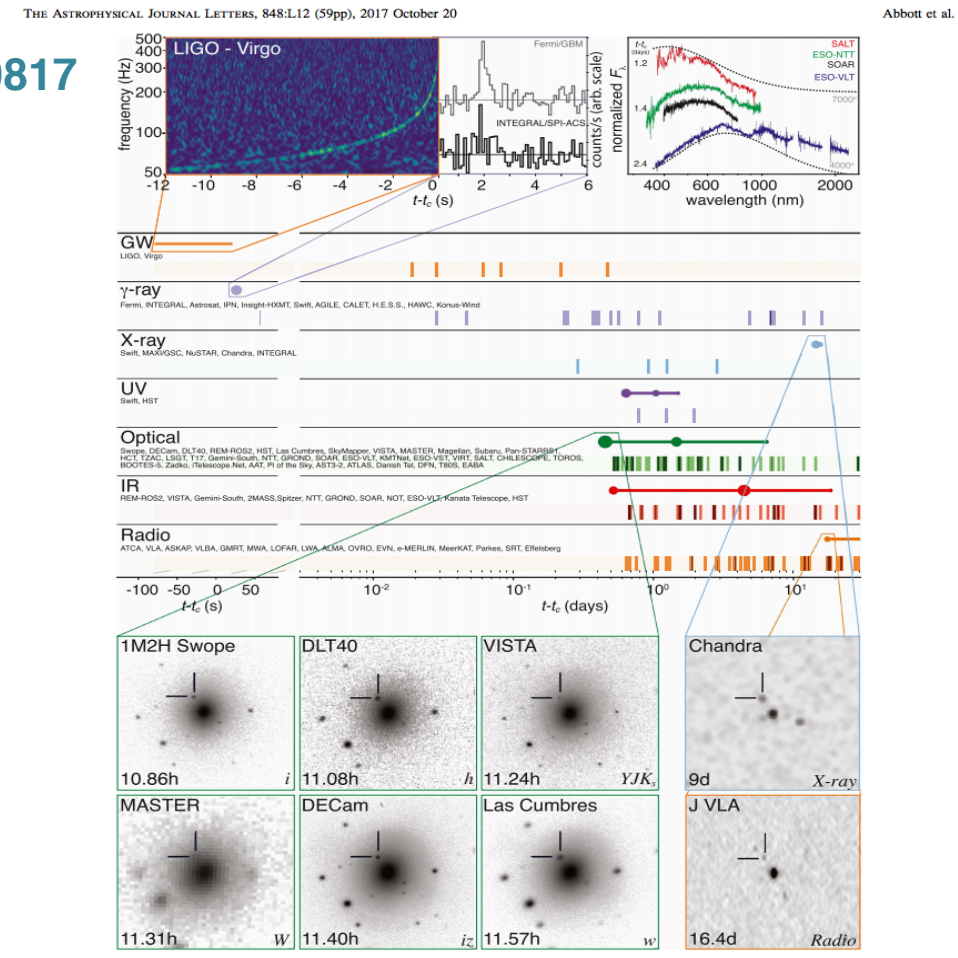
Exploring Time Domain Multi-Messenger Astronomy through the Virtual Observatory

Ada Nebot & the CDS team

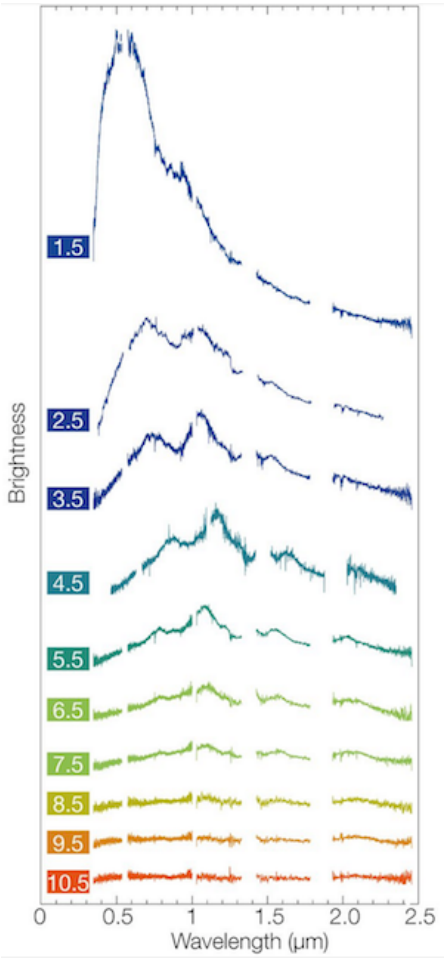
TS2020-III 26 September 2019

Time Domain Multi-messenger Astronomy

GW170817



Abbott et al. 2017



X-shooter spectra in the kilonova in NGC 4993 over 12 days. Image credit: ESO/Pian et al./Smartt & ePESSTO.

Time Domain Astronomy Challenges/Needs

To characterise and classify sources…

- Multi-wavelength / messenger approach is (sometimes) needed
- Follow-up observations and reaction time for that can be crucial
- Visualisation & navigation thought the data
- Coordination & transmission of information

The VO (IVOA) should match user's needs
So, what is available through the VO?

The VO and the IVOA

What is the VO?

- Astronomical datasets, tools, services should work seamlessly together

What is the IVOA?

- An organisation that debates and agrees the technical standards that are needed to make the VO possible
- A focal point for VO aspirations, a framework for discussing and sharing VO ideas and technology
- Promoting and publicising the VO

The VO and the IVOA

Who is the IVOA?

- 6 Working Groups, 7 Interest Groups
  - ➡ There is a Time Domain Interest Group
    - ➡ Chair & Vice-chair: A. Nebot & D. Morris
  - ➡ Completely open to participation

How to join the IVOA?

- **2 interoperability meetings per year**
  - ➡ Next IVOA meeting in Groningen 11-13 Oct.
    following ADASS 6-10 oct.
    https://www.adass2019.nl/ivoa/ivoa-participants/
  - ➡ Register to email lists for discussion of topics
  - ➡ Asking me directly can work too ada.nebot@asto.unistra.fr

http://ivoa.net/

The VO and the IVOA

Who is the VO?

- VO is integrated in many Astronomy data centres and archives
  - Often behind the scenes…

The VO and the IVOA

Who is the VO for?

- **Research astronomers**
- Data Centres and Archives
- Software developers
- Educators
- …

Idea of the VO?

- In a seamless way for the user:
  - Data discovery & access
  - Visualisation & analysis
  - Through Services & tools

- **Research astronomers — Time Domain Astronomers**

Time Domain Astronomy Challenges/Needs

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Time Domain Astronomy Challenges/Needs

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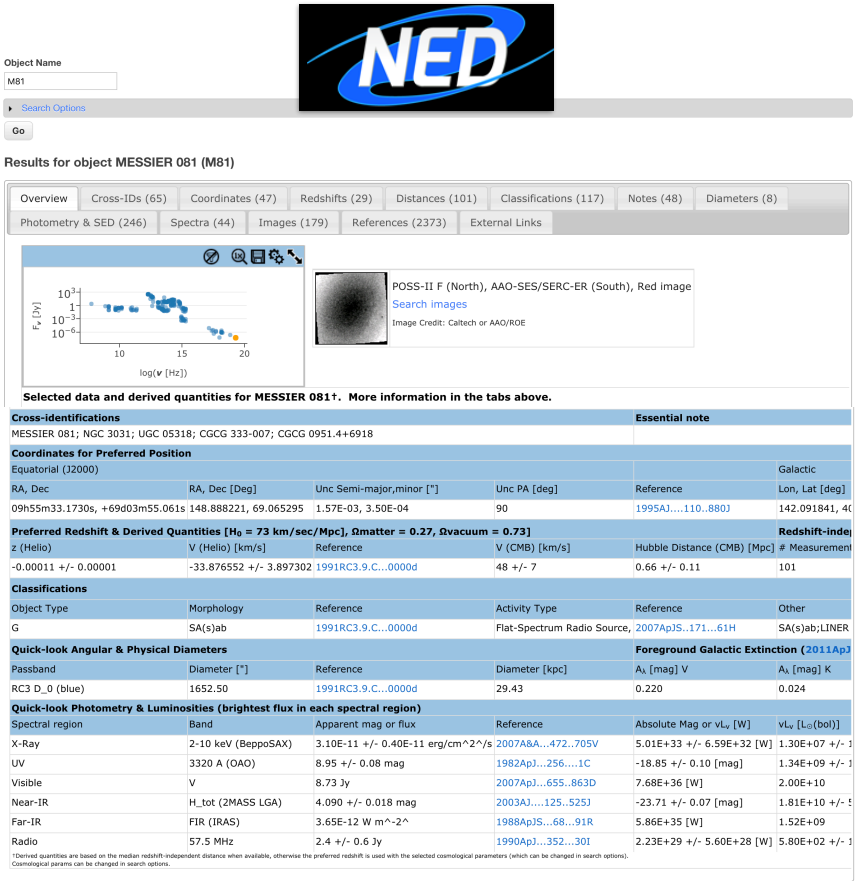
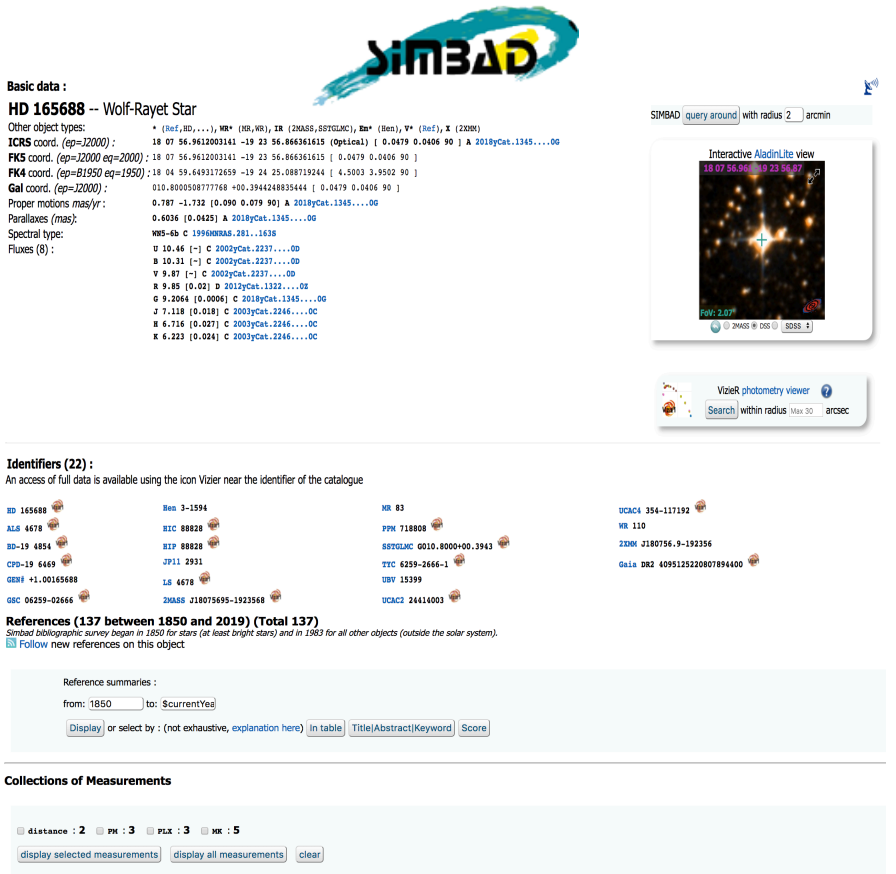
- **Multi-wavelength/messenger**
- Combining data from missions covering different wavelength ranges
  - ➡ Source identification
  - ➡ Cross-matching techniques

Minimum information about objects

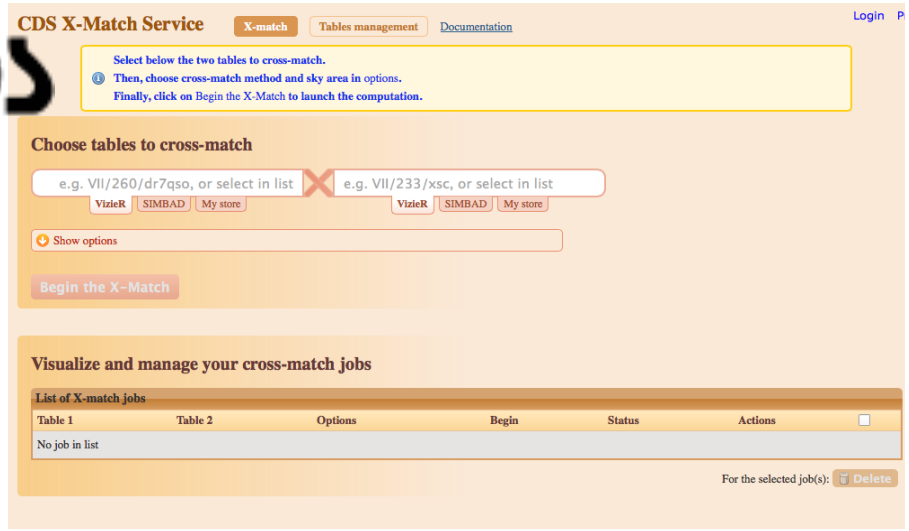
- Which objects around this area are already known and have a classification?
- Give me a minimum information about this object / list of objects (e.g. it's a Galaxy at redshift z)

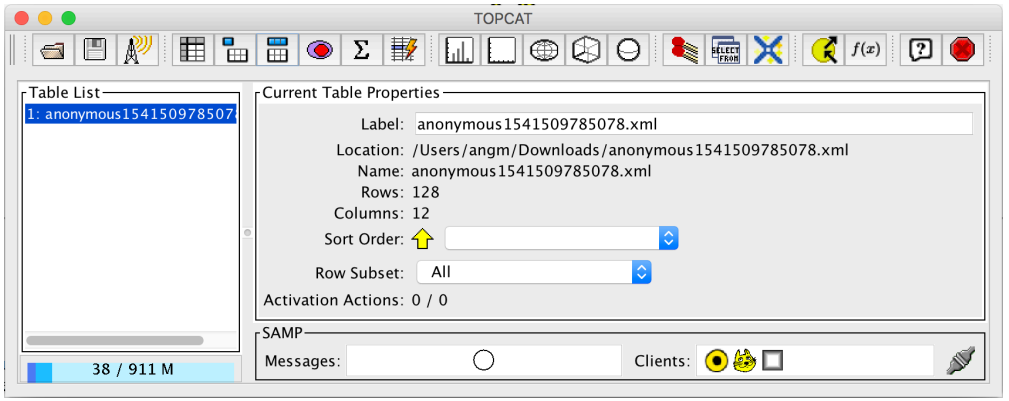




Cross-matching — A key point

- CDS dev. **F. X. Pineau et al.**
- Positional cross-correlation of sources in 2 tables (VizieR tables, simbad, user uploaded lists)
- Result in different formats (VOTable, CSV or ASCII)
- Programatic access too (http API)
- New developments for a multi-catalogue cross-match
- Available through TOPCAT and stilts too





Cross-matching

Positional cross-match performance, radius 5”

Table 1	Table 2	Computation time	Result generation	Result size	Total time
SDSS DR9 *469M rows*	**2MASS** *470M rows*	3 min	7 min	19 GB	10 min
2MASS *470M*	**GAIA-DR1** *1.1 billion*	16 min	65 min	193 GB	81 min
Tycho-2 *2M*	**SIMBAD** *8M*	6 sec	25 sec	1 GB	35 sec
List of *40k positions*	**SIMBAD** *8M*	1 second	4 seconds	10 MB	5 sec

Under dev.: add the time as a possible information to cross-matches

Time Domain Astronomy Challenges/Needs

To characterise and classify sources…

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- **Follow-up observations** & reaction time for that can be crucial
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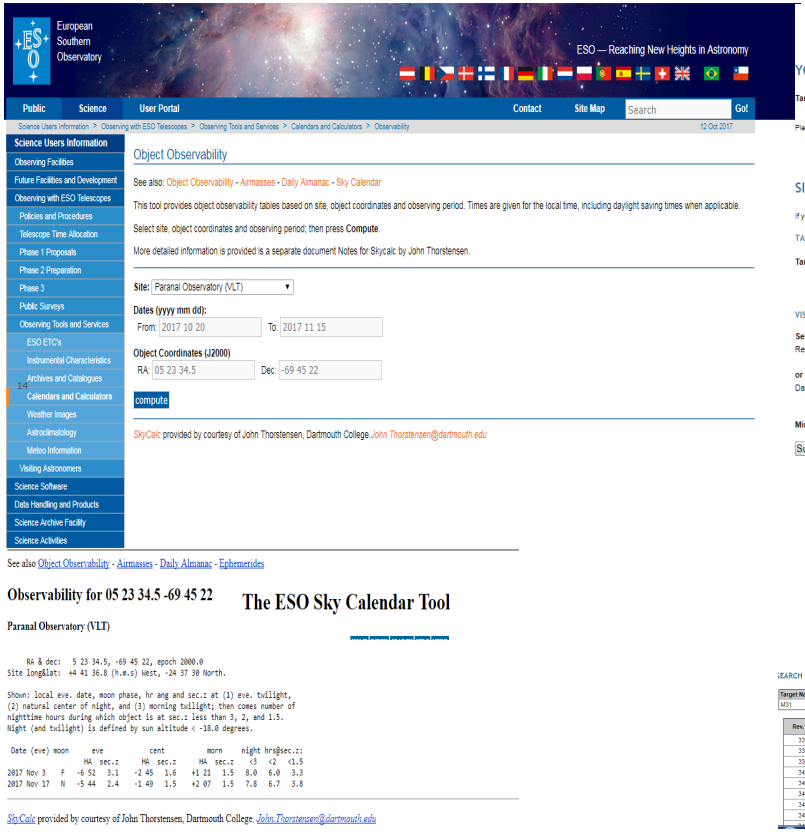
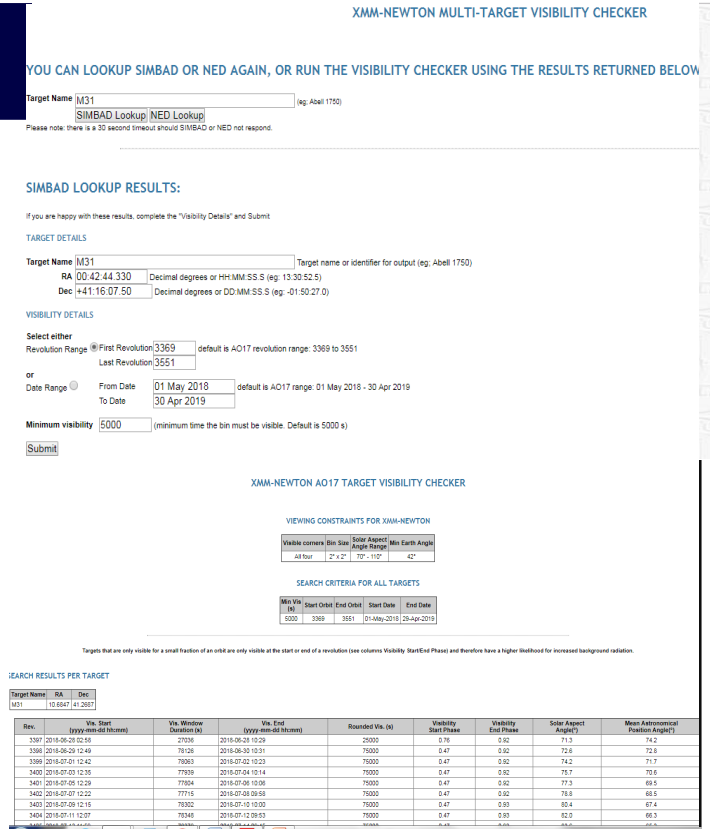
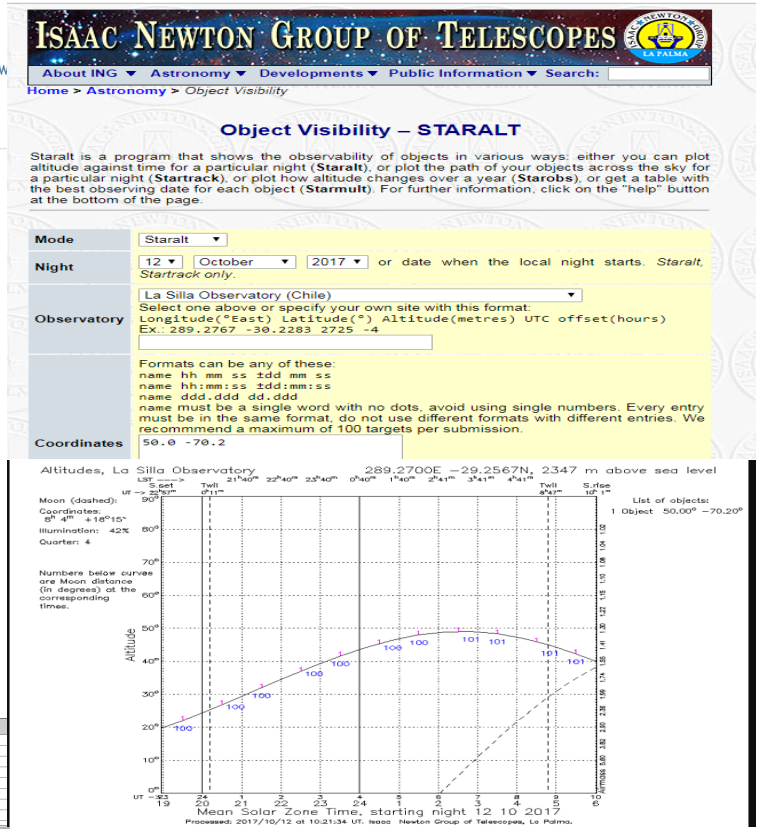
- **Follow-up observations**
  - ➡ **Transmission of events: VOEvent**, **IVOA Standard**
    - ➡ VOEvent Standard for Fast Radio Bursts FRBs, Petroff et al. 2017
    - ➡ Damien Dornic yesterday mentioned: VOEvent Standard for Neutrino ! :)
    - ➡ VOEvent Standard for other science / mission specific field?
  - ➡ **Planning observations: visibility, available telescope time** **2 IVOA Standards in process**

Planning observations: visibility services







Different services have different inputs / outputs

Facilitate the work by having same inputs / outputs

Object Visibility Simple Access Protocol
Aitor Ibarra, Richard Saxton, Jesús Salgado et al. 2019
http://www.ivoa.net/documents/ObjVisSAP/index.html

Planning observations: coordination of observations

Integral Target and Scheduling Information

Schedule: All executed | Current revolution (1872) | Future schedule | Revolution 1872 to 1872 | Show... | show plot

Schedule for revolution 1872

(this list is also available in csv-format, click here to download)

Rev	Start time (UTC)	End time (UTC)	Exp. time (s)	Target	Ra (J2000)	Dec (J2000)	Pattern	PI	Proposal	Observation	Notes
1872	2017-10-10 13:29:15	2017-10-10 17:10:51	12600	Gal. Bulge region	17:45:36.00	-28:56:00.0	HEX	Erik Kuulkers	1420001	1420001 / 0022	Public
1872	2017-10-10 17:13:34	2017-10-11 07:55:55	50000	Galactic Center	17:52:11.21	-25:21:49.7	5x5 Seq	Joern Wilms	1420009	1420009 / 0011	
1872	2017-10-11 08:16:46	2017-10-11 11:58:32	12600	Galaxy (l=0, b=0)	17:42:23.76	-29:38:02.4	HEX	Rashid Sunyaev	1420021	1420021 / 0039	
1872	2017-10-11 12:26:36	2017-10-11 12:56:36	1800	Galaxy (l=0, b=-30)	20:02:16.80	-41:20:31.2	HEX	Rashid Sunyaev	1420021	1420021 / 0038	
1872	2017-10-11 13:27:21	2017-10-11 14:29:17	3600	Galaxy (l=0, b=-30)	19:59:40.80	-41:05:16.8	HEX	Rashid Sunyaev	1420021	1420021 / 0040	
1872	2017-10-11 15:00:12	2017-10-11 17:38:07	9000	Galaxy (l=0, b=-30)	19:59:40.80	-41:05:16.8	HEX	Rashid Sunyaev	1420021	1420021 / 0040	
1872	2017-10-11 18:41:00	2017-10-12 08:01:56	45000	GRS 1915+105	19:15:11.79	+10:56:45.7	5x5 Seq	Jerome Rodriguez	1420029	1420029 / 0008	
1872	2017-10-12 09:06:18	2017-10-12 12:47:54	12600	Galaxy (l=0, b=0)	17:50:46.80	-28:55:30.0	HEX	Rashid Sunyaev	1420021	1420021 / 0041	
1872	2017-10-12 13:16:06	2017-10-12 14:49:58	5400	Galaxy (l=0, b=-30)	20:07:12.96	-40:00:10.8	HEX	Rashid Sunyaev	1420021	1420021 / 0042	

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Observing schedules

Short Range Observatory Schedule

Download

This is the confirmed schedule of NuSTAR observations. This sequence of observations has been uploaded to the spacecraft and will execute autonomously unless interrupted by a new schedule, Target of Opportunity, or instrument and spacecraft anomalies. This schedule will cover various time ranges depending on the exposure time goal of the observations, but will usually be for a period of at least one week.

The times reported here are the start and end of the on-target period (day of year UTC). The estimated exposure time takes into account Earth occultation and the SAA passage time where detector background is increased. The end time of the observation is the start of the slew to the next target. Please examine the NuSTAR As-Flown Timeline (AFT) for the log of past observations.

Table Header Explanations

obs_start	obs_end	sequenceID	Name	J2000_RA	J2000_Dec	Exp	Notes
2017:281:19:05:02	2017:283:00:30:00	90201021006	Kepler	262.671620	-21.491957	60.6	DDT
2017:283:01:11:23	2017:283:02:40:00	90311211001	Sol_17282_AR2683_POS11	195.15715	-6.38520	3.4	ToO
2017:283:02:40:32	2017:283:04:20:00	90311212001	Sol_17282_AR2683_POS12	195.21879	-6.41062	3.4	ToO
2017:283:04:20:32	2017:283:05:50:00	90311213001	Sol_17282_AR2683_POS13	195.28046	-6.43604	3.4	ToO
2017:283:06:55:11	2017:284:09:20:00	60376001002	2MASXJ19301380p3410495	292.557500	34.180500	55.3	Extragalactic Legacy Survey
2017:284:09:45:09	2017:284:20:35:00	60360008002	SDSSJ152132d21p391206d9	230.3874232	39.2007671	22.0	Extragalactic Legacy Survey
2017:284:21:10:03	2017:285:21:00:00	90301320002	NGC_6440	267.218083	-20.358944	49.5	ToO
2017:285:21:20:06	2017:286:08:20:00	30302020004	GRS_1915p105	288.79813	10.94578	21.9	(2/4) coordinated with XMM and VLT
2017:286:08:35:06	2017:286:19:30:00	60160701002	2MASXJ18560128p1538059	284.00210000	15.63200000	23.3	BAT AGN
2017:286:20:05:11	2017:287:15:05:00	60376007002	UGC06728	176.316800	79.681500	61.4	Extragalactic Legacy Survey
2017:287:15:50:11	2017:288:03:20:00	60368001002	NGC_1144	43.80083	-0.18361	22.0	
2017:288:04:05:09	2017:288:23:00:00	60301004002	ESO_103m35	279.58458	-65.4275	50.3	
2017:288:23:30:08	2017:290:05:45:00	30301026002	AX_J1841d0m0536	280.25179	-5.59625	59.7	phase constrained
2017:290:06:00:04	2017:290:17:00:00	60160670002	2E1739d1m1210	265.47600000	-12.19700000	23.5	BAT AGN
2017:290:17:15:01	2017:291:04:20:00	30363001002	GX_3p1	266.98333	-26.56361	21.8	

Long Range Observatory Schedule

Download

This is the latest NuSTAR long-term schedule. Observations have been sorted into one-week intervals, taking into account Sun, Moon, required exposure time, and other constraints. So the date is the Monday of the week in which the observation is scheduled to begin.

```
09-Oct-2017 18:48:29      ---   Preliminary  HST  Observing  Timeline  Report  for  SMS:   172888A4   ---              Page 1
                  SMS Start: 2017.288:22:10:00 (15-OCT-2017 22:10:00), End: 2017.296:00:00:00 (23-OCT-2017 00:00:00)


         Scheduling  Unit             Principal                          Science                                Spectral     Exposure
         Begin UT End   UT   SU Id    Investigat Exp #  Target           Instrume Mode   Apertures              Elements     Time(sec) OB AL EX
-------- -------- --------  -------   ---------- ------ ----------       -------- ------ -----------            -----------  --------- -- -- --
2017.288 23:00:00 23:35:07  14835Z1   Lockwood   Z1-001 DARK             STIS/MA2 TIME-T F28X50LP               MIRVIS         1300.00 Z1 01 01
2017.288 23:14:45 06:30:55  1476735   Sing       35-001 WASP-69          COS/NUV  ACQ/SE PSA                    G230L            12.00 35 01 01
2017.288 23:14:45 06:30:55  1476735   Sing       35-002 WASP-69          COS/NUV  ACQ/PE PSA                    G230L            12.00 35 02 01
2017.288 23:14:45 06:30:55  1476735   Sing       35-003 WASP-69          COS/NUV  ACQ/PE PSA                    G230L            12.00 35 03 01
2017.288 23:14:45 06:30:55  1476735   Sing       35-004 WASP-69          COS/FUV  TIME-T PSA                    G130M          1917.00 35 05 01
2017.288 23:14:45 06:30:55  1476735   Sing       35-005 WASP-69          COS/FUV  TIME-T PSA                    G130M          2706.00 35 07 01
2017.288 23:14:45 06:30:55  1476735   Sing       35-006 WASP-69          COS/FUV  TIME-T PSA                    G130M          2706.00 35 09 01
2017.288 23:14:45 06:30:55  1476735   Sing       35-007 WASP-69          COS/FUV  TIME-T PSA                    G130M          2706.00 35 0B 01
2017.288 23:14:45 06:30:55  1476735   Sing       35-008 WASP-69          COS/FUV  TIME-T PSA                    G130M          2706.00 35 0D 01
2017.289 00:00:00 00:28:32  14819JF   Riley      JF-001 DARK             STIS/CCD ACCUM  F28X50LP               MIRVIS         1100.00 JF 01 01
2017.289 00:00:00 00:28:32  14819JF   Riley      JF-002 DARK             STIS/CCD ACCUM  F28X50LP               MIRVIS           60.00 JF 01 02
2017.289 00:00:00 00:28:32  14819JF   Riley      JF-003 DARK             STIS/CCD ACCUM  F28X50LP               MIRVIS           60.00 JF 01 03
2017.289 00:00:00 00:46:10  145333B   Bourque    3B-001 DARK-NM          WFC3/UVI ACCUM  UVIS                   F373N           900.00 3B 01 01
2017.289 00:00:00 00:46:10  145333B   Bourque    3B-001 DARK-NM          WFC3/UVI ACCUM  UVIS                   F373N           900.00 3B 02 01
2017.289 00:39:46 01:08:18  14819JG   Riley      JG-001 DARK             STIS/CCD ACCUM  F28X50LP               MIRVIS         1100.00 JG 01 01
2017.289 00:39:46 01:08:18  14819JG   Riley      JG-002 DARK             STIS/CCD ACCUM  F28X50LP               MIRVIS           60.00 JG 01 02
2017.289 00:39:46 01:08:18  14819JG   Riley      JG-003 DARK             STIS/CCD ACCUM  F28X50LP               MIRVIS           60.00 JG 01 03
2017.289 00:46:10 01:32:20  145333C   Bourque    3C-001 DARK-NM          WFC3/UVI ACCUM  UVIS                   F467M           900.00 3C 01 01
2017.289 00:46:10 01:32:20  145333C   Bourque    3C-001 DARK-NM          WFC3/UVI ACCUM  UVIS                   F467M           900.00 3C 02 01
2017.289 01:27:12 01:56:24  148219U   Riley      9U-001 BIAS             STIS/CCD ACCUM  F28X50LP               MIRVIS            0.00 9U 01 01
2017.289 01:27:12 01:56:24  148219U   Riley      9U-001 BIAS             STIS/CCD ACCUM  F28X50LP               MIRVIS            0.00 9U 01 02
2017.289 01:27:12 01:56:24  148219U   Riley      9U-001 BIAS             STIS/CCD ACCUM  F28X50LP               MIRVIS            0.00 9U 01 03
2017.289 01:27:12 01:56:24  148219U   Riley      9U-001 BIAS             STIS/CCD ACCUM  F28X50LP               MIRVIS            0.00 9U 01 04
2017.289 01:27:12 01:56:24  148219U   Riley      9U-001 BIAS             STIS/CCD ACCUM  F28X50LP               MIRVIS            0.00 9U 01 05
2017.289 01:27:12 01:56:24  148219U   Riley      9U-001 BIAS             STIS/CCD ACCUM  F28X50LP               MIRVIS            0.00 9U 01 06
2017.289 01:27:12 01:56:24  148219U   Riley      9U-001 BIAS             STIS/CCD ACCUM  F28X50LP               MIRVIS            0.00 9U 01 07
2017.289 01:27:12 01:56:24  148219U   Riley      9U-001 BIAS             STIS/CCD ACCUM  F28X50LP               MIRVIS            0.00 9U 01 08
2017.289 01:27:12 01:56:24  148219U   Riley      9U-001 BIAS             STIS/CCD ACCUM  F28X50LP               MIRVIS            0.00 9U 01 09
2017.289 01:27:12 01:56:24  148219U   Riley      9U-001 BIAS             STIS/CCD ACCUM  F28X50LP               MIRVIS            0.00 9U 01 0A
2017.289 01:27:12 01:56:24  148219U   Riley      9U-001 BIAS             STIS/CCD ACCUM  F28X50LP               MIRVIS            0.00 9U 01 0B
2017.289 01:27:12 01:56:24  148219U   Riley      9U-001 BIAS             STIS/CCD ACCUM  F28X50LP               MIRVIS            0.00 9U 01 0C
2017.289 01:27:12 01:56:24  148219U   Riley      9U-001 BIAS             STIS/CCD ACCUM  F28X50LP               MIRVIS            0.00 9U 01 0D
2017.289 01:27:12 01:56:24  148219U   Riley      9U-001 BIAS             STIS/CCD ACCUM  F28X50LP               MIRVIS            0.00 9U 01 0E
2017.289 01:27:12 01:56:24  148219U   Riley      9U-002 BIAS             STIS/CCD ACCUM  F28X50LP               MIRVIS            0.00 9U 01 0F
2017.289 01:27:12 01:56:24  148219U   Riley      9U-002 BIAS             STIS/CCD ACCUM  F28X50LP               MIRVIS            0.00 9U 01 0G
2017.289 01:27:12 01:56:24  148219U   Riley      9U-002 BIAS             STIS/CCD ACCUM  F28X50LP               MIRVIS            0.00 9U 01 0H
2017.289 01:40:00 02:09:22  14518F0   Golimowski F0-001 BIAS             ACS/WFC  ACCUM  WFC                    F502N             0.00 F0 01 01
                                                                                                                F660N
2017.289 01:40:00 02:09:22  14518F0   Golimowski F0-002 DARK             ACS/WFC  ACCUM  WFC                    F502N          1000.50 F0 01 02
                                                                                                                F660N
2017.289 02:09:22 02:38:56  14518F1   Golimowski F1-001 DARK             ACS/WFC  ACCUM  WFC                    F502N             0.50 F1 01 01
                                                                                                                F660N
2017.289 02:09:22 02:38:56  14518F1   Golimowski F1-002 DARK             ACS/WFC  ACCUM  WFC                    F502N          1000.50 F1 01 02
                                                                                                                F660N


09-Oct-2017 18:48:29      ---   Preliminary  HST  Observing  Timeline  Report  for  SMS:   172888A4   ---              Page 2
                  SMS Start: 2017.288:22:10:00 (15-OCT-2017 22:10:00), End: 2017.296:00:00:00 (23-OCT-2017 00:00:00)


         Scheduling  Unit             Principal                          Science                                Spectral     Exposure
         Begin UT End   UT   SU Id    Investigat Exp #  Target           Instrume Mode   Apertures              Elements     Time(sec) OB AL EX
-------- -------- --------  -------   ---------- ------ ----------       -------- ------ -----------            -----------  --------- -- -- --
2017.289 02:38:56 03:08:18  14518F2   Golimowski F2-001 BIAS             ACS/WFC  ACCUM  WFC                    F502N             0.00 F2 01 01
                                                                                                                F660N
2017.289 02:38:56 03:08:18  14518F2   Golimowski F2-002 DARK             ACS/WFC  ACCUM  WFC                    F502N          1000.50 F2 01 02
                                                                                                                F660N
```

esa

› Short Term Schedule

XMM-NEWTON SHORT-TERM SCHEDULE

The Short-term Schedule gives an overview of scheduled observations covering the time range from the past week until the upcoming ~2-4 weeks.

Background: The planning and scheduling procedure is described in Sect. 8.2 of the Policies and Procedures. In addition, the process of scheduling XMM-Newton observations is described in A guided tour to the scheduling of an XMM-Newton orbit.

Description: Each row lists the revolution number (REV#), Observation Identifier (ObsID), target name, pointing coordinates plus position angle (PA), start and stop times, prime instrument, accumulated exposure times (in kiloseconds) for each instrument (without overhead), and name of the Principal investigator (PI). The start and stop times refer to the instrument activities required to perform the observation. The exposure times are accumulated over all exposures taken with the same instrument. Especially for OM, the observation can be split in shorter exposures with different filter/mode. EPIC exposure times in brackets indicate that one or all exposures use the closed filter. Details can be seen when clicking on the ObsID.
The row marked in blue indicates the target that is scheduled for the time of the last table update. The creation date is given at the top of the table.

Caveats: The scheduling of an XMM-Newton revolution may have to be revised (see Sects. 8.2, 8.3, and 5.2.2 of the Policies and Procedures). Contingencies of any type and solar flaring activity may impact at different levels the scheduled programme. The Observation Log Browser can be checked to see what was actually done.

Update frequency: Every 8 hours or when the schedule is updated (new revolution planned or any existing updated). The latest available version can be viewed after clearing the browser buffer from the contents of any previous sessions.

Last updated on: 2017-10-10 12:42:00 UT (Current Rev = 3267)

Revn #	Obs Id.	Target Name	RA hh:mm:ss	DEC dd:mm:ss	PA ddd.dd	UTC Obs Start yyyy-mm-dd hh:mm:ss	UTC Obs End yyyy-mm-dd hh:mm:ss	Prime Instr.	PN Dur Ks	MOS1 Dur. Ks	MOS2 Dur. Ks	RGS1 Dur. Ks	RGS2 Dur. Ks	OM Dur. Ks	PI
3276	0805150401	ESO 018-G009	08:24:07	-77:46:57	88.63	2017-10-29 19:34:26	2017-10-30 00:54:26	EPIC	16.7	18.1	18.1	18.2	18.2	18.0	Peter Boorman
3276	0801870801	HD 81809	09:27:46	-06:04:17	92.00	2017-10-29 15:00:13	2017-10-29 18:20:13	EPIC	9.5	10.9	10.9	11.0	11.0	10.8	Fabio Favata
3276	0561381201	zeta Puppis	08:03:40	-40:00:36	112.00	2017-10-29 01:21:41	2017-10-29 14:08:21	RGS	44.5	44.9	44.9	45.0	45.0	37.3	Fred Jansen XMM-Newton MM
3276	0803950401	SDSS 102714.77+35431	10:27:14	+35:43:17	119.93	2017-10-28 15:44:35	2017-10-28 23:31:15	EPIC	25.5	26.9	26.9	27.0	27.0	26.8	Guido Risaliti
3276	0803240201	J072637.95+394558.0	07:26:37	+39:45:58	91.37	2017-10-28 11:02:32	2017-10-28 14:55:52	EPIC	11.5	12.9	12.9	13.0	13.0	12.9	Nathan Secrest
3275	0801990201	0457-6739	04:57:33	-67:39:06	136.67	2017-10-27 12:22:47	2017-10-28 01:07:47	EPIC	43.4	44.8	44.8	44.9	44.9	43.7	Patrick Kavanagh
3275	0801990401	0449-6903	04:49:34	-69:03:34	138.62	2017-10-26 23:32:47	2017-10-27 12:02:47	EPIC	42.5	43.9	43.9	44.0	44.0	42.8	Patrick Kavanagh
3275	0803952601	SDSS [illegible]	08:26:19	+31:48:48	101.78	2017-10-26 [illegible]	2017-10-26 [illegible]	EPIC	36.0	37.4	37.4	37.5	37.5	37.3	Guido [illegible]

What object has been (or will be) observed when and in which wavelength?

Observation Locator Table Access Protocol, Aitor Ibarra, Jesús Salgado et al. 2019

http://www.ivoa.net/documents/ObsLocTAP/20190227/index.html

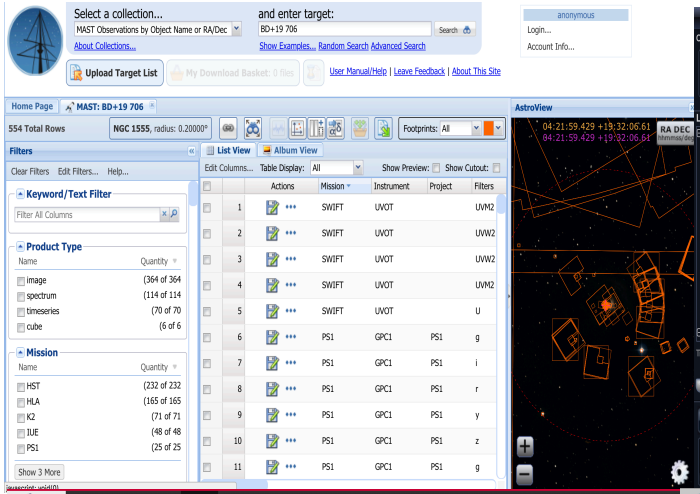
Time Domain Astronomy Challenges/Needs

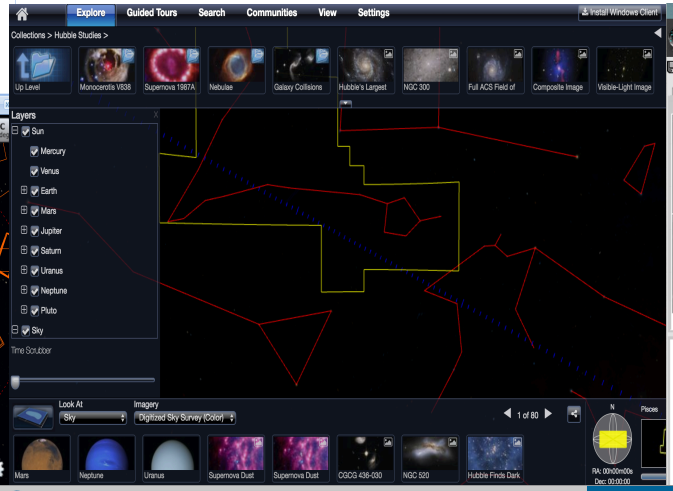
To characterise and classify sources…

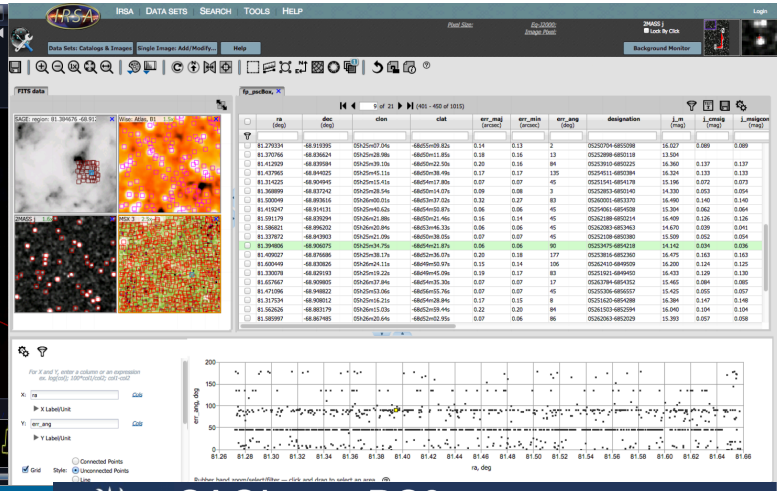
- Multi-wavelength/messenger approach is (sometimes) needed
- Follow-up observations & reaction time for that can be crucial
- **Visualisation & navigation** thought the data
- Coordination & transmission of information

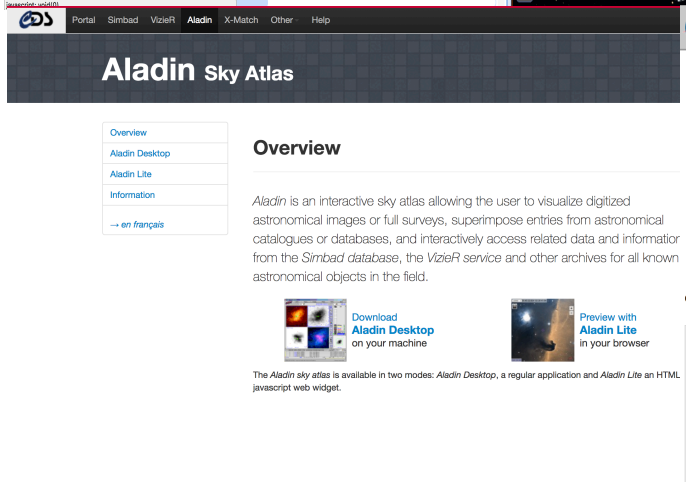
- **Visualisation & navigation**
  - ➡ sequences of images, spectra, photometry, positions, … and all interoperable
  - ➡ tools

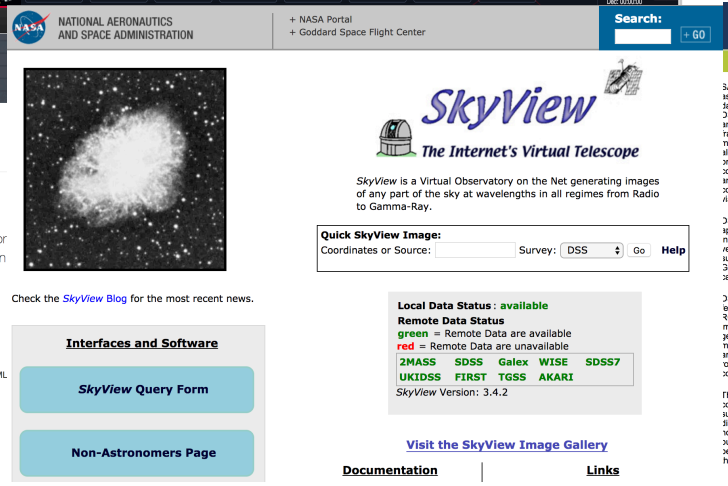
Visualisation of the sky

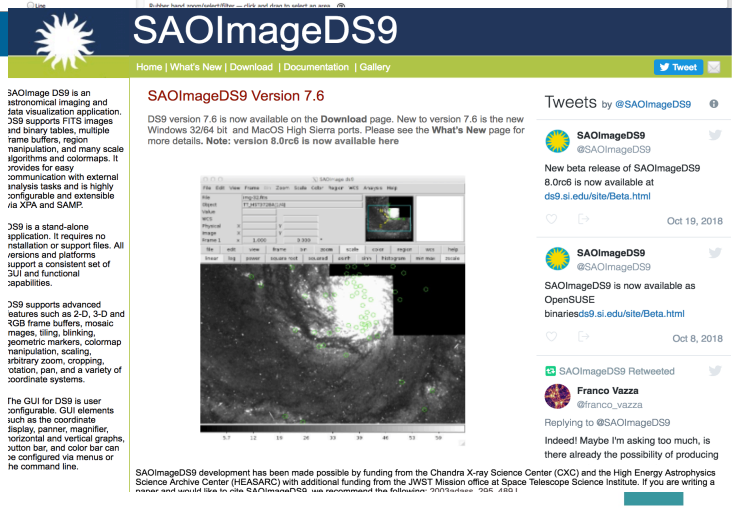






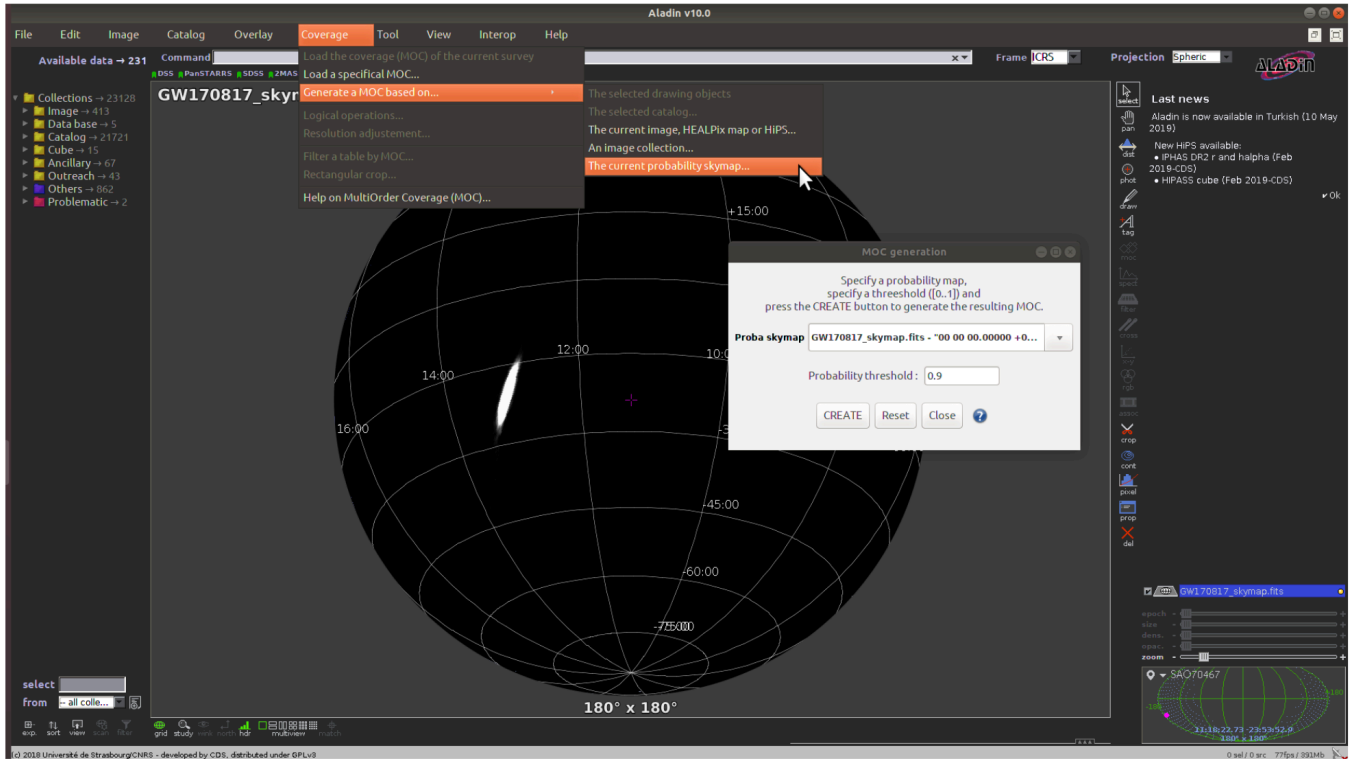






Visualisation of the sky in Aladin

- GW localisation in the sky in Aladin using **MOC** **IVOA standard**
- Background image can be DSS, 2MASS, WISE, XMM, Fermi,…
- We can overlay catalogues of interest, query Simbad, … by region



➡ https://emfollow.docs.ligo.org/userguide/tutorial/aladin.html

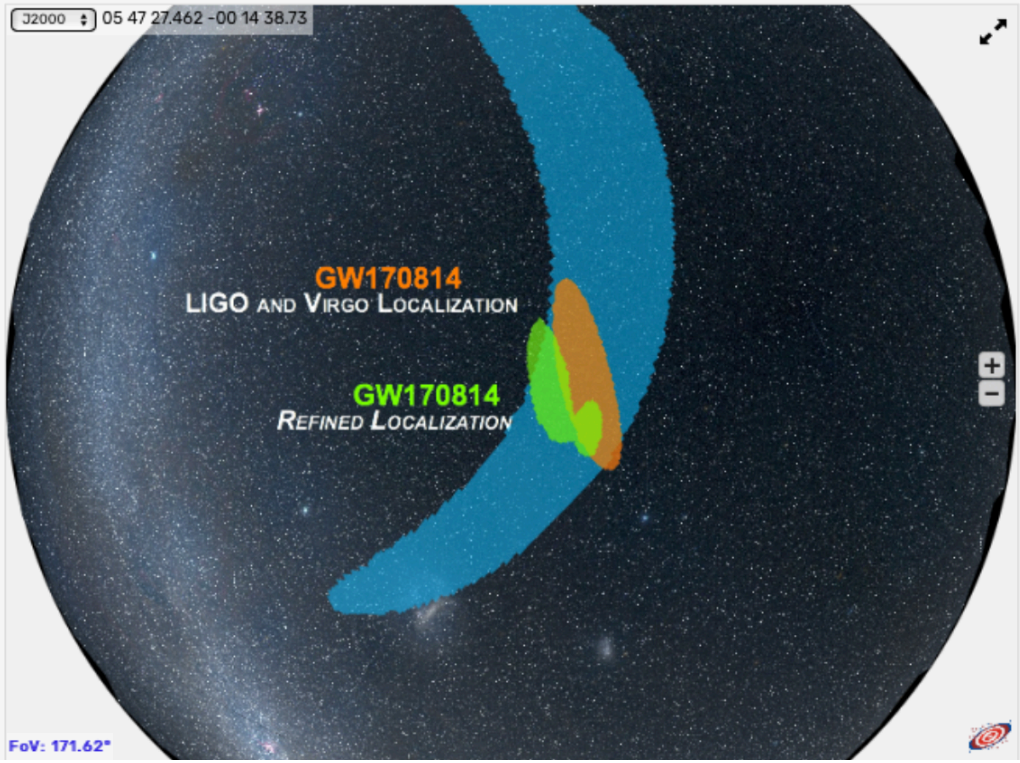
Visualisation of the sky in AladinLite

The CDS is very pleased that our Aladin and Aladin-Lite tools are being used to visualise the sky locations of GW170814, and that the images are on Astronomy Picture of the Day and the New York Times.

www.virgo-gw.eu/skymap.html

apod.nasa.gov/apod/astropix.html

www.nytimes.com/2017/09/27/science/black-holes-collision-ligo-virgo.html



Using the skymap

Click on the various options below to display information relating to each detection.

Detection	Sky localisation	Label	Pop-up info
GW170814 - L1/H1 only	✓	☐	☐
GW170814 - L1/H1/V1	☑	☑	☐
GW170814 - refined skymap	☑	☑	☐
GW150914	☐	☐	☐
GW151226	☐	☐	☐
GW170104	☐	☐	☐

Backgrounds

If you want to see the extension of these sky regions through the constellations you can select an artistic background image ○ **Constellations.**

You can also select various background images at different wavelengths, combining the electromagnetic data with the gravitational-wave information: ◉ **Mellinger (default)** ○ **WISE** ○ **2MASS** ○ **DSS color** ○ **XMM** ○ **Fermi**

Visualisation of the sky in AladinLite

Tutorial on usage of VO tools for EM follow-up of GWs

jupyter nbviewer

JUPYTER FAQ

Fourth ASTERICS School

International Virtual Observatory school

Observatoire Astronomique de Strasbourg, France

Electromagnetic follow-up of gravitational-wave events

by G. Greco giuseppe.greco@uniurb.it, E. Chassande-Mottin ecm@apc.univ-paris7.fr and M.Branchesi marica.branchesi@gmail.com and many others

The tutorial focuses on some basic strategies for working with gravitational-wave sky localization maps in the context of electromagnetic follow-up activities. Here we propose the usage of Aladin, TOPCAT and GWsky. The following main topics are addressed.

1. Gravitational-Wave sky localization map: visualization and tiling
2. Access to existing catalogs using the Multi-Order Coverage map (MOC)
3. Planning for EM follow-up observations

Visualisation of the sky in AladinLite

LIGO Scientific Collaboration

VIRGO

Public Alerts

User Guide

Primer on public alerts for astronomers from the LIGO and Virgo gravitational-wave observatories.

Navigation

Sky Map Visualizations and Credible Regions in Aladin

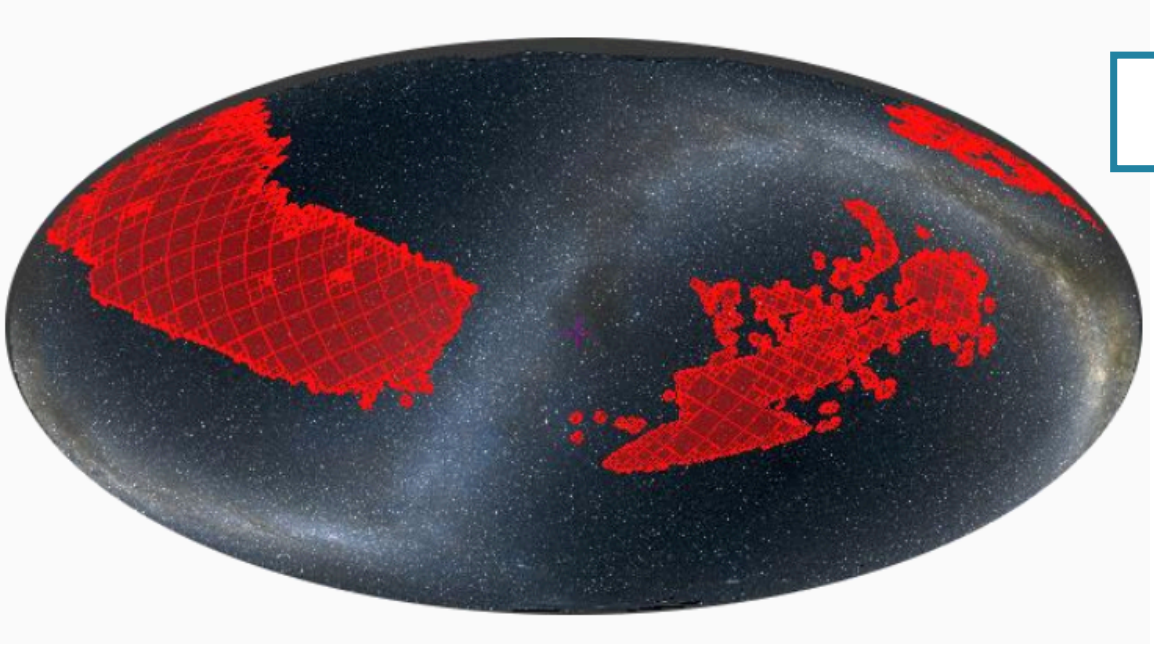
In this section, we demonstrate working with gravitational-wave sky localizations in Aladin Desktop. The following main topics are addressed.

MOC and GW Sky Localizations

The enclosed area within a given probability level contour of a GW sky map can be effectively described with a Multi-Order Coverage (MOC) map [1]. MOC is a standard of the Virtual Observatory which provides a representation of arbitrary regions on the unit sphere using the HEALPix sky tessellation.

Visualisation of sky coverages

- Coverage maps based on MOC IVOA standard are created from positions
  - ➡ We know where but we don't know when!
  - ➡ Need to add the time dimension

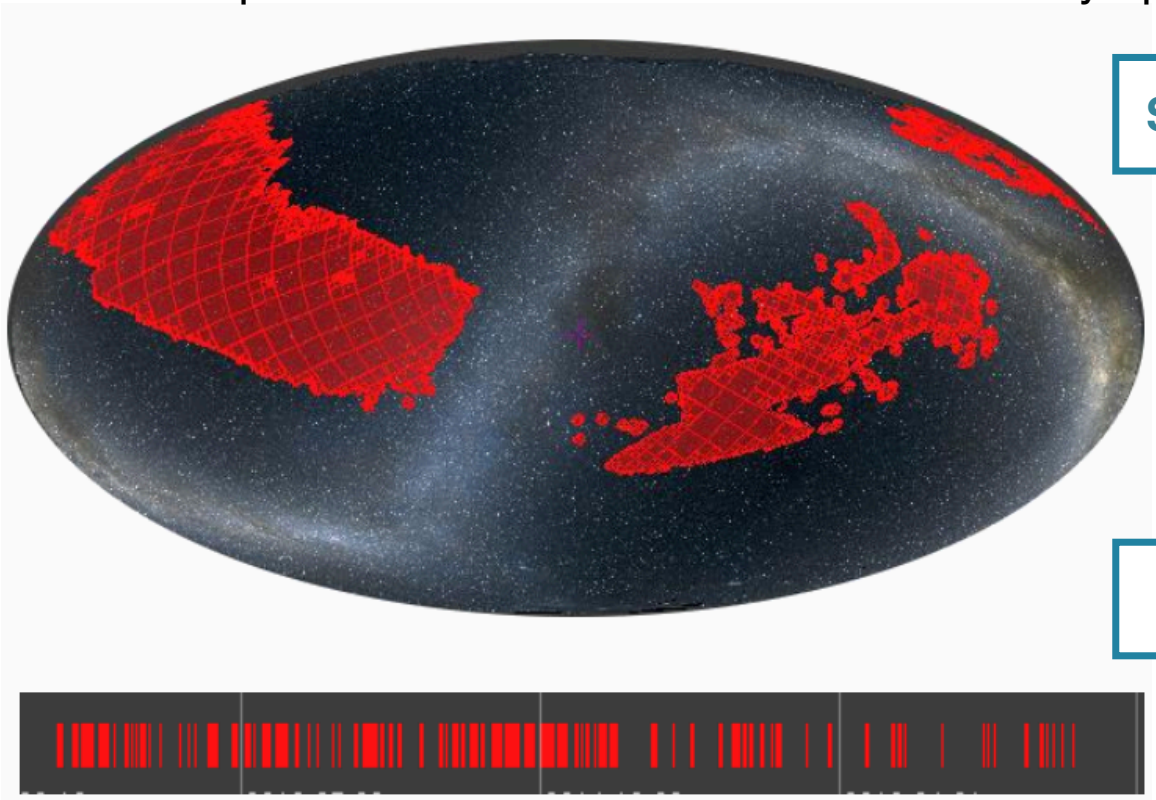


SPACE COVERAGE

ST-MOC: Connecting space and time coverages

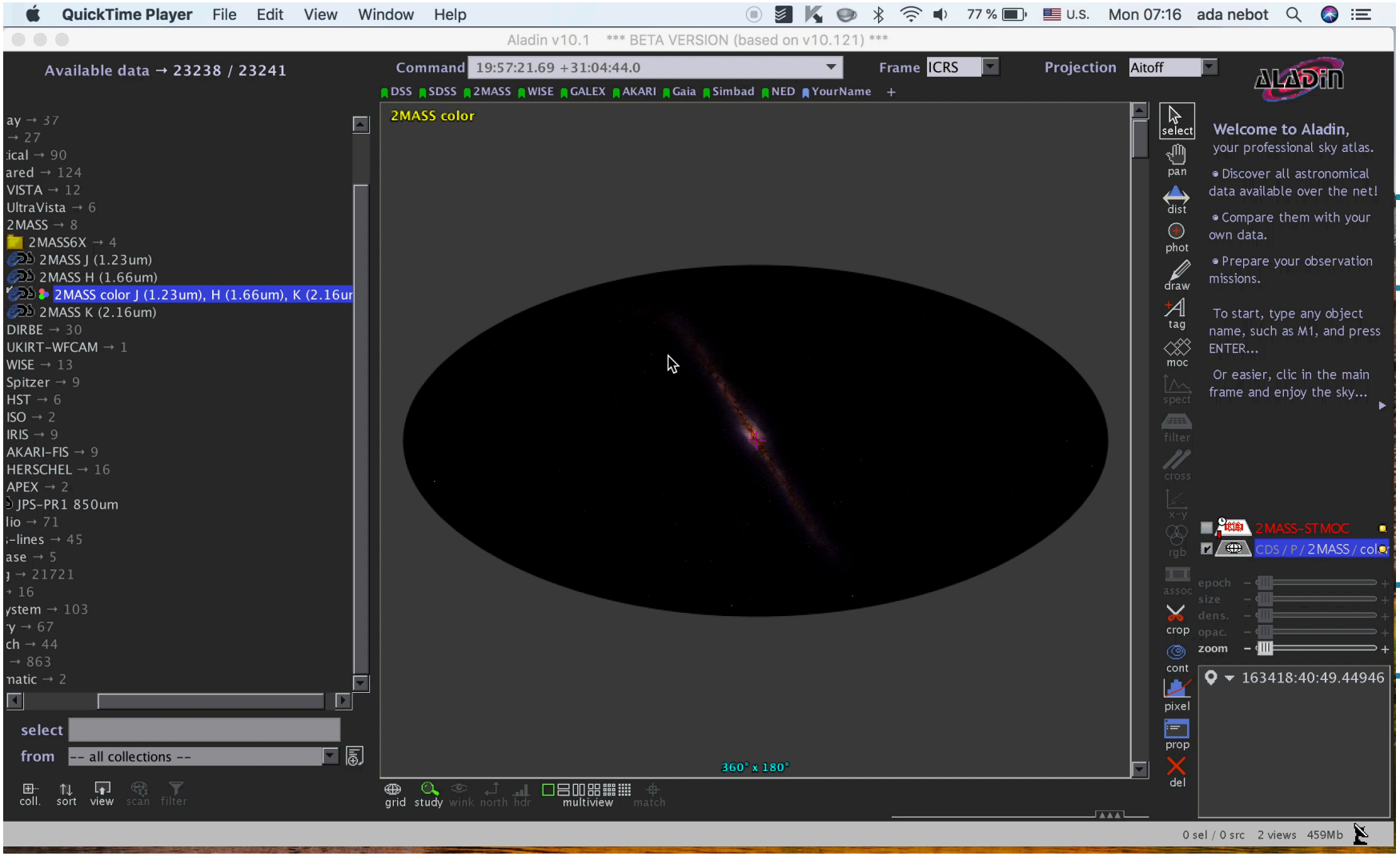
- The STMOC = Space Time MultiOrder Coverage
- Merge together both dimensions in a unique MOC in order to have simultaneously space and time coverage

2 years of CDS&Co R&D driven by the IVOA Time Domain Interest Group



➡ https://wiki.ivoa.net/twiki/bin/view/IVOA/IvoaVOEvent#Time_Series_Data

ST-MOC: Connecting space and time coverages



SPACE

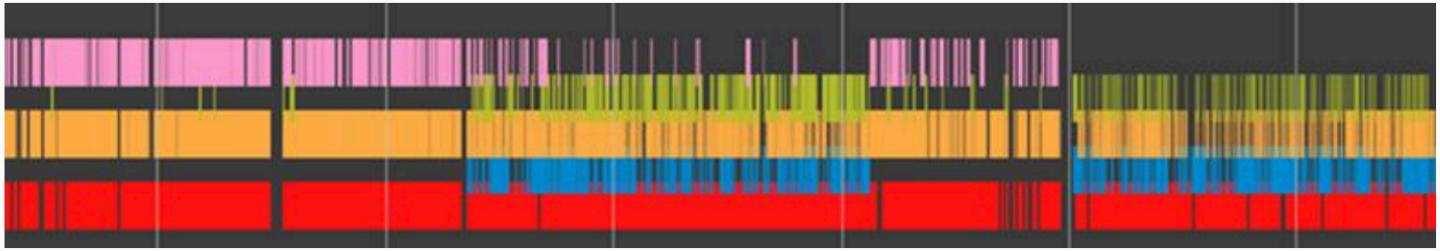
TIME

ST-MOC: Connecting space and time coverages

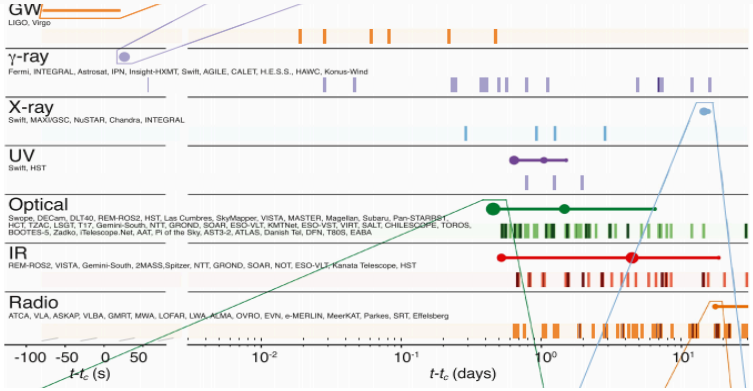
- **Possibility of extremely fast**
  - ➡ computations (generate from catalog, images, regions)

    The only thing you need is a list of positions and times, spatial and temporal resolution)
  - ➡ operations (unions, intersections,…)

    E.g. Have these two telescopes observed the same sky region within this interval of time?



Does it remind you of anything in particular?



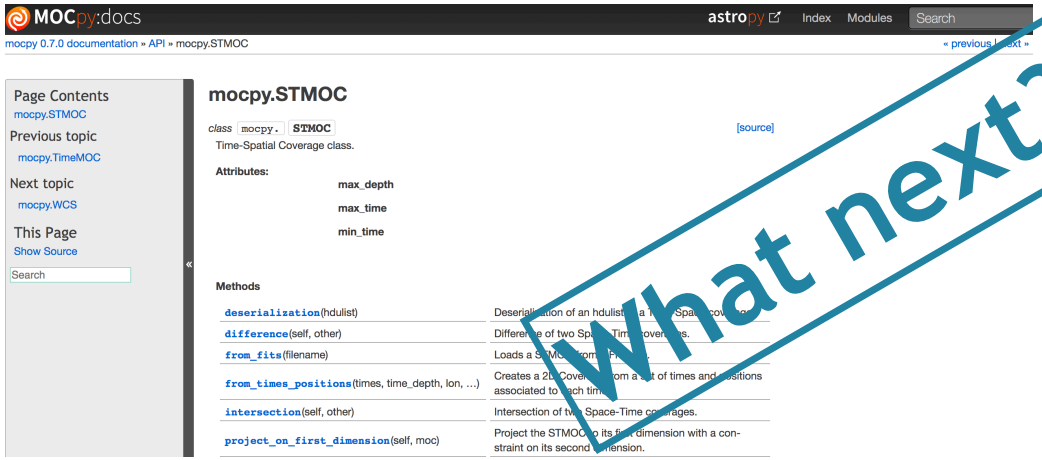
ST-MOC: Connecting space and time coverages

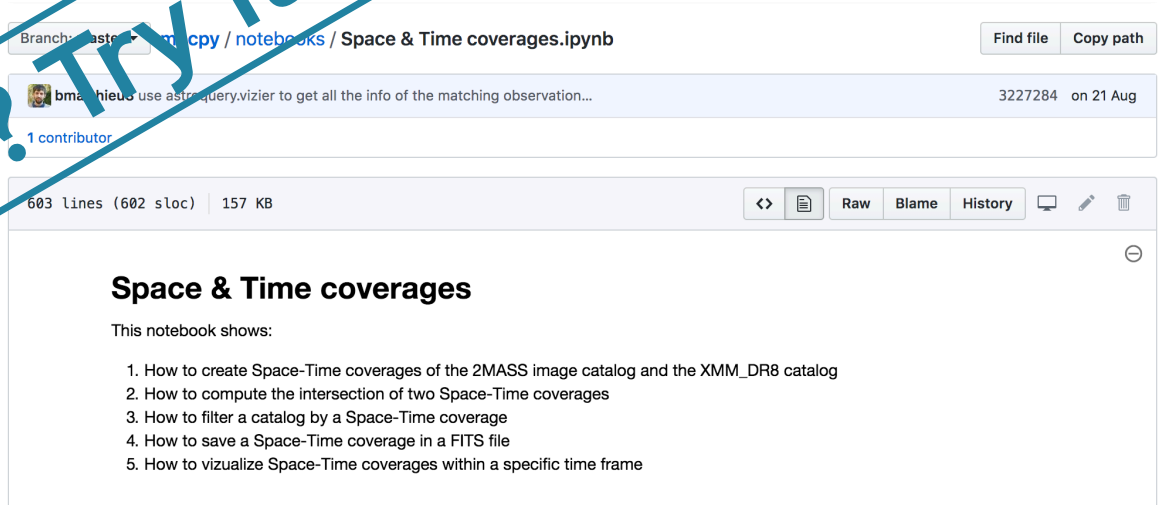
- **Example use:**
  - What is the 2MASS mission coverage in space & time ?
  - Are there common observations in space and time for XMM and Chandra missions ?
  - Which observations are available for this Gravitational Wavelength probability area detected at this epoch ?
  - What are the LSST alerts in this sky region and in this interval of time?

ST-MOC: Find where and when

- **IVOA Note with technical details (Durand, Fernique, Nebot et al 2018)**
- Precomputed for 150 catalogues in VizieR (and more to come!)

  http://alasky.u-strasbg.fr/footprints/STMOC/
- Precompute for solar system body ephemerides
- Available in MOCPy
- Jupyter Notebook showing examples





What next? Try it!!

➡ **Where can I find more info ? @ IVOA**

https://wiki.ivoa.net/twiki/bin/view/IVOA/IvoaVOEvent#Time_Series_Data

Visualisation of data: search, find and retrieve

KEY POINT: IVOA Standardisation of time annotation

Time Scale: UTC, TT, TAI, TCB,…

Format: JD, MJD, ISO, truncated ISO,…

Offset: e.g. JD-XXX (e.g. Gaia…)

Reference position: Topocentre, Geocentre, Barycentre,… (light-travel correction)

TIMESYS element in VOTables (Demleitner, M., Nebot, A., Bonnarel, et al. 2018)

Time Domain Astronomy Challenges/Needs

To characterise and classify sources…

- Multi-wavelength/messenger approach is (sometimes) needed
- Follow-up observations & reaction time for that can be crucial
- Visualisation & navigation
- **Coordination & transmission** of information

- **Coordination & transmission**
  - ➡ collect what was/will observed, when, in which wavelength, …
  - ➡ alerts, emails, webpages, references,…
    - ➡ A multi-messenger platform ?

Summary

- To enable access, discovery and interoperability the VO is based on standards
- The Time Domain standards needed for time domain multi-messenger astronomy are:
  - ➡ Existing (e.g. VOEvent, TAP, VOTable, MOC, HiPS…)
  - ➡ or under development:
    - Definition of the minimum metadata for time (TIMESYS in VOTables)
    - Space + time coverage (STMOC)
    - Visibility & Observation locator (ObjVisSAP & ObsLocTAP)