Massively Parallel High-Performance Ray-Tracing in Astrophysics

High-performance Signal and Data Processing Workshop

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What do we want to do?

In terms of physics,

- We want to test the predictions of the theory of General Relativity in the strong gravitational field regime.
- We want to do this by analysing the pulse arrival times for a pulsar in a binary system with a black-hole.

In terms of computations,

- We must perform an intensive statistical analysis on a very large data set.

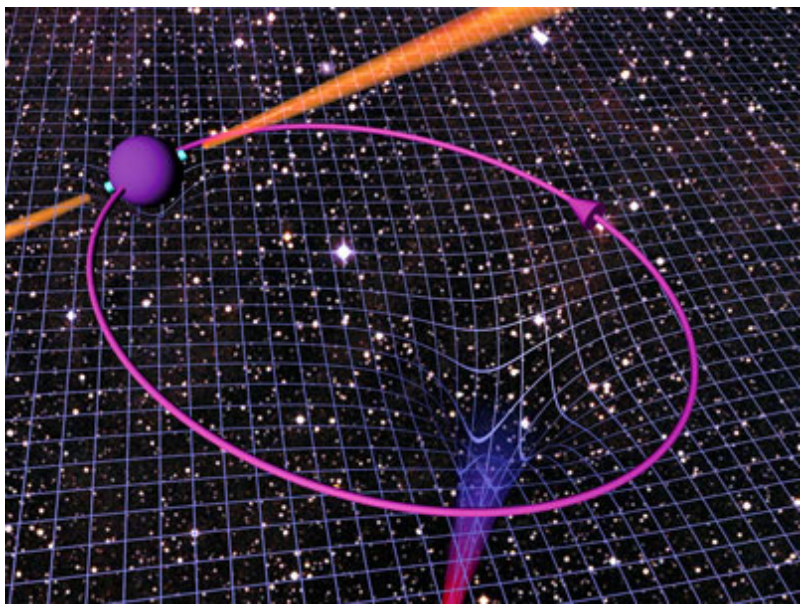
What is a black-hole?

- A black-hole is a site of immense gravitational attraction.
- It is the result of the deformation of space-time caused by a compact mass.
- A black-hole is ‘black’ because is absorbs ‘all’ incident radiation.
- The defining feature of a black-hole is the appearance of an event horizon.
- Event horizon is a space-time boundary through which you can only pass inwards towards the center of the black-hole.

What is a pulsar?

- A pulsar is a rotating neutron star that emits two beams of electromagnetic radiation.
- The rotation of the beam gives the pulsar an appearance much like a lighthouse that is only visible when the beam is directed at the observer.
- Pulsars are very dense and have short regular rotational periods. This gives precise pulse intervals.
- The precise periods of some pulsars make them the most accurate time keepers known.

A graphical representation of our system.

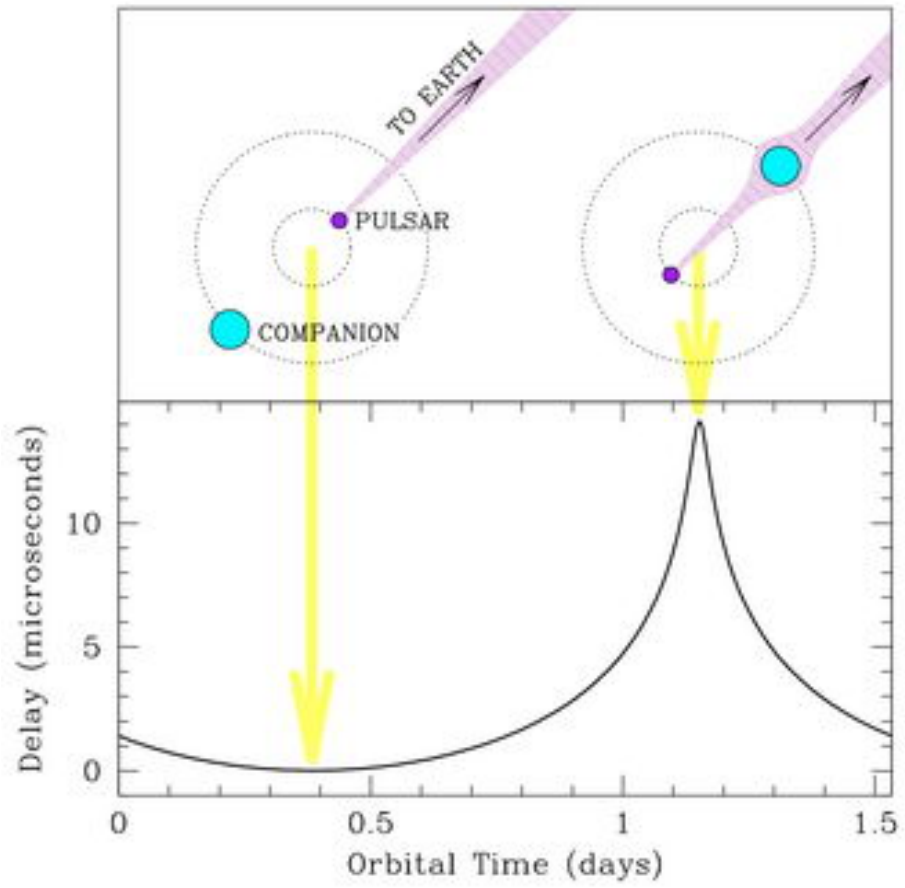


Source [*http://www.news.cornell.edu/stories/march09/cordes.palfa.einstein.html*].

What makes this choice of system a good one?

- Black-hole - pulsar binary systems are laboratories for strong gravitational field physics.
- We use the periodicity of pulsar signal to test the theory of General Relativity.
- Pulsars exhibit the most regular period of any known object.

What should we look for?

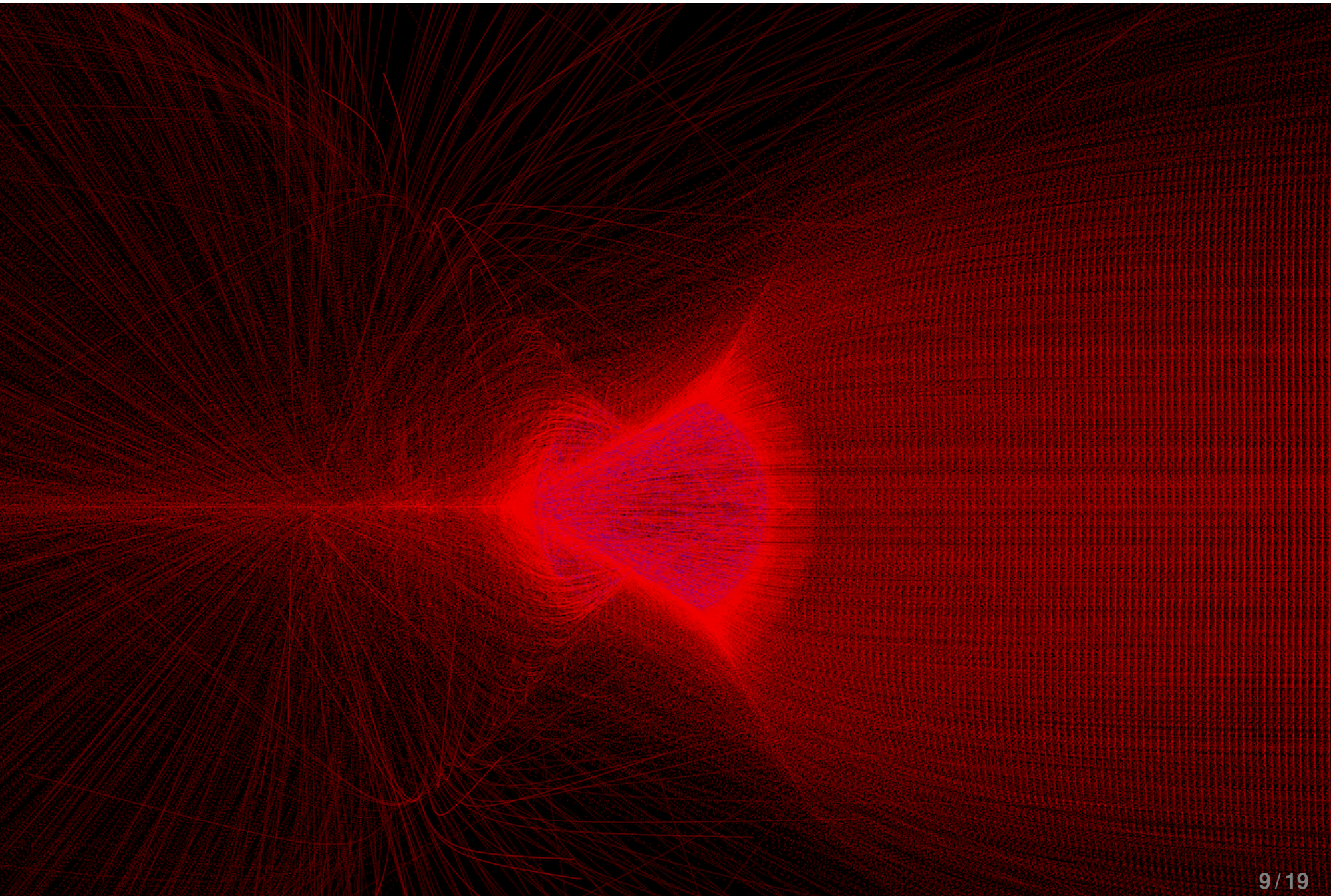


A signal emminating from a source behind a gravitating body is delayed as it moves through the gravitational of that body.

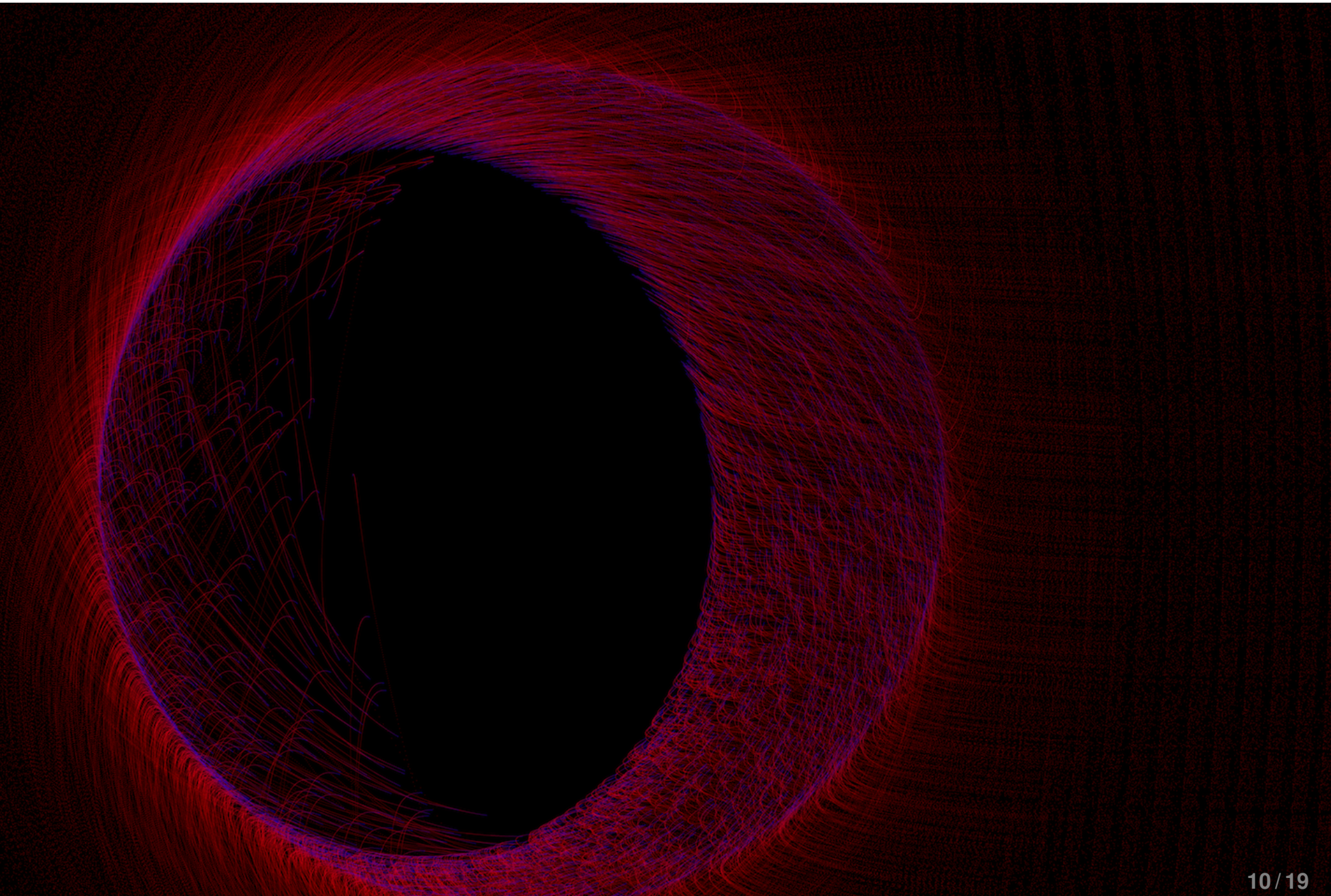
How would we like to do this?

- Generate photon trajectories eminating from a pulsar.
- Numerically integrate photon trajectories through the spacetime.
- Measure the signal at a detector.
- Set sights on 10^{12} photons (might need more).

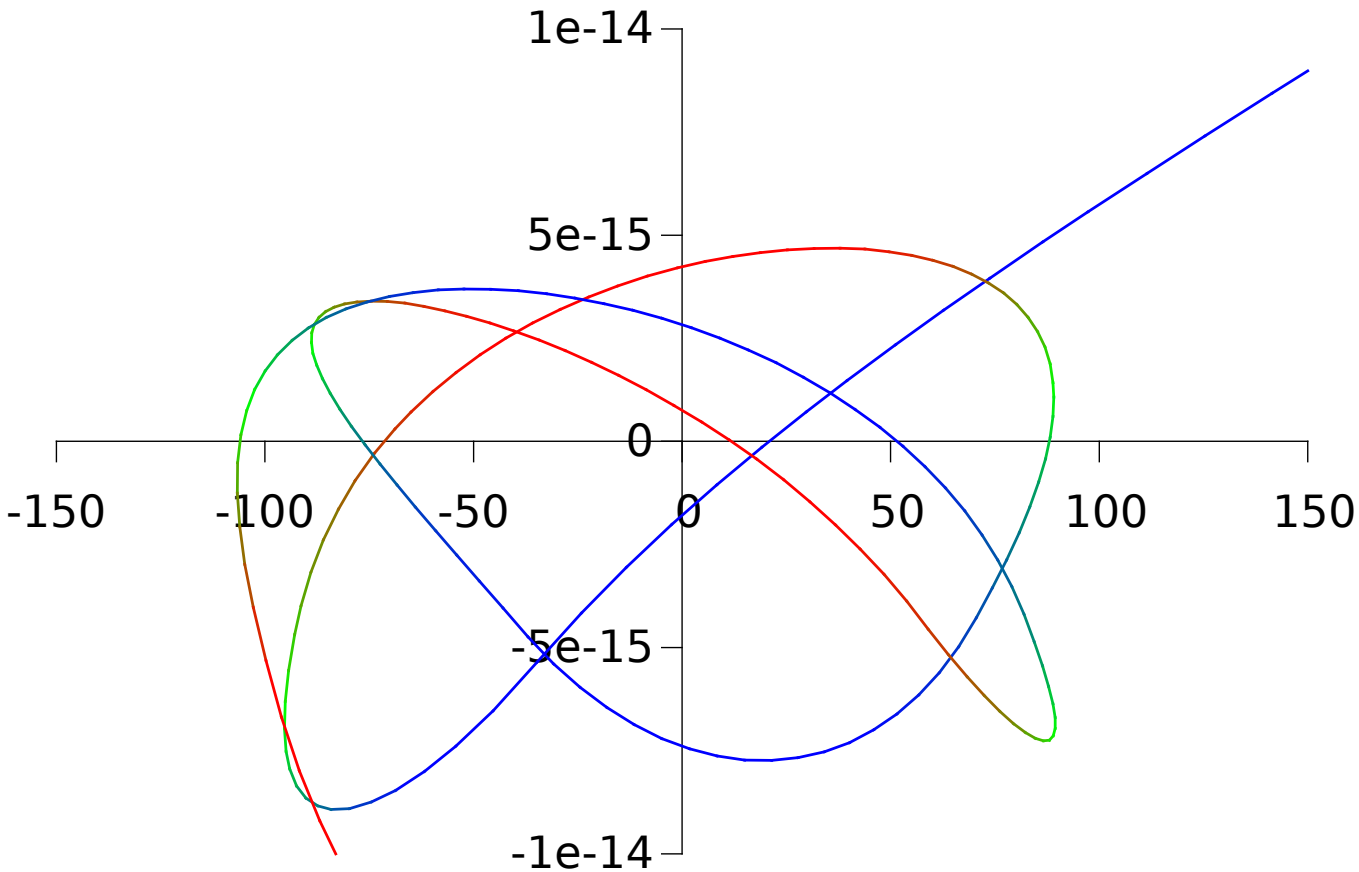
Simulated side on scatter of photon trajectories by a rotating black-hole.



Simulated scattering exclusion zone above a rotating black-hole.



A complicated scattering problem



Quasi-stable orbits near the black-hole exibit chaotic motion.

Problem of computational load

Consider a minimal single photon computation:

- four coupled, second order ODEs.
- $\sim$ 1000 integration steps.
- $16 \times 9 = 144$ floating point operations per integration.
- Operation count for 10^{12} photons: $\sim 1.5 \times 10^{17}$ operations.
- Intel Corei7 CPU @ 3GHz: $\sim$ 40 GFLOPS $\Rightarrow \sim$ 5 weeks.

Why is this a good example for grid computing?

Consider the parameter space,

- $(\mu, \alpha, t, T, a, \theta, \nu)$,
- Prograde/Retrograde.

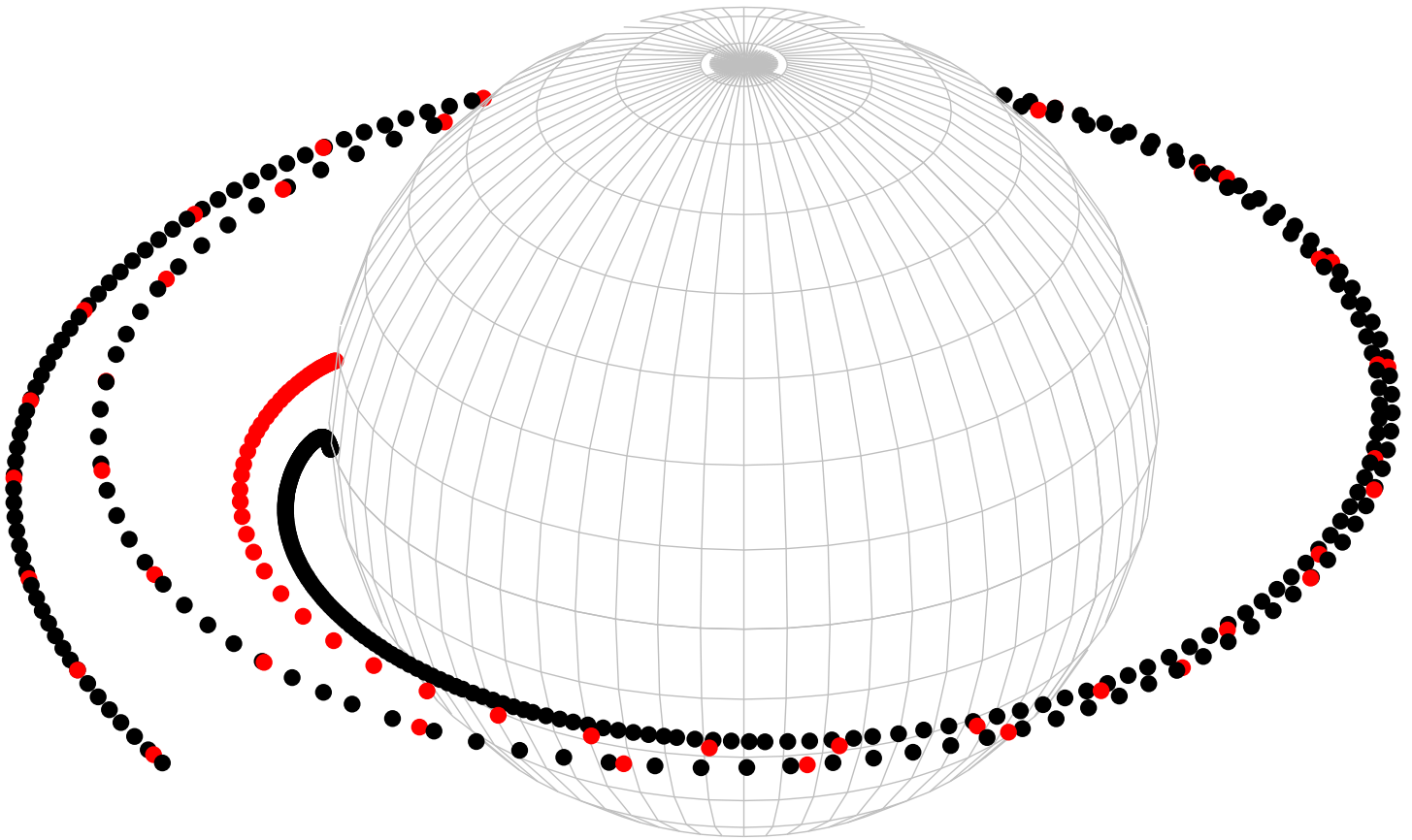
To explore five values of each parameter, we must do this calculation $5^7 \times 2 \sim 156000$ times.

In the strong gravity regime, the dynamics of the system are dominated by the black-hole:

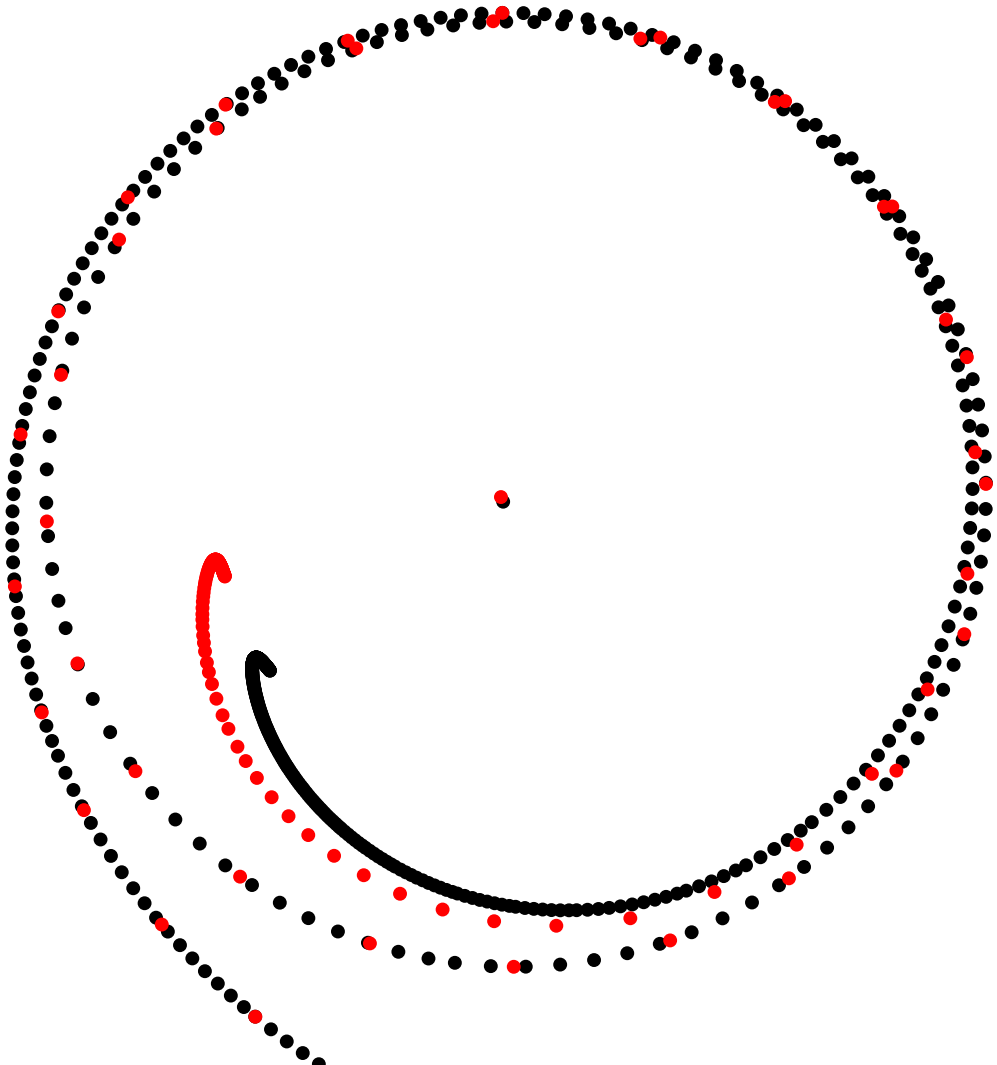
- Each photon computation is dependent on the dynamics of the black-hole alone.
- Given the initial conditions, each photon trajectory is computed independently.

- **Question:** How is our simulator better?
- **Answer:** We do less!

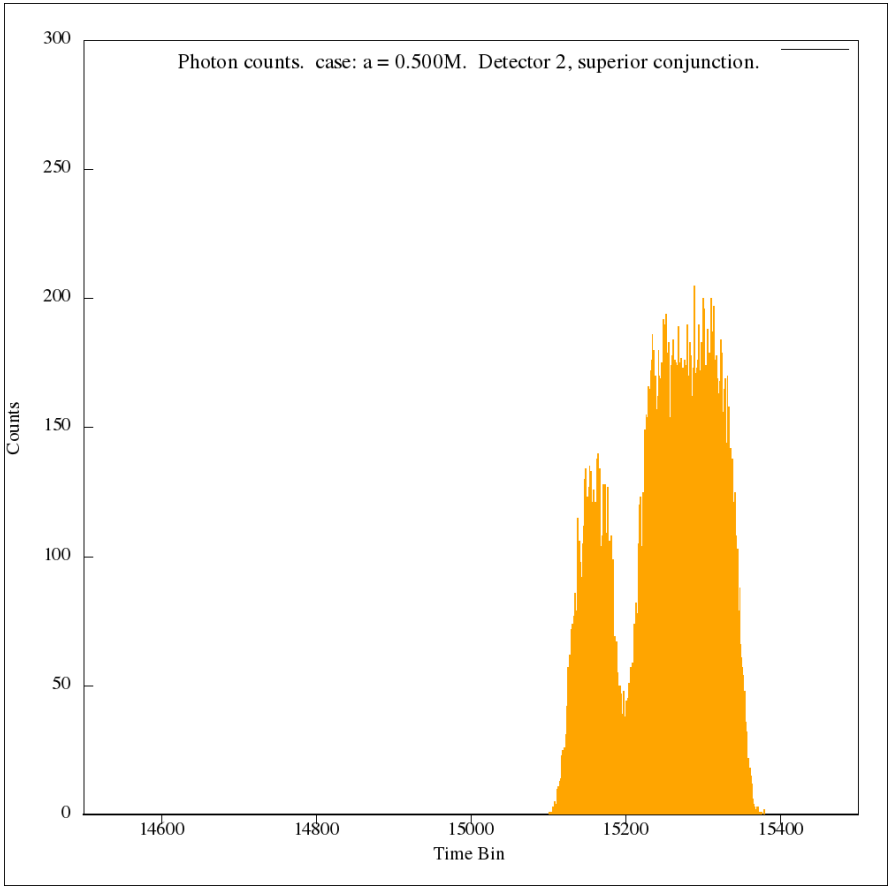
3D integration tracer points **standard** vs **improved**

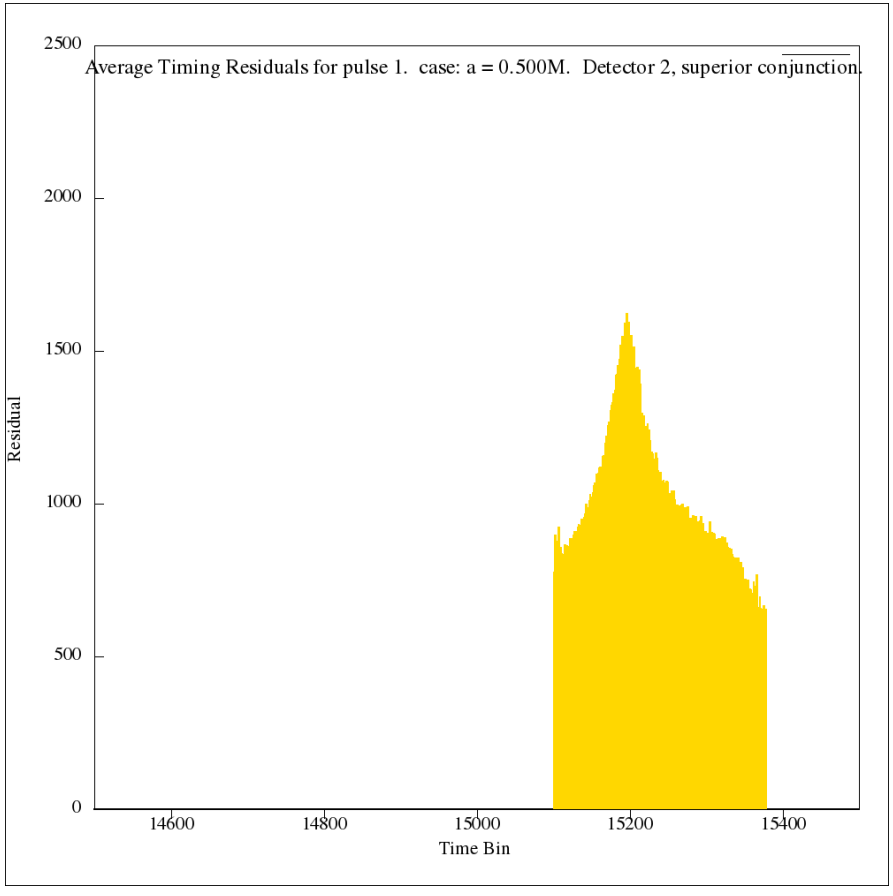


2D integration tracer points **standard** vs **improved**



Fluxes and residuals





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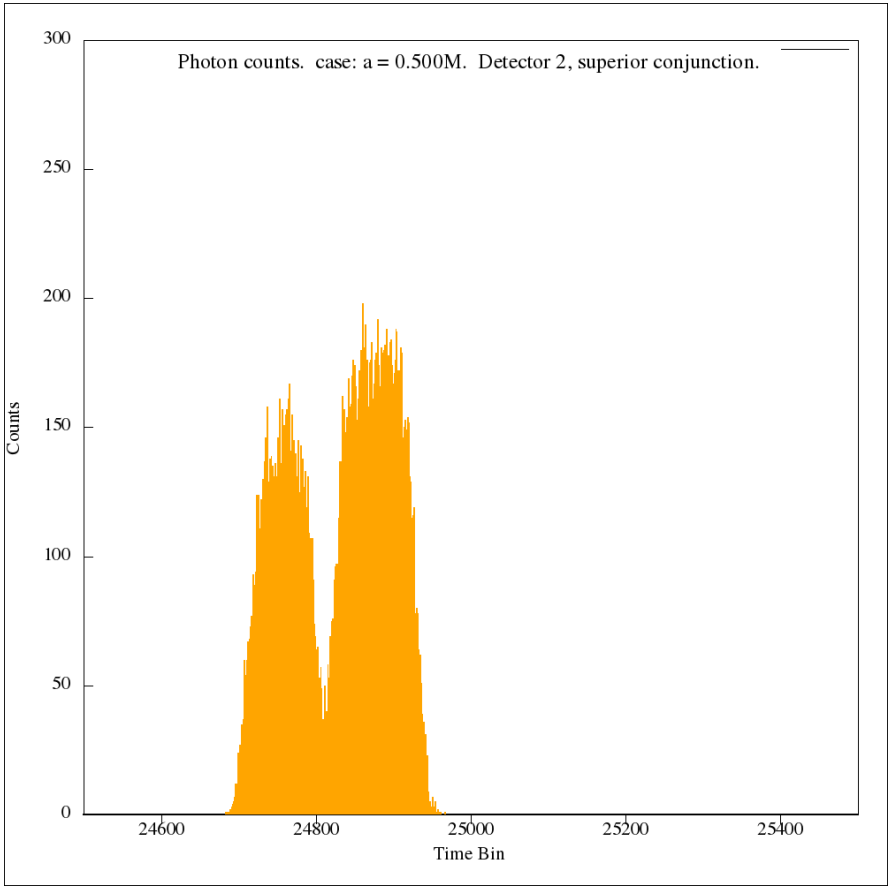

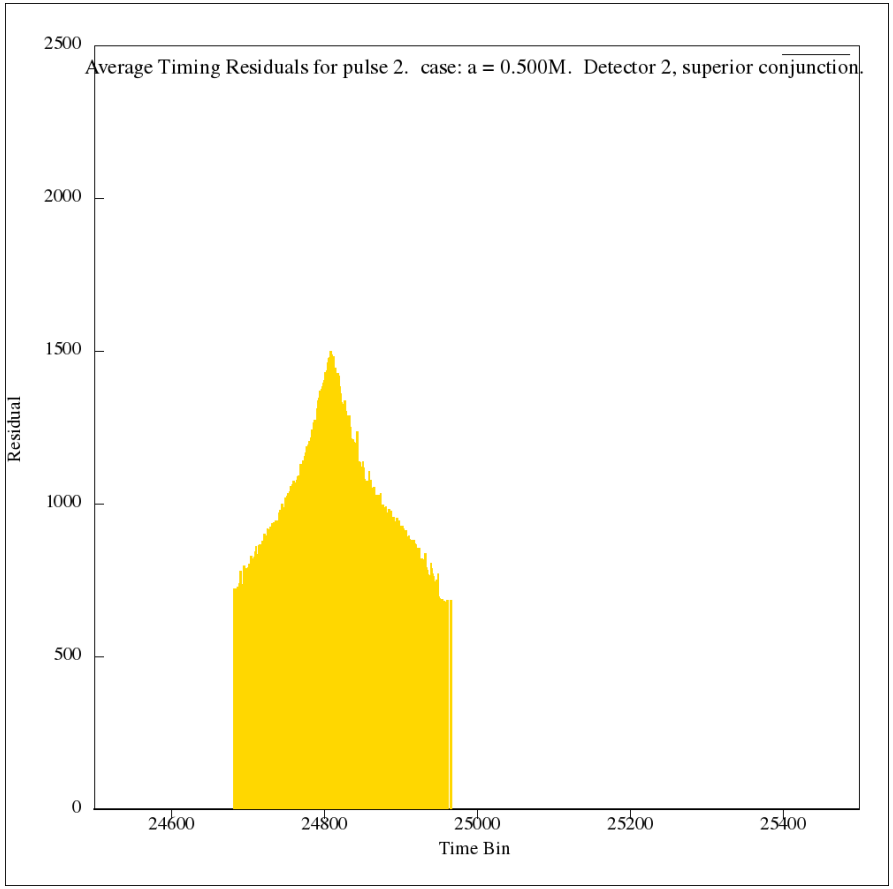

Where do we go from here?

This simulation:

- Implement more complicated physics.
- Predict black-hole - pulsar binary signal.
- Find black-hole - pulsar binary system.
- Compare simulation to measured data.

Apply these methods other problems:

- Particle physics simulations.
- Signal Processing.
- etc. ....