

EP在黑洞X射线双星领域的科学机遇

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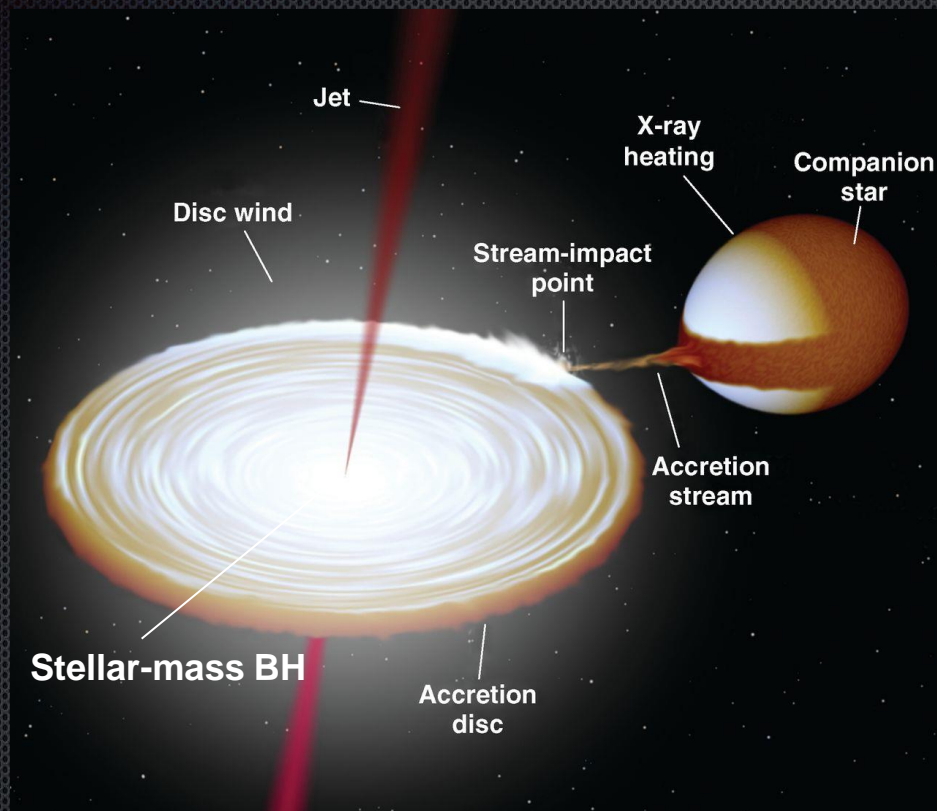
中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

2023年06月06日, EP科学讨论会

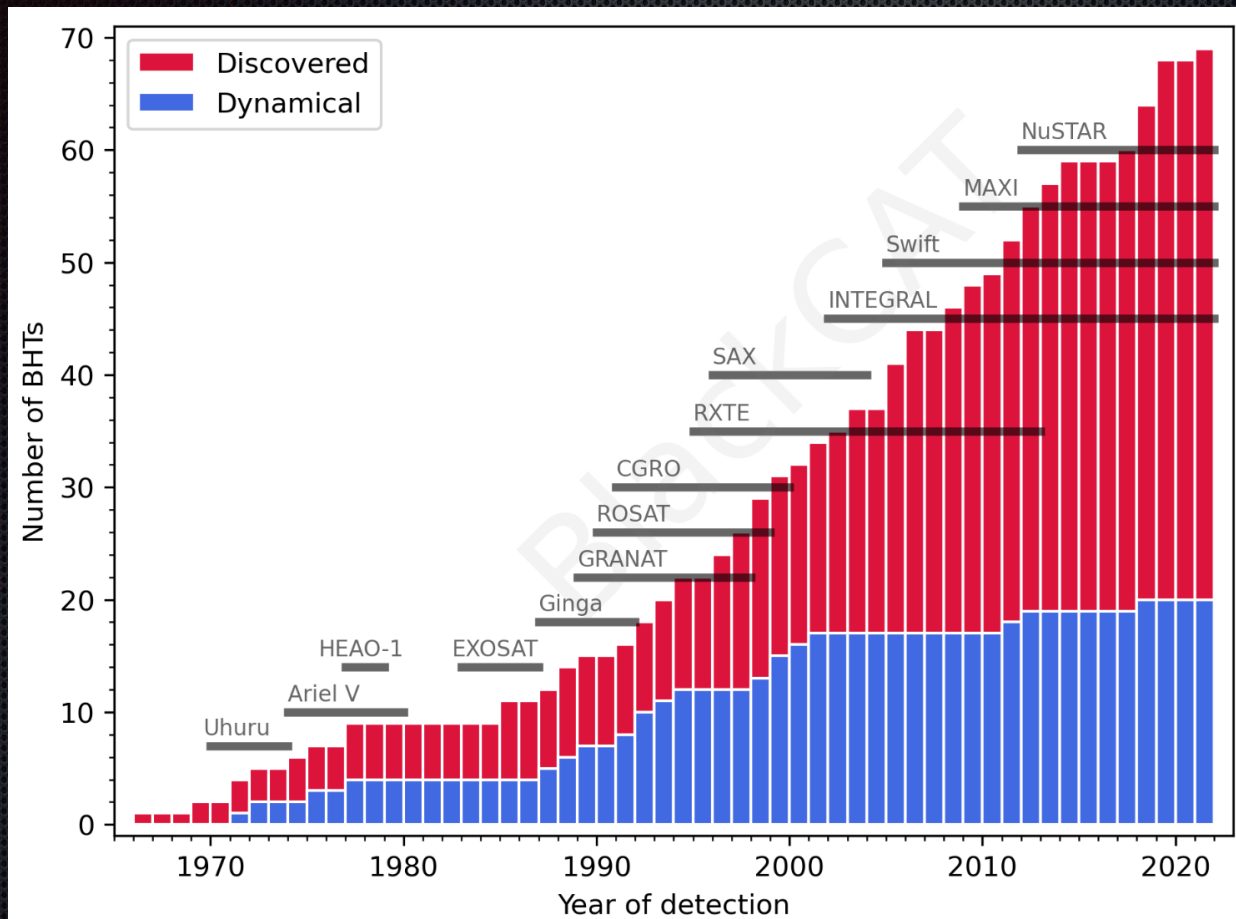
报告提纲

- ◆ 黑洞X射线双星简介
- ◆ EP在黑洞X射线双星领域的科学机遇
- ◆ 总结

黑洞X射线双星



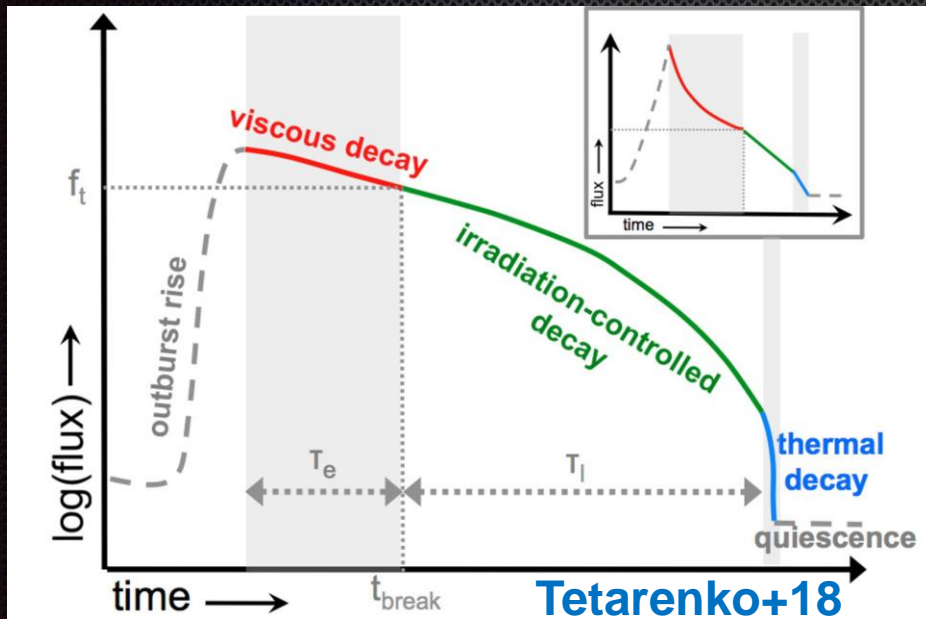
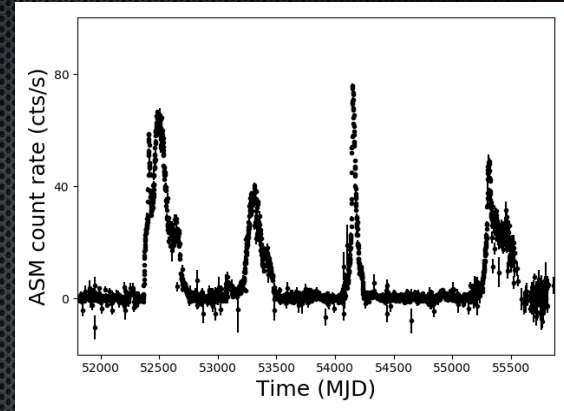
黑洞X射线双星



BlackCAT: <https://www.astro.puc.cl/BlackCAT/>

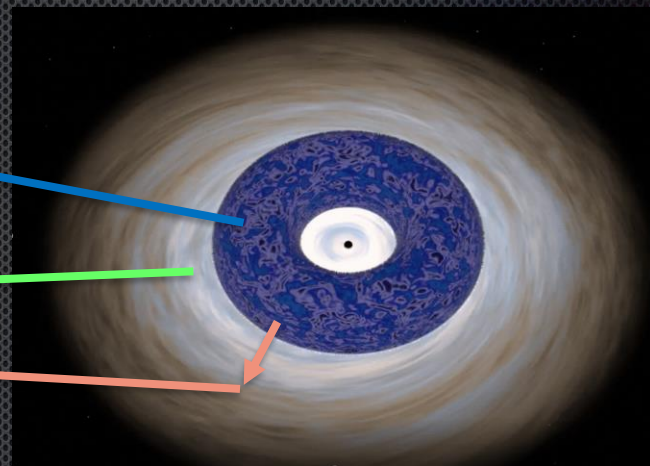
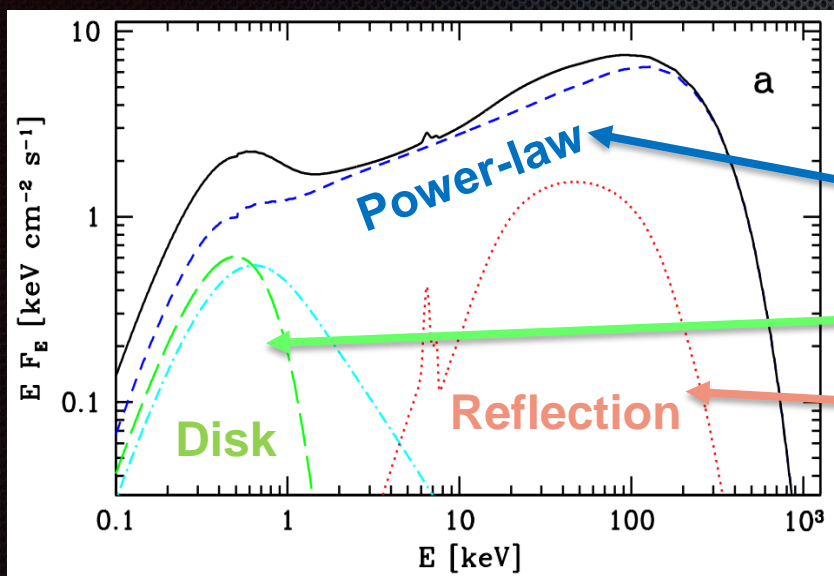
黑洞X射线双星的爆发

- 黑洞X射线双星大多是暂现源
- 吸积盘不稳定性模型 (DIM) : 宁静态期间物质在吸积盘堆积, 盘温度逐渐升高, 在某临界处触发粘滞不稳定性, 不稳定性向内传播, 物质开始大量掉入黑洞, 产生X射线。



- 上升时标: 1-10天
- 下降时标: 几个月
- 幅度: 变化4-5个量级

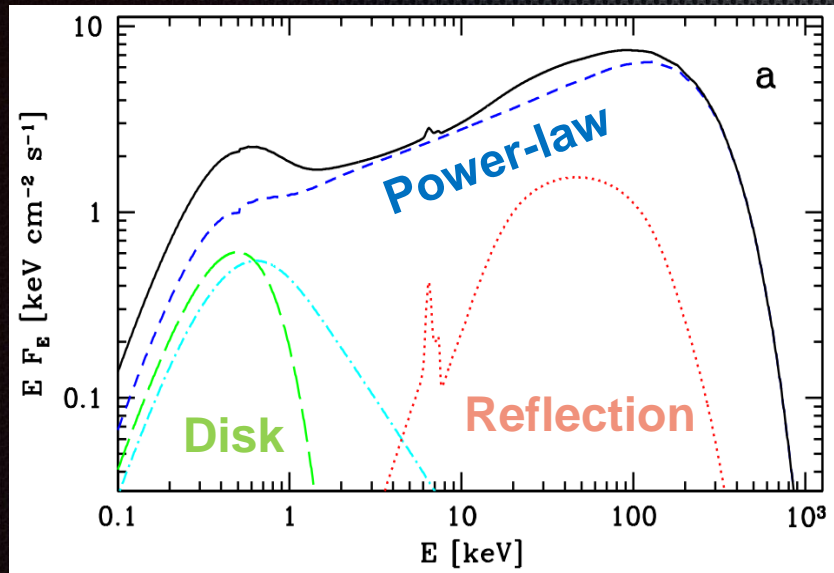
黑洞X射线双星的辐射成分



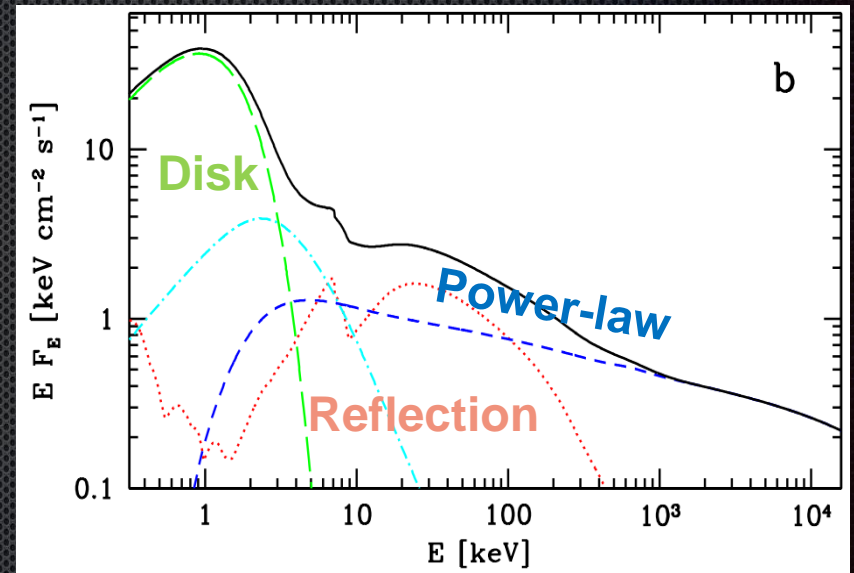
- 盘成分：几何薄、光学厚的吸积盘
- 幂律成分：盘光子被“冕”中热电子逆康普顿化
- 反射成分：冕辐射的高能光子照射吸积盘

黑洞X射线双星的谱态

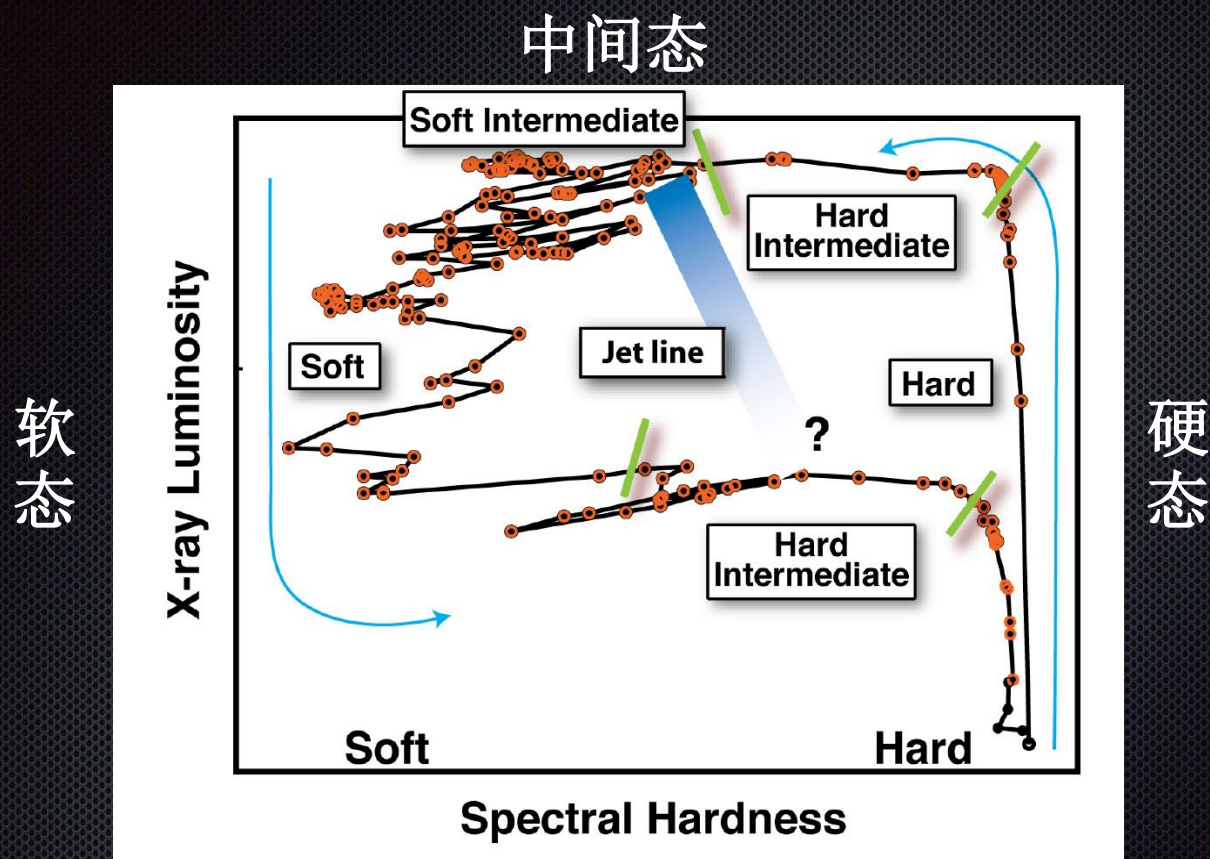
硬态 (高能康普顿成分主导)



软态 (低能吸积盘成分主导)



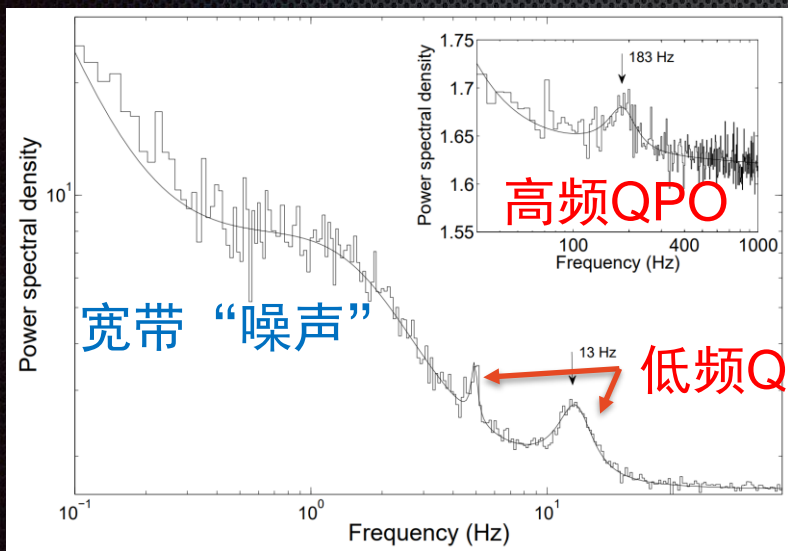
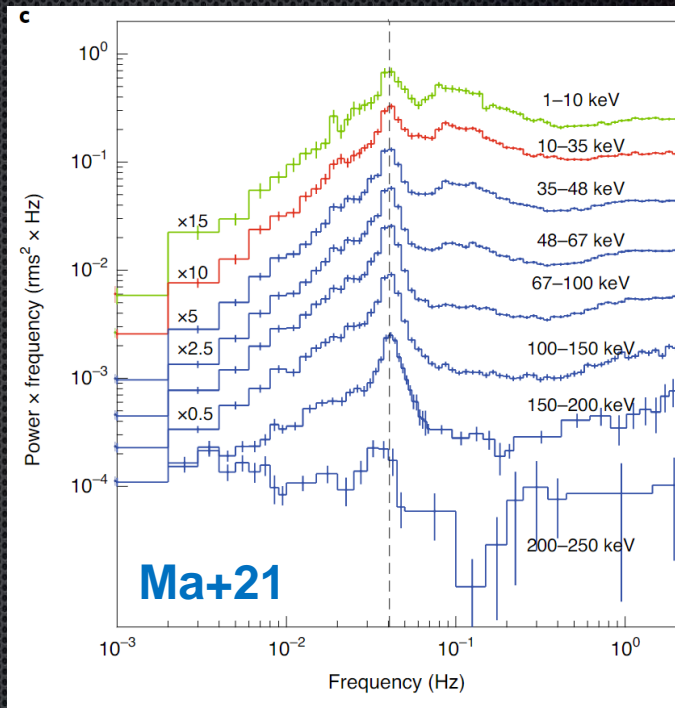
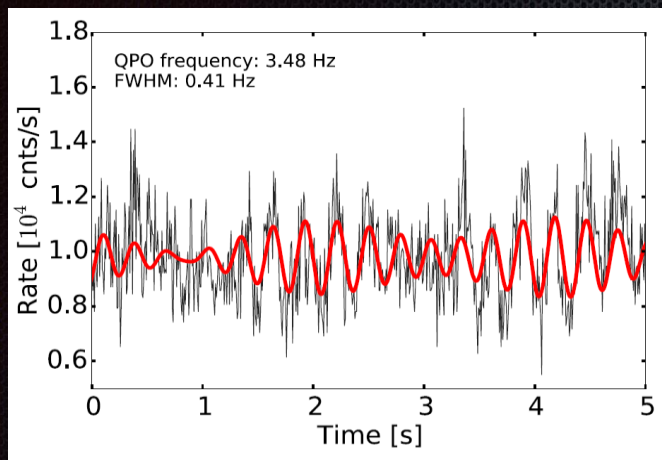
爆发期间的能谱演化



硬度-强度图

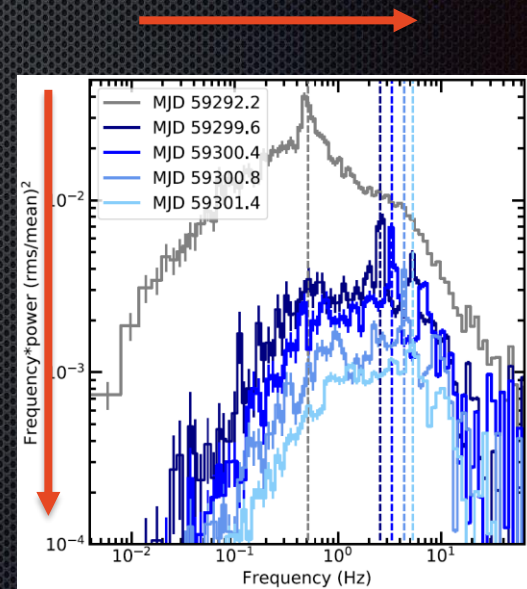
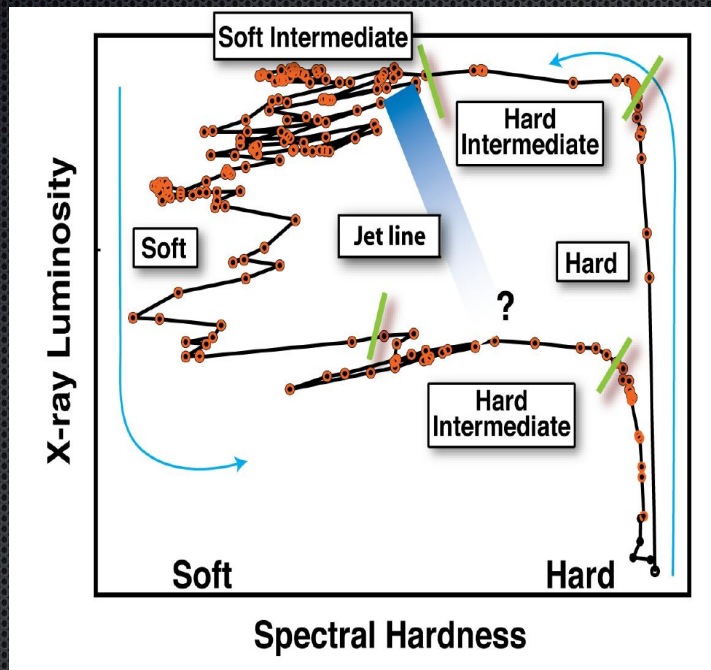
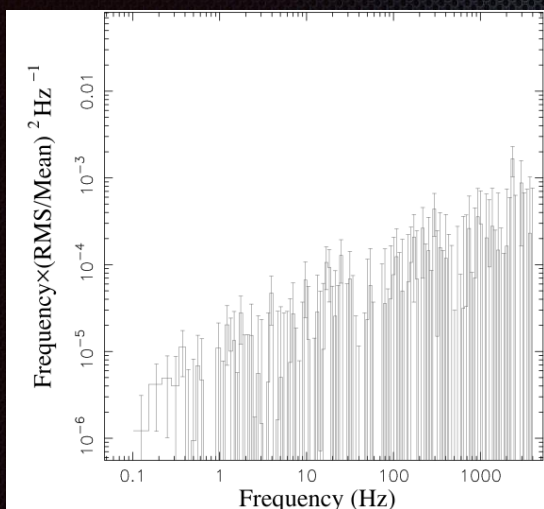
- 爆发演化轨迹沿逆时针方向，呈“q”形
- 上升阶段能谱由硬态到软态，下降阶段由软态到硬态

时变特征



慧眼卫星探测到 >200 keV QPO, 证实QPO来源于非热成分

时变性质演化

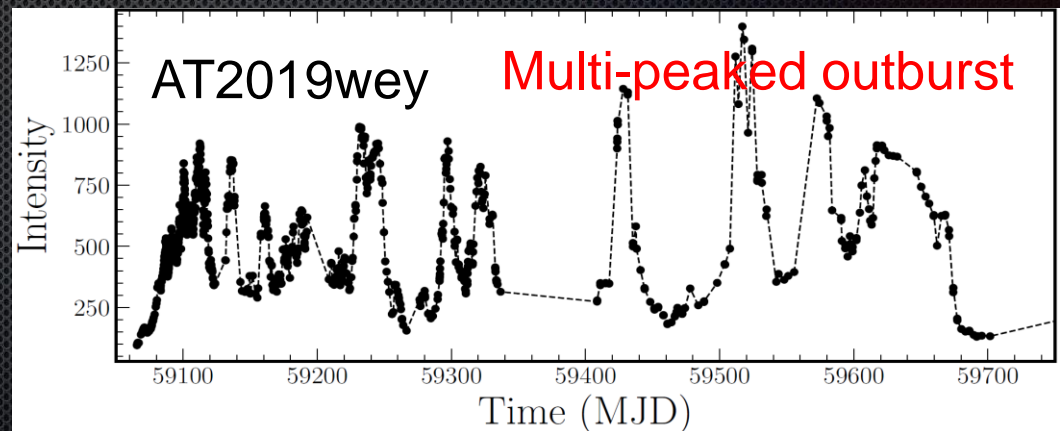
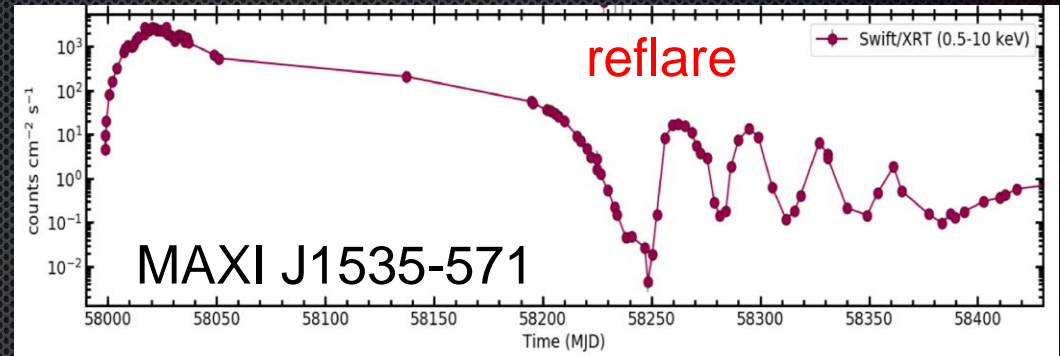
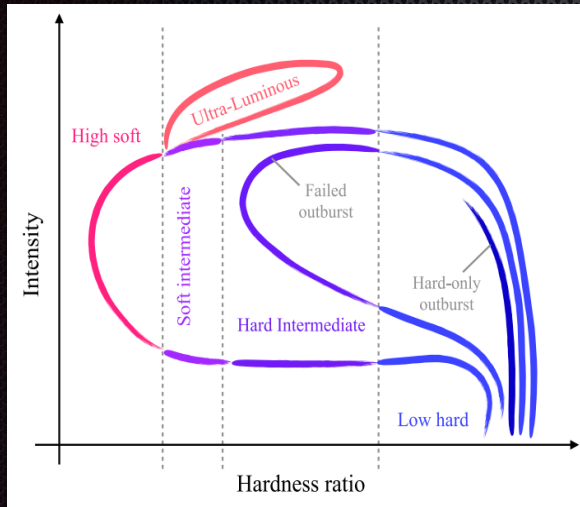


- 特征频率随能谱的变软逐渐增高
- 振幅随能谱的变软逐渐减弱

Open questions (issues)

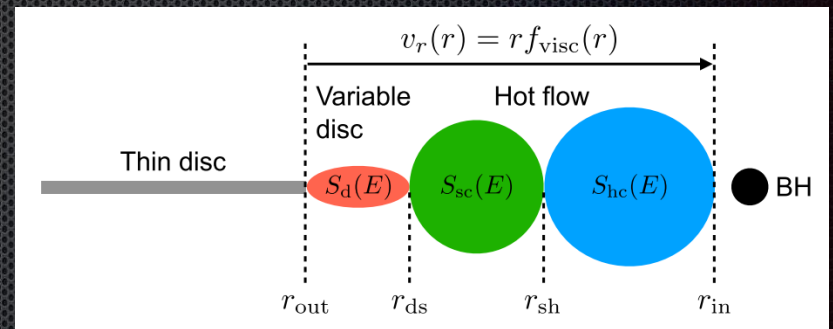
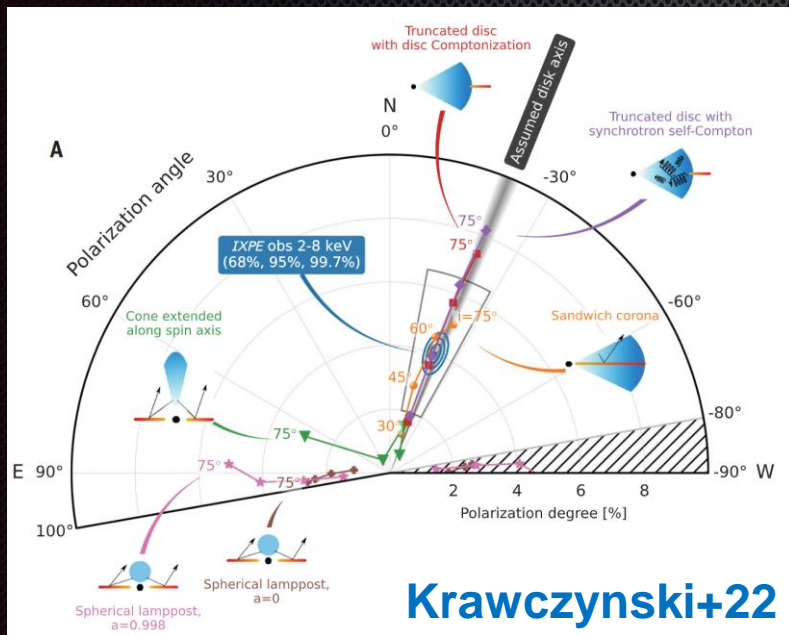
- 吸积盘不稳定性模型

- 该模型没有在X射线双星系统中得到广泛的验证
- 是否可以解释黑洞X射线双星不同形式的爆发



Open questions (issues)

- 硬态期间的吸积几何以及冕的性质
 - 吸积盘什么时候演化到最内稳定轨道？硬态期间是否截断？
 - Lamppost or 延展的冕？
 - 非均匀冕？

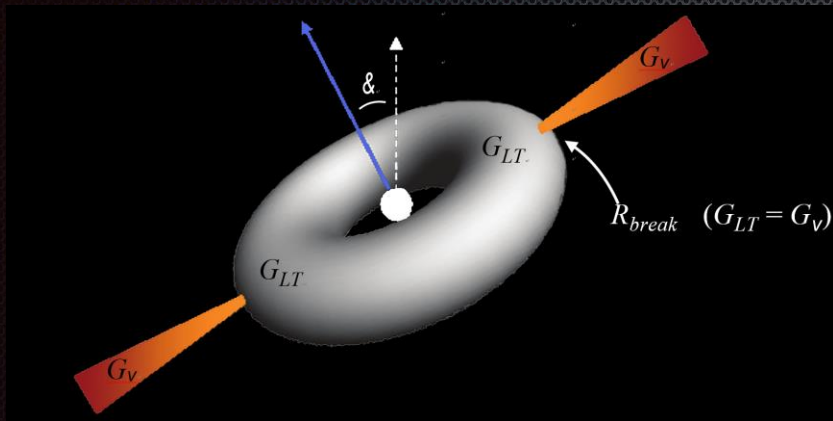


解释硬态的能谱和时变特征
需要多个不同的康普顿区域

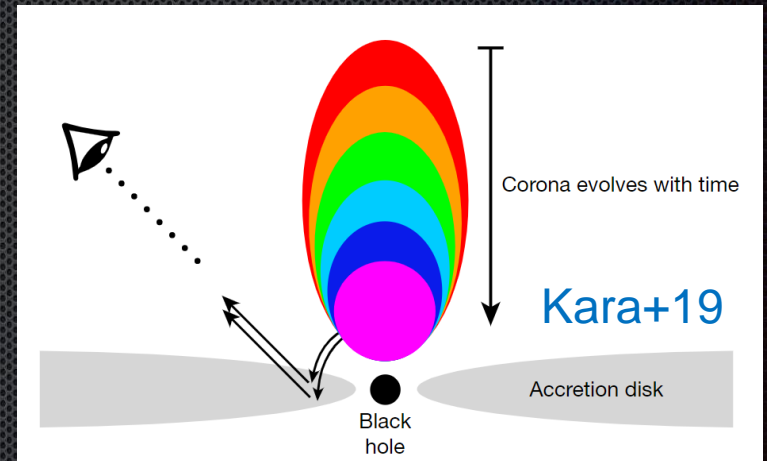
偏振结果支持延展的冕几何

Open questions (issues)

- QPO的物理起源
 - QPO来自于延展的冕or喷流？几何效应？
 - 热流进动模型在理论和观测上均遇到挑战 (Marcel+21)



Ingram+09; Miller-Jones+19

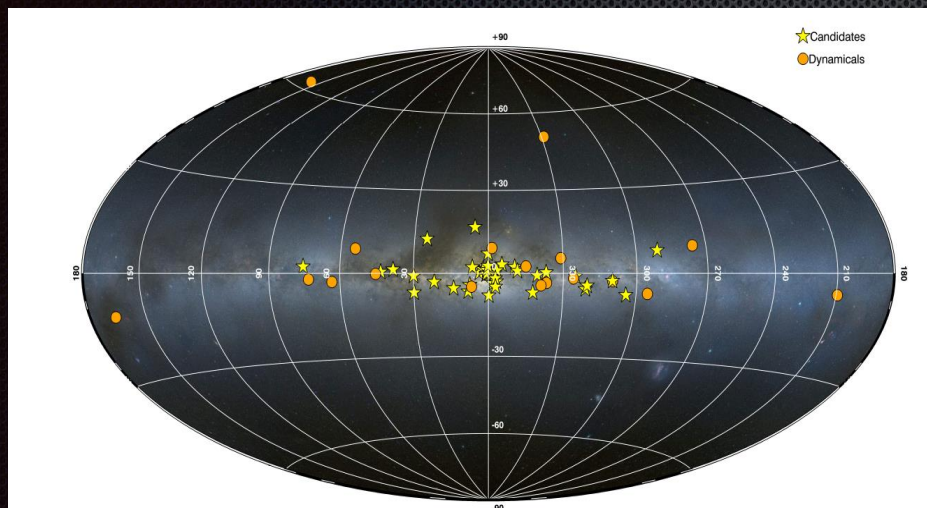


报告提纲

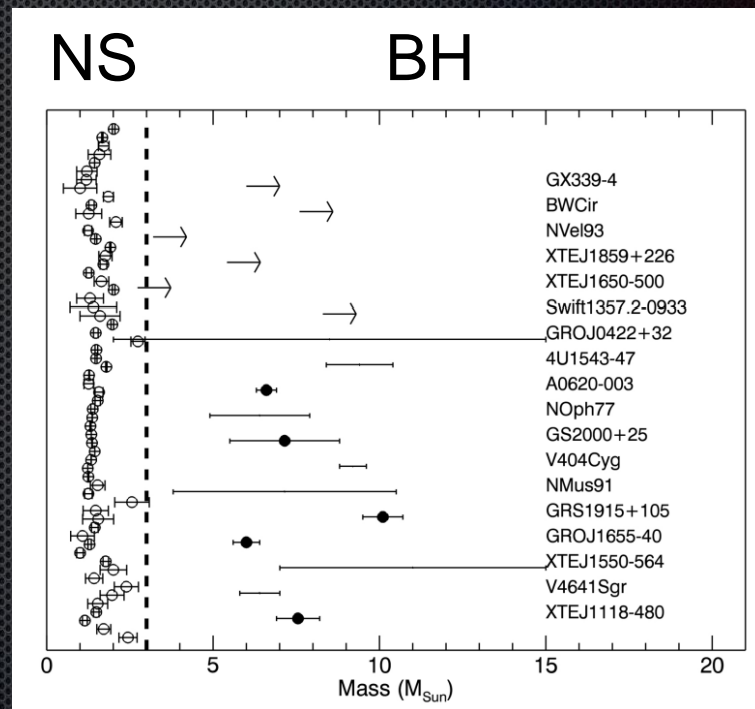
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EP发现新的黑洞暂现源

据估计，银河系内存在 >1000 个黑洞暂现源，目前被探测到的只有不到5% (Yungelson+06, Corral-Santana+16)。



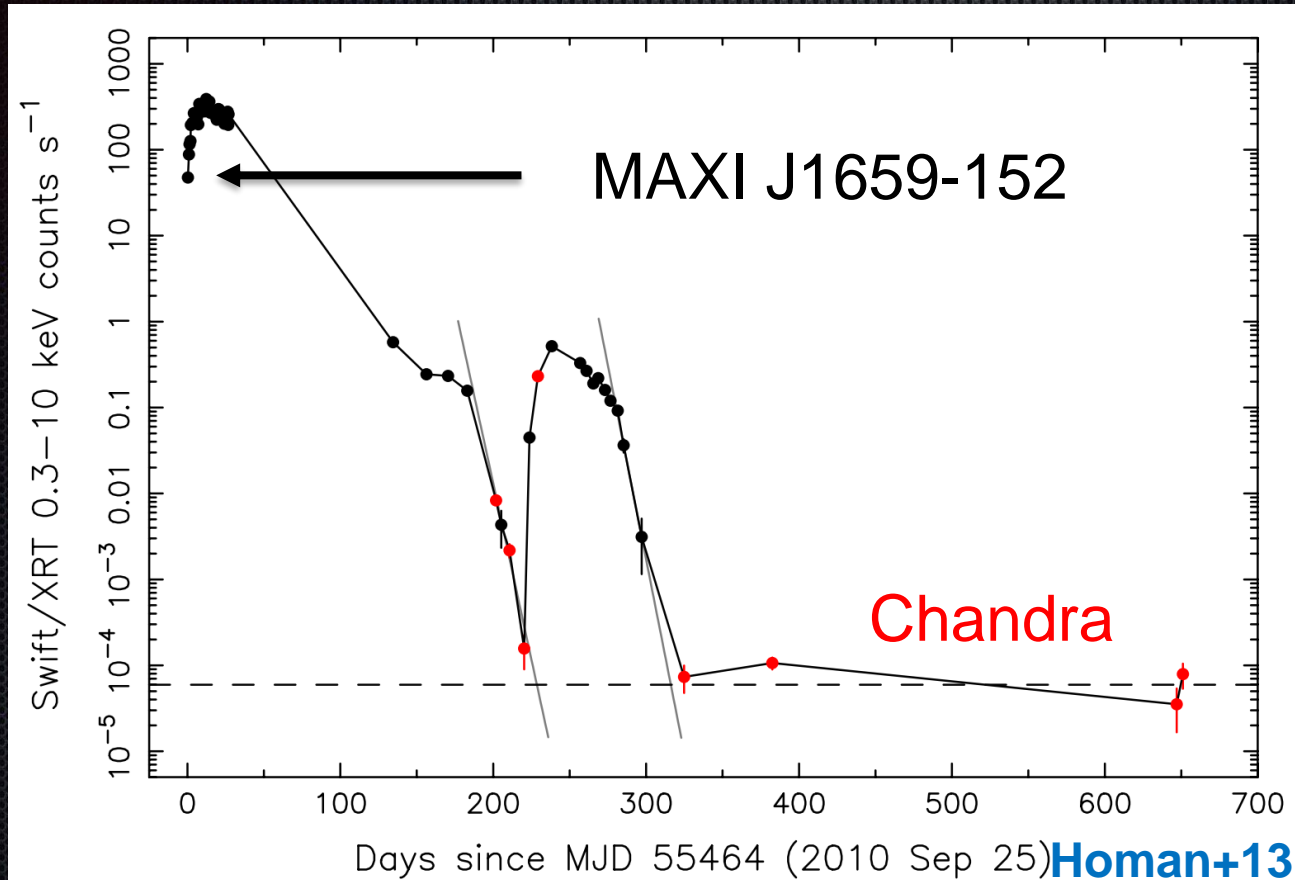
空间分布



黑洞质量分布

Corral-Santana+16

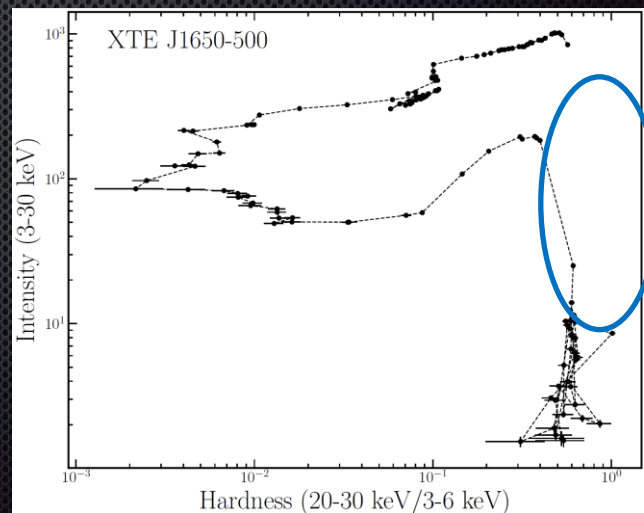
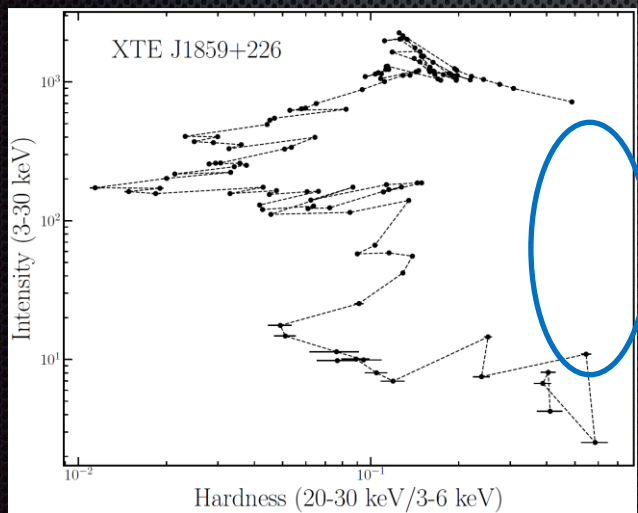
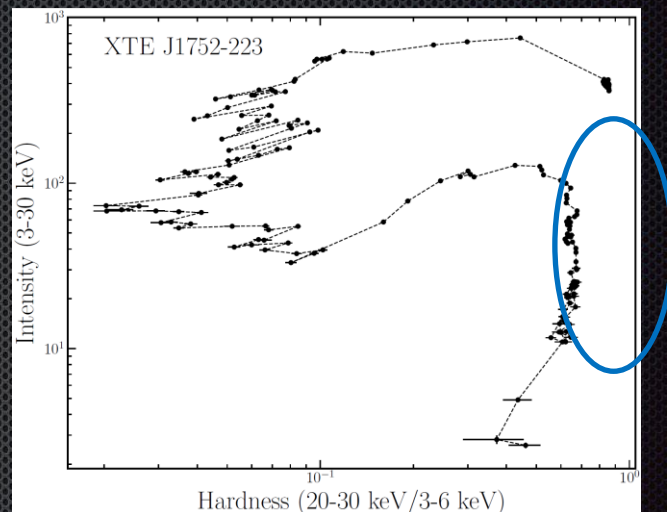
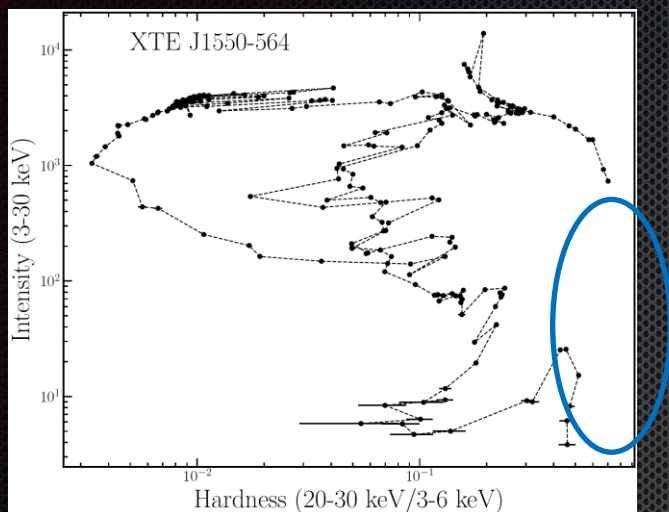
EP观测爆发早期演化



第一个Swift/XRT观测的流量比宁静态时期高~6个量级

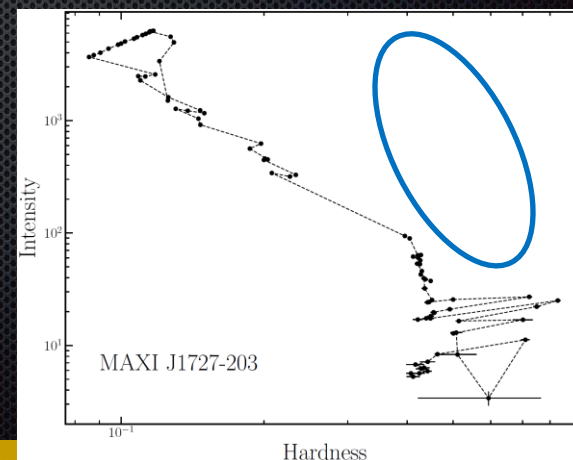
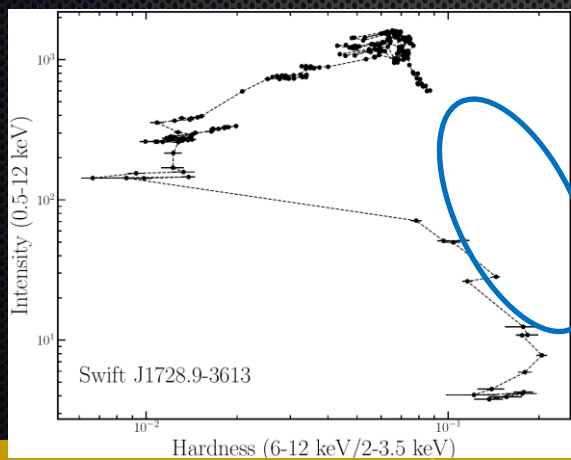
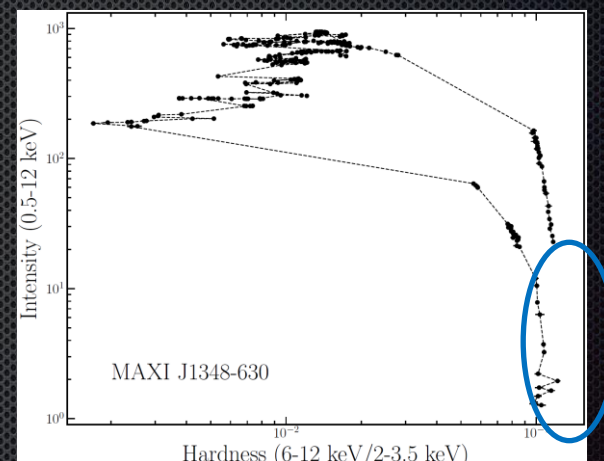
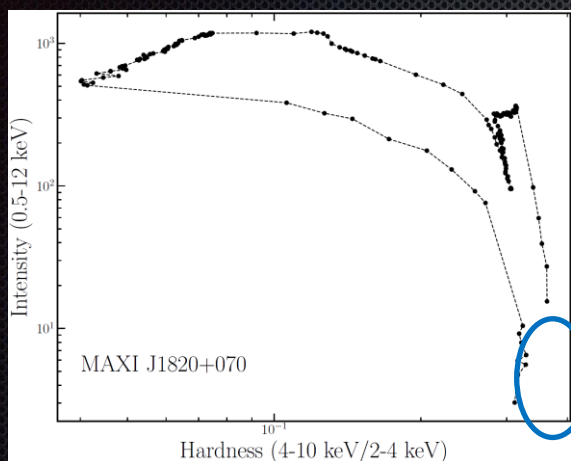
爆发早期观测的缺失

RXTE 时期 (1995–2012): ASM 触发 PCA 和 HEXTE 的后随观测

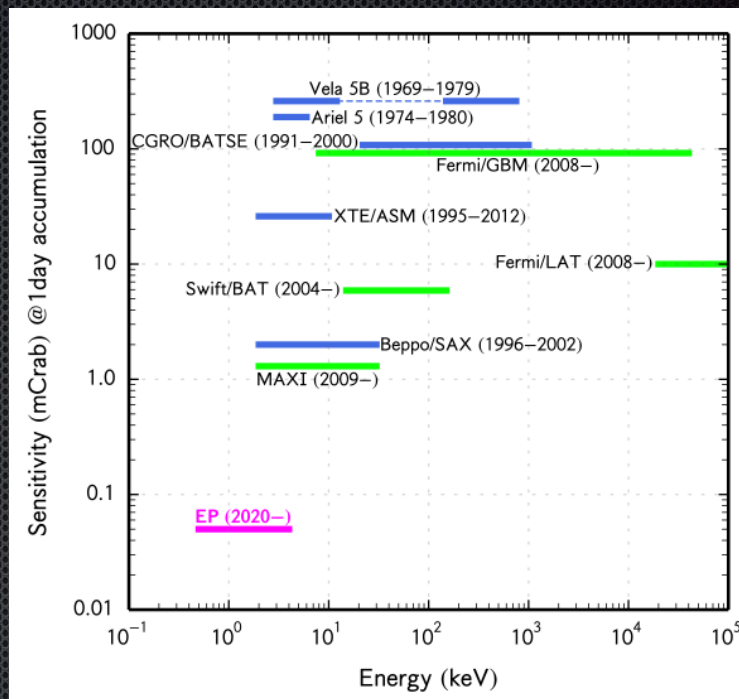
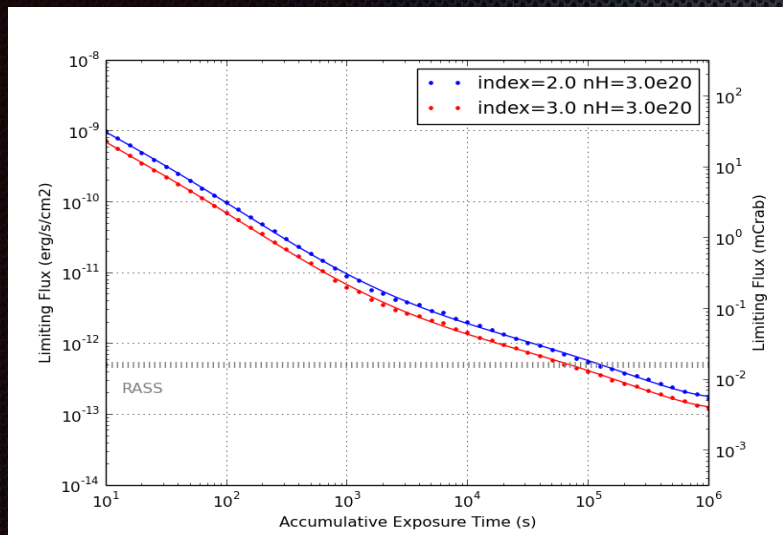


爆发早期观测的缺失

- MAXI 时期 (2009-) : MAXI触发 NICER (2017-) 的后随观测
- OHMAN (On-orbit Hookup of MAXI And NICER): 后随观测响应时间由之前的**3小时缩短到10分钟**



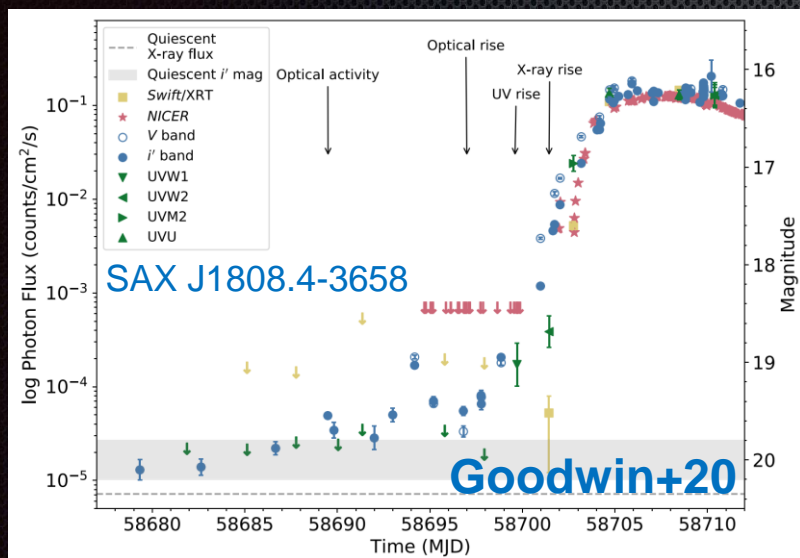
EP观测爆发早期演化的优势



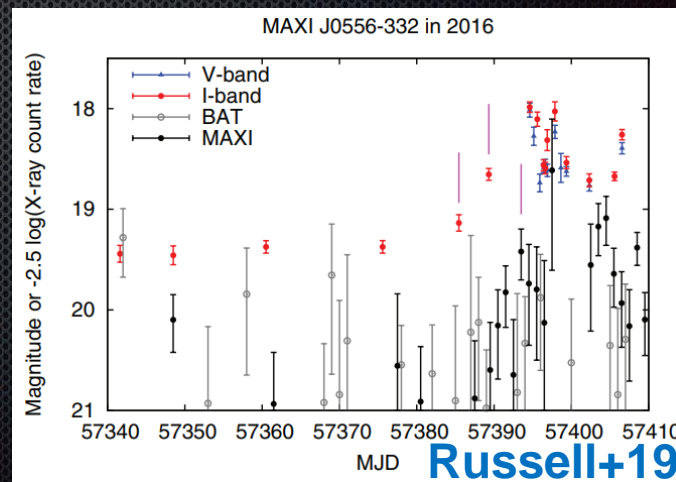
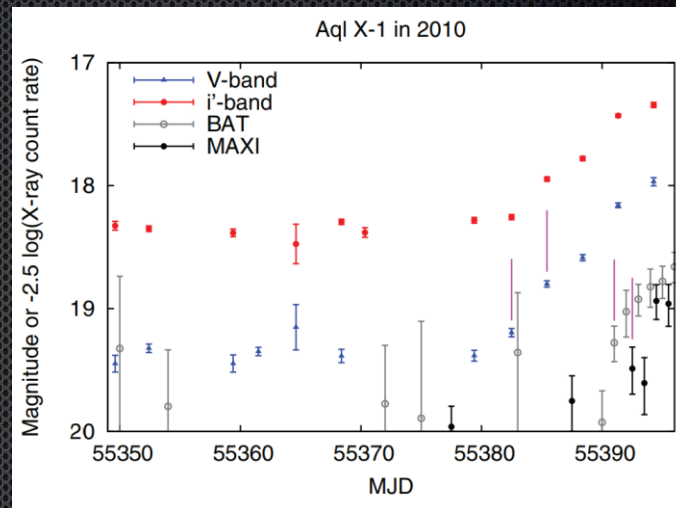
- WXT具有**更高的**灵敏度：比 MAXI, Swift/BAT, RXTE/ASM 等高至少1个量级
- **极短的**响应时间：WXT星上触发FXT后随观测 (~5 分钟)
- 触发慧眼观测：对爆发早期阶段进行宽能段研究

爆发的产生机制

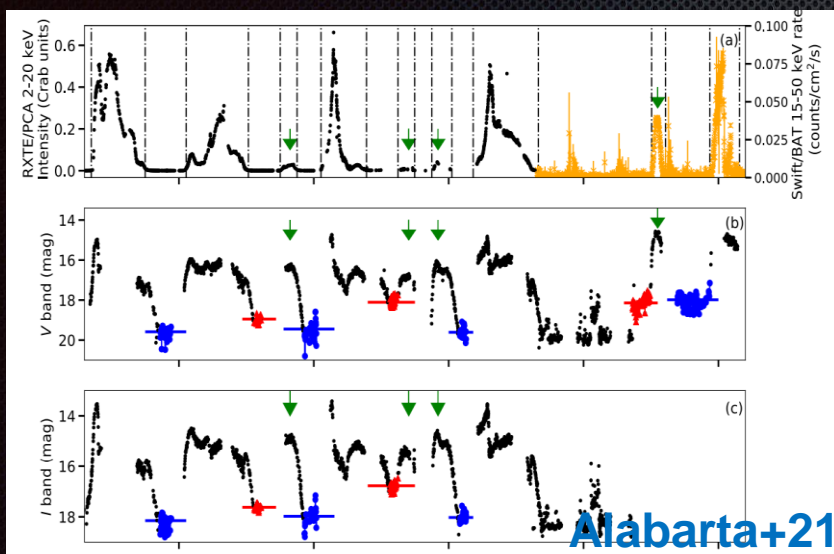
- 检验吸积盘不稳定性模型(DIM): 模型预言光学波段的快速上升要**早于**X射线波段
- X射线存在很大不确定性



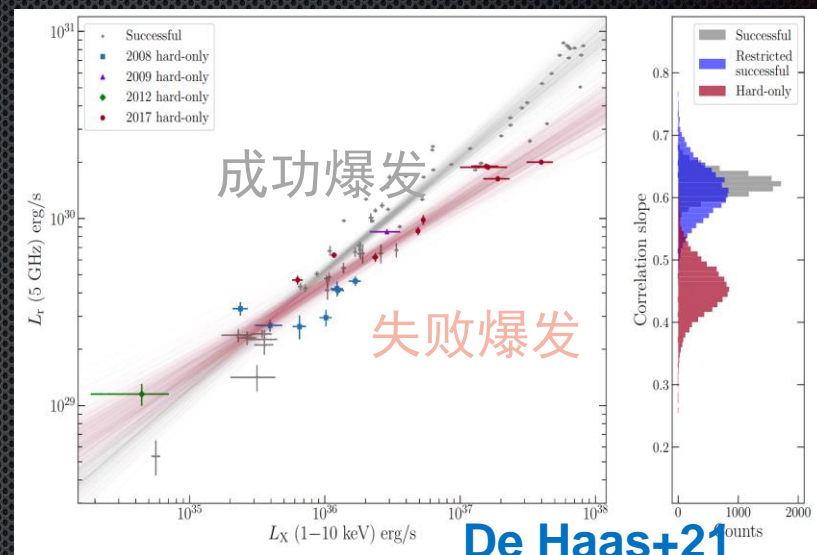
光学波段的快速上升比X射线波段早~4天



成功的爆发 vs. 失败的爆发



失败的爆发之前宁静态的光学辐射比成功的爆发高

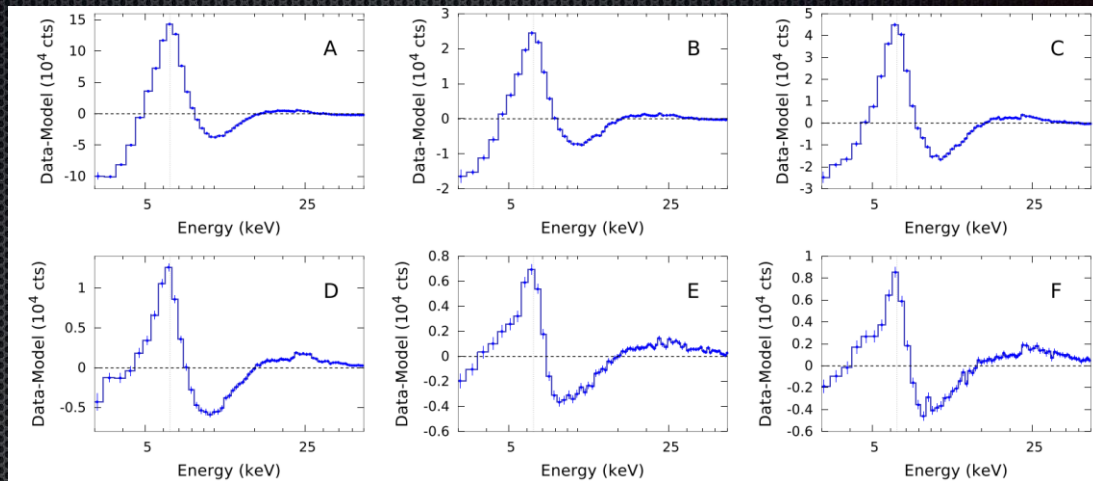
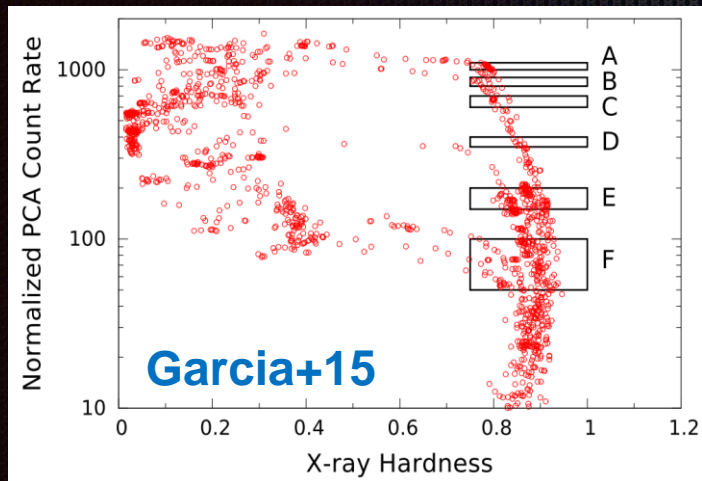


射电-X射线流量关系失败的爆发更平

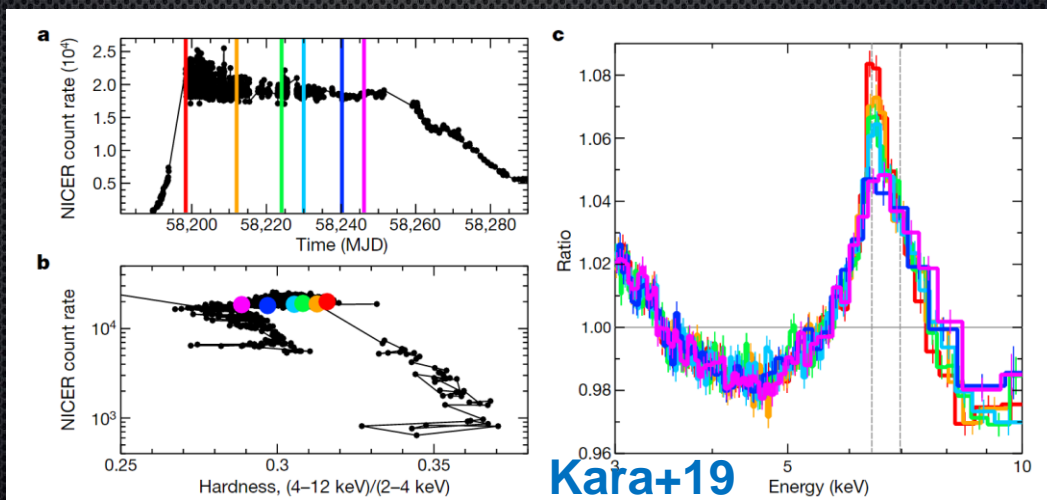
成功的爆发和失败的爆发光学和X射线的时延，上升阶段的能谱和时变性质是否存在显著差异？

爆发早期的吸积几何

爆发早期吸积盘是否截断？

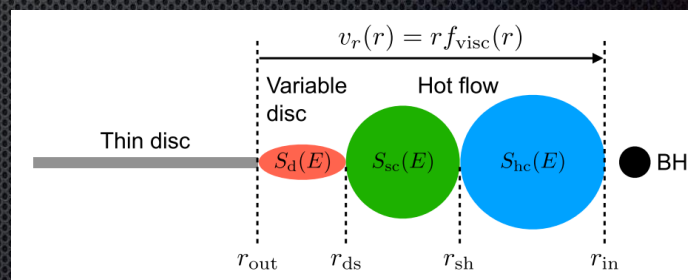
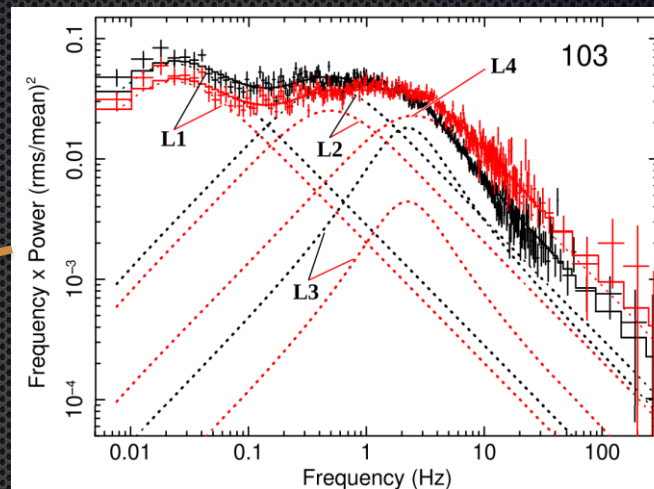
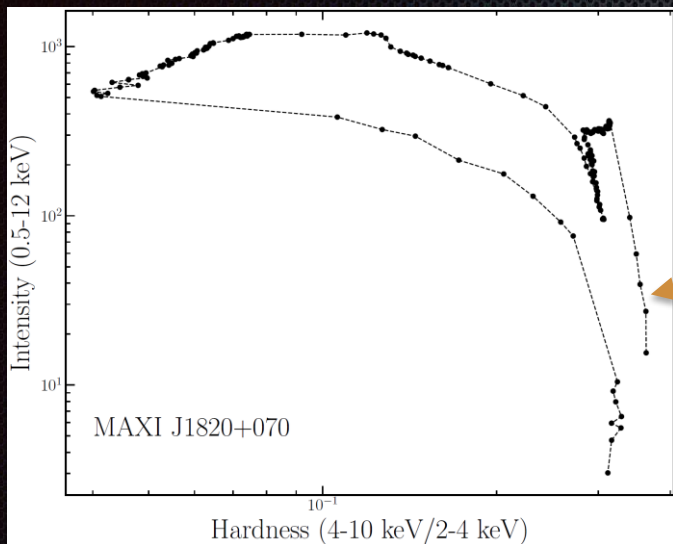


$> 2\% L_{\text{Edd}}$ 时, $R_{\text{in}} < \sim 5 R_g$



冕的结构

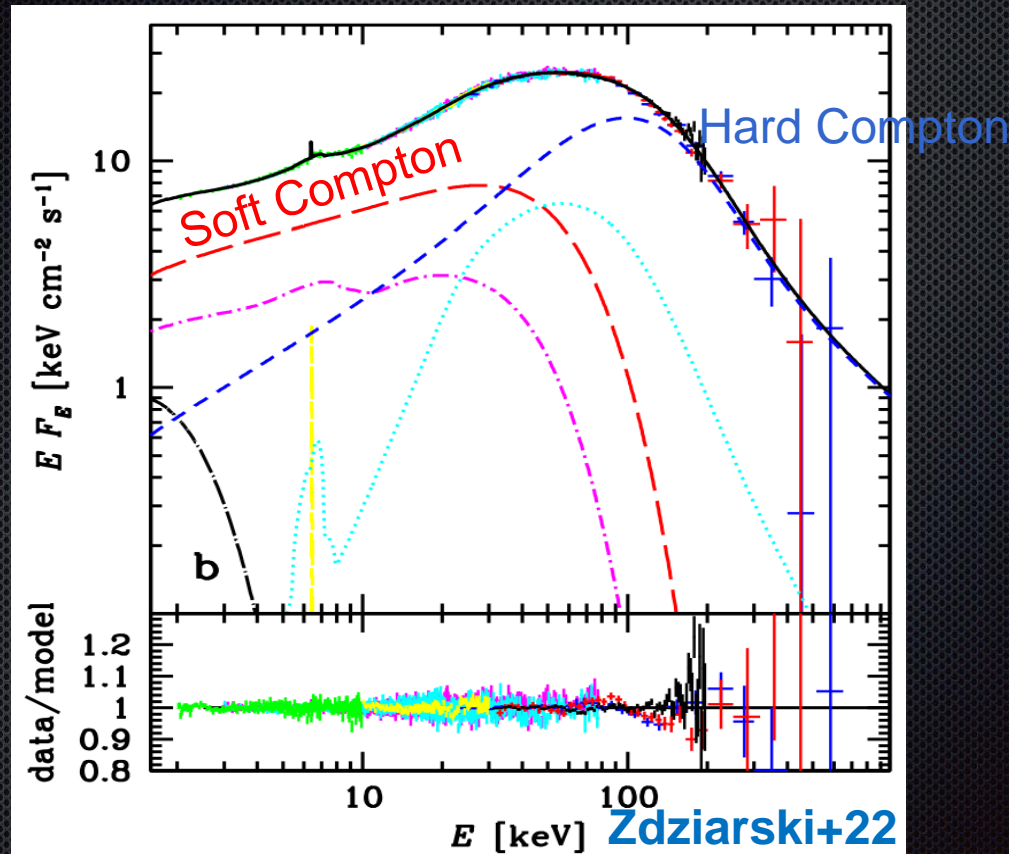
硬态的能谱和功率谱存在复杂的结构 \longrightarrow 冕是非均匀的！



Dzielak+21, Yang+22, Kawamura+22

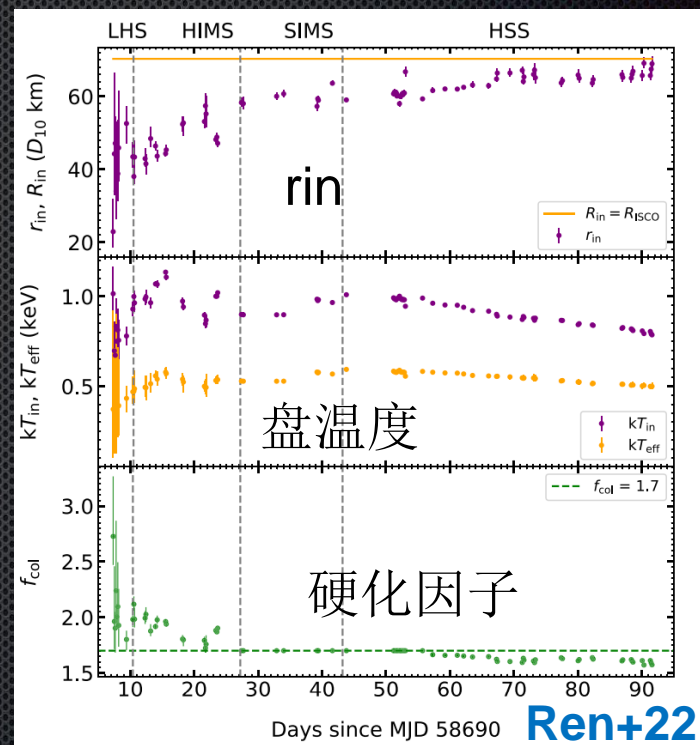
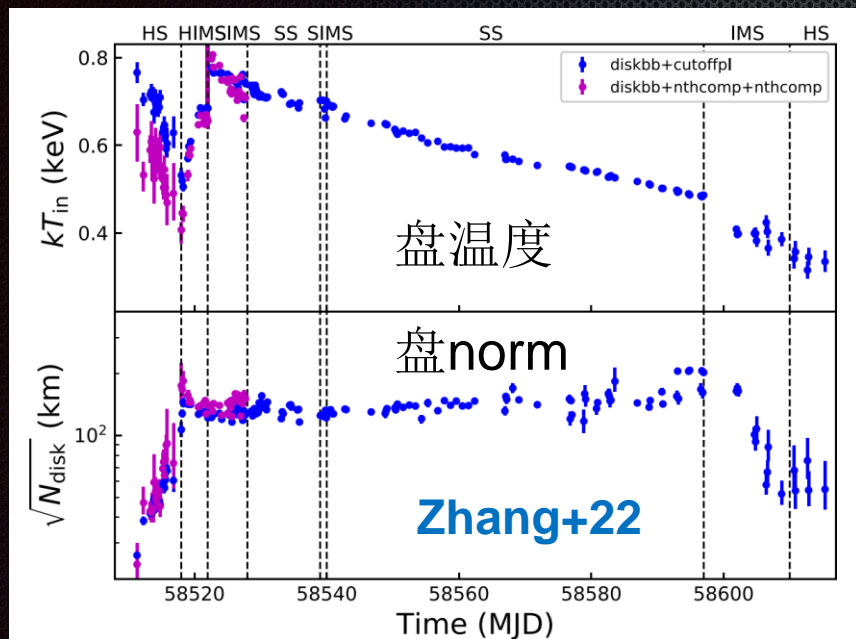
冕的结构

硬态的能谱和功率谱存在复杂的结构 \longrightarrow 冕是非均匀的！



盘成分在硬态期间的演化

硬态期间吸积盘成分的演化存在不确定性



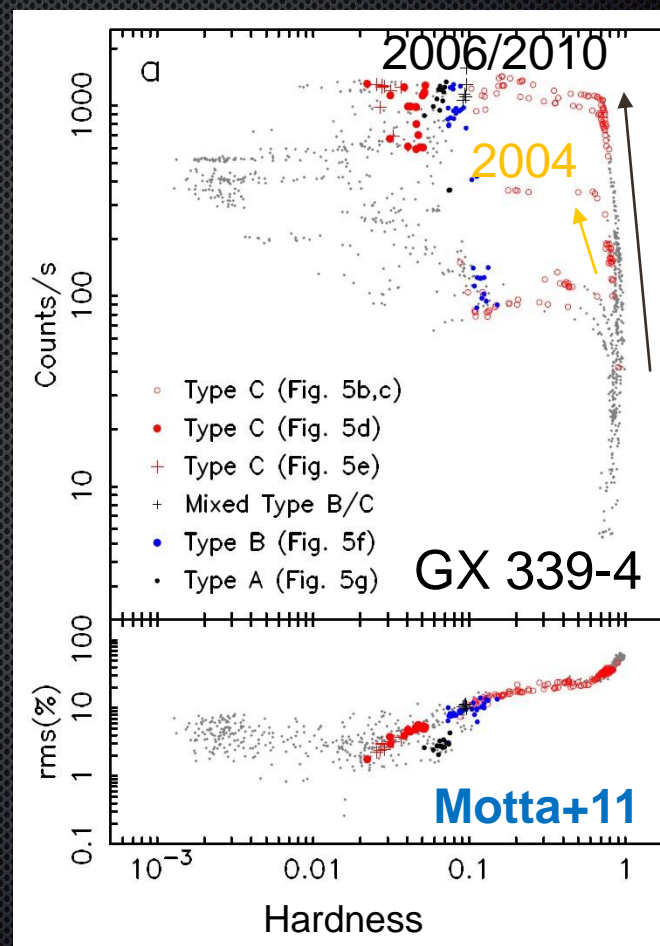
其中

$$R_{\text{in}} = r_{\text{in}} \xi f_{\text{col}}^2 = \sqrt{N_{\text{dbb}} / \cos \theta} \xi f_{\text{col}}^2 D_{10},$$

QPO的产生机制和触发条件

QPO在爆发的什么时候开始出现？

- 对同一个源不同强度的爆发，QPO的演化趋势十分相似，但是出现时刻对应的光度存在显著差异
- QPO的出现与吸积流的性质紧密相关



QPO的产生机制和触发条件

热流进动模型:

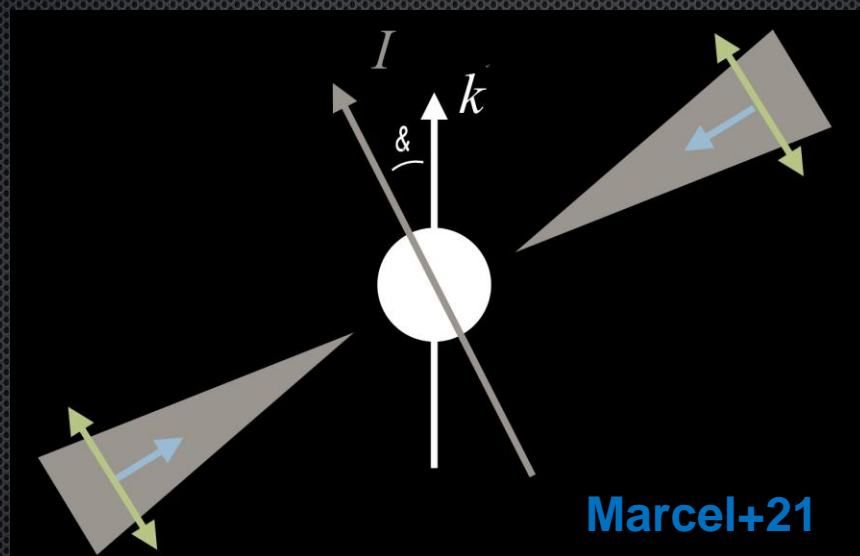
Viscous torque

$$G_\nu = |\vec{G}_\nu| = -2\pi R\nu\Sigma R^2 \frac{\partial\Omega_\phi}{\partial R}$$

<

Lense-thirring torque

$$G_{\text{LT}} = |\vec{G}_{\text{LT}}| = 2\pi RH |\vec{\Omega}_p \times \vec{L}|$$

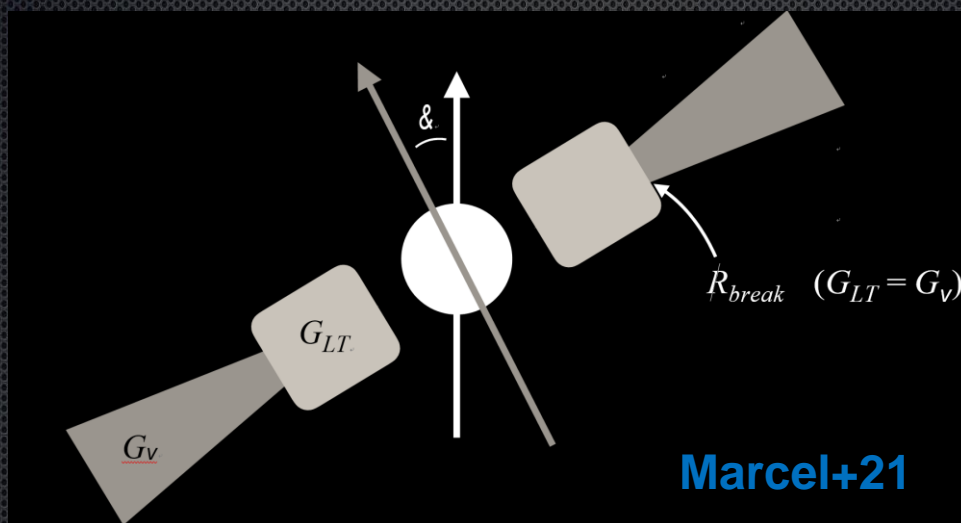


QPO的产生机制和触发条件

热流进动模型：

$$\frac{G_{LT}}{G_v} \simeq \frac{4}{3} \frac{a|\sin(\theta)|}{\alpha \epsilon} r^{-3/2}.$$

其中 $\epsilon = h/r$



总结

- EP将发现一批新的黑洞X射线双星，增加现有样本；
- EP在观测黑洞X射线双星早期爆发演化方面具有突出优势；
- 利用FXT和慧眼的后随观测有望给出爆发早期黑洞X射线双星的吸积几何图像。

Thanks for your attention!