NICER analysis and NICER updates on J0030 & J0740 using X-PSI

NEUTRON STAR INTERIOR COMPOSITION EXPLORER

s.vinciguerra@uva.nl

-Serena Vinciguerra

IN COLLABORATION WITH:

Tuomo Salmi, Devarshi Choudhury, Thomas E. Riley, Anna L. Watts,
Ronald A. Remilliard, Paul S. Ray , Sebastian Guillot,
Slavko Bogdanov
+ other members of LCWG of NICER

OUTLINE

- INTRODUCTION to PPM/X-PSI
  - MASS-RADIUS AND EOS
  - PULSE PROFILE MODELLING
  - X-PSI AND ITS MODELS
- PUBLISHED RESULTS
  - J0030
  - J0740
- UPDATED ANALYSIS J0030
- LATEST RESULTS
  - NEW DATA SETS
  - PRELIMINARY ANALYSES J0030
  - RESULTS J0740
- CONCLUSIONS

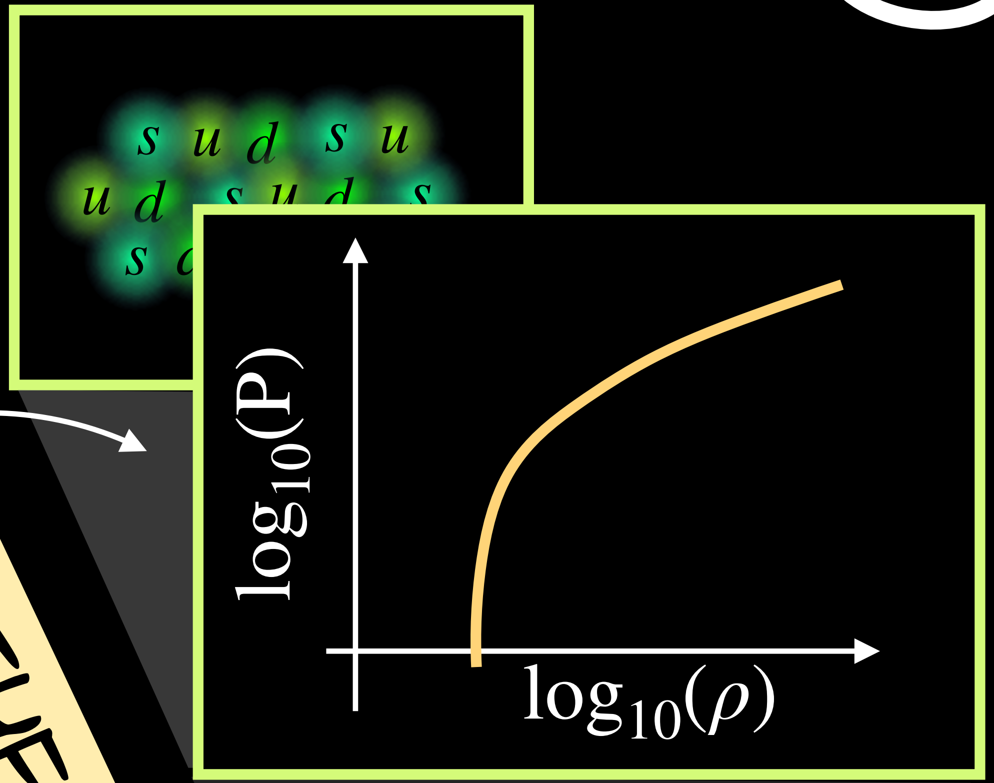
FROM MASS & RADIUS TO DENSE MATTER

FROM MASS & RADIUS TO DENSE MATTER

PROPOSED COMPOSITION

PARTICLE INTERACTIONS

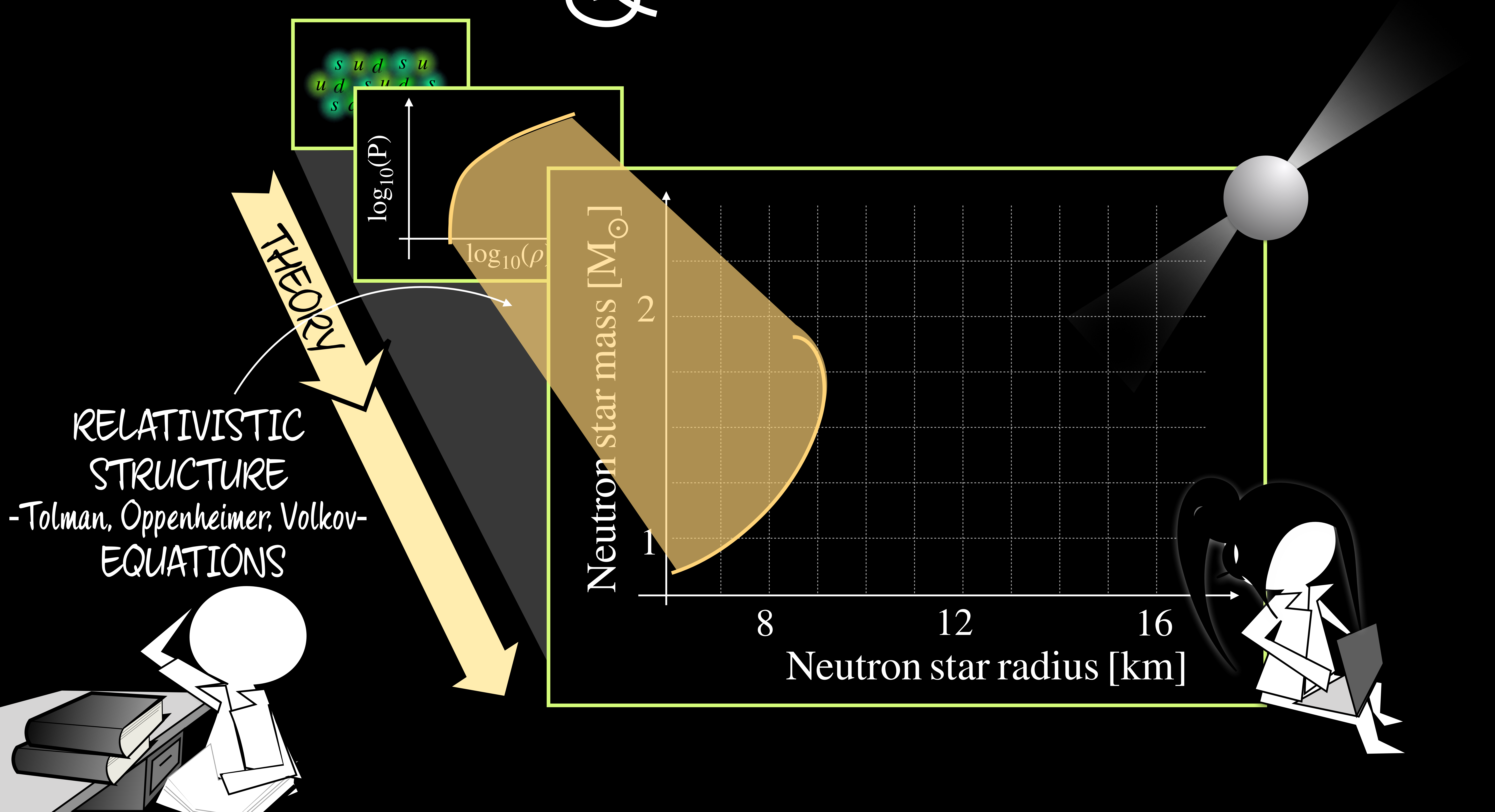
THEORY



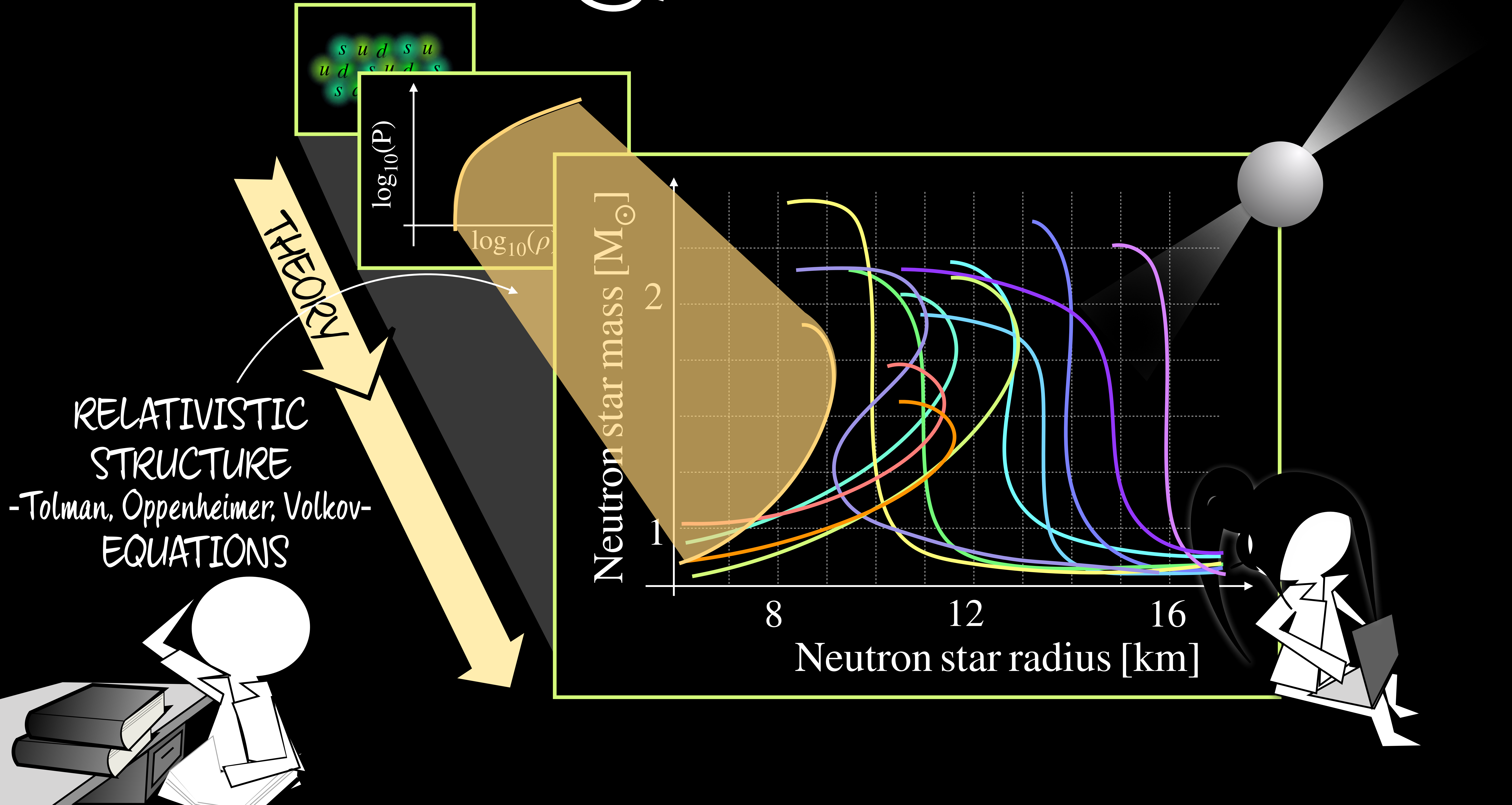
$\stackrel{\text{def}}{=}$ EQUATION OF STATE

(for cold, highly dense matter)

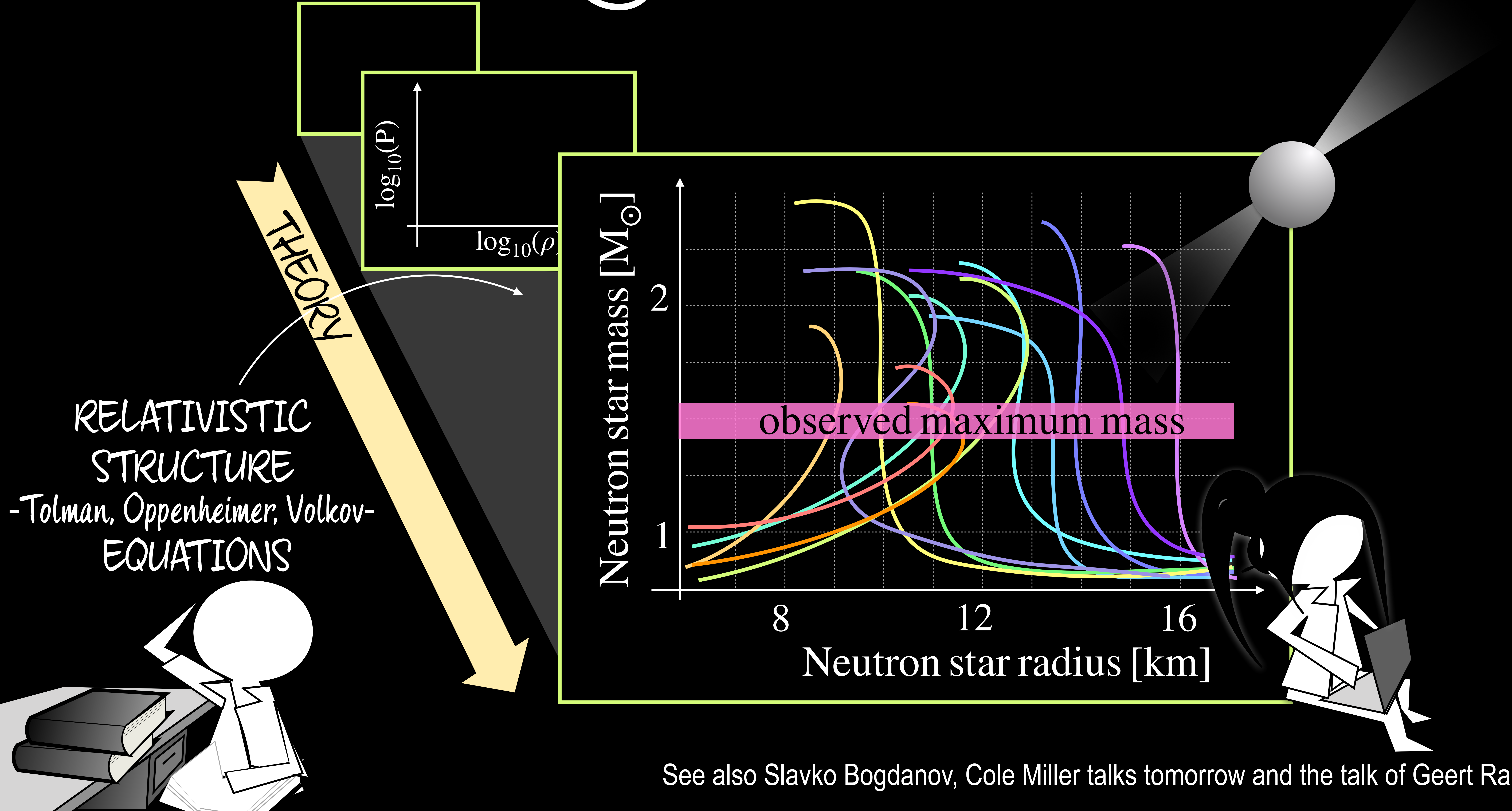
FROM MASS & RADIUS TO DENSE MATTER



FROM MASS & RADIUS TO DENSE MATTER

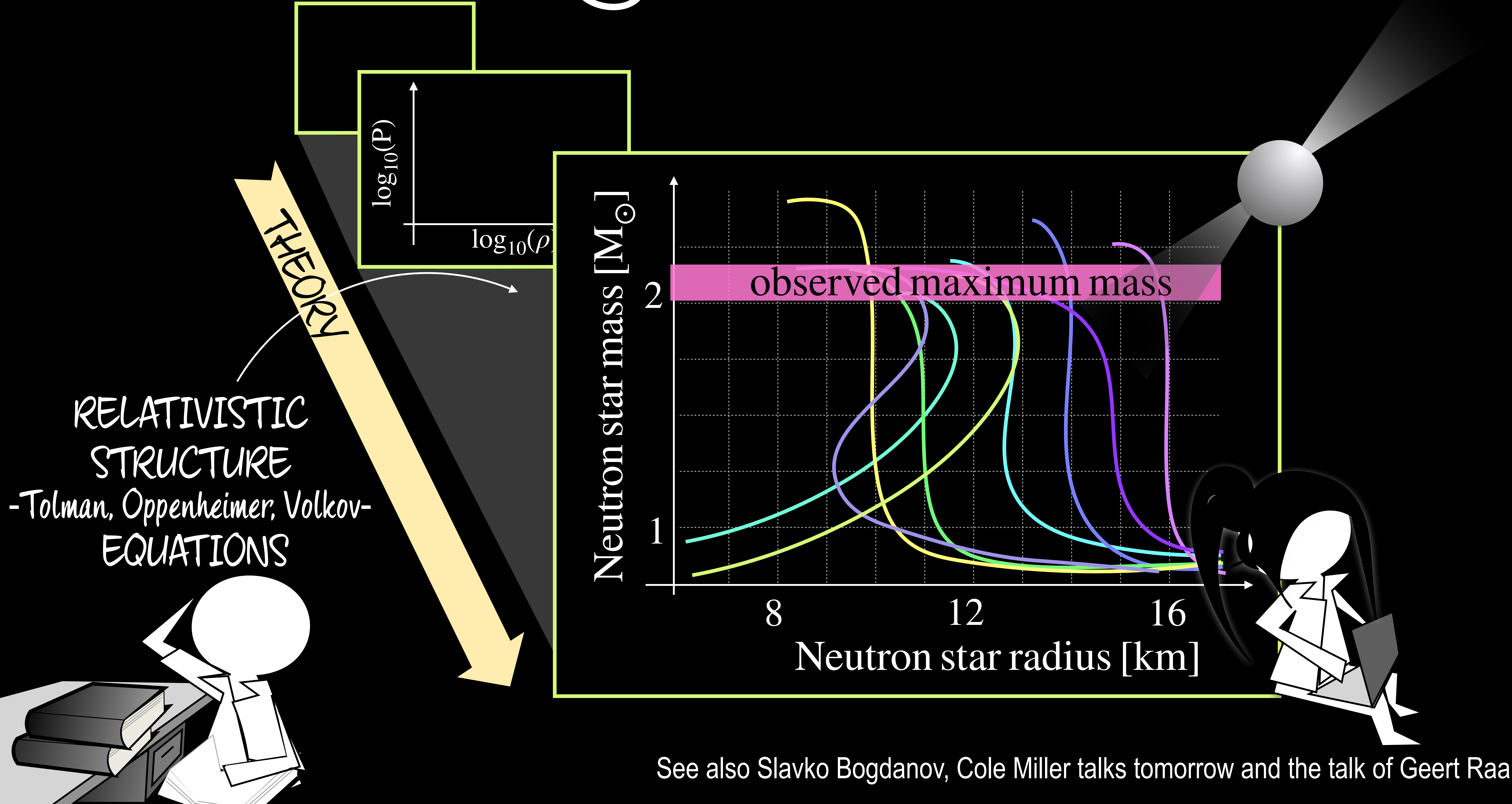


FROM MASS & RADIUS TO DENSE MATTER



See also Slavko Bogdanov, Cole Miller talks tomorrow and the talk of Geert Raaijmakers on Thursday

FROM MASS & RADIUS TO DENSE MATTER



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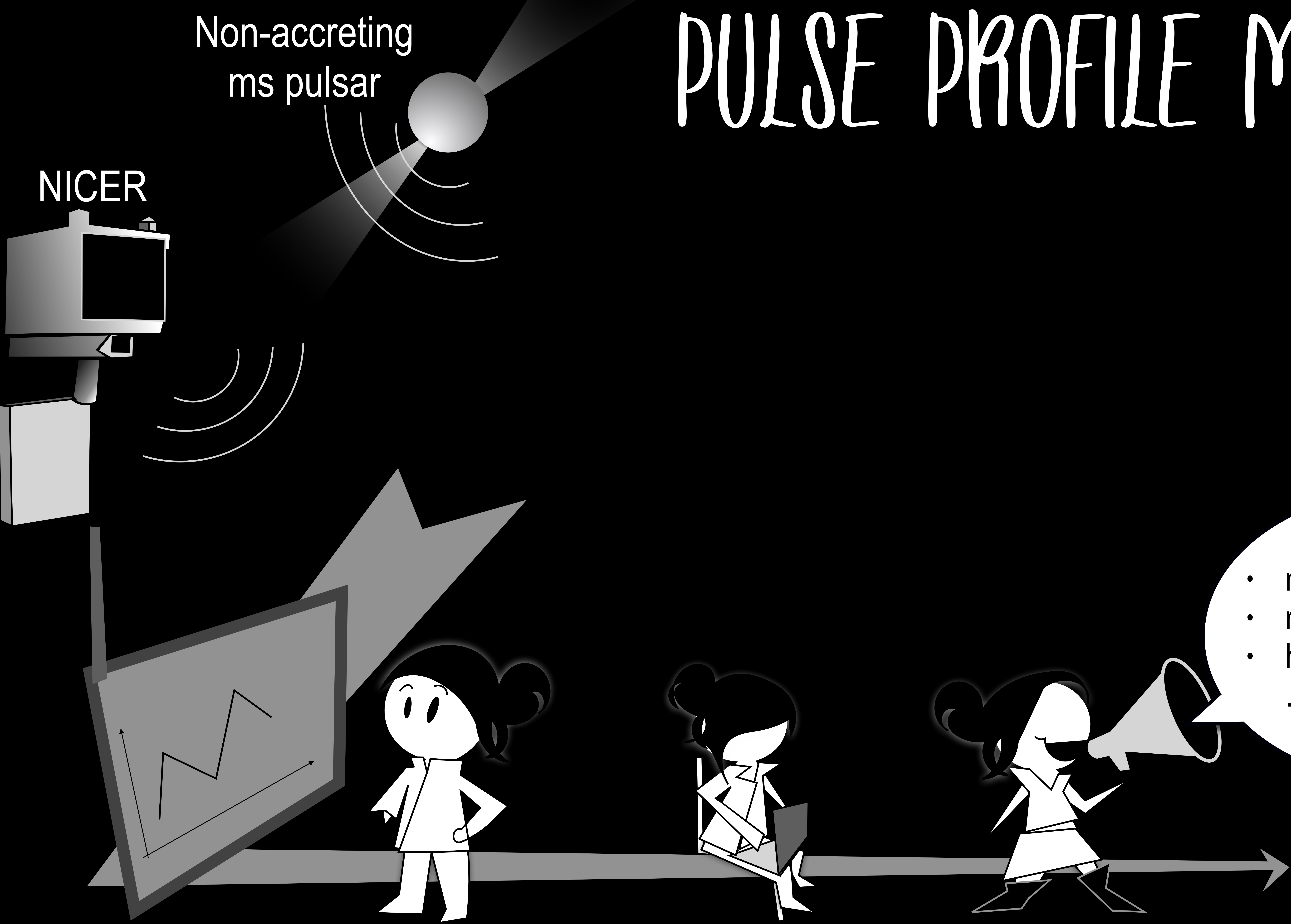
PULSE PROFILE MODELING



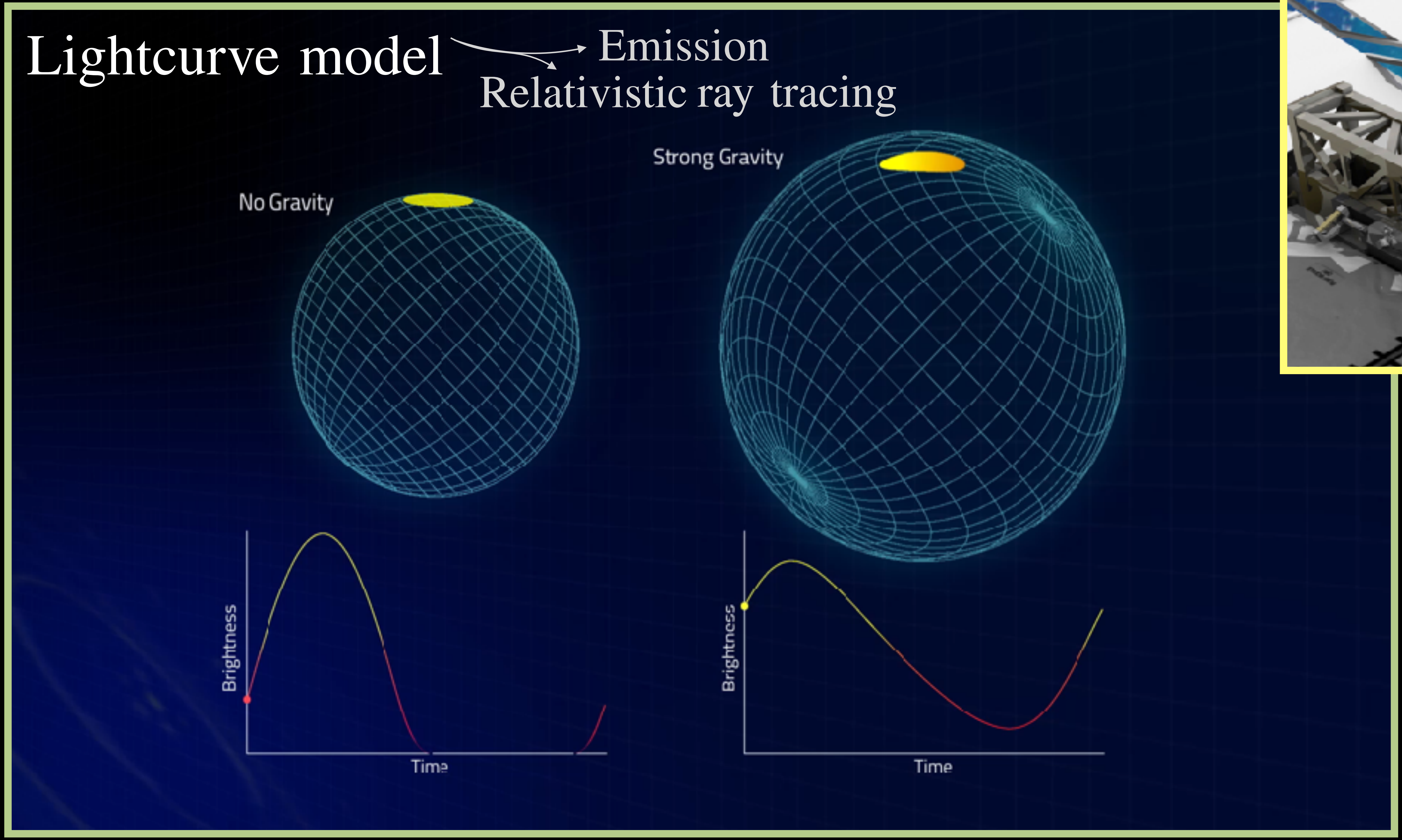
- masses
- radius
- hot spots configuration
- ..

See also Slavko Bogdanov, Cole Miller talks tomorrow

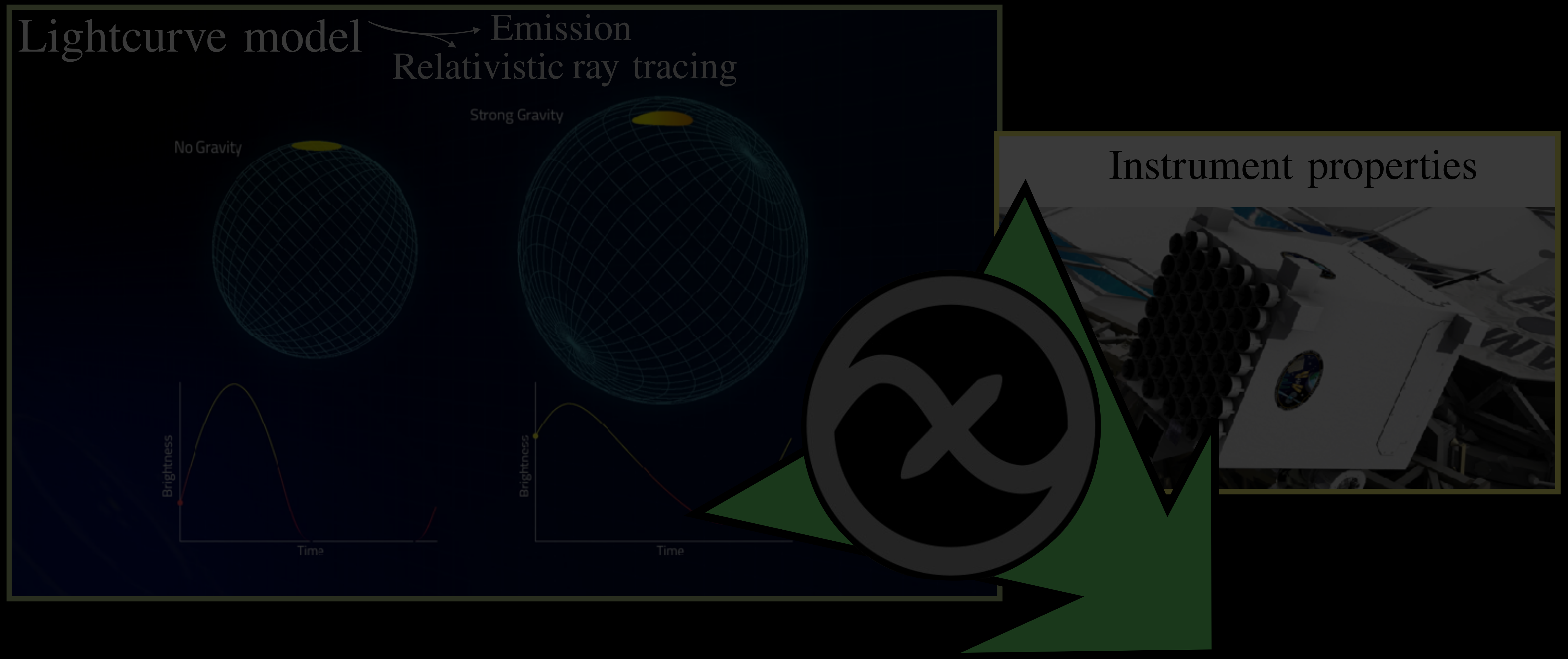
PULSE PROFILE MODELING

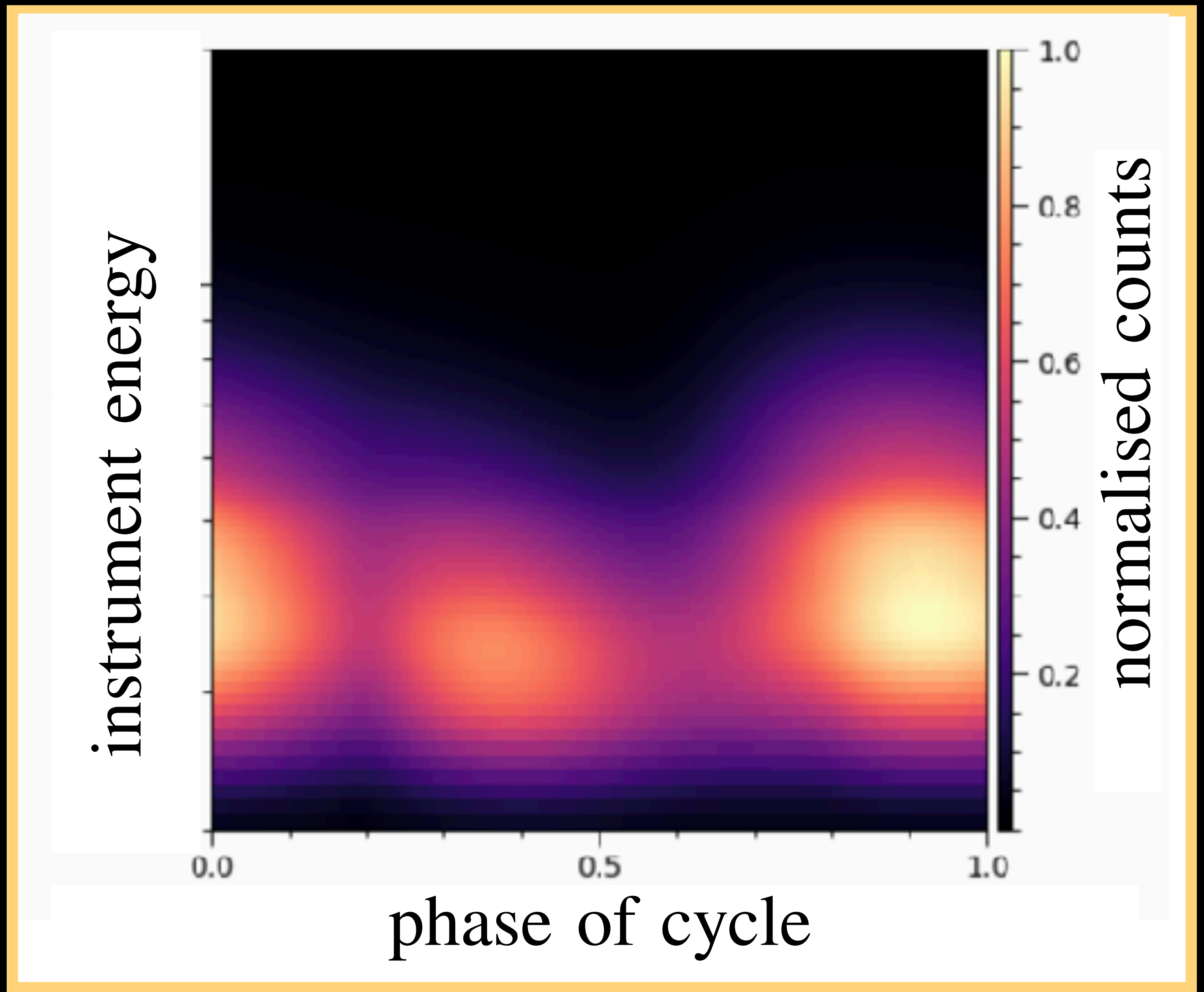
See also Slavko Bogdanov, Cole Miller talks tomorrow

PULSE PROFILE MODELING X-PSI

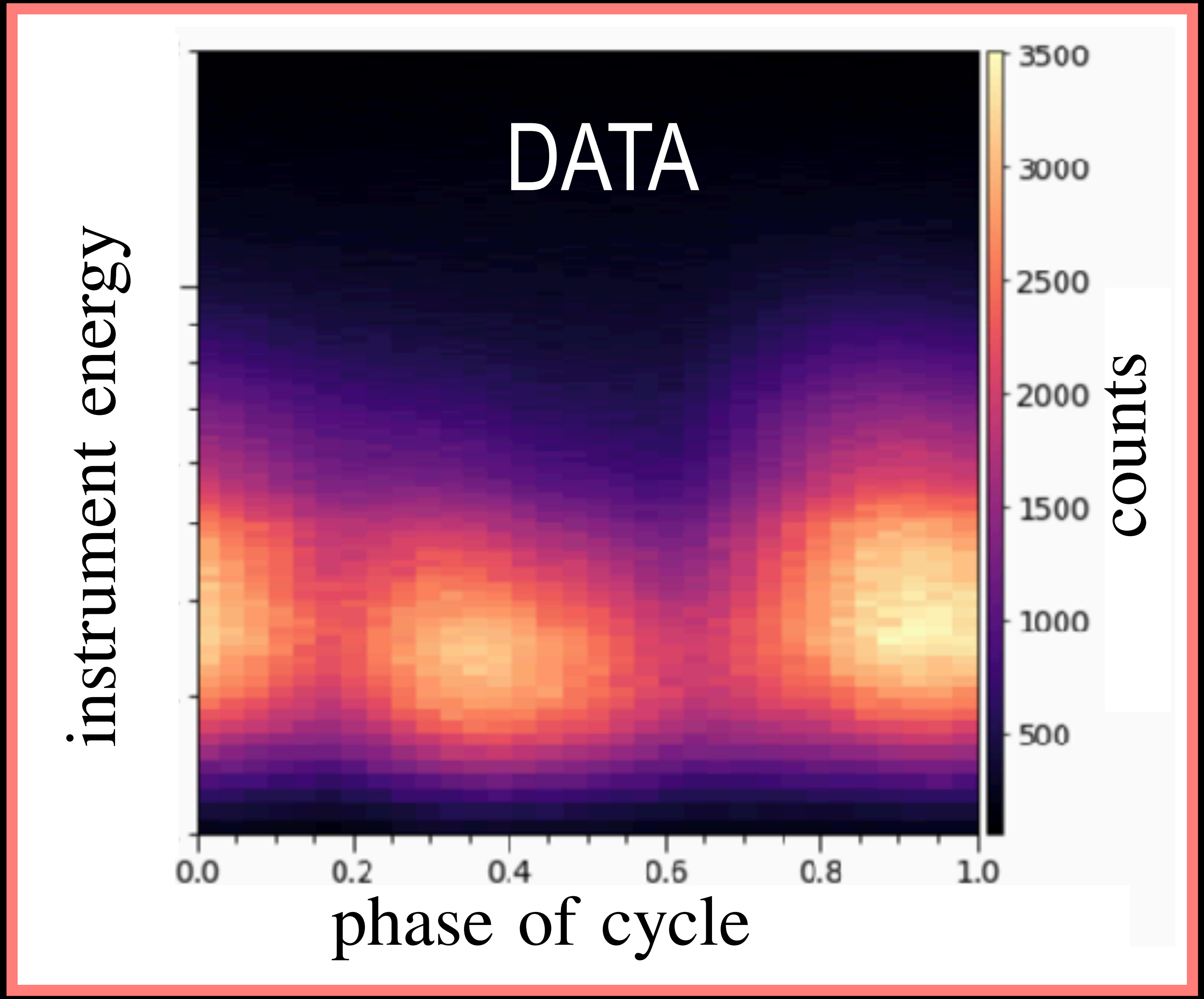


PULSE PROFILE MODELING X-PSI

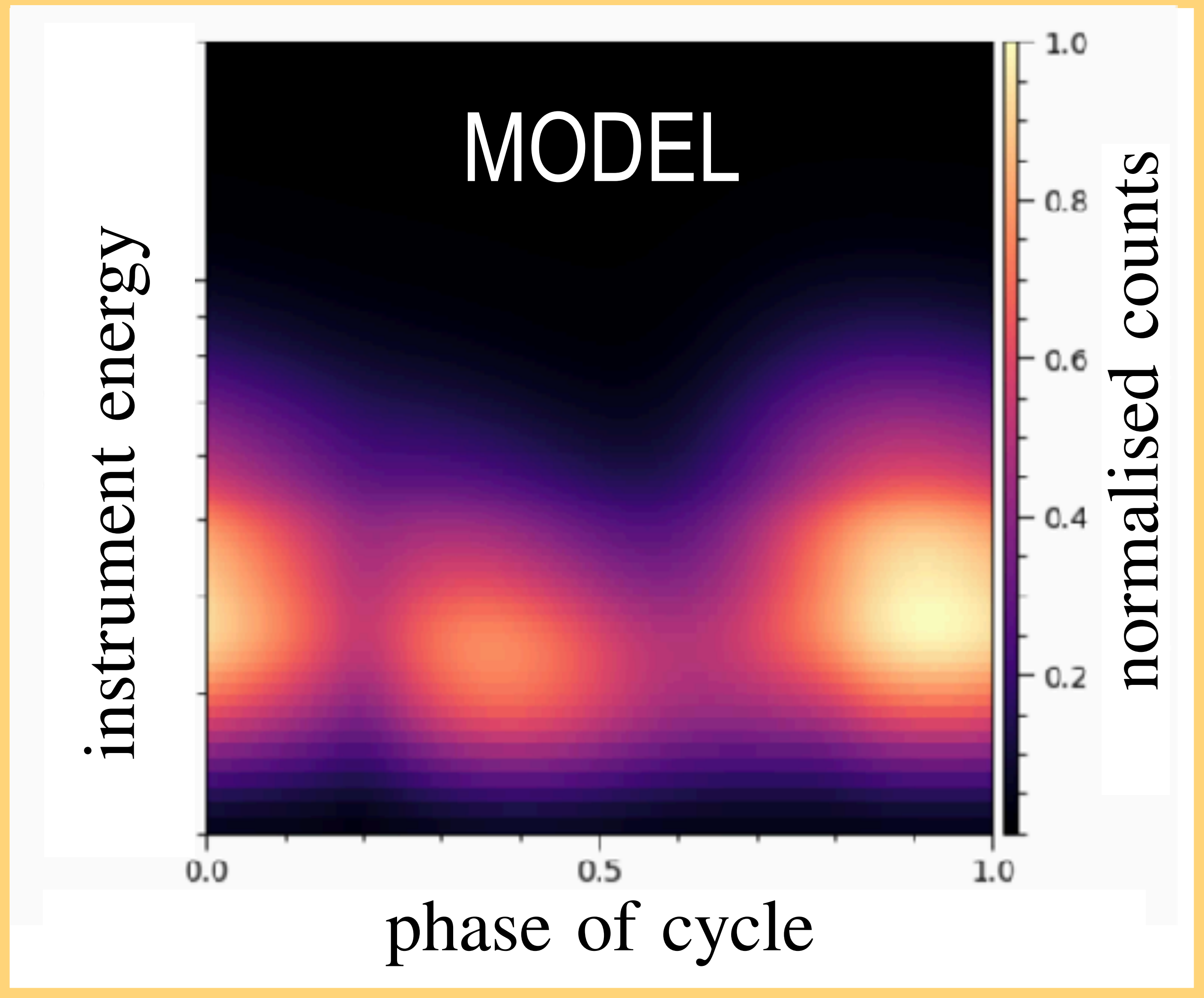




PULSE PROFILE MODELLING X-PSI

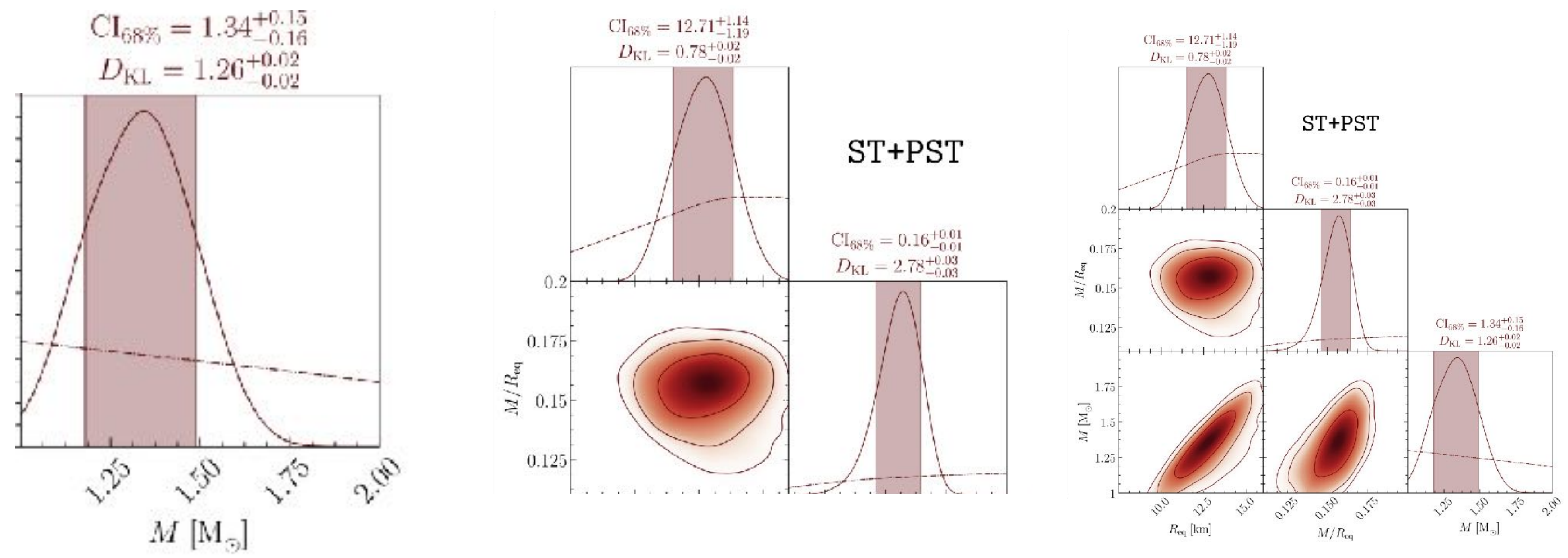


X-PSI
Riley 2021

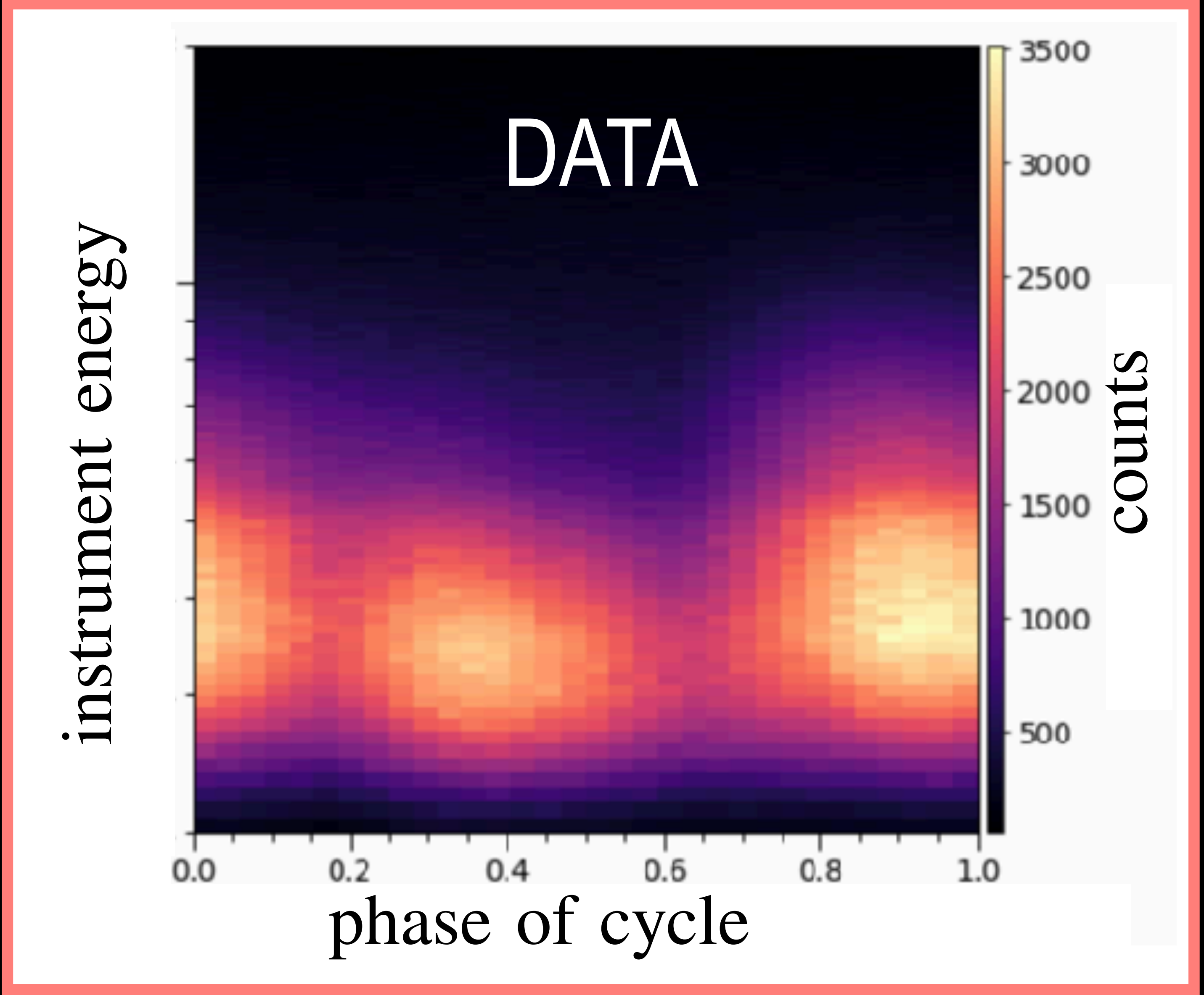


PULSE PROFILE MODELLING X-PSI

Probability distributions of :

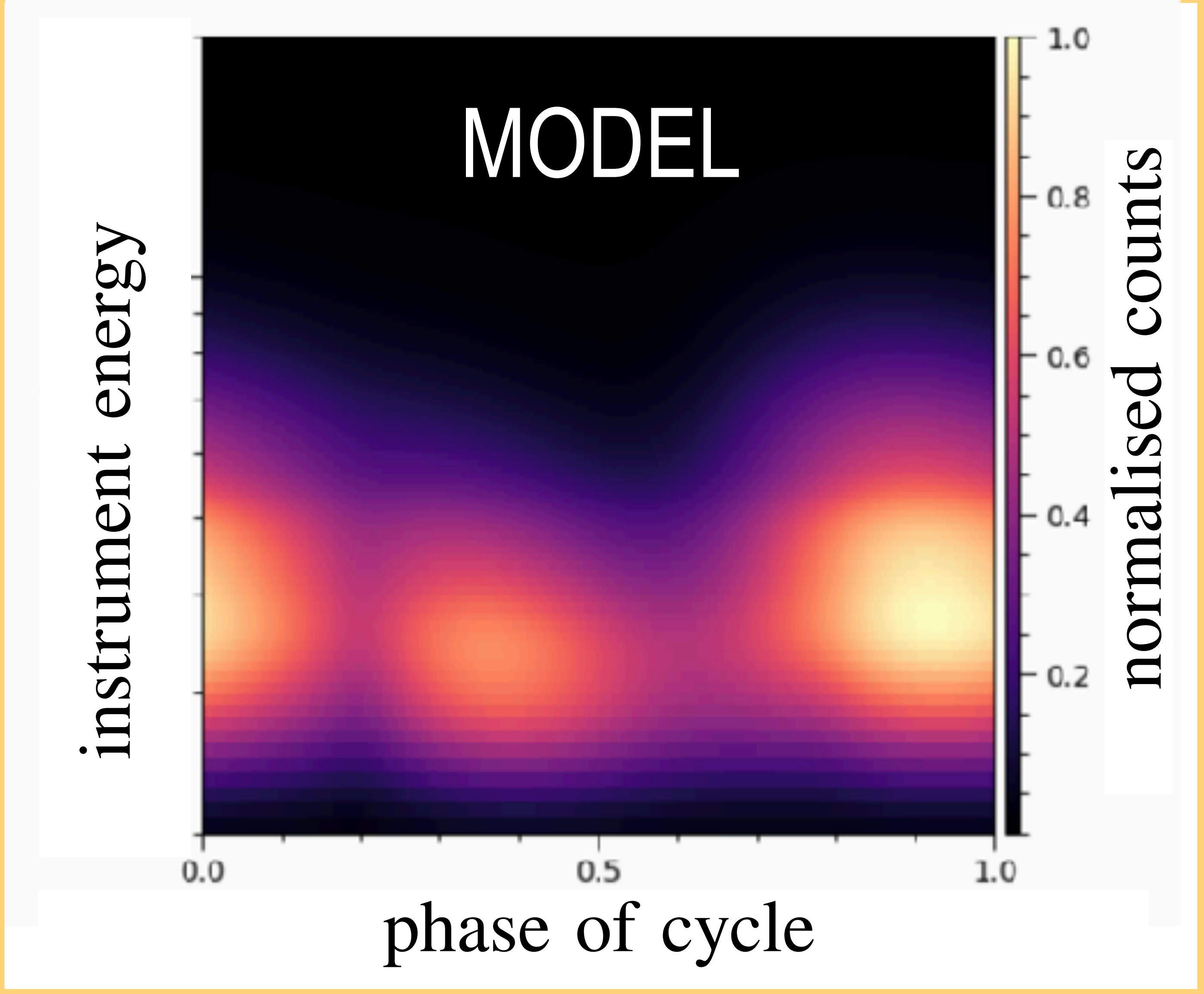


Mass, Radius, Geometrical parameters . . .

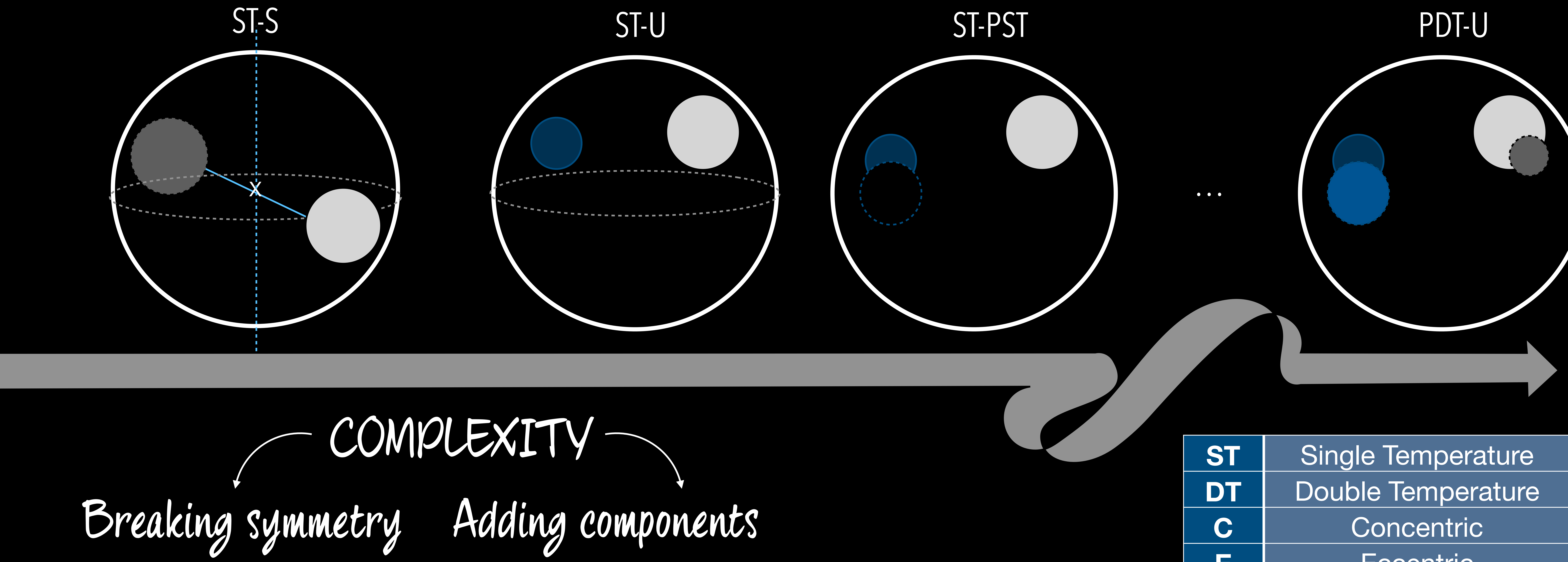


X-PSI

Riley 2021

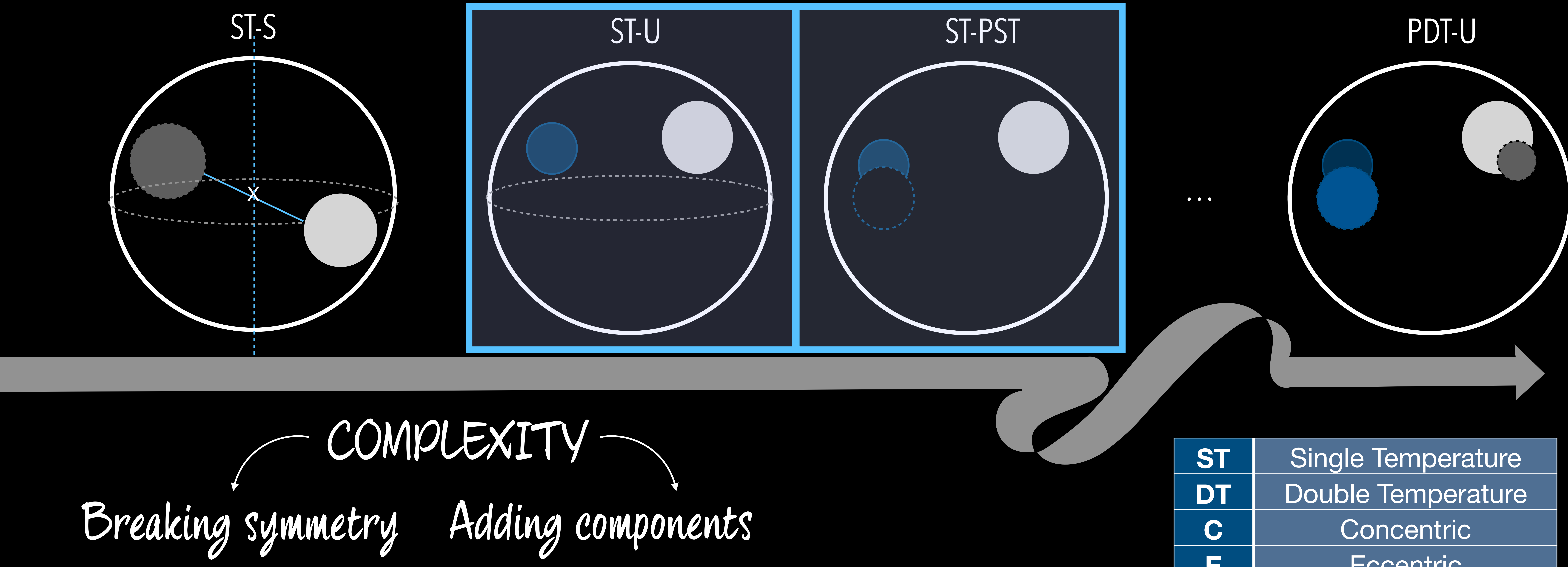


MODEL GENERATION XPSI



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

MODEL GENERATION XPSI



ST	Single Temperature
DT	Double Temperature
C	Concentric
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-U	-Unshared
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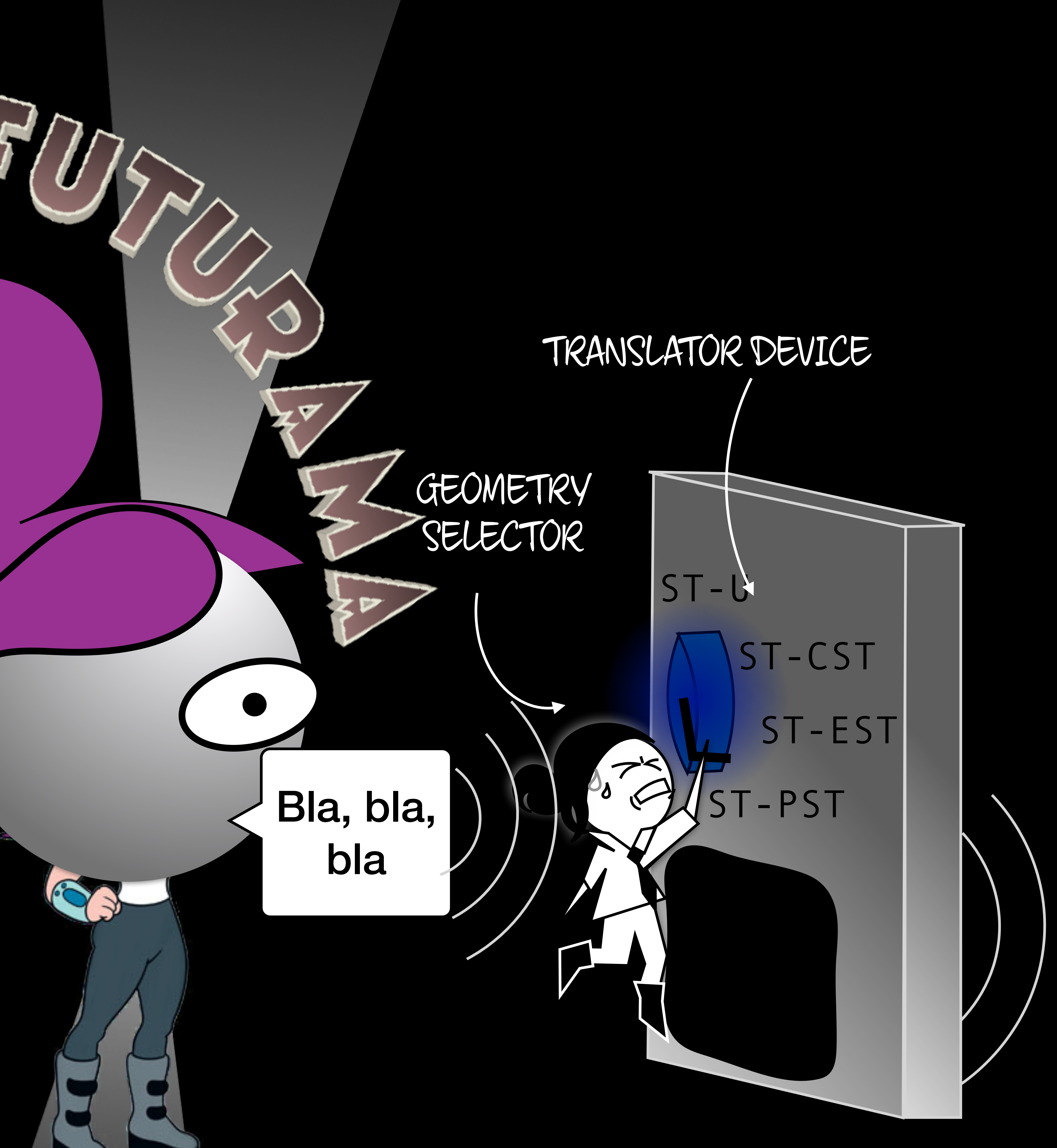
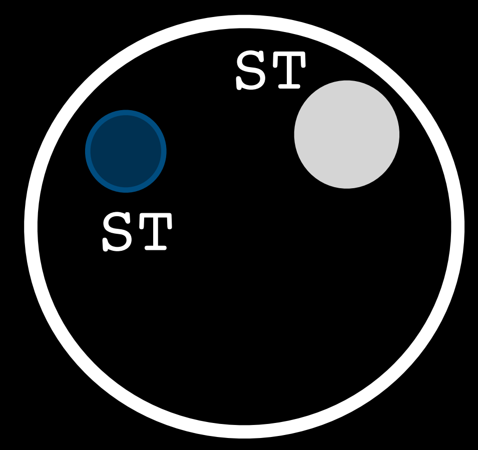
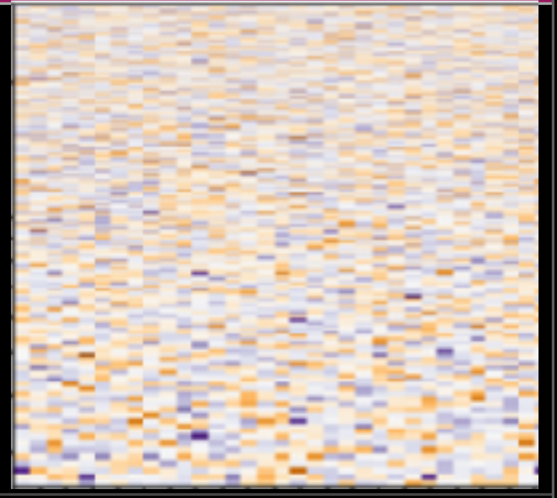
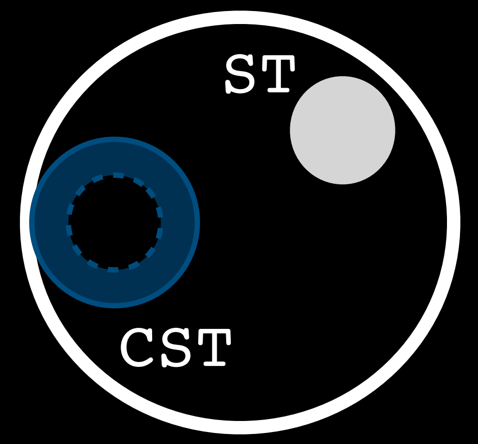
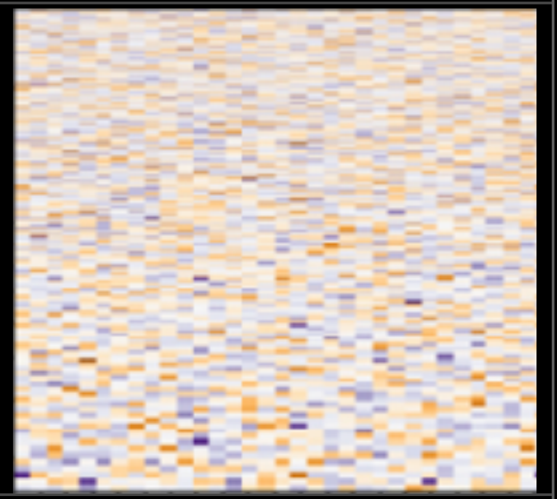
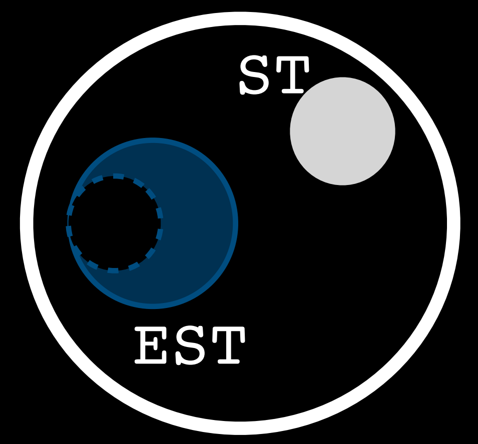
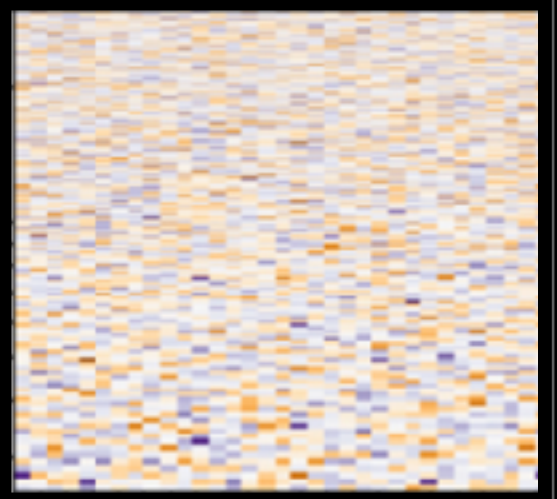
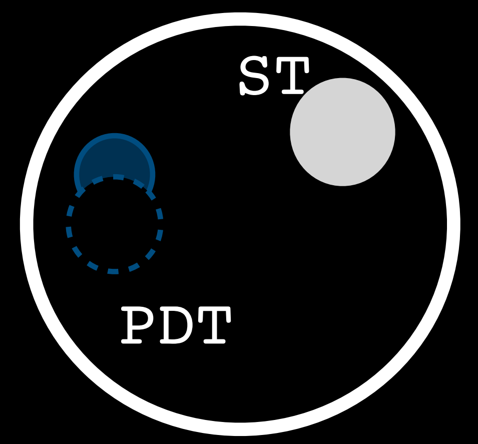
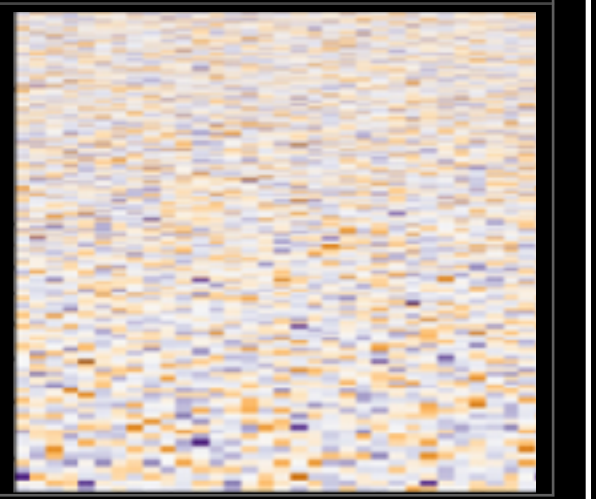
EXAMPLE J0030+0451



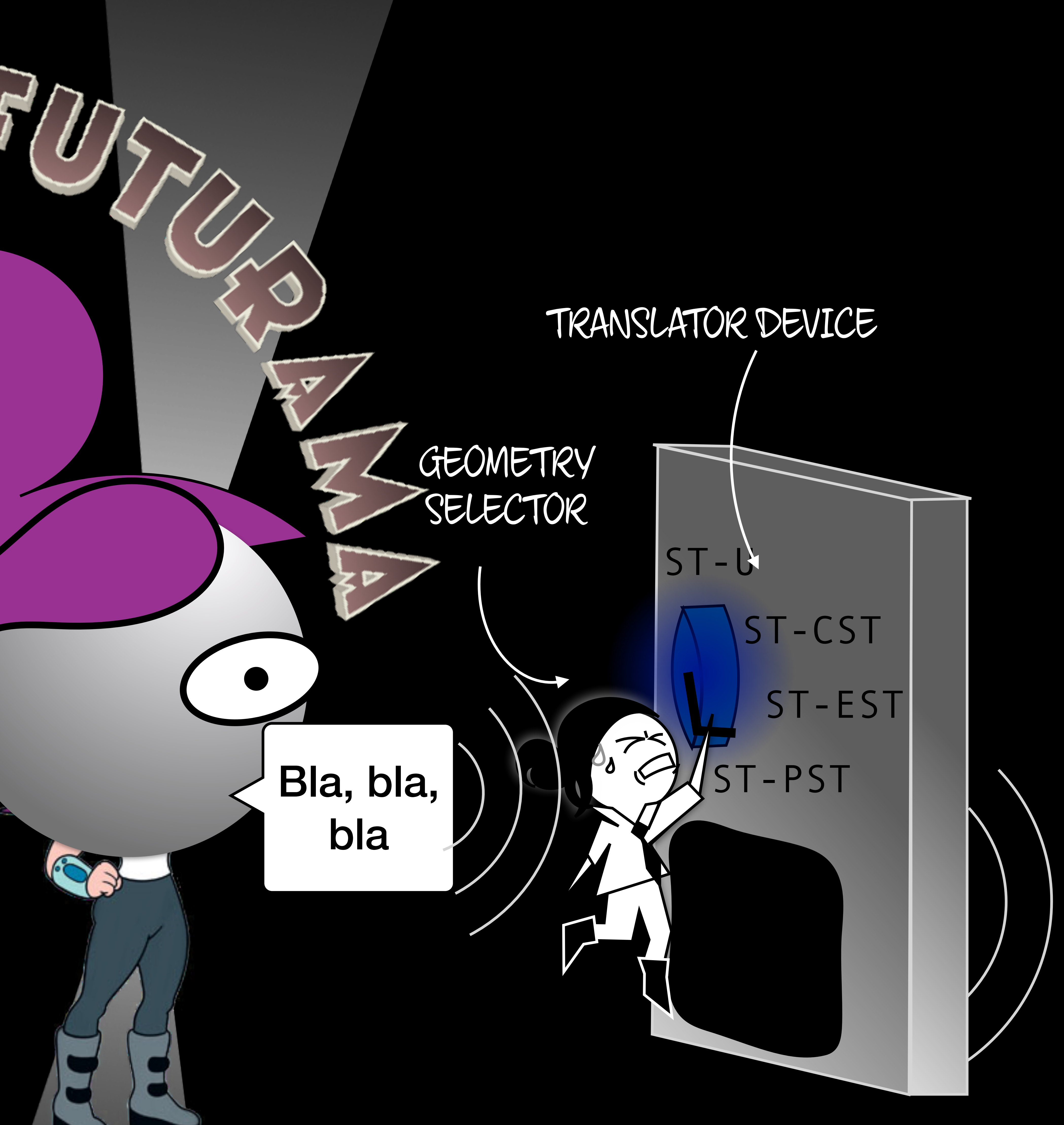
Riley et al 2019

	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-CST Single Temperature - Concentric Single Temperature		$1.44^{+0.18}_{-0.19}$	$13.88^{+1.23}_{-1.38}$	
ST-EST Single Temperature - Eccentric Single Temperature		$1.46^{+0.17}_{-0.18}$	$13.89^{+1.14}_{-1.30}$	
ST-PST Single Temperature - Protruding Single Temperature		$1.34^{+0.15}_{-0.16}$	$12.71^{+1.14}_{-1.19}$	

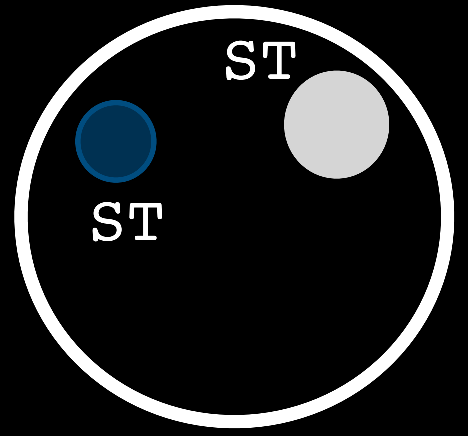
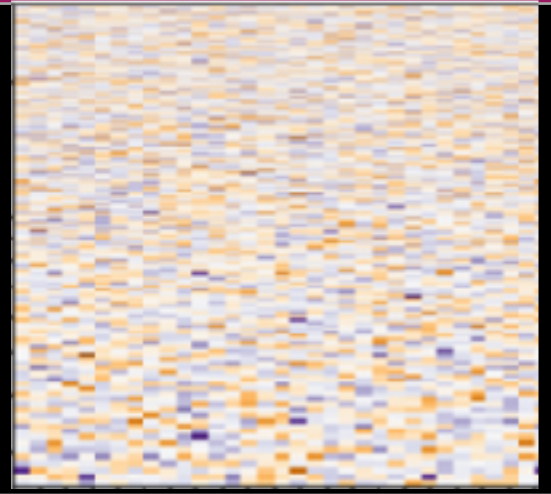
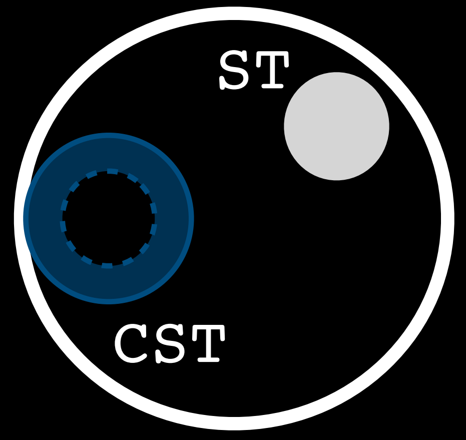
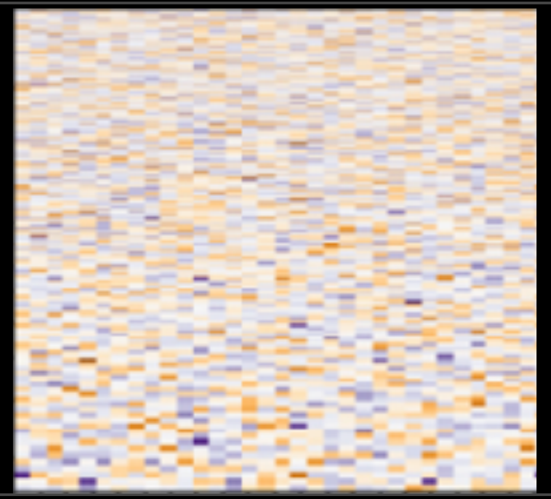
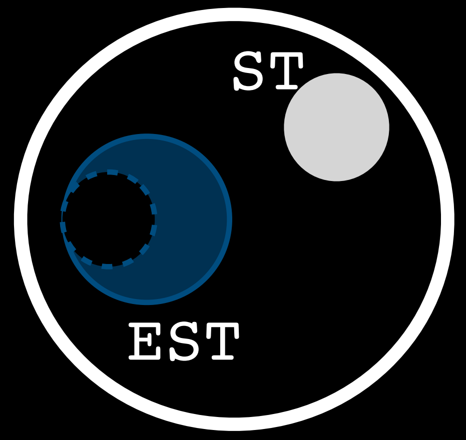
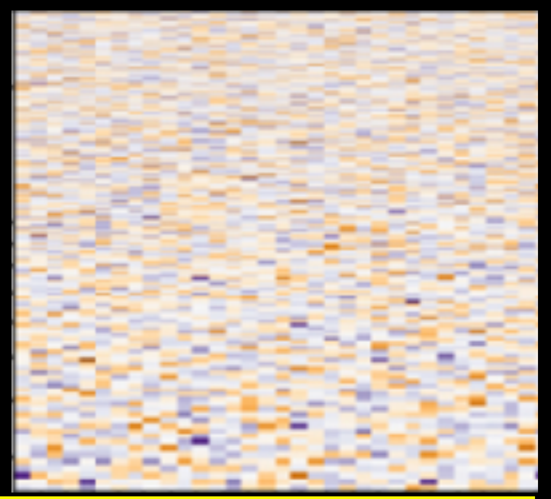
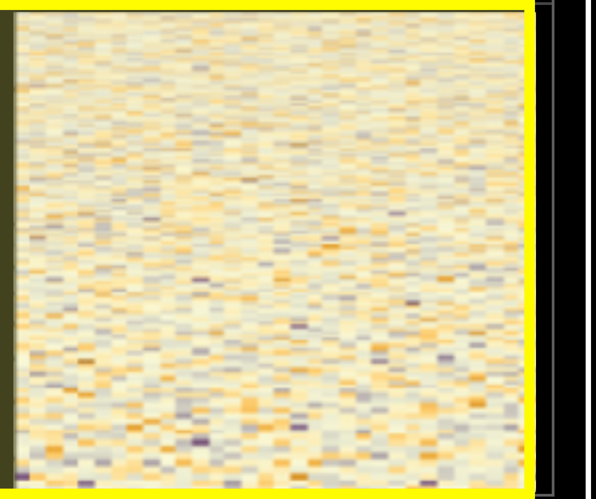
Channels

Phase [cycle]

EXAMPLE J0030+0451



Riley et al 2019

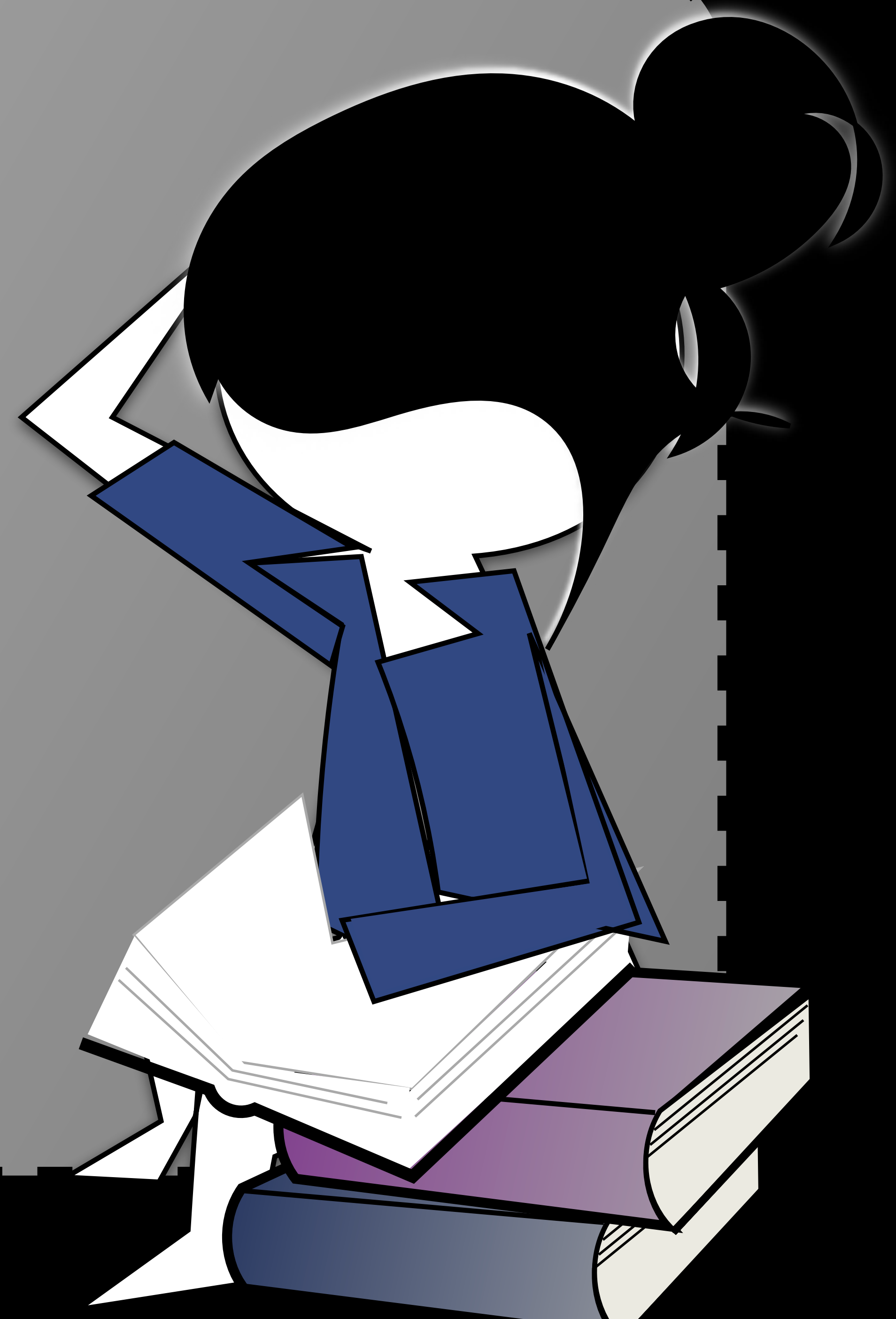
	Model	Mass [M_{Sun}]	Radius [km]	Residuals Normalised difference between model&data
ST-U Single Temperature - Unshared		$1.09^{+0.11}_{-0.07}$	$10.44^{+1.10}_{-0.86}$	
ST-CST Single Temperature - Concentric Single Temperature		$1.44^{+0.18}_{-0.19}$	$13.88^{+1.23}_{-1.38}$	
ST-EST Single Temperature - Eccentric Single Temperature		$1.46^{+0.17}_{-0.18}$	$13.89^{+1.14}_{-1.30}$	
ST-PST Single Temperature - Protruding Single Temperature		$1.34^{+0.15}_{-0.16}$	$12.71^{+1.14}_{-1.19}$	

Channels

Phase [cycle]

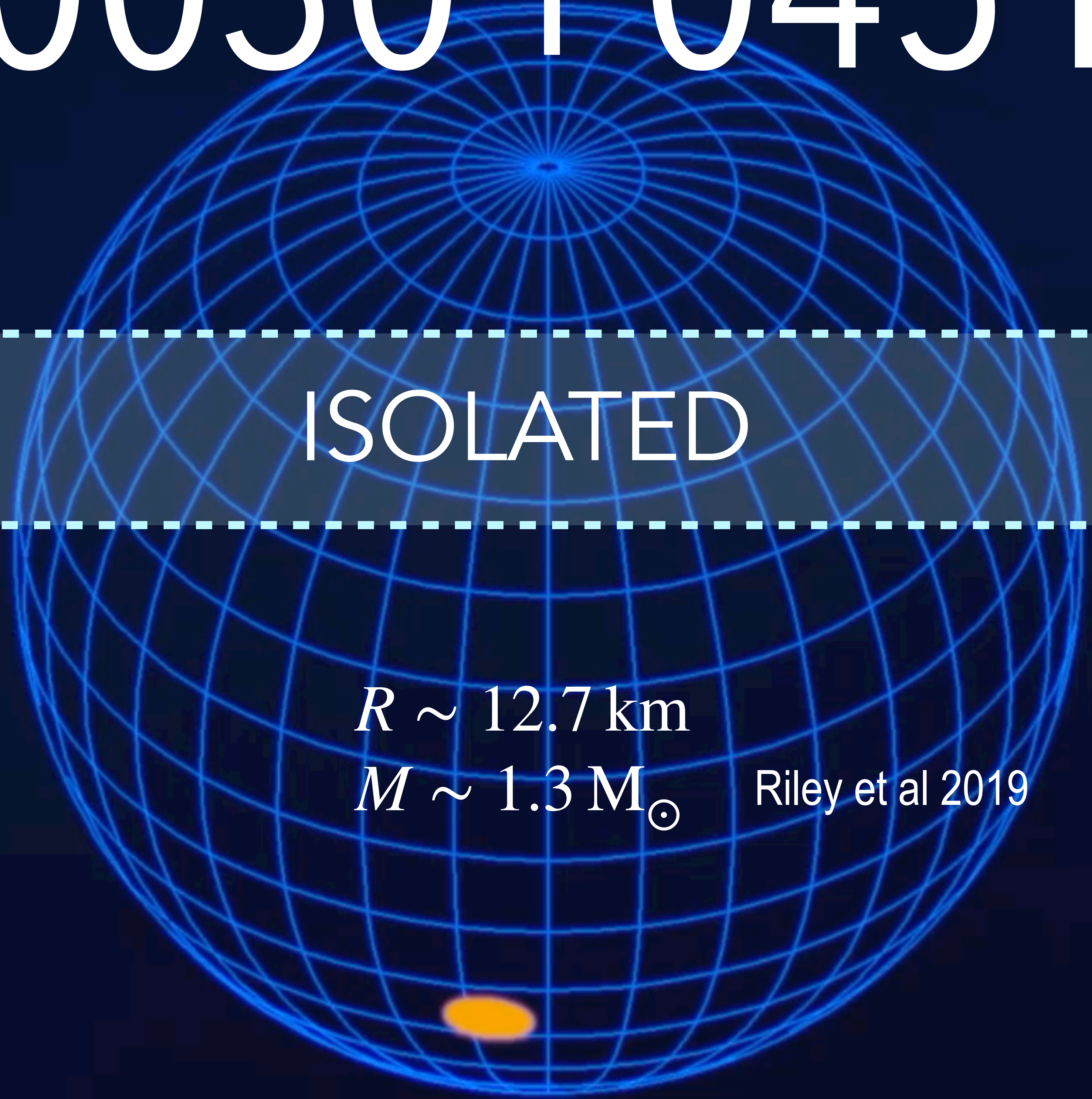
PUBLISHED RESULTS

QUICK OVERVIEW



J0030+0451

J0740+6620



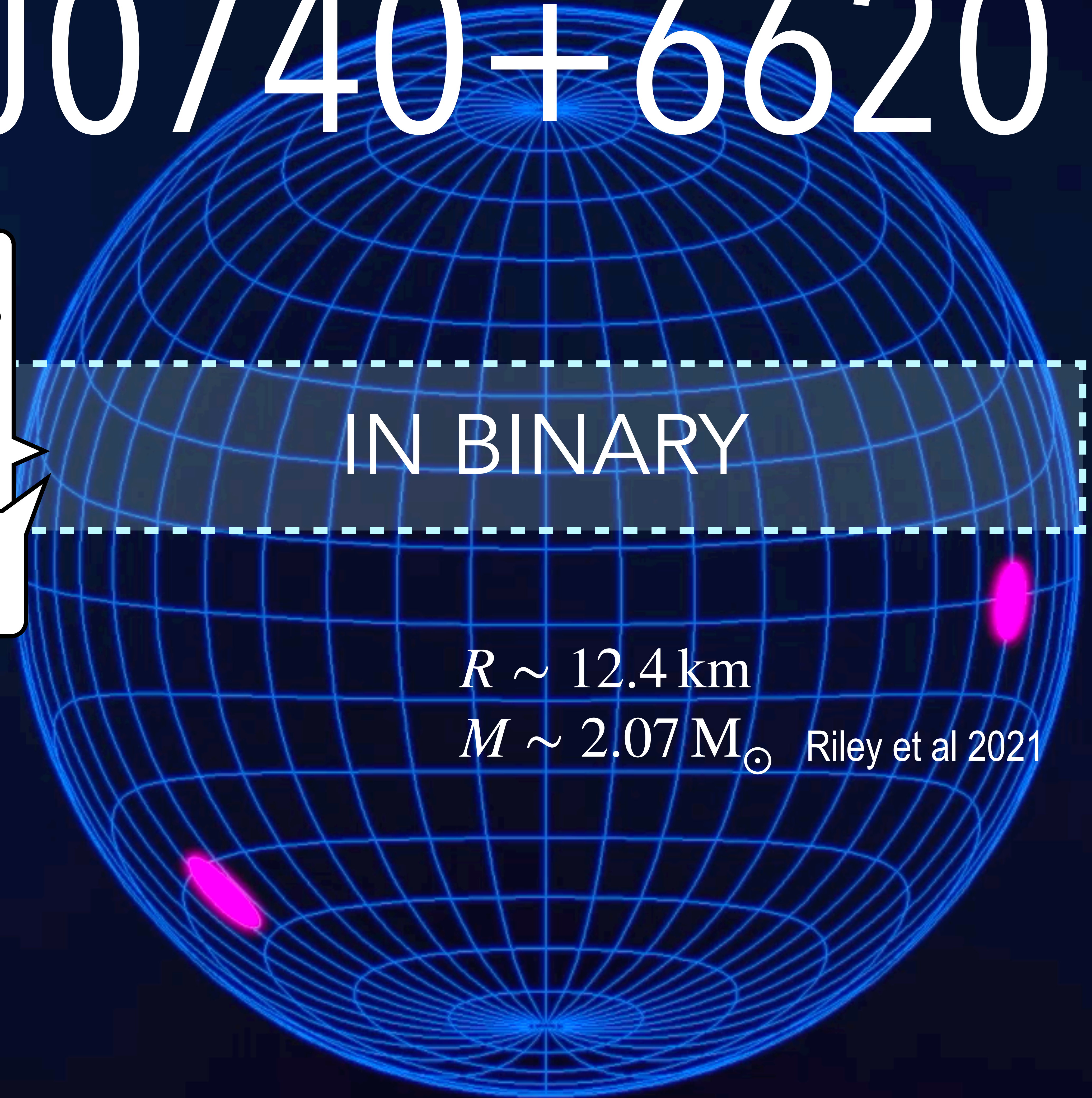
ISOLATED

$R \sim 12.7\,\mathrm{km}$

$M \sim 1.3\,\mathrm{M}_\odot$ Riley et al 2019

Constraints on MASS & INCLINATION from NANOGrav and CHIME Pulsar collaborations

NEUTRON STAR MASS $2.08 \pm 0.07\mathrm{M}_\odot$



IN BINARY

$R \sim 12.4\,\mathrm{km}$

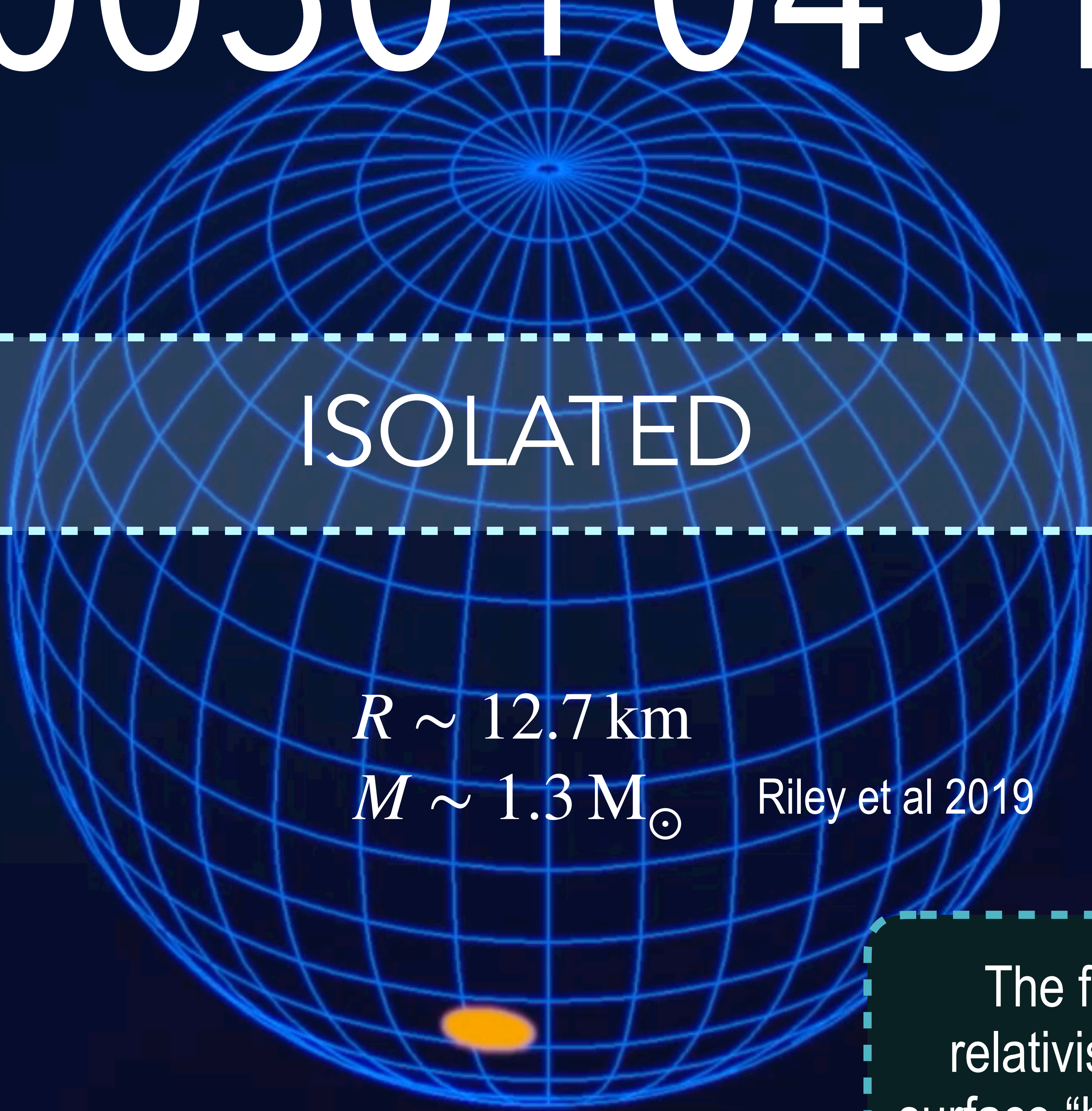
$M \sim 2.07\,\mathrm{M}_\odot$ Riley et al 2021

IOP Focus on NICER webpage

Bogdanov et al 2019a, Bogdanov et al 2019b, Miller et al 2019, Riley et al 2019, Wollf et al 2021, Miller et al 2021, Riley et al 2021, …

J0030+0451

J0740+6620



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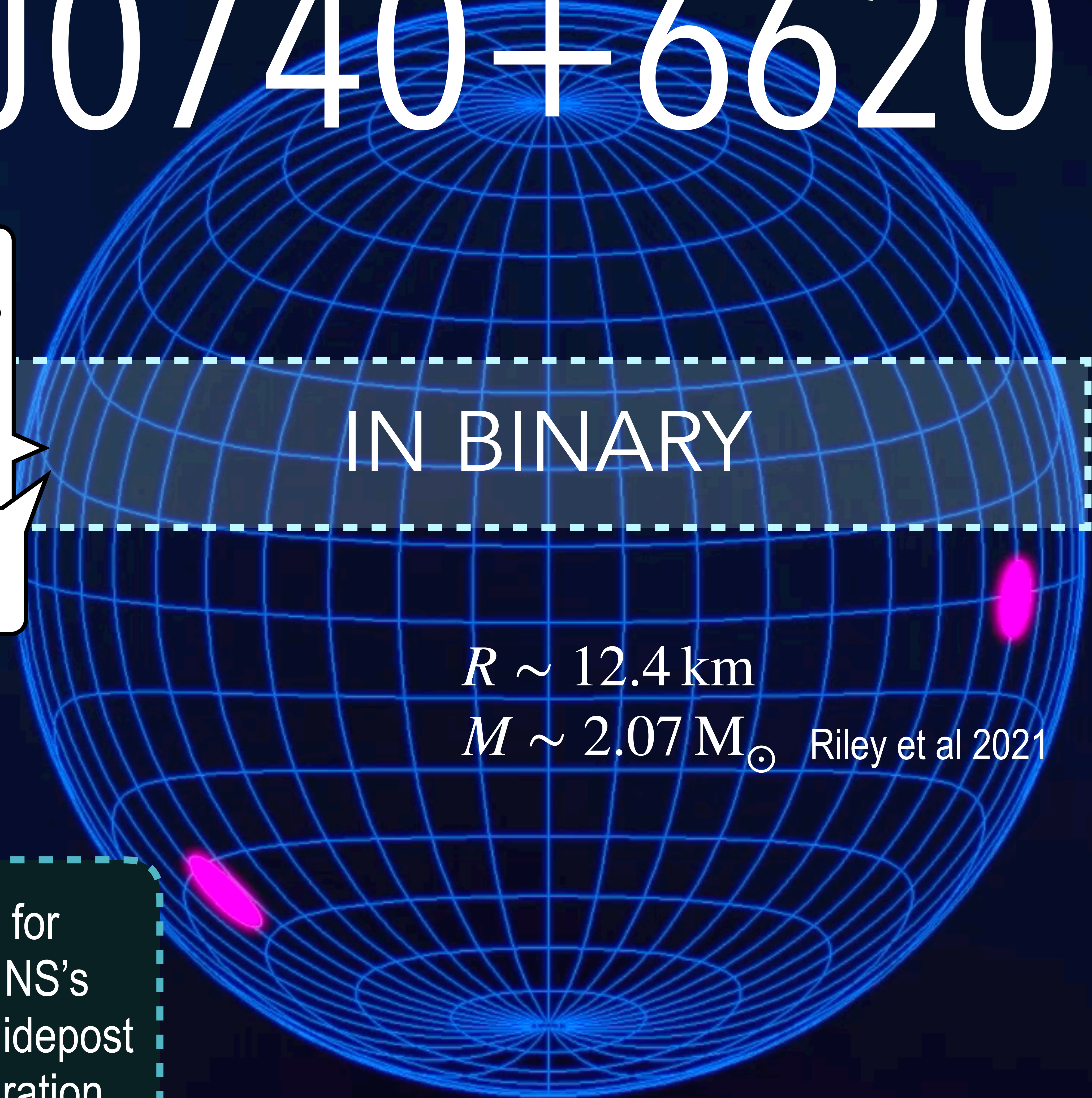


The first map—fully accounting for relativistic light deflection—of an NS's surface "hot spots," serving as a guidepost to the star's magnetic field configuration.

The first precise (±10%, 1 sigma) mass and radius measurements for the same star

The first detection of X-ray pulsations from PSR J0740 (Wolff et al. 2021).

IOP Focus on NICER webpage

The first mass measurement for an isolated (i.e., non-binary) NS

Bogdanov et al 2019a, Bogdanov et al 2019b, Miller et al 2019, Riley et al 2019, Wolff et al 2021, Miller et al 2021, Riley et al 2021, …

A fairly stiff EoS is implied when PSR J0740's radius is included with other astrophysical constraints.

LATEST RESULTS

1) NEW DATA SETS

2) PRELIMINARY ANALYSES J0030

3) RESULTS J0740

NEW DATA SETS

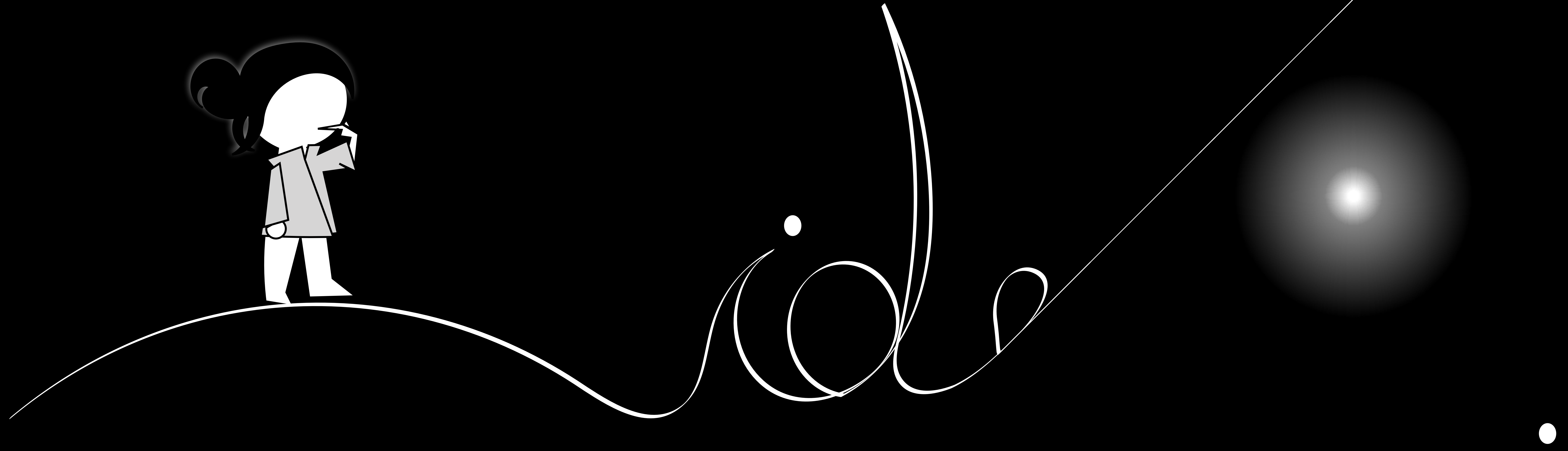
PUBLISHED	J0030	J0740
CLASSIC [exposure time] {Obs. period}	Bogdanov et al 2019a [~1.94 Ms] {up to 9 December 2018}	ALPHA (Wolff et al 2021) [~1.60 Ms] {up to 17 April 2020}

NEW	J0030	J0740
CLASSIC [exposure time] {Obs. period}	CHARLIE [~2.98Ms] {up to 22 July 2021}	-
3C50 [exposure time] {Obs. period}	X [~2.07Ms] {up to 24 December 2021}	X [~1.56 Ms] {up to 28 December 2021}

BKG LOWER LIMITS
(Space weather SW)
Gendreau 2020

BKG ESTIMATES
(All but other sources in the FoV)
Remillard et al 2022

What is the



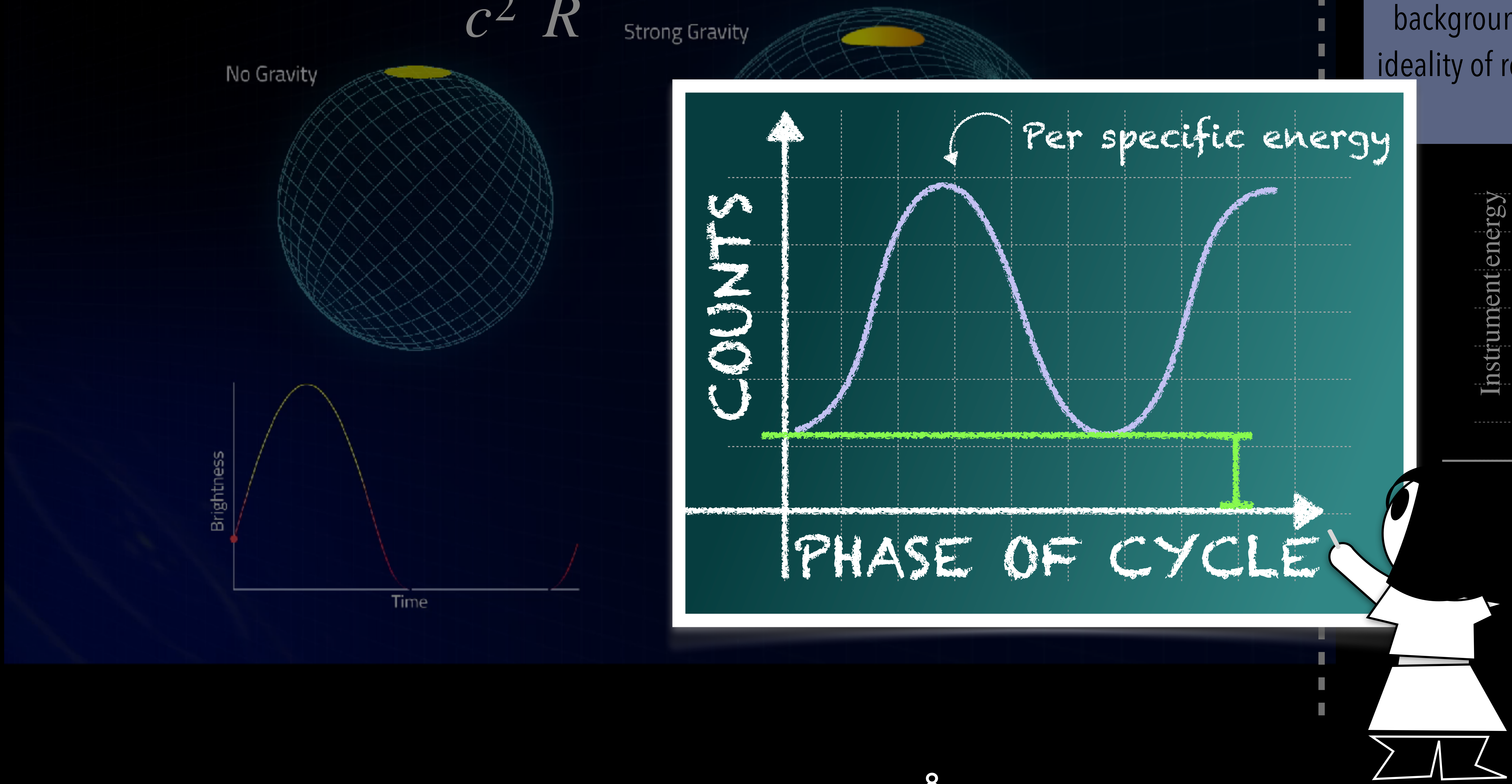
BKG MODEL:
With #of parameters = # of (considered) energy bands of the instrument.
Independent from phase.

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

WITH BACKGROUND (BKG) here we really mean everything which is not the thermal emission form the hot spot on the NS surface

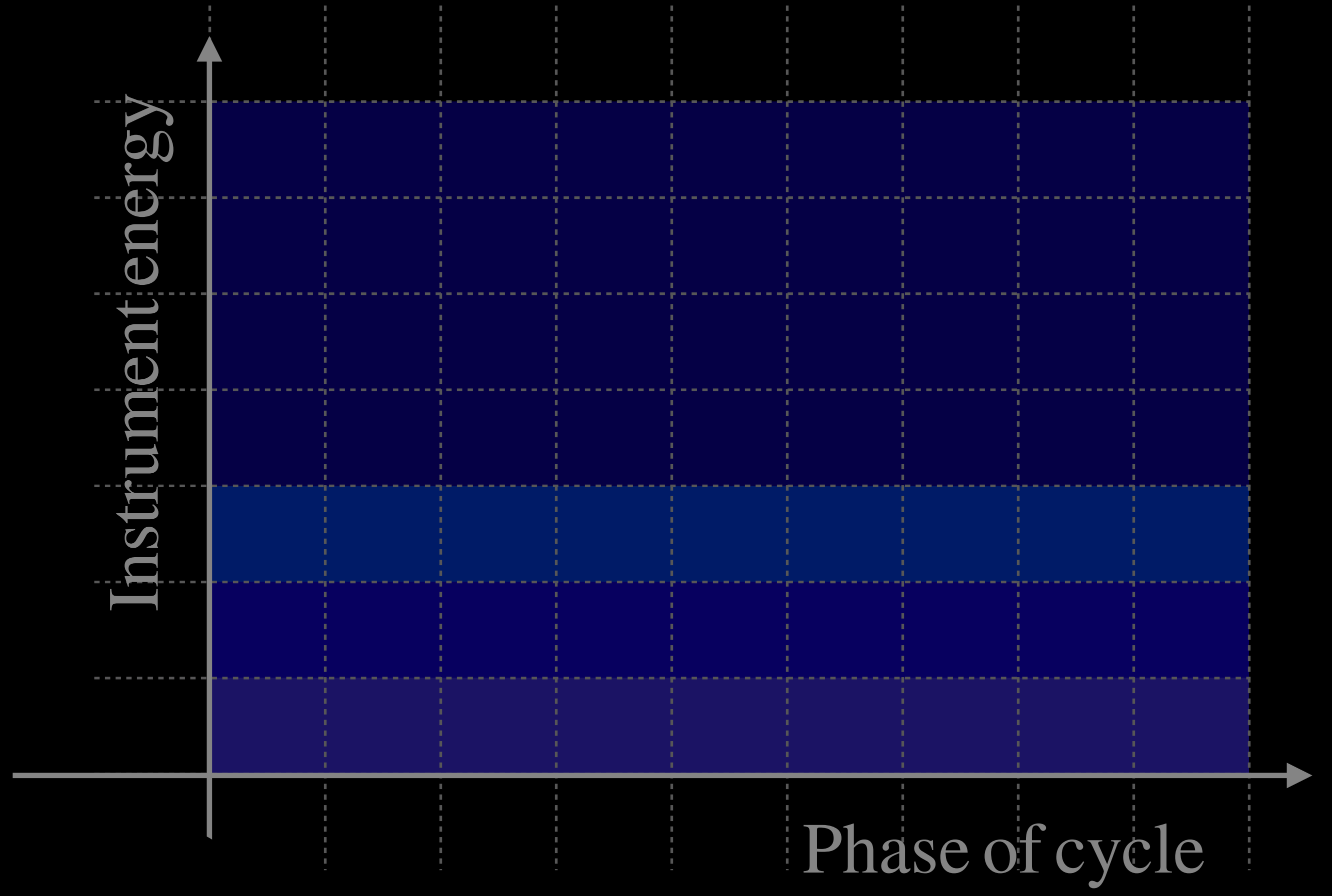
IMPORTANCE OF BKG ESTIMATES

COMPACTNESS $C = \frac{G}{c^2}\frac{M}{R}$



BACKGROUND (BKG)

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



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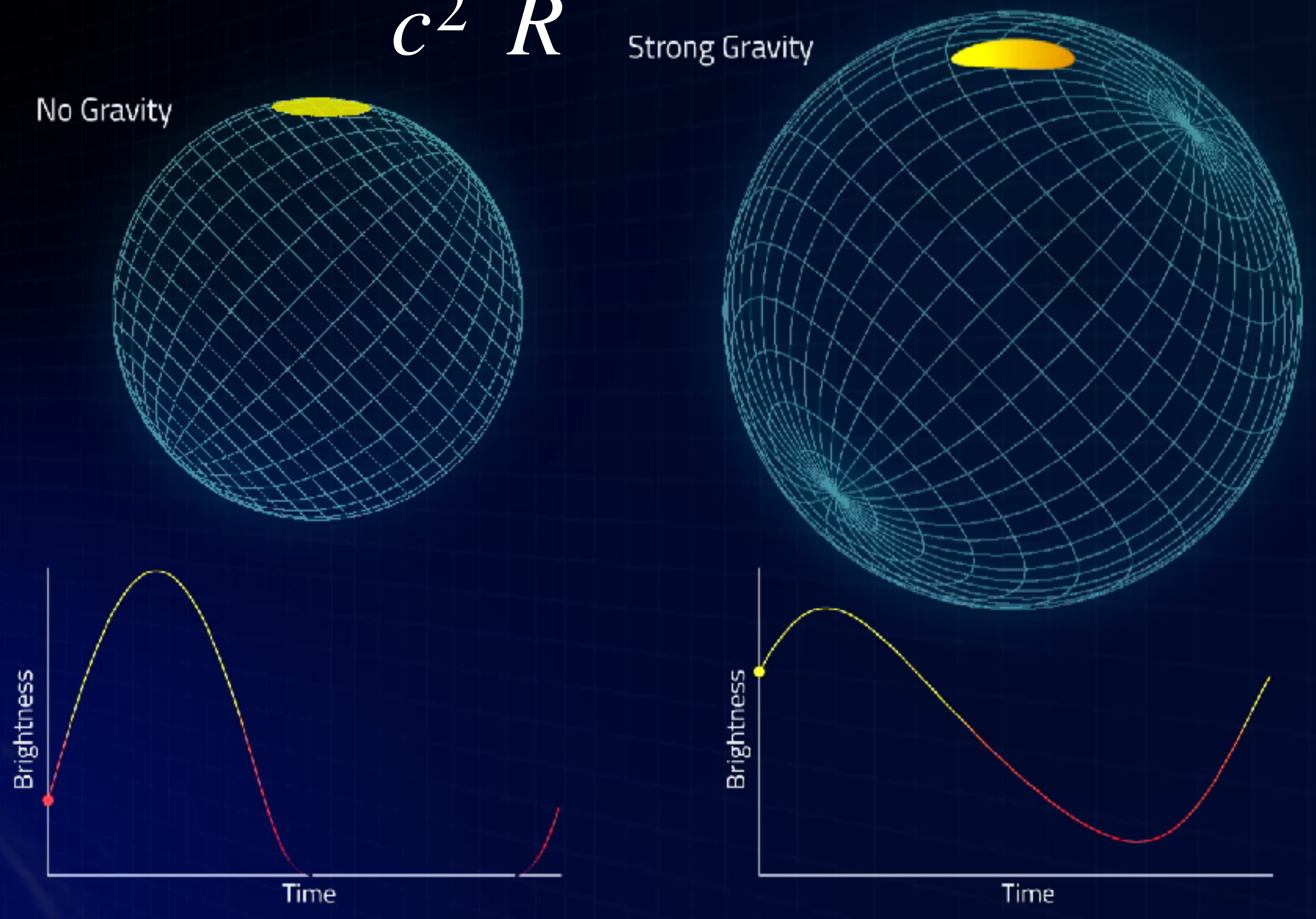
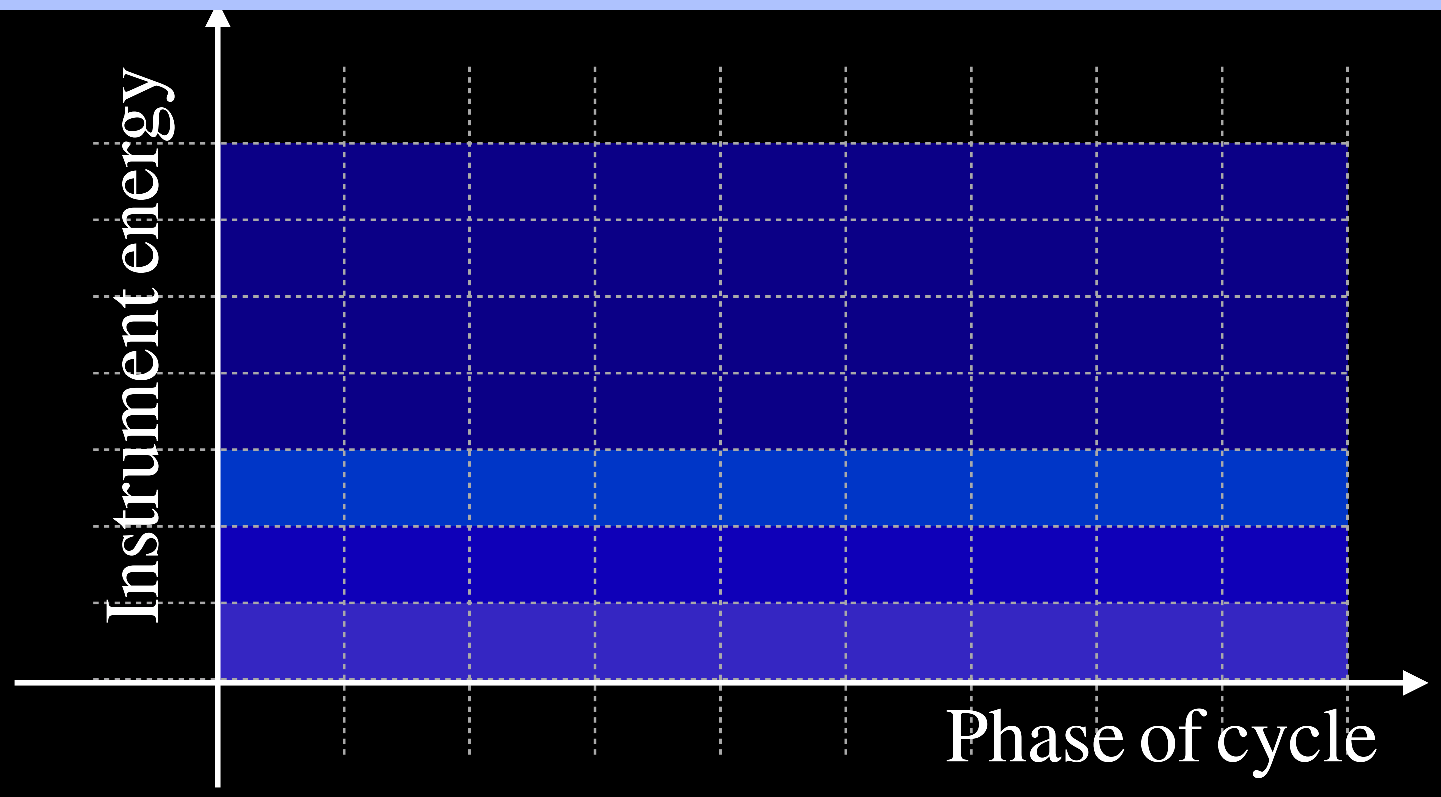


HOT-SPOTS

BACKGROUND (BKG)

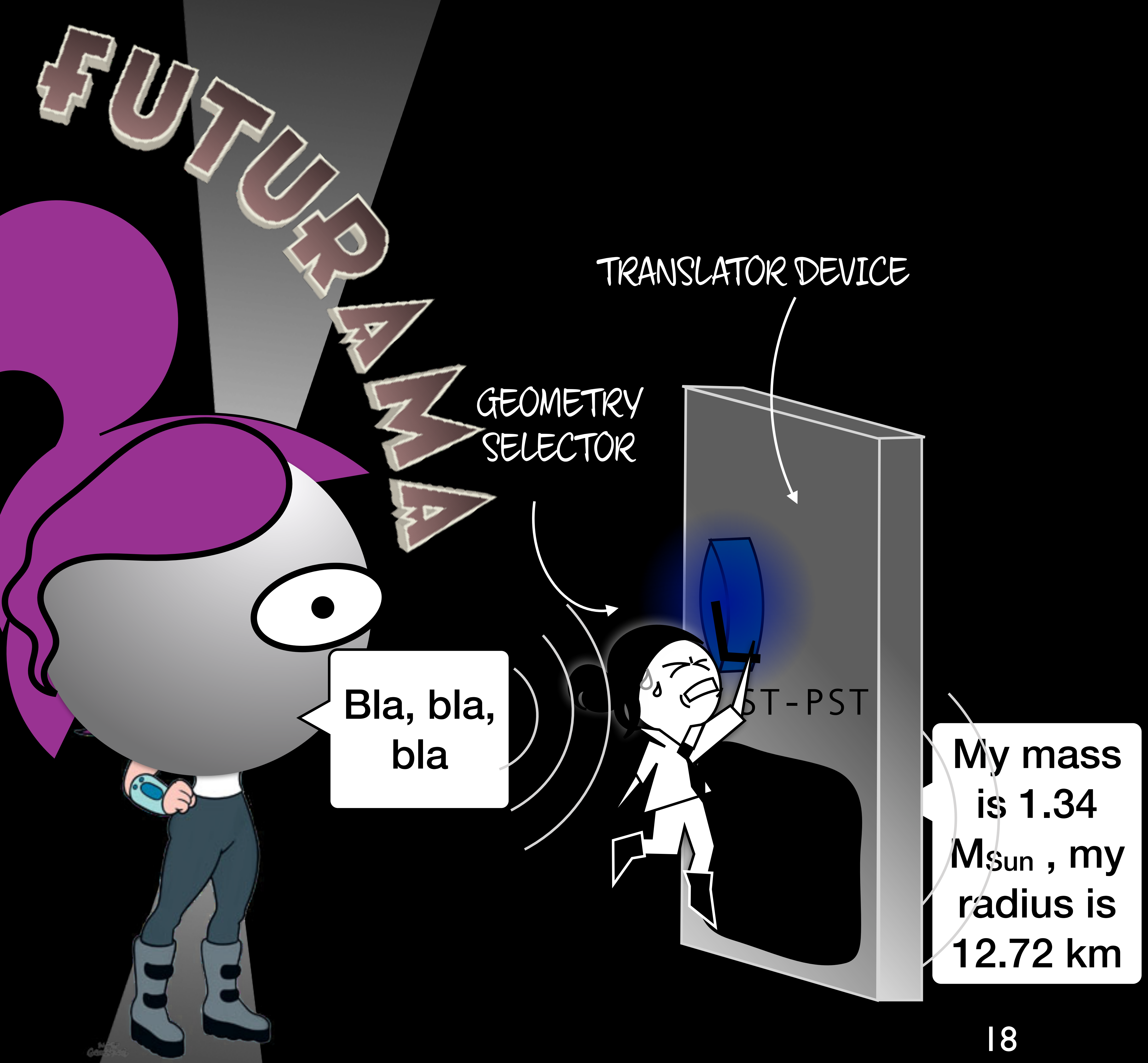
Sources of background can be: additional sources in the FoV, non-ideality of real instruments, space-weather, optical loading (the Sun), etc



NON HOT-SPOTS

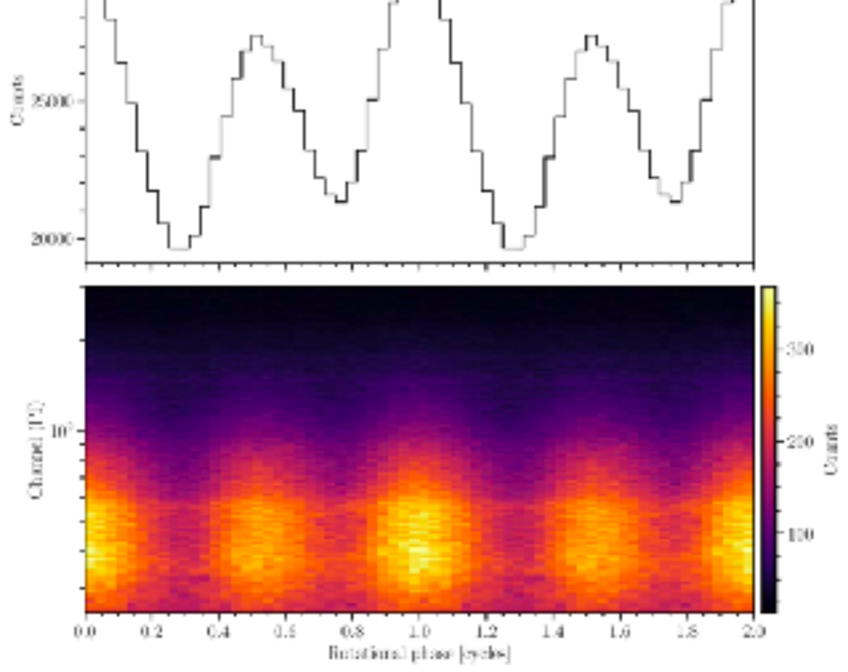
Relevant for Tuomo Salmi's talk as well

THE CASE OF J0030+0451



STATUS	ISOLATED
REFERENC	Riley et al 2019
INSTRUME	NICER

PULSE PROFILE



See also independent analysis: Miller et al 2019

J0030+0451

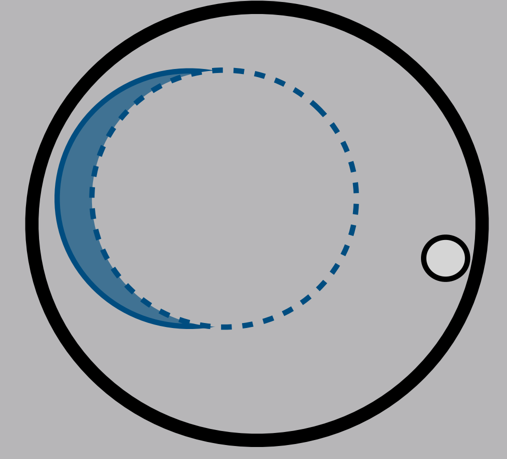
About | Photos | History

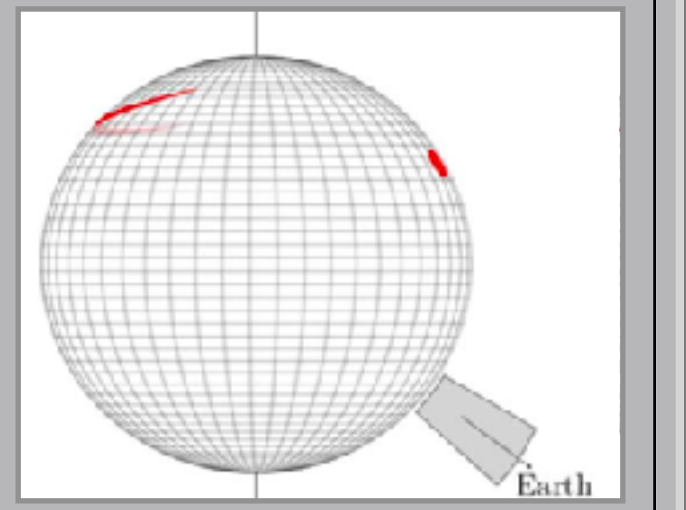
Its details

Mass [M_{Sun}]	1.34
Radius [km]	12.71
Compactness	0.16

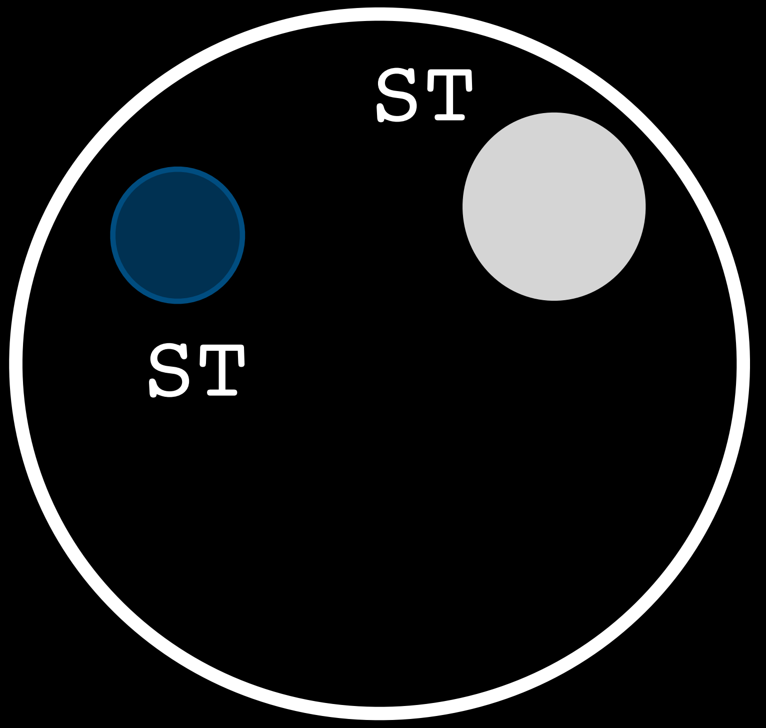
MODEL

ST-PST

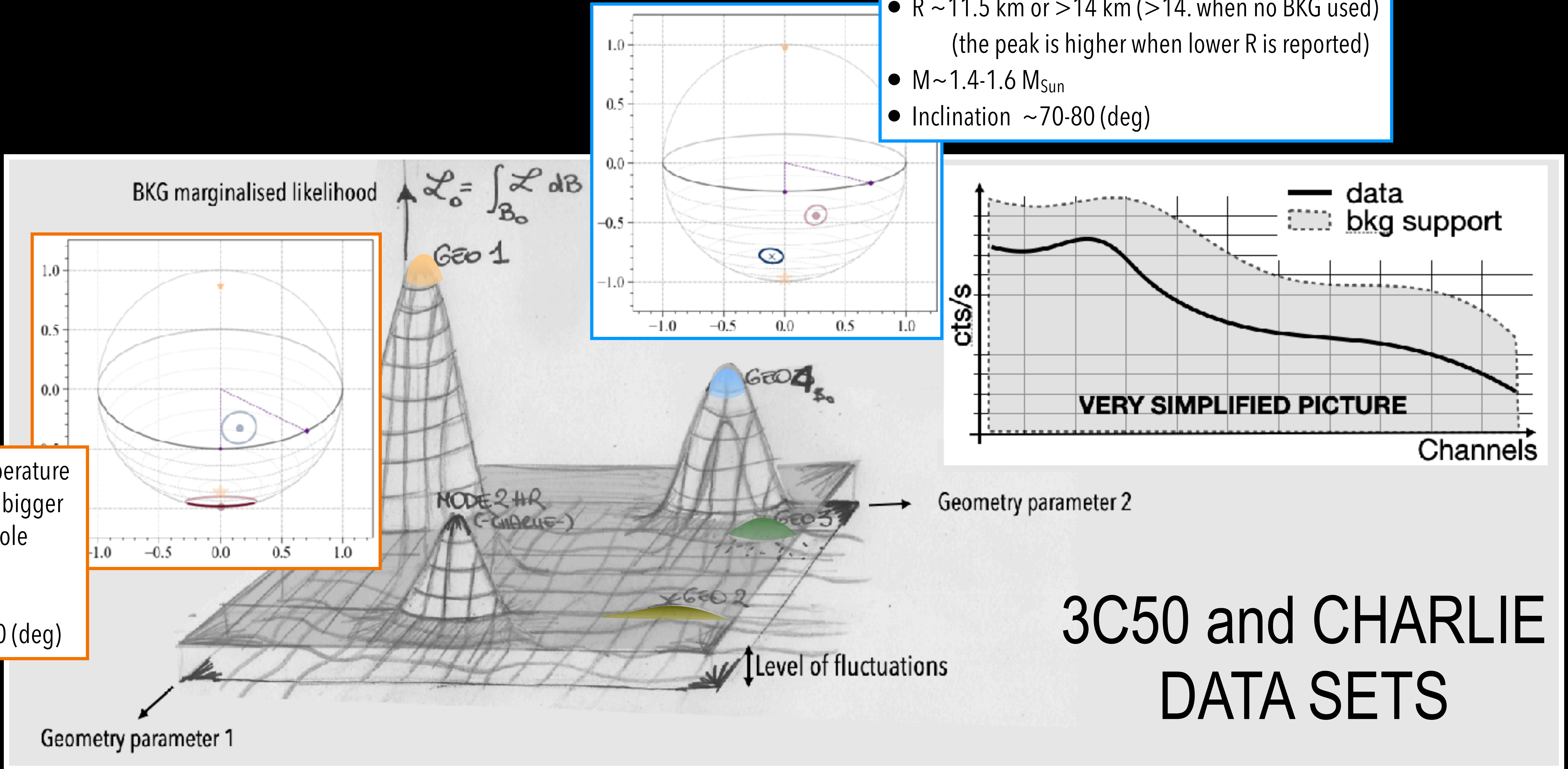




BKG CONSTRAINYS FOR J0030



ST-U ONLY
(NOT PREFERRED MODEL)

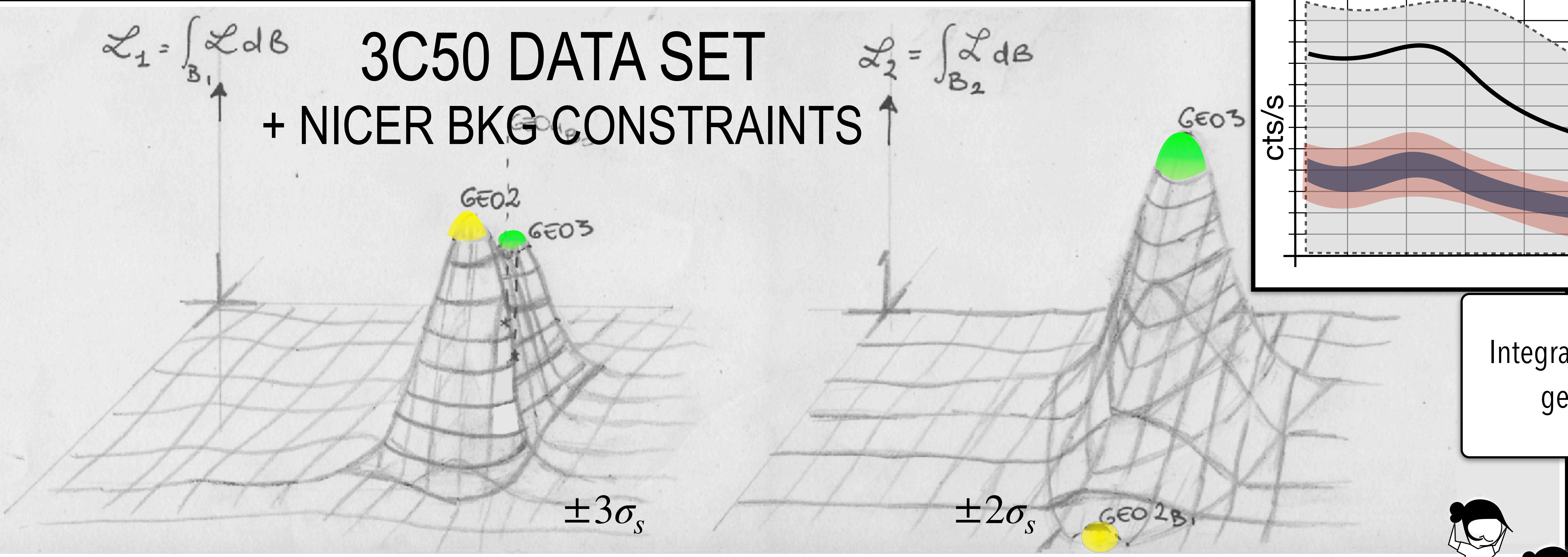


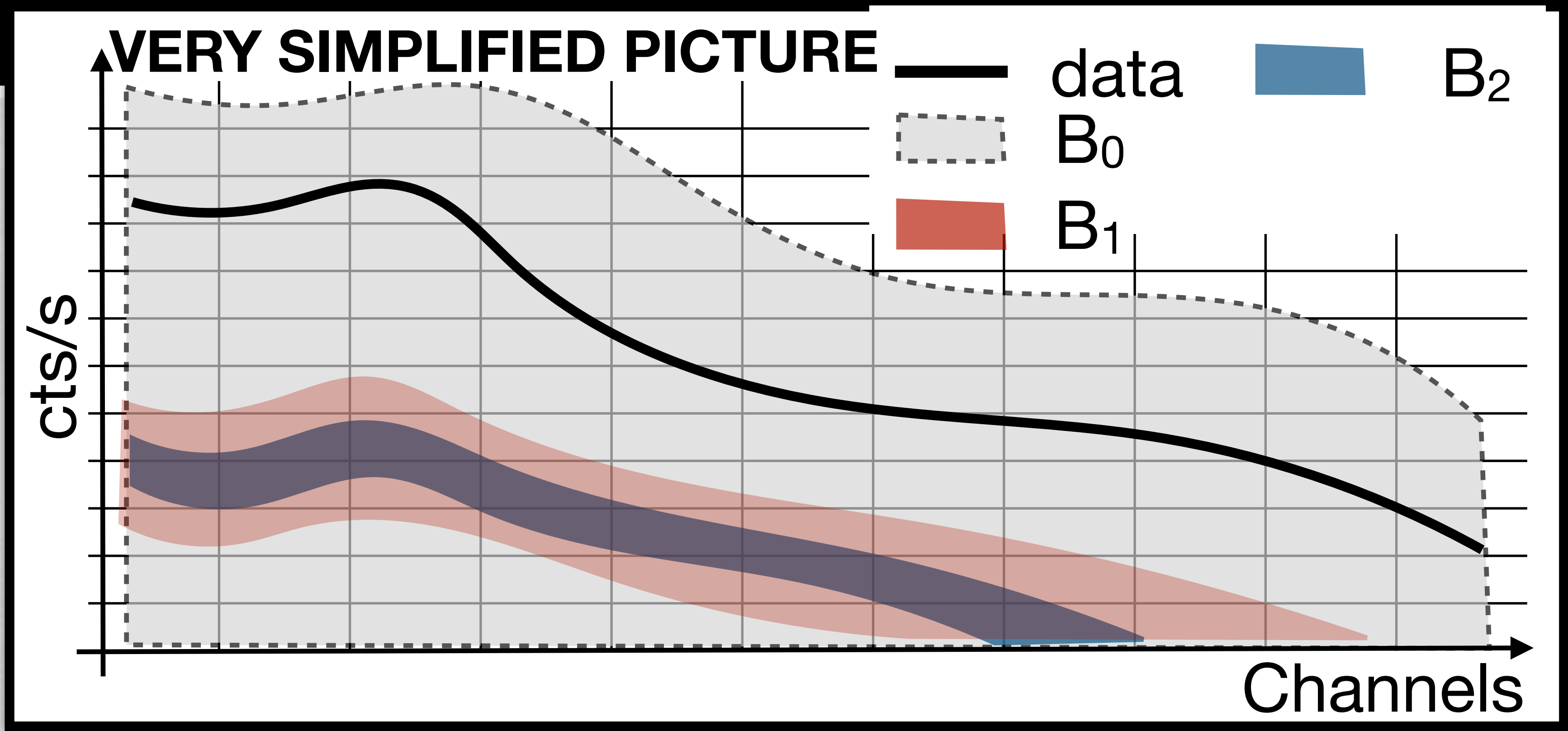
- Similar temperature and size for both hot spots
- R ~11.5 km or >14 km (>14. when no BKG used) (the peak is higher when lower R is reported)
- M~1.4-1.6 M_{Sun}
- Inclination ~70-80 (deg)

- Quite similar temperature for both hot spots, bigger one closer to the pole
- R ~10/11 km
- M~1 M_{Sun}
- Inclination ~60-70 (deg)

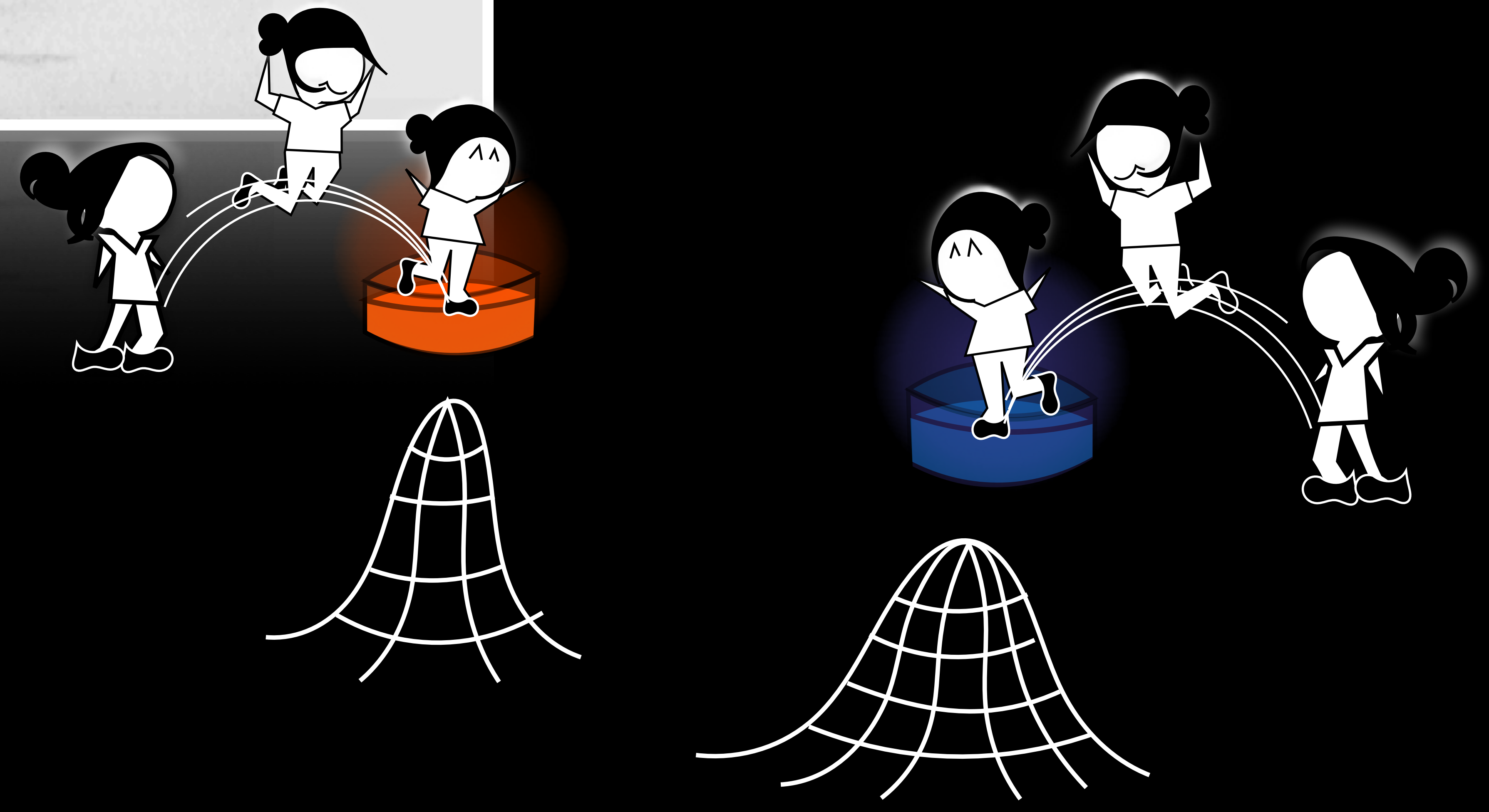
3C50 and CHARLIE DATA SETS

BKG CONSTRAINYS FOR J0030



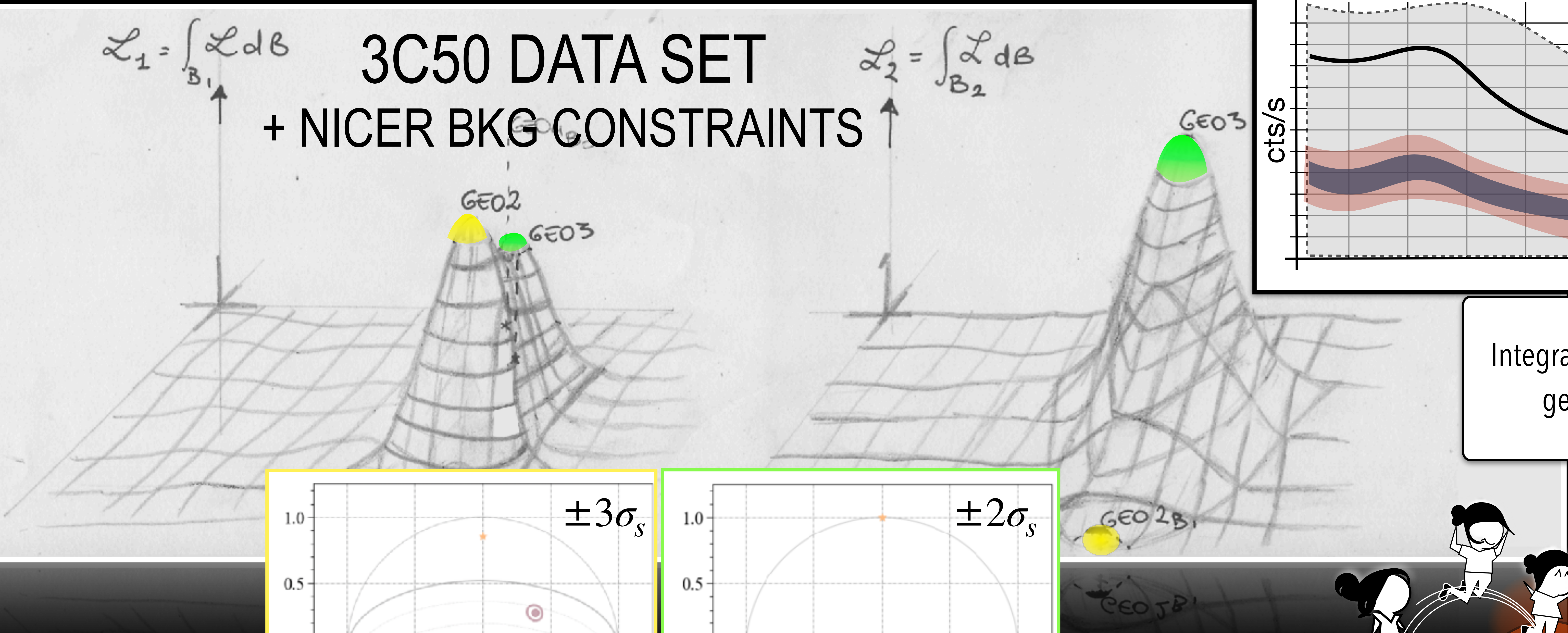


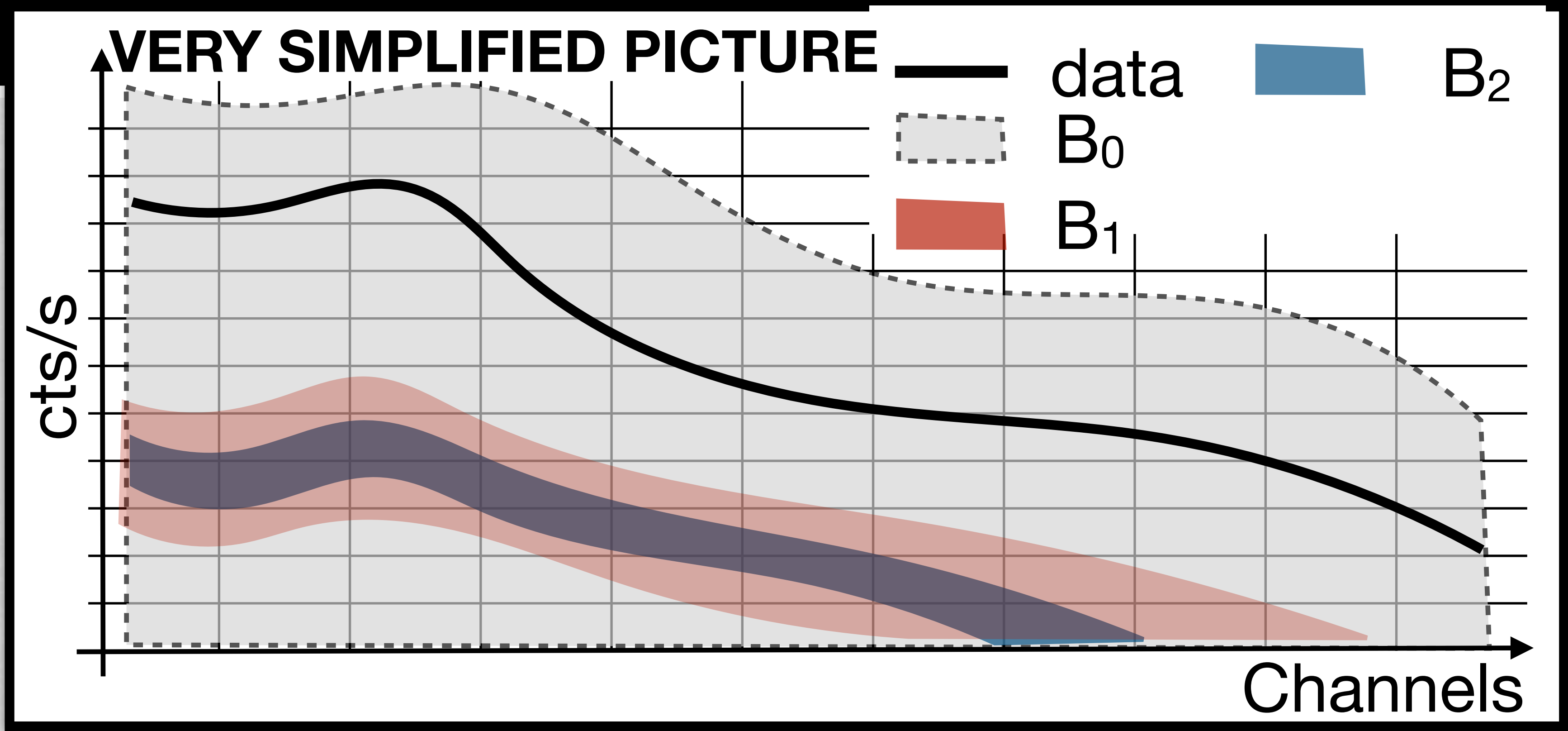
Integrated over different BKG ranges, some of the geometry parameter can slightly change



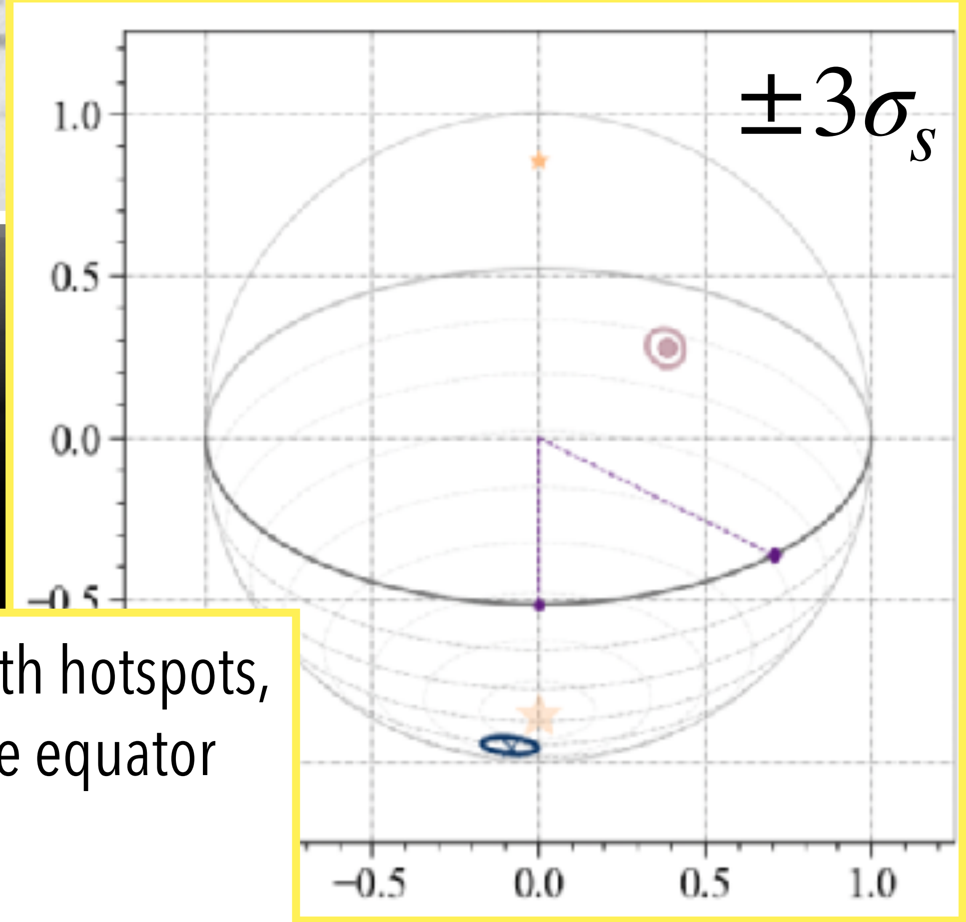
BKG CONSTRAINYS FOR J0030

3C50 DATA SET
+ NICER BKG CONSTRAINTS

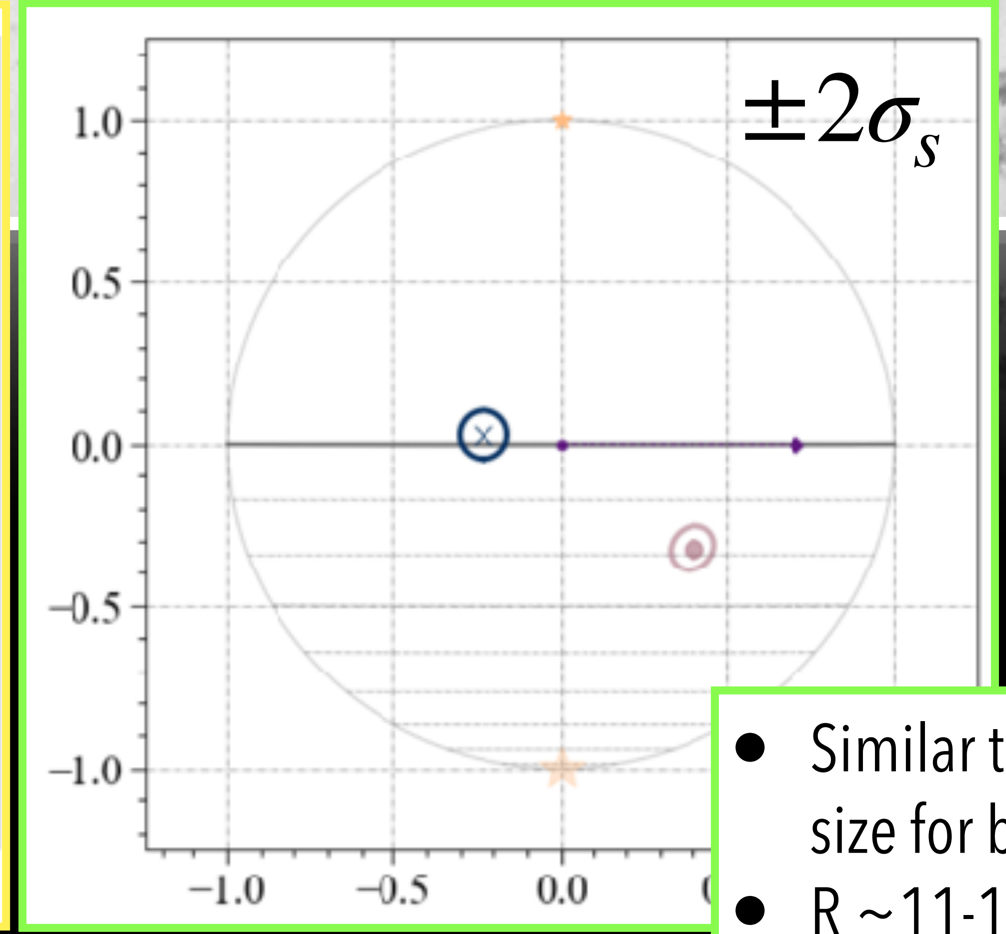




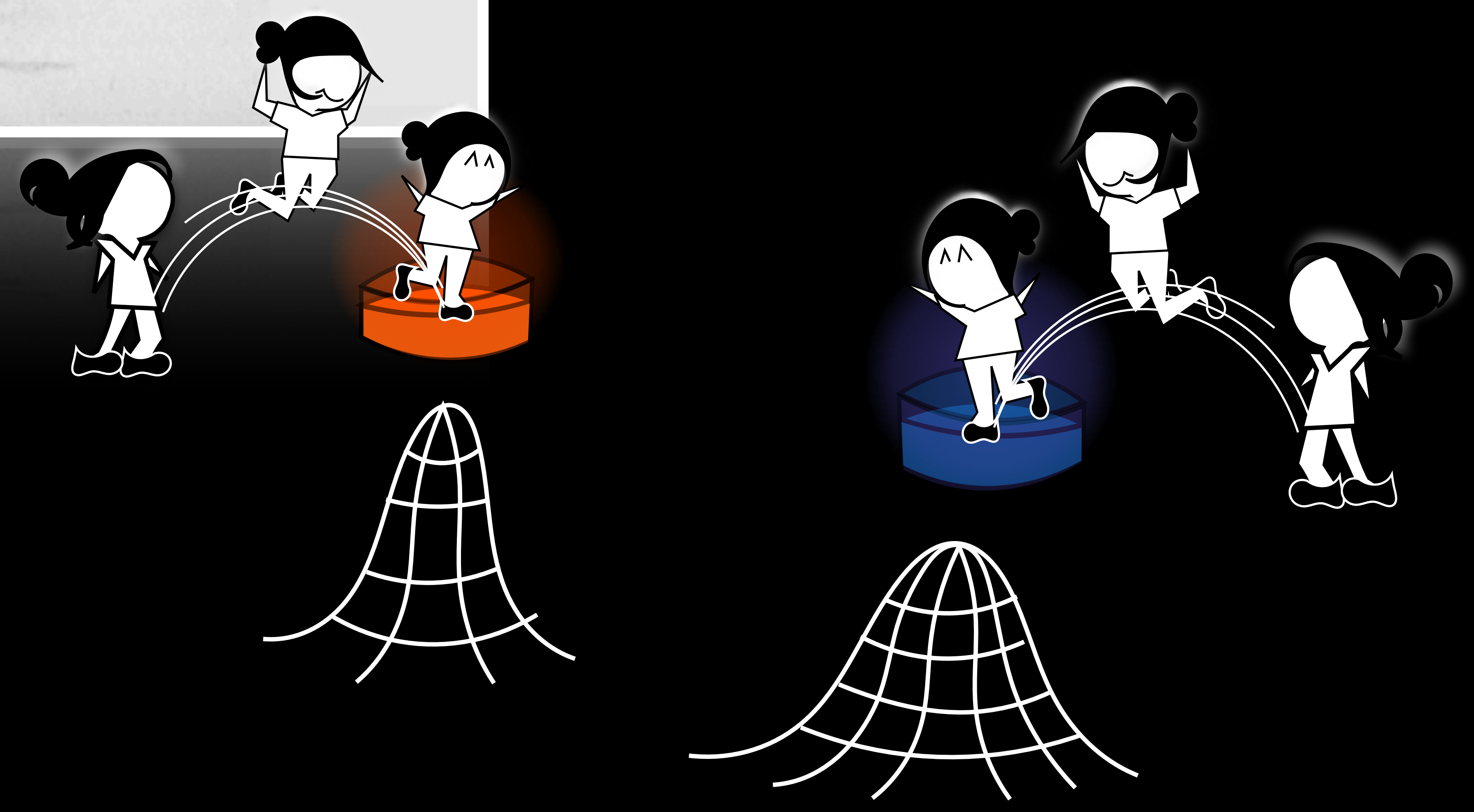
Integrated over different BKG ranges, some of the geometry parameter can slightly change



- Similar size for both hotspots, colder closer to the equator
- R ~14-16 km
- M~2 Msun
- Inclination 50-60 (deg)



- Similar temperature and size for both hot spots
- R ~11-13 km
- M~1.4-1.6 Msun
- Inclination 80-90



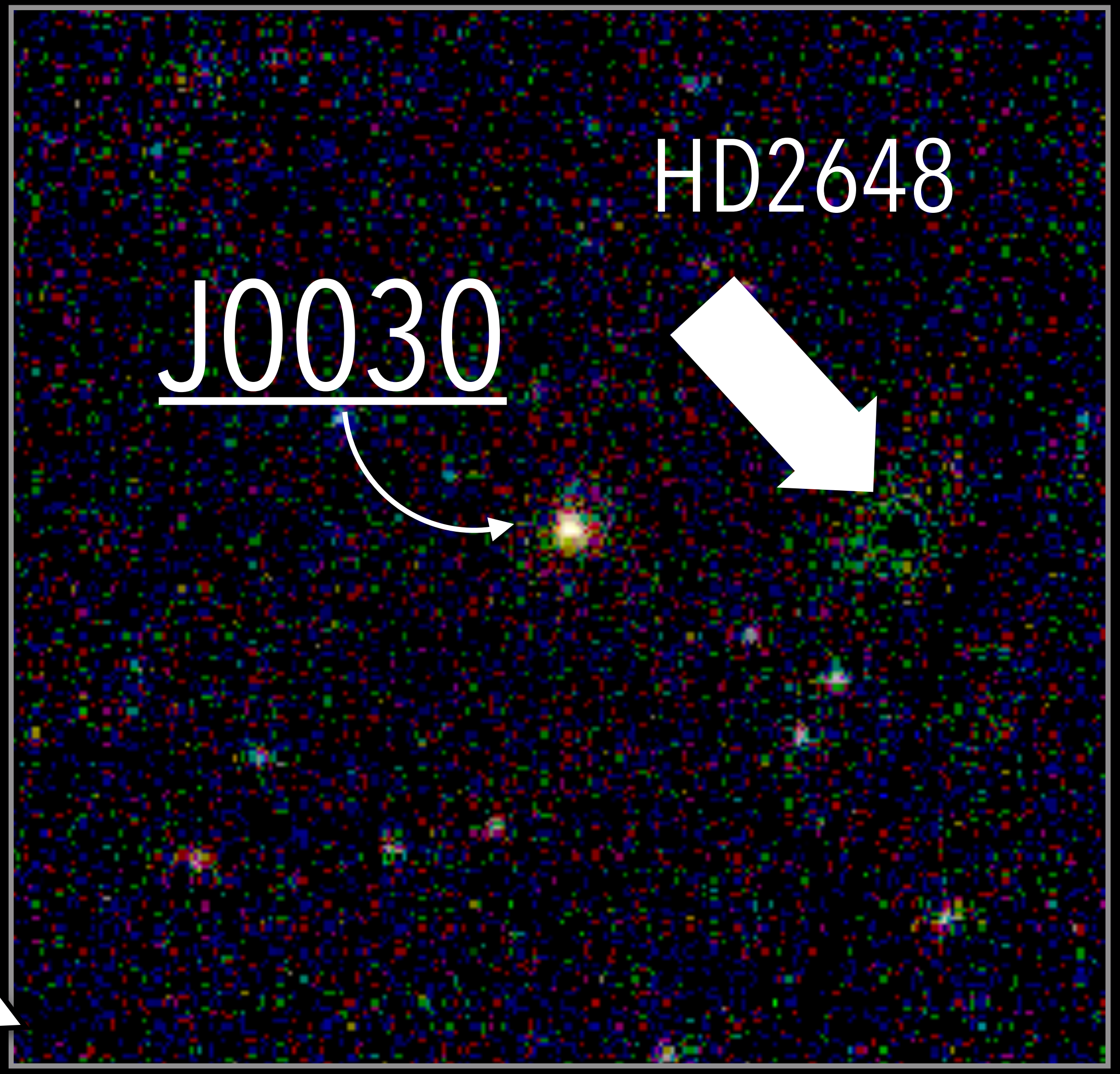
BKG CONSTRAINYS FOR

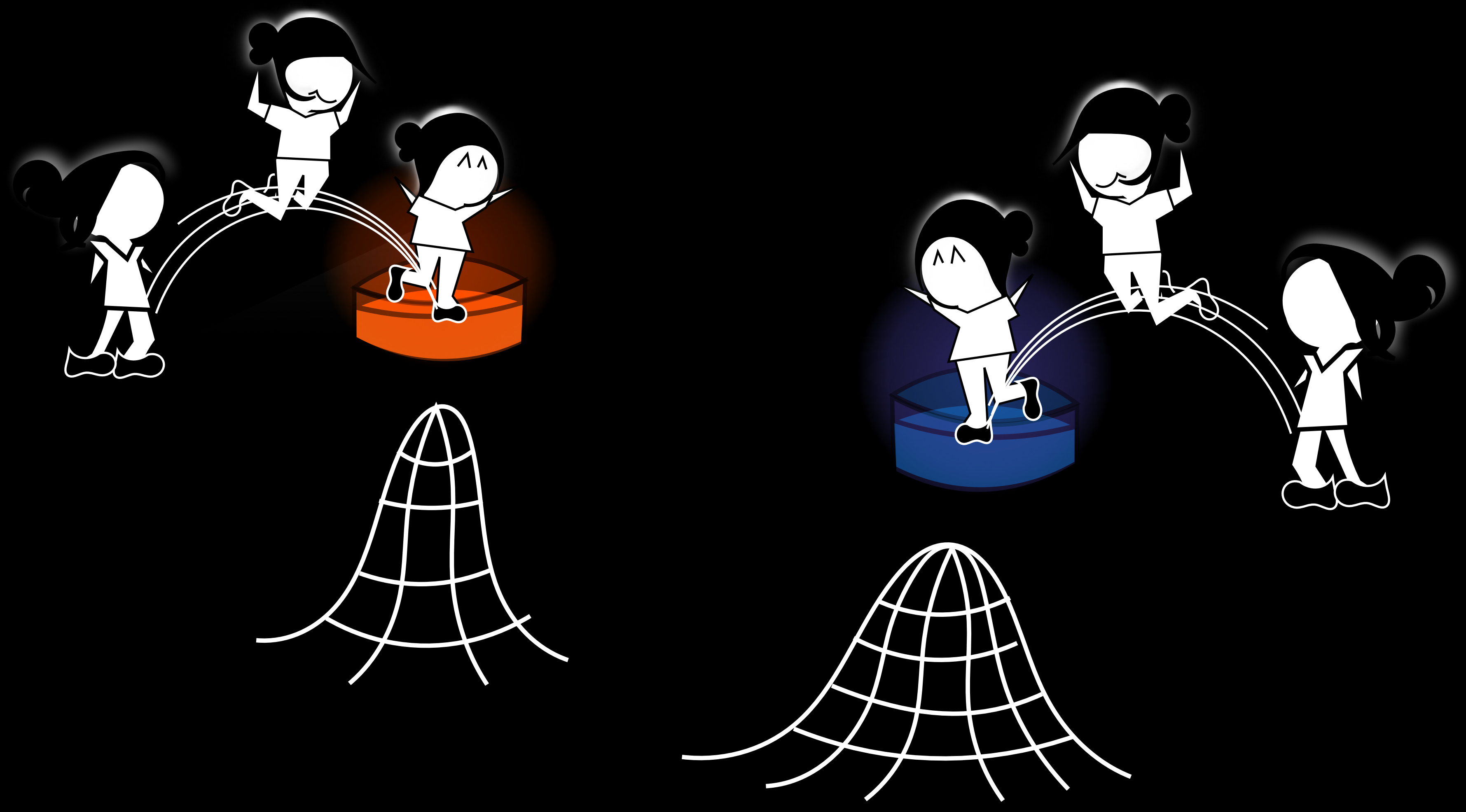
BIGGEST EFFECTS MADE BY UPPER LIMITS

$\mathcal{L}_1 = \int_{B_1} \mathcal{L} \, dB$

BUT

WE DID NOT CONSIDER THE CONTRIBUTION OF THE HD2648 STAR
(i.e. our analysis applied upper limits too stringent as the contribution of the star was not accounted for)

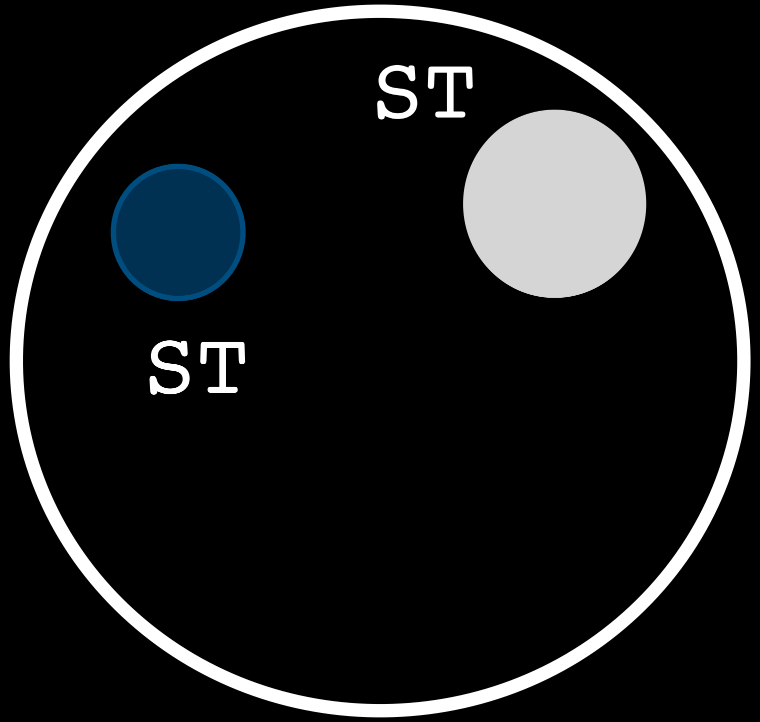


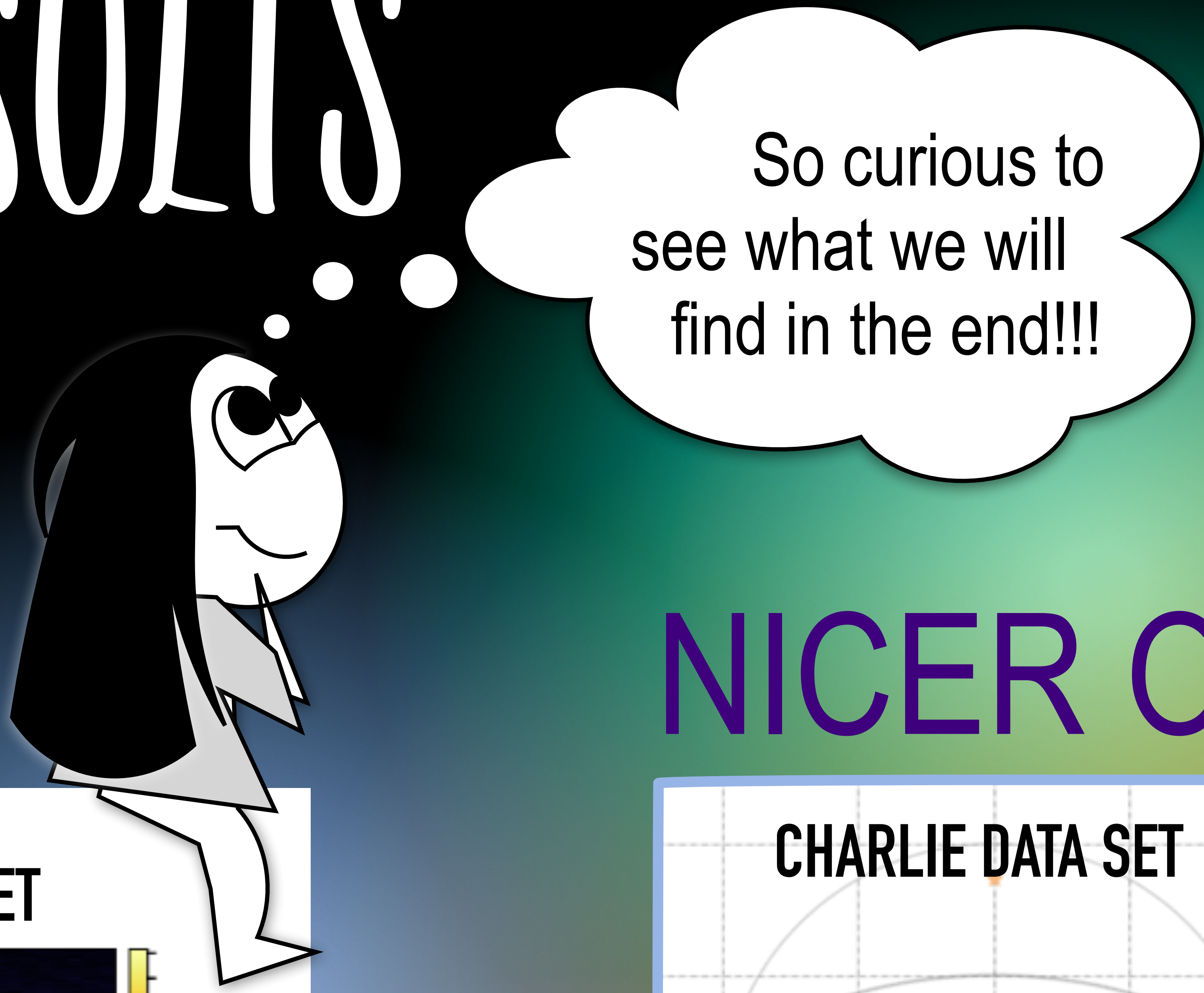


pots
km
1.4-1.6 Msun
- Inclination 80-90

RESULTS

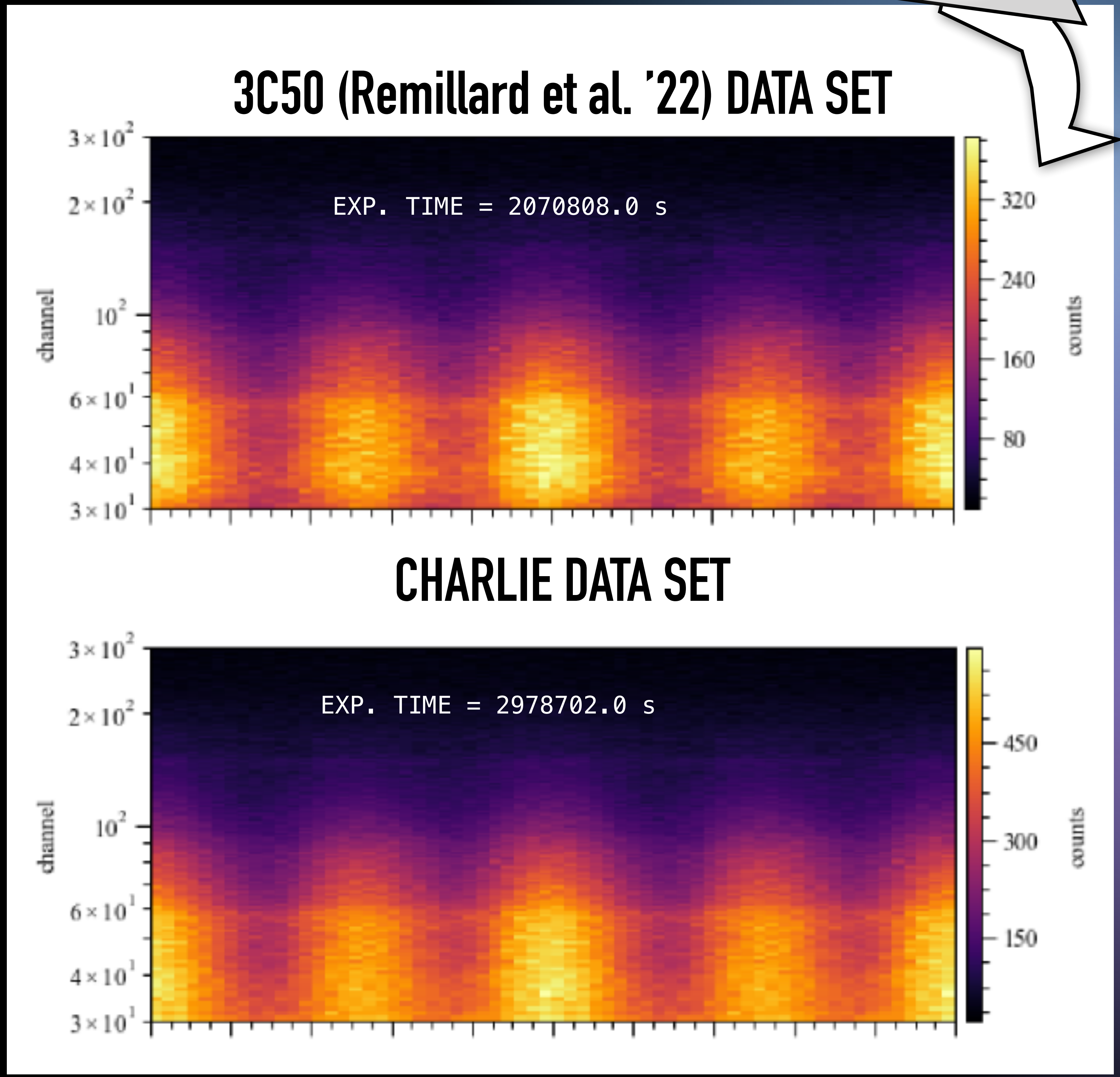
J0030+0451



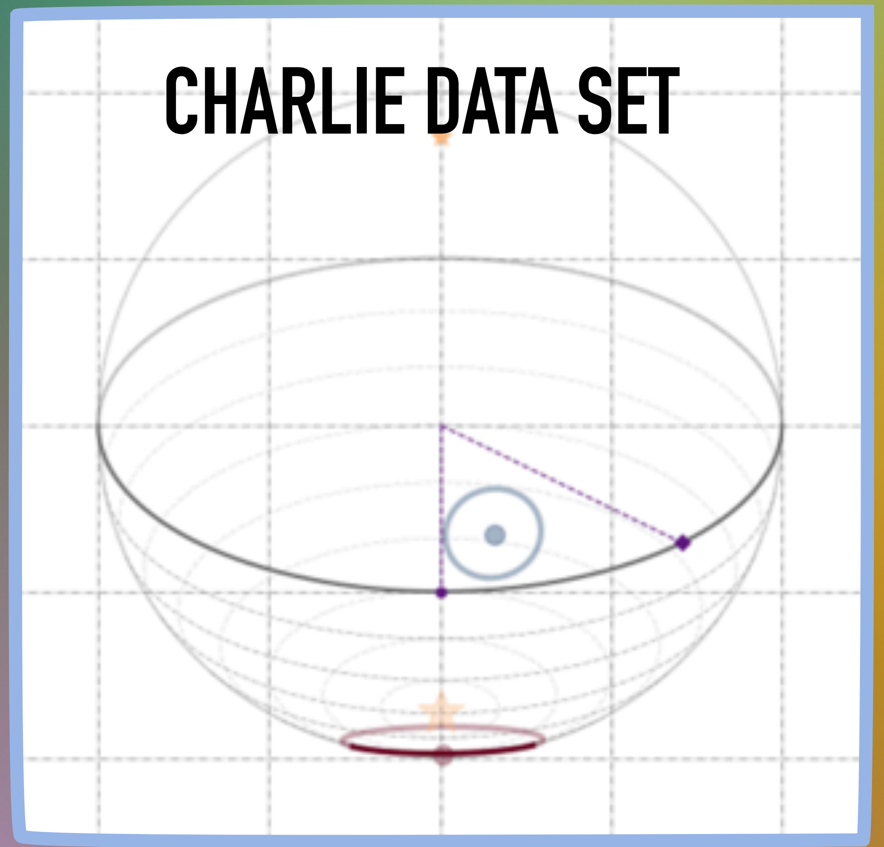


ST-U ONLY

(NOT PREFERRED MODEL)

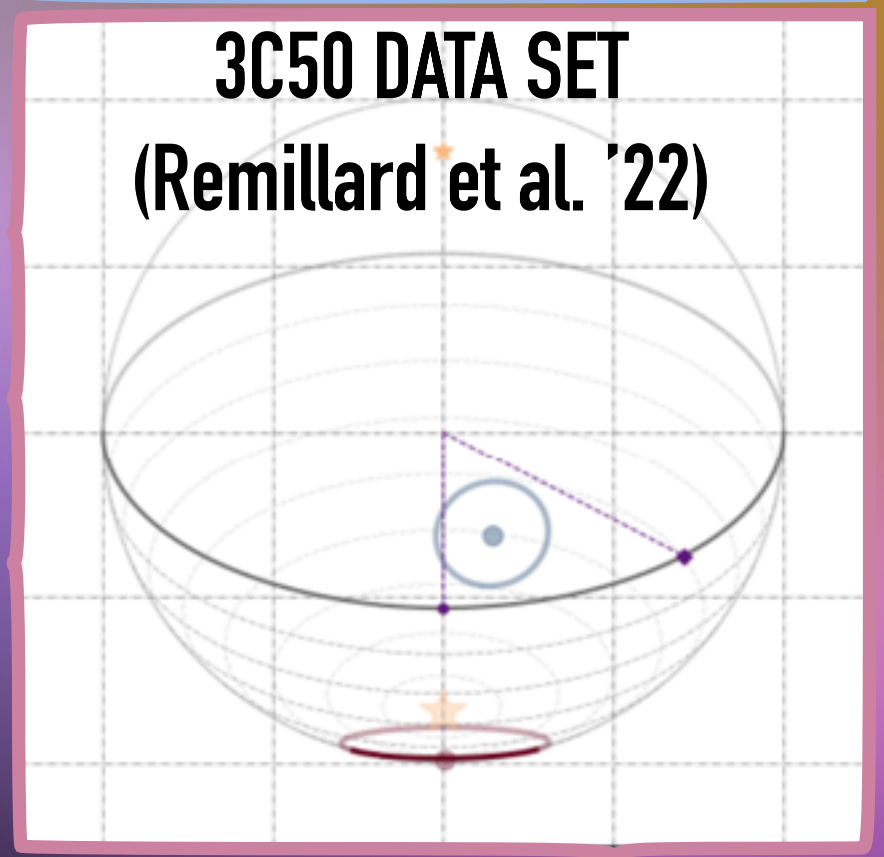


NICER ONLY



$R \sim 10\,\mathrm{km}$

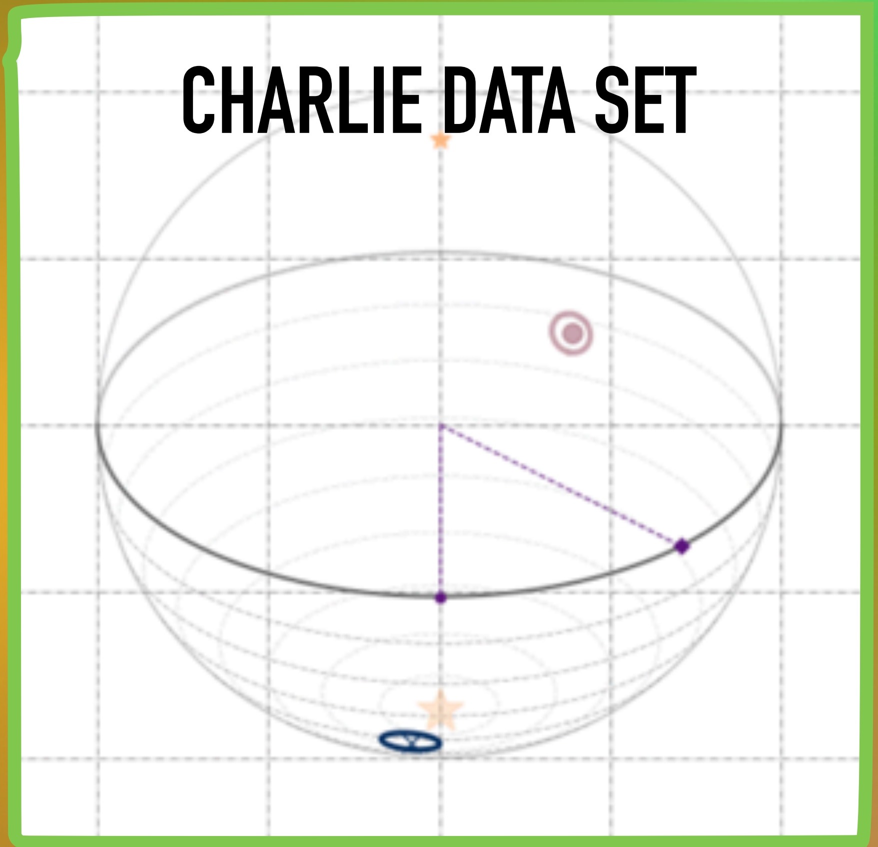
$M \sim 1.1\,\mathrm{M}_\odot$



$R \sim 11.5\,\mathrm{km}$

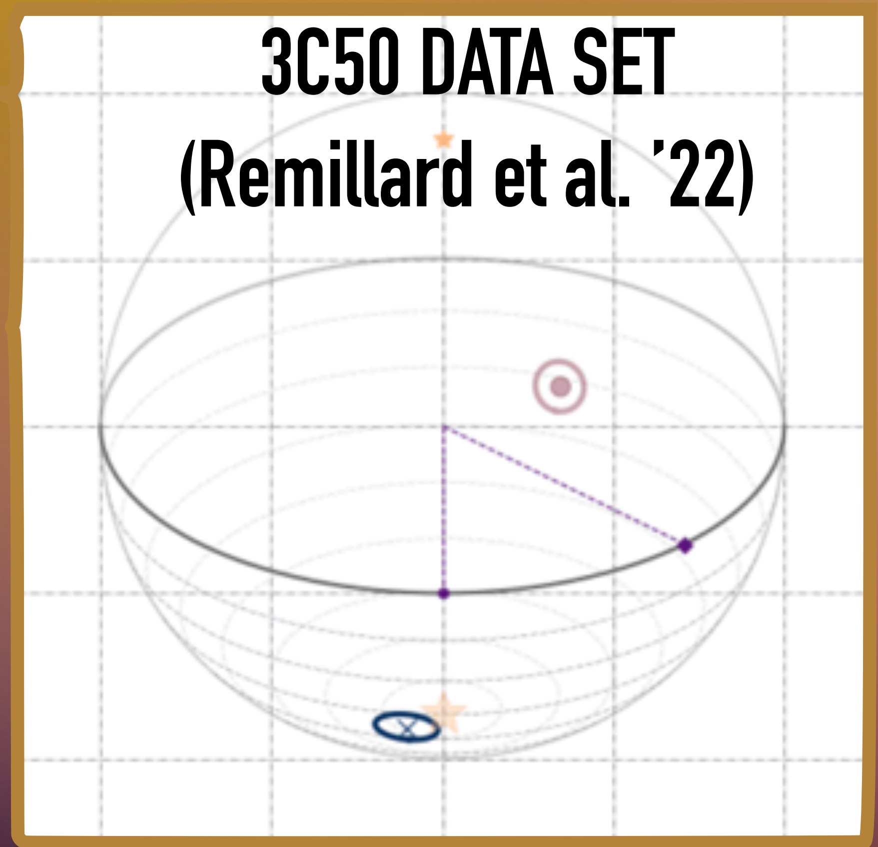
$M \sim 1.1\,\mathrm{M}_\odot$

NICER&XMM



$R \sim 16\,\mathrm{km}$

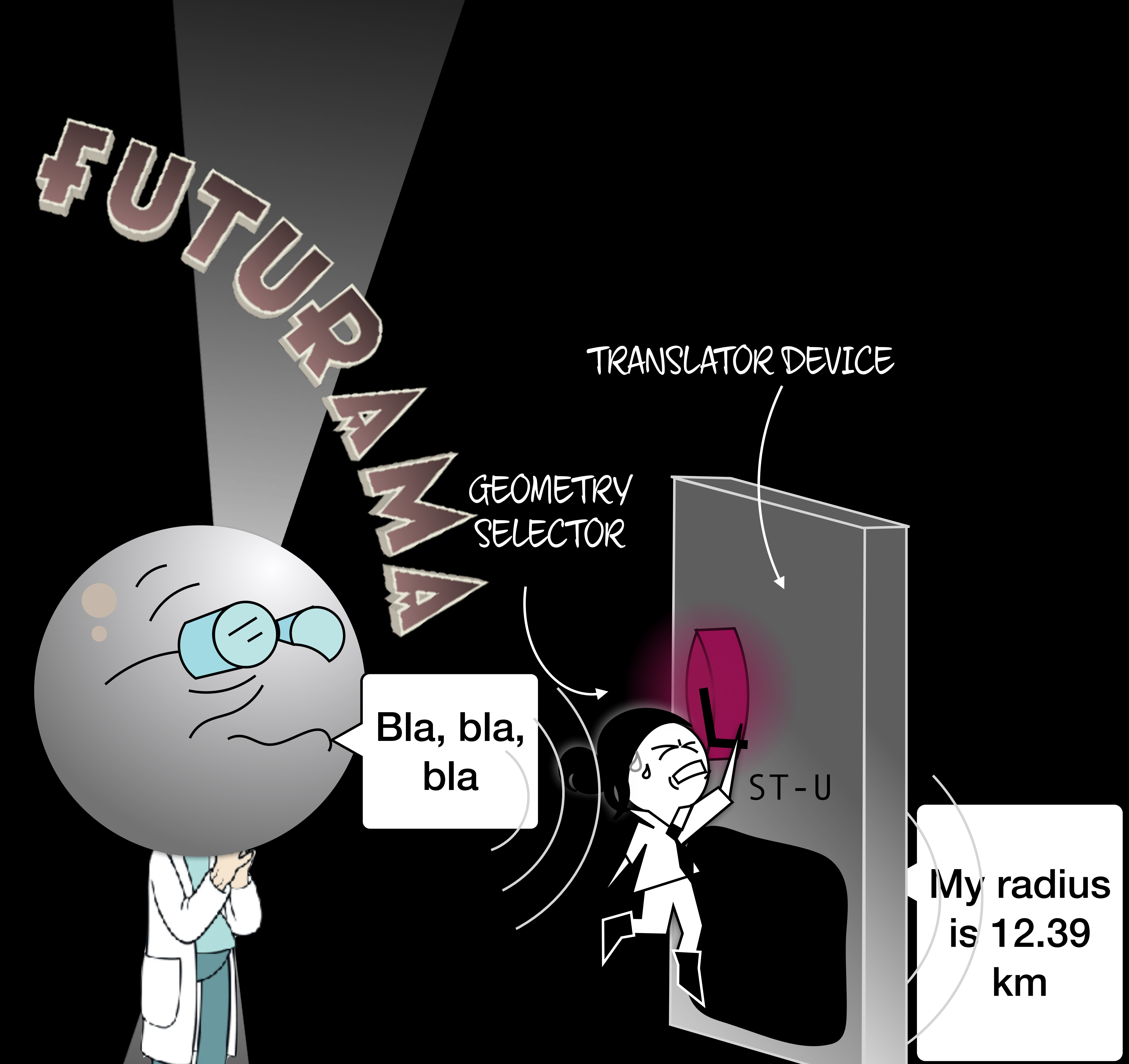
$M \sim 2\,\mathrm{M}_\odot$



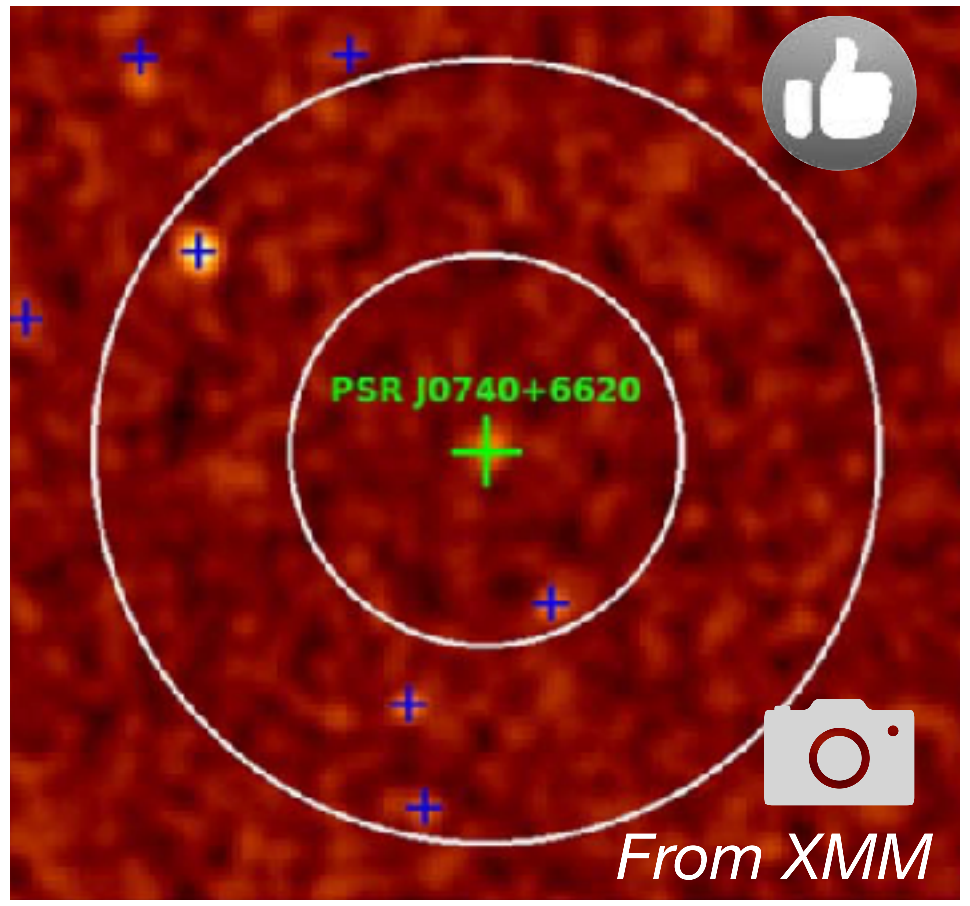
$R \sim 14.5\,\mathrm{km}$

$M \sim 1.9\,\mathrm{M}_\odot$

THE CASE OF J0740+6620

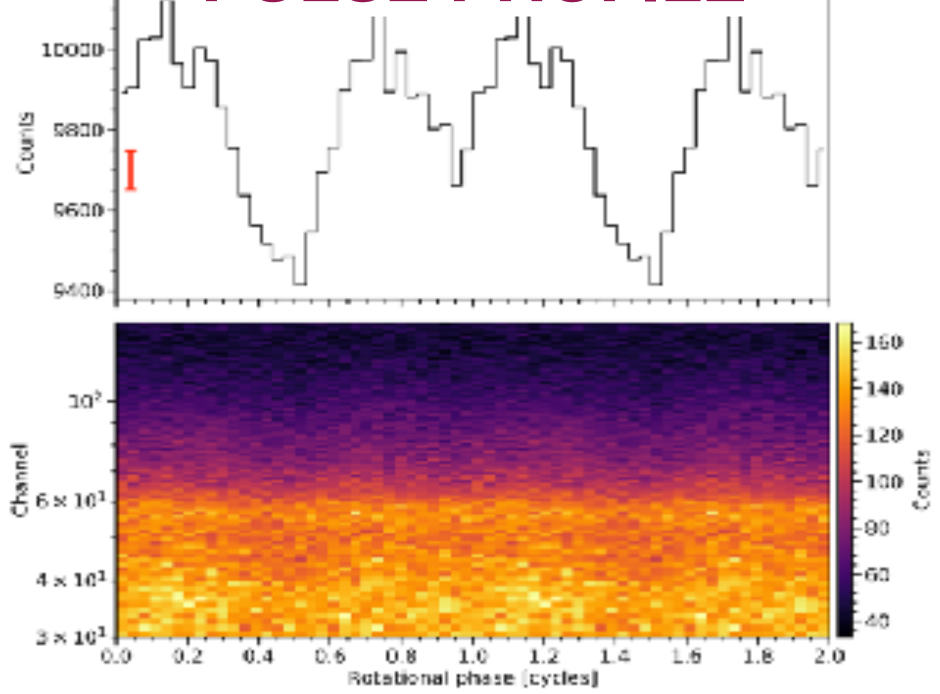


Riley et al 2021



STATUS	BINARY
REFERENC	Riley et al 2021
INSTRUME	NICER

PULSE PROFILE



See also independent analysis: Miller et al 2021

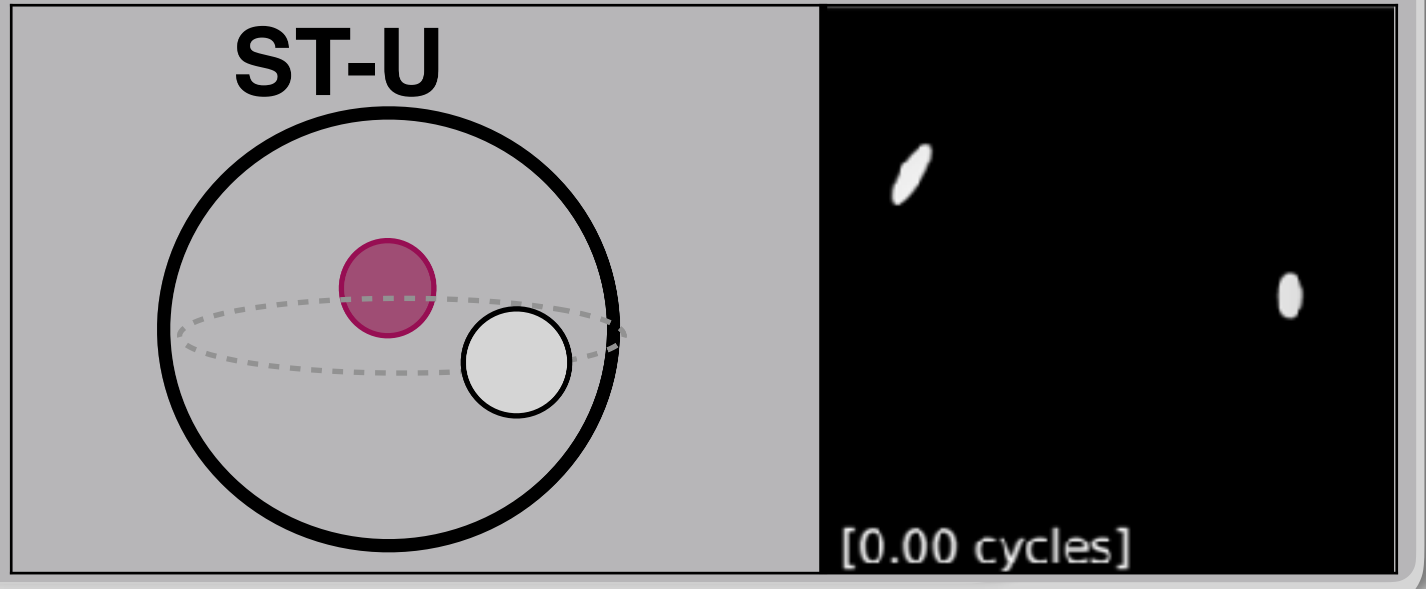
J0740+6620

About | Photos | History

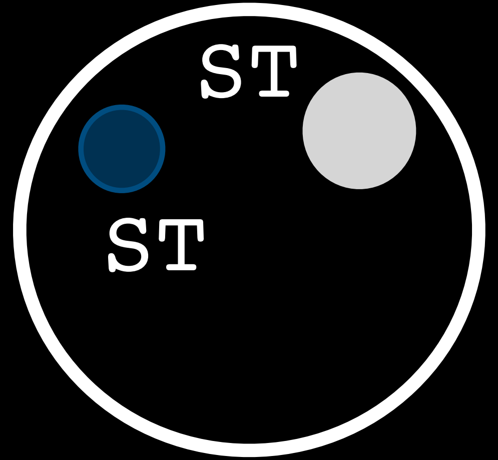
Its details

Mass [M_{Sun}]	2.07
Radius [km]	12.39
Compactness	0.16

MODEL

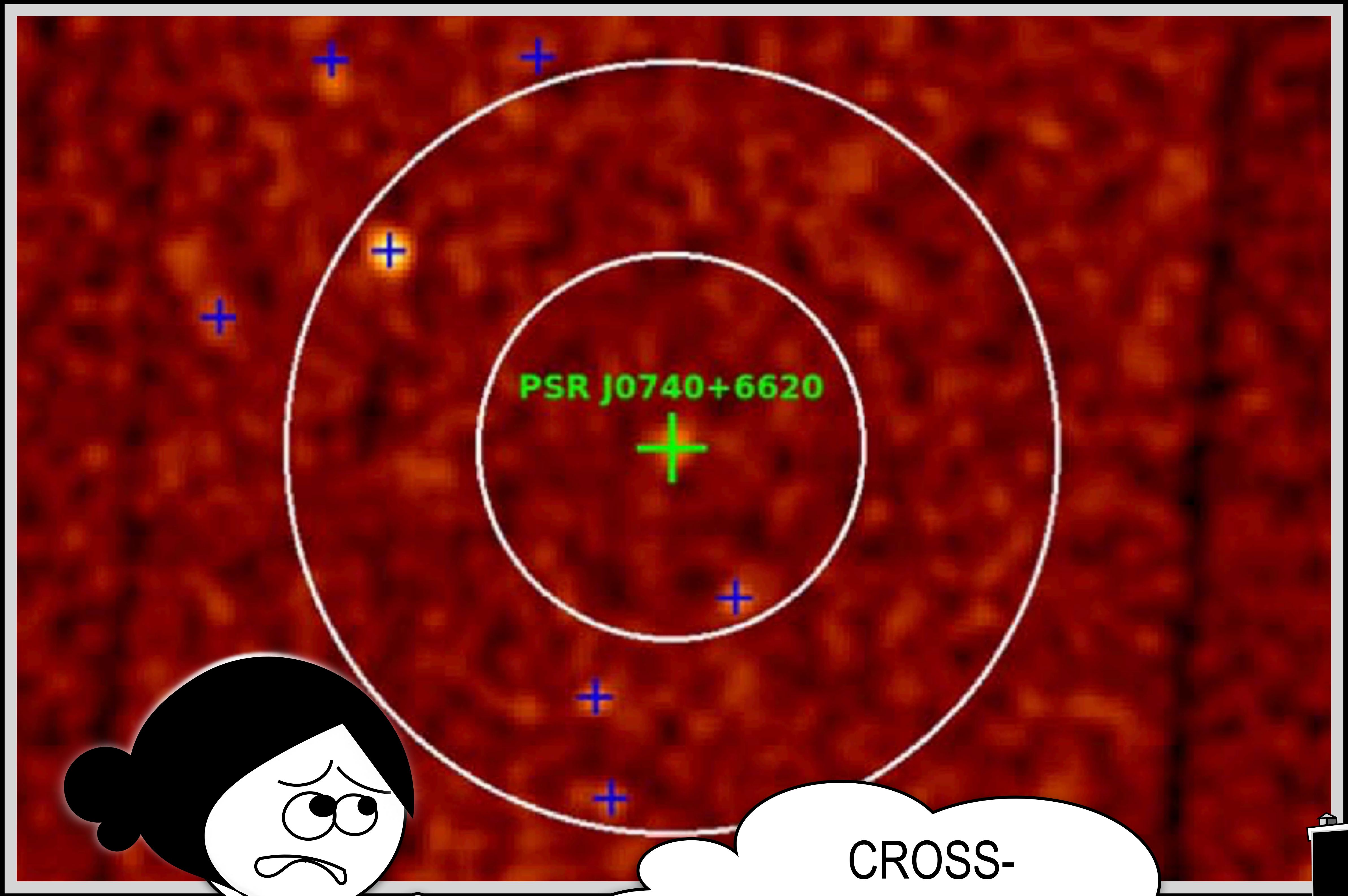


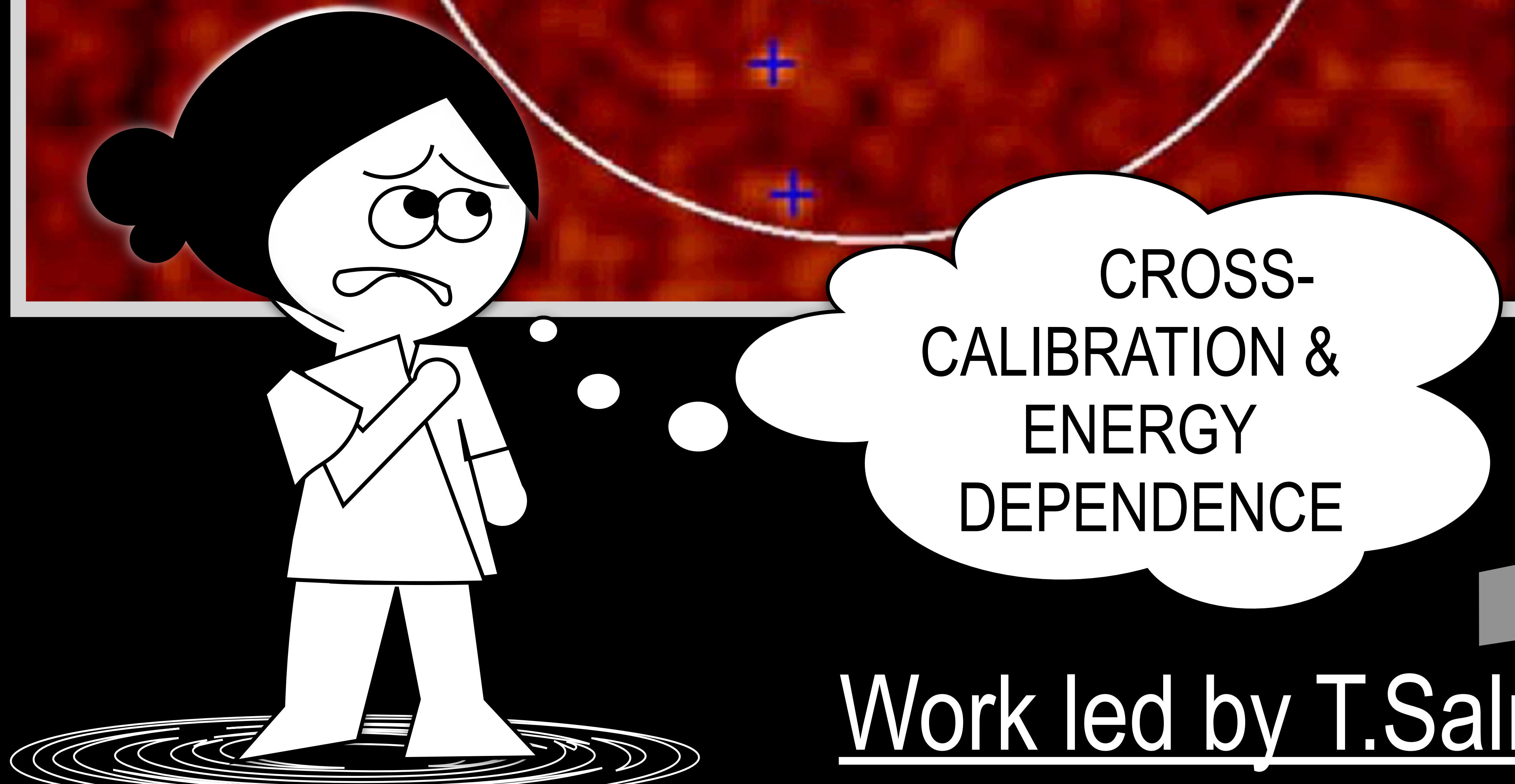
THE CASE OF J0740+6620

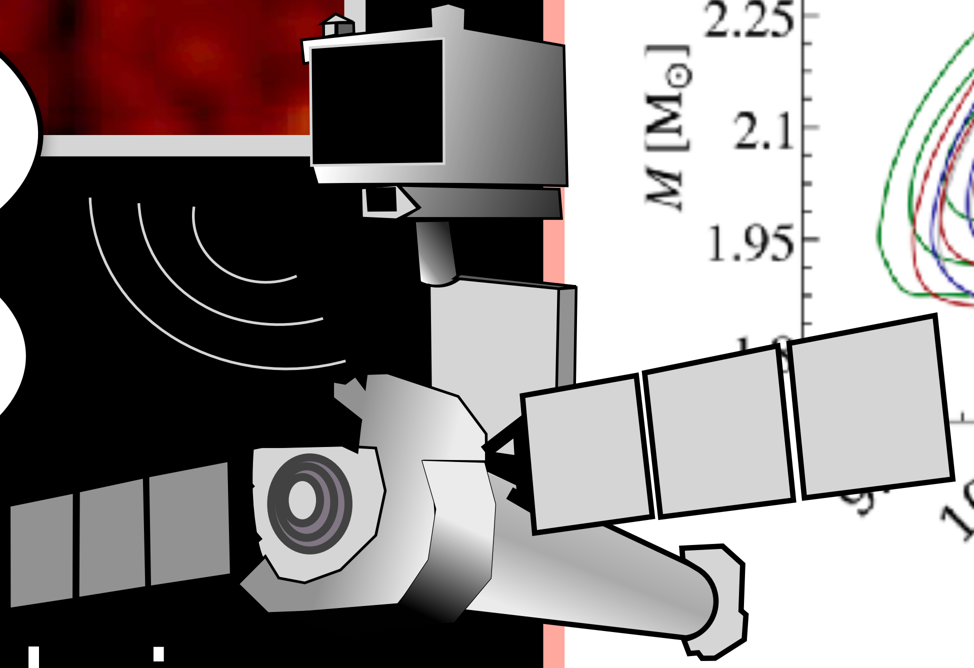


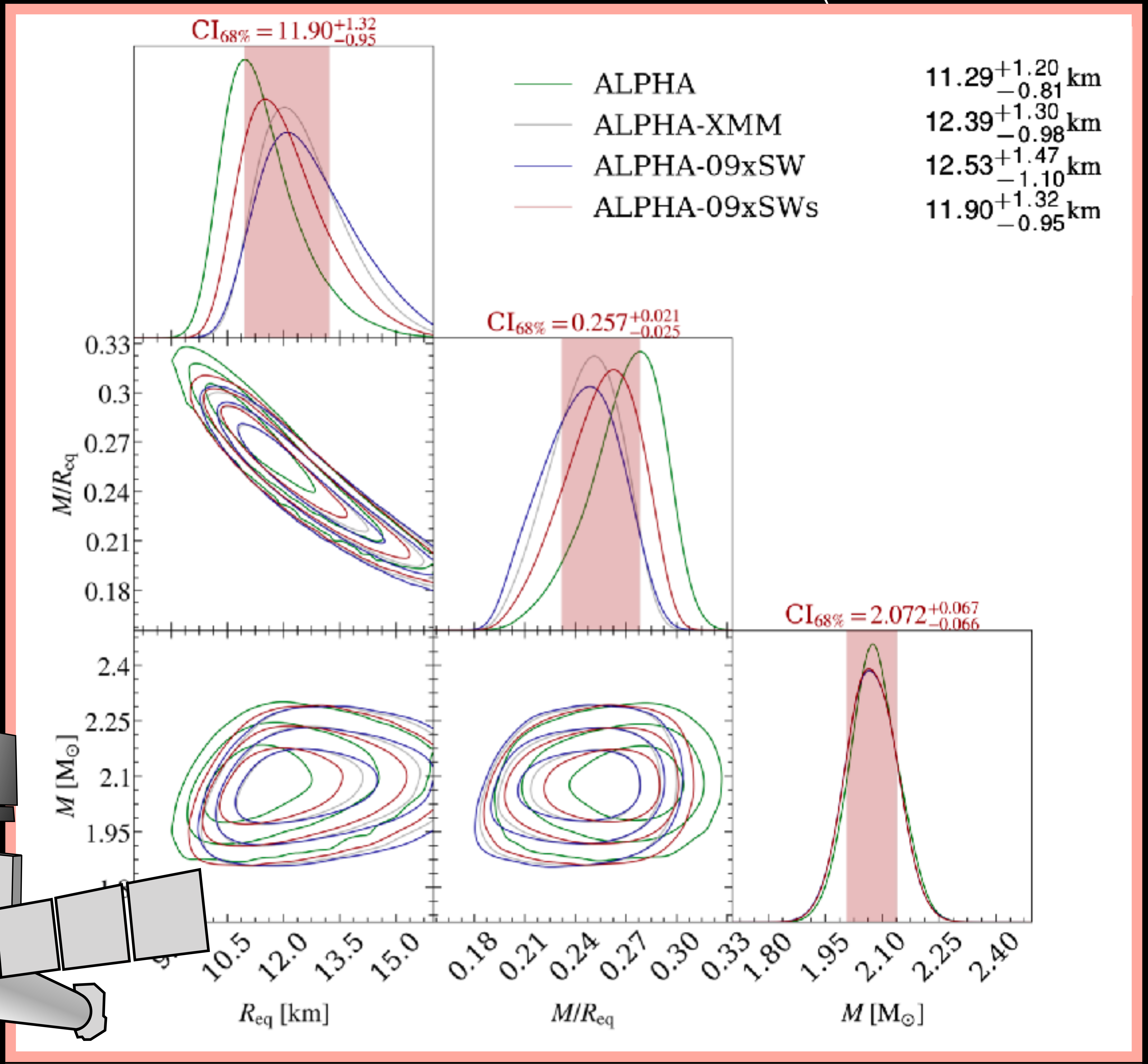
Wolff et al 2021

ST-U (PREFERRED MODEL)



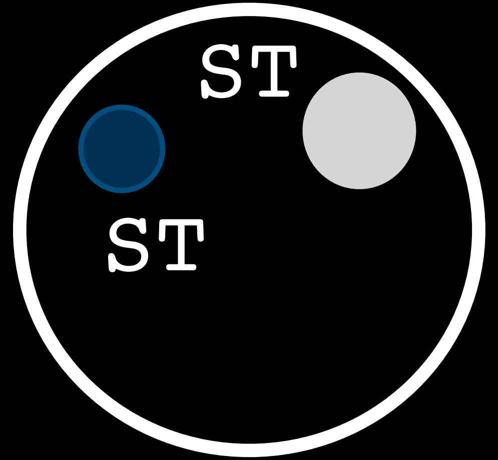




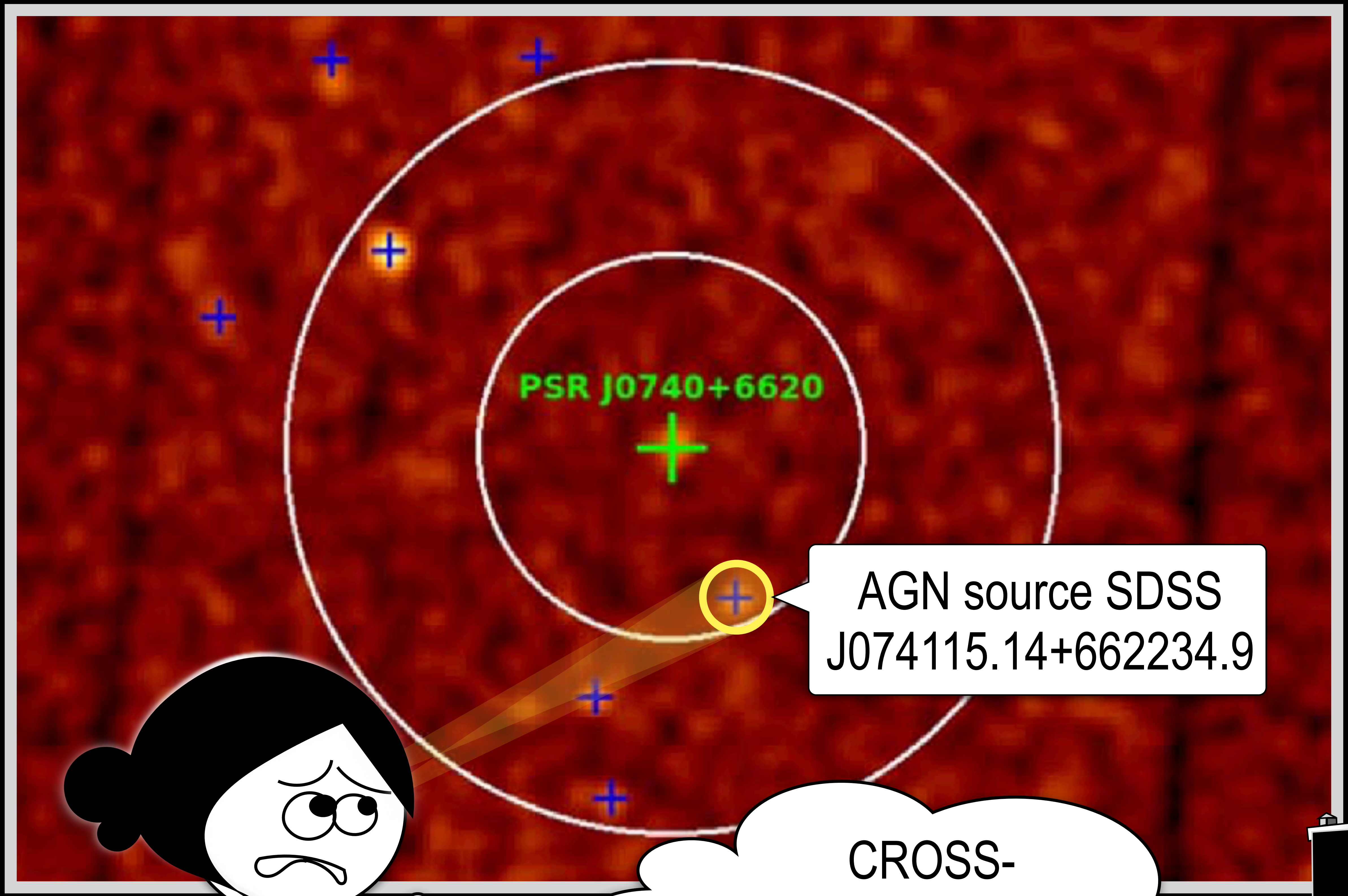


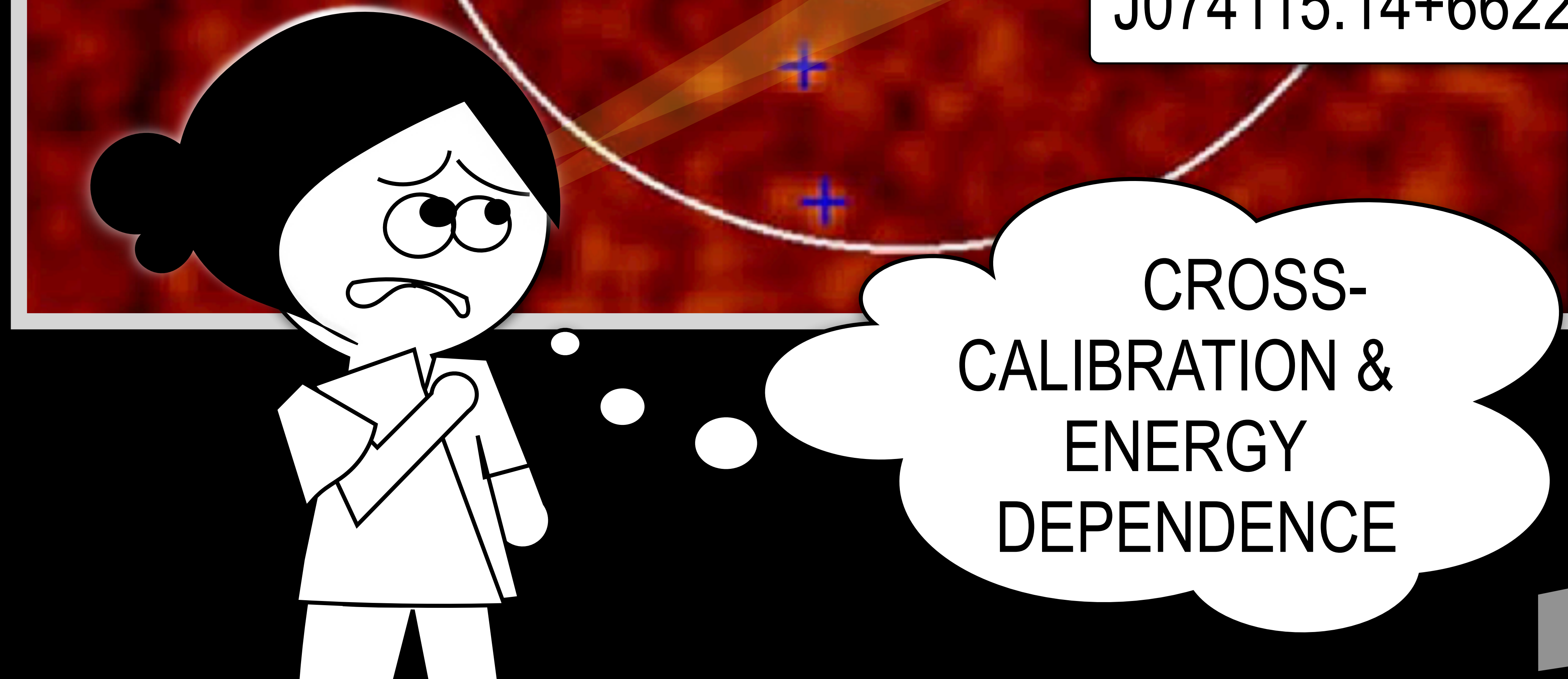
Work led by T.Salmi

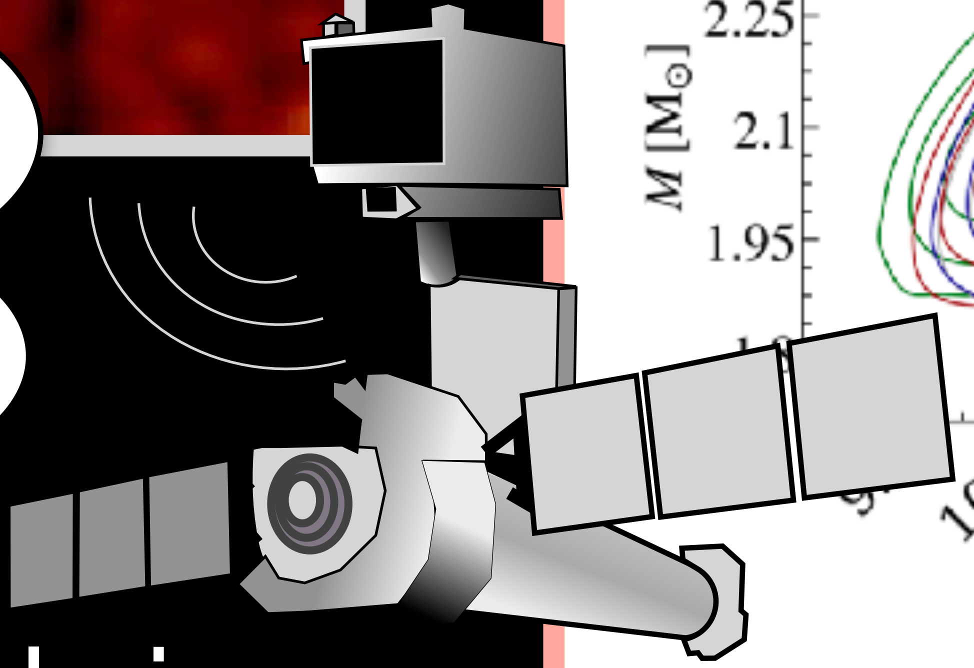
THE CASE OF J0740+6620



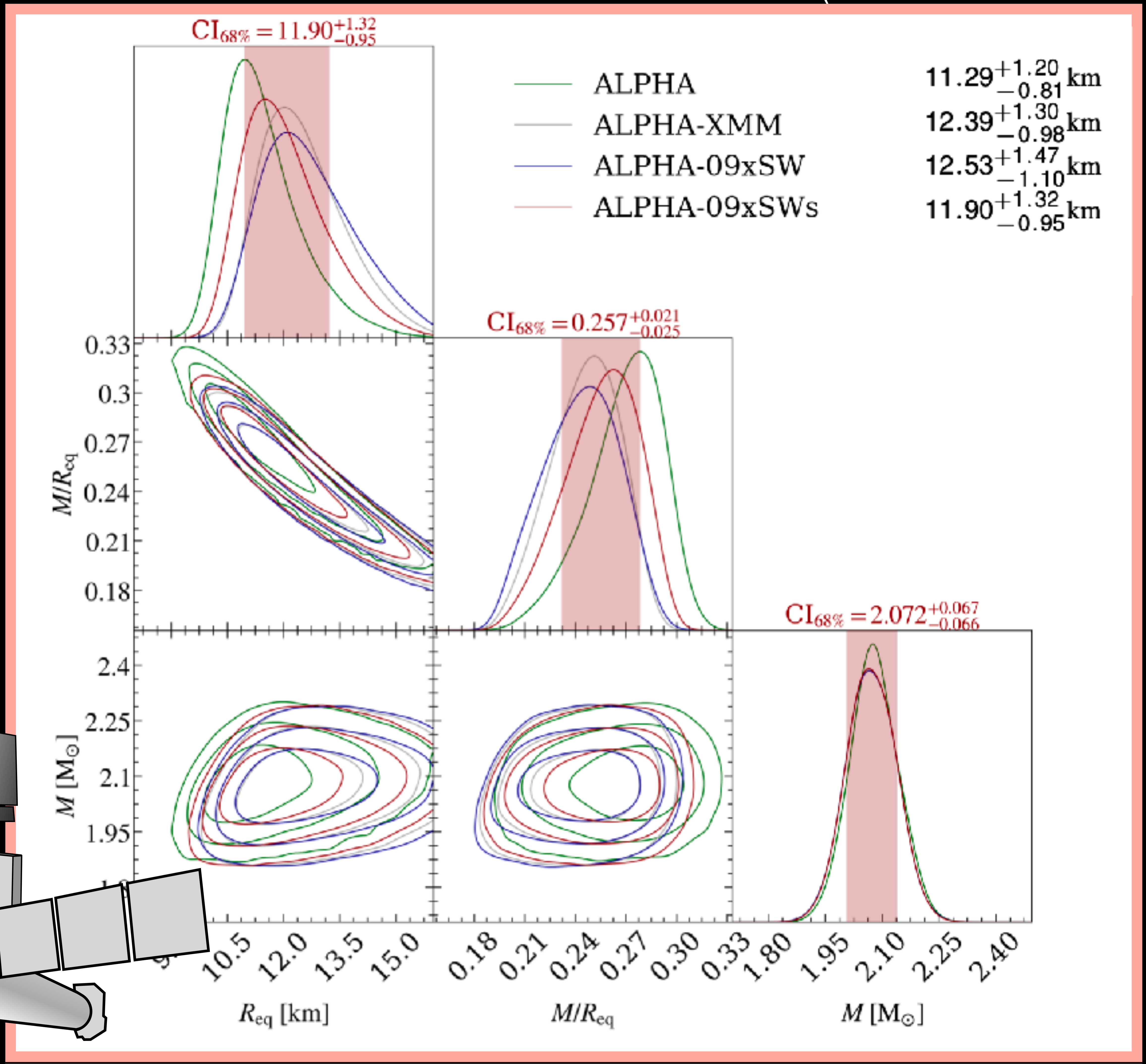
Wolff et al 2021







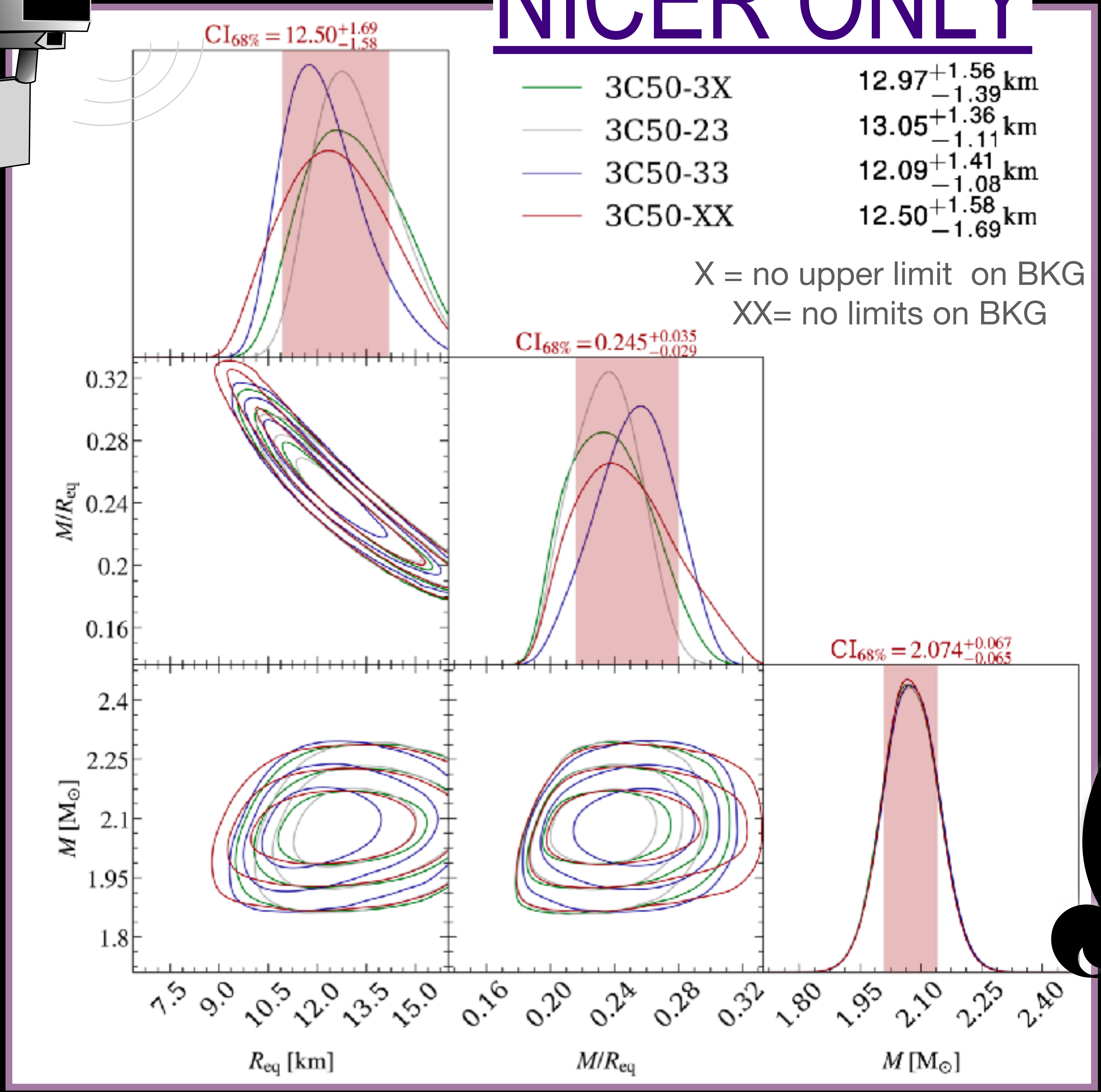
ST-U (PREFERRED MODEL)



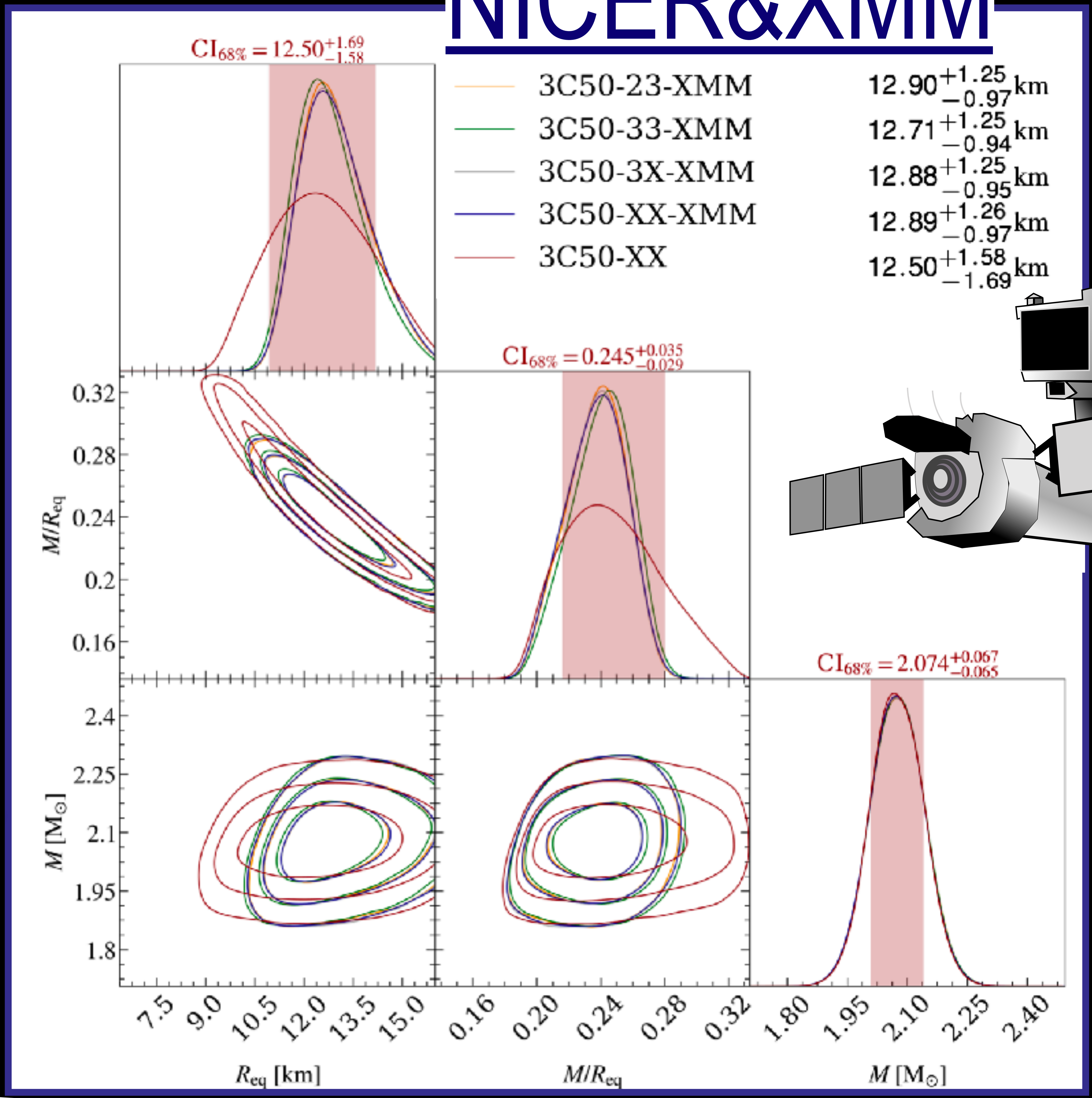
Work led by T.Salmi

BKG CONSTRAINYS FOR J0740+6620

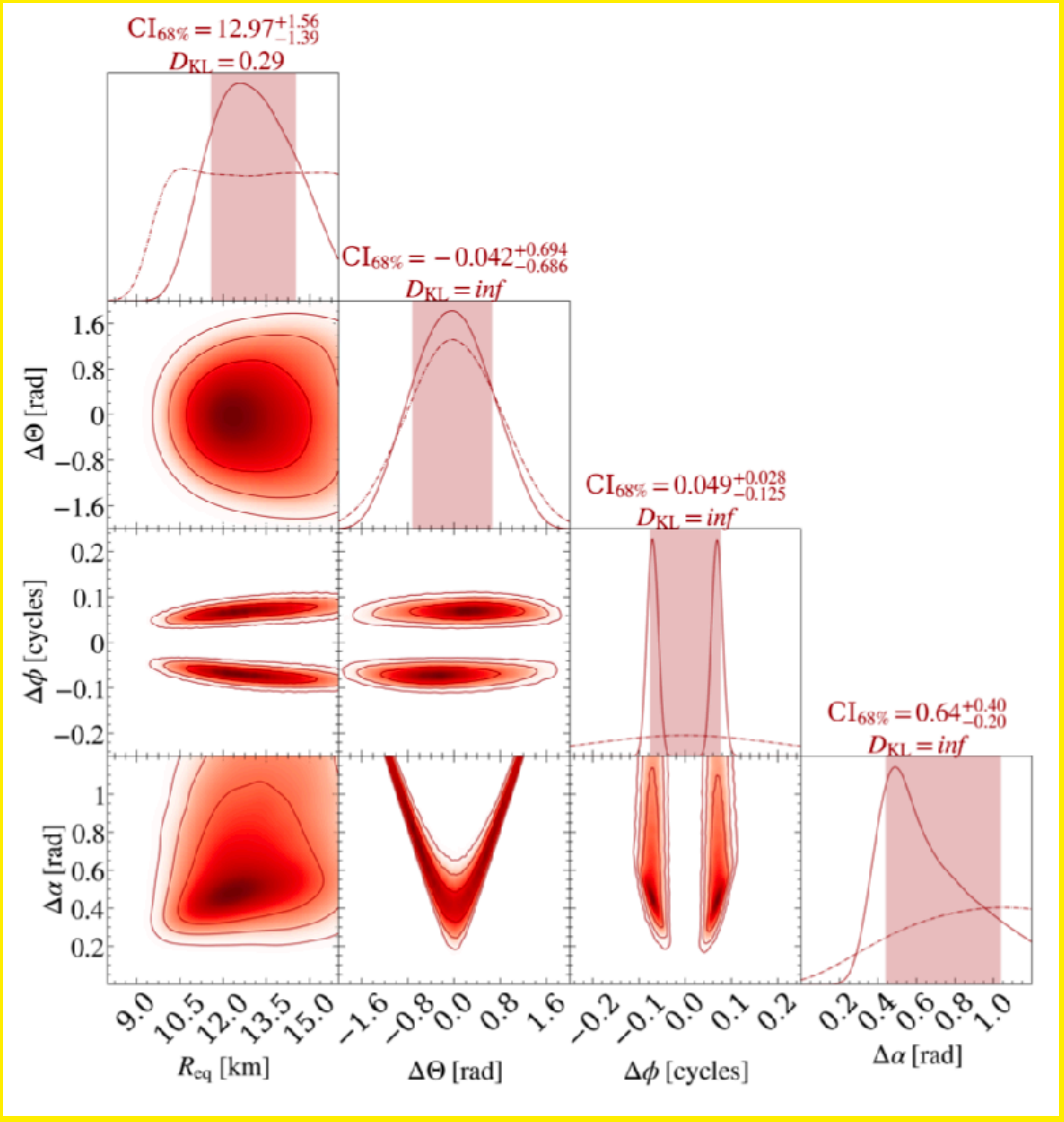
NICER ONLY



NICER&XMM



ANTIPODALITY



For all our analyses, most of the parameters are found to be consistent with Riley et al 2021 (few differences for 3C50 can be explained by different data)

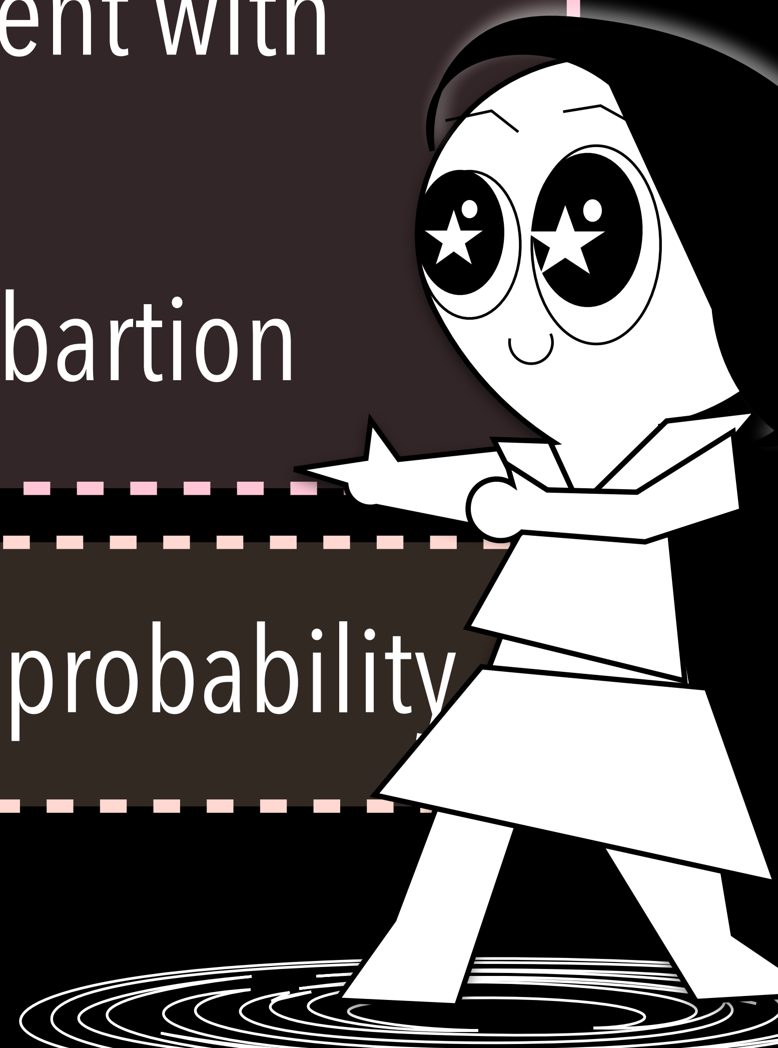
R is consistent with the inferred value in Riley et al 2021

No need to revise analyses for EoS

Constraints on BKG are helpful to lower the credible interval

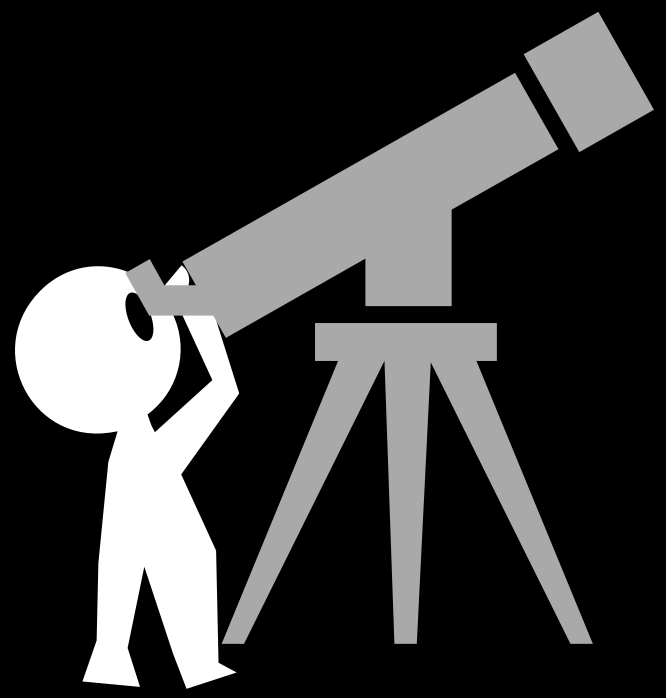
The NICER-BKG constraints seem consistent with constraints from XMM
=> No evidence for problems with cross calibartion

Offset from antipode > 25 deg with ~84% probability



Salmi et al in prep

WHAT'S NEXT



We are **working** on **J0437**

We will **soon** have a **publication for J0740**

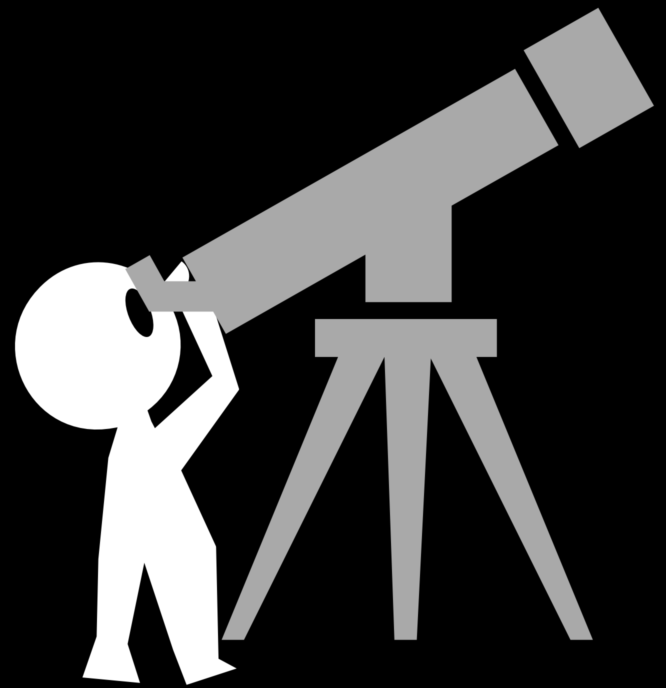
A new **larger data set** for **J0740** is currently being produced and about to be analysed

We are working on evaluating the **HD2648 star contribution** to the NICER data for **J0030**

For **J0030** we will test it and finalise findings for **ST-U** and **ST-PST**

Investigating why for **J0030** the **residuals** have worsen since the updated instrument response

WHAT'S NEXT



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For **J0030** we will test it and finalise findings for **ST-U** and **ST-PST**

Investigating why for **J0030** the **residuals** have worsen since the updated instrument response

We want to do more **simulation** tests

We are testing **scaling relations** with <u>exposure time</u> and <u>background</u>

We are **testing** the sensitivity of our analysis to assumptions and **improving** it.

CONCLUSIONS

J0030 results: analyses of new calibration and new data (ST-U model) without BKG constraints, are consistent with results published in Riley et al 2019

BACKGROUND ESTIMATES ARE CRUCIAL (for reliability -particularly for J0030-like SOURCES- and for tightening constraints)

FOR J0030 THE RADIUS HAS A "SECONDARY" ROLE COMPARED TO THE EMITTING GEOMETRY, SO THAT IT CAN RELATIVELY EASILY BE CHANGED

J0740 results: analyses with NICER-only + NICER-BKG CONSTRAINTS are CONSISTENT with previous NICERxXMM analyses. -NO NEED for EOS RE-ANALYSIS-

For J0740: compactness compensates the changes in the BKG

<u>OBSERVATIONAL CONSTRAINTS</u> (mass, distance, inclination and background measurements) PLAY A FUNDAMENTAL ROLE IN BREAKING THE DEGENERACIES OF OUR INFERENCE ANALYSES

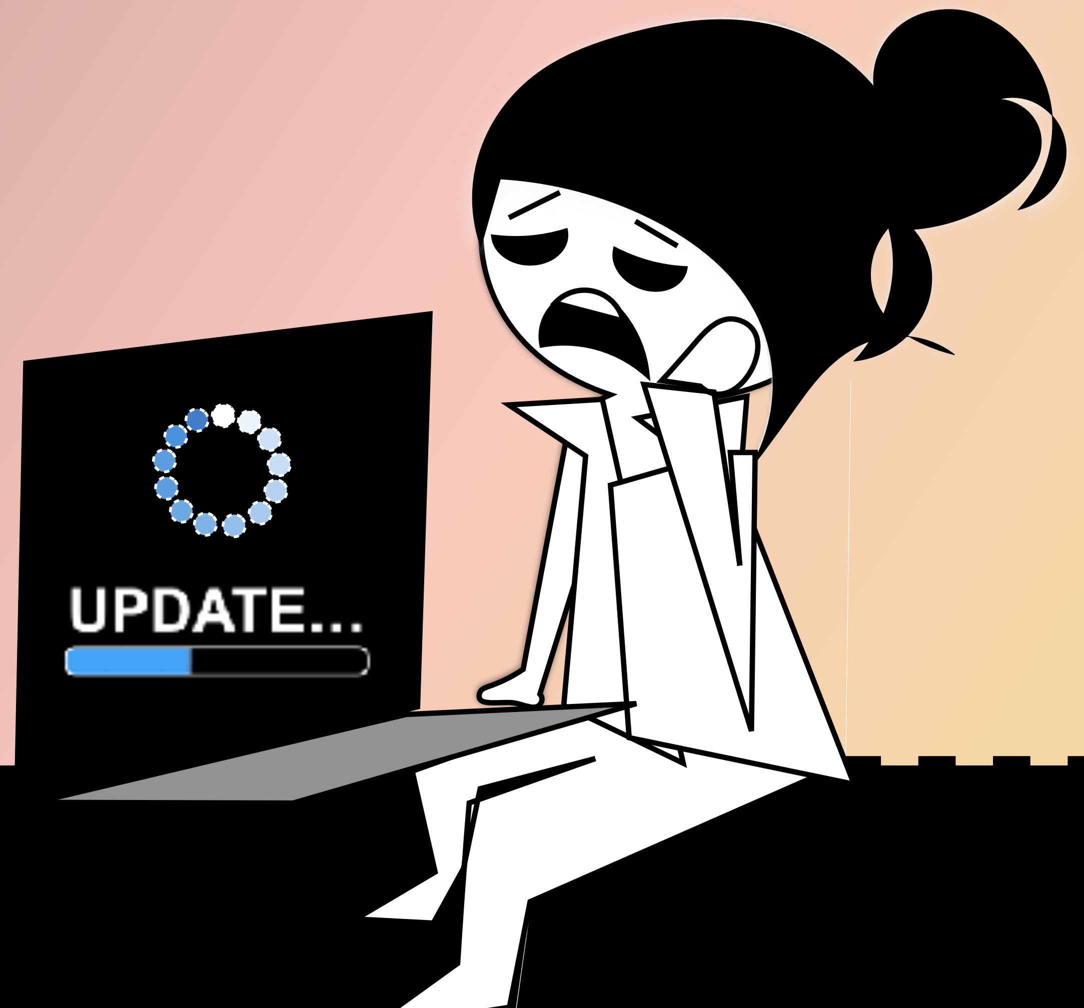
<u>THEORETICAL CONSTRAINTS</u> COULD PLAY A KEY ROLE IN REDUCING THE PARAMETERS/MODELS/PARAMETER SPACE THAT WE NEED TO EXPLORE IN OUR INFERENCE RUNS

Thank you

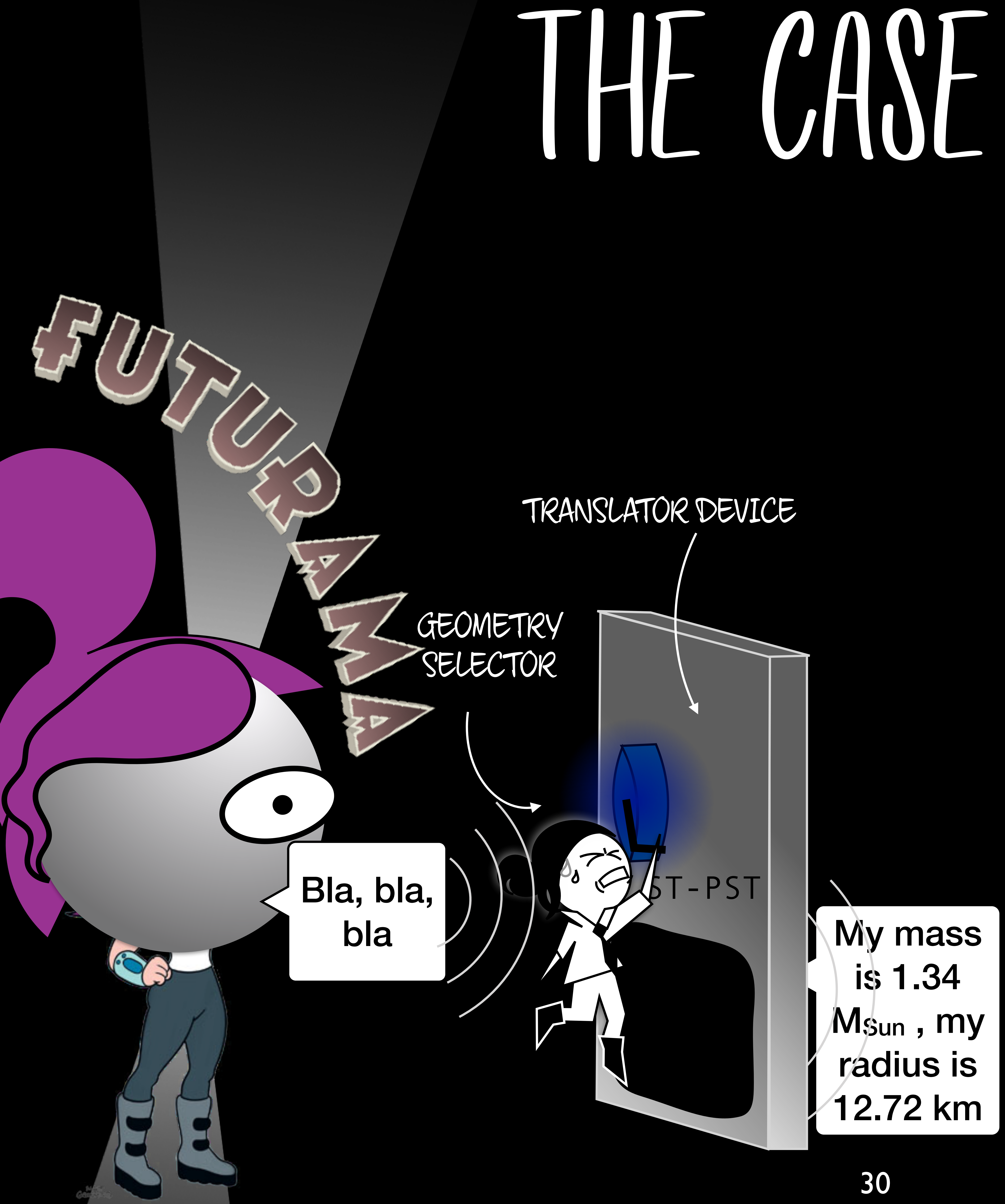
s.vinciguerra@uva.nl

J0030

UPDATED ANALYSIS of PUBLISHED DATA

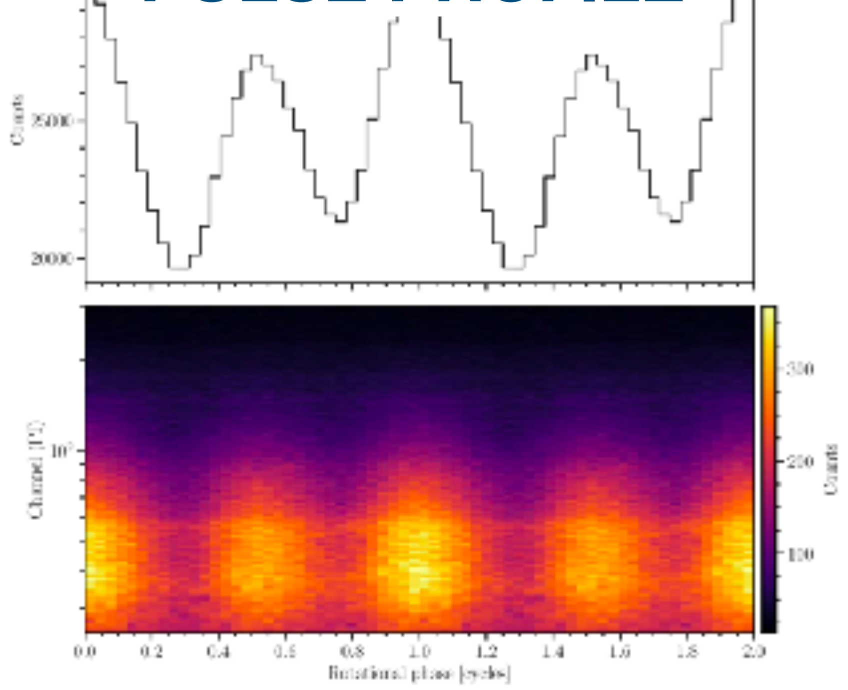


THE CASE OF J0030+0451



STATUS	ISOLATED
REFERENC	Riley et al 2019
INSTRUME	NICER

PULSE PROFILE



See also independent analysis: Miller et al 2019

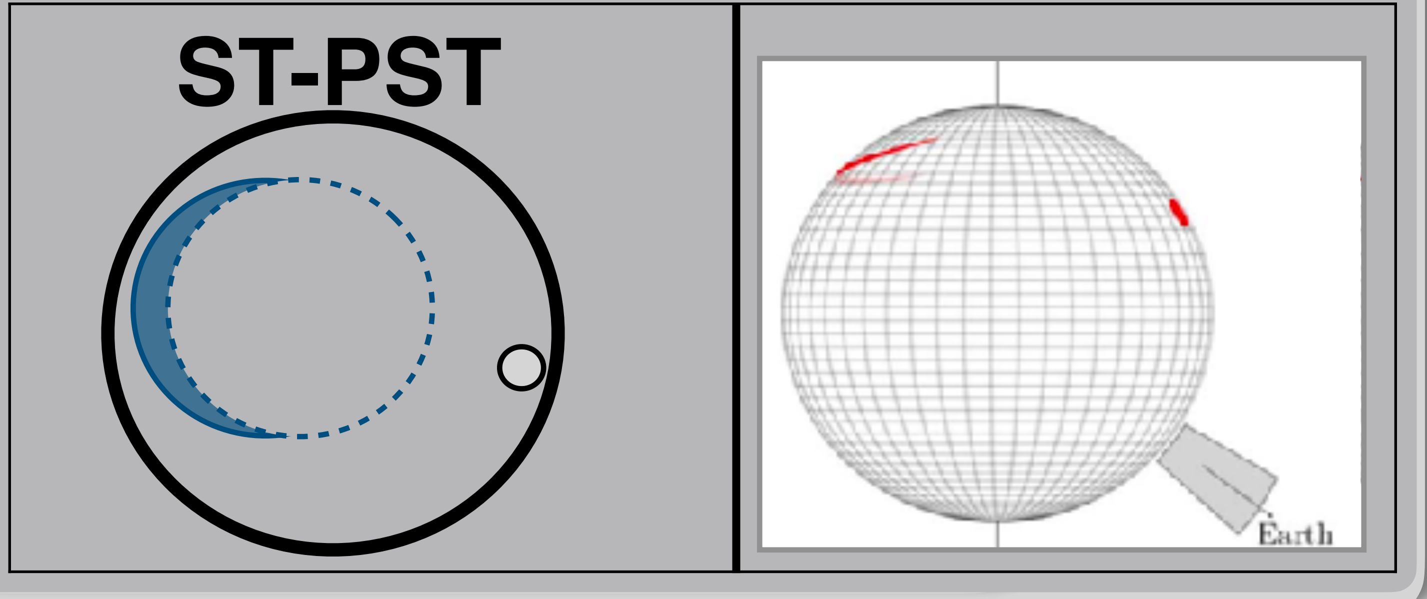
J0030+0451

About | **Photos** | **History**

Its details

Mass [MSun]	1.34
Radius [km]	12.71
Compactness	0.16

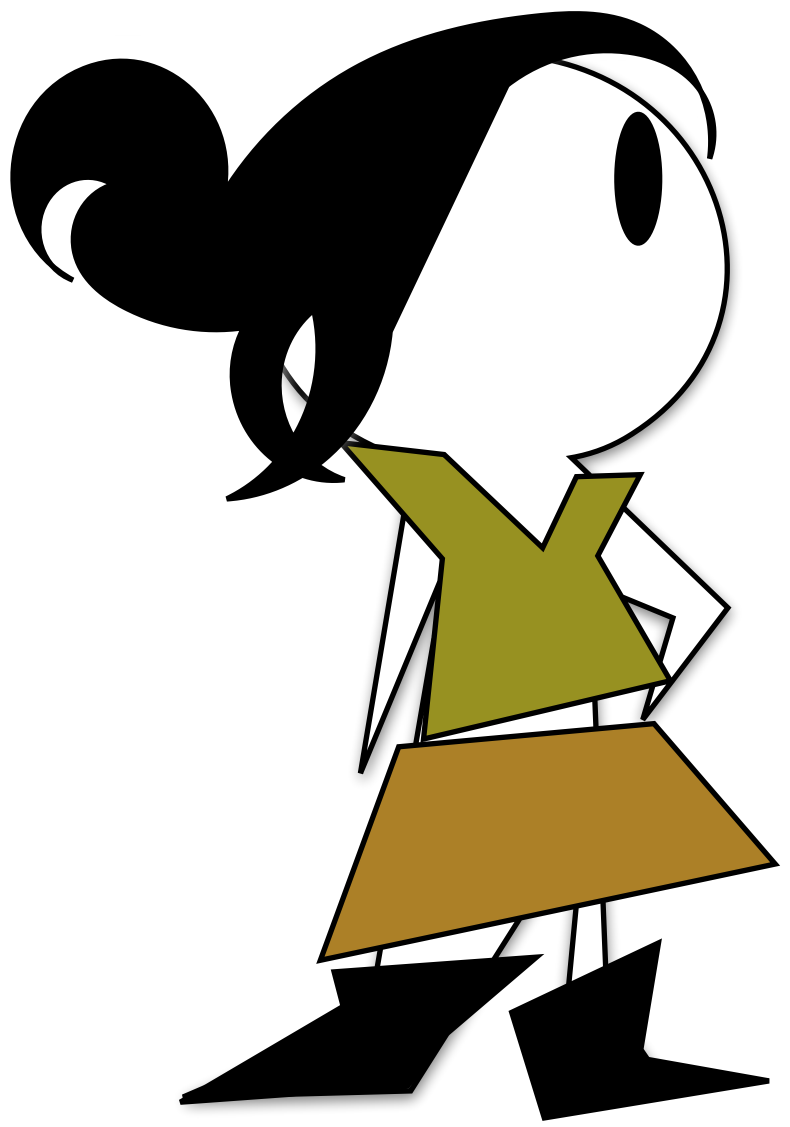
MODEL

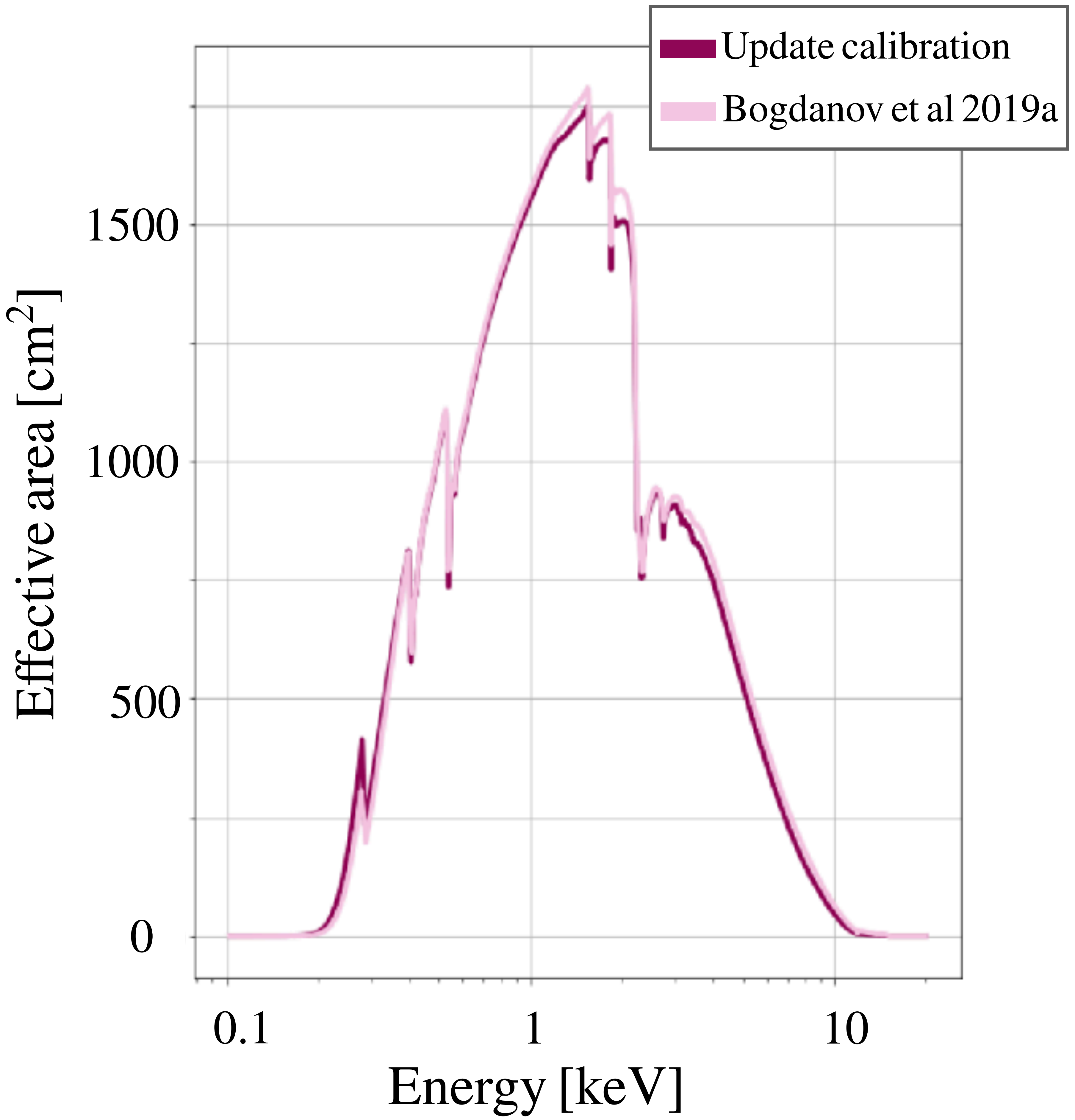


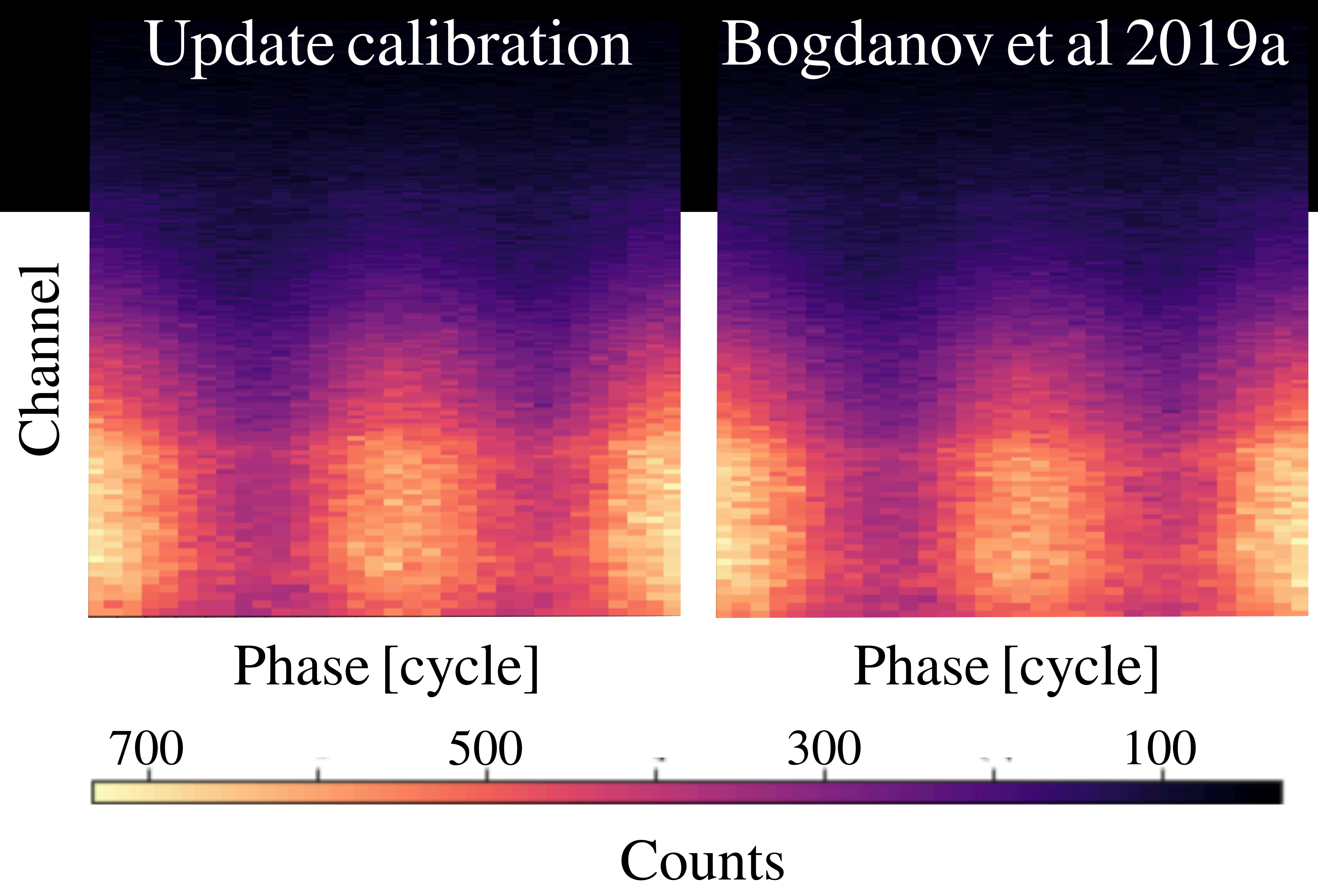
6

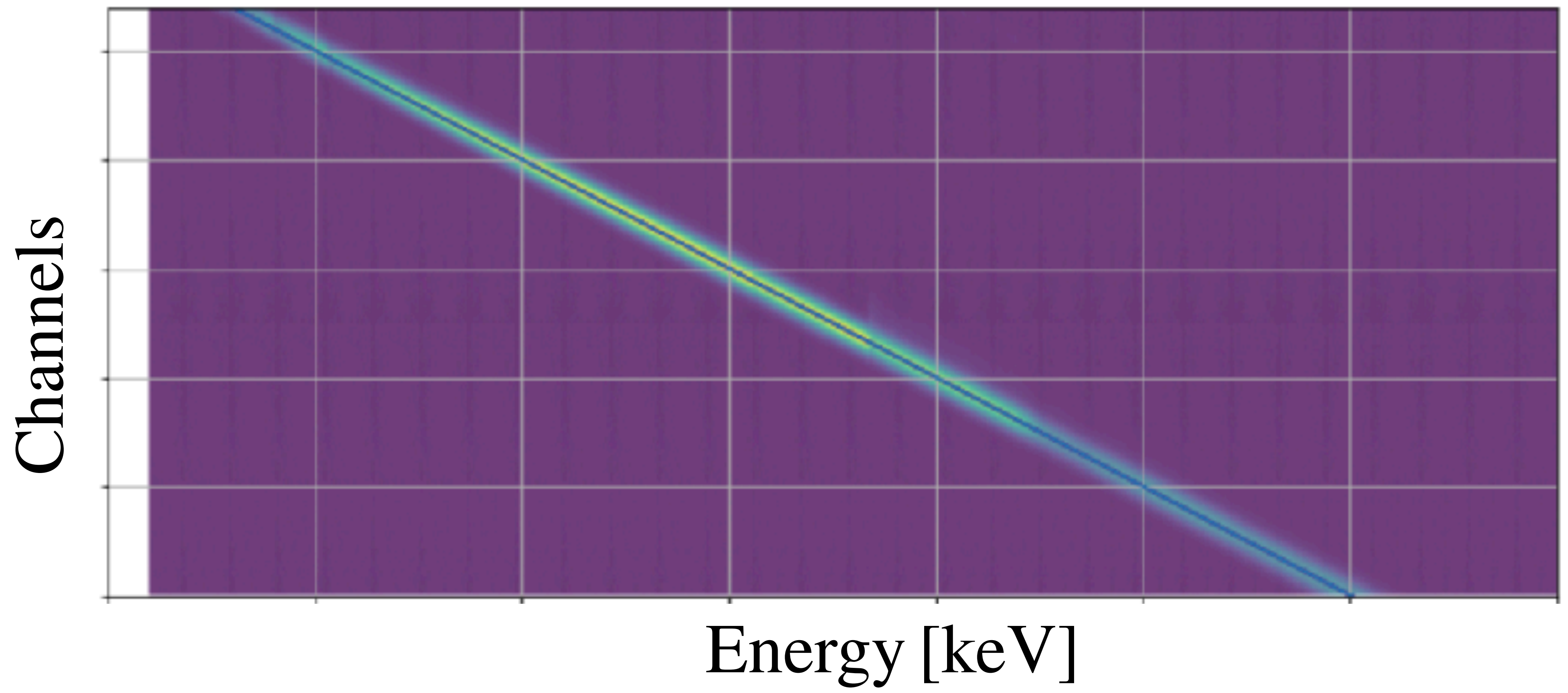
UPDATED ANALYSIS

1. DIFFERENT CALIBRATION









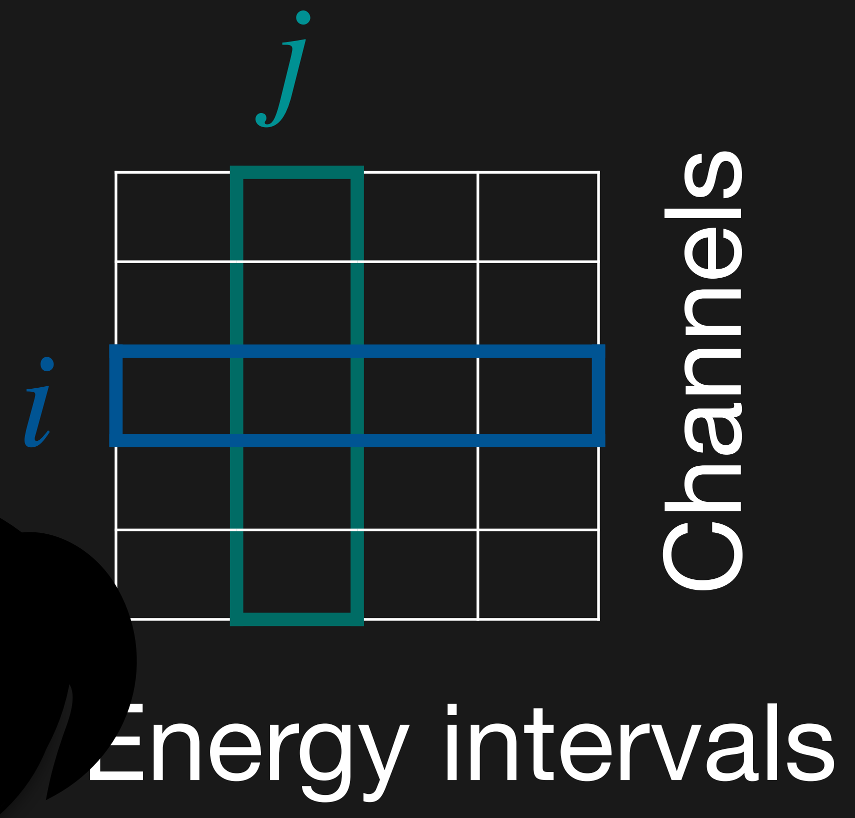
UPDATED ANALYSIS

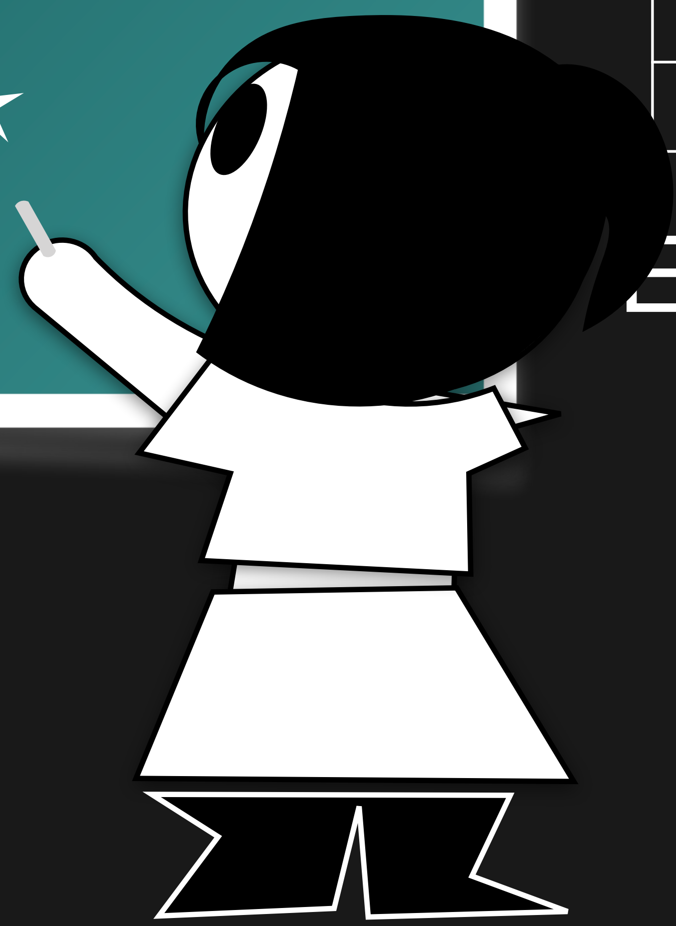
2. DIFFERENT INSTRUMENT MODEL

Measured response matrix

Calibration from Crab

$$R_{ij} = (1-\beta)\gamma R^{\star}_{ij} + \beta\alpha\mathscr{R}_i R^{\star}_{ij}$$





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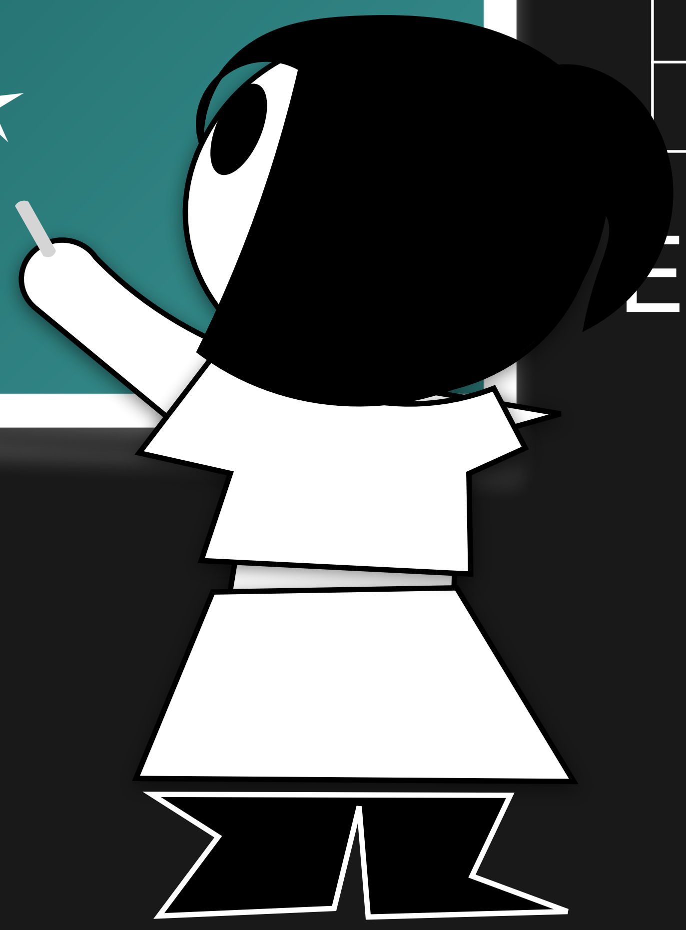

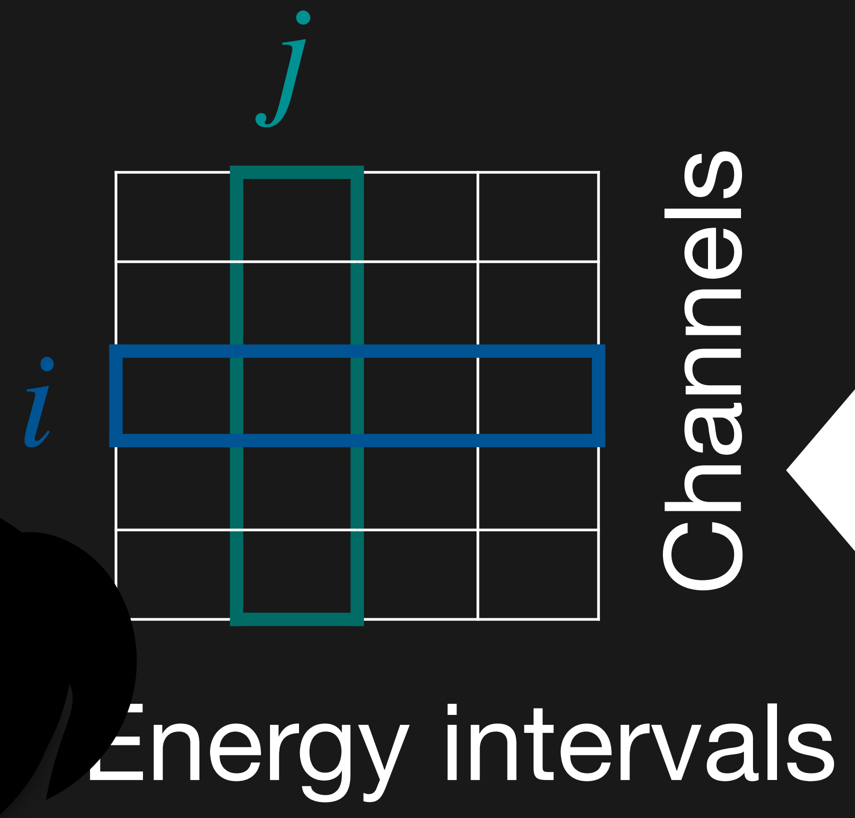

Now/This talk

$$\beta = 0$$

(also Riley et al 2021)

UPDATED ANALYSIS

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Measured response matrix

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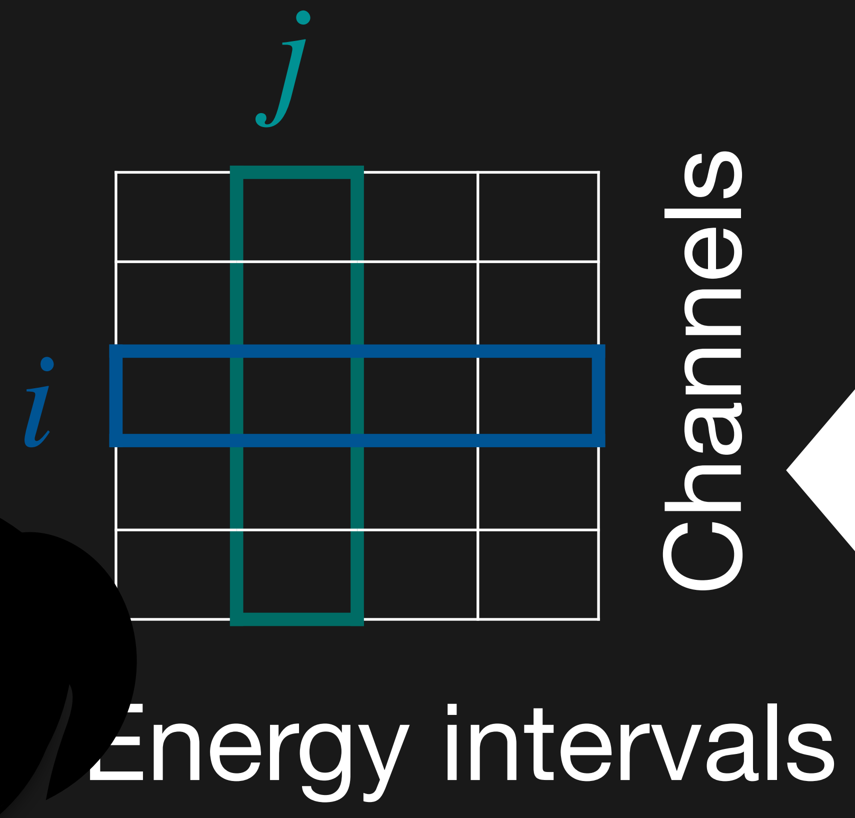
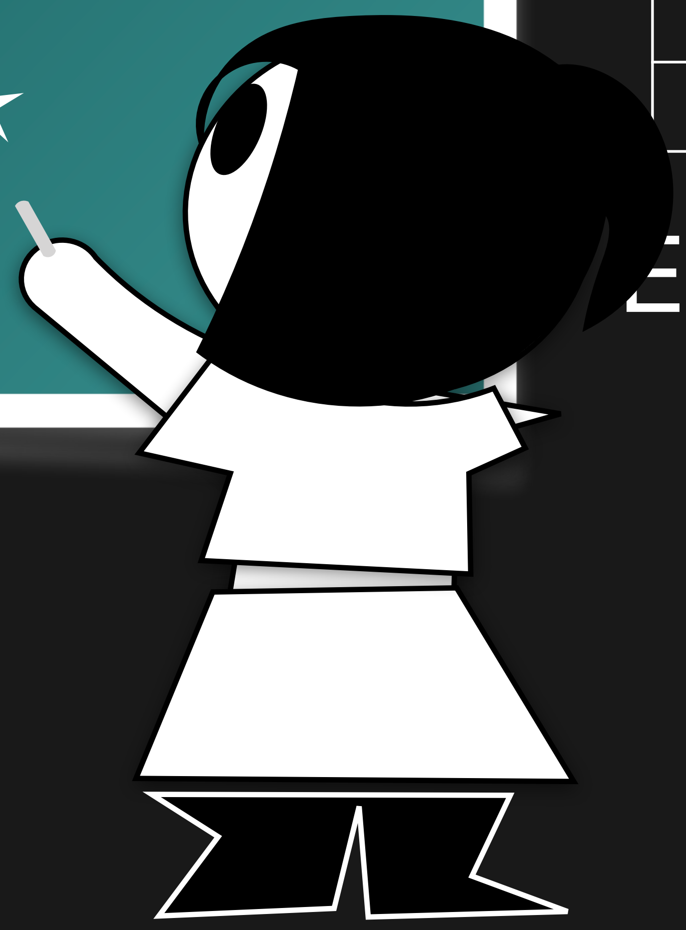




Now/This talk

$\beta = 0$

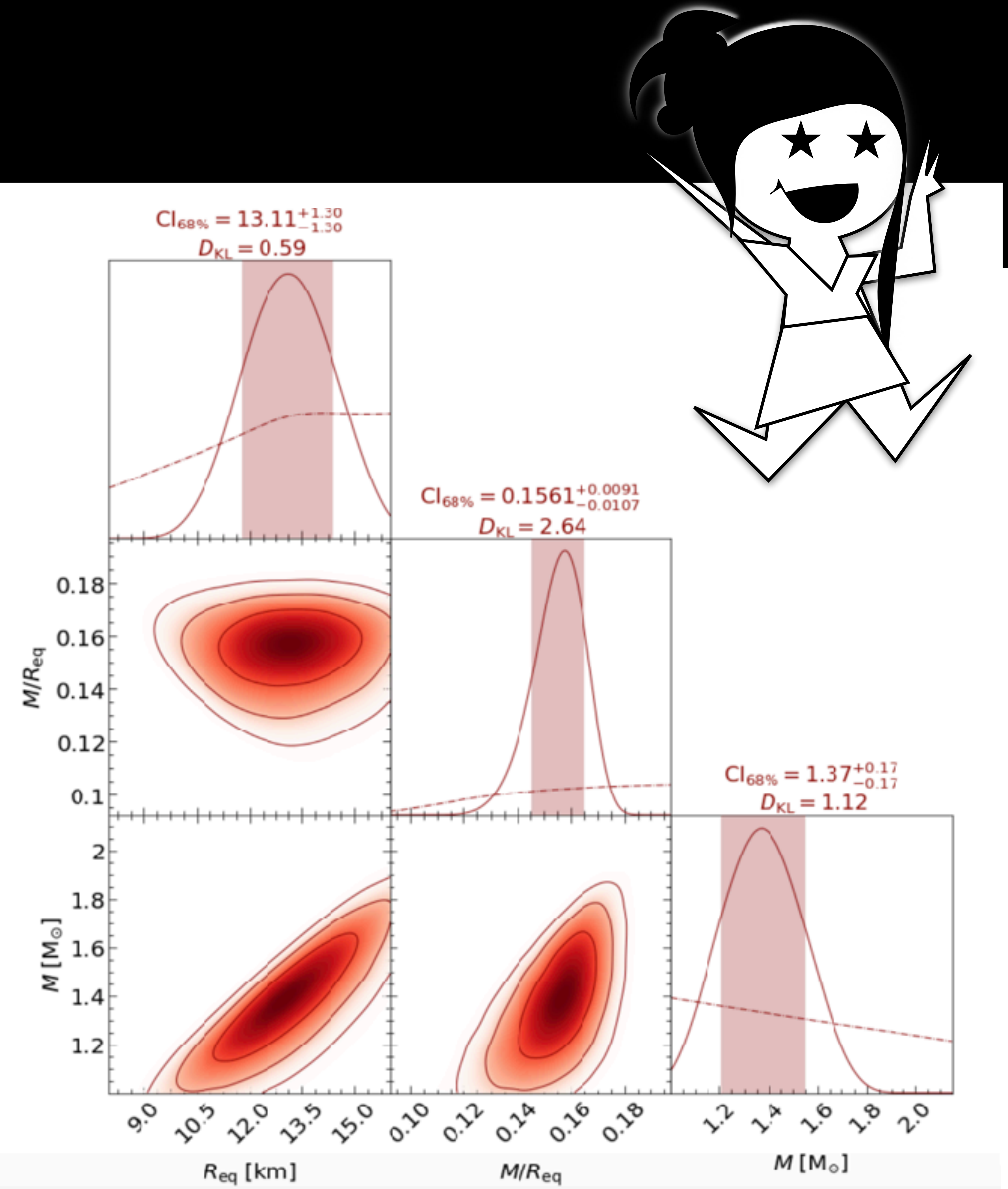
(also Riley et al 2021)

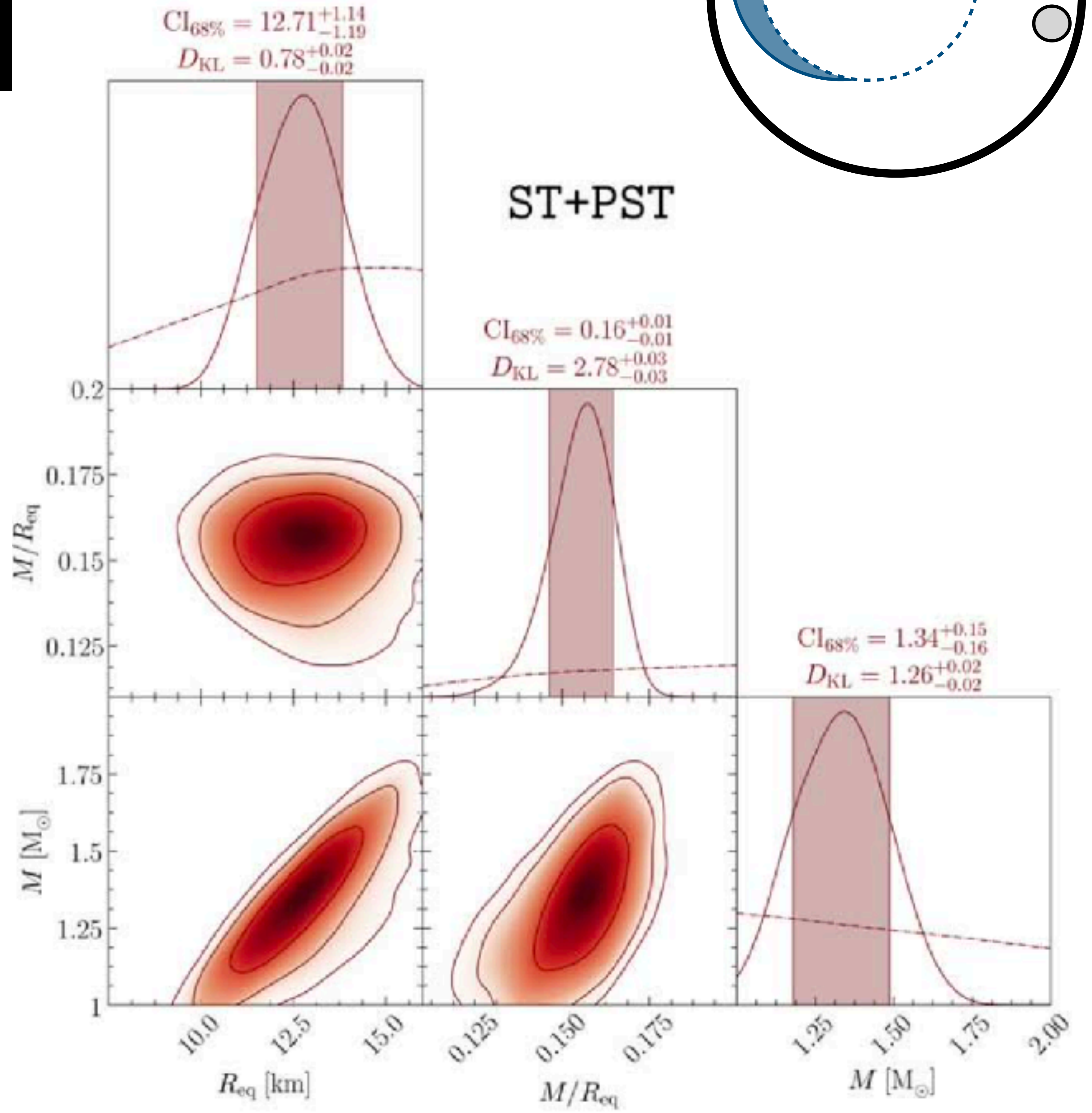
3. DIFFERENT SETTINGS

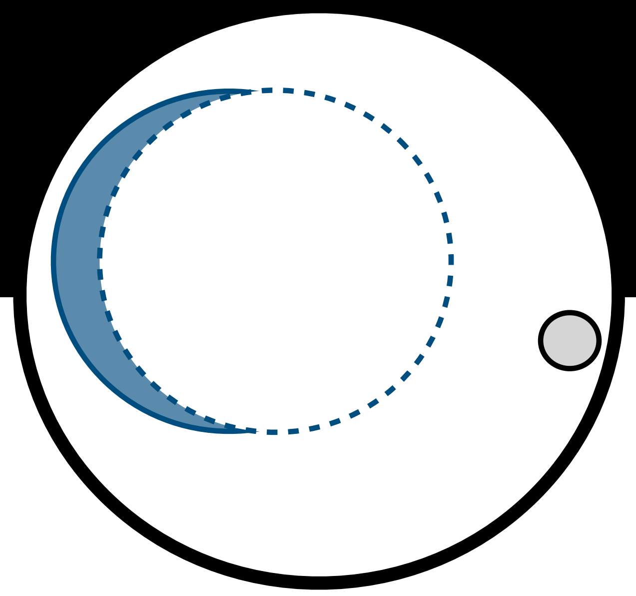
- LIVE POINTS
- CHANNELS
- PRIORS
- MULTI-MODE

RESULTS

ST-PST

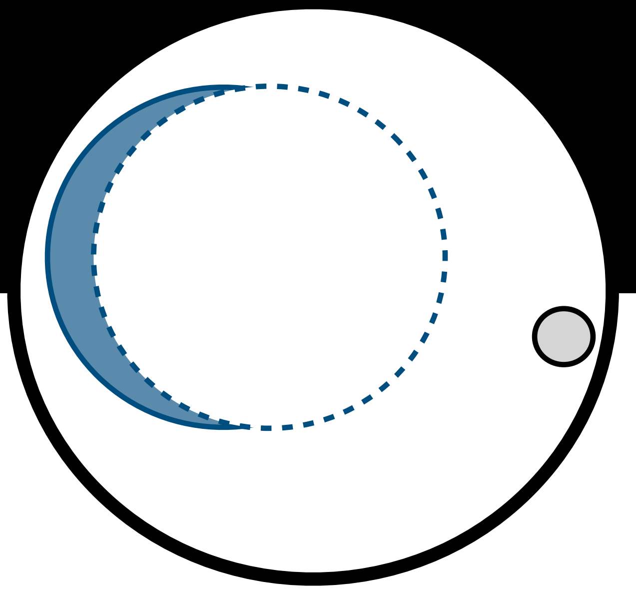


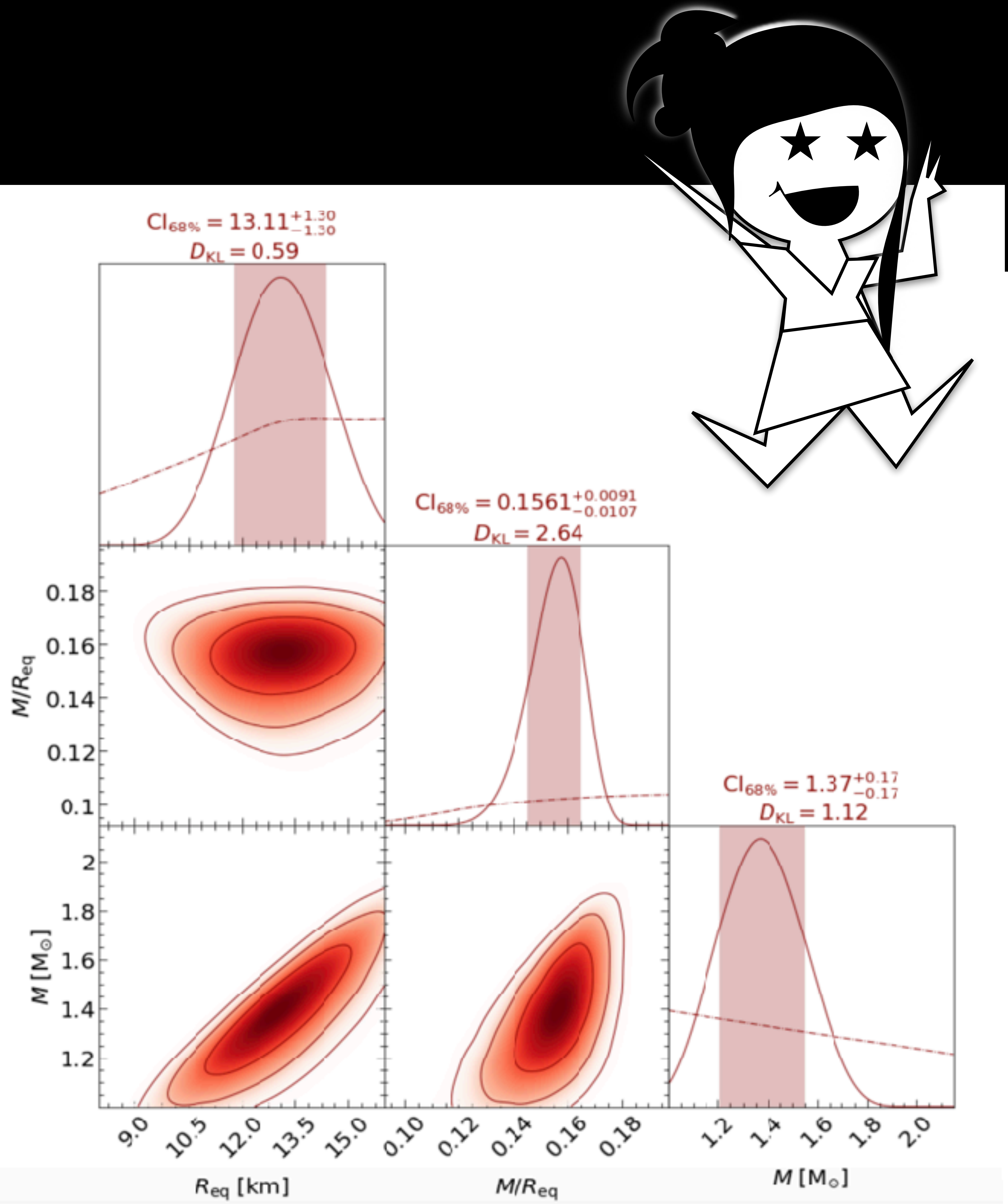




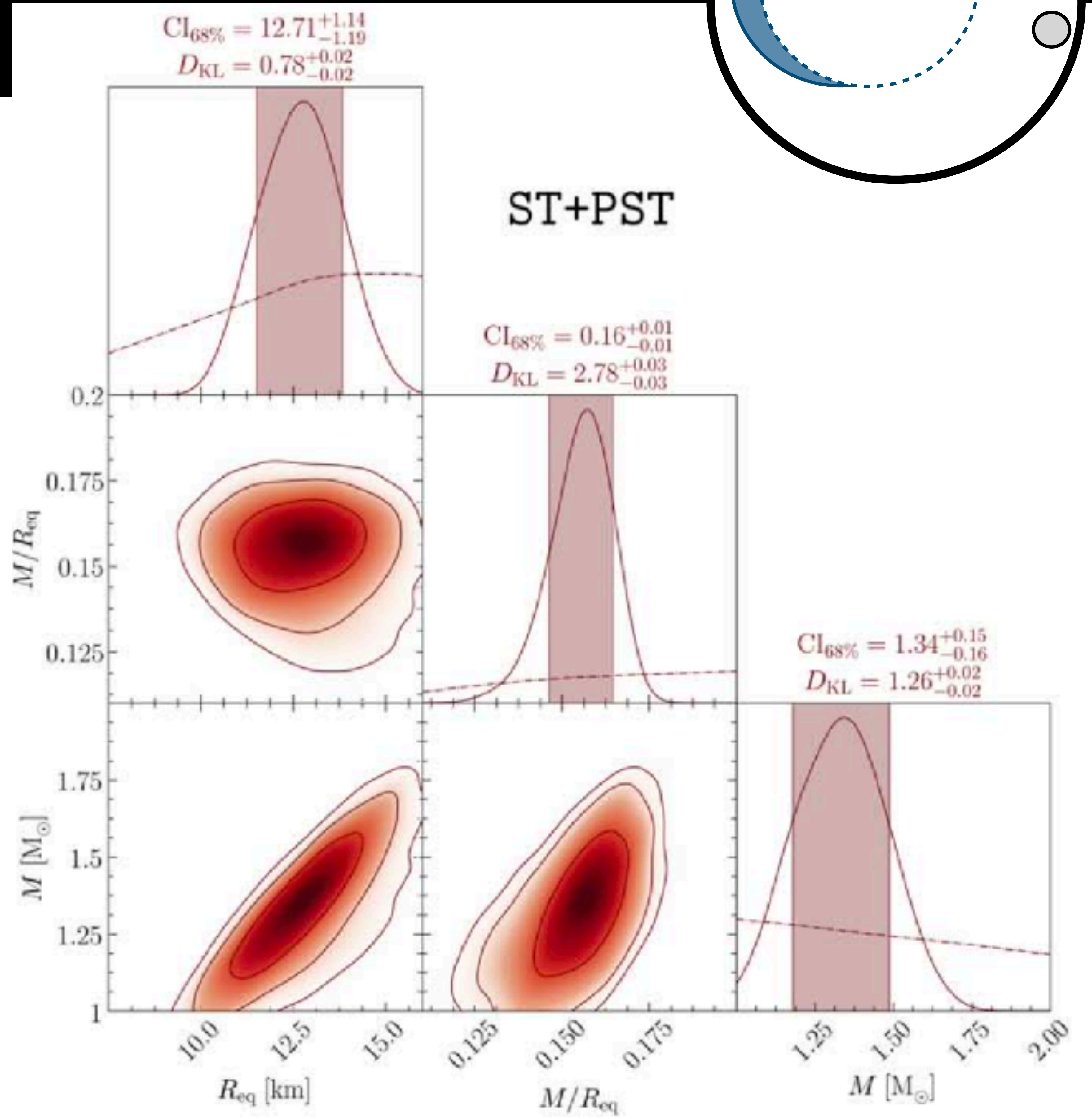
RESULTS

ST-PST

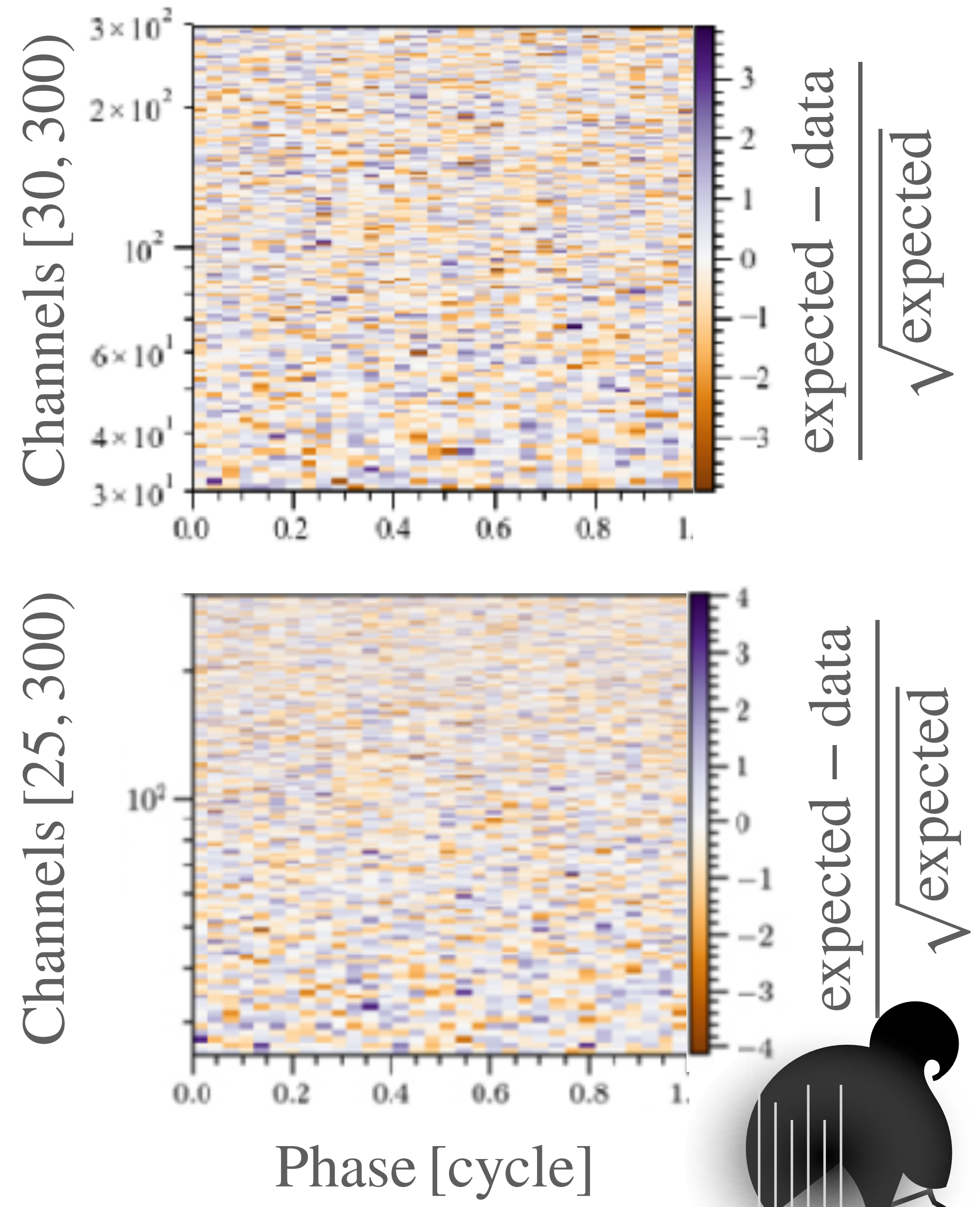




ST+PST

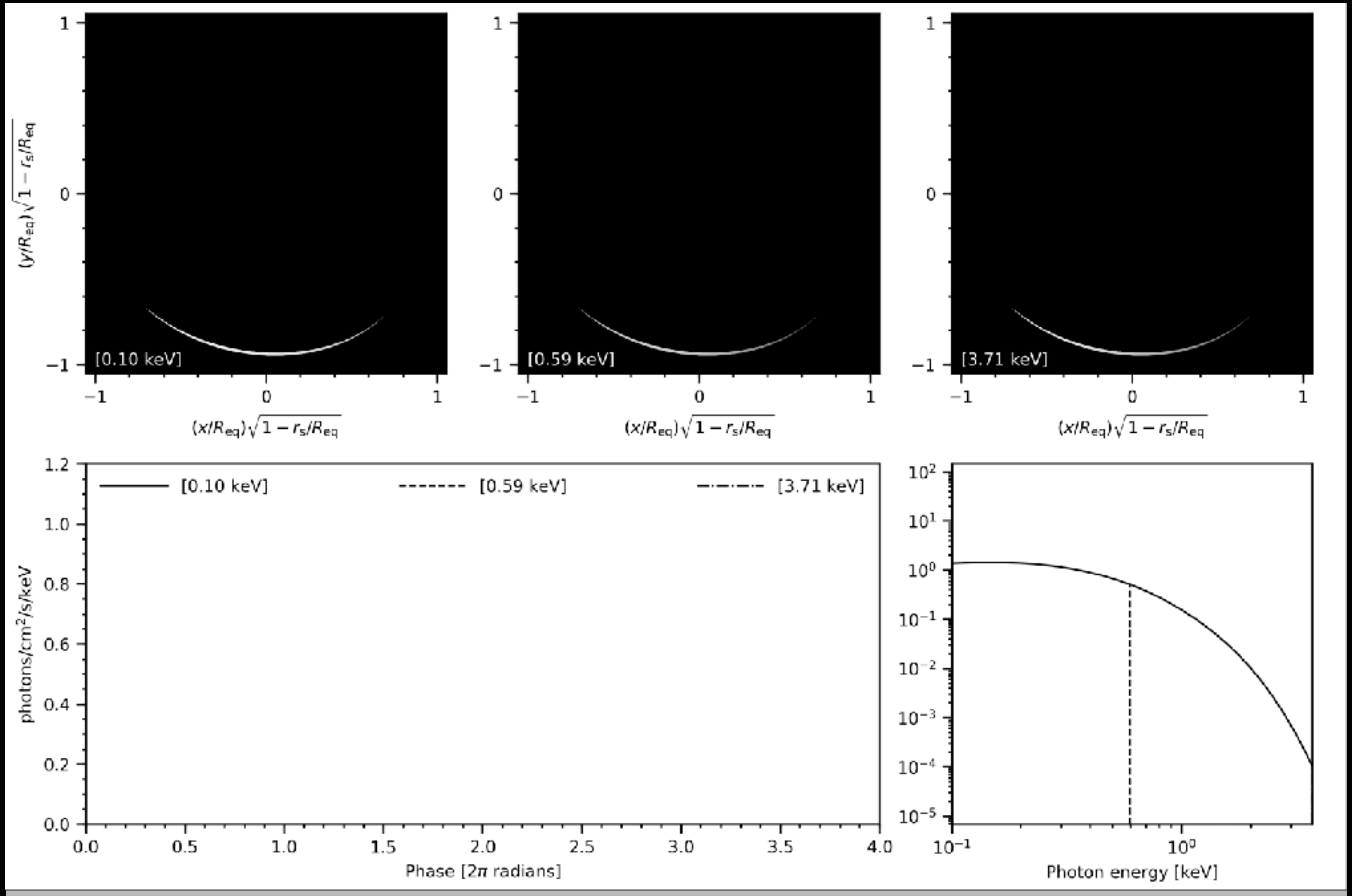


RESIDULS



RESULTS UPDATES

J0030 results of updated data and response matrix are consistent with what was found in Riley et al 2019, despite the many differences ..



- NEW GAIN
- INSTRUMENT RESPONSES
- CHANNELS (30:300) vs (25:300)
- MODEL INSTRUMENT UNCERTAINTIES
- PRIORS (now flat in cos(i); also flat in cos for colatitude of hotspots)
- UPDATED XPSI SOFTWARE
- RESOLUTION (10k live points vs 1k live points)
- MULTIMODE: ON vs OFF
- SETTINGS (number of cells to describe hot regions; number of frequencies; number of leaves)