COSMIC EXPLOSIONS & X-RAY ASTRONOMY

DIEGO GÖTZ

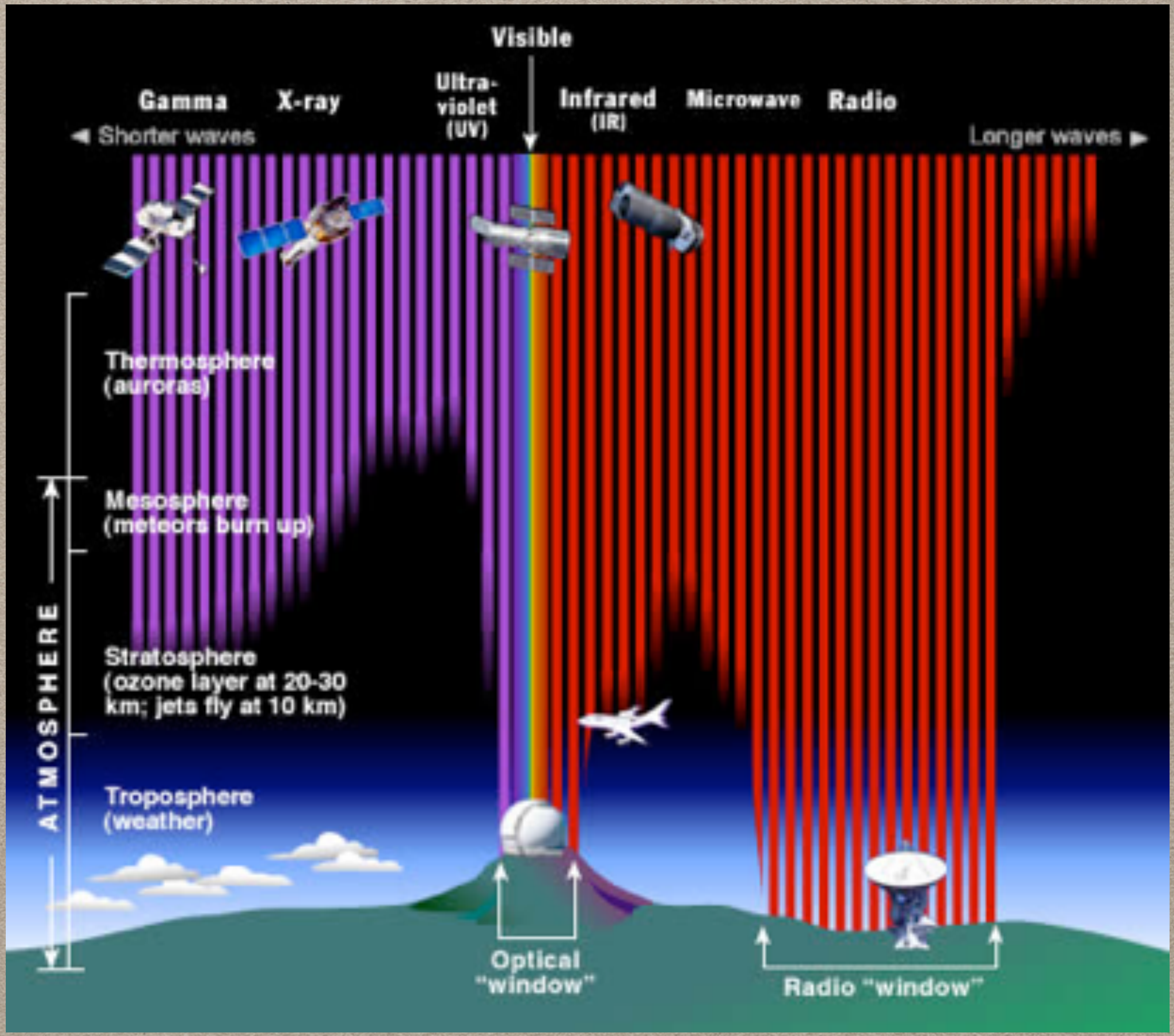
CEA SACLAY - IRFU/DÉPARTEMENT D'ASTROPHYSIQUE

OUTLINE OF THE LECTURE

- Historical Notes
- Detection principles
- Scientific Topics (personal selection)
- The future

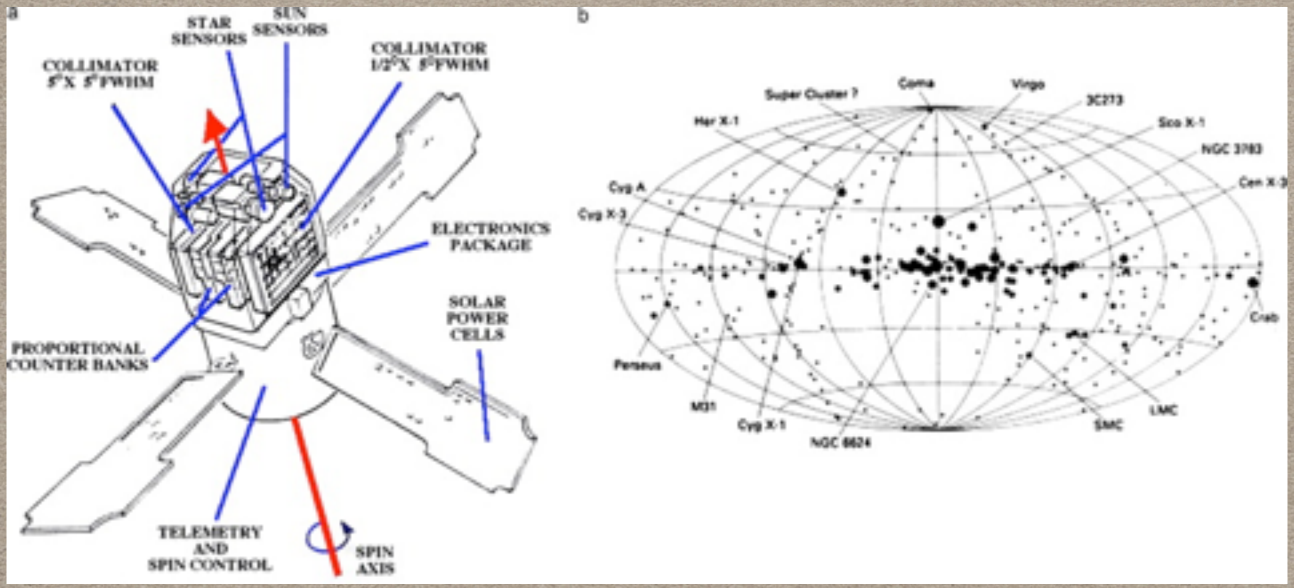
X-RAY ASTRONOMY IS A SPACE BUSINESS…

- X-ray astronomy can be performed only at very high altitude due to absorption by the Earth atmosphere
- Thus it was only after rockets were available to lift payloads above the atmosphere that X-ray astronomy coud be fully developed



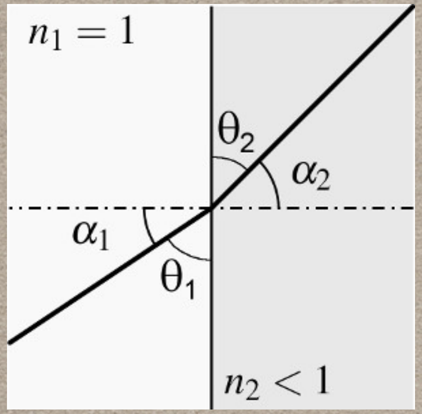
EARLY YEARS

- Already after the first rocket flights in 1962 and 1963 lasting just a few minutes it was clear that the sky was full of X-ray sources
  - The team lead by the Nobel Prize winner Riccardo Giacconi (1931-2018) discovered the brightest X-ray source, Sco X-1, while looking for fluorescence X-rays from the Moon surface.
- The first all-sky map in X-rays has been performed using the data from the UHURU satellite
- X-ray allow to test thermal and non-thermal emission processes, both in compact objects (binaries, isolated NS, GRBs,…) and diffuse environments (SNRs, Galaxy Clusters,…)
- X-ray spectroscopy allows to determine the elemental composition of the observed plasmas



THE ADVENT OF X-RAY IMAGING

At X-ray energies imaging is only possible for small incidence (grazing) angles



Reflection of X-rays (Snell's law)

$$\frac{\sin \alpha_1}{\sin \alpha_2} = \frac{n_2}{n_1}$$

If α_2 reaches 90° we have a reflection. So if we assume n_1=1, the critical angle to have a reflection is $\alpha_{critical} = \arcsin n_2$

As n_2 is slightly below 1 in the X-rays (for example for gold for photon energies of 12.4 keV, $n_2 = 1-1.88\cdot10^{-5}$), the maximum angle for total external reflection to occur is close to 90° (for gold at 12.4 keV $\alpha_{critical}$ = 89.65° = 90°-0.351°). For X-rays total external reflection occurs only under grazing incidence. So the reflection angles α are always close to 90°.

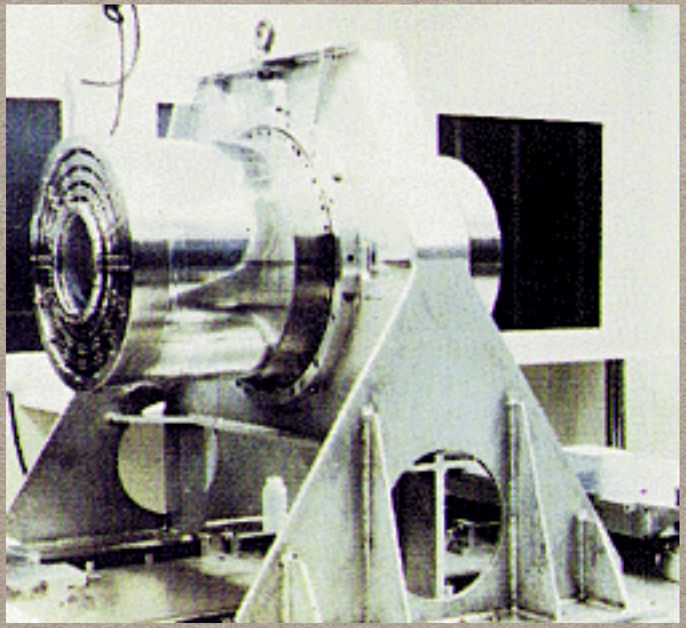
Normally the reflection angles are measured as angles θ between the incoming ray and the mirrors surface. The critical angle $\theta_{critical}$ is then expressed as

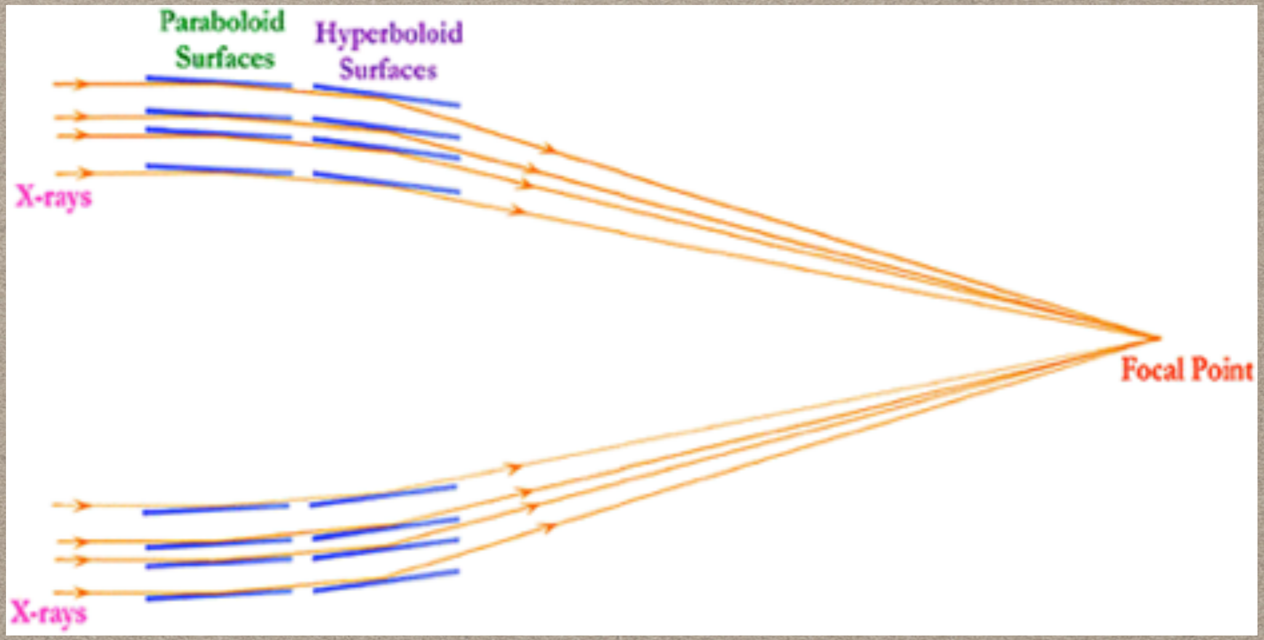
$$\cos \theta_{critical} = n_2$$

For example $\theta_{critical}$ is ~ 1° for 3 keV photons on metals such as Nickel or Gold

X-RAY IMAGING

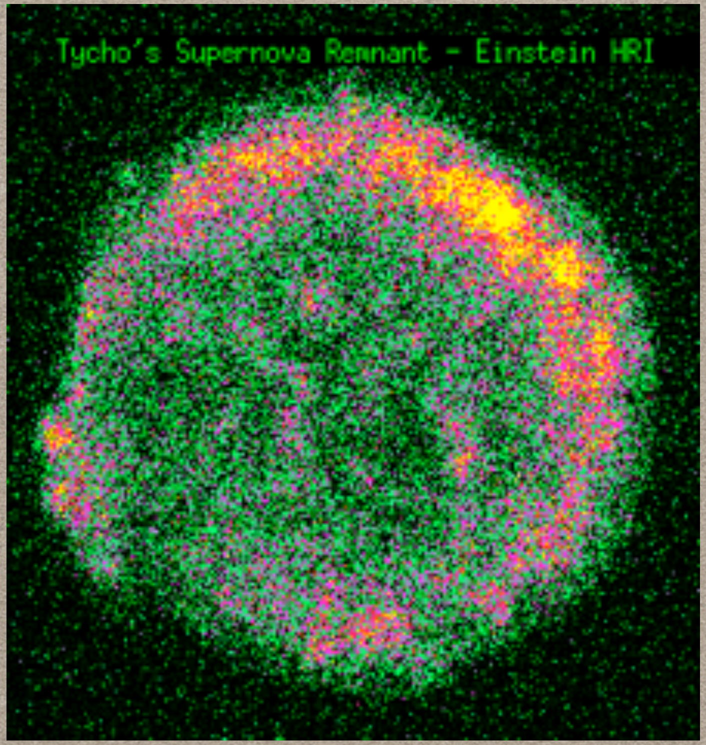
- In 1978 the Einstein X-ray Telescope was launched
- In provided the first high resolution X-ray images of many sources, thanks to the grazing incidence reflection technique (in a Wolter I configuration)

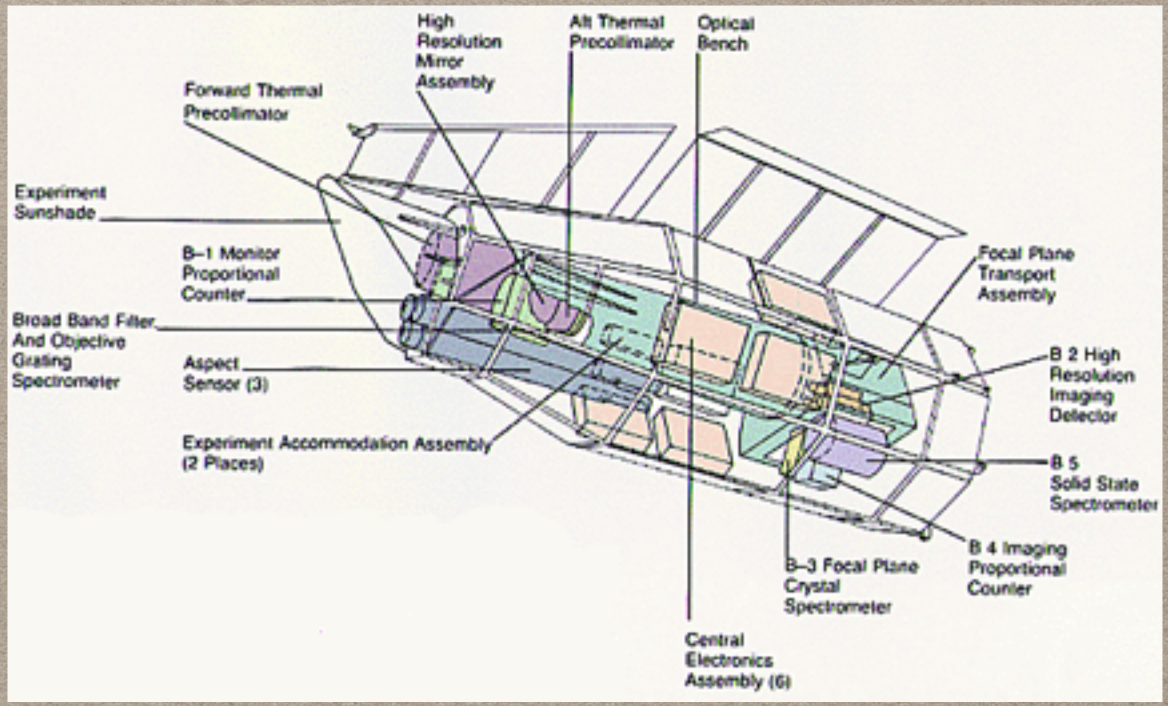




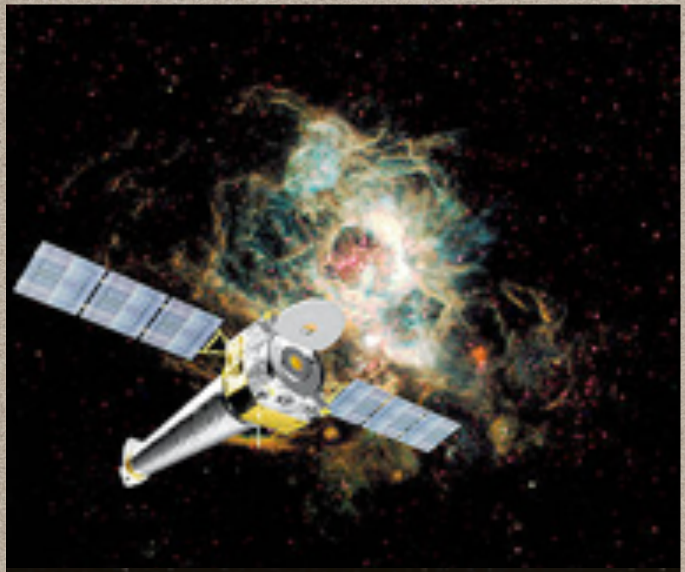
X-RAY IMAGING

- The sky background radiation was largely reduced wrt UHURU
- This allowed for the first time to image faint and extended sources
- Main result: all the celestial objects are X-ray emitters (stars, galaxies, AGNs, clusters, etc.)





MODERN X-RAY ASTRONOMY

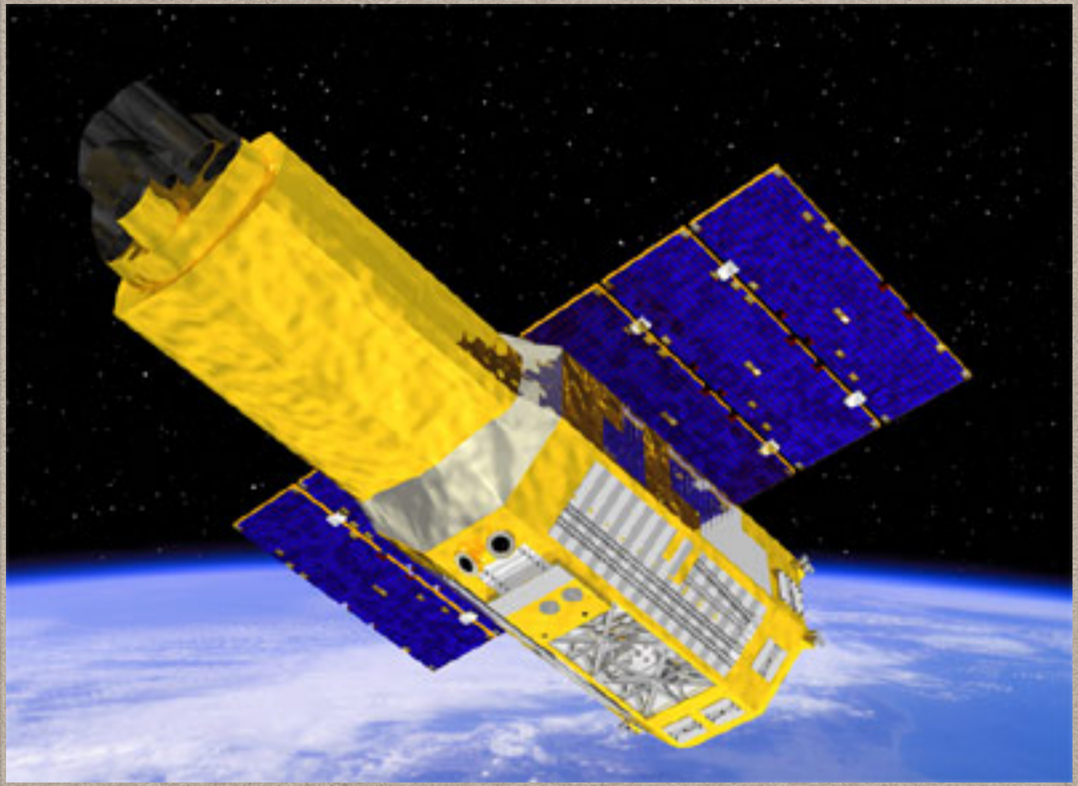


Chandra X-ray Observatory
launched in 1999 by NASA
10 m focal length, 0.1-10 keV
600 cm^2 @ 1.5 keV, PSF: 0.5 arc sec

ESA XMM Newton, launched in 2000
7.5 m focal, length 0.1-12 keV
1500 cm^2 @ 1 keV, PSF: 6 arc sec

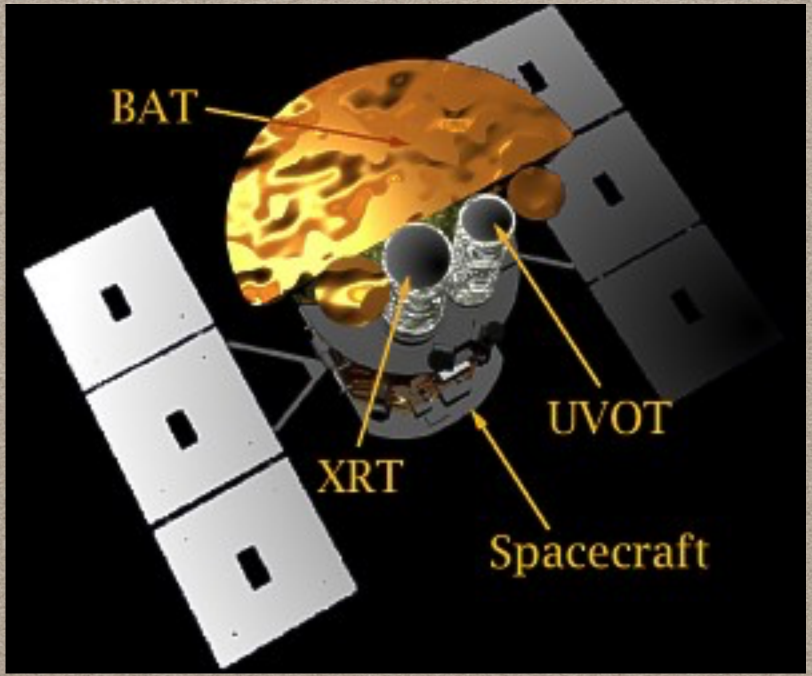
Nustar, launched in 2012 by NASA
10.15 m focal, length 6-79 keV
849 cm2 @ 9 keV, 60 cm2 @ 78 keV
PSF: 9.5 arc sec

MODERN X-RAY ASTRONOMY II



Suzaku (JAXA)
2005-2015
7.3 m focal length, ~400 cm^2@1.5 keV
Micro-calorimeter (failed soon after launch, cooling)
Non-imaging Hard X-ray detector

JAXA launched Astro-H (Hitomi) in 2016 carrying also a micro-calorimeter but the satellite failed 1.5 months after launch (attitude control)

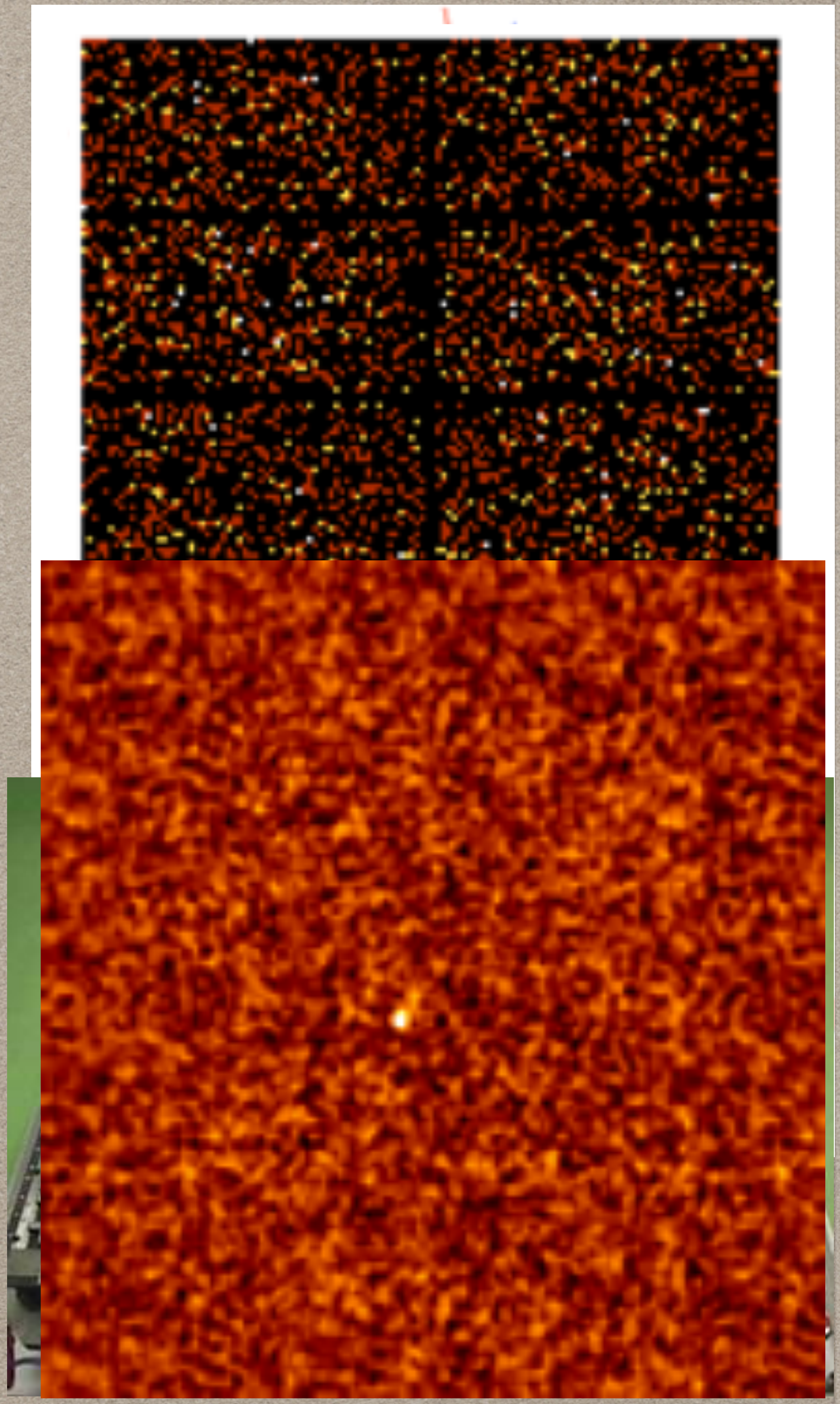


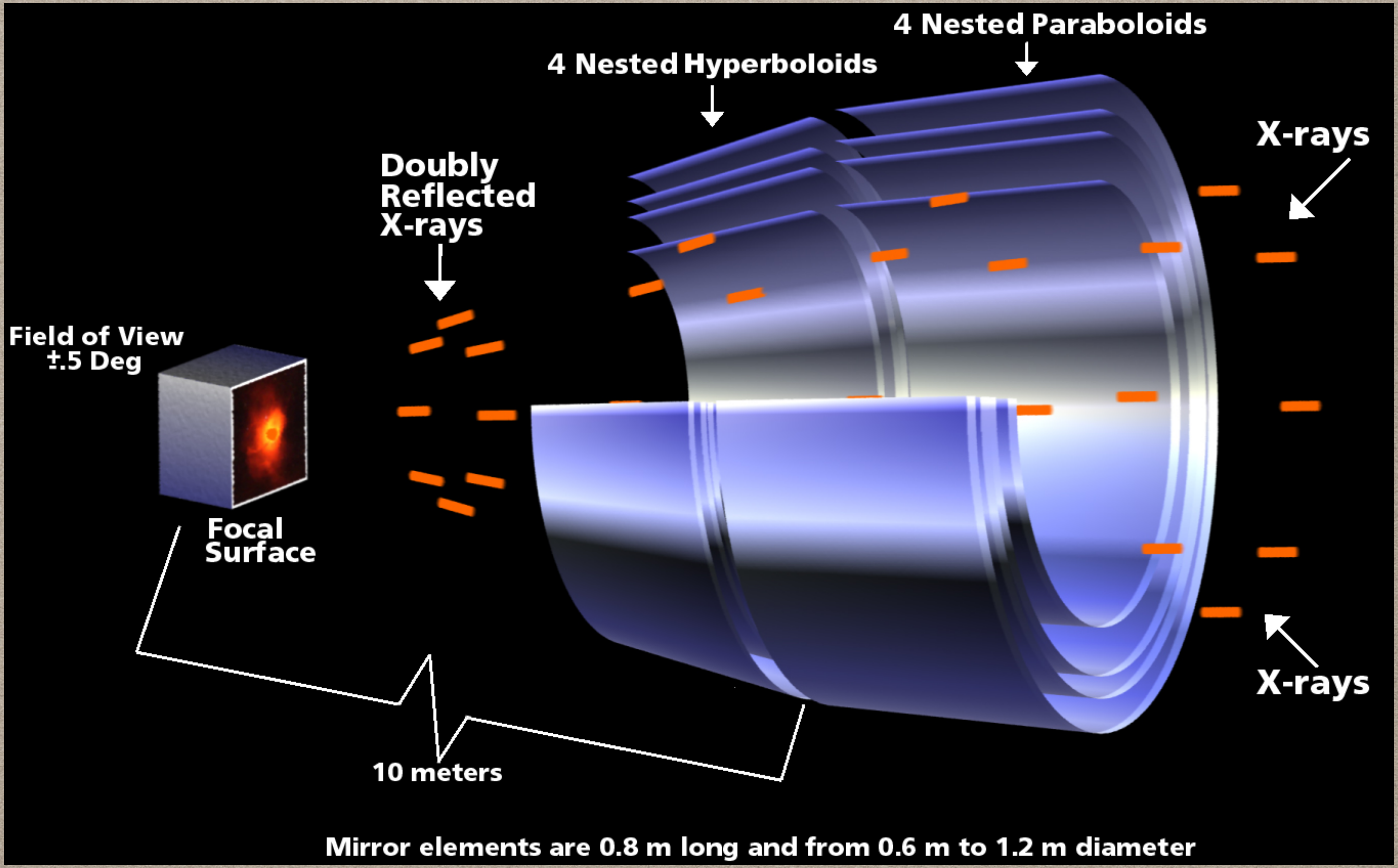
Swift/XRT (NASA)
launched in 2004
3.5 m focal length, ~110 cm^2@1.5 keV
0.2-10 keV
Very versatile, adapted for fast ToO

+ MAXI, RXTE, ASCA,…

HARD X-RAY IMAGING

- Above 10 keV it is very difficult to perform direct imaging with mirrors (the maximum energy is proportional to the focal length)
- Coded mask (indirect) imaging is a solution (INTEGRAL/IBIS and SPI, BeppoSAX/WFC, Swift/BAT, GRANAT/SIGMA, etc.) often coupled to pixellated CdTe detectors
- Each pixel records background and possibly source(s) photons
- Image deconvolution techniques are required to reconstruct the sky
- Wide field of view → all-sky monitoring of the transient sky, optimal for Gamma-Ray Burst searches (BAT on board Swift or IBIS on board INTEGRAL)
- State of the art PSF ~ 12 arc min @ 100 keV
- It is difficult to image diffuse sources, and its sensitivity limited (mCrab) due to the high background
- Can be used up to a few MeV (SPI on board INTEGRAL)




4 Nested Paraboloids
4 Nested Hyperboloids
X-rays
Doubly
Reflected
X-rays
Field of View
±.5 Deg
Focal
Surface
X-rays
10 meters
Mirror elements are 0.8 m long and from 0.6 m to 1.2 m diameter

INSTRUMENTAL SENSITIVITY

- The observation of a weak point source of X-ray flux *F* (photons/cm2/s/keV) is always made in the presence of unwanted background *B* (counts/cm2/s/keV)
- *B* is the sum of an intrinsic detector background B_i (arising from the interaction of cosmic rays and the detection medium) and the diffuse X-ray sky background B_d, discovered at the same time of Sco X-1.
- If the quantum efficiency of the detector is Q counts/photon and its aperture is Ω in steradians
    - $B_d = Q\,\Omega j_d$ where j_d is the diffuse background flux (ph/cm2/s/keV/sr)
- If all quantities are constant over the observation time *t*, then statistical fluctuations in the background *B* determine the sensitivity of the instrument
- The minimum detectable flux F_{min} for a given signal-to-noise ratio *S* is that flux that produces a count *S* standard deviations above *B*
- Assuming the bandwidth of the instrument δE, the geometric area for the collection of source photons (and diffuse X-ray background) is A_s and A_b the equivalent detector background area then
    - $F_{min} = (S/QA_s)\,\{B_i A_b + Q\,\Omega j_d\, A_s)/t\delta E\}^{1/2}$

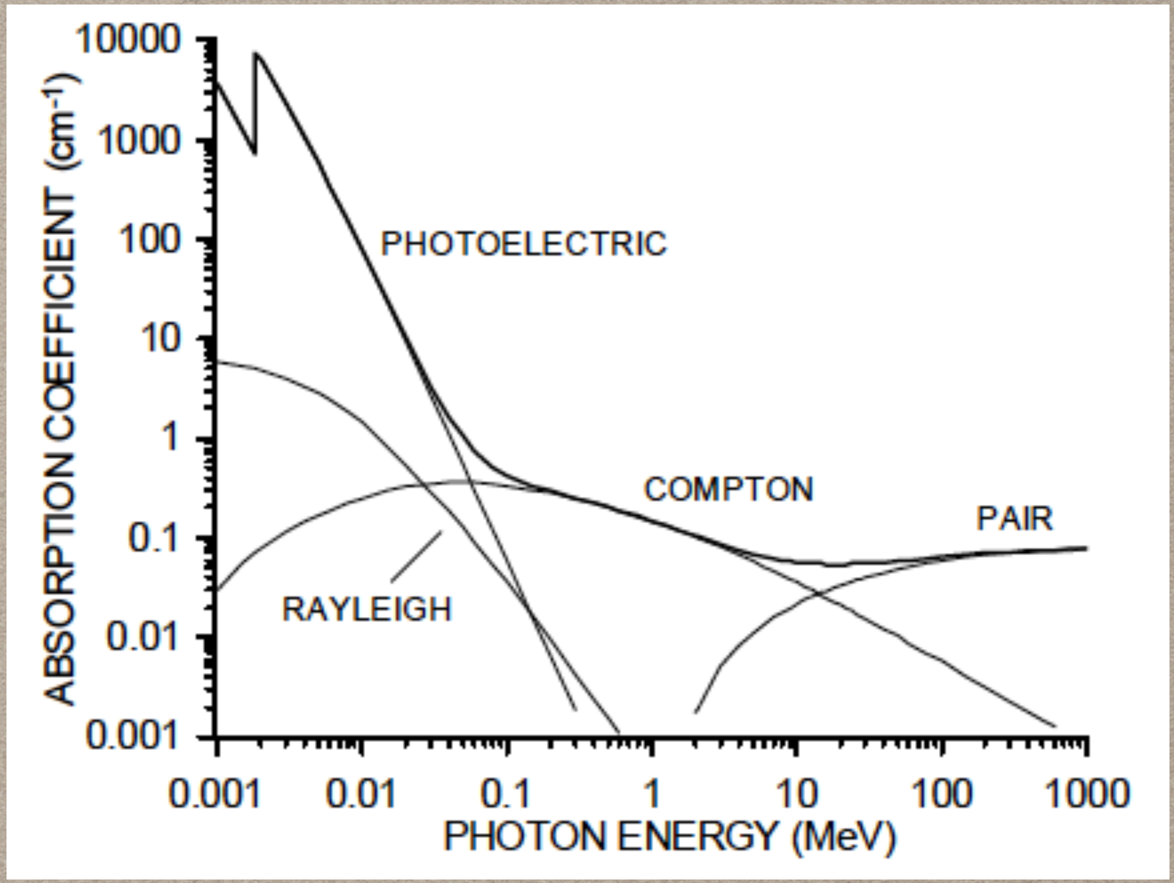
X-RAY DETECTION

In passing through a medium, photons will traverse a certain distance unaffected, until depositing energy either by

a) Photoelectric absorption

b) Compton scattering

c) Pair production



The probability of undergoing an interaction is an exponential function of distance. The fraction of photons that suffered any interaction after traversing a distance *x* is $f=1-\exp(-\mu x)$, where μ is the total absorption coefficient expressed in cm^{-2}.

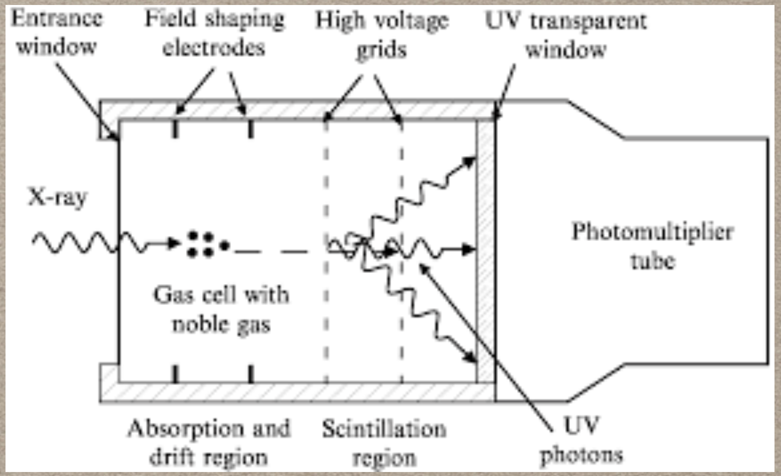
Photoelectric Absorption

An electron is emitted with the energy $E_{PE}=E_X-E_b$, where E_b is the binding energy of the photo electron.

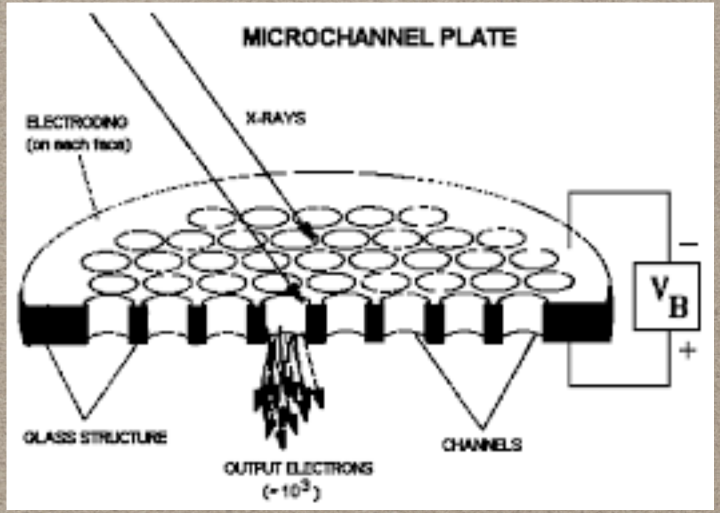
X-RAY DETECTORS

- Generally speaking X-ray detectors are based on the conversion of X-ray photons into electrical charge through the photoelectric effect

- In the early times gas proportional counters were used to convert X-rays in electrical signals. These detectors had the advantage to be simple in operation, but the drawback of the possibility of leakage and that a relatively large volume of gas is needed to de efficient in the detection. Spectral resolution is moderate

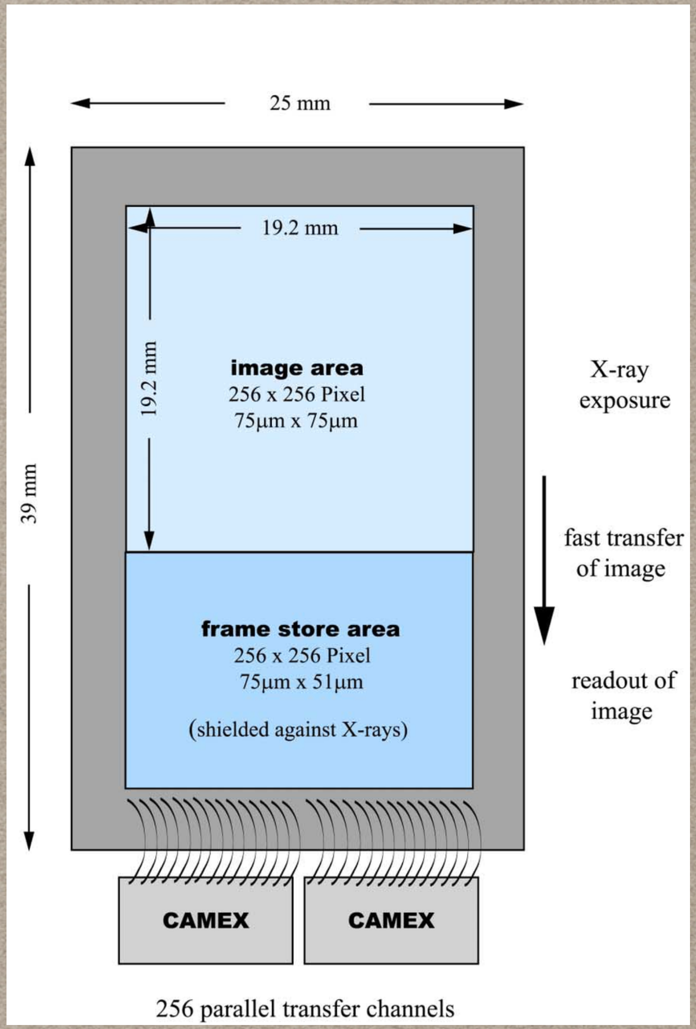


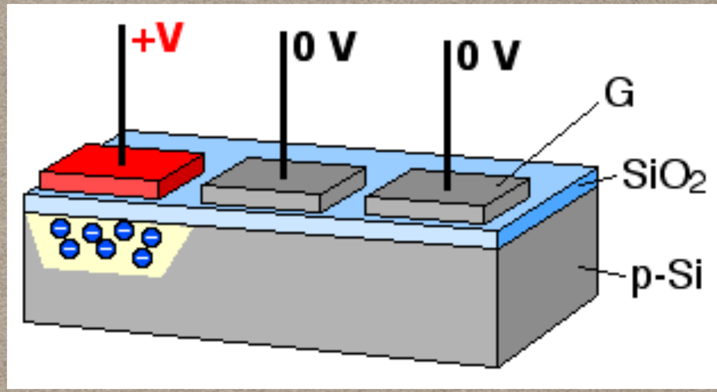
- Microchannel plates (MCPs) are compact electron multipliers of high gain. Channels can be as small as 2 μ providing excellent imaging properties (Chandra HRC). Energy resolution is poor.



MODERN DETECTORS

- The most used detectors those days in X-ray astronomy are the ones based on semiconductors (Si, Ge, CdTe,…).
- Such devices are the solid state analogues of gas-filled ionisation chambers, in the sense that there is no multiplication of the charge within the detecting material, and the generated charges/holes (collected after drifting within the semiconductor) are proportional to the energy of the incident particle. Advantage: can be in principle manufactured in any shape, is more dense than gas -> higher efficiency
- In order to have the best performances in terms of spectroscopy these detectors need to be cooled well beyond room temperature (to reduce thermal noise), but they are much more compact then gas filled detectors (which is a huge advantage in space applications)
- In X-ray astronomy Si based CCD are implemented in all current space missions: they allow for low readout noise and hence good energy resolution (~100 eV) and at the same time they provide a high quantum efficiency Q.
- The minimum energy required to create a pair/hole is only 3.66 eV

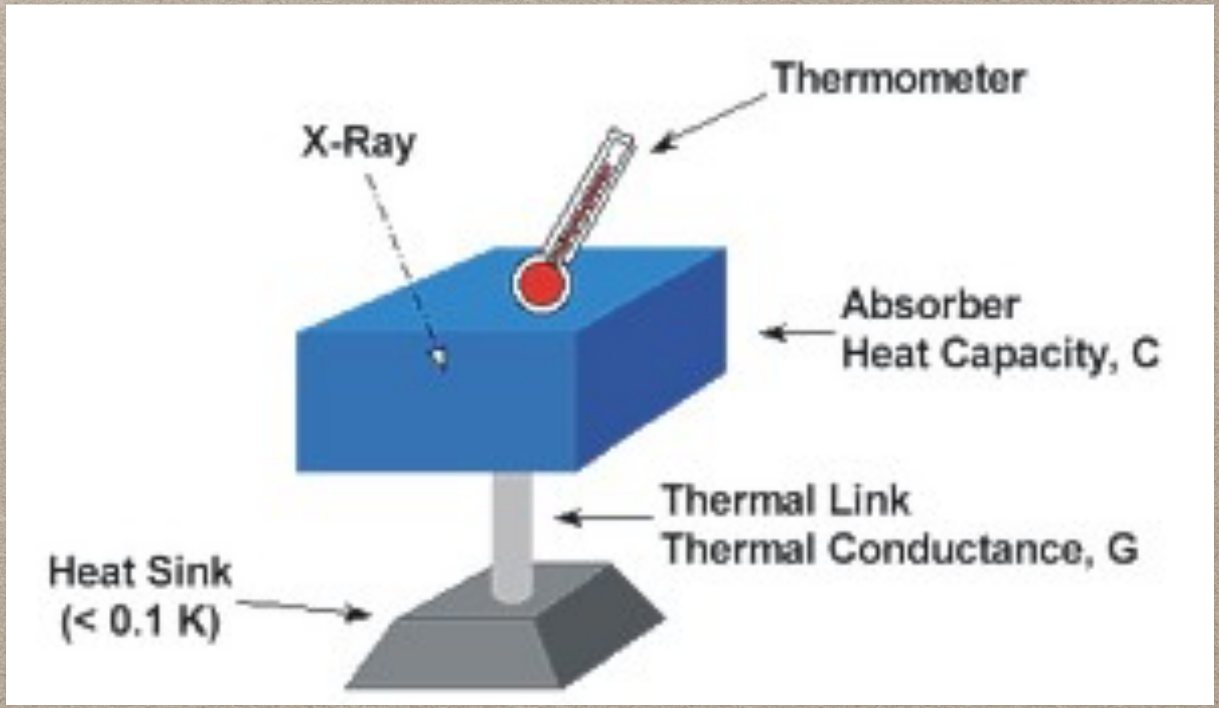




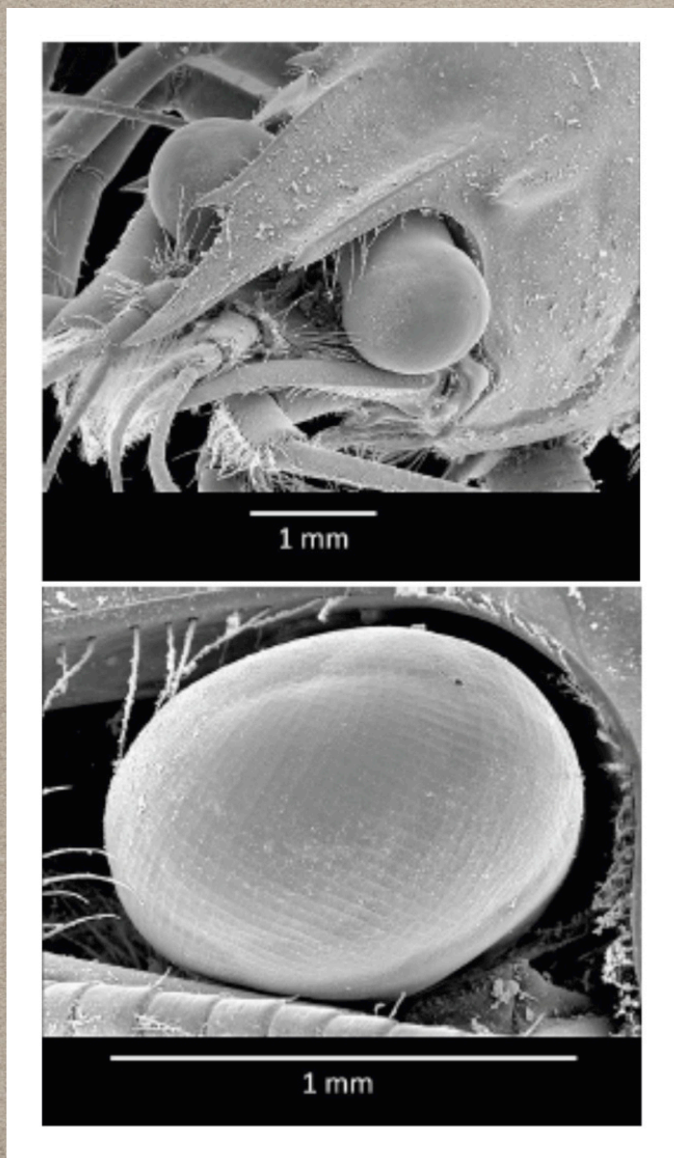
MODERN DETECTORS

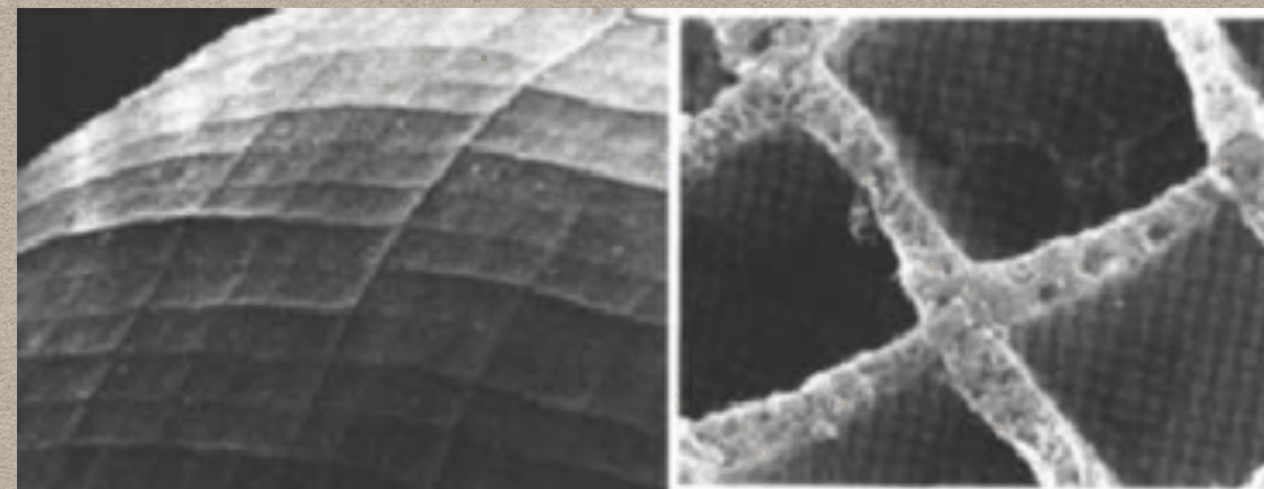
- The future of X-ray detection is nowadays represented by single photon calorimeters in which X-rays are detected via temperature pulses they induce in small absorbers, cooled to a fraction of a degree kelvin.

- Advantage: excellent energy resolution (few eV). Drawback: limited spatial resolution, complex thermal system

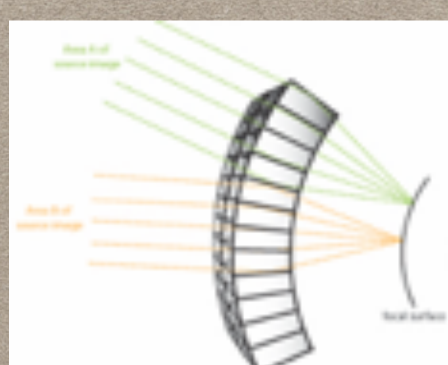


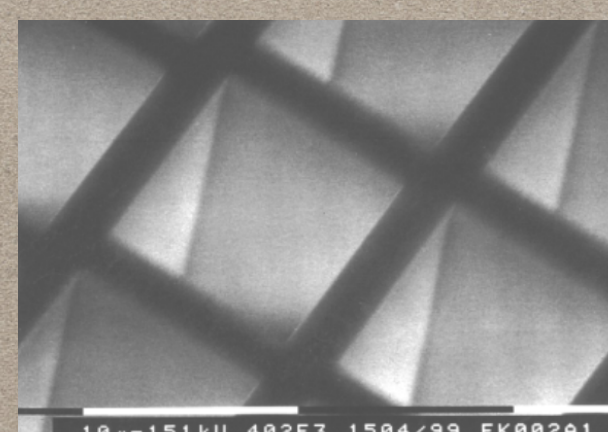
X-RAY ASTRONOMY FUTURE





Lobsters and other kind of decapods are a rare example in Nature where the vision is obtained by reflection and not by refraction. This kind of vision is adapted for low-background wide vision (like the dark deep sea). Can be adapted to X-rays (Angel 1979).

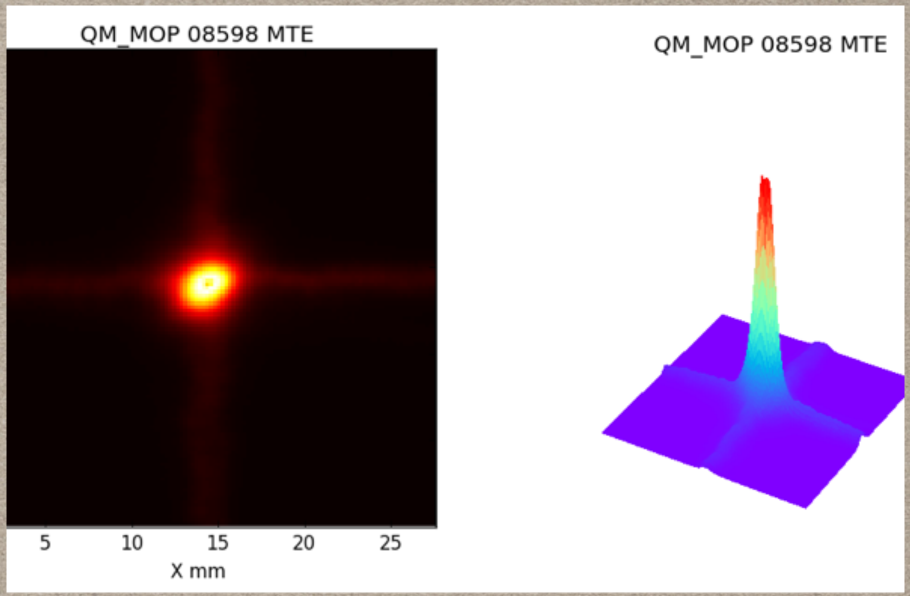


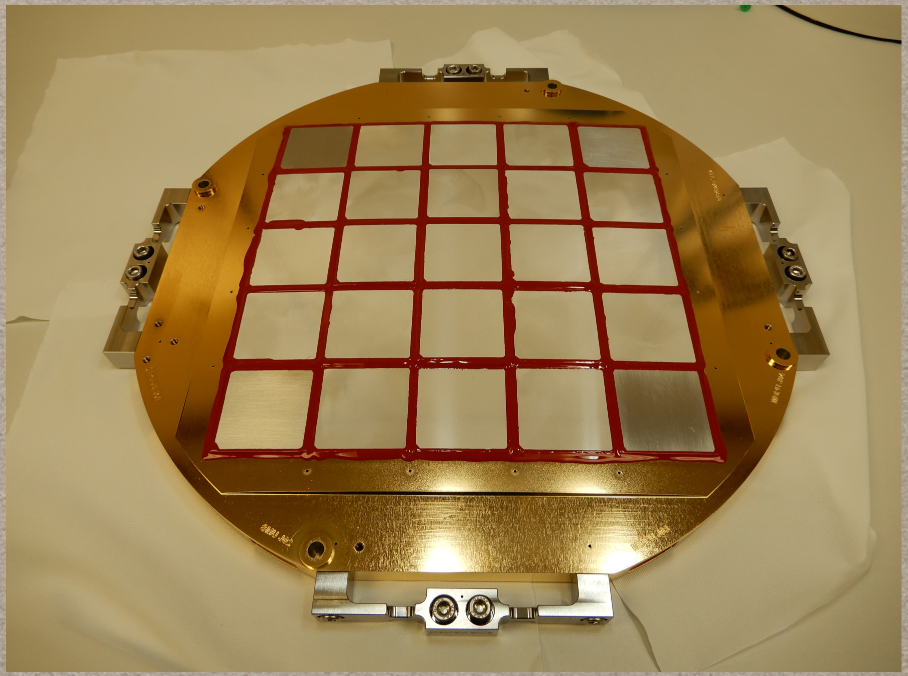


40 microns pitch lead glass plates produced by Photons

LOBSTER EYE OPTICS

- Lobster Eyes are very light (few kg vs. several tens of kg for traditional X-ray optics)
- Hence they are adapted for small missions like SVOM (total mass 1000 kg) or SMILE and Einstein Probe (small mission developed jointly by ESA and CAS)
- They have a peculiar PSF (The one of MXT is shown, small FOV version, to be flown on SVOM)
- 50% of the flux in the central peak.22% in each arm, the rest in a diffuse patch
- But micropore optics in general can be used also in a Wolter-I approximation (single peaked PSF, small FOV) as foreseen for the next major X-ray observatory ATHENA (bases on Si)



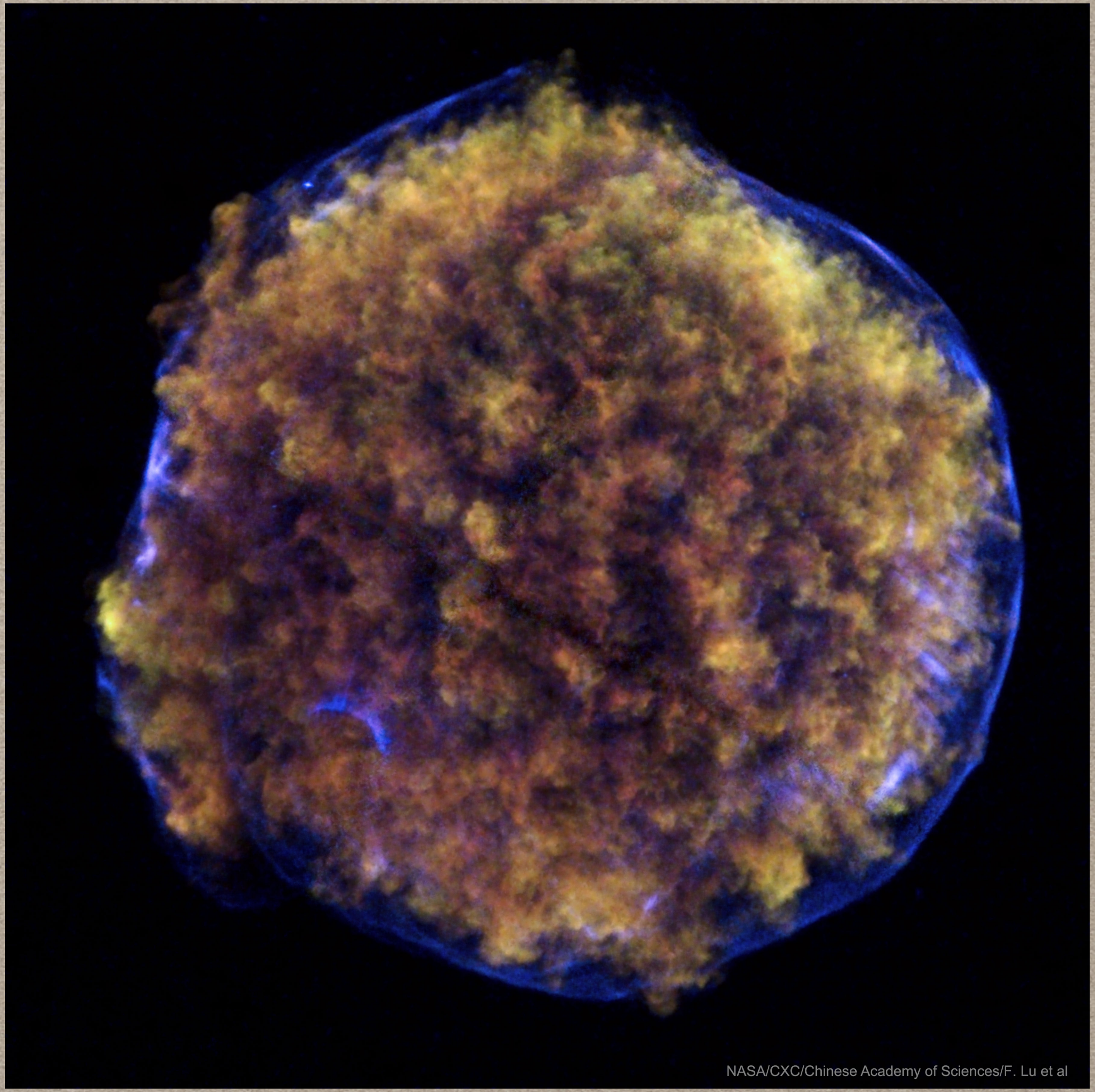


WHAT CAN BE OBSERVED IN X-RAYS?

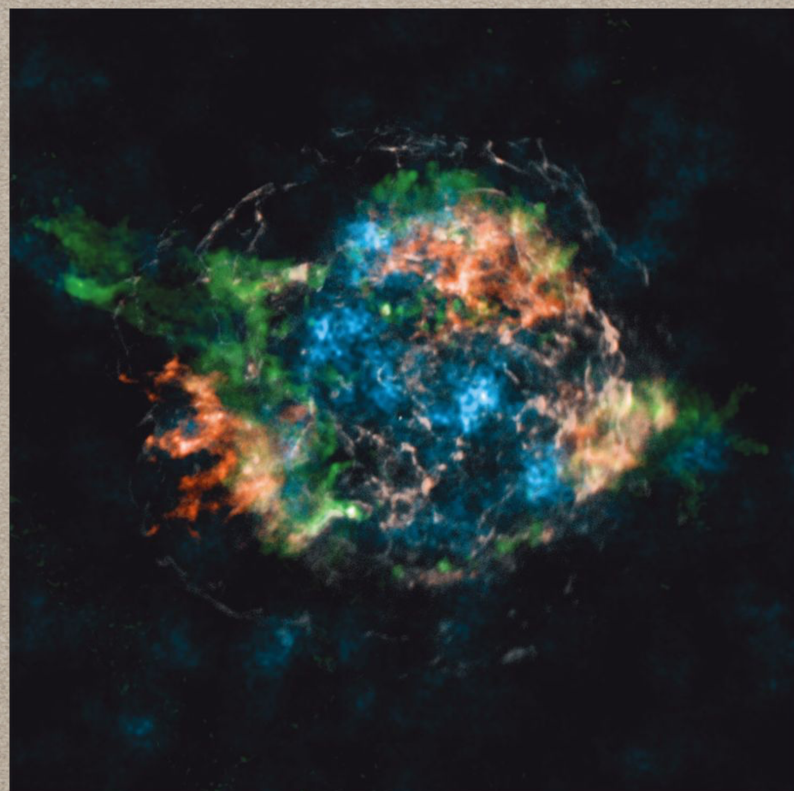
- X-ray astronomy is now more than 50 years old
- Almost all sky objects emit in X-rays
  - stars (including the Sun)
  - galaxies and AGNs
  - galaxy clusters
  - **SN and their remnants**
  - **compact objects** (INSs, Binaries, GRBs)
  - ISM gas
- The power of X-ray astronomy is that is can inform us both on thermal and non-thermal processes that are on going at the sources

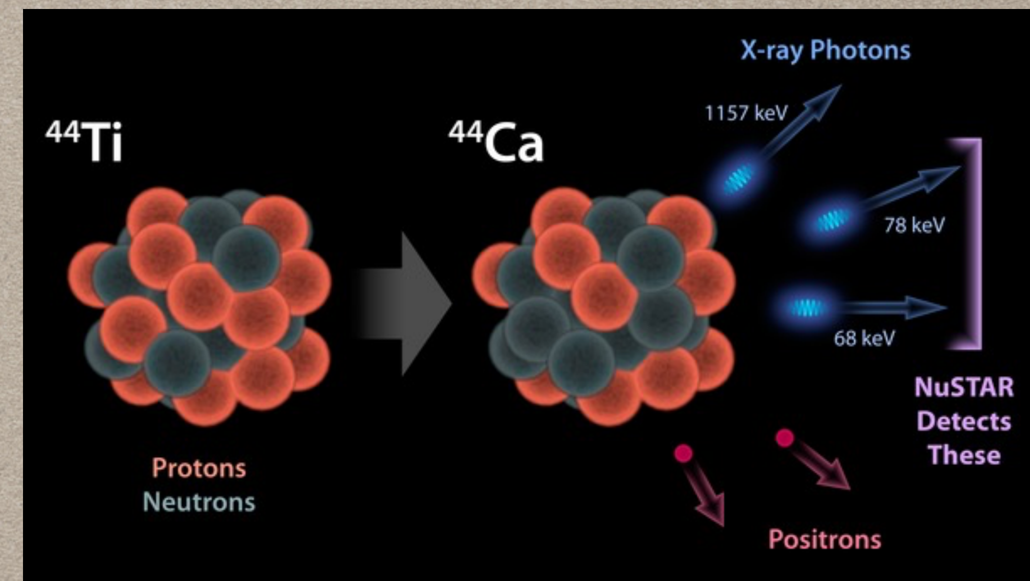
SUPERNOVA REMNANTS
(MORE DURING J. VINK LECTURE)

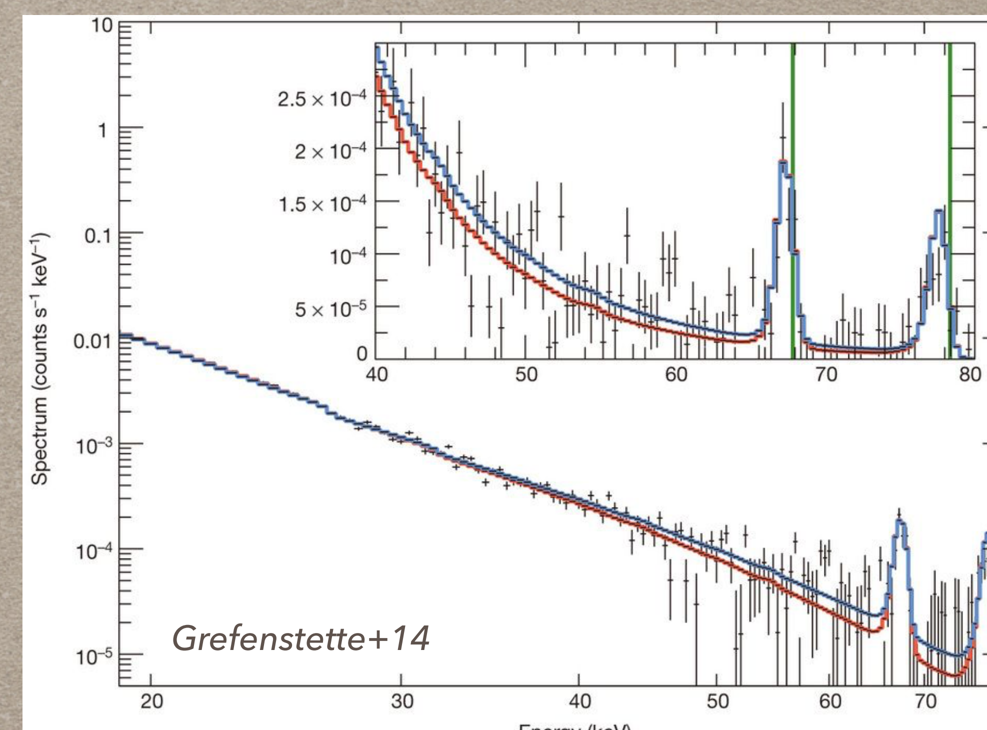
- X-ray data (spectroscopy) are unique because they allow to access the abundances of the freshly synthesised elements (in a hot plasma of a few keV), namely the so-called alpha elements (O, Ne, Mg, Si, S, Ar, Ca) and the iron-group elements (mainly Fe, Ni)
- All these elements present relatively strong emission lines in the 0.2-10 keV range
- Shock physics can also be addressed through X-rays: lines provide information about the temperature and ionisation state of the shocked plasma, but direct observation of synchrotron continuum can also be performed.
- The size of the synchrotron emitting regions can be used to infer magnetic field strength, and more generally the properties of the emitting electron population



SNRS (CONT.)



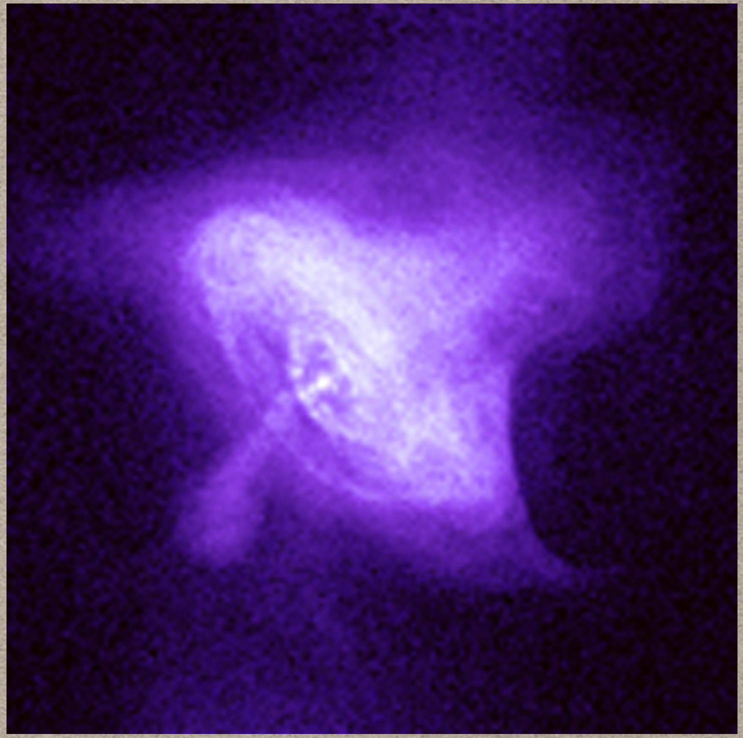


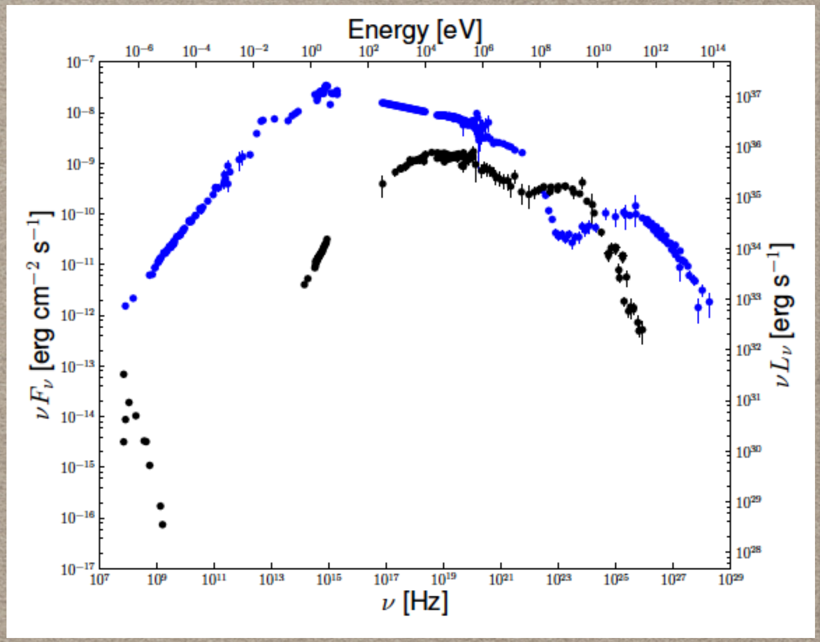


- Nucleosynthesis can be observed also at hard X-rays
- ^{44}Ti decay lines have been observed by INTEGRAL and Nustar (Cas A, SN 1987A)
- Nustar could prove the asymmetry of the Ti ejecta ruling out symmetrical SN explosions (not correlated to e.g. Fe)
- These observations prove the power of precise imaging at hard X-rays

ISOLATED NEUTRON STARS
(MORE DURING M. BURGAY LECTURE)

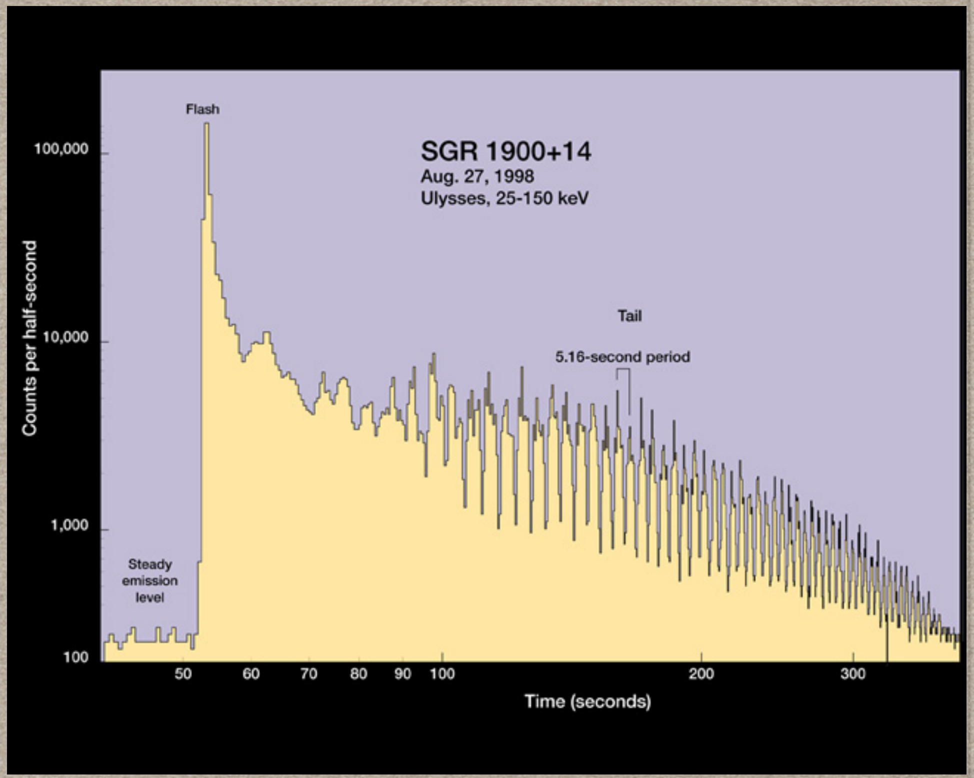
- Rotation powered (radio) pulsars are the most common form of isolated neutron stars (INSs)
- However some INSs are X-ray emitters, in particular the youngest and most energetic (like the Crab pulsar), or old nearby like XDINs and CCOs
- The origin of the X-ray emission can be internal heat, rotational energy, and magnetic field decay (magnetars)
- INSs can have internal temperatures of 10^{11} K at birth and then rapidly drop to 10^9 K. For the following $10^{5\text{-}6}$ years the main cooling mechanism i neutrino emission from the star core. This leads to surface temperatures of $10^{5\text{-}6}$ K with thermal emission peaking in the soft X-ray band. Temperature gradients on the surface produce observable modulations.
- Board-band Non thermal emission can originate from charged particles accelerated in the NS magnetosphere, producing strongly variable emission patterns (X-ray pulsations). These particles will eventually feed X-ray nebulae, called PWN (pulsar wind nebulae)

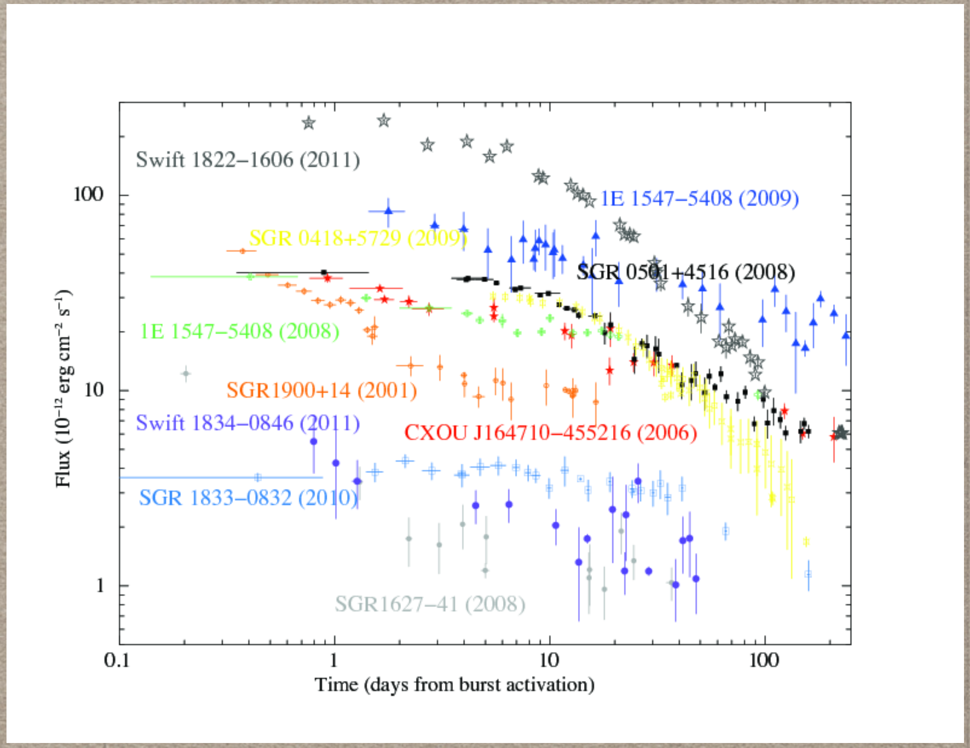




INS - MAGNETARS

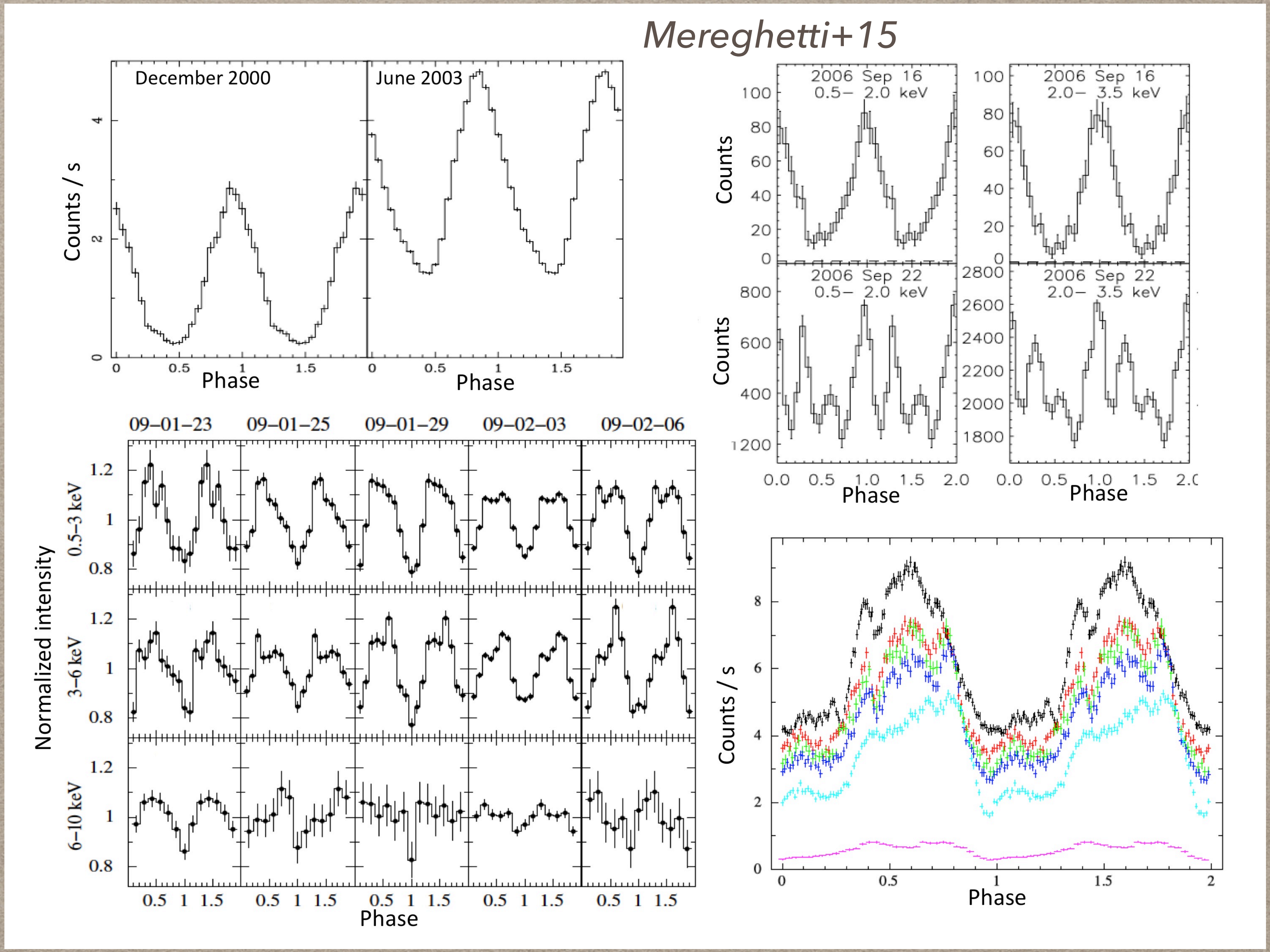
- Magnetars (AXPs & SGRs) are a peculiar class of INSs, whose source of energy is believed to be a huche magnetic field B~$10^{13\text{-}15}$ G
- They are extremely variable sources on different time scales
  - short bursts (~0.1 s) with thermal spectra (kT~25 keV), can be emitted individually or in bunches
  - intermediate bursts lasting a few seconds
  - giant flares, lasting several hundred of seconds
  - outbursts: the persistent X-ray flux increases of a few orders of magnitude and decays over hundreds of days
- The Magnetars phenomenology chan be explained by a magnetic field which is highly twisted, and the energy released indicates moments or re-arrangement of the magnetic field configuration towards a more simple dipole





X-RAY TIME SERIES

- Magnetars used as an example of diversity
- Their pulse periods span 2-12 s and they have significant period derivatives (10^{-13}-10^{-11} s s^{-1})
- Pulsed fraction as well as pulse profile are variable (as a function of source flux)
- Measured Period and its derivative change over time; glitches
- These data provide inputs for modelling of the magnetosphere and returning currents (hot spots on the NS surface)



TIME SERIES: THE P-PDOT DIAGRAM

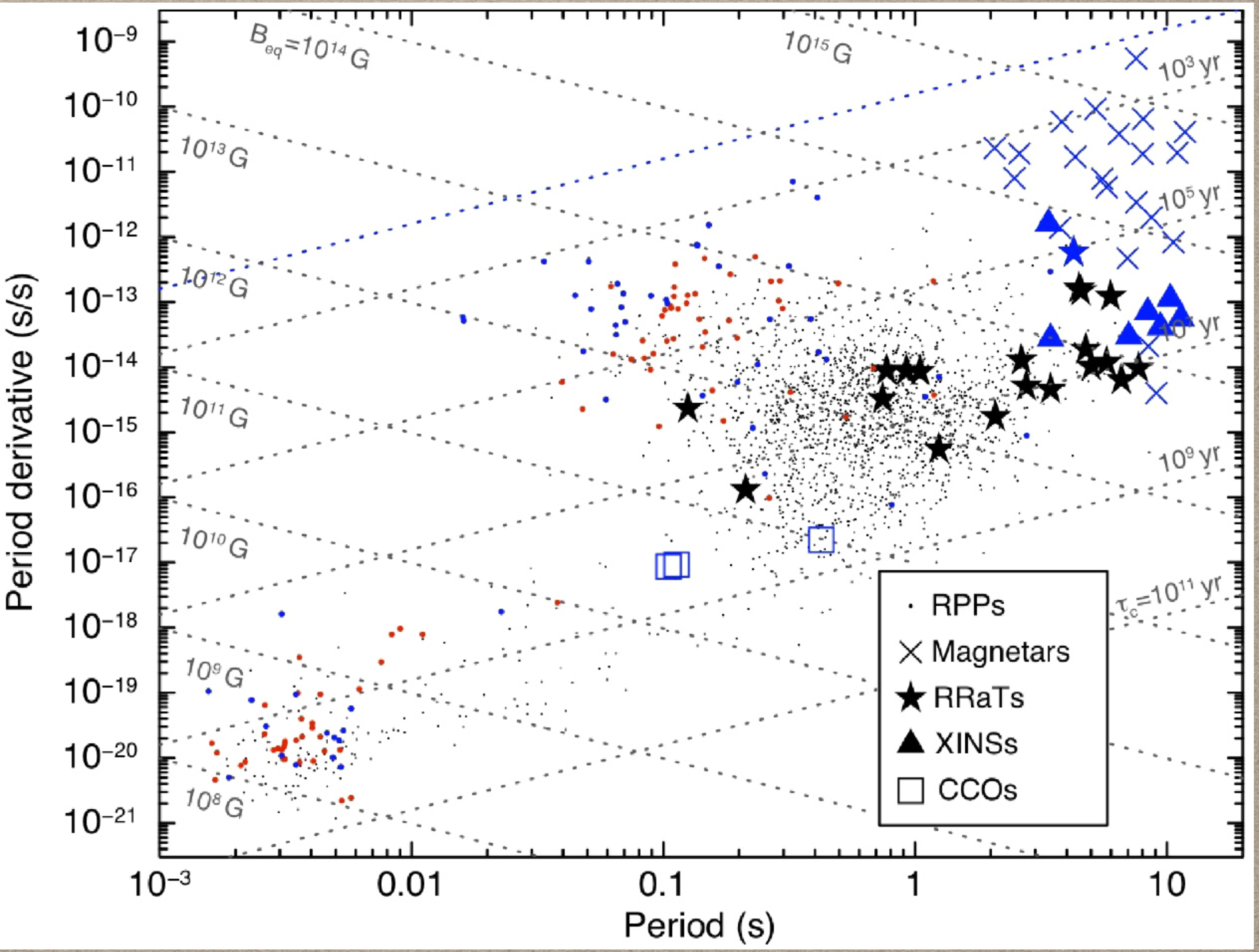
- A tool to derive preliminary characteristic age and magnetic field values for pulsars

$$\tau = \frac{P}{2\dot{P}}$$

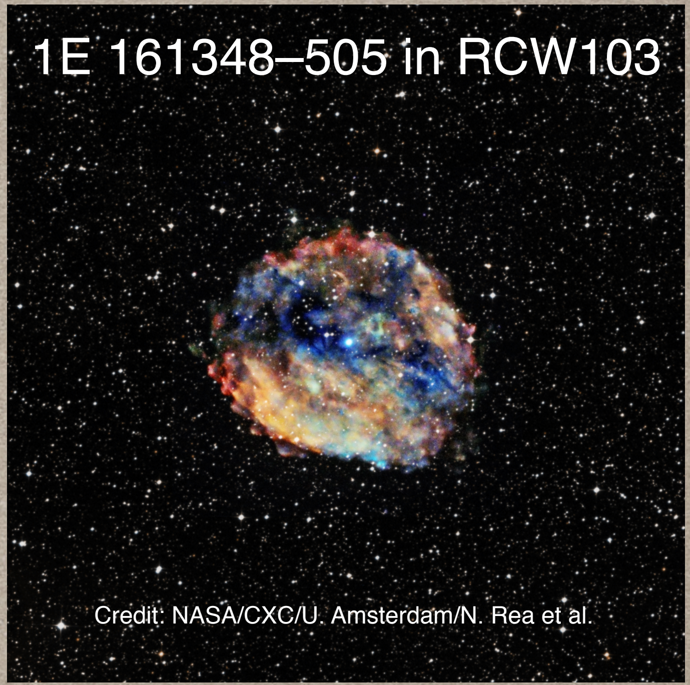
$$B > \left(\frac{3c^3 I}{8\pi^2 R^6}\right)^{1/2} (P\dot{P})^{1/2}$$

$$\frac{B}{Gauss} > 3.2 \times 10^{19} \frac{(P\dot{P})^{1/2}}{s}$$

assuming canonical values for NS moment of inertia I and NS radius



INS - CENTRAL COMPACT OBJECTS



- Point like sources near the centre of young SNRs (0.3-7 kyrs). A dozen are known
- No counterparts at other wavelengths
- Thermal-like spectra (0.2-0.5 keV) with tiny emission regions (0.1-few km)
- L_X ~ few 10^{33} erg/s
- Very small pulsed fraction (if any), fast pulsations (< 1s for 3 of them) and tiny period derivative. B~10^{10-11} G

CCO in RCW103 is the most puzzling:

Long term (6.67 hrs) modulation

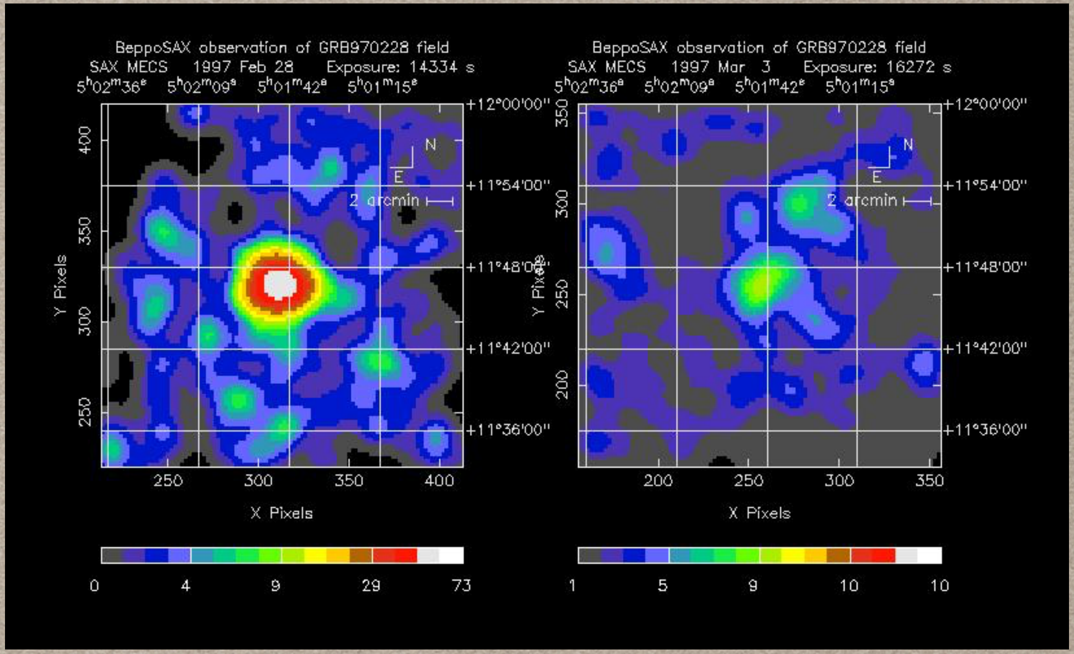
A magnetar-like burst has been detected in 2016, followed by a magnetar-like outburst

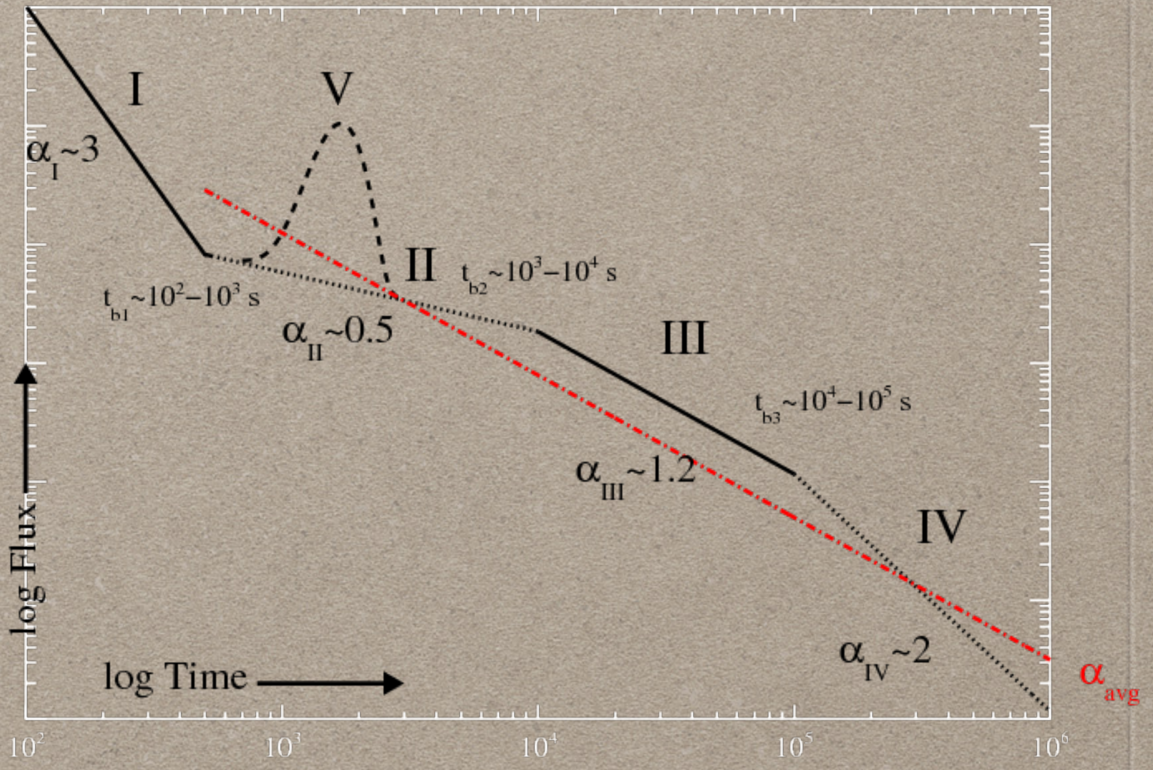
Difficult to explain the slowing down of the NS from millisecond to hours in a few kyrs. Fallback disk?

GAMMA RAY BURSTS

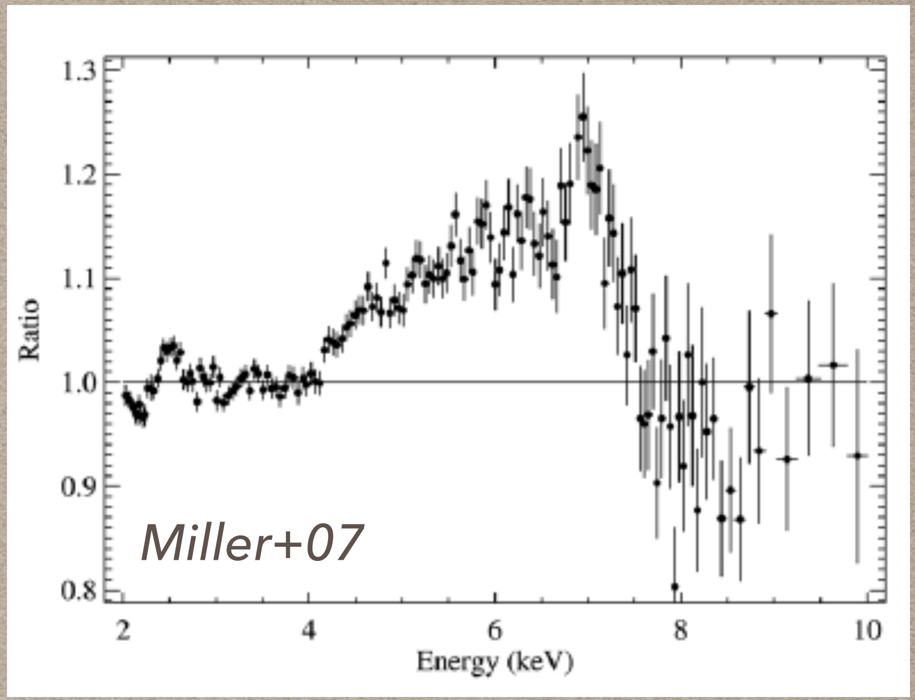
(MORE DURING F. DAIGNE LECTURE)

- A major contribution from X-ray measurement of GRB afterglows is, in the first place, the ability of producing precise images (which is much more complex in gamma-rays). Indeed thanks to Beppo*SAX* data a GRB afterglow could be localised at the arc minute scale (GRB 970228), which in turn allowed optical astronomers to follow-up the event from the ground and determine its distance and energy content -> GRBs are cosmological!
- X-ray spectroscopy can be used to investigate the shock accelerated electrons emission properties, as well as the intervening matter density (N_H absorption) and hence the GRB environment
- X-ray light curves can provide information about the geometry of the relativistic outflow and on the progenitors of GRBs





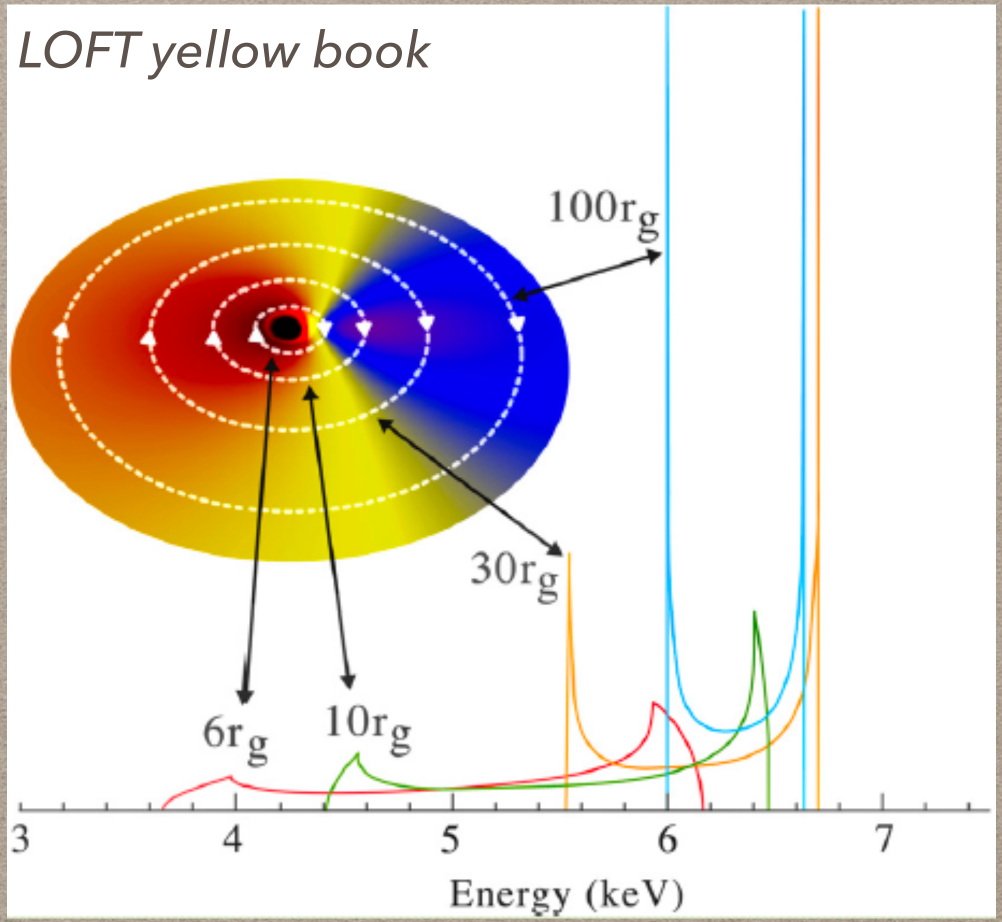
BLACK HOLES
(MORE DURING S. MARKOFF LECTURES)



- Relativistic doppler shifts, gravitational redshift, photon bending and beaming affect the spectral shape and the flux observed from each point in the accretion disk flow, leading to a variety of quantifiable distortions of the Fe line profile.
- Redshift z from a point on the disk at radius r and azimuthal angle φ is given in Schwarzschild geometry by

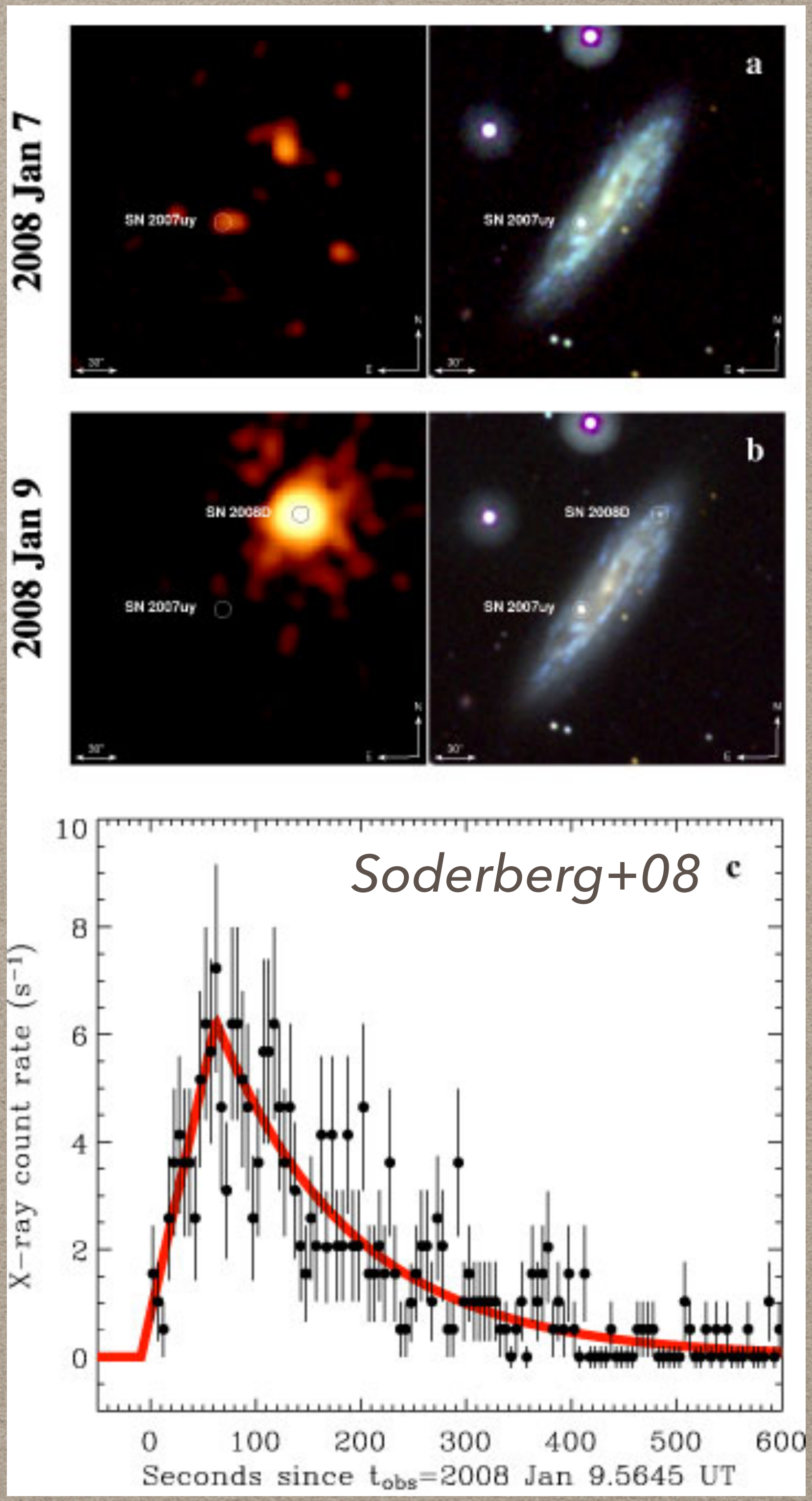
$$1 + z = \frac{1 + (b r_g^{\frac{3}{2}} / r^{\frac{3}{2}}) \sin i \sin \phi}{\sqrt{1 - 3 r_g / r}}$$

- where i is the disk inclination and b the impact parameter at infinity of the photon relative to the BH. An equivalent calculation can be done for a Kerr BH
- Measurements of Fe line profile can constrain BH spin



SUPERNOVA SHOCK BREAKOUT
(MORE DURING J. VINK LECTURE)

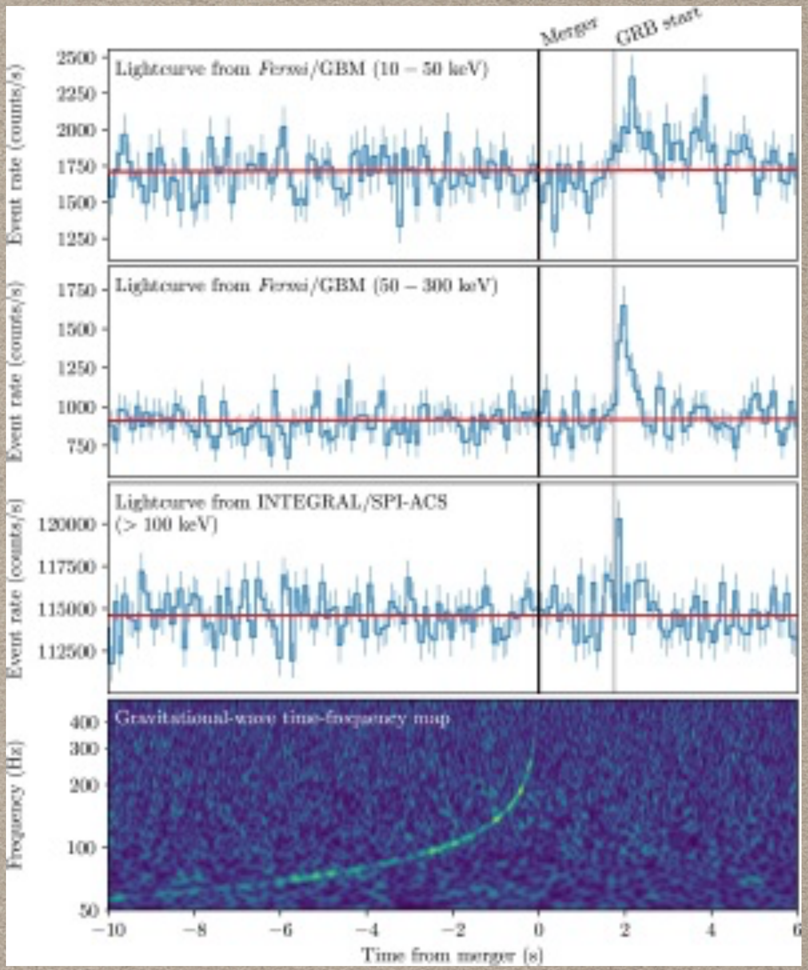
- Supernovae are routinely discovered by optical surveys, but usually days to weeks after the actual explosion
- In 2008 Swift UVOT was monitoring a SN (2007uy) in NGC 2770 when another SN when off (2008D, type Ib/c)
- A luminous X-ray transient (L_X~10^{44} erg s^{-1}) was detected by XRT lasting just a few minutes. Interpreted as the shock breakout i.e. when the shocked material becomes optically thin. Can be used to infer the properties of the SN progenitor: in this case a Wolf-Rayet star
- No contemporaneous flash was recorded by the UVOT until two hours later
- Coupled analysis of radio and X-ray data allowed to constraint the speed of the ejected material (0.25 c) and its energy of 10^{48} erg (0.1% of the total explosion energy)

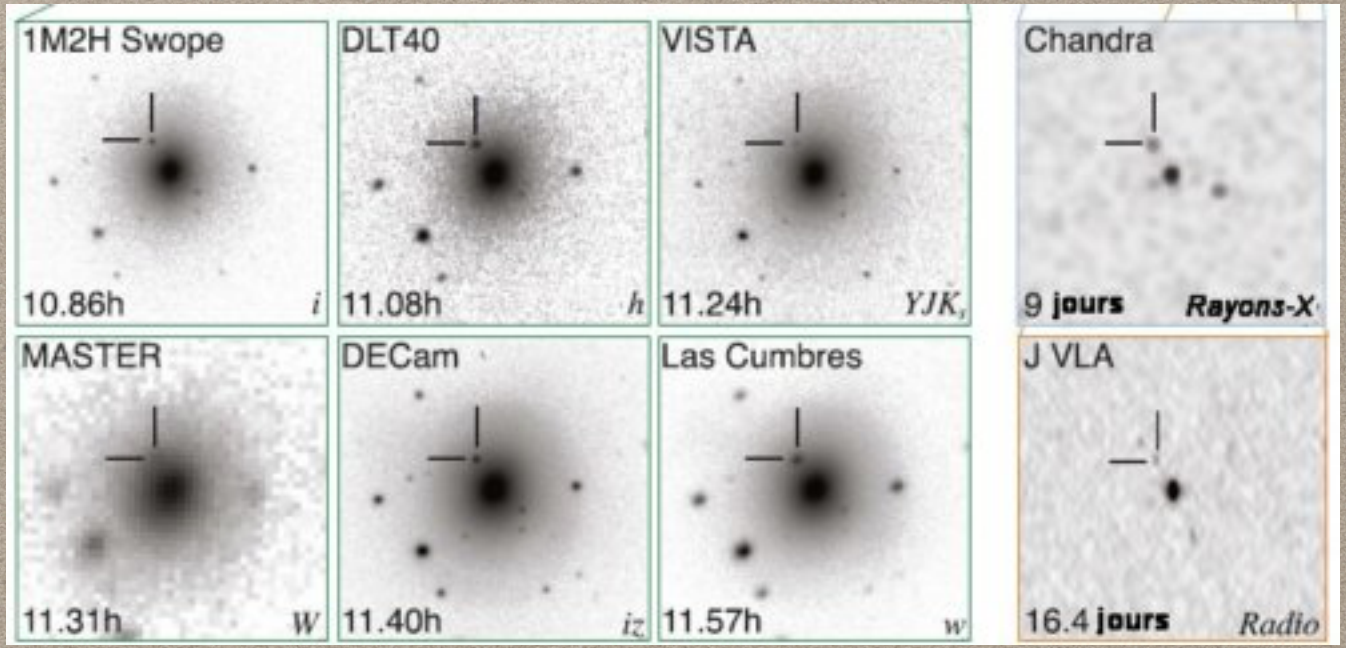


MERGERS

(MORE DURING E. PORTER/N. LEROY LECTURE)

- The detection of GW170817 (binary neutron star merger) and its association with a short GRB detected by Fermi/GBM and INTEGRAL/ACS marked the beginning of a new era for multi-messenger astrophysics
- First direct link between NS mergers and short GRBs!
- A kilonova was associated to this event and was observed by many telescopes in different wavelengths from radio to X-rays
- The nature of the observed prompt radiation was unclear (jet or cocoon or both?). Difficult to conclude based on gamma-ray data only



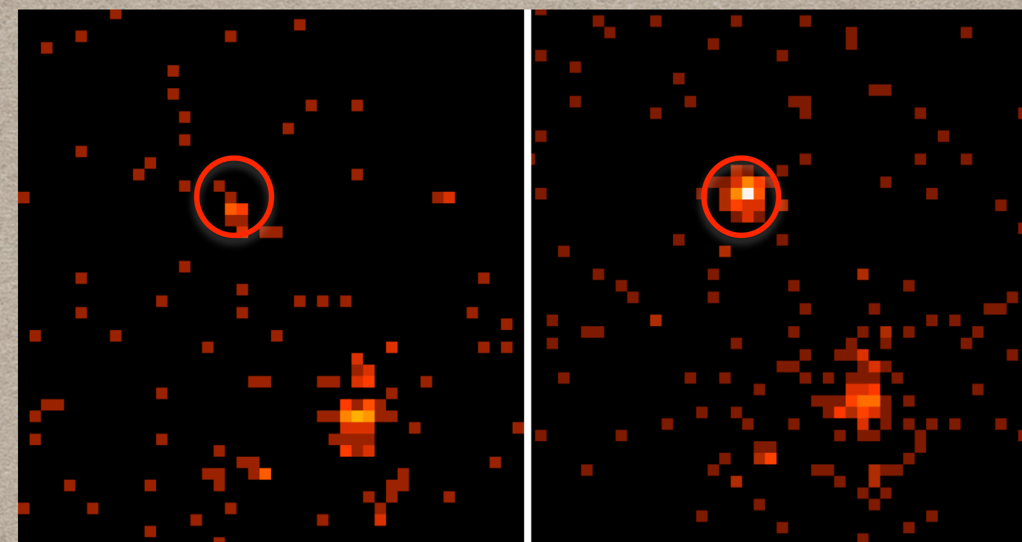


MERGERS

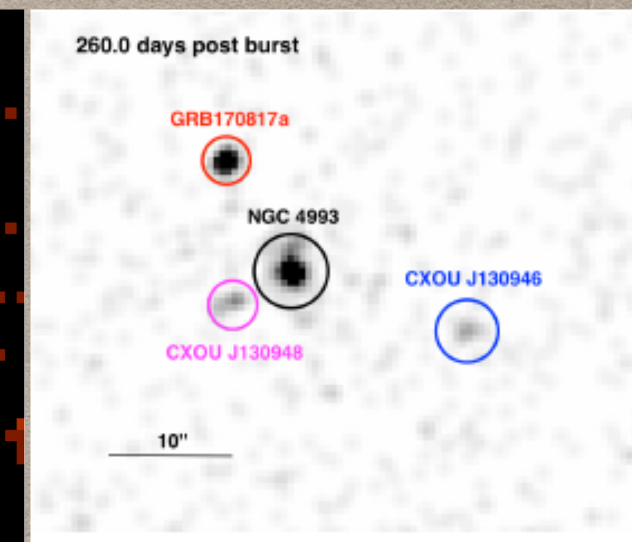
An off-axis GRB afterglow:

structured jet models are favoured from X-ray observations, and confirmed by radio observations (Ghirlanda+19).

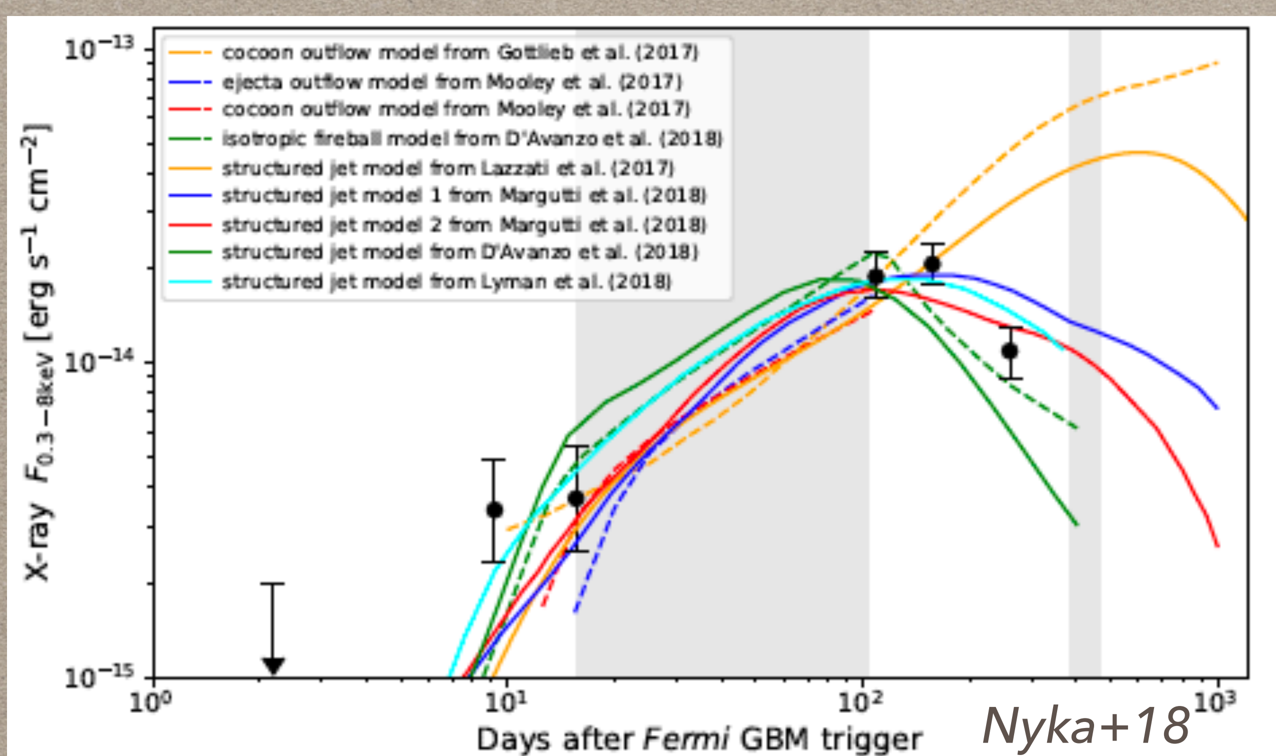
9 days 108 days 260 days

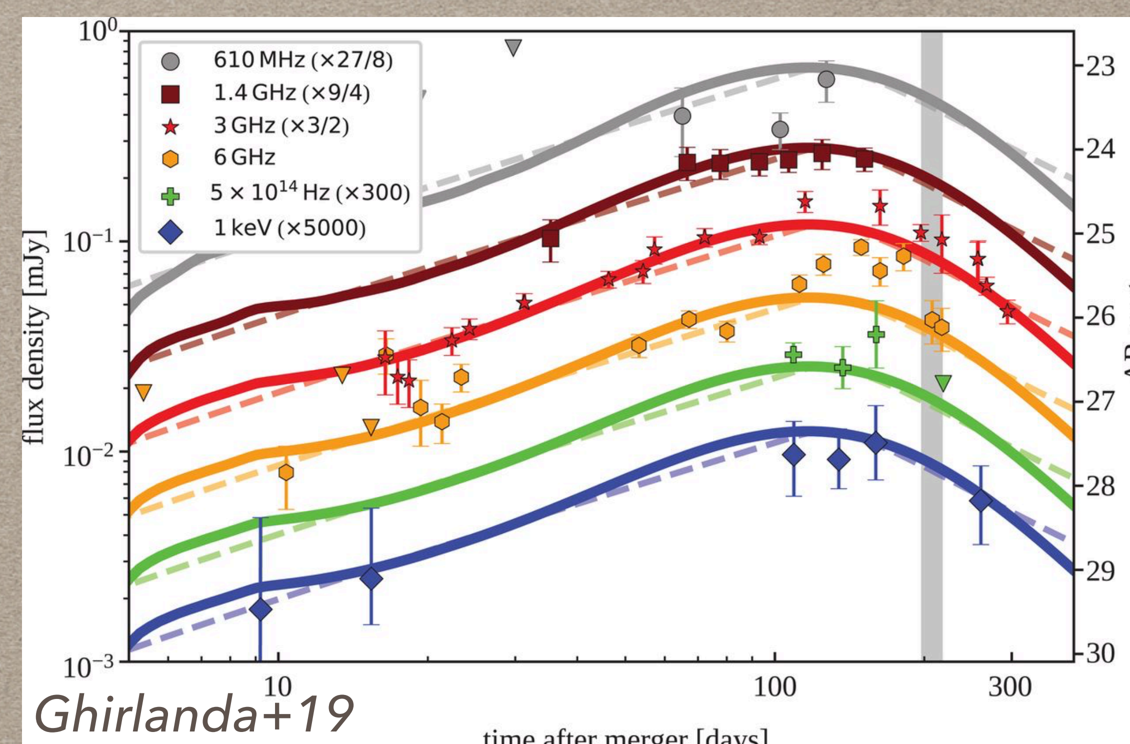


Troja+18



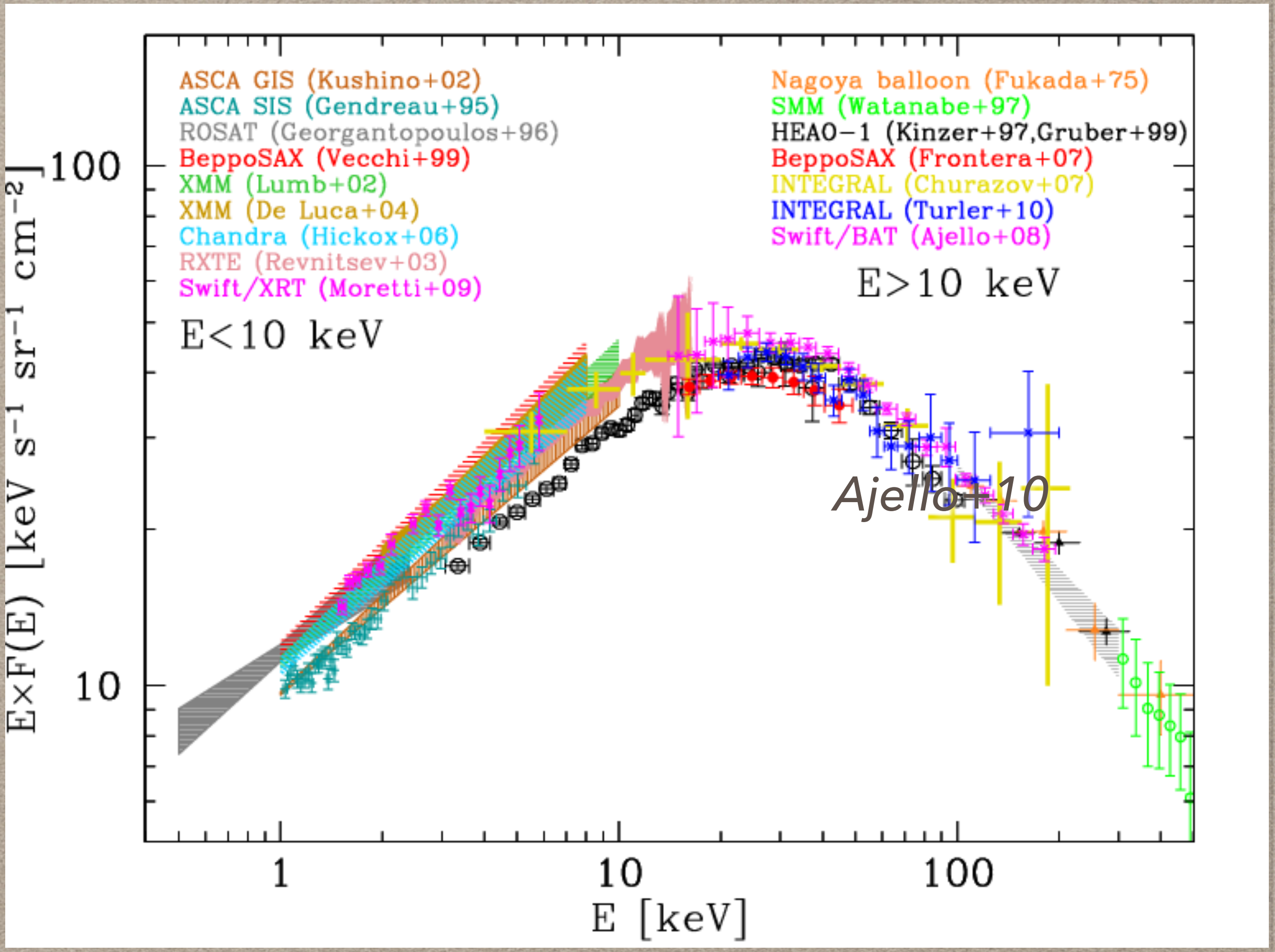
Nyka+18





DIFFUSE X-RAY BACKGROUND

- The cosmic X-ray background (CXB) was discovered in 1962, at the same time as Sco X-1.
- Even after subtraction of all possible local effects there was still a truly uniformly distributed component which suggested that its origin was extra-galactic. It has been studied for many decades
- The assumption was that the XRB was made up from X-rays from Active Galactic Nuclei which were not bright enough to be detected as sources in the instruments.
- In the current era of X-ray astronomy the *CHANDRA* Satellite has taken two deep images of the X-ray sky - the Chandra Deep Fields North and South (23 and 11 day exposures respectively); and the *XMM-NEWTON* Satellite has taken a 9 day exposure of the Lockman Hole area of the sky. They were able to resolve most of the CXB.
- But there is still a large fraction of the hard band missing (Compton thick AGN?).



THE FUTURE: THE ATHENA OBSERVATORY

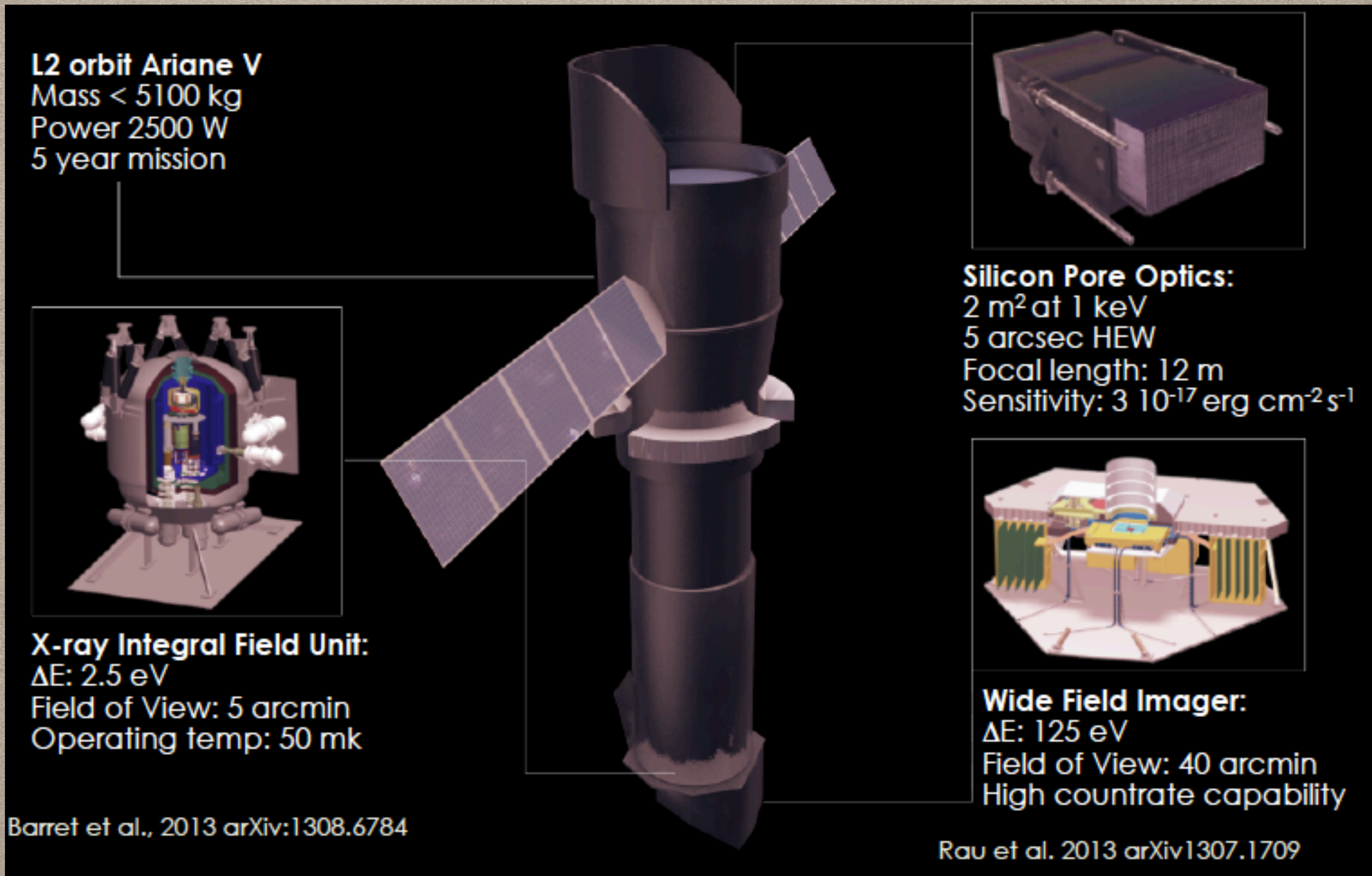
The Hot and Energetic Universe has been selected by ESA for the L2 Comsic Vision slot, to be launched in ~2031

Two instruments:

WFI: Wide Field Imager

X-IFU: X-ray Integrated Field Unit

ATHENA



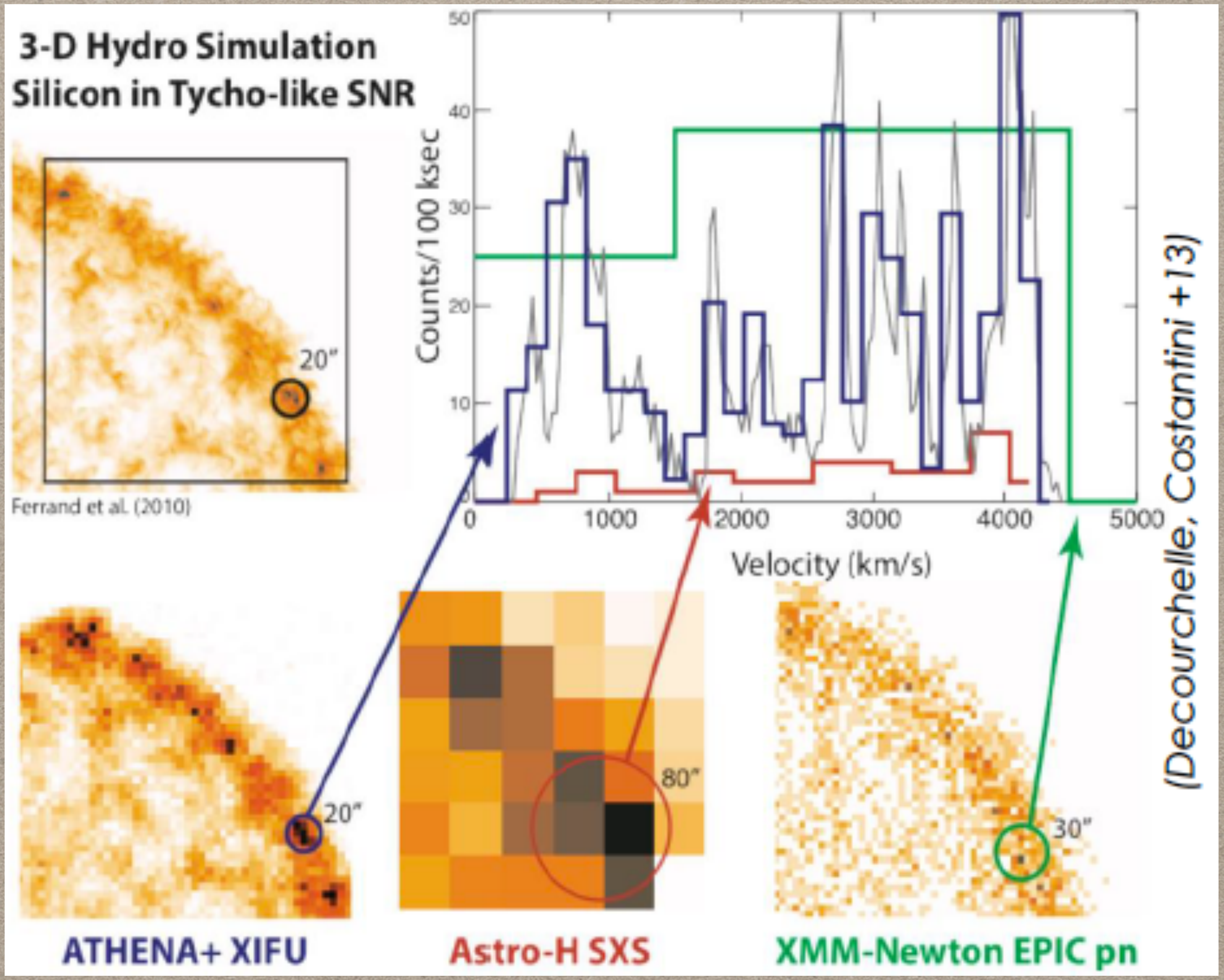
L2 orbit Ariane V
Mass < 5100 kg
Power 2500 W
5 year mission
Silicon Pore Optics:
$2\ m^2$ at 1 keV
5 arcsec HEW
Focal length: 12 m
Sensitivity: $3\ 10^{-17}$ erg $cm^{-2}\ s^{-1}$
X-ray Integral Field Unit:
ΔE: 2.5 eV
Field of View: 5 arcmin
Operating temp: 50 mk
Wide Field Imager:
ΔE: 125 eV
Field of View: 40 arcmin
High countrate capability
Barret et al., 2013 arXiv:1308.6784
Rau et al. 2013 arXiv1307.1709

ATHENA REQUIREMENTS

Parameter	Requirements	Enabling technology/comments
Effective Area	2 m^2 @ 1 keV (goal 2.5 m^2) 0.25 m^2 @ 6 keV (goal 0.3 m^2)	Silicon Pore Optics developed by ESA. Single telescope: 3 m outer diameter, 12 m fixed focal length.
Angular Resolution	5" (goal 3") on-axis 10" at 25' radius	*Detailed analysis of error budget confirms that a performance of 5" HEW is feasible.*
Energy Range	0.3-12 keV	Grazing incidence optics & detectors.
Instrument Field of View	*Wide-Field Imager:* (**WFI**): 40' (goal 50')	Large area DEPFET Active Pixel Sensors.
	X-ray Integral Field Unit: (**X-IFU**): 5' (goal 7')	Large array of multiplexed Transition Edge Sensors (TES) with 250 micron pixels.
Spectral Resolution	**WFI**: <150 eV @ 6 keV	Large area DEPFET Active Pixel Sensors.
	X-IFU: 2.5 eV @ 6 keV (goal 1.5 eV @ 1 keV)	*Inner array (10"x10") optimized for goal resolution at low energy (50 micron pixels).*
Count Rate Capability	> 1 Crab[1] (**WFI**)	*Central chip for high count rates without pile-up and with micro-second time resolution.*
	1 mCrab, point source (X-IFU) with 90% of high-resolution events	*Filters and beam diffuser enable higher count rate capability with reduced spectral resolution.*
Target of Opportunity Response	4 hours (goal 2 hours) for 50% of time	*Slew times <2 hours feasible; total response time dependent on ground system issues.*

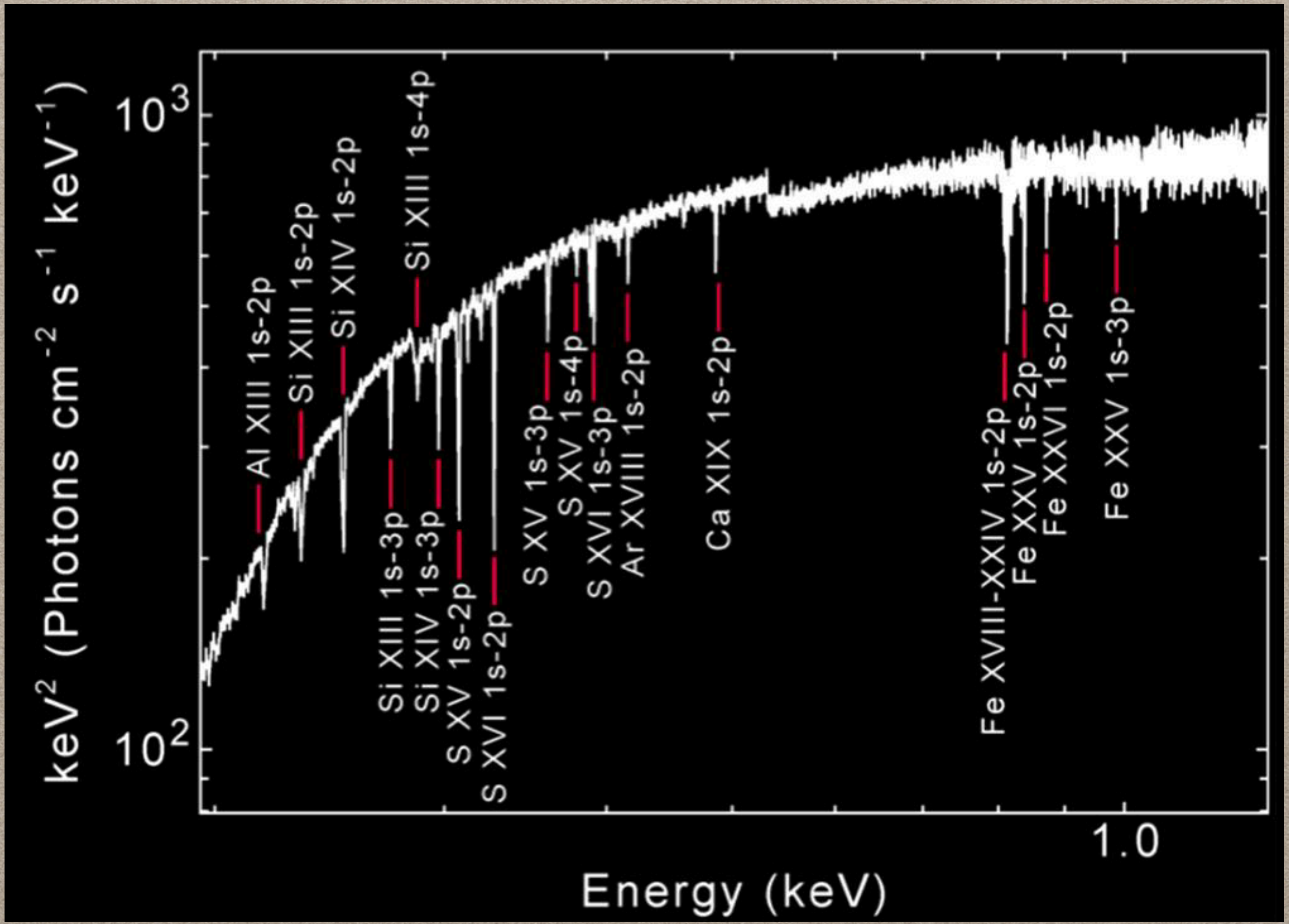
ATHENA & SNRS

Improved effective area and energy resolution wrt to previous experiments: provides detailed view of elemental distribution in SNRs to be compared with hydrodynamical explosion codes



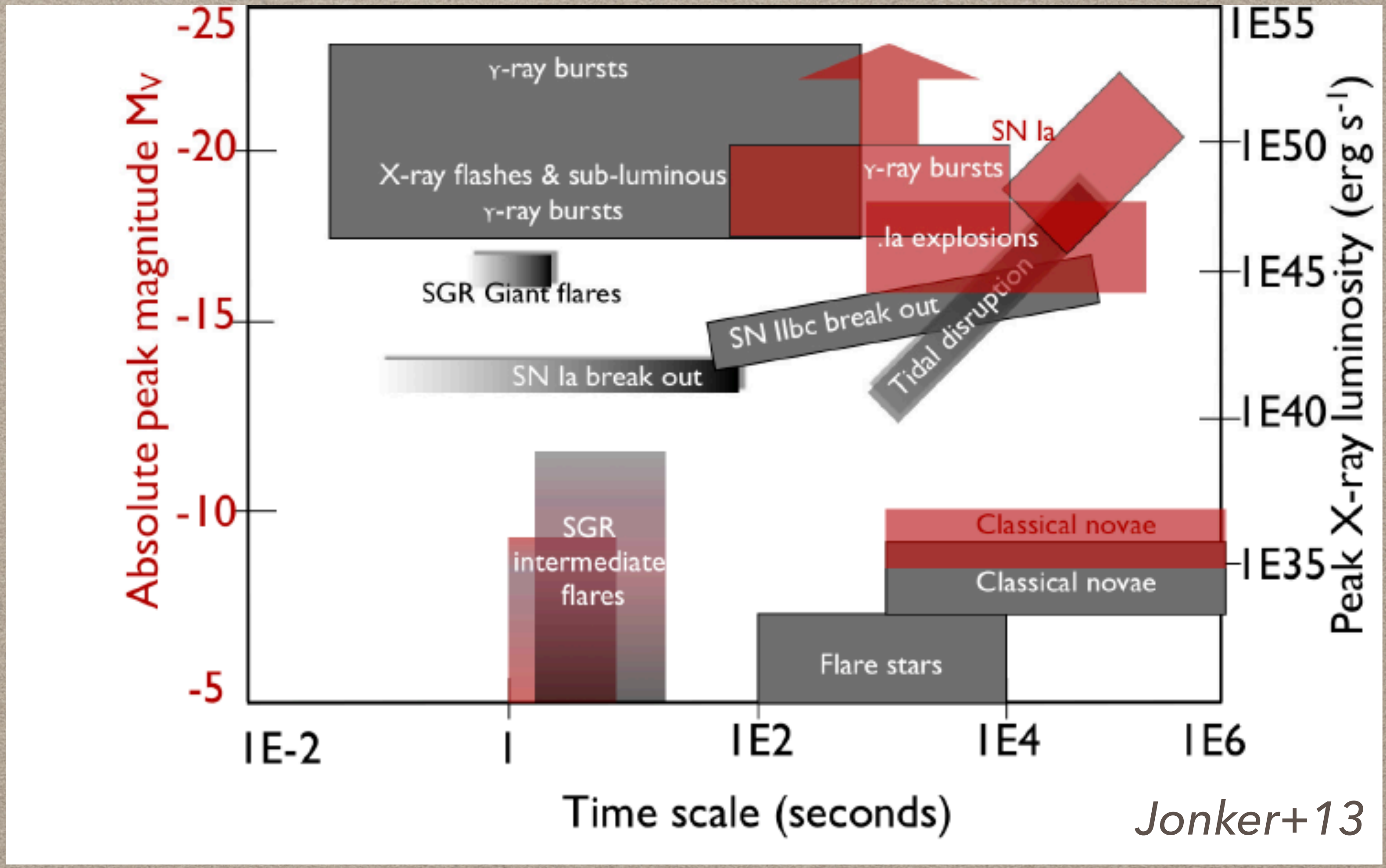
ATHENA TRANSIENTS

The detection of a bright GRB at redshirt ~7 would allow for absorption spectroscopy constraining metal abundances in the early Universe. These galaxies would be inaccessible to other wavelength (too faint even for ELT/JWST)



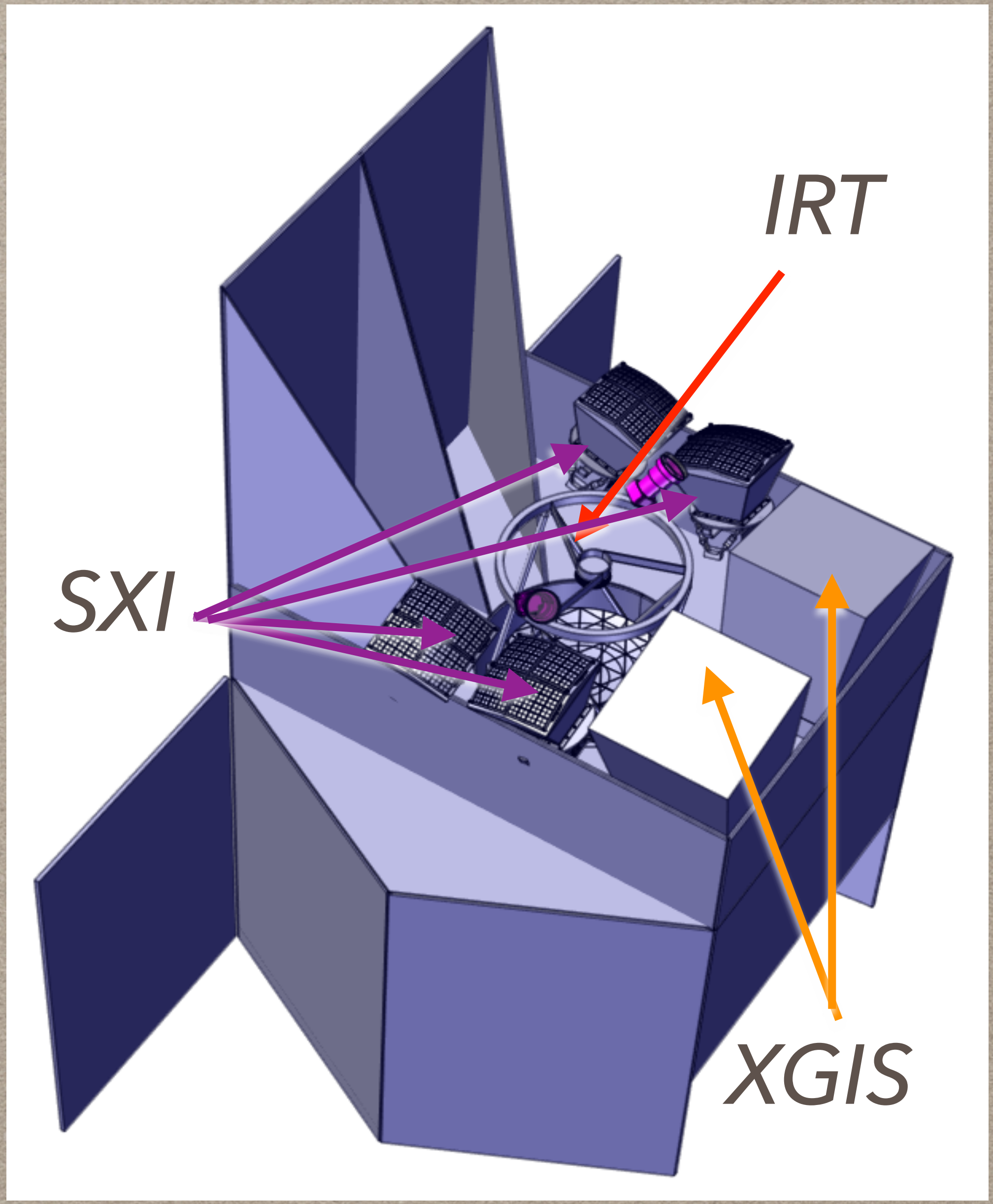
THE FUTURE: WIDE FIELD X-RAY IMAGING

- Time Domain Astronomy (the systematic study of the variable sky) is becoming a hot topic in X-ray astronomy
- Several future projects (Einstein Probe (CAS), THESEUS (ESA), TAP (NASA), High-z Gundam (JAXA)) will make use of « Lobster Eye » optics in order to survey the variable X-ray sky



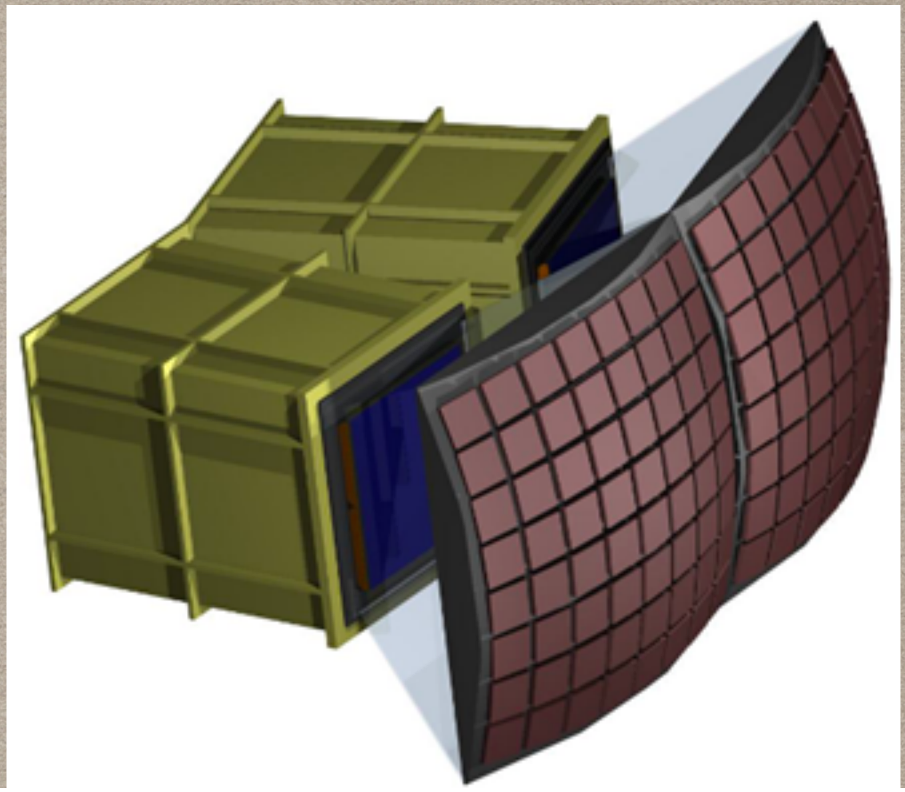
THESEUS: TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

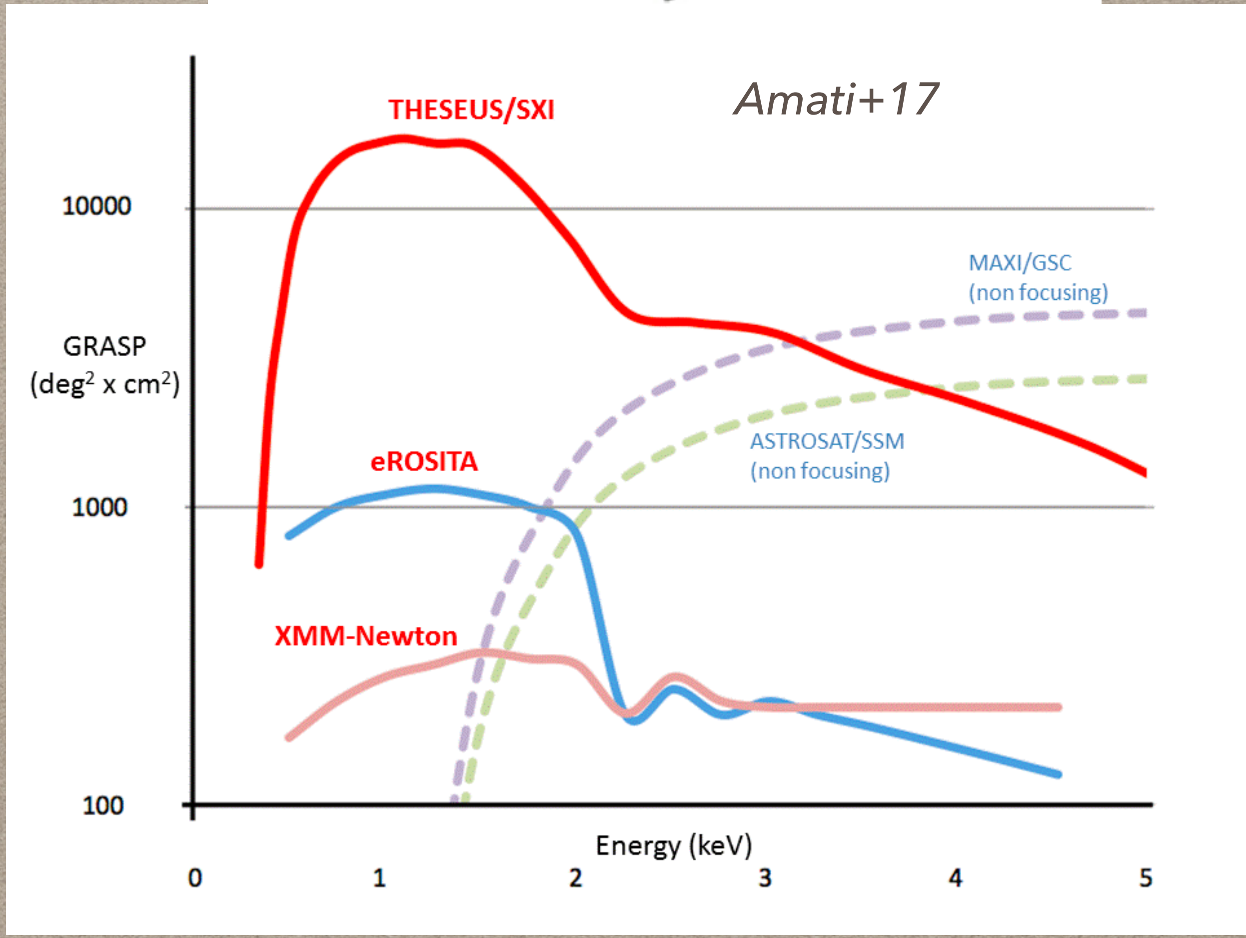
- ESA M5 mission candidate (launch 2032). Currently in phase A (ends 2021). LEO with 6° inclination and ~600 km altitude.
- Dedicated to deep Universe astrophysics and cosmology (FD talk), and transient (multi-messenger) sky
- Carries a wide FOV X-ray telescope (SXI, 4 units, 0.3-6 keV, ~1 arc min accuracy), a coded mask system (XGIS, 2 units, 2 keV-10 MeV), a NIR telescope (IRT, 0.7-1.8 μ)
- 1 sr FOV for the X-ray monitor -> several hundreds GRBs detected per year, and hundreds of other X-ray transients (TDEs, AGNs, magnetars, binaries, stellar flares,…)



SXI GRASP

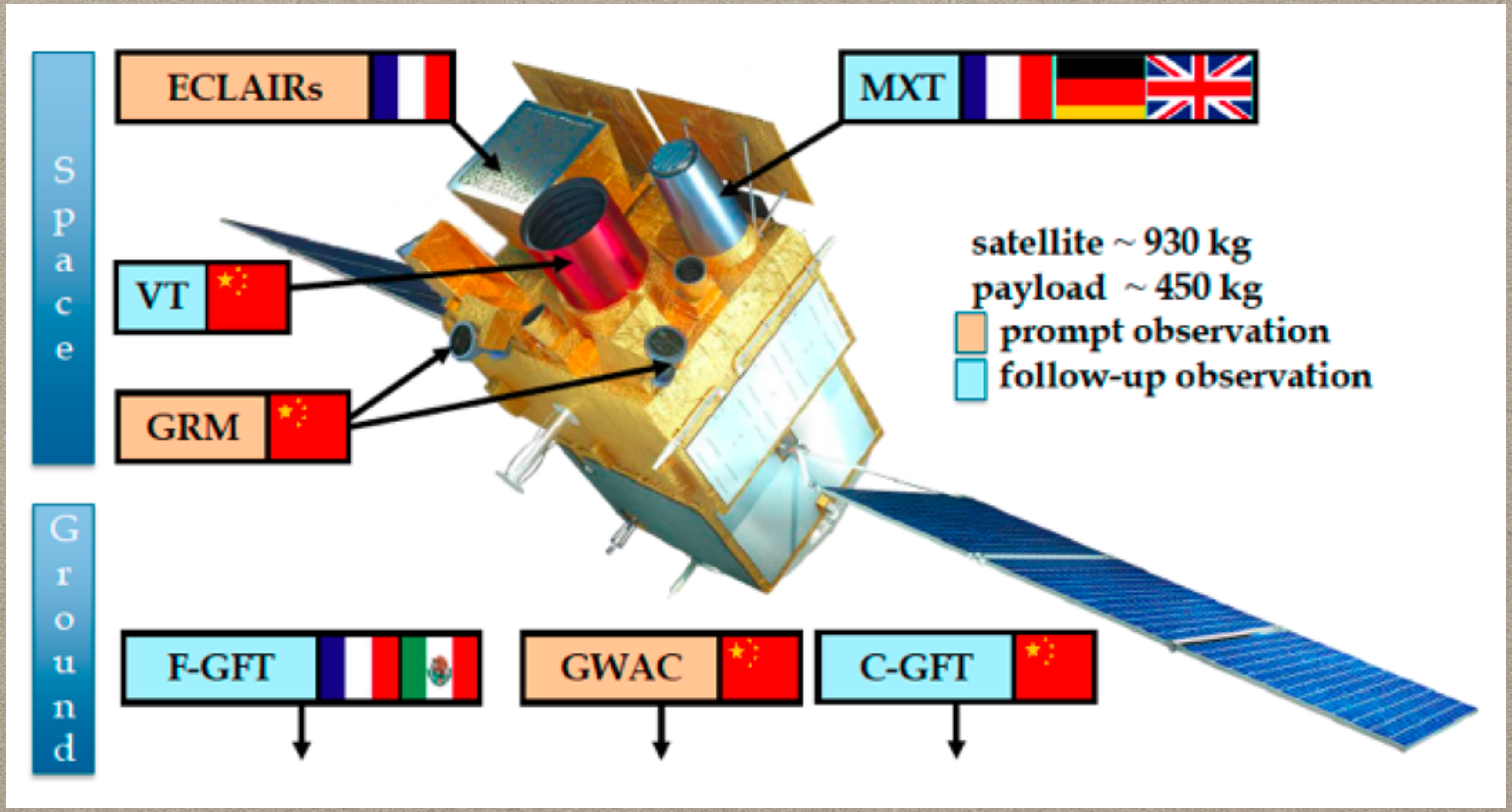
- The Grasp is the product of the effective area of an X-ray telescope and the covered sky area
- Despite the fact that « Lobster Eye » optics do not provide a high effective area, their large field of view makes them the best suited telescopes for hunting new X-ray transients with un-precedented sensitivity
- Difficulty: requires large detectors (~half of the optics surface). Challenging thermal setup.





THE NEAR FUTURE: SVOM

- Sino-French Collaboration, to be launched by 2021
- Will carry multi-wavelength payload
- Dedicated ground follow-up telescope
- Optimized pointing strategy (anti-solar) to enhance red shift determination
- Wide field (2sr) monitoring of the X-ray sky starting at 4 keV



SUMMARY

- We are witnessing the « golden era » of X-ray astronomy. It is now a mature branch encompassing most of the known celestial objects.
- Several facilites are available at the same time, each one with specific unique characteristics (unfortunately not all available at the same time)
    - Chandra -> excellent spatial resolution
    - XMM -> large collecting area
    - Nustar -> unique hard X-ray imaging
    - Swift/XRT -> flexible ToO follow-up
- In the future ATHENA will provide a combination of large collecting area, excellent spectral resolution, combined with a fairly good PSF (worse then Chandra)
- Swift/BAT and INTEGRAL/IBIS are detecting and localizing routinely transient sources (> 20 keV), but a major leap forward is expected by the advent of soft X-ray wide field focussing telescopes, and several projects may be completed before the end of the next decade

Thank you for your attention!