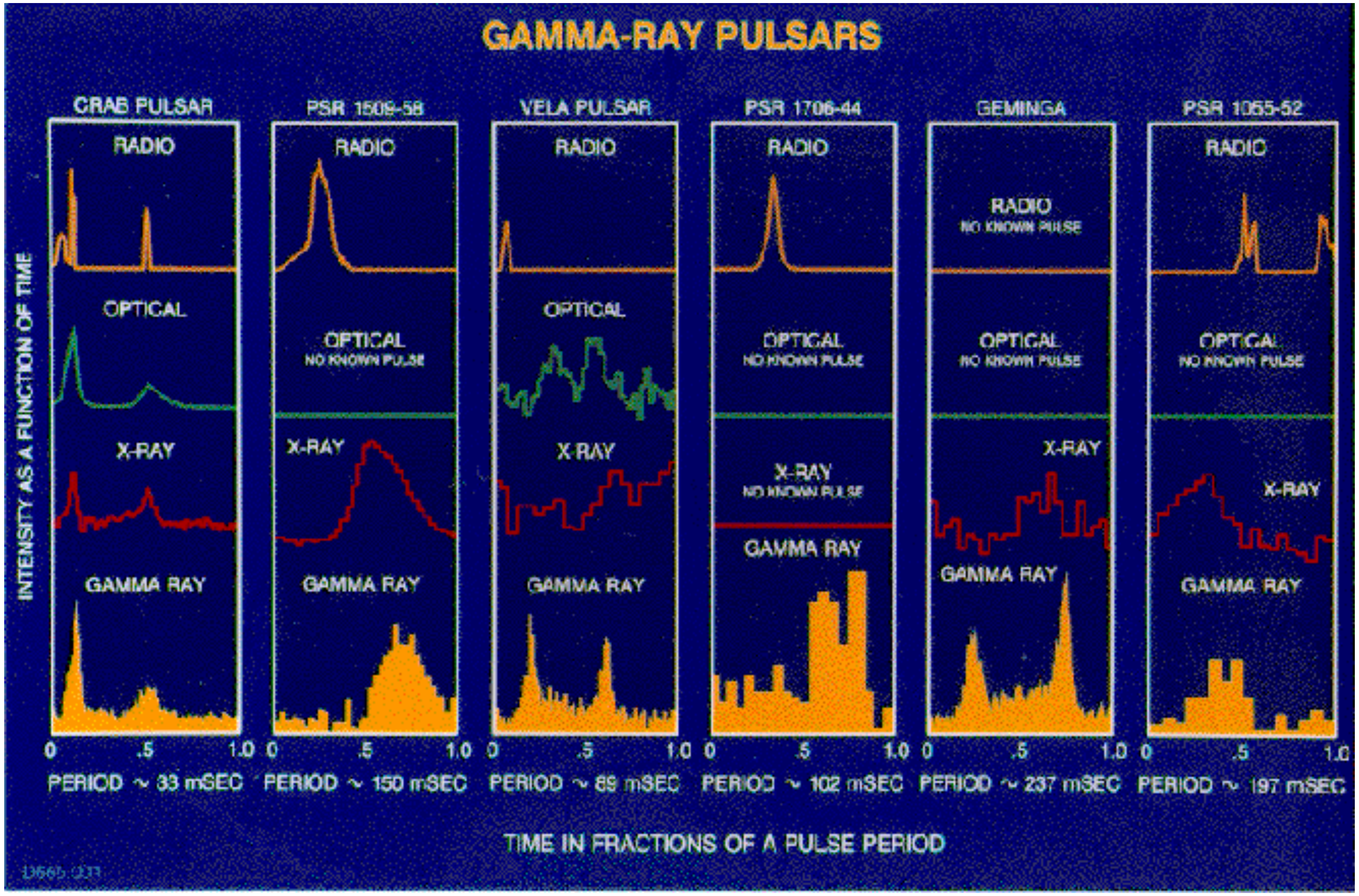
- Light curves

Some refined, light curves of observed pulsars:



Credit: Jim Napolitano

To try to reproduce this light curves: assume your favourite magnetic field configuration, find all directions of emission, cut at certain observation angle.

3. Preamble: the single pulsar case

- Light curves

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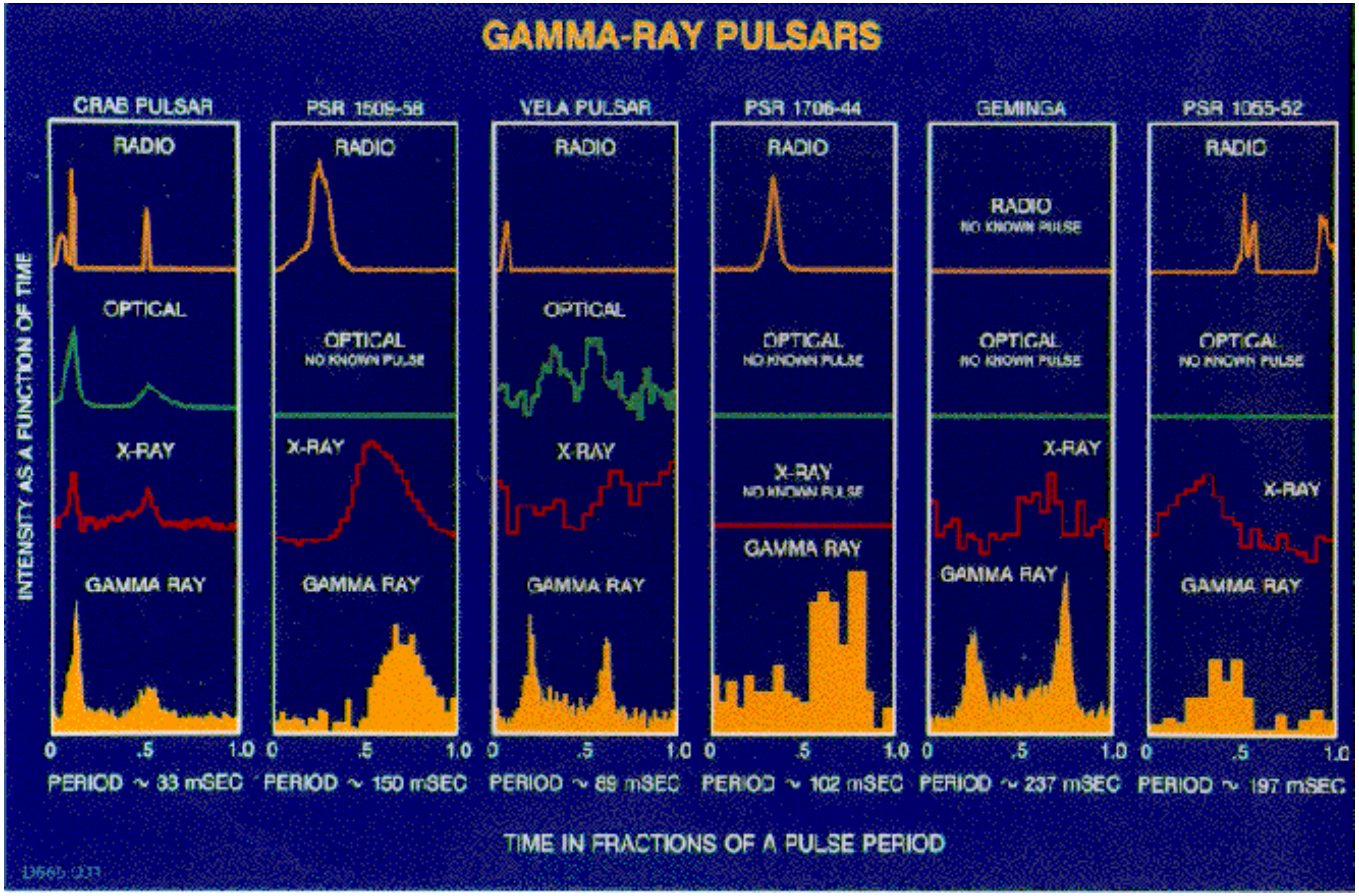

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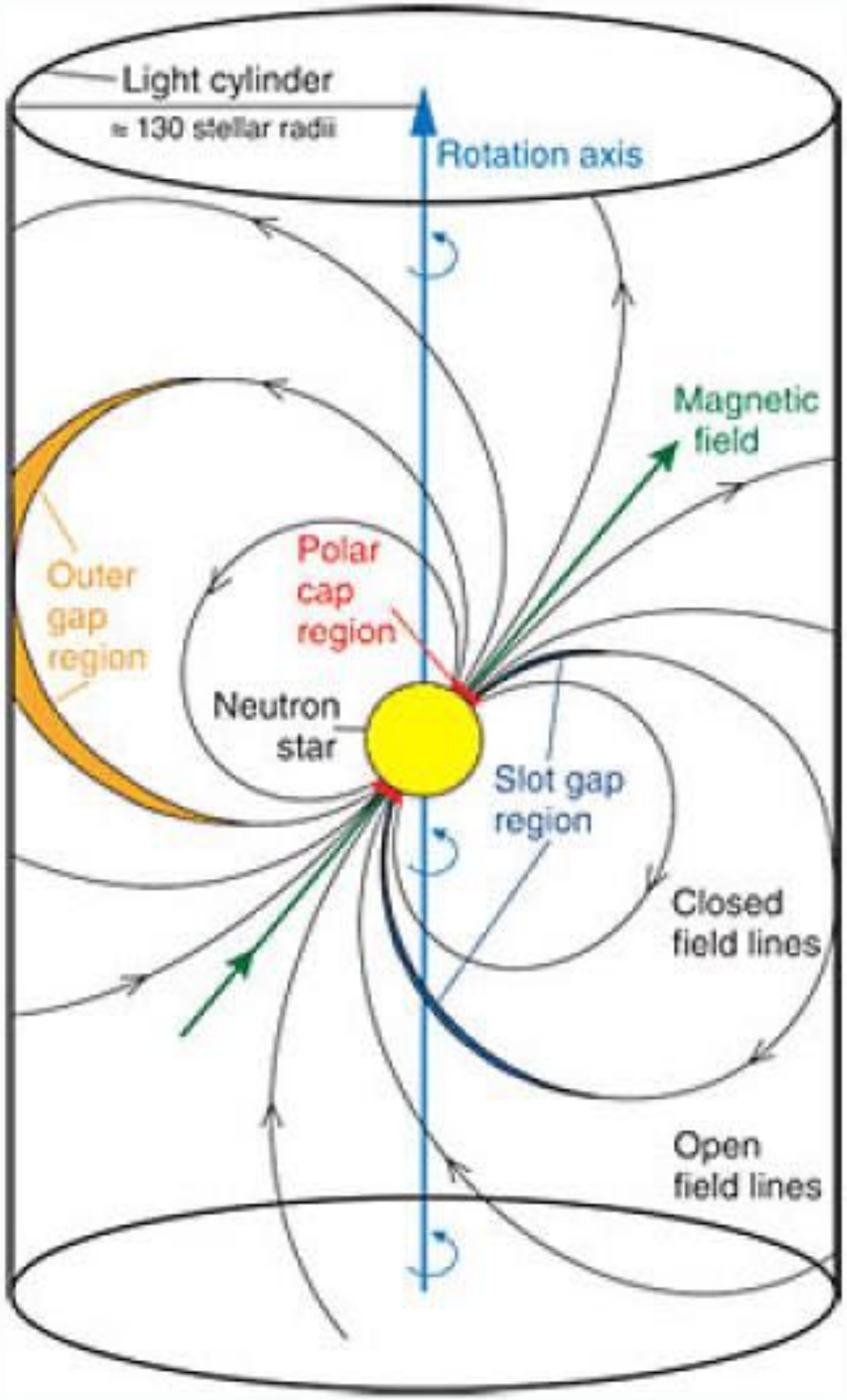
To try to reproduce this light curves: assume your favourite magnetic field configuration, find all directions of emission, cut at certain observation angle.

Key ingredient: Magnetosphere model. Will discuss some of them soon…

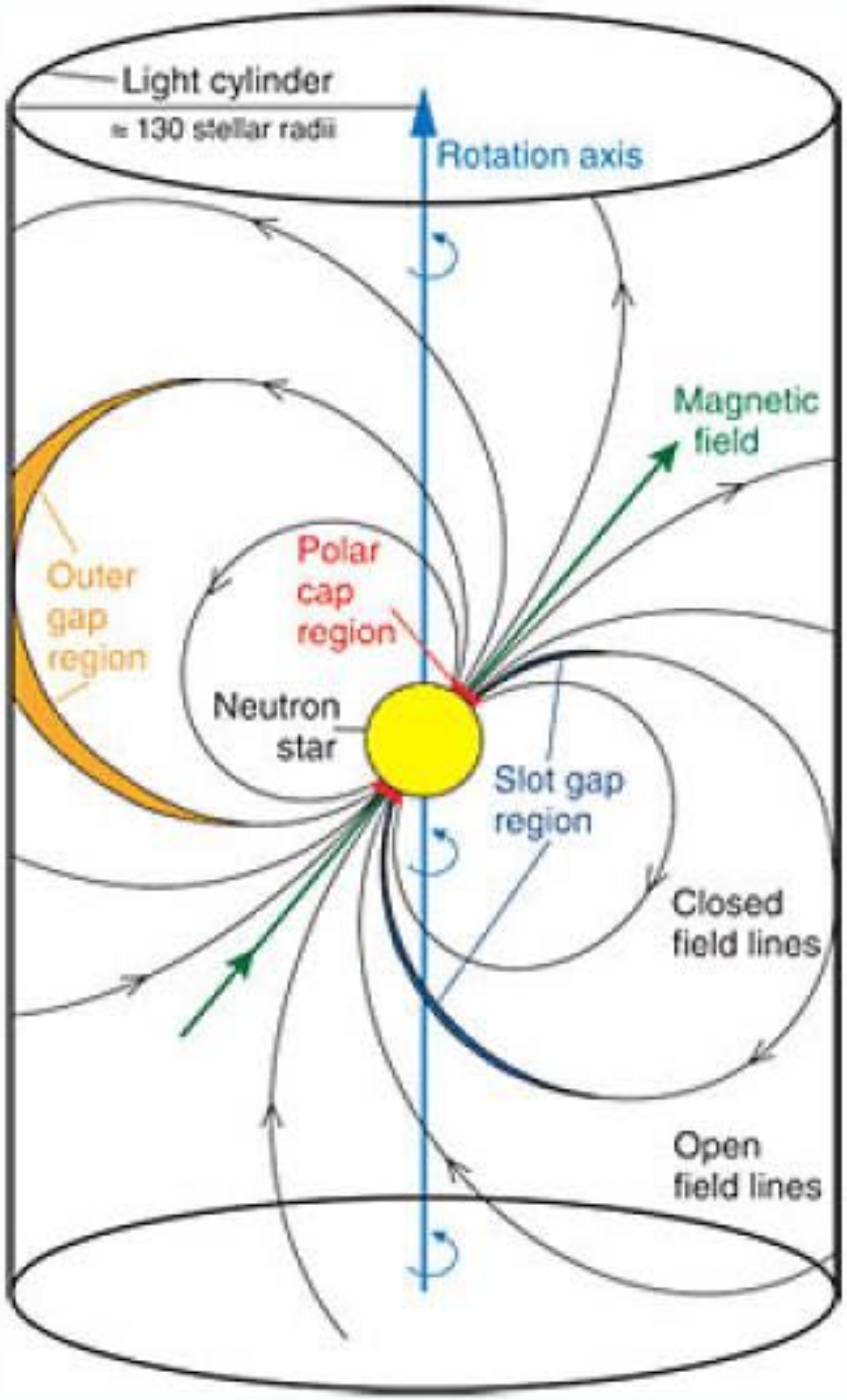
3. Preamble: the single pulsar case

- Pulsar configuration



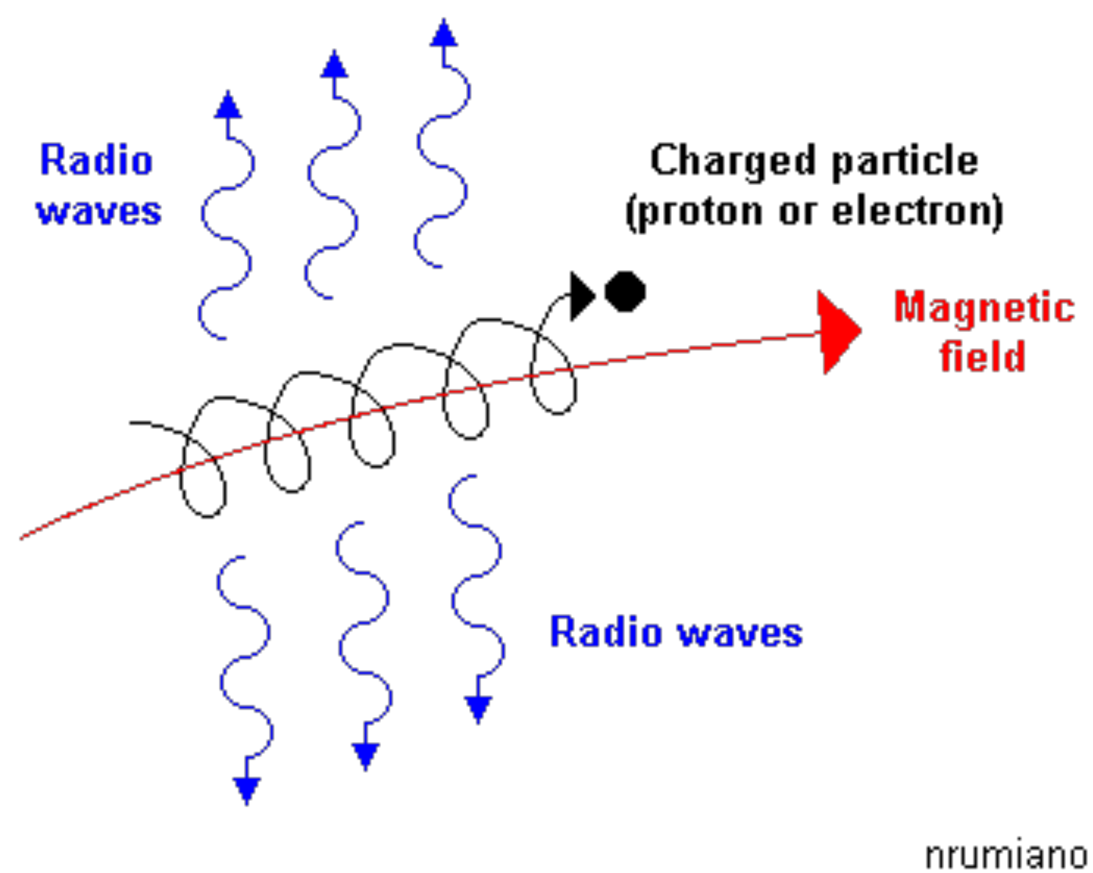
Credit: Robert Mallozzi, University of Alabama.

3. Preamble: the single pulsar case - Pulsar configuration



Credit: Robert Mallozzi, University of Alabama.

Main emission process:
Synchrotron + Inverse Compton scattering



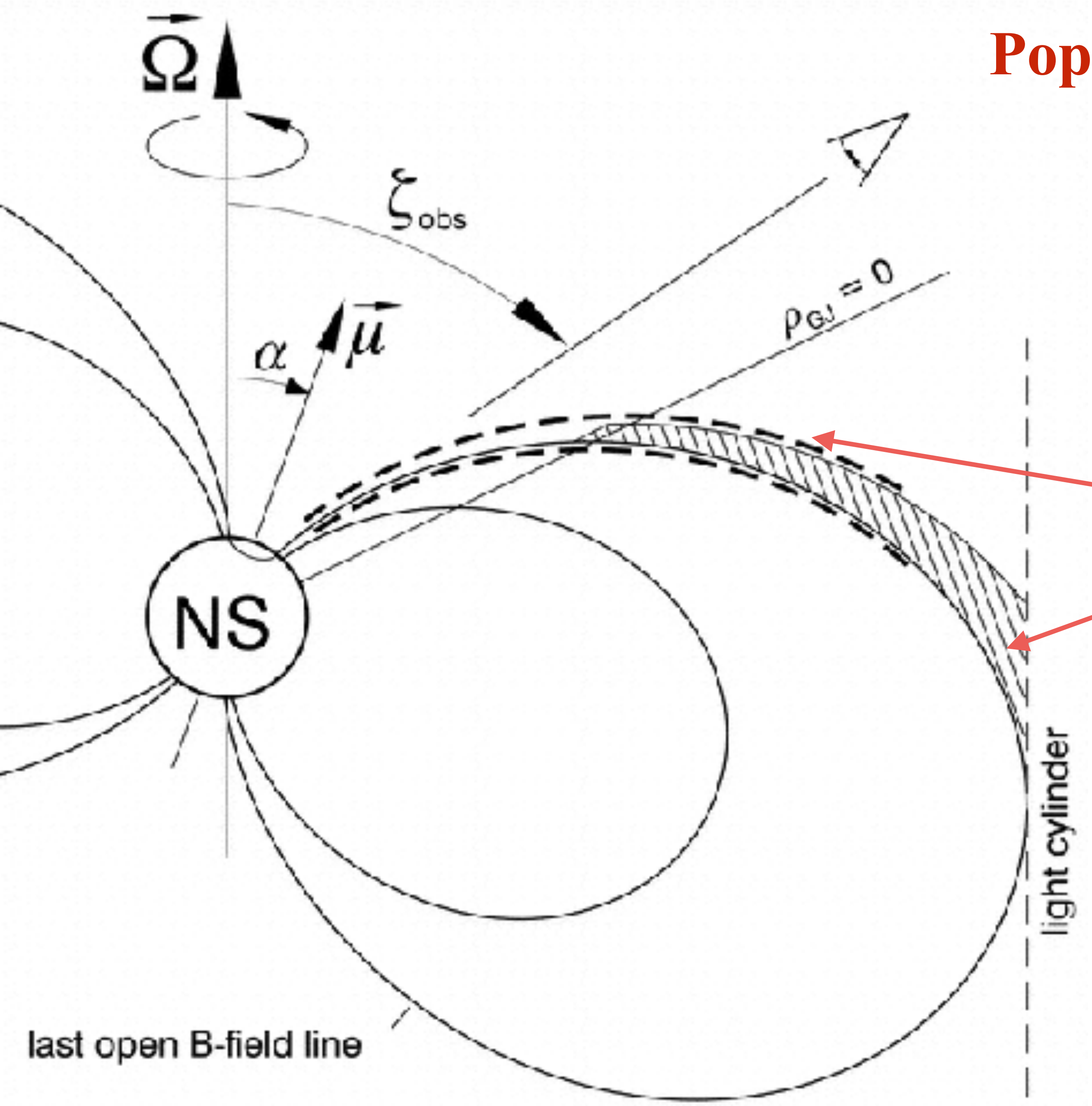
http://lightandcolourinmoderntechnology.com/

Popular/successful magnetosphere models

- Dipole in vacuum
- Force-free plasma $\longrightarrow$ $\rho\mathbf{E} + \mathbf{J} \times \mathbf{B} = \mathbf{0}$

  [Goldreich and Julian, 1969]

- Magnetosphere models



[Dyks and Rudak, 2003]

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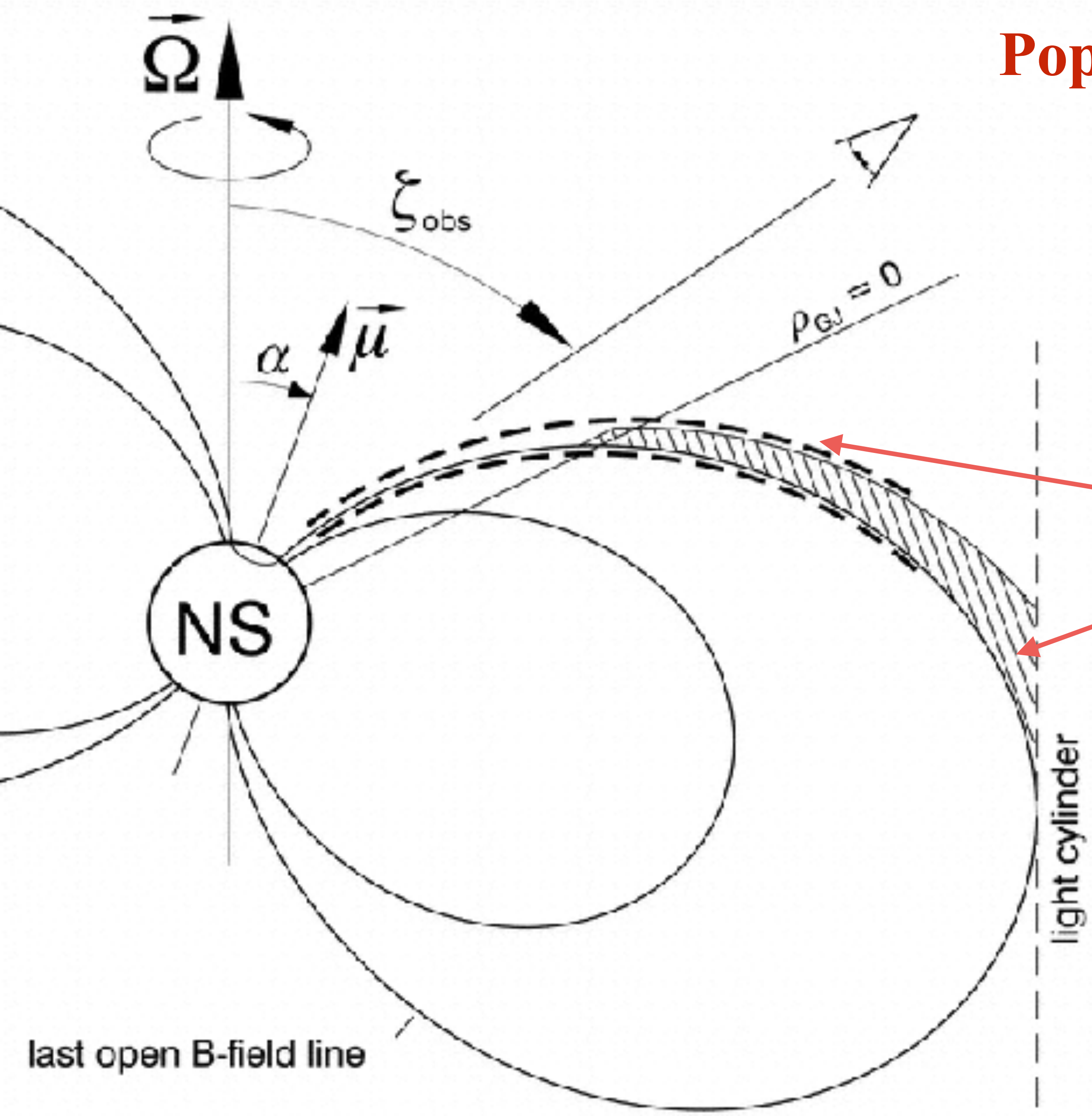
Different emission zones



[Dyks and Rudak, 2003]

Popular/successful magnetosphere models

- Dipole in vacuum
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[Goldreich and Julian, 1969]

Different emission zones

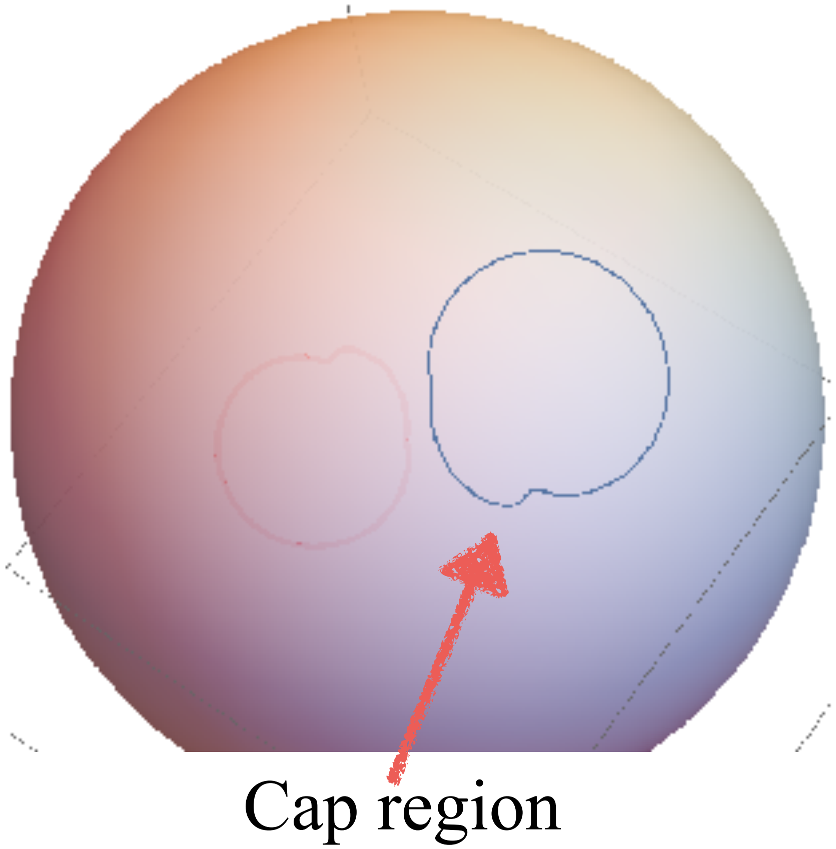
We adopt the *Two Polar Caustics Model*

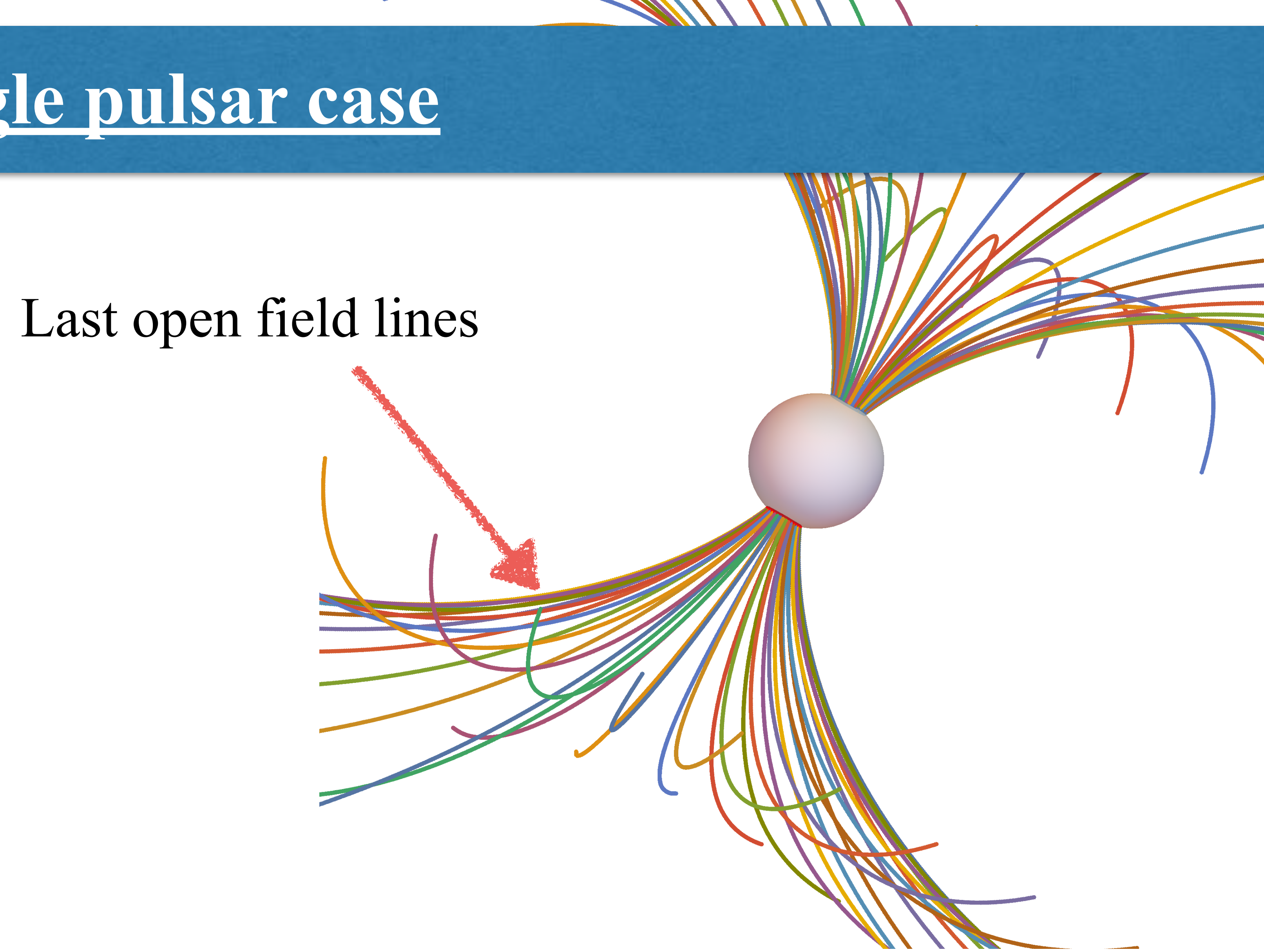
Main assumptions:

- Vacuum magnetosphere
- Emission along Last Open Field Lines
- Emission up to the Light Cylinder

[Arons and Scharlemann 1979; Arons 1983; Muslimov and Harding 2003, 2004; Dyks et al 2004]

3. Preamble: the single pulsar case





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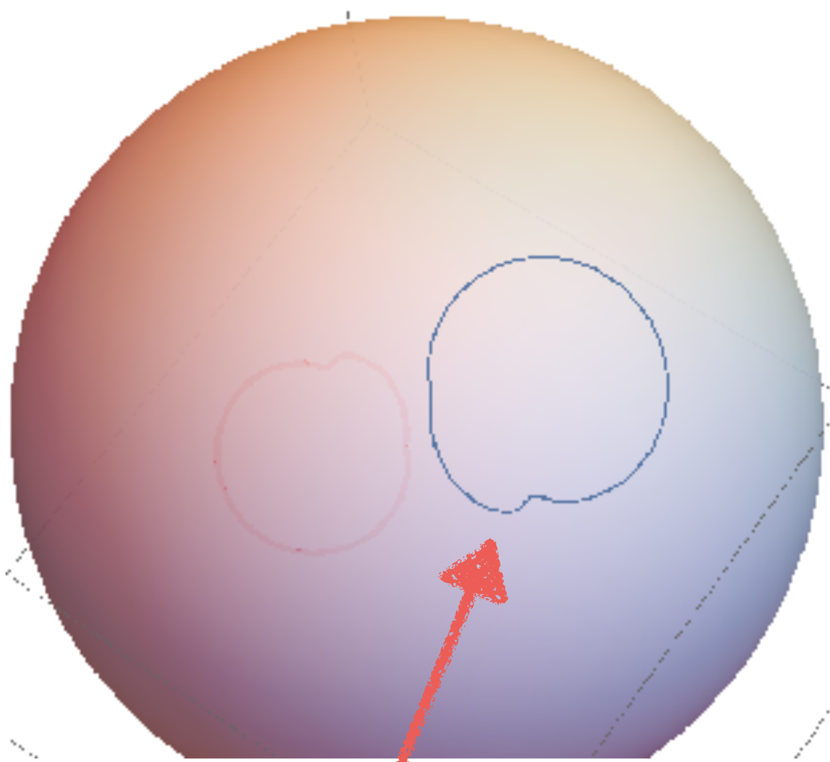
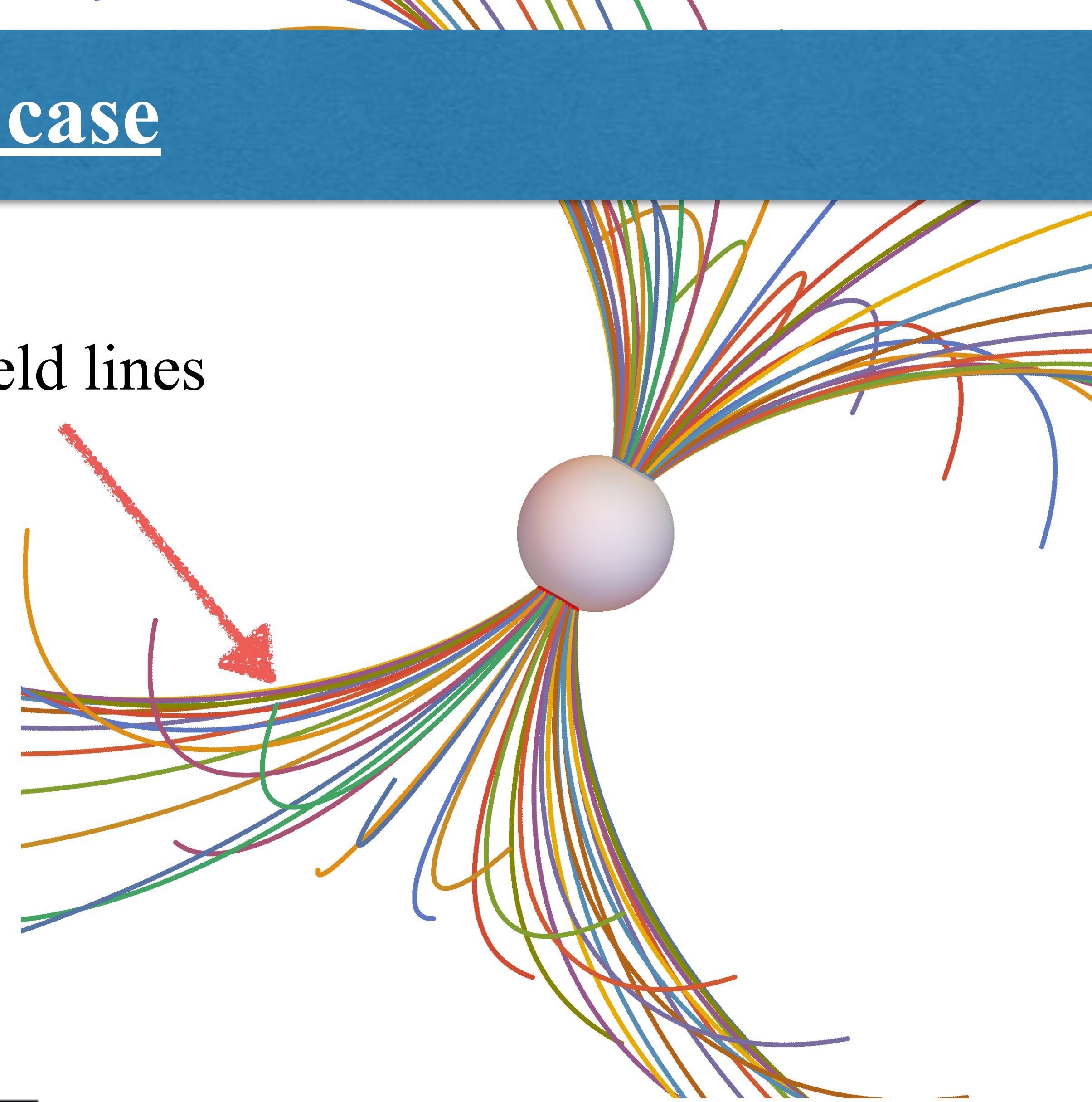
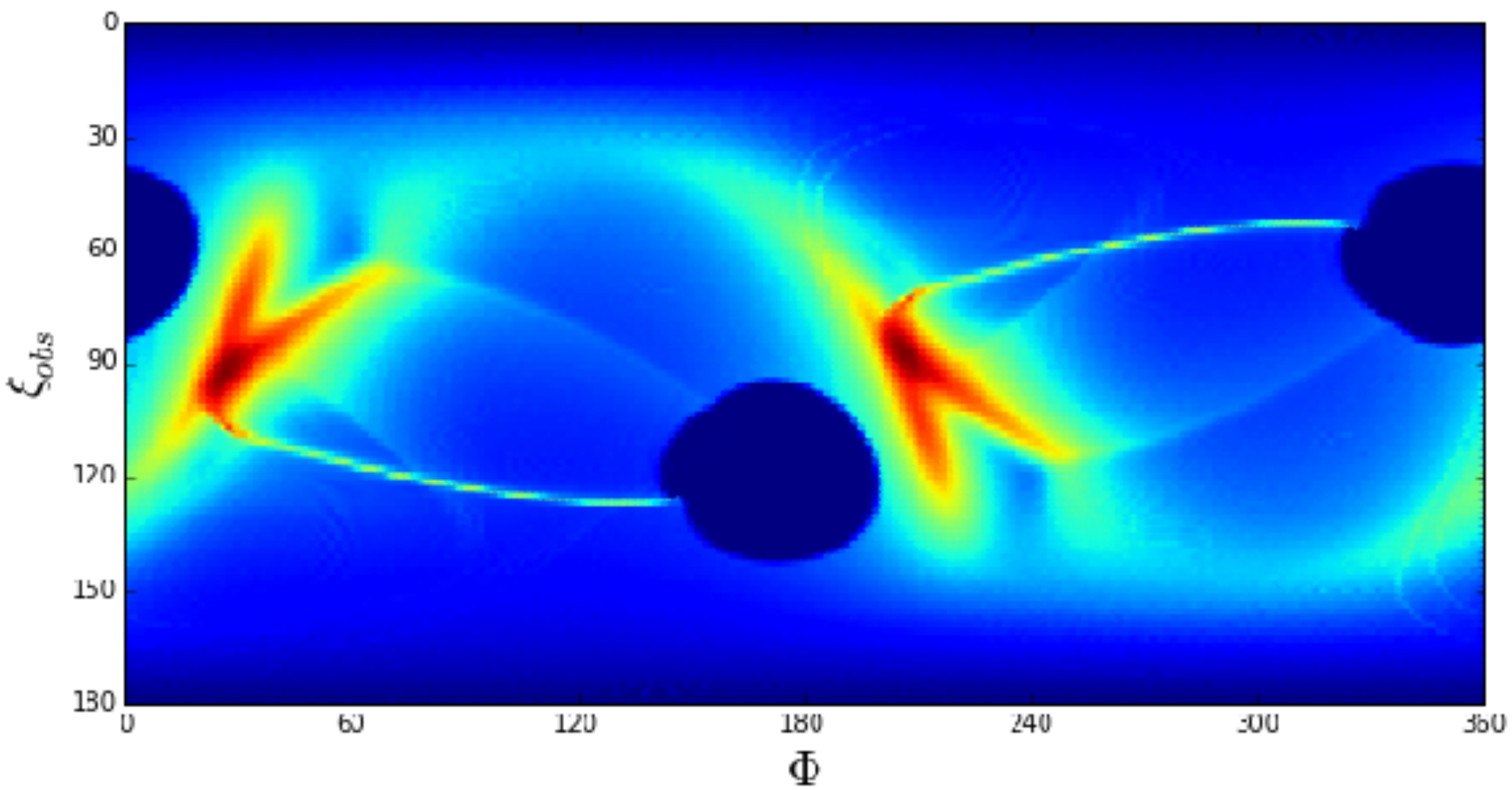


Cap region

Last open field lines



Sky map



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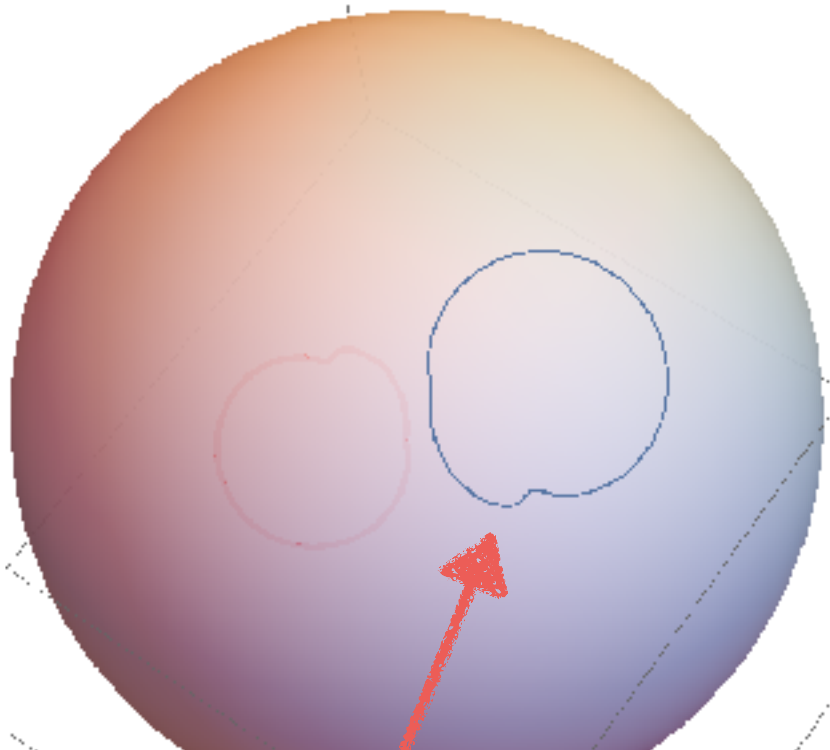

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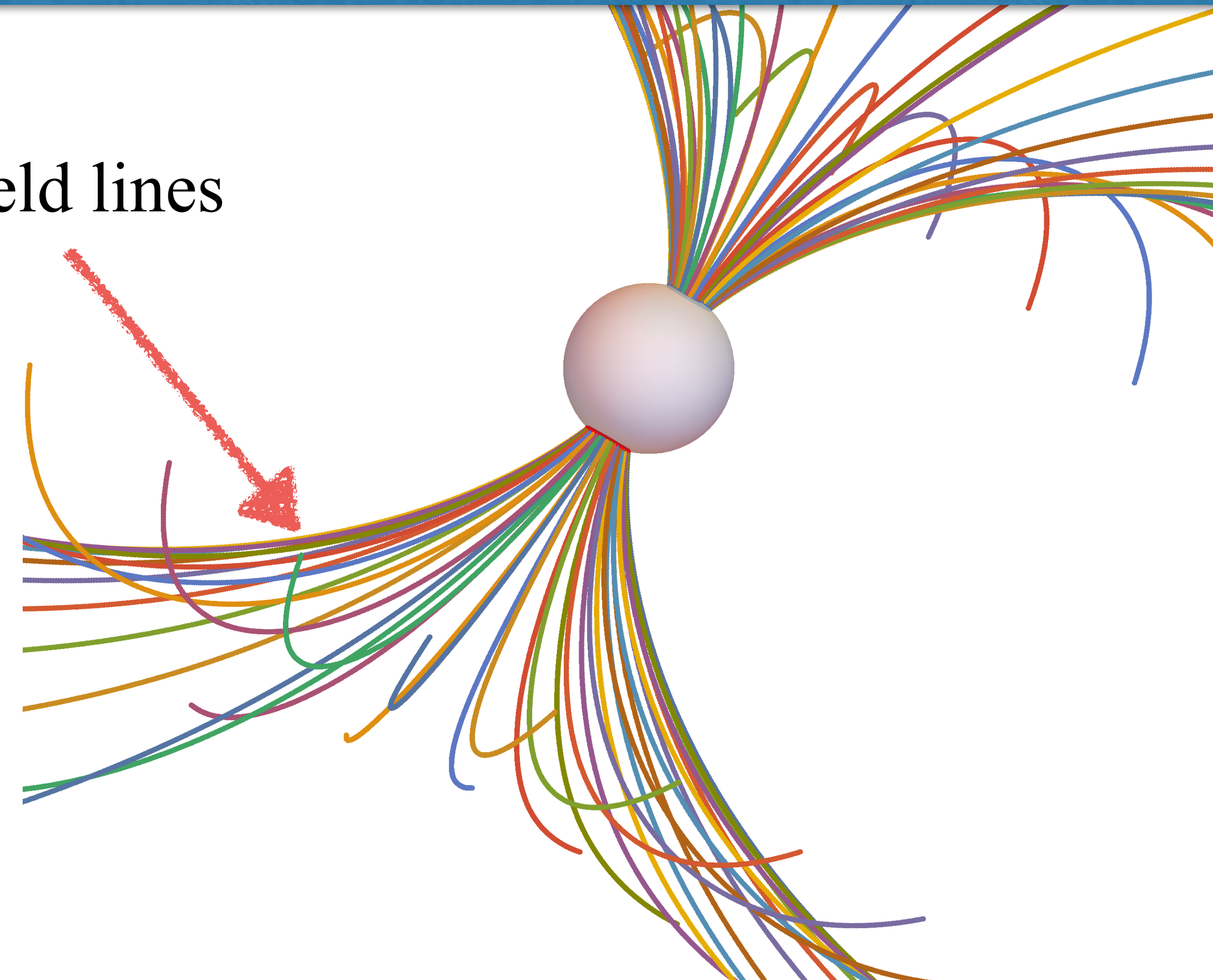

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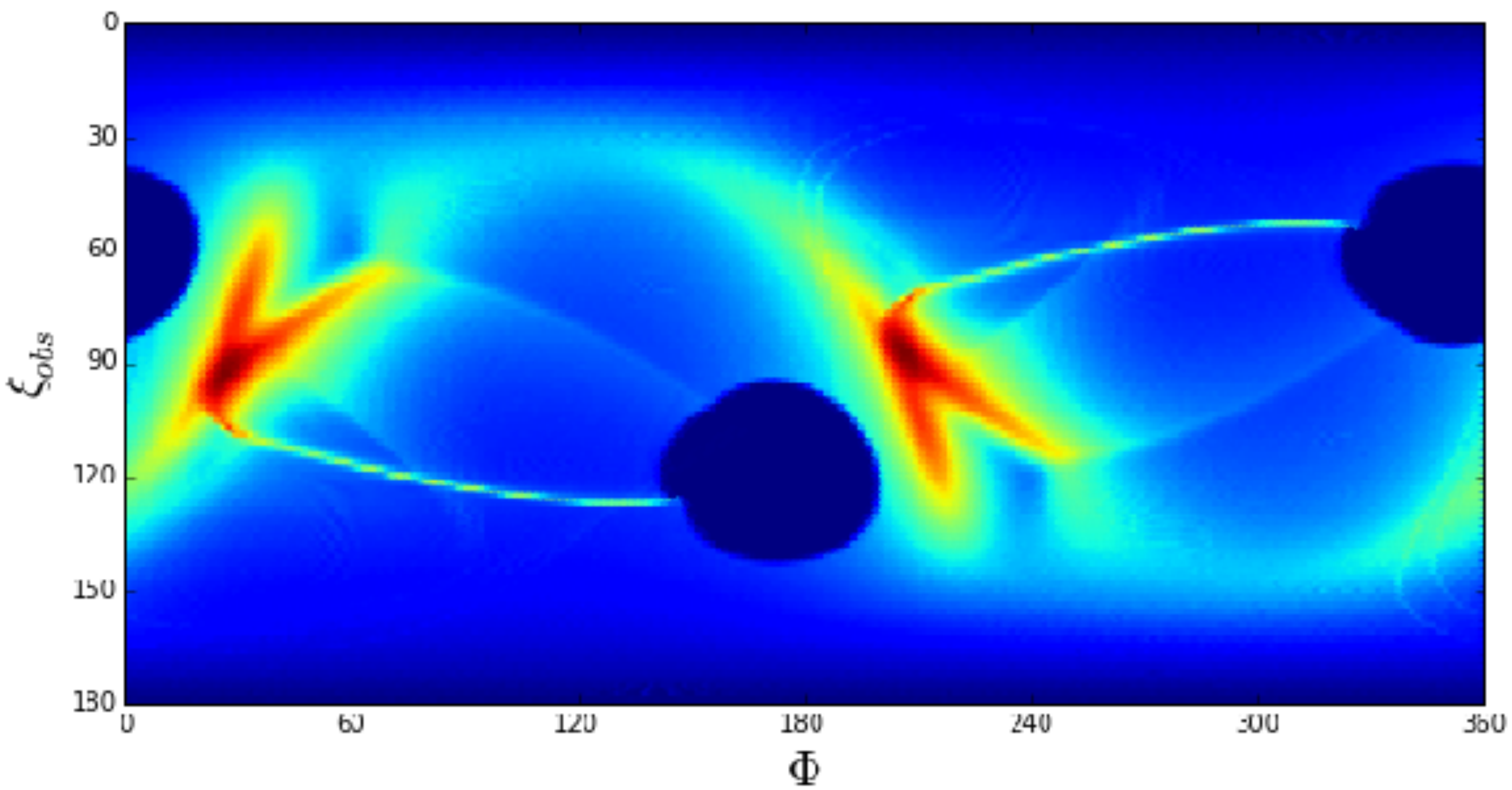

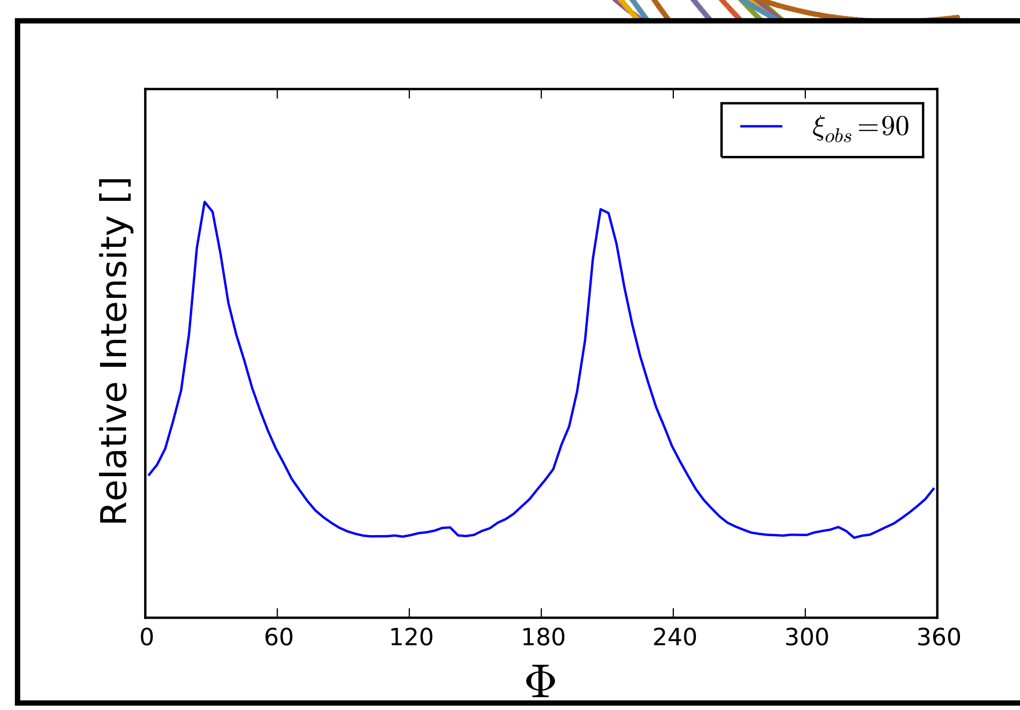

Light curve example

Plan of the talk

1. Motivation

- The role of electromagnetic (EM) counterparts
- EM counterparts of binary systems mergers
- Short Gamma-ray Bursts afterglows

2. An alternative EM counterpart

3. Preamble: the single pulsar case

- Light curves
- Pulsar configuration
- Magnetosphere models

4. The binary neutron star case

5. Summary

4. Binary Neutron Star case

We extracting EM fields from
BNS simulations prior to merger

Data kindly provided by Carlos Palenzuela

Main ingredients:

- Plasma magnetosphere
- Force Free approximation
- Aligned magnetic dipoles

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We extracting EM fields from
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Main ingredients:

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We adopt the Separatrix Layer Model,
and extension of the Two Polar Caustic approach

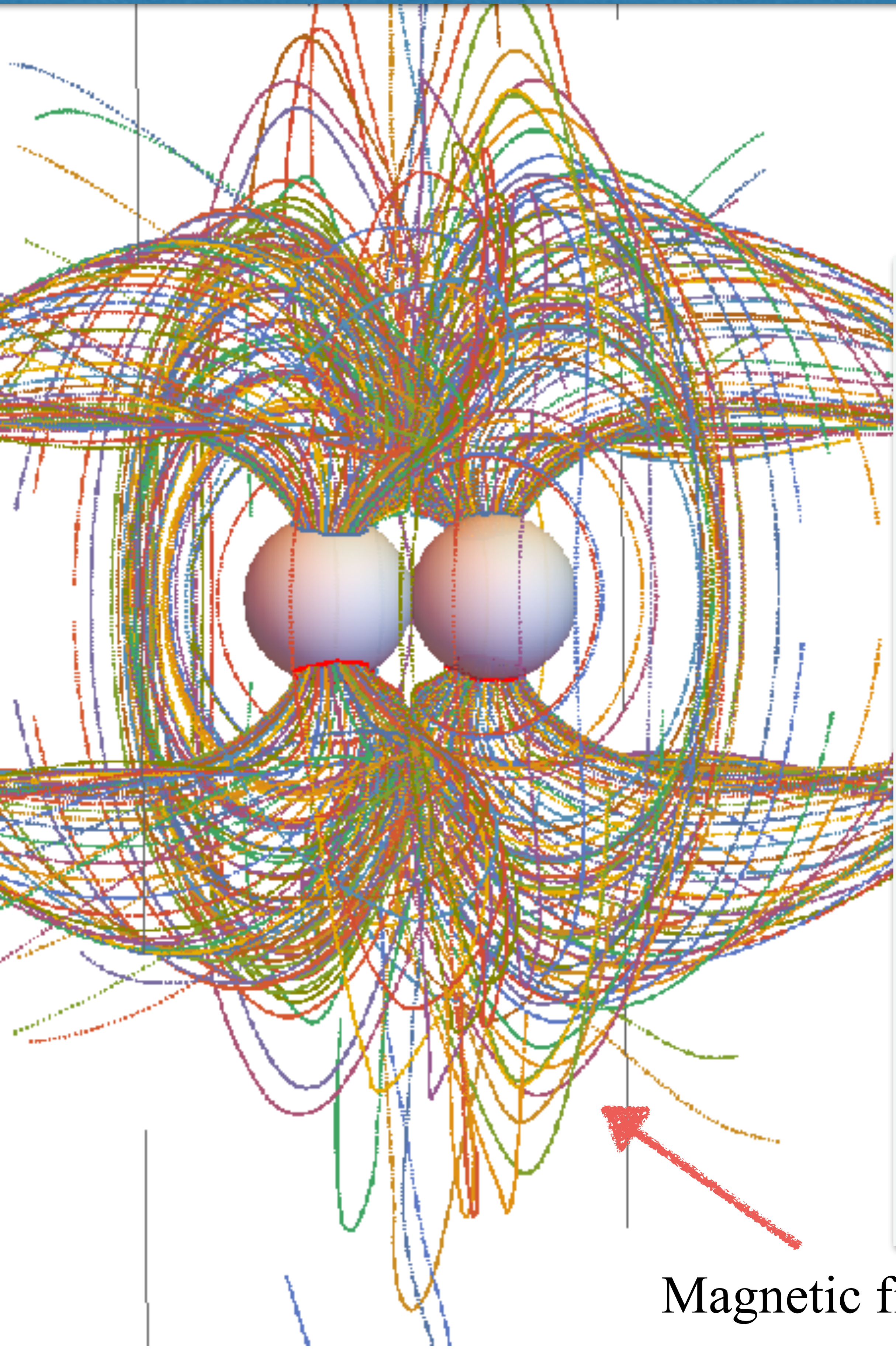
[Bai and Spitkovsky 2010]

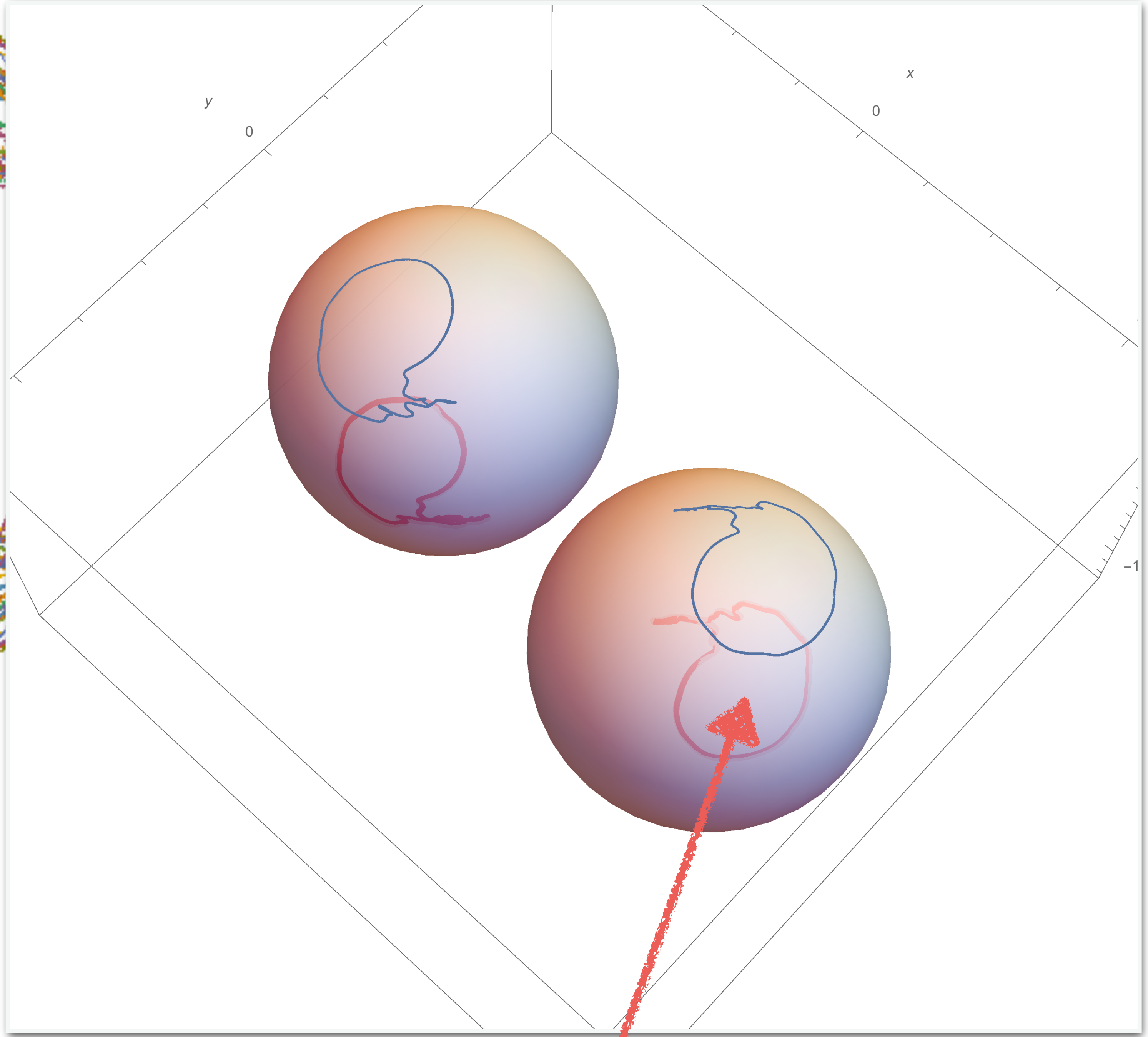
Assumptions:

- Emission along Open Field Lines
- Emission from strong current layers
  beyond the Light Cylinder

4. Binary Neutron Star case

t ~ -4.6ms (around 1 orbit prior to merger)

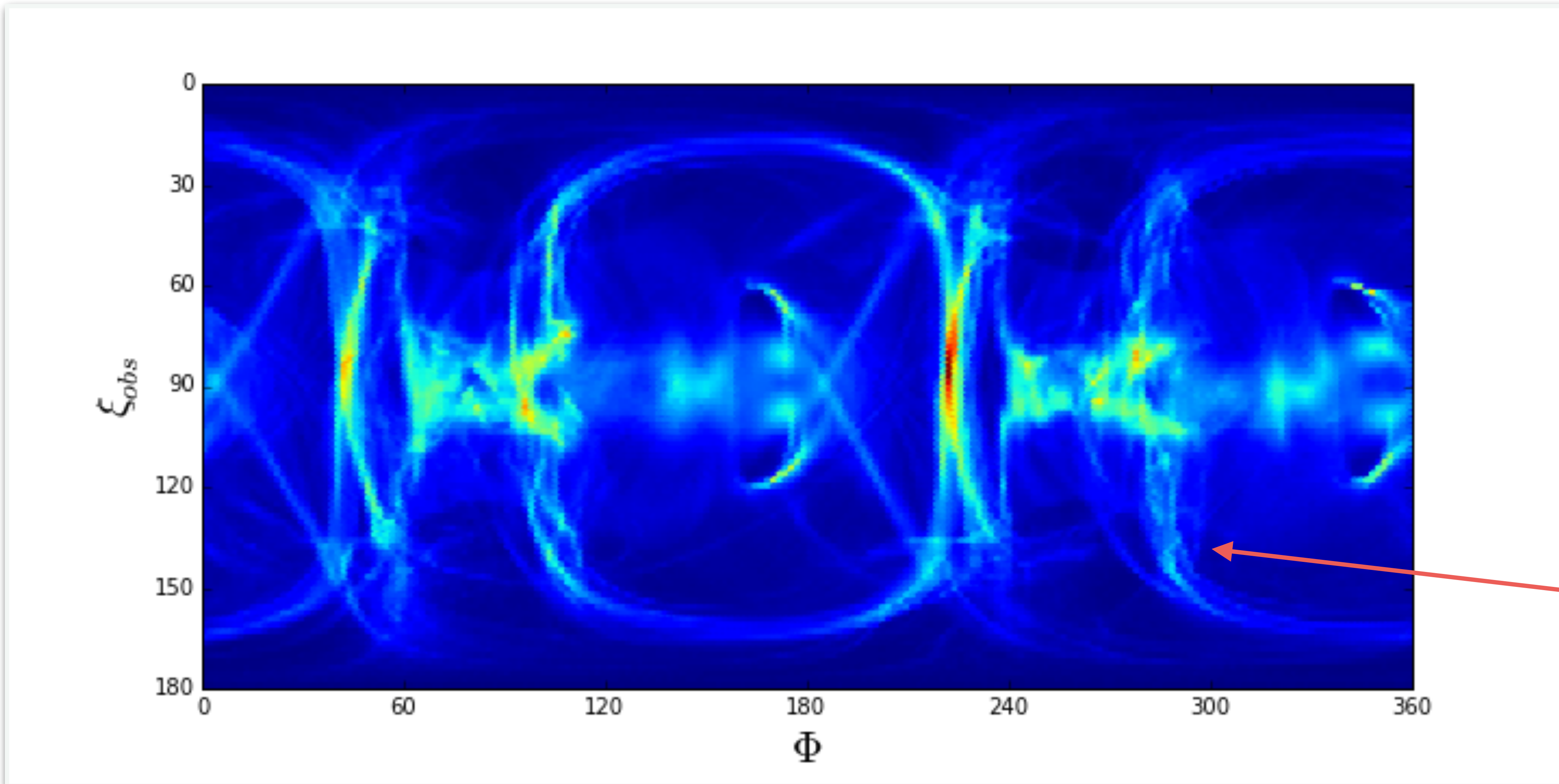




Magnetic field lines

Cap regions

4. Binary Neutron Star case

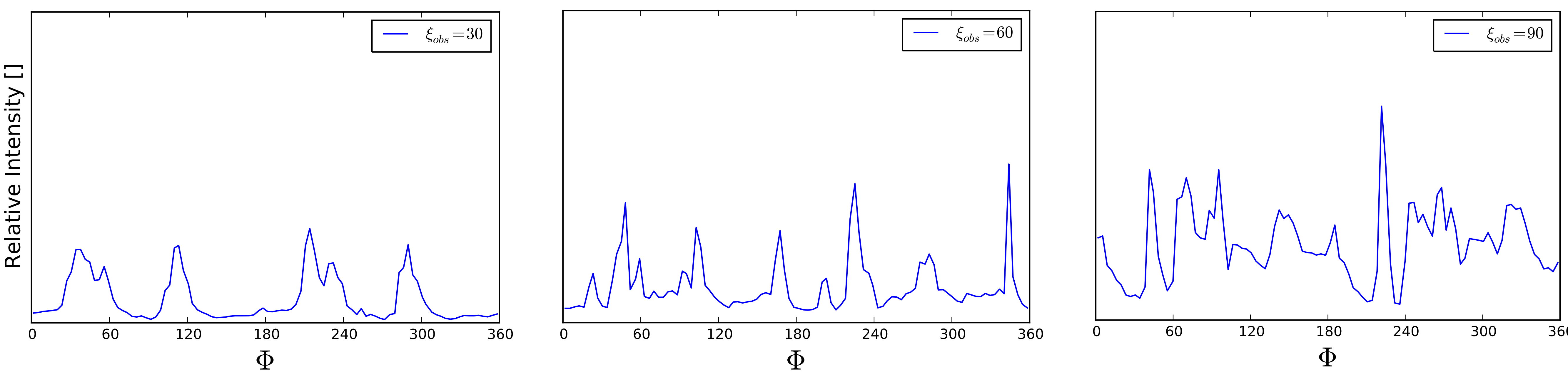


Resulting sky map

t ~ -4.6ms
(around 1 orbit
prior to merger)

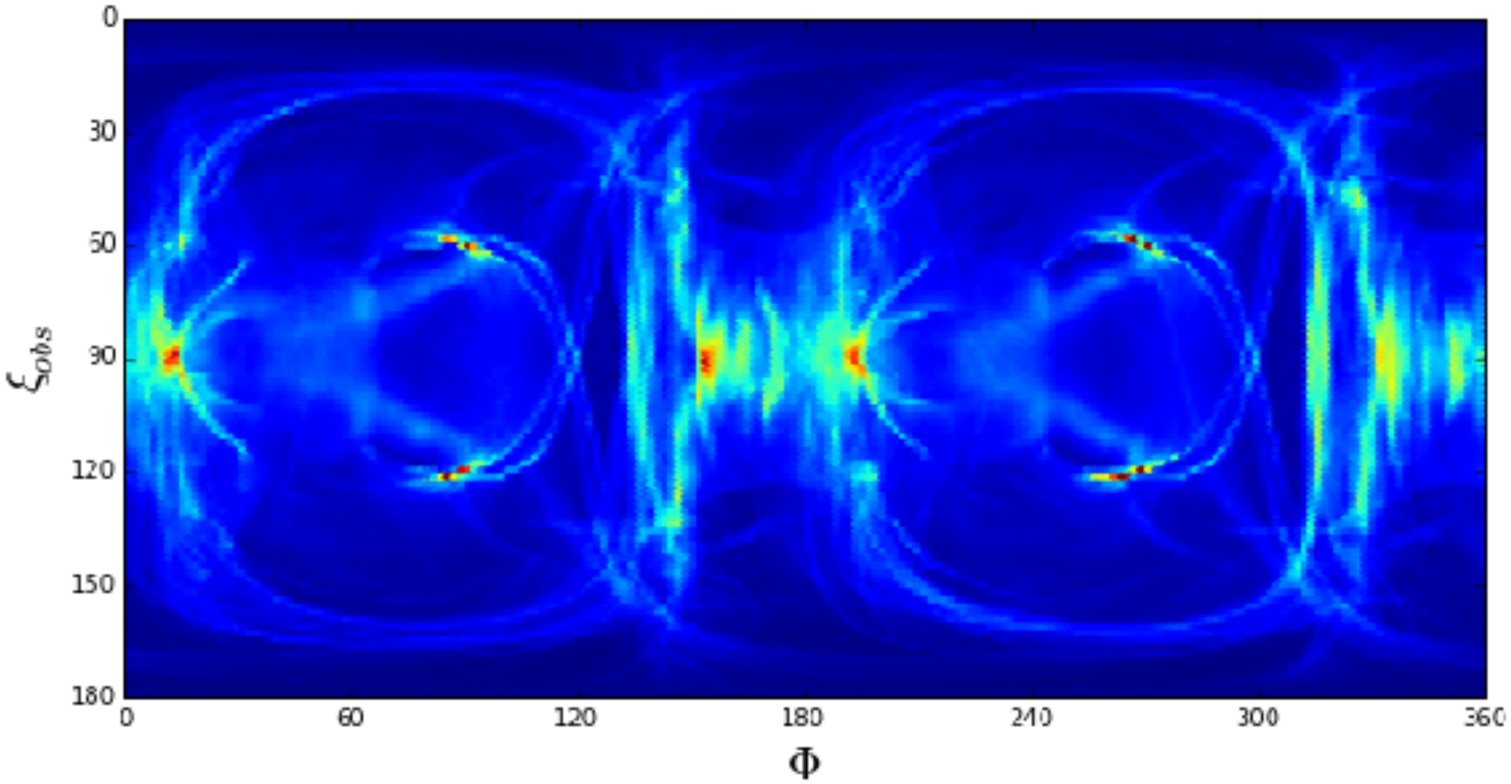
Notice not collimated
emission!

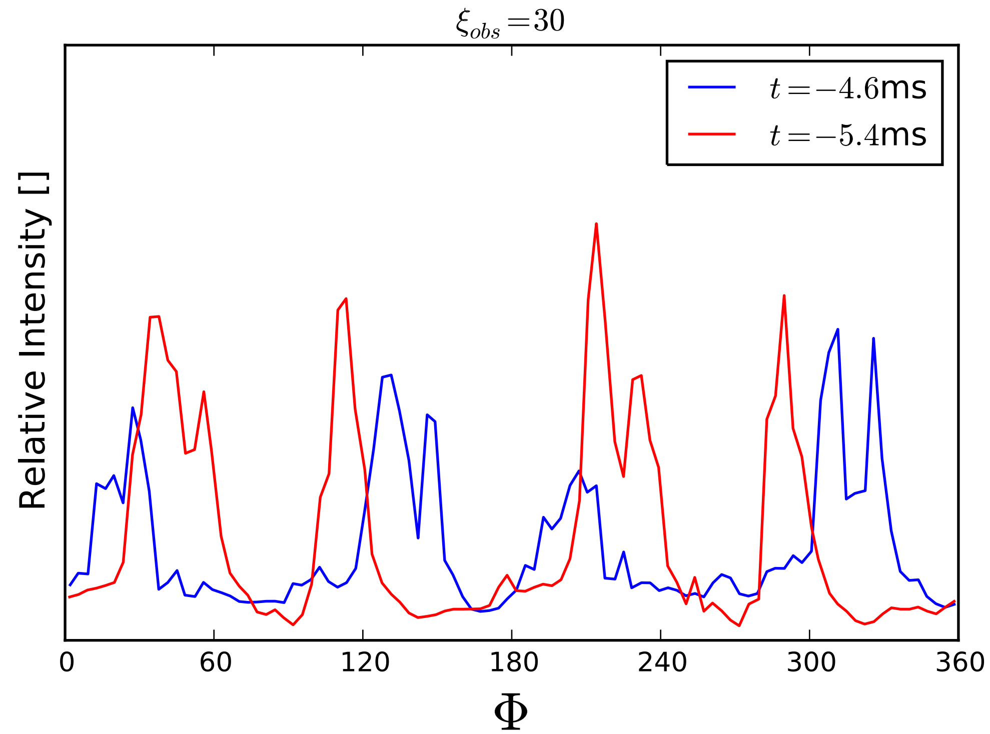
Some light curves



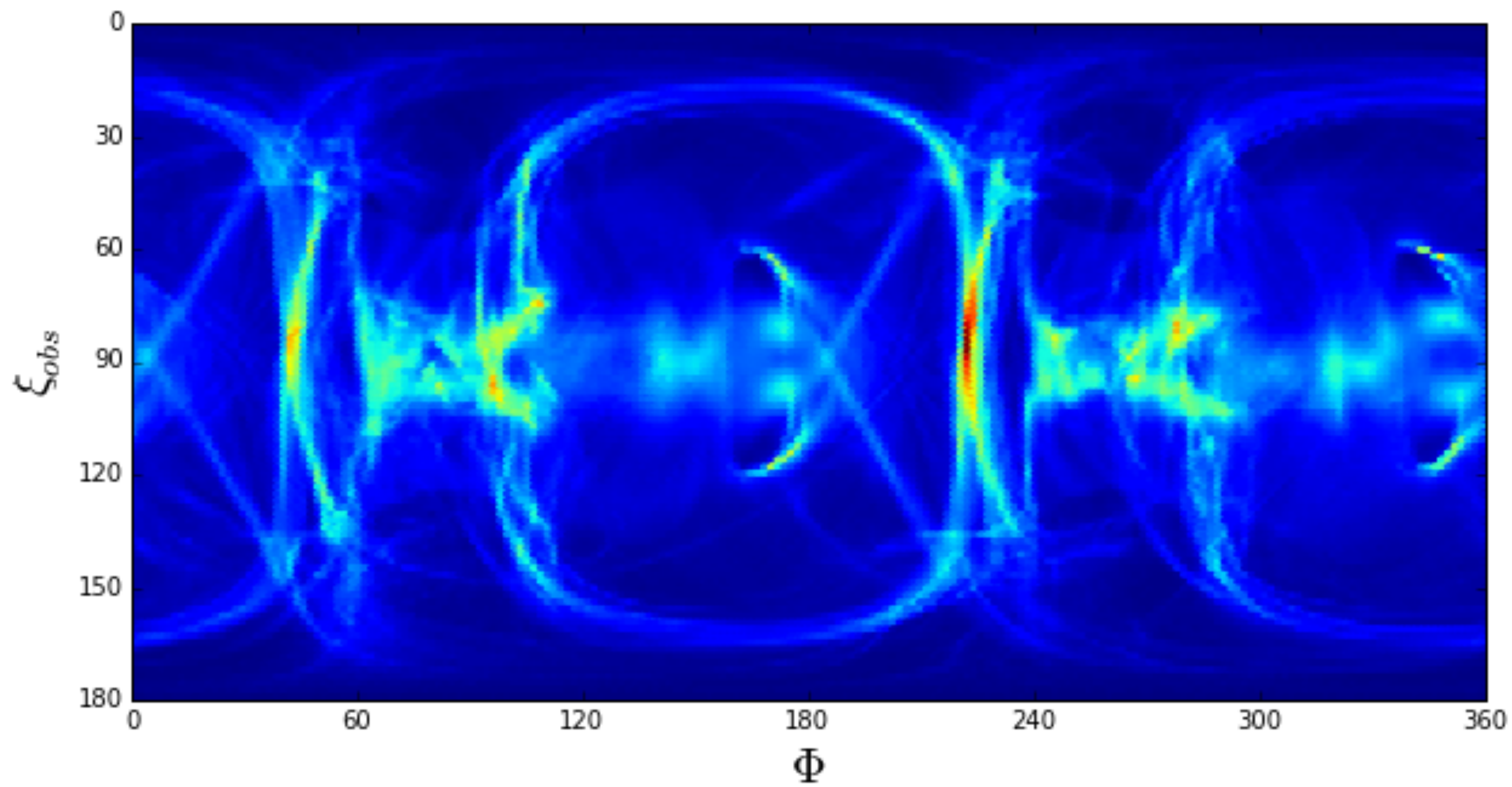
4. Binary Neutron Star case

Comparing the emission at different times before merger…





t=-4.6ms



t=-5.4ms

5. Summary

- Detection of EM counterparts will enable exciting advances in the field of gravitational wave astronomy

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- We are exploring Gamma-ray emission due to magnetosphere interaction in BNS systems as an EM counterpart because:

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- It is almost coincidental with merger time
- Its characteristics are tied to the orbital behaviour
- It is powerful enough to be detected on Earth

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- Misaligned spins case.
- Exploring EM counterparts in modified theories of gravity

Report appearing soon… we hope.