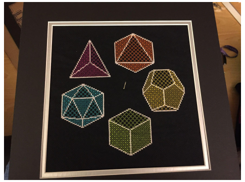
Using Computer Simulations to Shine a Light on Pulsars and Neutron Star Mergers

Hannah Klion (Lawrence Berkeley National Laboratory)



Congratulations!

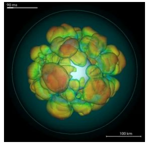
You solved a **Tuesday** Crossword in **8:02**.

★ YOU HAVE A 590-DAY STREAK

Grew up in Indianapolis, IN

BS Physics + minor in CS (Caltech, 2011-2015)

Rotating supernovae
Particle physics
Stellar evolution



einstein toolkit

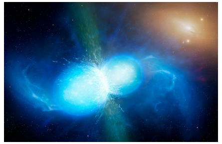
Mu2e

PhD in Physics (UC Berkeley, 2015-2021)

DOE Computational Science Graduate Fellowship, ORNL Summer 2017
Dissertation: Monte Carlo Radiation Transport Simulations of Asymmetric Neutron Star Mergers

OAK RIDGE National Laboratory

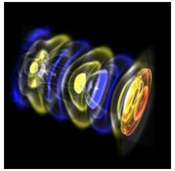
DOE CSGF

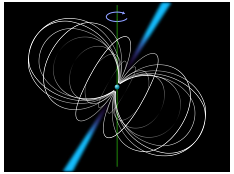


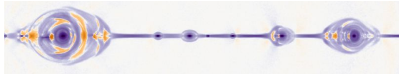
Sedona

Postdoc in AMCR at LBL (2021-now)

WarpX ECP
Pulsar emission
Magnetic reconnection

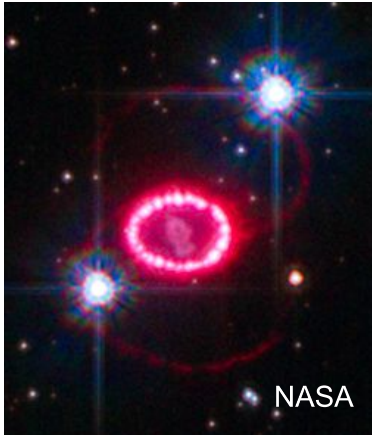


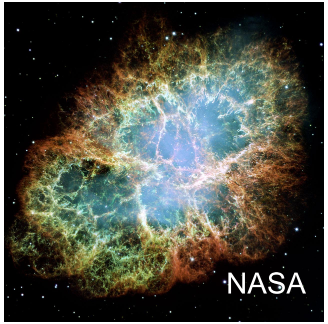




Neutron stars are unique laboratories for extreme physics

Massive star (> 8 M_{sun}) exhausts fuel at its core – collapses & undergoes a supernova

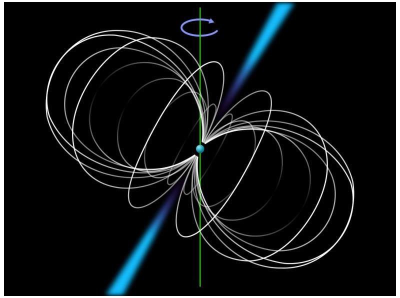

NASA


NASA

Scales:
- $M \sim 1 - 2\ M_{sun}$
- R ~ 10 - 12 km
- T ~ 1 million K

Challenge: even with the most powerful telescopes, what we can see is very limited!

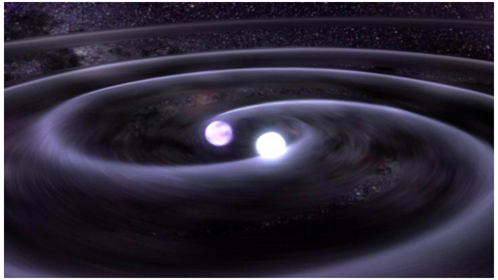
Simulate neutron star emission with particle-based methods



Pulsars: rapid rotation and high magnetic field

– pulses across spectrum, mostly radio

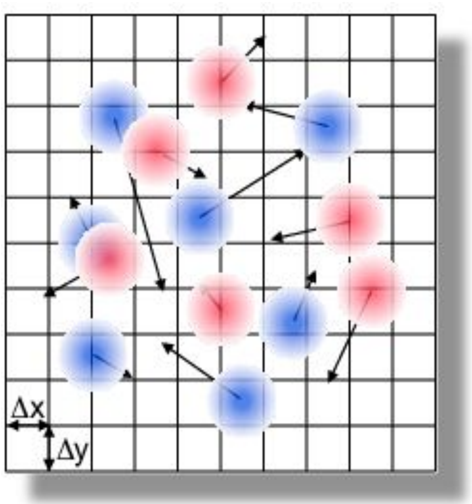
– gamma ray flares



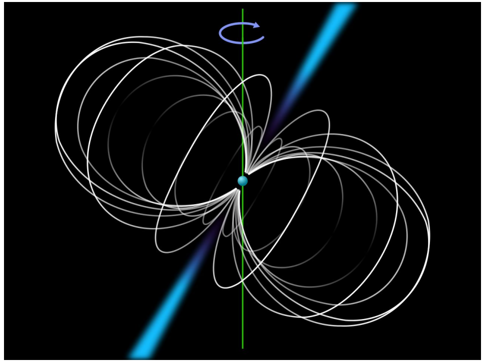
Binaries: with second neutron star or black hole

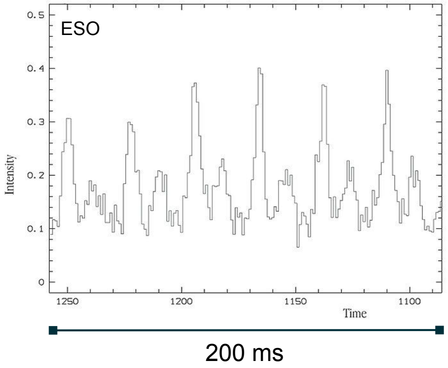
– Gravitational waves

– Merger: hot, glowing, radioactive outflow



How do pulsars emit light?



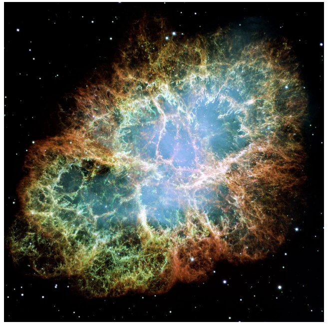


highly regular beamed pulses, from radio to gamma rays

Scales:

- M ~ 1 - 2 M_{sun}
- R ~ 10 - 12 km
- Period ~ 1 ms - 1 s
- Magnetic field ~ 10^8 T

gamma ray flares: very high energy electrons & non-ideal physics

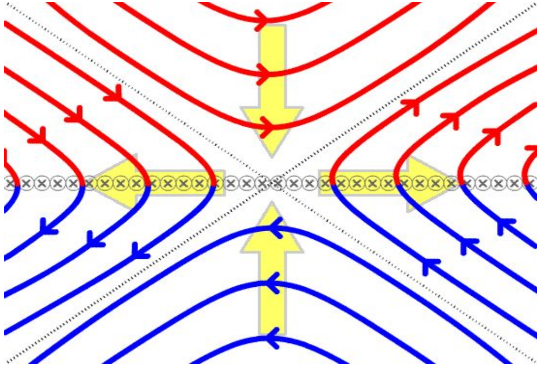


NASA

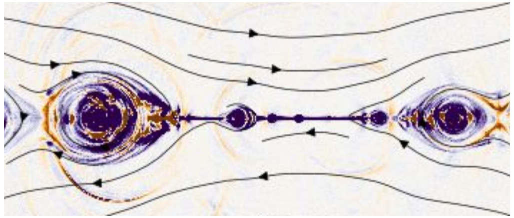
Starting from basic physics, can we simulate of pulsar particle acceleration & emission?

Magnetic reconnection is a particle accelerator

Magnetic field energy → Plasma kinetic energy (heating & bulk motion)



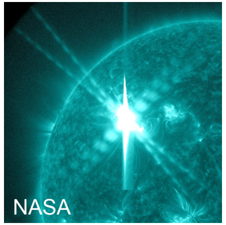
Modified from ChamouJacoN, Wikipedia



current sheets fragment into plasmoids

Reconnection accelerates particles near pulsars, and also is a cause of

Solar Flares

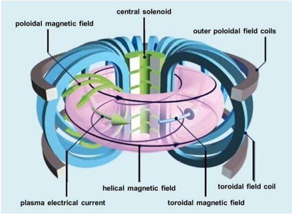


NASA

Aurora Borealis

NPS

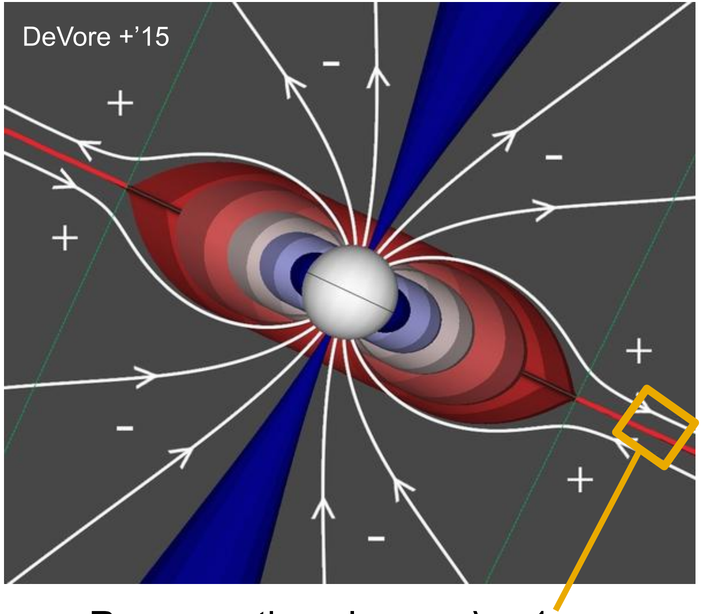
Fusion Disruptions



EUROfusion

Cannot simultaneously capture pulsar and reconnection scales

Pulsar: R ~ 10 km



DeVore +'15

Reconnection plasma: λ ~ 1 cm

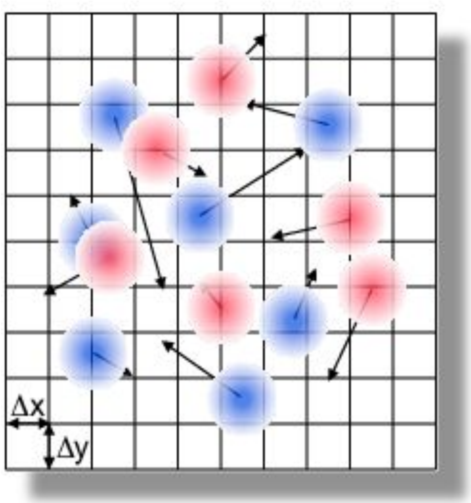
$$\frac{R}{\lambda} \sim 10^6$$

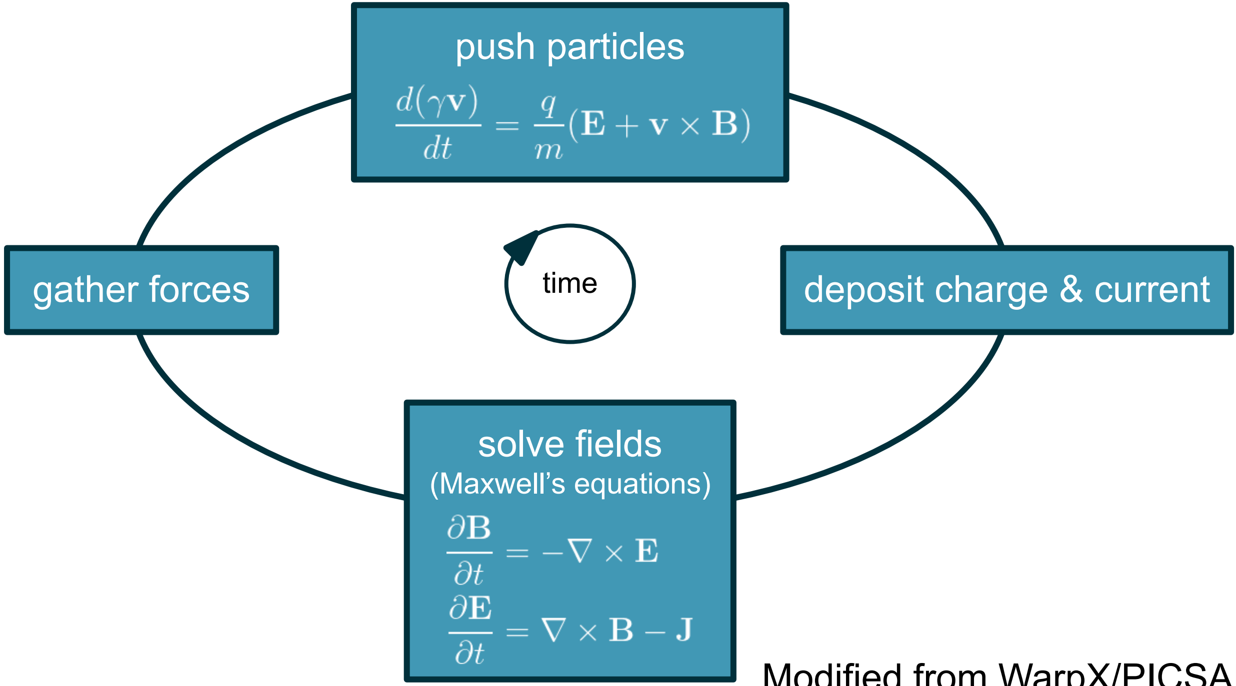
N ~ $10^7 \times 10^7 \times 10^7$

1. Scale down pulsar simulations so R/λ is smaller. How does scaling affect results?

2. Detailed simulations of reconnection only. Can we develop physically-informed models of reconnection to apply to #1?

Use particle-in-cell (PIC) methods to capture particle kinetics from first principles





push particles

$$\frac{d(\gamma \mathbf{v})}{dt} = \frac{q}{m}(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

deposit charge & current

solve fields
(Maxwell's equations)

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

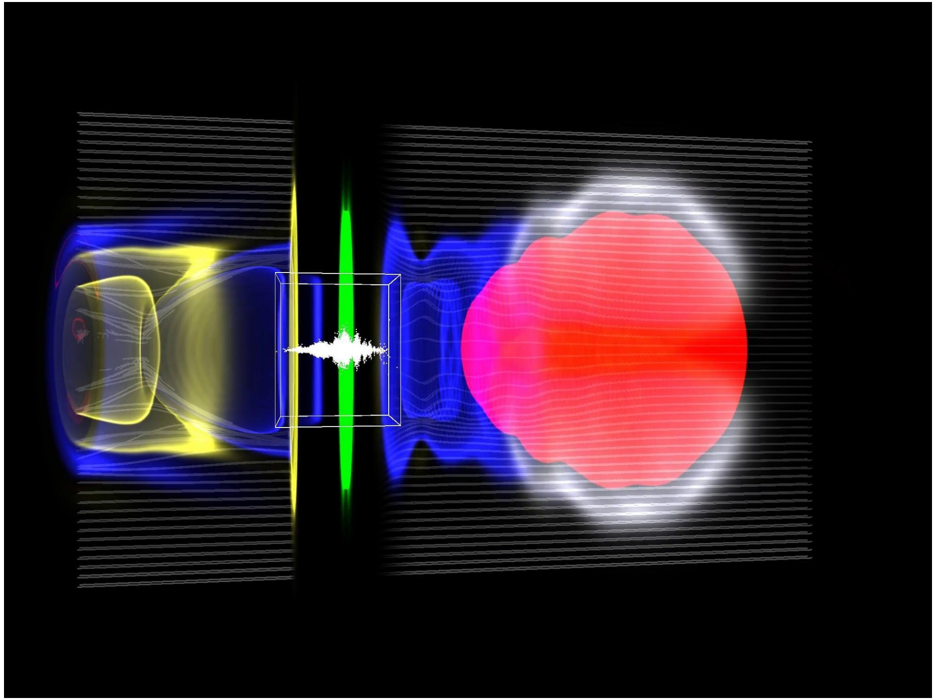
$$\frac{\partial \mathbf{E}}{\partial t} = \nabla \times \mathbf{B} - \mathbf{J}$$

gather forces

time

Modified from WarpX/PICSAR

WarpX + AMReX: Open-source particle-in-cell methods on the fastest supercomputers



EXASCALE COMPUTING PROJECT

- DoE Exascale computing project (PI: Jean-Luc Vay)
- Built on AMReX (LBNL: ECP co-design center)
- Advanced algorithms for plasma accelerators
- Mesh refinement: very challenging in PIC

Plus enhancements for pulsar/reconnection:

- Cell-averaged particle quantities
- Particle tagging & injection
- Relativistic momentum initialization
- Pair production & radiation reaction forces
- Multiple/adaptive mesh refinement

How to solve Maxwell’s equations: finite difference & pseudo-spectral

$$\frac{dy}{dx} \approx \frac{\Delta y}{\Delta x}$$

1. **F**inite **D**ifference **T**ime **D**omain (FDTD)

- Most popular algorithm
- Subject to numerical errors at high velocity

2nd order finite difference in space

+

2nd order finite difference in time

2. **P**seudo-**S**pectral **A**nalytical **T**ime **D**omain (PSATD)

Vay+’13, Vincenti & Vay ‘16

- More accurate
- Allows longer time steps
- **Never before been applied to relativistic reconnection**

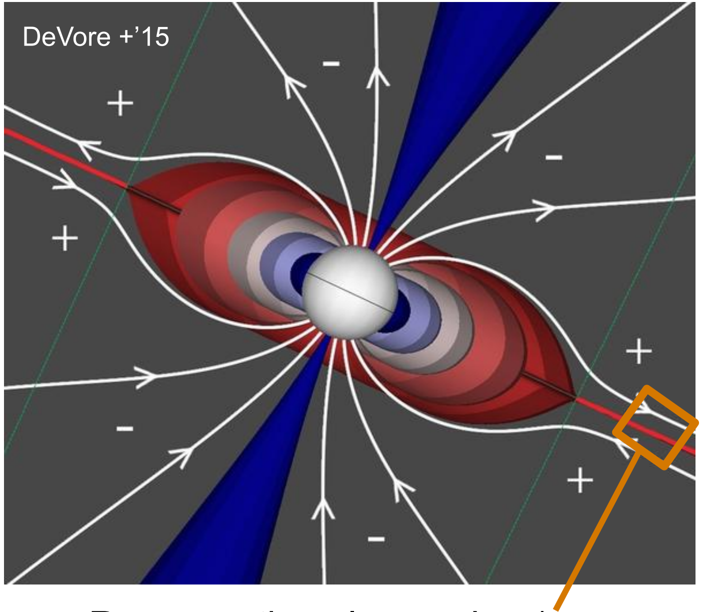
compute spatial derivatives in Fourier space

+

integrate analytically in time

Focus on detailed simulations of reconnection

Pulsar: R ~ 10 km



Reconnection plasma: λ ~ 1 cm

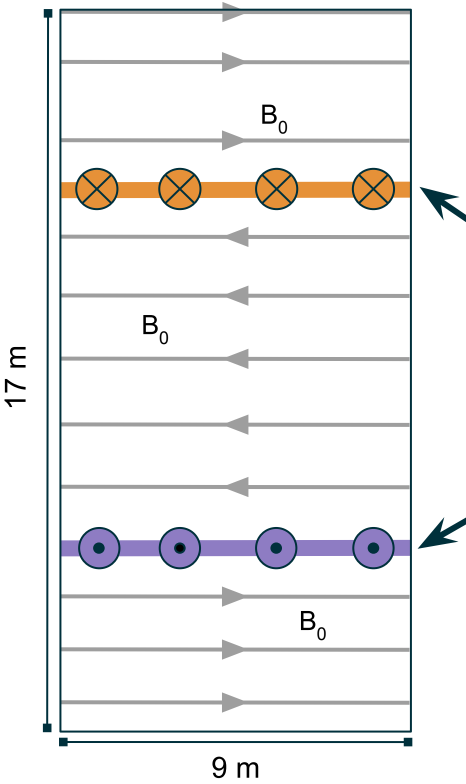
$$\frac{R}{\lambda} \sim 10^6$$

N ~ $10^7 \times 10^7 \times 10^7$

1. **Scale down pulsar simulations so R/λ is smaller.** How does scaling affect results?

2. **Detailed simulations of reconnection only.** Can we develop physically-informed subgrid models of reconnection?

Detailed simulations of reconnection



hot current sheets
$\delta = 5$ cm

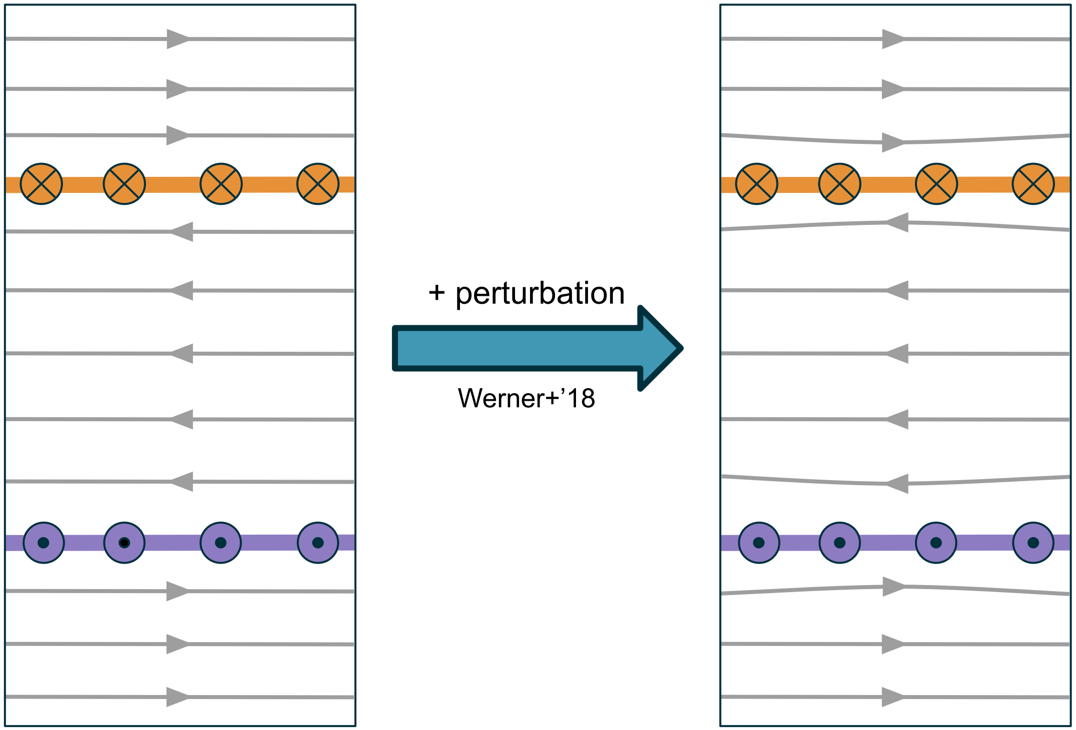
Equilibrium 2D double current sheet

Same plasma scale as physical pulsar problem: $\lambda = 1$ cm

Main physics results to extract:

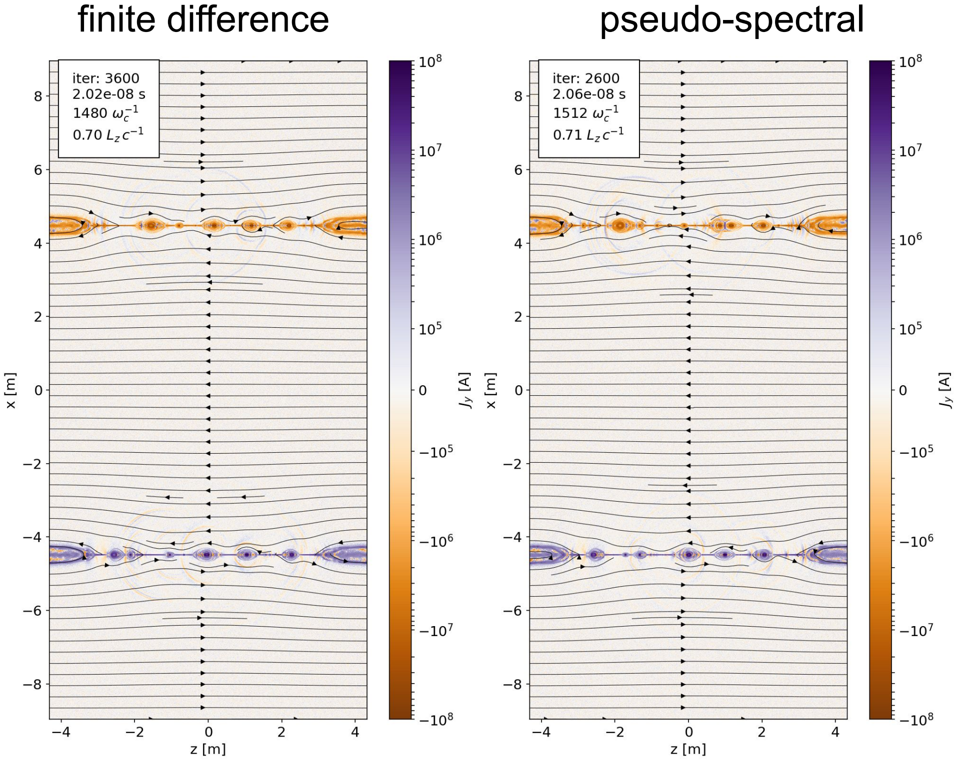
- particle energy distribution
- rate of magnetic reconnection

Trigger reconnection consistently across simulations



- ➔ Reconnection that starts in the same place across simulations, not triggered by statistical noise
- ➔ Apples-to-apples comparison of solvers

First simulations of relativistic reconnection with a pseudo-spectral Maxwell solver


finite difference

pseudo-spectral

- 126 GPUs on Summit
- Grid: 7200 X 3600
- Particles: 3 Billion
- 1 - 2 hours of wall time
- 10,000 time steps

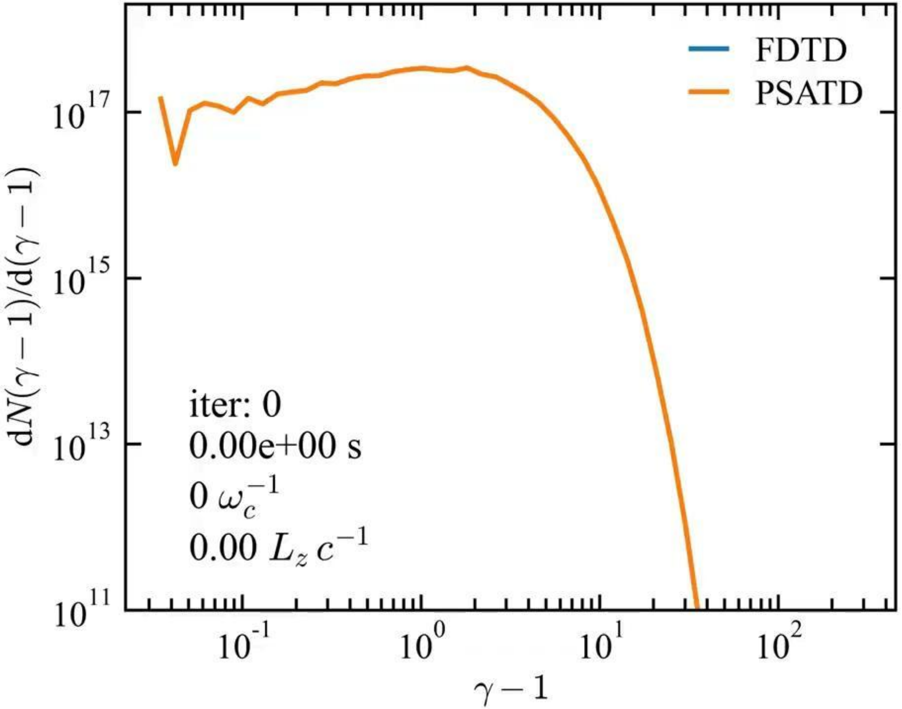
Qualitatively, results from different solvers look similar

Pseudo-spectral is more efficient than finite difference

	Finite difference	**Pseudo-spectral**
Wall time per timestep:	0.29 seconds	0.28 seconds
Simulation timestep:	5.6×10^{-12} seconds	7.9×10^{-12} seconds
Wall time per simulation:	**1.6 hours**	**1.1 hours**

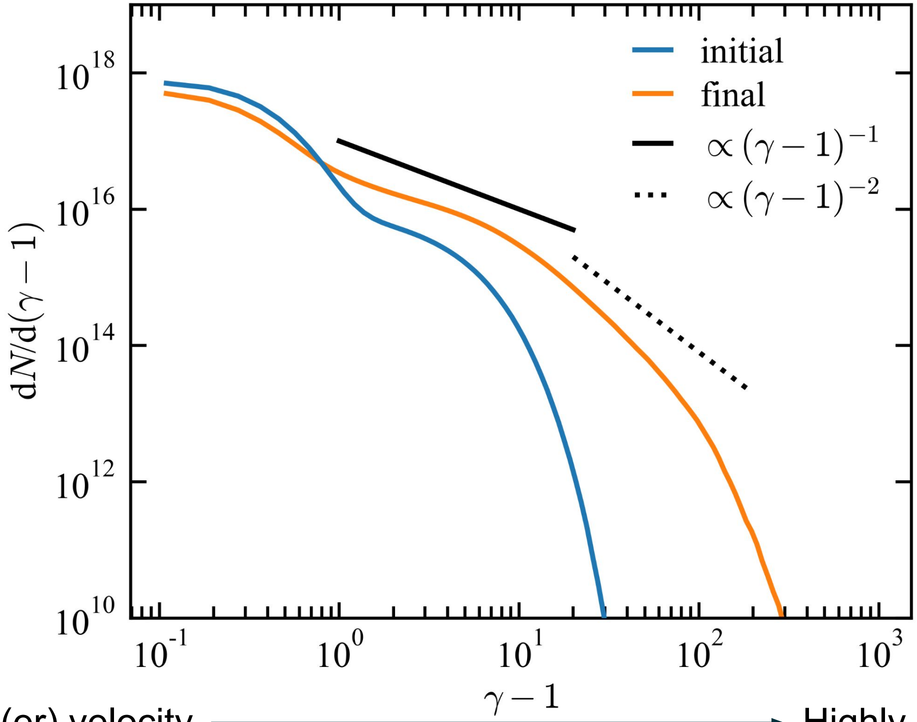
Particles are accelerated to highly relativistic energies

Abundance



Low(er) velocity → Highly relativistic

Final energy spectral slopes match the literature



Abundance

Low(er) velocity → Highly relativistic

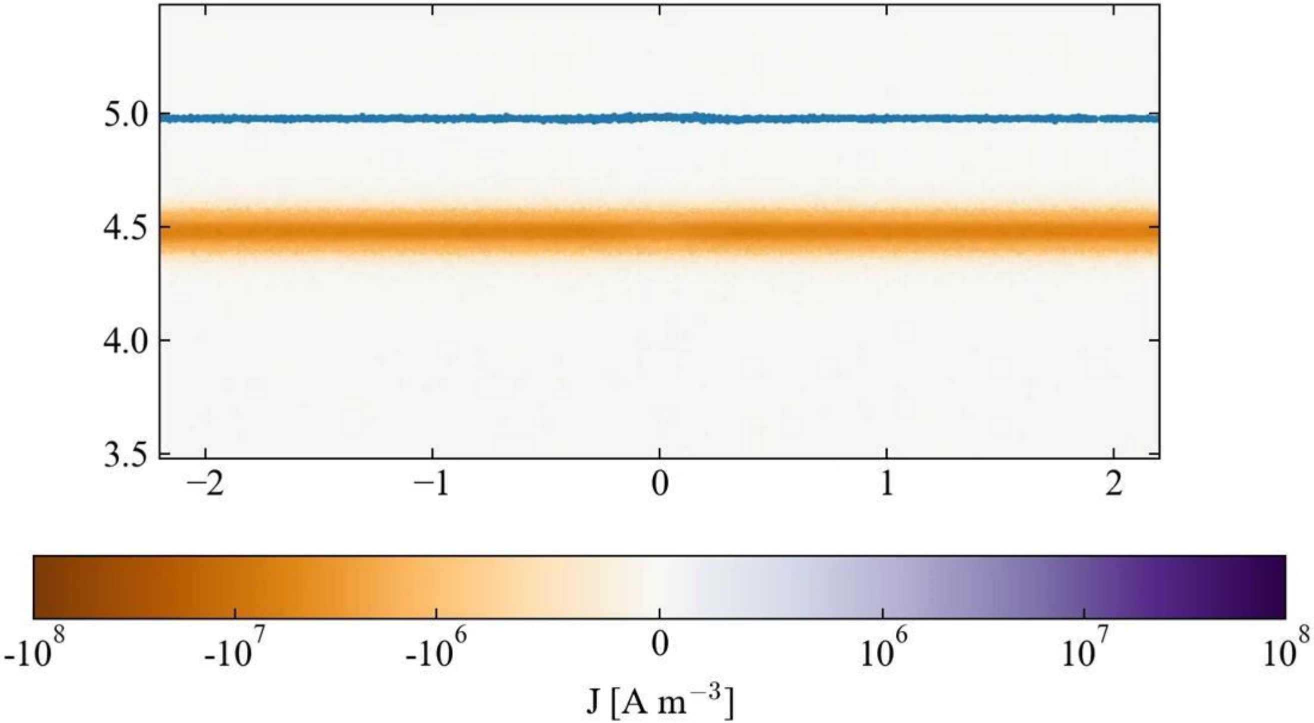
Equilibrium 2D double current sheet

Main physics to extract:

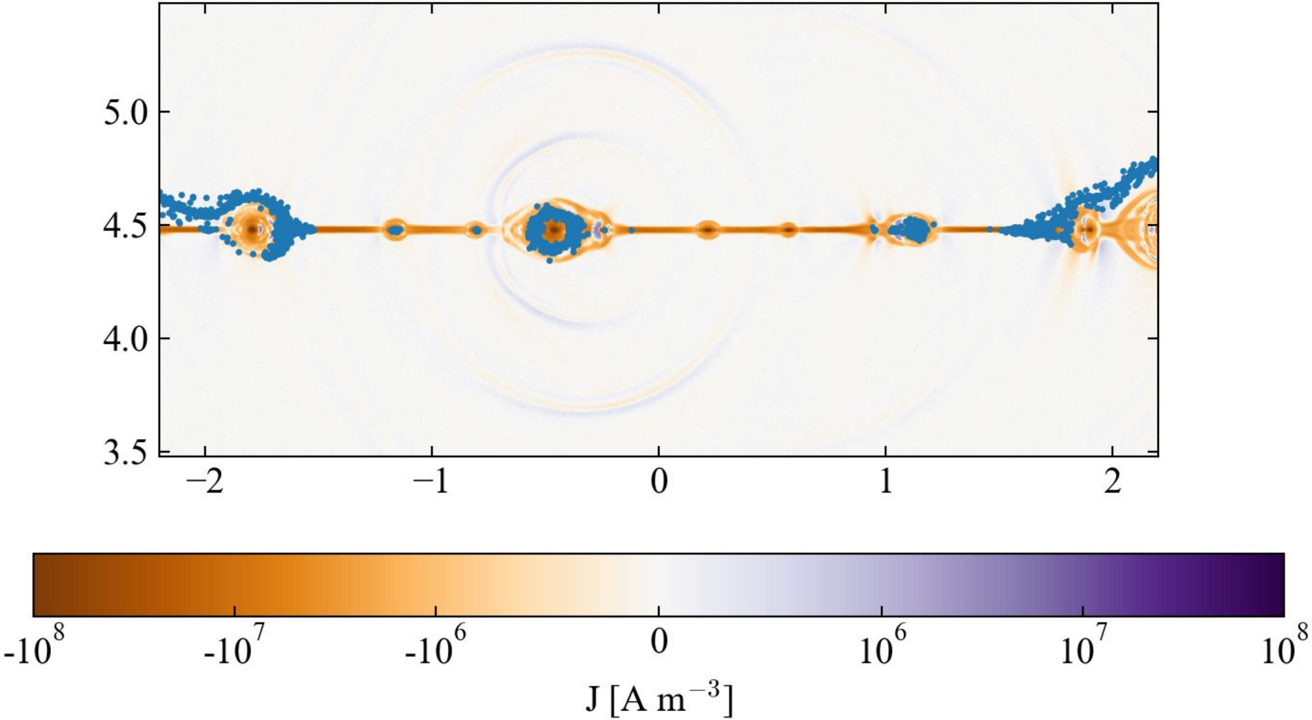
- particle energy distribution
- rate of magnetic reconnection

Typical distribution has a power law with a slope between -1 and -2 (e.g. Guo+'15)

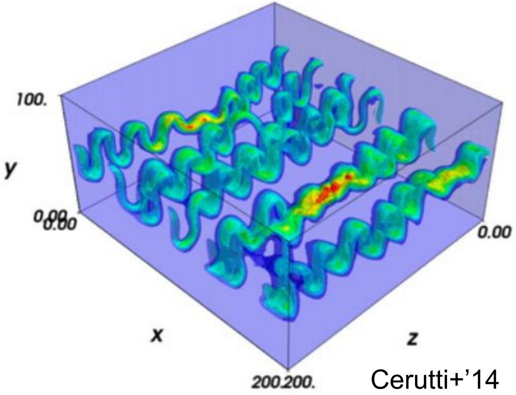
Particle trajectories to observe acceleration and flow into current sheet



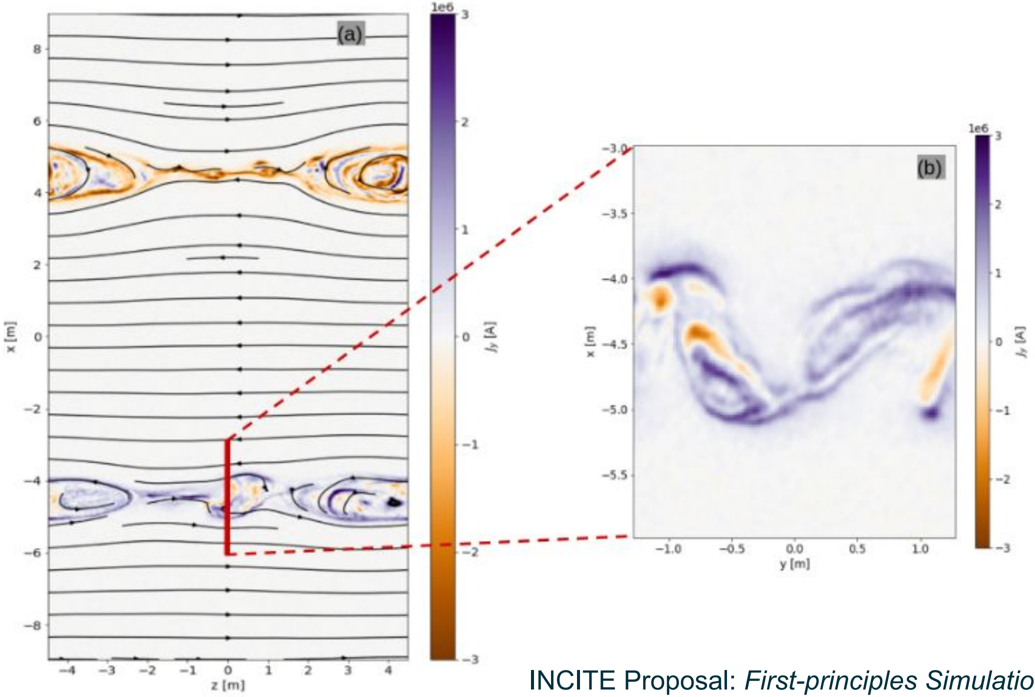
Particle trajectories to observe acceleration and flow into current sheet



What’s next? Additional instabilities in 3D

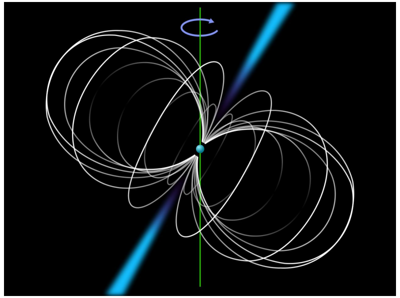


Cerutti+’14



INCITE Proposal: *First-principles Simulations of Relativistic Magnetic Reconnection*, submitted. Jambunathan (PI), co-PI incl. **Klion**

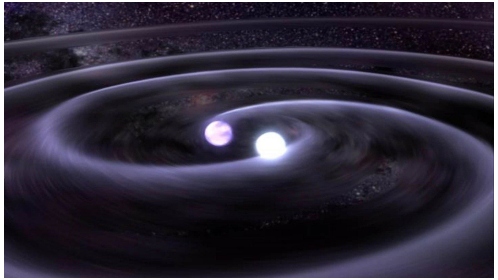
Simulate neutron star emission with particle-based methods



Pulsars: rapid rotation and high magnetic field

– pulses across spectrum, mostly radio

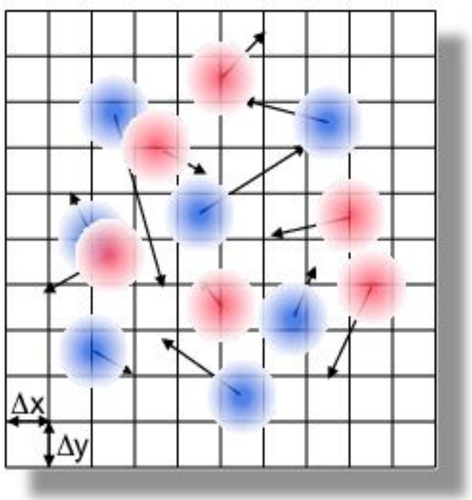
– gamma ray flares



Binaries: with second neutron star or black hole

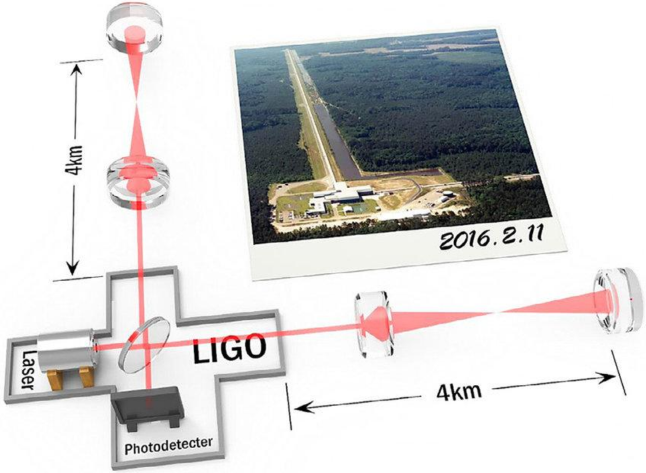
– Gravitational waves

– Merger: hot, glowing, radioactive outflow



Gravitational waves are ripples in spacetime

R. Hurt, Caltech/MIT/LIGO Lab



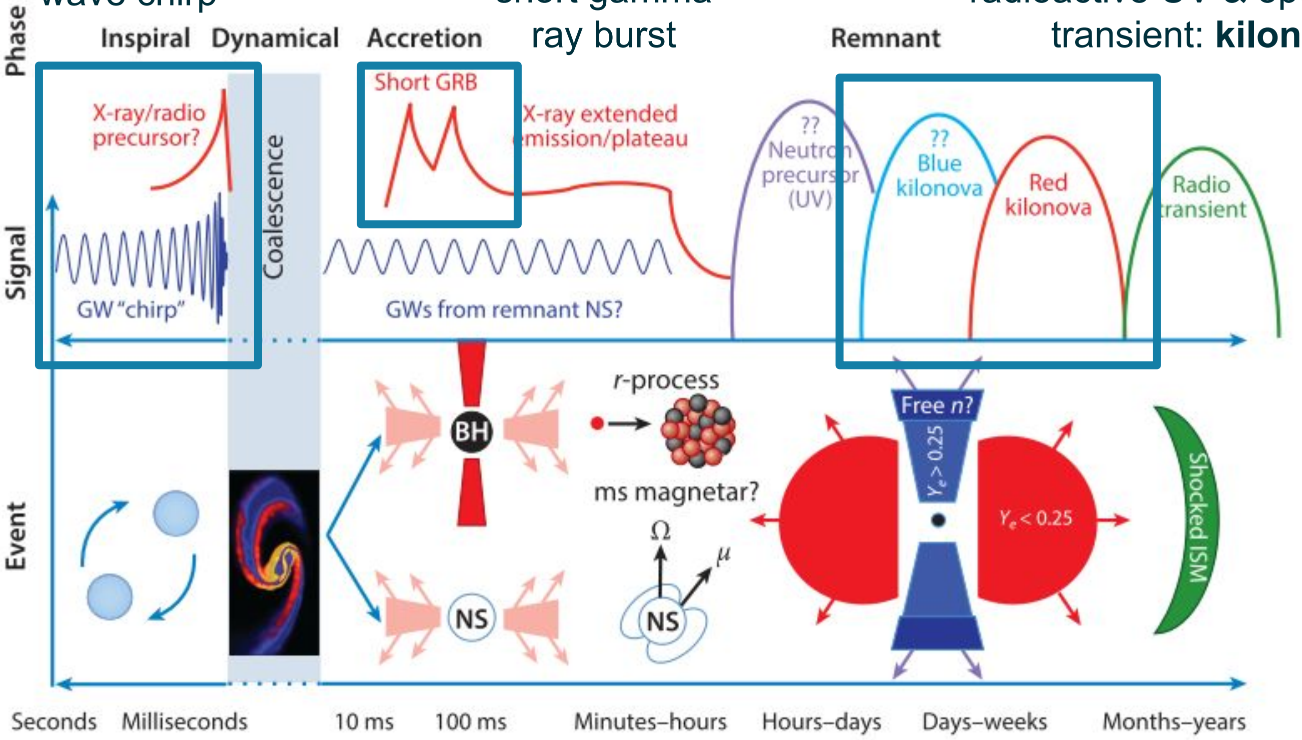
Zuo + ‘20

Neutron star mergers can be observed in multiple ways

gravitational wave chirp

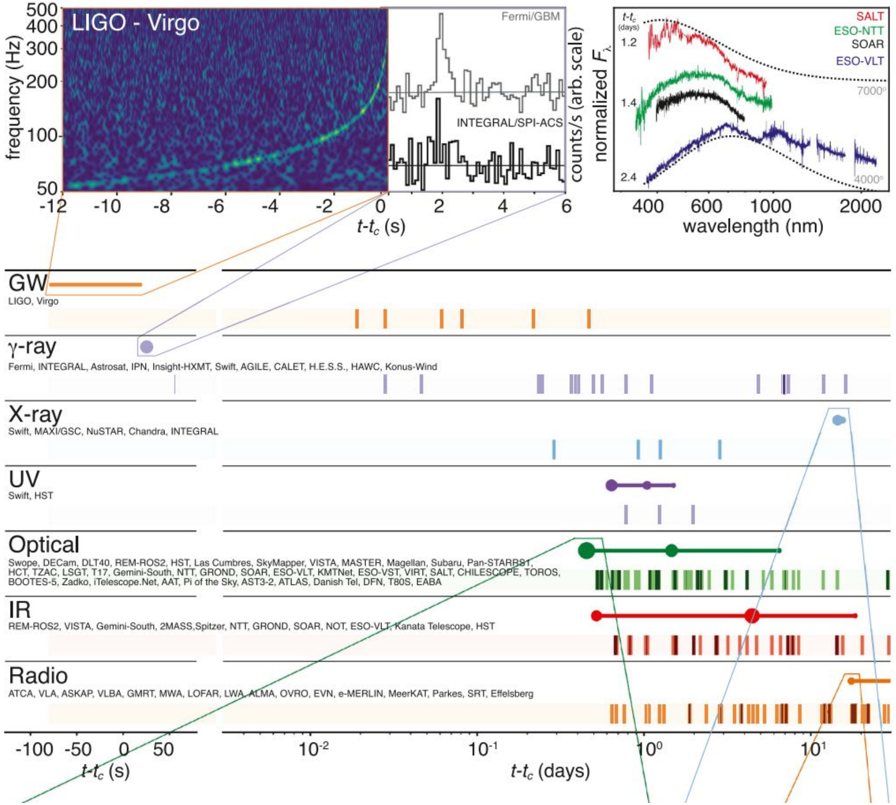
short gamma ray burst

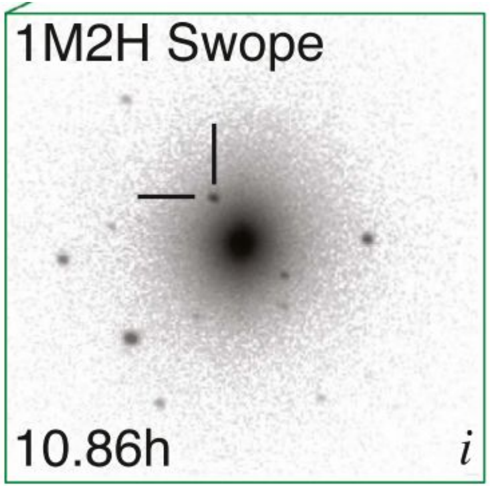
radioactive UV & optical & IR transient: **kilonova**



Fernández & Metzger '16

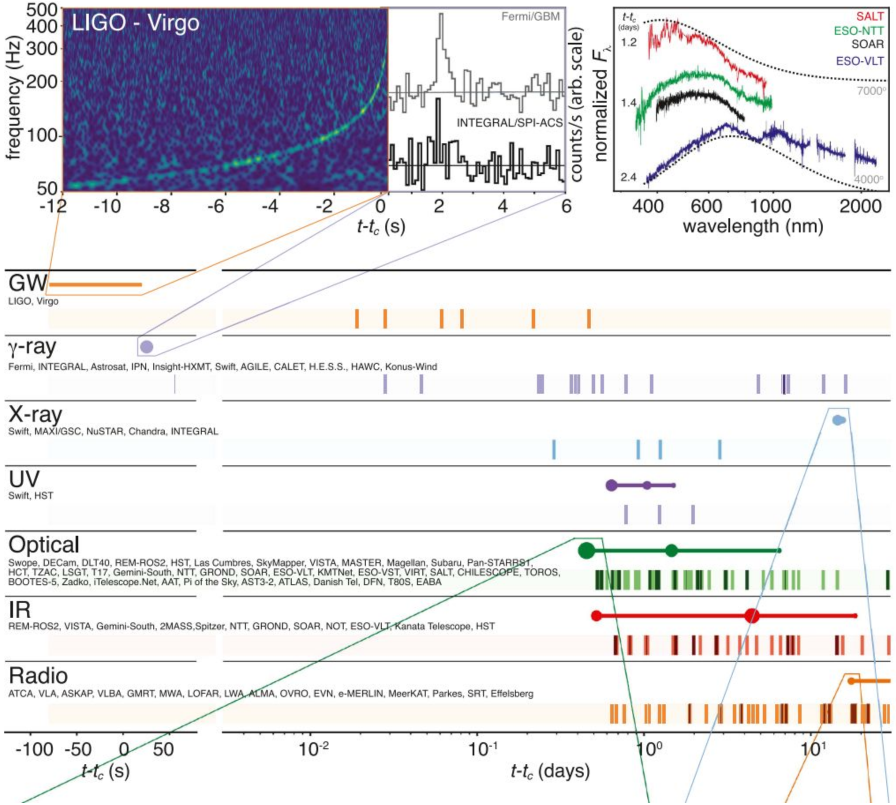
Years of theory confirmed by single event in 2017



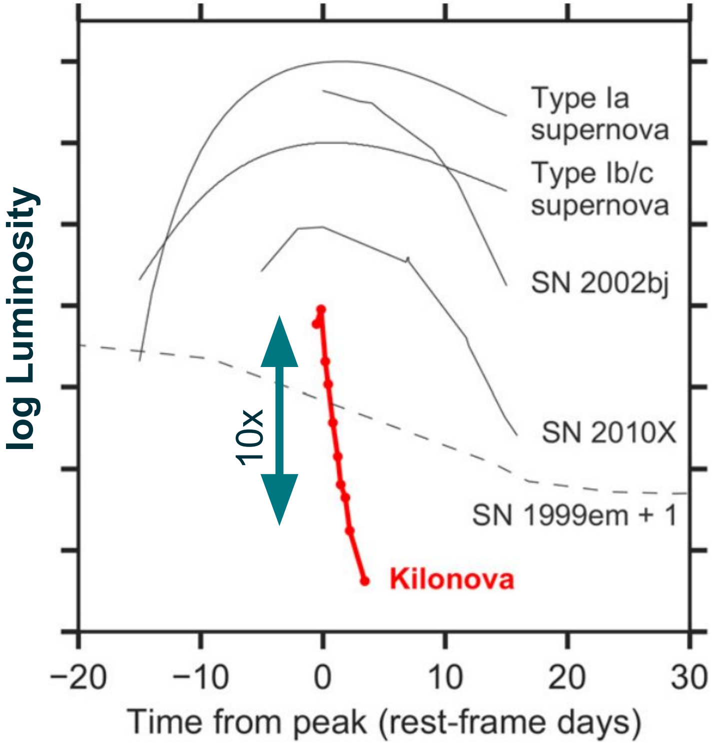


LIGO Collaboration '17

Discovered transient unlike a supernova

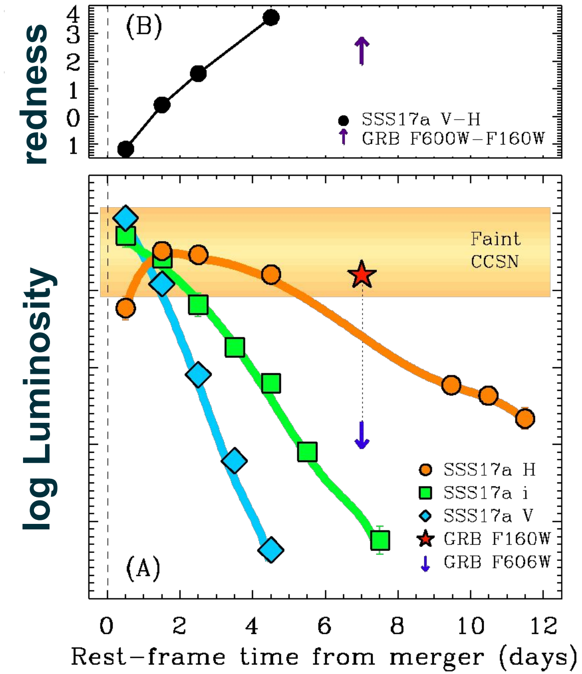


LIGO Collaboration ‘17

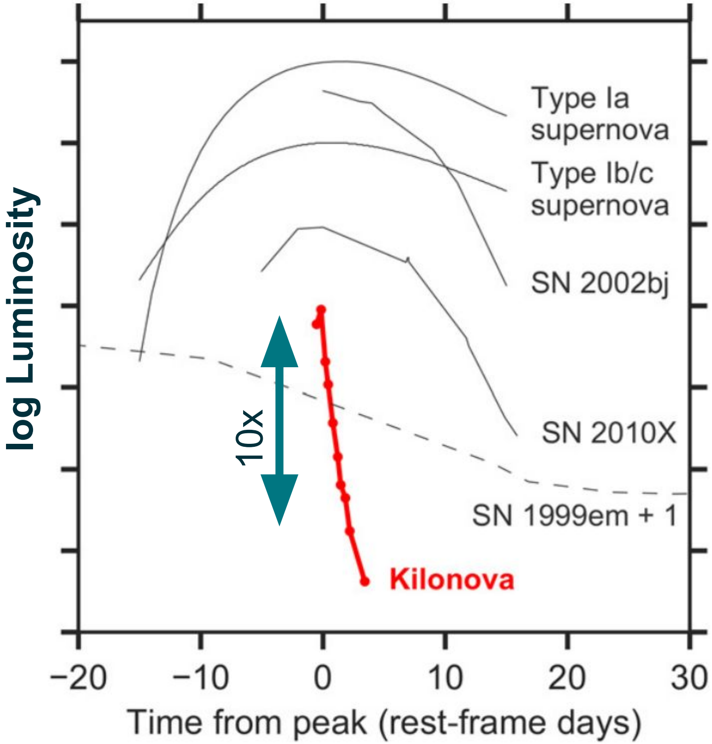


Arcavi + ’17

Evolved quickly and was bright in red & infrared

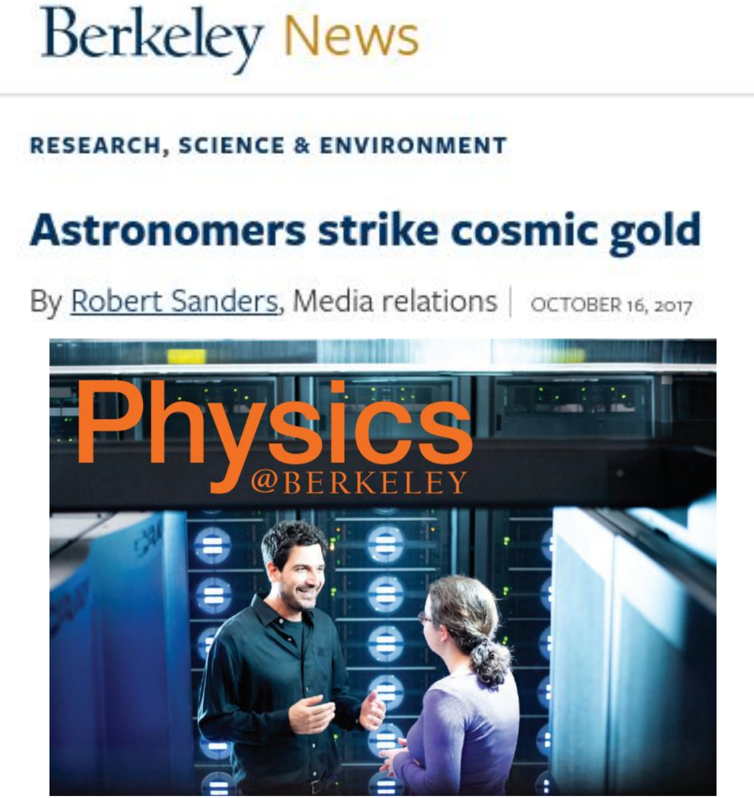


Drout + ‘17



Arcavi + ’17

Red color suggests presence of heavy elements



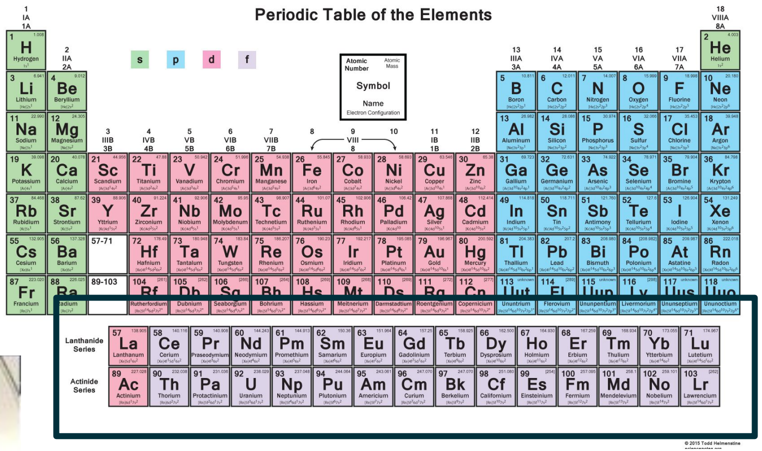
Berkeley News

RESEARCH, SCIENCE & ENVIRONMENT

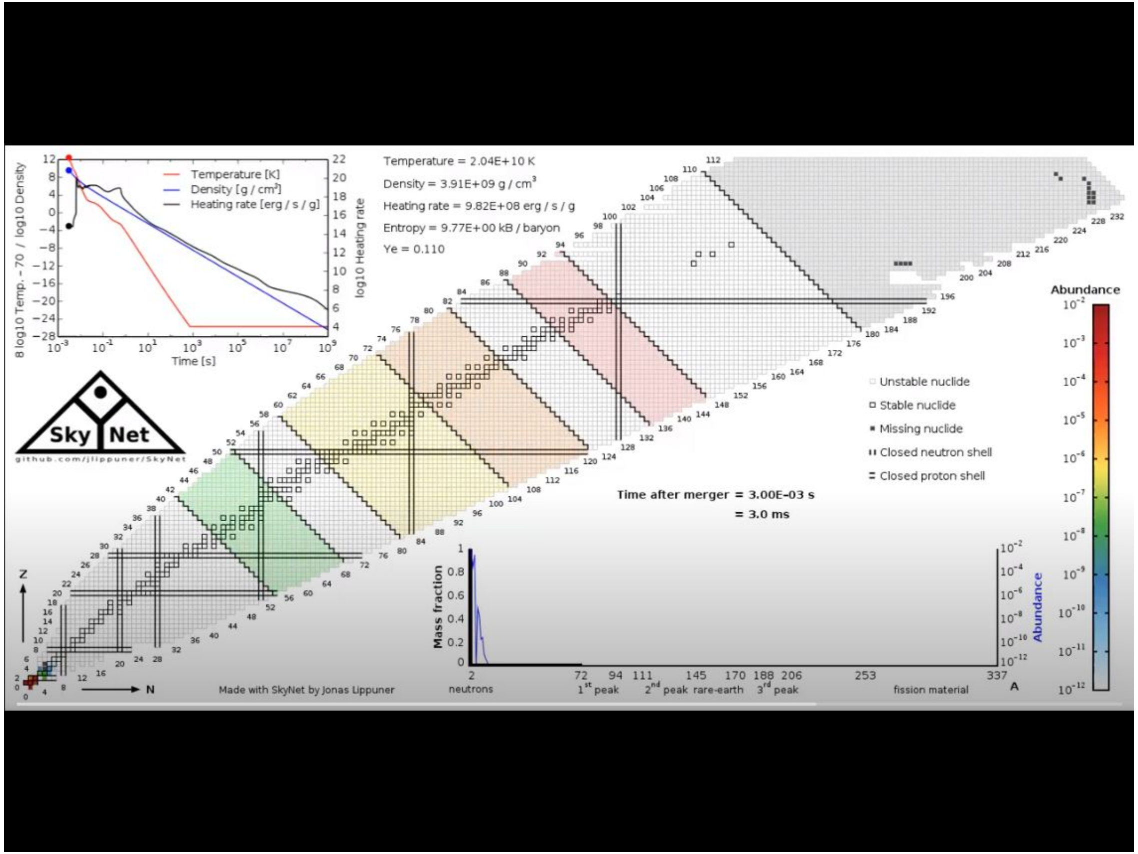
Astronomers strike cosmic gold

By Robert Sanders, Media relations | OCTOBER 16, 2017

Jennifer Barnes
Postdoctoral Scholar
KITP



R-Process Nucleosynthesis



Temperature = 2.04E+10 K

Density = 3.91E+09 g / cm^3

Heating rate = 9.82E+08 erg / s / g

Entropy = 9.77E+00 kB / baryon

Ye = 0.110

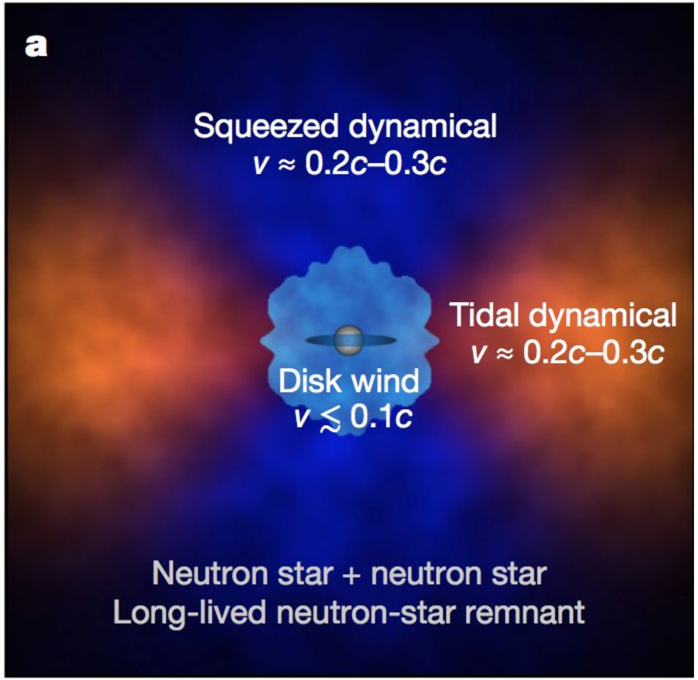
Time after merger = 3.00E-03 s

= 3.0 ms

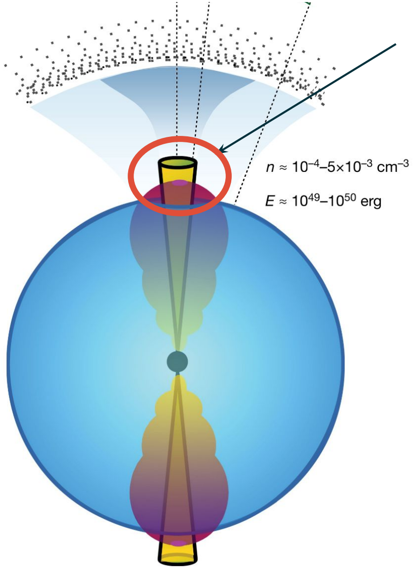
Made with SkyNet by Jonas Lippuner

Jonas Lippuner
(LANL)

Observations consistent with radioactive material + highly relativistic outflow



+



v ~ speed of light

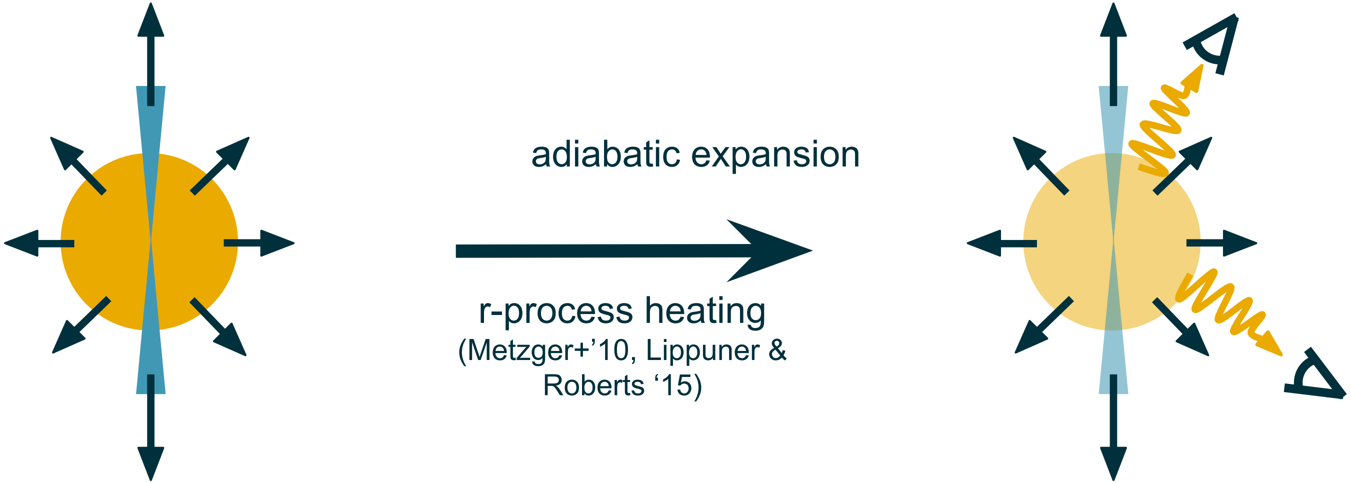
Kasen + ’17
Mooley + ‘18

What next?

How would the same event look from different viewing angles?

How will the interaction between slower radioactive material and relativistic jet affect that?

Approach: hydrodynamics, then radiation transport



t ~ 10 ms to t ~ 100 s

t ~15 min to t ~ 10 days

adiabatic expansion

r-process heating
(Metzger+'10, Lippuner &
Roberts '15)

2D relativistic hydrodynamic simulation (in JET) of jet interacting with expanding outflow
(Duffell, Quataert, Kasen, **Klion**) '18)

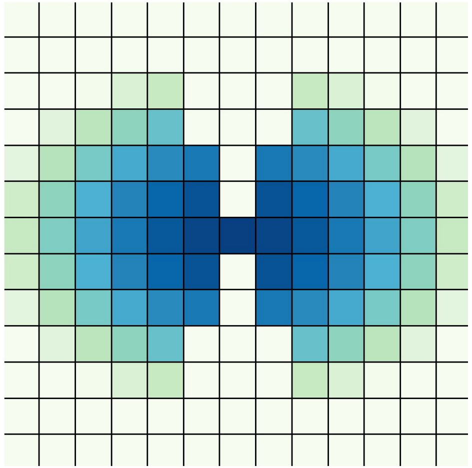
2D Monte Carlo radiation transport simulations with Sedona
(**Klion** + '21)

Sedona

- **Parallel Monte Carlo radiation transport code (Kasen + ’06, update in prep)**
  - Line expansion, bound-free, free-free, electron scattering opacities
  - 3D geometry and transport (implicit Monte Carlo & discrete diffusion Monte Carlo)
  - **Parallelized with MPI and OpenMP**
  - **Checkpoint & restart**
  - ~15 users, code paper and public release forthcoming

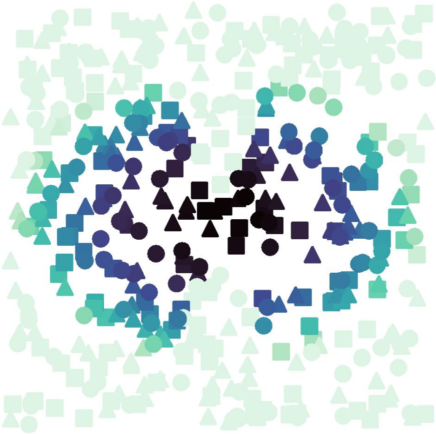
Sedona

Background gas



+

Particles



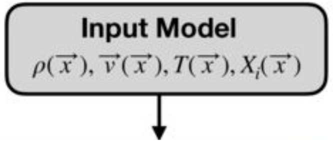
@ each cell

- Opacity (also varies w/ light wavelength)
- Temperature
- Composition

for each particle

- Photon frequency
- Total energy
- Direction

Sedona

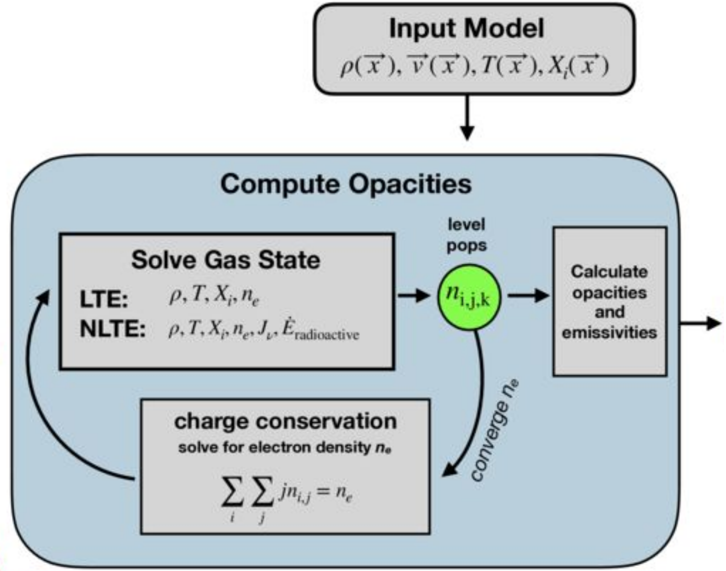


Input Model

$\rho(\vec{x}), \vec{v}(\vec{x}), T(\vec{x}), X_i(\vec{x})$

modified from methods paper (in prep)

Sedona



Input Model

$\rho(\vec{x}), \vec{v}(\vec{x}), T(\vec{x}), X_i(\vec{x})$

Compute Opacities

Solve Gas State

LTE: ρ, T, X_i, n_e

NLTE: $\rho, T, X_i, n_e, J_\nu, \dot{E}_{\rm radioactive}$

level pops

$n_{\rm i,j,k}$

Calculate opacities and emissivities

charge conservation

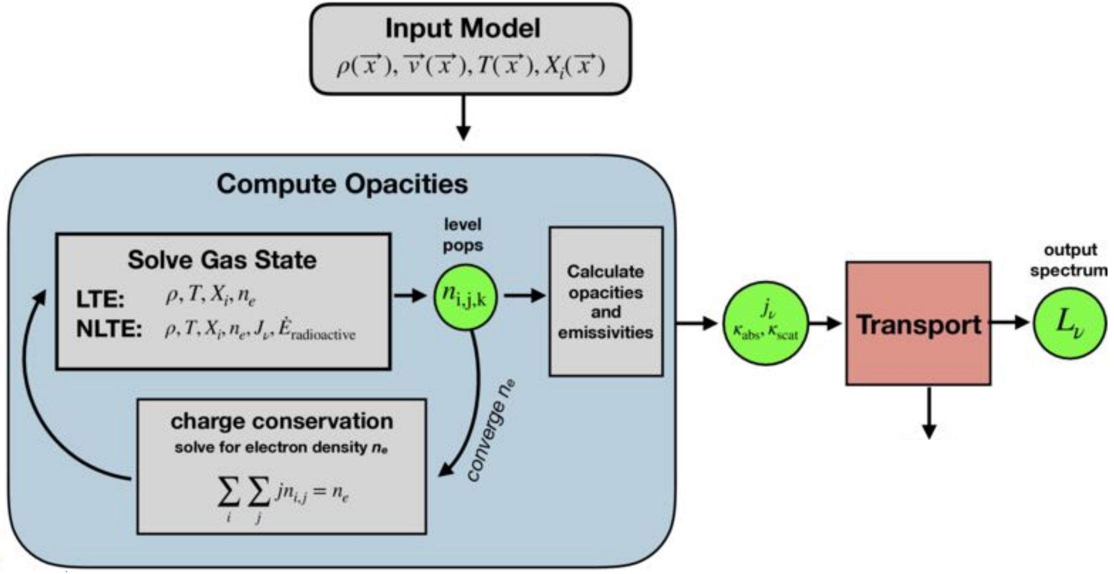
solve for electron density n_e

$$\sum_i \sum_j j n_{i,j} = n_e$$

converge n_e

modified from methods paper (in prep)

Sedona



Input Model

$\rho(\vec{x}), \vec{v}(\vec{x}), T(\vec{x}), X_i(\vec{x})$

Compute Opacities

Solve Gas State

LTE: ρ, T, X_i, n_e

NLTE: $\rho, T, X_i, n_e, J_\nu, \dot{E}_{\text{radioactive}}$

level pops

$n_{\text{i,j,k}}$

Calculate opacities and emissivities

converge n_e

charge conservation

solve for electron density n_e

$$\sum_i \sum_j j n_{i,j} = n_e$$

j_ν

$\kappa_{\text{abs}}, \kappa_{\text{scat}}$

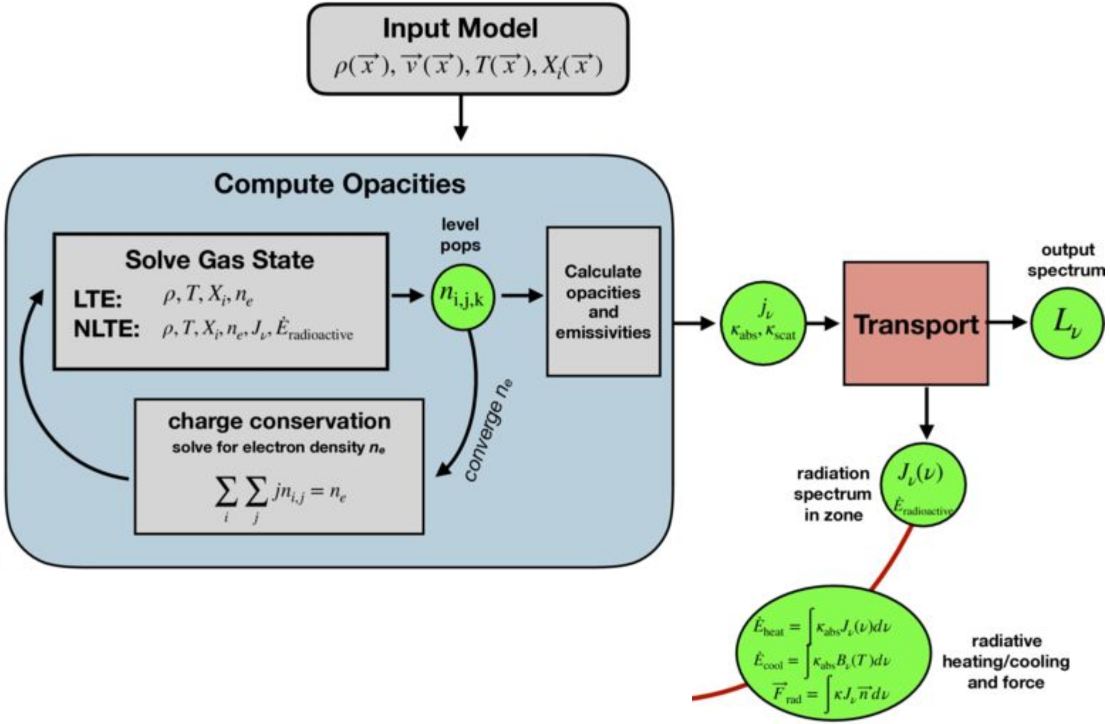
Transport

output spectrum

L_ν

modified from methods paper (in prep)

Sedona



Input Model

$\rho(\vec{x}), \vec{v}(\vec{x}), T(\vec{x}), X_i(\vec{x})$

Compute Opacities

Solve Gas State

LTE: ρ, T, X_i, n_e

NLTE: $\rho, T, X_i, n_e, J_\nu, \dot{E}_{\text{radioactive}}$

level pops

$n_{\text{i,j,k}}$

Calculate opacities and emissivities

converge n_e

charge conservation

solve for electron density n_e

$$\sum_i \sum_j j n_{i,j} = n_e$$

j_ν

$\kappa_{\text{abs}}, \kappa_{\text{scat}}$

Transport

output spectrum

L_ν

radiation spectrum in zone

$J_\nu(\nu)$

$\dot{E}_{\text{radioactive}}$

$$\dot{E}_{\text{heat}} = \int \kappa_{\text{abs}} J_\nu(\nu) d\nu$$

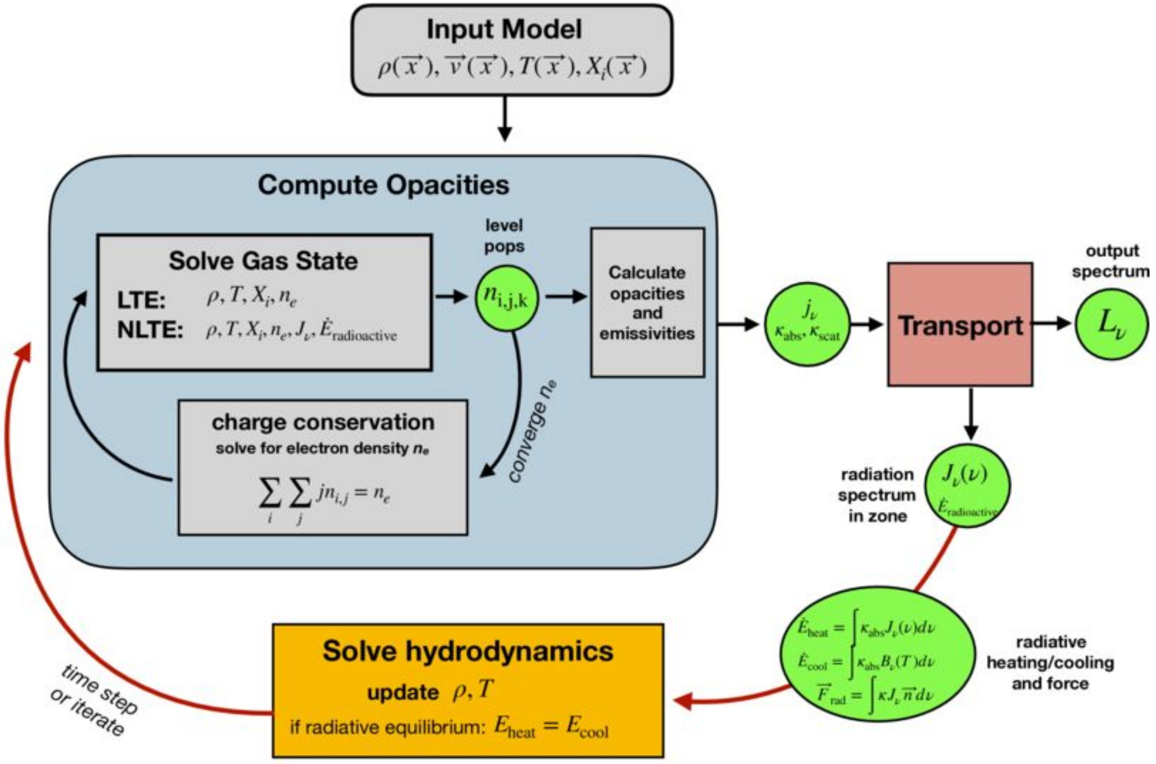
$$\dot{E}_{\text{cool}} = \int \kappa_{\text{abs}} B_\nu(T) d\nu$$

$$\vec{F}_{\text{rad}} = \int \kappa J_\nu \vec{n} d\nu$$

radiative heating/cooling and force

modified from methods paper (in prep)

Sedona



Input Model

$\rho(\vec{x}), \vec{v}(\vec{x}), T(\vec{x}), X_i(\vec{x})$

Compute Opacities

Solve Gas State

LTE: ρ, T, X_i, n_e

NLTE: $\rho, T, X_i, n_e, J_\nu, \dot{E}_{\rm radioactive}$

level pops

$n_{\rm i,j,k}$

Calculate opacities and emissivities

converge n_e

charge conservation

solve for electron density n_e

$$\sum_i \sum_j j n_{i,j} = n_e$$

j_ν $\kappa_{\rm abs}, \kappa_{\rm scat}$

Transport

output spectrum

L_ν

radiation spectrum in zone

$J_\nu(\nu)$ $\dot{E}_{\rm radioactive}$

$$\dot{E}_{\rm heat} = \int \kappa_{\rm abs} J_\nu(\nu) d\nu$$

$$\dot{E}_{\rm cool} = \int \kappa_{\rm abs} B_\nu(T) d\nu$$

$$\vec{F}_{\rm rad} = \int \kappa J_\nu \vec{n} d\nu$$

radiative heating/cooling and force

Solve hydrodynamics

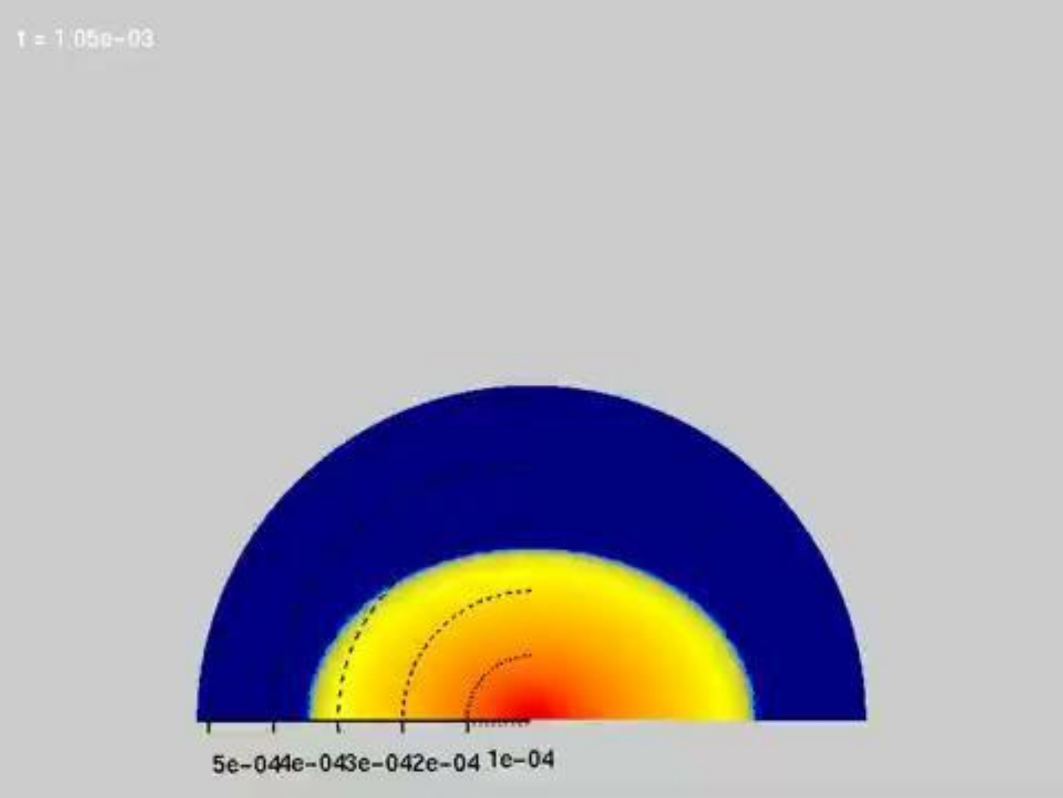
update ρ, T

if radiative equilibrium: $E_{\rm heat} = E_{\rm cool}$

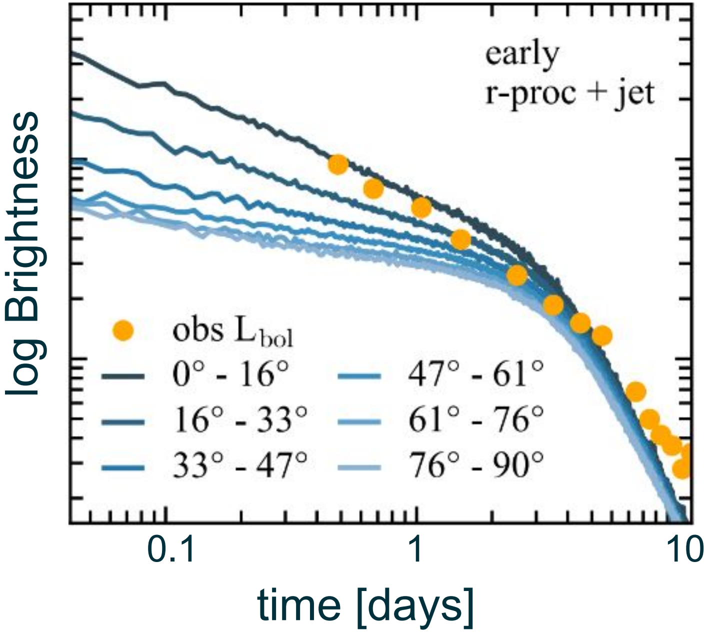
time step or iterate

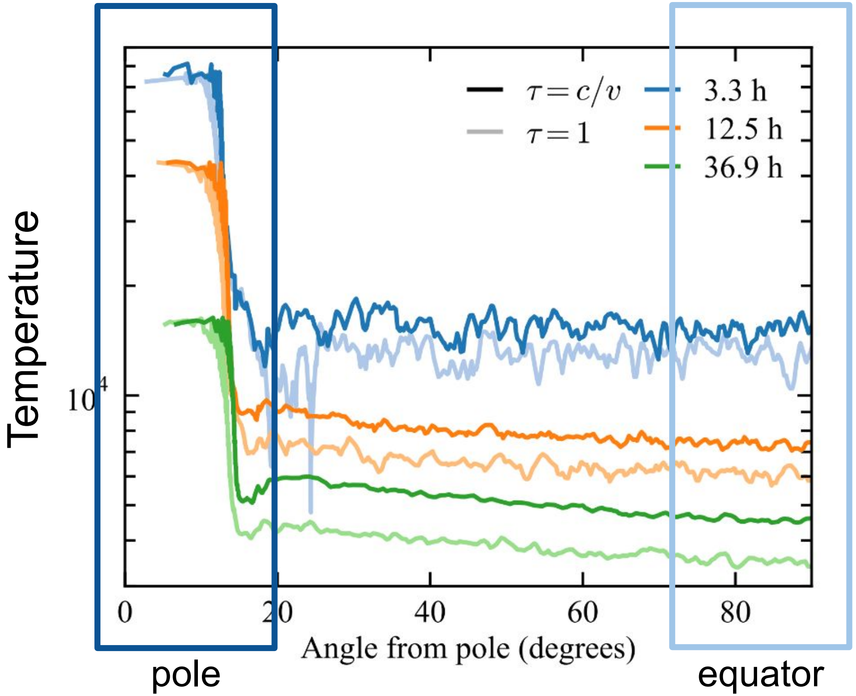
modified from methods paper (in prep)

Jet punches a hole through the ejecta



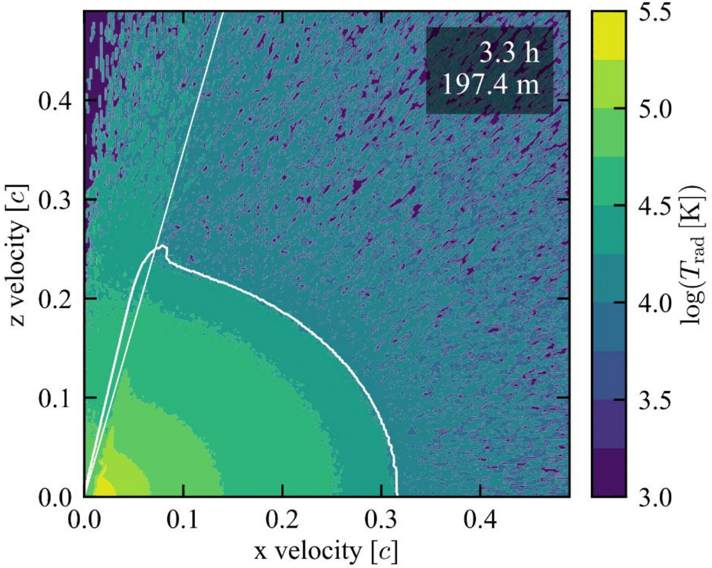
Brighter on pole because pole is hotter $L \propto T^4$

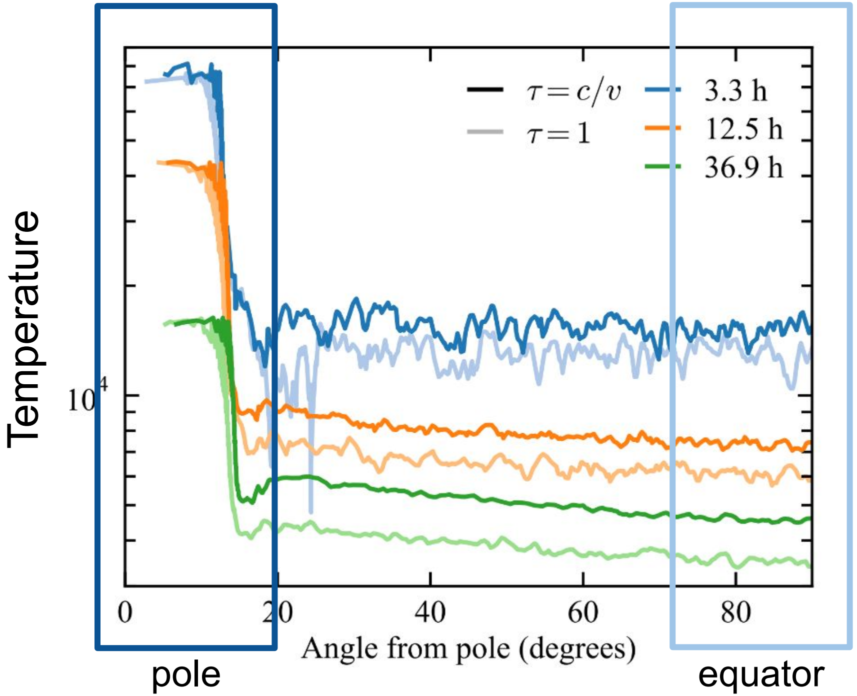




Klion + ’21

Brighter on pole because pole is hotter $L \propto T^4$

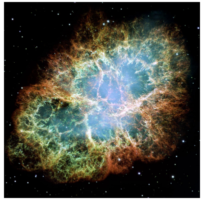




Klion + ’21

Conclusions

Regular pulses and
gamma ray flares
from pulsars

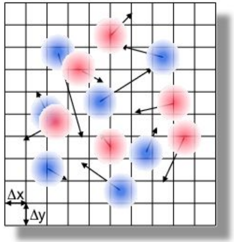


Goal: predict emission from certain neutron stars

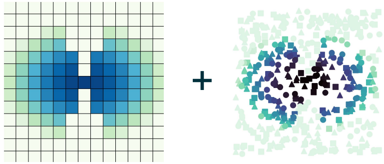
University of Warwick/Mark Garlick

Jets and radioactive
outflows from
neutron star mergers

First-principles simulations
of magnetic reconnection
with particle-in-cell

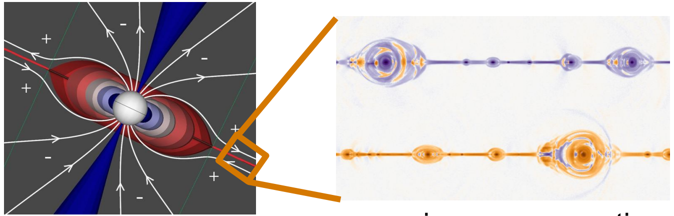


Computational methods: particle + grid



Monte Carlo
radiation
transport

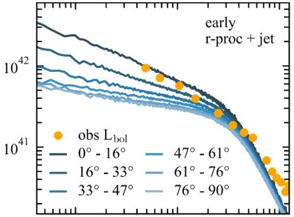
10^6 scale difference between pulsar and plasma kinetic scale

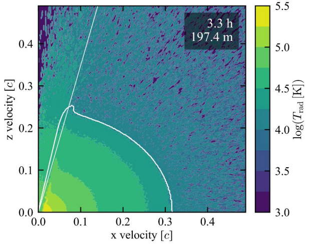


scale down pulsar

zoom in on reconnection

Jet can affect emission by disrupting ejecta





Thank you to WarpX and Sedona development teams and Astro-Plasma group

Jean-Luc
Vay (PI)

Axel
Huebl

Rémi
Lehe

Olga
Shapoval

Yinjian
Zhao

Edoardo
Zoni

ATAP
ACCELERATOR TECHNOLOGY &
APPLIED PHYSICS DIVISION

Ann
Almgren (coPI)

John
Bell

Kevin
Gott

(NESAP)

Prabhat
Kumar

Weiqun
Zhang

Revathi
Jambunathan

Andrew
Myers

Eloise
Yang

Hannah
Klion

Donald
Willcox

Michael
Rowan

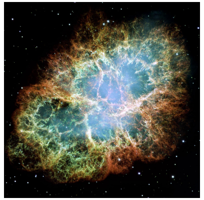
Sedona

- Dan Kasen (PI; UCB/LBNL)
- Jennifer Barnes (UCSB)
- Siva Darbha (UCB)
- Paul Duffell (Purdue)
- Kiran Eiden (UCB)
- Chelsea Harris (MSU)
- Jakob Hein (UCB)
- David Khatami (UCB)
- Brenna Mockler (UCSC)
- Abigail Polin (Carnegie/Caltech)
- Sherwood Richers (UCB)
- Nathaniel Roth (LLNL)
- Ken Shen (UCB)
- Benny Tsang (UCB)

+ Eliot Quataert (Princeton/UCB)

Conclusions

Regular pulses and
gamma ray flares
from pulsars

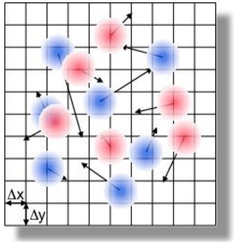


Goal: predict emission from certain neutron stars

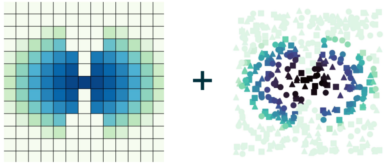
University of Warwick/Mark Garlick

Jets and radioactive
outflows from
neutron star mergers

First-principles simulations
of magnetic reconnection
with particle-in-cell

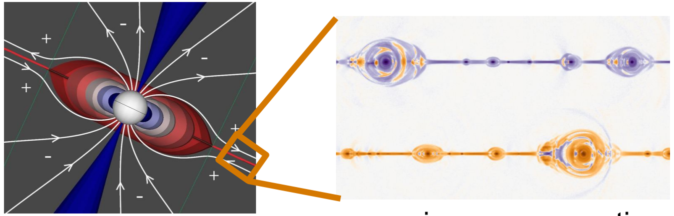


Computational methods: particle + grid



Monte Carlo
radiation
transport

10^6 scale difference between pulsar and plasma kinetic scale



scale down pulsar

zoom in on reconnection

Jet can affect emission by disrupting ejecta