Major facilities by 2030

Table 1 Summary of operational and planned facilities

Wavelength		Ground based			Space missions		
	In operations	Under construction	Under study	In operation	Under construction	Under study	Proposals
Radio (m to mm)	GMRT, WSRT, J-VLA, eMerlin, VLBI arrays, Effelsberg, GBT, Arecibo, LOFAR, MWA, LWA, PAPER	SKA-P(MeerKAT, ASKAP), FAST, SKA1, SKA2,	SKA1, SKA2,?	RadioAstron		Millimetron	Low-frequency arrays 10-50 MHz
mm/submm/FIR	SMA, NOEMA, APEX, IRAM-30m, mm-VLBI, GMVA, BICEP3,..	CCAT, ASTE-2, LST	mmVLBI-LLAMA, Dome A	SOFIA		SPICA, Millimetron	Far-IR interferometers (FIRI), PRISMA,
IR/optical/UV	2-6.5 m telescopes, VLTs, GTC, VLTI, LBTi, Subaru, Kecks, Geminis	TAO, LSST, EELT, GMT, TMT		HST, Gaia,	JWST, Euclid, TESS, CHEOPS,	WFIRST-AFTA, HDST,	PFI Large apertures (>8 m): ATLAST
X-rays/Gamma rays	MAGIC,HESS, VERITAS	CTA		INTEGRAl,Swift, FGST, AGILE, Chandra, XMM-Newton, Suzaku, NuSTAR	Astro-H, eRosita, Athena, NICER		SMART-X GRAVITAS LOFT, ..
Solar System				Chang'e, LRO, Messenger Venus express, DAWN, ROSETTA, JUNO CASSINI, NEW HORIZON Mars Odissey Mars exploration rover Mars Express MRO, MSL/Curiosity MAVEN, MOM	Bepi Colombo Hayabusa II OSIRIS-REX JUICE INSIGHT Exomars Mars2020	MarcoPolo Europaclipper	LABSR ARM Comethopper TSSM Saturn Uranus

Connection between facilities 2030 and science themes

By 2030 it is expected that ALMA could be contributing to the main scientific topics to be addressed by the operational and planned facilities summarised in table 1:

Radio (m to cm)	ALMA
Dark ages: HI at z=30-50	Primordial chemistry?: HD, H2,.
End of Reionization: z=6-20	Dust + lines
Prebiotic chemistry	Lines?
Structure evolution of the Universe through HI	? Multibeams?
Exoplanets: Magnetospheres	Time variability?
Polarization: Cosmic magnetism	Continuum
Fundamental Gravity through pulsar timing	Time variability, Band 1?
Census of Galactic star formation through astrometry	Continuum
Zooming in on Black Holes and the onsets of jets	mm-VLBI (Continuum)

mm/submm/FIR	
Planet formation and evolution	Continuum +(lines?)
Star formation	Continuum +(lines?)
Large scale structure	**?Multibeams**
Galaxy formation and evolution (z = 0 to 10?)	Continuum+lines
Prebiotic chemistry??	??
Primordial B-mode (CMB)	Continuum ??
Astrometry (relative)? Exoplanet detection?	Continuum??
…	

UV/optical/IR	
Exoplanets: transits: detection of earth type at the Habitable Zone	??
Exoplanets: transits: characterization of atmospheres of super-earths at the Habitable Zone?	??
Exoplanets: direct image and characterization of super-earths	??
Exoplanets: microlensing detections	**?? Continuum**
Astrometry at µas, sub-µas and nas?.	**Continuum**
Exoplanet detection…	**Continnum**
Star formation	**Continuum+lines?**
Dark energy and matter	??
Large scale structure	**Multibeams??**
…..	

X-rays/Gamma rays	
Growth of SMBH up to z ~6	**Continuum + lines**
First population of stars through GRB at high z	**Continuum + lines**
Strong gravity	??
Black hole spin determinations	??
Equation of state of neutron stars	??

• **Evolution of large scale structure**	**Lines??**
• **Detection of the WHIM**	**No**
• **AGN feedback**	**Lines+ continuum**
• …..	

Brief description of facilities by 2030

Radio (m to cm)

Ground based

In operations

- **VLA: Jansky Very Large Array.** Likely to remain the most capable radio interferometer through to ~2020, possibly a little later depending on progress with SKA1 (see later). Offers full coverage across 1 to 50GHz and a powerful high-bandwidth correlator (WIDAR). Ultimately, an array covering New Mexico is envisaged. About to entering a new phase, conducting legacy surveys, following up NVSS and FIRST.
- **VLBI arrays:** A number of continent sized arrays with different characteristics in operation and construction. A recognized science case for high frequency and long global baselines in synergy with the SKA pathfinders.
- **LOFAR:** low frequency array with long baselines, looking for EOR signature, pulsars, transients.
- **eMERLIN:** niche imaging, at a spatial resolution between those possible with JVLA/Westerbork/etc. and VLBI, at 1.4 and 5 GHz. Probably retired by 2030.
- **GMRT, WSRT.** Possibly developing more fast survey capabilities with multi-pixel arrays. Studying galaxies through HI over large redshift ranges
- Other current cm single-dish facilities: GBT, Effelsberg-100m and Arecibo likely will not be operational by 2030.

Under construction

- SKA Precursors: MeerKAT, ASKAP - ought to be part of SKA by 2030
  The MeerKAT array is an international collaboration led by and based in South Africa, and expected to reach completion in 2017. It will be composed of 64 antennas, with a maximum baseline of 8 km, and receivers operating in UHF (0.6 to 1 GHz), L band (1 to 1.75 GHz) and X band (8 to 14.5 GHz). MeerKAT will likely be used mainly for large surveys and VLBI. The current top science science goals for MeerKAT are geared for L band. Two top priority projects focus on pulsar timing, and high-z HI. A list of 8 other MeerKAT science projects are planned, mainly on extragalactic and transient science.
  ASKAP timescale: early science in end 2015, full surveys starting mid-2017, focus on fast HI surveys with focal plane array receivers.

- **FAST:** Five-hundred-meter Aperture Spherical radio Telescope, first light expected in 2016. 500m dish, 300m illuminated aperture at a given time, 70 MHz to 3GHz.
- **Low-frequency arrays:** LOFAR, MWA, LWA, PAPER, etc. Evolving to HERA and SKA-Low (- 350 MHz) Emphasis on EoR. By 2030 might have EoR imaging leading to potential synergy with ALMA.

Under study

- **SKA1**: Phase 1 has 3 parts - SKA1-MID (250 dishes, 350 MHz - (maybe) 14 GHz; SKA1-Survey 64 dishes each with 36 beams, 700 - 1600 MHz; SKA1-low (see later). Should be fully operational before 2030. Synergies: Galaxy HI, evolution of SFR, protoplanetary disks (large pebbles - need high freqs), magnetic fields. Currently being re-baselined to fit within funding envelope of ~600ME.
- SKA2: operational at earliest in mid 2020's, which probably means around 2030, depending on speed of relevant technology development. Note: no frequencies above 14 GHz approved yet: up to at least 22GHz would give better synergy with ALMA. Compared with SKA1: longer baselines by a factor of 10; ten times the number of dish antennas; mid-frequency aperture arrays. Factor of 10 increase in sensitivity at least.

mm/submm/Far-IR

Ground based

Operating facilities

- Current mm/submm telescopes: IRAM 30m, IRAM NOEMA, APEX, SPT, LMT, ARO, JCMT, Nobeyama, Onsala, CARMA, SMA, NANTEN2, ASTE, .. It unclear how many of these will be operating in 2030. These deserve a global mention, but not going into the details, with the exception of NOEMA that will reach full upgrade in the second half of this decade and most likely will run at full capacity at least through the 2020-2030 decade. All others is unclear how long or in what model they will be operating long term. Many of these are capable of fast shallow mapping in the continuum and/or spectral lines, and we need to keep that in mind when recommending what capabilities to develop in ALMA. It is likely that some of these will still be very relevant in ~2030, e.g. LMT may be providing wide ~1-mm imaging at relatively high spatial resolution and competitive 3-mm spectroscopy.

- APEX instrumentation is now being upgraded with the next generation of multi-band bolometer cameras (thousands of bolometers e.g, ArTeMiS, A-MKID camera). They will produce large area shallow surveys/catalogs (at about 350 micron) which need to be exploited by ALMA in the next decades. Multi-beam heterodyne receivers are being deployed at many of these (IRAM-30m, APEX).

- NOEMA: major upgrade of the IRAM interferometer. The upgrades will consist of a doubling of the number of antennas (from 6 to 12 antennas), an increase of the bandwidth (from 8GHz to 32GHz), a doubling of the correlator for simultaneous dual-band imaging and a doubling of the East-West baseline (max=1.6km). So sensitivity multiplied by 4 and a resolution than can reach 0.2”. The correlators will provide full spectral coverage over the receiver bandpass with variable resolution (from 20 KHz to 2 MHz). The lower number of antenna and the smaller number of baseline: due to the smaller number of antennas, it may be easier to update with new instruments or new technology compared to ALMA. The receivers that are being deployed on NOEMA are indeed already next-generation as compared to the ones ALMA is operating at the moment. NOEMA will eventually cover the 70-375 GHz frequency bands, the final spectral line sensitivity will be within ~40% of the ALMA sensitivity, the continuum sensitivity ~60% of the ALMA one (in the common frequency bands, obviously). The development of a prototype 3-element heterodyne focal plane array that will serve to prepare for future multibeam FPA receivers for NOEMA is currently under investigation. NOEMA is designed to allow VLBI observations.

- IRAM 30m: the most sensitivity single-dish antenna in the 3mm, 2mm, 1mm, and 0.8mm bands. IRAM has a continuous upgrade strategy for heterodyne receivers and bolometers e.g. the integration of a dual-band KIDs array camera for the 1mm and 2mm atmospheric windows (NIKA2) is scheduled for 2015/2016. The telescope is part of the 3mm-GMVA and is also used for VLBI at 2mm and 1.3mm (BHC). It is key to complement NOEMA data with short spacing information.

- SMA: Future upgrade to increase the total bandwidth to 32 GHz. This will imply a significant increase in the sensitivity for the continuum. High efficiency for spectral surveys toward bright sources. Ability to efficiently cover large areas in the sky. It will operate at 230 GHz and 345 GHz only (690 GHz decommissioned). .Current plans foresee that the SMA will be operational until, at least, 2020.

- CARMA: Major funding issues, mid-scale facility proposal submitted, but future is uncertain.
- mmVLBI, the Global mm VLBI Array (GMVA), BlackHoleCam and the Event Horizon Telescope. Global array of mm/sub-mm telescopes capable of VLBI. Includes ALMA, LLAMA, SPT, Greenland Telescope, ARO, IRAM NOEMA/30m, as well as other

mm-capable single dish and interferometers. mmVLBI and GMVA are organized as common user access facilities, while the ETH and BlackHoleCam are dedicated experiments/collaborations to observe the event horizon of SgrA* and the M87 supermassive Black Holes. Extension of mmVLBI to include extremely long baselines with space missions (simialr to the cm-wave Radioastron) have been discussed and could dramatically improve resolution (Millimetron is proposed to do this, see below http://millimetron.asc.rssi.ru/index.php/en/).

- BICEP3 - BICEP3 will deploy to the Dark Sector Laboratory at Amundsen-Scott South Pole Station in the 2014-2015 Austral summer season. It will field 2560 detectors operating at 100 GHz. http://www.cfa.harvard.edu/CMB/bicep3/

Under construction

- CCAT: The Cornell Caltech Atacama Telescope is a planned 25m diameter single-dish facility which will operate at 5,600 m of altitude in Cerro Chajnantor, with construction recommended by the Astro2010 decadal survey in the US. Its instrumentation will span the 0.2-3.3 mm range. CCAT is optimized for fast wide-field continuum imaging, providing also wide field and multi-object spectroscopic capabilities. The median transmission of the CCAT site enables routine observations at a wavelength of 350um and as short as 200um for more than 10% of the time. It is thought that CCAT will operate primarily in the “large program” mode, rather than servicing smaller individual proposals. Its main goals encompass galaxy formation and evolution (surveying the population of submm sources), SZ effect, nearby galaxies, molecular cloud and star formation, and solar system (e.g., TNO, comets) studies (see http://www.ccatobservatory.org/docs/pdfs/CCAT_Science_Requirements_R1.pdf) The current thoughts on the planned first-light instrumentation include: 1) SWCam, a 63,000 pixel camera providing simultaneous imaging at 200, 350, and 450 um with FOV diameters of approximately 3’, 5’ (×3), and 7’ (×3) respectively, designed to measure SFRs and dust mass in galaxies through cosmic time. 2) LWcam, a 37,000 pixel camera with simultaneous diffraction limited imaging at 750, 860, 1100, 1300, 2000, and 3300 um and an equivalent FOV of 20’ diameter. Key science includes Sunyaev-Zel’dovich effect observations. 3) X-spec, a direct detection multi-object R~700 spectrometer in the 200-900 GHz range capable of obtaining simultaneous spectra for dozens of sources located over a 1 deg field. 4) CHAI, a dual-band (460-490 and 800-870 GHz) multi-object heterodyne spectrometer for 64 objects.

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- LLAMA: The Long Latin-American Millimeter Array is one ALMA-design 12m Vertex antenna operating at the Alto Chorrillos site in the Argentine province of Salta, close to the city of San Antonio de los Cobres, built and operated by Brasil (FAPESP) and

Argentina (CONICET). (presentation in Spanish) The baseline subtended to the ALMA site is approximately 183 km. The antenna is expected to operate in VLBI mode, and the resulting resolution would be 1 milli-arcsecond at 1 mm, thus filling the intermediate baselines gap between ALMA and the global VLBI network. In principle, other similar projects like LLAMA can be developed in the next decade, (let's say within South America) since the cost is relatively cheap, antennas are just a copy of ALMA antennas (so therefore well characterized) and could help filling the intermediate baselines of the global mm-VLBI array.

- Dome A Observatory: a 15-meter THz telescope to build in Antarctica after 2015. A prototype called DATE5 (The Dome A 5-m terahertz telescope) is currently being built.
  - see page 6 of this PPT
  - science news

- ASTE-2 - Japanese initiative in the ~25m single-dish class, possibly intended for high site, near CCAT. Seems to be progressing slowly, but there would be widespread interest from Europe and elsewhere if it were to gain momentum.

- LST: The Large Submillimeter Telescope is a Japanese plan to construct a 50m mm/sub-mm singe-dish antenna optimized for wide-area imaging and spectroscopic surveys in the 70-420 GHz range. The current plan is to build the telescope near the CCAT site. The telescope should also allow VLBI observations. The LST is designed to perform cosmological surveys on very large areas (100-1000 deg^2) and to work in synergy with ALMA, SPICA, etc.

Space

Under study

- **SPICA**: the Space Infrared Telescope for Cosmology and Astrophysic is a JAXA-ESA collaboration to launch the next large far infrared astrophysics mission around 2025. It will be equipped with 3 meter class cryogenic telescope (<6 K) operating in the L2 orbit. The instrumentation will cover the 5-210um wavelength range. The payload will consist of three instruments: SAFARI (SpicA FAR-infrared Instrument), a FIR imaging spectrometer (30 - 210 μm, spectral resolution of 10 to 10000), and two mid-infrared instruments, namely the MIR coronograph (3.5/5 - 27 μm) and the MIR camera/spectrometer (5 - 38 μm). SPICA will study the evolution of galaxies, stars and planetary systems. http://www.ir.isas.jaxa.jp/SPICA/SPICA_HP/index_English.html

- **Millimetron:** Millimetron ("Spektr-M" project) is a project of the Russian Federal

Space Agency. It is a space observatory with a 10-m cooled deployable telescope (<10K) To be equipped with state-of-the-art receivers, enabling observations in the mm/submm to far-infrared wavelength range between 200 microns and 17 mm. It will operate in single-dish mode or as a station in a space-ground VLBI network. In the VLBI mode the Millimetron, will provide extremely high angular resolution allowing for example imaging studies of the direct environment of black holes. As a single dish observatory, Millimetron will provide unique capabilities to conduct detailed and deep imaging and high resolution spectroscopy with unrivalled sensitivity, probing and characterizing the earliest epochs of the Universe as well as the complete evolutionary track of star formation and exo-planetary systems. http://millimetron.asc.rssi.ru/index.php/en/

Proposals

- **FIRI:** Far-infrared Interferometer. Extremely ambitious (complex, costly, risky, potentially high-impact) concept developed in EU and NA, typically with 2-3 free-flying or tethered SPICA-class (~3.5-m, cold) telescopes in its most ambitious form, or a couple of smaller ~1-2-m telescopes mounted on a boom.
- **Other concepts:** Large single dish concepts are also being considered (e.g. SAFIR, GISMO. Also some partially-filled-aperture ideas are proposed in the White Paper written for the 2013 ESA L-class call, which include the three concepts outlined. http://www.firi.eu/

IR/Optical/UV

Ground based

In operations

- **Wide field imaging telescopes** using very small apertures (professional cameras and lenses). "A la Dragonfly" to probe the Optical light (very deep, maybe down to 31 mag/arcsec^2?)

- **2-4 meter class telescopes:** WHT, LAMOST, AAT (SAMI), APO (BOSS, APOGEE, MaNGA, and SDSS 5?)
    a. **WEAVE**: is designed to exploit Gaia's scientific legacy and is a prime focus spectrometer for the William Herschel Telescope (WHT). It will have a field-of-view of 2 degrees and about 1000 fibres. It will provide a low resolution survey for radial velocity measurements of stars that are too faint to be observed by the Gaia spectrometer, along with a high resolution survey to make accurate

determinations of the metallicities and temperatures of the bright stars observed by Gaia. The instrument PDR took place in early 2013, and the start of the surveys should be in 2017, provided adequate funding is secured by all partners (UK, Netherlands, Sweden, France, Spain).

b. **DESI**: Other projects are under study or in a development phase elsewhere; such as the Dark Energy Spectroscopic Instrument, (DESI-formally Big BOSS) on the 4m Mayall telescope at Kitt Peak. This has a field-of-view of 3 degrees and 5000 fibres. These other projects present opportunities for bi-lateral collaboration from European countries.

- **10m-class telescopes**
  - **Subaru** telescope, 8.2 m optical and infrared telescope located at the top of Mauna Kea will continue its operation at least until 2033. It will most likely focus on prime focus instruments to conduct wide field surveys.
  - ***VLT - Paranal*** - Equipped with multi-object near-IR integral field unit (IFU) spectrometer, KMOS, and wide-field optical IFU, MUSE, covering a square arcmin (or rather less at much higher spatial resolution with AO enabled). ESO roadmap currently foresees VLT instrument development continuing into the 2020s at a rate of one new instrument or upgrade per year. New instruments will likely include MOONS and 4MOST, both wide-field spectrometers, the former optimised for redshift surveys in the "optical redshift desert", the latter optimised for Gaia-related spectroscopic observations. Also, ERIS (**E**nhanced **R**esolution **I**mager and **S**pectrograph) on UT4, exploiting powerful new 4-laser Adaptive optics facility. Gravity, (etc.)
  - ***Keck (add info)***
  - ***Gemini*** provides two 8.1m telescopes located on Mauna Kea and Cerro Pachon equipped with instruments operating from 360-5000nm to provide imaging and spectroscopy. Niche is high spatial resolution in near-infrared over relatively small field of view. GPI (Gemini Planet Imager - an extreme AO imaging polarimeter/integral field 0.9-2.4-micron spectrometer) has been a recent success.

  - **GTC** (Gran Telescopio de Canarias). Diameter of 10.4 m, equipped with instrumentation covering optical, up to MIR wavelengths (OSIRIS and Canaricam are operational) and many more instrumentation like EMIR in development.

- **VLTi:** ESO's Very Large Telescope Interferometer consists of an array of four 8m telescopes (UTs) and four 1.8m telescopes (ATs). Two second generation instruments will be installed during 2015 and 2016, which can both combine four UTs or ATs simultaneously, thereby yielding measurements of visibility amplitude and closure phases on six baselines.

  - The `Gravity' instrument will enable spectro-interferometric observations (with a resolving power of ~5000), in K-band, of objects much fainter than previously possible (down to K=11 for spectroscopy). It includes the capability of observing two sources separated by up to 2 arcsec, so that a fainter source can be observed while tracking fringes on a brighter neighboring star. Off-axis fringe tracking will allow sources as faint as K=15 to be observed, and narrow-angle astrometry with 10 microarcsecond accuracy. The main science goal for Gravity is precision astrometry, in particular in the neighbourhood of Sgr A*, but also for exoplanet searches.
  - The `Matisse' instrument will provide dispersed visibility data in the thermal IR (L, M and N bands, with resolving power of 30-1000), and will achieve its full potential once paired with an external, four-telescope fringe tracking instrument (under consideration at ESO). Its main goals are 1) image synthesis (of circumstellar environments, but also possibly AGNs), 2) detection of hot jupiters or protoplanets, and 3) observations of minor bodies of the solar system.
  - The development of third generation instruments will soon be considered. The serious contenders at the moment are 1) a visible instrument with high spectral resolution capabilities (~30000) and 2) a high dynamic range imager in the near-infrared. A possible expansion of the VLTI imaging capability is also part of the prospective exercise at the same timescale as ALMA2030.

- LBTI provides a baseline of 22 m and most probably an increased sensitivity with respect to VLTI, this corresponds to a 100 mas resolution. It possesses a possibility for nulling interferometry in the 8-14 micron regime tailored for exozodis detection (~1sigma = 10 zodis).

Under construction

- **GMT:** The Giant Magellan Telescope is a 24.5 m telescope being developed by an international consortium that will be located at Las Campanas Observatory in Chile. Construction is scheduled to begin in 2014, and first light is expected in 2020. GMT will have nearly five times the light-gathering power of today's largest telescopes, and angular resolution an order of magnitude better than that of the Hubble Space Telescope. The three instruments selected to be built for first light are the GMT-Consortium Large Earth Finder (G-CLEF), the optical multi-object spectrograph GMACS, and the GMT Integral Field Spectrograph (GMTIFS). G-CLEF is a high-resolution optical spectrograph that will enable both unprecedentedly sensitive radial-velocity searches for extrasolar planets and pioneering studies of the intergalactic medium and the first stars. GMACS is a workhorse low and medium resolution optical spectrograph with applications from nearby stars to the most distant galaxies, and GMTIFS is a near-infrared AO-fed integral field spectrograph and imager that will be used to study the black hole at the center of the Milky Way and the dynamics of high-redshift galaxies. Other future capabilities include the MANIFEST fiber feed and positioning system that will enable all of the GMT spectrographs to access the telescope's full ~20' field of view and achieve higher spectral resolution, a multi-object near-IR spectrograph, and near-IR high-resolution echelle spectrograph.

E-ELT The European Extremely Large Telescope (E-ELT) is a 39.3-m telescope being designed by ESO and its partner institutes for Cerro Armazones in Chile, the top of which (at a height of 3060m) is being levelled in June 2014. E-ELT will have 798 mirror segments, each 1.4m, with a 4.2-m secondary mirror. The adaptive 1.6-m M4 mirror has over 6000 actuators and will compensate for atmospheric turbulence using six laser guide stars. The first-light instruments are a wide-band integral field spectrograph (HARMONI) and a diffraction-limited near-IR camera (MICADO), the latter fed by the MAORY adaptive optics facilty, and these will be followed by a MOS, a high-resolution spectrometer (HIRES) and a mid-IR instrument.

- E-ELT/HARMONI: 0.4-2.4microns IFU spectrograph with four different plate scale settings to cover diffraction limited to natural seeing observations (4masx4mas; 10masx10mas;20masx20mas;60masx30mas); max field of view 9x6.5arcsecs with the widest scale down to 0.6x0.9 arcsecs; spectral resolution R~500; 4k; 10k; 20k. Simultaneous opt-NIR planned.
- E-ELT/MICADO: 50arcsec diameter field of view with 4mas pixels and slit spectroscopy with TBC resolving power. <40mas astrometric performance.
- E-ELT/MIDIR instrument based on METIS; 30arcsec imaging field; R~100,000 IFU spectroscopy 3-5um (perhaps also N band - 14um); Q-band (to 28um) as a goal. E-ELT/HIRES R>50 0000 spectral resolving power; could be broad wavelength coverage (0.4-2.4um). MOS - wide range of facilities foreseen from multi-IFU AO assisted (multiplex of 10s) to seeing limited, fibre fed (multiplex of 100s). On longer timescales,
- ELT-PCS planetary camera and spectrograph (a SPHERE-type instrument for the E-ELT) - potential to image exo-Earths.

- **TMT:** TMT is the Thirty Meter Telescope, a wide-field telescope with 30 meter diameter. The optical beam of this telescope will feed at least eight different adaptive optics AO/instrument combinations covering a broad range of spatial and spectral resolution. TMT will couple unprecedented light collection area (almost 10 times more than one of the Keck telescopes) with diffraction-limited spatial resolution. The first light instruments are the **Wide Field Optical Spectrometer (WFOS), the Infrared Imaging Spectrometer (IRIS) and the Infrared Multi-object Spectrometer (IRMS).**

- The Wide Field Optical Spectrometer (WFOS) will provide near-ultraviolet and optical (0.3 – 1.0 μm wavelength) imaging and spectroscopy over a more than 40 square arcminute field-of-view. Using precision cut focal plane masks, WFOS will enable long-slit observations of single objects as well as short-slit observations of hundreds of objects simultaneously. WFOS will use natural (uncorrected) seeing images.
- The Infrared Imaging Spectrometer (IRIS) will be mounted on the observatory MCAO system and be capable of diffraction-limited imaging and integral-field spectroscopy at near-infrared wavelengths (0.8 – 2.5 μm).
- The Infrared Multi-object Spectrometer (IRMS) will allow close to diffraction-limited imaging and slit spectroscopy over a 2 arcminute diameter field-of-view at near-infrared wavelengths (0.8 – 2.5 μm).

- **LSST** : LSST is the Large Synaptic Survey Telescope - an 8m-class optical survey telescope with a very large field of view of 10 square degrees. It will survey the full Southern Sky every couple of days down to a approximately r ~ 24.5 mag per visit. Each field is visited a few thousand times in ~10 years of operation. It will operate in the 300-11000 nm range in six photometric bands (ugrizy, similar to Pan-STARRs). Two of the main science drivers are time-domain astrophysics and dark energy. In particular, LSST will open a completely unexplored window into transient phenomena, and is planning on making all their transient alerts public in real time. First light is expected around 2020, with regular operations starting 2023ish.

- **TAO**
  The University of Tokyo Atacama Observatory project is going to have a 6.5m infrared-optimized telescope at the summit of Co. Chajnantor (5640m alt.) in northern Chile. The construction is now underway, and the first light is expected in 2017-2018. Thanks to the low water vapor (PWV~0.5mm) and the high altitude, a new atmospheric window at 25-38 micron, as well as a continuous band at 1-2 micron including Paschen-alpha at 1.875 micron, become available. Two first generation instruments are currently under development: SWIMS, a NIR wide-field multi-object camera/spectrograph capable of simultaneous 0.9-2.5 micron MOS spectroscopy with R~1000 in a FoV of 9.6 arcmin. SWIMS is expected to be a workhorse instrument to cover from Galactic objects to distant galaxies/AGNs. The other is an MIR camera/spectrograph MIMIZUKU covering 2-40 micron with high spatial resolution of <1 arcsec and capable of high -precision relative photometry. MIMIZUKU is expected to carry out studies of stellar disks and extrasolar planet formation.

Under study

- ***MSE***: Mauna Kea Spectroscopic Explorer ⇒ maybe include the potential multi-spectro dedicated 10m replacing CFHT. Not clear if this will happen and when. http://www.cfht.hawaii.edu/en/news/MSE

Space missions

In operations

- **HST** - The Hubble Space Telescope is a 2.4m UV/optical/IR space telescope, launched in 1990. Through five servicing missions it has received numerous upgrades to its instrument complement. Many of the capabilities of HST are not replicated elsewhere. At present there are four operating instruments on HST:

    - The Space Telescope Imaging Spectrograph (STIS) offers a variety of imaging and spectroscopy in the ultraviolet and optical wavelength ranges (1140 - 11000 A) at low and medium resolution, as well as a high spectral resolution echelle capability.
    - The Cosmic Origins Spectrograph (COS) offers high throughput UV spectroscopy in the 900 - 3000 A wavelength range at low and medium resolution, through a 2.5" aperture. It is optimized for point sources.
    - The Wide Field Camera 3 (WFC3) provides a range of UV, optical and near infrared imaging capabilities as well as grism observations. The field of view of the UV and visible detector (UVIS) is 2x162"x162" at 0.04"/pixel, and the IR detector has 136"x123" spatial coverage, at 0.13"/pixel.
    - The Advanced Camera for Surveys (ACS) has two sets of detectors, the Wide Field Camera (WFC) with 2x2048x2096 pixels, 0.05"/pixel, and an area coverage of 202"x202". The Solar Blind Channel (SBC) has a 1024x1024 pixel detector with 0.032"/pixel, spanning 34"x31".

  HST's ability to provide deep, precise, and stable pan-chromatic imaging, as well as slitted and slitless spectroscopy, coronography, and astrometry make it a versatile observatory, capable of tackling science problems ranging from the architecture of the universe, mysteries of dark matter and dark energy, births and deaths of stars, and the recipes for building planets. The current and projected status for HST is good. At present, operations into the early 2020 timeframe appear feasible, and based on orbital analyses and instrument performance, continuing further into the 2020 decade is realistic. http://www.stsci.edu/hst

Under construction

- **JWST:** JWST is NASA's flagship mission, a 6.5 m diameter segmented telescope operating at near- and mid-infrared wavelengths (0.6-28 micron). Scheduled to launch in 2018, JWST will probe the early universe, address questions of galaxy formation and evolution, the birth of planetary systems, and search for the ingredients of life. Its instrument complement contains a diverse array of observing modes, from imaging to grism, slit less, multi-object and integral field unit spectroscopy, coronography, and aperture masking interferometry.
  - The Near Infrared Camera (NIRCam) covers a 2.2x4.4 arc minute field of view from 0.6-5 micron, with 0.032" pixels from 0.6-2.3 micron, and 0.065" pixels from 2.4-5.0 microns. A variety of filters provide imaging capability along with grism spectroscopy at a resolution of 2000, and NIRCAM has a coronographic capability from 0.6-2.3 micron. T
  - he Near Infrared Imager and Slitless Spectrograph (NIRISS) provides imaging over a 2.2x2.2 arc minute field of view, covering the 0.9-5 micron range at 0.065" per pixel. It also provides slit-less spectroscopic capability from 0.6-2.5 micron at resolutions from 150-700, as well as aperture masking interferometry from 3.8-4.8 microns.
  - The Near Infrared Spectrograph (NIRSpec) has a variety of spectroscopic modes, from single slit and multi-object spectroscopy to IFU spectroscopy, at wavelength ranges of 0.6-5.0 microns, and resolving powers from 100 to 2700. The sizes of the slits range from a few arcseconds to 3.4x3.4 arc minutes (for the multi-object spectrograph, with 0.5" shutters).
  - The Mid-Infrared Instrument MIRI covers the 5-28 micron wavelength range, with imaging (0.11" pixels, field of view 1.23'x1.88'), single slit and IFU spectroscopy (resolution up to 3500, slit widths of a few arc seconds), and coronography at several wavelengths.

  A more complete description of the science questions driving the instrumentation can be found in Gardner et al. (2006 Space Science Reviews, vol. 123, p 485), with updated white papers available at http://www.stsci.edu/jwst/doc-archive/white-papers. A summary of JWST's contribution to particular science questions, as discussed in recent peer-review literature can also be found at http://www.stsci.edu/jwst/jwst-science-corner/.

- **Euclid:** Euclid is a mission led by the European Space Agency designed to study dark matter and dark energy through high precision studies of weak gravitational lensing and baryonic acoustic oscillations. Its planned launch is 2020, to the L2 point. The mission lifetime is 6 years and it is designed to map 15,000-20,000 sq. deg., with very deep mapping of 40 sq. deg. Euclid is a 1.2m diameter wide-field

telescope that will produce a legacy dataset with images and photometry for over a billion galaxies and several million spectra, out to a redshifts $z>2$. At low redshift it will resolve the stellar populations of all galaxies within 5 Mpc. The instrumentation consists of an optical camera (VIS, 550-900 nm, 0.18" PSF), and a NIR camera/spectrograph (NISP, equipped with Y, J, H filters for imaging at 920-2000 nm and capable of R=250 spectroscopy for wavelengths 1100-2000 nm). Euclid is also expected to detect hundreds of galaxies $6.3<z<8.5$, brighter than J~26 (see EUclid Definition Study Report at http://sci.esa.int/euclid/48983-euclid-definition-study-report-esa-sre-2011-12/#).
Euclid is also gonna be used for exoplanets science using microlensing and transients.

- **Gaia:** The satellite (**Gaia**) was launched on 19 December 2013 (nominal mission end is 2018 after 5yr). This space satellite is designed to deliver a three-dimensional map of the Milky Way. Gaia will provide unprecedented positional measurements for about one billion stars in our Galaxy - about 1 per cent of the Galactic stellar population - and Local Group, together with radial velocity measurements for the brightest 150 million objects. While the mission itself will likely not be active in 2020-2030 time-frame its products (catalogs) will have important impact. Astrometric precision is ~25 microarcseconds (GRAVITY 10 microarcseconds). Astrometric characterization of known and discovery of new exoplanets (measurement of real mass).

- **PLATO :** Recently selected by ESA as the M3 mission, it is expected to be launched in 2024. PLATO will discover and characterize a large number of close-by exoplanetary systems, with a high precision in the determination of the planet mass, of planet radius, and of stellar age. It will provide the key information needed to determine the potential habitability of the new detected exoplanets. PLATO has also been designed to investigate seismic activity in stars, enabling the precise characterisation of the planet host star, including its age. PLATO will be equipped with 32 telescopes (pupil diameter of 120 mm) with a focal plane array of 4 CCDs each with 45102 pixels providing a very wide FoV of 1100 deg. The cameras are arranged in four groups of eight. Each group has the same FoV but is offset by a 9.2° angle, allowing to survey a total field of ~2250 deg2 per pointing. The proposed total mission lifetime is about 6 years.

- **Cheops :** The CHaracterizing ExOPlanet Satellite (CHEOPS) will be the first mission dedicated to search for transits by means of ultrahigh precision photometry on bright stars already known to host planets. By being able to point at nearly any location on the sky, it will provide the unique capability of determining accurate radii for a subset of those planets for which the mass has already been estimated from ground-based spectroscopic surveys. It will also provide precision radii for new planets discovered by the next generation ground-based transits surveys (Neptune-size and smaller).

- **TESS :** Transiting Exoplanet Survey Satellite (TESS) has been selected for development in Sep 2011 of Explorer-class mission proposals. The satellite is scheduled to launch in 2017. The satellite will work on much the same principle as the Kepler satellite: planetary transit photometry. The advantages with respect to Kepler:
    a. TESS will survey the entire sky through the use of four wide-field telescopes. This survey area is over 400 times larger than Kepler's field of view.
    b. TESS each of those four telescopes will have a CCD detector. Combined those cameras will have a total of 192 megapixels, compared to Kepler's 95 megapixel CCD.
    c. TESS will study approximately 2,000,000 stars, compared to Kepler's 150,000

Under study

- **WFIRST:** The Wide-Field Infrared Survey Telescope (WFIRST) is a NASA observatory designed to perform wide-field imaging and slitless spectroscopic surveys of the near infrared (NIR) sky for the community. The current Astrophysics Focused Telescope Assets (AFTA) design of the mission makes use of an existing 2.4m telescope to enhance sensitivity and imaging performance. **WFIRST-AFTA** will settle essential questions in both exoplanet and dark energy research and will advance topics ranging from galaxy evolution to the study of objects within the Galaxy and within the Solar System.

- **HDST** - High definition space telescope (12 m) telescope under discussion in USA; main science goals are (1) Exoplanets; (2) Universe in High-definition - resolving 1pc out to 25 Mpc, resolving 100pc star forming regions throughout the universe. UV (90 nm) to near-IR (2.5 mm, non-cryo): http://www.aura-astronomy.org/news/hdst.asp - note that HDST is an offshoot from the *ATLAST* 8-12 m UV-to-IR space telescope concept (http://www.stsci.edu/institute/atlast)

- **SPICA** - see submm/FIR facilitties section. http://www.ir.isas.jaxa.jp/SPICA/SPICA_HP/index_English.html

Proposals

- **PFI** (Planet Formation Imager) is a proposed space interferometry project probably beyond 2030-2030 time frame, http://planetformationimager.org. Optical interferometry is destined to play the crucial role in advancing our understanding of planet formation and that PFI will be required to explain the increasing wealth of exoplanet demographic information anticipated in the coming decades. PFI will be a powerful complement to and extension of ALMA, ELTs, and JWST in our quest to understand the origin of the planets and to fully explore notions of habitability. PFI will target planet-forming disks as well as warm, newly-born planets around stars in nearby star forming regions. PFI must operate at near- and mid-IR wavelengths with 0.1 to 1 AU resolution to resolve structures in dusty disks at solar system scales. The PFI facility will have the potential to unmask all the major stages of planet formation, from initial dust coagulation, gap formation, evolution of transition disks, mass accretion onto planetary embryos, and eventual disk dispersal. PFI images will directly detect the cooling, newly-formed planets themselves, opening up both spectral investigations and also providing a vibrant look into the early dynamical histories of planetary architectures. Only long-baseline interferometry can provide the needed angular resolution and wavelength coverage to reach these goals and from here we launch our planning efforts."

- ***ATLAST:*** The Advanced Technology Large Aperture Space Telescope (ATLAST) is a NASA concept study for the next generation of UV/optical space observatory. ATLAST will have a primary mirror diameter in the 8m to 16m range that will allow us to perform some of the most challenging observations to answer some of our most compelling astrophysical questions. ATLAST will have an angular resolution that is 5 - 10 times better than the James Webb Space Telescope (JWST) and a sensitivity limit that is up to 2000 times better than the Hubble Space Telescope (HST)

X-rays/Gamma rays

Ground based

In operations

- **MAGIC:** The MAGIC Collaboration has built in 2002 / 2003 a first large atmospheric imaging Cherenkov telescope. Placed in Canary Islands, it has two telescopes (MAGIC-I and II), with a surface of 236 m^2 each. With the accent of these instruments on large mirror surface and best light collection, cosmic gamma-rays at an energy threshold lower than any existing or planned terrestrial gamma-ray telescope have become accessible. So far achieved has been a threshold of 25 GeV. https://magic.mpp.mpg.de/

- **HESS:** High Energy Stereoscopic System study the very high energy gamma-ray astrophysics. Placed in Namibia, it is a system of imaging atmospheric Cherenkov telescopes. It covers the rnage of 10s of GeV to 10s of TeV. https://www.mpi-hd.mpg.de/hfm/HESS/

- **VERITAS:** the Very Energetic Radiation Imaging Telescope Array System is placed in Arizona. It is an array of four 12m optical reflectors for gamma-ray astronomy in the GeV - TeV energy range. Their highest sensitivity is reached in the range 50 GeV - 50 TeV, being maximum in 100 GeV-10 TeV. This is complementary to the NASA Fermi mission.

Under construction

- **CTA:** Cherenkov Telescope Array (overlap with particle physics, but essentially astronomy). Large array(s) of telescopes for ground based detection of 100 GeV - 100 TeV gamma rays. 10x increase in sensitivity at least over current instruments. The aims of the CTA can be roughly grouped into three main themes, serving as key science drivers: a) Understanding the origin of cosmic rays and their role in the Universe, b) Understanding the nature and variety of particle acceleration around black holes and c) Searching for the ultimate nature of matter and physics beyond the Standard Model. https://portal.cta-observatory.org/Pages/Home.aspx

Space missions

In operations

- **INTEGRAL:** The INTErnational Gamma-Ray Astrophysics Laboratory was launched in October 2002, and it is a project of the European Space Agency, woth contributions of Russia and NASA. It is providing a new insight into the most violent and exotic objects of the Universe, such as neutron stars, active galactic nuclei and supernovae. INTEGRAL is also helping us to understand processes such as the formation of new chemical elements and the mysterious gamma-ray bursts, the most energetic phenomena in the Universe. Environments of extreme temperature and density, near the event-horizons of black holes, are a major topic of study with INTEGRAL. INTEGRAL is dedicated to the fine spectroscopy (E/E = 500) and fine imaging (angular resolution: 12 arcmin FWHM) of celestial gamma-ray sources in the energy range 15 keV to 10 MeV with concurrent source monitoring in the X-ray (3-35 keV) and optical (V-band, 550 nm) energy ranges. http://heasarc.gsfc.nasa.gov/docs/integral/inthp_about.html

- **Swift:** Swift is a first-of-its-kind multi-wavelength observatory dedicated to the study of gamma-ray burst (GRB) science, built by NASA with international participation. Its three instruments work together to observe GRBs and afterglows in the gamma-ray, X-ray, ultraviolet, and optical wavebands. The main mission objectives for Swift are to: Determine the origin of gamma-ray bursts; Classify gamma-ray bursts and search for new types; Determine how the burst evolves and interacts with the surroundings; Use gamma-ray bursts to study the early universe; Perform the first sensitive hard X-ray survey of the sky. The observatory covers gamma-ray, X-ray, UV and optical. Spectrosocpy from 180-600 nm and 0.3-150 keV. GRBs positions with precision 0.5"-5"   http://swift.gsfc.nasa.gov/about_swift/

- **AGILE:** AGILE is a small Scientific Mission of the Italian Space Agency (ASI) with participation of INFN, IASF/INAF and CIFS. AGILE is devoted to gamma-ray astrophysics and it is a first and unique combination of a gamma-ray (AGILE-GRID) and a hard X-ray (SuperAGILE) instrument, for the simultaneous detection and imaging of photons in the 30 MeV - 50 GeV and in the 18 - 60 keV energy ranges. http://agile.asdc.asi.it/

- **Chandra:** The Chandra X-ray Observatory is the U.S. follow-on to the Einstein Observatory. The Chandra spacecraft carries a high resolution mirror, two imaging detectors, and two sets of transmission gratings. Important Chandra features are: an order of magnitude improvement in spatial resolution (up to 0.4"), good sensitivity from 0.1 to 10 keV, and the capability for high spectral resolution (up to 0.012 A) observations over most of this range. Chandra's capabilities provide unprecedented science and Chandra Users are making important contributions to all areas of astronomy, including the solar system, stars, interacting binaries, compact objects, supernovae, galaxies, and AGN. http://cxc.harvard.edu/

- **XMM-Newton:** XMM-Newton, the X-ray Multi-Mirror Mission, is the second cornerstone of the Horizon 2000 program of the European Space Agency (ESA). The observatory consists of three coaligned high throughput 7.5m focal length telescopes with 6" FWHM (15" HPD) angular resolution. XMM-Newton images over a 30' field of view with moderate spectral resolution using the European Photon Imaging Camera (EPIC), which consists of two MOS and one PN CCD arrays. High-resolution spectral information (E/dE~300) is provided by the Reflection Grating Spectrometer (RGS) that deflects half of the beam on two of the X-ray telescopes. The observatory also has a coaligned 30 cm optical/UV telescope, the Optical Monitor (OM). http://heasarc.gsfc.nasa.gov/docs/xmm/xmmgof.html

- **Suzaku:** is an X-ray mission developed by ISAS/JAXA and NASA and some japanese and U.S. institutions. Suzaku covers the energy range 0.2 - 600 keV with the two instruments. Suzaku also carries a third instrument, an X-ray microcalorimeter, that lost all its cryogen before scientific observations could begin. http://heasarc.gsfc.nasa.gov/docs/suzaku/index.html

- **NuSTAR:** The Nuclear Spectroscopic Telescope Array Mission (NuSTAR) is a Small Explorer mission led by Caltech and managed by JPL for NASA's Science Mission Directorate. NuSTAR is the first mission to use focusing telescopes to image the sky in the high-energy X-ray (3 - 79 keV) region of the electromagnetic spectrum. Our view of the universe in this spectral window has been limited because previous orbiting telescopes have not employed true focusing optics, but rather have used coded apertures that have intrinsically high backgrounds and limited sensitivity. The objectives of NuSTAR are related to AGNs, hard X-ray emitting compact objetcs in the Galaxy, non-thermal radiation in young supernova remnants (SNR), and observe supernovae on the Local Group.

- **Fermi (FGST):** The Fermi Gamma-ray Space Telescope was built by NASA to unveil the mysteries of the high-energy universe. FGST's main instrument, the Large Area Telescope (LAT), operates more like a particle detector than a conventional telescope. Fermi studies the cosmos in the range 8 keV-300 GeV. http://www.nasa.gov/mission_pages/GLAST/spacecraft/index.html

- **MAXI:** the Monitor of All-sky X-ray image (MAXI) has as main purpose to monitor for events such as flares and bursts in X-rays watching all the sky all the time. MAXI, is developed to be mounted on the Japanese Experimental Module of the International Space Station. MAXI monitors the X-ray variability once every 96 minutes for more than 1,000 X-ray sources covering the entire sky on time scales from a day to a few months. Continuously monitors astronomical X-ray objects over a broad energy band (0.5 to 30 keV). http://maxi.riken.jp/top/

Under construction

- **Astro-H:** is a facility-class mission to be launched (2015) on a JAXA H-IIA into low Earth orbit. It carries out a Calorimeter Spectrometer (XCS), providing non-dispersive 7 eV resolution in the 0.3-10 keV bandpass. Other three instruments include the Hard X-ray Imager (HXI) will perform sensitive imaging spectroscopy in the 5-80 keV band; the non-imaging Soft Gamma-ray Detector (SGD) extends Astro-H's energy band to 300 keV; and the Soft X-ray Imager (SXI) expands the field of view with a new generation CCD camera. http://astro-h.isas.jaxa.jp/en/

- **eROSITA:** the primary instrument on-board the Russian "Spectrum-Roentgen-Gamma" (SRG) satellite which will be launched in 2016. It will perform the first imaging all-sky survey in the medium energy X-ray range up to 10 keV with an unprecedented spectral and angular resolution. It will cover the range 0.3-10 keV, with a resolution of 138 eV at 6 keV. The effective area is higher than in XMM up to 3 keV, but with lower resolution. http://www.mpe.mpg.de/eROSITA

- **ATHENA:** The Advanced Telescope for High-Energy Astrophysics is an ESA observatory type mission expected to be launched in 2028. Athena will address key aspects of structure formation and evolution from the epoch of re-ionization to the present and the still poorly understood and complex feedback processes involved. In particular, the heating history of the Universe due to both gravitational and non-gravitational processes, as well as the role of feedback from massive black holes to their host galaxies and in chemical evolution of the intergalactic and intracluster mediums will be studied. Detecting the typical AGN beyond z=6 and observing absorption lines from gas during the epoch of re-ionisation by observing bright z>6 gamma-ray bursts are key observations to investigate the formation and growth of the first black holes and the first stars. This X-ray telescope will combine unprecedented collecting area (2m2 at 1 ke V) with an excellent angular resolution (5") and a wide field of view (40'x40') . It will be equipped with two instruments: a wide field (5') instrument performing spectrally-resolved (2.5 eV) imaging over a broad energy band (0.31-10? KeV) and a very wide field imager (40'x40') with an energy resolution of 150 eV at 6 keV.

- **NICER:** The Neutron star Interior Composition ExploreR Mission (NICER) is a NASA mission dedicated to the study of the extraordinary gravitational, electromagnetic, and nuclear-physics environments embodied by neutron stars. NICER will enable rotation-resolved spectroscopy of the thermal and non-thermal emissions of neutron stars in the soft (0.2-12 keV) X-ray band with unprecedented sensitivity, probing interior structure, the origins of dynamic phenomena, and the mechanisms that underlie the most powerful cosmic particle accelerators known. It is planed to be launched in late 2016, to be placed in the ISS. The instruments will perform x-ray timing and spectroscopy. The effective area is up to twice that of XMM-Newton pn at 1 keV. http://heasarc.gsfc.nasa.gov/docs/nicer/

Proposals

- **Smart X:** SMART-X is a single-telescope X-ray observatory with 0.5" angular resolution, working in the 0.2-10 keV. The effective area expected will be 100 times (at 0.3 keV9 and 30 times (at 1 keV) that of Chandra. It will include a calorimeter. The gratings will reach R~5000 at less than 1 keV (well above Chandra), with 10" resolution. http://smart-x.cfa.harvard.edu/

- **LOFT:** The Large Observatory for X-ray Timing (LOFT) was a candidate mission for the M3 ESA launch. Discarded from the selection it is now in a frozen state. Main target is "How does matter behave under extreme conditions?" The main advantage is its high-time-resolution. It would cover 2-50 keV range. http://sci.esa.int/loft/

- **AXSIO:** Advanced X-ray Spectroscopic Imaging Observatory, a NASA concept for a broad-bandpass, high-sensitivity, high-resolution X-ray imaging spectroscopy mission.

- **Concepts http://heasarc.gsfc.nasa.gov/docs/heasarc/missions/concepts.html** Basically NASA focus their concepts in a notional calorimeter mission (N-CAL), a notional X-ray grating spectrometer, AXSIO (see below), a notional wide-field imager (N-WFI), and various combinations of these capabilities on a single platform.

- **Other missions from European countries, China and multinational collaborations are:** A-STAR, DAMPE, EDGE, GRAVITAS, MIRAX, NHXM, PheniX, XIPE.

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