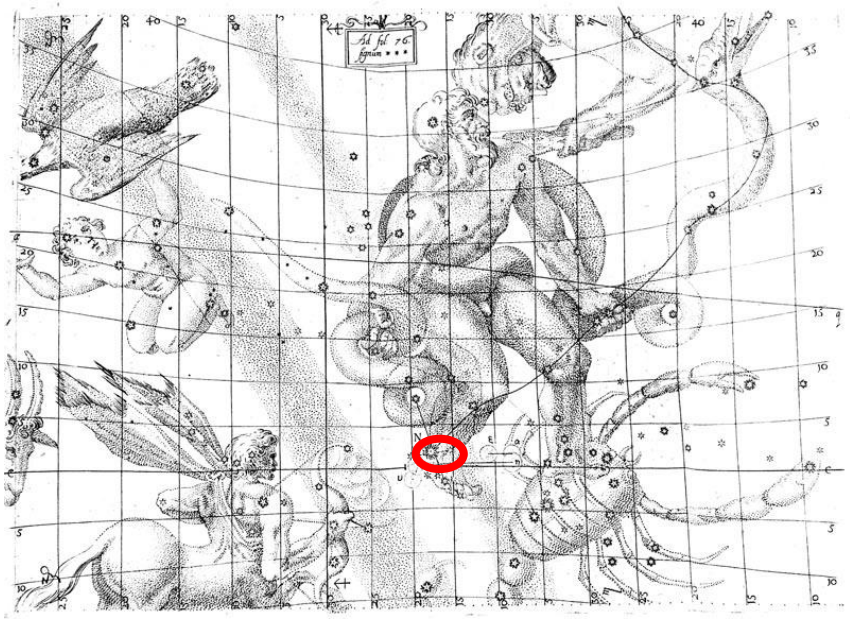
The variable sky:
a developing branch of Astrophysics
Detection of transients and Follow-up

Michel Dennefeld
IAP and Sorbonne-U, Paris

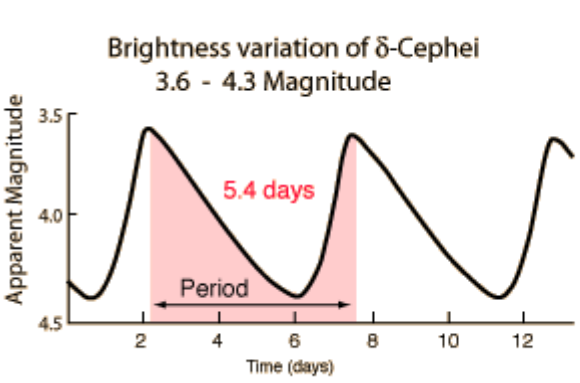
Etoiles variables, ou Nouvelles (Nova…)

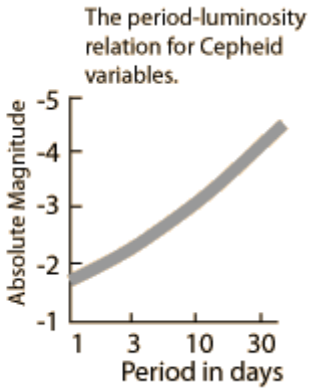
- "Interesting" since 16th (e.g. Mira Ceti (1596) or SNe 1572 or 1604)
- Variable stars used for distance scale (20th) (e.g. Cepheids: Miss Leavitt, 1890-1920)
- Accuracy limited by detector: eye, then photographic plate

  (some PM though…)
- Chance discovery (little systematic searches)
- **Today, many surveys !!**



De Stella Nova in pede Serpentarii (1604)





Les Alertes aujourd'hui

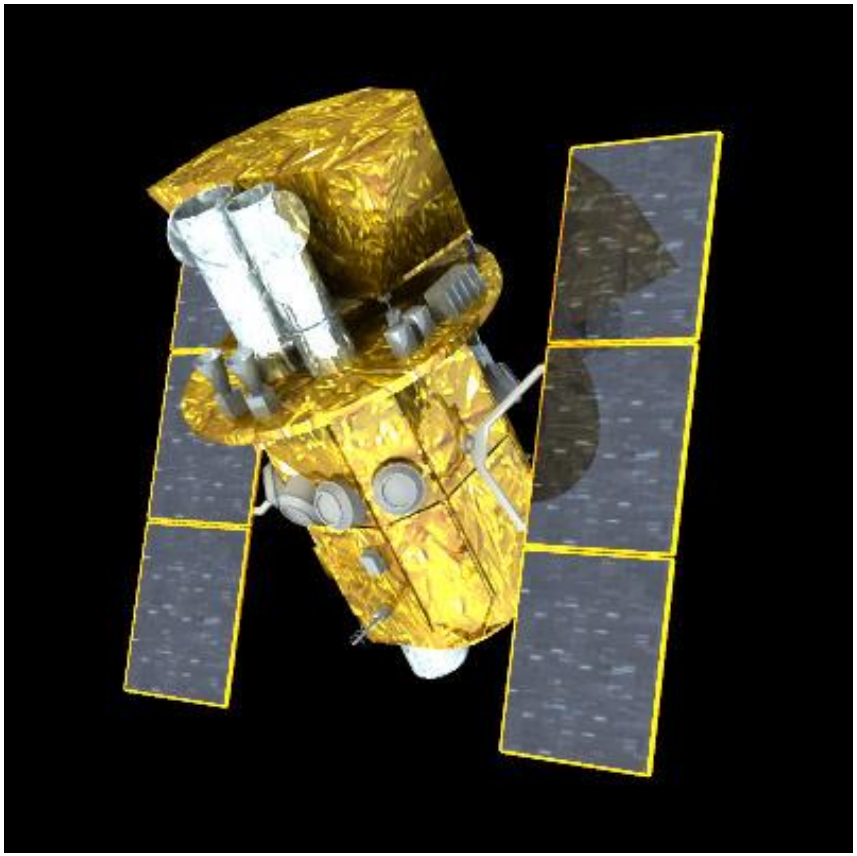
- Come from Space…

(Fermi, Swift, Gaia, …

- Or from Ground…

(various surveys)

- Speed of response depends on type of object…(e.g. GRB's= mns, SNe=hours, variable stars = days



SWIFT (2004): BAT 1.4 Str, PSF 17'
XRT 23' FoV, 18", UVOT 17', 2"5

To ground within 90 sec…!

Beaucoup de surveys depuis le sol…

- Not dedicated to SNe only… (e.g. lensing, planets)
- Mainly Near-Earth Orbiting asteroids…(fear!)
- Only partial sky coverage (e.g. North, or South…)
- Some data are public, others not
- CRTS, PTF/ZTF, PanStarrs, MASTER, OGLE, (LaSilla Quest), SkyMapper, Asas-SN, etc…

- **But all need a large amount of telescope time for follow-up !**

Catalina Real Time Survey

CSS 0.7m Schmidt
8.1 Square D, V 19.5

MLS 1.5m Cass
1.2 Squ D, V 21.5

SSS 0.5m Schmidt
4.2 Squ D, V 19.0

About 2000°² /night, 1-4 times per lunation

Telescope	All OTs	Supernovae	Cataclysmic Variables	Blazars	Asteriods/Flares	CV or SN	AGN	Other
CSS	4408	1345	854	241	314	511	573	660
MLS	4633	690	91	90	286	771	2155	756
SSS	697	105	254	18	12	109	33	171
SNhunt	197	197	0	0	0	0	0	0
Total	9935	2337	1199	349	612	1391	2761	1587

On average, only a ~ dozen objects confirmed spectroscopically per month!!

CRTS Data

1. Automatically selected transient candidates (updated in real-time, table info):

CRTS Events												
ID	New	Alert Time (UT)	Event Date (UT)	RA (deg)	Dec (deg)	R1	R2	R3	R4	Finder	Data Link	DataScope
1505301211124110625	yes	2015-05-30T11:36:37	2015-05-30T10:04:29	332.7153000	20.2232800	19.23	18.95	19.08	18.99	625	625	View data
1505301180584103599	no	2015-05-30T11:23:59	2015-05-30T04:46:32	169.4343000	17.2503600	12.83	12.80	12.80	12.83	3599	3599	View data
1505301150564112335	no	2015-05-30T11:08:55	2015-05-30T04:24:32	160.2136200	15.1927300	15.92	15.88	15.87	15.92	2335	2335	View data
1505301120584121330	no	2015-05-30T10:56:36	2015-05-30T04:27:26	165.0613900	13.2644400	14.35	14.35	14.39	14.37	1330	1330	View data
1505291291084133681	no	2015-05-29T11:03:01	2015-05-29T10:56:26	342.8520900	29.6629400	15.41	15.40	15.39	15.41	3681	3681	View data
1505291600484128199	no	2015-05-29T09:29:11	2015-05-29T09:31:56	258.5290600	60.7895700	15.16	15.16	15.15	15.16	8199	8199	View data
1505291460504131731	no	2015-05-29T06:10:01	2015-05-29T06:08:32	197.5486300	47.7525900	13.07	13.05	13.06	13.04	1731	1731	View data
1505291490504116681	yes	2015-05-29T06:07:17	2015-05-29T06:04:56	206.6053900	49.2058500	18.56	17.02	19.04	18.91	6681	6681	View data
1505291460544110639	no	2015-05-29T05:59:43	2015-05-29T06:02:46	215.1602200	46.0419400	13.70	13.68	13.69	13.67	639	639	View data
1505291460544131663	no	2015-05-29T05:59:43	2015-05-29T06:02:46	213.8091000	47.7873100	15.61	15.61	15.57	15.56	1663	1663	View data
1505291460624115886	no	2015-05-29T05:30:09	2015-05-29T05:33:24	246.8497000	46.1943700	18.90	19.09	19.29	19.15	5886	5886	View data
1505291460624138404	no	2015-05-29T05:30:09	2015-05-29T05:33:24	247.1566500	47.5694600	18.38	18.29	18.17	18.18	8404	8404	View data
1505291400514120160	no	2015-05-29T05:05:34	2015-05-29T05:01:27	184.2138500	41.3361100	18.41	18.22	18.30	18.55	160	160	View data
1505291400514125641	yes	2015-05-29T05:05:34	2015-05-29T05:01:27	183.6693700	41.8220000	17.51	17.42	17.57	17.51	5641	5641	View data
1505291350554114510	no	2015-05-29T05:00:33	2015-05-29T05:00:44	186.6448400	35.2194500	17.10	17.00	17.07	17.24	4510	4510	View data
1505291400534102756	yes	2015-05-29T04:56:44	2015-05-29T04:57:08	189.2142900	39.7543700	16.23	16.13	n/a	16.17	2756	2756	View data
1505291350584118330	no	2015-05-29T04:52:08	2015-05-29T04:54:14	194.5389000	35.3286300	16.02	16.04	16.04	16.05	8330	8330	View data
1505291460464129735	no	2015-05-29T04:43:41	2015-05-29T04:26:23	182.2812700	47.6002600	13.50	13.51	13.49	13.50	9735	9735	View data
1505291460464129856	no	2015-05-29T04:43:41	2015-05-29T04:26:23	182.2814000	47.5918400	14.32	14.36	14.35	14.36	9856	9856	View data
1505291460464118043	no	2015-05-29T04:43:41	2015-05-29T04:26:23	182.9139900	46.6624300	18.89	18.94	18.64	18.80	8043	8043	View data

Autres Surveys dans le nord: ZTF

- D'abord Palomar Transient Factory

Uses the 1.2m Schmidt, with
a 12k x 8k camera, since ~ 2009
2d release in August 2015 (but < 2012 !)

Supernovae Discovered by PTF			
All SNe	SNe Ia	SNe Ibc	SNe II
2,367	1,587	107	587

- Then iPTF 2013-2016 (refurbished)

R band, 60 sec, ~ 20.5m - 3σ, More SNe
(cadence: few mn to ~ 5 days, depending on topic)

- Now ZTF 2017-2023--, new 47°² camera,
high cadence to 21th mag., full (N-)sky every night
- Follow-up with the 1.5m and 5m telescopes at Palomar…

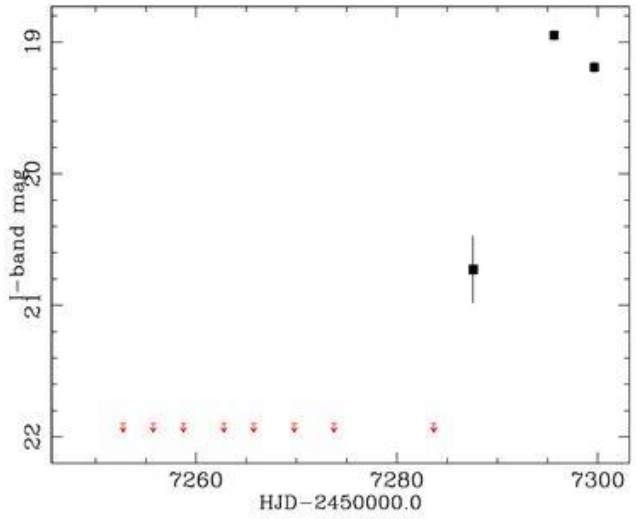
(SN Factory used NEAT cameras, Palomar + Maui,
+ 2.2m MaunaKea with SNIFS (IFU))

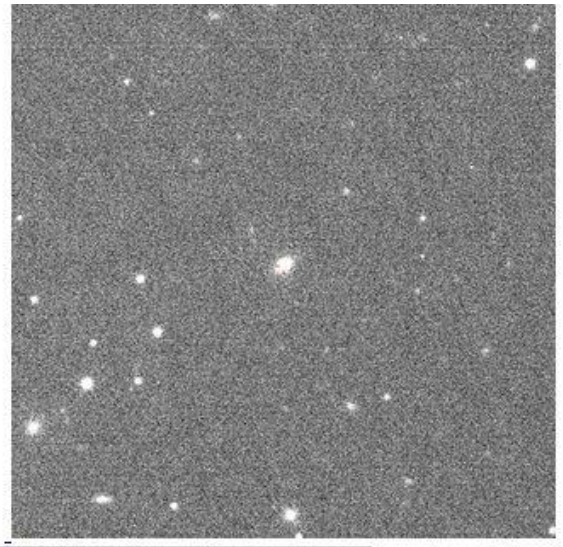
Et encore…

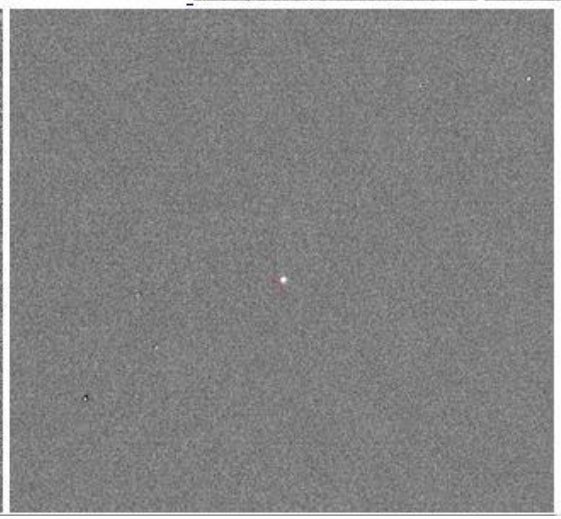
- MASTER (Russia) 40cm tel, FOV 8 squ. deg.,
~ 20th mag, + smaller VWF (14th mag)
(Kislovodsk, Ural, SAAO, IAC,…)
No spectral classification…!
- Pan-Starrs PS1 1.8m in Haleakala
8 x 8 (4k x 4k) OTA-CCD's, ~ 3° FOV, ~ 24th mag.
Data not public immediately…2d Telescope operating
- ASAS-SN: V 17, Hawaii: 4x14cm, CTIO: 4x14cm
½ sky per night; 150th SN in May 2015, 400 in Nov. 16
- "Publishing" on Atel or AstroNotes (TNS)

Southern surveys

- **OGLE IV**: 1.3
  Grav. Lensing, F
  32, 2k x 4k CCD
  50-70 fields/ni
  3000°² covered
  now extending
- Early Warning
- On-line data b







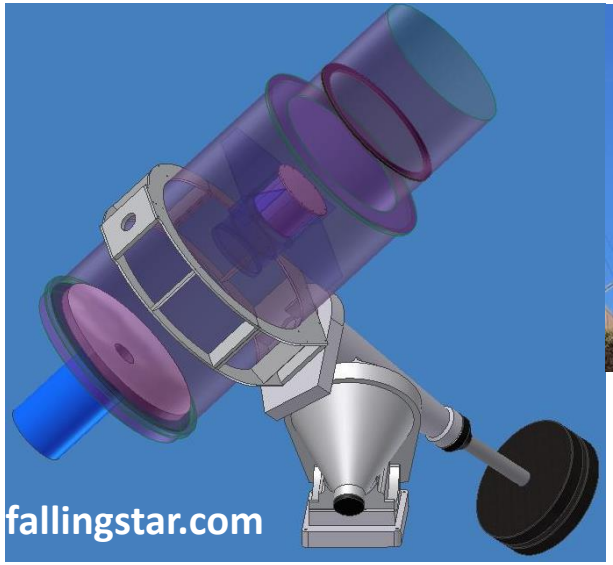
En 4 ans: 457 SN candidates, 119 class. (1/4)

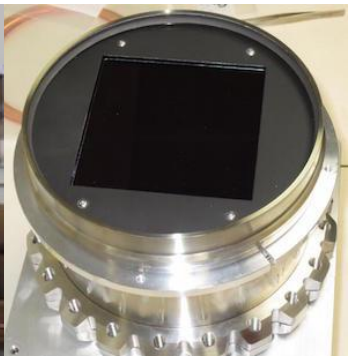
Now: OGLE-V

Autres surveys dans le Sud:

- LaSilla Quest: Yale at ESO 1m Schmidt, 10°², 112 CCD's
  from Sept. 2009 till March 2016
  2 day cadence, south of +25°, 60s exposures (21.5 mag)
  390 out of 459 candidates are SNe…
  (classified mainly by PESSTO…) Terminé 2016
- SkyMapper: 1.35m telescope in Siding Springs
  20' field, 100s exposures, ugriz, 19-21 mag
  mainly Galaxy and MC's stars…
  but some SN search also (follow-up mainly at MountStromlo)

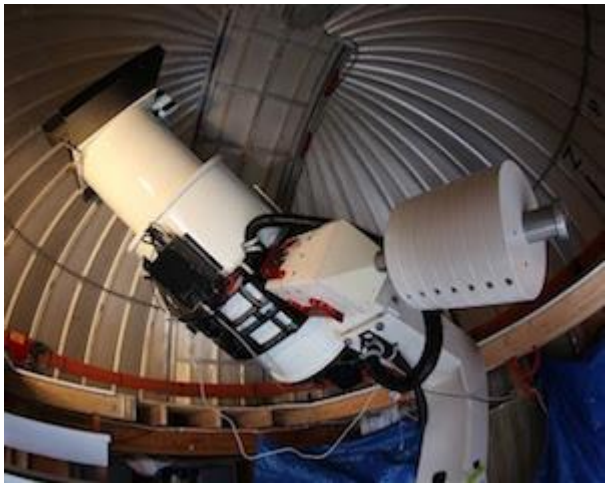
ATLAS : Asteroid Terrestrial impact Last Alert System





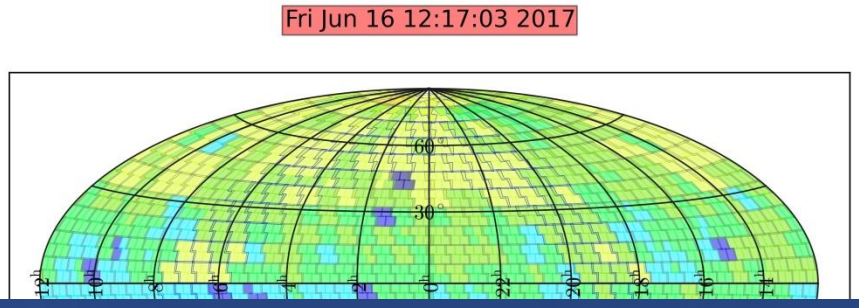
NASA funded (PI: J. Tonry)
Project team (IfA): Tonry, Denneau, Stalder, Koposov, Rest
QUB software team : Smith, Smartt
2 Units : Haleakela and Mauna Loa

- 2 x 50cm Schmidt telescopes : 7^{o} diameter, with 10k x 10k CCDs (from STA), 1”8 pixels
- **60,000 sq degrees per night , to Mag. ~ 20**
- ***All sky (from δ -40° up) twice per night to m ≈ 20 (W-band AB)***
- *Installed and running,* Science started from July/August 2015
- Huge potential for all sky (north of -40) transient searches
- Data available via Transient Name Server
- So far, 36 NEA, 5 hazardous, 5 Comets,
- 553 Supernovae !



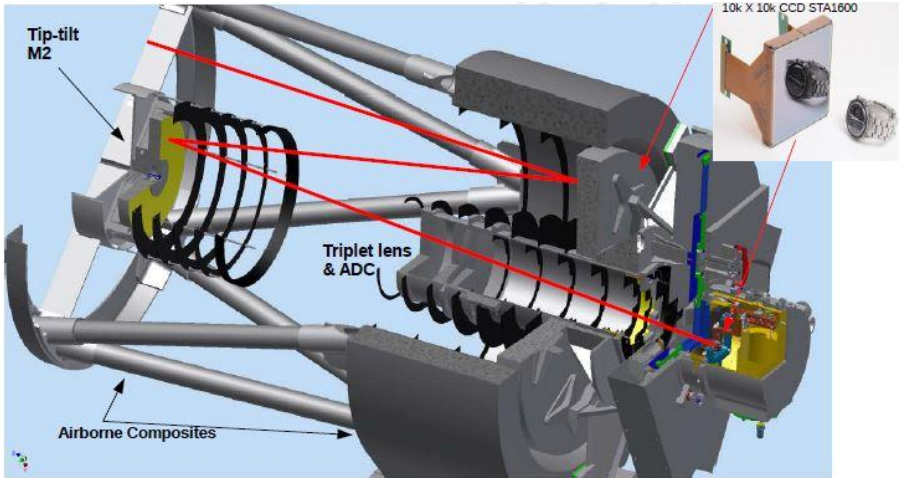
ASAS-SN or… SSST ! (by OSU)

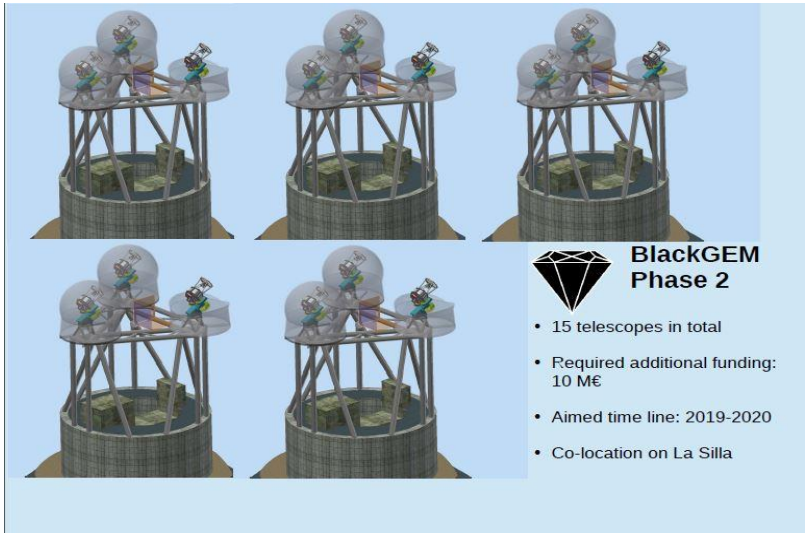
- 4 x 14cm in Haleakala
- 4 x 14cm at CTIO
- 8 more to come
- 20,000 square d /night ! to V ~ 1
- 480 SNe, 58 in 2
- Published on At
- Many other vari



Black GEM - MeerLicht

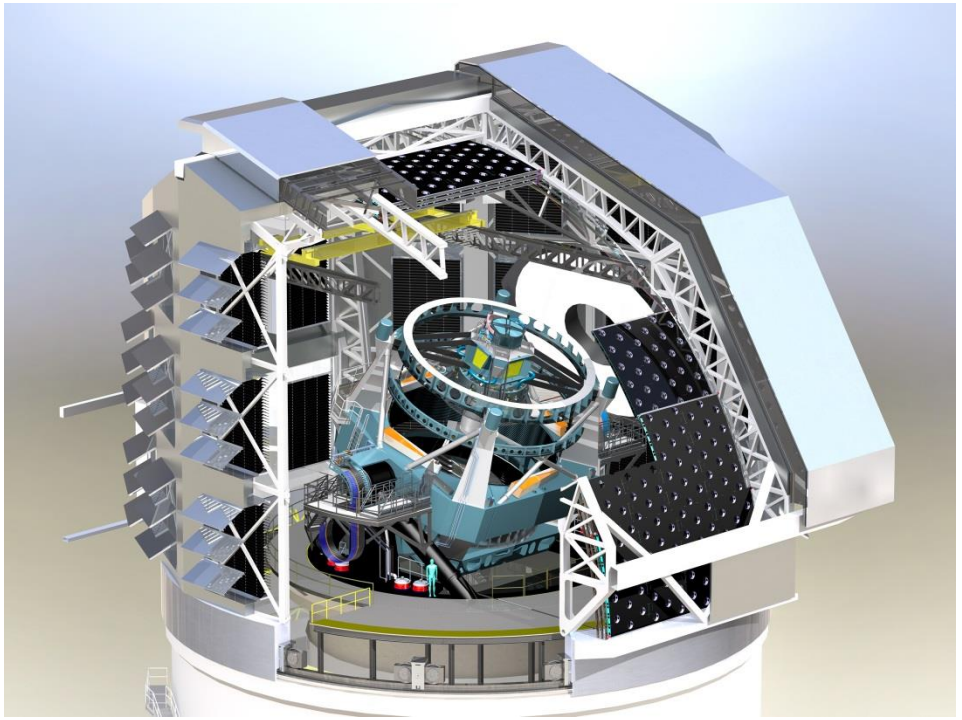
- Dedicated optical array for Gravitational Waves
- 15 telescopes Ø 65cm
- FOV 2.7 ^{o2}, total 40+
- u,g,r,l,z,q, 0”57/pix
- ESO LaSilla (GPO site)
- Prototype tel. 2017, ZA
- 15 in 2020-2023 in Chile
- Radbout Univ. (NL), Paul Groot PI
- 100 KE for joining…





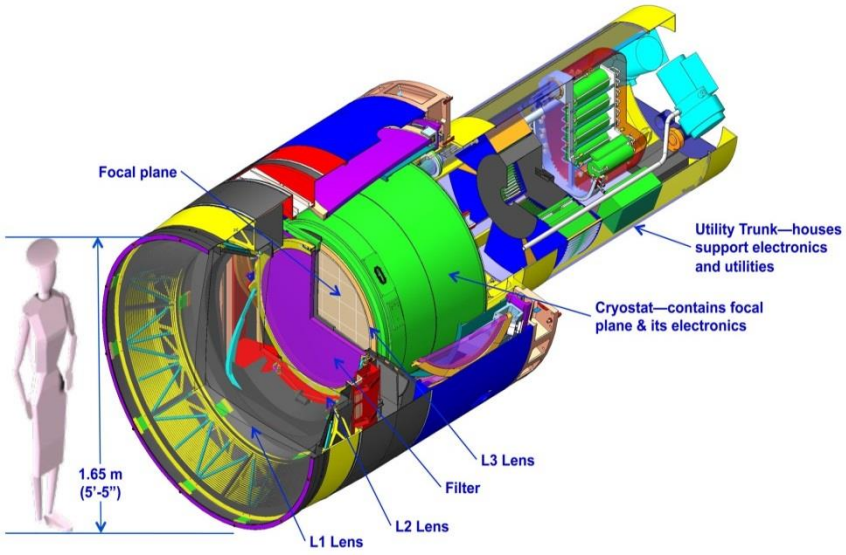
The Large Synoptic Survey Telescope (Vera Rubin telescope)

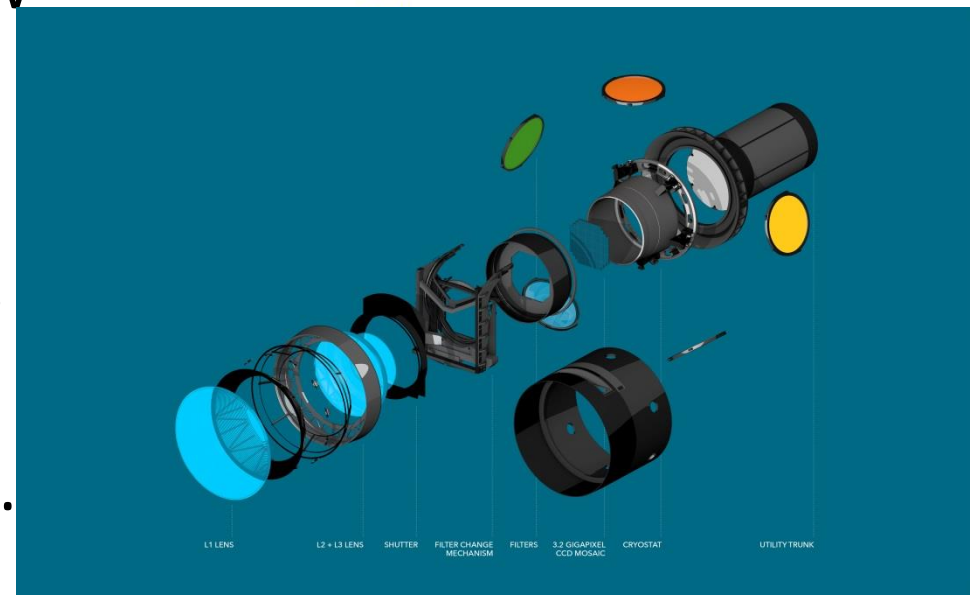
- 8.4m telescope
- 3.5° FOV
- ugrizy filters
- 22-25 mag/visit
- Cerro Pachon
- Start: ~ 2023



La camera du LSST et la strategie

- 189 4k x 4k, 10µ, CCD' s
- Readout 2 sec !
- Pairs of exposures: 15s +1s +2s +15s +1s +5s, thus new position every 39s
- Revisit after 15-60 mn
- Visit pairs every 3-4 nights
- + special (deep, 1h; fast time domain; LMC-SMC; …





Total: 2 10^{10} Gal., and Stars; ~ 2 10^{6+} alerts per nights….

Alertes depuis l'Espace: GAIA Scanning Trigerred by Vis. Phot.: (Full Sky Coverage)

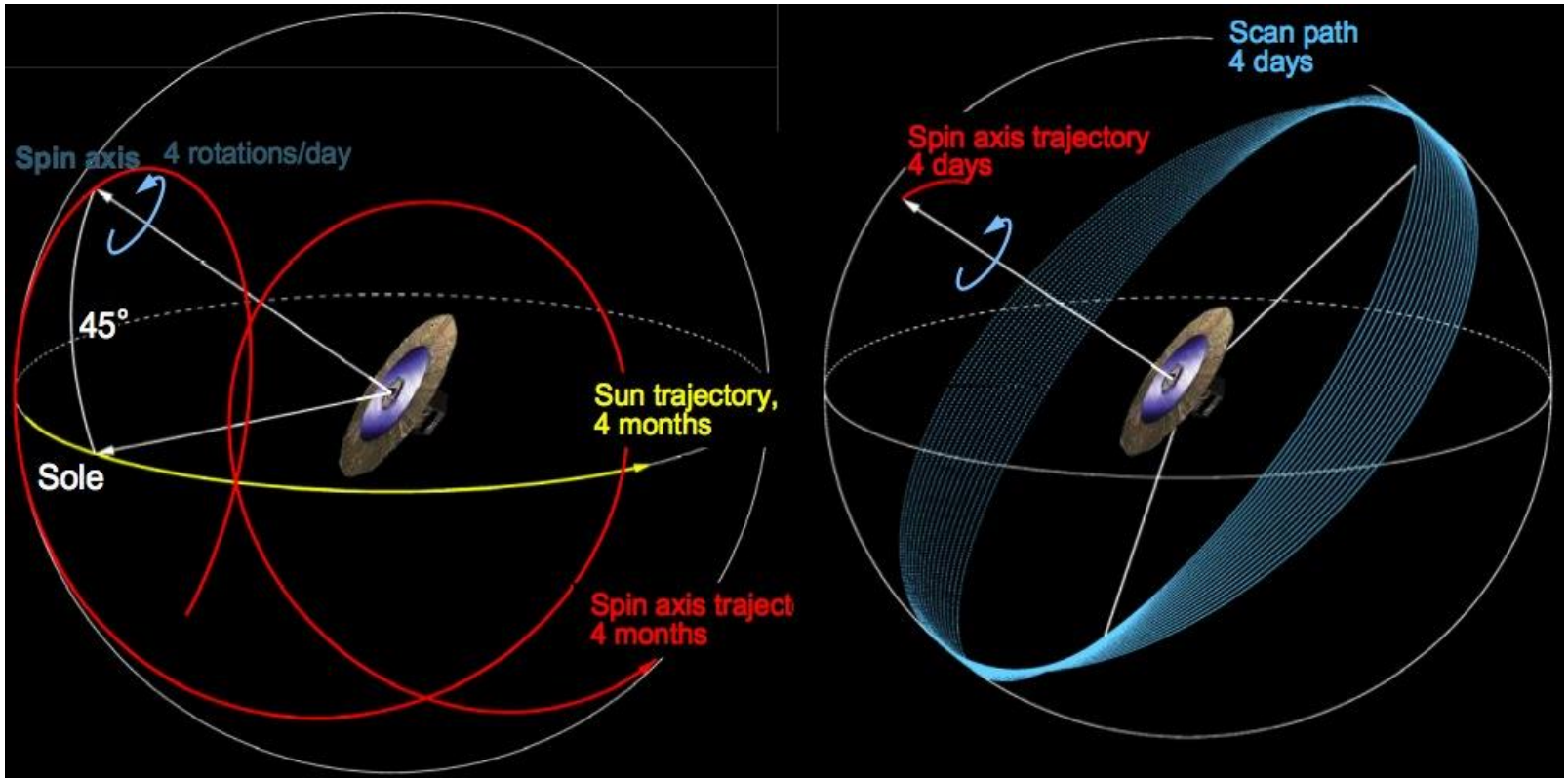
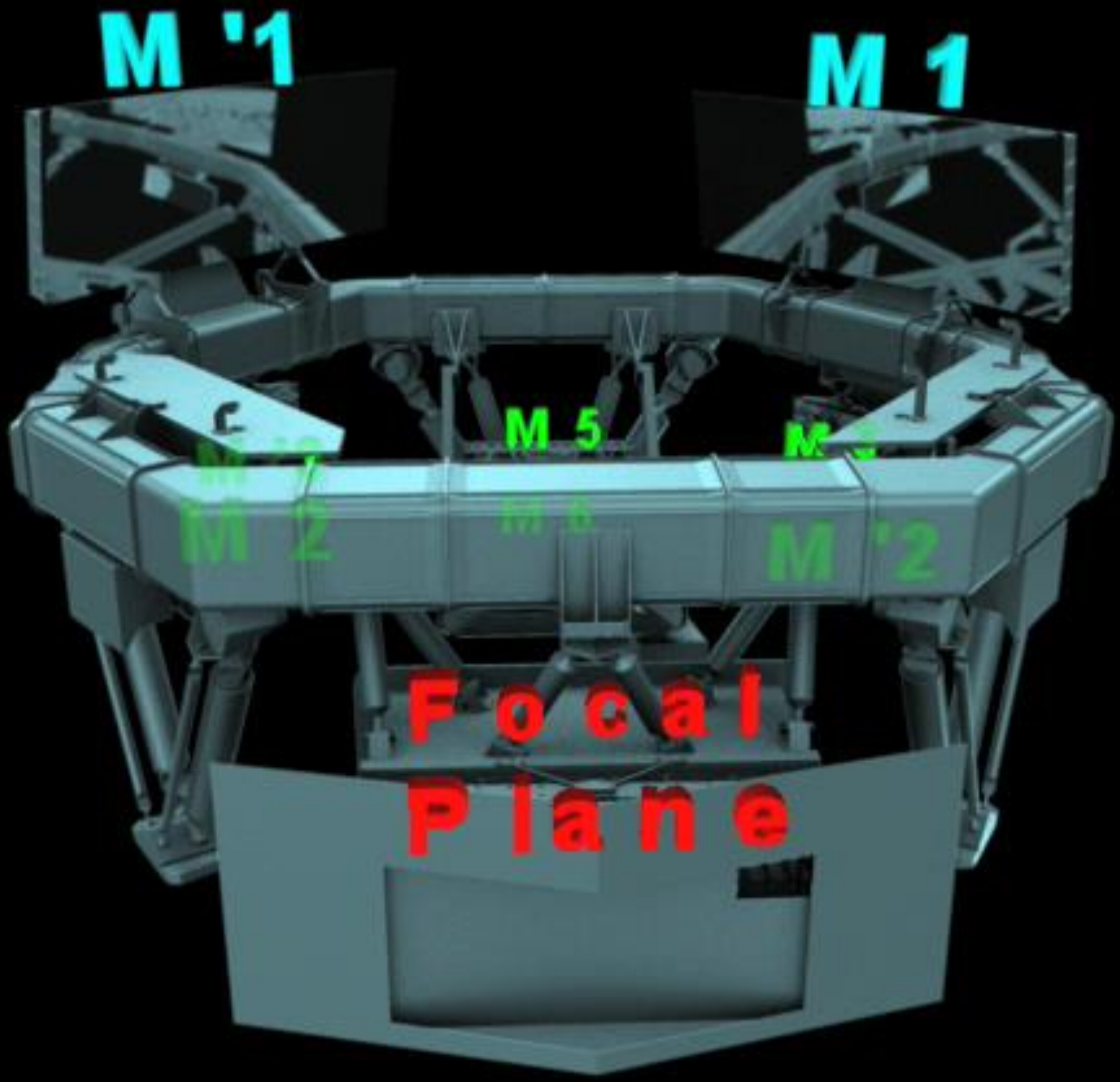
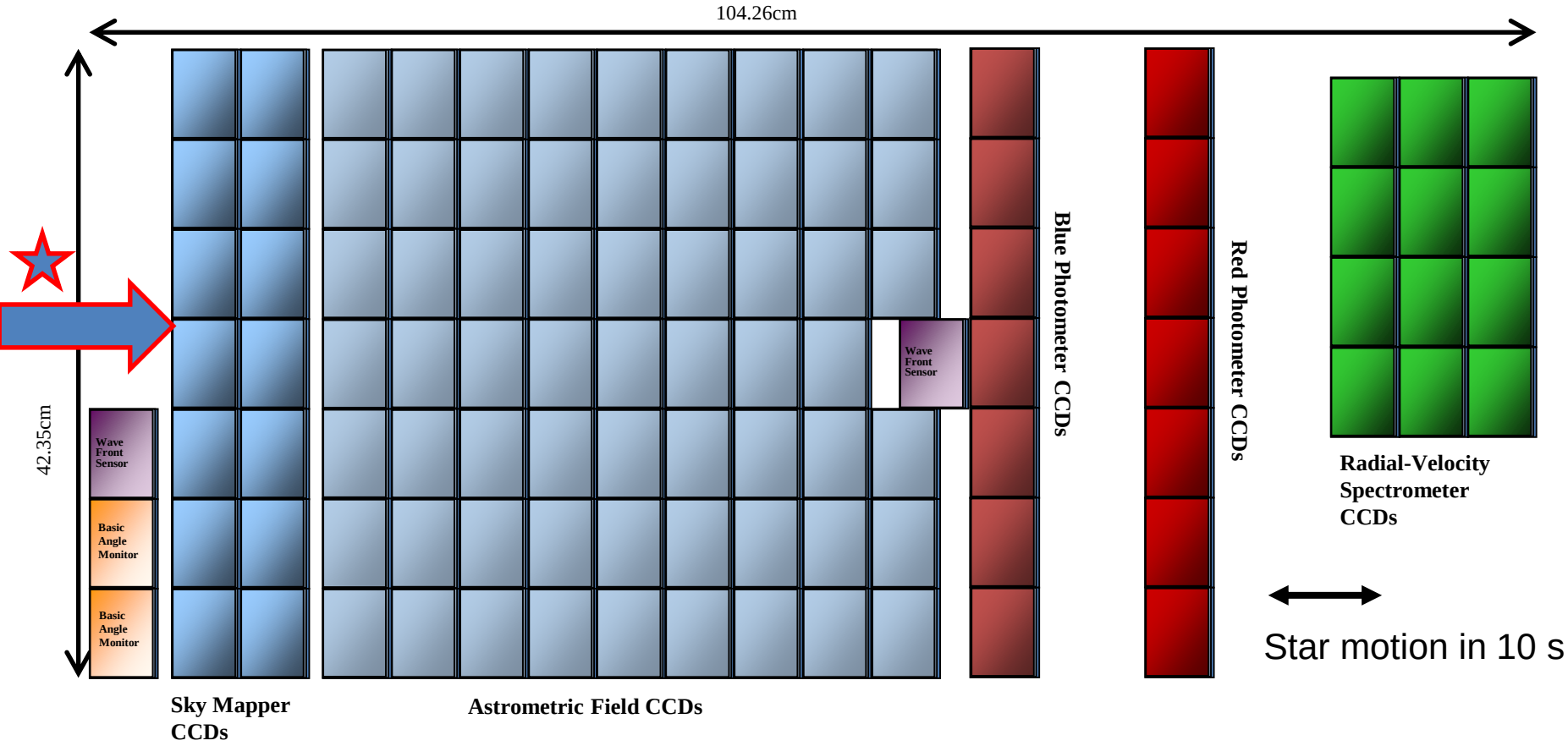


Figure courtesy Karen O'Flaherty

Spin axis :	45° to Sun
Scan rate:	60 arcsec/s (1° / mn)
Spin period:	6 hours
Precession:	63 days


M '1
M 1
M 5
M '2
Focal
Plane

Focal Plane



Total field:

- active area: 0.75 deg^2
- CCDs: 14 + 62 + 14 + 12
- 4500 x 1966 pixels (TDI)
- pixel size = 10 µm x 30 µm
  = 59 mas x 177 mas

Sky mapper:

- detects all objects to 20 mag
- rejects cosmic-ray events
- FoV discrimination

Astrometry:

- total detection noise: 6 e$^-$

Photometry:

- spectro-photometer
- blue and red CCDs

Spectroscopy:

- high-resolution spectra
- red CCDs

Figure courtesy Alex Short

GAIA Alerts

- Time coverage:
  - 4.4 sec/CCD, ~ 40 sec total crossing time
  - 106mn (two independant viewings, 1'/s)
  - 6 hours (spin rate)
  - Again after 63 days (precession period)
  - On average, 80 times over 5 years

- Alerts generated on photometric variablity on those irregular time scales (except maybe the shortest one)

Timeline for the data flow

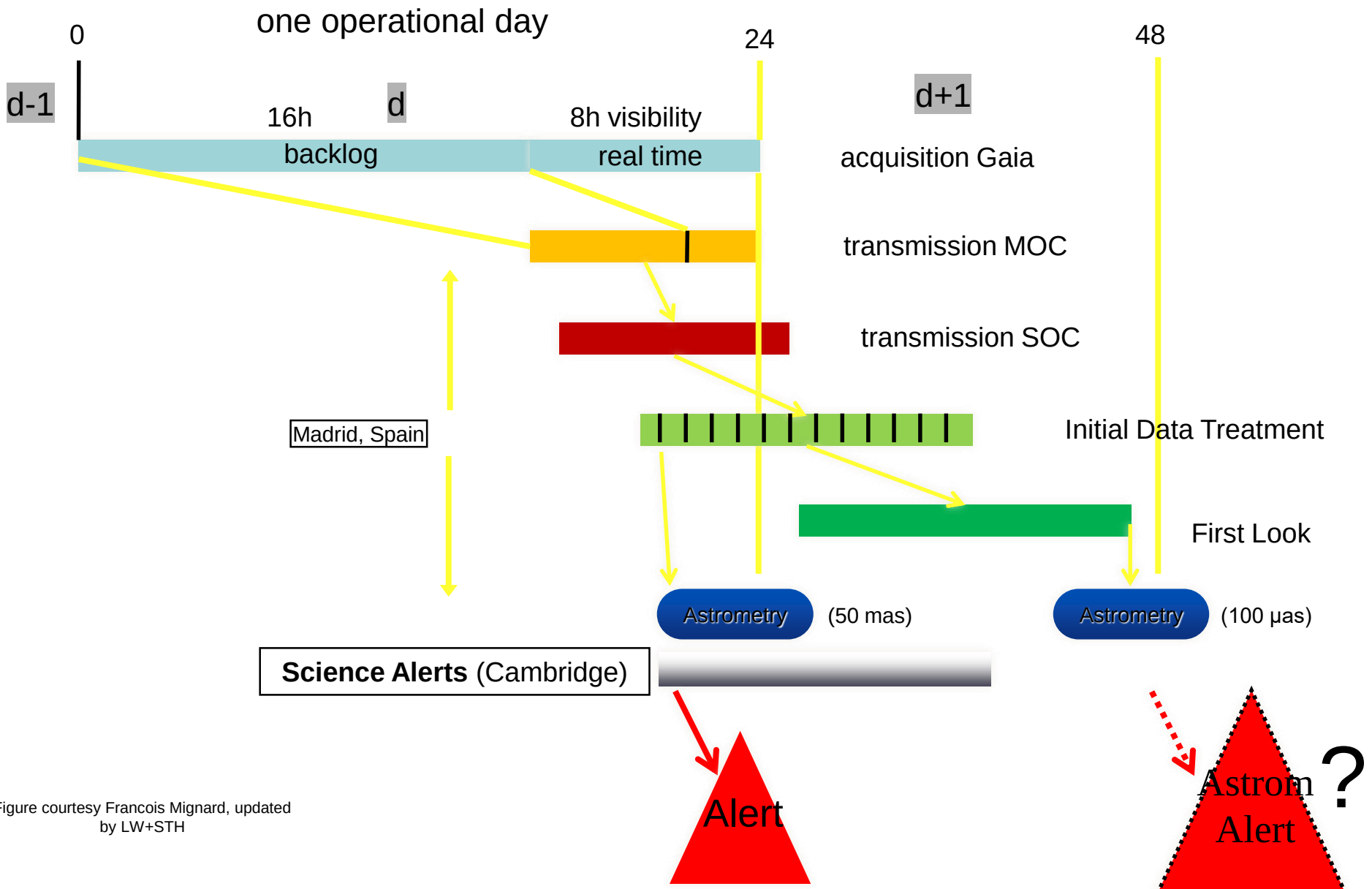


Figure courtesy Francois Mignard, updated by LW+STH

Alertes Gaia: Exemples

Show 10 entries

Search:

Name	TNS	Observed	RA (deg.)	Dec. (deg.)	Mag.	Historic mag.	Historic scatter	Class	Published	Comment
Gaia16ceu	AT2016jaa	2016-12-21 19:00:35	149.13117	-3.66027	18.62			unknown	2016-12-23 10:18:48	candidate SN near galaxy 2MASX J09563092-0339454
Gaia16cet	AT2016izz	2016-12-21 21:25:17	324.40953	-22.30277	18.65			unknown	2016-12-23 10:15:30	blue transient near galaxy MRSS 531-134909, GS-TEC predicts SN Ia
Gaia16ces	AT2016izy	2016-12-21 02:00:56	181.46059	-67.95879	17.17			unknown	2016-12-23 10:12:49	hostless blue transient near Galactic plane
Gaia16cer	AT2016izx	2016-12-21 01:47:48	167.33976	-55.03898	18.67			unknown	2016-12-23 10:10:37	hostless blue transient near Galactic plane
Gaia16ceq	AT2016izw	2016-12-21 14:46:30	149.42166	-3.21282	17.74			unknown	2016-12-23 10:08:15	rising candidate SN, GS-TEC predicts SN Ia
Gaia16cep	AT2016izv	2016-12-21 01:02:17	151.68953	-6.19608	18.36			unknown	2016-12-23 10:04:07	blue transient, candidate SN near galaxy 2MASX J10064452-0611584
Gaia16ceo	AT2016izu	2016-12-21 01:02:25	151.69571	-6.34140	18.76			unknown	2016-12-23 09:59:56	hostless blue transient
Gaia16cen	SN2016ijc	2016-12-20 10:54:49	321.46732	-37.40385	17.62			SN Ia	2016-12-22 23:07:35	confirmed SN Ia near galaxy 2MASX J21255058-3724071
Gaia16cem	AT2016izt	2016-12-20 08:03:07	193.13214	-69.08113	18.56			unknown	2016-12-22 23:04:59	blue transient
Gaia16cel	AT2016izs	2016-12-10 10:04:14	267.80840	-75.26208	20.39			unknown	2016-12-22 23:03:52	rising, hostless, blue transient

Showing 1 to 10 of 1,750 entries

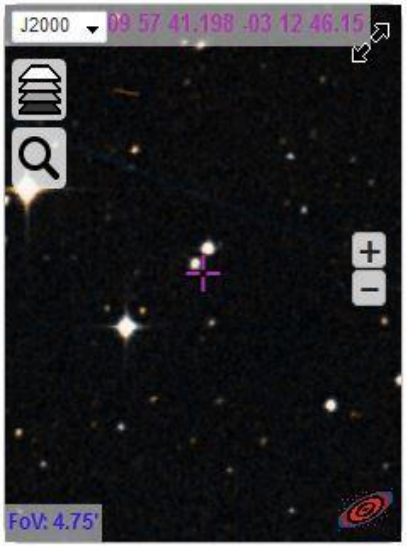
Previous 1 2 3 4 5 ... 175 Next

http://gsaweb.ast.cam.ac.uk/alerts/alertsindex

Details: comment, finding-chart, light-curve, SED, etc…

Gaia16ceq

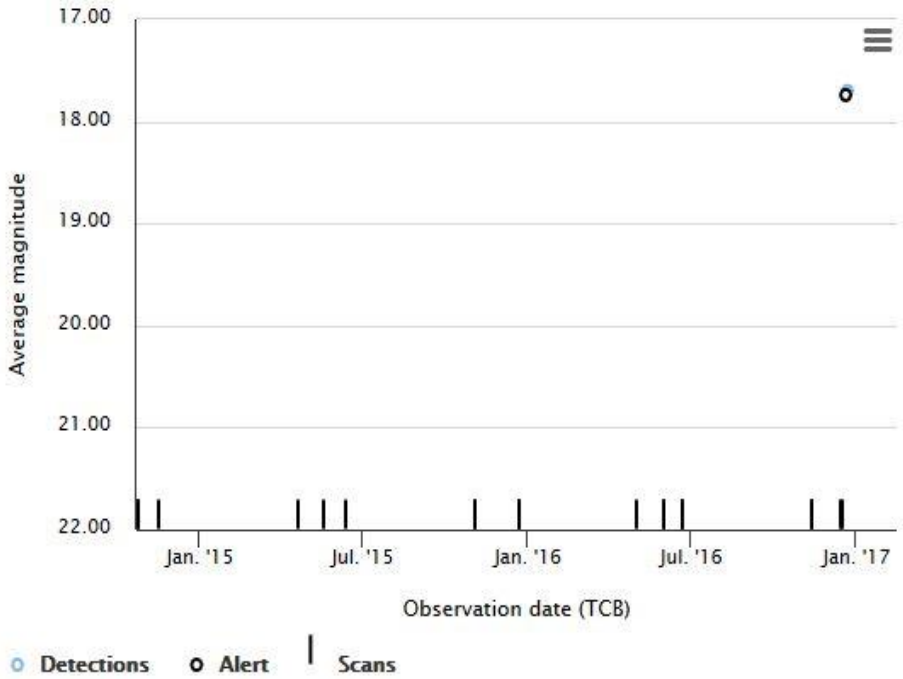
Details | Follow-up



RA - DEC
149.42166 -3.21282
09:57:41.20 -03:12:46.15

Alerting date
2016-12-21 14:46:30
Julian date
2457744.12
Alerting magnitude
17.74
Historic magnitude
None
Historic StdDev
None
Class
unknown
Publication date
Dec. 23, 2016, 10:08 a.m.

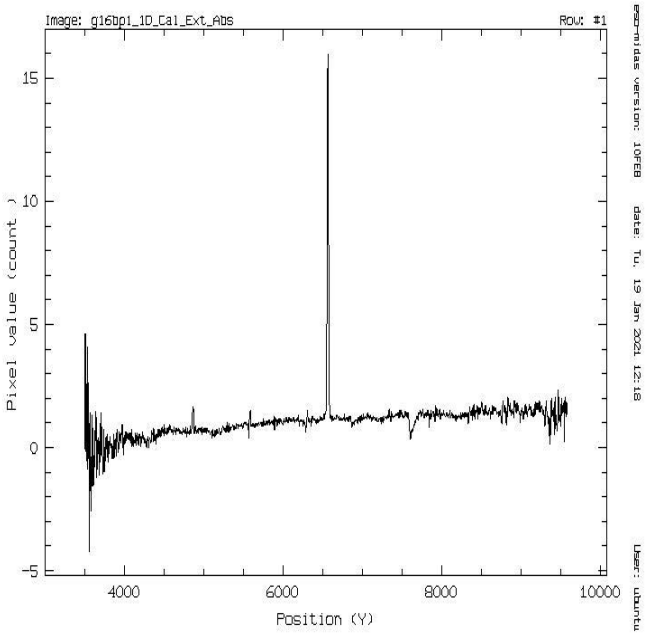
Other surveys detections
None
Comments
rising candidate SN, GS-TEC predicts SN Ia
ATels
None

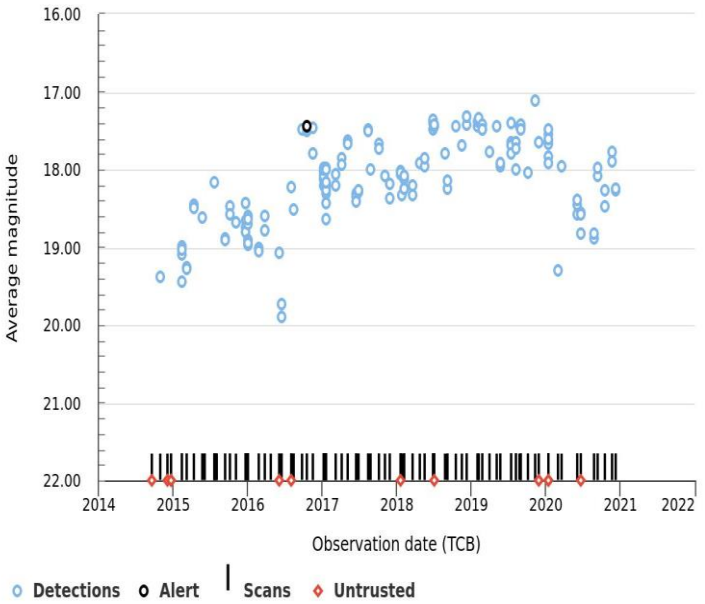


Get lightcurve data

Follow-up necessary…

- Any telescope > ~ 2m for spectroscopy
- Classification of « older » objects





Be, or YSO, not AGN as thought…

GAIA Alerts: Expected results

- Millions of « ordinary » variable stars
- ~ 70,000 RR Lyrae, ~8,000 Cepheids
- ~ 100 Novae/yr: complete Galactic census
- Symbiotic stars, Be stars, LBV's, etc...
- Cataclysmic variables: full census to ~2 kpc
- ~ 6000 SNe /5yrs, ~ 1/3 before maximum
- Thousands of AGN'S and Quasars (+10^6 ...)
- Orphan γ-rays burst, etc...
- **and many UNKNOWNS !**

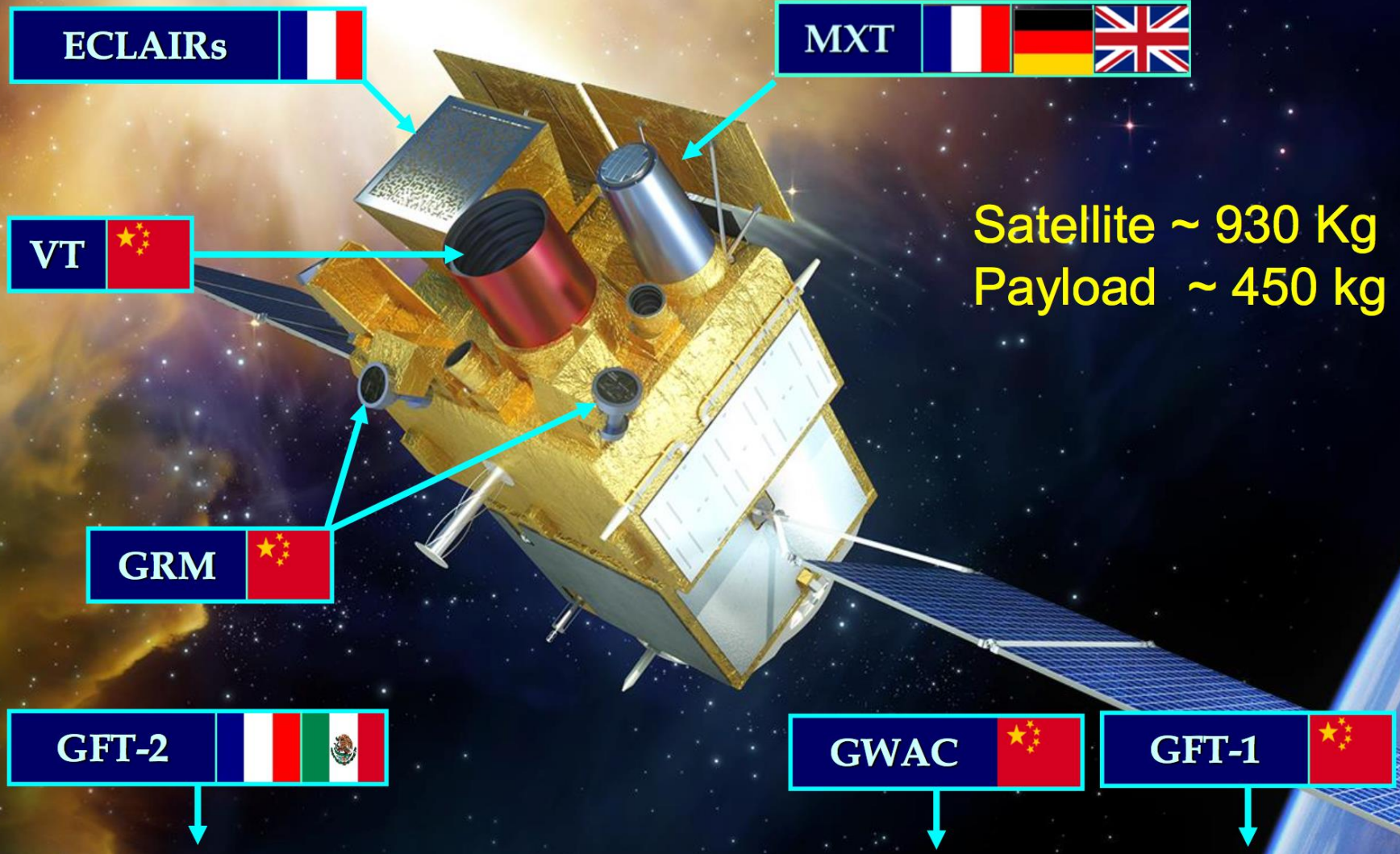
All brighter than V ~ 19.5 - 20

GAIA Alerts: present situation

- At the moment, ~ two dozen per day
- Semi-automatic selection (irregular…) but human intervention…
- Δm ~~ 0.5 mag, to avoid false alerts
- Try to do pre-classification with BP, RP (60%)
- Early classification improving
- Found SNe, CV, eruptive stars, ….
- Many AGN's (or TDE's ??)

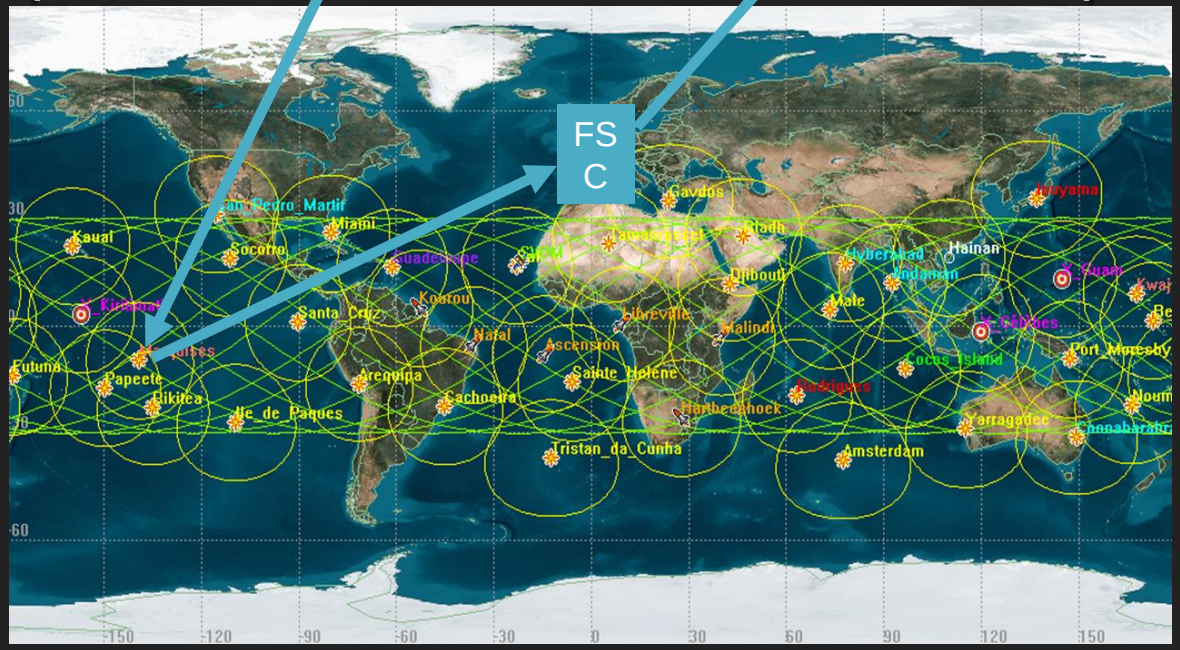
- GAIA alerts worskhop every year, since 11 years!

SVOM scientific instrument arrangement

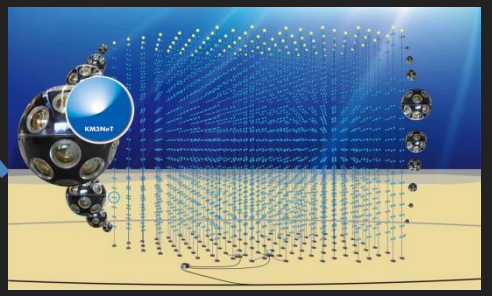


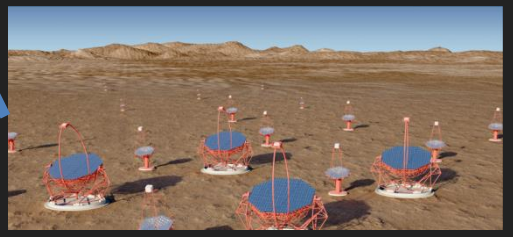
Alerts from space: Top-down
SVOM alerts triggered by Eclairs

Alerts are sent through VHF link
(65% of the alerts received within 30s)



GCN
VOEvent





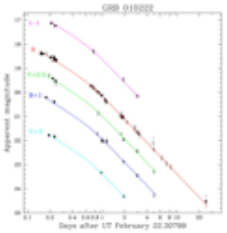
All transients
will be notified

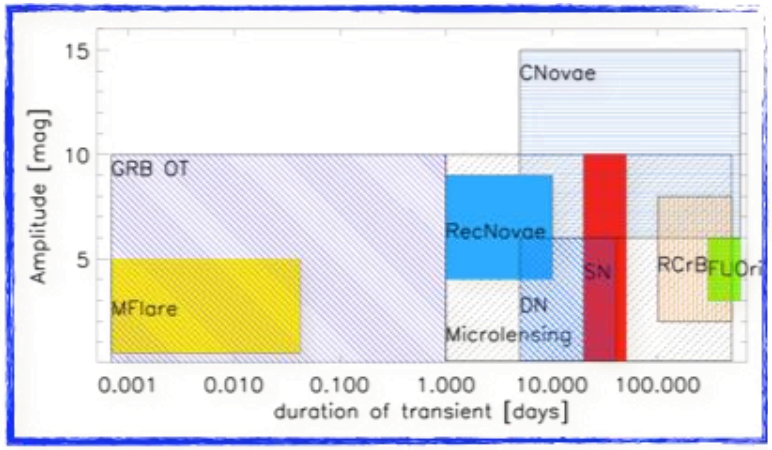
Pas la peine d' attendre LSST… ou SVOM…

- Il y a beaucoup a faire avec les surveys actuels…
- Entrainement, Stratégie de sélection ?
- Choisir les domaines scientifiques
- Organiser/coordonner le suivi
- Mobiliser les communautés
- Moderniser l'équipement
- Enroler les amateurs et le public

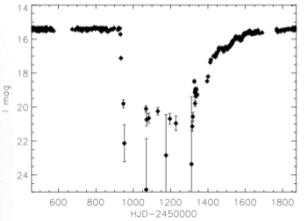
Potential Triggers

GRBs optical counterparts

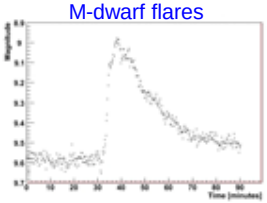




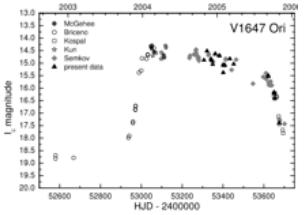
R Coronae Borealis



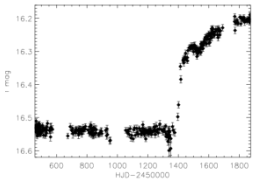
M-dwarf flares



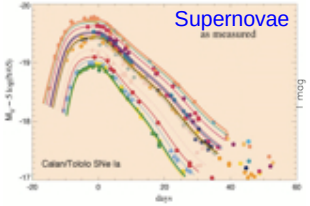
FU Orionis and similar

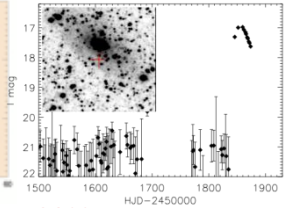


Be stars

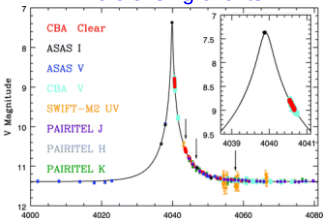


Supernovae





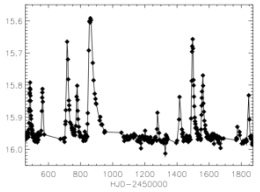
Microlensing events



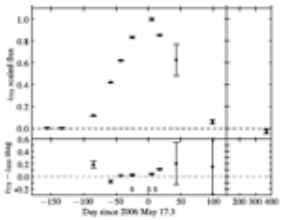
Asteroids

QuickTime™ and a
GIF decompressor
are needed to see this picture.

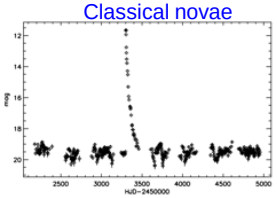
Dwarf novae



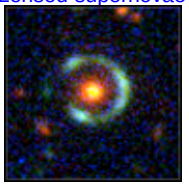
NEW THINGS??



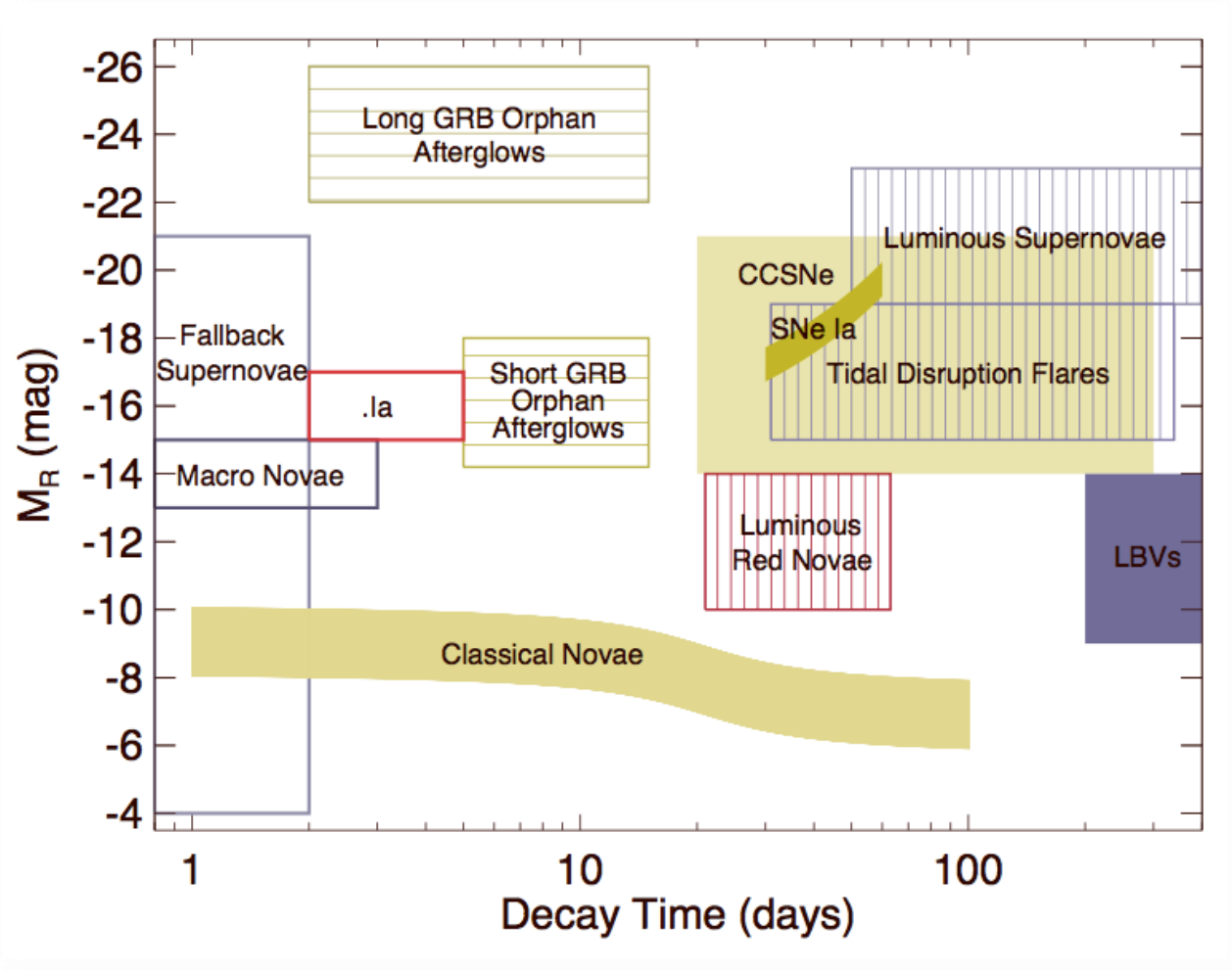
Classical novae



Lensed supernovae



The transient zoo



EXPLORING THE OPTICAL TRANSIENT SKY WITH THE PALOMAR TRANSIENT FACTORY, Kulkarny et Kasliwal 2009

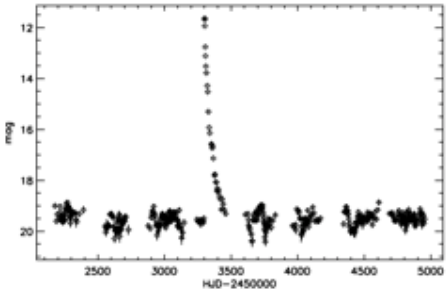
Cf. Kulkarny and Kasliwal (2009)

Distinguish between transient, and variable source!

Other interesting triggers

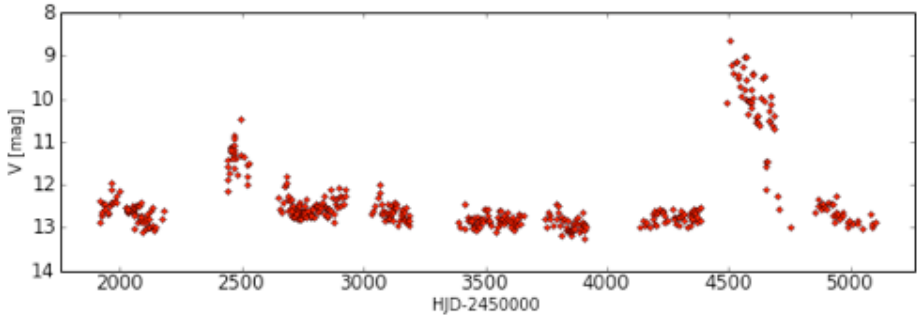
Classical and recurrent novae

- potential distance indicators
- can be detected in MW and other galaxies
- large amplitudes, wide range of time-scales



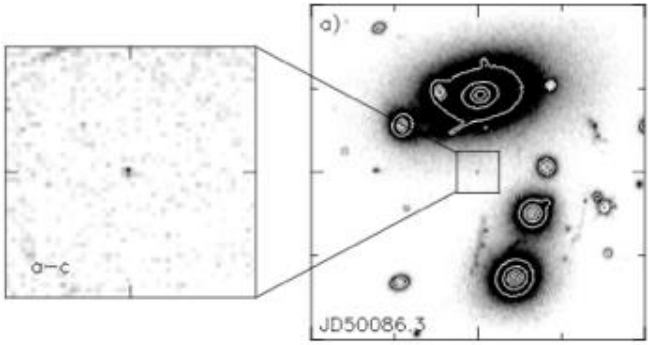
FU Orionis/EX Lupi

- unstable pre-MS stars
- rare class (few known)
- several magnitudes up
- X-ray variability
- long time-scales
- FU Ori repeats every ~40 years!



Gravitationally lensed distant supernovae

- unique uniform all-sky monitoring
- high redshift SNe rates, distances, H0



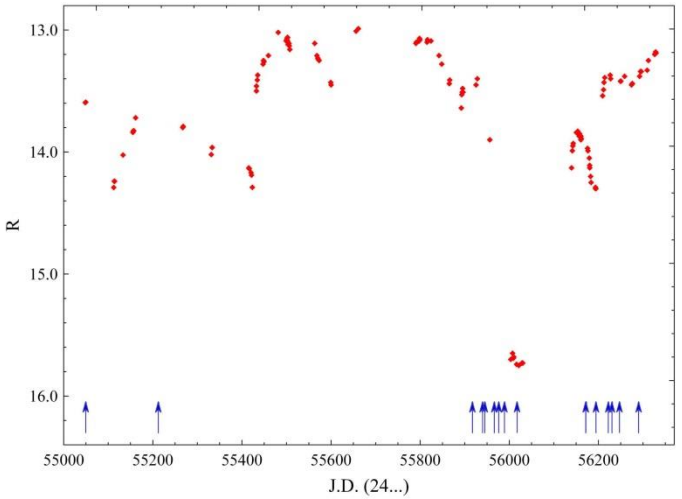
Tidal Disruption Events

- tens of candidates found so far

Exemple de V582Aur: FU Or type

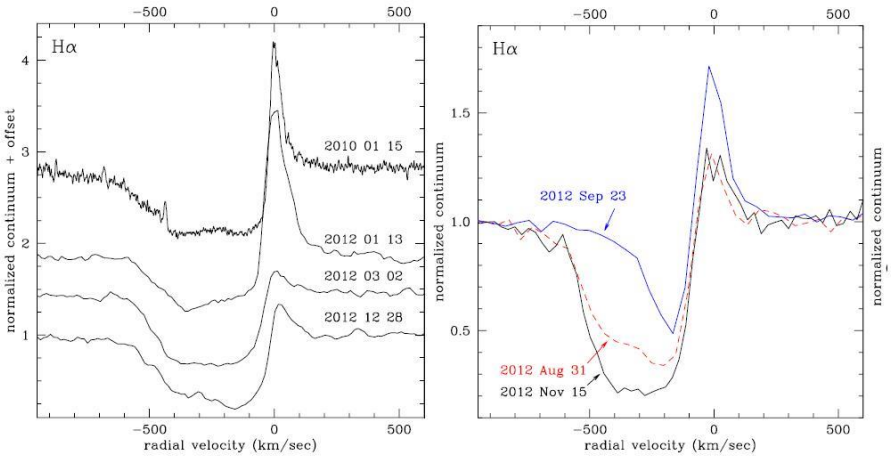
- Photometric monitoring

Variations = changes in accretion rate from circumstellar disk



- Spectroscopy:

Variation in Hα profile = strong, time-variable outflow ?



Semkov et al., 2013

R CrB-type stars

Very few known (~50), but ~3000 expected

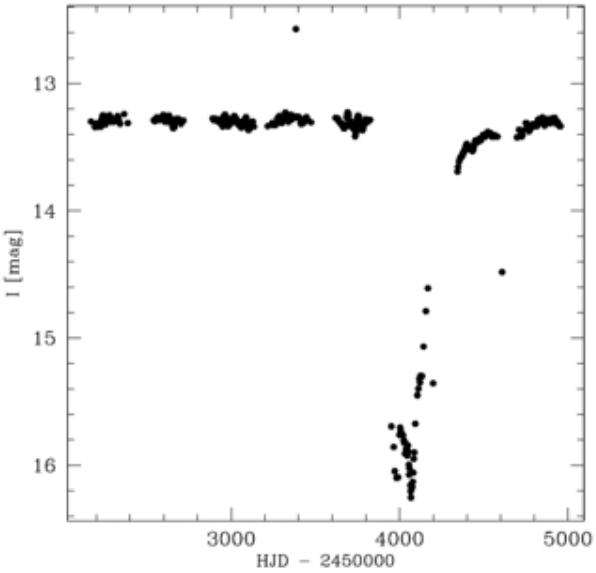
can drop up to 8 mag in brightness over a week - ideal time-scale for Gaia sampling

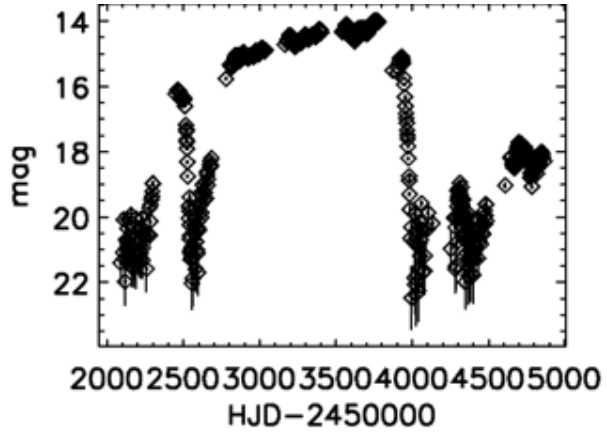
mechanism of these dimings remains unknown

most found in the Bulge and MCs by microlensing surveys EROS, MACHO, OGLE

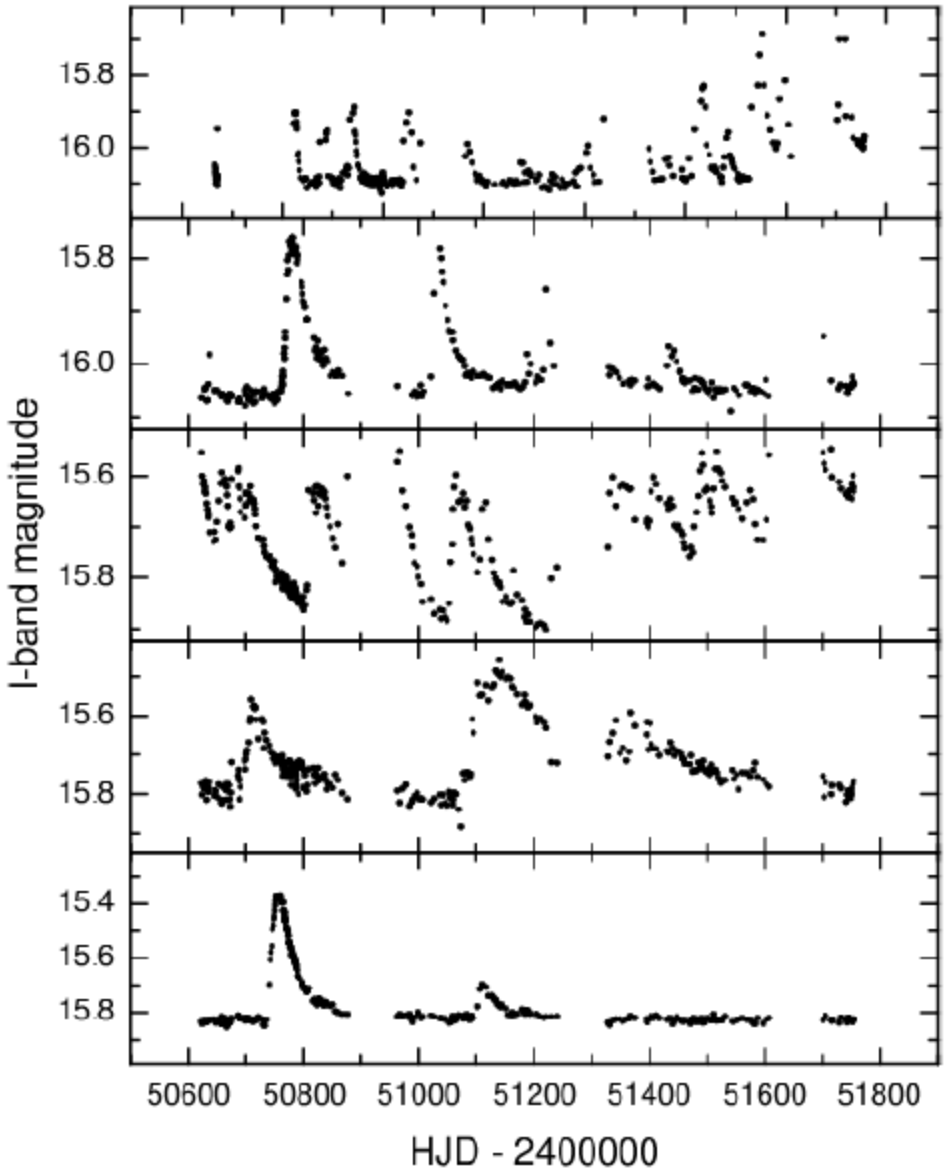
Gaia easily finds new much fainter RCrB

Spectroscopic follow-up during the event can help solve their mystery





Exemple of Be stars



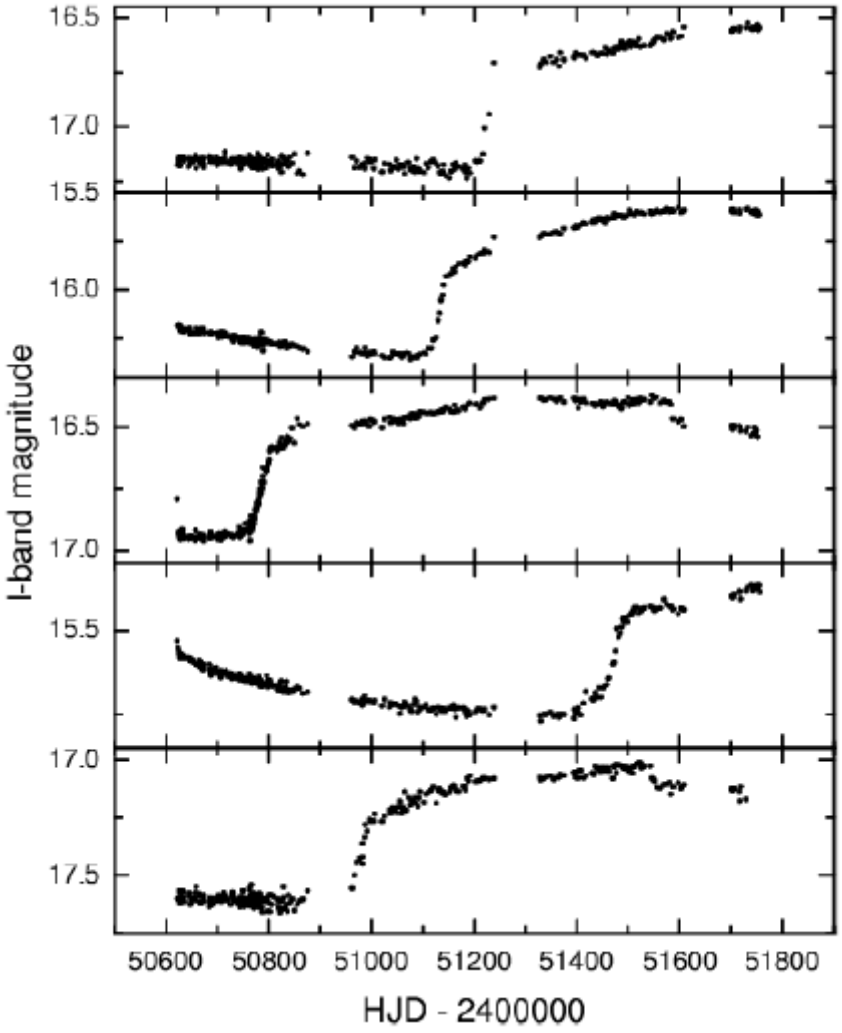
Bumpers…

The sudden rise (some days) or decrease of light can reveal the presence of discrete mass ejections that interest the study of the Circumstellar Envelope formation

Be stars
in the **SMC**

Mennickent et al. 2002
A&A 393, 887

Be stars with « light step »



Light steps…

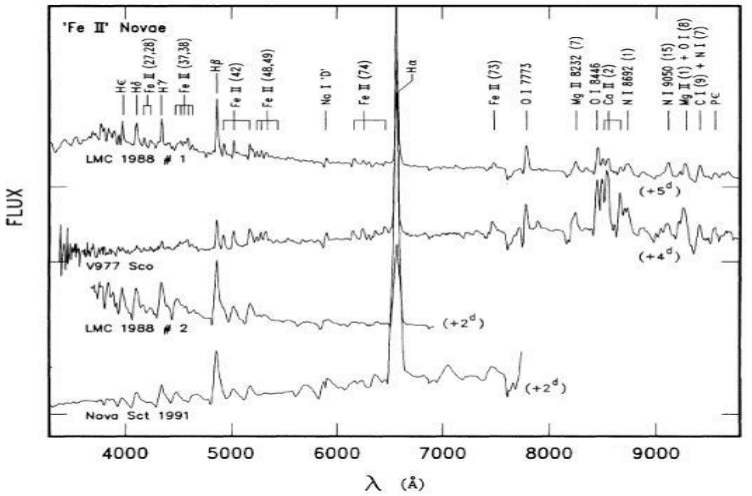
A light step can be due either to a sudden loss of an absorbing CE or the formation of an emitting CE envelope

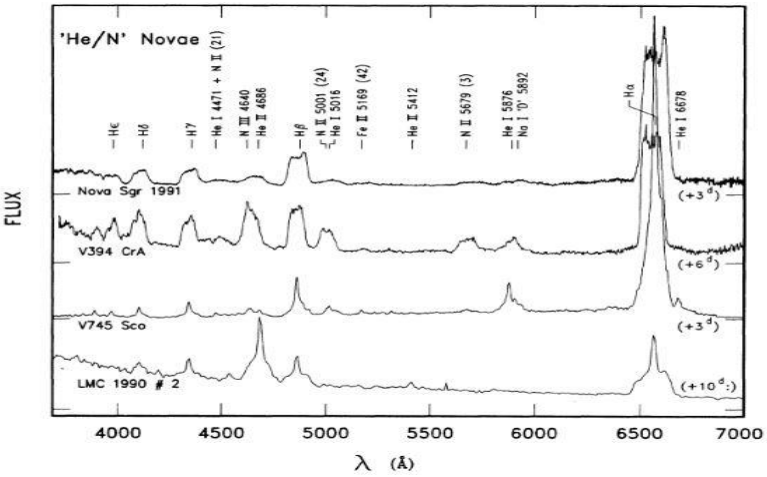
Be stars in the **SMC**

Mennickent et al. 2002 A&A 393, 887

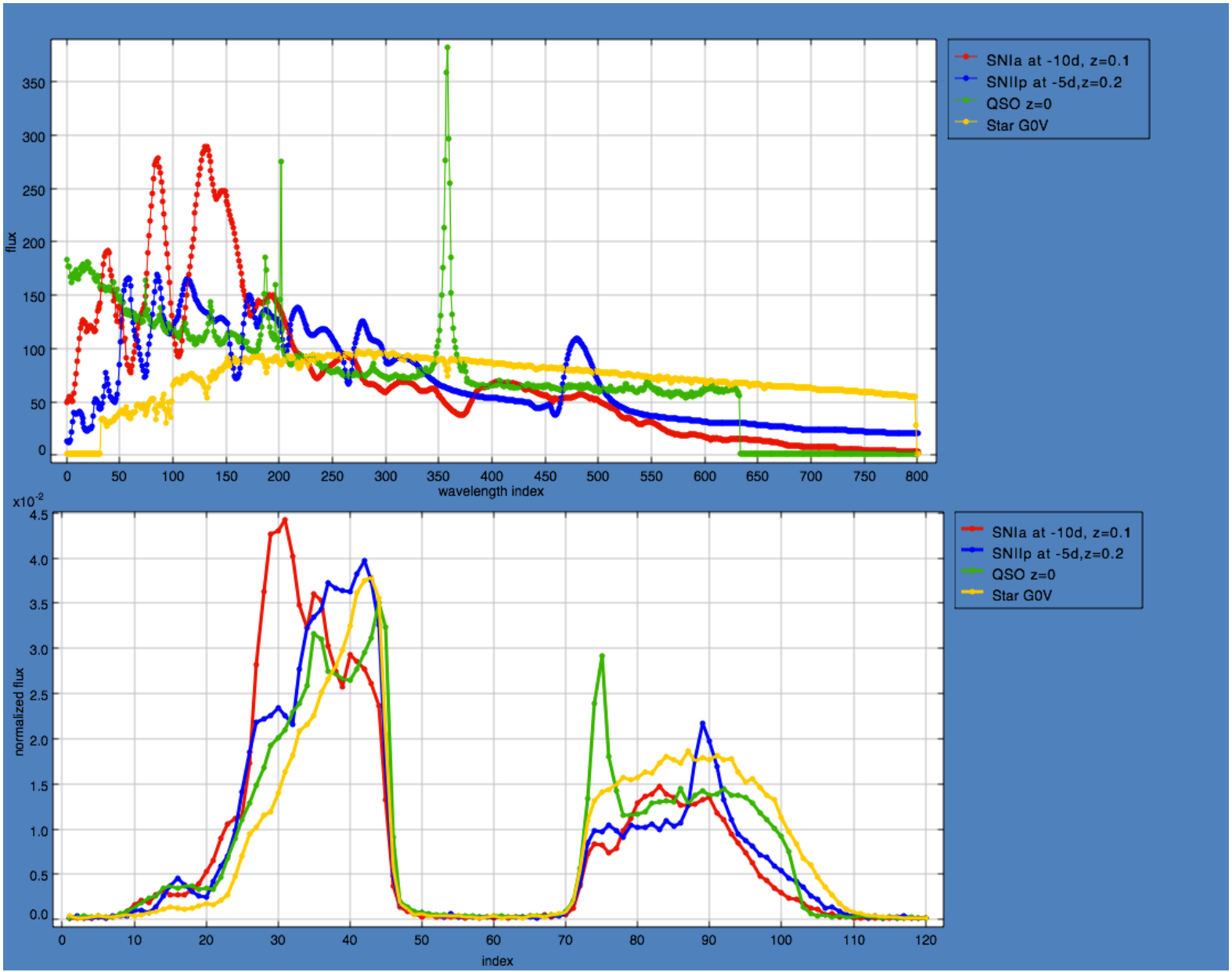
Novae

- 2 main classes, defined from non-H lines
- FeII Class: FeII lines with P-Cyg absorption, low velocity, slow nova. Wind ejection?
- He/N Class: high excit., broad lines, boxy profiles, high vel., fast nova. Disk ejection?
- Some hybrids exist
- Need more statistics and follow-up
- See R. Williams, 2012





GAIA SED avec BP/RP



SNe Classification

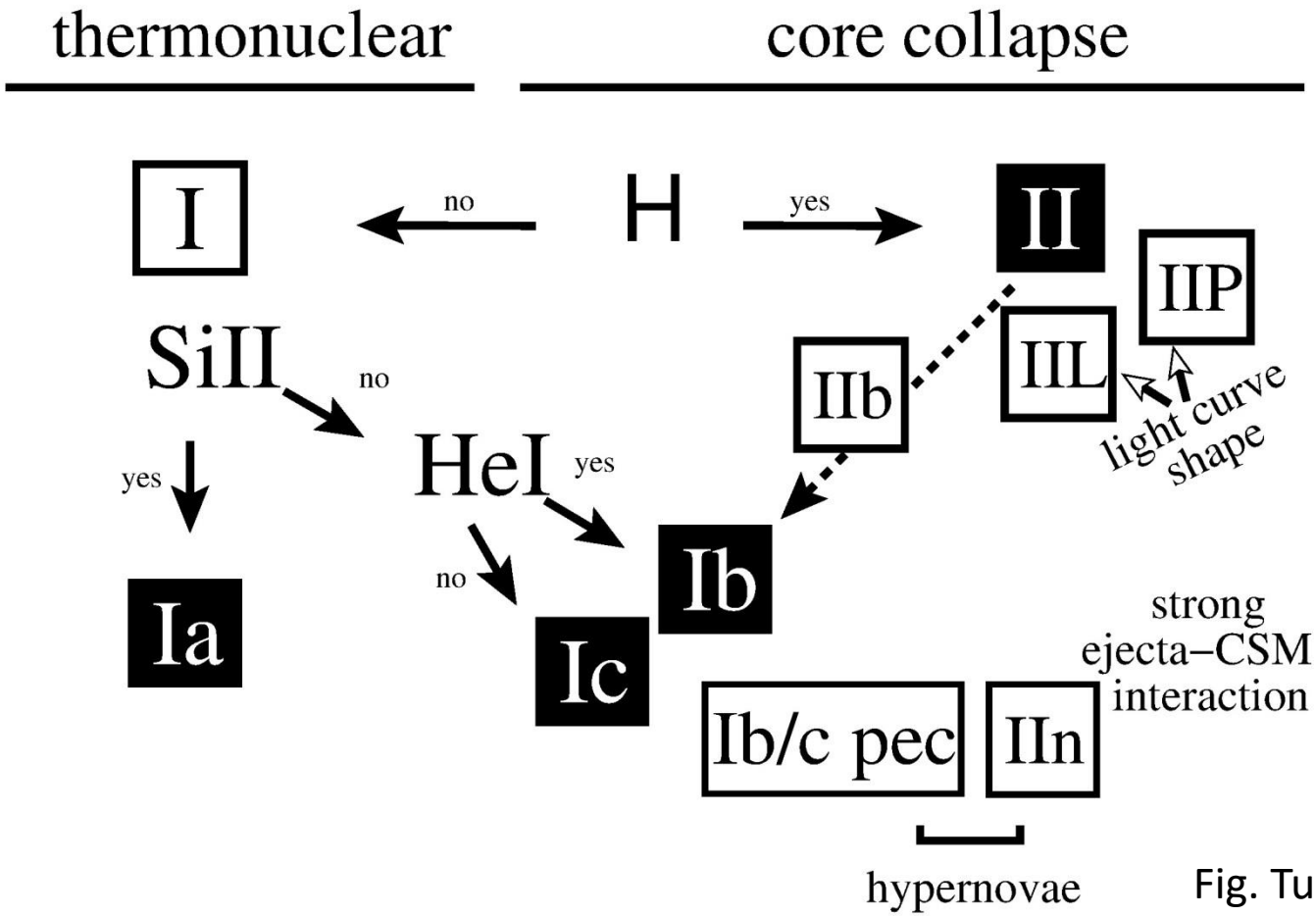
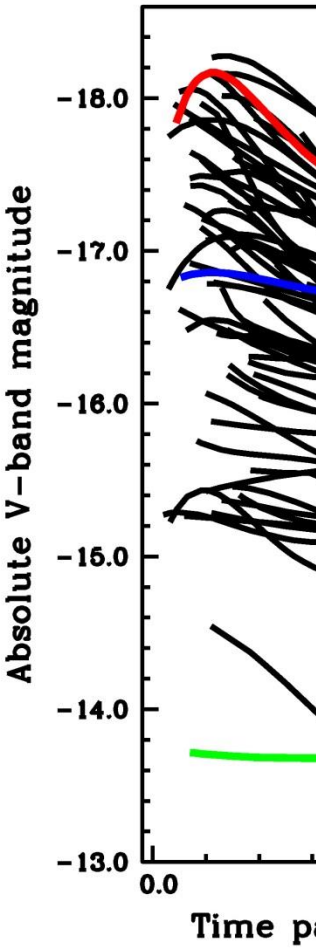


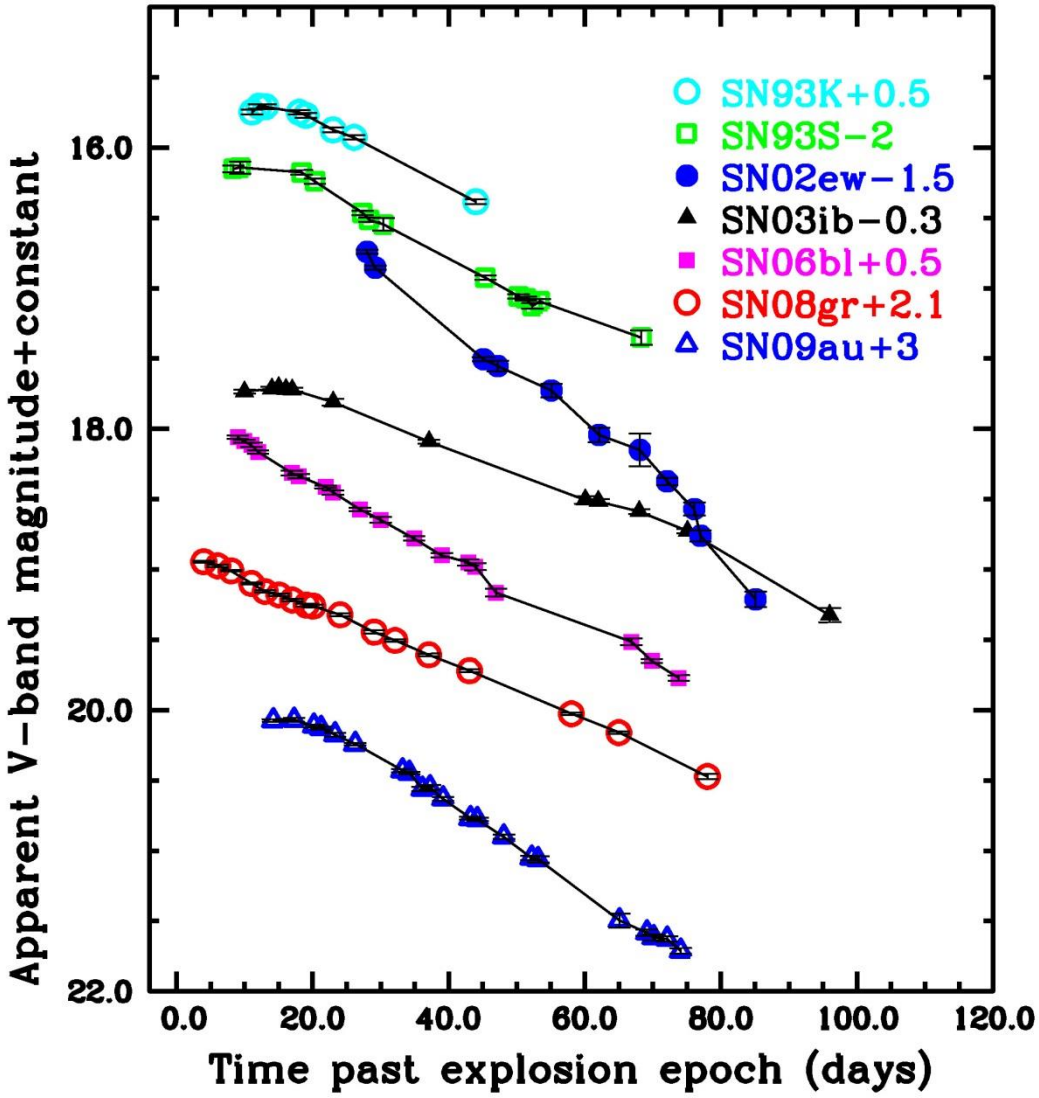
Fig. Turatto, 2003

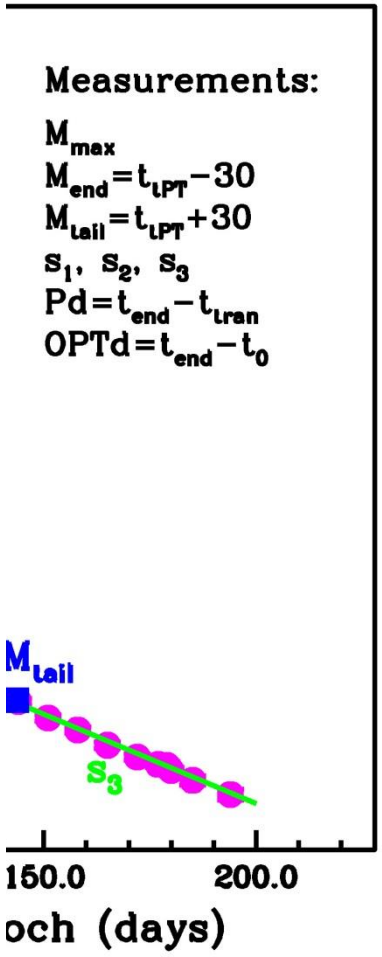
Purely empirical (Zwicky, 1943): no Hydrogen = type I

with H = type II

Core-Collapse SNe lightcurves

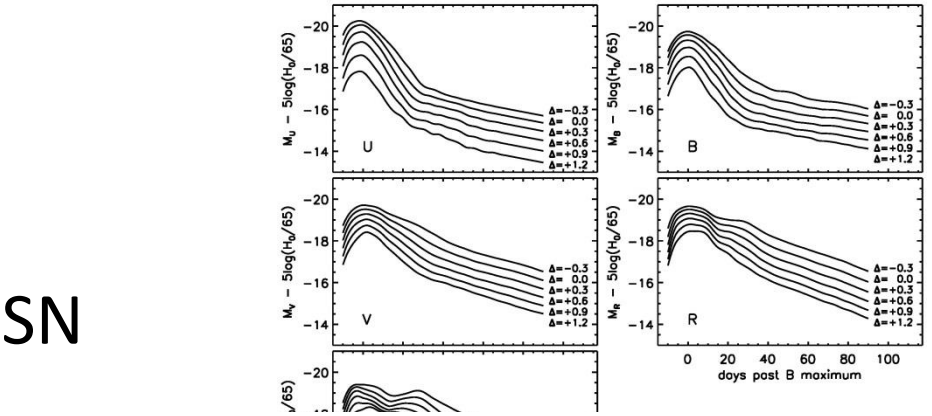


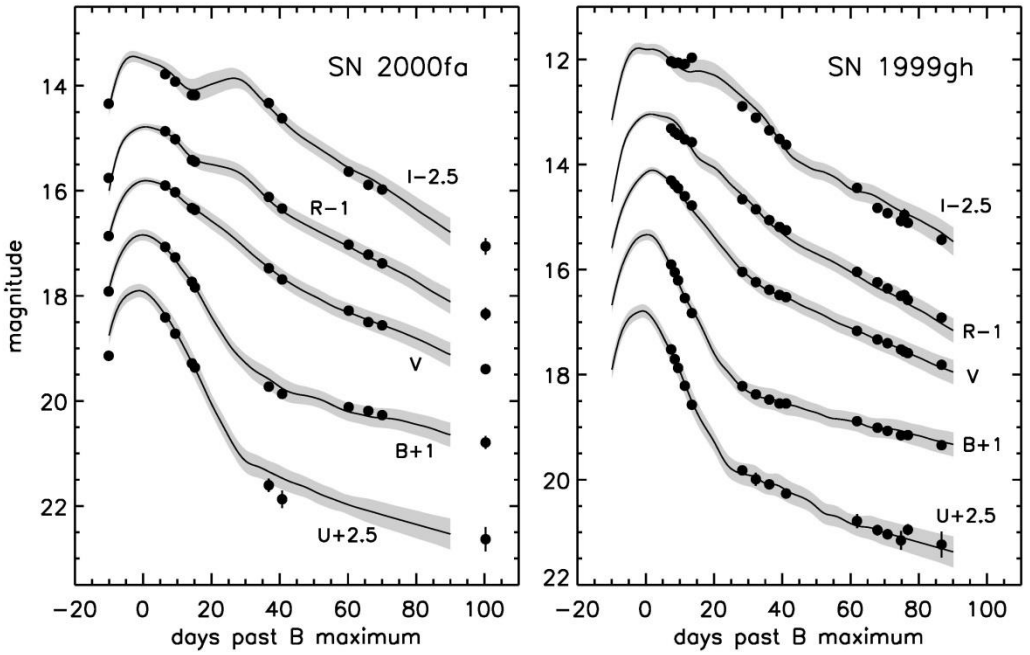




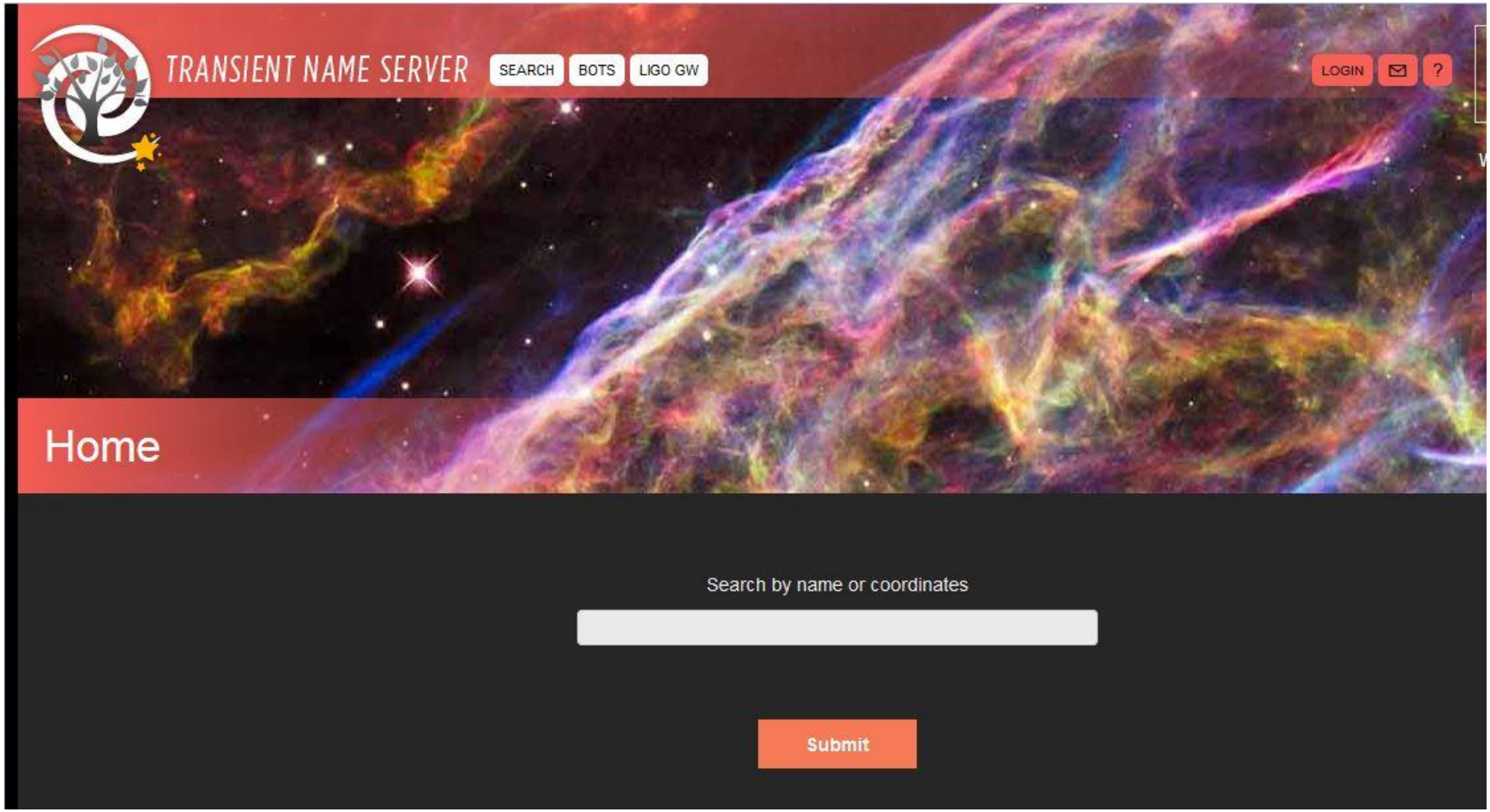
SNe: photometric follow-up

- Uncomplete light-curves to fill-in…
- Use of templates per SN type (e.g. Jha et al. 2007 for Ia's)
- Can easely complete Gaia scarce sampling
- Important to find Ia's maximum





Transient Name Server



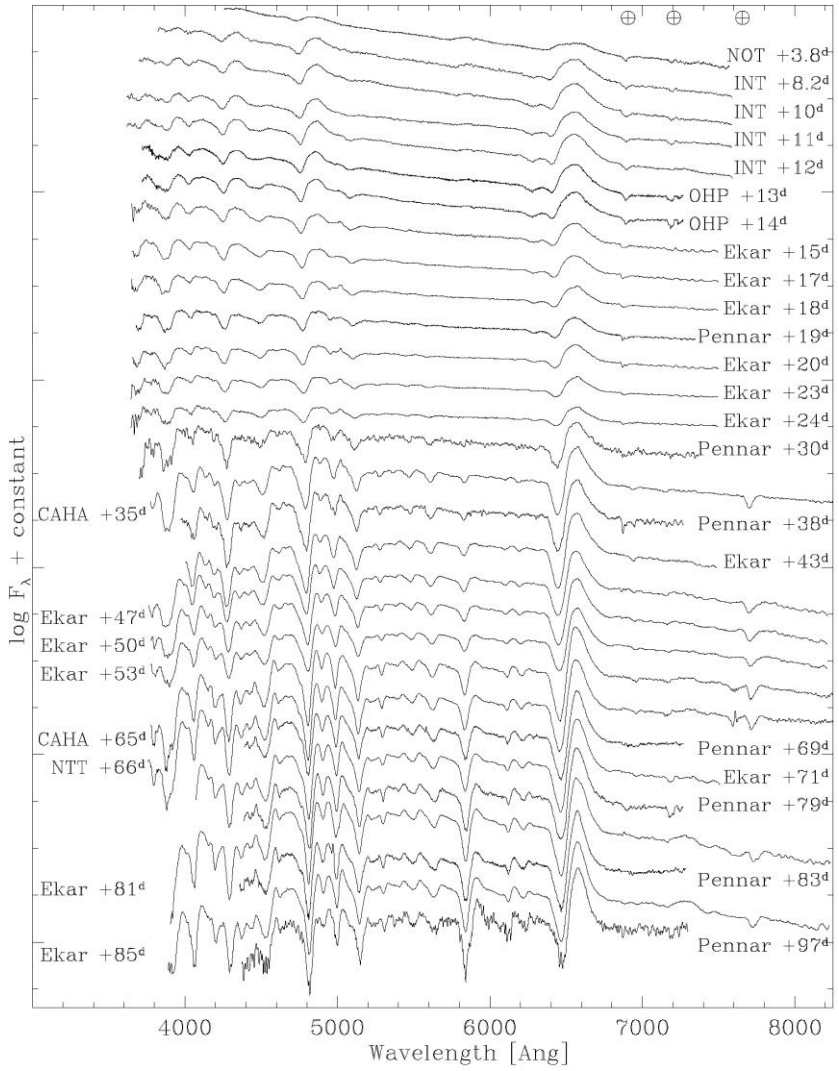
https://wis-tns.weizmann.ac.il/

9522 public AT's, 878 SNe since Jan.1, 2016

Spectroscopic follow-up

- Long-term follow-up (here SN 2012 A)
- To determine Mass and Nickel mass (II P here)
- Need of regular observing time
- Low dispersion adequate

  (R ~ 1000)



Example of Gaia14aee: an AM CVn (Campbell et al. 2015)

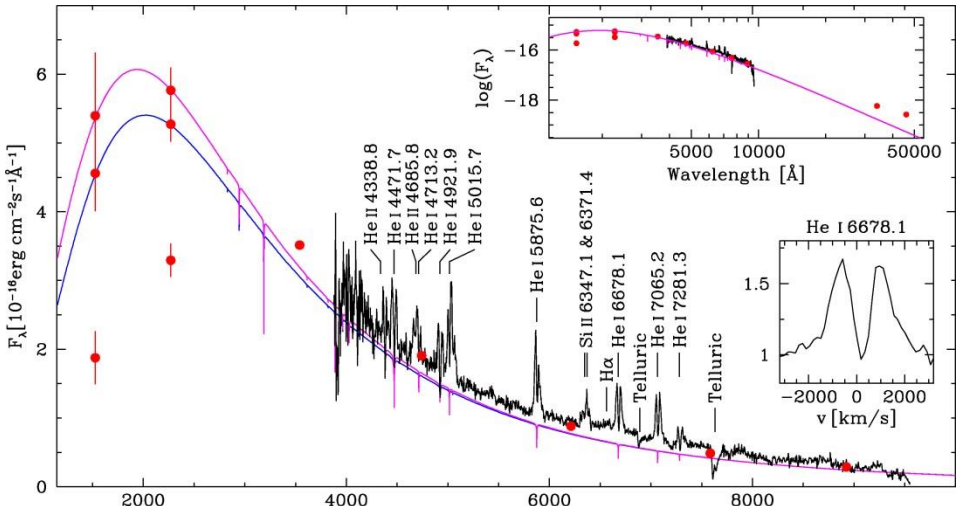
- AM CVn , H-deficient
- Also ASSASN-14cn
- Double-peaked

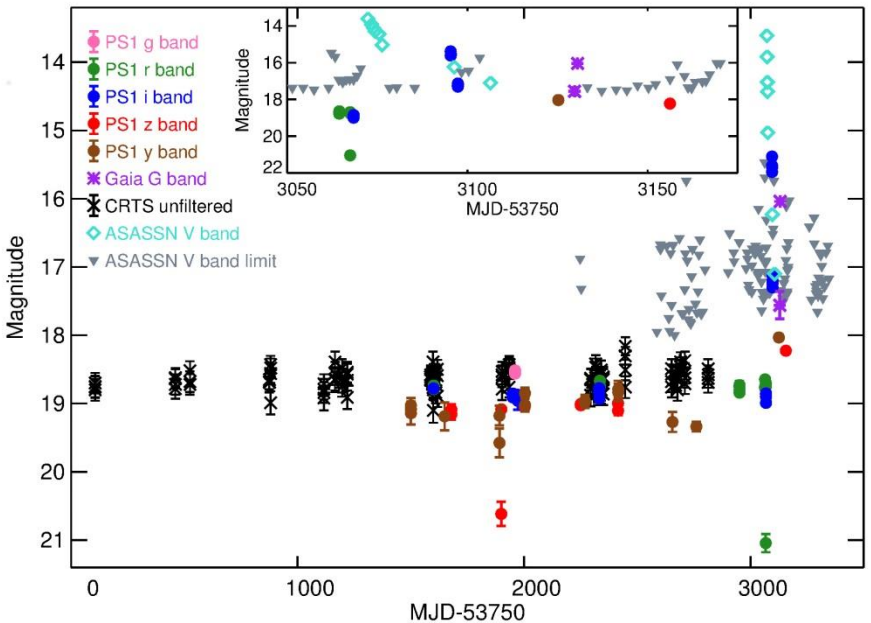
= accreting double deg.

- First eclipsing CVn where the He-WD is eclipsed
- > 0.78 and 0.015 M_o
- Can find weird objects…

(no outbursts were detected by Catalina…)

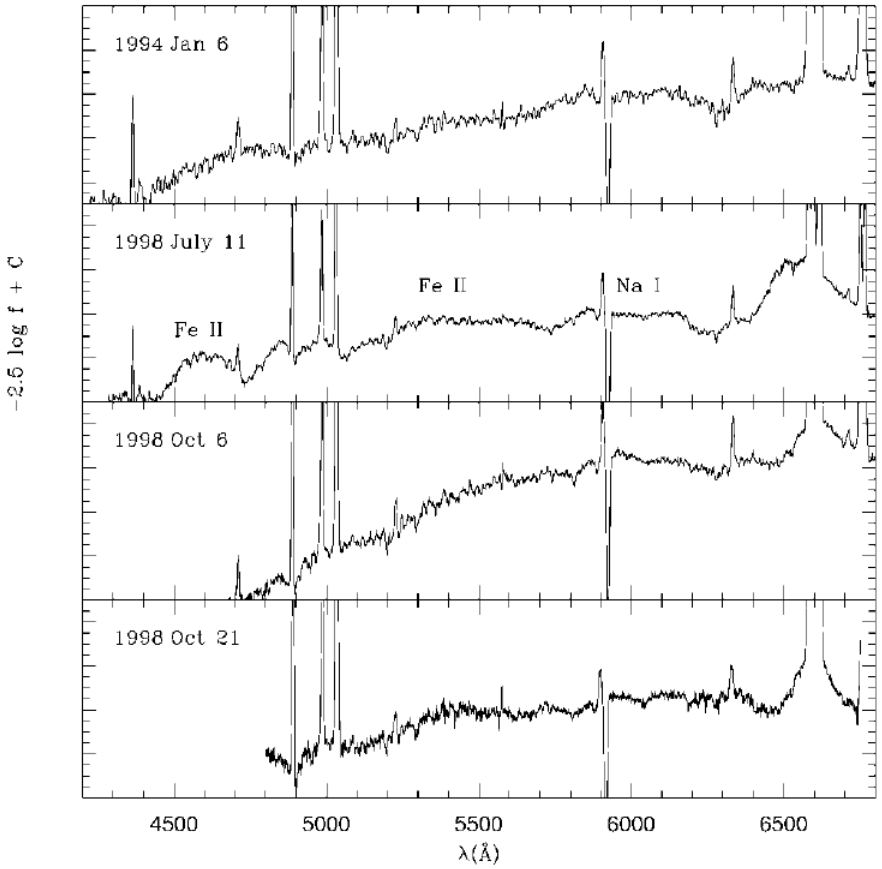
Needed a lot of follow-up…



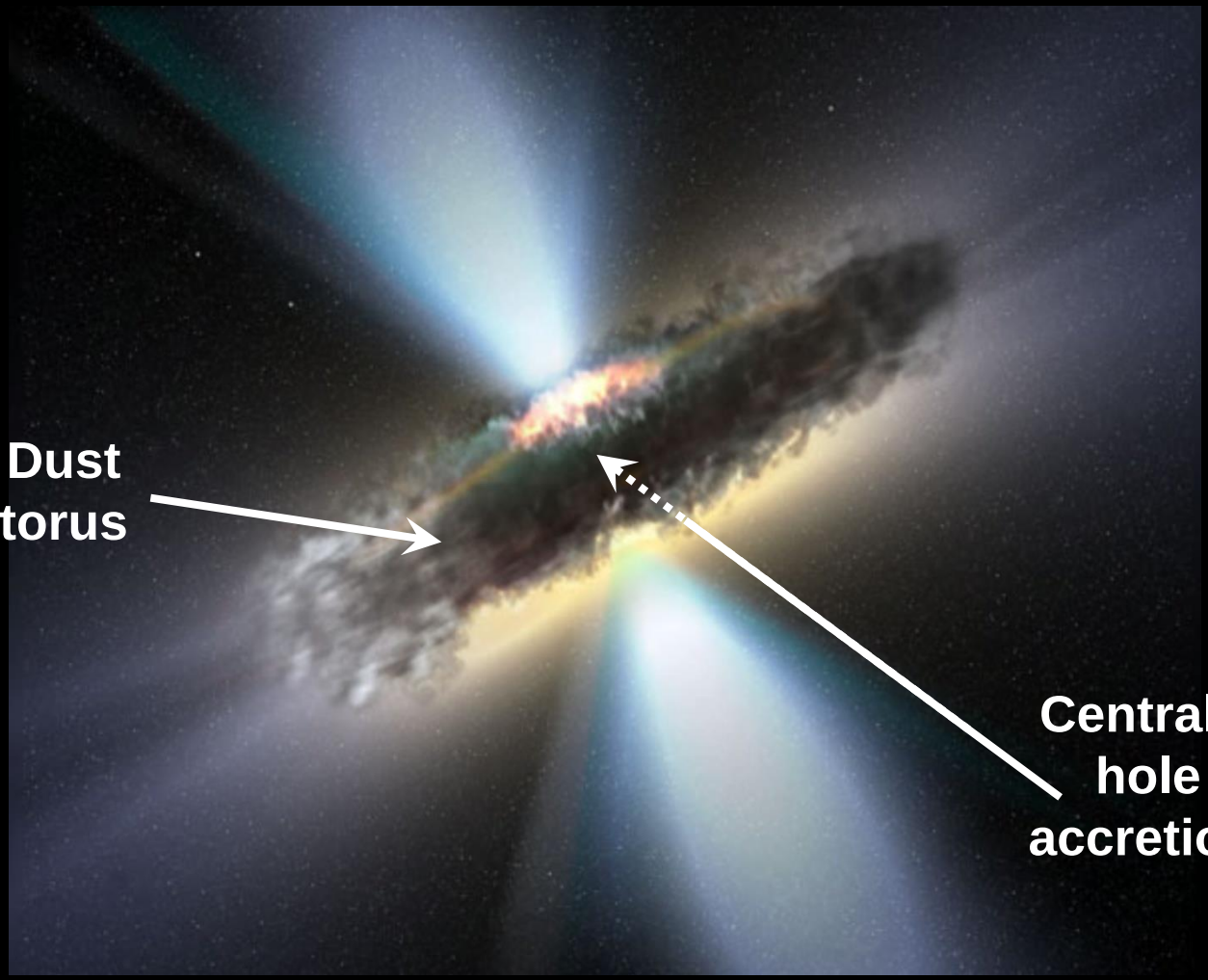


Variability of AGN' s

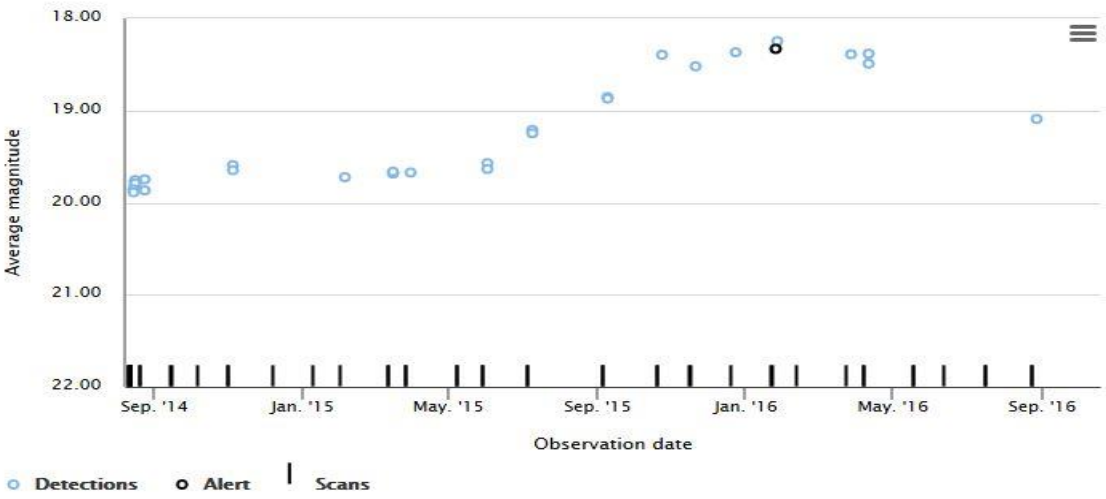
- Variability from 0.01 to ~ 0.5+ magnitudes
- Change of accretion rate?
- Change in obscuration?
- Spectral changes e.g. N7582 (Aretxaga et al. 1999), Torus?
- Any correlated X-rays variability ?

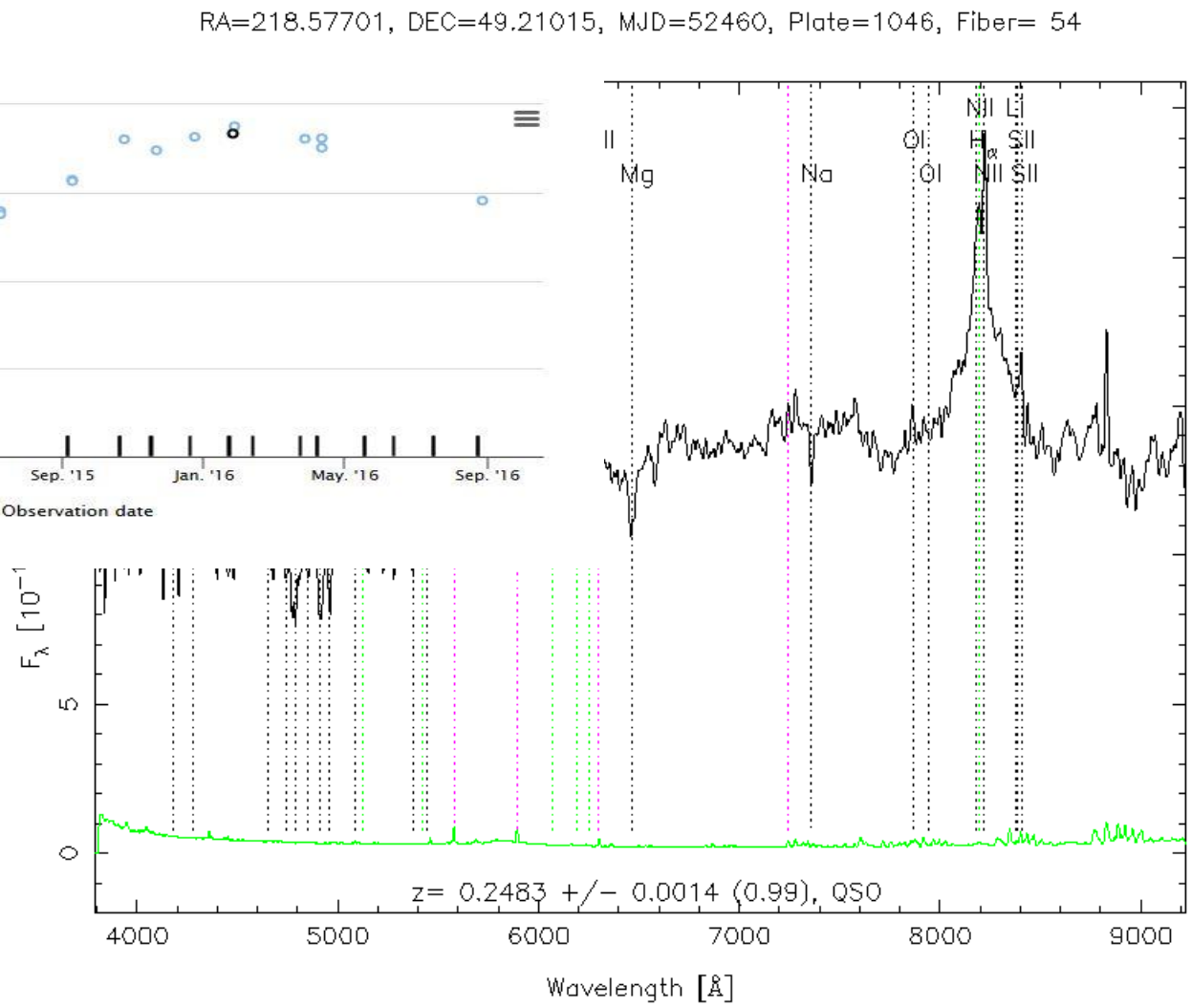


Heavily Obscured Active Galactic Nuclei



Ex. of AGN variability: Gaia 16aax





- Slowly rising tr
  galaxy core
- Spectrum gets
- To be followed
- Others coming…(aqe/apt)

Ground based follow-up

- We need a lot of telescope time (2-4m class) for the initial spectral classification
- And 1-2m class time for photometry

  (e.g. light-curve of Ia' s to get the Max)
- The situation is difficult in the North, and even more difficult in the South…
- A PESSTO-like organisation could be generalised,

  Gaia-Alerts is going that way.

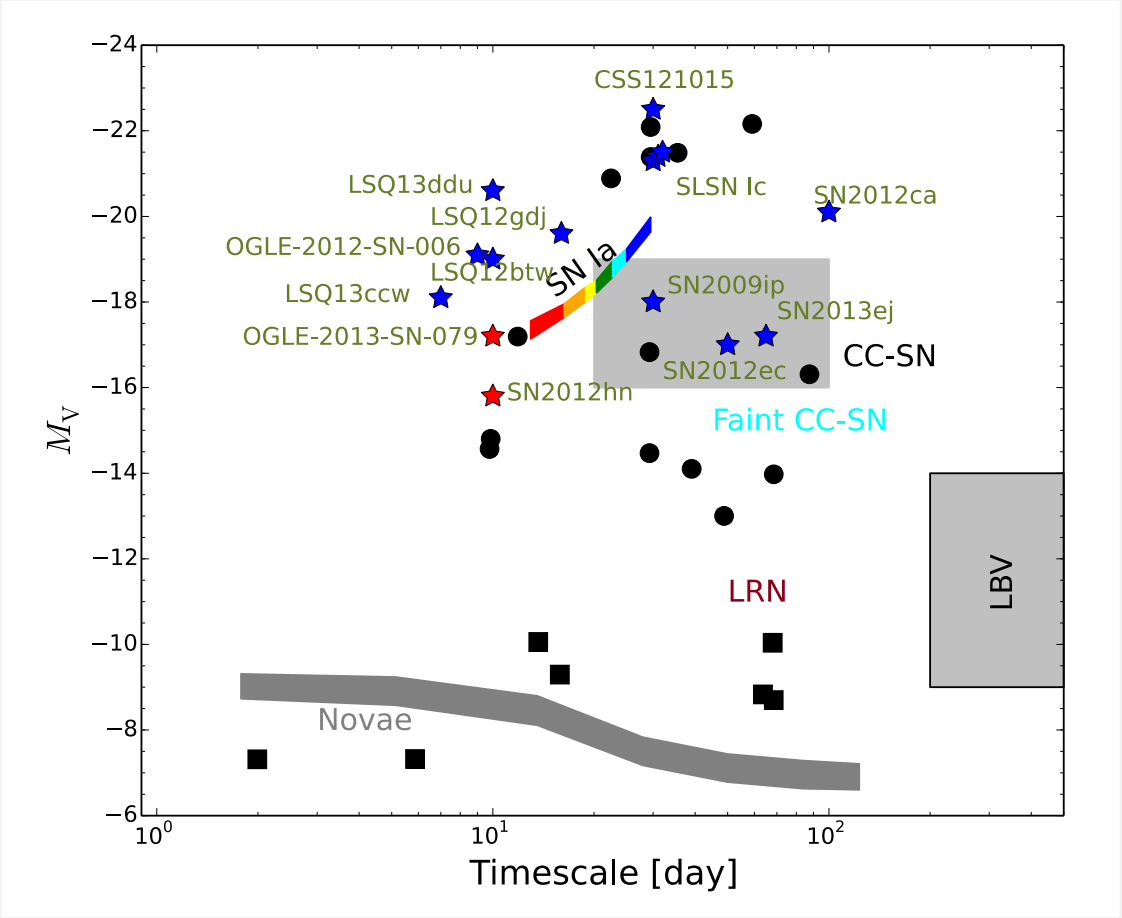
The PESSTO follow-up

- S. Smartt (QUB) et al. (~ 100 co-I's)
- 90n per year : 9 months, 10n per month at the 3.5m NTT in LaSilla
- 4 yrs (2012-2016), then extension

- Classification of ~2000 (667) SNe – all spectra reduced, classified and released within 24hrs (WiseRep)
- Follow-up approx 150 (131) with full spectr. and phot. time series coverage
- >200 papers published up to now
- New extension until 2023, e-Pessto+)

Transients : current science

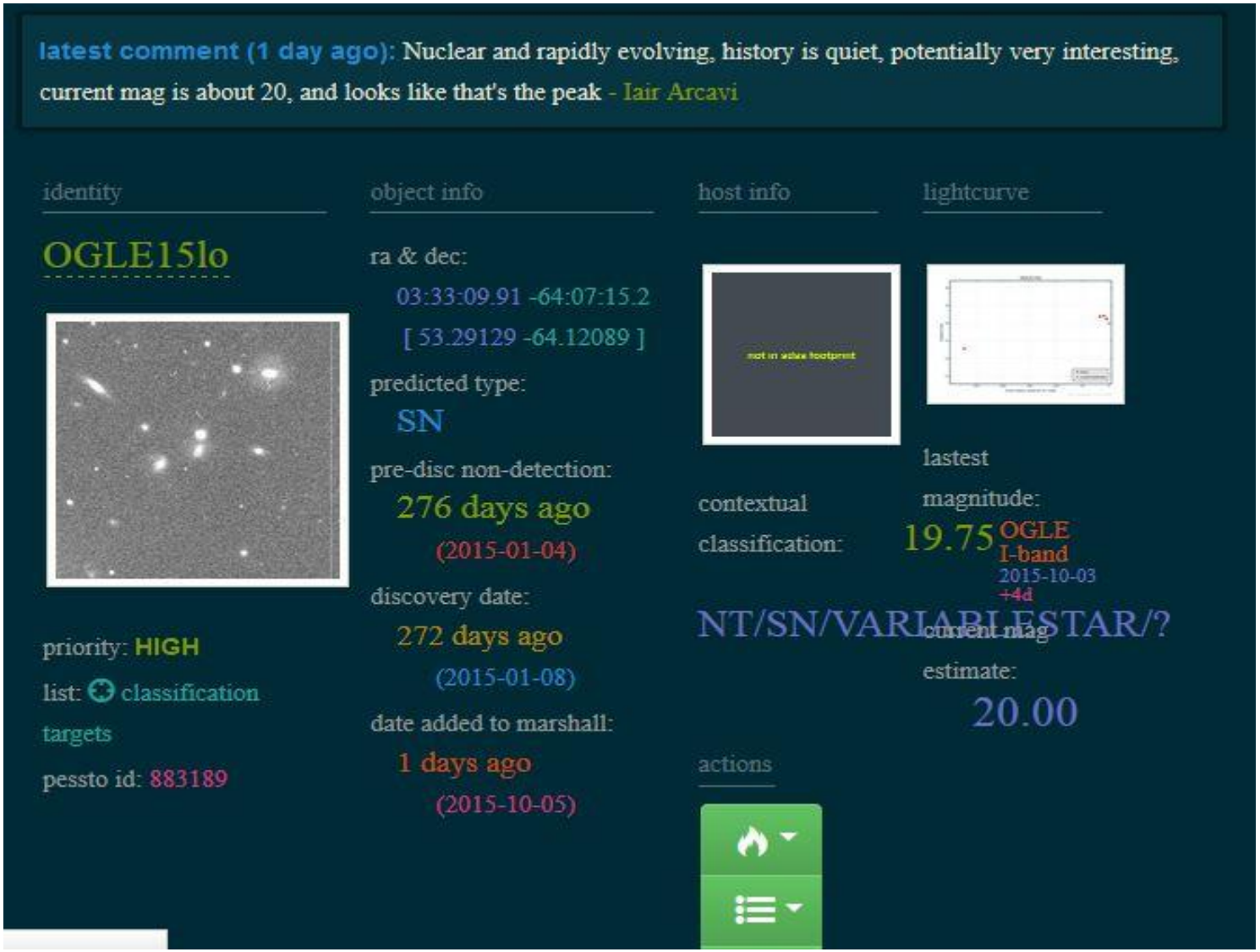
Smartt et al.
2015:
Survey description and products from the first data release by PESSTO,
A&A, 579, 40



What are the limits of physical explosions and transients ?

Image credit : Shri Kulkarni, Mansi Kasiwal, C. Inserra

PESSTO Marshall



Collecte les Alertes des differents surveys

Ground-based classification/follow-up: Need 1-2-4m class telescopes

Various observatories interested

For photometry:

- Asteroids, SNe… follow-up (+GBOT)
- FOV ~~10 arcmin ideal
- CCD Pixel : 1/3 seeing
- Large infrastructure preferable

to allow flexibility (several telescopes)

For spectroscopy:

- Low dispersion for classification
- Large spectral range (3500-10000+)
- Single set-up adequate for most targ
- Teams agreements
- Select topics of interest
- Can expect a few alerts/week

Telescopes interested in variables could join similar process combining SSO and Phot. Alerts
Smaller telescopes usefull for photometry

How to operate?

- Alerts = Targets of Opportunity
- Not all objects need a fast response…(24h +)
- Team agreements to **choose/combine topics**
- Photometric alerts: a few frames only…
- SSO: maybe deveral per week?
- Alerts: One classification spectrum to start with…
- To contribute, one needs to provide observing time!
- **Good opportunities for international collaborations and for Amateur Astronomers**