

GPU-Accelerated X-ray Pulse Profile Modeling

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大质量恒星的演化与致密遗骸

① 大质量恒星



质量为太阳的数倍到数十倍

② 核心燃料耗尽



无法继续通过核聚变支撑自身

③ 核心坍缩



核心在引力作用下迅速坍缩

④ 超新星爆发



外层物质被抛出形成超新星爆发

低质量核心
(约 < 1.4 倍太阳质量)

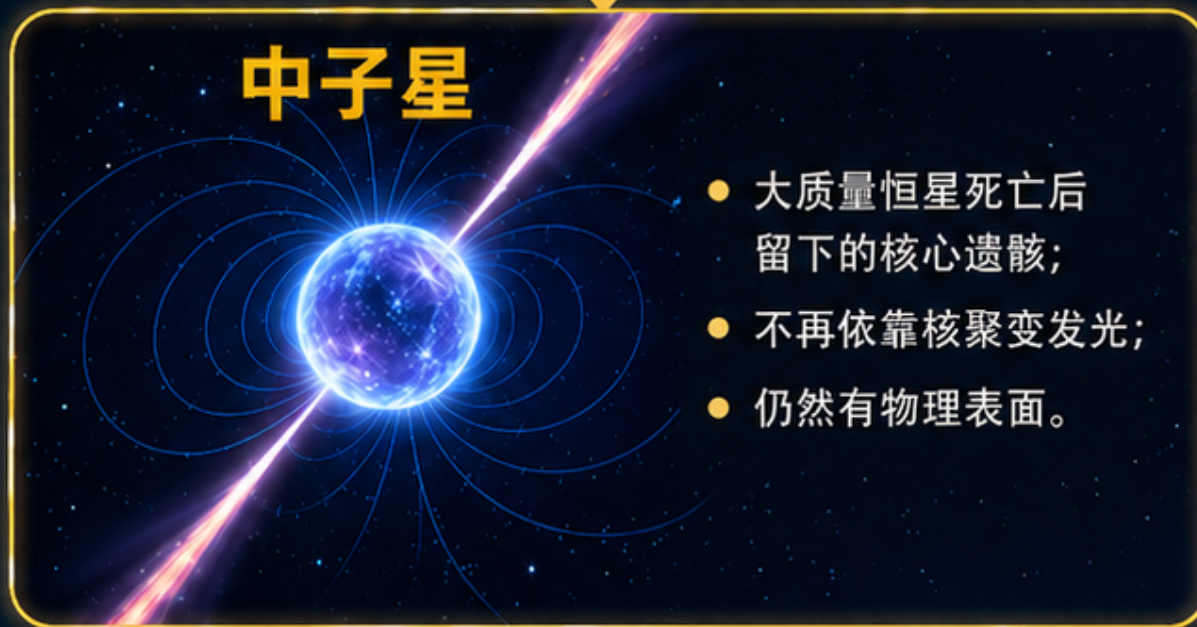
白矮星



体积接近地球，
由电子简并压支撑

中等质量核心
(约 $1.4 \sim 2 \sim 3$ 倍太阳质量)

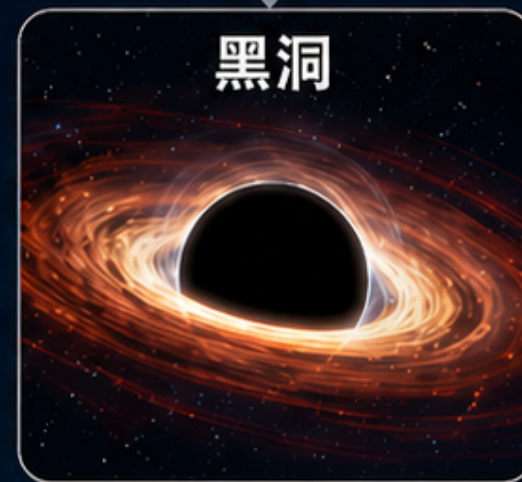
中子星



- 大质量恒星死亡后留下的核心遗骸；
- 不再依靠核聚变发光；
- 仍然有物理表面。

更高质量核心
(约 $> 2 \sim 3$ 倍太阳质量)

黑洞

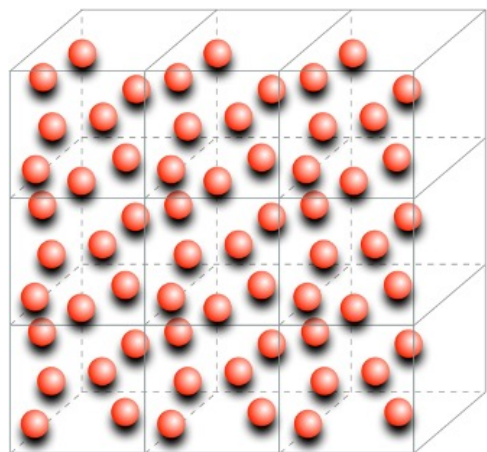


引力极强，连光也无法逃逸，
具有事件视界

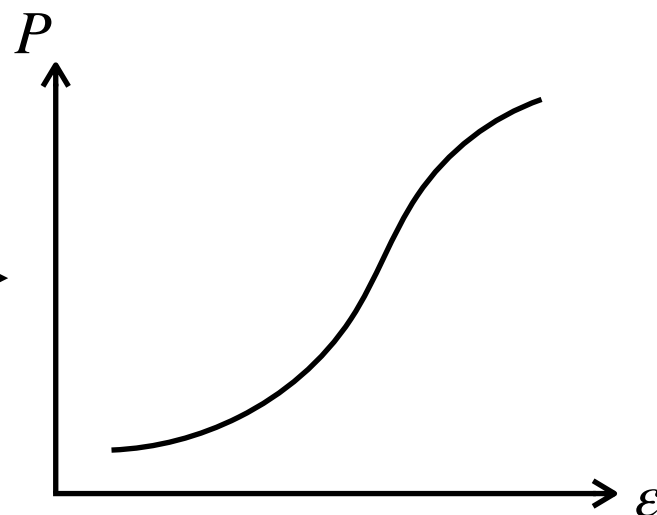
中子星是恒星演化的终点之一。

X-ray Data Analysis Pipeline

Micro Physics



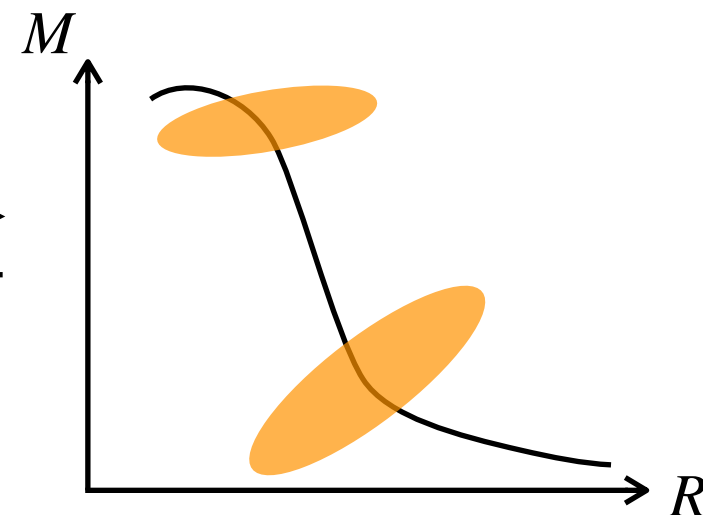
Equation of State



TOV

Inference

Mass and Radius

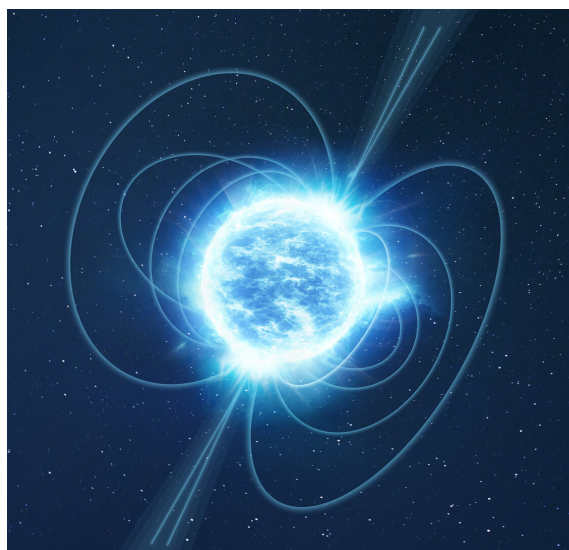


Inference

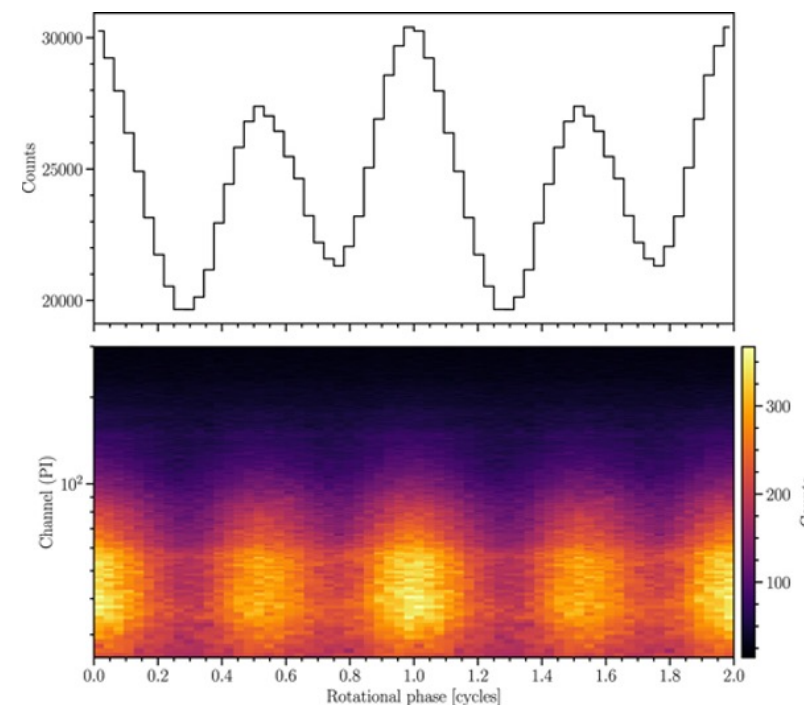
PPM

Pulse Profile

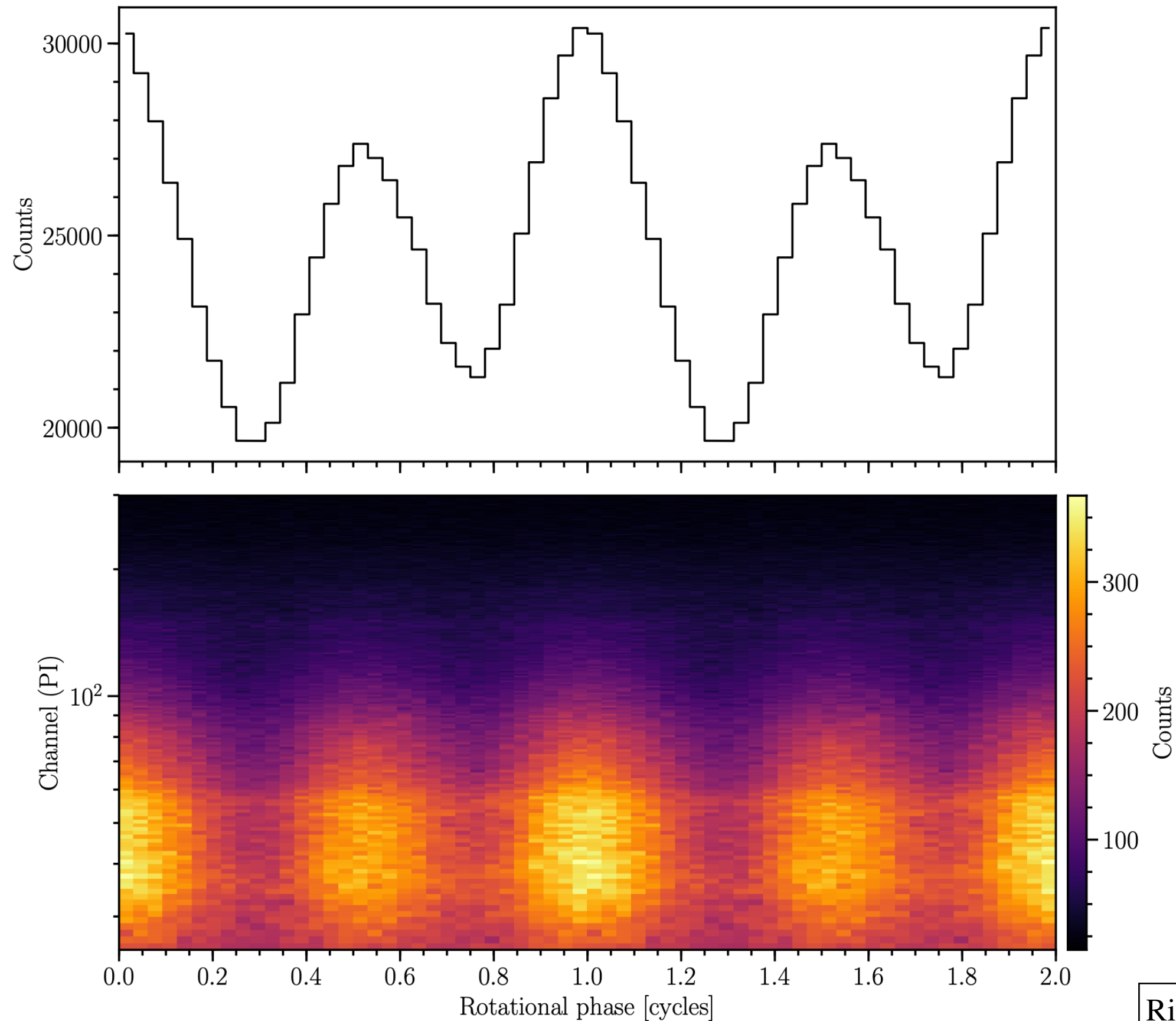
Neutron Star



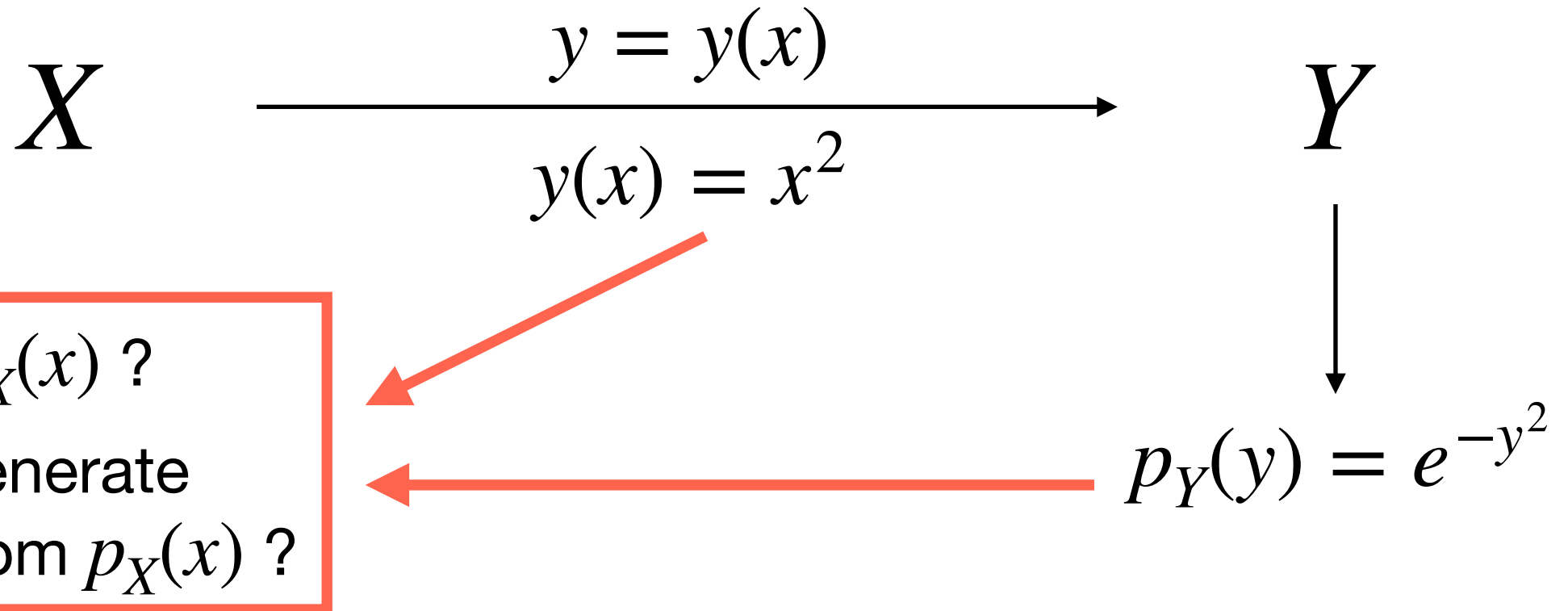
Detectors



Phase-resolved pulse profile



Inference: Sampling techniques



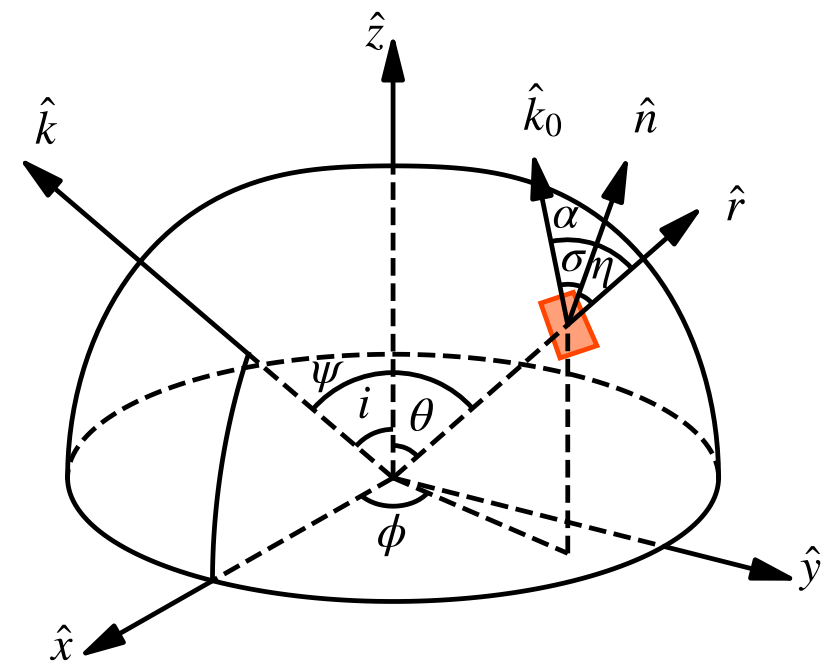
Various sampling algorithms try to answer these question:

- MCMC: HMC/NUTS, Affine Invariant Ensemble sampler, Parallel-Tempering...
- Nested Sampling: Multi-ellipsoid decomposition, mixed slice sampler...

Sufficiently exploring a high-dimensional parameter space
requires typically $\sim 10^7$ - 10^9 likelihood evaluations

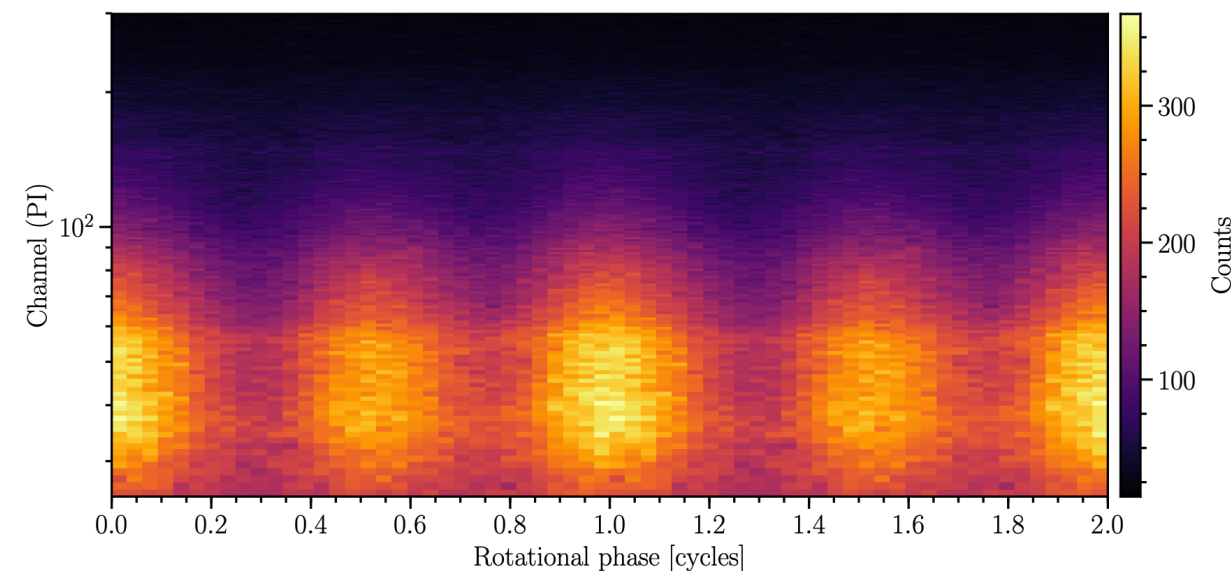
A simple pulsar model

- Spherical star & slow rotation
- Schwarzschild spacetime
- Blackbody spectrum, Given star's mass M , radius R , frequency ν , inclination i , hotspots(location, shape, temperature)
- How to calculate phase-resolved spectrum for a distant observer?



$$\frac{dN}{dt dA dE} = \sqrt{1 - u} \delta^3 \gamma \cos \sigma' \frac{d \cos \alpha}{d \cos \psi} \frac{I(E', \sigma')}{E} \frac{dS'}{D^2}$$

```
# First divide NS surface
# into small patches
for each rotational_phase:
    for each energy_bin:
        for each surface_patch:
            calc_flux()
# This computation paradigm is
# naturally parallelized.
```



A realistic millisecond-pulsar model

Often include:

1. Atmosphere(chemical composition, spectrum, beaming pattern)
2. Temperature distribution(spot location/size/shape)
3. Spin-induced oblate shape
4. Doppler effect induced by rotation
5. GR multi-image effect
6. GR redshift and time dilation
7. Interstellar medium(ISM) caused energy-dependent attenuation
8. Optic efficiency of telescope/detector

Inference requires substantial computing resources

NICER-only

Model	Mass [$M_{\odot}$]	Radius [km]	$\log(\mathcal{E})$	$\max(\log(\mathcal{L}))$	$\max(\log(\mathcal{L}_N))$	$\max(\log(\mathcal{L}_{N\&XMM}))$	Core hours
ST-U	$1.12^{+0.13}_{-0.08}$	$10.53^{+1.15}_{-0.89}$	-35788	-35735	-	-42950	11462
ST+PST	$1.37^{+0.17}_{-0.17}$	$13.11^{+1.30}_{-1.30}$	-35778	-35722	-	-42942	133970
ST+PDT	$1.20^{+0.14}_{-0.11}$	$11.16^{+0.90}_{-0.80}$	-35779	-35729	-	-42705	33069
PDT-U	$1.41^{+0.20}_{-0.19}$	$13.12^{+1.35}_{-1.21}$	-35777	-35721	-	-42659	74333

NICER and XMM-Newton

Model	Mass [$M_{\odot}$]	Radius [km]	$\log(\mathcal{E})$	$\max(\log(\mathcal{L}))$	$\max(\log(\mathcal{L}_N))$	$\max(\log(\mathcal{L}_{N\&XMM}))$	Core hours
ST-U	$1.88^{+0.13}_{-0.19}$	$15.12^{+0.64}_{-1.31}$	-42714	-42661	-35760	-	41219
ST-U*	1.35 ± 0.16	11.44 ± 1.14	-42718	-42666	-35769	-	-
ST+PST	$1.93^{+0.10}_{-0.13}$	$15.12^{+0.64}_{-1.31}$	-42711	-42662	-35761	-	84620
ST+PDT	$1.40^{+0.13}_{-0.12}$	$11.71^{+0.88}_{-0.83}$	-42684	-42625	-35730	-	3261
PDT-U	$1.70^{+0.18}_{-0.19}$	$14.44^{+0.88}_{-1.05}$	-42677	-42617	-35723	-	12421

Vinciguerra et al. (2024)

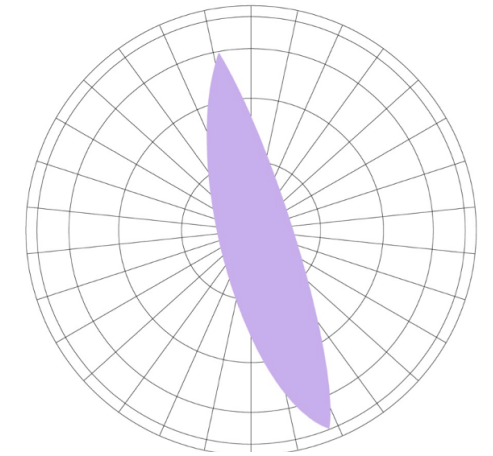
For many models, accurate computations are **time-consuming**.

Low resolution can fail for challenging hotspots

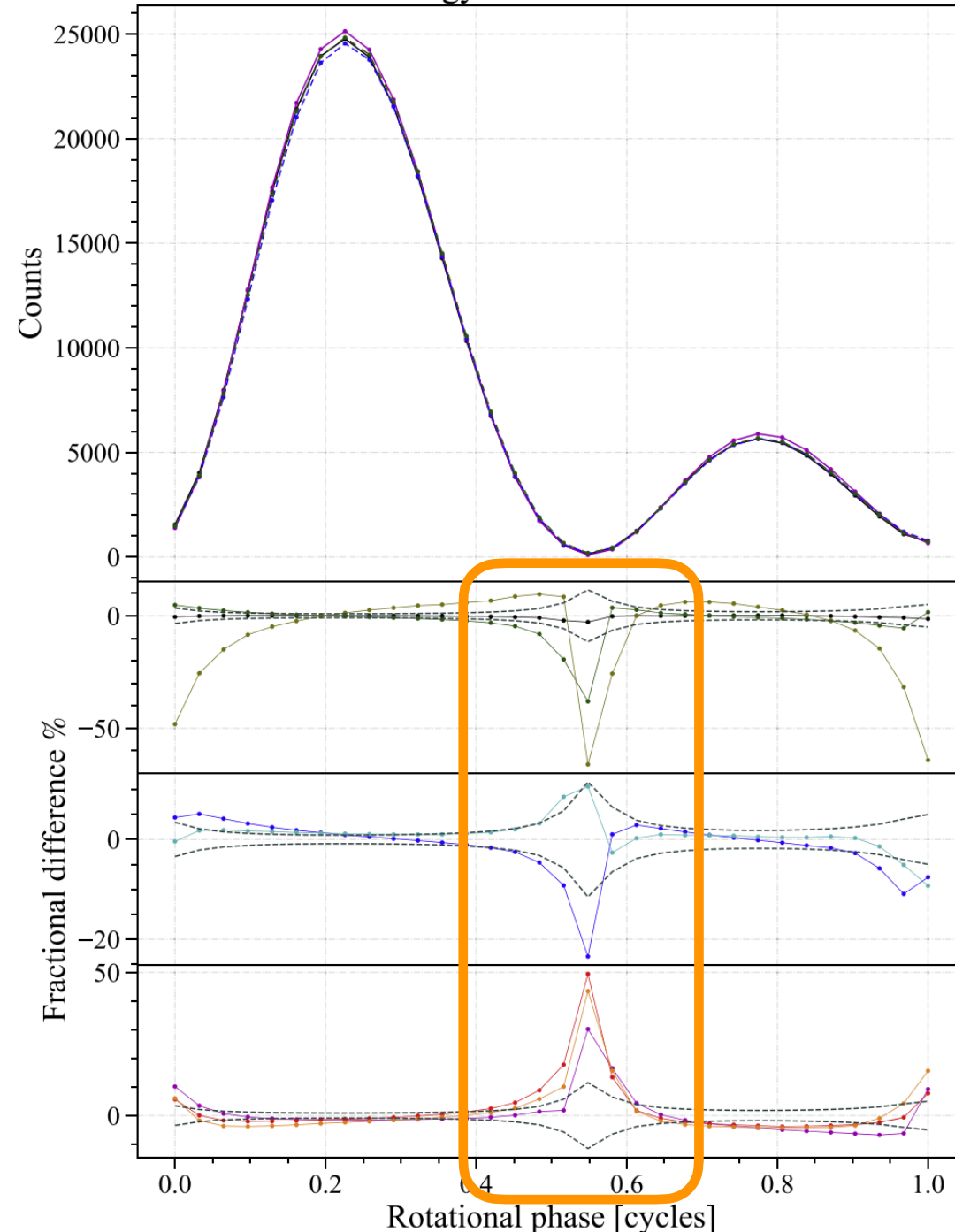
Extreme hotspots **can mismatch** by **~50%** without high-resolution computations.

This creates a seemingly impossible **accuracy-speed tradeoff** for pulse profile modeling.

Crescent-Polar



Crescent-Polar energy-summed waveform & frac. diff.

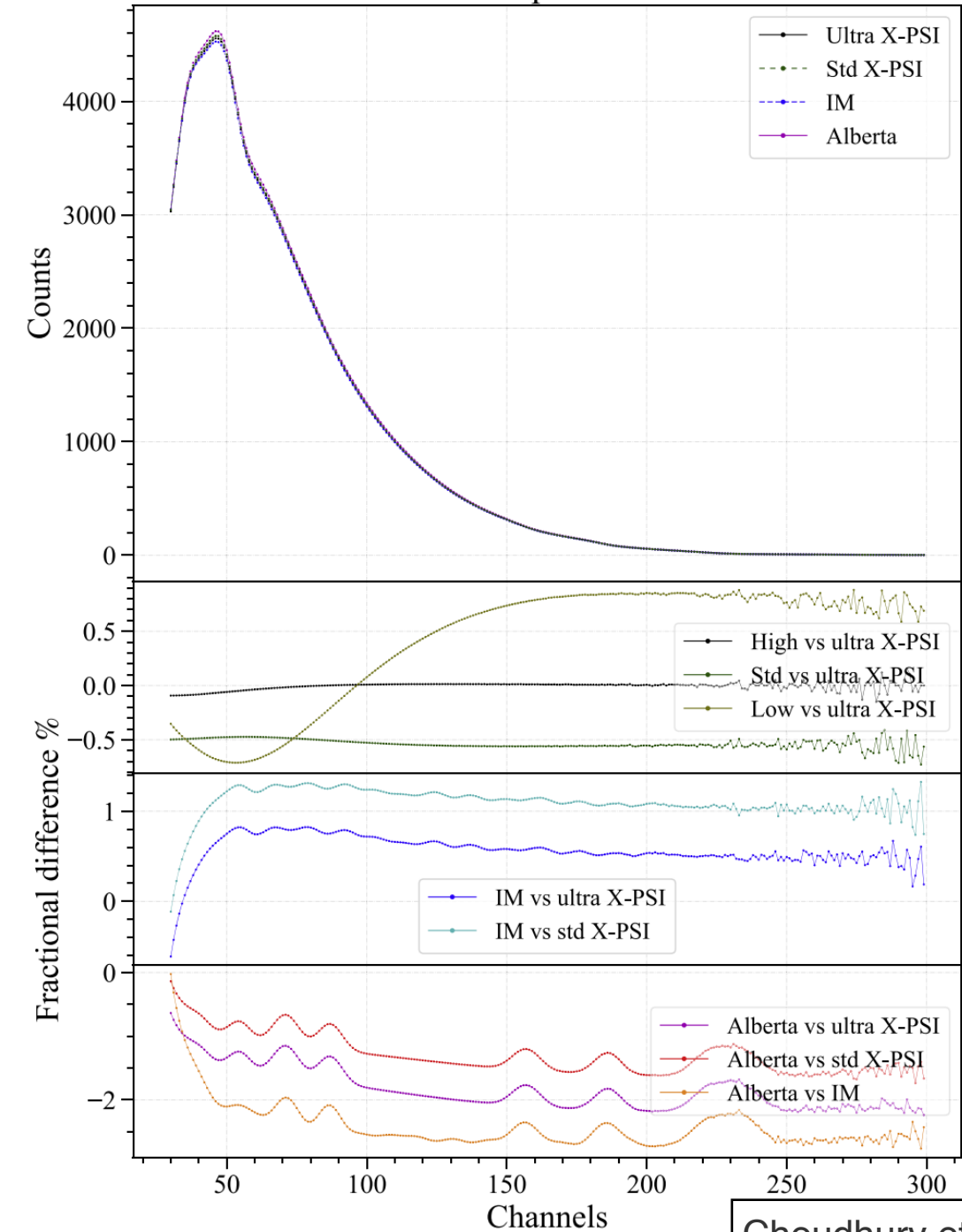


X-PSI

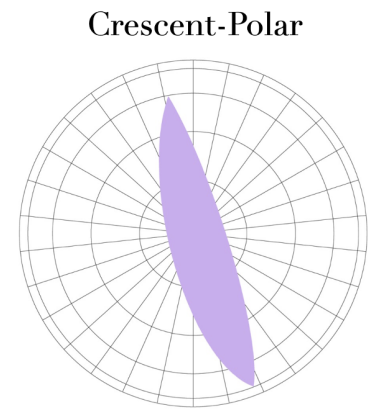
IM

Alberta

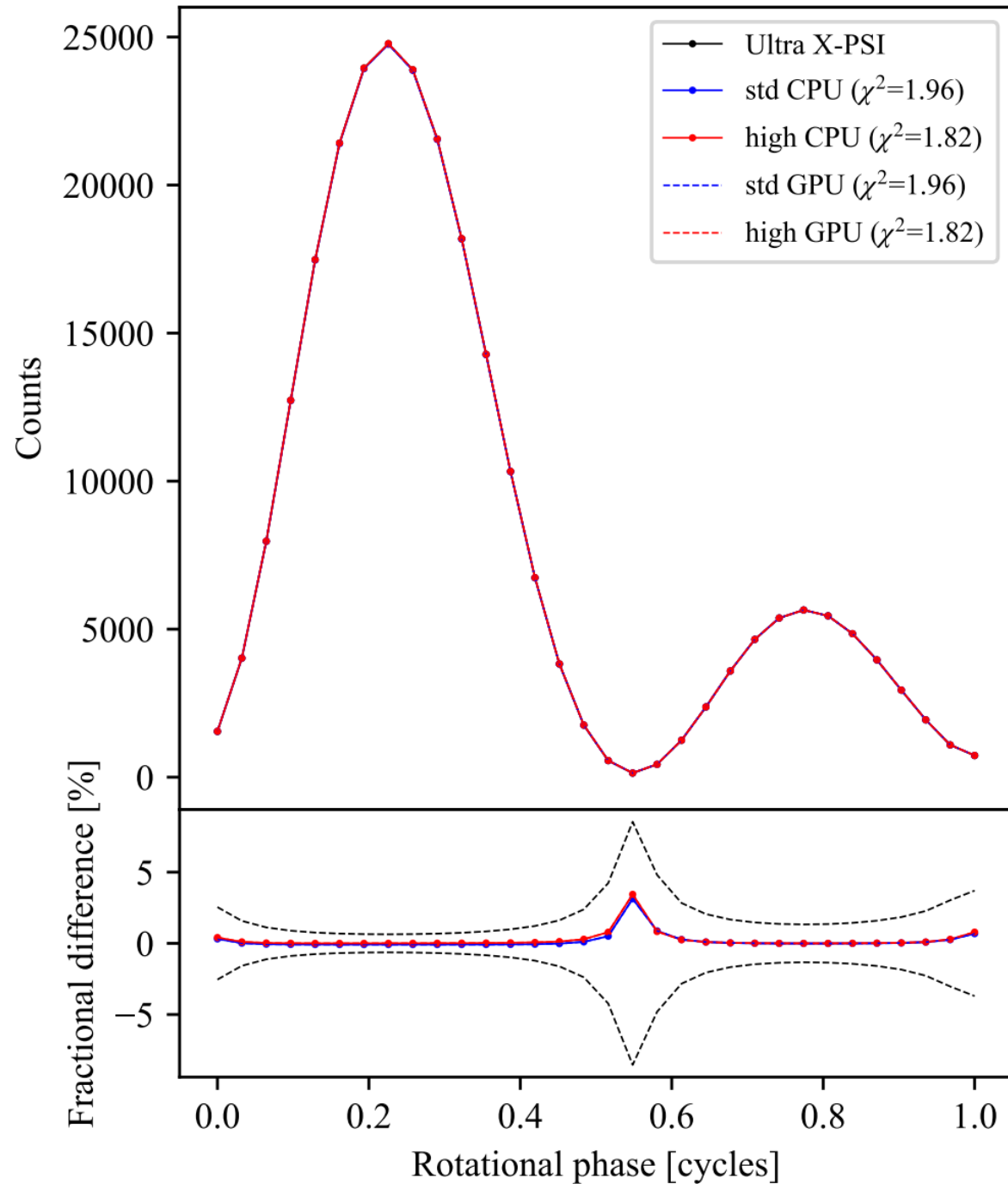
Crescent-Polar spectra & frac. diff.



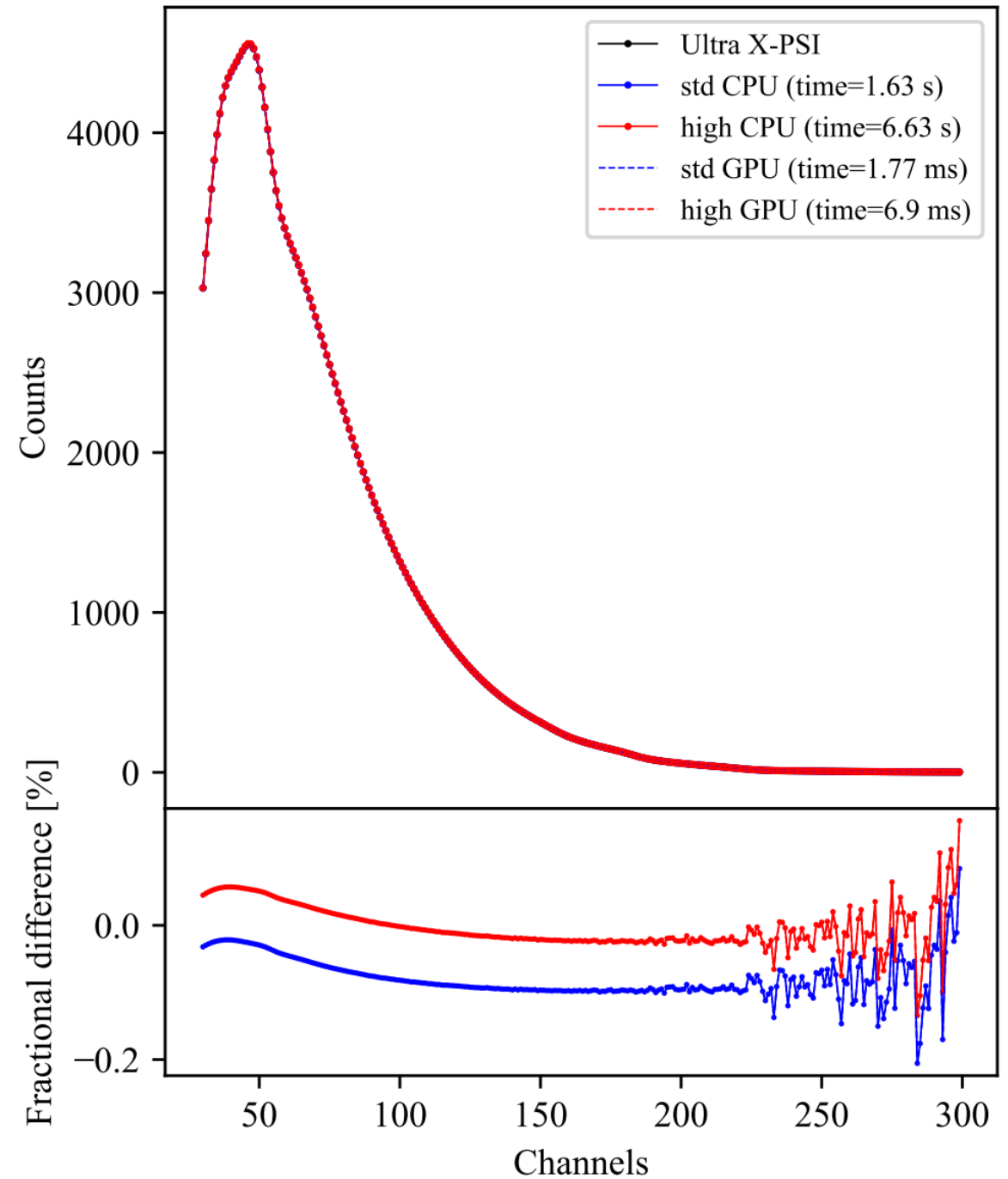
Benchmark agreement at millisecond cost



Crescent_Polar energy-summed waveform & diff.



Crescent_Polar spectra & diff.



GPU evaluations are about 1000× faster than single-core CPU implementation

Table 3
Approximate Pulse Profile Computation Time

Code	Computation Time
X-PSI low	$\lesssim 0.1$ s
X-PSI std	$\sim 0.1\text{--}0.5$ s
X-PSI high	$\sim 0.3\text{--}5$ s
X-PSI ultra	$\sim 1\text{--}5$ minutes
IM	$\sim 5\text{--}10$ s
Alberta	$\sim 5\text{--}30$ s

Note. The exact times depend on the model chosen and the CPU architecture of the system the code is being run on, and therefore we only provide approximate times.

Choudhury et al. (2024)

Our new code:

CPU-std $\sim 1\text{--}5$ s

CPU-high $\sim 6\text{--}20$ s

GPU-std $\sim 1\text{--}3$ ms

GPU-high $\sim 6\text{--}12$ ms

Platform: i7-13700KF+RTX4080



zhoutz/gpu_ppm

High-performance C++20/CUDA code for generating phase-resolved pulse profiles and energy-phase counts for neutron star surface emission.

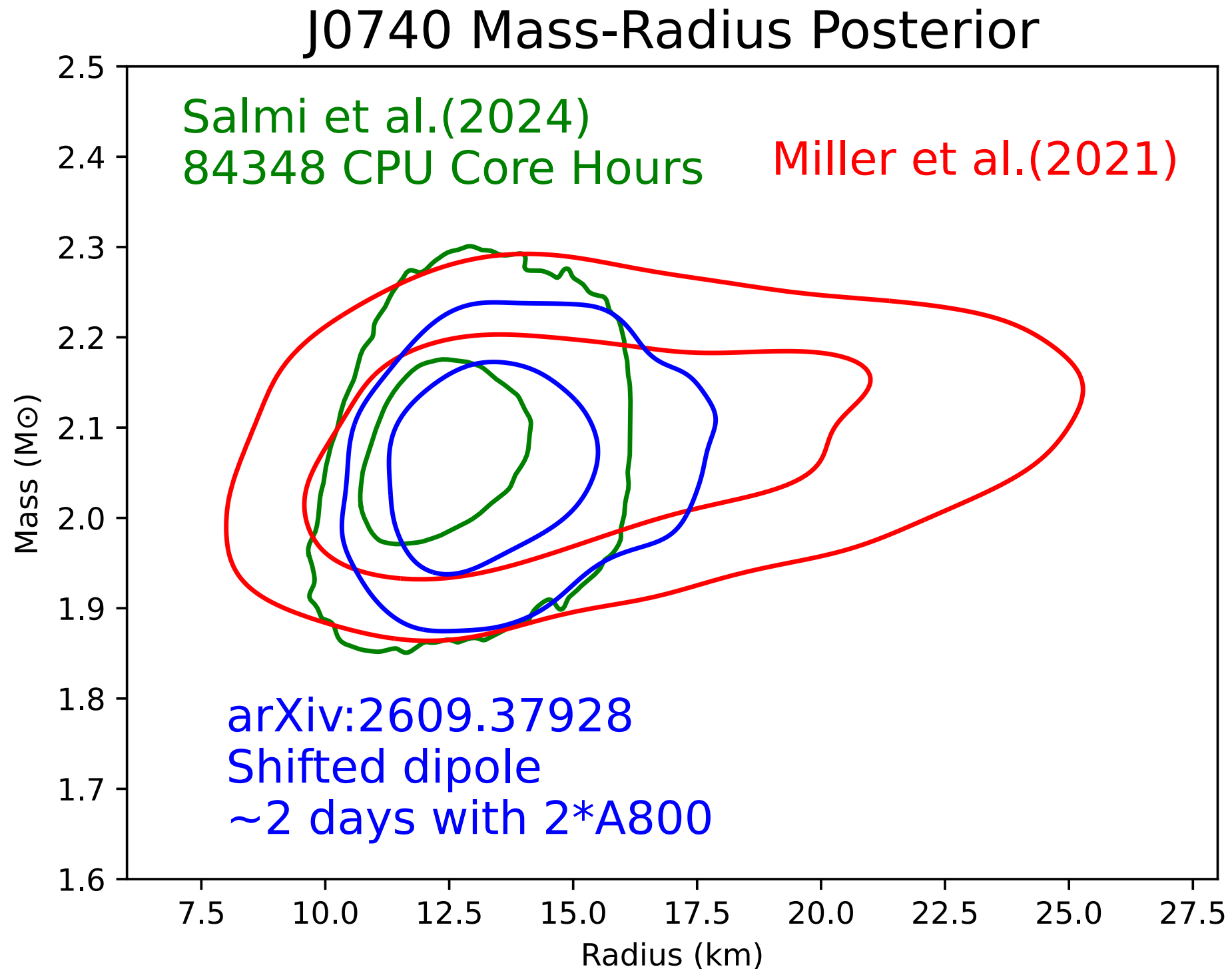
STARS

3

FORKS

2

Physics driven MR analysis of J0740



Summary

- We developed and validated a GPU-based pulse profile modeling code, achieving close agreement with reference calculations even for challenging hotspot geometries.
- GPU acceleration reduces model evaluation times from seconds to milliseconds, delivering an approximately 1000-fold speedup over single-core CPU implementation.
- Physics driven analysis of pulsar J0740 demonstrates practical mass–radius inference in 2 days, opening opportunities to explore more complex surface emission models without heavy computation resources.