



大视场时域天文学前沿

报告人：王晓锋

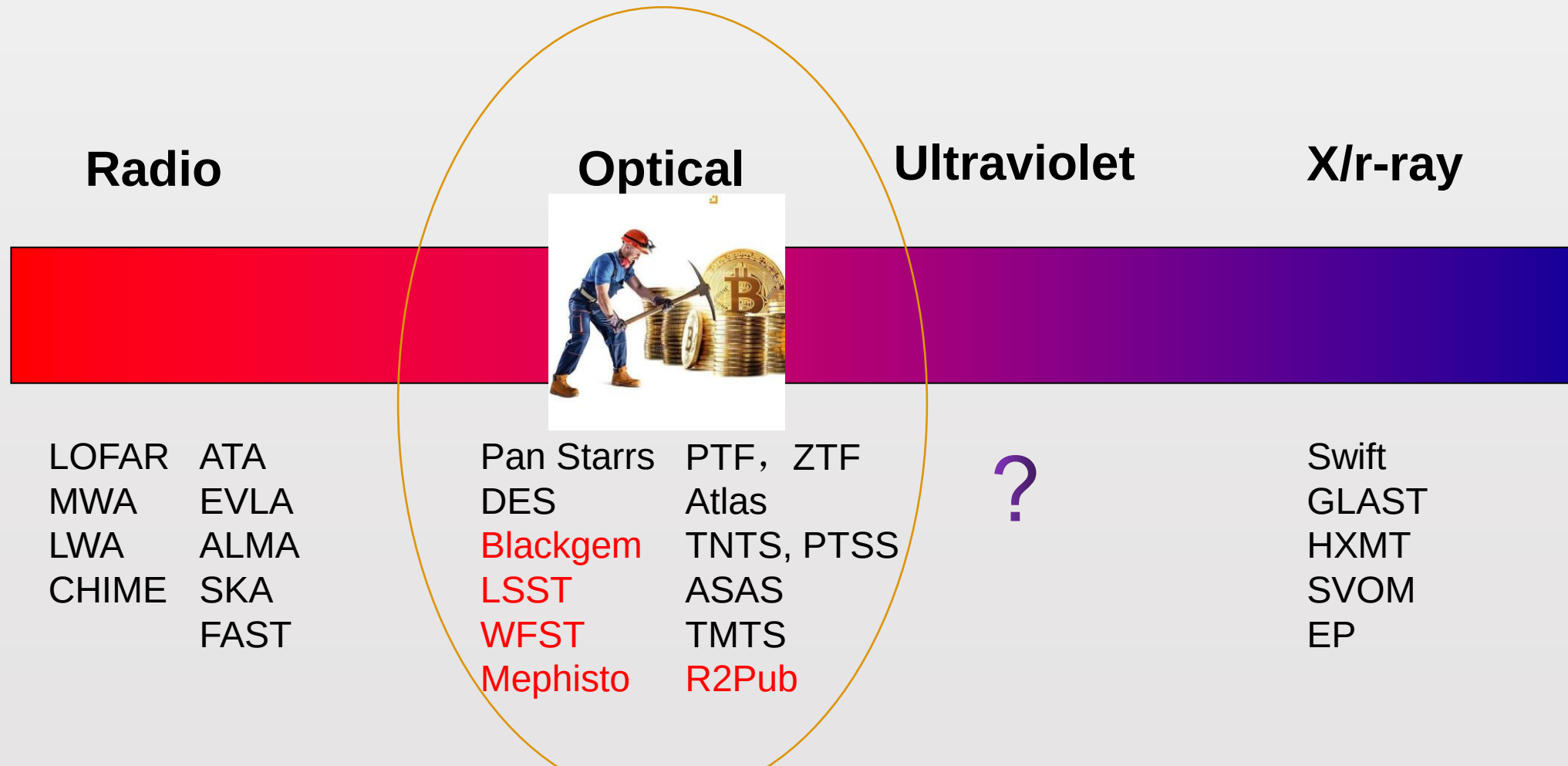
紫金山天文台，2021，10，13

Outlines

- Background
- Impact of Wide-field Surveys Time-domain Astronomy
- Minute-cadence Wide-field Surveys

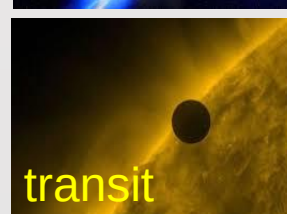
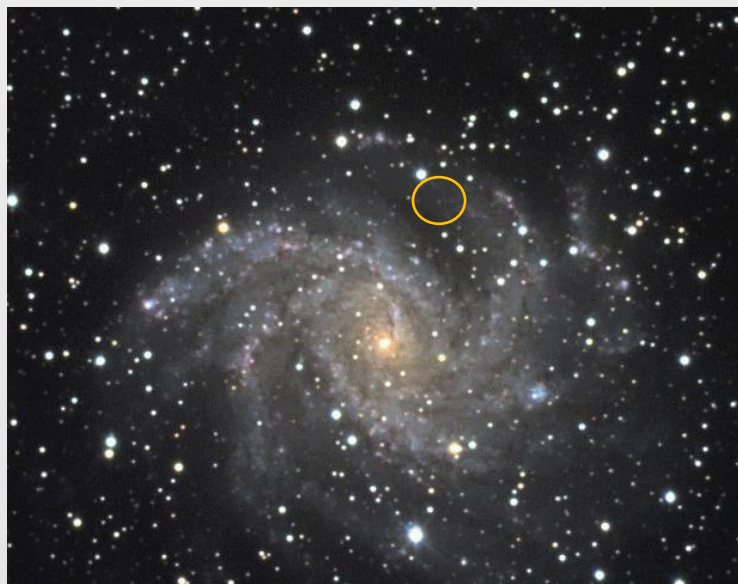
Time-domain Astronomy

Golden Mine of Astronomy



时域天文学主要研究对象

- 超新星, 新星, 耀星
- 伽马射线暴, 快速射电暴, 引力波电磁对应体
- 黑洞潮汐瓦解, 活动星系核
- 掩食双星, 行星凌日, 小行星

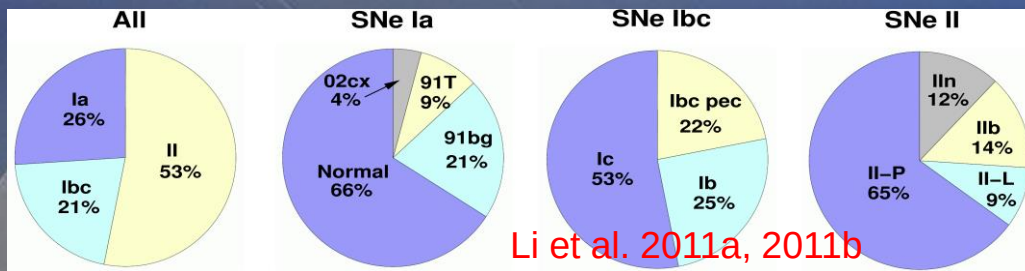
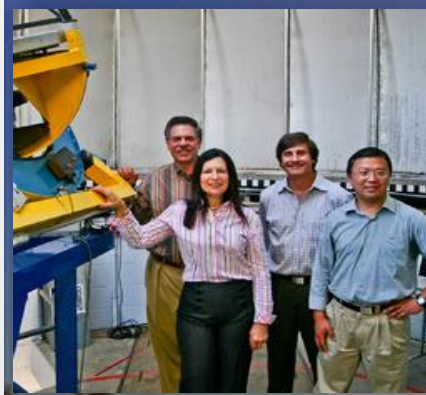


与恒星演化、宇宙学、致密天体、黑洞演化、系外星系等密切相关

Outlines

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窄视场巡天：Katzman Automatic Imaging Telescope



Li et al. 2011a, 2011b

The KAIT SN Search at Lick Obs.

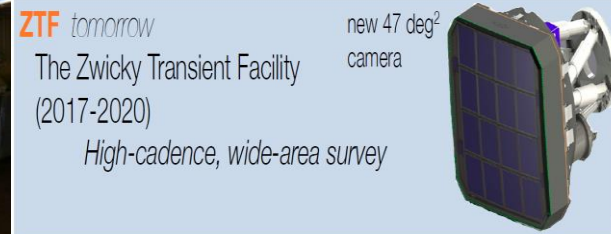
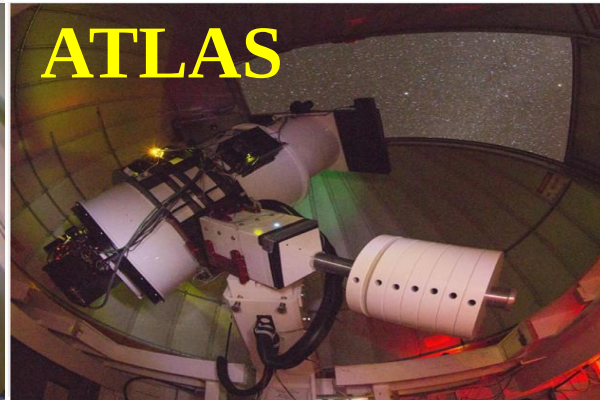
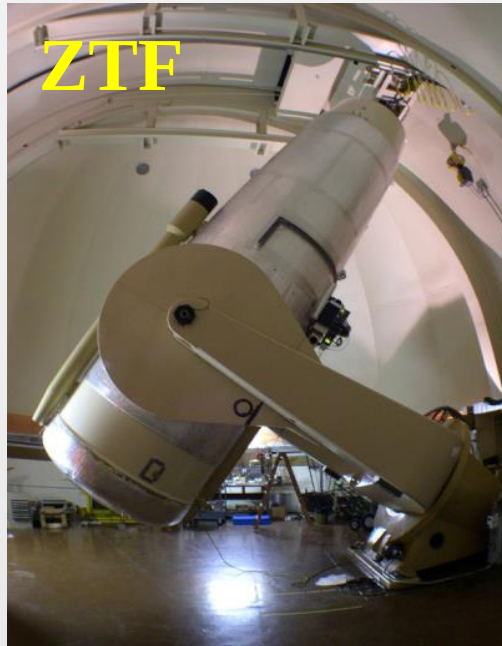
- 1997: 1 (SN 1997bs)
- 1998: 20 (world record)
- 1999: 40 (world record)
- 2000: 38 (including SN 2000A)
- 2001: 68 (world record; SN 2001A)
- 2002: 82 (world record)
- 2003: 95 (world record)
- 2004: 83 2005: 82 2006: 84
- 2007: 69 2008: 77 2009: 58

<http://astro.berkeley.edu/~bait/kait.html>



(Laurie Hatch)

Ground-based Wide-field Survey Projects



Parameters of Ground-based Survey Projects

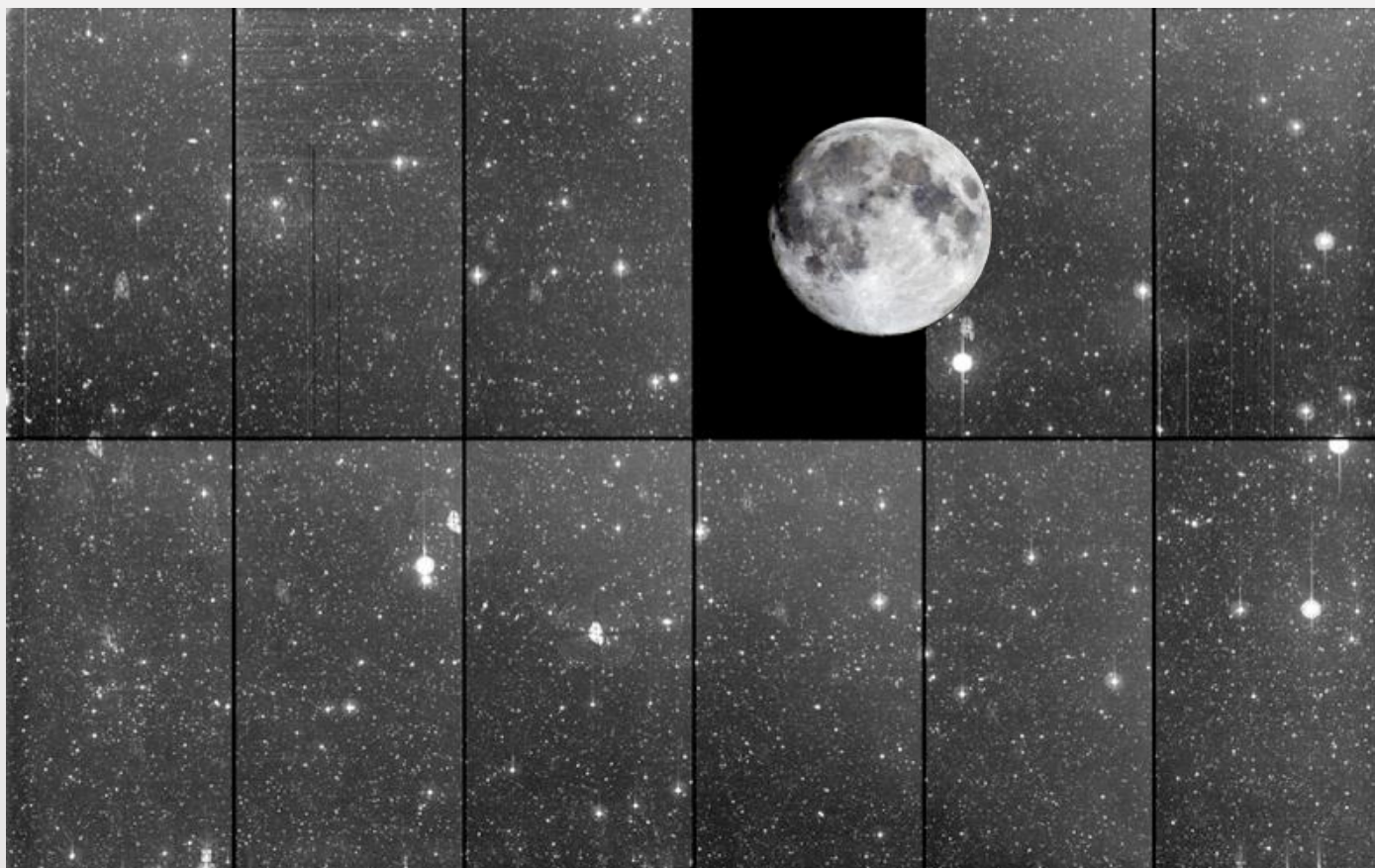
Ground-based Optical Transient Surveys Relevant with Supernova Search Around the World

Surveys	Telescope (m)	FoV (deg ²)	Mag. Limit.	Survey Area	Cadence	Status
LOSS	0.76	0.012	W ~ 19.0	5000 nearby galaxies	3 ~ 5 days	Since 1997
DLS	4.0	4.0	W ~ 24.0	High galactic latitude	Minutes ~ month	1999–2005
ESSENCE	4.0	0.36	W ~ 24.0	Equatorial area	4 days	2002–2008
SNLS	3.6	1.0	R ~ 24.3	1300 deg ²	3 days ~ 5 yr	2003–2008
ROTSE-III	0.45	3.42	W ~ 18.5	Entire sky	...	Since 2003
SDSS-II SN	2.5	1.5	g ~ 23.2	Southern stripe 82	2 days	2005–2008
CRTS(CSS)	0.7	8.1	V ~ 19.5	+70° ≥ decl. ≥ -30°	10 minutes ~ year	Since 2007
Pan-STARRS1 3π	1.8	7.0	g ~ 23.3	decl. ≥ -30°	7 days	Since 2009
SkyMapper	1.35	5.7	g ~ 21.2	Entire southern sky	Hours ~ years	Since 2009
PTF	1.2	7.9	R ~ 21.0	decl. ≥ -30°	1 minute ~ 5 days	2009–2012
LSQ	1.0	9.6	V ~ 20.5	+25° ≥ decl. ≥ -25°	Hours ~ days	2009–2015
KISS	1.05	4.6	g ~ 20.0–21.0	SDSS fields with high SFR	~1 hr	Since 2012
ASAS-SN	24 × 0.14	4 × 20.25	g ~ 18.0	Entire sky	1 day	Since 2013
iPTF	1.2	7.3	g ~ 21.0	decl. ≥ -30°	90 s ~ 5 days	2013–2017
DES	4.0	3.0	i ~ 24.0	The South Galactic Cap	~7 days	2013–2019
Evryscope	2 × 27 × 0.061	8600 + 8150	g ~ 16.0	Entire sky	2 minutes ~ hours	Since 2015
ATLAS	2 × 0.5	2 × 30	g ~ 19.5	+90° ≥ decl. ≥ -45°	1 ~ 2 days	Since 2015
DLT40	0.41	0.027	r ~ 19.0	Nearby galaxies ≤ 40 Mpc	1 day	Since 2016
ZTF	1.2	47.0	R ~ 20.7	decl. ≥ -30°	3750 deg ² hr ⁻¹	Since 2017
LSST	8.4	9.6	R ~ 24.5	Entire southern sky	1 minute ~ 10 yr	Future
TNTS	0.6	2.3	V ~ 19.5	+60° ≥ decl. ≥ 0°	3 ~ 4 days	Since 2012
PTSS	1.04	9.0	V ~ 20.5	decl. ≥ -30°	3 ~ 5 days	Since 2016
TMTS	4 × 0.4	4 × 4.5	W ~ 19.4	+70° ≥ decl. ≥ 10°	10 s ~ 1 day	Since 2019

Zhang, Wang, et al. 2020, PASP

Wide-field Transient Survey

极大提高了天文观测和发现的效率



PTF *yesterday*

The Palomar Transient Factory
(2009-2012)

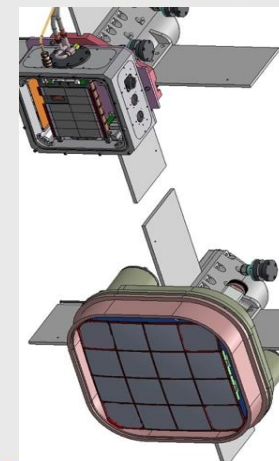
General synoptic transient survey

iPTF *today*

Intermediate Palomar Transient Factory
(2013-2016)

Focused mini-surveys

104+ papers, 3283+ citations

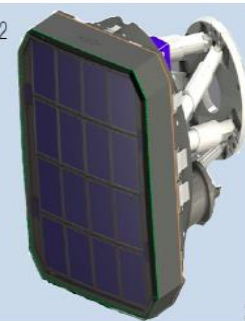


ZTF *tomorrow*

The Zwicky Transient Facility
(2017-2020)

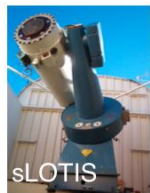
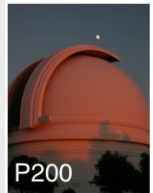
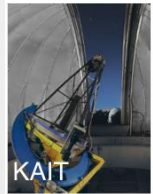
High-cadence, wide-area survey

new 47 deg²
camera



Followup facilities

▼► Detected transients will be followed up using a wide variety of optical and IR, photometric and spectroscopic followup facilities.



The power of Time-domain Sciences resides in its diverse science goals and follow-up facilities;

Accurate transient event classification is the key to their follow-up and physical understanding.

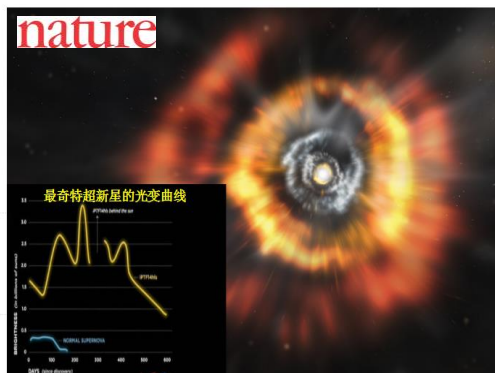
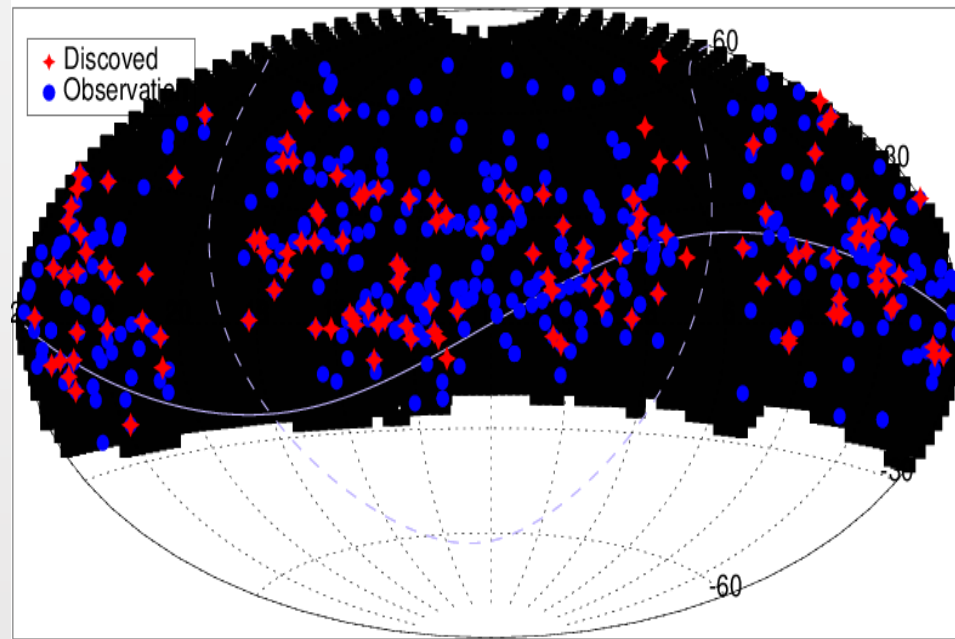
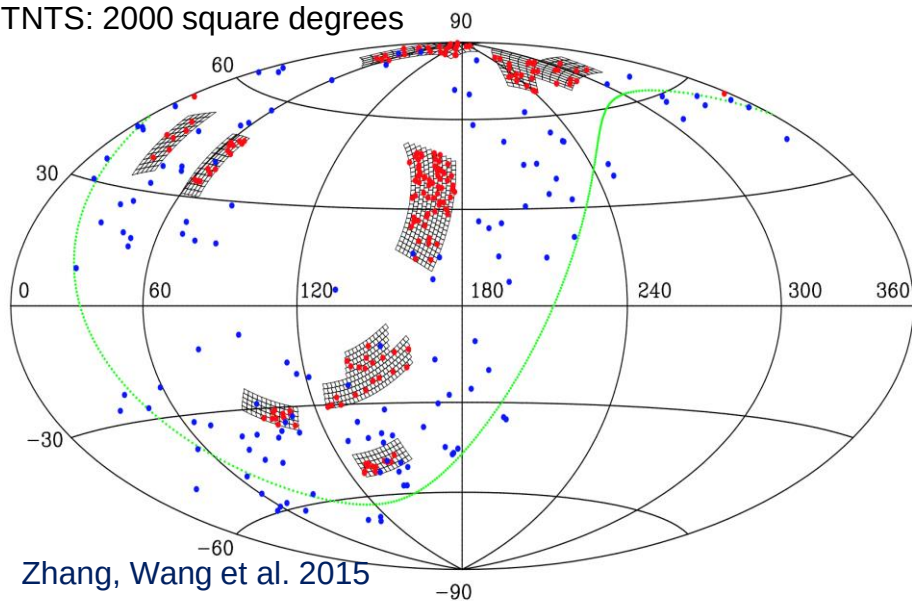
Key Projects

Various SNe	Dwarf novae
Transients in nearby galaxies	Core collapse SNe
RR Lyrae	Solar system objects
CVs	AGN
AM CVn	Blazars
Galactic dynamics	LIGO & Neutrino transients
Flare stars	Hostless transients
Nearby star kinematics	Orphan GRB afterglows
Rotation in clusters	Eclipsing stars and planets
Tidal Disruption Events	FBOT

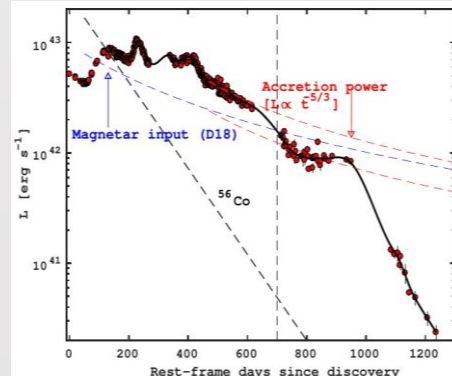
Nature: 2011a (SN Ia), 2011b(SN Ia), 2013, 2014 (IIb), 2015 (Ia), 2017 (Luminous SN II), 2019 (double WDs), 2021 (SN Icn), 2021 (WD);
Science: 2012 (Ia), 2018

Supernovae discovered by TNTS & PTSS (N>400)

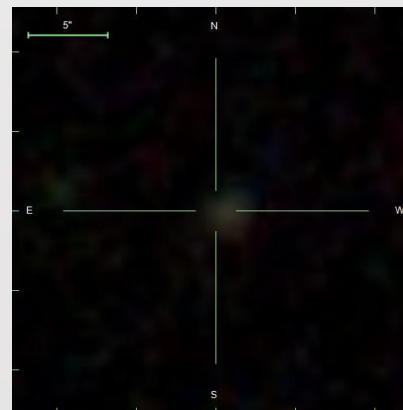
TNTS: 2000 square degrees



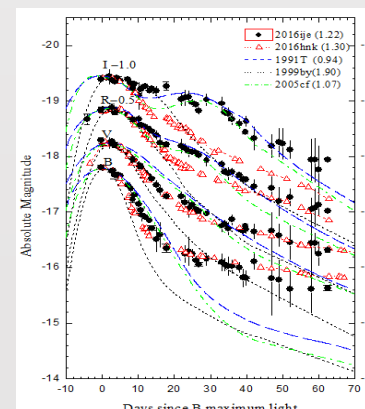
Acarvi et al. 2017



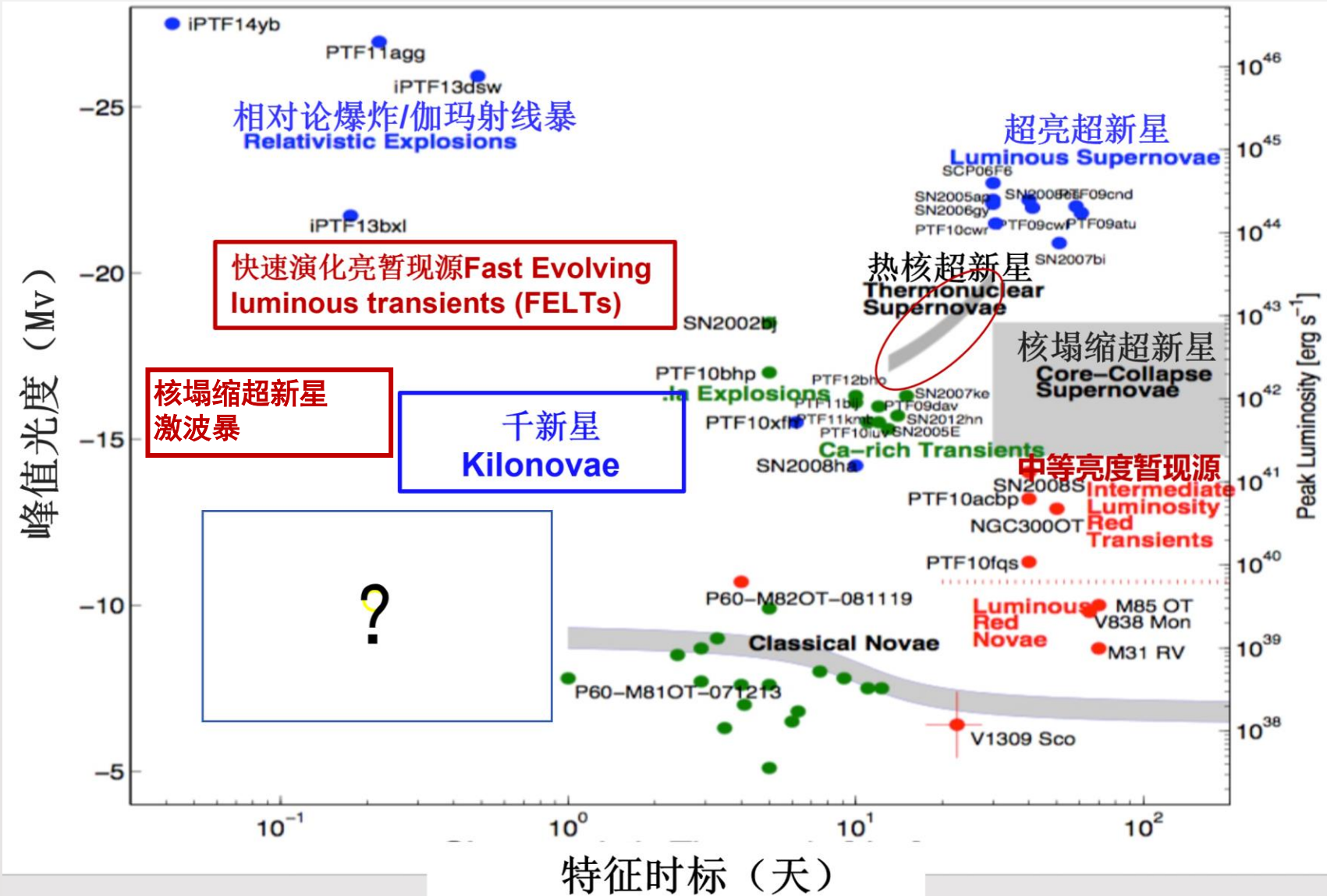
Sollerman et al. 2019



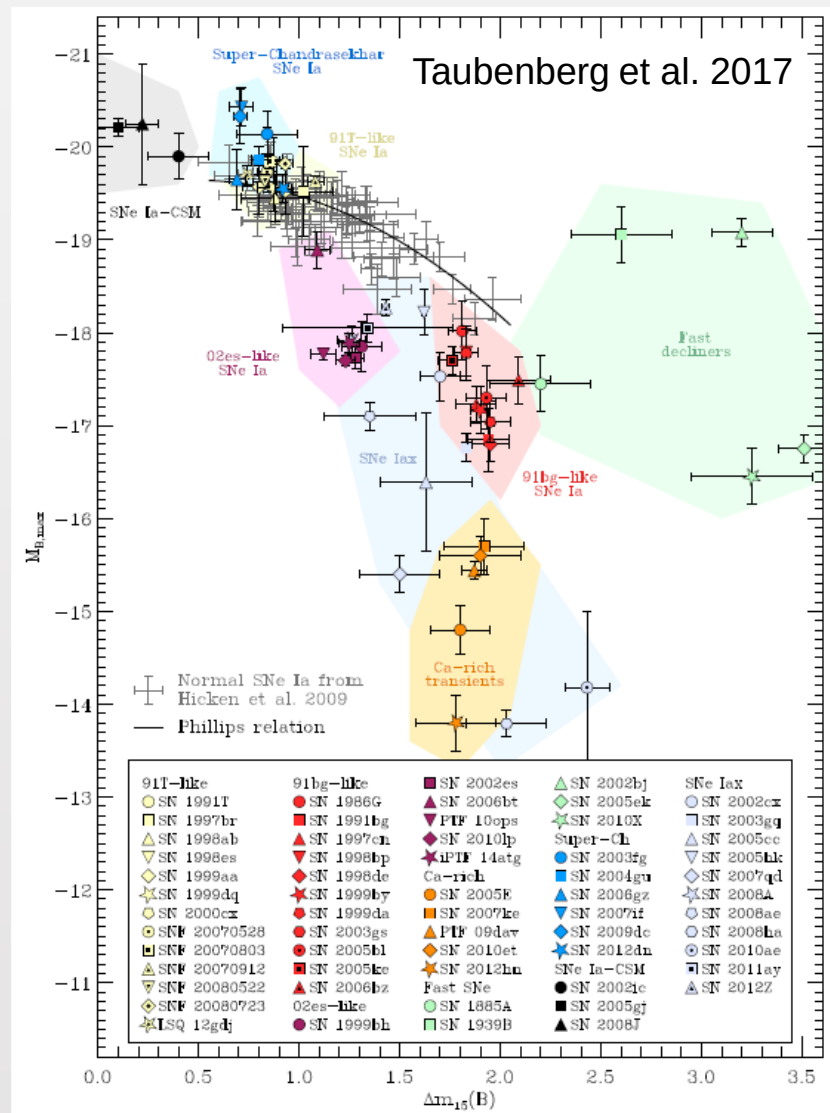
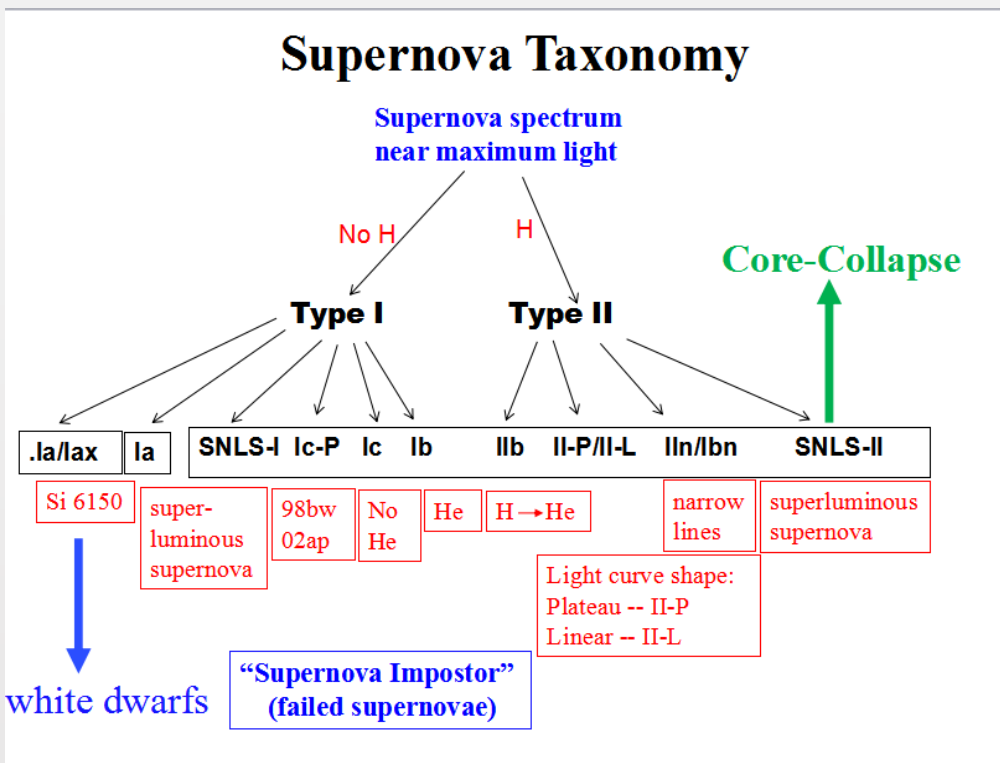
Wang et al. 2020



宽视场时域巡天发现引领恒星领域发展



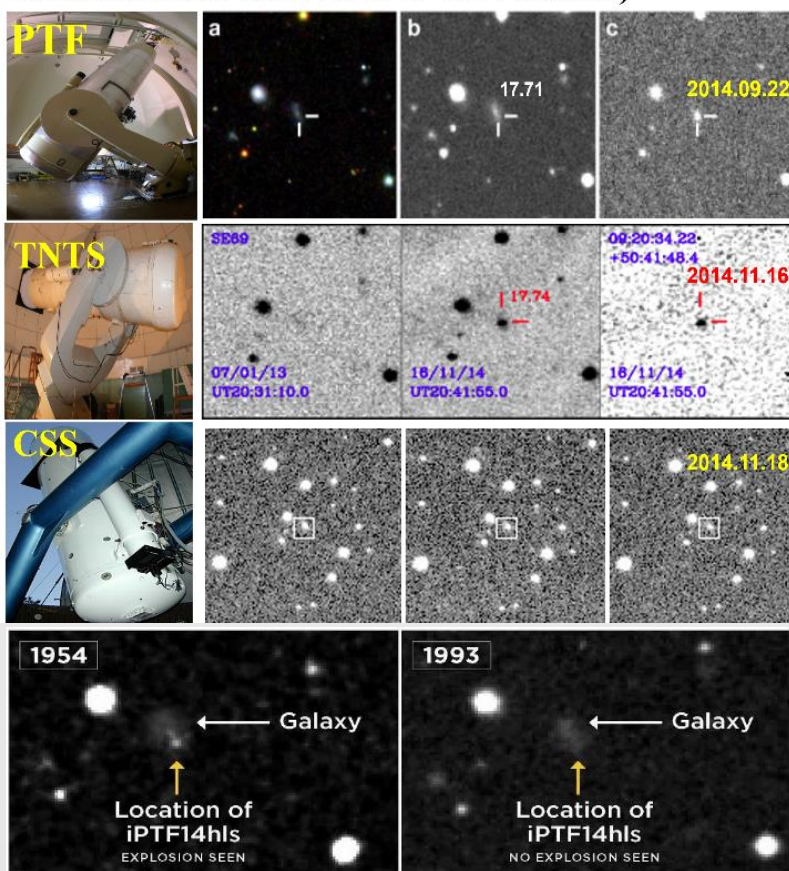
超新星：发现数量及种类大幅增加



超新星：发现最奇特恒星爆发

超大质量恒星的脉动爆发

CSS141118:092034+504148=SN 2016bse)



The Astronomer's Telegram

[Previous | Next | ADS]

Spectroscopic Classification of CSS141118:092034+504148 as a Type II-P Supernova

ATel #6898; Wenxiong Li, Xiaofeng Wang (Tsinghua University),
Yanneng Zhang (National Astronomical Observatories of China)
on 11 Jan 2015; 05:46 UT
Distributed as an Instant Email Notice Supernovae
Credential Certification: Xiaofeng Wang (wang_xf@mail.tsinghua.edu.cn)

Subjects: Optical, Supernovae, Transient

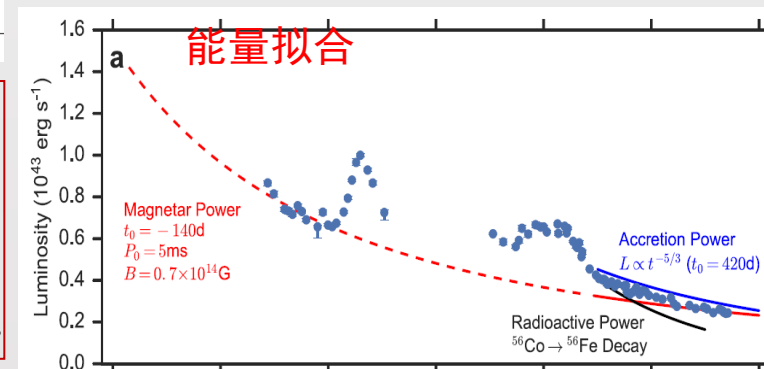
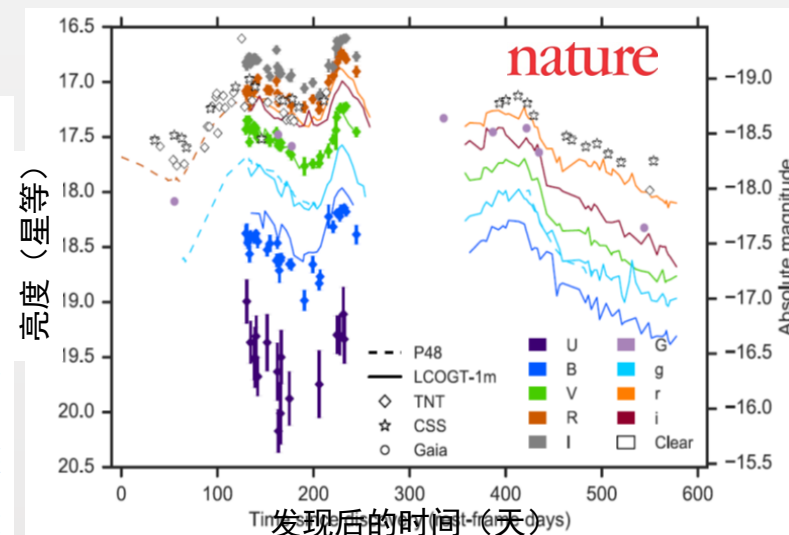
Tweet

We report an optical spectrogram (range 370-850 nm) of CSS141118:092034+504148 that was obtained on 2015 Jan.08.71 UT with the 2.16-m telescope (+BPOSC) at Xinglong Station of NAOC. The spectrum is similar to that of a type II-P supernovae over one month after explosion, with prominent P-Cygni profiles of Balmer lines. Cross-correlation with a library of supernova spectra using the comparison tool Gelato (Harutyunyan et al. 2008, A&A, 488, 383) shows that it matches with SN 2012A at $t=50$ days since explosion. Given a redshift of 0.028 for the host galaxy (from emission features of supernova lines), an expansion velocity of about 6300 km/s can be deduced from the H α absorption minimum.

wang_xf@mail.tsinghua.edu.cn

中方团组贡献：

独立发现，做出早期光谱性质证认，2016年初再次发现，确定独特光变性质，多色光变数据。



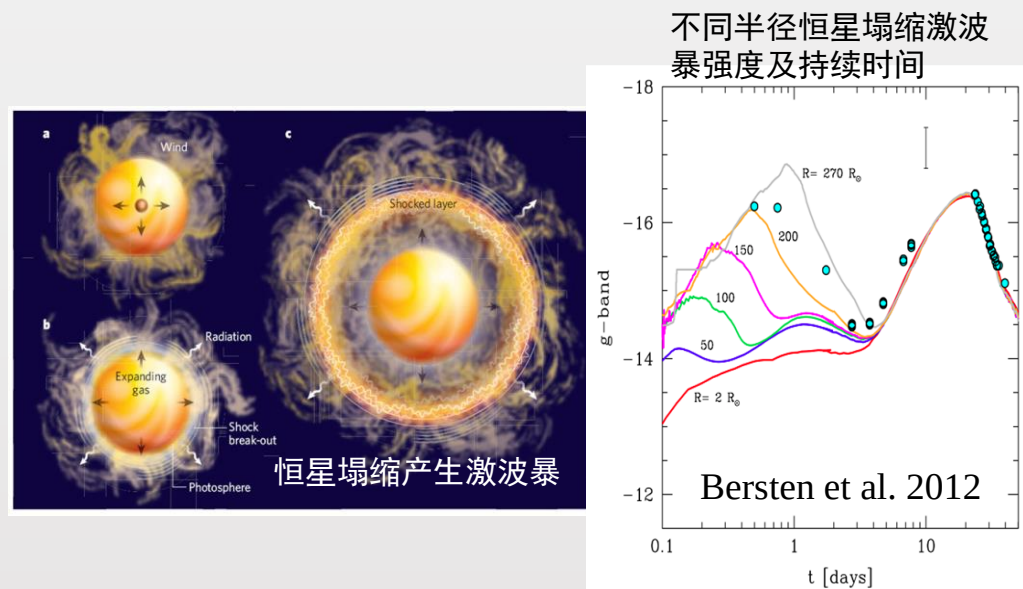
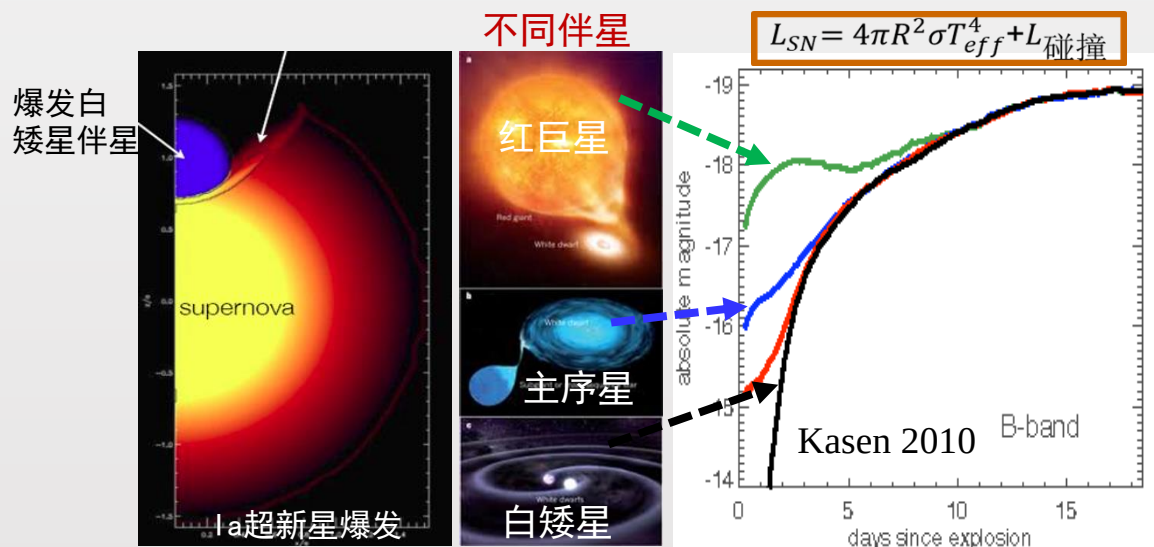
Arcavi+Wang group et al. 2017, *Nature*, 551,210

该项研究对现有超新星形成和演化理论及爆发机制提出挑战。

大视场：捕捉超新星爆发的第一缕光

科学问题：

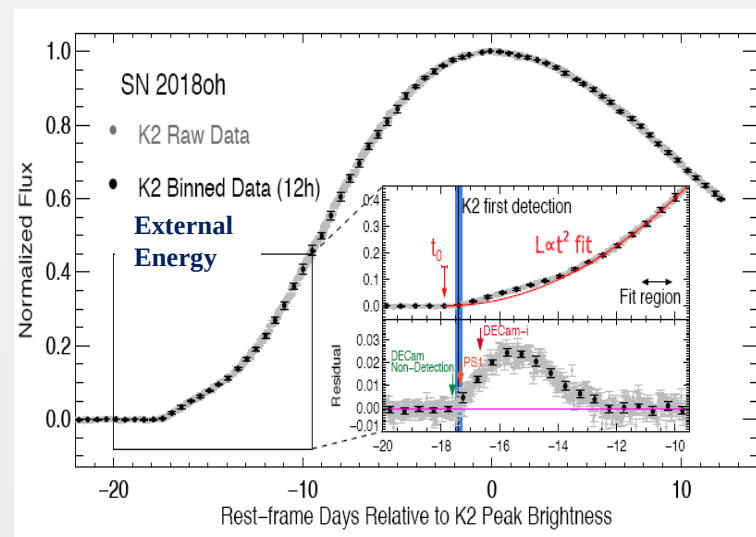
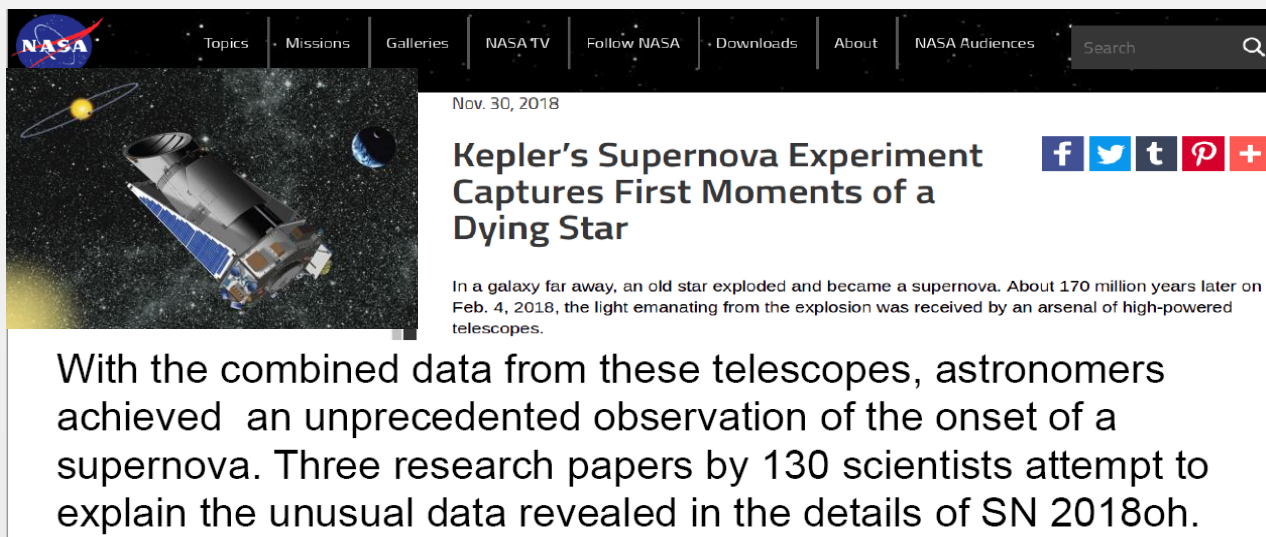
- 1) Ia型超新星前身星—Ia超新星是重要的宇宙学探针，但其前身星性质未知。
- 2) II/Ibc型超新星前身星—核塌缩超新星爆发早期会形成短时标激波暴，其持续时间可限制大质量星晚期演化。



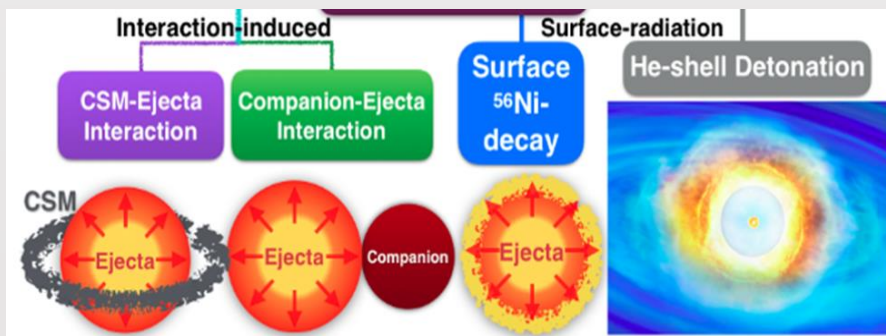
区分不同前身星模型：爆发白矮星的抛射物与伴星碰撞产生额外能量，强度与伴星大小相关。

激波暴探测：II/Ibc超新星爆发产生的激波暴强度与前身星的大小及周围星风性质密切相关。

捕捉超新星爆发的第一缕光

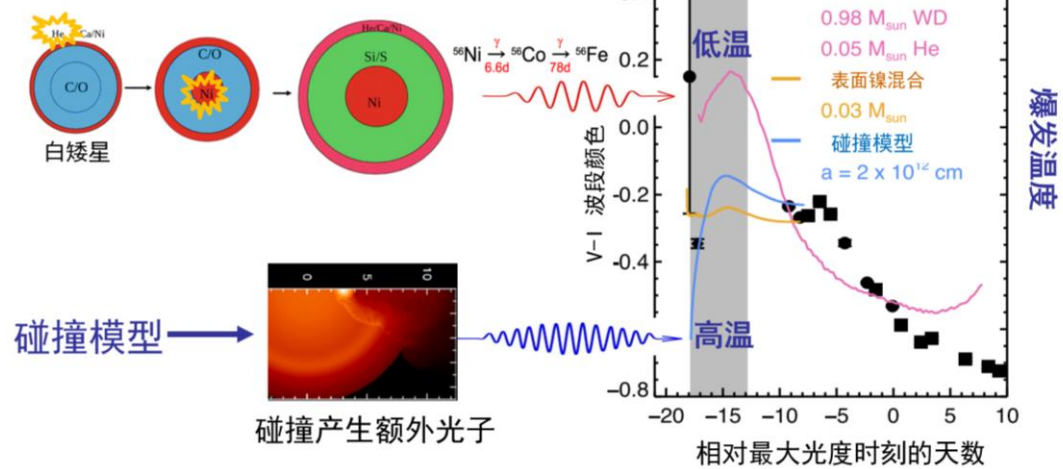


产生早期能量超的主要过程



Li et al. 2019

表面辐射模型：表面放射性元素衰变光子



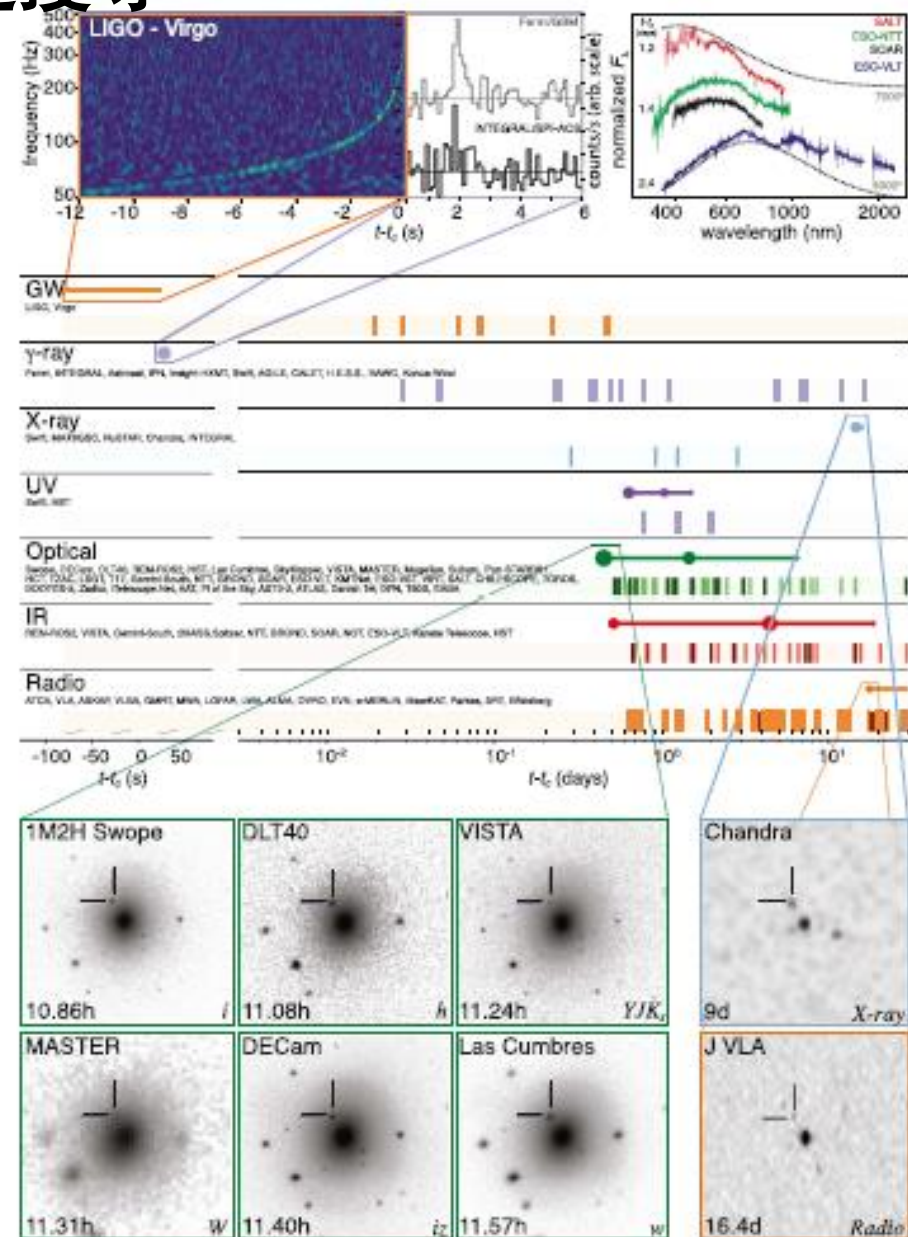
Dimitriadis et al. 2019

大视场：引力波电磁对应体快速搜寻

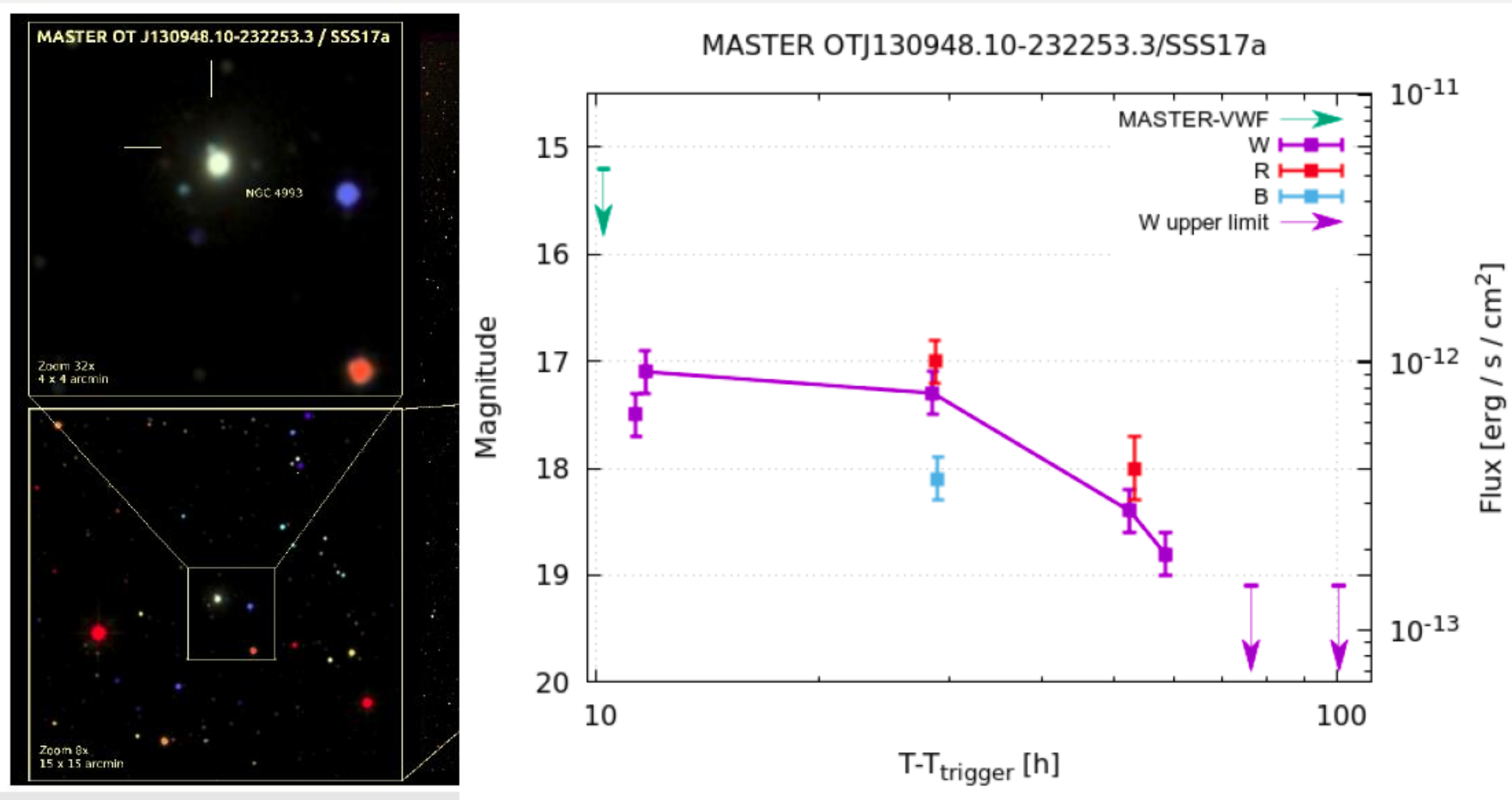
Master Survey



Lipunov et al. 2017 (including X. Wang)

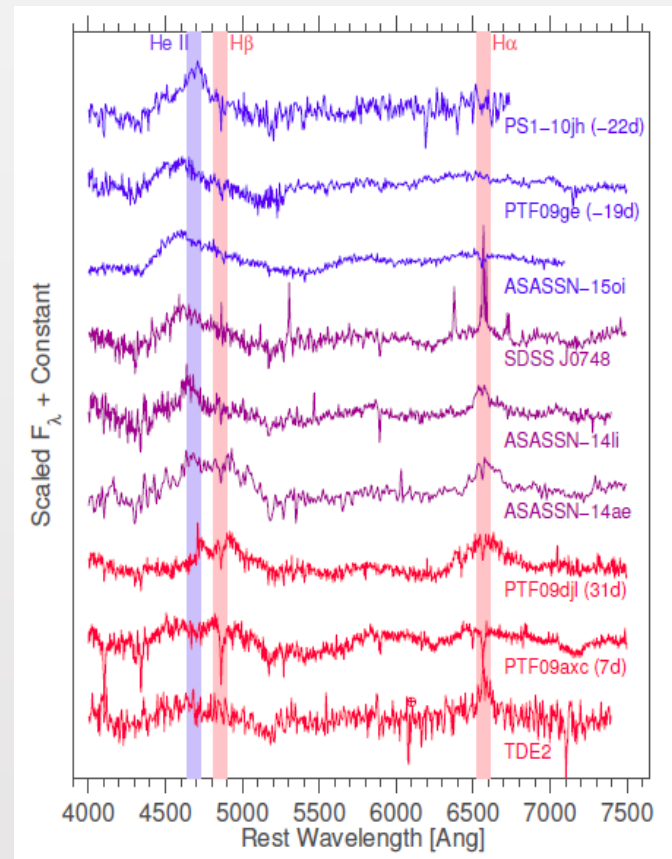
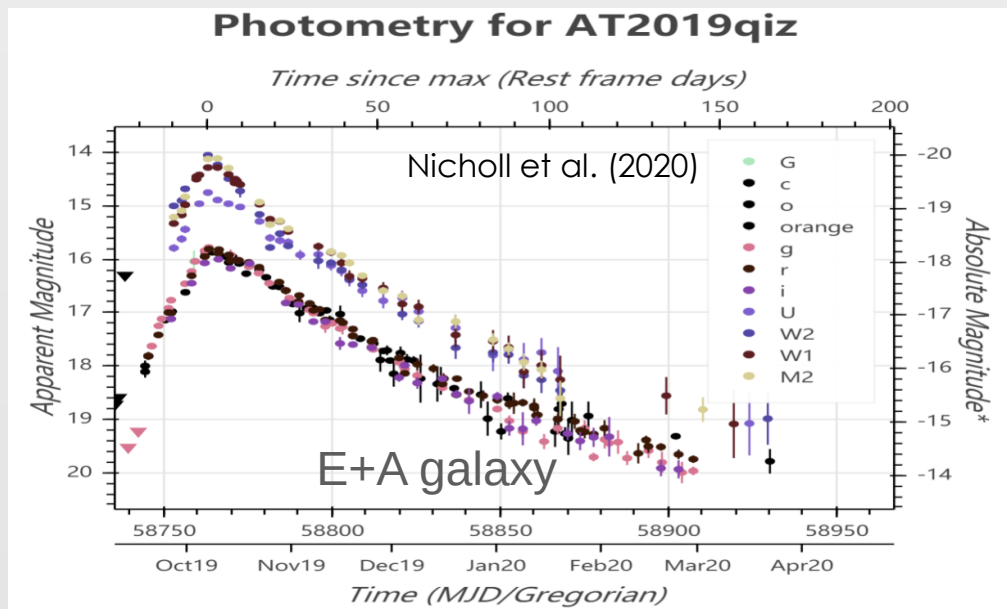


引力波电磁对应体搜寻



V.M. Lipunov et al. (including X. Wang), 2017, ApJL, 850, L1

黑洞潮汐瓦解事件的探测

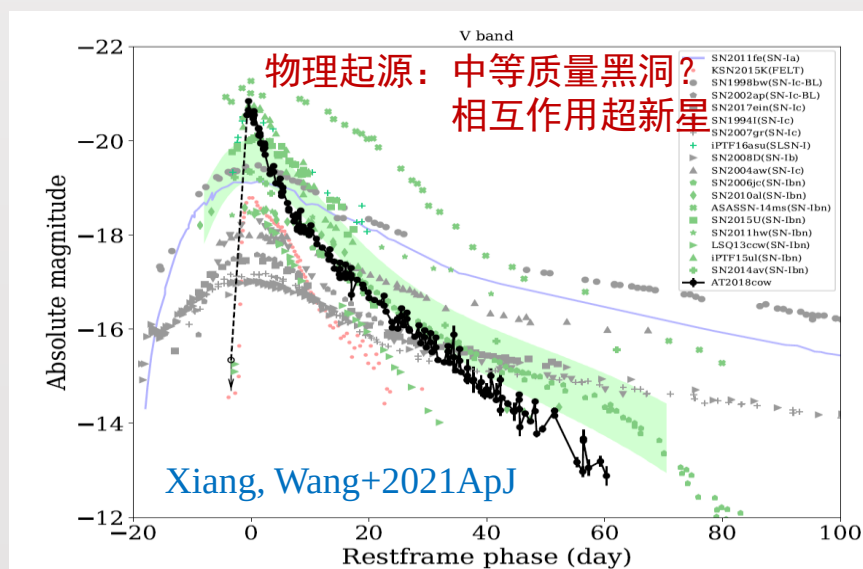
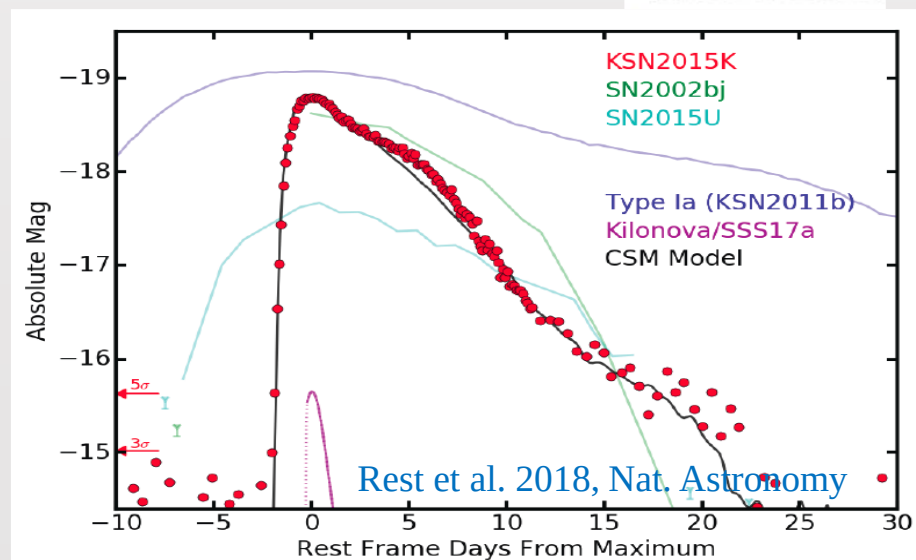
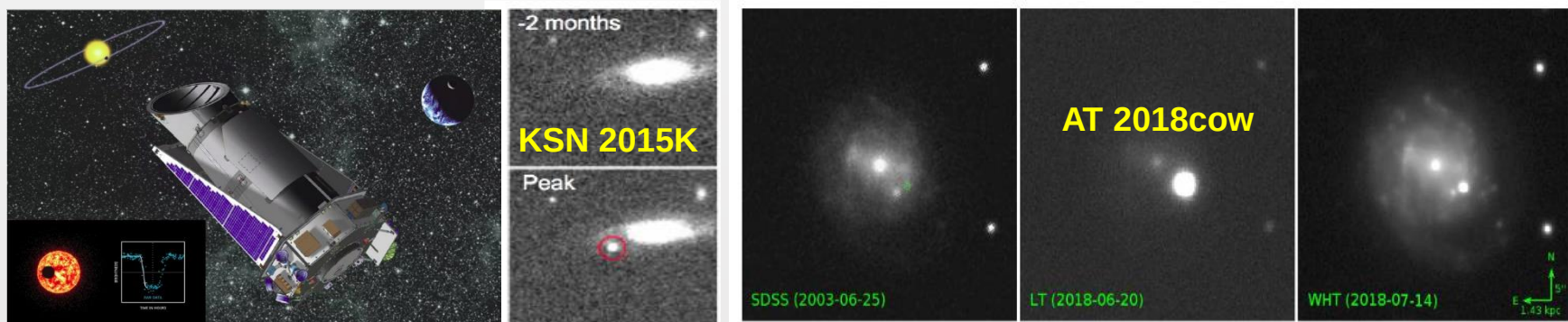


潮汐瓦解事件非常罕见，在一个典型星系通常每1万年才会发生一次，是探测沉寂黑洞的有效手段，大视场时域巡天是主要发现手段。

当前大部分TDE由宽视场巡天发现

新发现：快速演化蓝色暂现源

$L \sim 10^{43} - 10^{44}$ erg/s, Fast Evolving Luminous Transients (FELTs) or Fast Blue Optical Transients (FBOTs) or TDE?



The Upcoming Survey Projects



BlackGEM

Science:

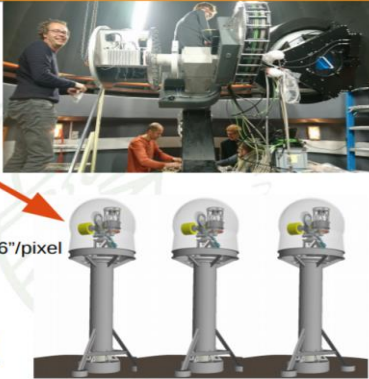
- **Gravitational wave counterparts**
- Southern All Sky Survey
- Fast Transients & Variables
- Nearby Universe Survey

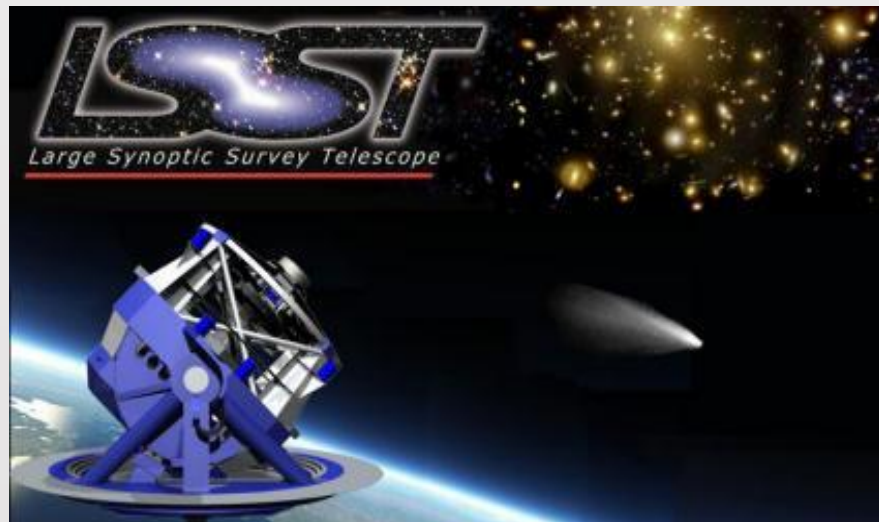
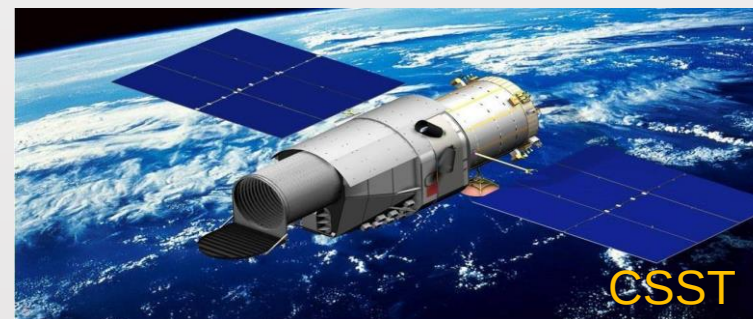
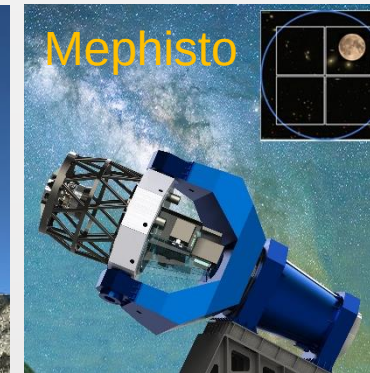
Phase 1:

- 3 wide field telescopes (8.1 square degr. total)
- Primary mirror: 65cm diameter
- Sensitivity: $g=23$ in 5 minutes
- Location: ESO La Silla
- Optical quality: seeing limited, 0.9" median
- Camera: 1 CCD/telescope, 10k x 10k, 0.56"/pixel
- Filters: u, g, r, i, z filter set, change in 3s

Phase 2:

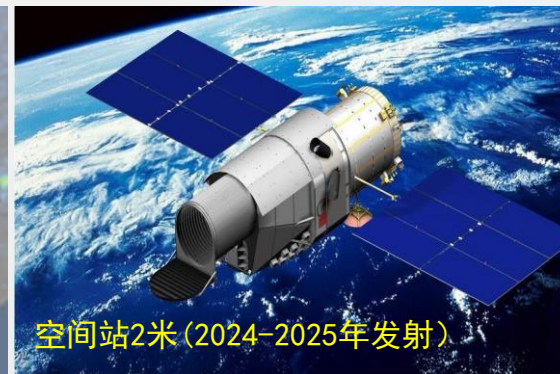
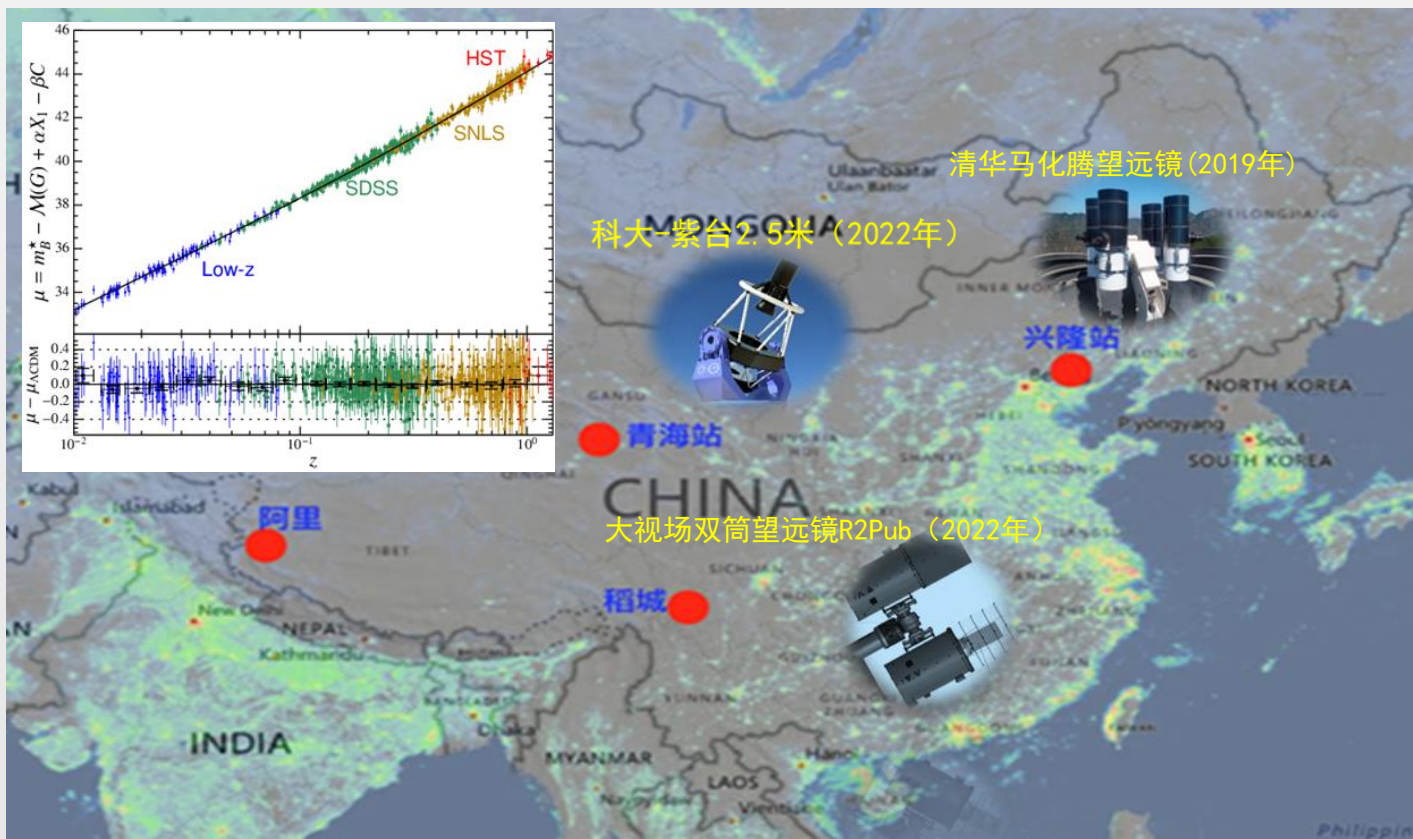
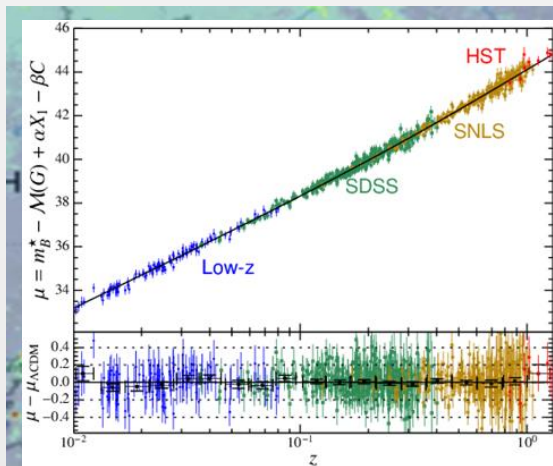
- Expansion to 15 telescopes
- 40 square degrees total field of view (@ 0.56"/pix)
- Location: ESO La Silla; or combi ESO, NZ and SA





- USTC-PMO 2.5-m WFST (7 square degrees)
- R2Pub-60cm wide field (18 square degrees in ug and ri bands)
- Yunnan Univ. 1.6-m Mephisto
- CSST 2.0-m space telescope (1.1 square degrees, 0.07"/pixel)

基于国内大视场巡天设备的大样本超新星宇宙学研究



R2Pub: 18平方度 (双色)
TMTS: 9平方度 (双色)
WFST: 6.7平方度 (单色)
CSST: 1.0平方度 (单色)



Outlines

- Background
- Impact of Wide-field Surveys on Time-domain Astronomy
- Minute-cadence Wide-field Surveys

短周期致密双星探测及应用

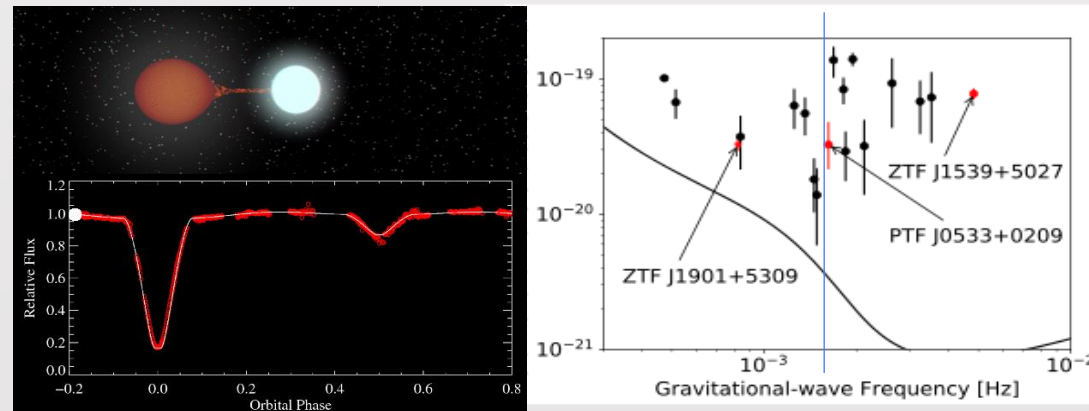
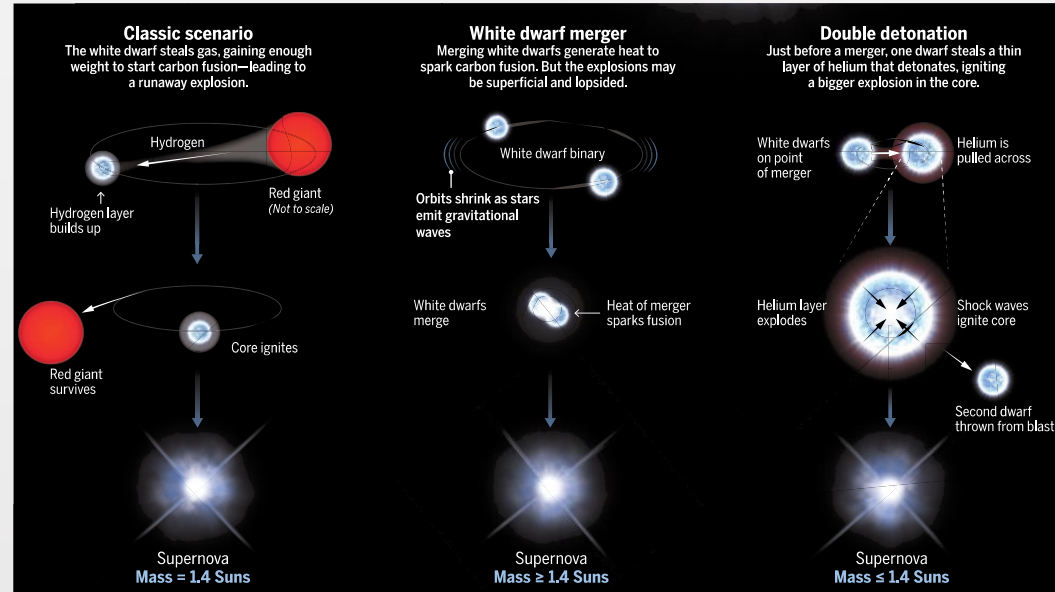
背景：短周期掩食双致密星系是精确测量致密天体质量和半径的金样本。

主要对象：

- CO WD+CO WD
- CO WD+He WD
- He WD+He WD
- WD +sdOB
- sdOB+sdOB
- Red dwarf binary

天体物理应用：

- ✓ Ia超新星前身星
- ✓ 空间引力波探测对象
- ✓ 白矮星内部结构



Geier et al. 2007; Wang et al. 2013, 2019
Polin et al. 2019; Pala et al. 2020

现状：

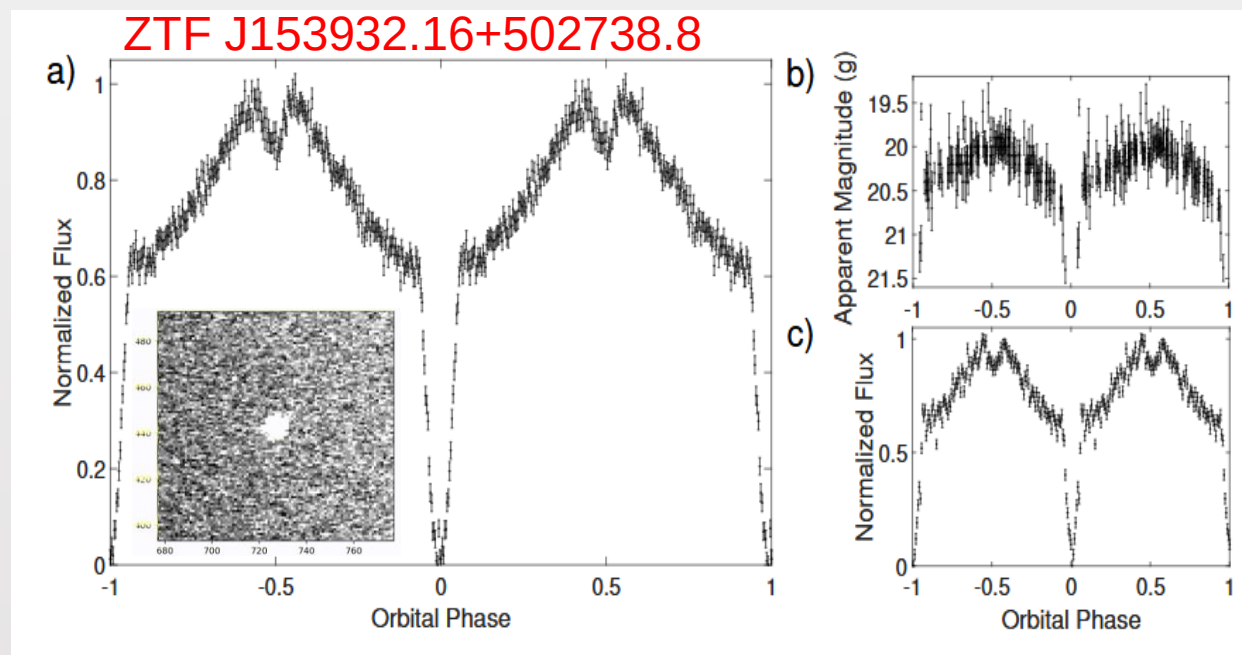
欧南台的SPY巡天项目以及极低质量白矮星巡天项目ELM~100例 双白矮星系统

- 短周期的非常少(10多对)；
- 具有掩蚀的短周期系统更少；

SDSS J065133.338+284423.37
(12.75 minutes)

ZTF J153932.16+502738.8
(6.91 minutes)

ZTF J1901+5309
(40.6 minutes)



Burdge + 2019, Nature

TMTS巡天项目

Tsinghua-Ma Huateng Telescopes for Survey

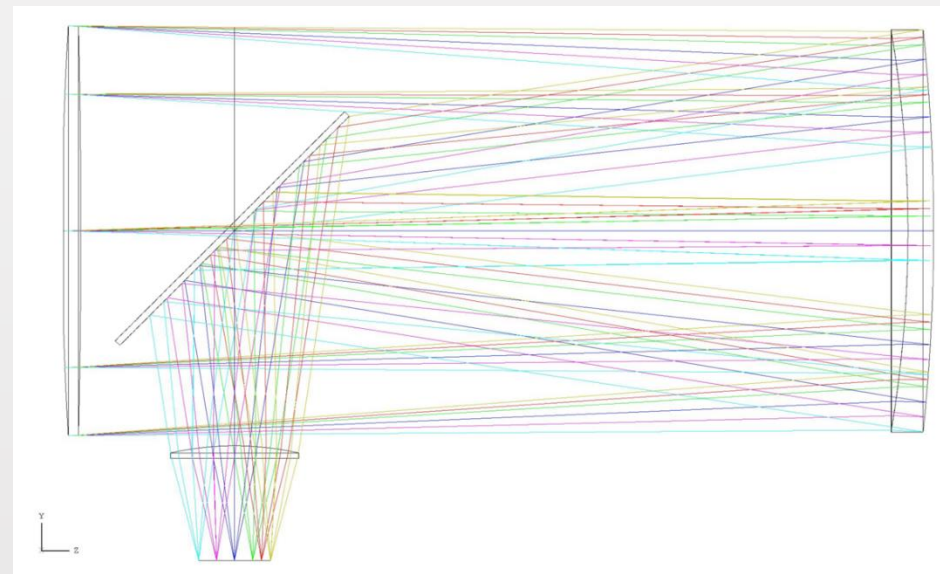
项目拟基于清华大学多镜筒巡天望远镜在5年时间内开展10000平方度天区的高时频的双色巡天观测（每个天区持续观测时间>10小时），其中部分天区与lamost巡天同时进行。开展快速演化暂现源、中等亮度暂现源、双致密星、耀星等的观测研究。



望远镜观测系统介绍



望远镜光学系统

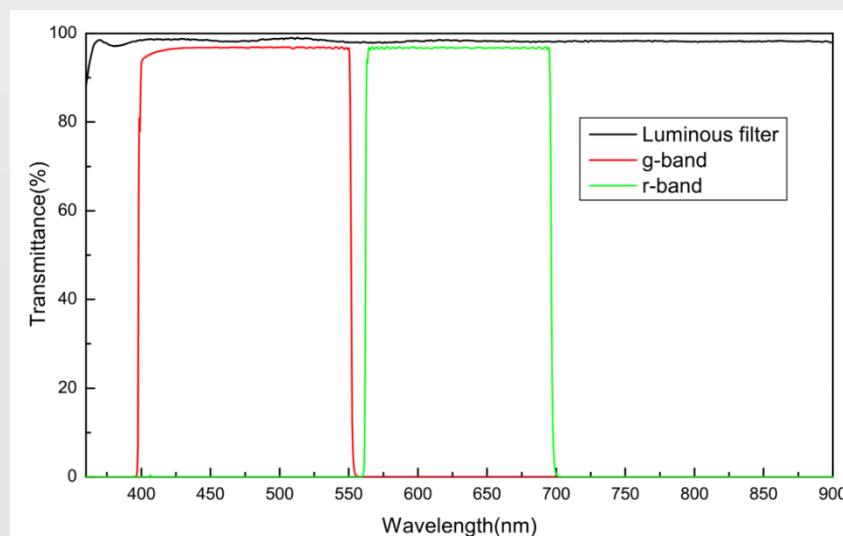
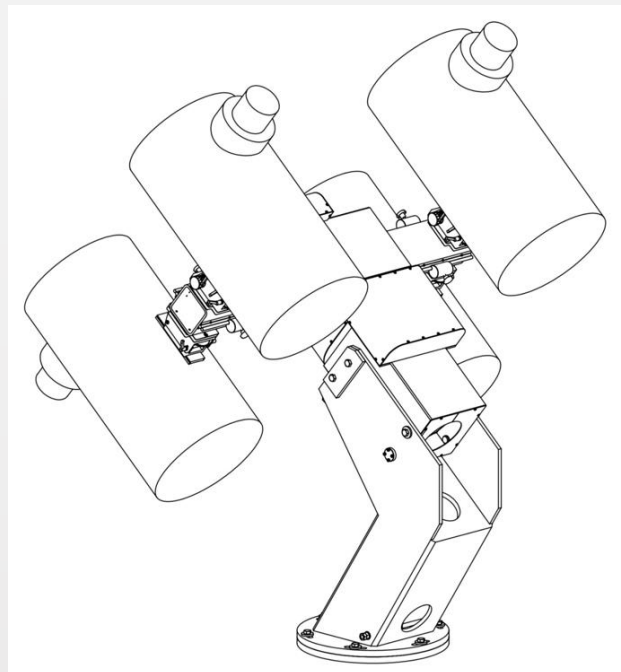
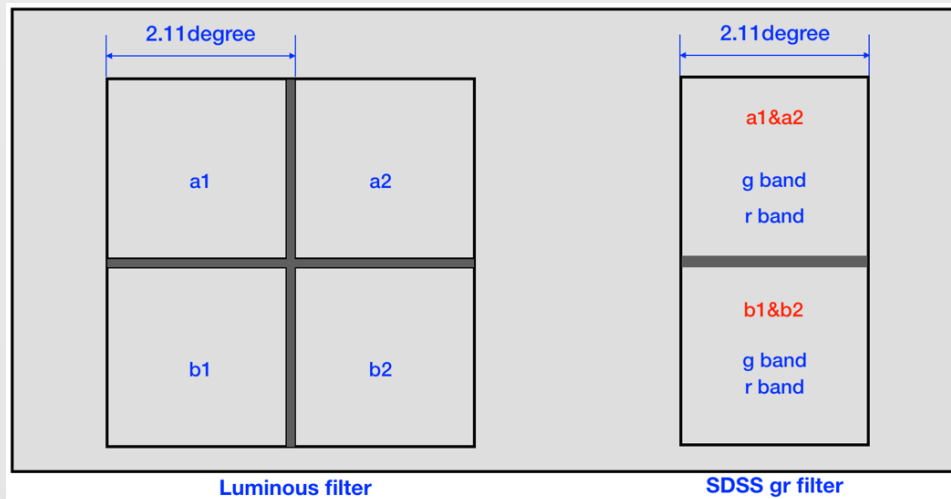


- 4.5平方度的观测视场,4个镜筒可达到~18平方度天区
- 4K x 4K CMOS相机 (1.86角秒/像素)
- 极限星等 (60s曝光) $L \sim 19.4$

望远镜观测系统介绍

滤光片系统

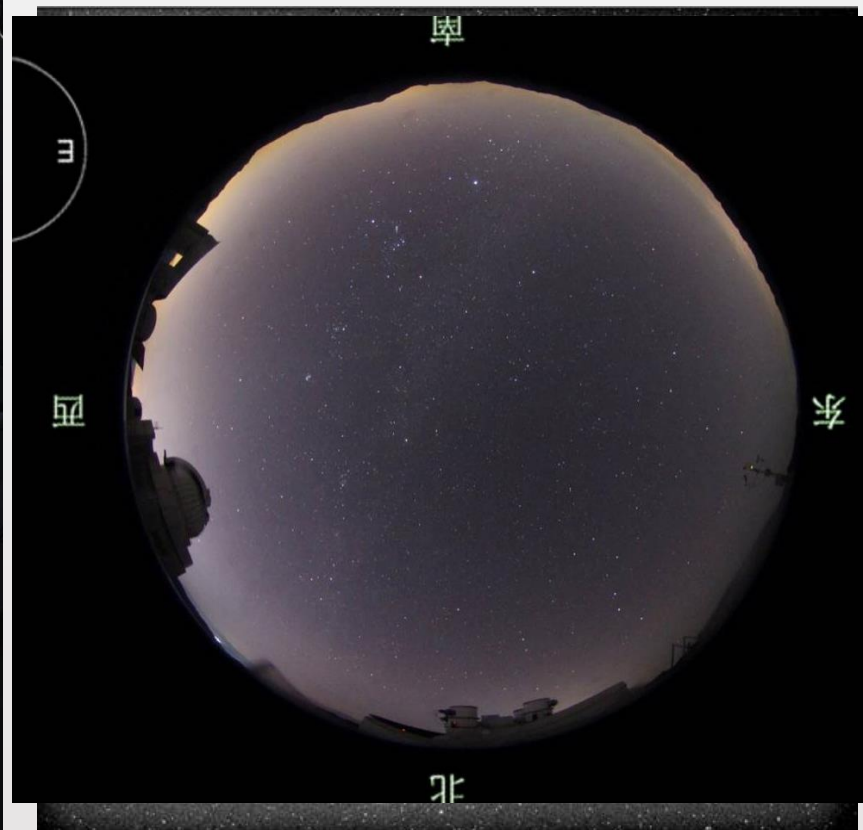
- 由于光学望远镜系统工作波段设计集中在400~900nm，结合项目组巡天科学需求及光路设计，我们最终定制了65mm*65mm*5mm的大尺寸滤光片。
- 目前多镜筒望远镜观测模式详见下图，左侧为模式I，即大视场单色巡天模式，配备单色Luminous滤光片；右侧为模式II，即双色巡天模式，采用SDSS的gr滤光片，主要覆盖400~700nm的可见光波段。



TMTS 观测系统安装调试



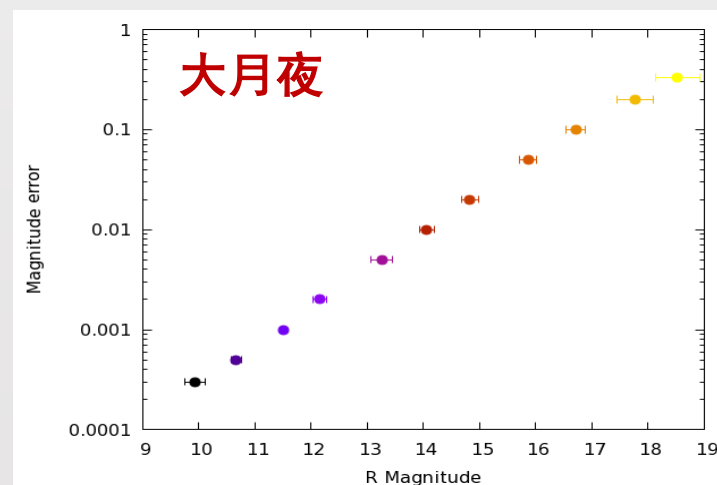
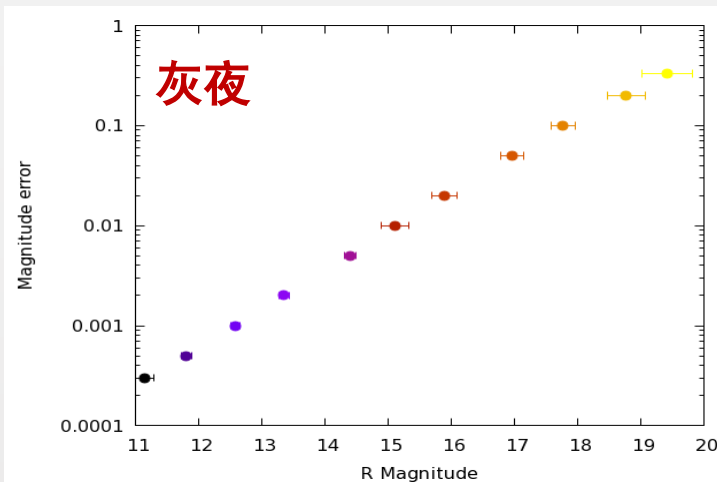
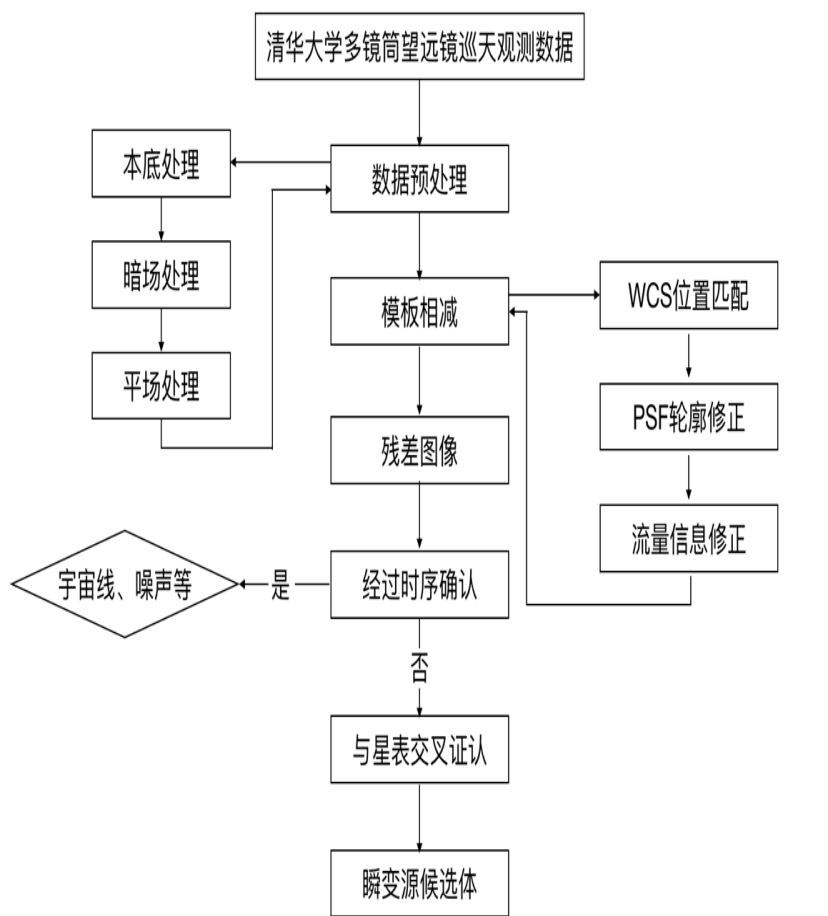
观测系统初装完成图



观测系统初光测试图

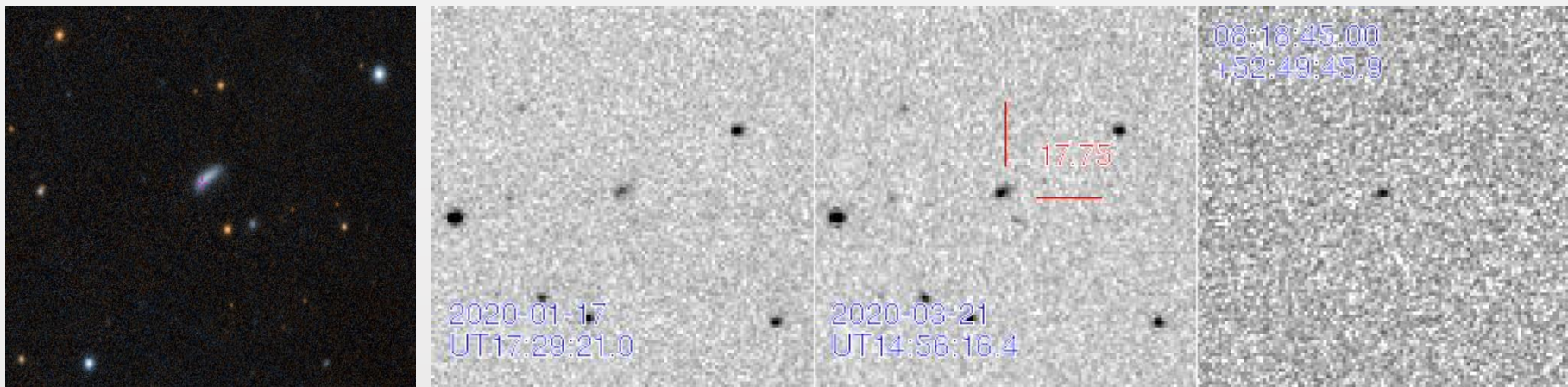
TMTS 数据处理观测性能

TMTS数据处理流程

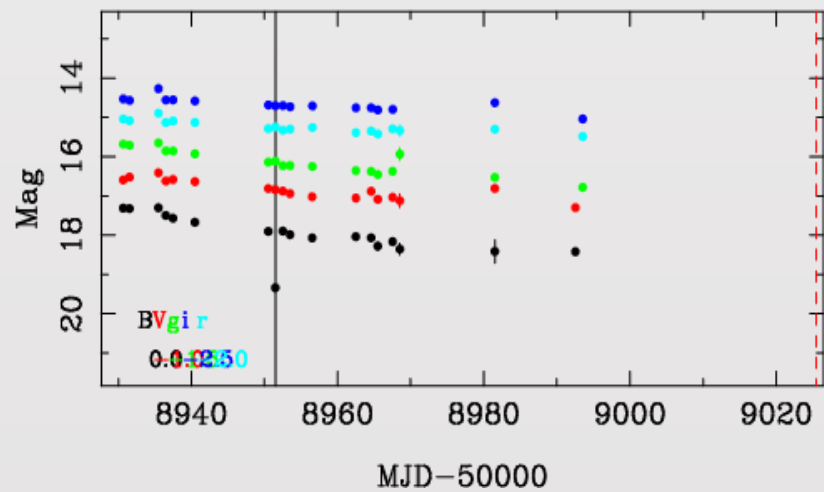
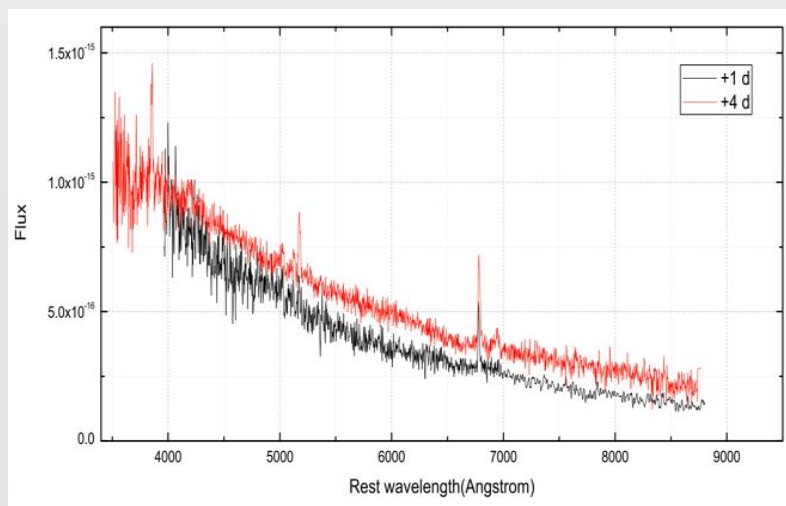


Zhang, Wang, Mo, et al. 2020, PASP

TMTS常规巡天：发现超新星

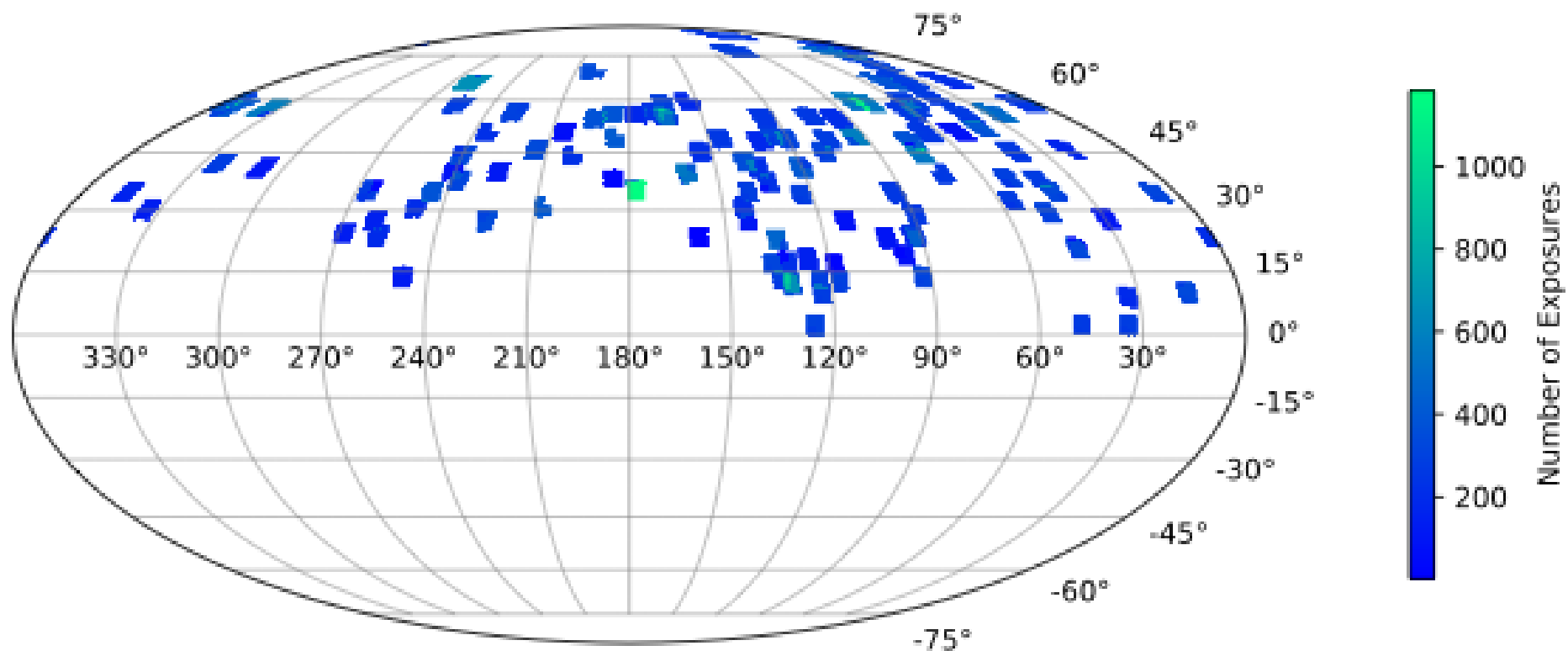


图为该观测系统在2020. 03. 22正式发现命名的运行后第一颗17. 8等的处于爆发早期的II型超新星SN 2020esx
sn2020esx



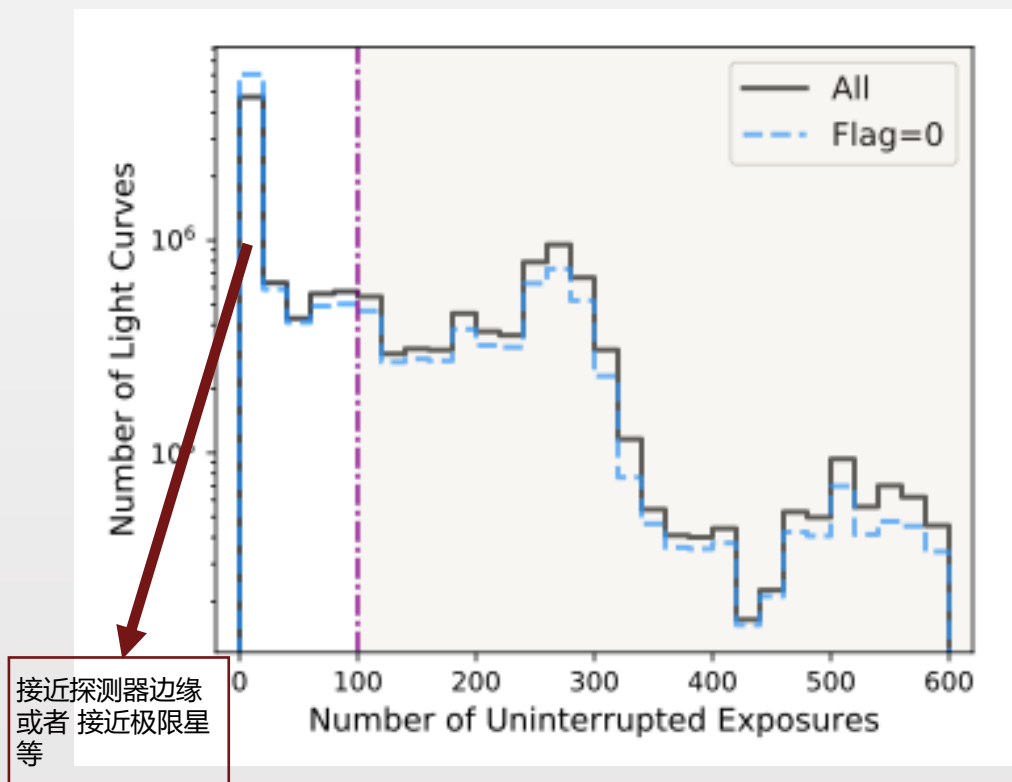
TMTS高频巡天：发现极短周期变源

Observations of the LAMOST fields



- Uninterrupted observations of the LAMOST fields for the whole night;
- 10s for each exposure; scanning **188** LAMOST fields in 2020, covering about **1970 square degrees**

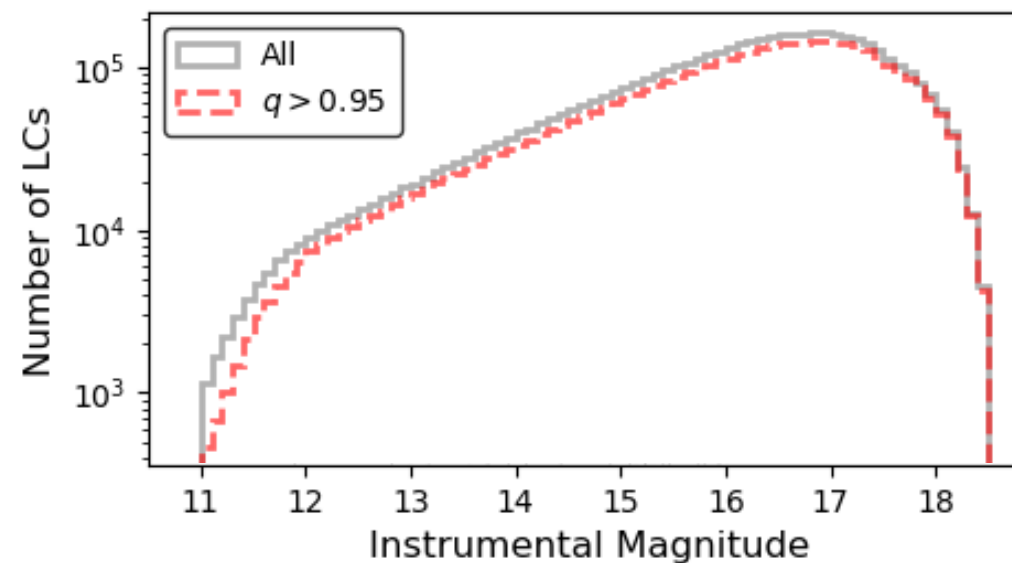
TMTS的光变曲线



在第一年对LAMOST天区的观测中

TMTS 产生了约1300万条连续的光变曲线，
具有100次以上**可靠测量**的光变曲线，约有**490万条**
(i.e. TMTS**第一年观测的光变曲线数据集**)。

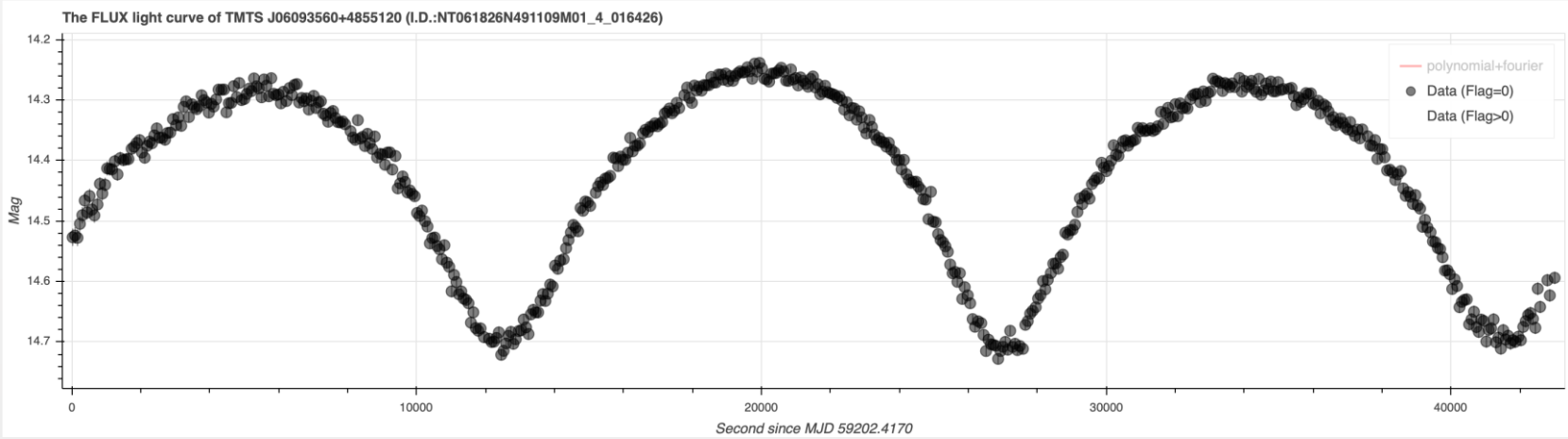
与Qian et al. (2019)的**26万个SBVCs**相交，TMTS具有其中**2.4万个源**的光变曲线



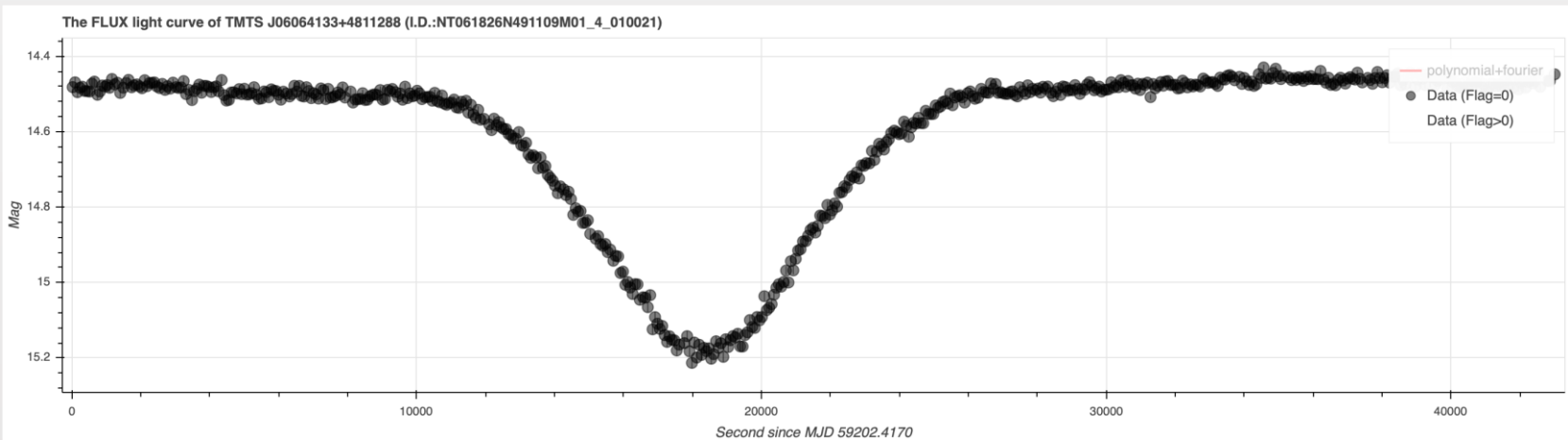
TMTS光变曲线数据集中的光变曲线的
平均星等主要分布在12—18星等。

契合**LAMOST**的观测范围

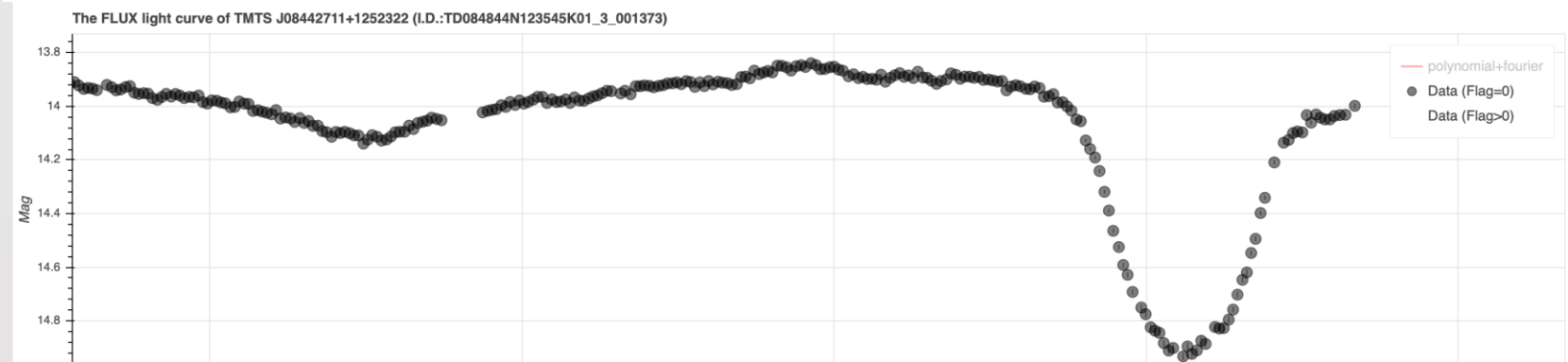
光变曲线样本



EB WUMa

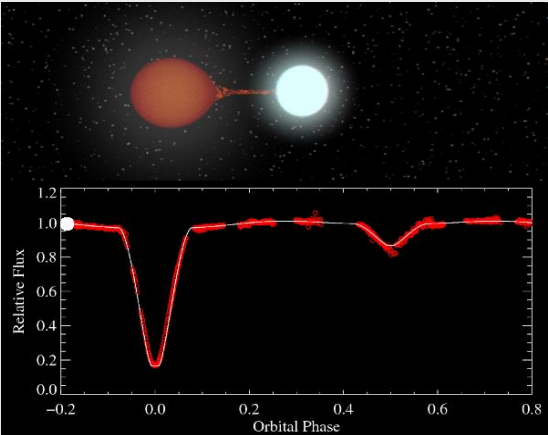
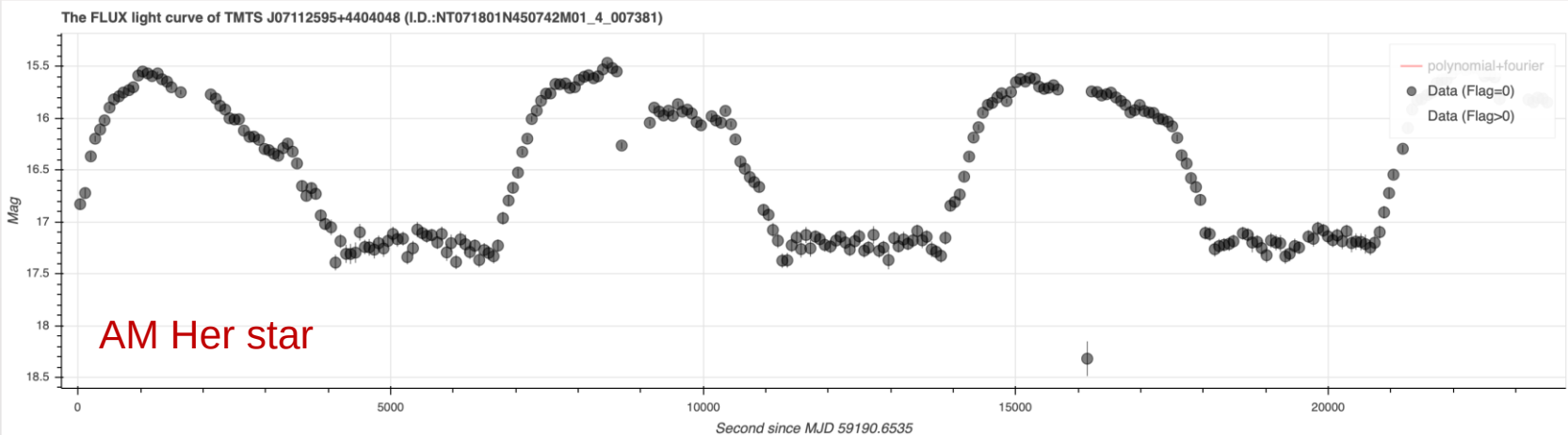
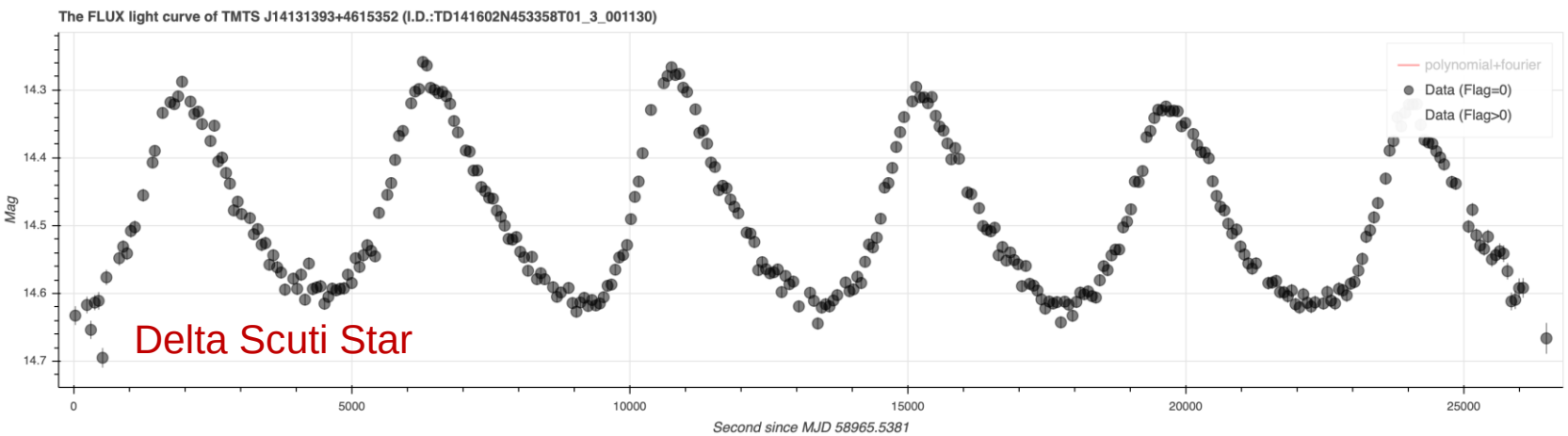


EB Algol

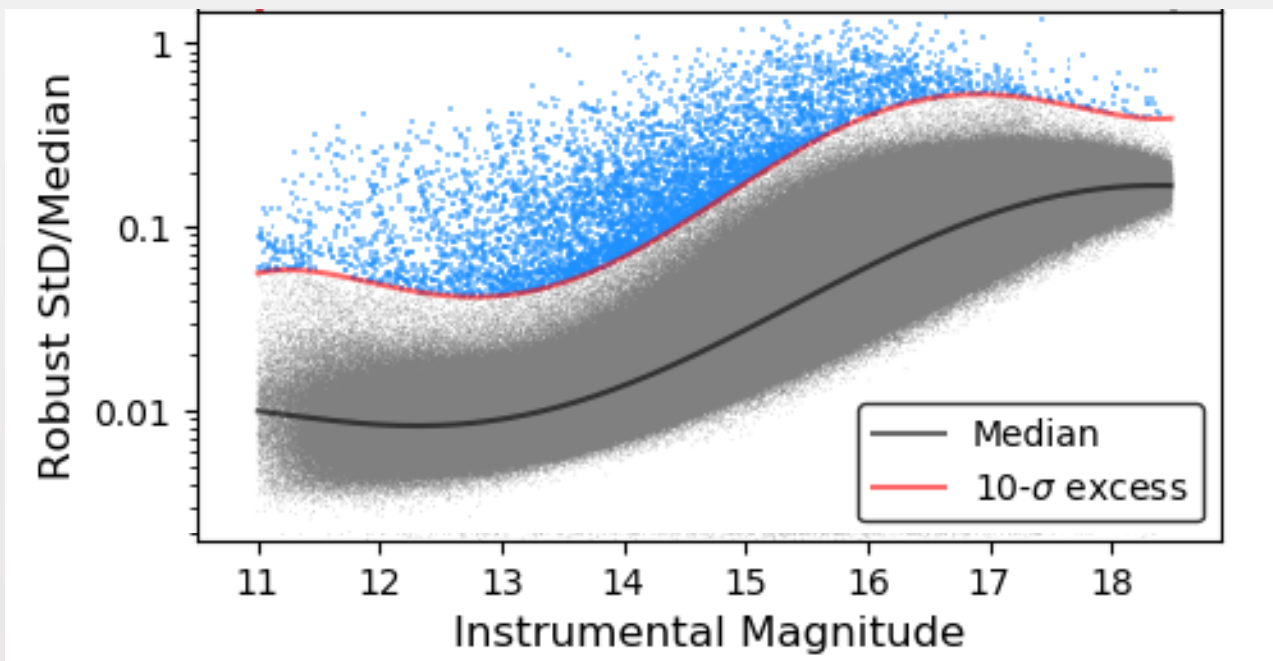


EB betLyr?

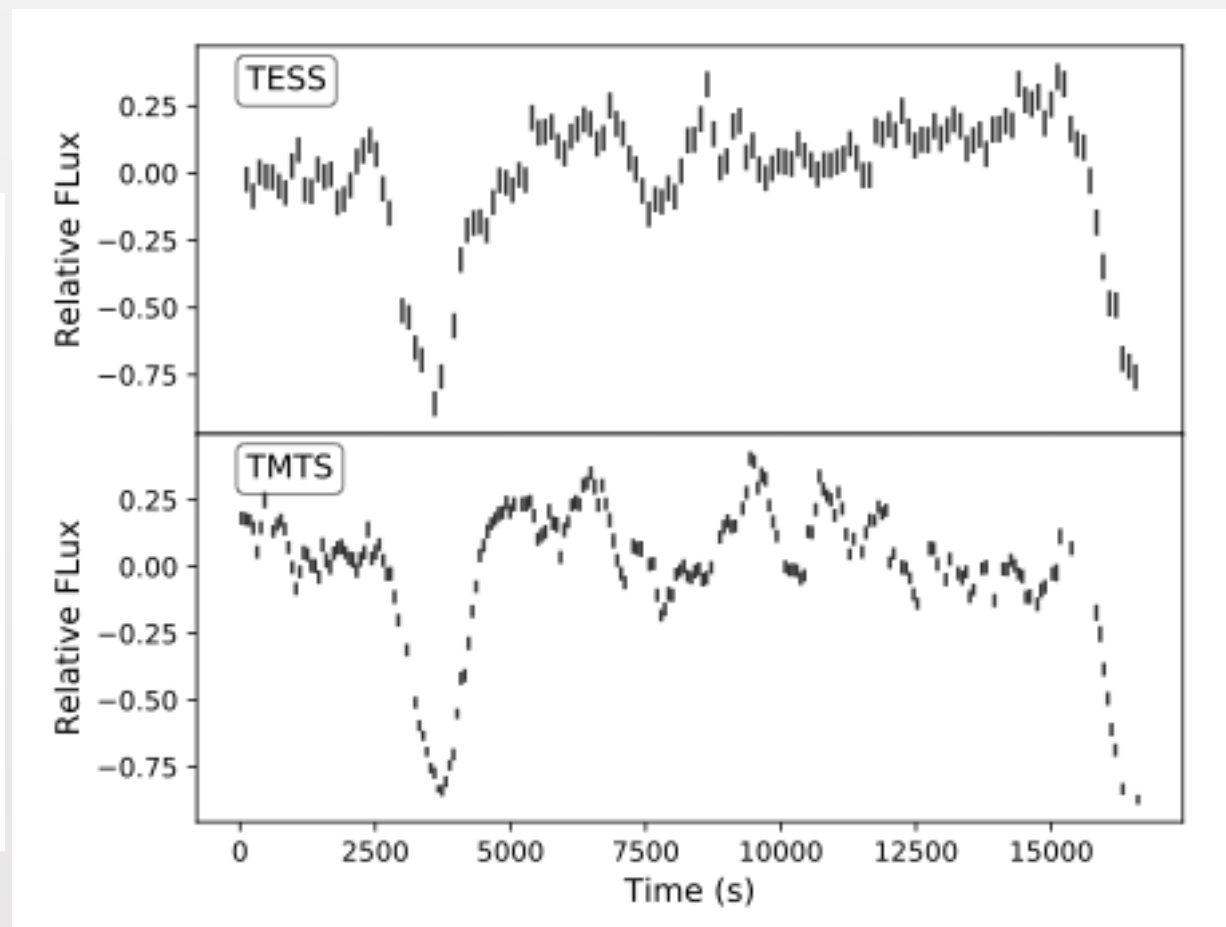
光变曲线样本



TMTS的探测精度

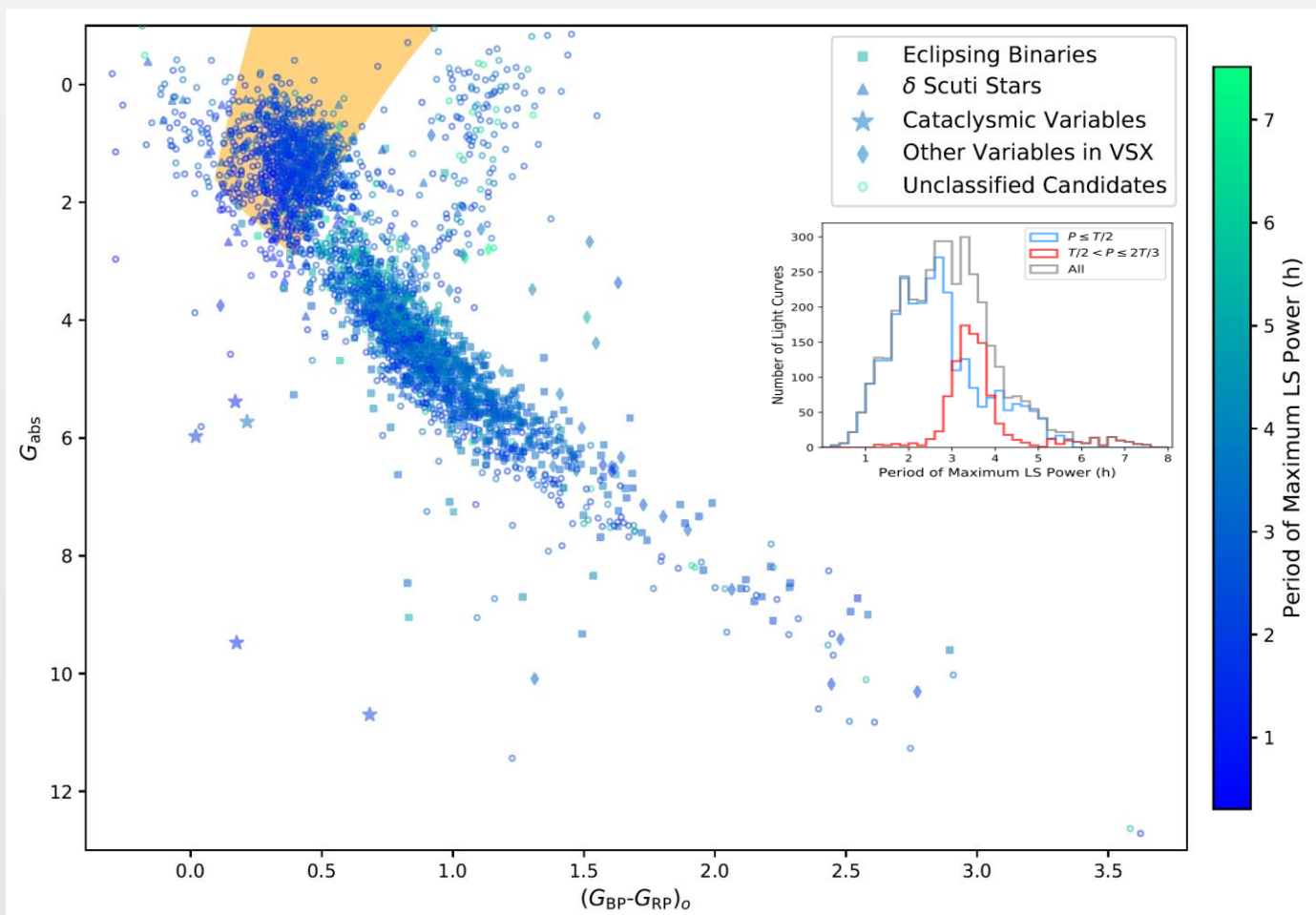


流量测量的不确定度，最低可达千分之几



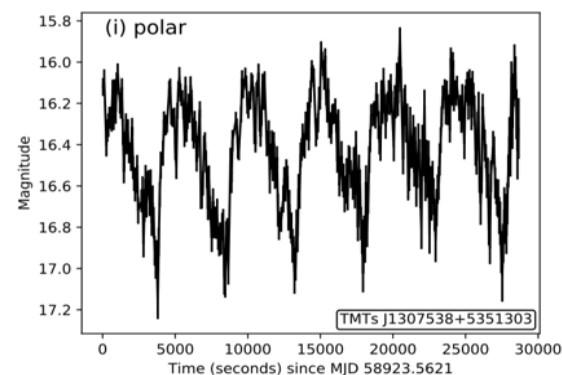
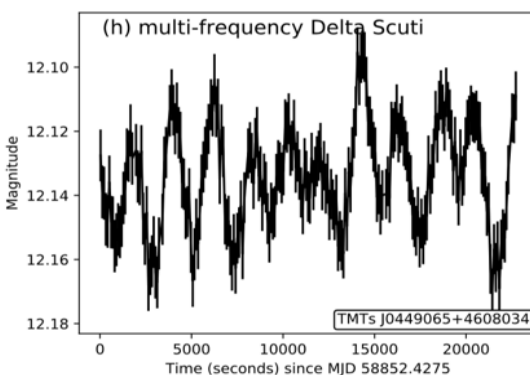
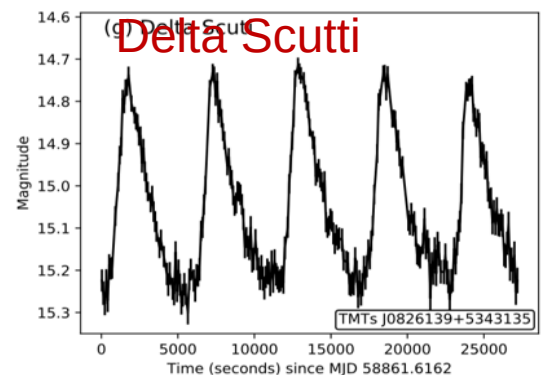
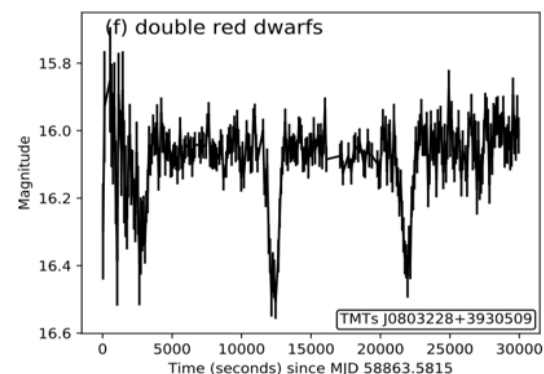
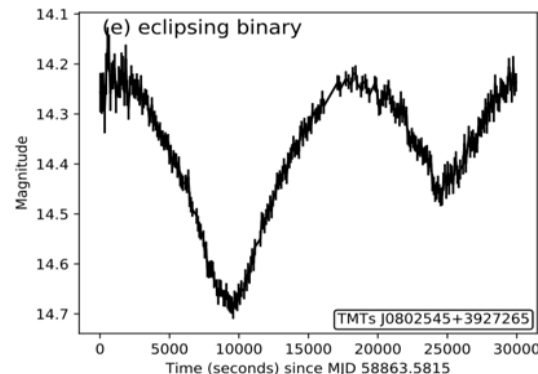
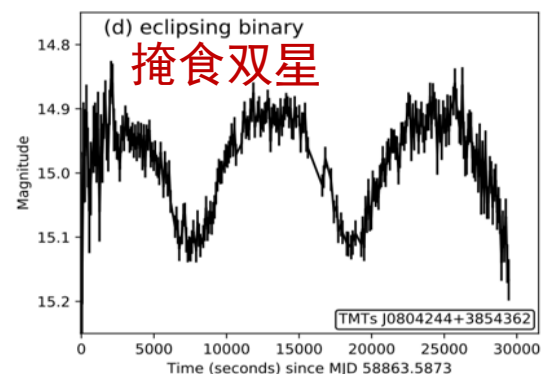
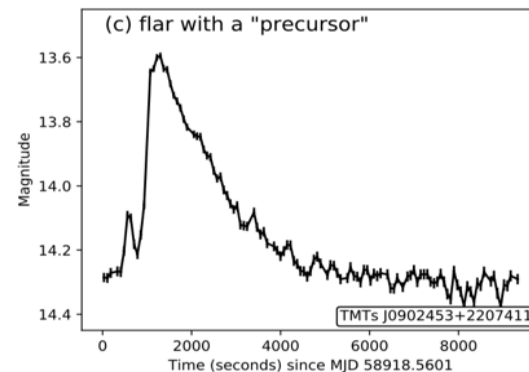
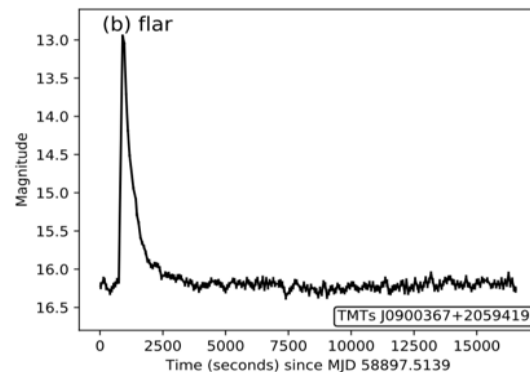
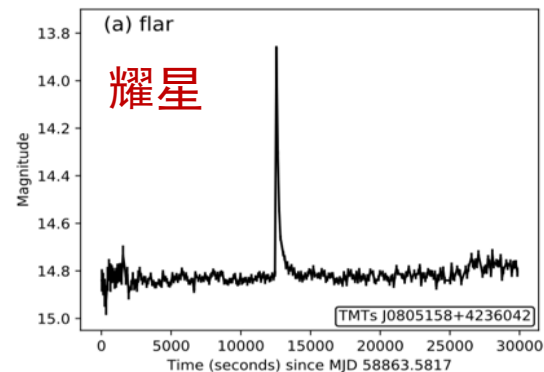
TMTS对暗源 (e.g. L~17) 的探测精度显著优于TESS

TMTS发现得短周期变源



- 在约3700个具有周期性的Gaia DR2-TMTS变源候选体中, **其中约3000个**源具有B-R颜色测量和可靠的视差测量 (如图) ;
- 根据绝对星等和颜色, 可以粗糙估计TMTS第一年观测到的Delta Scuti stars至少有**1300个**, 观测到的食双星至少有**1400个**;
- 与AAVSO的VSX目录相交: 已知的EBs约有900个, Delta Scuti stars约有200个, CV有5个。可以预测TMTS在一年的观测中**新发现了约500个**掩食双星以及**超过1000个**Delta Scuti stars.

发现的部分短时标恒星爆发及掩食双星



可查询数据库

TMTS Results with High Cadence

Load Time: GMT 2021-07-11 14:45:06 & MJD 59406.615

Topic **Periodic** Variable ▾ Flare/Burst ▾ Dip/Eclipse ▾ Statistic Catalog ▾ ULC1st ▾
SELECTing ▾ Search Notes Frames Status

Time Travel:

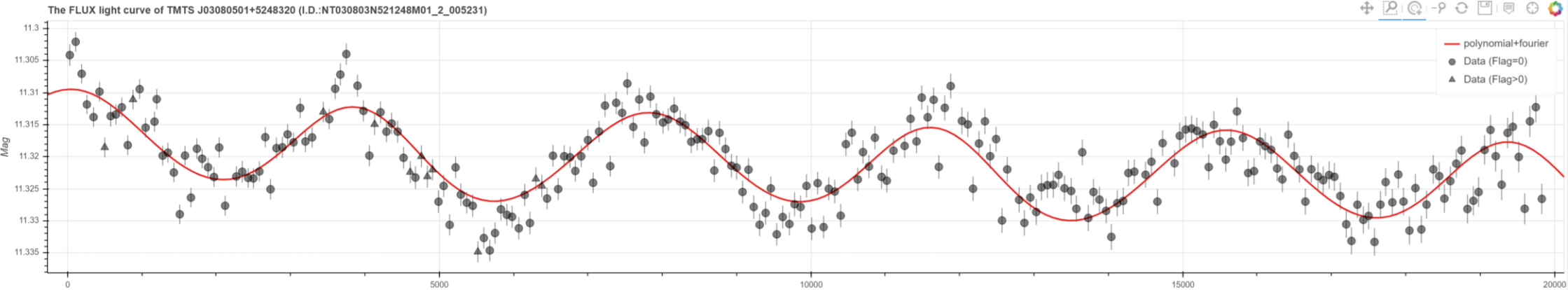
2021-01-26

Hello, staff

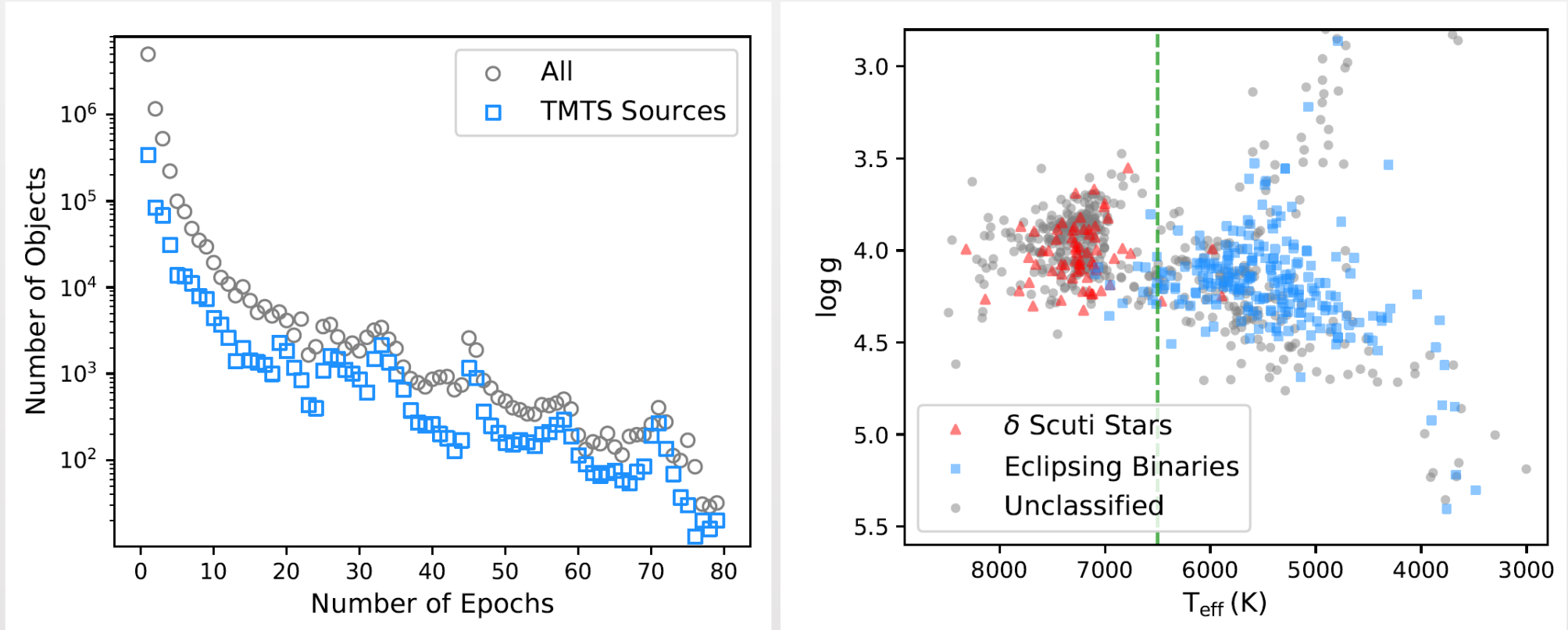
[Logout](#)

Name		I.D.	Coordinate (decimal)	Coordinate (sexagesimal)	Galactic Coordinate	All Obs. Date
TMTS J03080501+5248320 (Download)		NT030803N521248M01_2_005231	47.0209, 52.8089 (Query in Simbad)	03:08:05.01 +52:48:32.02	,	20210126,
VSX Type / Period	VSX Name / Sources	Simbad Type / Sources	Gaia Distance (kpc)	Abs. Mag G (without/with extinction)	B - R (without/with extinction)	Gaia Sources
/	/	Star / 1	0.37+/-0.00	/ 3.54	/ 0.78	1
Lamost Designation*	Spectral Classification	Total Lamost Spectra/Sources	Gaia Cross Match?	Delta RV max (significance), nrv	Average Temperature (K)	Average Log g
J030804.97+524832.7		10 / 1	True			
Classification					Topic	
☐ Eclipsing Binary ☐ Delta Scuti ☐ EB or DS ☐ Flare Star ☐ Compact Binary ☐ Short Period ☐ Special ☐ Spurious Variation					☐	

Obs. Date (Version)	Initial X,Y	Valid Points/All Points (Quality)	Ref. Source Number	Zero Mag.	Flux
20210126	445.7, 1215.0	238/249 (0.96)	5569	25.449	447943+/-2621
Mag	Abs. Ave Mag (without/with extinction)	Inversed Neumann Ratio/Level	Local/Global/uncorr PhiVV Prob (Max Phi VV)		A21/median_ratio
11.321+/-0.006	/ 3.49	1.767 /1.1	0.764 / 0.771 / 0.501 (3.46)		0.19 / 1.06
Candidate Period (hour)	Local/Global/Uncorr FAP (Max Power)	Red Noise?/Double Period Covered?	Adjusted R^2	Fourier Amplitude in Flux/Mag	Mass Function min (Solar Mass)
1.0784	4.38e-08 / 1.11e-05 / 3.09e-26 (63.5)	No / Yes	0.663	0.006 /0.007 mag	



与LAMOST光谱库交叉



搜寻黑洞候选体

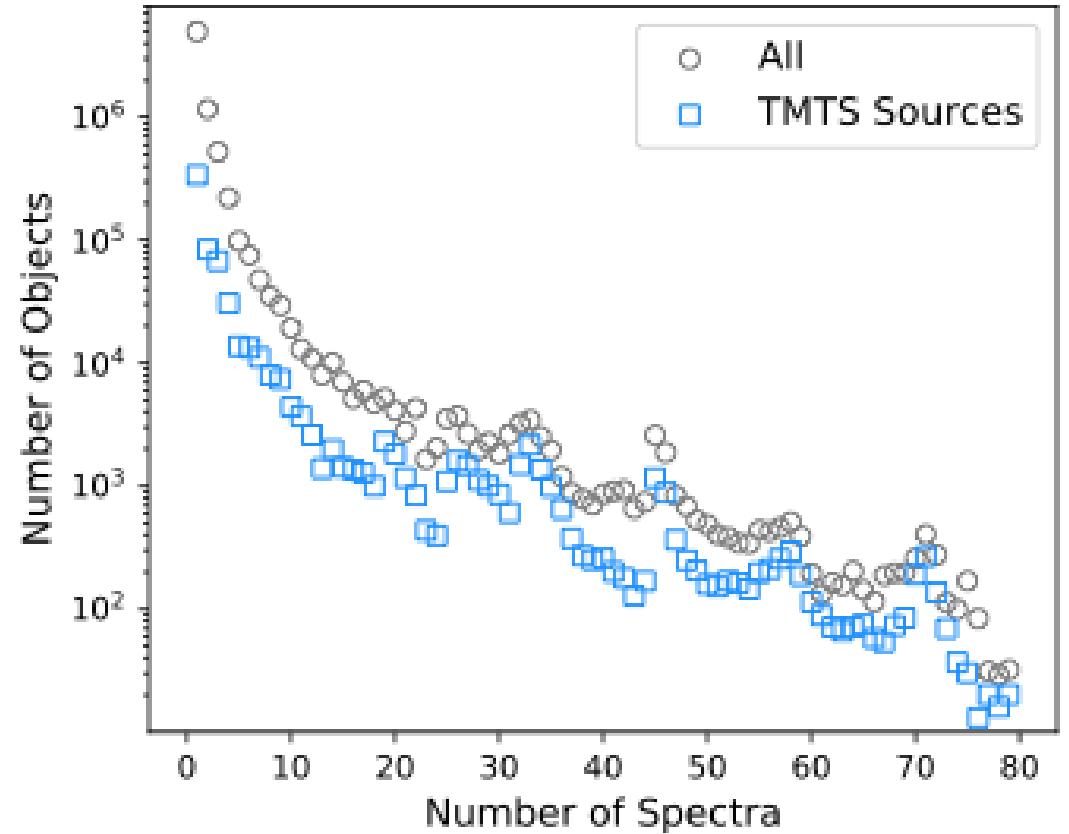
$$f(M) \equiv \frac{M_{\text{CO}}^3 \sin^3 i_{\text{orb}}}{(M_{\text{giant}} + M_{\text{CO}})^2}$$

$$= \frac{K^3 P_{\text{orb}}}{2\pi G} (1 - e^2)^{3/2}$$

视向速度半振幅
可以通过LAMOST的光谱估计

轨道周期
可以由TMTS的光变曲线给出

BH UC(X)Bs?

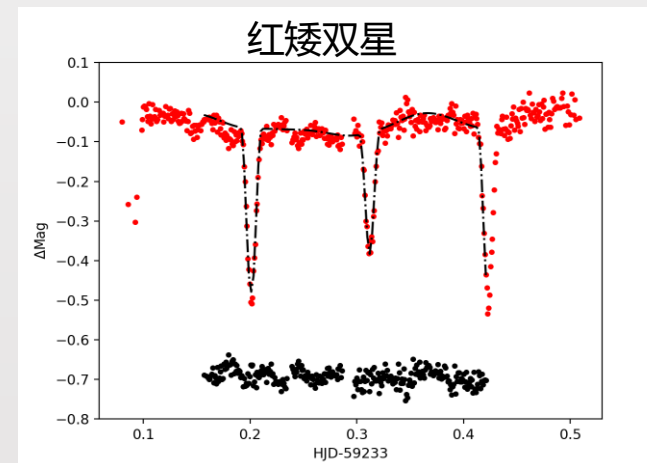
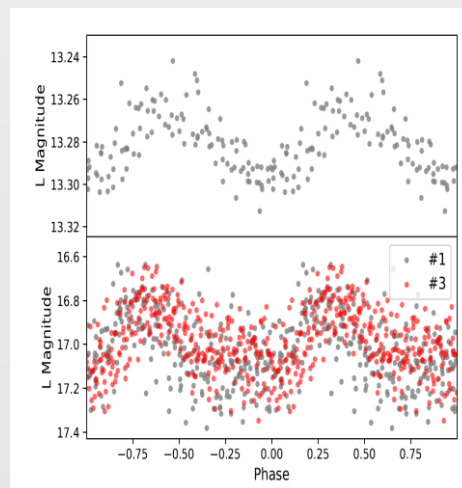
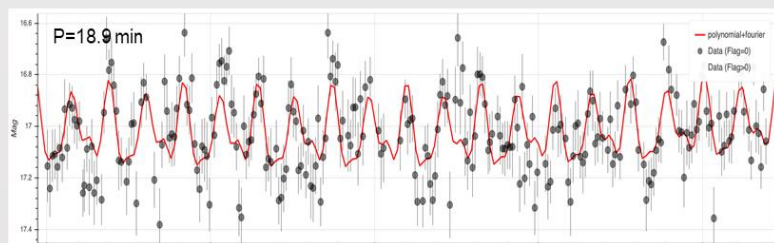
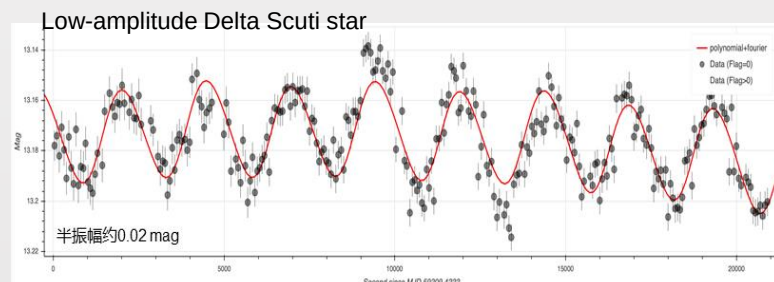
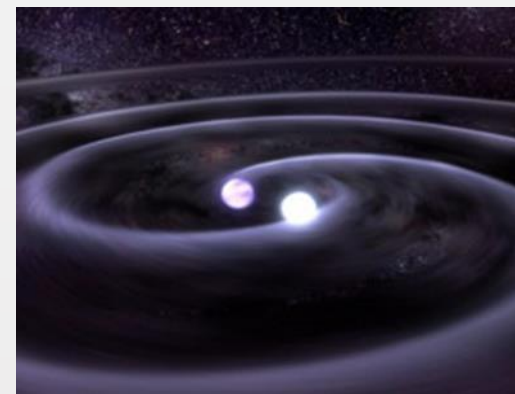


约**235万个**LAMOST源具有**多时期的光谱观测** (LAMOST DR7 LRS+MRS),
其中约**28.5万个源**在2020年被TMTS观测过。

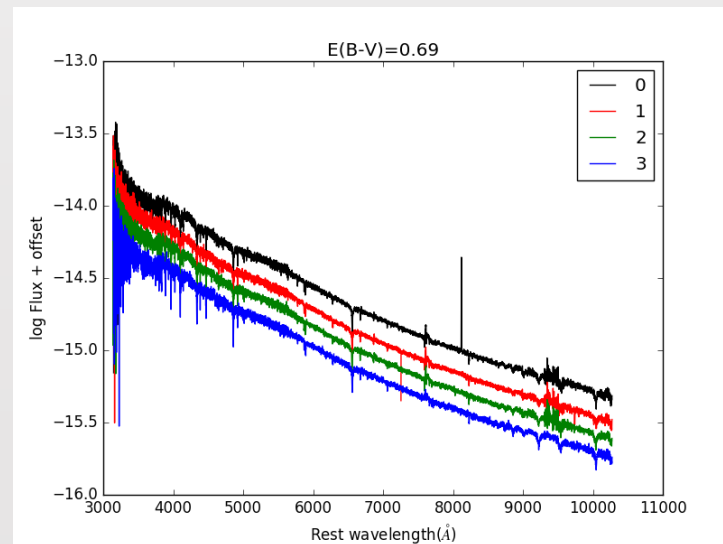
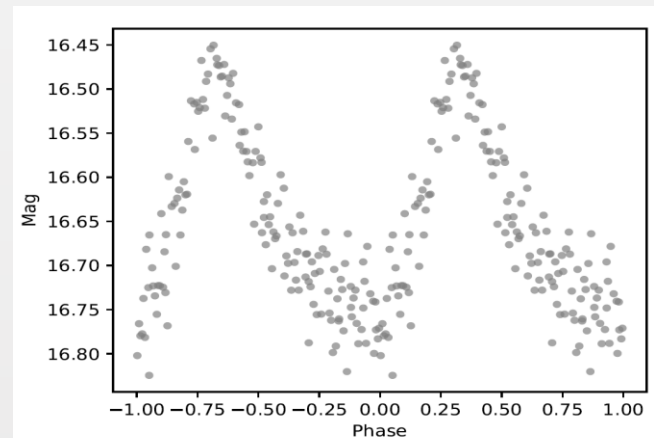
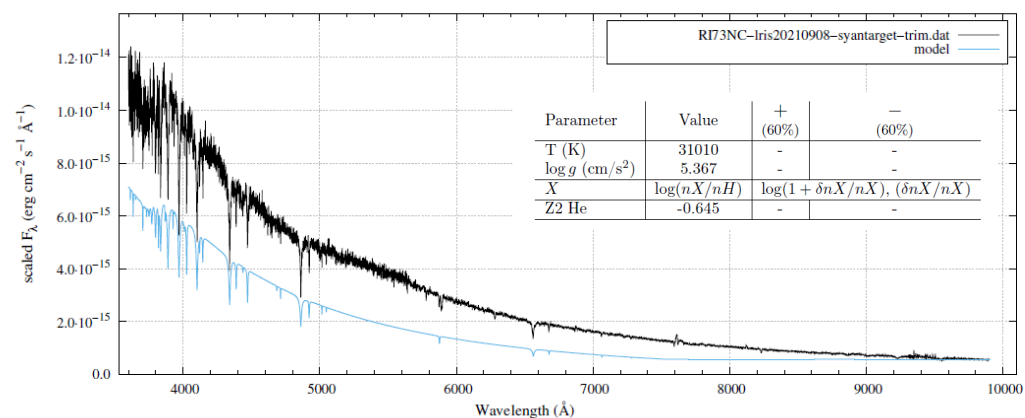
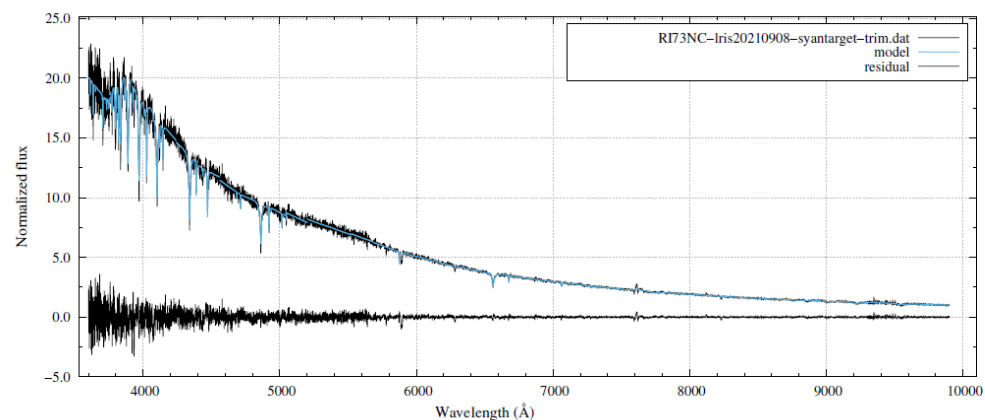
搜寻引力波校验双星

方案：搜寻最短周期的光变(e.g. < 30 mins) ->
高时间分辨的光谱+高质量光变曲线 -> 解轨 -> 计算引力波强度；

- TMTS已经发现一系列极短周期 (< 1 hour) 的周期性变源；
- AAVSO的VSX目录中共收录**887个**周期短于1小时的变源，而TMTS仅在一年的观测中便发现了**77个**新的极短周期变源 (< 1 hour) 的候选体；



蓝色大振幅脉动变星(BLAPS)

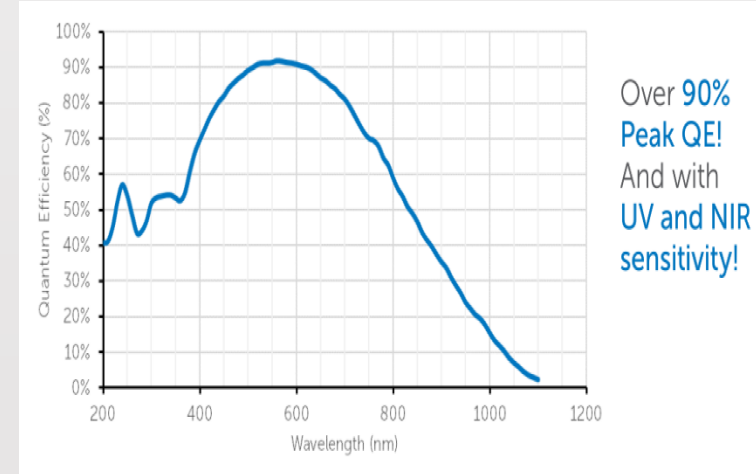
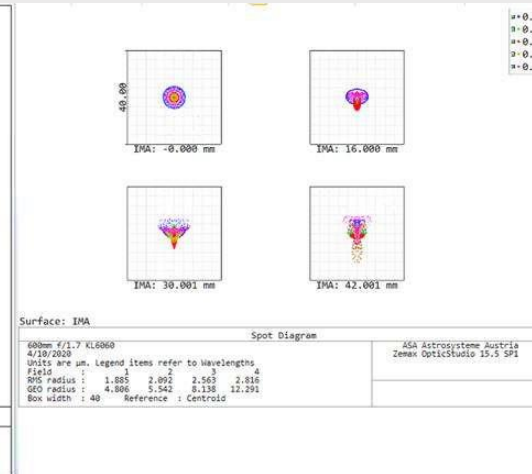
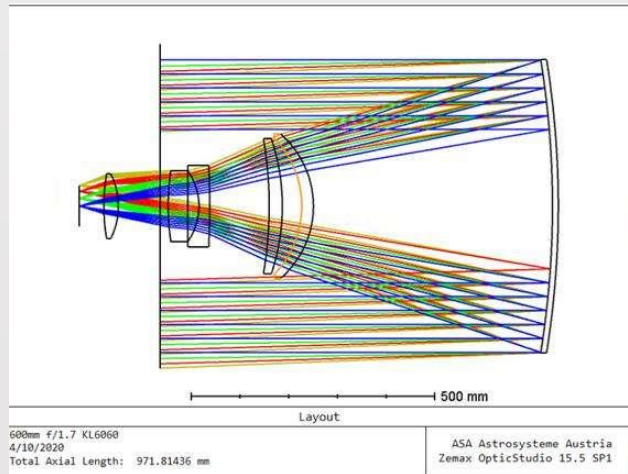
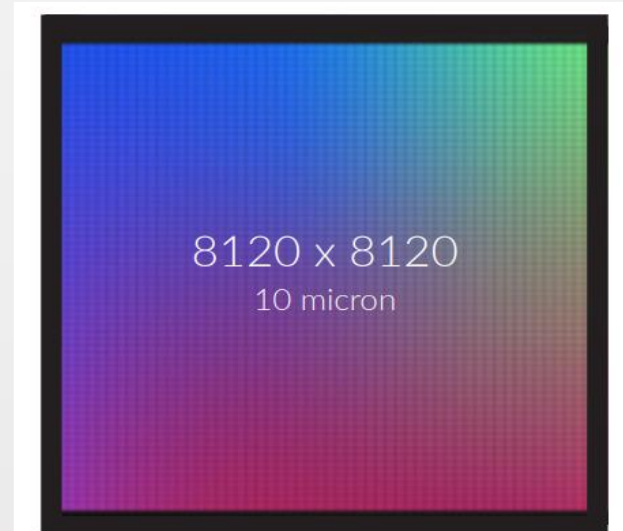
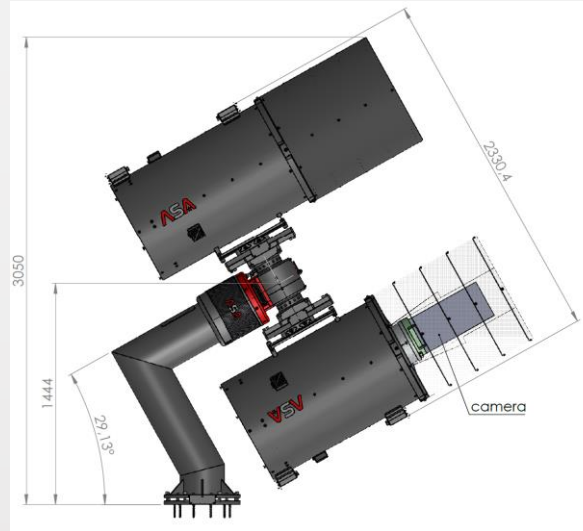


Lin, Wang et al. 2021b

下一步计划： R2Pub双筒大视场望远镜

望远镜参数：

- 口径60cm主焦大视场望远镜
- 视场18平方度（覆盖81个月亮）
近紫外光学双色同步，比
TMTS深>1.5个星等
- 1分钟g波段巡天深度达到20.0等 (5σ)
- 高速8.1k CMOS相机
(毫秒曝光)

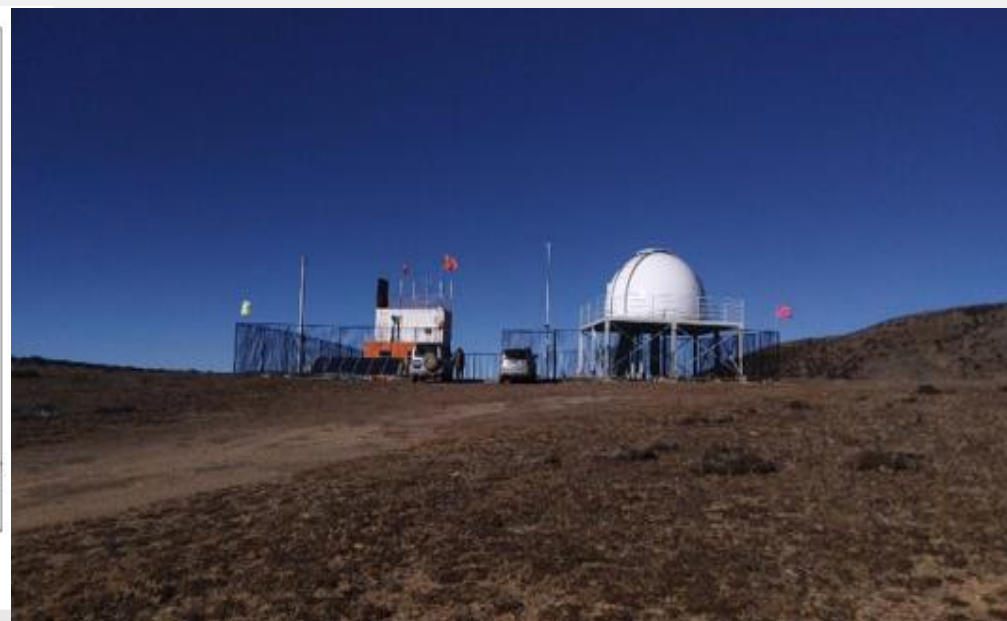
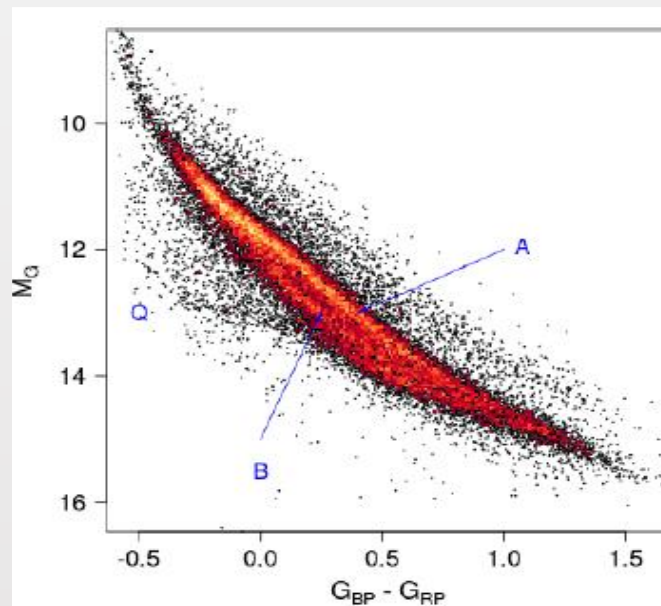


R2Pub双筒大视场望远镜台址

- 望远镜及探测器合同已经完成招标
- 7月开始基建，预计2022年上半年建成试运行

主要科学：

- ✓ 可探测Gaia大部分白矮星
- ✓ 矮星双星掩食系统；
- ✓ 近场宇宙超新星；
- ✓ 黑洞潮汐瓦解；
- ✓ 活动星系核；
- ✓ 独特的同时双色数据



无名山1号点 (Longitude: 100 °04'12"east,
Latitude : 29°09'1"North, 海拔4680米)

总结

- 大视场光学时域巡天是开展超新星、黑洞潮汐瓦解以及奇特暂现源探测研究的主要手段，对恒星物理发展起到牵引作用；
- 基于国内大视场巡天设备的超新星探测有望获得精确宇宙学参数；
- 大视场高频巡天是开展致密天体双星及引力波源探测研究的有效手段。