University of Amsterdam
Anton Pannekoek Institute for Astronomy

Neutron Star Pulse Profile Modeling

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European Research Council
Established by the European Commission

Part 1/3: Introduction and overview

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Introduction

Millisecond pulsars (MPs)

- Rotation powered (RMPs)
  - Spun up via accretion
  - X-ray emitting hot spots (e.g. Muslimov & Harding 2001)
- Accretion powered (AMPs)
  - This talk
- Type 1 X-ray burst oscillation sources
  - Yves' talk

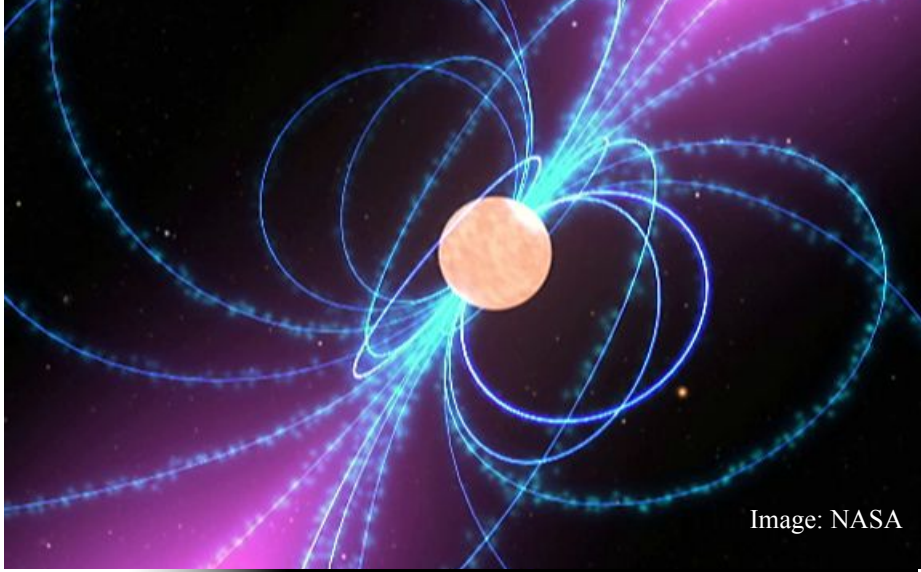
Image: NASA

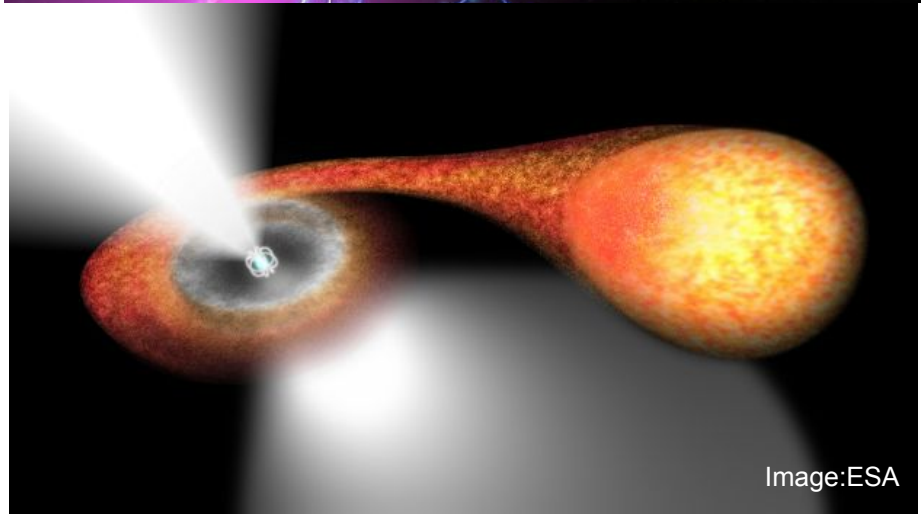
Image:ESA

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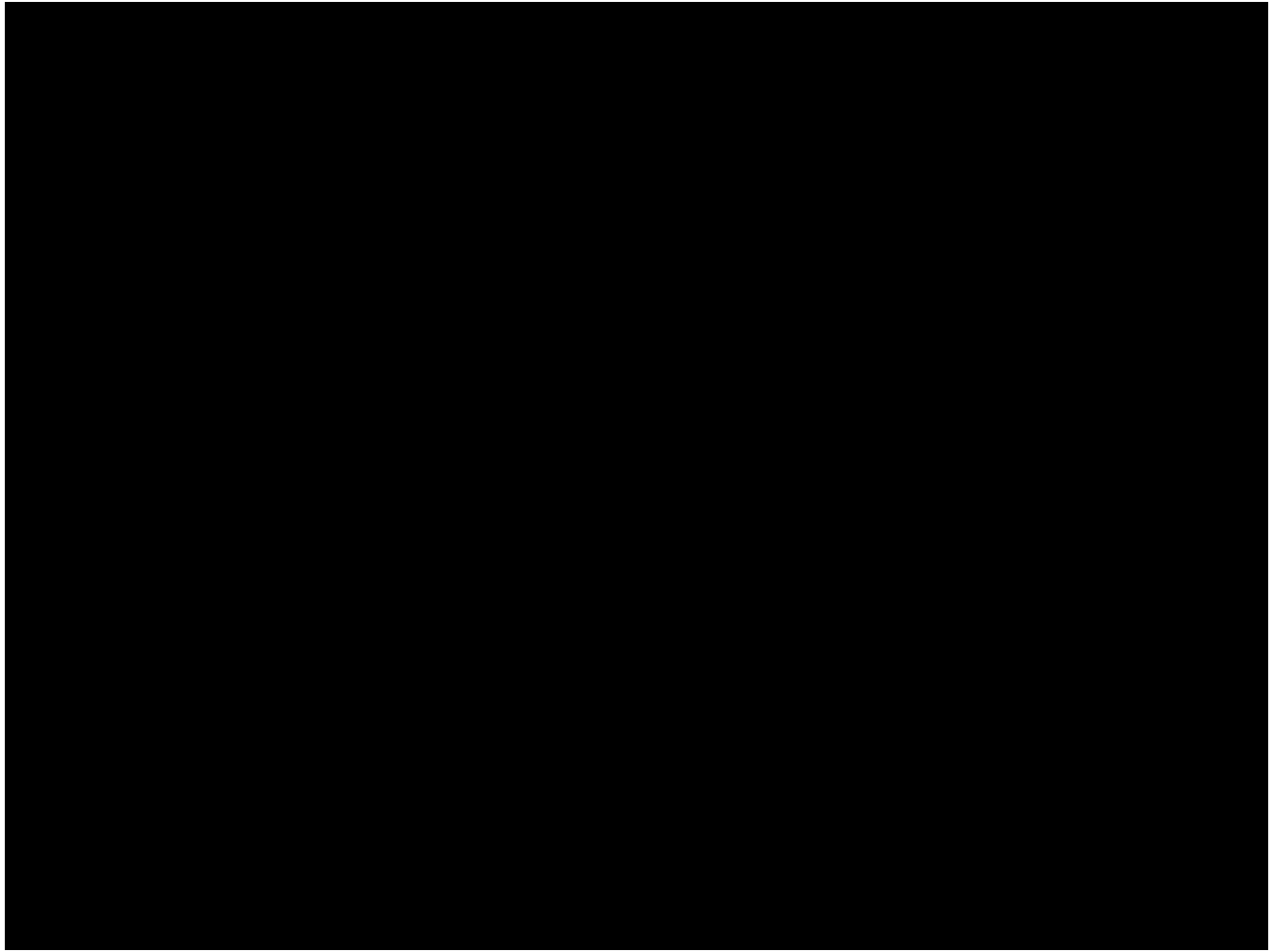
Pulse Profile Modeling (PPM)

Notice the GR light bending effect?



Video: Morsink/Moir/Arzoumanian/NASA

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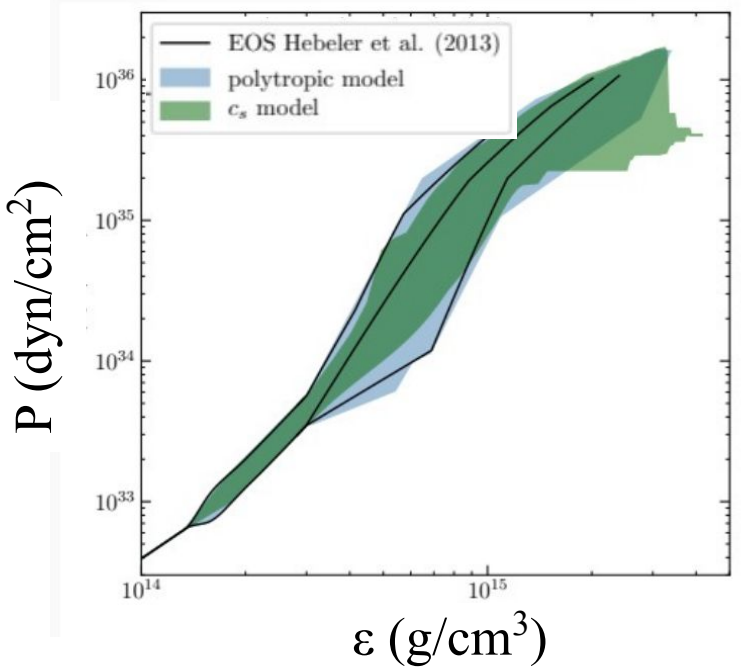
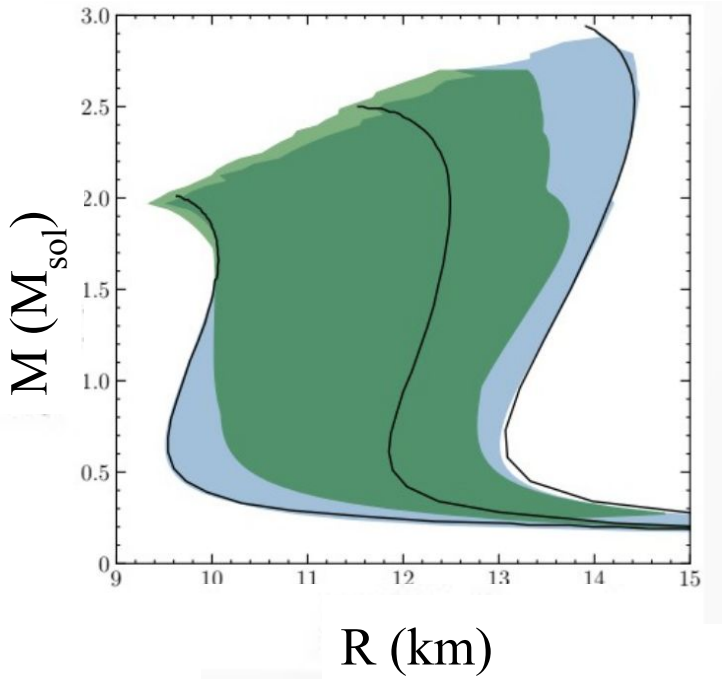
Goal: Constraining EoS alongside Mass and Radius

Figure: Greif+ 2019



Stellar Structure Equations



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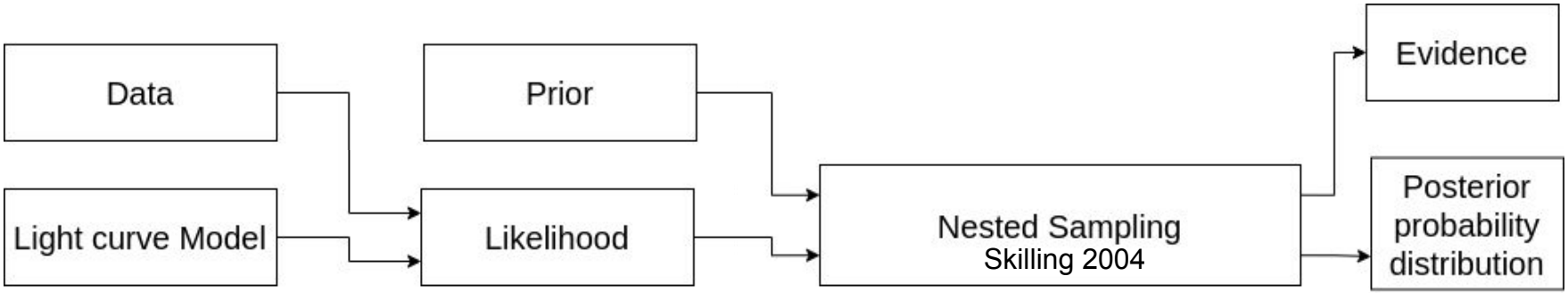
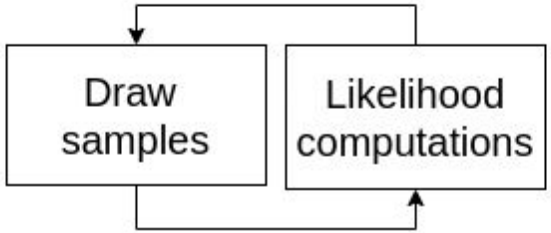
Method: Bayesian analysis

Model Comparison

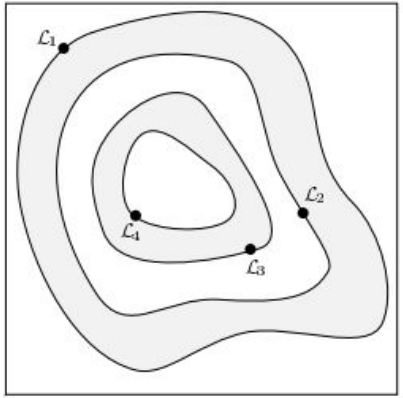


Parameter Estimation



MultiNest

Feroz, Hobson, Bridges 2008



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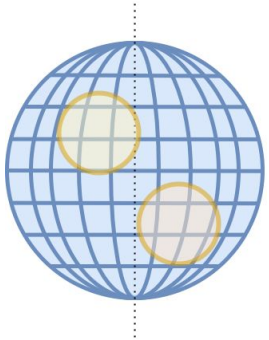
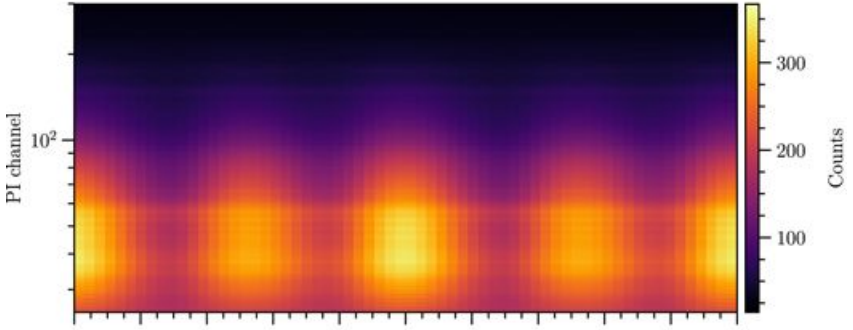
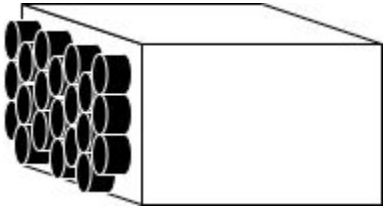
Constraining Mass and Radius from Pulse Profiles

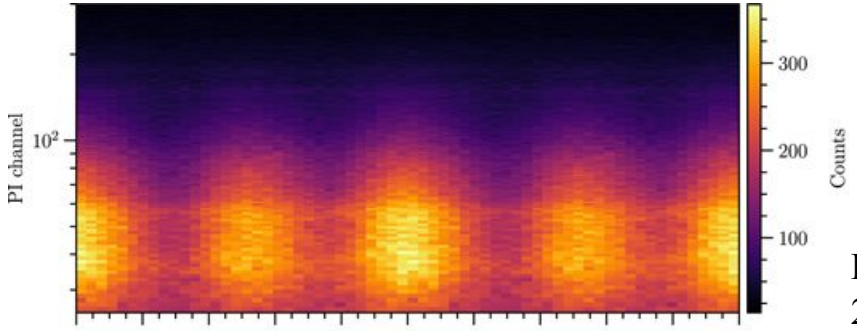
- Relativistic effects constrain Mass and Radius (MPs are good)





- But then we need data: Time resolution (< 10 μs), pulsed photons (~10^6)





Riley+ 2019

Neutron Star Interior Composition Explorer (NICER)

NICER sensitive in soft X-rays (~0.2 - 12 keV)

One of principal goals: Mass & radius measurements of RMPs.

Within NICER Collab: Amsterdam and Maryland-Illinois doing PPM with NICER data

This talk: X-PSI, other team has independent analysis

Video: NASA/GSFC

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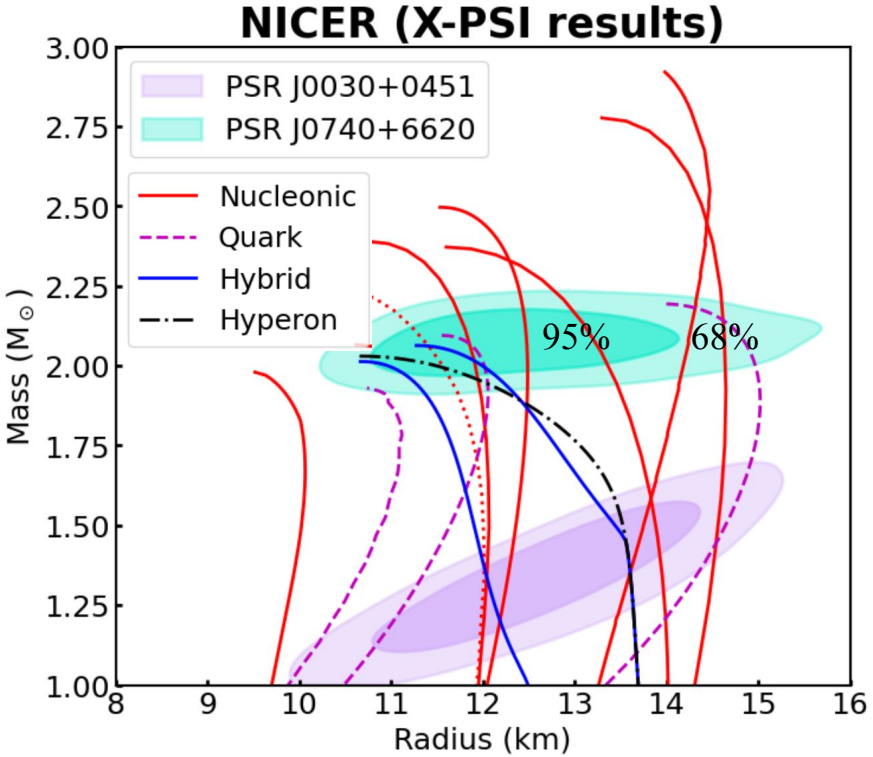
Previous work, current PPM efforts (Bayesian inference)



Current efforts:

- AMPs, J1808 (This talk)
- Reanalysis J0030 (Serena's talk)
- J0437 (Devarshi's talk)
- Atmospheric effects RMPs (Tuomo's talk)
- Bursters, J1814 (Yves' talk)
- J1614, J0614, J1231, J2124

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Part 2/3: How X-PSI Models Pulse Profiles

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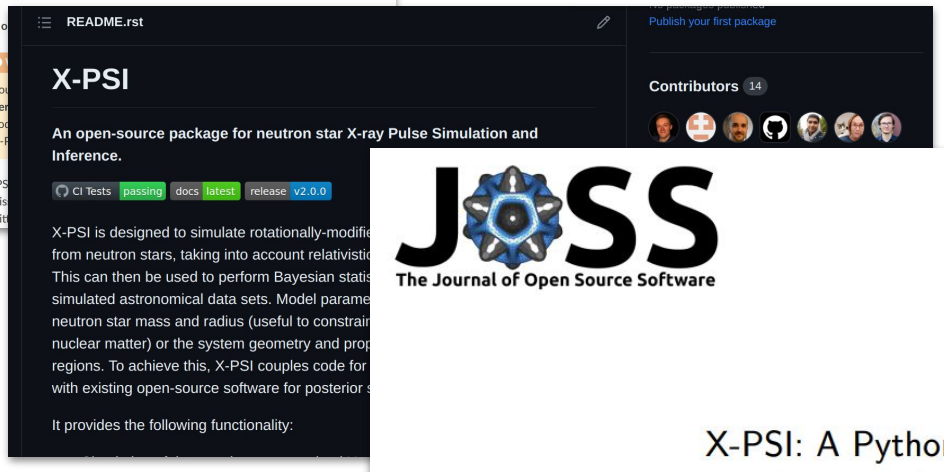
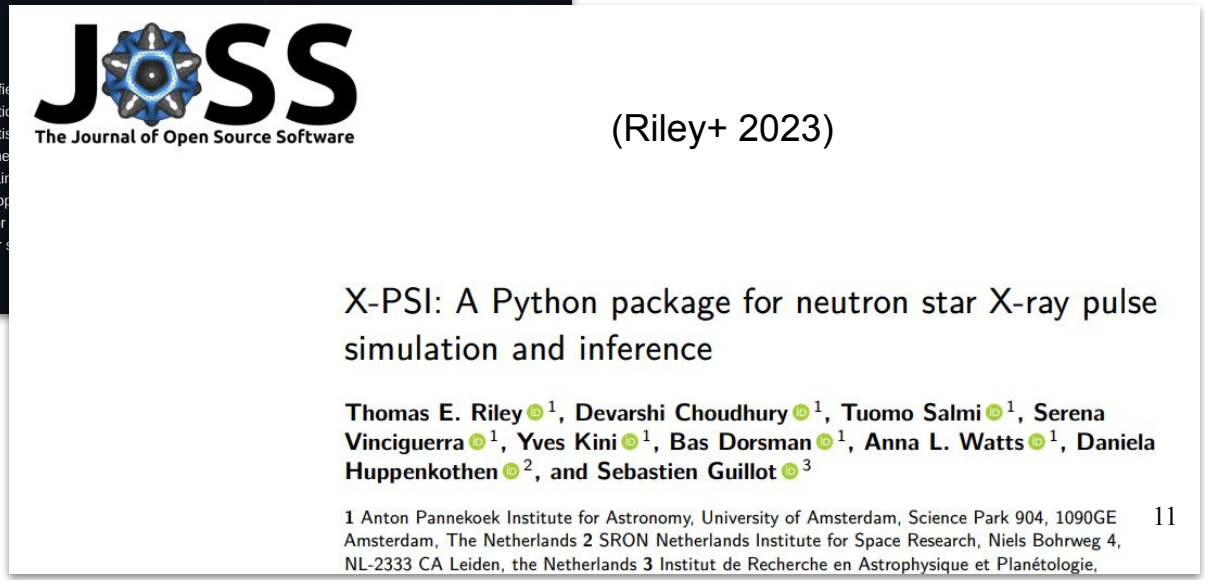
X-PSI

Well documented



Open Source

We even wrote a paper about it



(Riley+ 2023)

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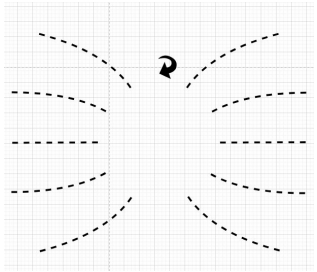
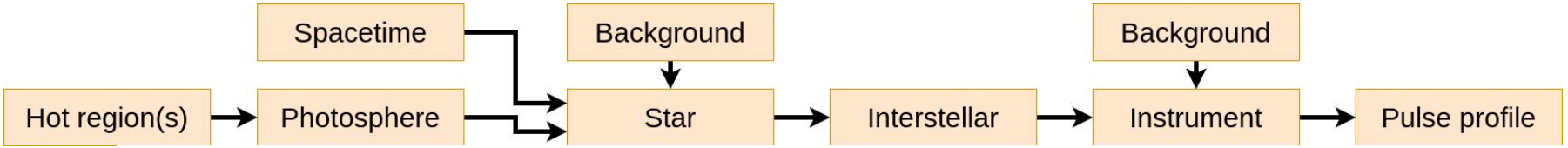
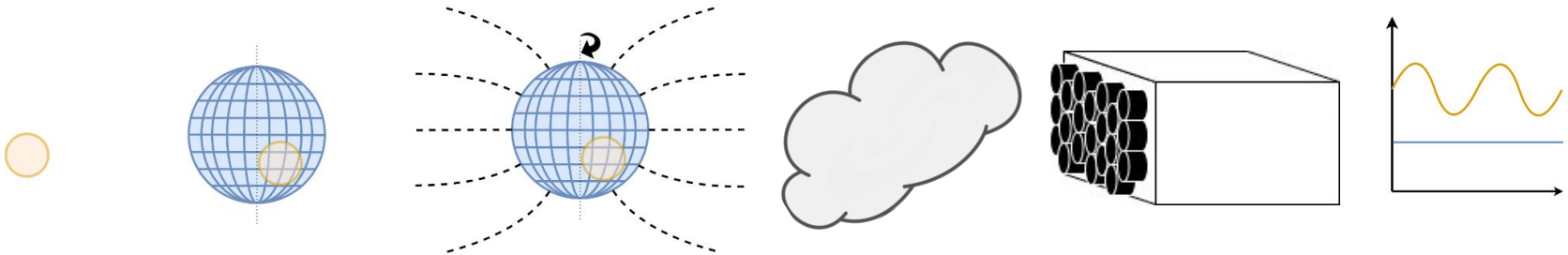
Modeling pulsed emission







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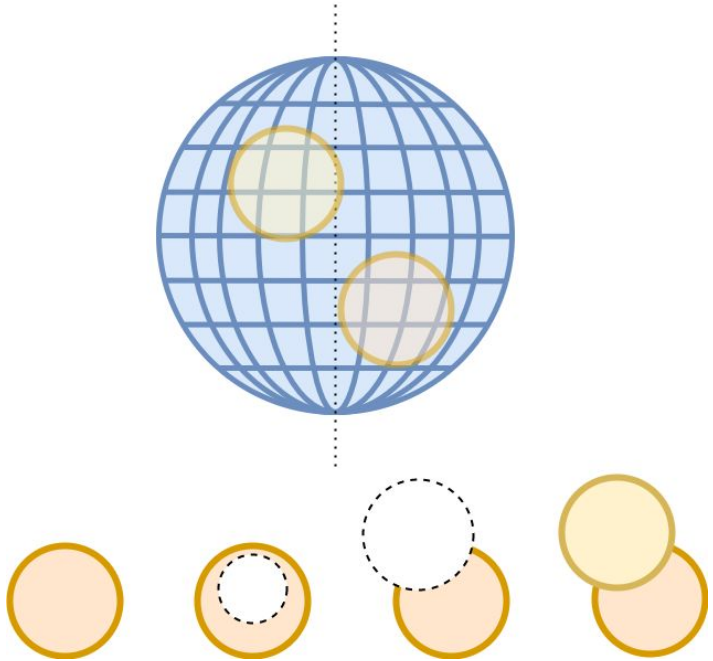
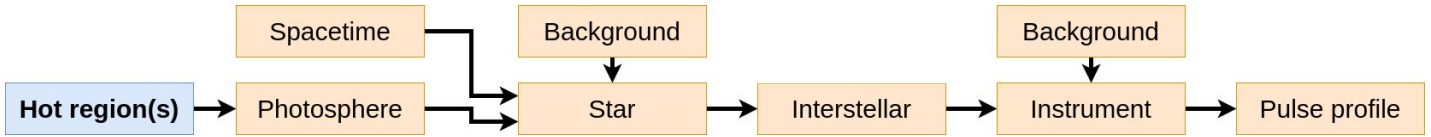
Hot region(s)

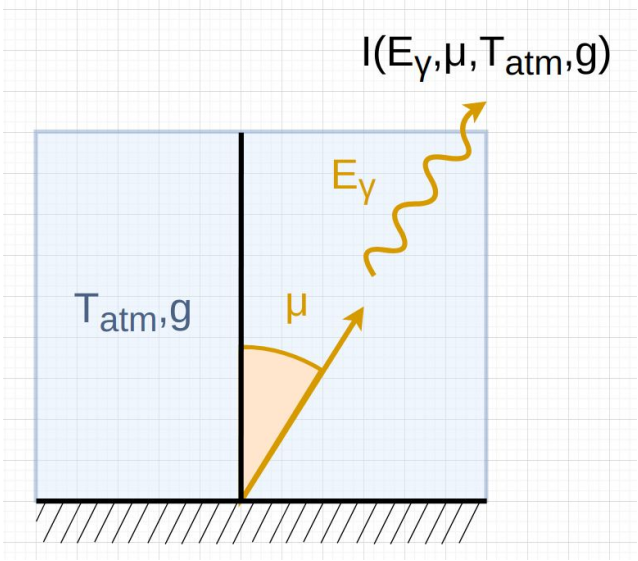
- Modeled geometries: circles or composed of circles
- Serena's talk

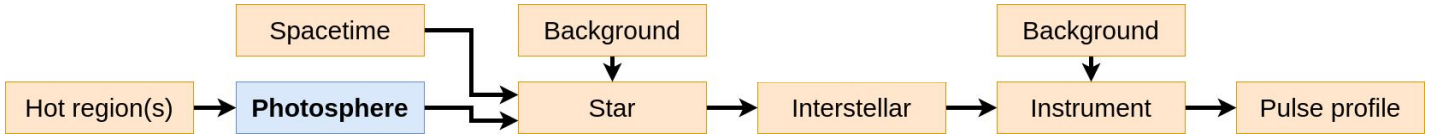




Photosphere

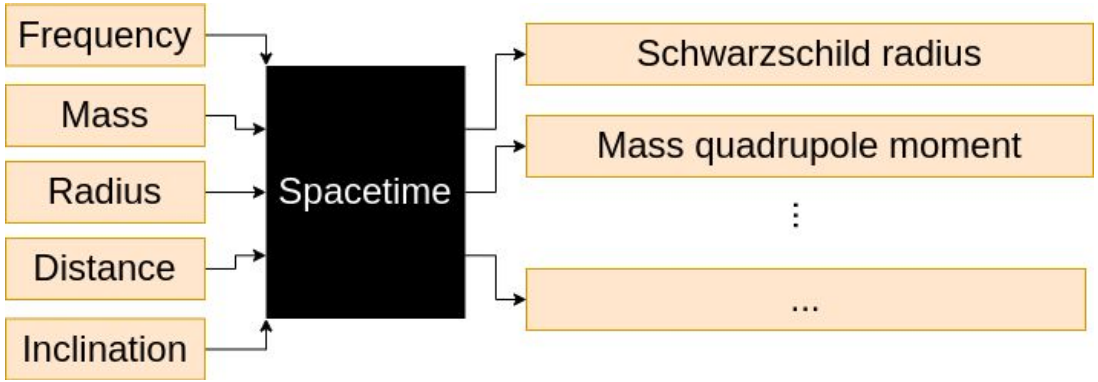
- Intensity via interpolation from atmosphere data table
- RMPs:
  - H/He, fully or partially ionized (e.g. Ho & Lai 2001)
  - Atmospheres: Tuomo's talk
- AMPs: later this talk

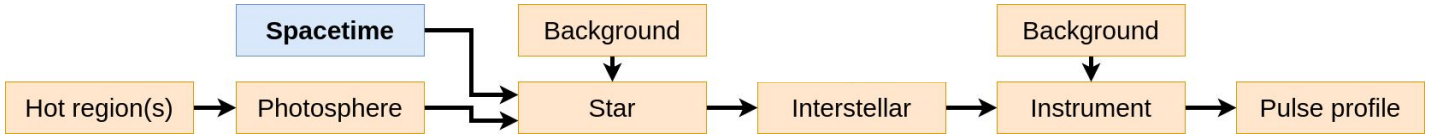




Spacetime

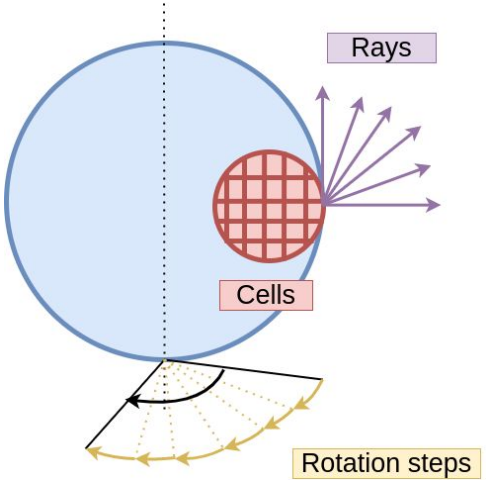
- Ideal: Ray tracing in numerically solved spacetime
- Faster: Oblate Star + Schwarzschild metric (Morsink+ 2007, AlGendy & Morsink 2014)

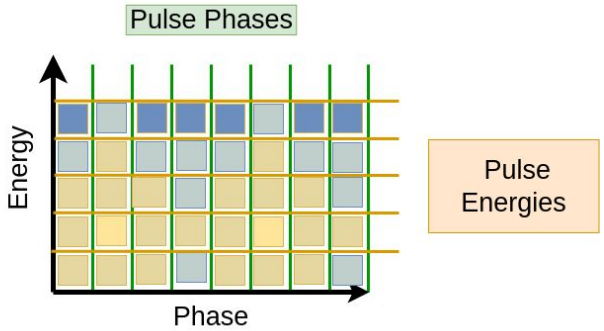


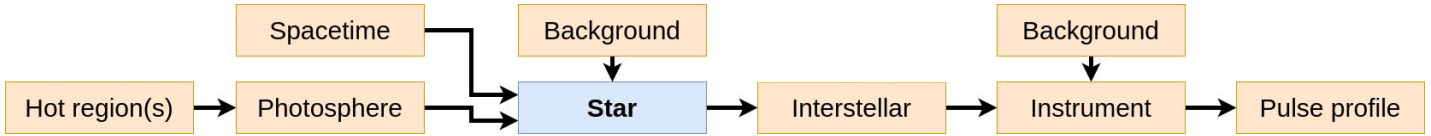


Star: discretizations

- Balance resolution and resources
- Discretizations:
  - Cells (hot spot)
  - Rays (ray-tracing)
  - Rotation steps
  - Pulse phases
  - Pulse Energies
- Backgrounds in field (e.g. Devarshi's talk)

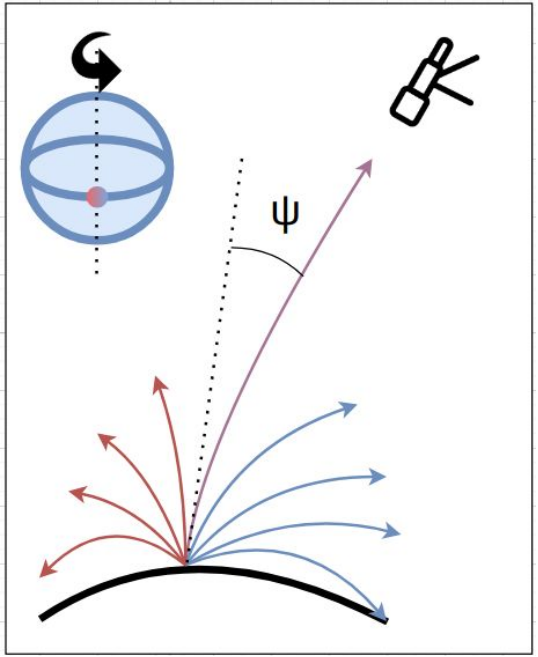


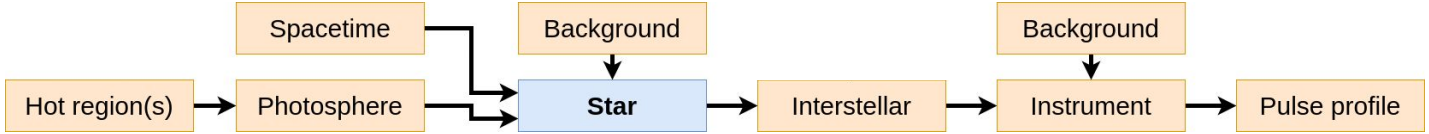




Star: Preparing ray grid

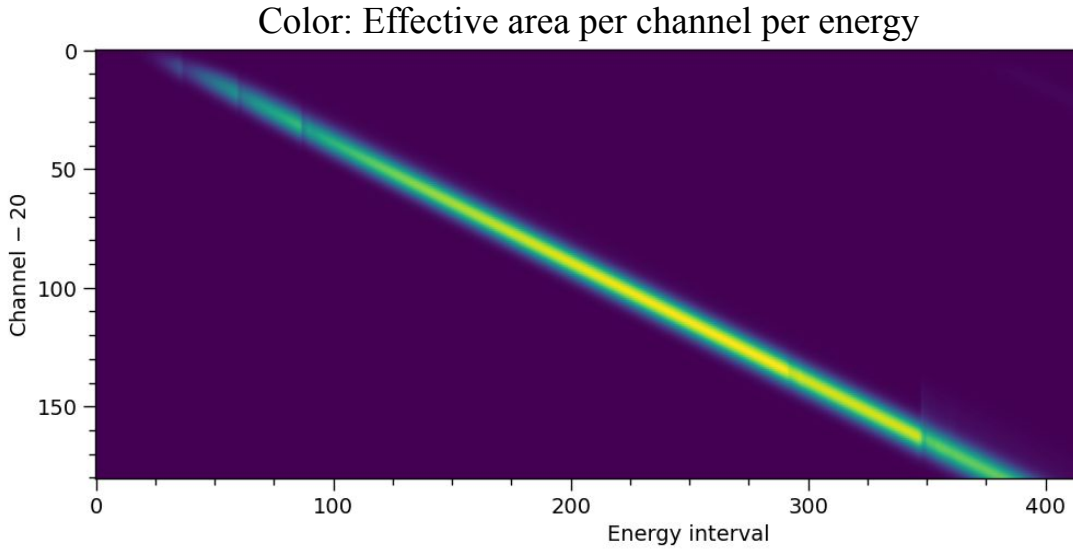
- Convert rays to observer frame
  - Doppler boost
  - Angle aberration
- Compute deflection angle ψ
  - GR light bending
  - GR redshift
- Compute time delays
- See also Bogdanov+ 2019b

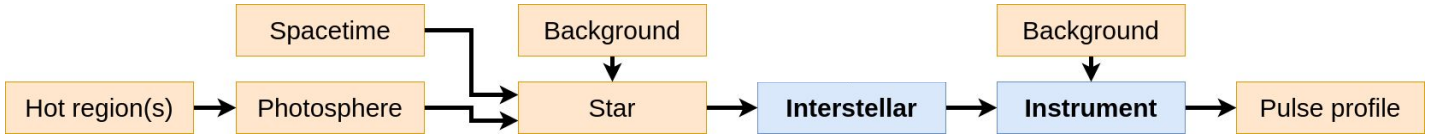




Interstellar, Instrument

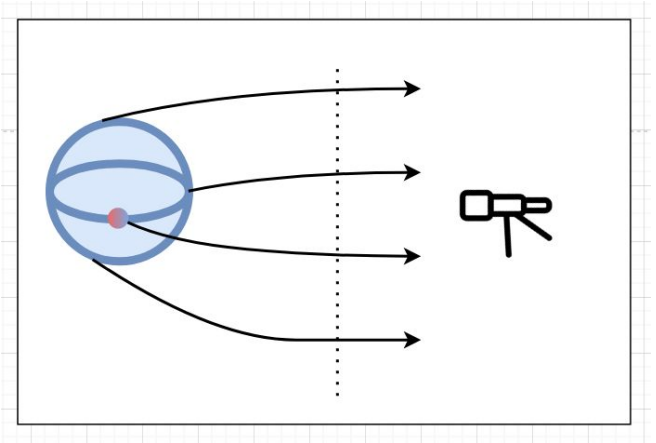
- Interstellar: any attenuation of flux due to ISM
- Instrument:
  - X-ray response matrix
  - Background (e.g. optical loading)

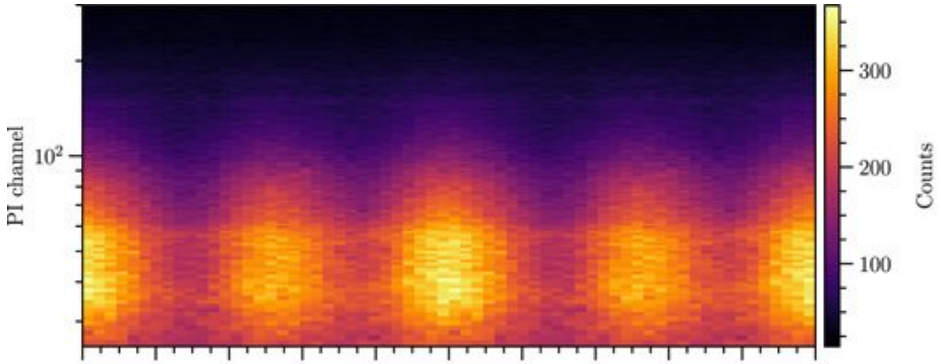


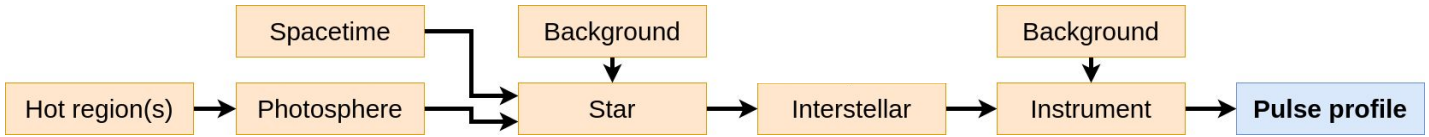


Observation

- Ray grid interpolation: observer receives rays emitted towards observer
- Integrate for rays: discretized cellmesh, rotation steps
- Add (non-pulsed) backgrounds to counts
- Build pulse profile



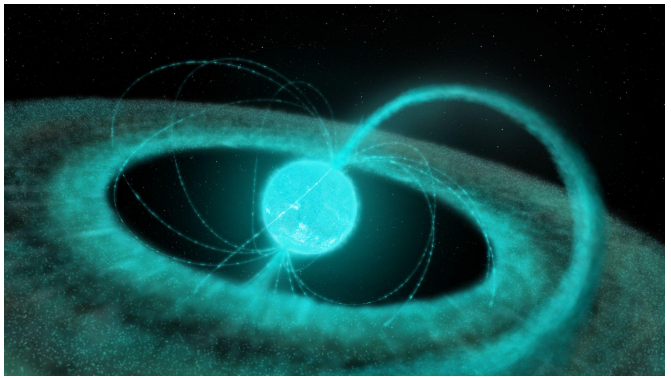




Part 3/3: PPM for AMPs

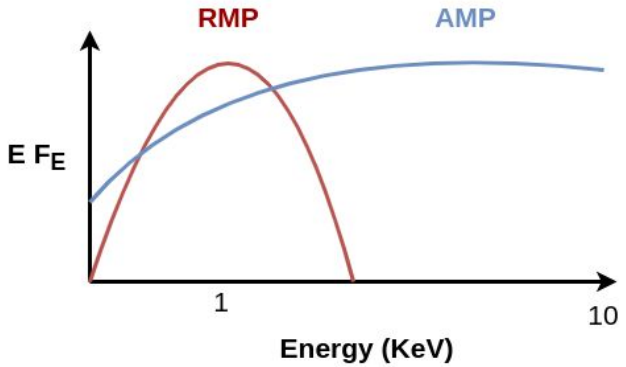
Accreting Millisecond Pulsars (AMPs)

Artist's impression of AMP



AMPs:

- Accretion onto magnetic poles
- Spectrum different from RMPs (e.g. Suleimanov+ 2018)
- Inverse compton, polarized emission (e.g. Salmi+ 2021)
- Environment more complex: Accretion column, disk



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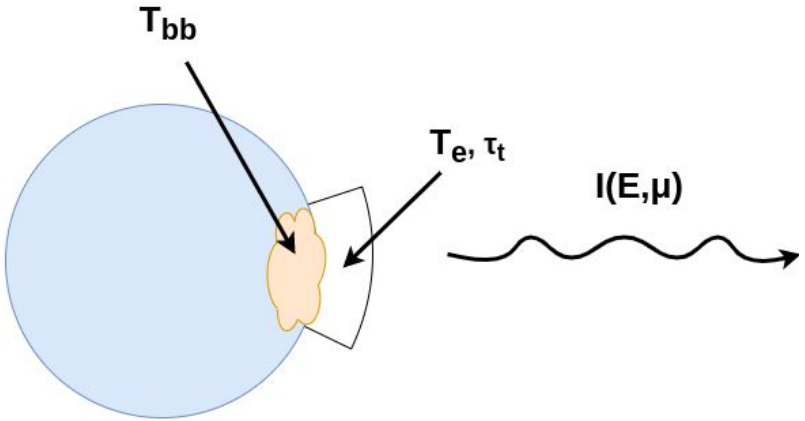
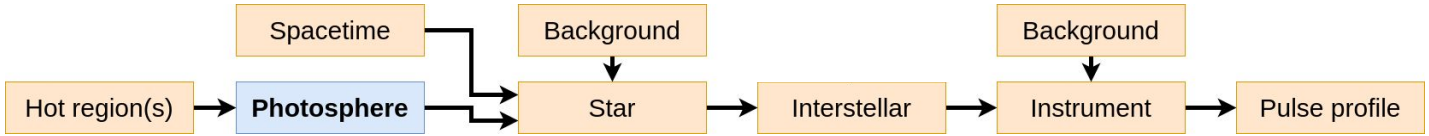
Compton slab model

Modeling approach: parametrized optically thin slab of hot electrons
(Salmi+ 2021, Bobrikova+ submitted)

- T_{bb} (seed photons)
- Inverse compton, hot electrons: T_e (Temperature), τ_t (optical depth)
- Photon emission: E_γ, μ

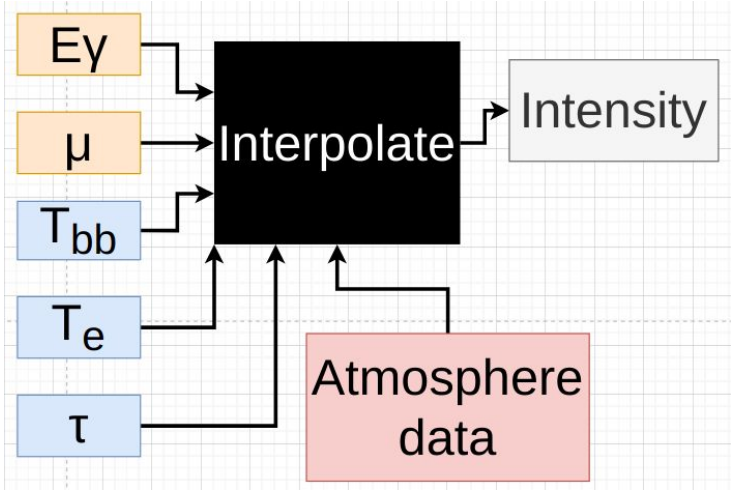


Previously 4, now 5 parameters!



Current status

- X-PSI Interpolation algorithm (Lagrangian polynomials) extended from 4 to 5 parameters
- But: Likelihood evaluation ~1s to ~4s
- Analyses already take days to weeks
- Efforts to optimize code (useful for RMPs and AMPs)



Code Optimization

- Identified atmosphere interpolation >~95% of computation time -> optimize this part
- Work with HPC experts at Dutch IT cooperative (SURF):
  - Optimization at single node level
  - Optimization at parallelization level
  - Exploring options specialized hardware

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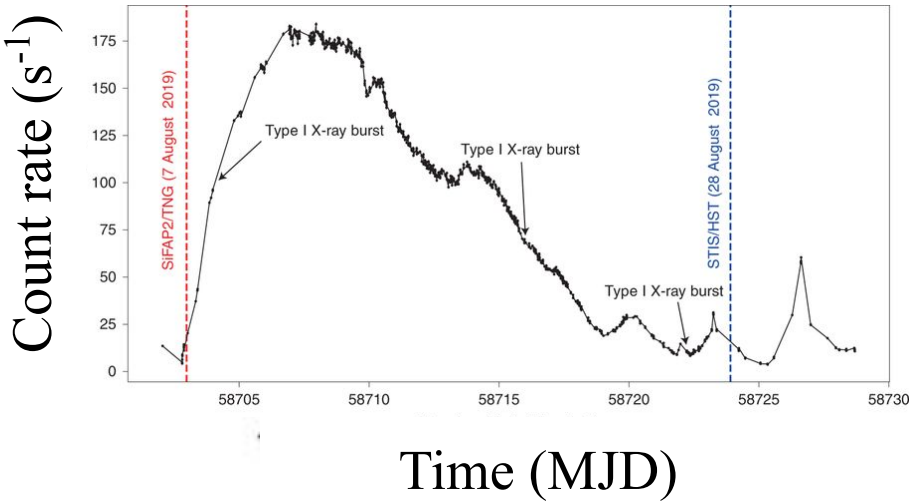
Outlook for analysis of AMPs

- Test parameter recoverability with simulated data
- Analysis of J1808 NICER data from 2019 and 2022 outbursts
- If code well optimized, unlock more advanced models:
  - Accretion disk
  - Accretion column

Ambrosino+ 2021



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Conclusions

- PPM has provided mass and radius constraints for J0030 and J0740, more in the works
- We discussed how PPM works in open source software X-PSI
- Next frontier: AMPs, but challenge due to accretion and complex environment
- Bottleneck is computational efficiency, working on code optimization

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Thank you!

Special thanks to:

- Devarshi Choudhury
- Pushpita Das
- Satish Kamath
- Yves Kini
- Mason Ng
- Tuomo Salmi
- Serena Vinciguerra
- Prof. Dr. Anna Watts

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EXTRA SLIDES

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Reminder on Bayesian parameter inference

$$P(\theta|D, M) = \frac{P(D|\theta, M)P(\theta|M)}{P(D|M)}$$

Likelihood Prior

Posterior probability

Evidence

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Deflection angle

$$\psi_{\rm p}(R,\alpha) = \int_R^\infty \frac{{\rm d}r}{r^2}\left[\frac{1}{b^2} - \frac{1}{r^2}\left(1 - \frac{R_{\rm S}}{r}\right)\right]^{-1/2}, \qquad (2.9)$$

where b is the impact parameter:

$$b = \frac{R}{\sqrt{1-u}}\sin\alpha. \qquad (2.10)$$

Taken from Tuomo's Thesis. See also: Misner et al. 1973; Pechenick et al. 1983

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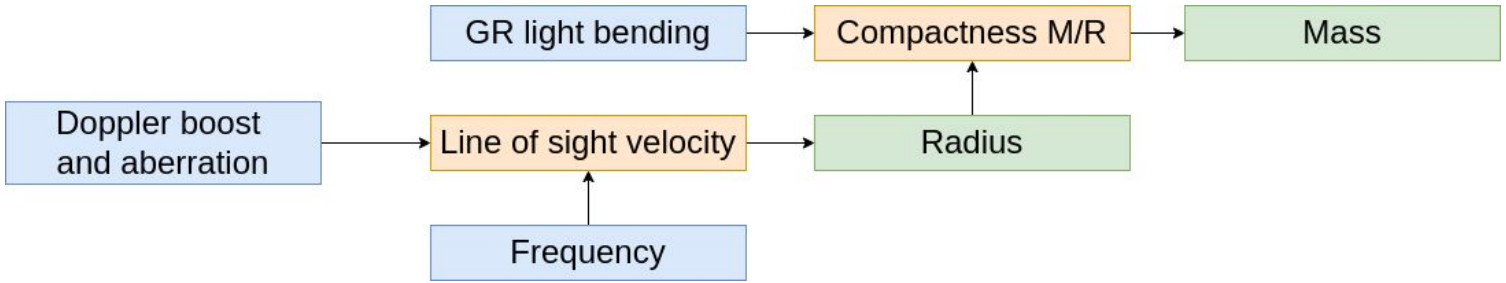
Pulse profile modeling: Constraining Mass and radius



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Previous work, current PPM efforts (Bayesian inference)

Pulsar	J0030 (RMP)	J0740 (RMP)	J0437 (RMP, AGN background)	J1614, J0614, J1231, J2124 (RMPs)	J1814 (Bursting)	J1808 (AMP)
Previous work	Riley+ 2019 *Miller+ 2019*	Riley+ 2021, *Miller+ 2021,* Salmi+ 2022			Kini+ 2023	*Salmi+ 2018*
Current efforts	Serena's talk	Re-analysis with new NICER data	Devarshi's talk	Toulouse/Amsterdam/NRL/Columbia/IM	Yves' talk	This talk

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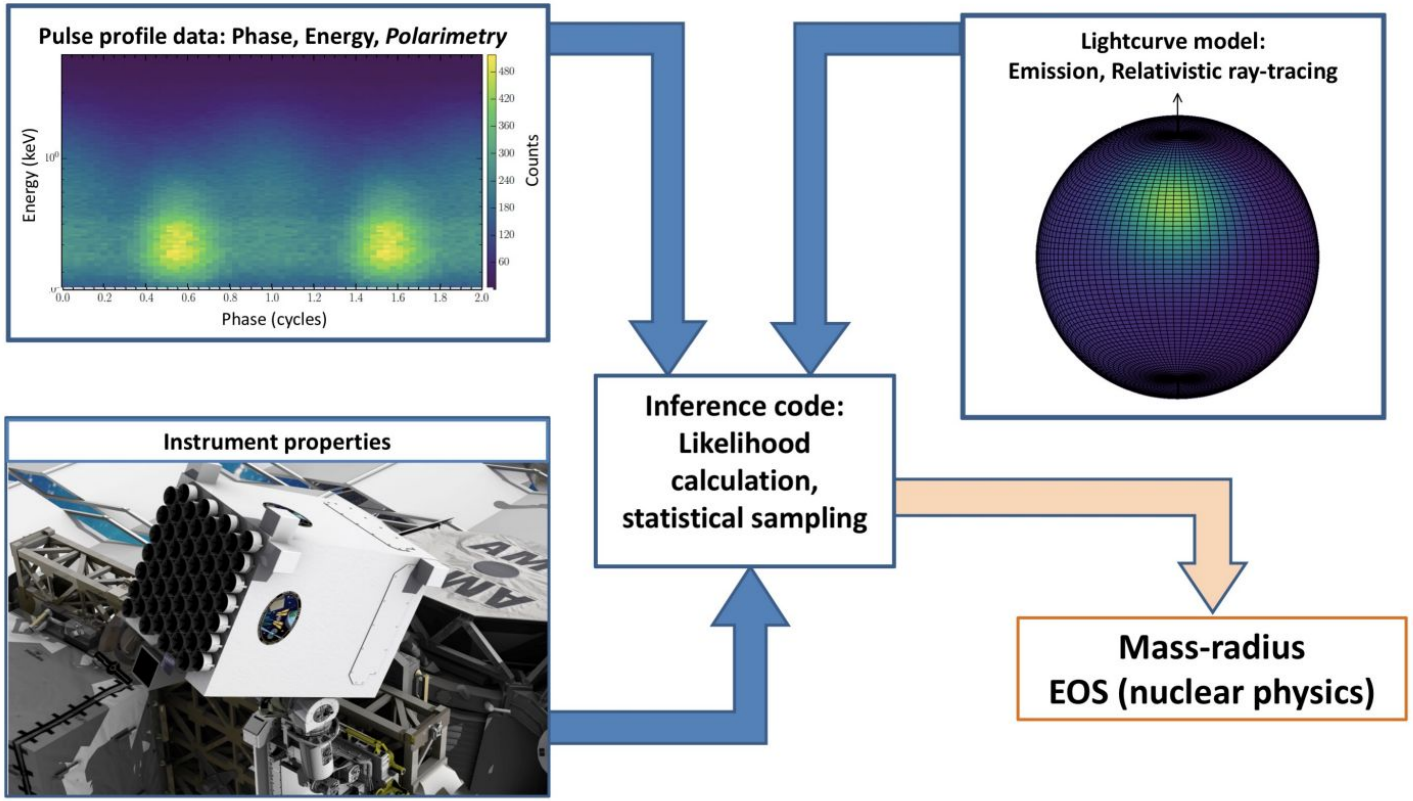
Overview: Pulse profile modeling



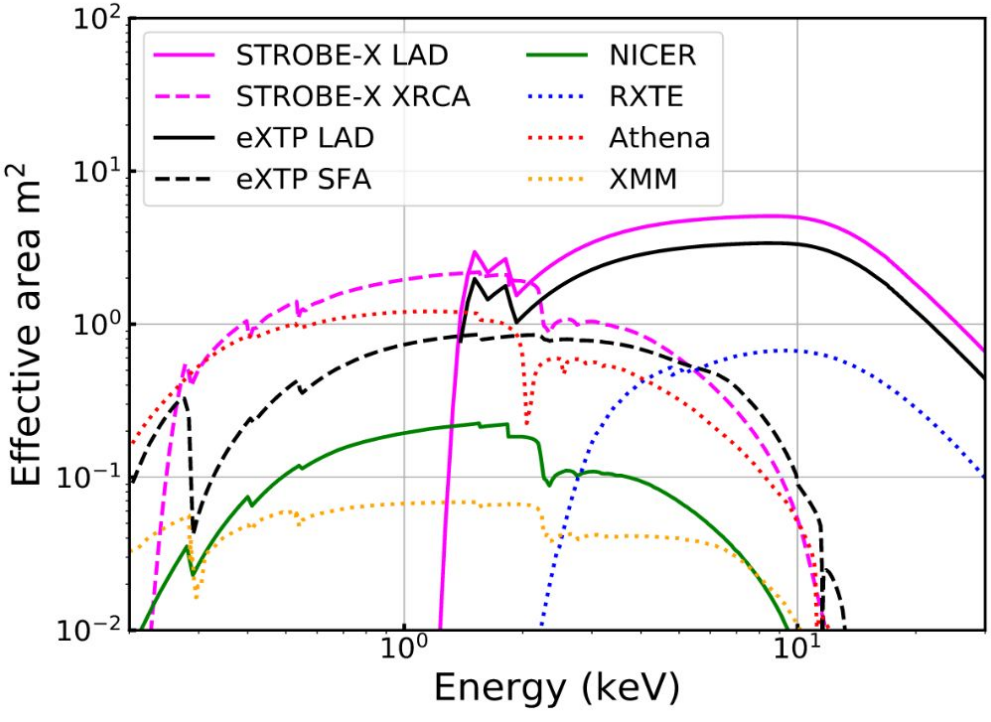
Instruments

Existing:

- RXTE, NICER, IXPE,

Planned/Proposed:

- Strobe-X, eXTP, Athena



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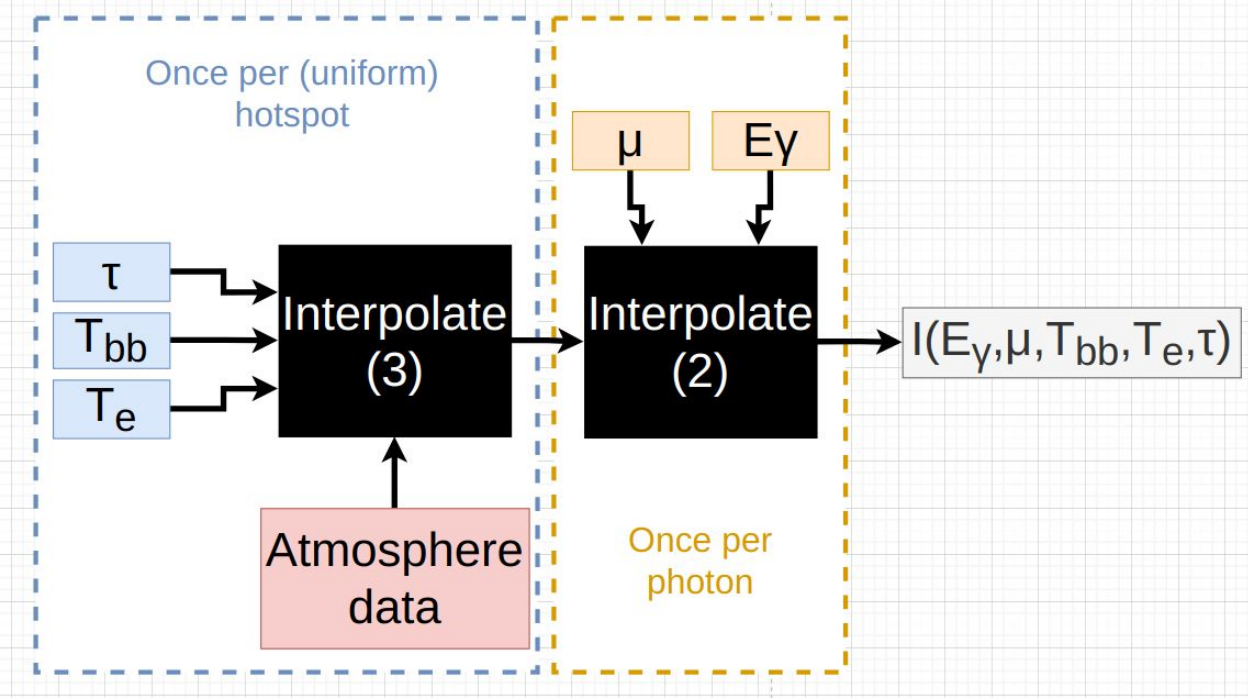
Code Optimization



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Measuring neutron stars

	Pulsar timing	**Spectral modeling** (e.g. Natilla 2017)	**Pulse profile modeling** (e.g. Watts 2019)	**NS mergers**
Objects:	RMPs	Bursters/quiescent NSs in LMXBs	RMPs, AMPs, Bursters	B(H)NS binaries
Messenger:	Radio pulsations	X-ray Phase averaged spectra	X-ray pulsations	Gravitational waves, EM counterparts
Constrains:	Mass (binaries)	Mass-radius	Mass, Radius, Emitting geometry	Tidal deformability, EoS

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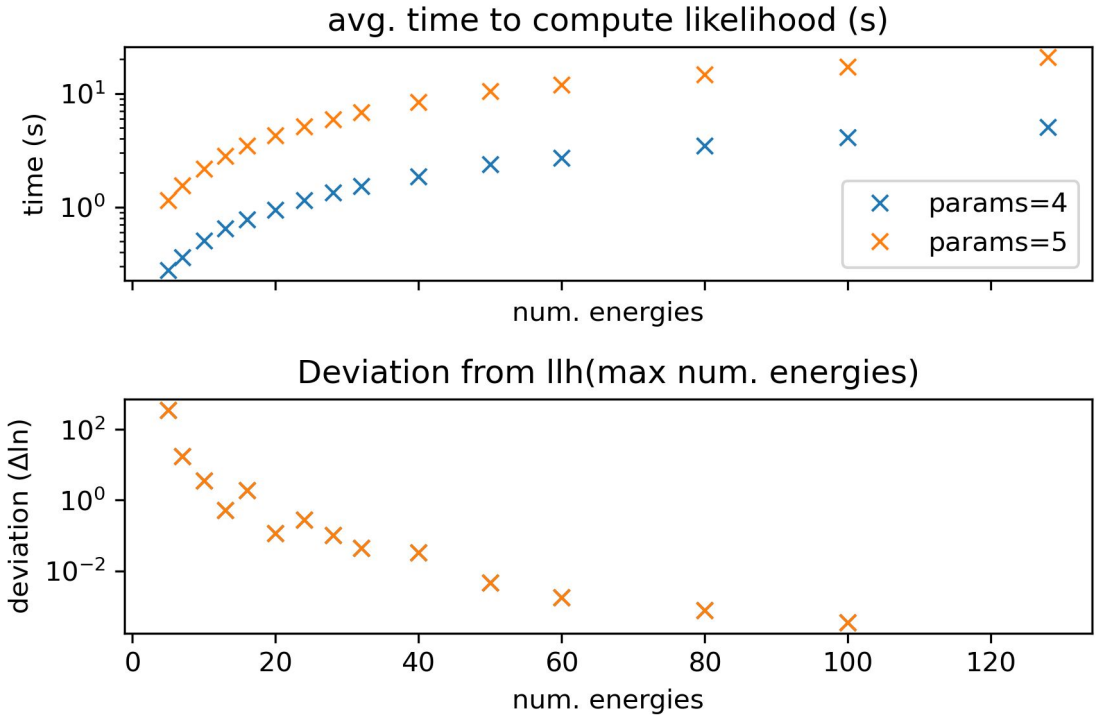
Speed and accuracy



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Model pulsed emission

Neutron Star

- Oblate spheroid in schwarzschild spacetime

Emission (pulsed)

- hot spots
- Elsewhere surface

Background (unpulsed)

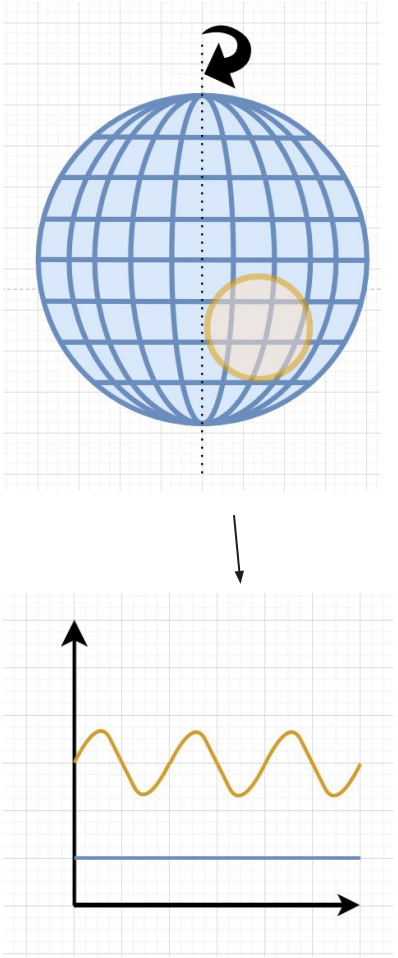
- Sometimes constraints, sometimes not

Radiative transfer

- Beaming pattern modulated by atmospheric effects
- Relativistic ray-tracing to observer

X-ray Photometry

- Energy channels, uncertainties



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Introduction

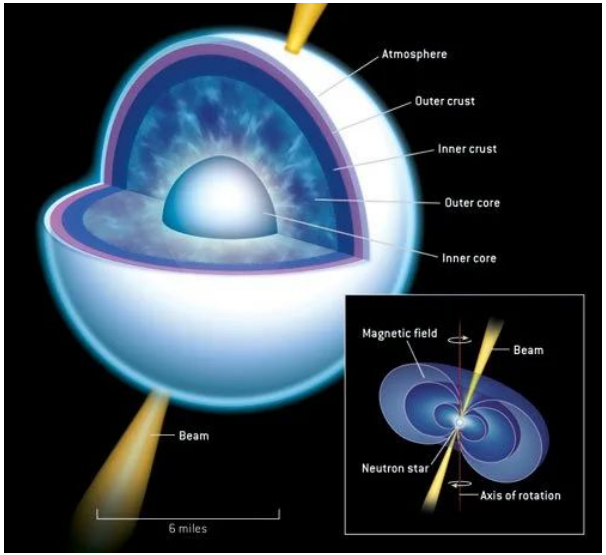
Neutron stars (NSs)

- Inner core uncertain: strange matter?
- Laboratories for equation of state (EoS) of cold dense matter

Millisecond pulsars (MPs)

- Rotation powered
- Accretion powered

Type 1 X-ray burst oscillation sources



Astronomy magazine, 2005

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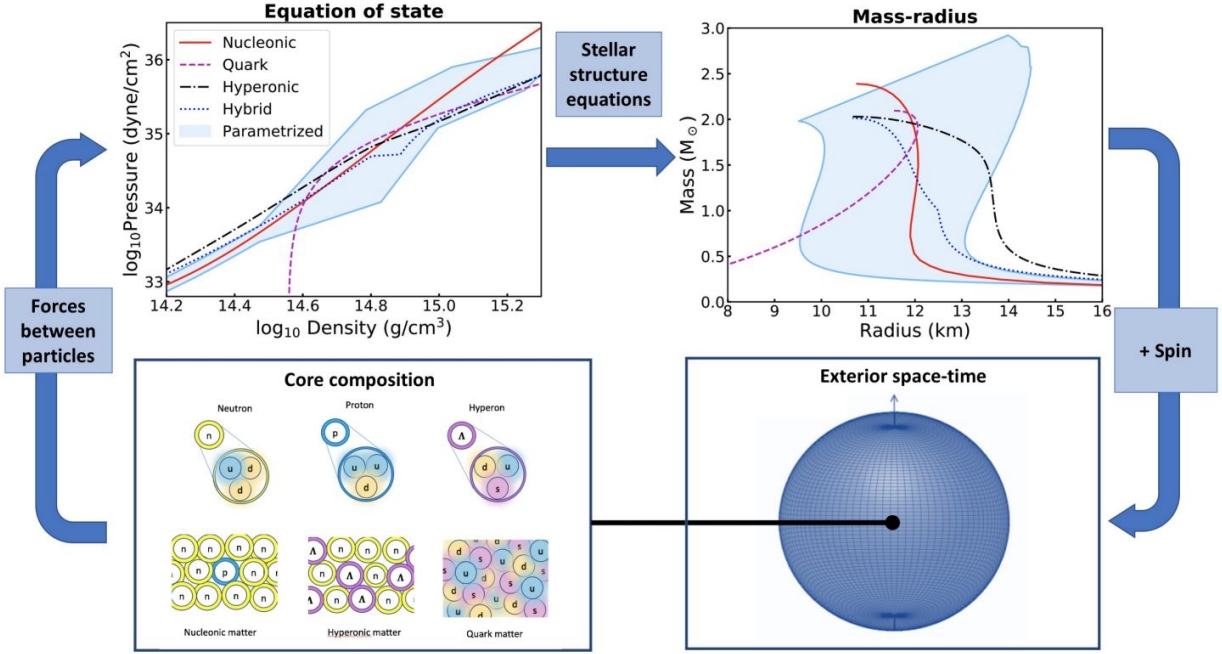
Introduction



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Watts 2019

Accreting MSPs: current status, modeling intricacies

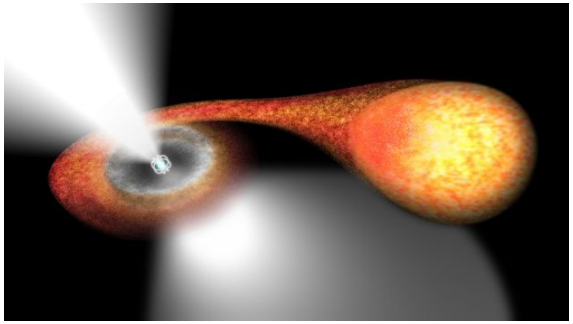
Discussion: Strobe-X whitepaper 2019, EXTP white paper 2019)

Salmi+ 2018 parameter estimation RXTE

Salmi+ 2021 polarimetry simulations for IXPE (Thomson scattering limit)

Complicating factors

- Accretion column
- Accretion disk
- plasma around the accretion disk



Artist's impression of Accreting pulsar, ESA, 2019

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