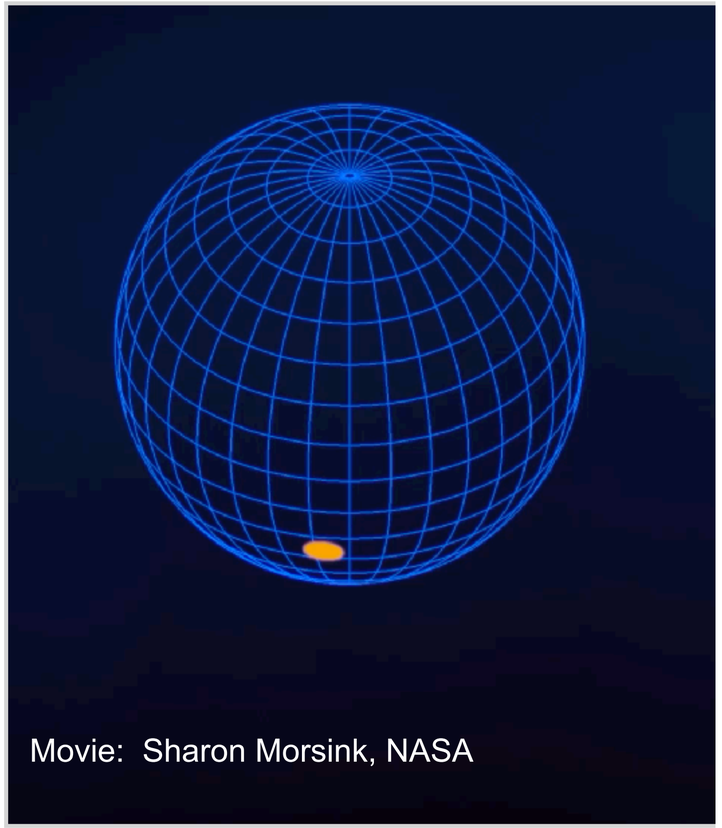
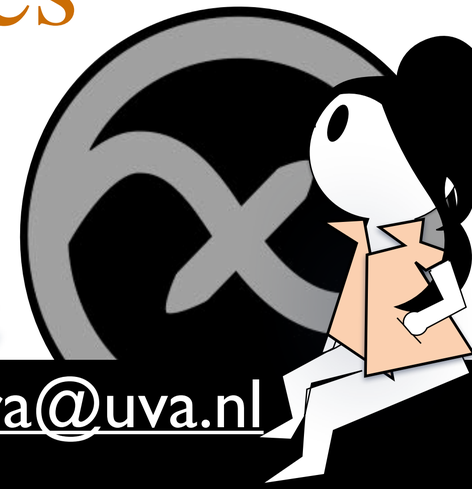
University of Amsterdam

erc



Movie: Sharon Morsink, NASA

Challenges in NICER Pulse Profile Modeling analyses



-Serena Vinciguerra

s.vinciguerra@uva.nl

NWO

NICER • SEXTANT

NASA • GSFC • ISS • MIT • MSOW • DTU

PULSU STELLARUM, SCIENTIA ET VIA CAELESTIS

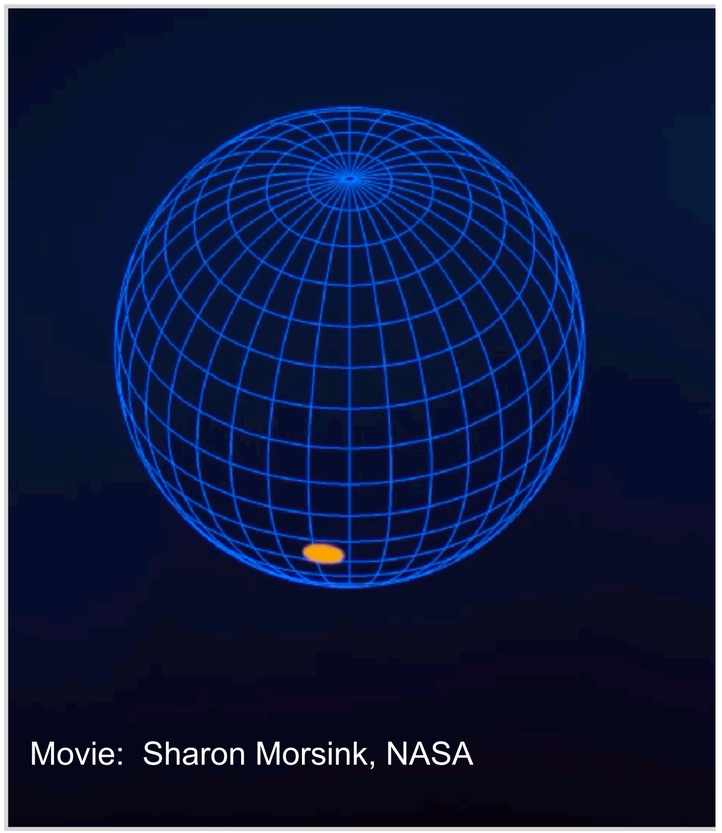
AEONS

IN COLLABORATION WITH:

Tuomo Salmi, Anna L. Watts, Devarshi Choudhury, Yves Kini,

Thomas E. Riley and other from the NICER collaboration

University of Amsterdam



Possible systematic uncertainties ~~Challenges~~ in NICER Pulse Profile Modeling analyses

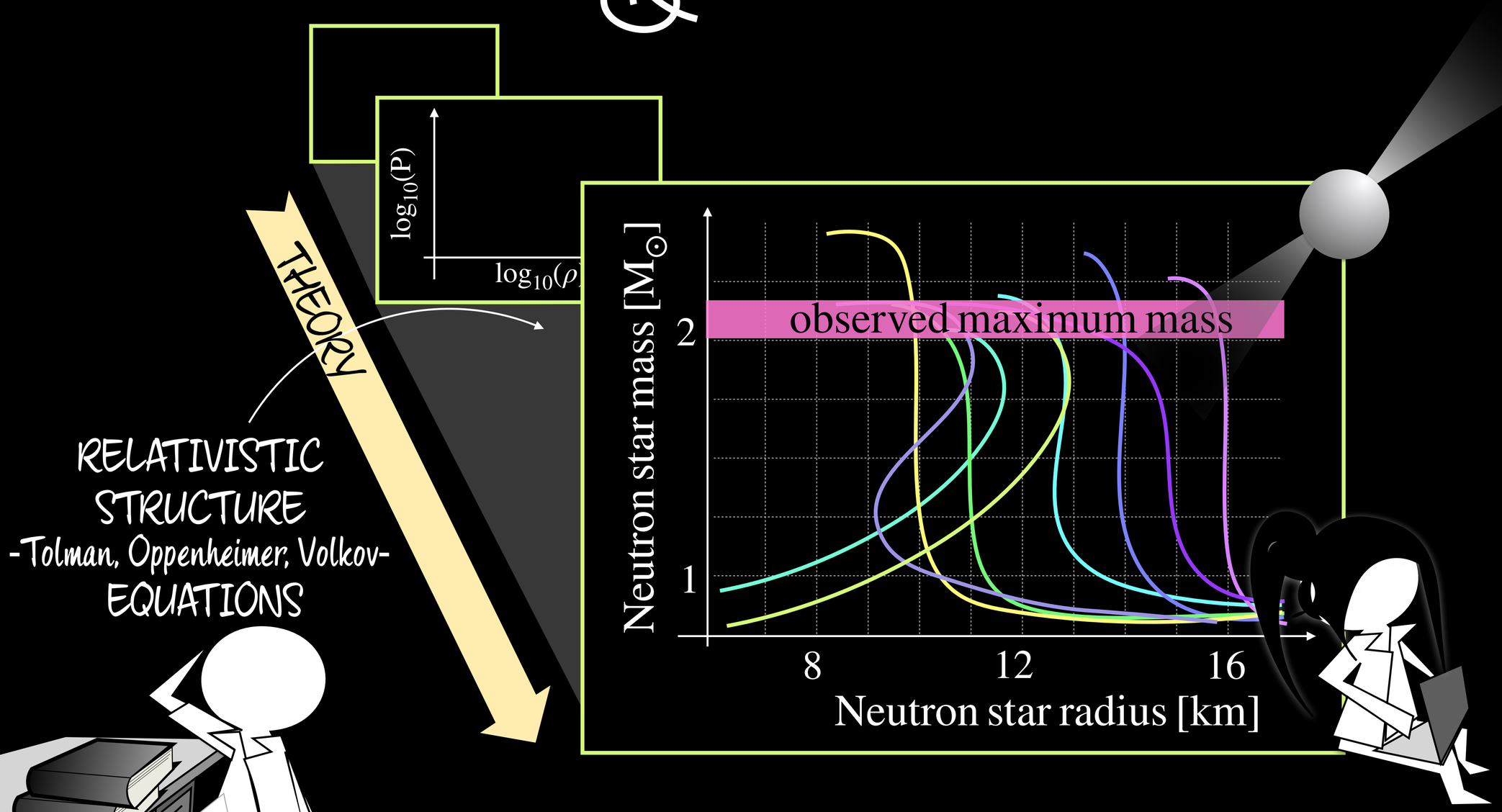
-Serena Vinciguerra

s.vinciguerra@uva.nl

IN COLLABORATION WITH:

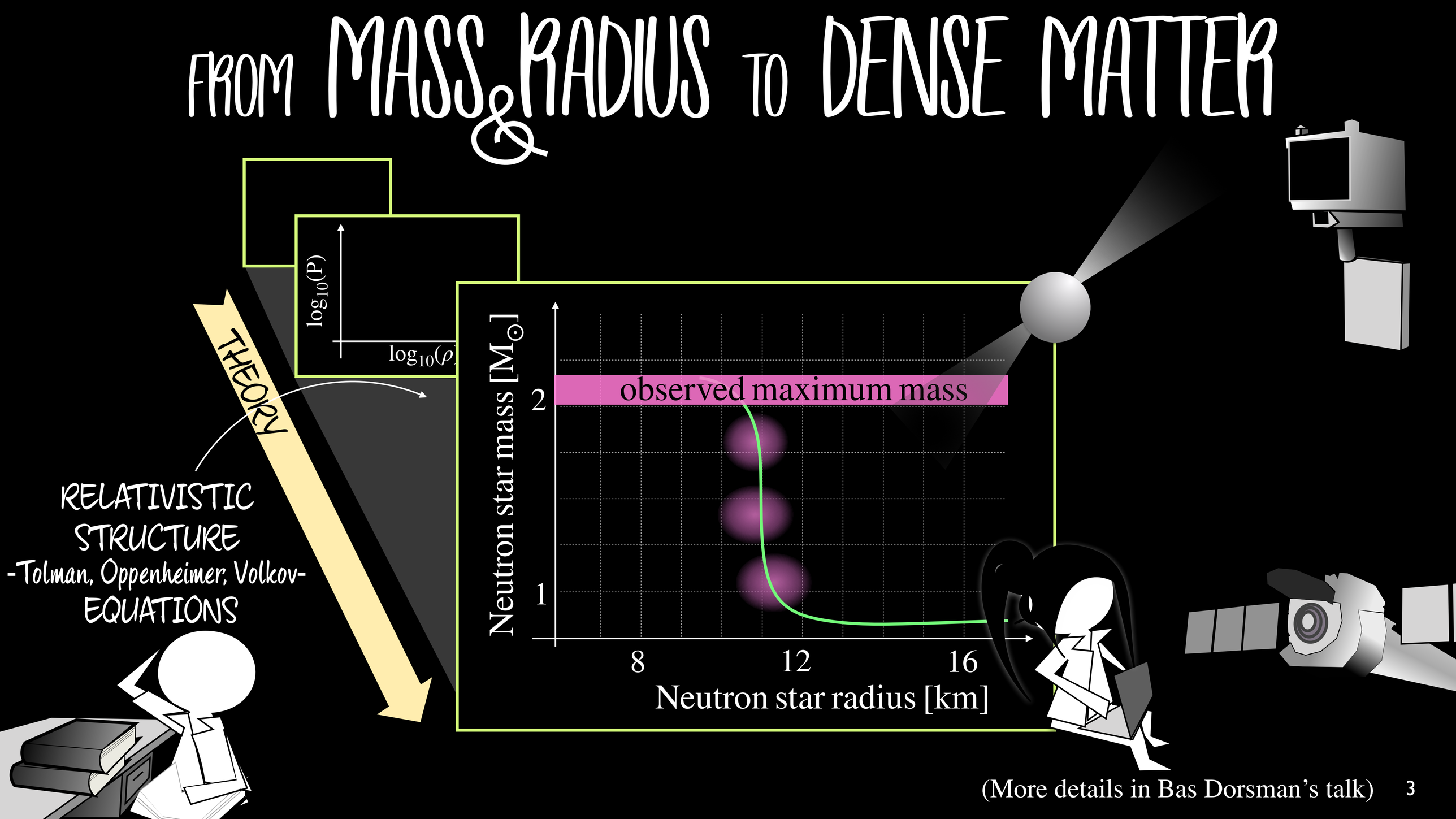
Tuomo Salmi, Anna L. Watts, Devarshi Choudhury, Yves Kini, Thomas E. Riley and other from the NICER collaboration

FROM MASS & RADIUS TO DENSE MATTER



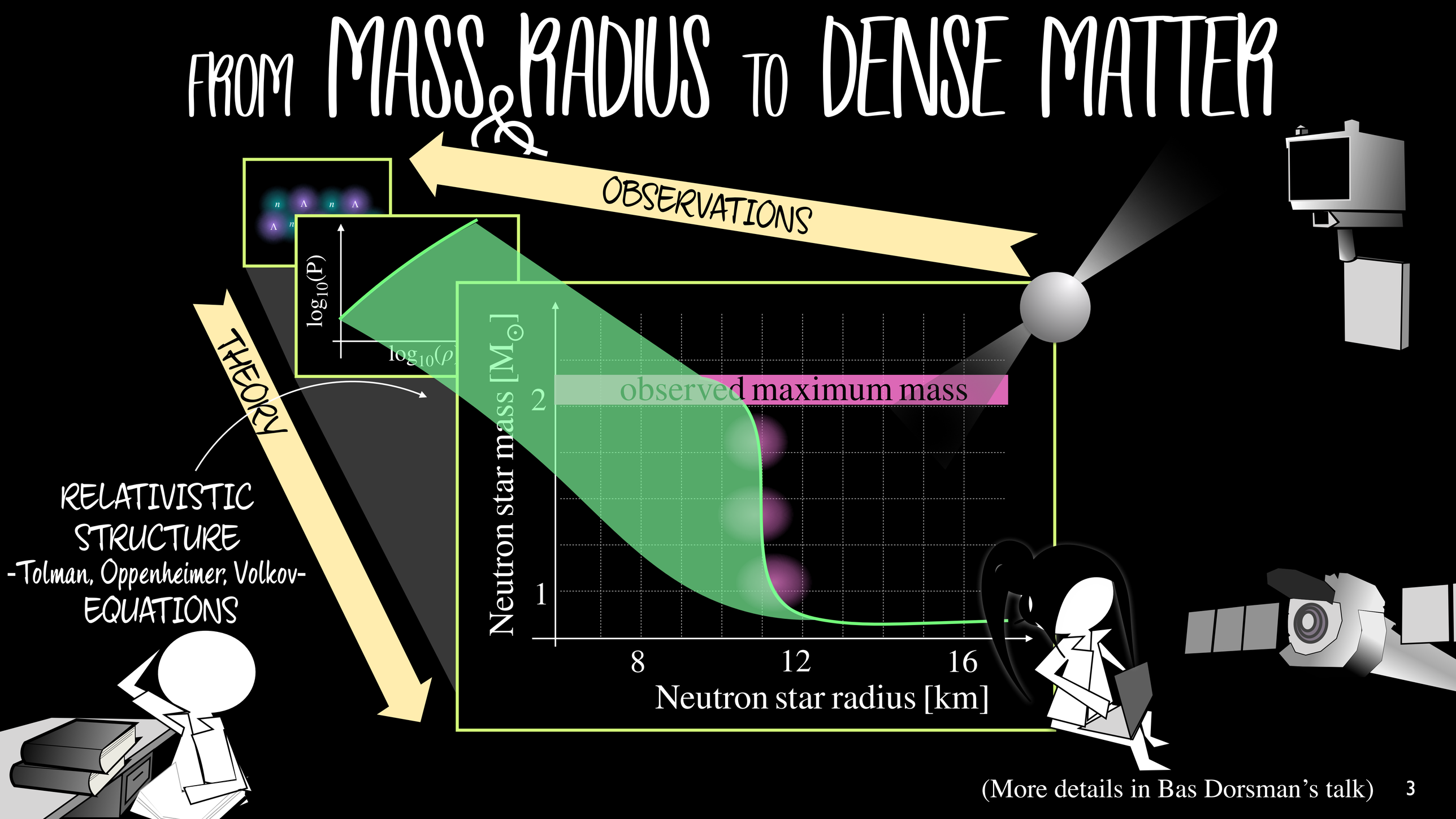
(More details in Bas Dorsman's talk)

FROM MASS & RADIUS TO DENSE MATTER



(More details in Bas Dorsman's talk)

FROM MASS & RADIUS TO DENSE MATTER

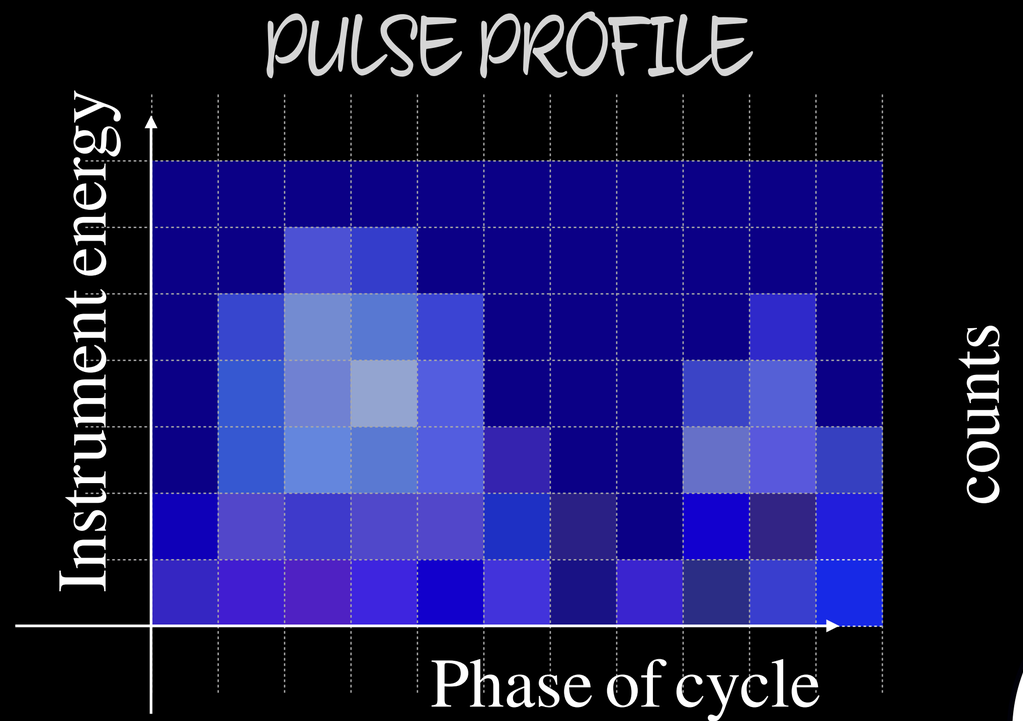


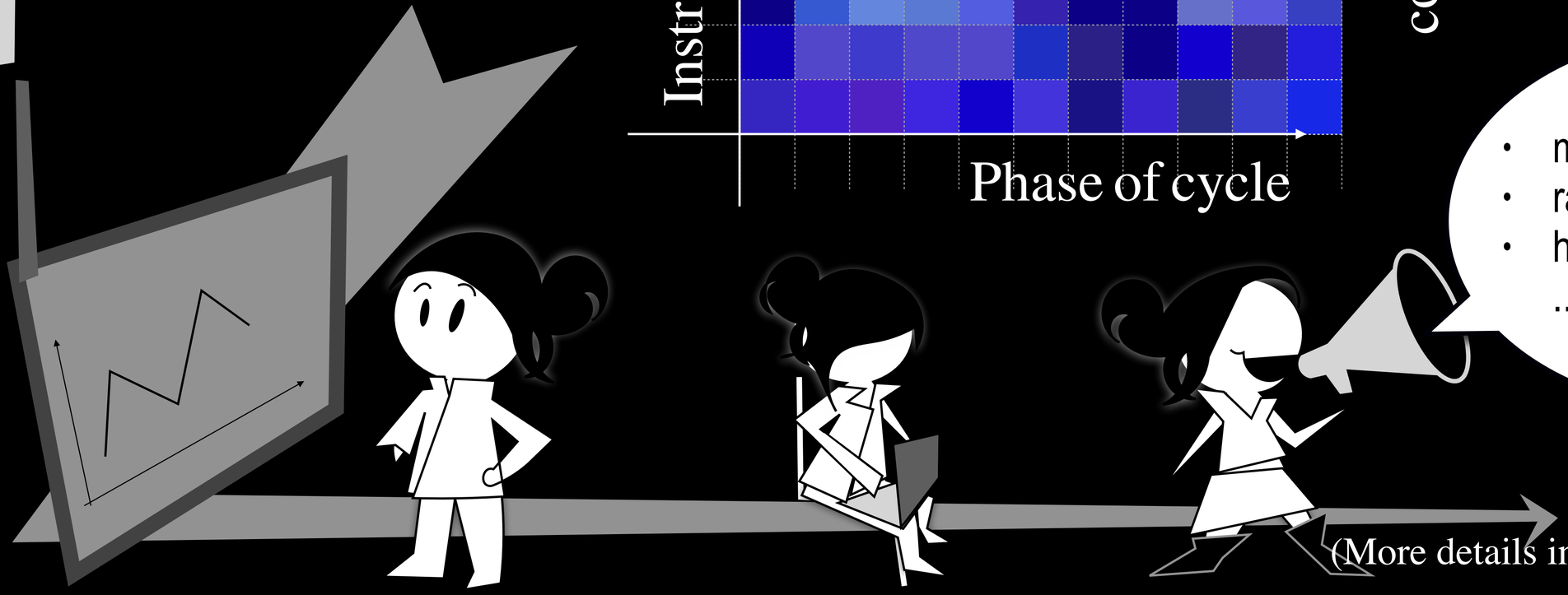
(More details in Bas Dorsman's talk)

PULSE PROFILE MODELING

Non-accreting
ms pulsar

NICER





- masses
- radius
- hot spots configuration
- ..

(More details in Bas Dorsman's talk)

MODEL

Hot Spots

Emission rest of the star

Photosphere

Spacetime

Star

Interstellar medium

Instrument response

Background

SIGNAL

$\bar{\theta}$

BAYESIAN FRAMEWORK

Definition parameter space

(&priors)

(Py)MultiNest

SAMPLING

Sampled

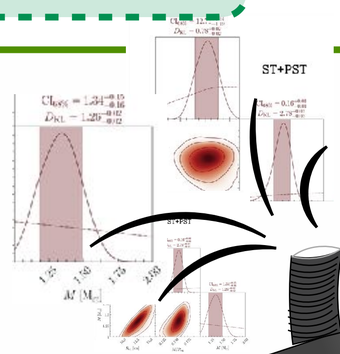
Parameter Vector

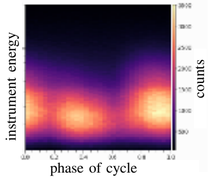
LIKELIHOOD

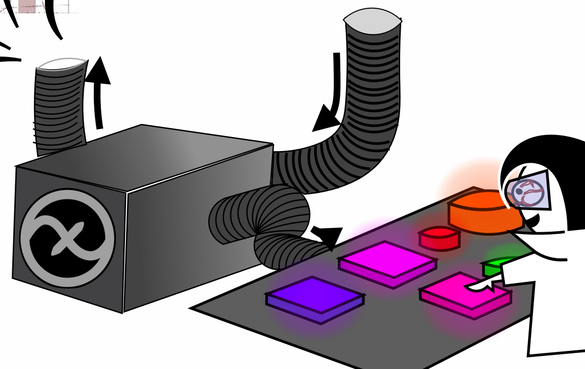
POSTERIOR

(Py)MultiNest

DATA



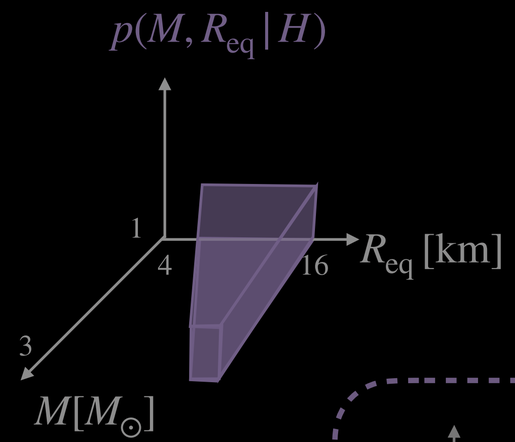


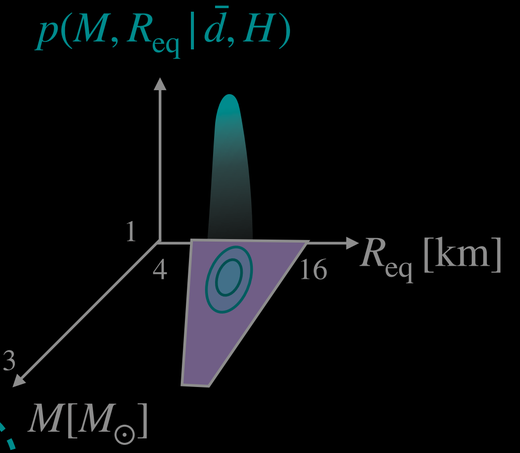


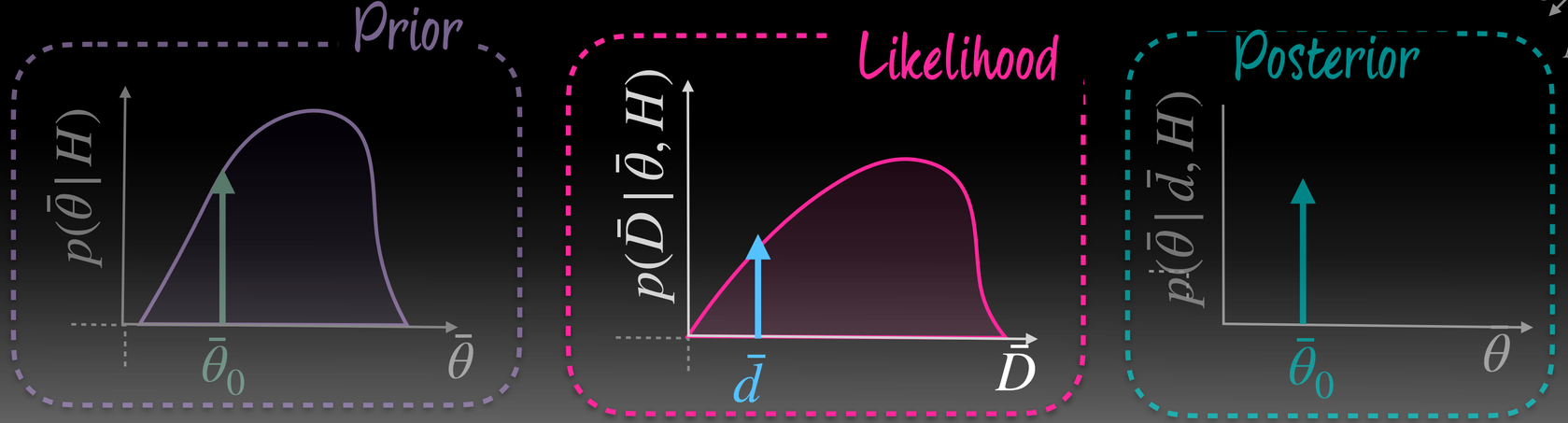
(More details in Bas Dorsman's talk)

AMSTERDAM GROUP PIPELINE: X-PSI

BAYESIAN FRAMEWORK



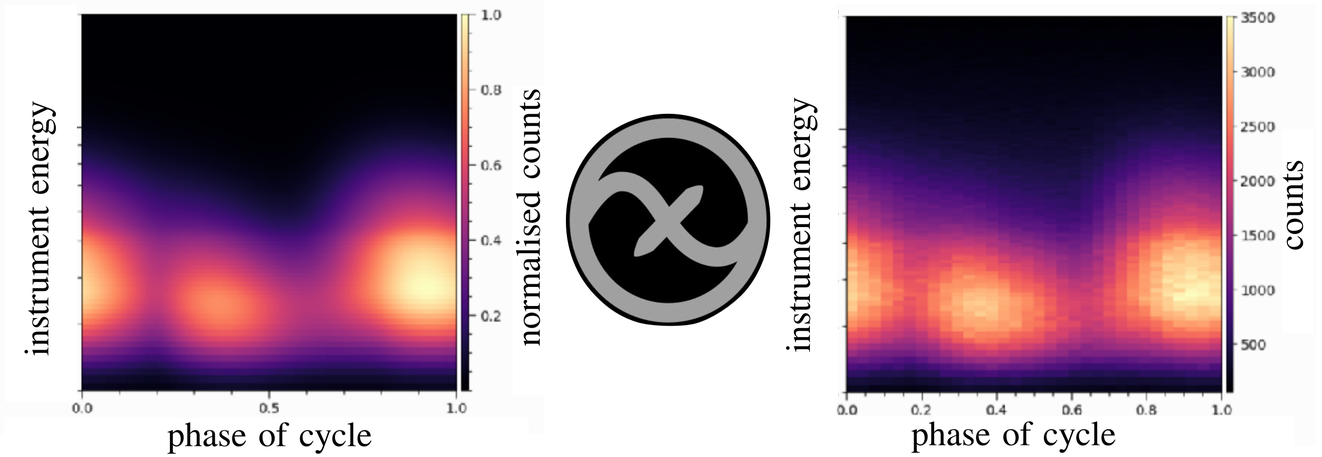




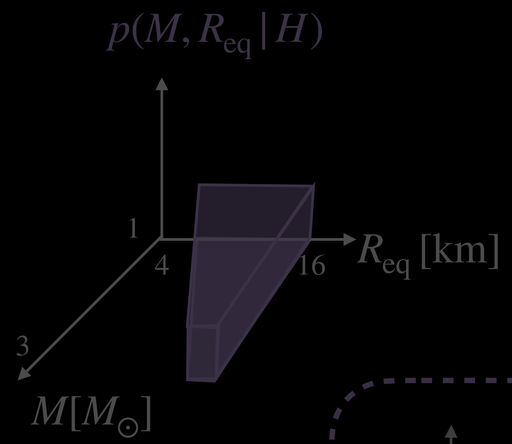
$\bar{d}$: data
$\bar{\theta}$: parameters
H : model

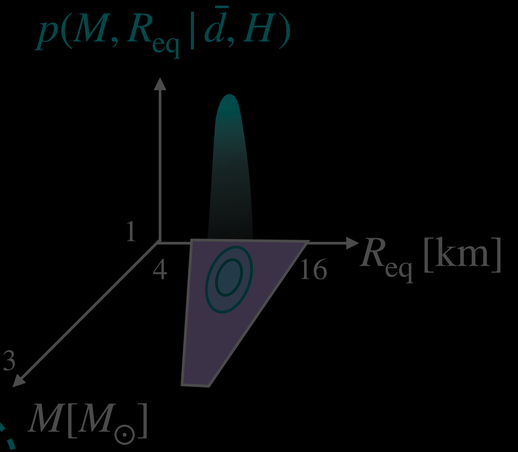
Open source code available @ https://github.com/xpsi-group/xpsi

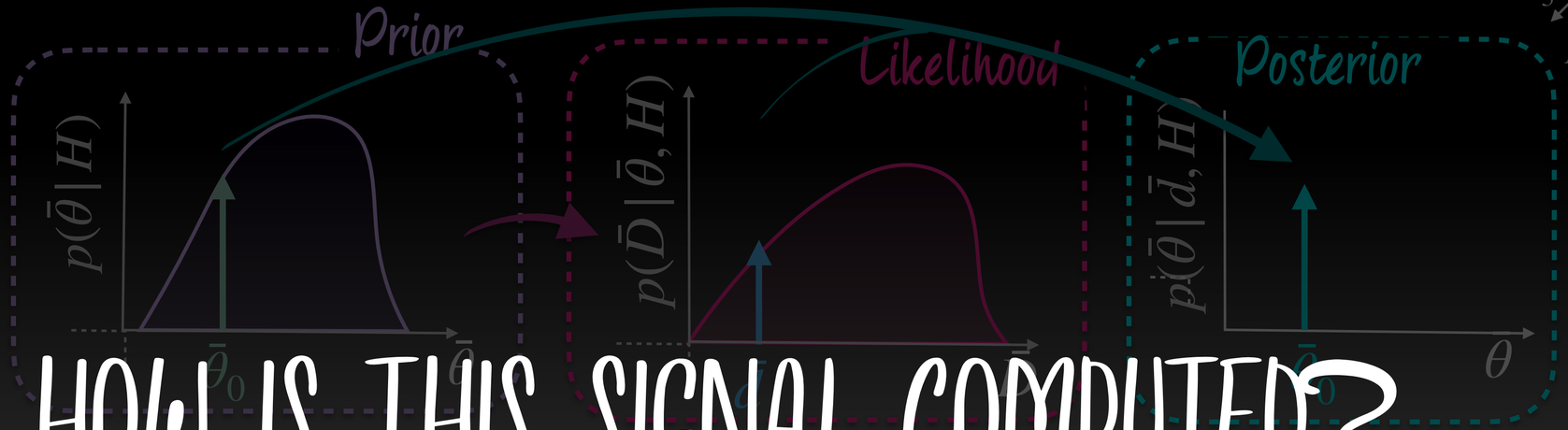
Riley et al 2023 (JOSS)



BAYESIAN FRAMEWORK



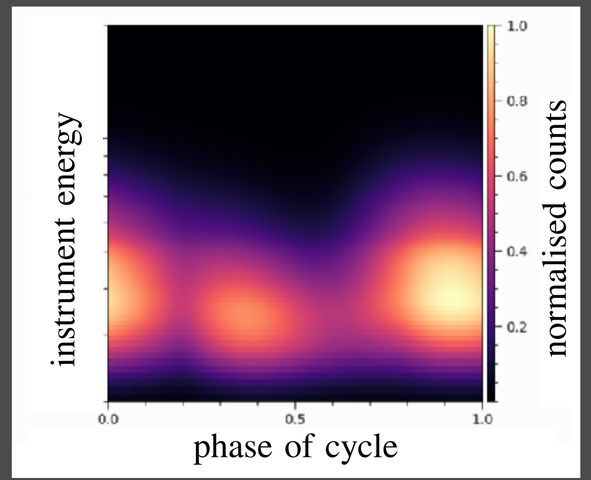


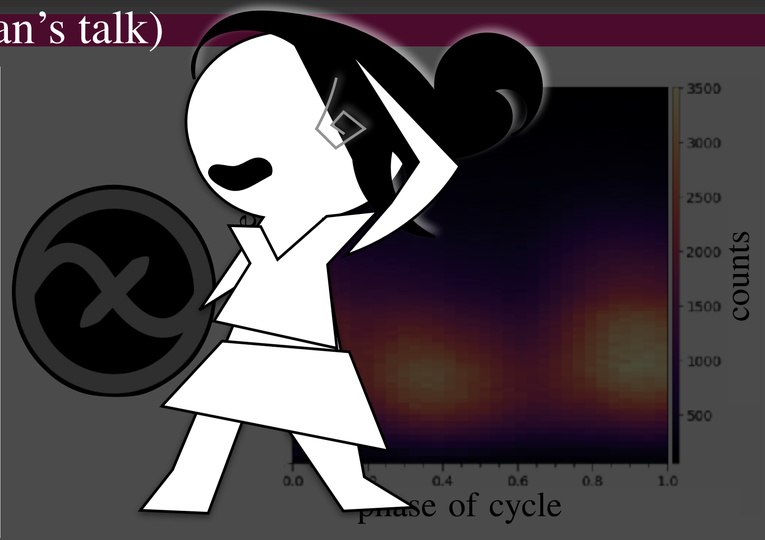


$\bar{d}$: data
$\bar{\theta}$: parameters
H : model

HOW IS THIS SIGNAL COMPUTED?

(Complementary details to Bas Dorsman's talk)



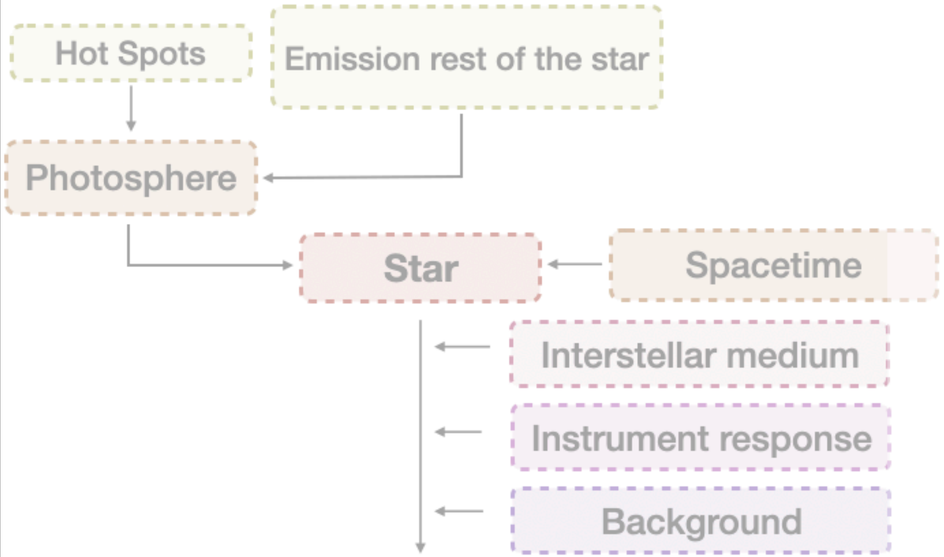


Open source code available @ https://github.com/xpsi-group/xpsi

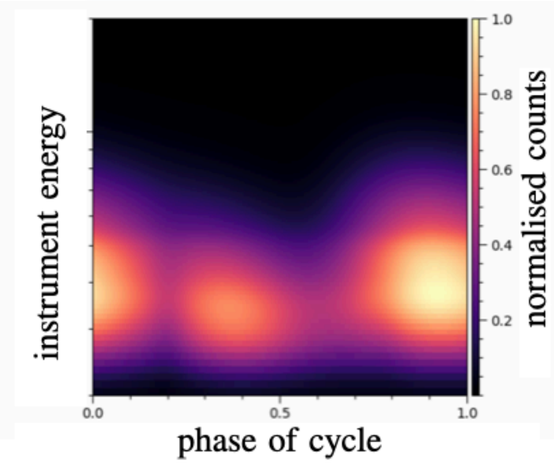
Riley et al 2023 (JOSS)

SIGNAL COMPUTATION

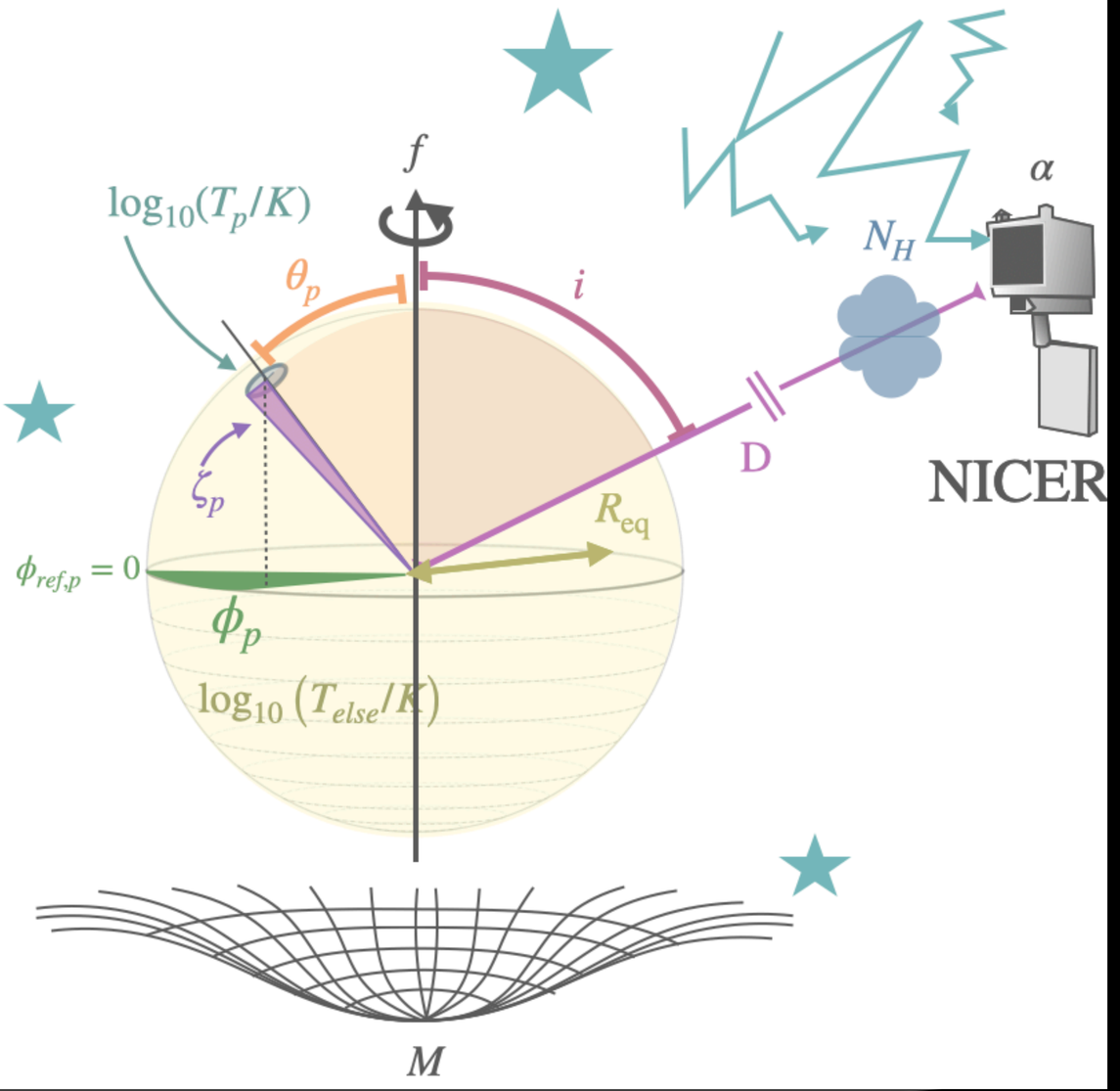
he modeling parameters



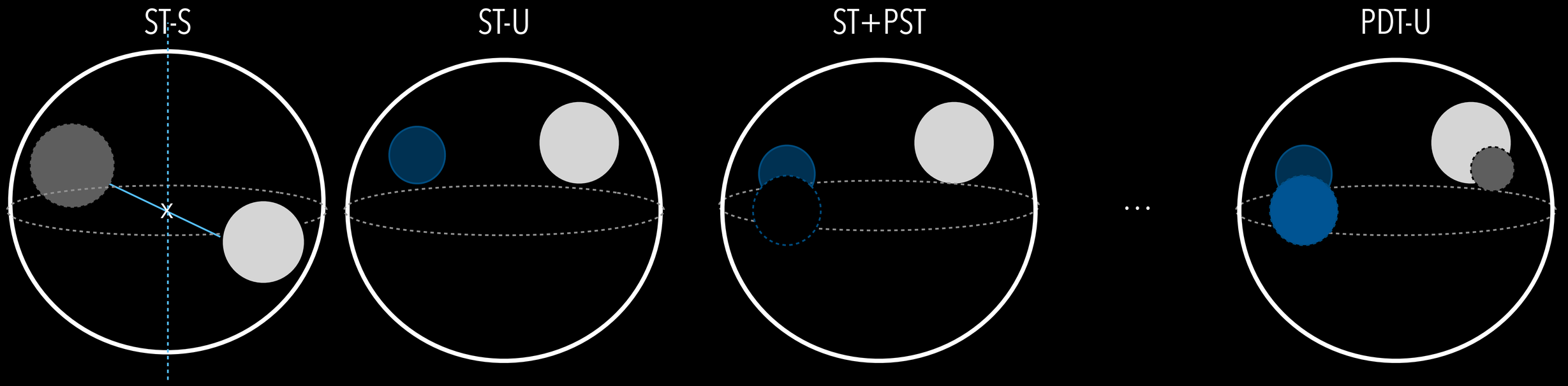
Mocked signal

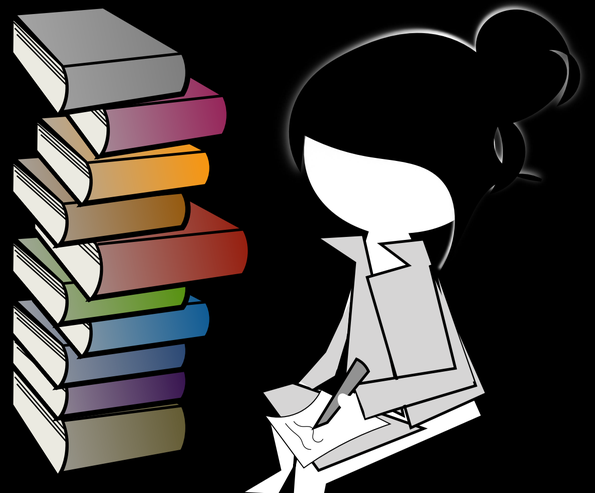


22



MODEL GENERATION X-PSI



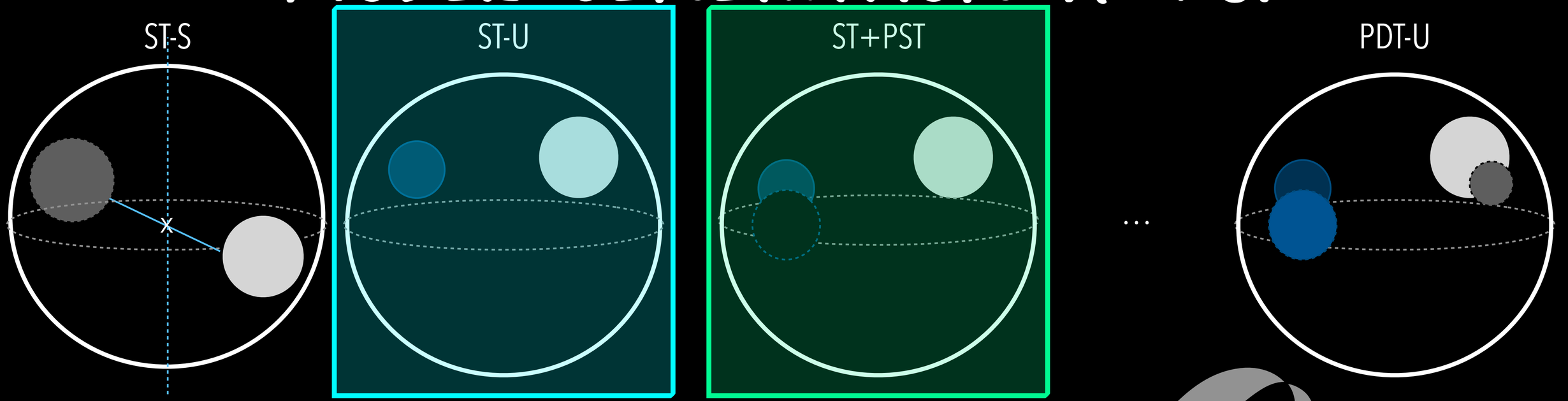


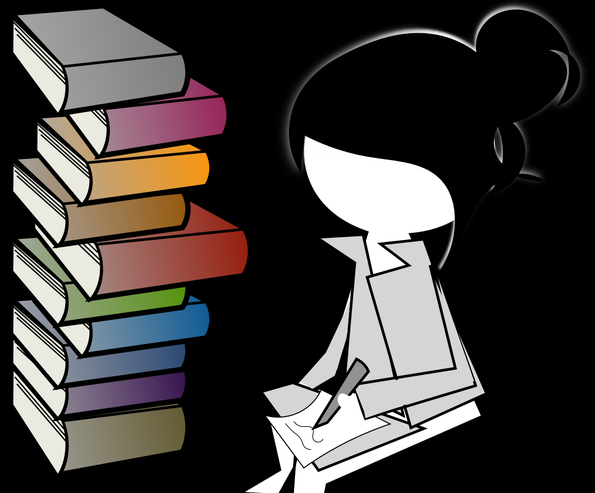
MODELS INSPIRED BY PULSAR THEORY

Harding & Muslimov 2011

ST	Single Temperature
DT	Double Temperature
C	Concentric
E	Eccentric
P	Protruding
-U	-Unshared
-S	-Shared

MODEL GENERATION X-PSI





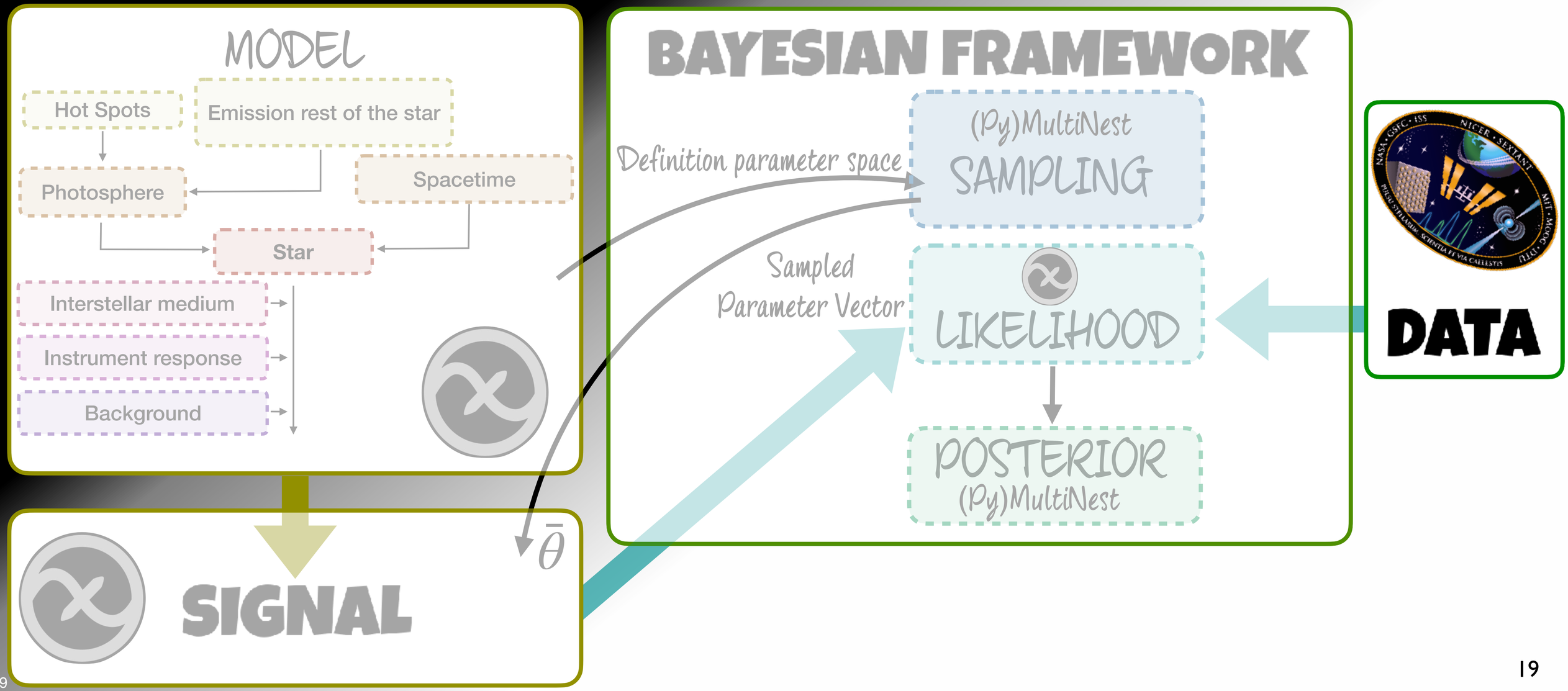
COMPLEXITY

MODELS INSPIRED BY PULSAR THEORY

Harding & Muslimov 2011

ST	Single Temperature
DT	Double Temperature
C	Concentric
E	Eccentric
P	Protruding
-U	-Unshared
-S	-Shared

UNCERTAINTIES



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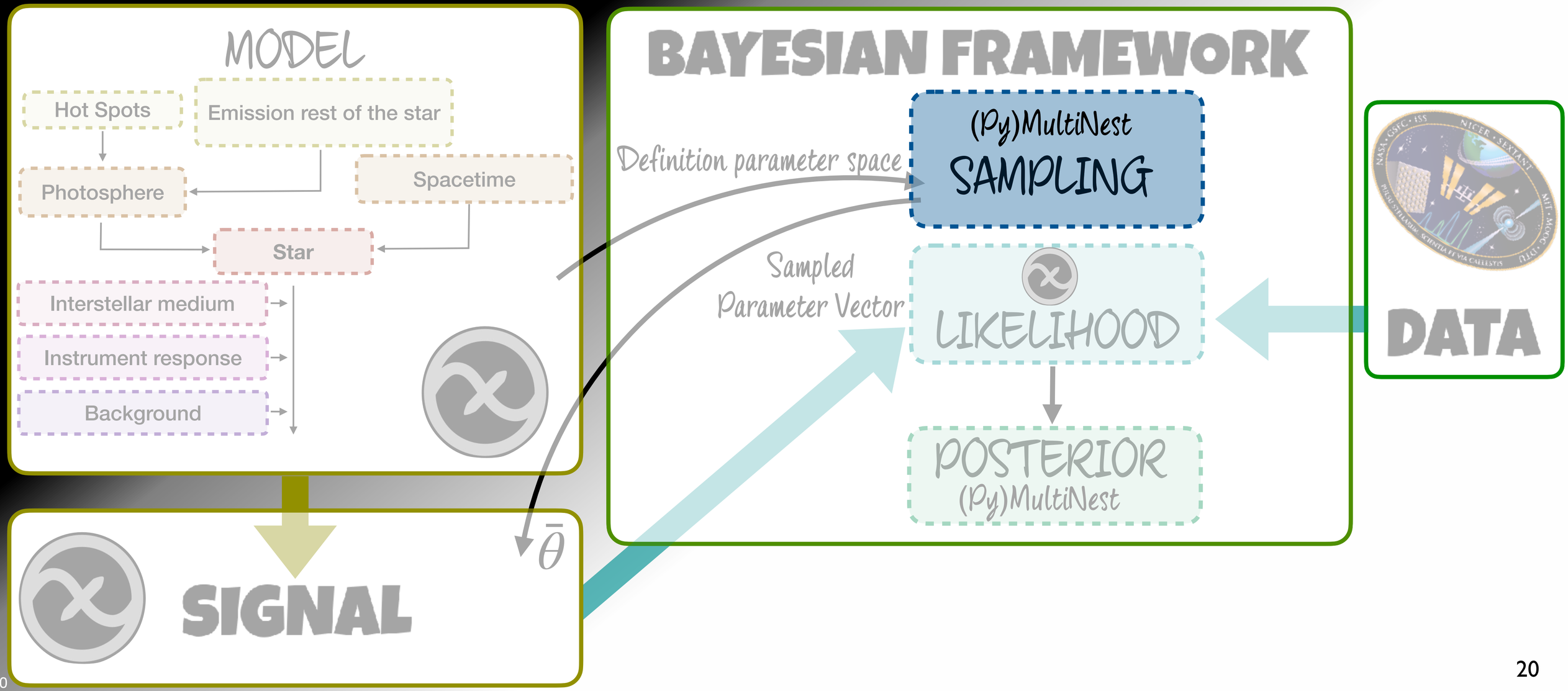
UNCERTAINTIES



20

UNCERTAINTIES

Assumptions, simplifications, approximations

Hot Spots

Emission rest of the star

Photosphere

Spacetime

Star

Interstellar medium

Instrument response

Background

SIGNAL

$\bar{\theta}$

BAYESIAN FRAMEWORK

Definition parameter space

(Py)MultiNest
SAMPLING

Sampled
Parameter Vector

LIKELIHOOD

POSTERIOR
(Py)MultiNest

DATA

21

UNCERTAINTIES

Assumptions, simplifications, approximations

Hot Spots

Emission re

Photosphere

Interstellar me

Instrument re

Background

SIGNAL

TEMPERATURE GRADIENTS?

MAGNETIC FIELD?

SURFACE PATTERNS ADEGUATE?

RESULTS ROBUST?

PRIORS?

WHICH ATMOSPHERE? (See Tuomo Salmi's talk)

RESULTS STABLE? Credible interval& solution?

SUFFICIENTLY EXPLORED PARAMETER SPACE? (I.e. are parameter settings adeguate?)

1-1 DATA TO MODEL PARAMETER SET?

IAN FRAMEWORK

(Py)MultiNest SAMPLING

KELIHOOD

STERIOR

(Py)MultiNest

DATA

22

UNCERTAINTIES

Assumptions, simplifications, approximations

Hot Spots

Emission rest of the star

Photosphere

Spacetime

Star

Interstellar medium

Instrument response

Backg

BAYESIAN

Definit

LIKELIHOOD

POSTERIOR

(Py)MultiNest

DATA

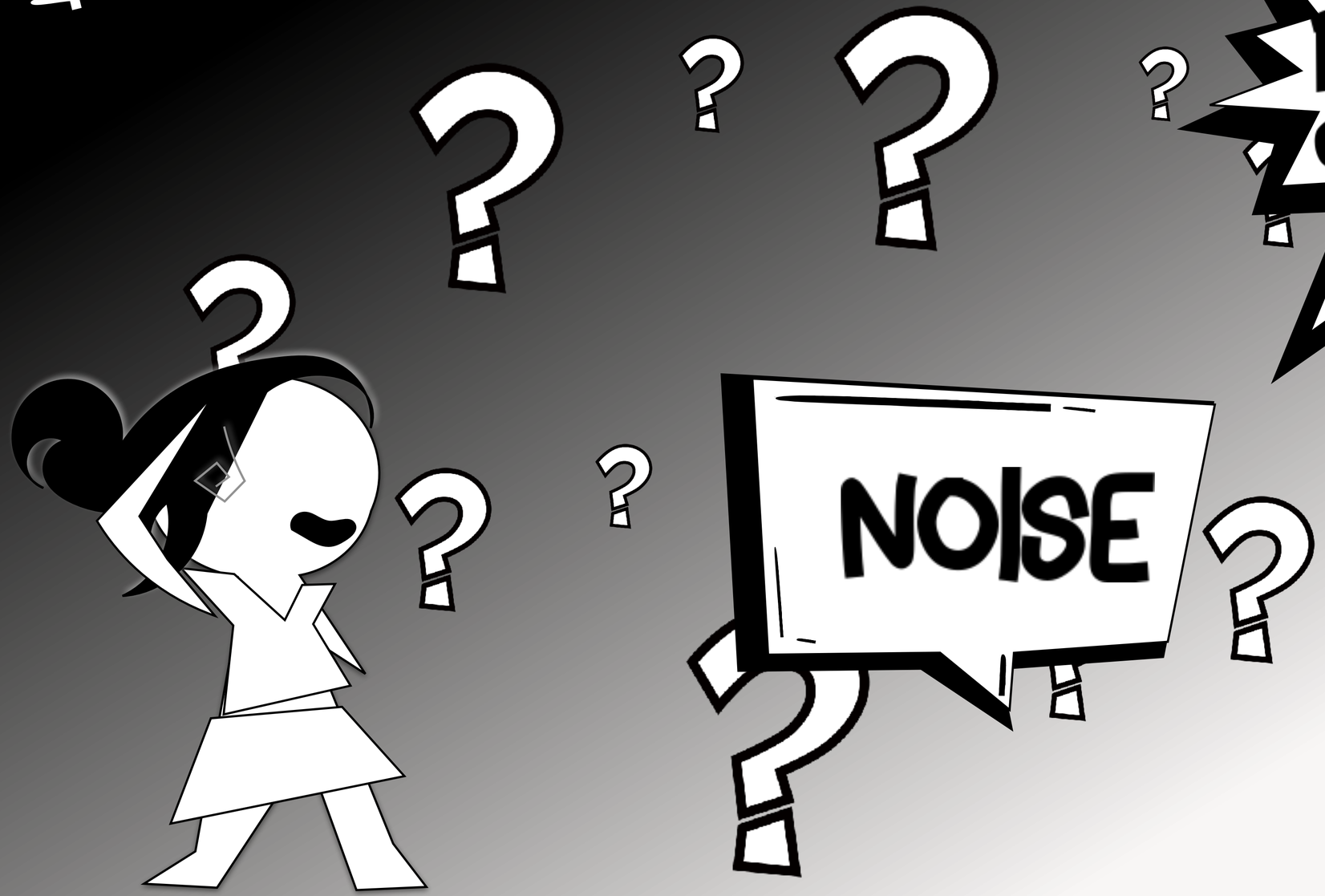
SIGNAL

$\vec{\theta}$

TESTING

23

QUESTIONS



Riley 2019, Bogdanov et al. 2019b, Bogdanov et al. 2021

J0030+0451

$f = 205\ Hz$

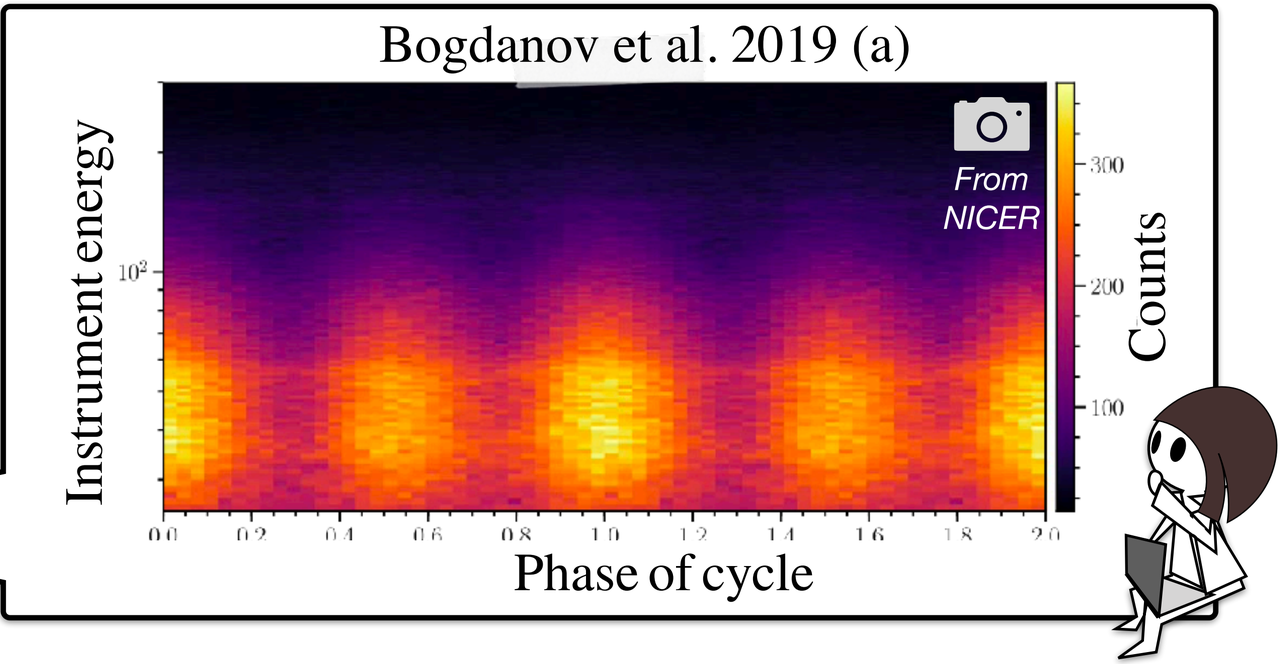
Arzoumanian et al. 2018

$D \sim 325 \pm 9\ pc$

$D \sim 329^{+6}_{-5}\ pc$

Ding et al. 2023

NICER



ISOLATED ⇨ No mass & inclination priors

J0030+0451

$f = 205\ Hz$

Arzoumanian et al. 2018

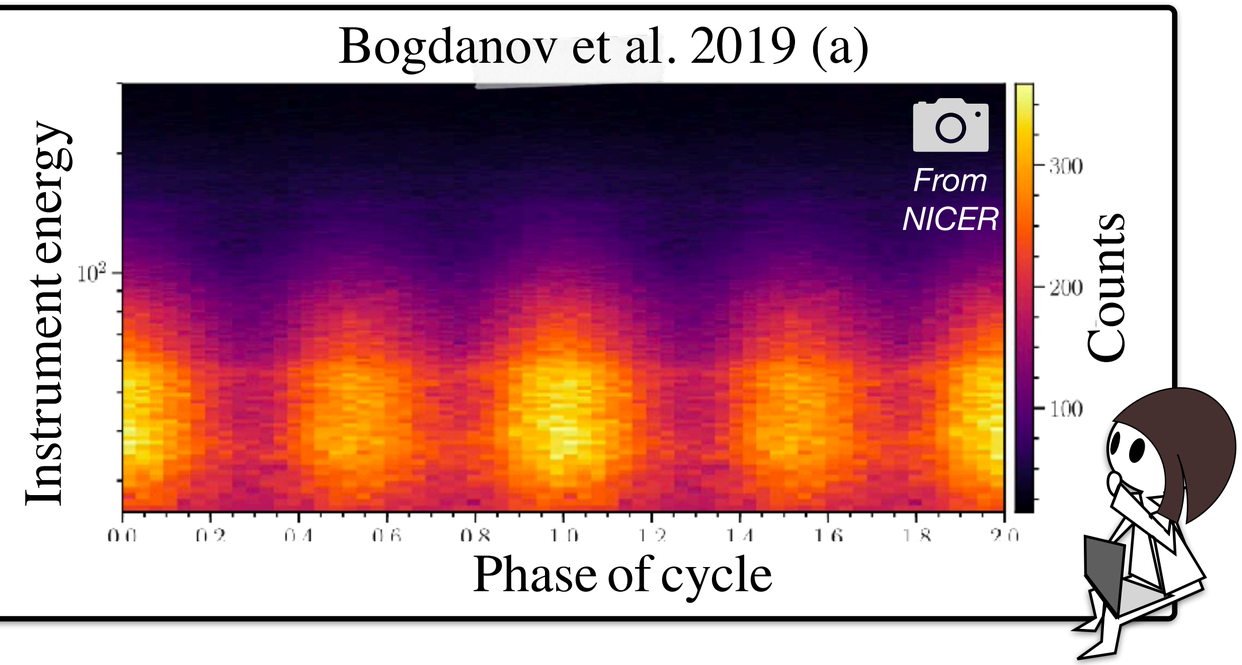
$D \sim 325 \pm 9\ pc$

$D \sim 329^{+6}_{-5}\ pc$

Ding et al. 2023

NICER

ISOLATED



	Model	Mass [M_{Sun}]	Radius [km]	Residuals Normalised difference between model&data
ST-U Single Temperature - Unshared		$1.09^{+0.11}_{-0.07}$	$10.44^{+1.10}_{-0.86}$	
ST+PST Single Temperature - Protruding Single Temperature		$1.34^{+0.15}_{-0.16}$	$12.71^{+1.14}_{-1.19}$	

Energy

Phase [cycle]

Riley et al 2019

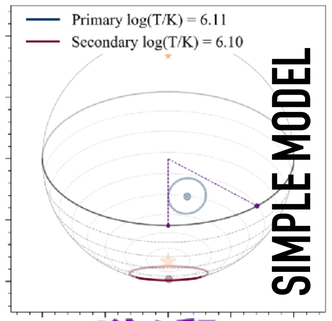
(Similar findings by Miller et al 2019)

SIMULATIONS

$M = 1.13 M_\odot$
$R = 10.20\,\mathrm{km}$

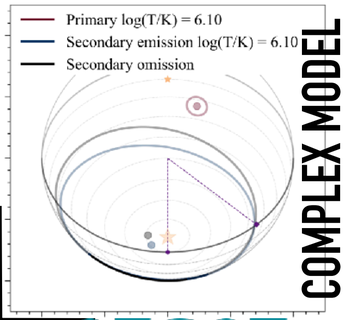
SIGNAL

$M = 1.33 M_\odot$
$R = 13.91\,\mathrm{km}$



SIMPLE MODEL

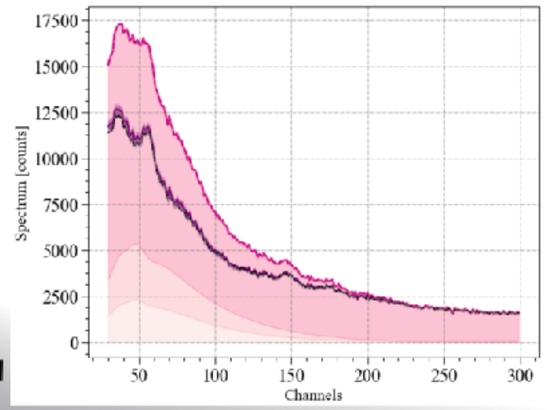
ST-U



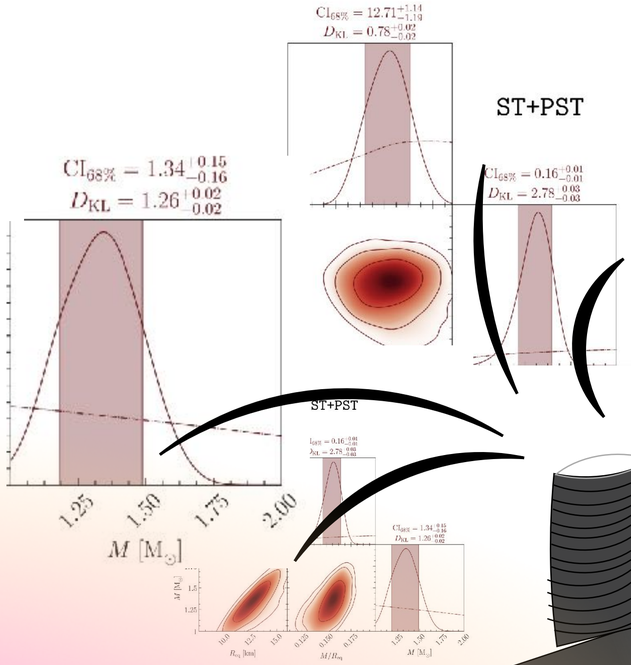
COMPLEX MODEL

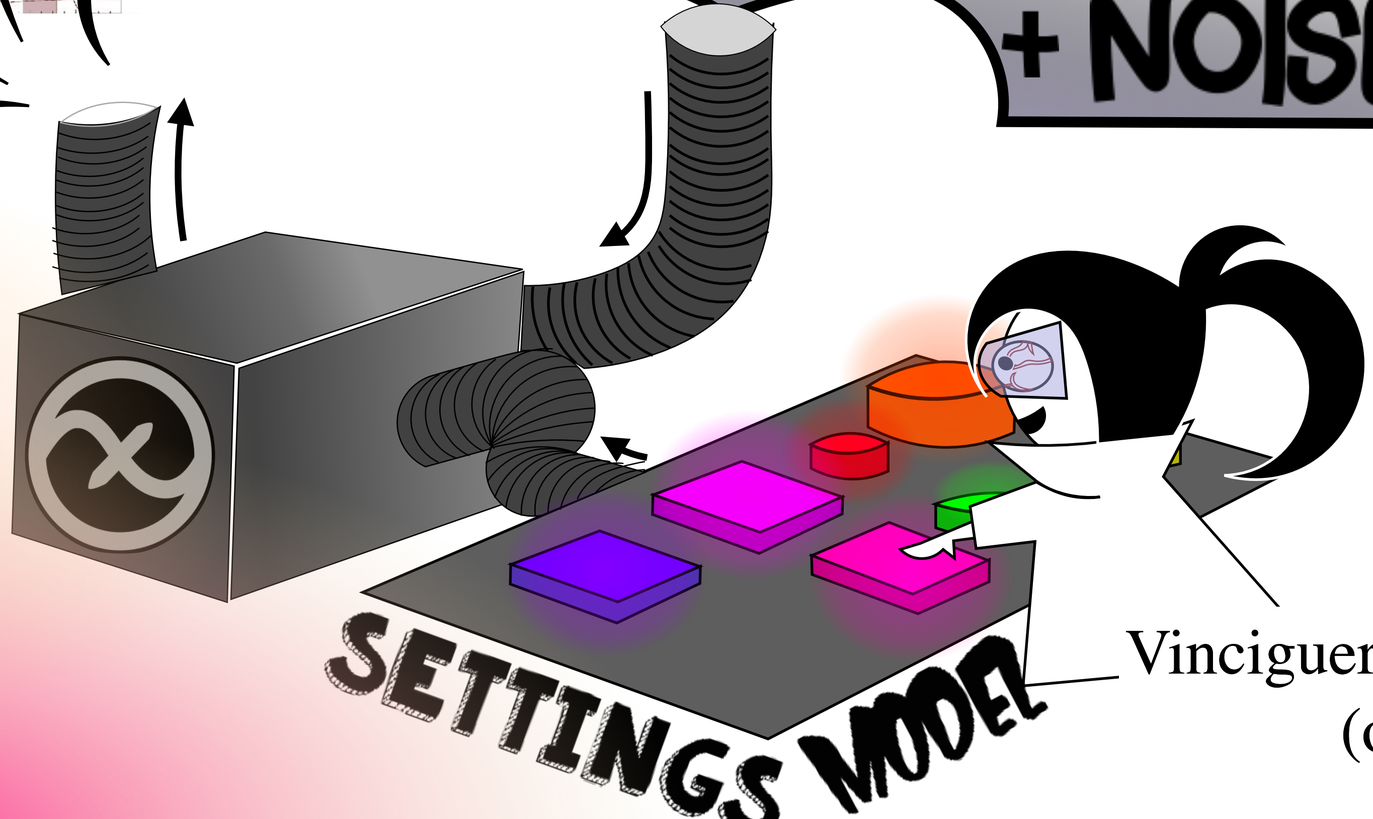
ST+PST

+ BACKGROUND



+ NOISE





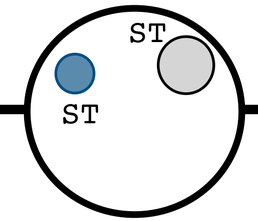
Vinciguerra et al 2023, submitted
(on arXiv soon!)

NOISE

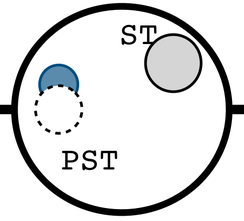
Vinciguerra et al 2023, submitted
(on arXiv soon!)

SIMPLE MODEL

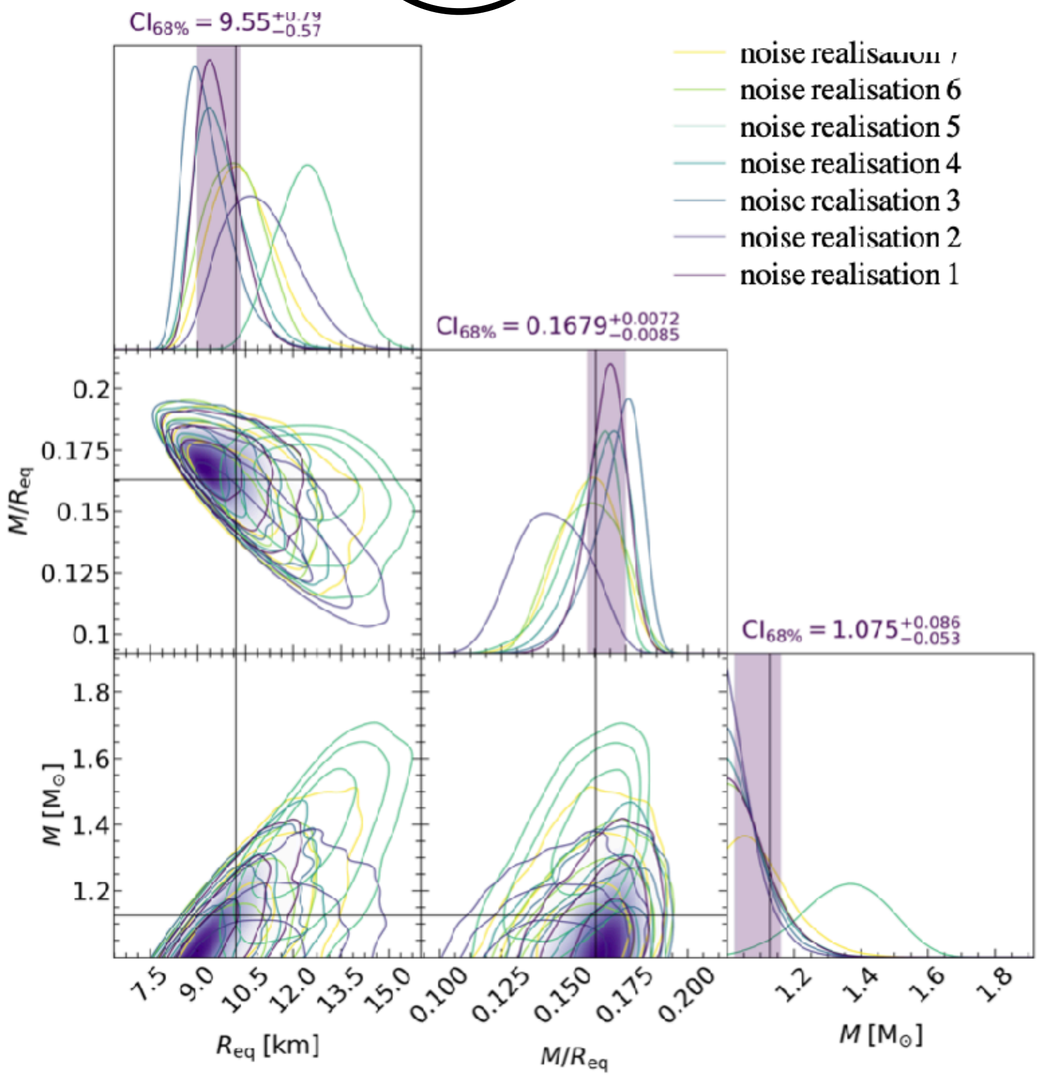
ST-U

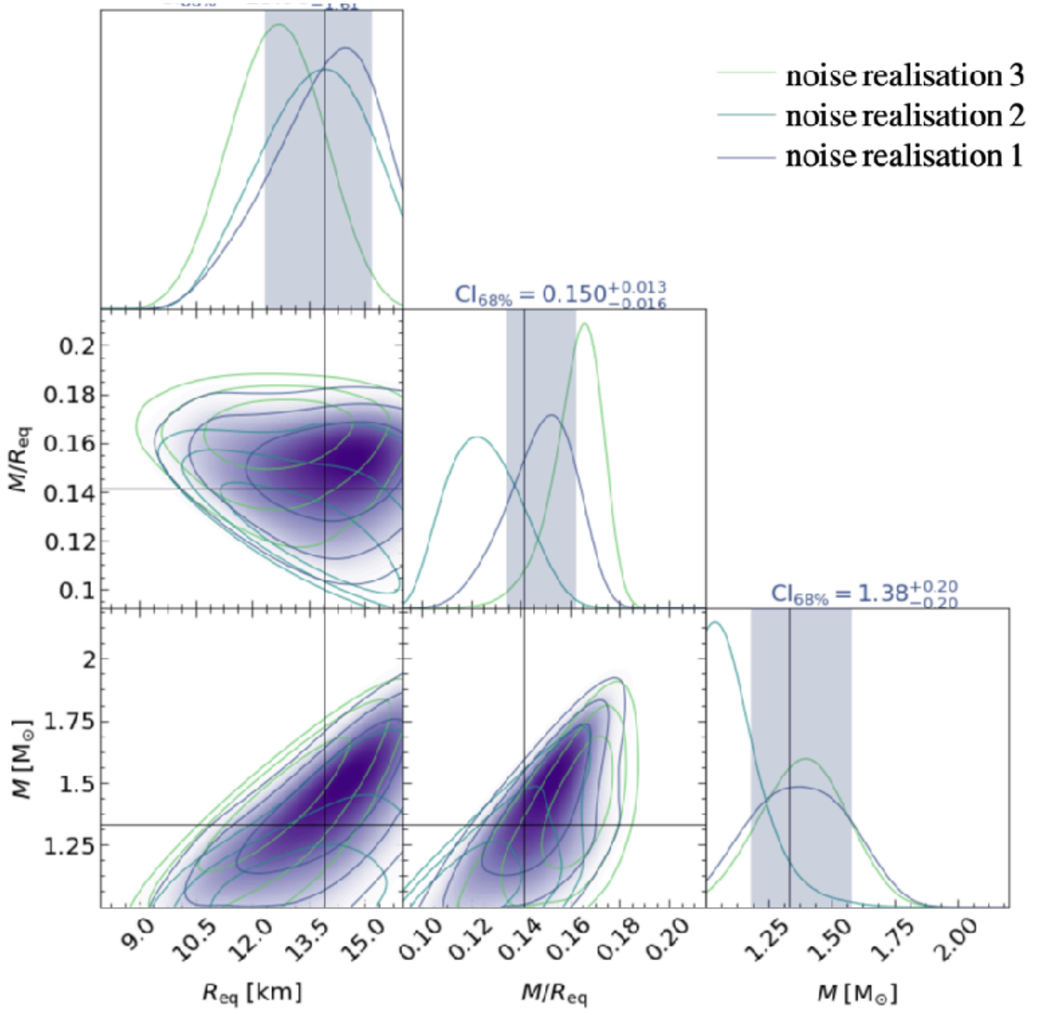


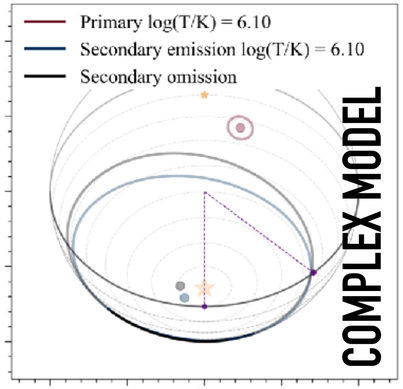
COMPLEX MODEL

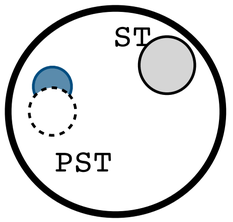


ST-PST



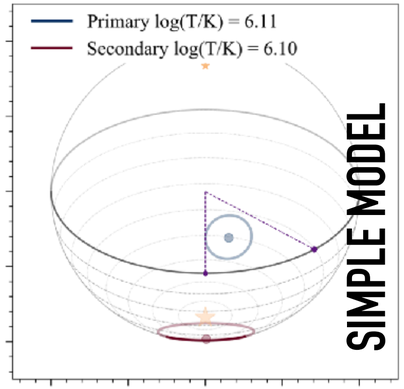






ST+PST ANALYSES

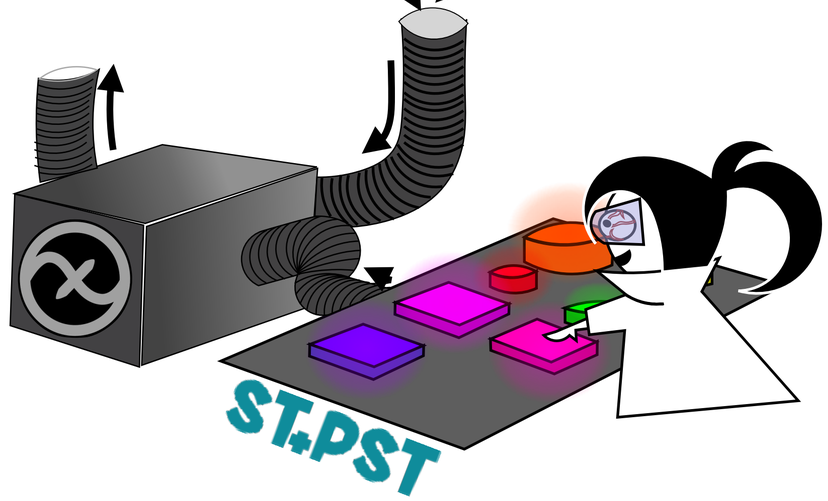
Vinciguerra et al 2023, submitted
(on arXiv soon!)

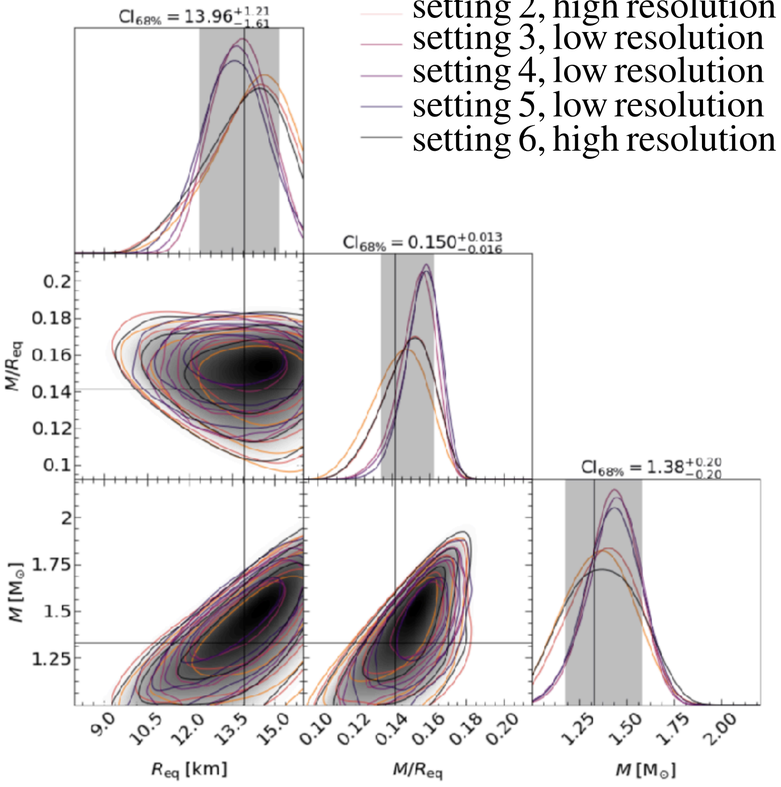


ST.PST

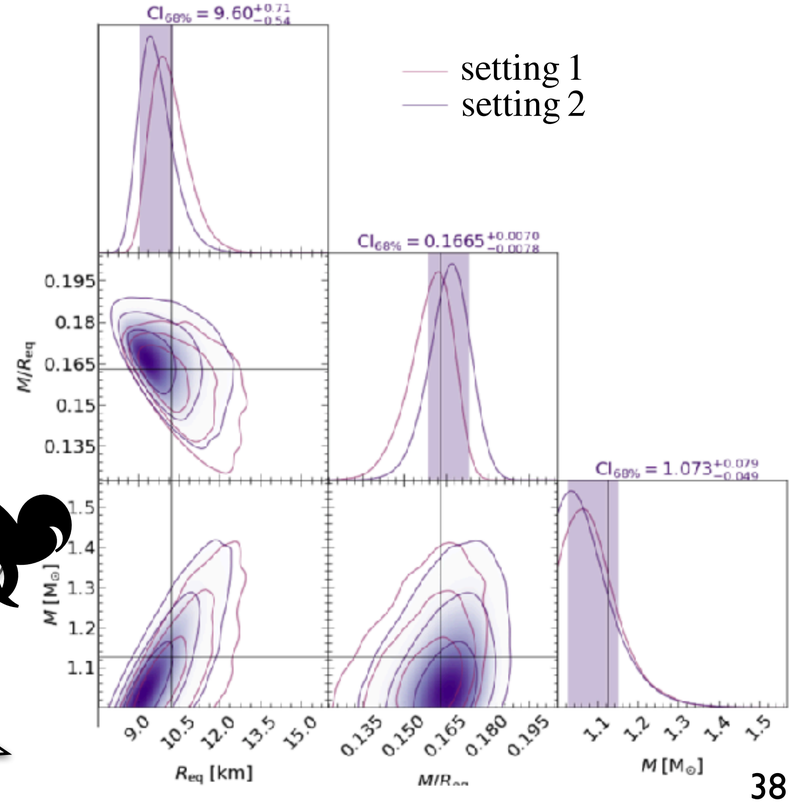
ST-U

setting 1, high resolution
setting 2, high resolution
setting 3, low resolution
setting 4, low resolution
setting 5, low resolution
setting 6, high resolution

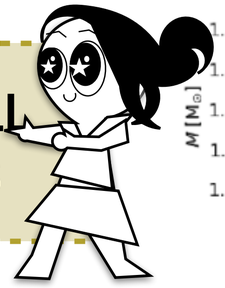


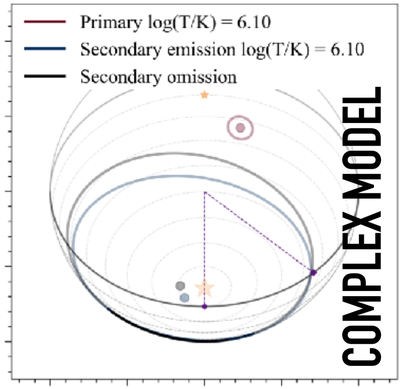


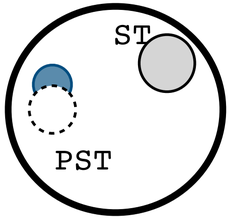
setting 1
setting 2



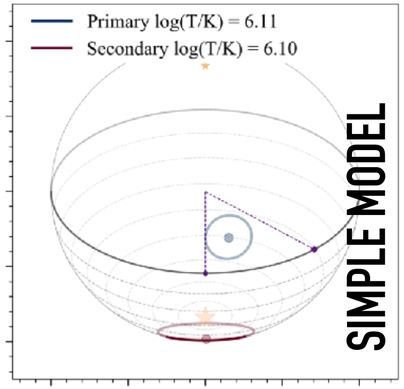
COMPLEX MODEL CAN STILL RECOVER MASS & RADIUS



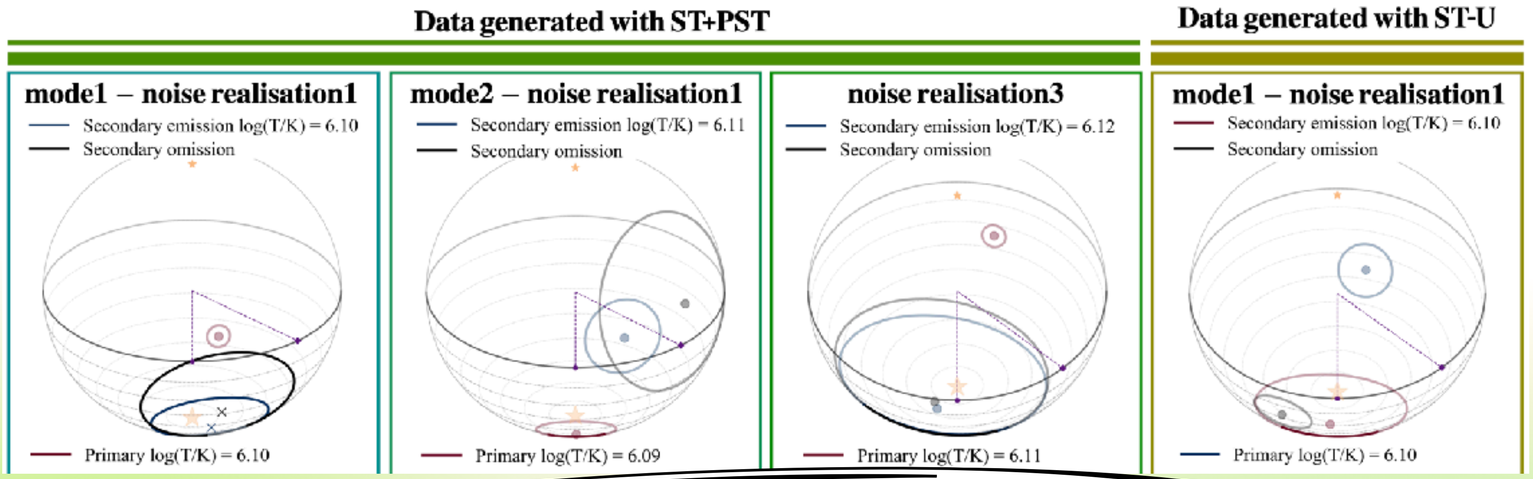




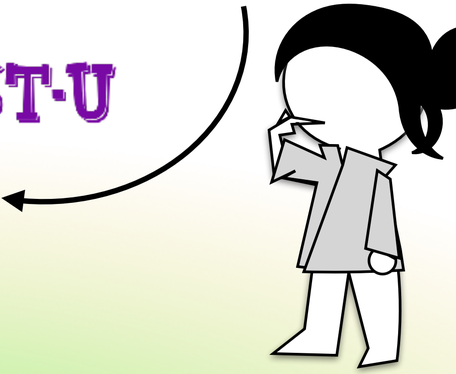
ST+PST ANALYSES

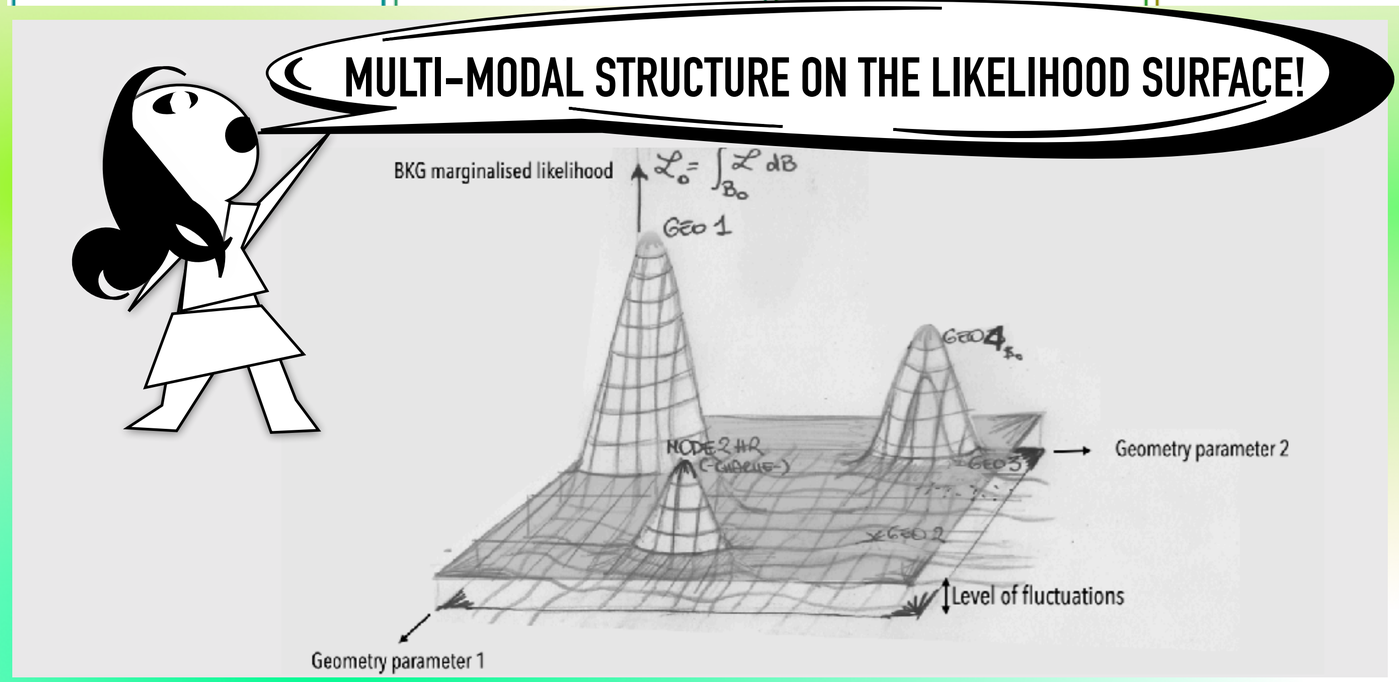


ST+PST



ST-U

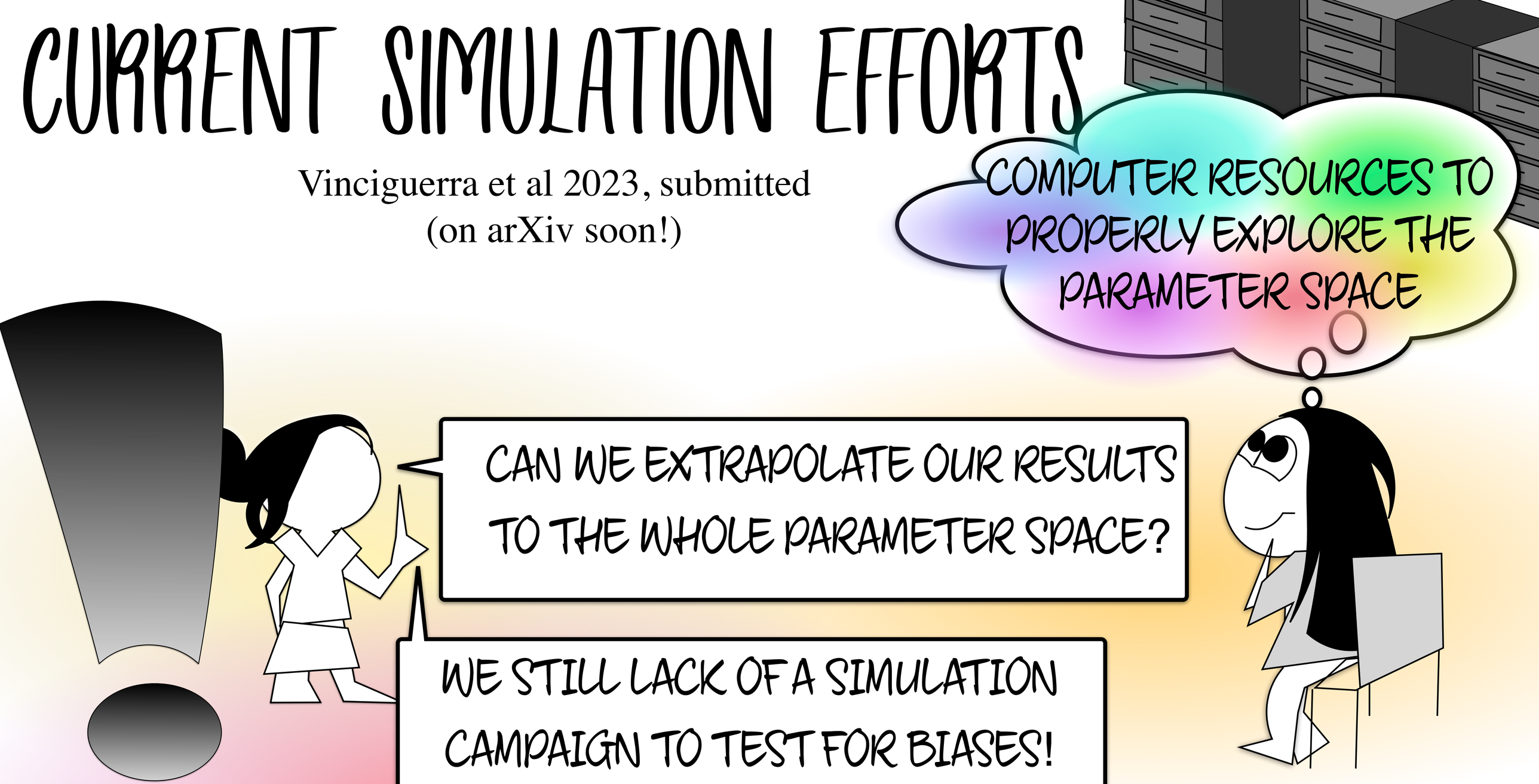




Vinciguerra et al 2023, submitted
(on arXiv soon!)

CURRENT SIMULATION EFFORTS

Vinciguerra et al 2023, submitted
(on arXiv soon!)

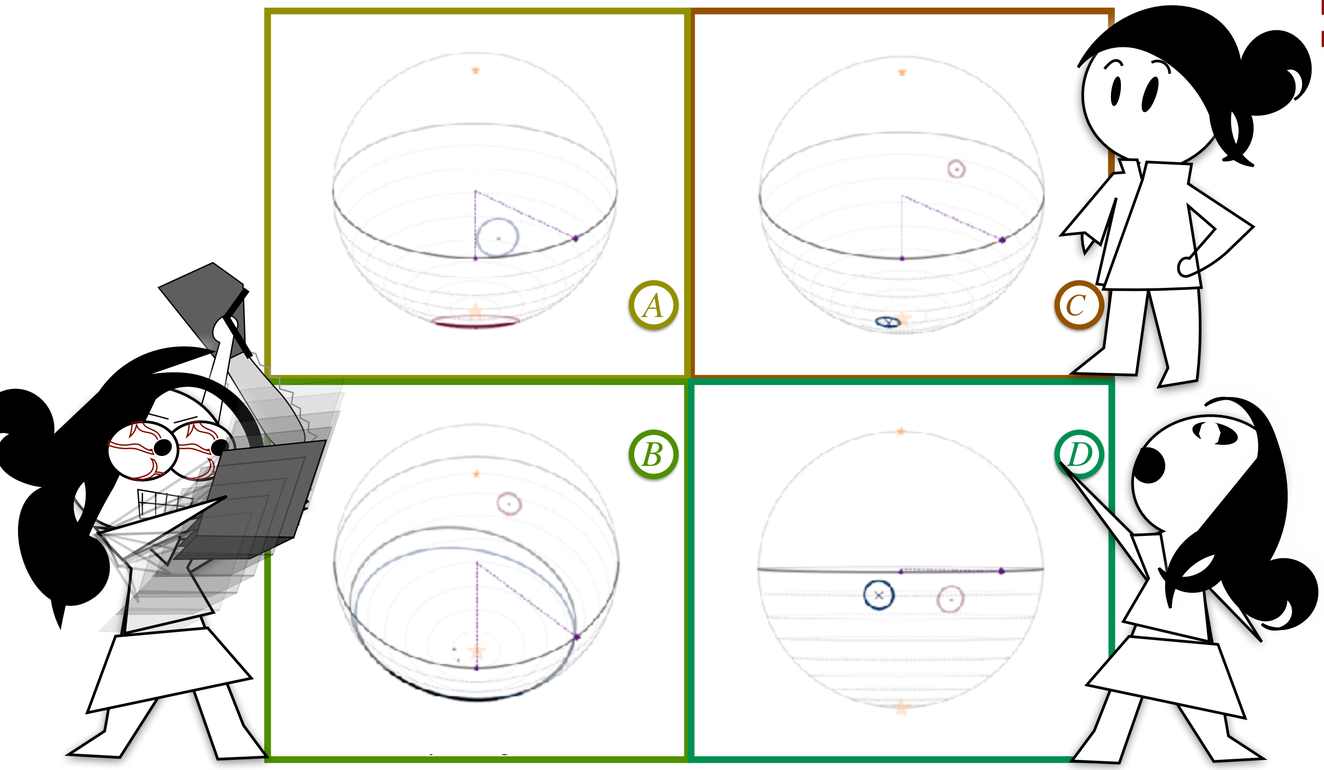


COMPARISONS WITH DATA

SIMILARITIES

GOOD RESIDUALS

MULTI-MODAL STRUCTURE!



DIFFERENCES

MODEL EVIDENCE DIFFERENCE

MASS AND RADIUS POSTERIORS DEPENDENCE ON THE MODEL

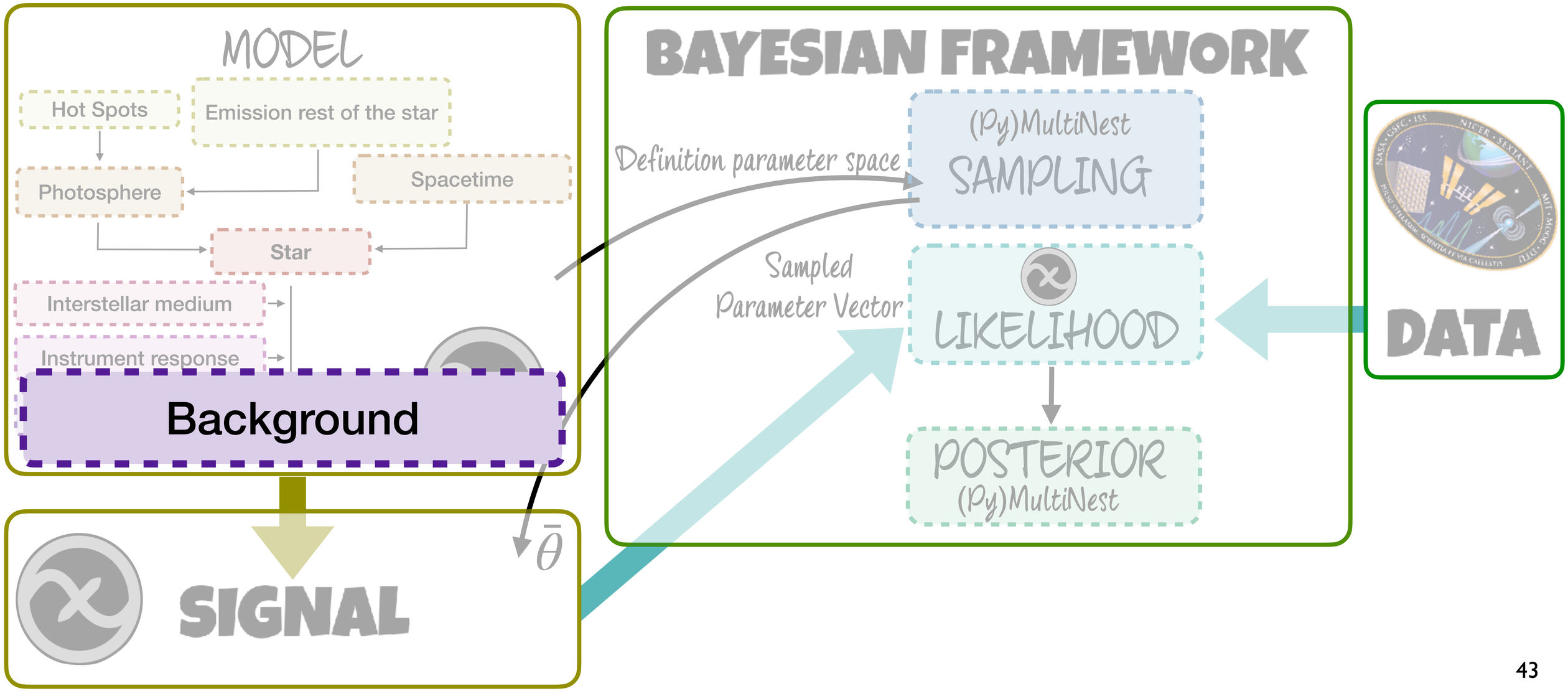
LIKELY REASONS:

MISSING PHYICS

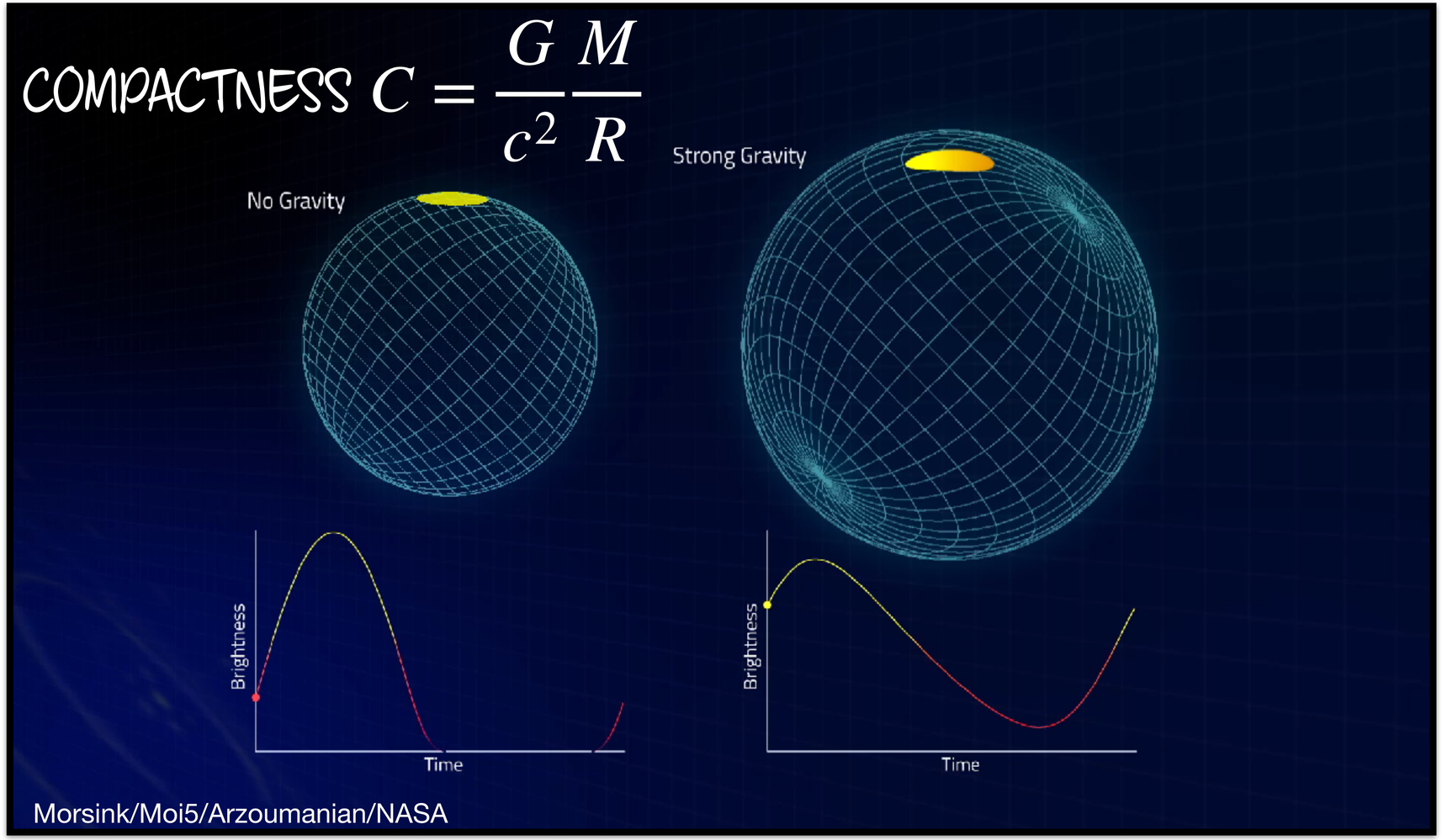
PARAMETER VECTORS

Vinciguerra et al 2023 submitted
Vinciguerra et al 2023 in prep.

UNCERTAINTIES

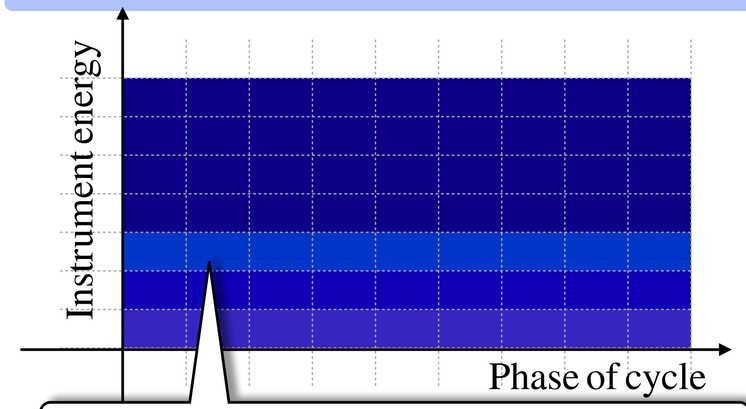


DEGENERACIES: BKG vs COMPACTNESS



BACKGROUND (BKG)

Sources of background can be: additional sources in the FoV, non-ideality of real instruments, space-weather, optical loading (the Sun), etc

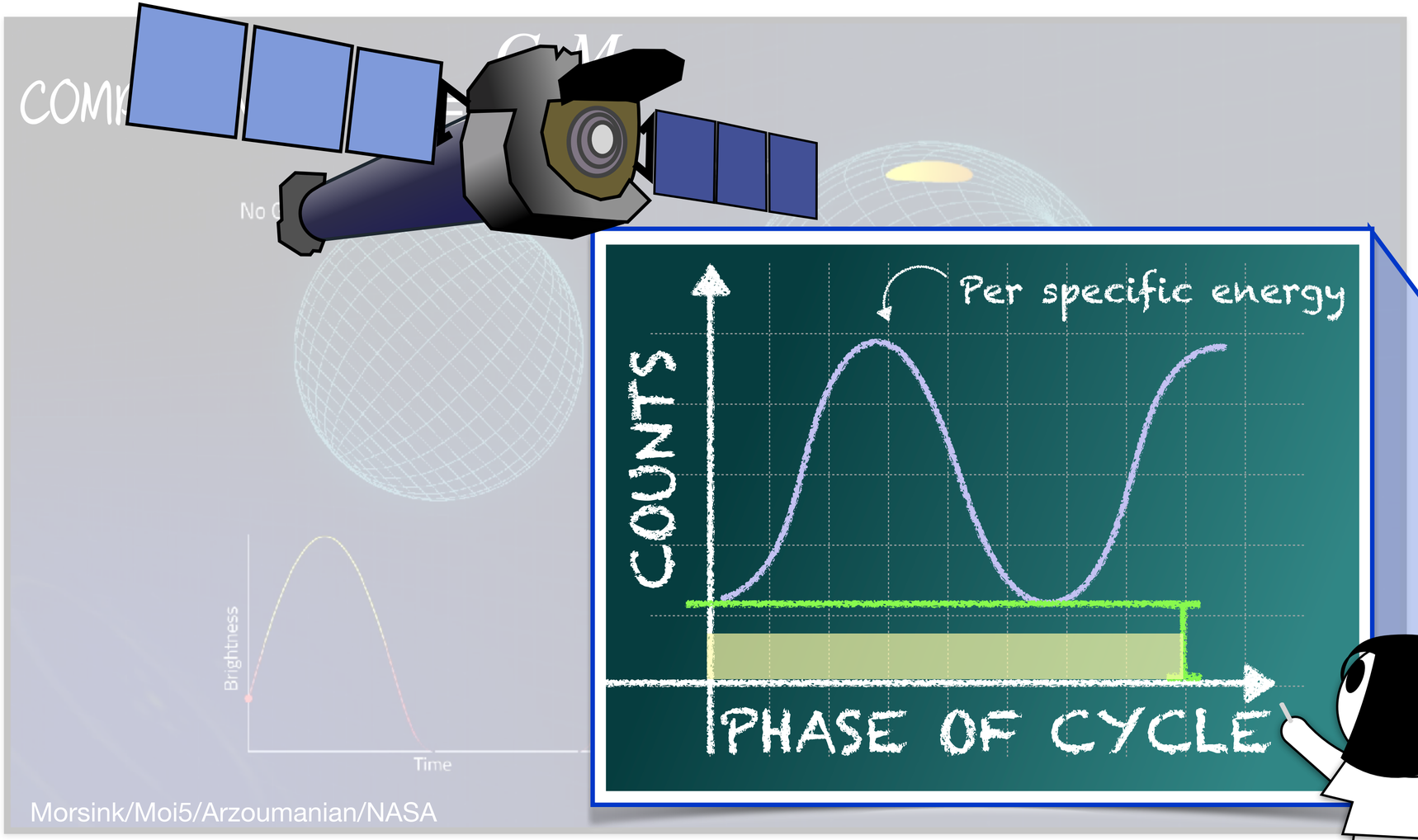


BKG MODEL:

With #of parameters = # of (considered) energy bands of the instrument. Independent from phase.

$$\mathscr{L} = \int_{\mathrm{BKG}} L \, d\mathrm{BKG}$$

DEGENERACIES: BKG vs COMPACTNESS



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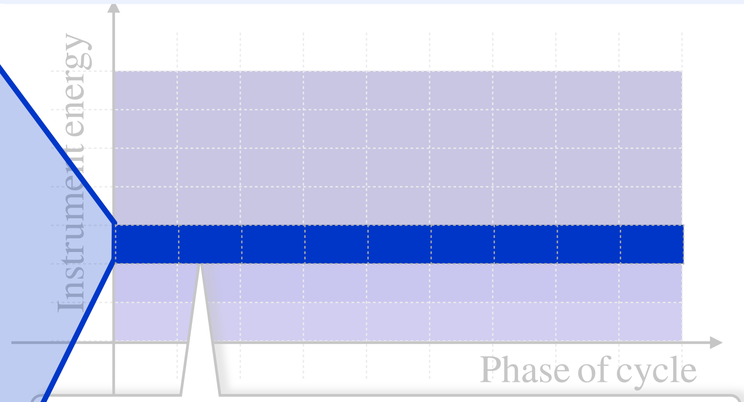
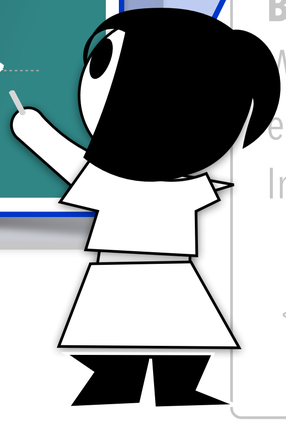




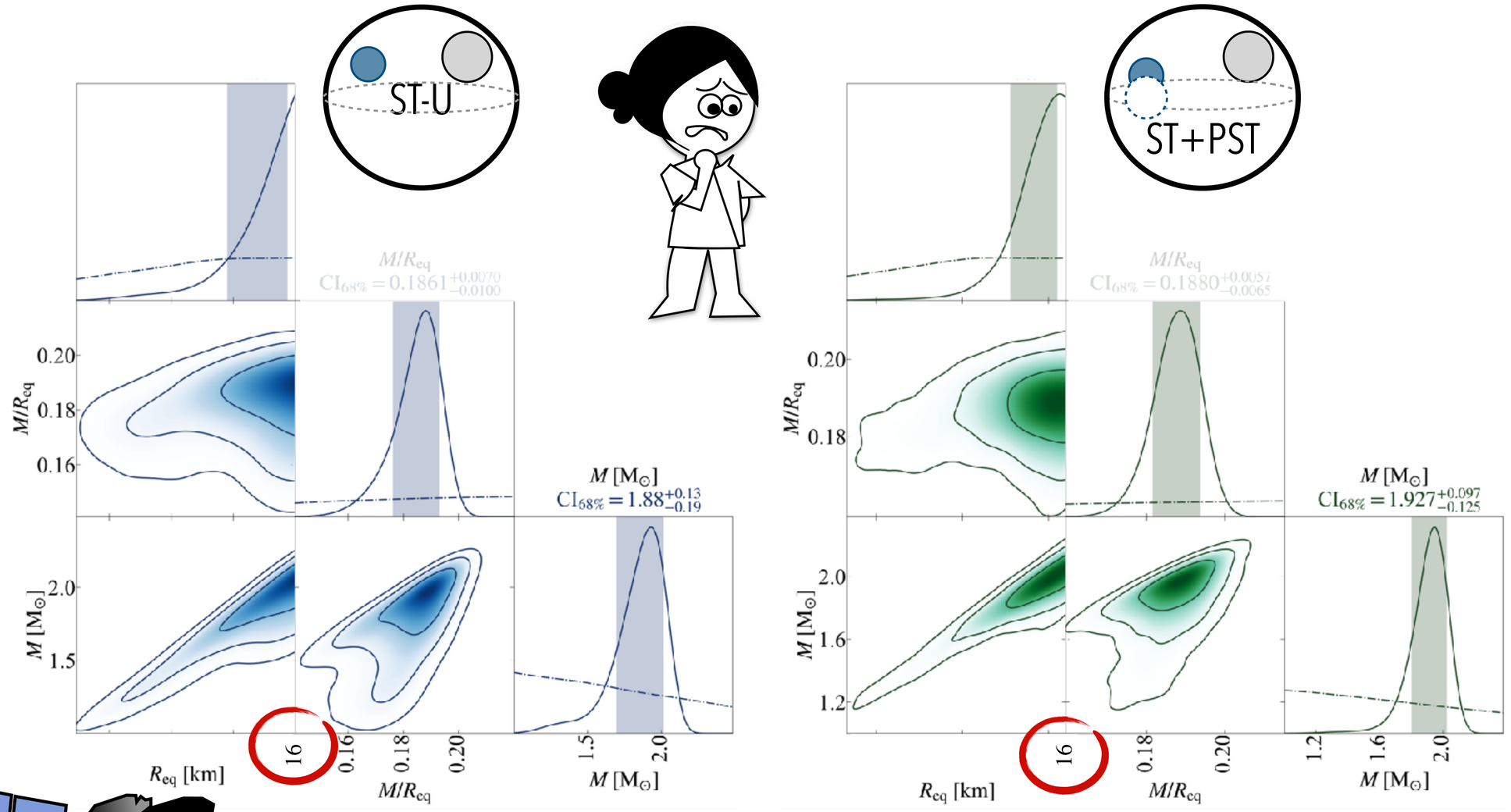
BKG MODEL:

With #of parameters = # of (considered) energy bands of the instrument. Independent from phase.

$$\mathscr{L} = \int_{\mathrm{BKG}} L \, d\mathrm{BKG}$$

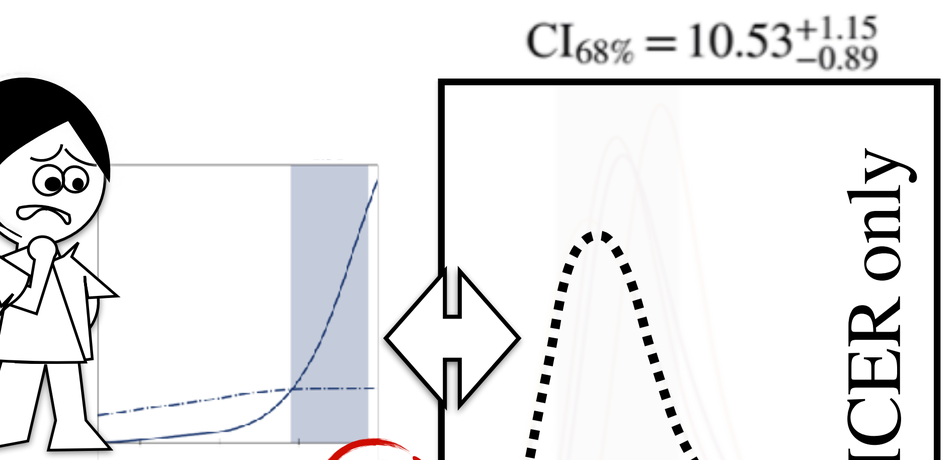
For J0740, Riley et al. 2021, Salmi et al 2022

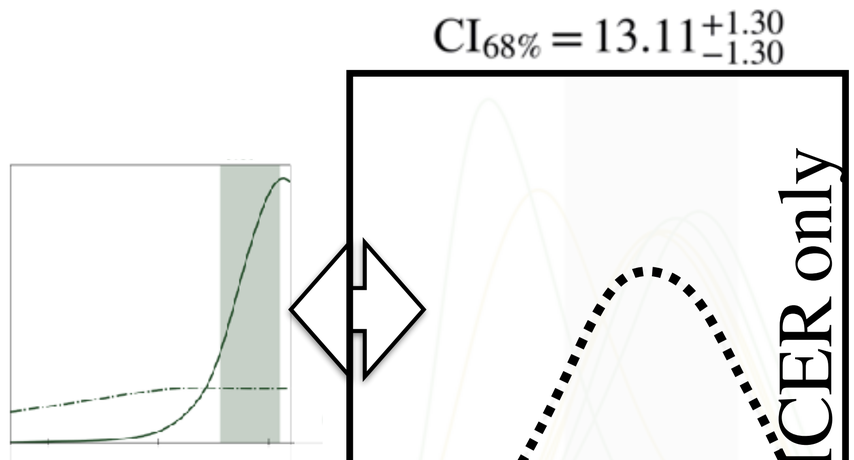
REAL DATA NICER & XMM-NEWTON

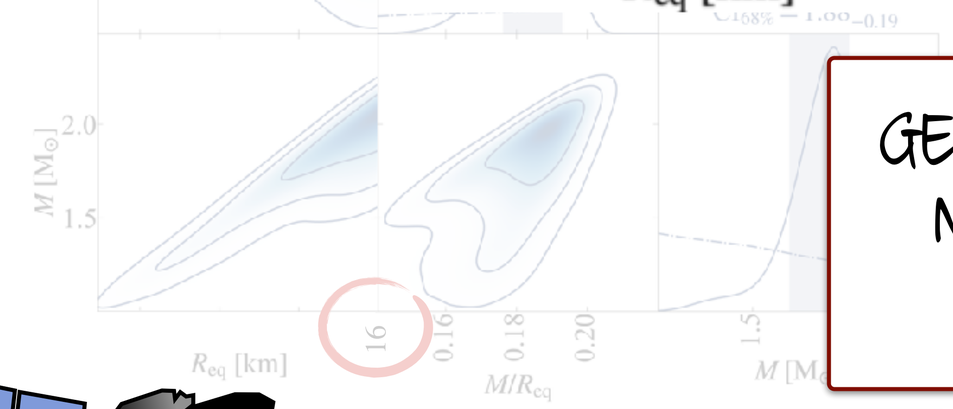


Vinciguerra et al 2023 in prep, through collaboration review

REAL DATA NICER & XMM-NEWTON



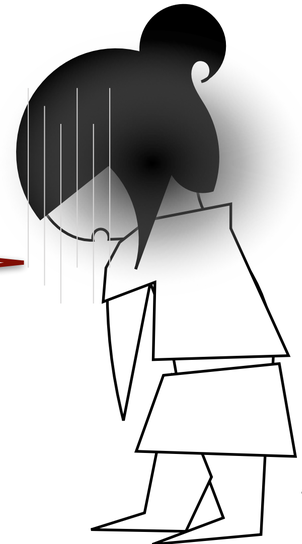




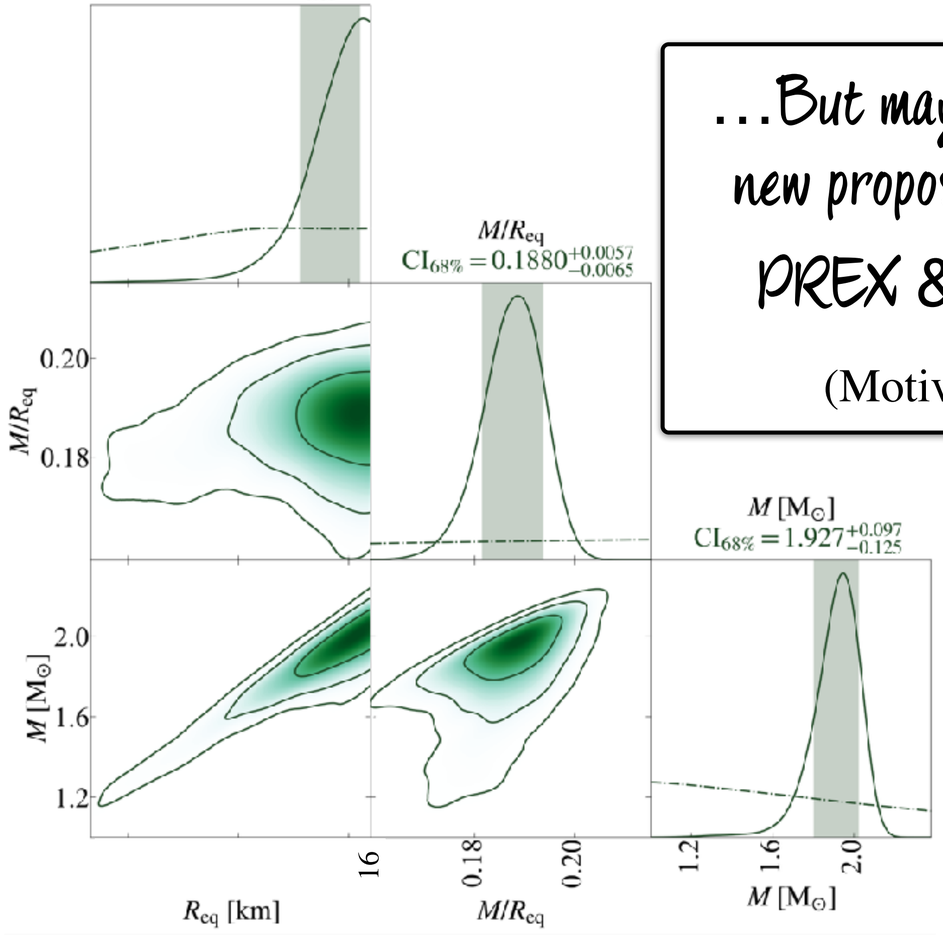
GENERAL SOLUTION COMPLETELY CHANGED!

New radius inference would be in tension with other observations!

Vinciguerra et al 2023 in prep, through collaboration review

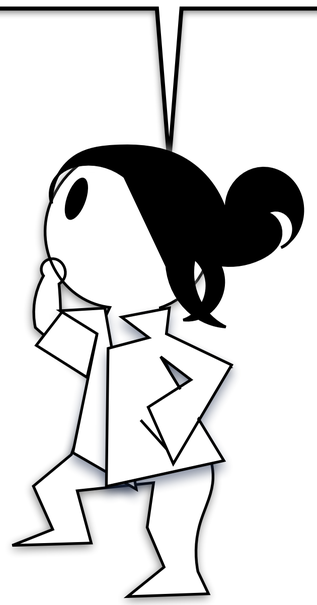


REAL DATA NICER & XMM-NEWTON



…But maybe in good agreement with new proposed models accommodating PREX & CREX measurements?

(Motivated by Brendan Reed's talk)



Vinciguerra et al 2023 in prep, through collaboration review

BUT . . . THERE ARE OTHER CARDS TO PLAY

Solutions even more compatible with gamma ray observations,

& much preferred (evidence)!

. . . COMING SOON!

Vinciguerra et al 2023 in prep, through collaboration review

SUMMARY AND CONCLUSIONS

RECOVERED M&R FOR COMPLEX MODEL!
IS THIS RESULT GENERAL?

A LOT OF <u>POSSIBLE</u> SYSTEMATICS

REPRODUCED RESULTS OF
RILEY ET AL. 2019 (X-PSI for J0030)

THINGS DRASTICALLY CHANGE ONCE
XMM-NEWTON DATA IS INTRODUCED

MORE COMPLEX MODEL ARE NEEDED &
SEEM ADEQUATE
(Vinciguerra et al 2023 in prep., coming soon)

LIKELIHOOD SURFACE: MULTI-MODAL

Possible solutions

MANY MORE SIMULATIONS TO PROPERLY TEST OUR CODE
(Necessary to lower computational costs)

CONSTRAINTS OBSERVATIONAL OR THEORETICAL SUPER-USEFUL
(More background also coming!)

ADD FURTHER OBSERVABLES (e.g. explain gamma rays at the same time)

USE MORE INFORMED PRIORS

UNIVERSITY OF AMSTERDAM

AEONS

NWO

Thank you

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