恒星活动及后期演化

顾盛宏，孟祥存

课题负责人：韩占文，顾盛宏

子课题1--恒星活动：顾盛宏，张立云，白宇，项越，曹东涛，陈兴浩

子课题2--恒星后期演化：韩占文，刘继峰，顾为民，孟祥存，王博，王松，刘纪认

成员单位：云南天文台，国家天文台，厦门大学，贵州大学，北京天文馆

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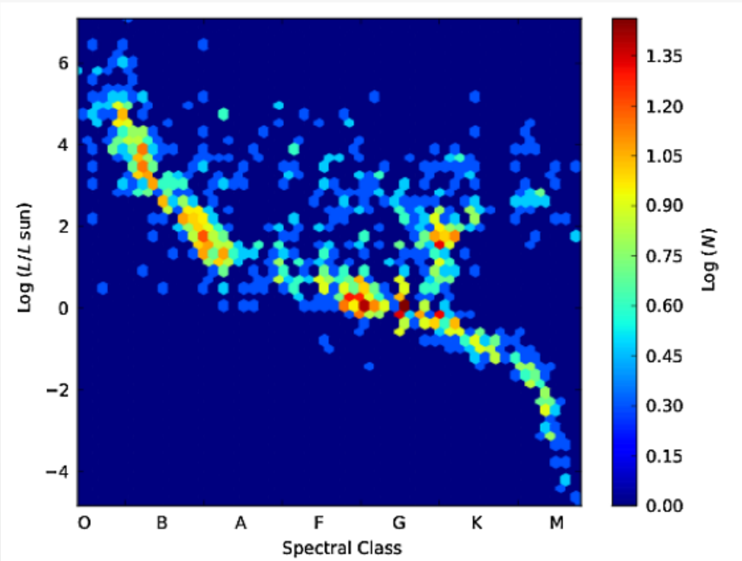
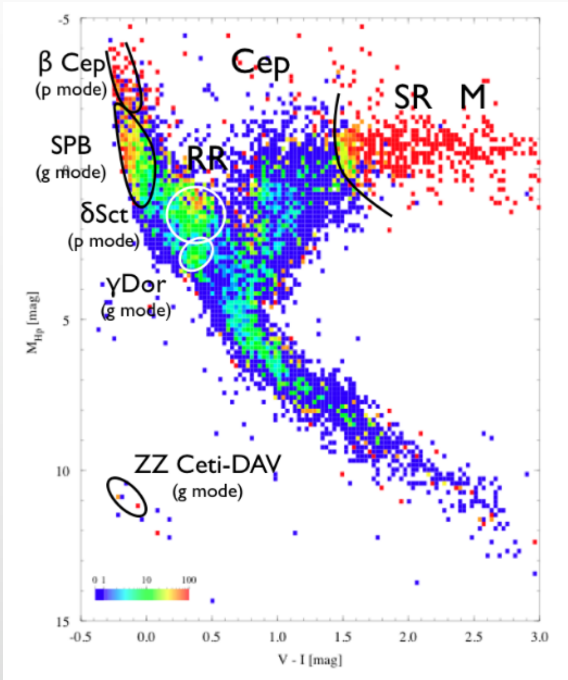
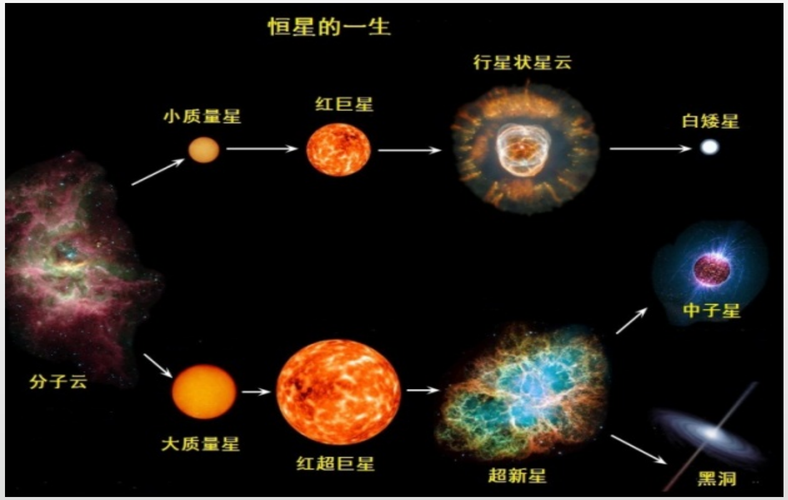
恒星活动和后期演化是非常关键的物理过程和阶段

- 磁场、脉动-->准确的恒星结构和演化建模
- 恒星后期演化形成的致密天体（白矮星、中子星、黑洞）-->诸多当今天体物理研究热点





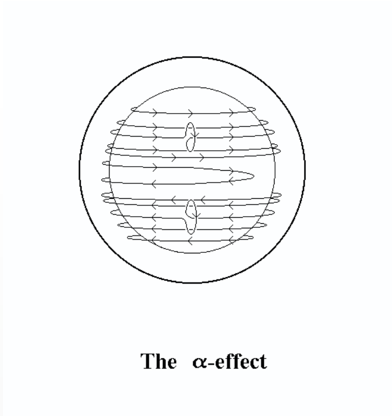


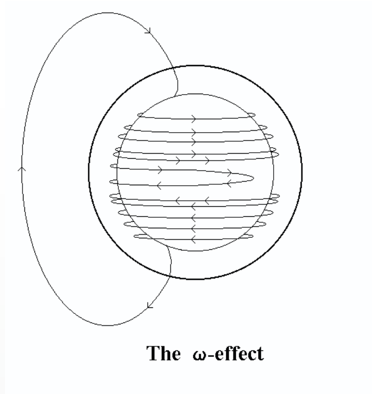
(Petit et al. 2014, **PASP**)　　(Eyer & Mowlavi 2008, **J. Phys.: Conf. Ser.**)

恒星活动

可观测现象

- 磁场活动
  - 对流和自转运动
    - 恒星磁场
  - 光球黑子、色球谱斑和耀斑等活动现象
    - 认识和理解恒星磁场
    - 为完善发电机模型提供准确的初始和边界条件
  - 磁场在恒星演化历史上的角色和作用?
- 脉动
  - 对流和物质交流过程?
  - δ Scuti脉动变星
    - δ Scuti-γ Doradus混合型变星-->星震学反演对流核表面位置及对流超射尺度
    - 有物质交流的脉动食双星系统-->精确恒星参数-->星震学反演-->物质交流信息





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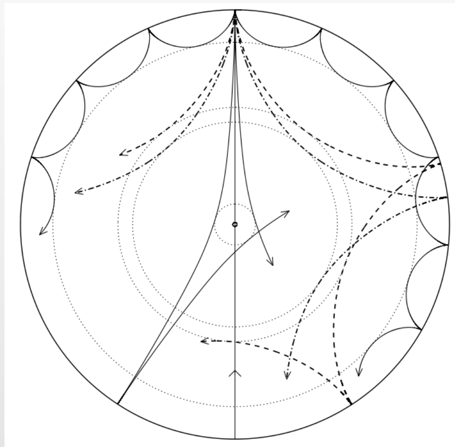


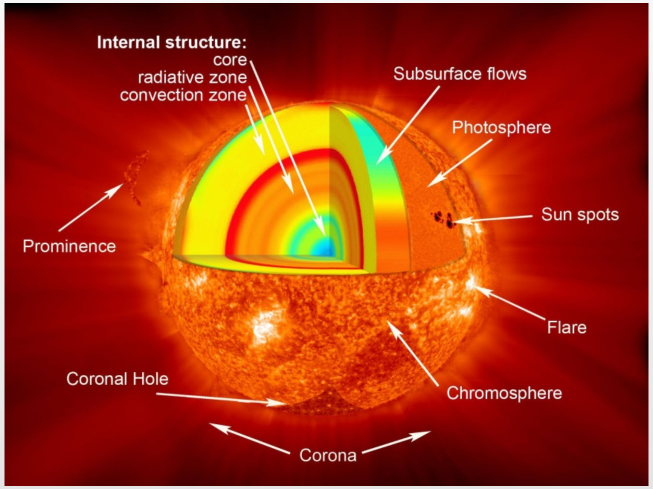
本征频率ν_{nlm}反映恒星内部的物理状态和结构 (Christensen-Dalsgaard 2003)

现行工作和未来观测需求

- CSST巡天带来的机遇
  - 极大地扩充现有的磁活动恒星样本，使得对磁场活动的“普查”成为可能
  - 克服统计偏差，完善磁场活动水平与恒星年龄、质量、演化阶段等基本参数之间的统计关系
  - 发现新型恒星磁场活动现象，从而探索不同类型的发电机过程
  - 为星震学提供更好的样本选择
- 建立光球和色球磁活动分析平台
  - 自动分析色球活动指标以及TiO分子吸收带
    - CSST巡天模式+无缝光谱
  - 大视场多目标黑子活动批量反演+白光耀斑捕获
    - CSST时域模式+多色测光：深场模式+共享其它时域模式课题数据
  - 紫外测光和光谱特征提取、多波段数据分析
    - CSST巡天模式+多色测光和无缝光谱
- 构建可靠的对流和物质交流分析模型
  - CSST时域模式+多色测光：深场模式+共享其它时域模式课题数据

恒星磁场活动

- 类太阳活动
- 更剧烈和复杂的磁场活动



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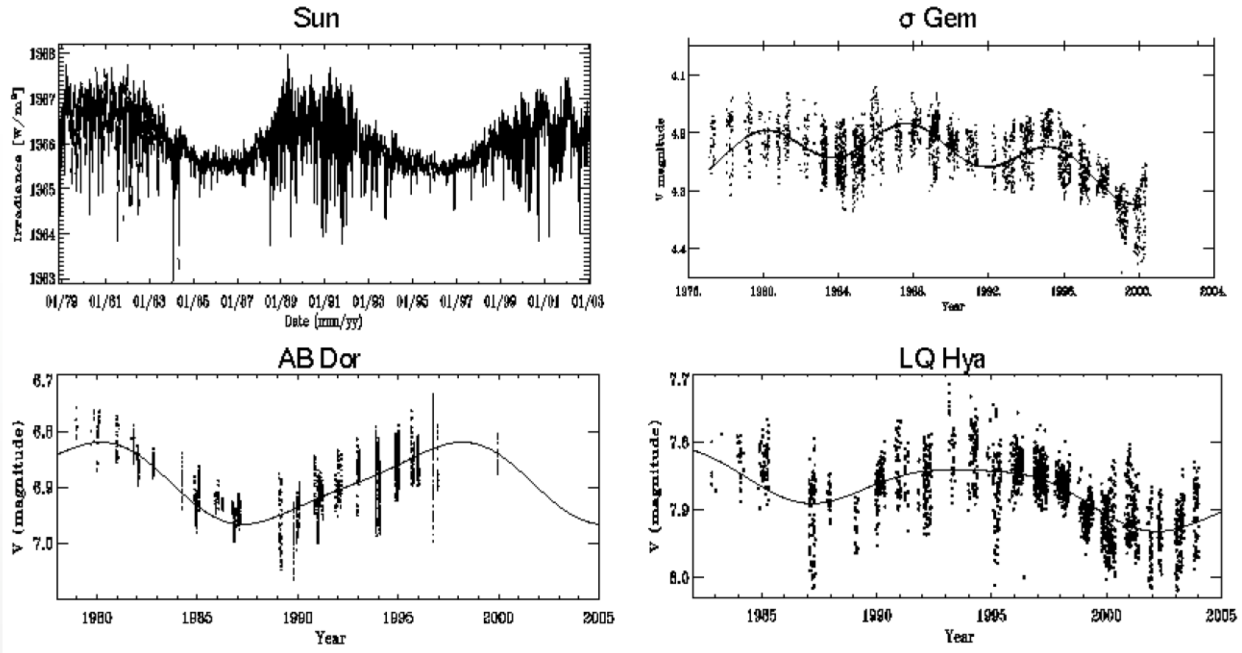
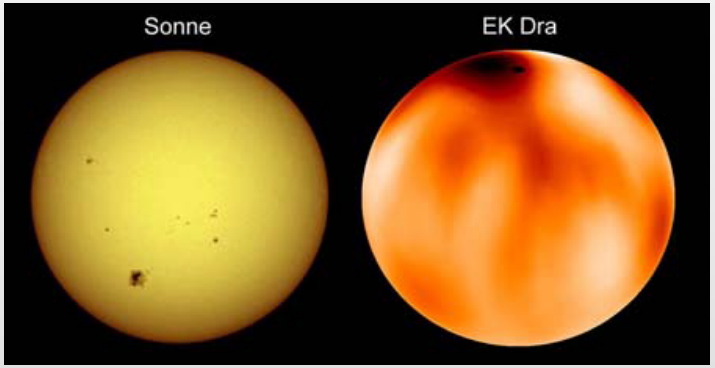
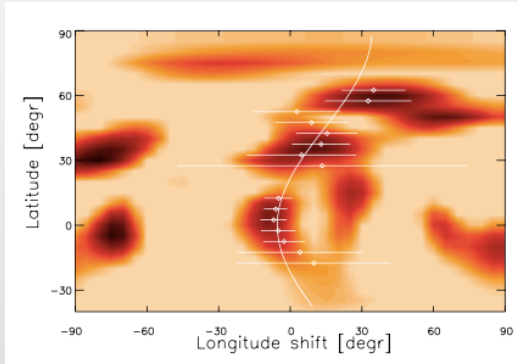


(Berdyugina 2005)



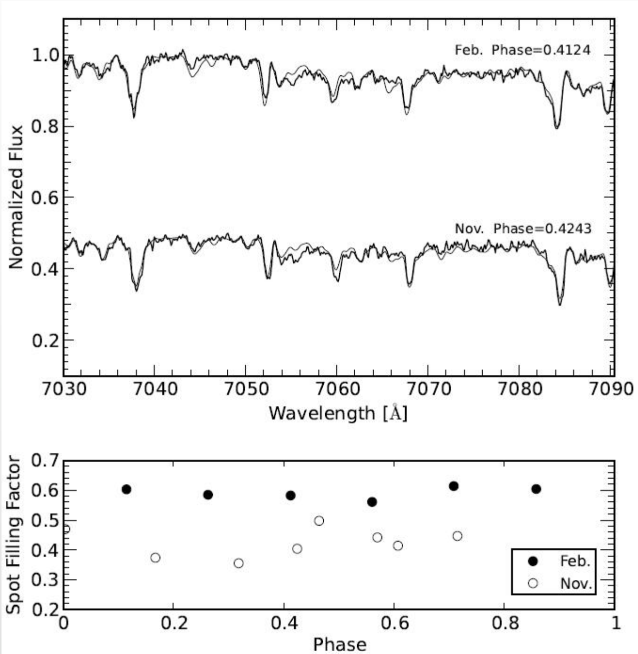
(Strassmeier 2009, **A&AR**)

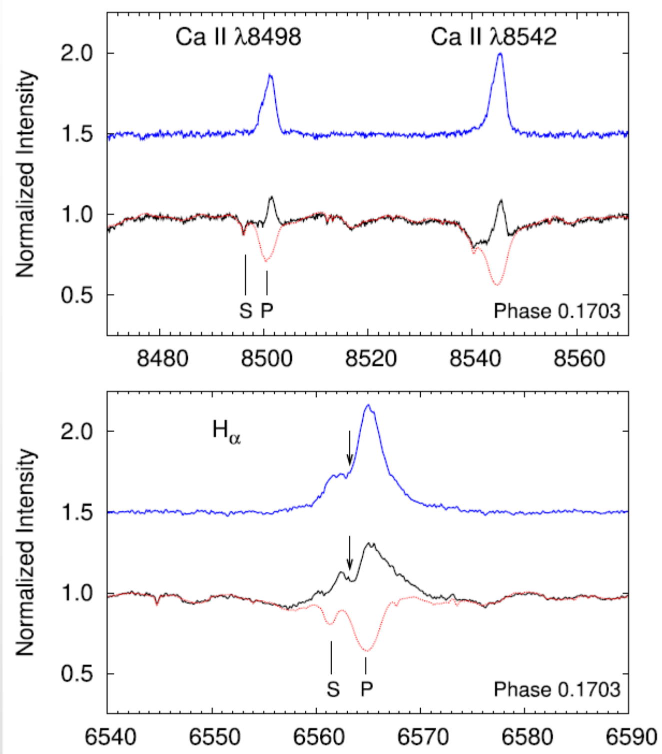


Anti-solar DR (Kriskovics et al. 2014, **A&A**)

TiO分子带和色球活动指标

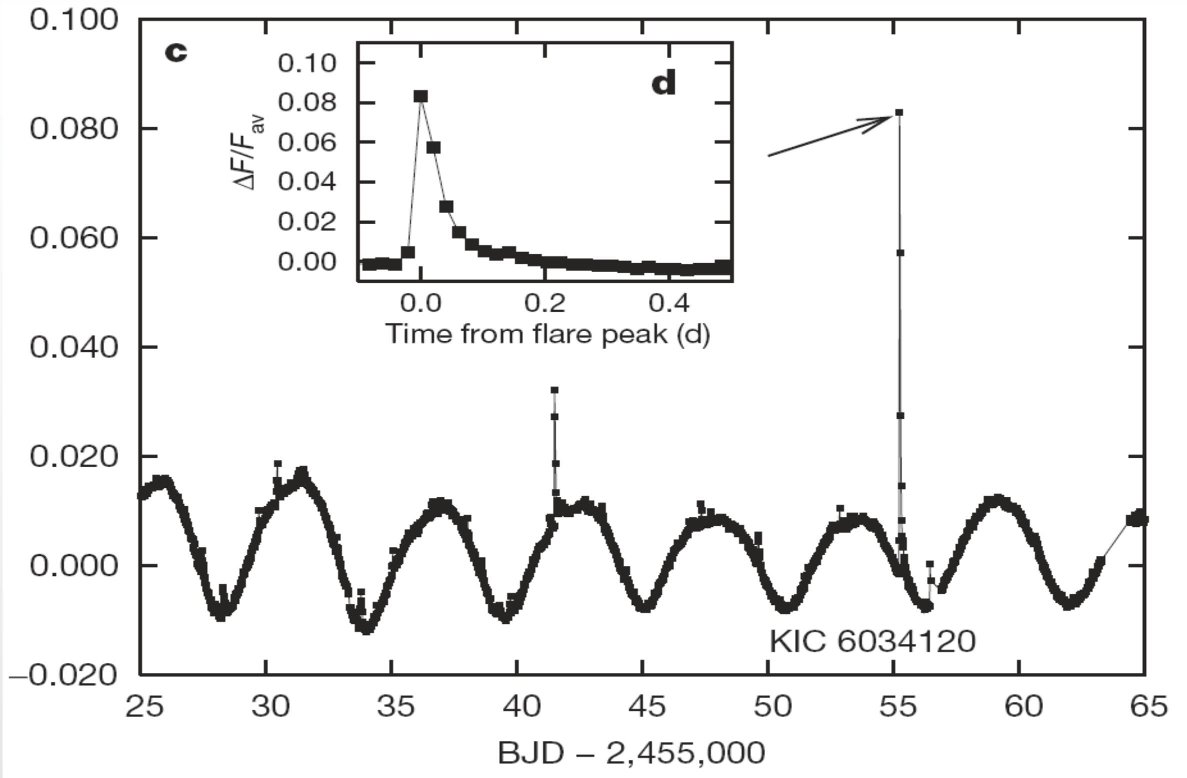
- TiO分子带深度：黑子温度与覆盖率
- 色球活动指标：非热辐射





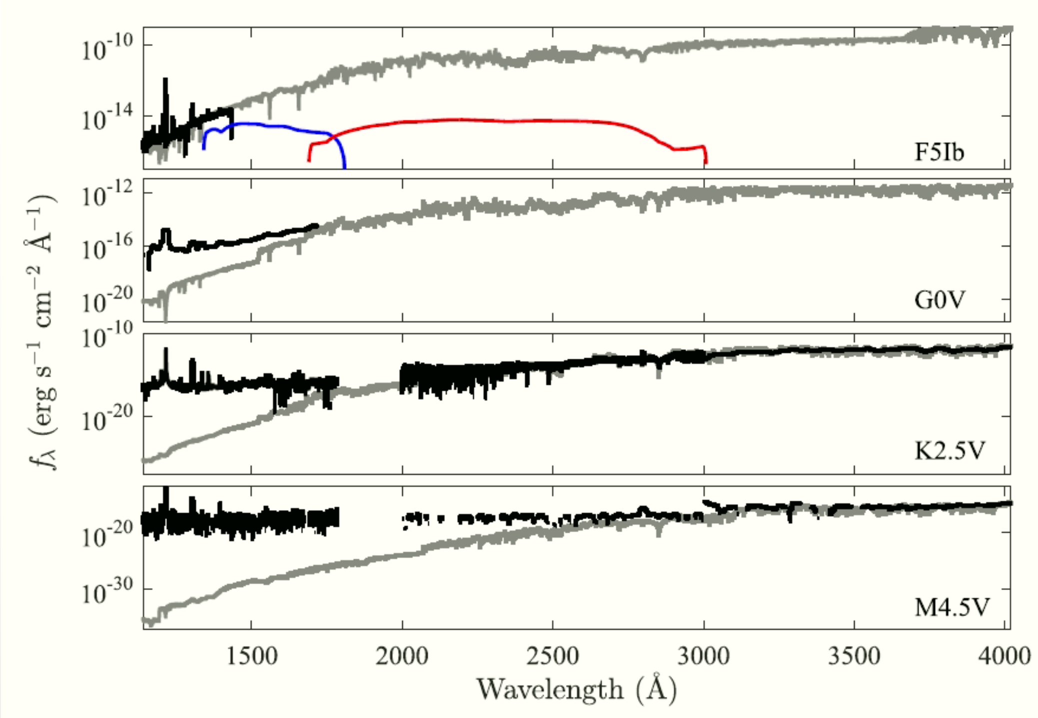
II Peg的TiO分子带 (Xiang, Gu et al. 2014, **MNRAS**)　SZ Psc的色球活动（Cao, Gu et al. 2019, **MNRAS**）

恒星超级耀斑



类太阳恒星KIC 6034120的耀斑事件，相对的流量和持续时间分别分8.4%和5.4小时，其对应热光度的峰值和总能量分别为6.8*10^31 erg/s 和 3.0*10^35 erg (Maehara et al. 2012, **Nature**)

磁场活动的多波段研究



- 样本筛选
  - 紫外样本（紫外超出+紫外光变剧烈）
  - GALEX+LAMOST-->CSST
- 多波段数据
  - 结合射电、X射线波段数据（Chandra、eROSITA等）
- 机器学习应用
  - 筛选磁活动星
  - 回归模型-->预言恒星紫外辐射性质

混合型变星的星震学诊断

δ Scuti (高频):

•周期： 0.008 - 0.42天

•振幅： < 0.3 星等

•质量：1.5 - 2.2太阳质量

•光谱型：A0 - F5

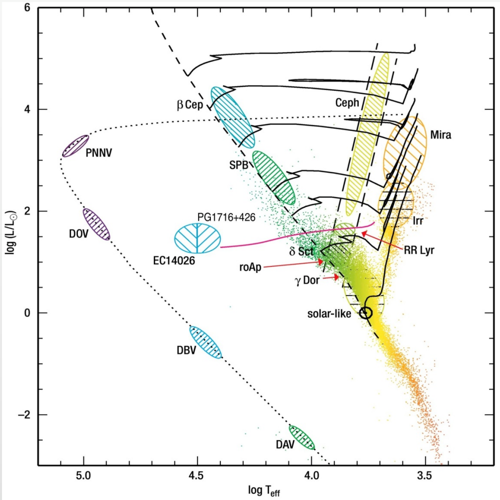
γ Dor (低频):

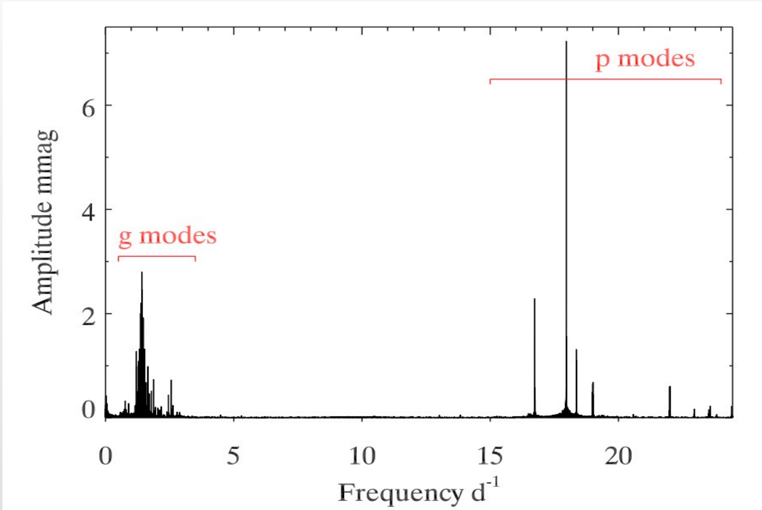
•周期： 0.3 - 3天

•振幅： < 0.1 星等

•质量：1.5 - 2.0太阳质量

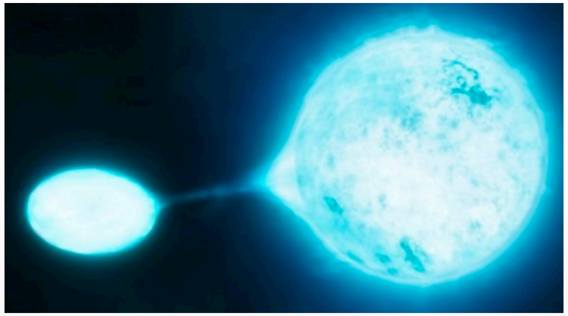
•光谱型：A7 - F5





混合型变星KIC 11145123（Kurtz et al. 2014）

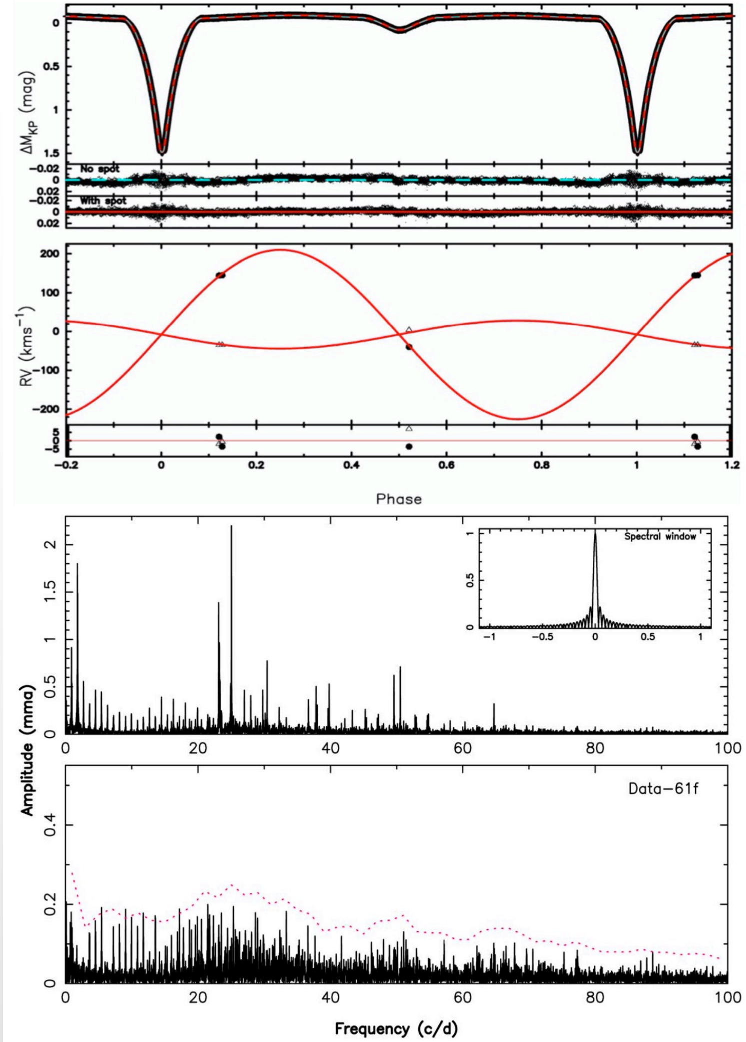
oEA型脉动食双星



◆双星分析：精确测定恒星的质量、半径、引力加速度等参数

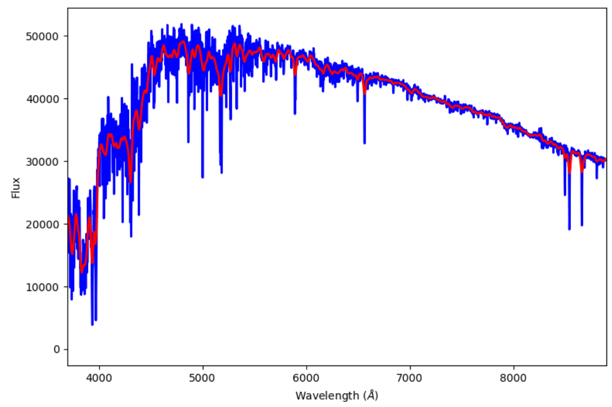
◆星震学：反演得到恒星内部不同位置处的结构信息

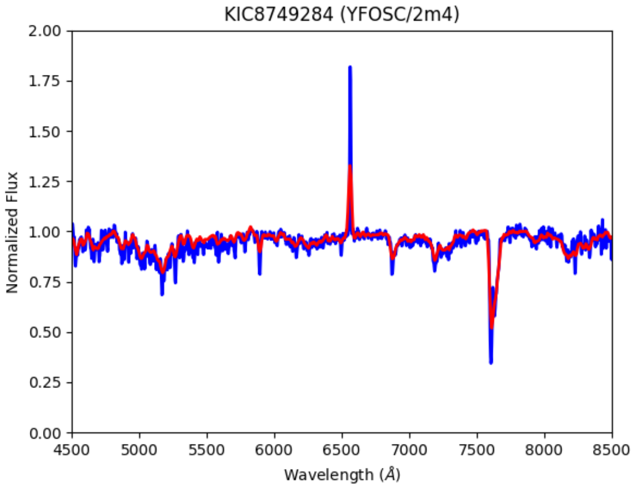
由物质交流对双星内部结构和演化的影响方式可以反推有关物质交流过程的信息



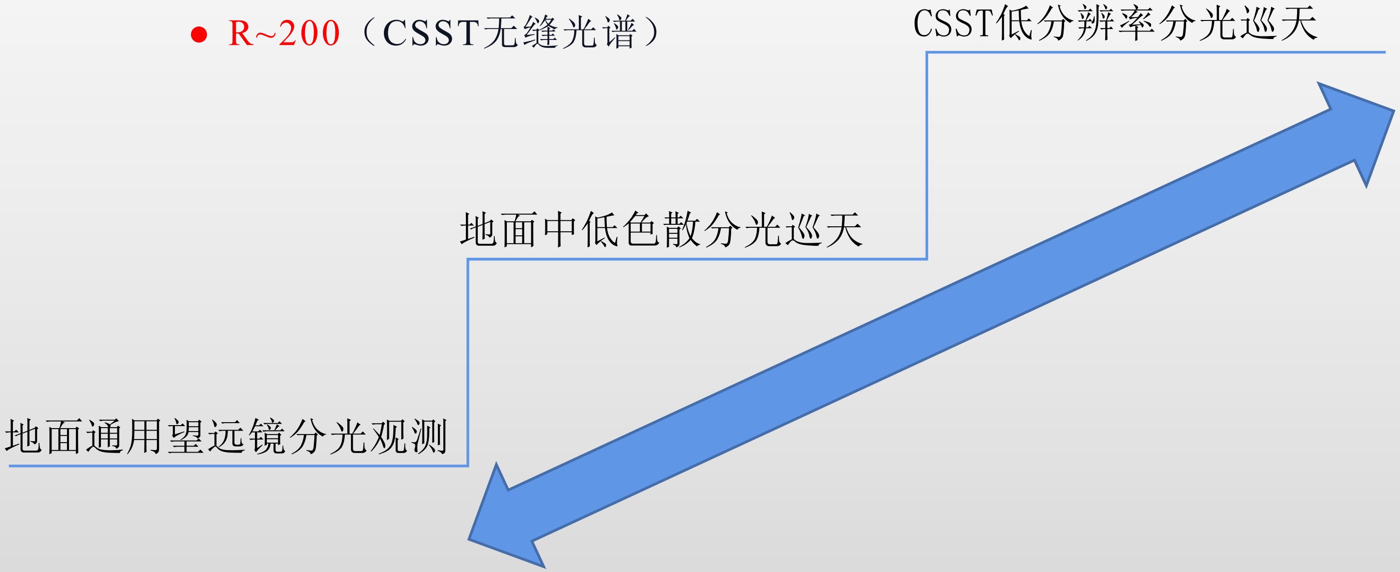
KIC 10736223（Chen et al. 2020, **ApJ**）

进展1：利用CSST无缝光谱搜寻磁活动恒星（项越等）



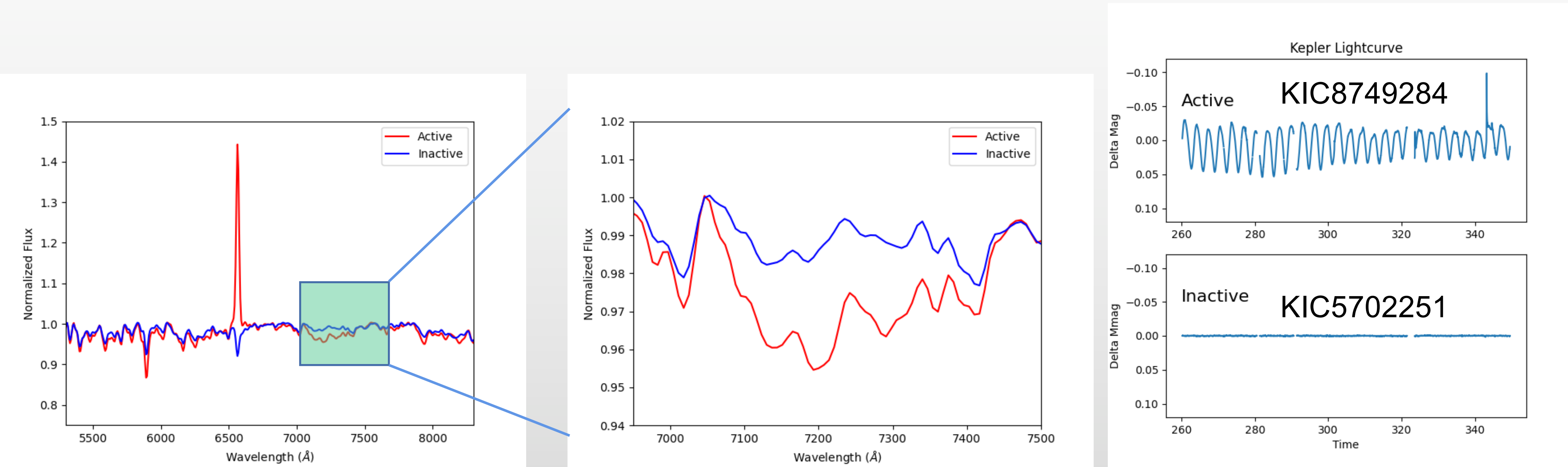


- 用地面观测光谱模拟CSST光谱
  - LAMOST低分辨率巡天光谱
    - 通过卷积高斯轮廓降低分辨率（R~200）
    - 低分辨率光谱依然保留较强原子谱线和分子吸收带
  - 丽江2.4米望远镜+YFOSC观测
    - R~1000（CSST-IFS）
    - R~200（CSST无缝光谱）



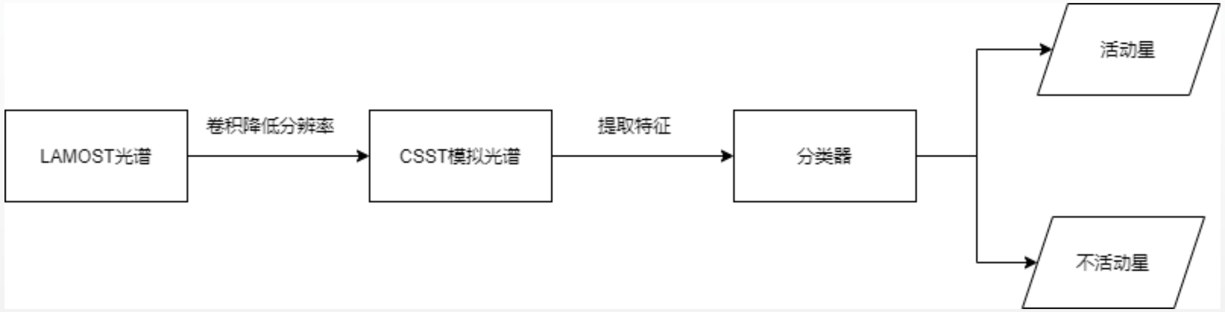
活动vs不活动

- 选取Frasca et al. (2016, **A&A**)的Kepler天区LAMOST活动恒星样本
  - 磁活动晚型恒星存在TiO、Hα等，可以在低分辨率光谱中看到
  - 可以与Kepler测光相互印证



利用机器学习方法搜寻磁活动星

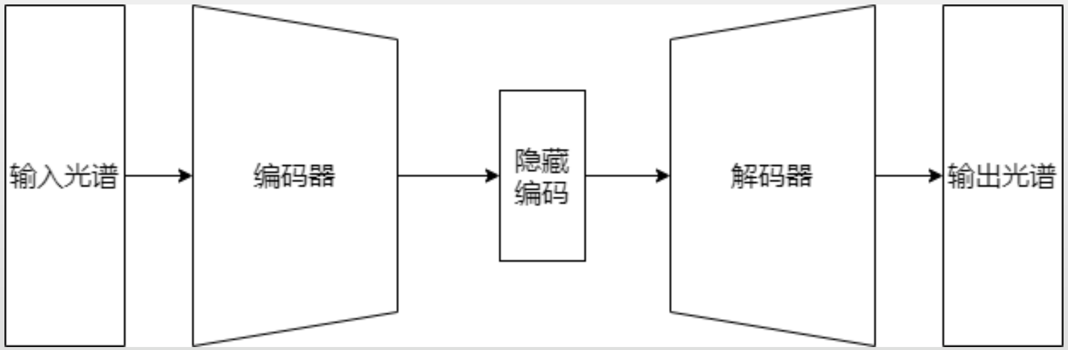
- 利用低分辨率（R~200）光谱寻找磁活动星
  - 属于监督学习中的二分类问题
  - 需要选取合适的特征



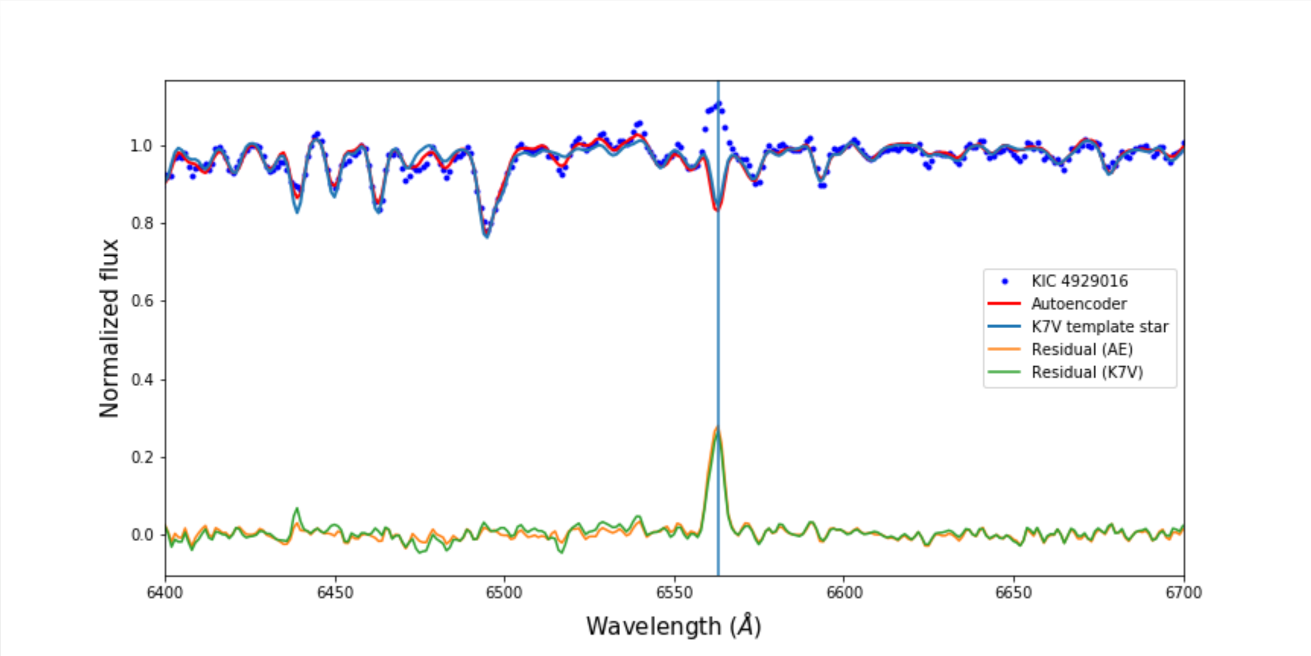
- 特征提取
  - 谱线区域流量积分/连续谱区域流量积分，获得相应指数
    - Hα index
    - TiO index
  - 宽波段色指数（B-V、V-R)
  - 依赖流量定标的精度
    - CSST大视场中有足够标准星，可获得较高精度的流量

利用自编码器搜寻磁活动星

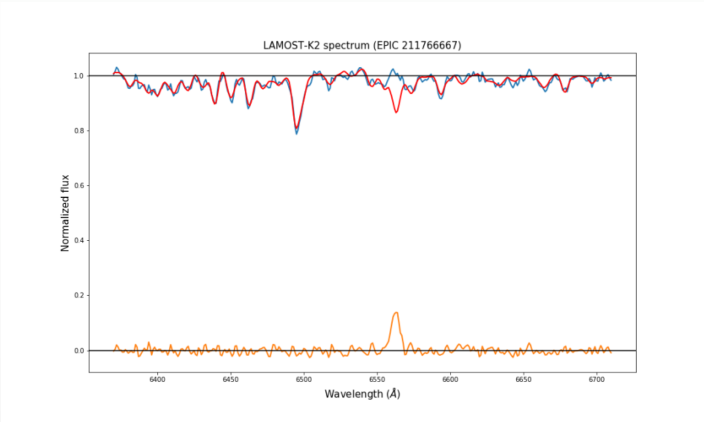
- 利用自编码器（Autoencoder）搜寻LAMOST巡天中的活动星，为恒星磁场活动搜寻分析方法研究提供更多样本
- 自编码器是一种神经网络，可以无监督地学习光谱特征（隐藏编码）提取，并由这些特征还原光谱，而无需提供恒星大气参数
- 我们利用自编码器学习不同光谱型的不活动星光谱，并与LAMOST光谱比较，寻找特定磁场活动谱线发射

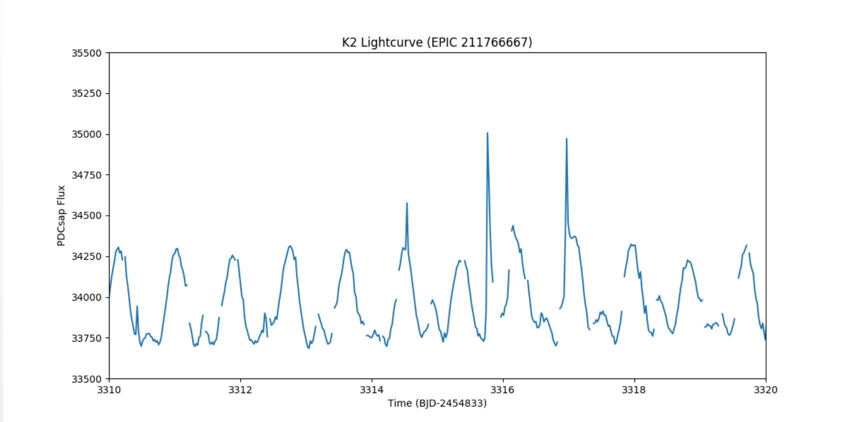


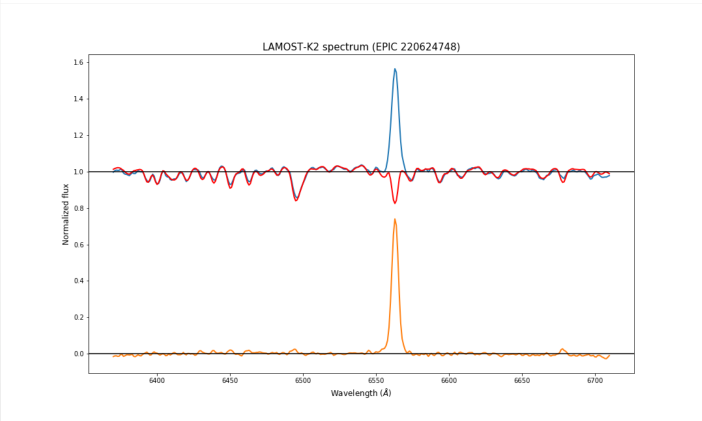
- 我们利用Frasca et al. (2016)的样本训练自编码器，寻找其中活动星样本
- 图中可以看到自编码器还原的不活动星光谱，与模板星光谱相近，可以通过光谱减测量Hα发射

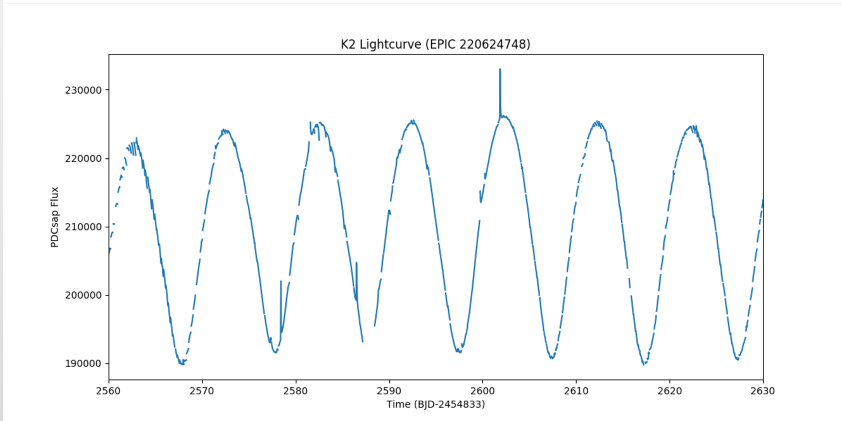


● 利用训练好的自编码器搜寻LAMOST-K2巡天中的活动星样本

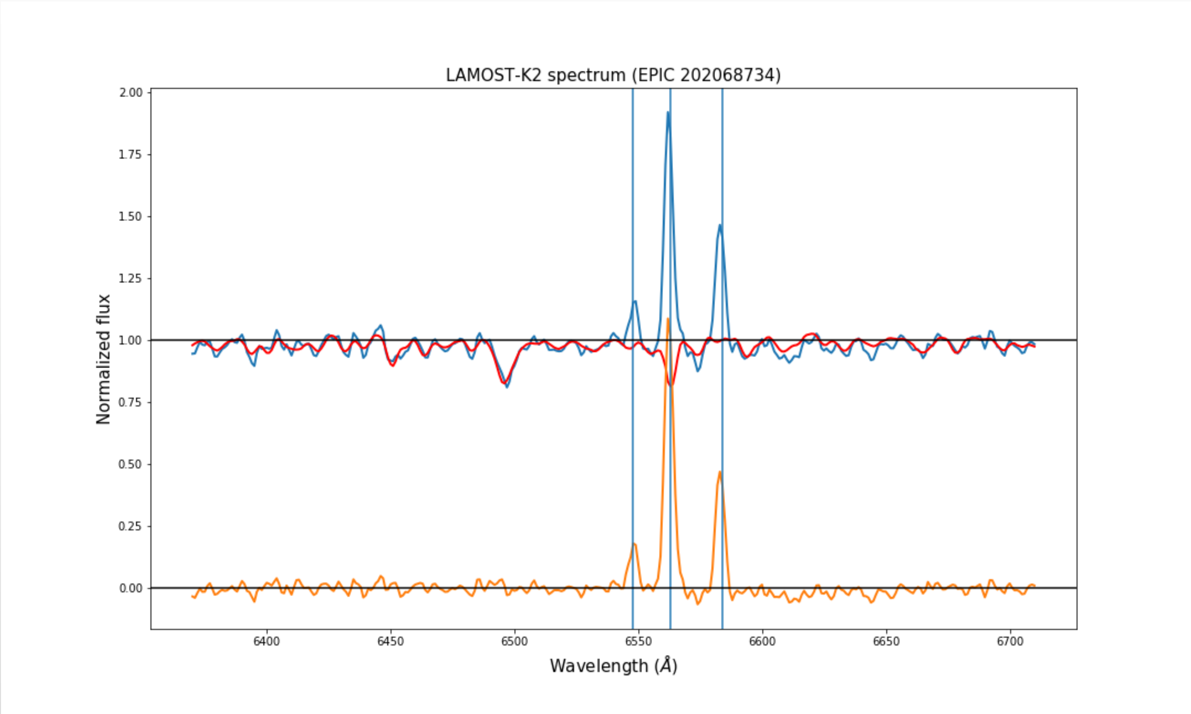






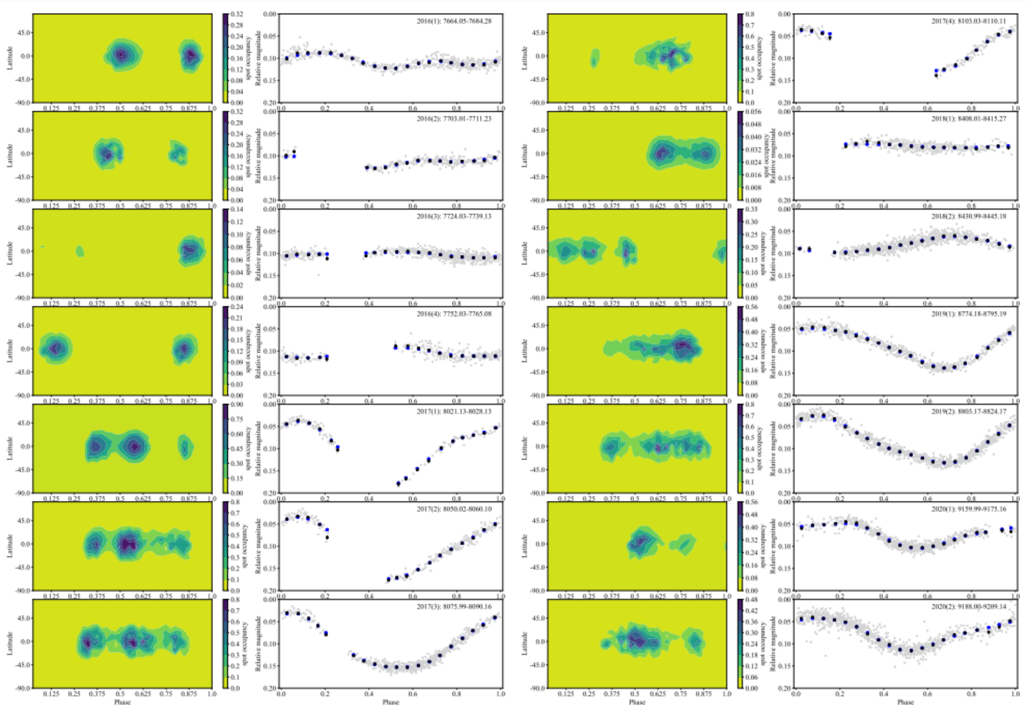


- 利用光谱减后的残差判断异常样本
  - 如星云发射线（6548、6584）

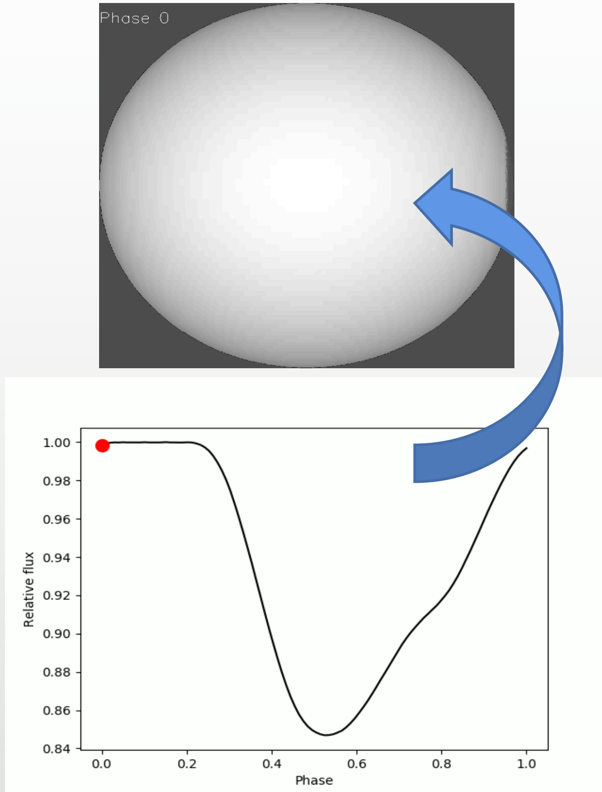


进展2：恒星黑子活动重构（罗翔，顾盛宏等）

- 无法直接成像
- 自转调制形成的光变曲线-->光球黑子图像



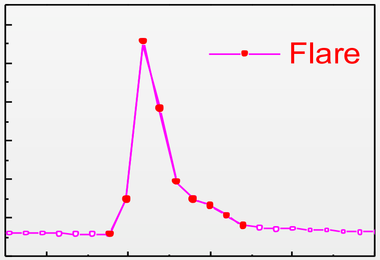
基于云南-香港0.45米望远镜时域观测(Luo, Gu et al. 2021, **MNRAS**, submitted)

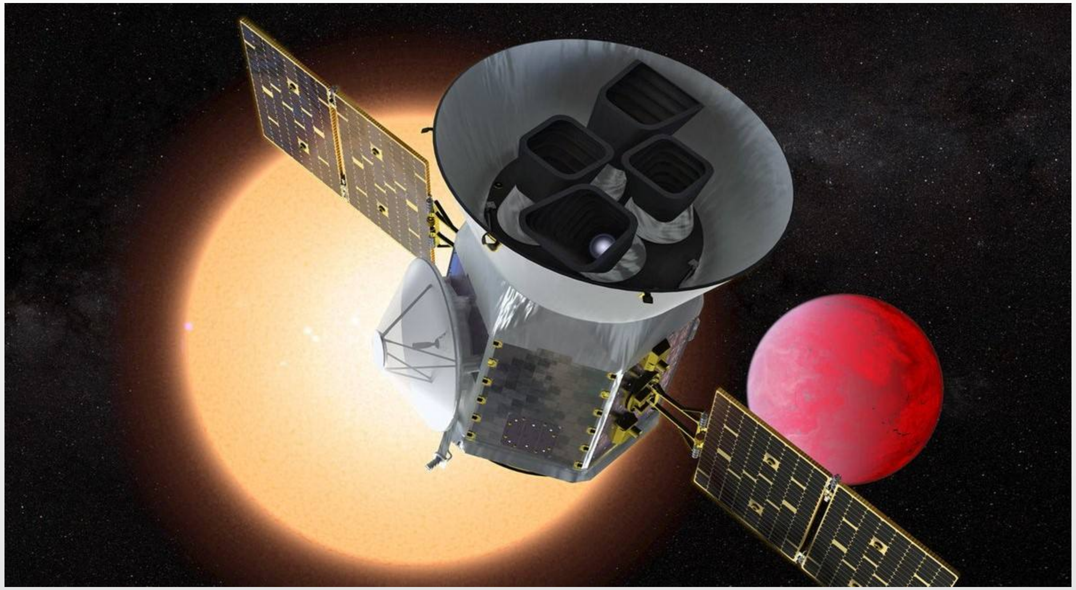


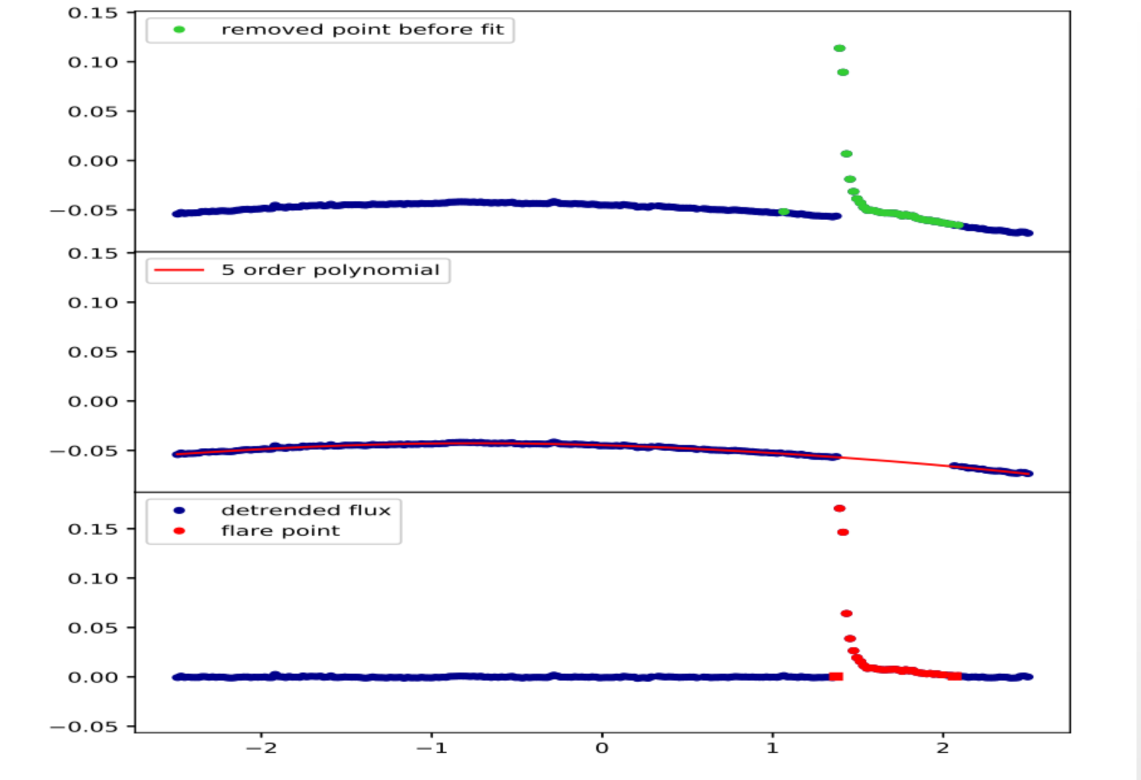
恒星黑子与光变曲线模拟

进展3：基于TESS数据研究恒星耀斑事件的统计规律（张立云等）

引入数据挖掘、人工智能等技术，快速精确捕捉恒星耀斑事件及分析其性质
评估CSST在恒星耀斑研究方面的潜力并展望未来可能得到的有显示度的研究成果

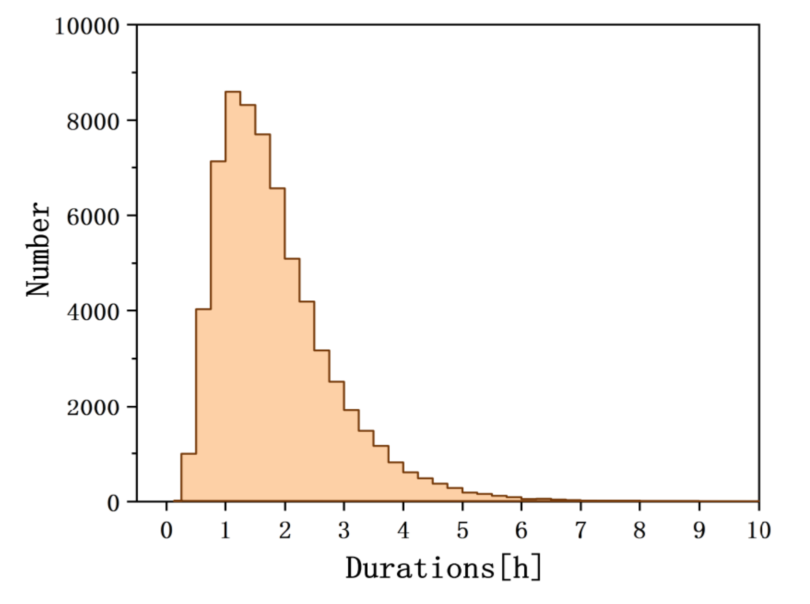


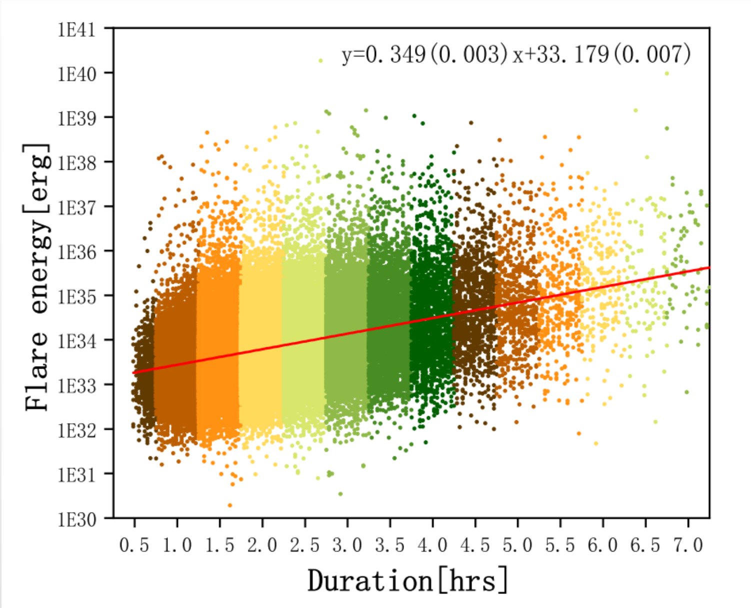




上部为利用TESS光变曲线寻找耀发候选体（绿色部分），中间为进一步拟合恒星本身光变的结果（红色曲线），下图为减去恒星本身光变，从而确定和刻画耀发事件（红色部分）(Meng, Zhang et al. 2021, in prep.)

利用TESS数据在14,391颗恒星上探测到61,954 恒星耀发事件，并确定恒星耀发的物理参数（持续时间、振幅、能量等），统计了其分布情况，为未来利用CSST数据更加精确统计恒星耀发规律积累经验

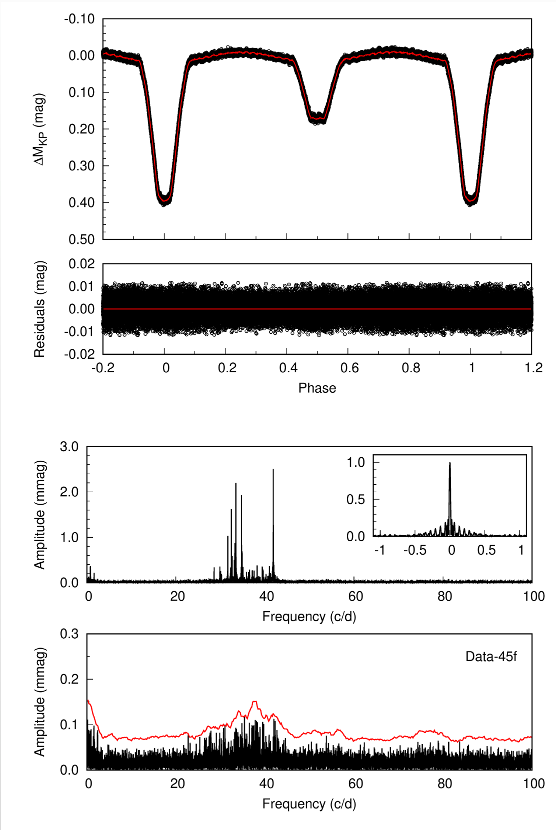


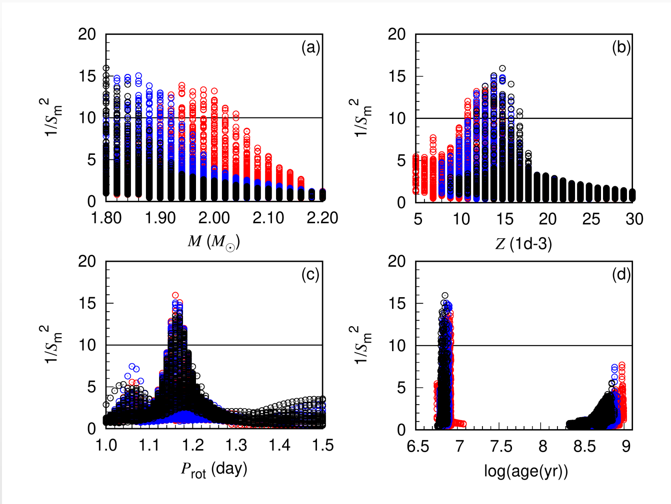


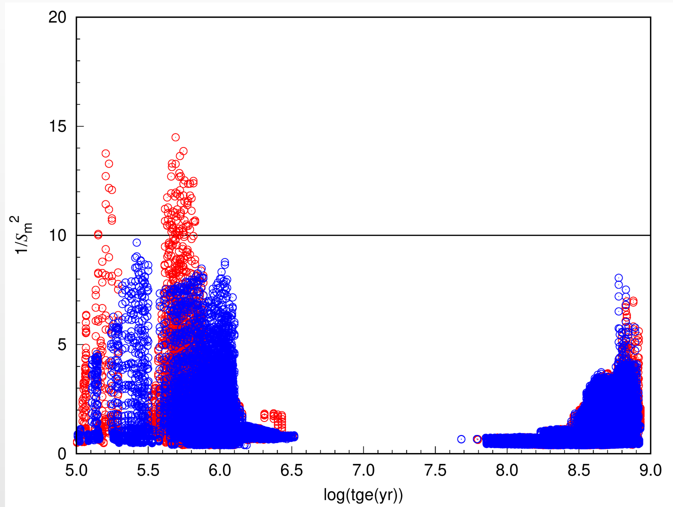
左图为恒星耀发持续时间的分布情况；右图为恒星耀发能量与持续时间之间的相关性，结果显示恒星耀发的持续时间越长其能量越大（Yang, Zhang et al. 2021, in prep.）

进展4：脉动食双星OO Dra的星震学（陈兴浩等）

- 脉动主星几乎未演化且其表面氦丰度非常低
- 确定脉动主星质量反转后的年龄为0.14 - 0.67百万年，OO Dra刚刚经历一个贫氦的快速物质转移过程





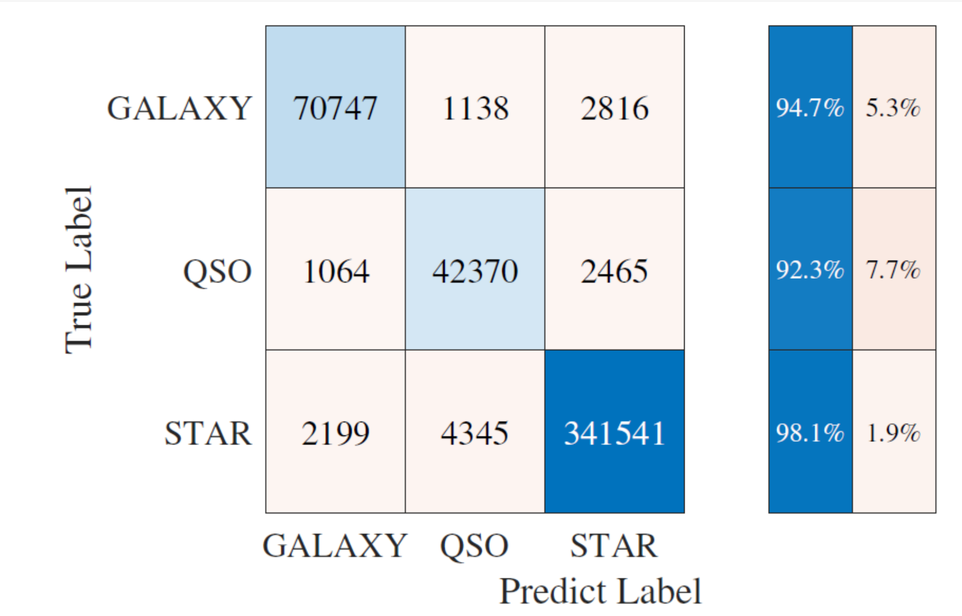


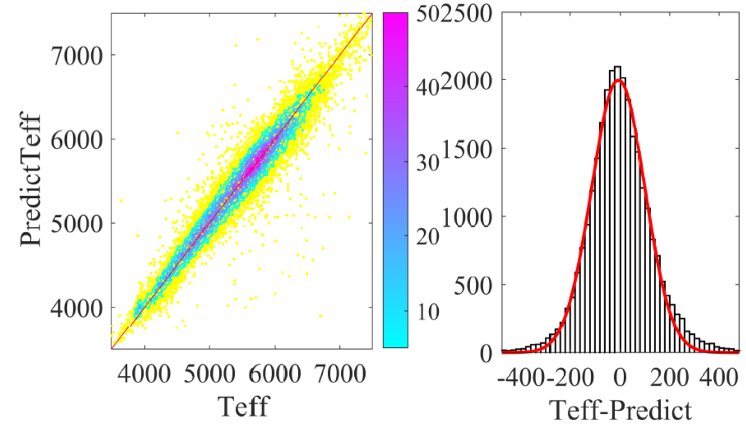
（Chen et al. 2021, **ApJ**）

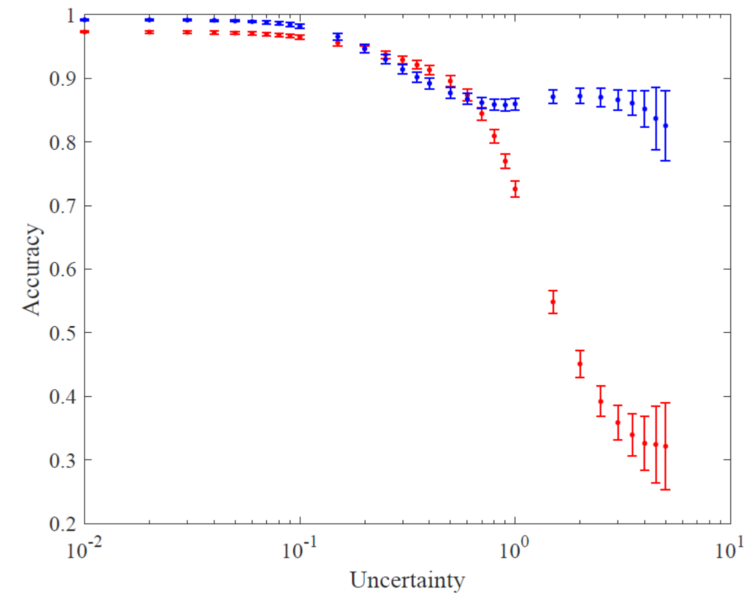
进展5：构建天体分类器、恒星参数回归器（白宇等）

基于LAMOST和J-PLUS，产出百万量级的天体分类样本和恒星基本参数星表

- 通过光学测光数据构建天体分类器、恒星参数回归器，建立全新的方法区分外插与内插数据集
- 国际上首次使用数值方法探索测光误差与天体分类准确性之间的联系，为机器学习的分类问题提供基础







恒星活动小结

- CSST的观测深度大，天区覆盖面积大、波段多，能够对暗弱的晚型恒星开展有效的测光与分光观测，观测数据包含了恒星磁场活动的重要探针，基于这些数据可对银河系晚型恒星的磁活动进行“普查”，加深对恒星磁场的理解
- CSST多色测光观测产生的高质量数据，将为δ Scuti脉动变星星震学研究提供更完备的数据支持
- 部分课题要求较高采样率的测光和分光观测，需要CSST望远镜在轨后能够对极少部分天区进行较为密集的监测采样

恒星后期演化

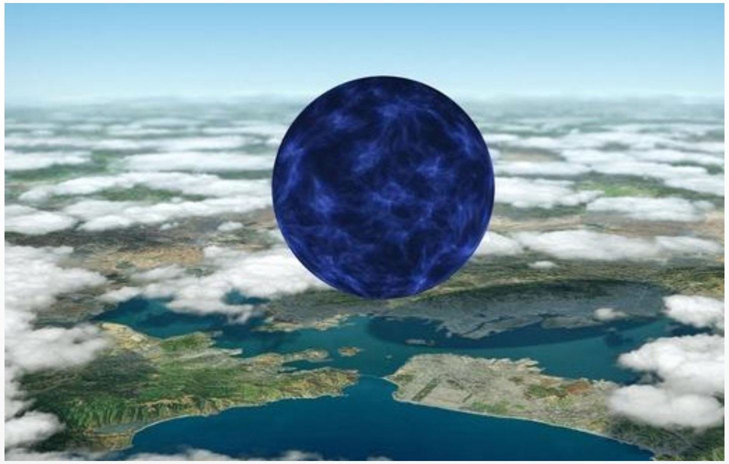
Accreting NS binary

孟祥存
Xiangcun MENG
Yunnan Observatories

Neutron star

NS appear at the end of the evolution of massive star after supernovae.

Mass range in 1.2-2.1$M_\odot$ and radius in 10-20 km.



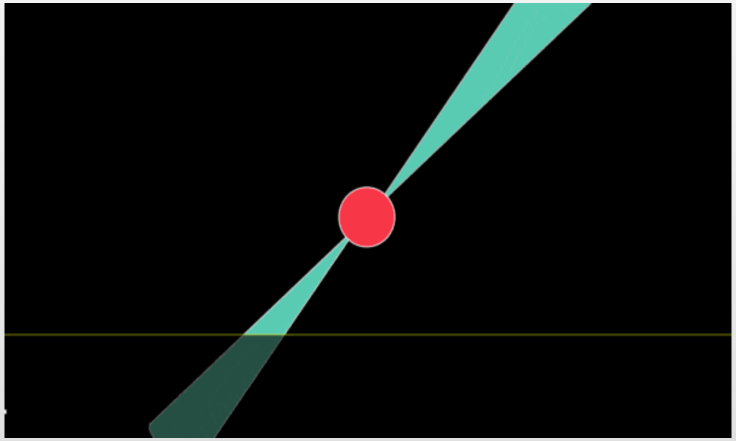
Pulsar

Highly magnetized and fast-rotating NS.

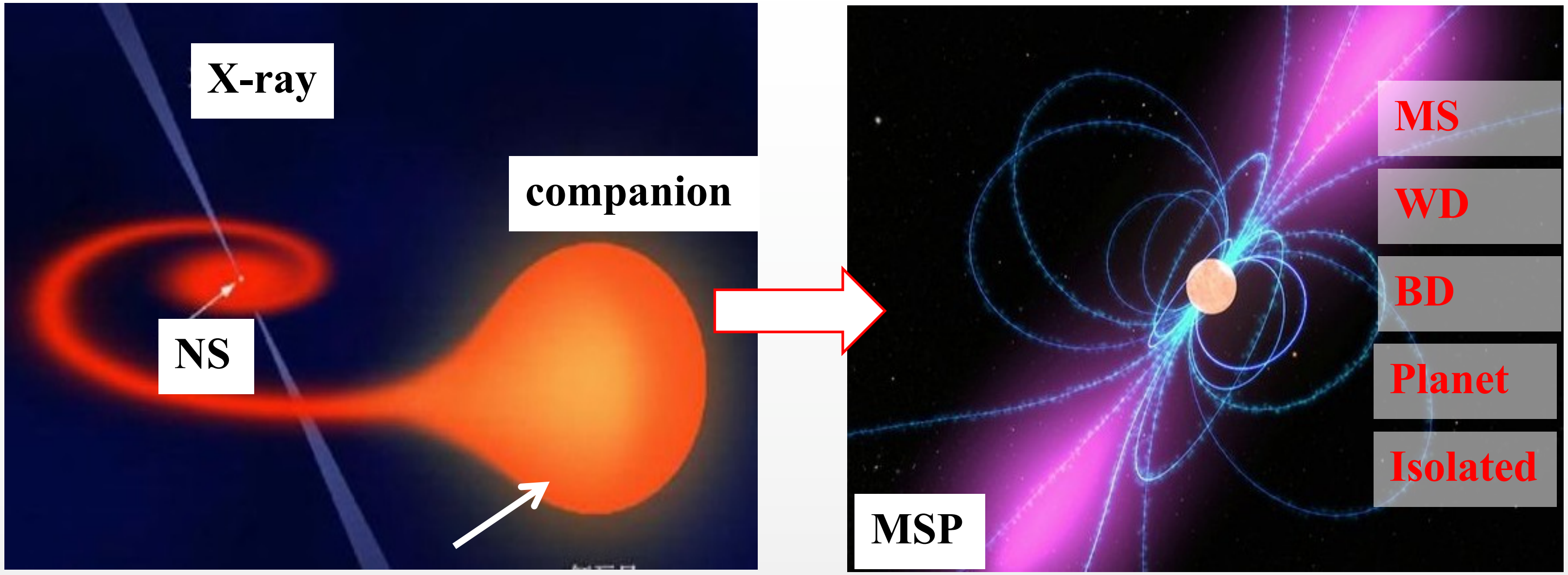
The most stable macroscopic clocks.

Testing gravity.

Gravitational wave source



Accreting NS binary-> binary MSP



Low mass X ray binary - accretion power

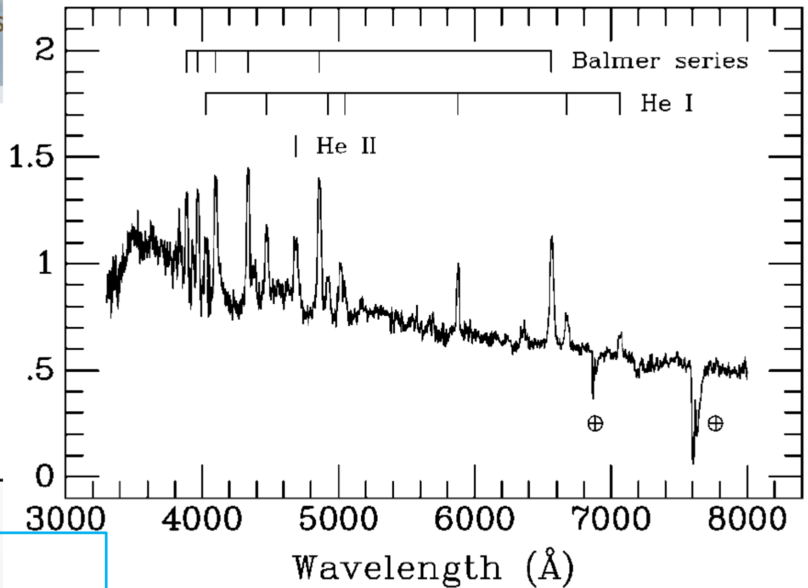
Radio binary MSP - rotation power

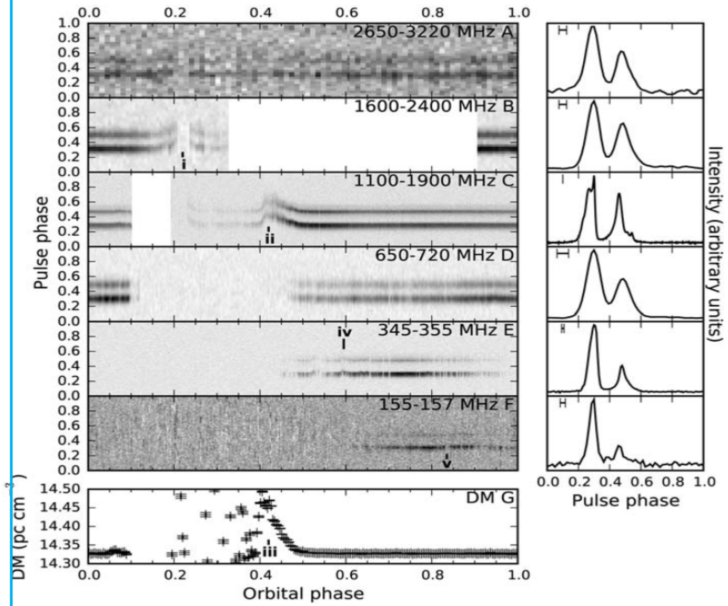
- **The connection between LMXB and BMSP**
- **The (accretion-induced?) decay of the surface B-field of a NS**
- **The maximum possible spin rate of an MSP**
- **The Roche-lobe decoupling phase**
- **The spin-up line and accretion torque reversals**
- **The progenitors of the isolated MSPs**
- **Not Pulsate for most LMXB**

Recycling scenario

- An old NS is recycled to become a MSP by accretion from its companion.
- During the accretion stage, the system is called a low-mass X-ray binary, powered by accretion.
- When the rate of mass transfer decreases in the later evolutionary stages, the binaries host a radio MSP, powered by rotation.
- Some systems can swing between the two states on very short timescale, depending on whether mass transfer exists.

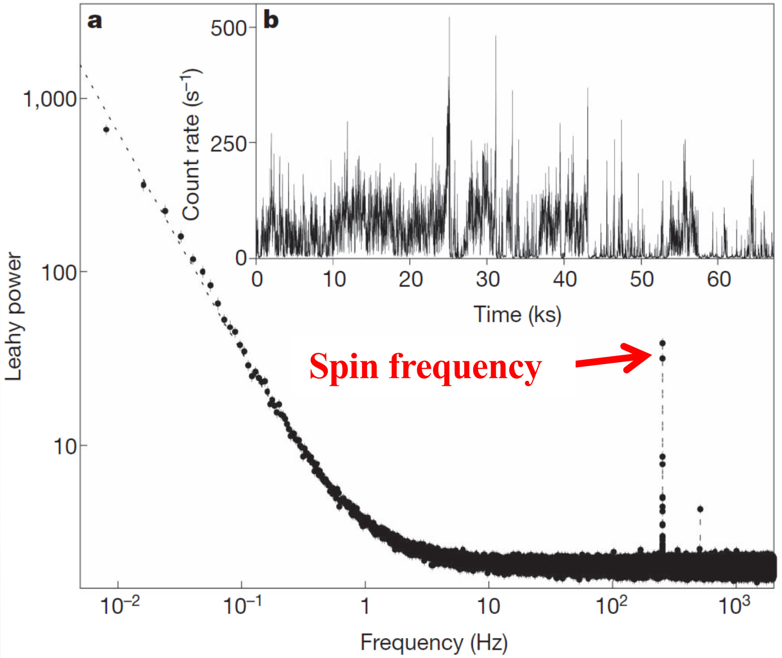
J102347.67+003841.2

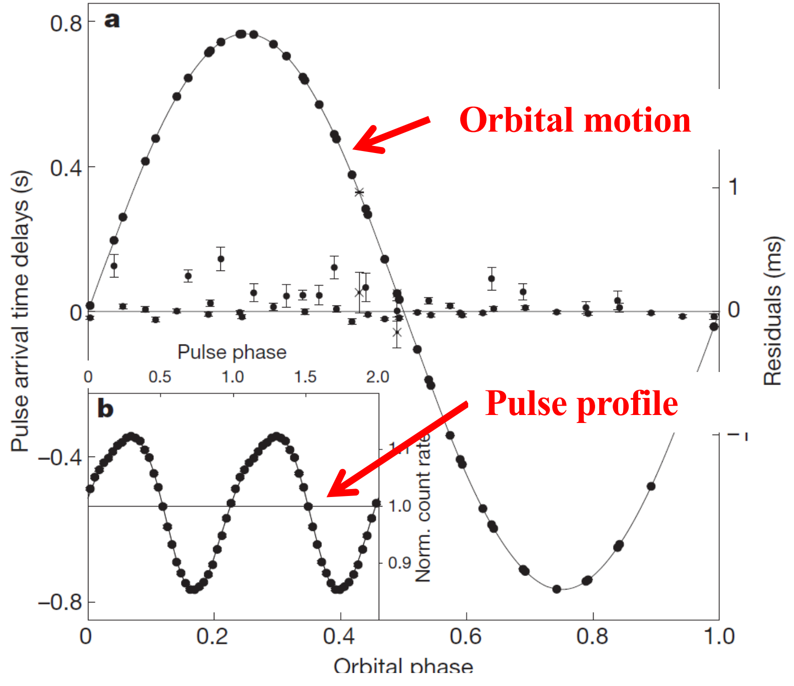




- Before 2002, blue spectrum with prominent double peaked emission lines and exhibited rapid flickering, without radio emission. The optical behavior is typical of an accretion flow and accretion disk -> Magnetic CV.
- After 2002, no sign of accretion and absence of emission lines in spectrum.
- In 2007, a bright MSP with a spin period of 1.69 ms was observd by Green Bank Telescope (GBT).

Bond+ 2002; Archibald+2009,Science





LETTER

X-ray: IGR J18245–2452

Radio: PSR J1824–2452I

doi:10.1038/nature12470

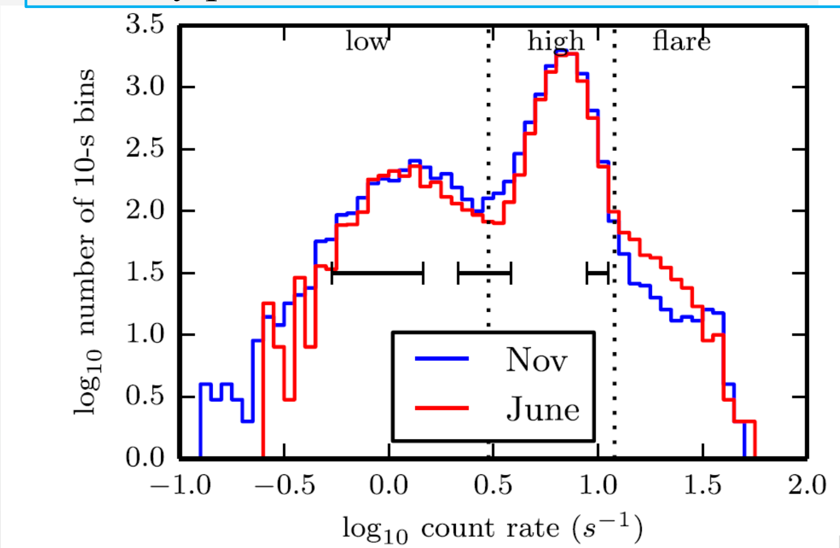
Swings between rotation and accretion power in a binary millisecond pulsar

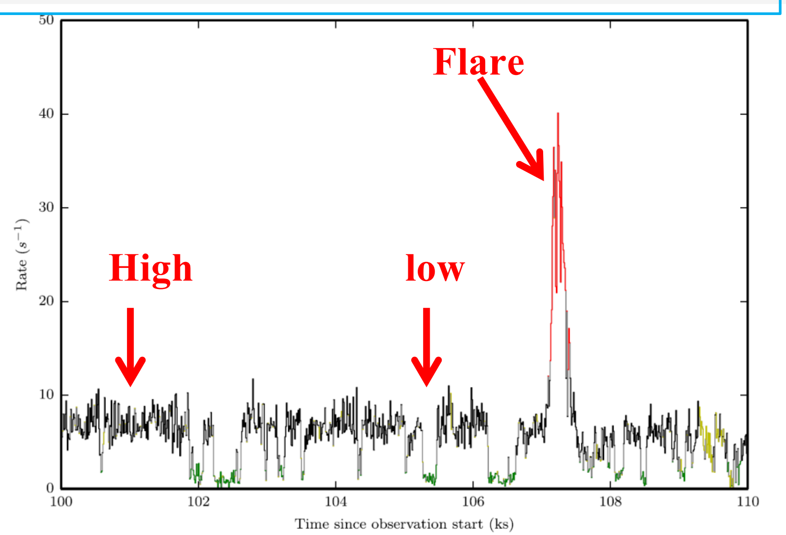
Radio MSP → Accelerating Millisecond X-ray Pulsar → Radio MSP

Papitto+, 2013, Nature

Properties of AMXP

- Show coherent pulsation with periods in the range 1.7-10 ms
- Very small donors are preferred and may be MS, WD and BD. NS with weak magnetic field (10^8-10^9 G).
- Most (if not all) of them are transient and X-ray luminosity usually low.
- The orbital period are always relatively short (less than 1day).
- The intermittency of the pulsations, which could bridge the gap between non-pulsating LMXBs and BMSPs.
- Some show three different states: high with, low without and flare without X-ray pulsation.





Archibald+2015,ApJ

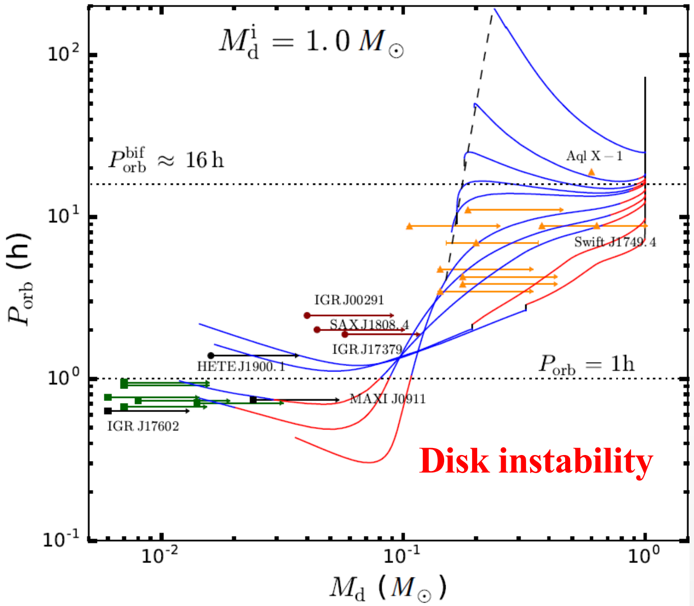
Table 4.1 Accreting X-ray pulsars in low mass X-ray binaries

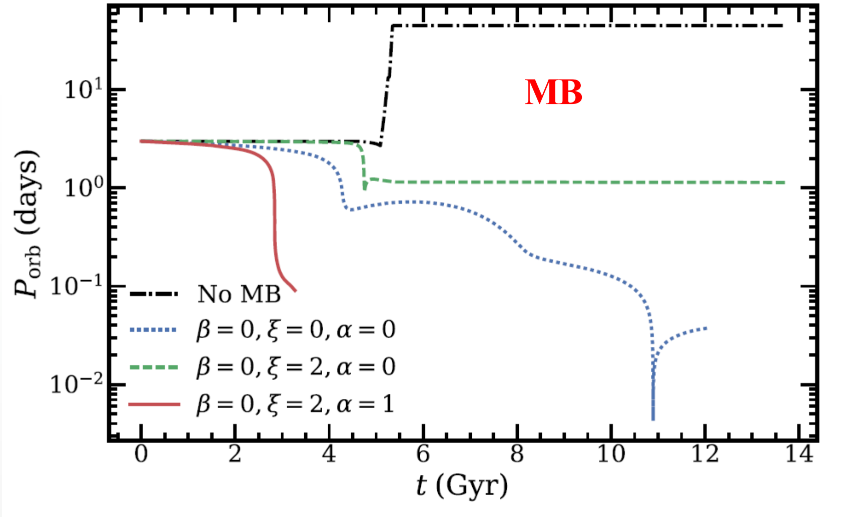
Source	ν_s/P (Hz)/(ms)	$P_{\rm orb}$ (h)	f_x ($M_\odot$)	$M_{c,min}$ ($M_\odot$)	Companion type	Ref.
Accreting millisecond pulsars						
XSS J12270−4859	593 (1.7)	6.91	3.9×10^{-3}	0.27	MS	Roy et al. (2015) and de Martino et al. (2014)
PSR J1023+0038	592 (1.7)	4.75	1.1×10^{-3}	0.20	MS	Archibald et al. (2009) and Coti Zelati et al. (2014)
Aql X-1	550 (1.8)	18.95	1.4×10^{-2}	0.56	MS	Casella et al. (2008) and Mata Sánchez et al. (2017)
Swift J1749.4−2807	518 (1.9)	8.82	5.5×10^{-2}	0.59	MS	Altamirano et al. (2011) and D'Avanzo et al. (2011)
SAX J1748.9−2021	442 (2.3)	8.77	4.8×10^{-4}	0.1	MS	Altamirano et al. (2008) and Cadelano et al. (2017)
IGR J17498−2921	401 (2.5)	3.84	2.0×10^{-3}	0.17	MS	Papitto et al. (2011b)
XTE J1814−338	314 (3.2)	4.27	2.0×10^{-3}	0.17	MS	Markwardt and Swank (2003) and Wang et al. (2017)
IGR J18245−2452	254 (3.9)	11.03	2.3×10^{-3}	0.17	MS	Papitto et al. (2013a)
IGR J17511−3057	245 (4.1)	3.47	1.1×10^{-3}	0.13	MS	Papitto et al. (2010)
IGR J00291+5934	599 (1.7)	2.46	2.8×10^{-5}	0.039	BD	Galloway et al. (2005)
SAX J1808.4−3658	401 (2.5)	2.01	3.8×10^{-5}	0.043	BD	Wijnands and van der Klis (1998) and Wang et al. (2013)
HETE J1900.1−2455	377 (2.7)	1.39	2.0×10^{-6}	0.016	BD	Kaaret et al. (2006) and Elebert et al. (2008)
XTE J1751−305	435 (2.3)	0.71	1.3×10^{-6}	0.014	He WD	Markwardt et al. (2002) and D'Avanzo et al. (2009)
MAXI J0911−655	340 (2.9)	0.74	6.2×10^{-6}	0.024	He WD?	Sanna et al. (2017a)
NGC6440 X−2	206 (4.8)	0.95	1.6×10^{-7}	0.0067	He WD	Altamirano et al. (2010)
Swift J1756.9−2508	182 (5.5)	0.91	1.6×10^{-7}	0.007	He WD	Krimm et al. (2007)
IGR J16597−3704	105 (9.5)	0.77	1.2×10^{-7}	0.006	He WD	Sanna et al. (2018)
XTE J0929−314	185 (5.4)	0.73	2.9×10^{-7}	0.0083	C/O WD	Galloway et al. (2002) and Giles et al. (2005)
XTE J1807−294	190 (5.3)	0.67	1.5×10^{-7}	0.0066	C/O WD	Campana et al. (2003) and D'Avanzo et al. (2009)
IGR J17062−6143	164 (6.1)	> 0.28	–	–	–	Strohmayer and Keek (2017)

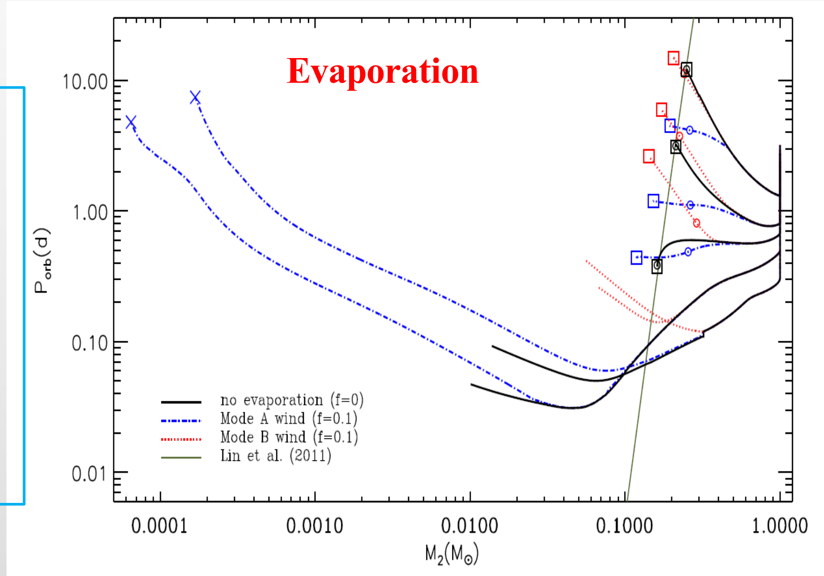
ν_s is the spin frequency, P_b the orbital period, f_x is the X-ray mass function, $M_{c,min}$ is the minimum companion mass for an assumed NS mass of 1.4 $M_\odot$. The companion types are: *WD* White Dwarf, *BD* Brown Dwarf, *MS* Main Sequence, *He Core* Helium Star

Adapted and updated from Patruno and Watts (2012)

Degenaar & Suleimanov, 2018





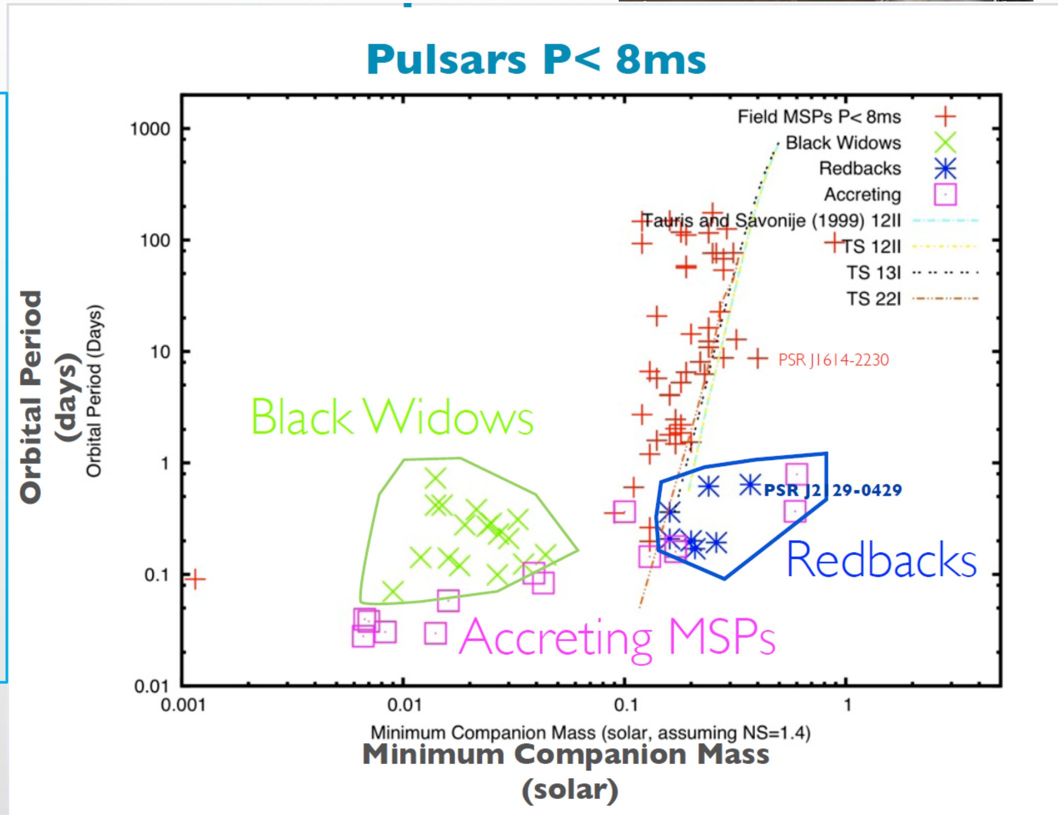


- An intermediate phase between LMXB and BMSP.
- Disk instability, pulsar wind, X-ray irradiation, magnetic braking, and so on, would play a key role.
- Playing a role together? one or some dominate(s)?

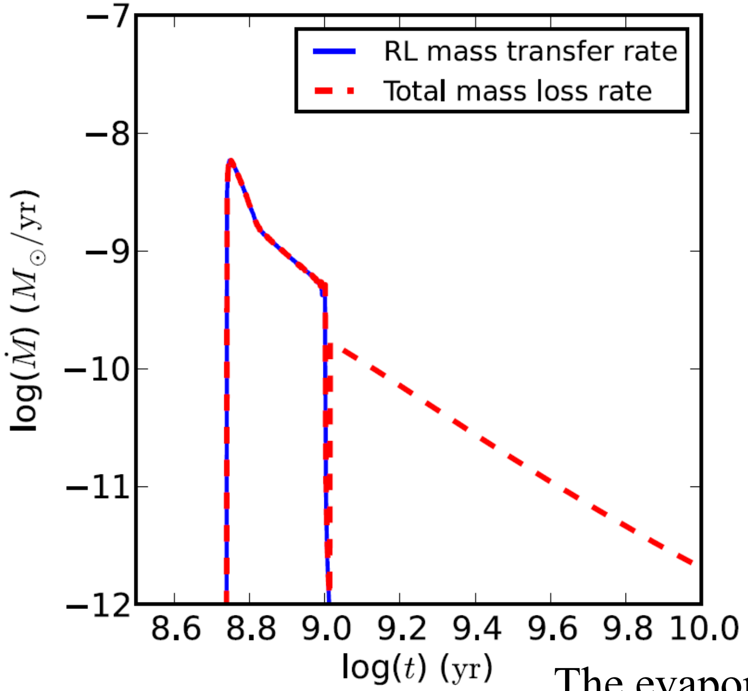
Jia & Li, 2016, ApJ; He et al. 2019, RAA; Chen et al., 2021, MNRAS

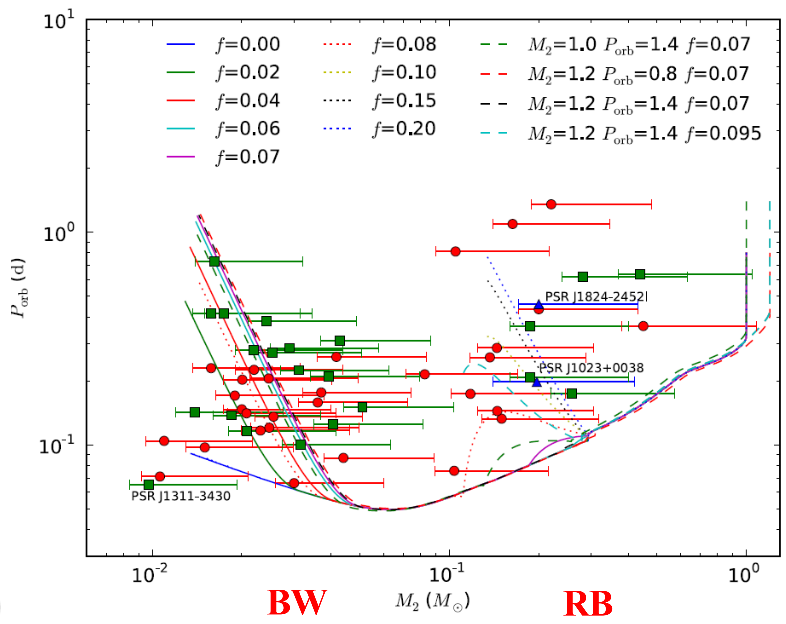
BW vs RB

- Low mass companion
- Show regular radio eclipses which is evidence of intrabinary material.
- X-rays from point source and nebular tail.
- Explanation: pulsar ablates companion and pulsar wind interacts with ablated material.



Roberts, 2013





The evaporation wind driven by the pulsar irradiation

- **The observations for the orbital period derivative show that some BW and RB may be from AMXP or some AMXP will become BW or RB.**
- **In theory, if an evaporation wind is considered in an AMXP system, the system will evolve to a BW or RB soon, but it's quite difficult to evolve back to AMXP again.**
- **What's the evolutionary connection between AMXP and BW, RB?**

Chen et al., 2013, ApJ

Angular momentum loss mechanism

- Gravitational wave
- M
- N
- C
- A
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- Orbital twin: IGR J00291+5934 vs SAX
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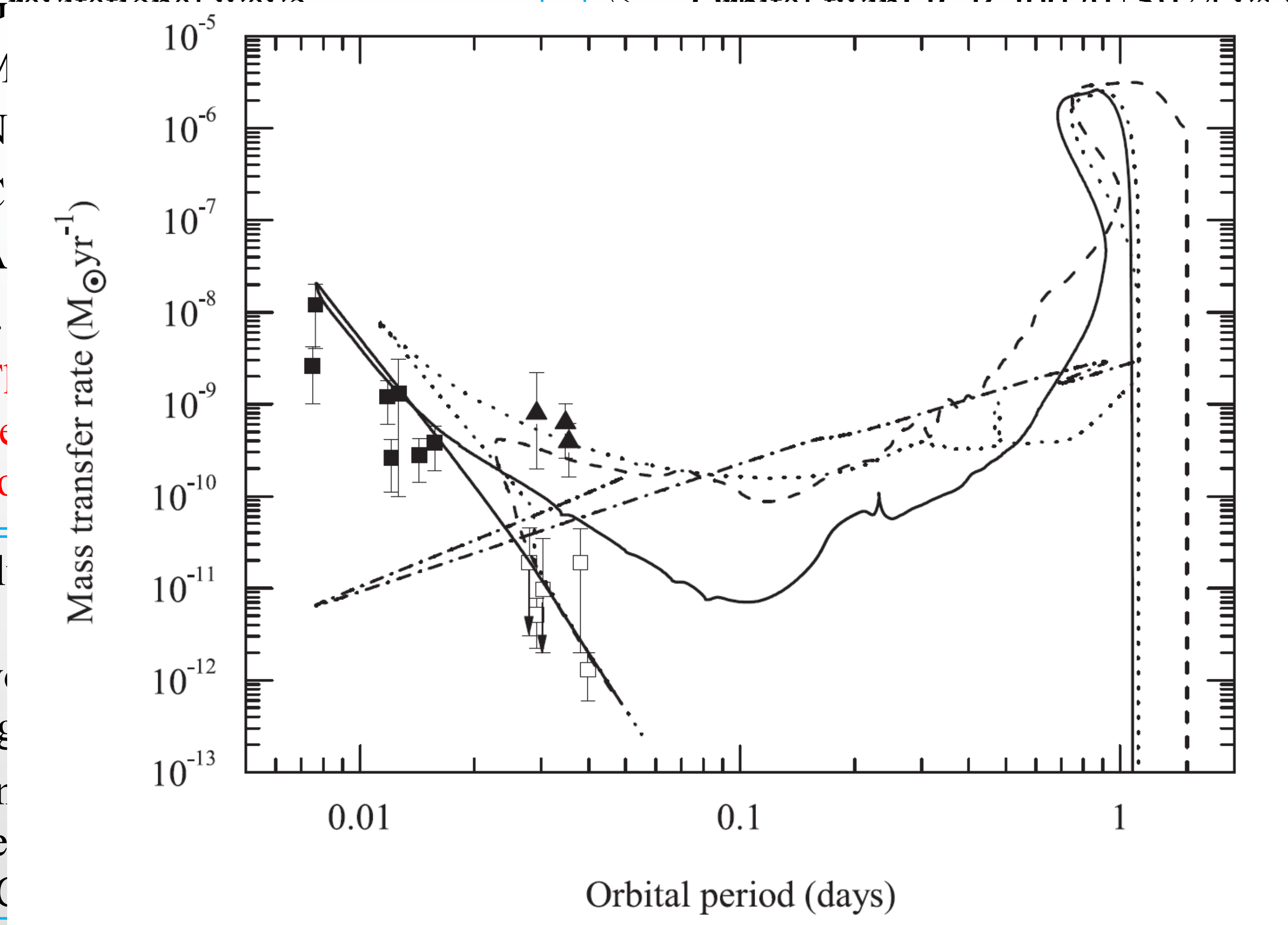

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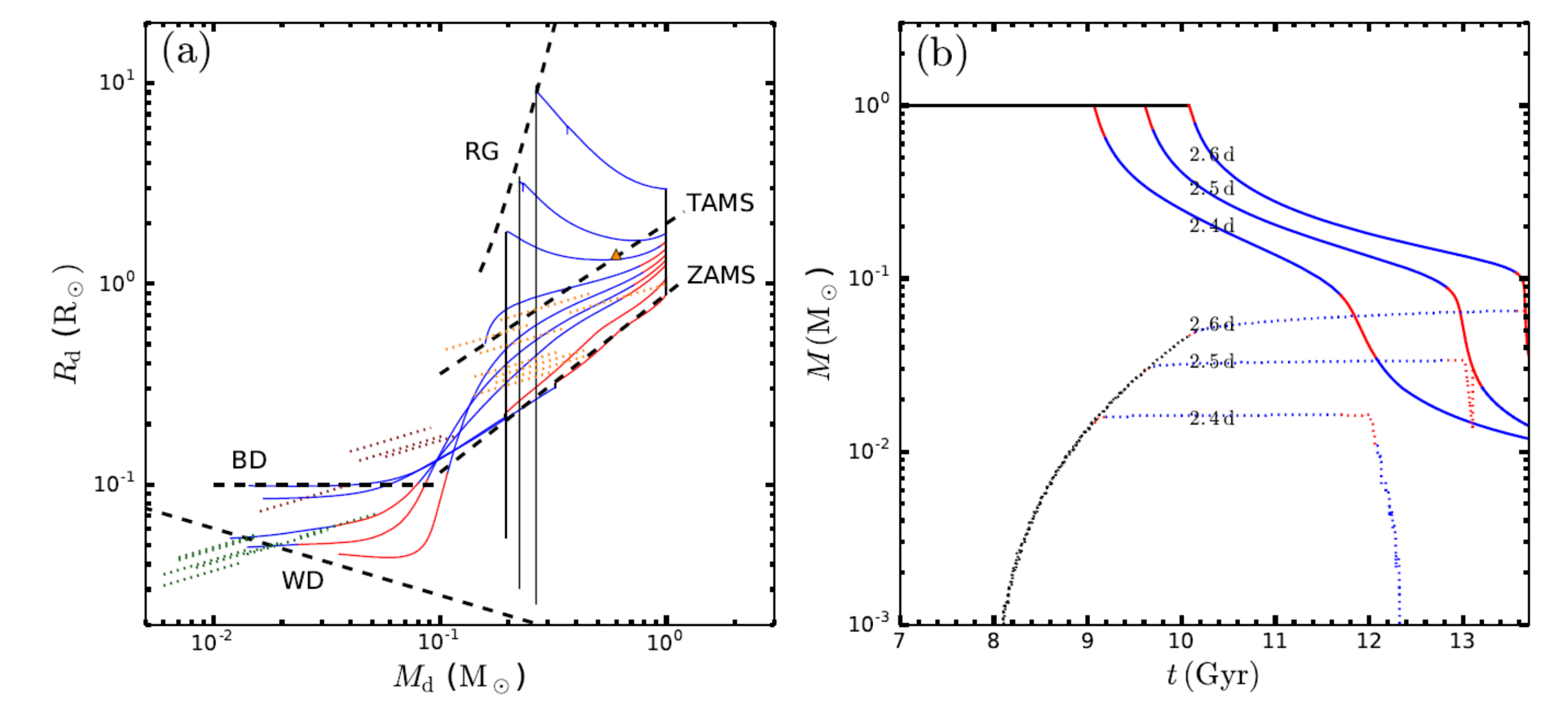
A&S: AS exchange between donor and orbit, resulting from variation of companion spin caused by magnetic activity driven by pulsar irradiation (Applegate & Shaham 1994）.

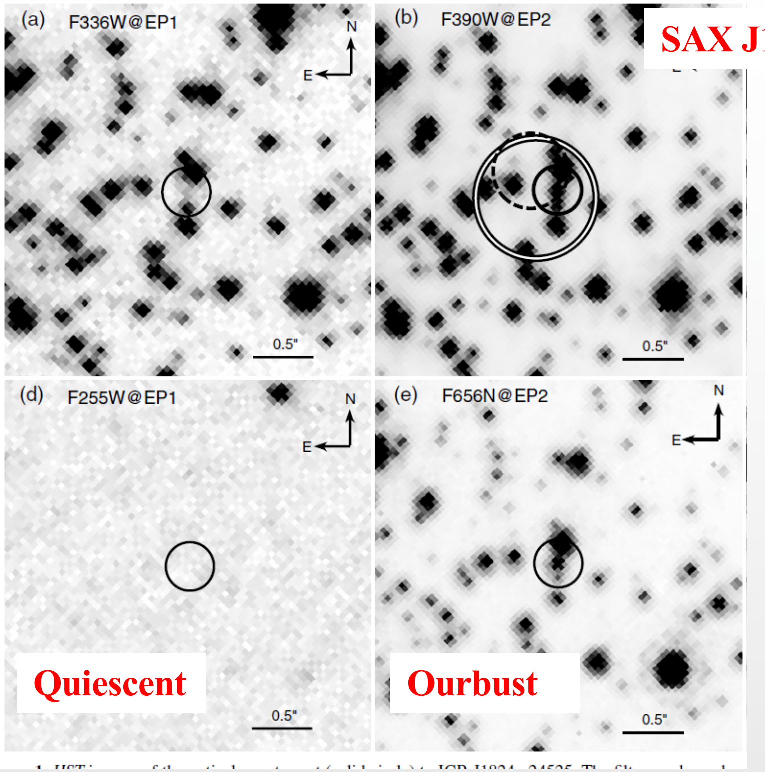
Misdiagnose the companion type?

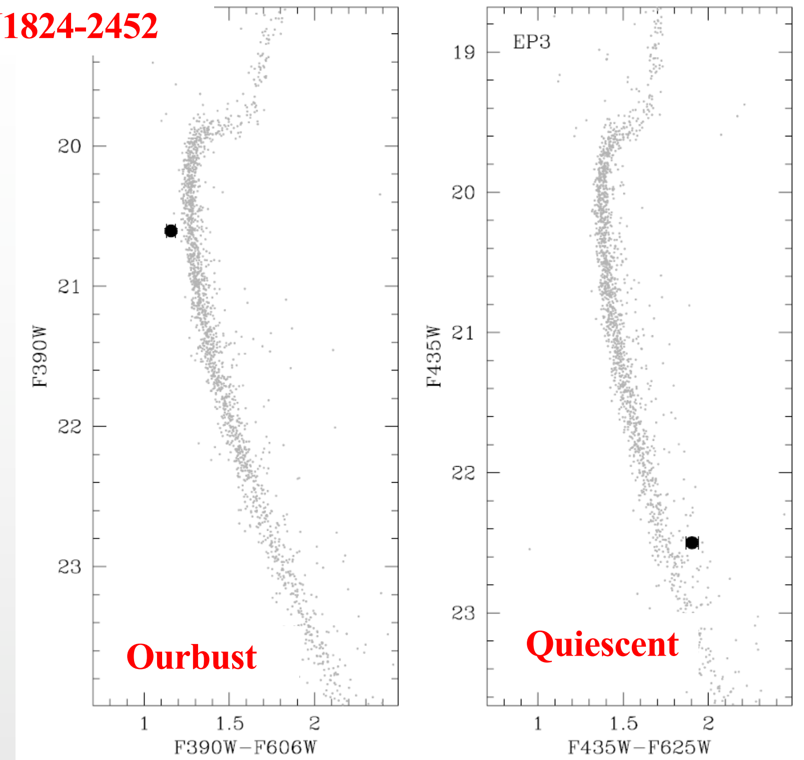


He et al., 2019

Optical counterpart

Thanks to HST

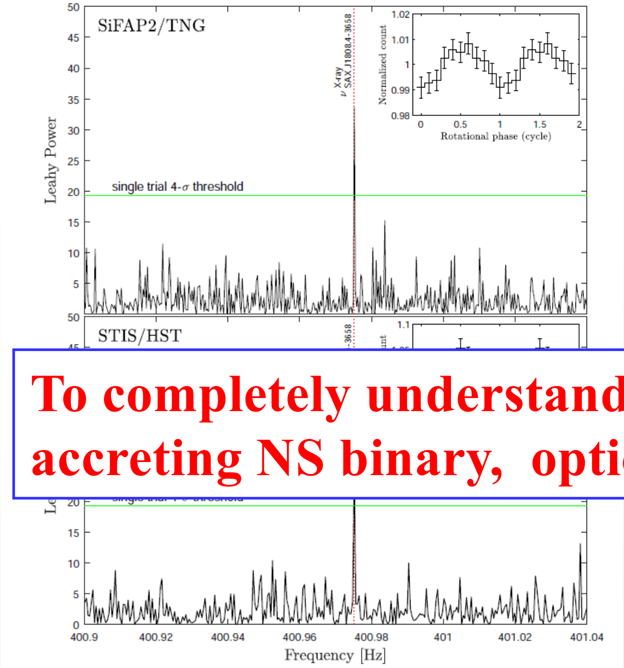


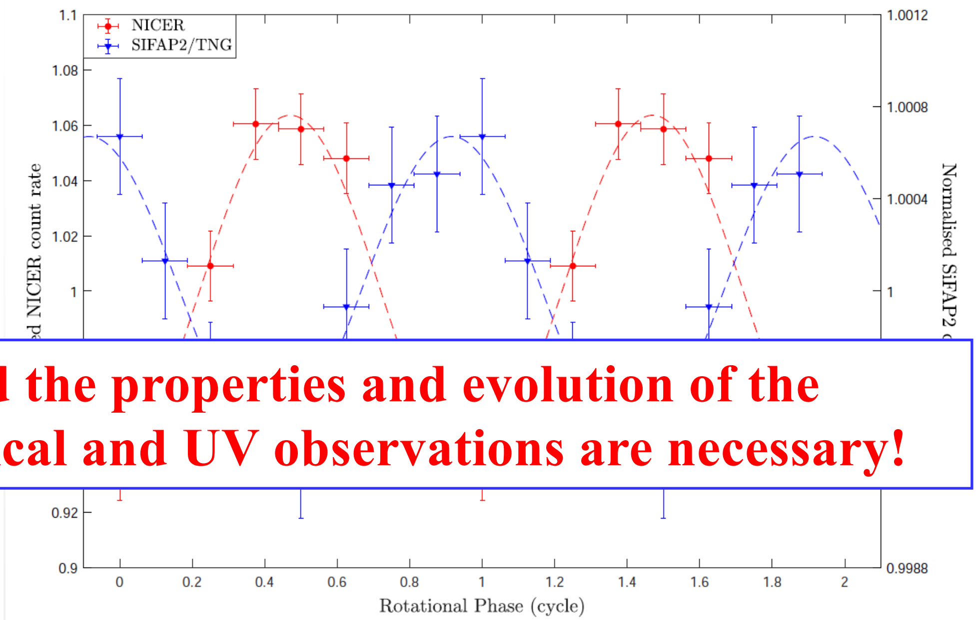


- Two magnitude increase from quiescence to outburst.
- The presence of Hα emission line indicate that accretion is taking place

Pallanca et al., 2013, ApJ

HST + ultra-fast photometer





To completely understand the properties and evolution of the accreting NS binary, optical and UV observations are necessary!

SAX J1808.4-3658 **PSR J1023+0038**

- **UV/optical pulsate with the same frequency of X-ray.**
- **an amplitude of 0.55% and 2.6% for optical and UV, respectively. 5.7% for X-ray.**
- **Anti-phase between X-ray and optical.**
- **Current accretion models fail to explain the luminosity of the pulsations.**
- **More likely driven by synchrocurvature radiation, implying that particle acceleration can take place during mass-accretion phase.**

Ambrosino et al., 2017, 2021, Nat. Ast

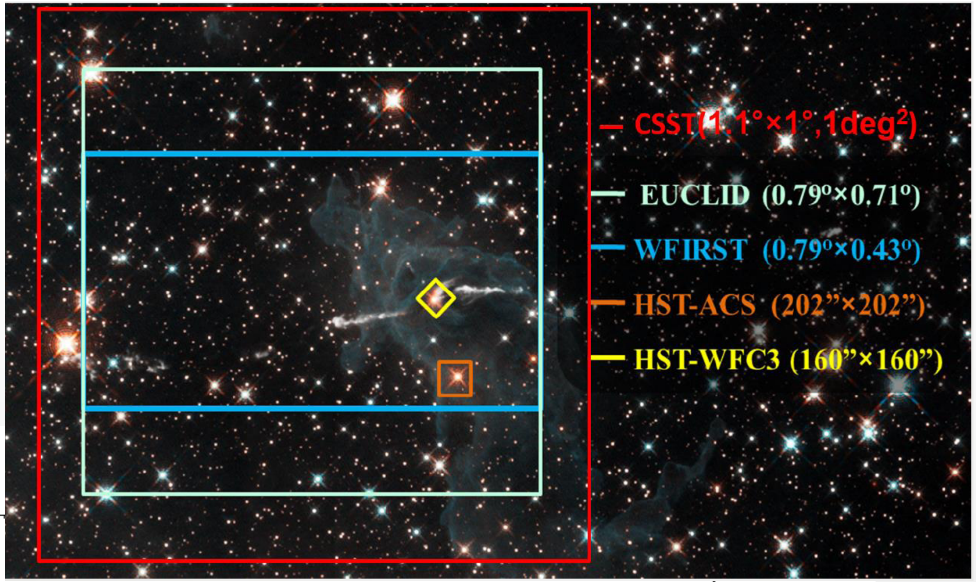
Open problems

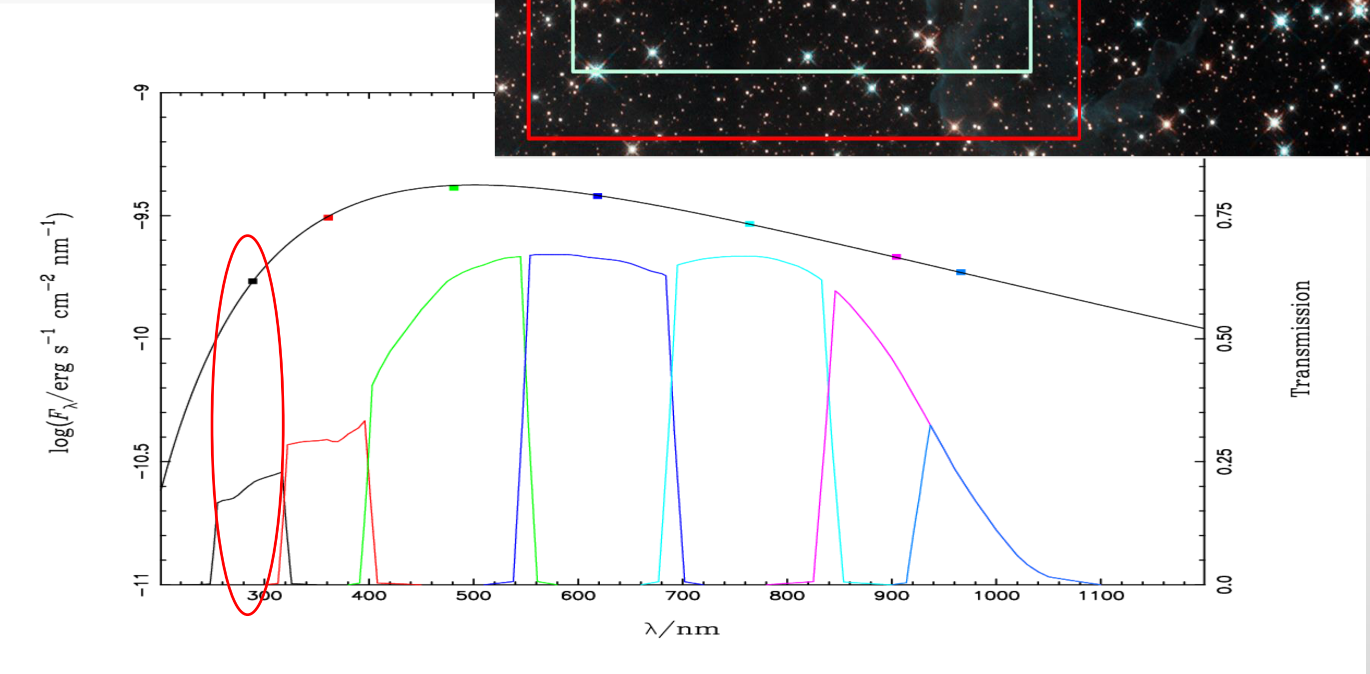
- The connection between LMXB and AMSP, or MSP. Must there be an AMXP phase between LMXB and radio MSP?
- Most of LMXBs are without pulsation.
- The lack of pulsed radio emission from AMXPs during quiescence. Are all AMXPs turning on as radio millisecond pulsars during quiescence ? And when and how?
- The mechanism for a TMSP swinging between rotation-powered and accretion-powered phases and their number (too rare).
- The relation between UCXB(TMSP) and BW, RB.
- Angular momentum loss mechanism
- The mechanism for optical/UV pulsation.
- Magnetic filed evolution.

To Build a complete sample!

CSST

- Wide
- Deep
- Multicolor



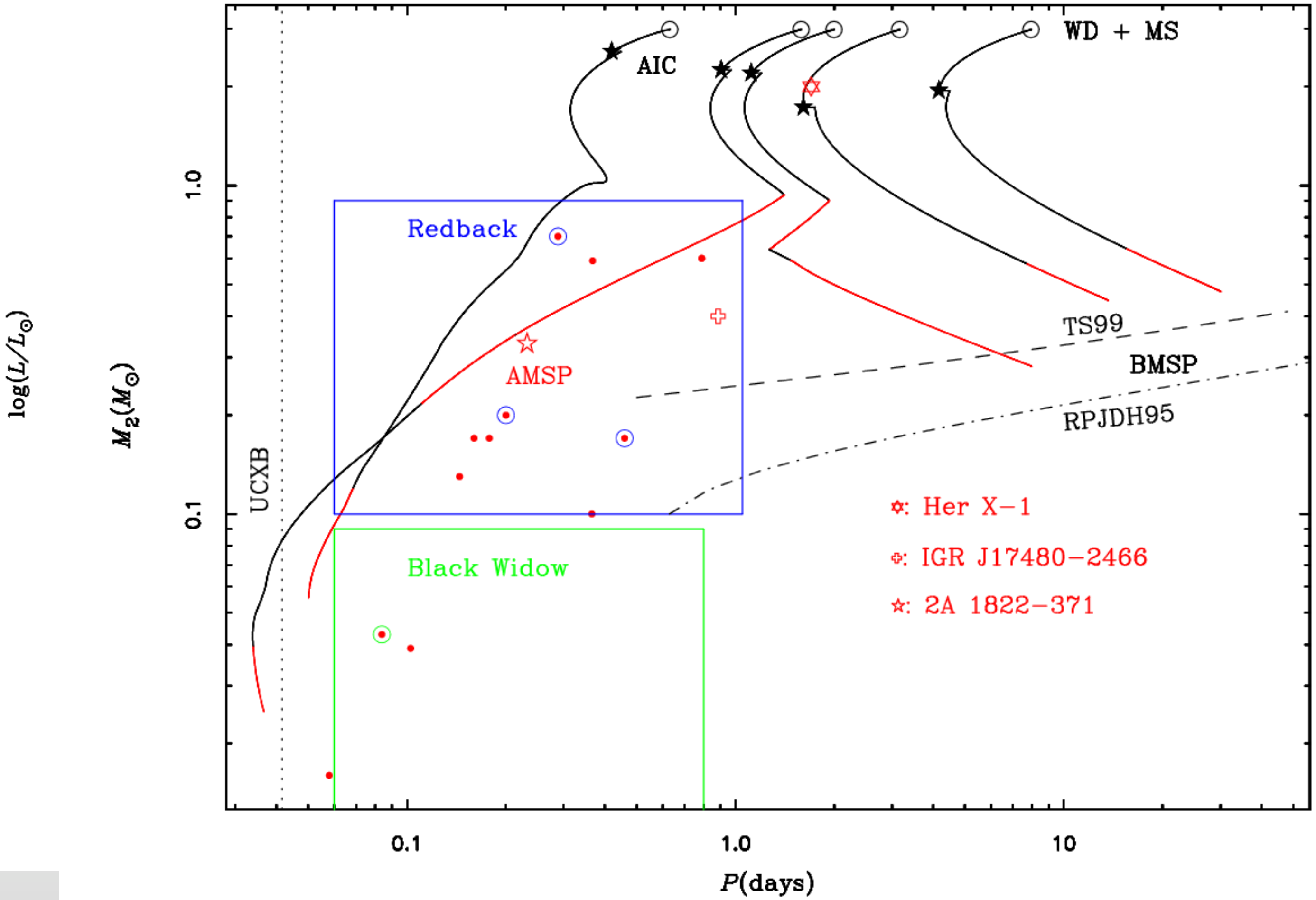


Aim

- Search for the potential candidate of accreting NS binary and try to build a complete sample.

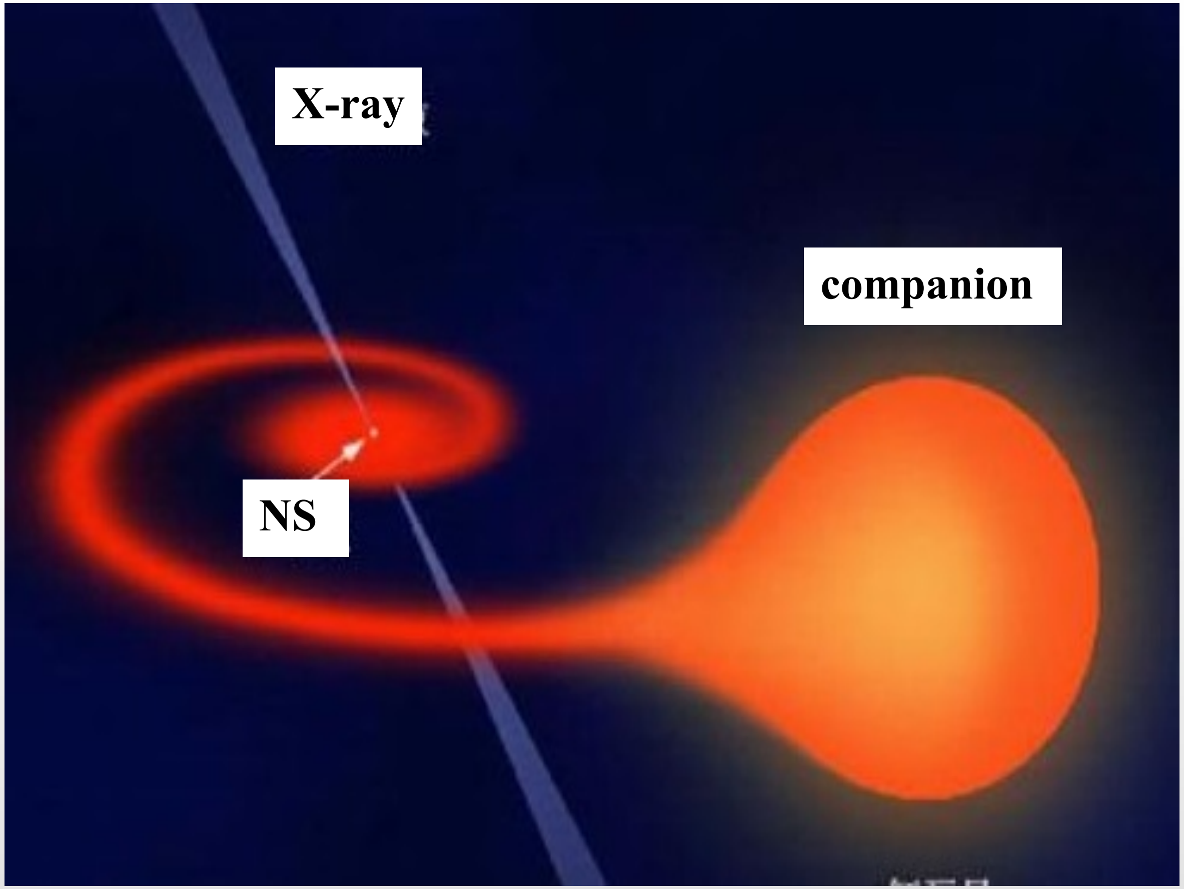
- Try to separate the companion and to obtain the properties of companion.

Two types

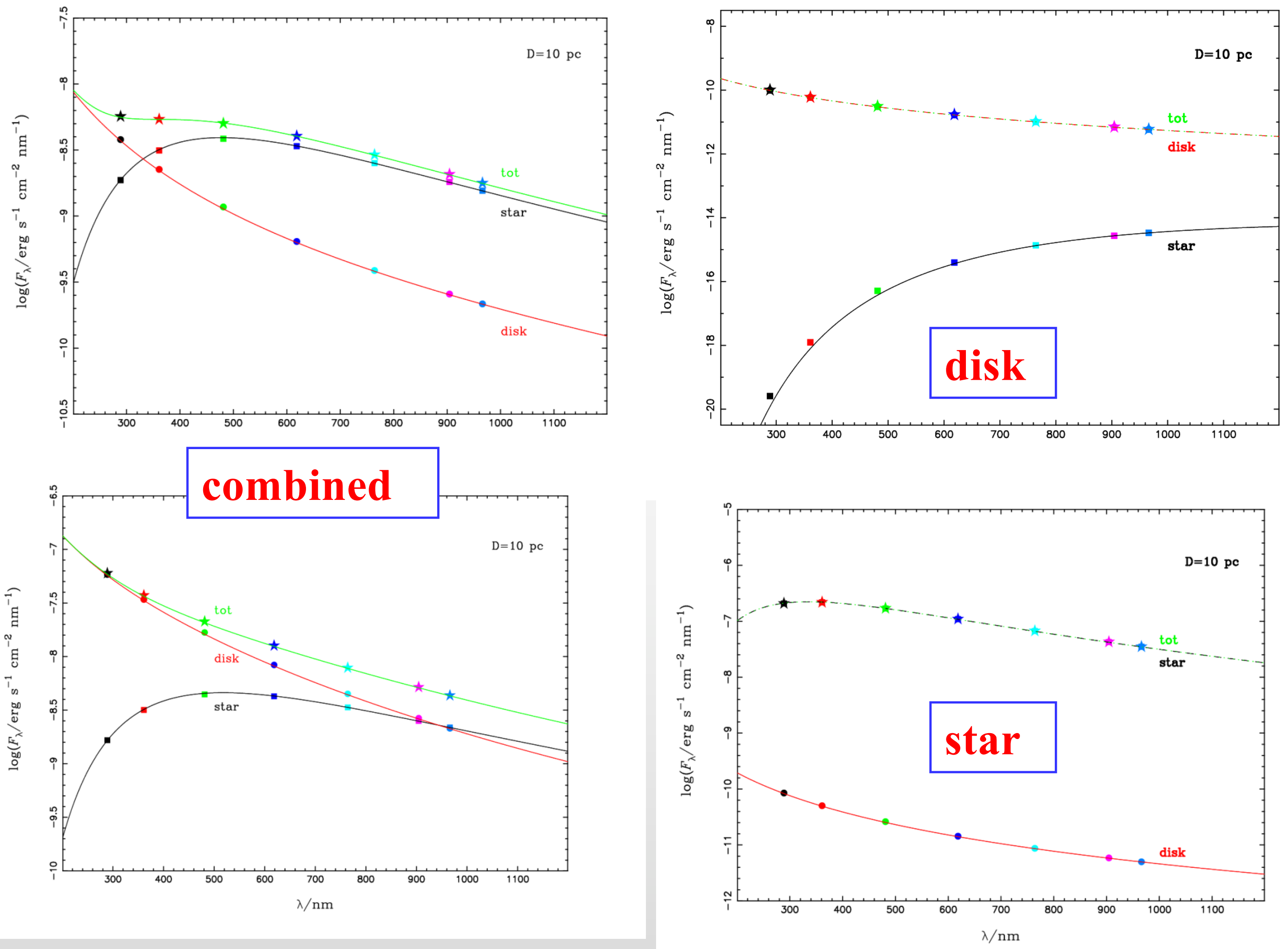


log$(L/L_\odot)$
$M_2(M_\odot)$
WD + MS
AIC
Redback
AMSP
TS99
BMSP
RPJDH95
UCXB
Black Widow
Her X−1
IGR J17480−2466
2A 1822−371
1.0
0.1
10
P(days)

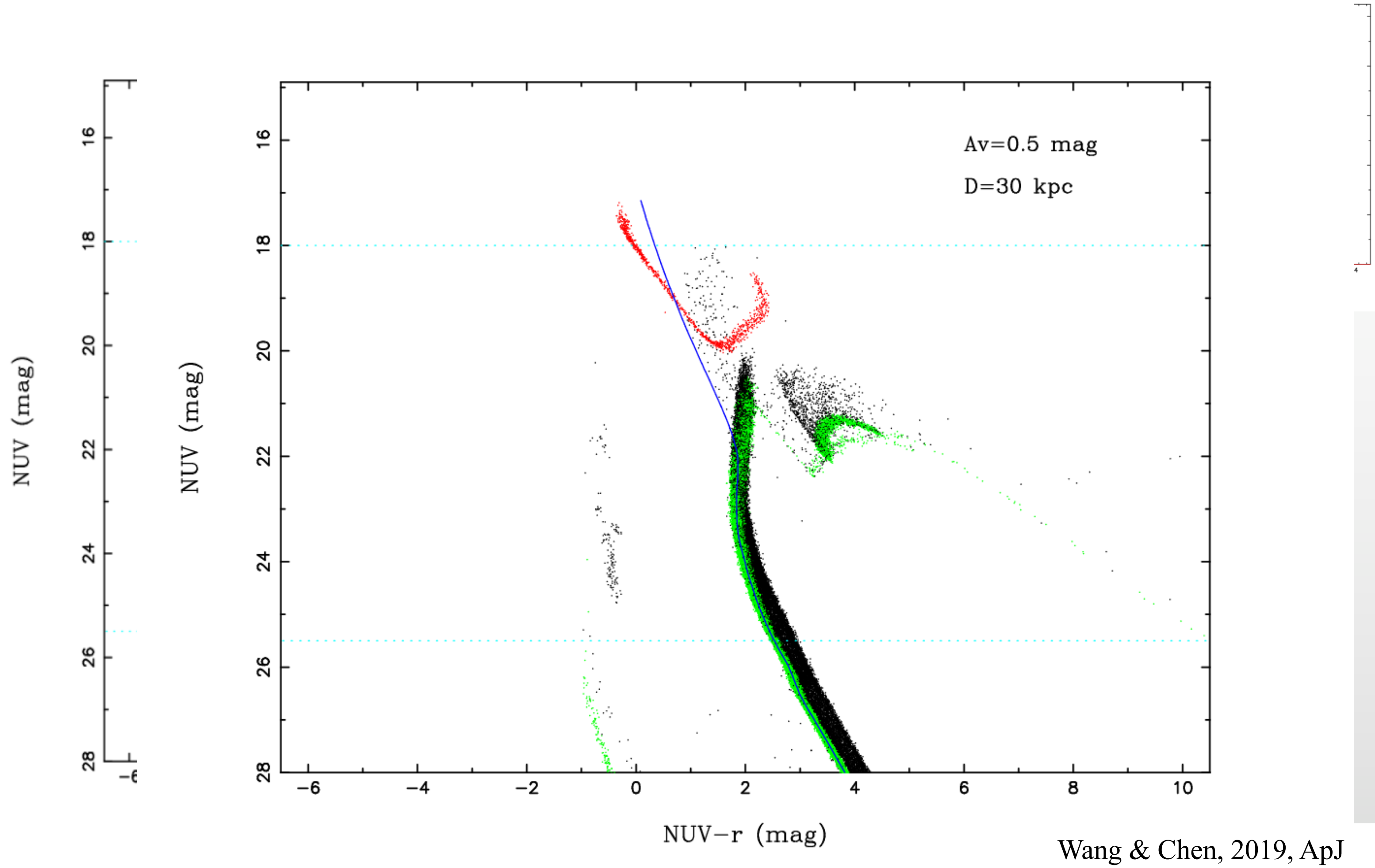
Multicolor disk + Companion



Shakura & Sunyaev, 1973, A&A; Mitsuda et al., 1984, PASJ

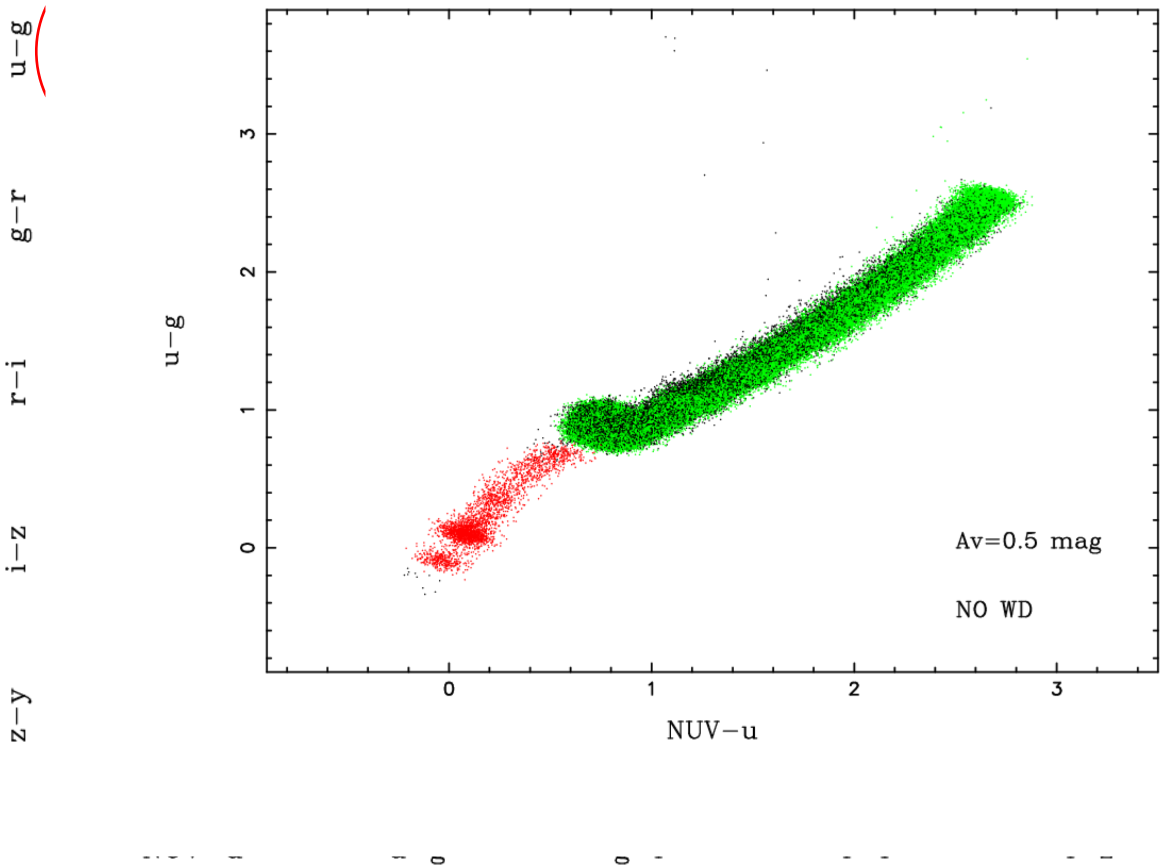

D=10 pc
tot
star
disk
log(F_λ/erg s^{-1} cm^{-2} nm^{-1})
D=10 pc
tot
disk
star
disk
combined
D=10 pc
tot
disk
star
λ/nm
D=10 pc
tot
star
star
disk
λ/nm

BS, sdB+MS, WD+MS



M31

Wang & Chen, 2019, ApJ



u−g
g−r
r−i
i−z
z−y
u−g
NUV−u
Av=0.5 mag
NO WD

predict

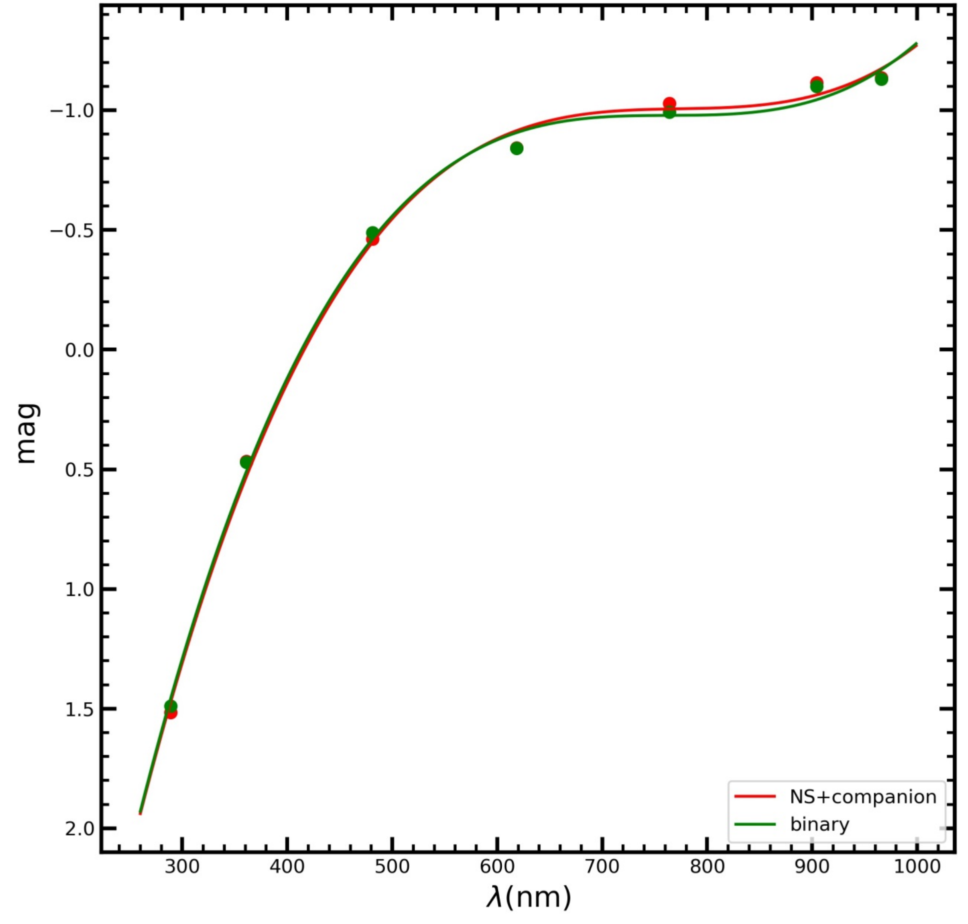
accuracy rate：>97%

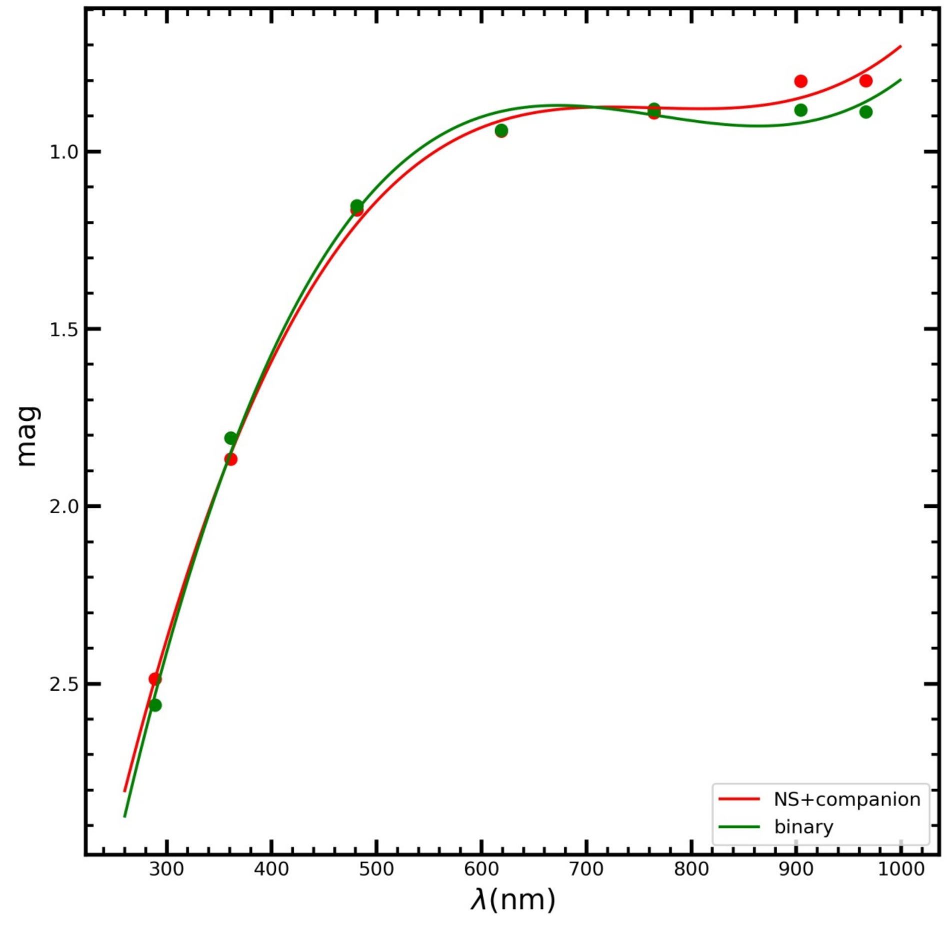
true

	Star	ANSB
star	1309447	502
ANSB	815	29011

Disk dimmer	Disk brighter
MS(>0.7)+MS(<0.7) (0.882%) MS(>0.7)+MS(>0.7) (7.76%) HG+MS(>0.7) (24.88%) GB+MS(>0.7) (5.29%) CHeB+MS(>0.7) (35.28%) CHeB+HG (2.998%) HeWD+MS(>0.7) (6.527%) COWD+MS(>0.7) (10.76%) COWD+HG (5.645%)	MS(>0.7)+MS(>0.7) (0.81%) HeMS+MS(>0.7) (29.44%) HeMS+HeMS (6.855%) HeHG+MS(>0.7) (59.7%) ONeWD+HeMS (3.227%)

Disk dimmer





NS+companion：1.3113$M_\odot$+0.3866 $M_\odot$
Binary: 2.8593 $M_\odot$+2.4476 $M_\odot$ → CHeB+MS(>0.7 $M_\odot$)

NS+companion：1.5128$M_\odot$+0.294 $M_\odot$
Binary: 2.1113 $M_\odot$+1.1774 $M_\odot$ → HG+MS(>0.7 $M_\odot$)

Summary

- Accreting NS binary systems look similar to BS, WD + Dwarfs and sdB + Dwarf.
- If WDs may be excluded by CMD, we may select the candidate by double color diagram.
- Machine learning may effectively identify the Accreting NS binary.

Thanks for your attention!