

The Rhythms of Chaos

Understanding Quasi-Periodic Eruptions

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R. ARCODIA, J. CHAKRABORTY, N. WEBB & others

LGWA 2025

Today's menu

- The observational story
What are QPEs ?
- Current state
What (we think) we know
- QPEs & GWs
Why should you care ?



The observational story

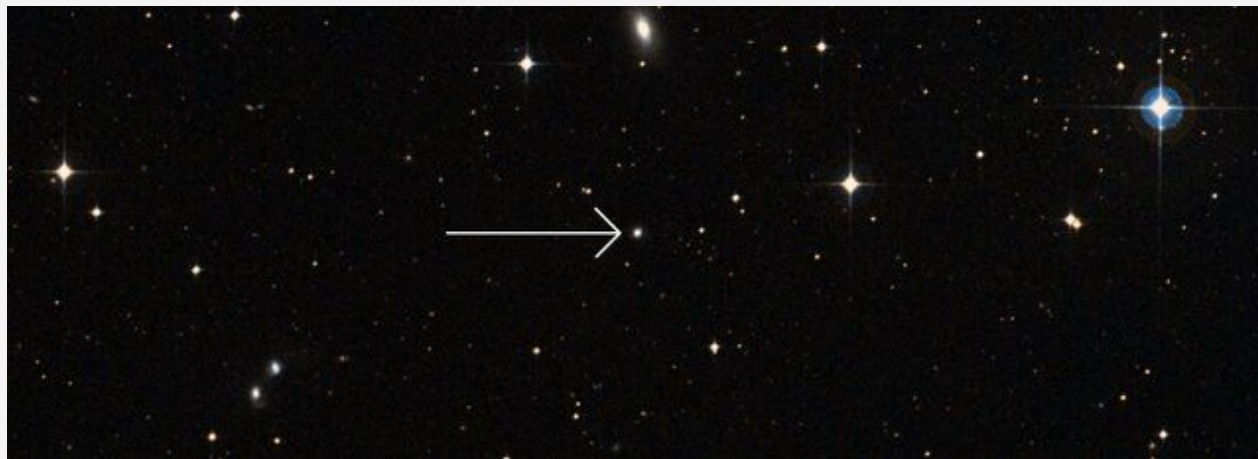
What's a QPE?



A Christmas story



- Introduction
 - GSN-069
 - TDEs
 - QPE sample
- Current state
- QPEs & GWs
- Conclusion



GSN 069 - Dwarf galaxy at 76 Mpc
Monitored as a Tidal Disruption Event candidate

Tidal Disruption Events (TDEs)



Tidal disruption event (TDE)

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Central regions of galaxies are busy:

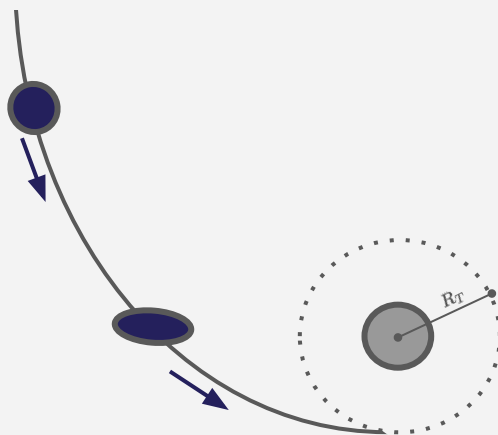
- a massive black hole
- gas (e.g. Active Galactic Nuclei)

Tidal disruption event (TDE)

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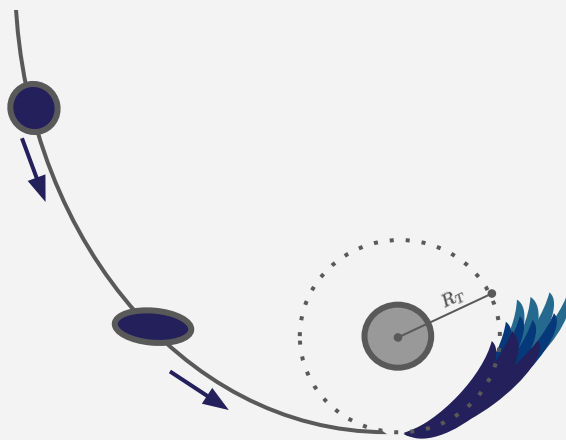
- a massive black hole
- gas (e.g. Active Galactic Nuclei)
- stars in chaotic motion



e.g. Rees 88

Tidal disruption event (TDE)

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At the tidal radius, tidal forces overcome the star's self-gravity

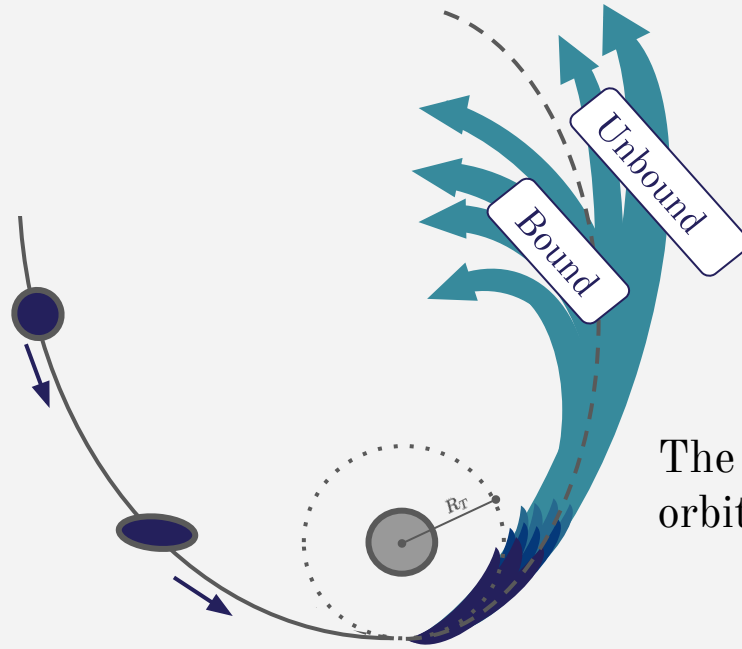
$$R_T \sim R_* (M_{BH} / M_*)^{1/3}$$

Need $M_{BH} \sim 10^5 - 10^8 M_\odot$

e.g. Rees 88

Tidal disruption event (TDE)

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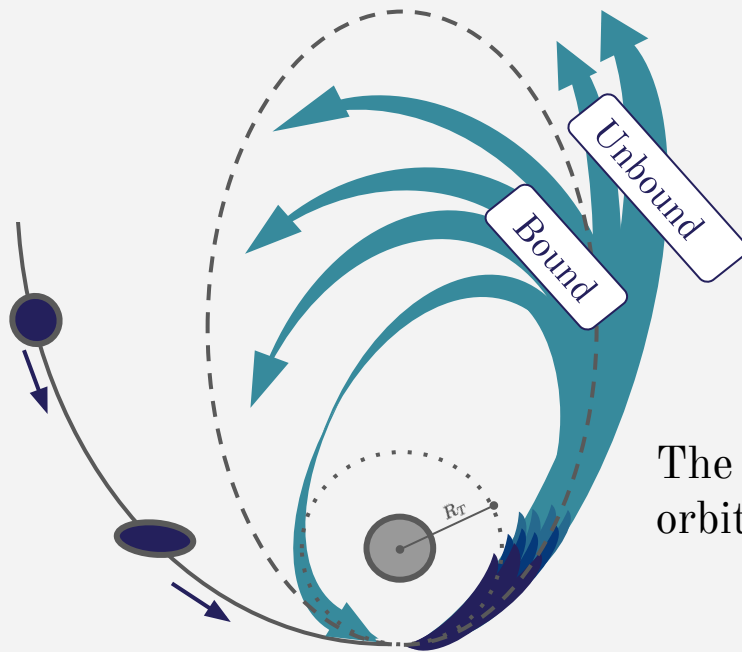


The resulting debris will remain in orbit ...

e.g. Rees 88

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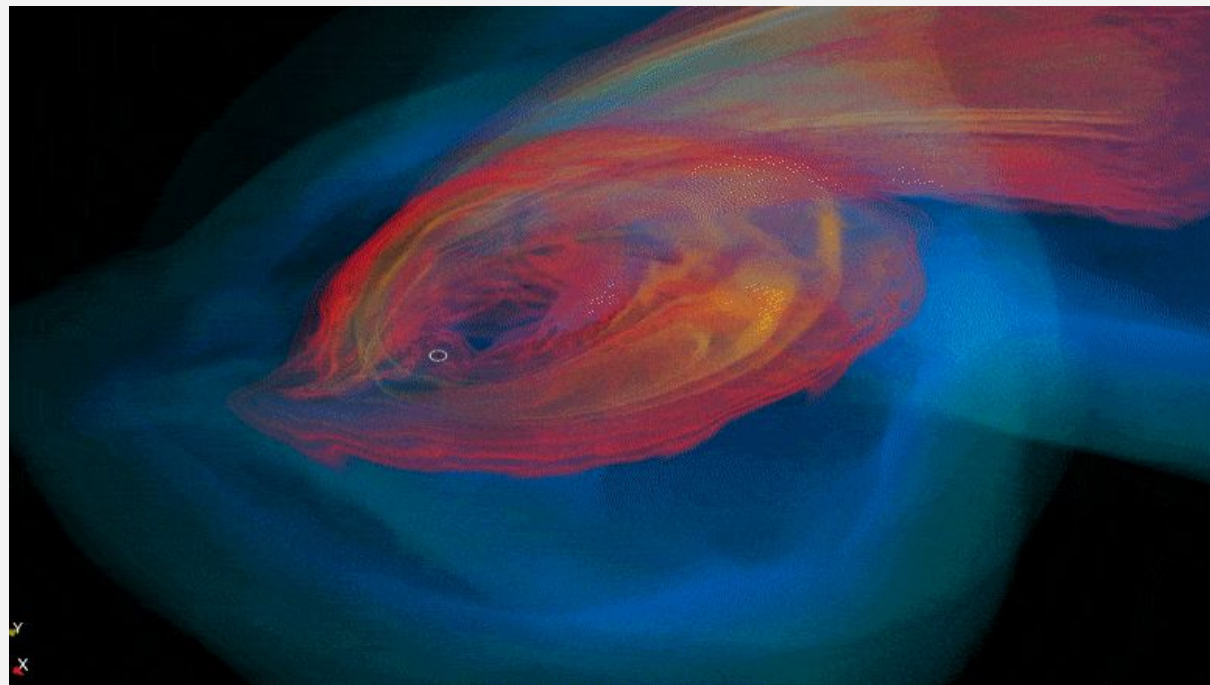


The resulting debris will remain in orbit ... and fall back

e.g. Rees 88

Tidal disruption event (TDE)

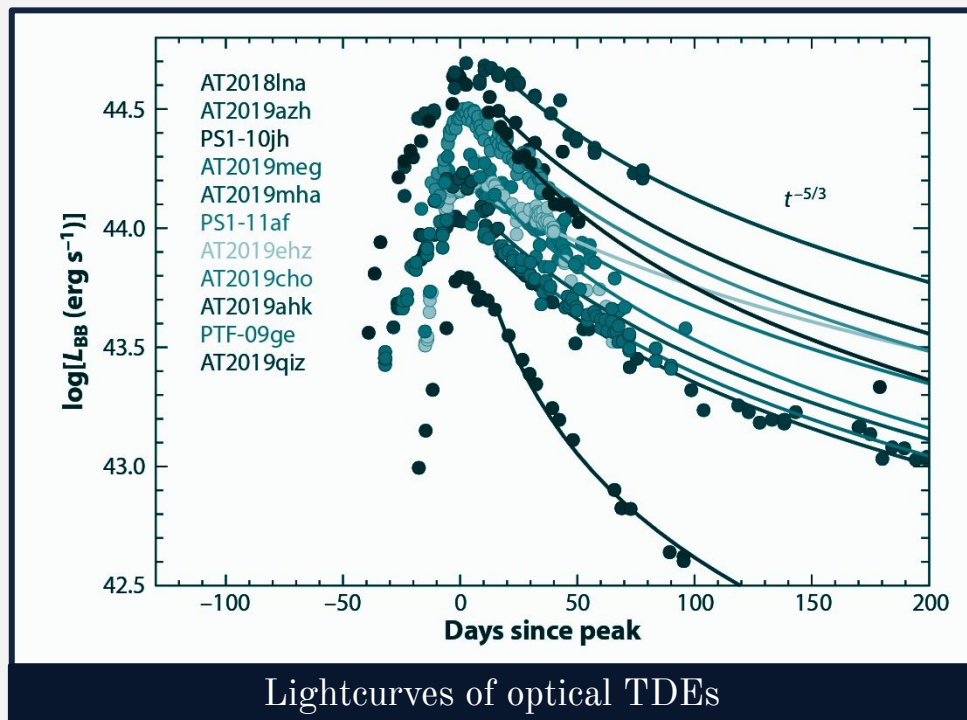
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J. Law-Smith, E. Ramirez-Ruiz

Observing TDEs

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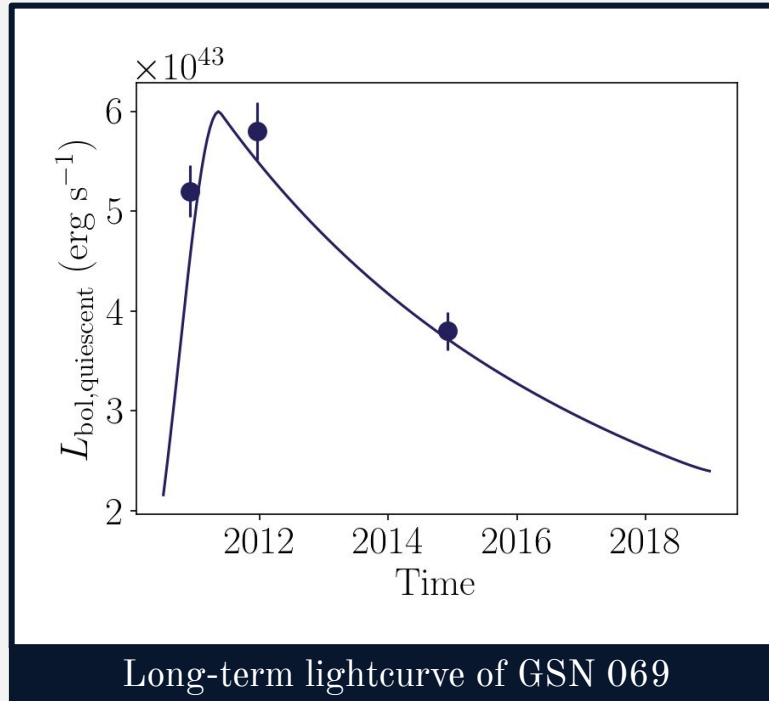


Gezari 21

& GW
(faint, better for
IMBH+WD)
e.g. Toscani+20,21

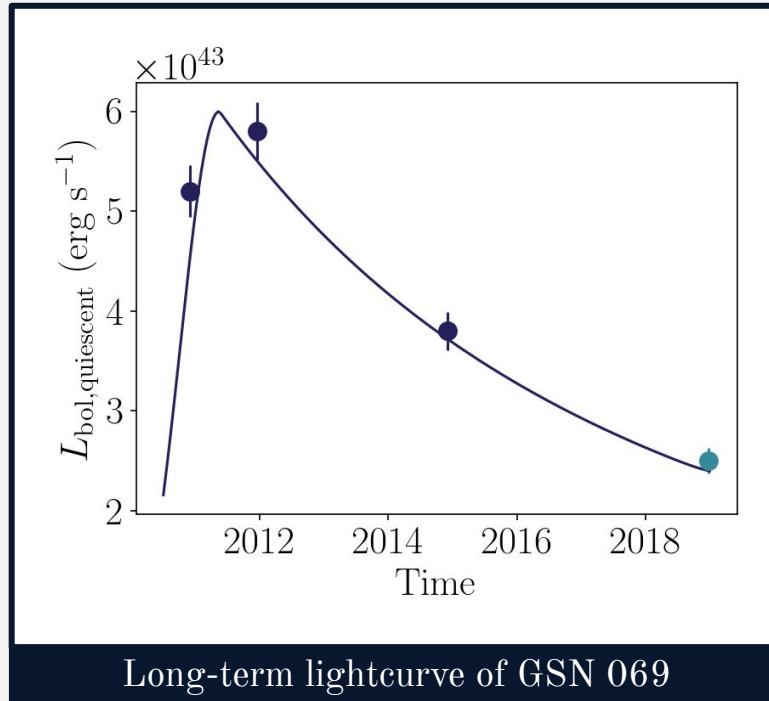
GSN 069: your usual X-ray TDE...

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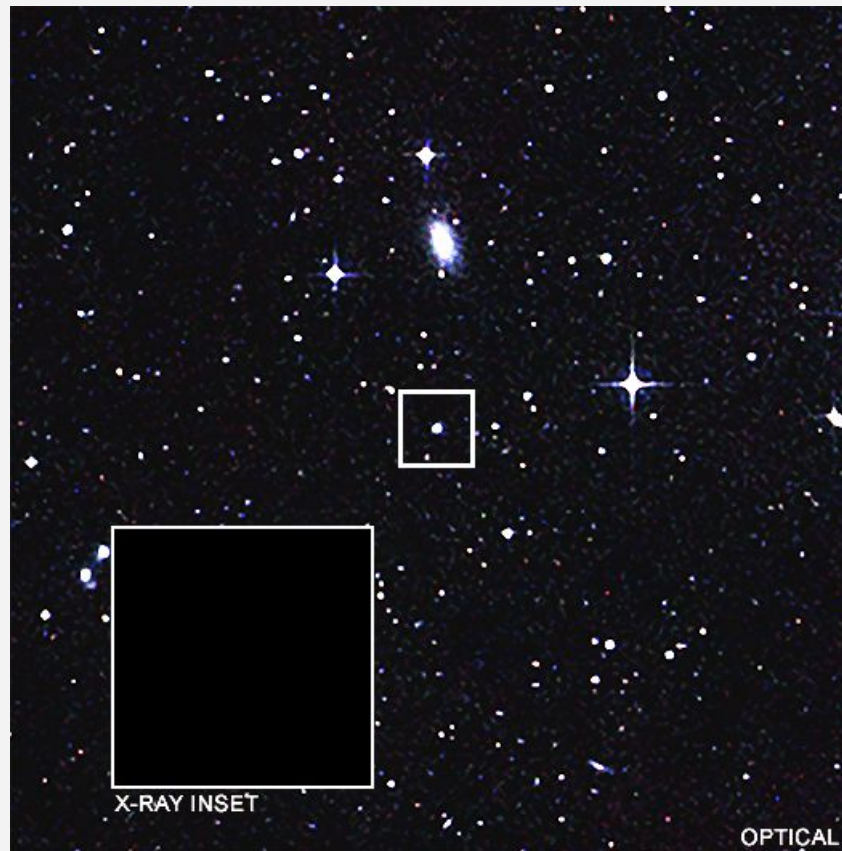
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GSN 069

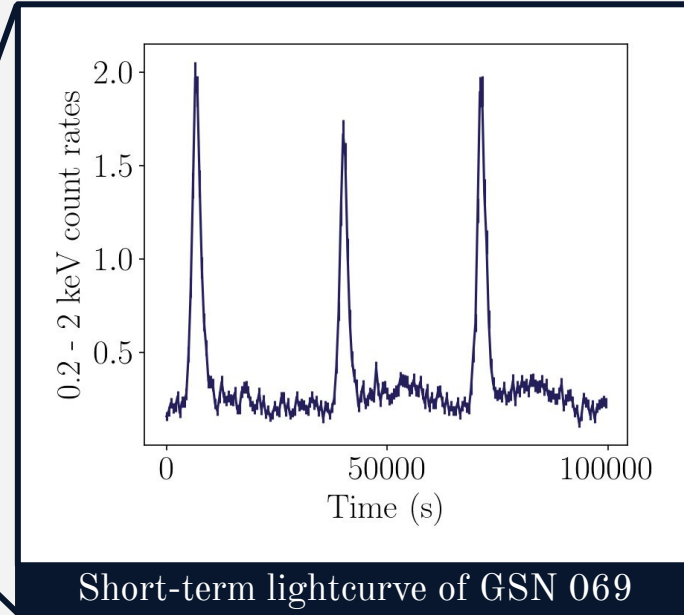
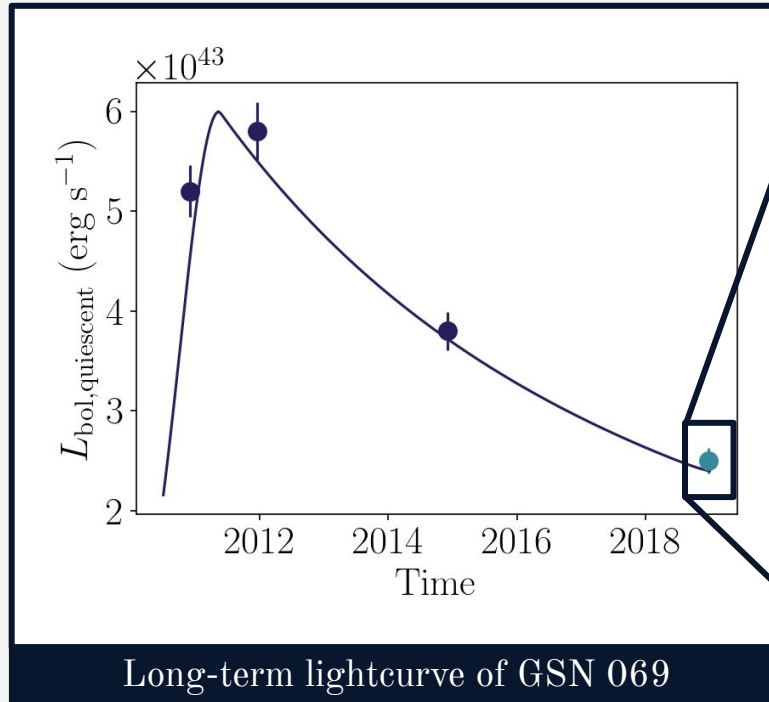
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ESA

GSN 069: your usual X-ray TDE...?

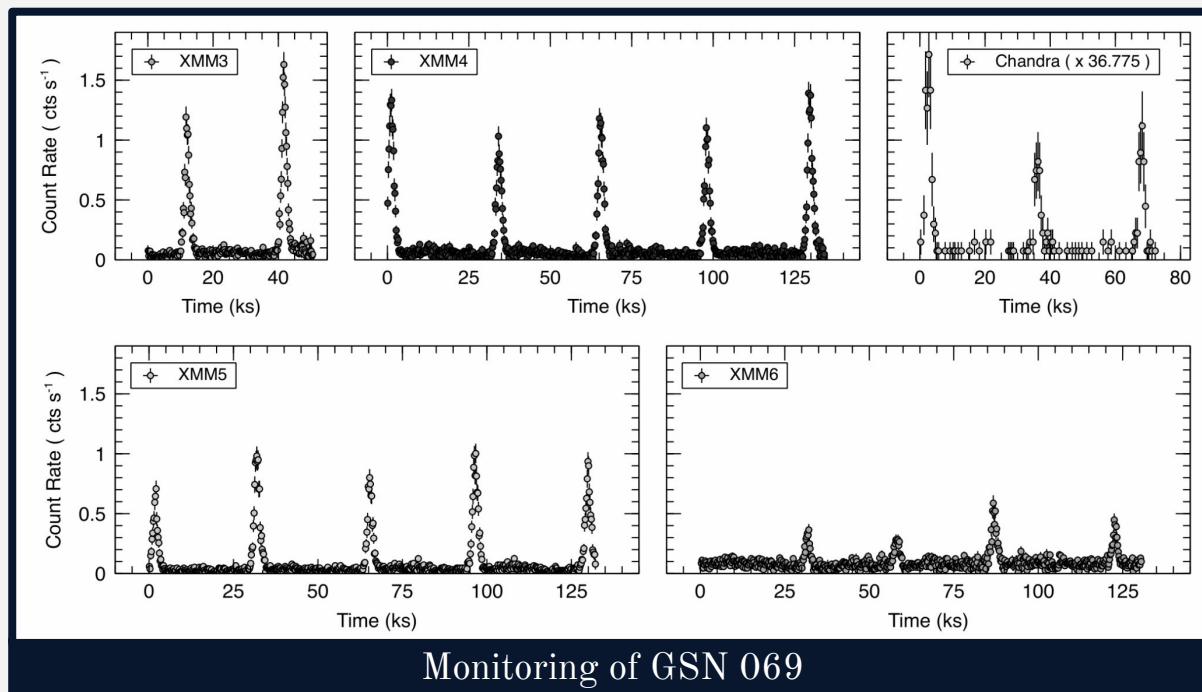
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Miniutti+19

GSN 069: the QPE prototype

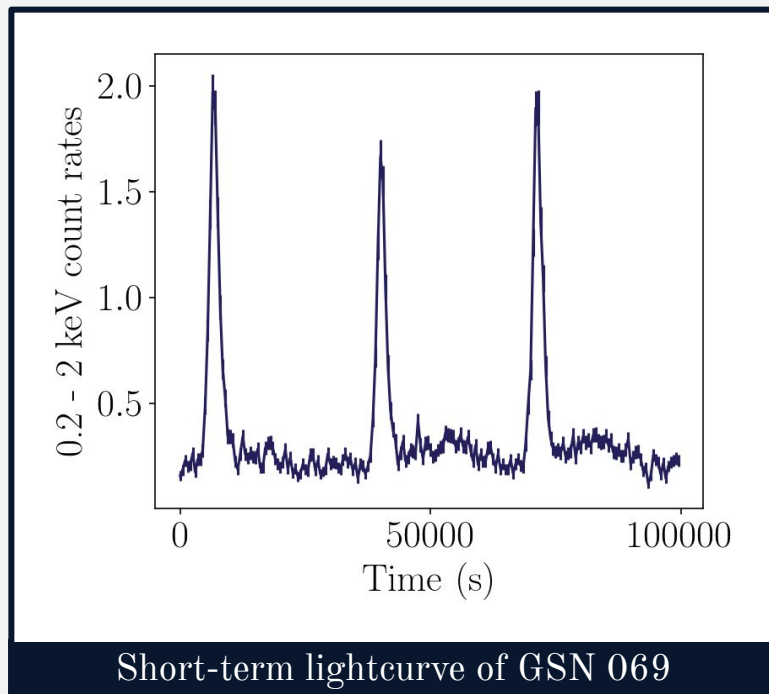
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Miniutti+23

GSN 069: the QPE prototype

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Timing properties

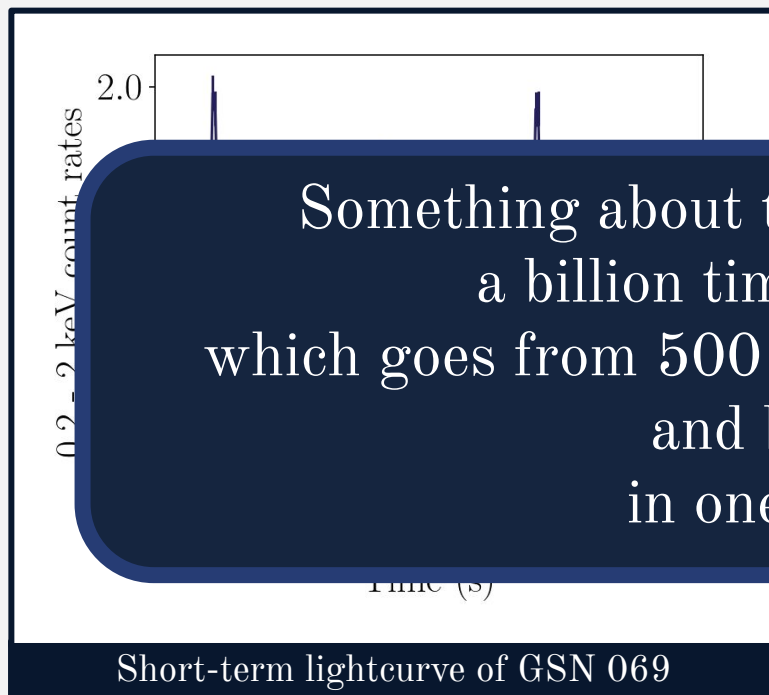
- Duration $\sim 1\text{h}$
- Recurrence $\sim 9\text{h}$
- Alternating strong/weak

Spectral properties

- Temperature:
 $\sim 5 \times 10^5 \text{ K}$ to $\sim 10^6 \text{ K}$
- Luminosity:
 2×10^{42} to $10^{43} \text{ erg s}^{-1}$

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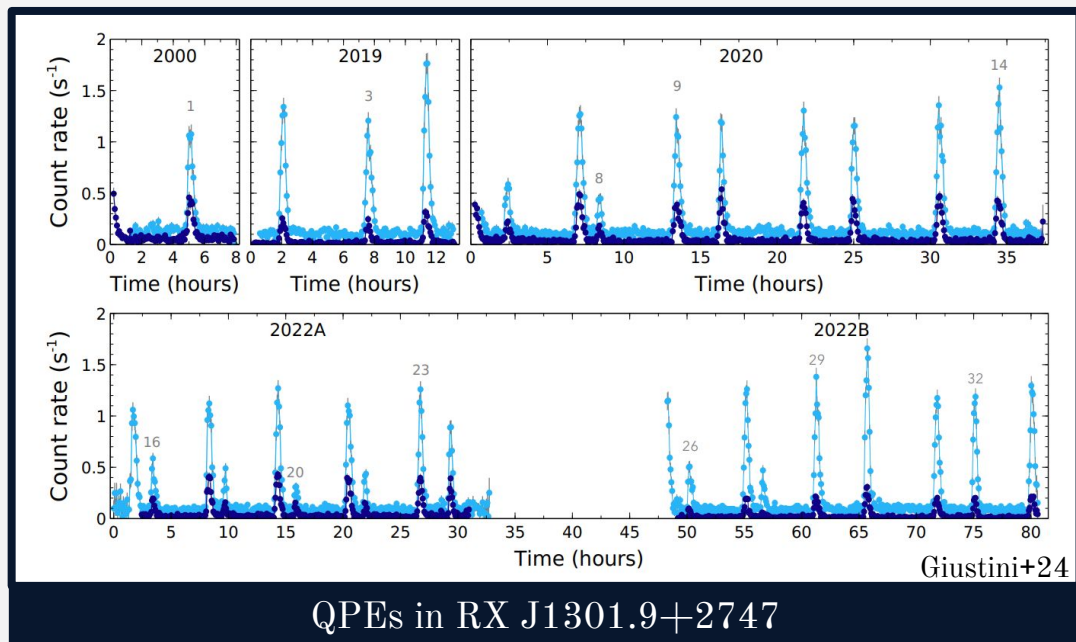
Timing properties

Something about the size of the sun,
a billion times brighter
which goes from 500 000 K to 1 million K,
and back,
in one hour

- Luminosity:
 2×10^{42} to $10^{43} \text{ erg s}^{-1}$

Hunt for other QPEs: in archive

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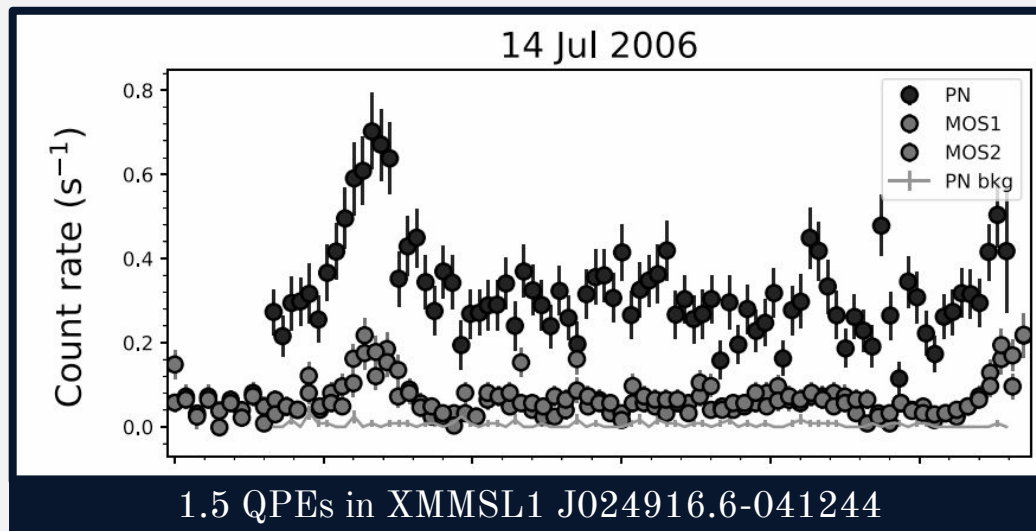


Has been active for at least 30 years

(Sun+13, Giustini+20)

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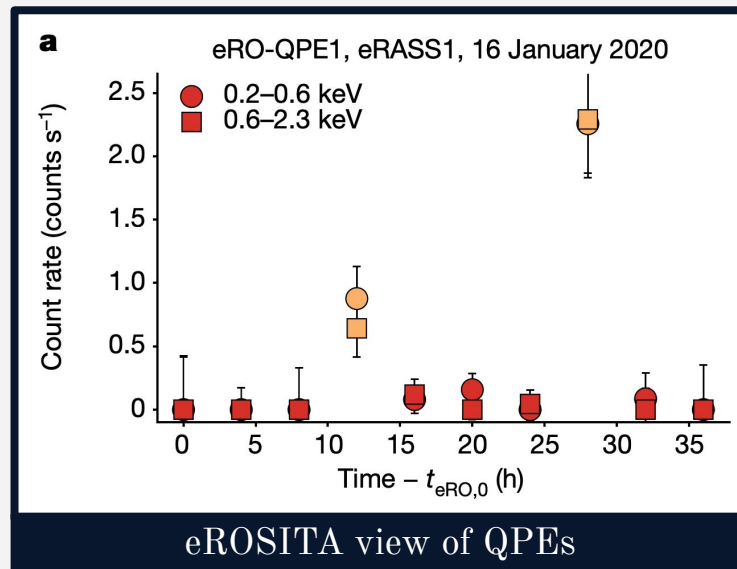
Chakraborty+21

Past behavior TDE-compatible

Hunt for other QPEs: eROSITA

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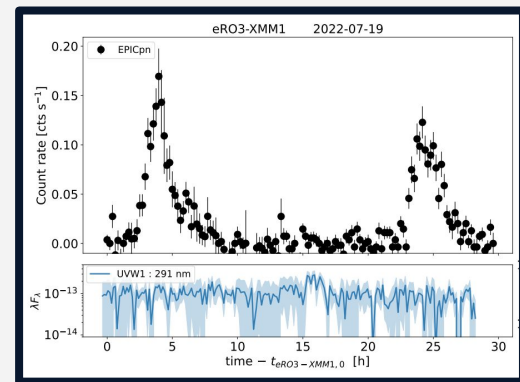
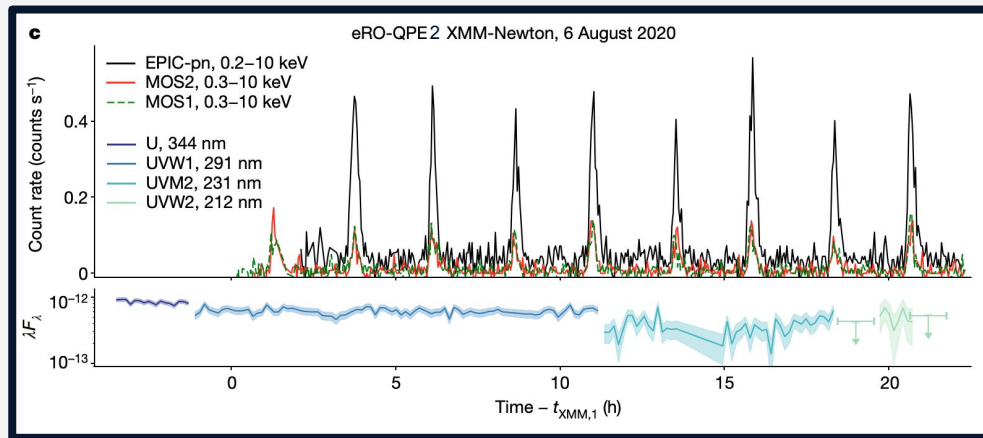
- Scanning strategy
- German half public



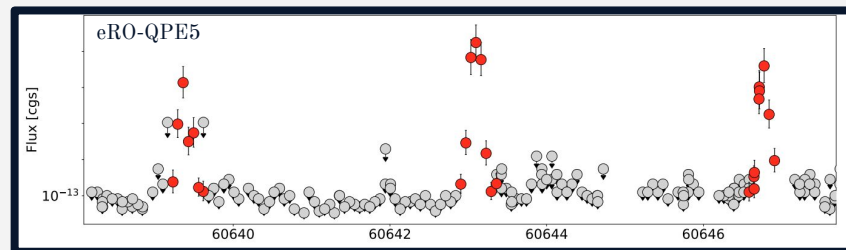
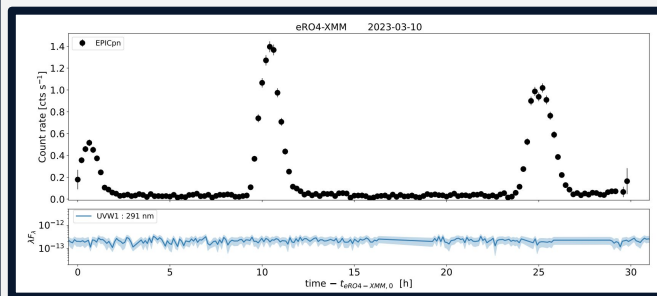
Arcodia+21

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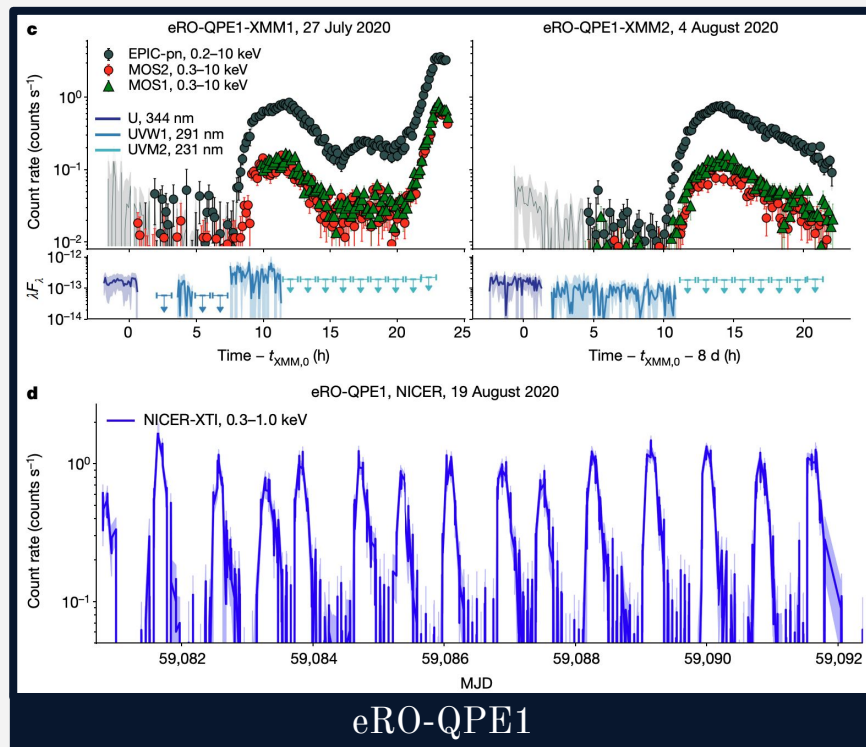


Arcodia+21, 24, 25



Hunt for other QPEs: eROSITA

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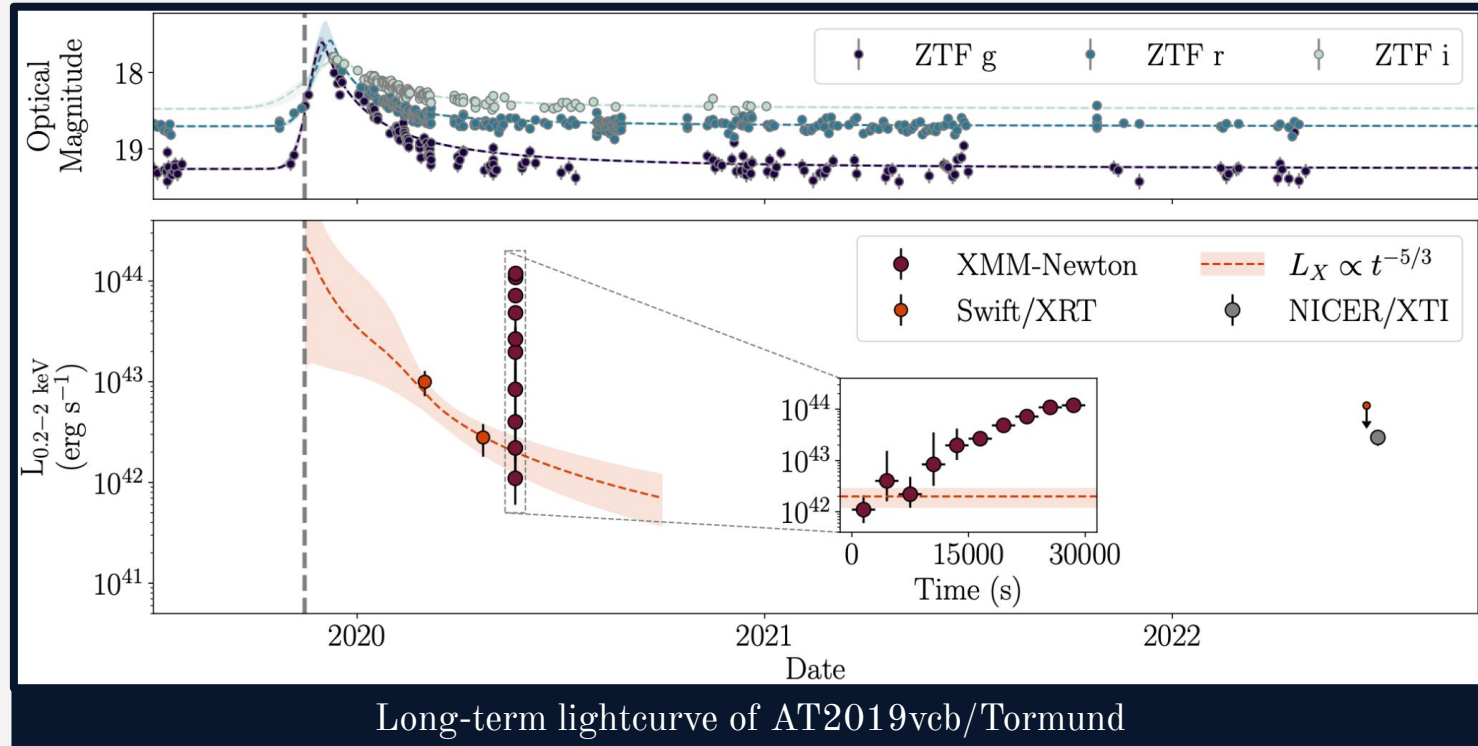


Arcodia+21

- Longer
- Brighter
- Transition from irregular to $\sim$ regular

Hunt for other QPEs: Tormund

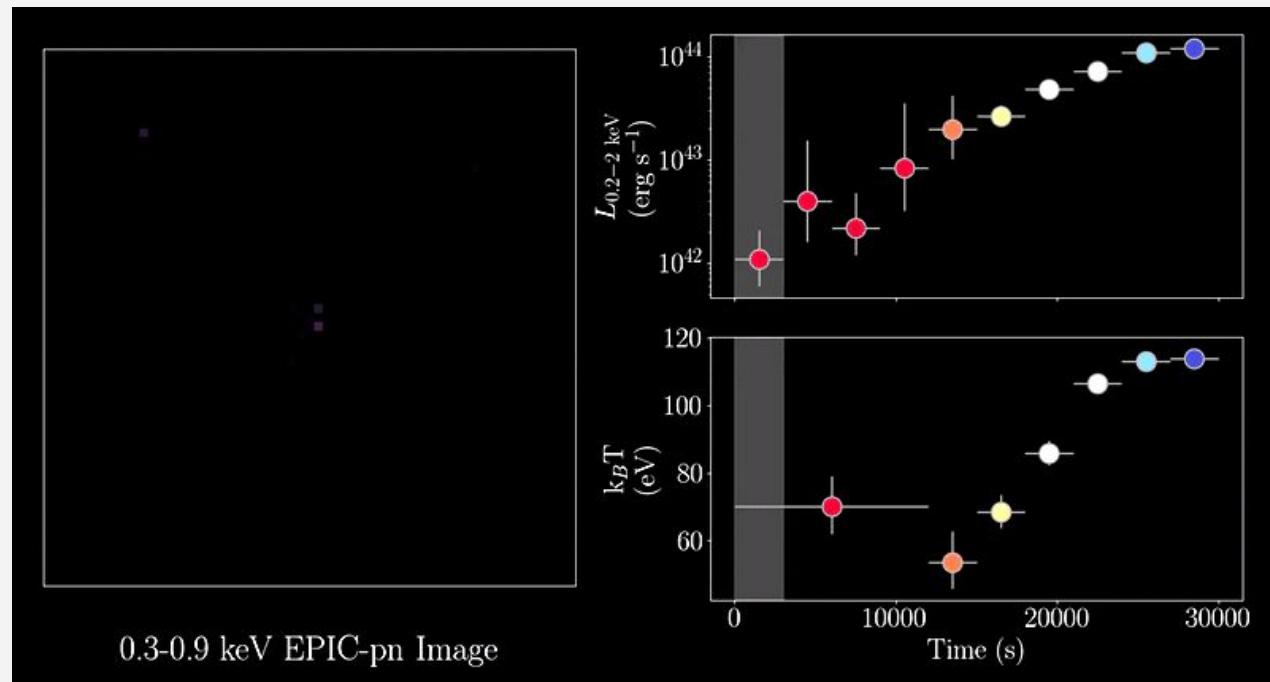
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Quintin+23

Hunt for other QPEs: Tormund

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Quintin+23

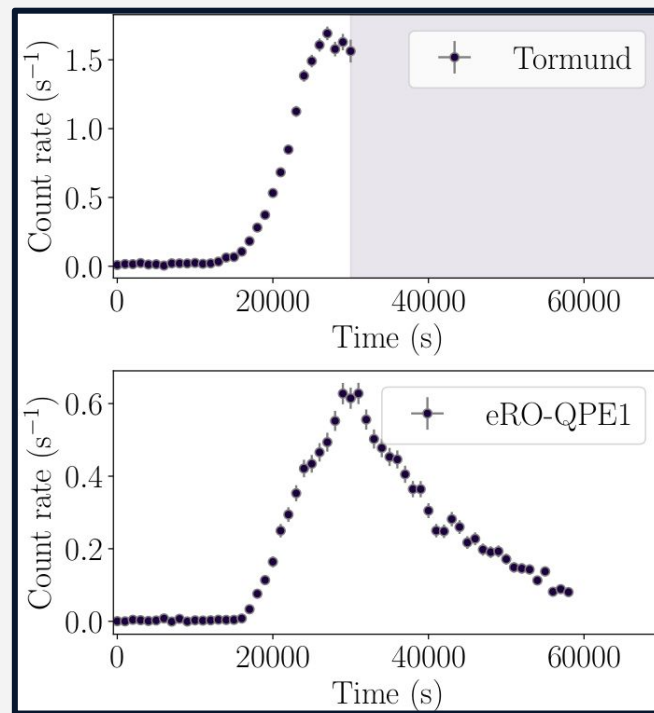
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Only half a peak
In Russian half of eROSITA

BUT

Spectral-timing properties all
correspond
No other interpretation
manages

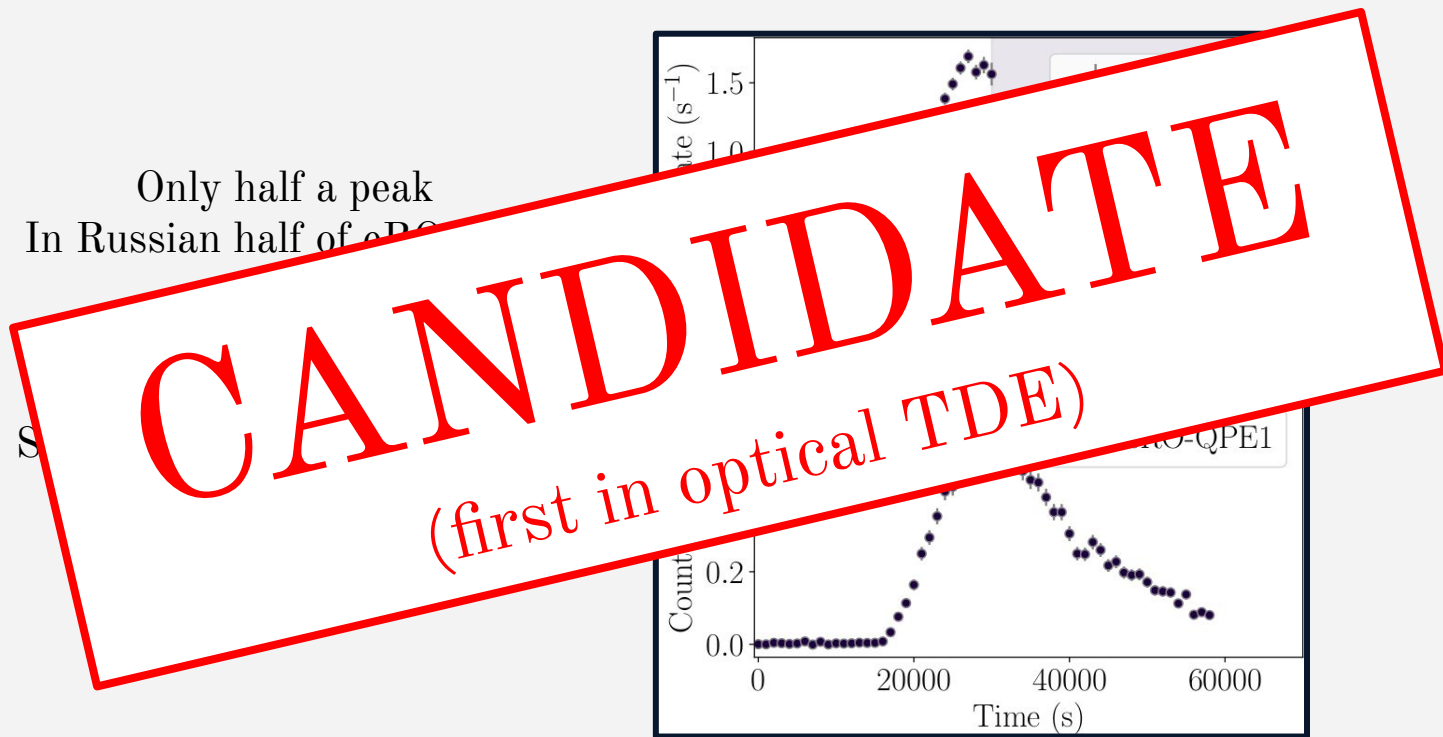


Quintin+23

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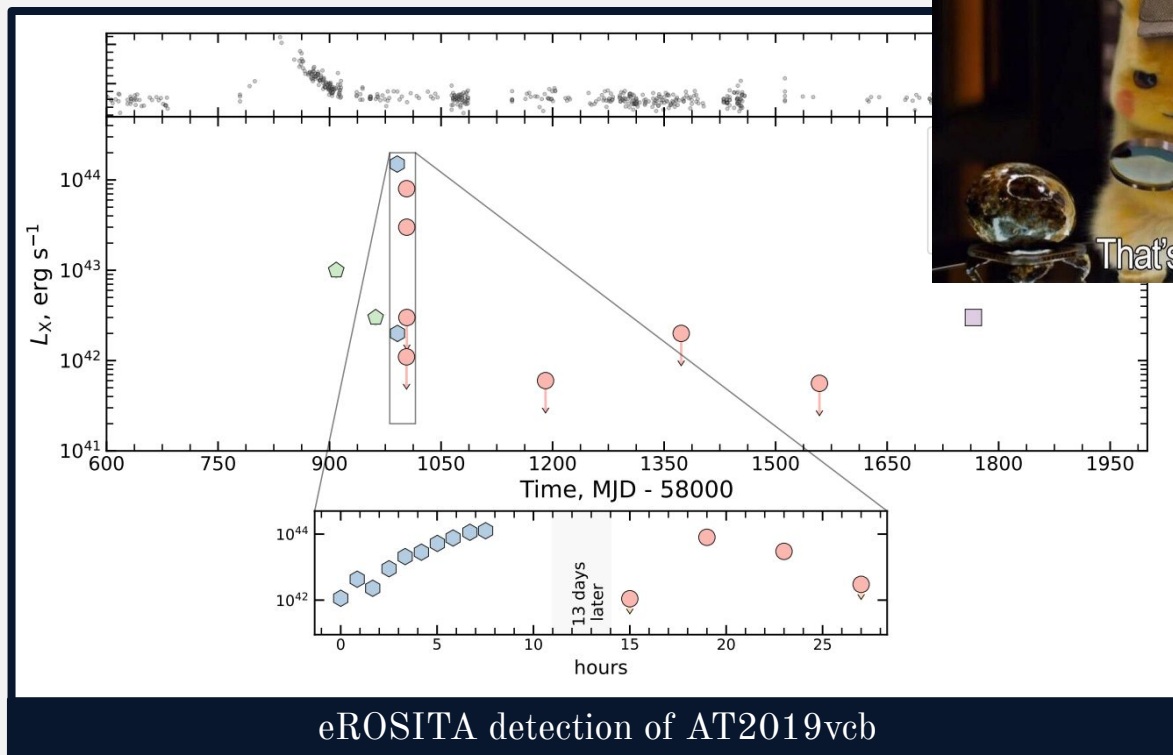
Only half a peak
In Russian half of ePC



Quintin+23

Hunt for other QPEs: Tormund

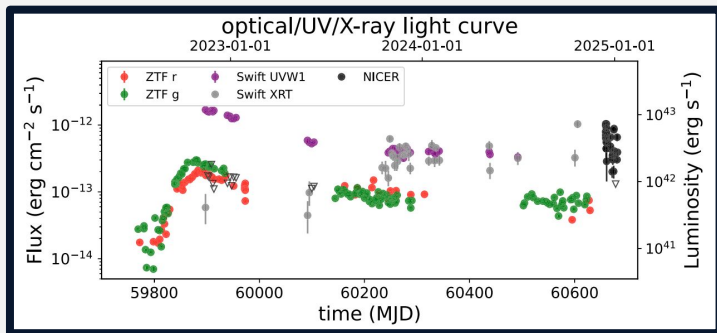
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Bykov+24

Hunt for other QPEs: latest additions

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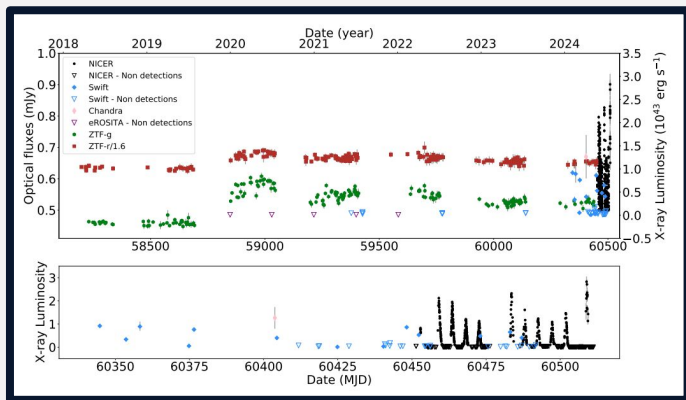


AT2022upj

Chakraborty+24

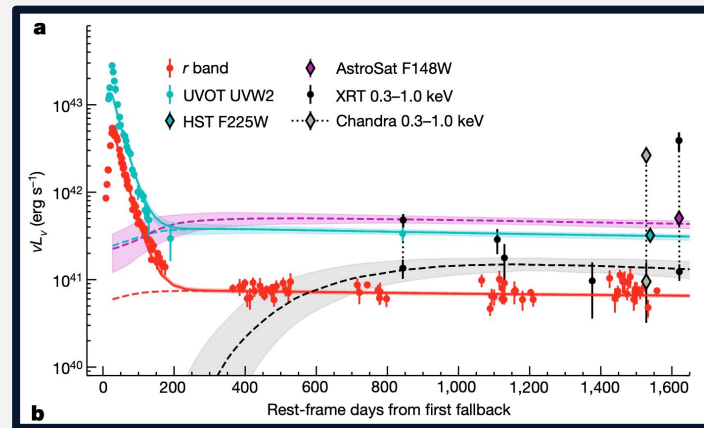
AT2019qiz

Nicholl+24



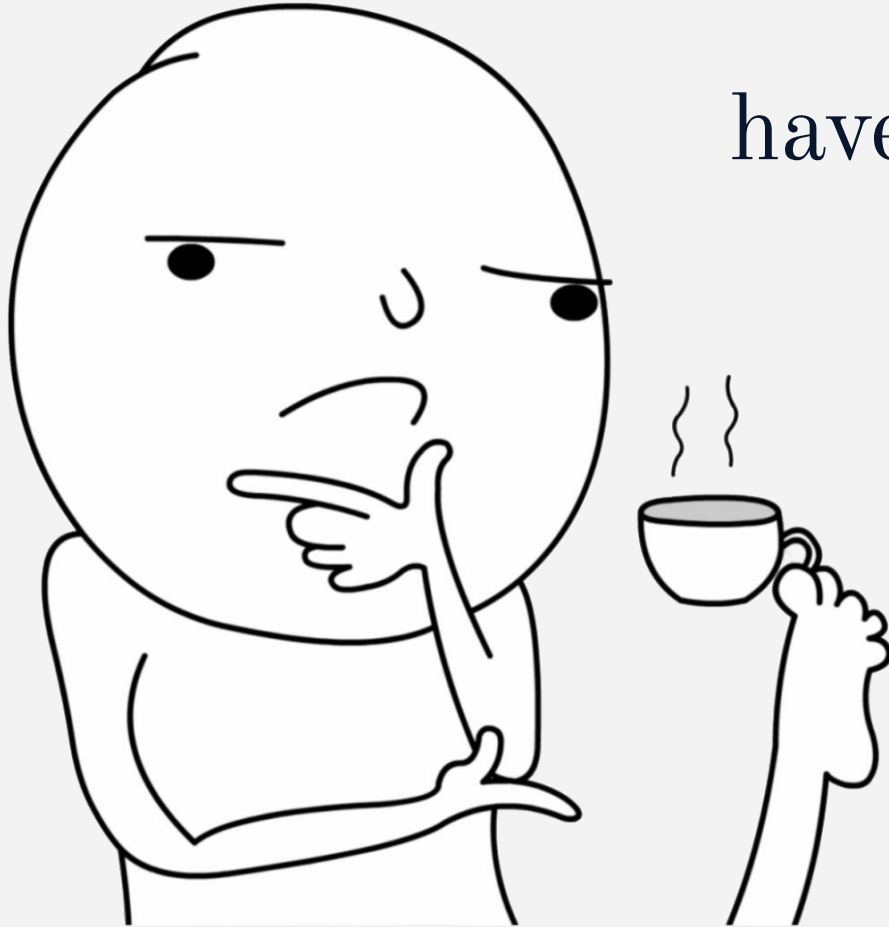
ZTF19acnsky

Hernández-García+25



Now that we
have this sample...

So what ?



The background is a complex, abstract composition. At the center is a circular vortex or eye-like shape, with a dark blue core surrounded by concentric rings of lighter blue and yellow. From this center, a multitude of sharp, dark lines radiate outwards, creating a starburst or explosion effect. The background is filled with various shades of blue, orange, and red, with some areas appearing more textured or painterly than others. The overall effect is one of intense energy and dynamic movement.

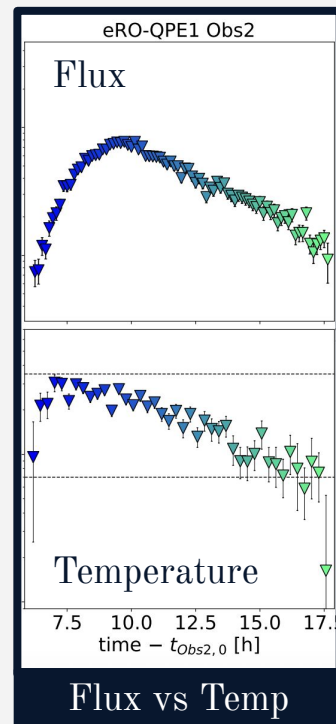
Current state

What we (think we) know

Summary of properties

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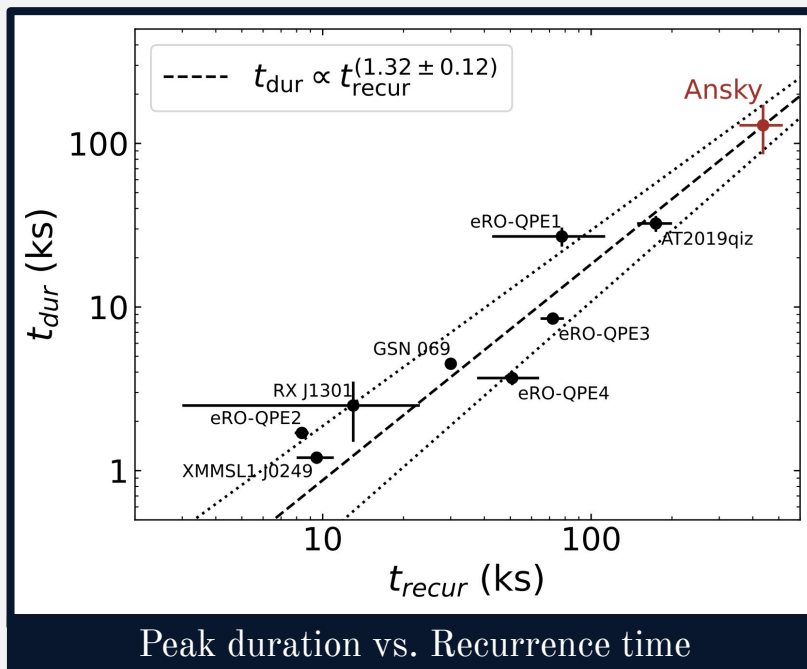
- Short, repeated burst of **thermal** X-rays
- A range of timing and amplitude properties over **~ 2 orders of mag**
- **Irregular** vs. regular
- **Activity** lasts < 6 months or > 40 years



Arcodia+22

Summary of properties

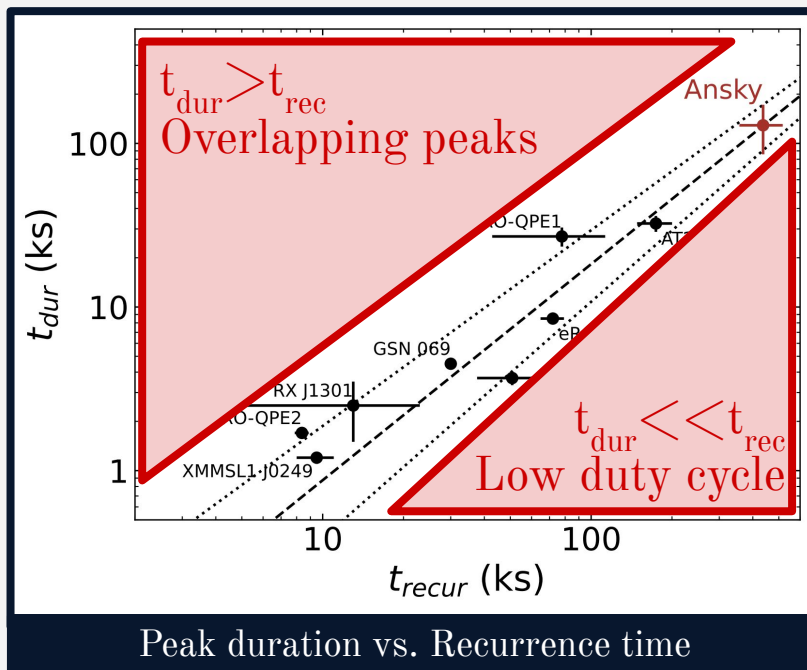
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Hernández-García+25

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Hernández-García+25

*caveat: non-diagonal are difficult to see

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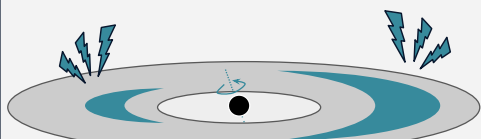
- **Strong correlation with TDEs**
 - At least 6/12
 - Rate: $\sim 10^{-5}$ /gal/year



Possible models

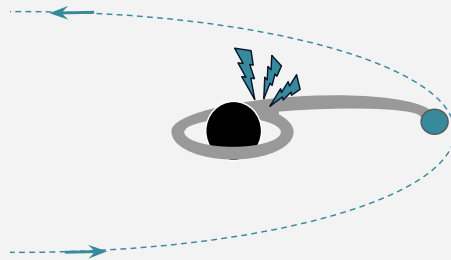
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Disk Instabilities



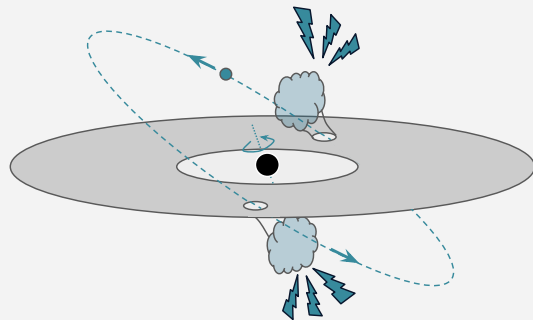
Raj & Nixon 2021; Pan et al. 2021a, 2022, 2023; Kaur et al. 2023; Sniegowska et al. 2020, 2023; Middleton et al. 2025

Repeated Partial TDEs



King 2020, 2022, 2023; Metzger et al. 2022; Zhao et al. 2022; Chen et al. 2022; Krolik & Linial 2022; Linial & Sari 2023; Yang et al. 2025; Lau & Yu 2025

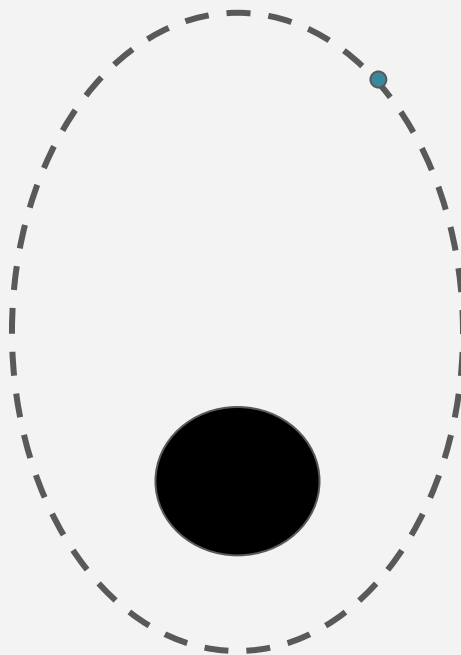
Disk Collision



Dai et al. 2010; Xian et al. 2021; Suková et al. 2021; Lu & Quataert 2023; Franchini et al. 2023; Tagawa & Haiman 2023; Linial & Metzger 2023, 2024; Zhou et al. 2024a, 2025b, 2024b, 2025a; Tsz-Lok Lam et al. 2025; Yao et al. 2025; Yao & Quataert 2025; Huang et al. 2025

Currently favored model

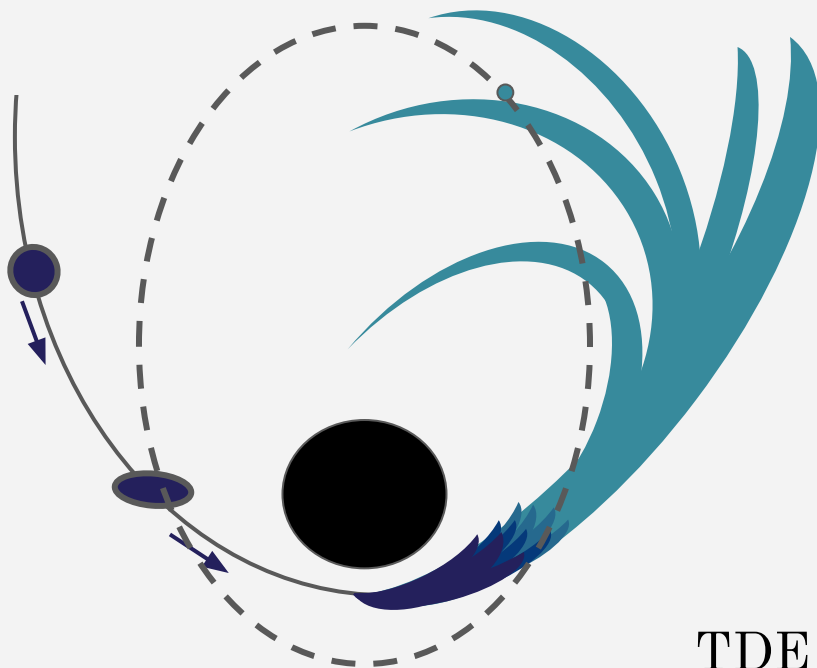
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Pre-existing (stellar?) Extreme Mass Ratio Inspiral (EMRI)

Currently favored model

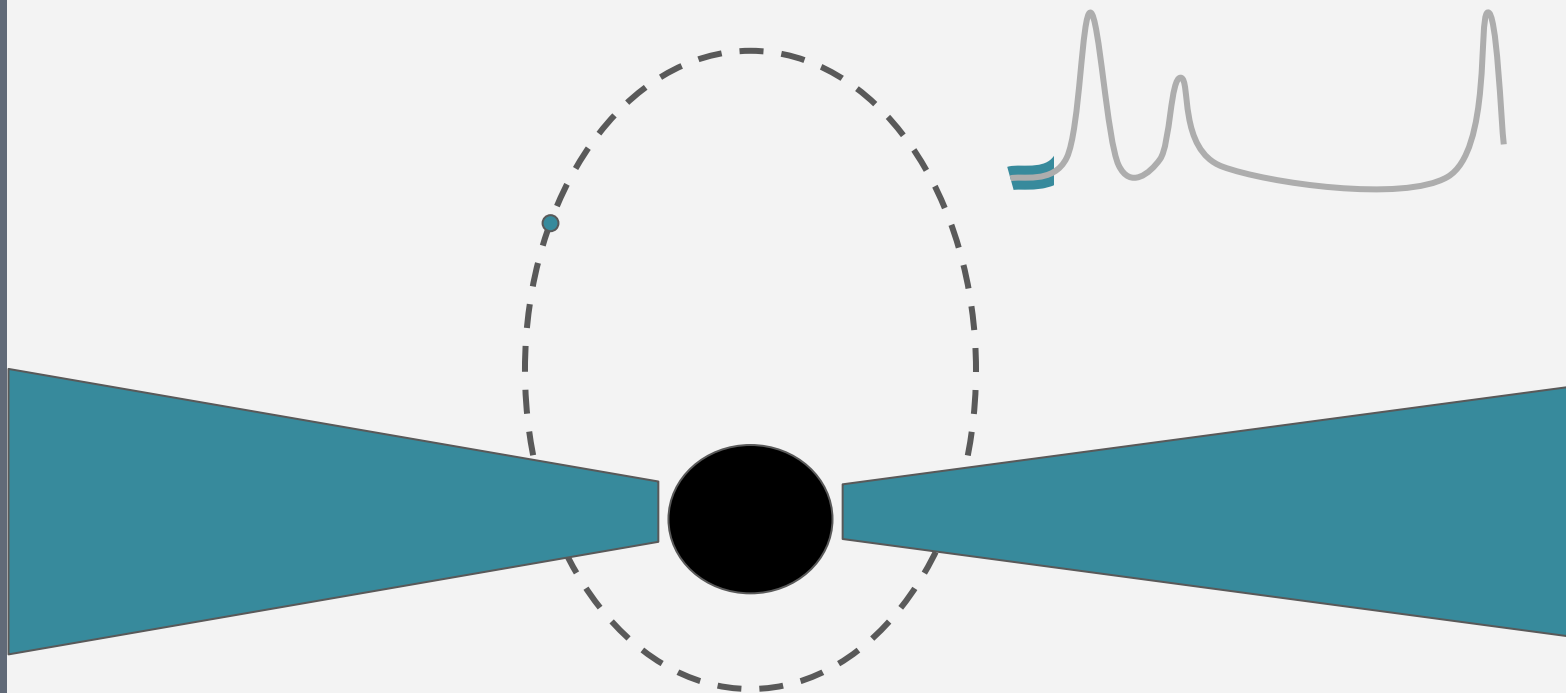
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TDE of other star

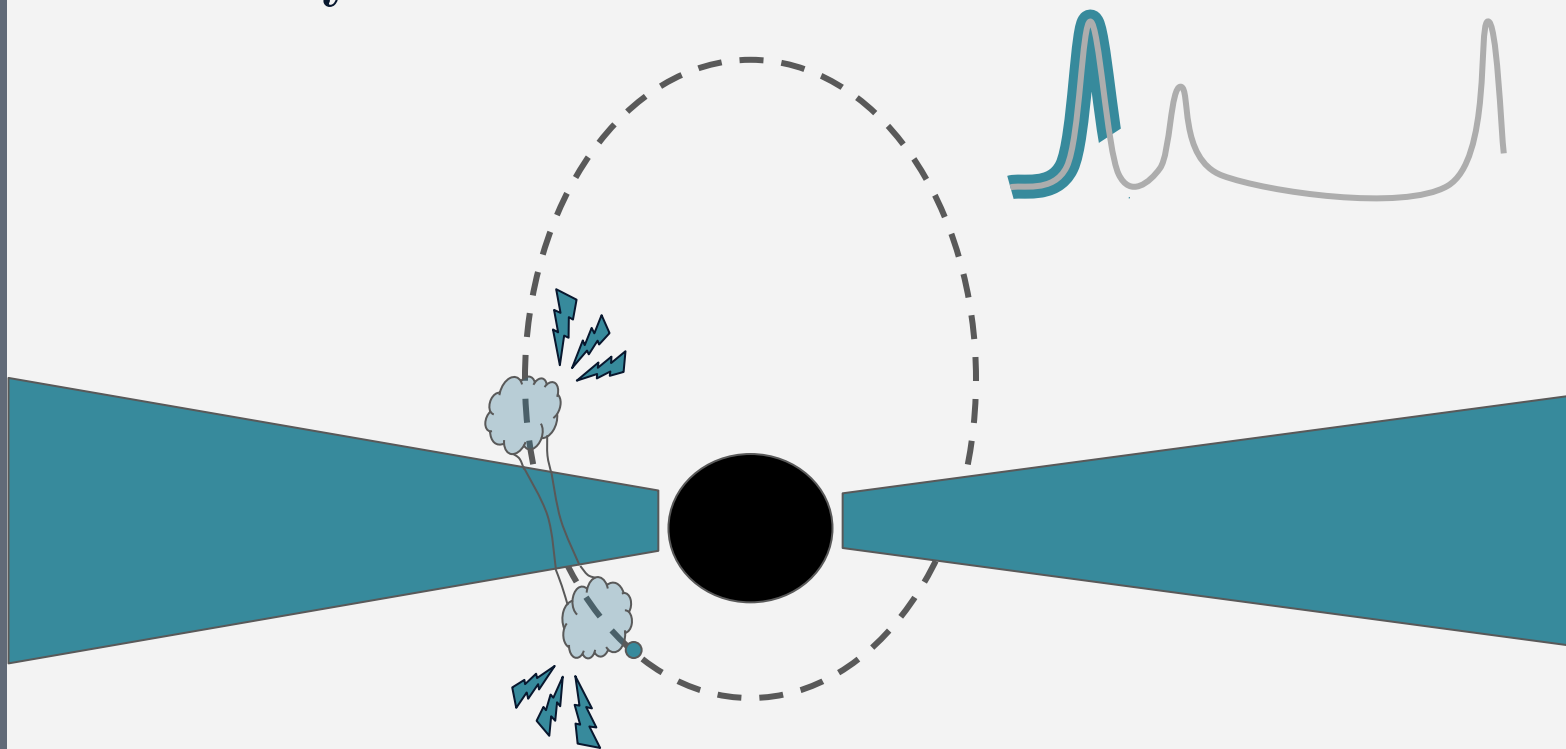
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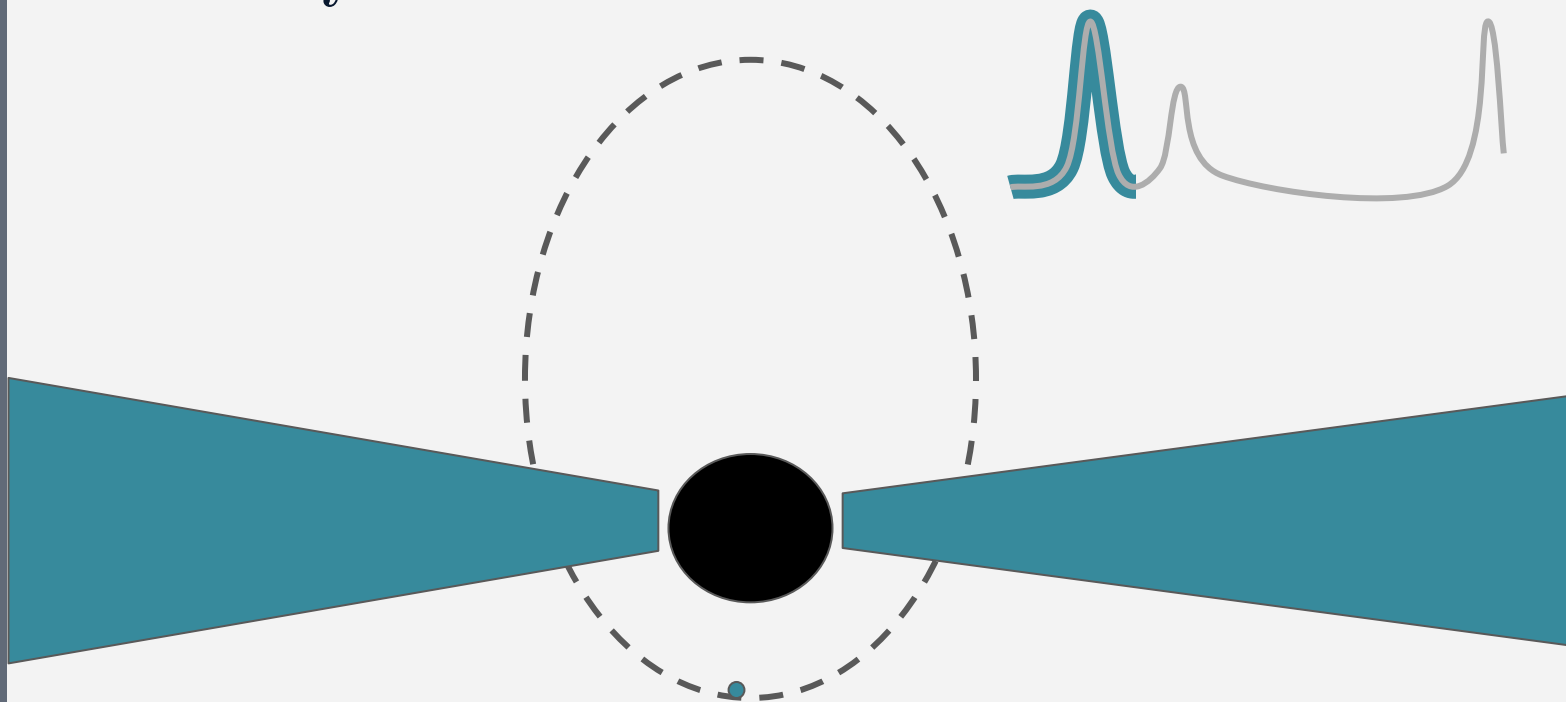
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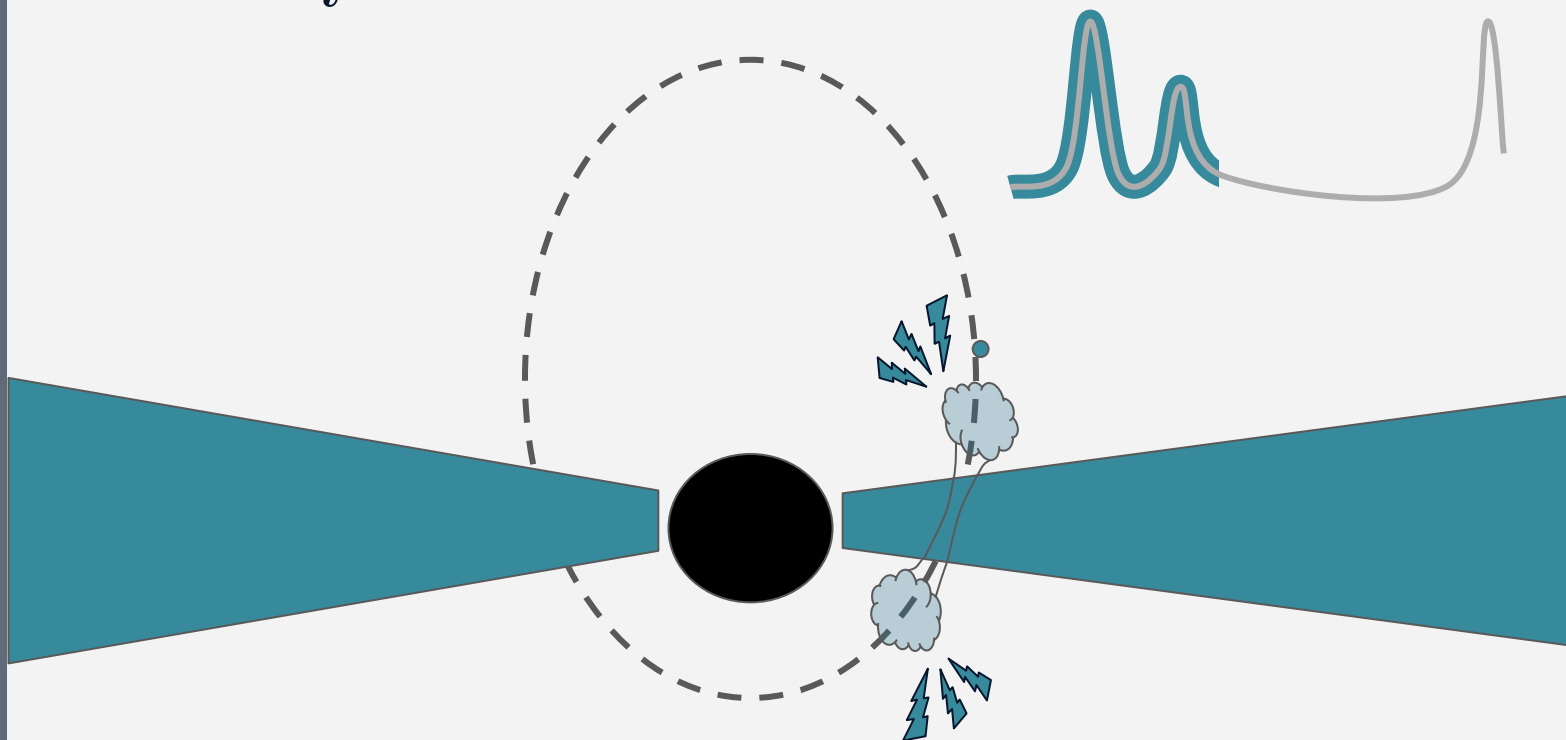
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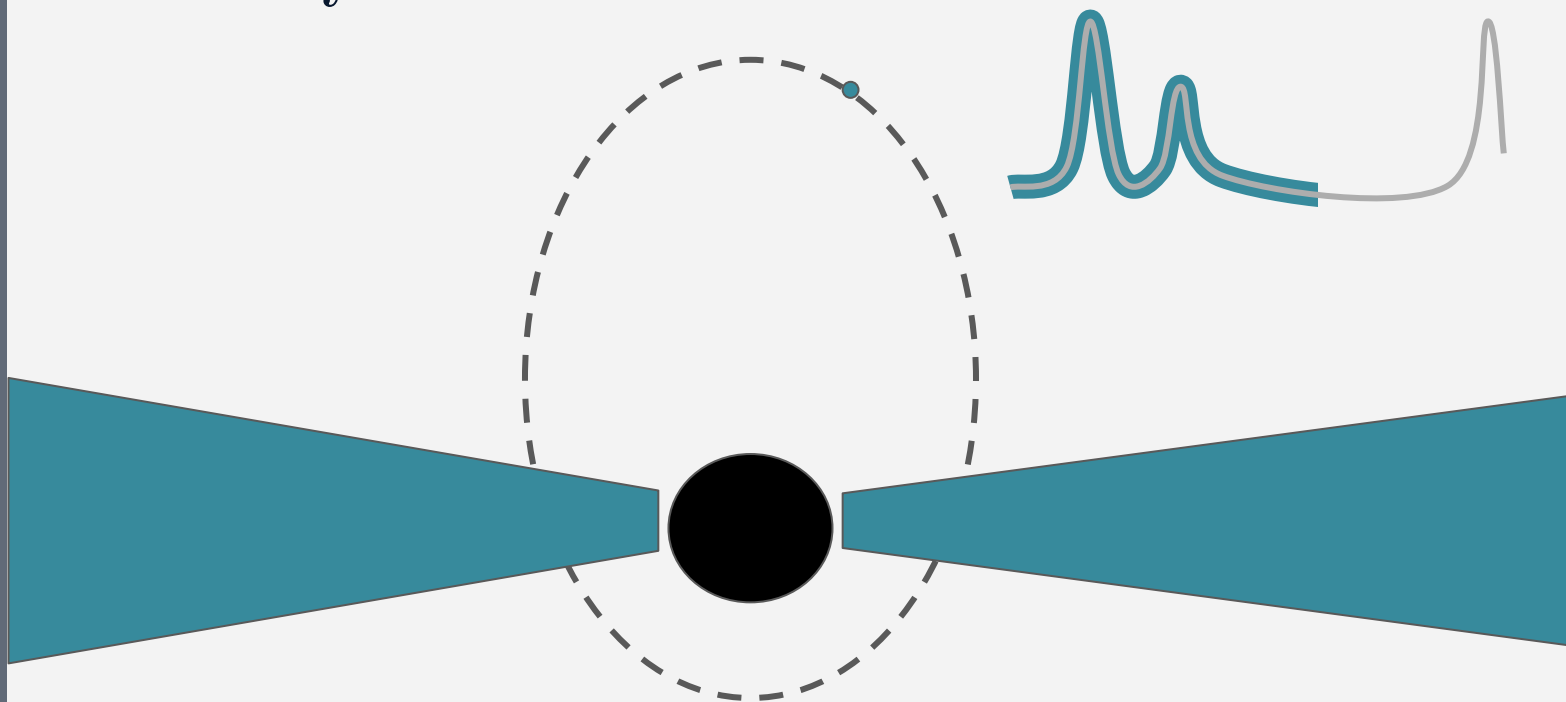
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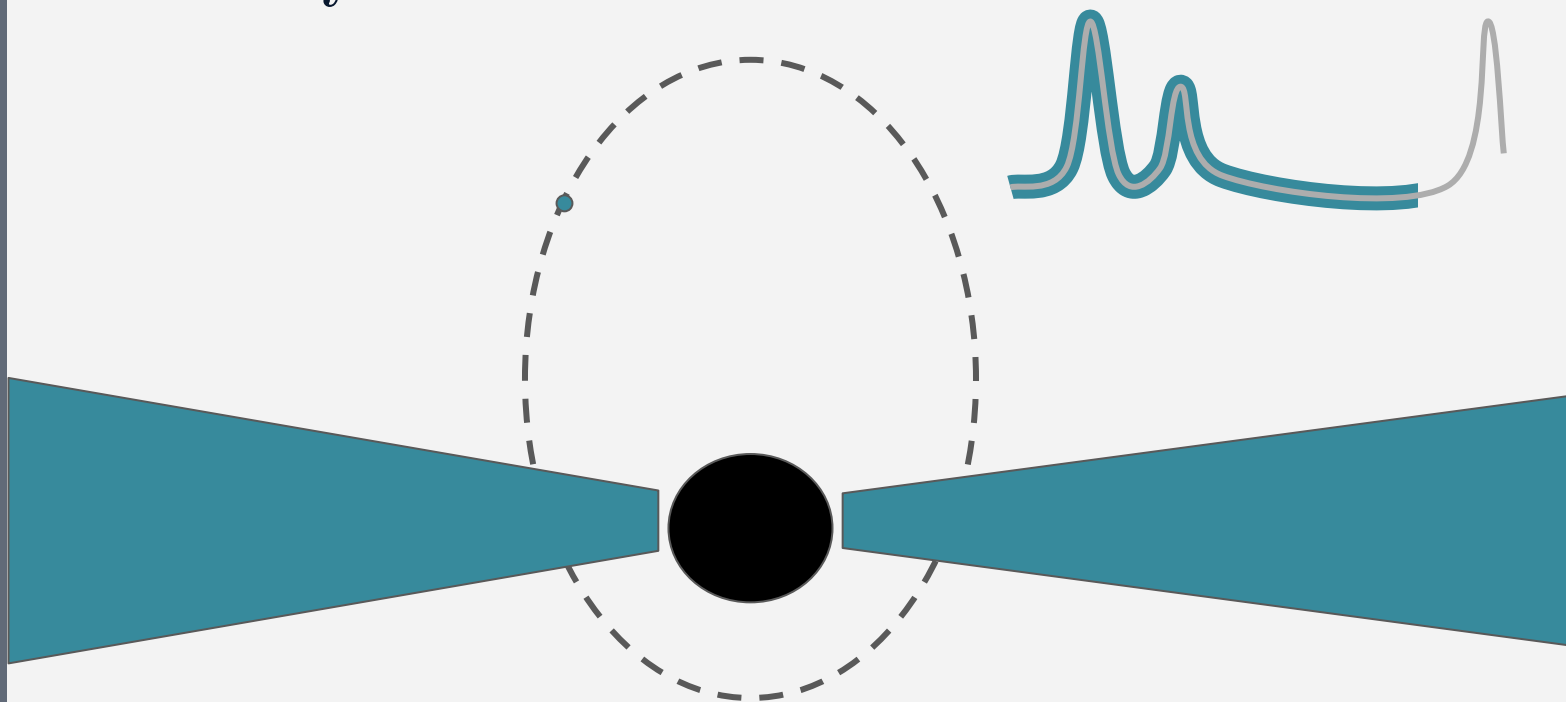
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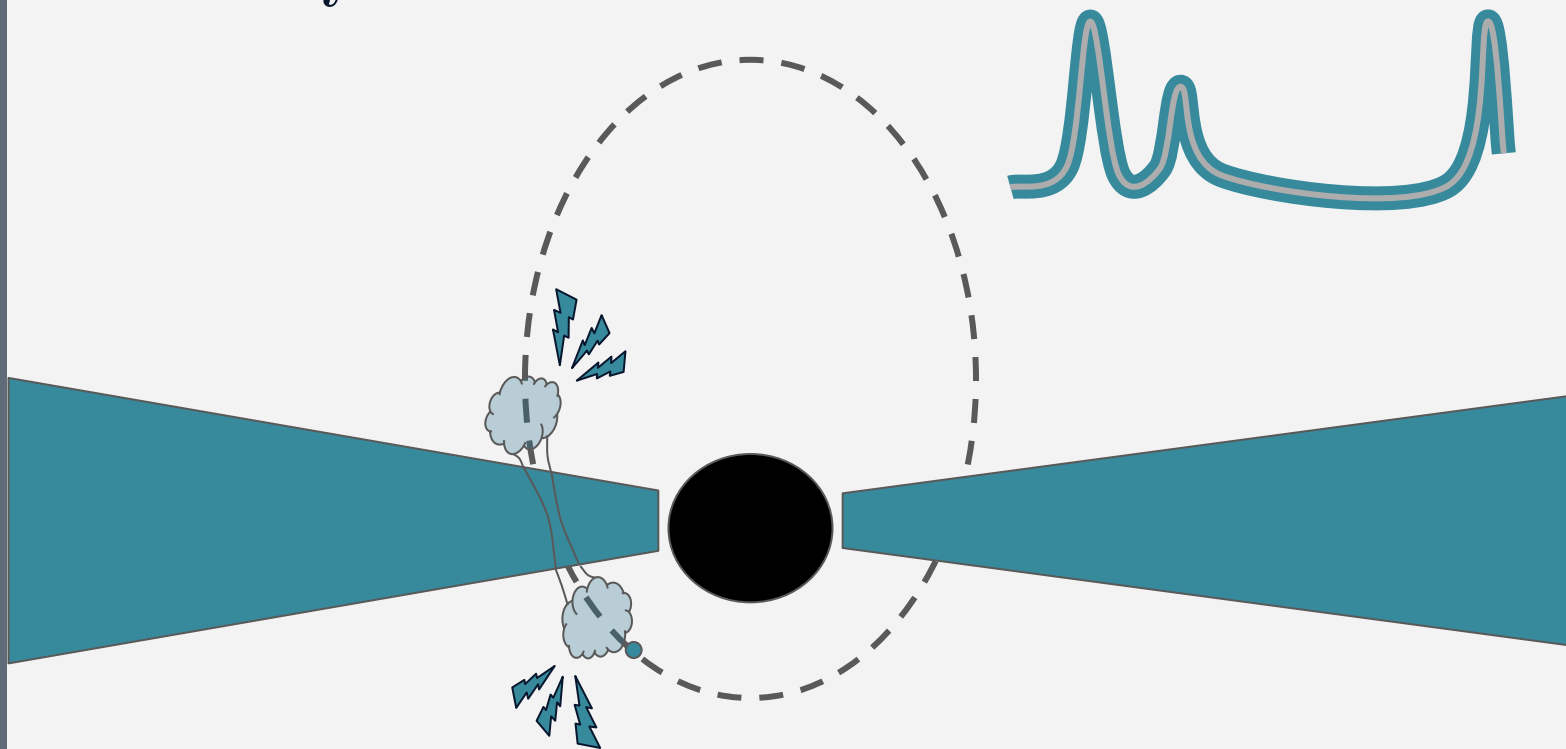
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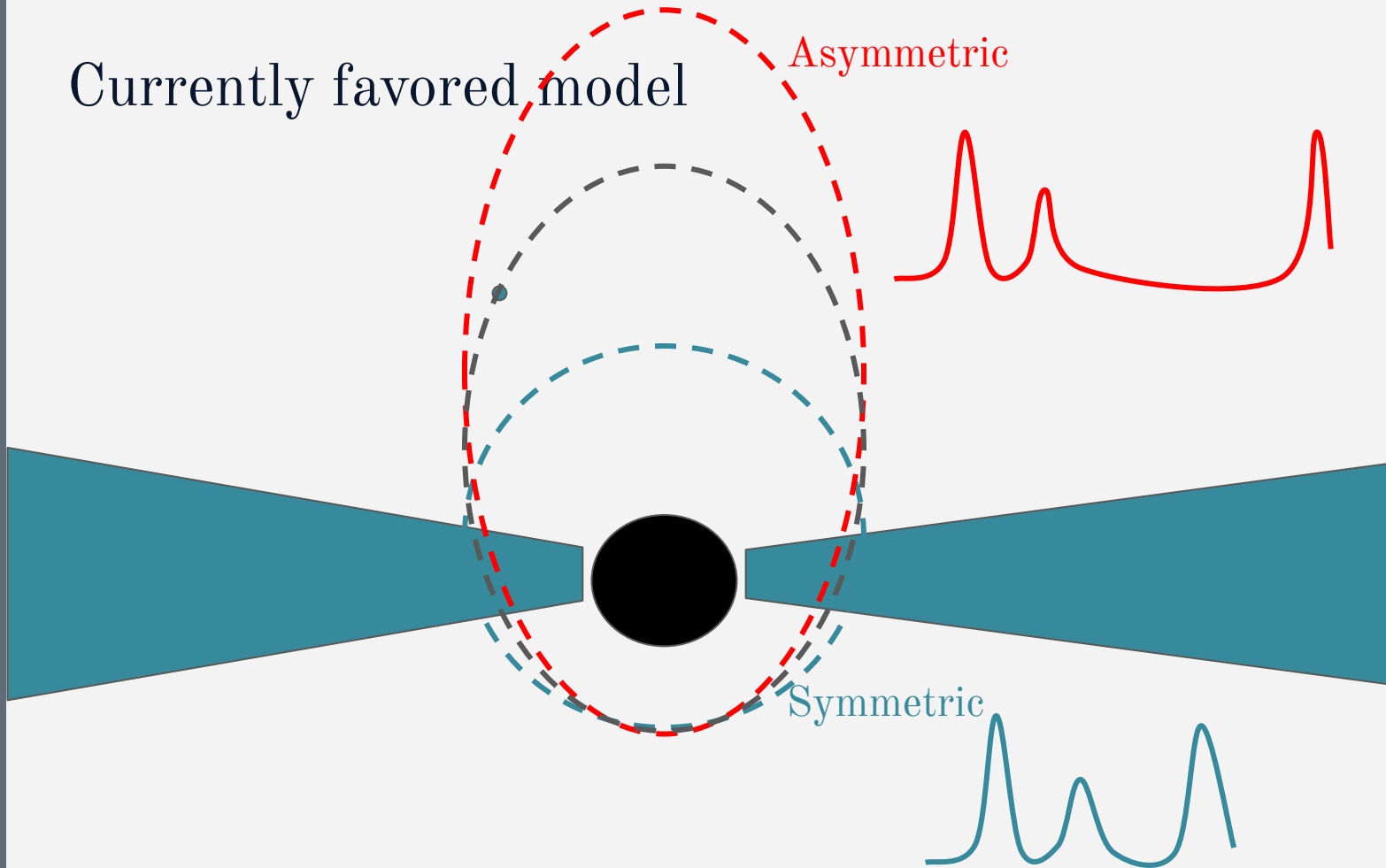
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Currently favored model

Asymmetric

Symmetric



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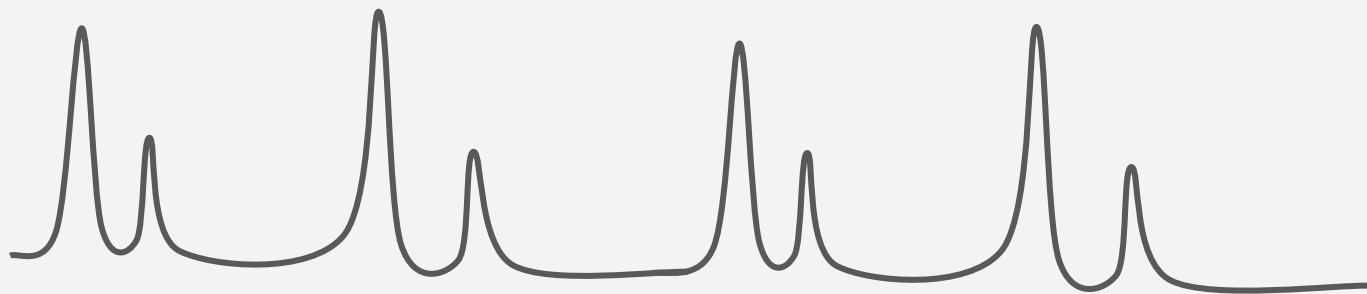
Latest progress

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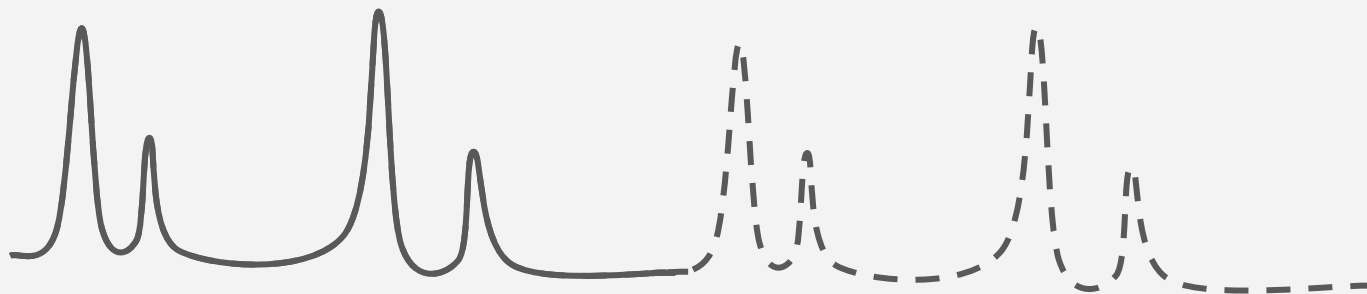
Latest progress #1: Modulations

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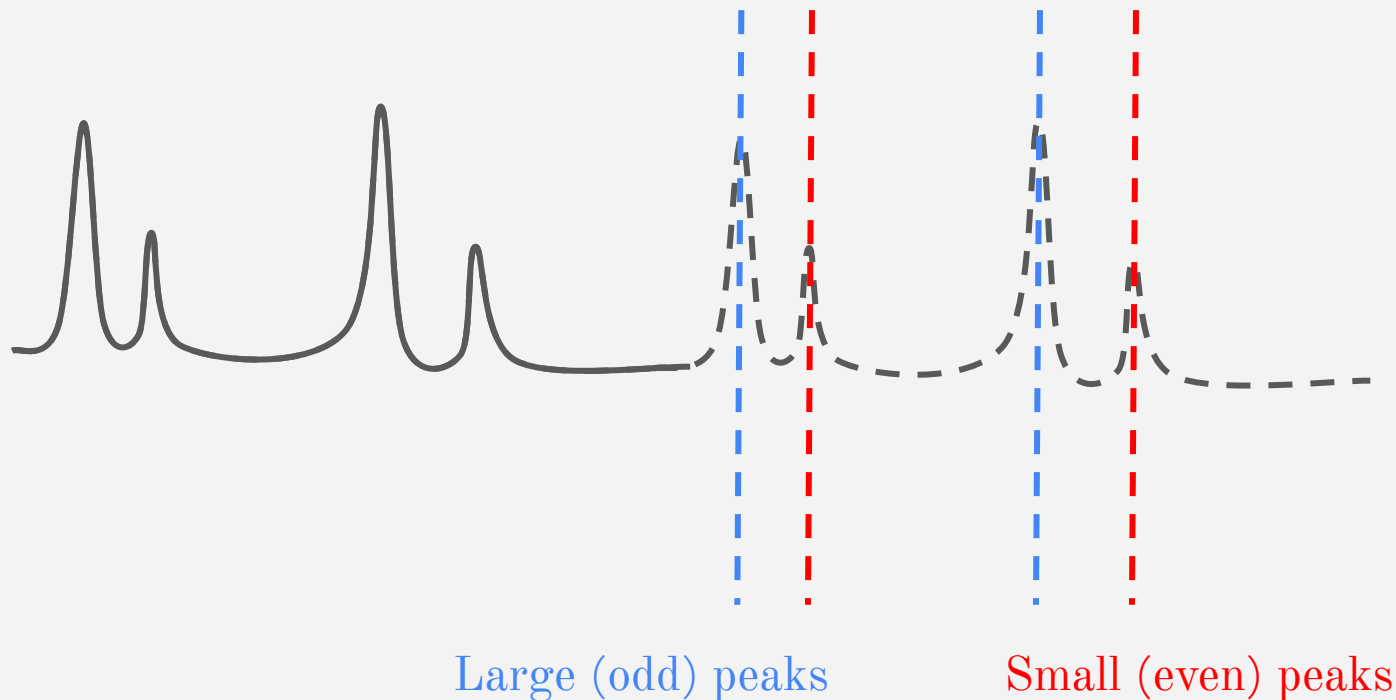
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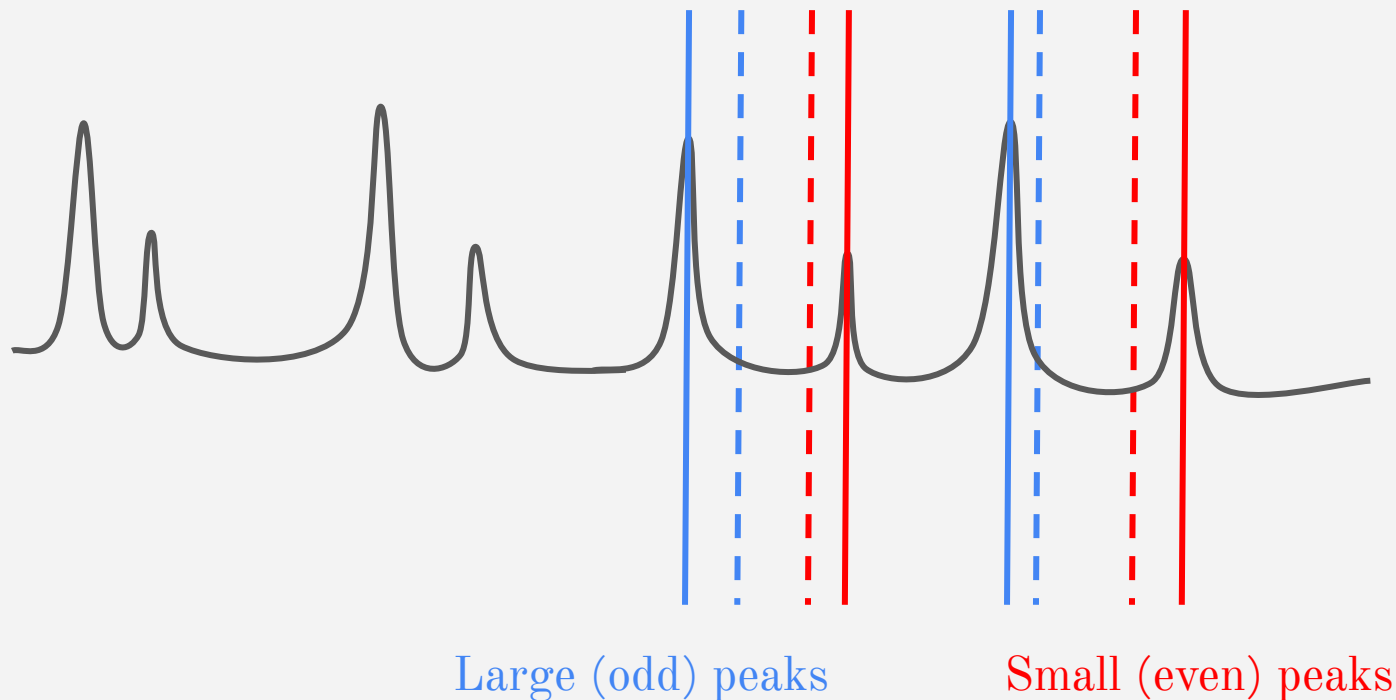
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Latest progress #1: Modulations

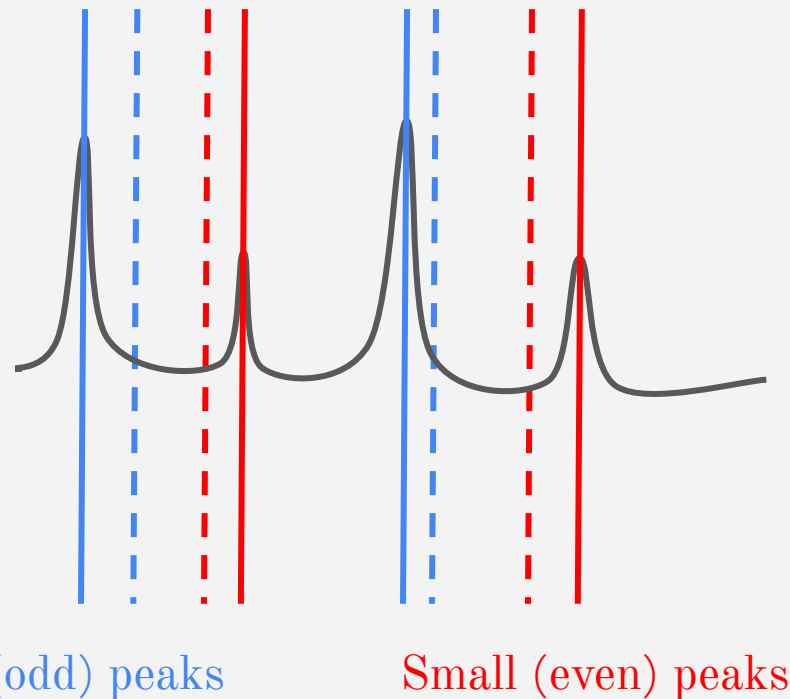
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Latest progress #1: Modulations

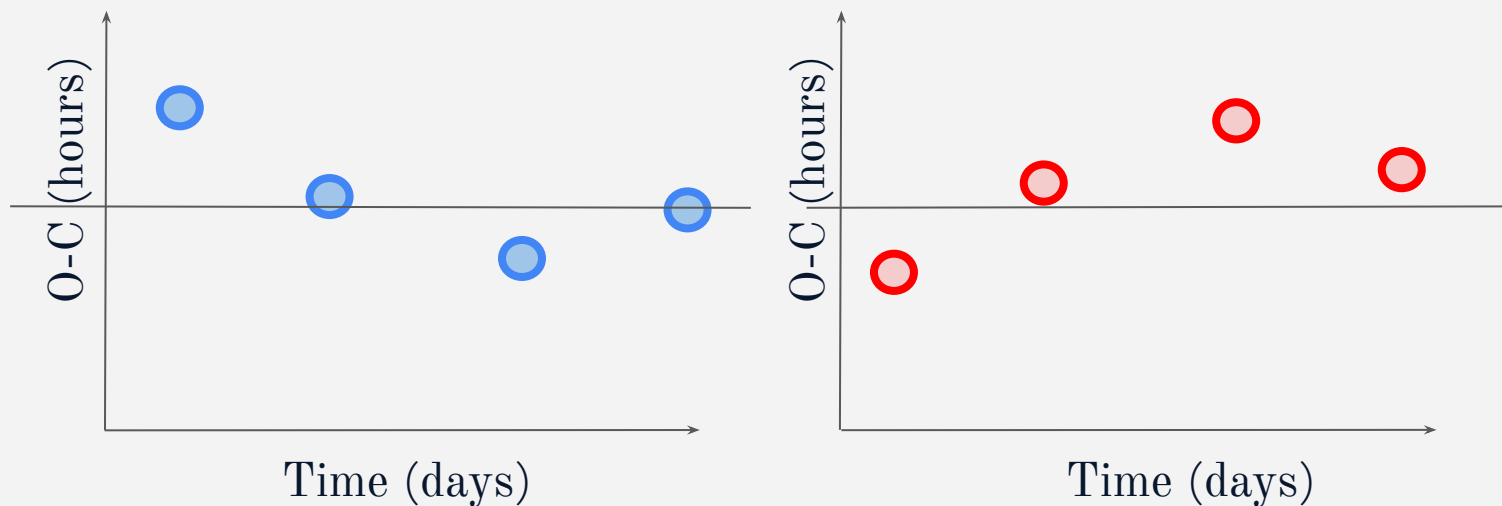
- Introduction
- Current state
 - Properties
 - Models
 - Latest Progress
- QPEs & GWs
- Conclusion

**Observed - Computed
(O-C) diagrams**



Latest progress #1: Modulations

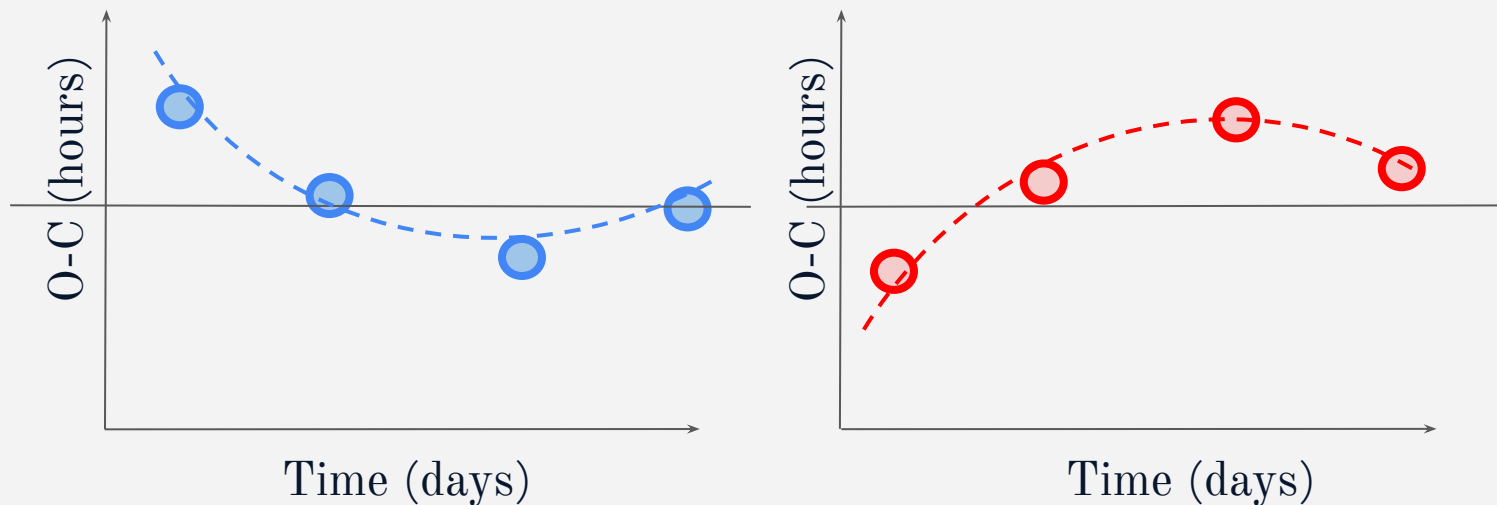
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Observed - Computed
(O-C) diagrams

Latest progress #1: Modulations

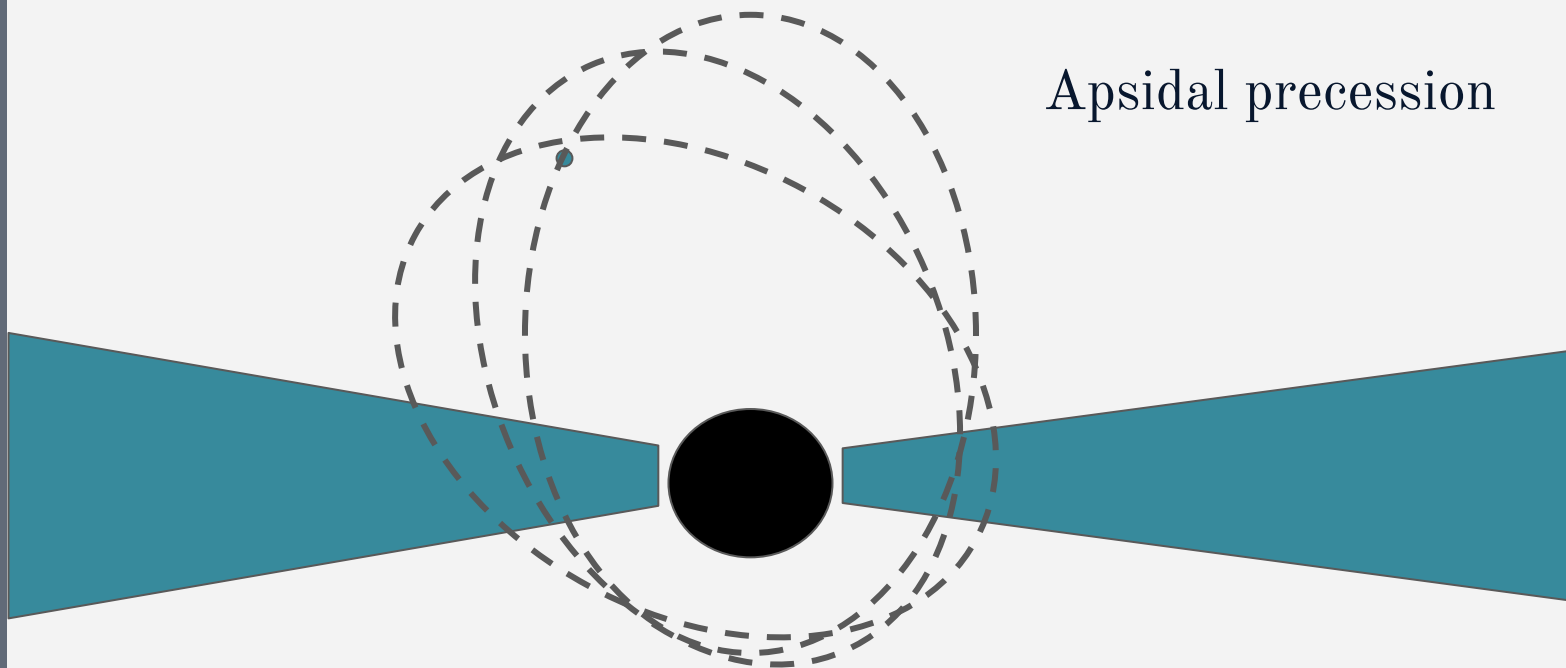
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Observed - Computed
(O-C) diagrams

Latest progress #1: Modulations

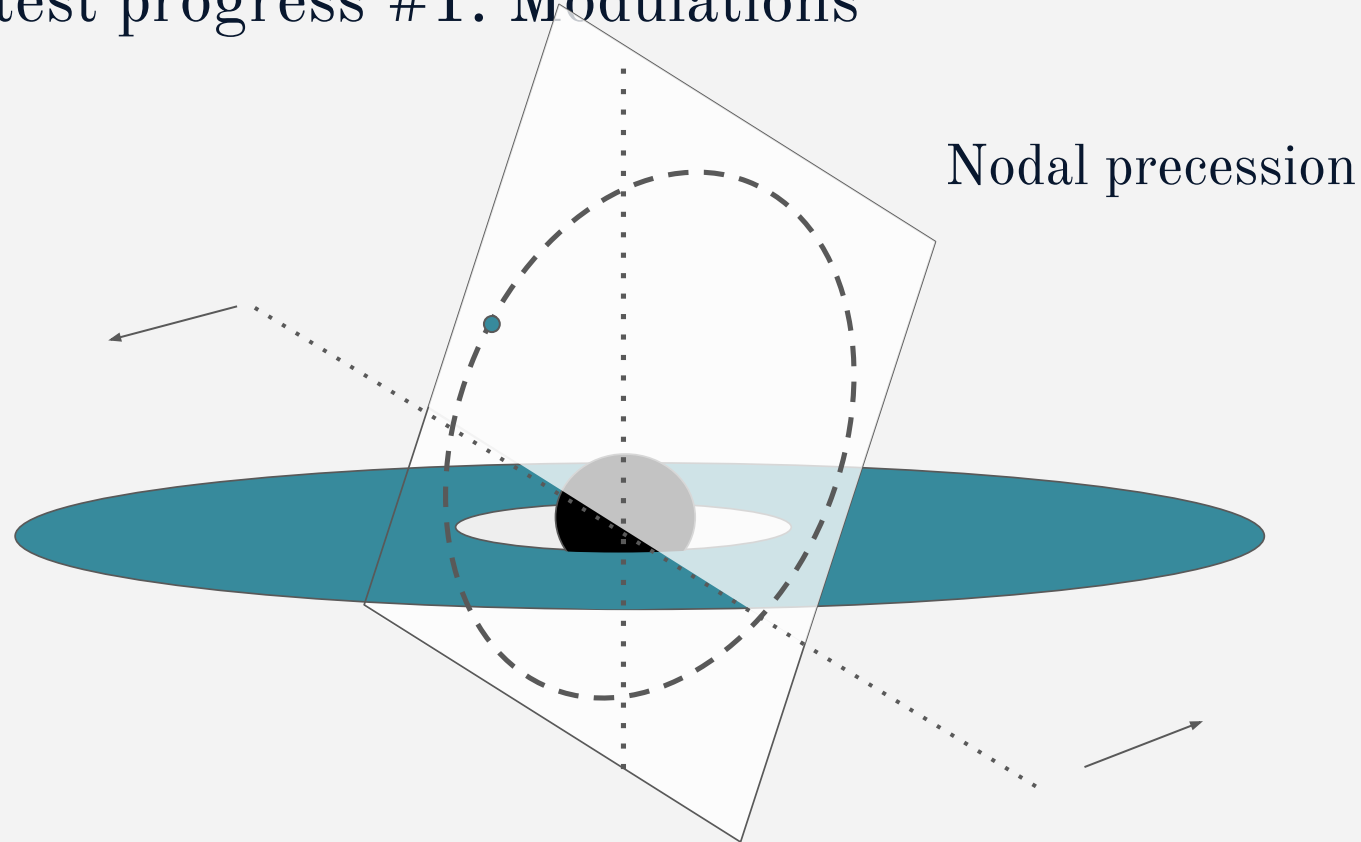
Apsidal precession



- Introduction
- Current state
 - Properties
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- QPEs & GWs
- Conclusion

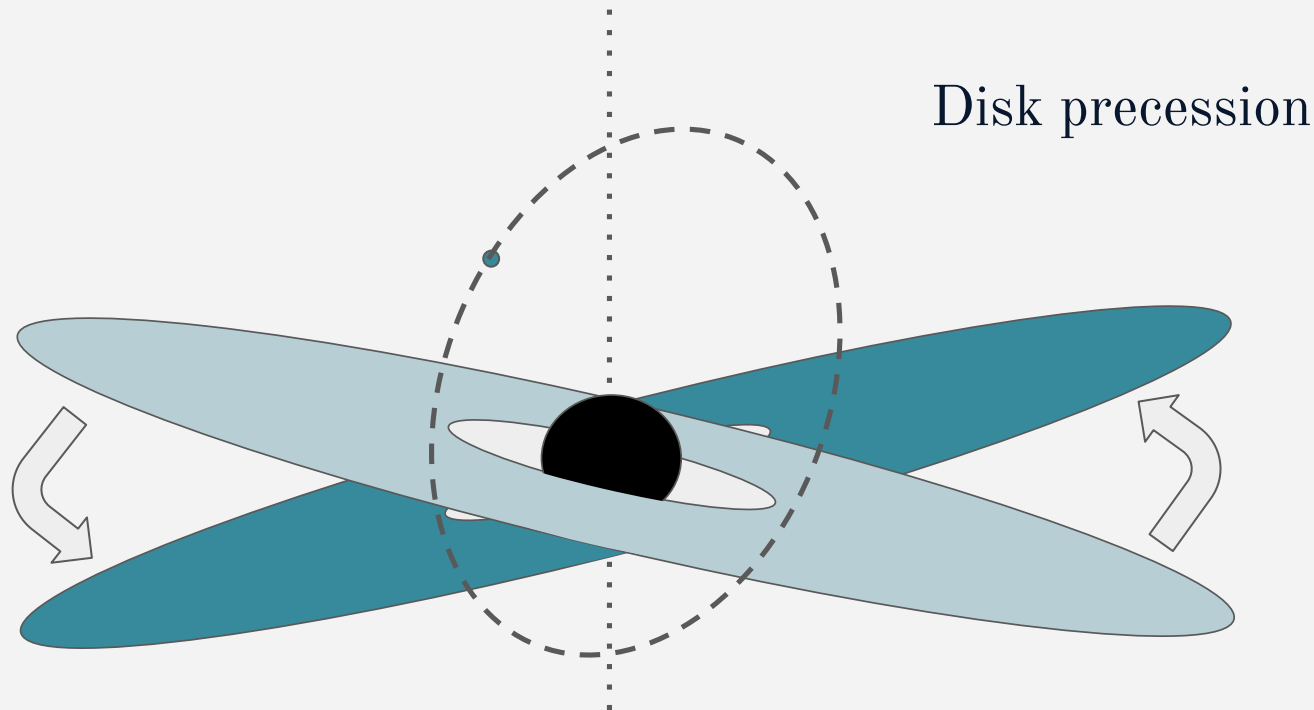
Latest progress #1: Modulations

- Introduction
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 - Models
 - Latest Progress
- QPEs & GWs
- Conclusion



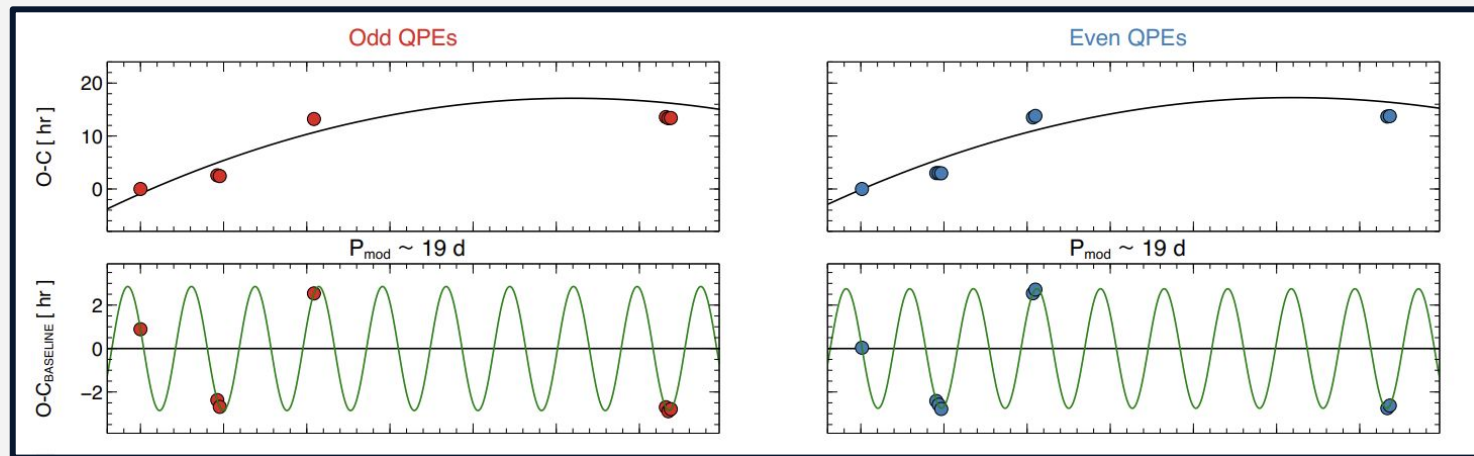
Latest progress #1: Modulations

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Latest progress #1: Modulations

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Miniutti+25

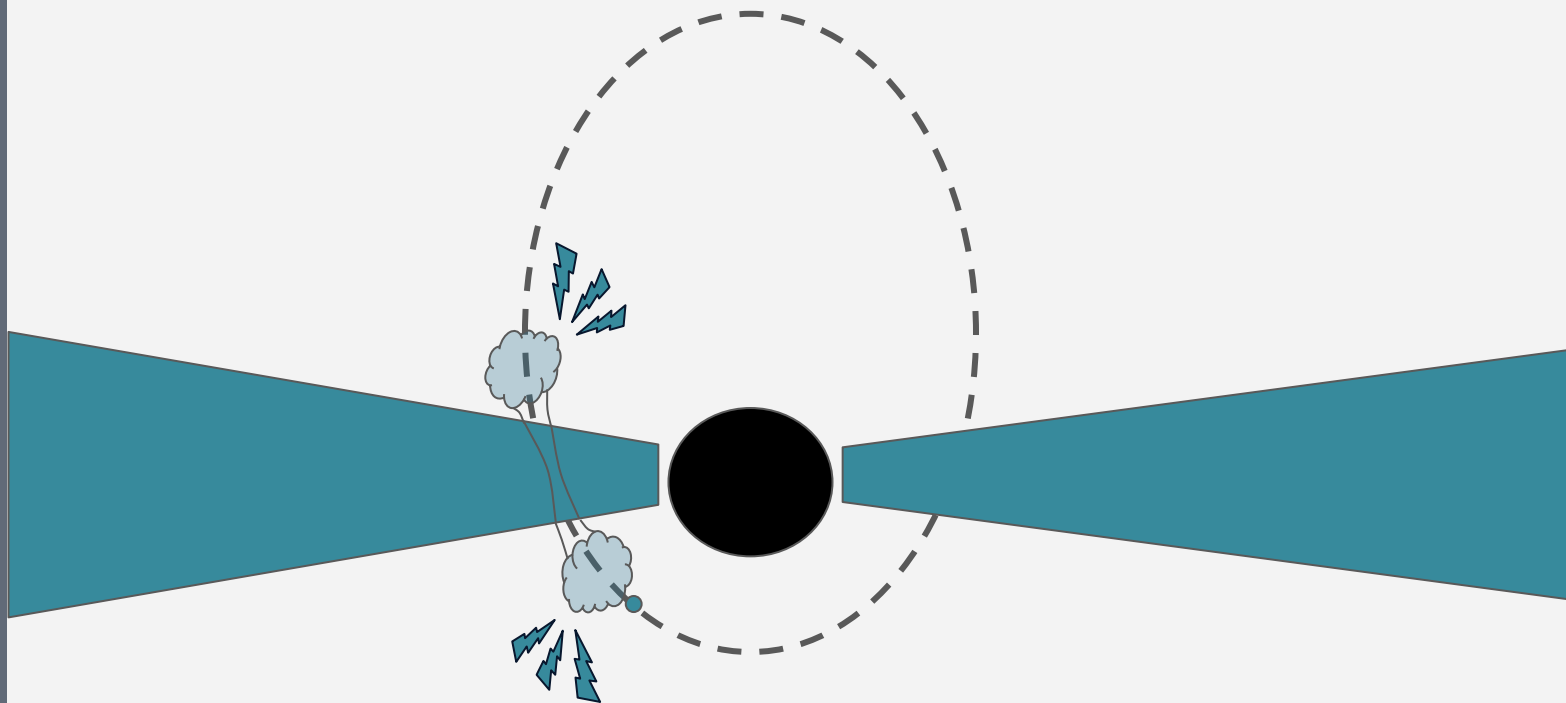
Latest progress #1: Modulations

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- Each precession has a different effect
- Each give physical info
 - Apidal precession: $M \sim 5-10\%$
- Require a lot of observations
 - In progress !

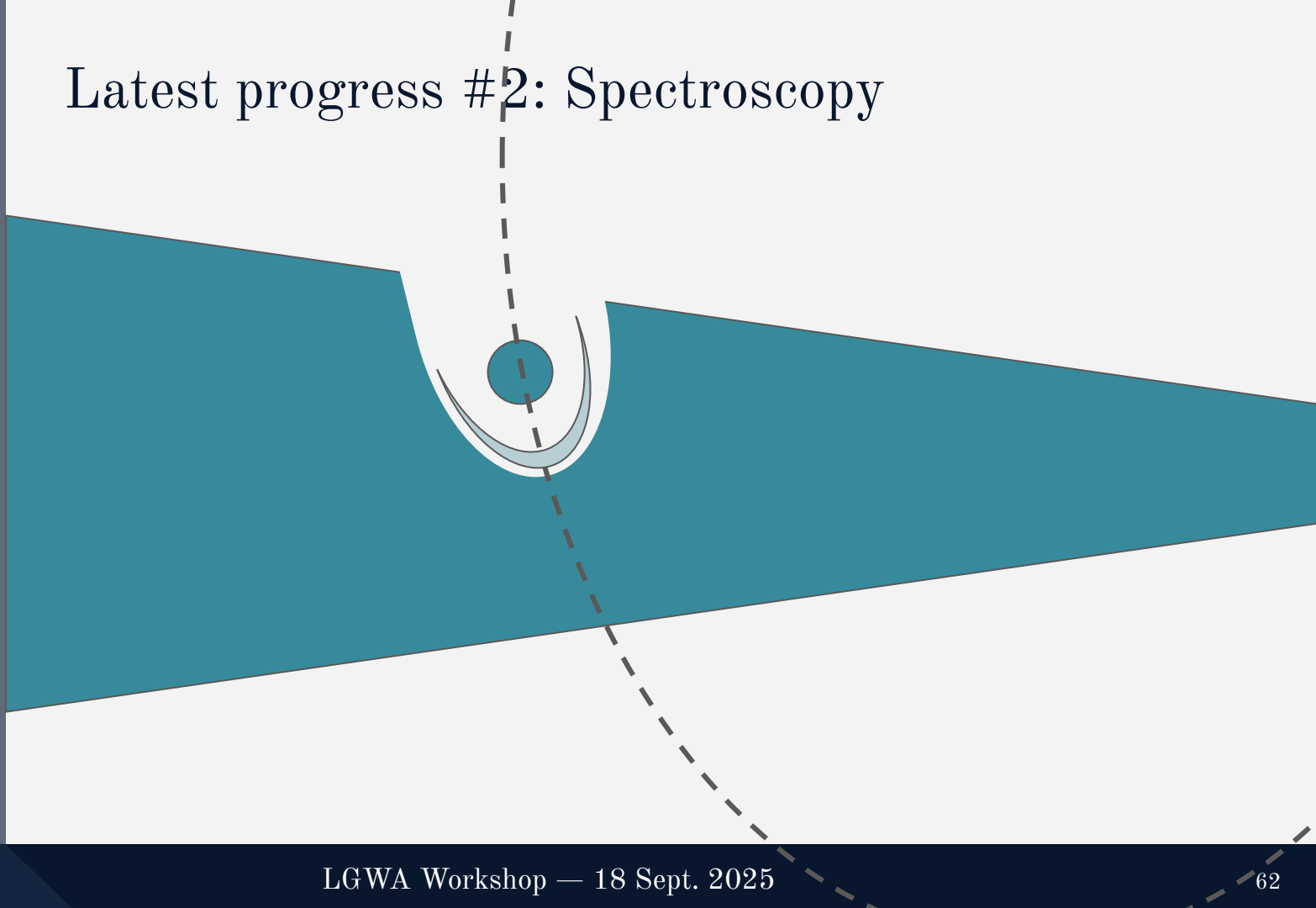
Latest progress #2: Spectroscopy

- Introduction
- Current state
 - Properties
 - Models
 - Latest Progress
- QPEs & GWs
- Conclusion



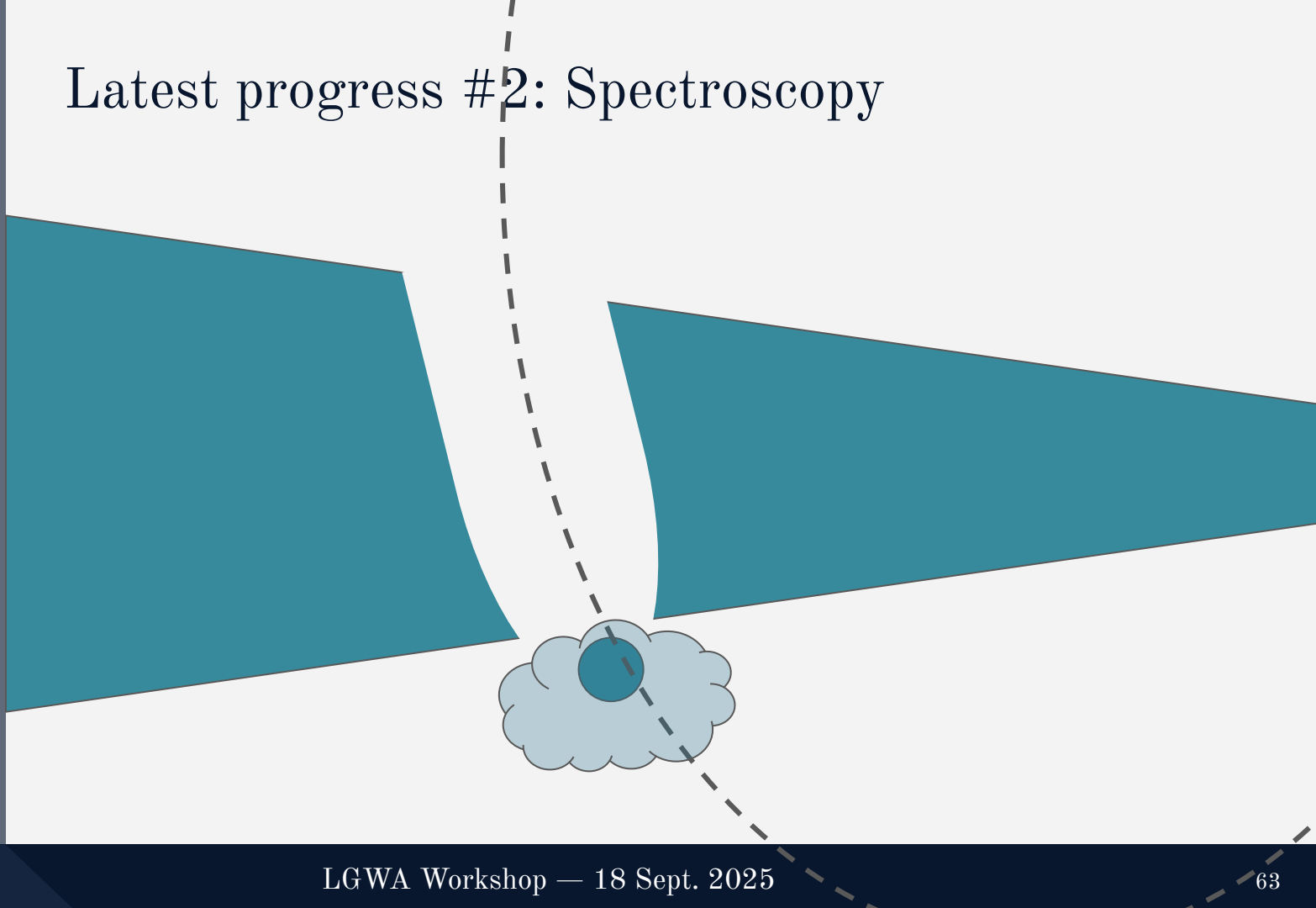
Latest progress #2: Spectroscopy

- Introduction
- Current state
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 - Latest Progress
- QPEs & GWs
- Conclusion



Latest progress #2: Spectroscopy

- Introduction
- Current state
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Latest progress #2: Spectroscopy

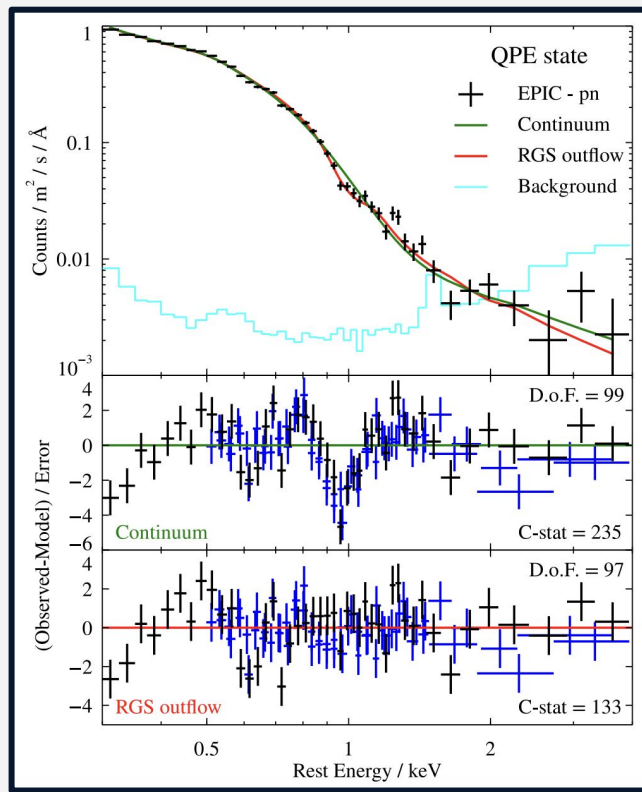
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Hot material is ejected at
high velocity

We can expect variable
blueshifted absorption

Latest progress #2: Spectroscopy

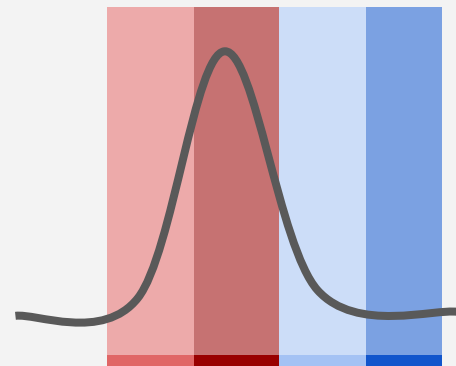
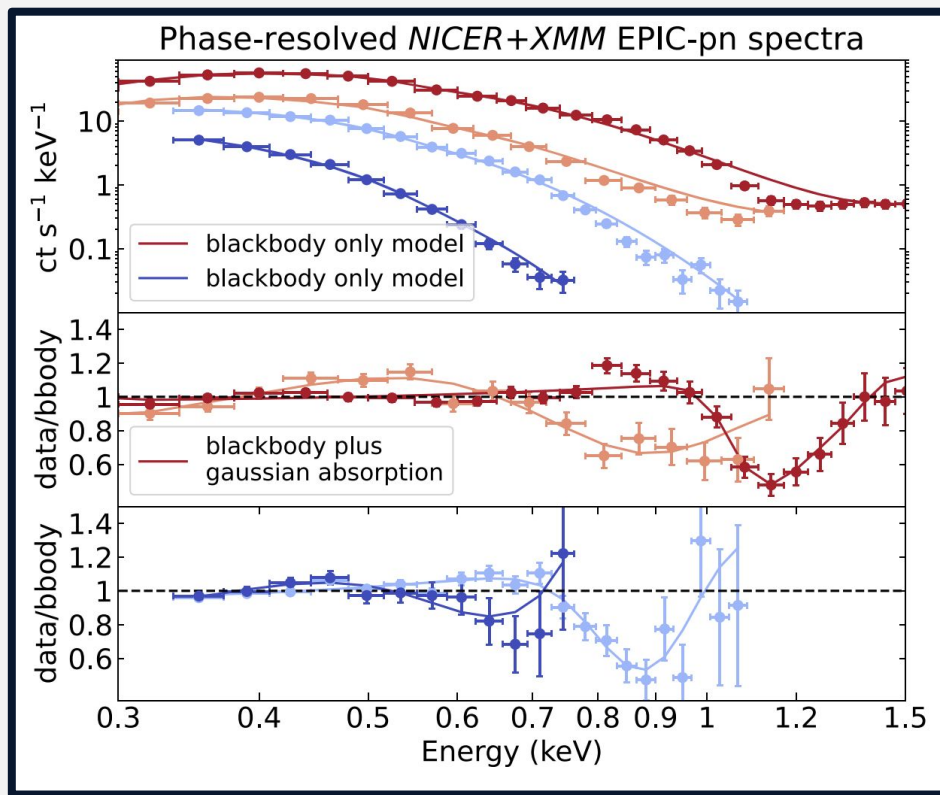
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Kosec+25
Stacked spectra

Latest progress #2: Spectroscopy

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Chakraborty+25
Time-resolved spectra

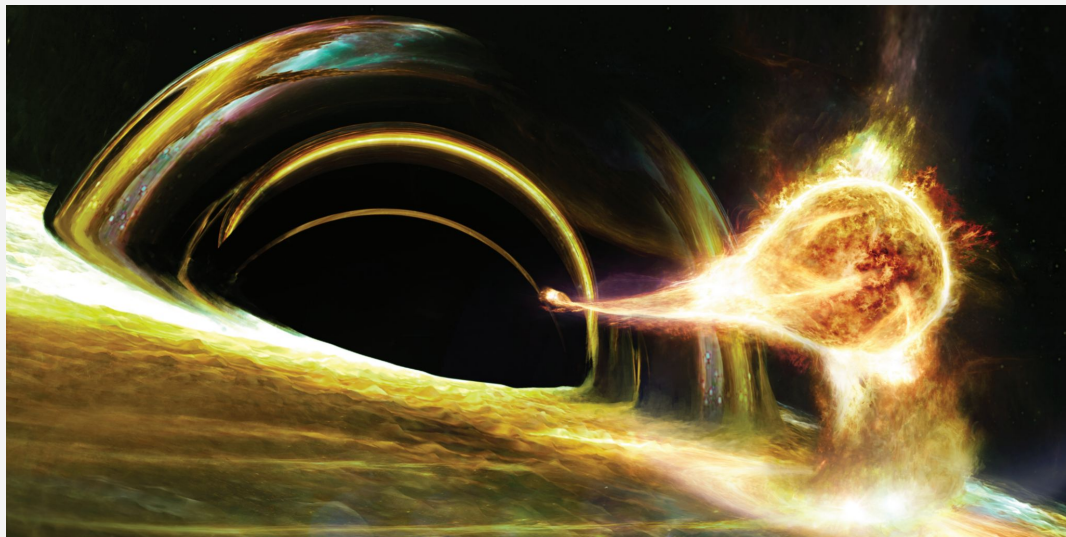
QPEs & GWs



QPEs as EMRIs

- Introduction
- Current state
- QPEs & GWs
- Conclusion

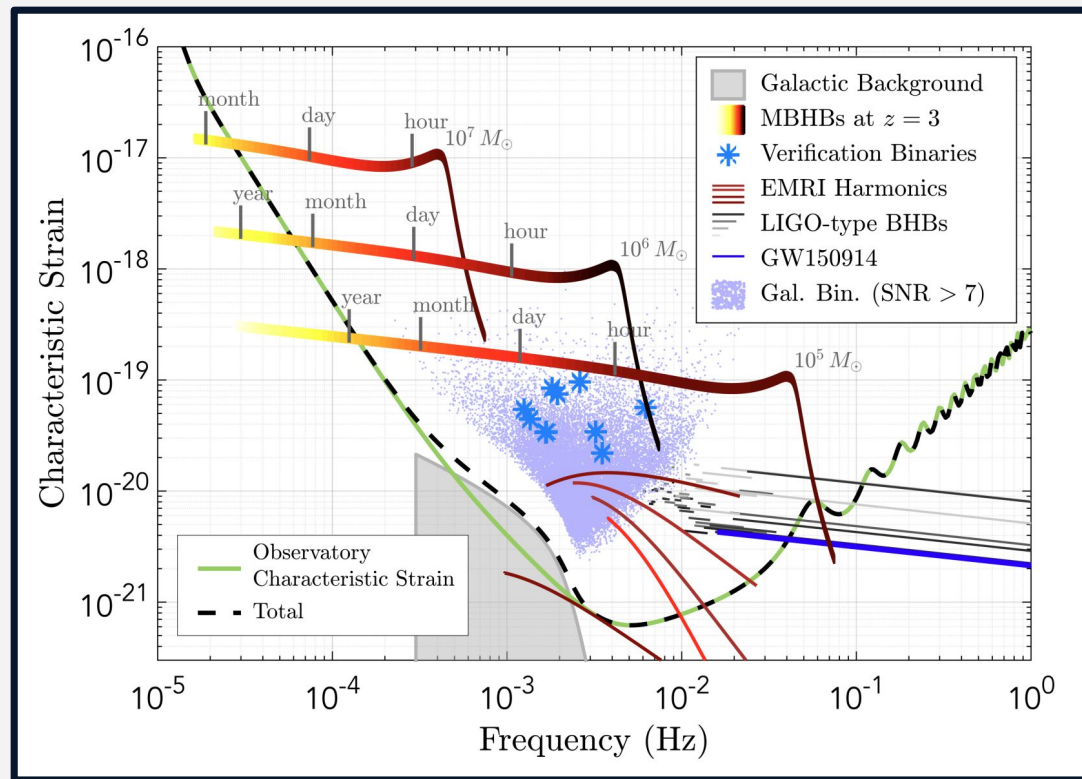
All current observables are compatible with the EMRI model



I de la Calle, ESA

QPEs as EMRIs

- Introduction
- Current state
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- Conclusion



LISA Collab. 2017

EMRIs emit
~mHz GW

No other EM
counterparts
(after formation)

QPEs as EMRIs

- Introduction
- Current state
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- Conclusion

We can use QPEs to...

QPEs as EMRIs

- Introduction
- Current state
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- Conclusion

We can use QPEs to...

- Constrain EMRI properties (QPE-FIT, Chakraborty+25)

Orbital time

Mass of BH / companion

Eccentricity

Impact of precession

QPEs as EMRIs

- Introduction
- Current state
- QPEs & GWs
- Conclusion

We can use QPEs to...

- Constrain EMRI properties
- Constrain EMRI rates

$9^{+9}_{-5}\%$ of TDEs show QPEs (Chakraborty+25)

9% of galaxies have EMRIs ? No - biased by host

Will require more careful approach

QPEs as EMRIs

- Introduction
- Current state
- QPEs & GWs
- Conclusion

We can use QPEs to...

- Constrain EMRI properties
- Constrain EMRI rates
- Constrain (wet) EMRI lifetime

Circularisation through GW & disk impacts

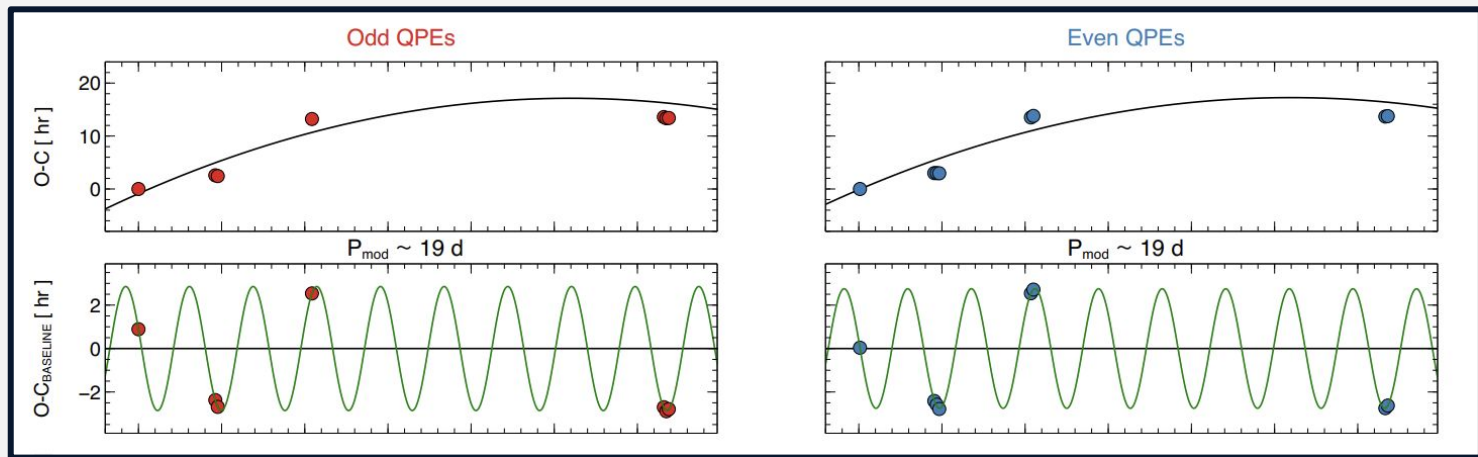
QPE lifetime limited by TDE disk lifetime ?
Why no QPEs in old, established AGN ?

The future of QPEs



The Future: More data

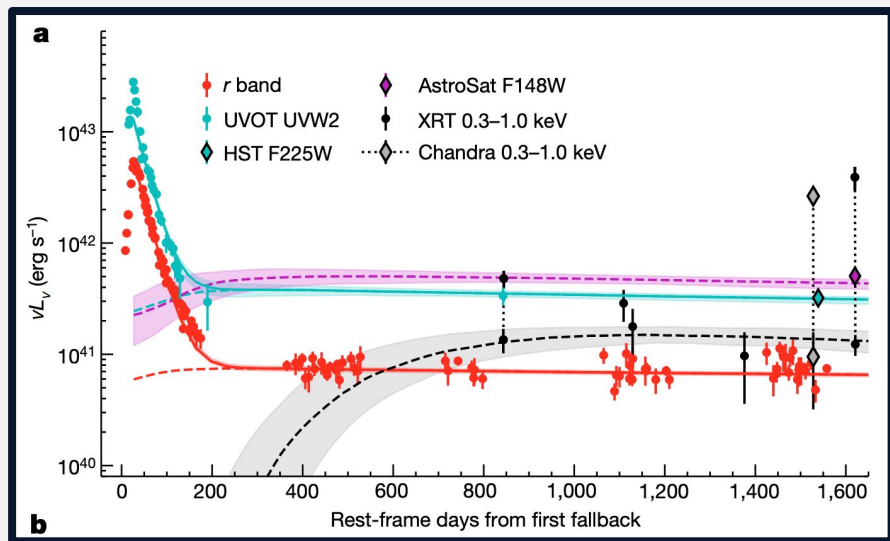
- Introduction
- Current state
- Finding more
- Conclusion



Miniutti+25

The Future: Optical TDE follow-ups

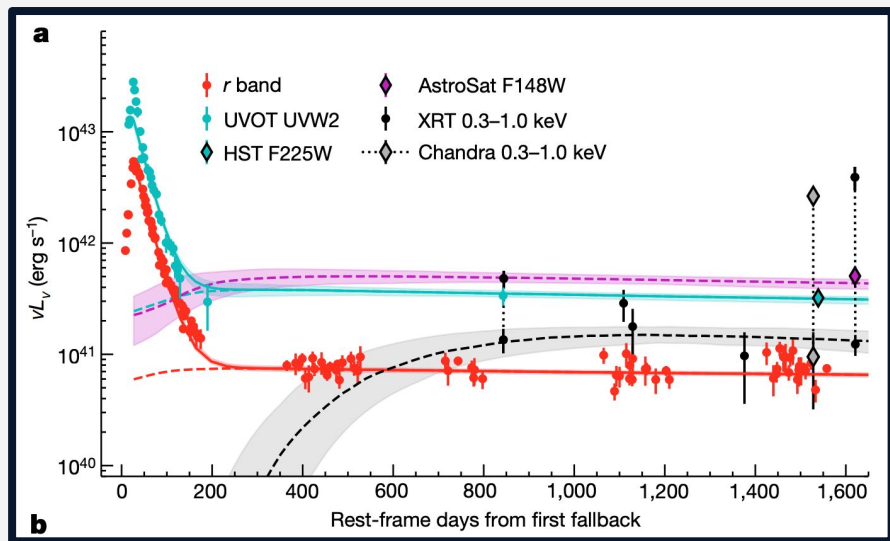
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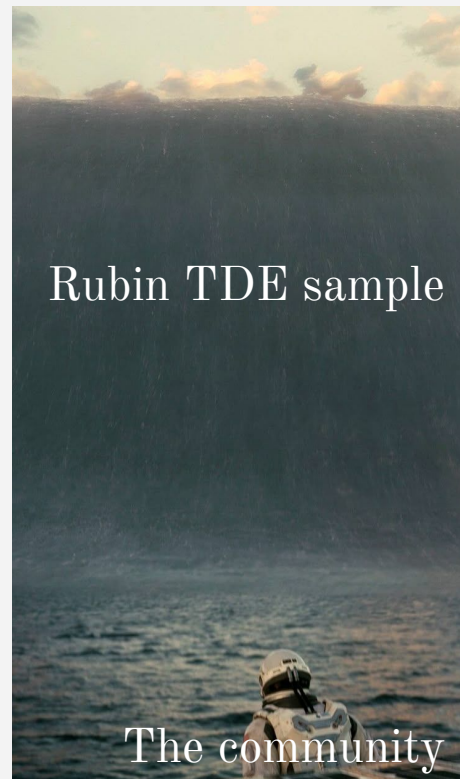
Nicholl+24

The Future: Optical TDE follow-ups

- Introduction
- Current state
- Finding more
- Conclusion



Nicholl+24



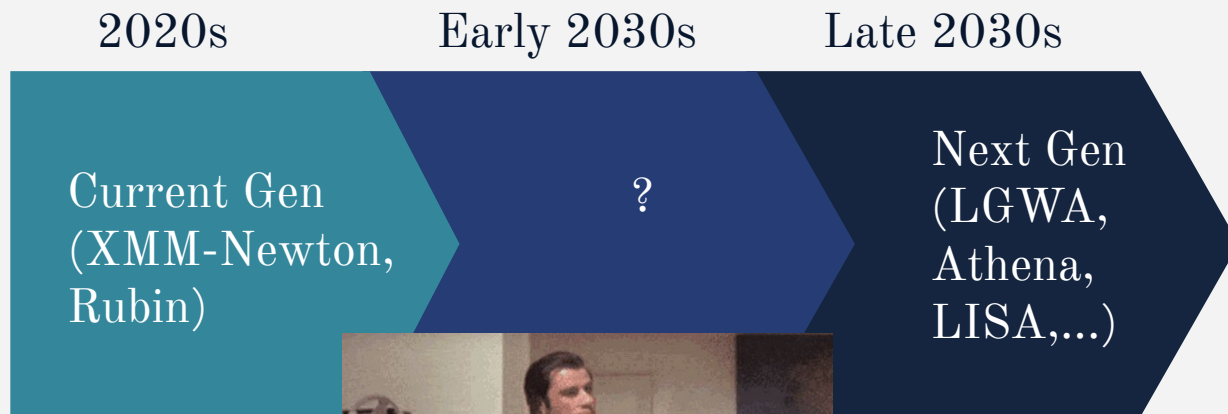
The Future: Long-term timeline

- Introduction
- Current state
- Finding more
- Conclusion



The Future: Long-term timeline & X-ray desert

- Introduction
- Current state
- Finding more
- Conclusion





You survived !

Conclusions

QPEs are cool (and rare)

We don't know a whole lot about them

- Current model: EMRI+TDE

If model is true: they can help understand EMRIs & their GWs

Questions ?

erwan.quintin@esa.int