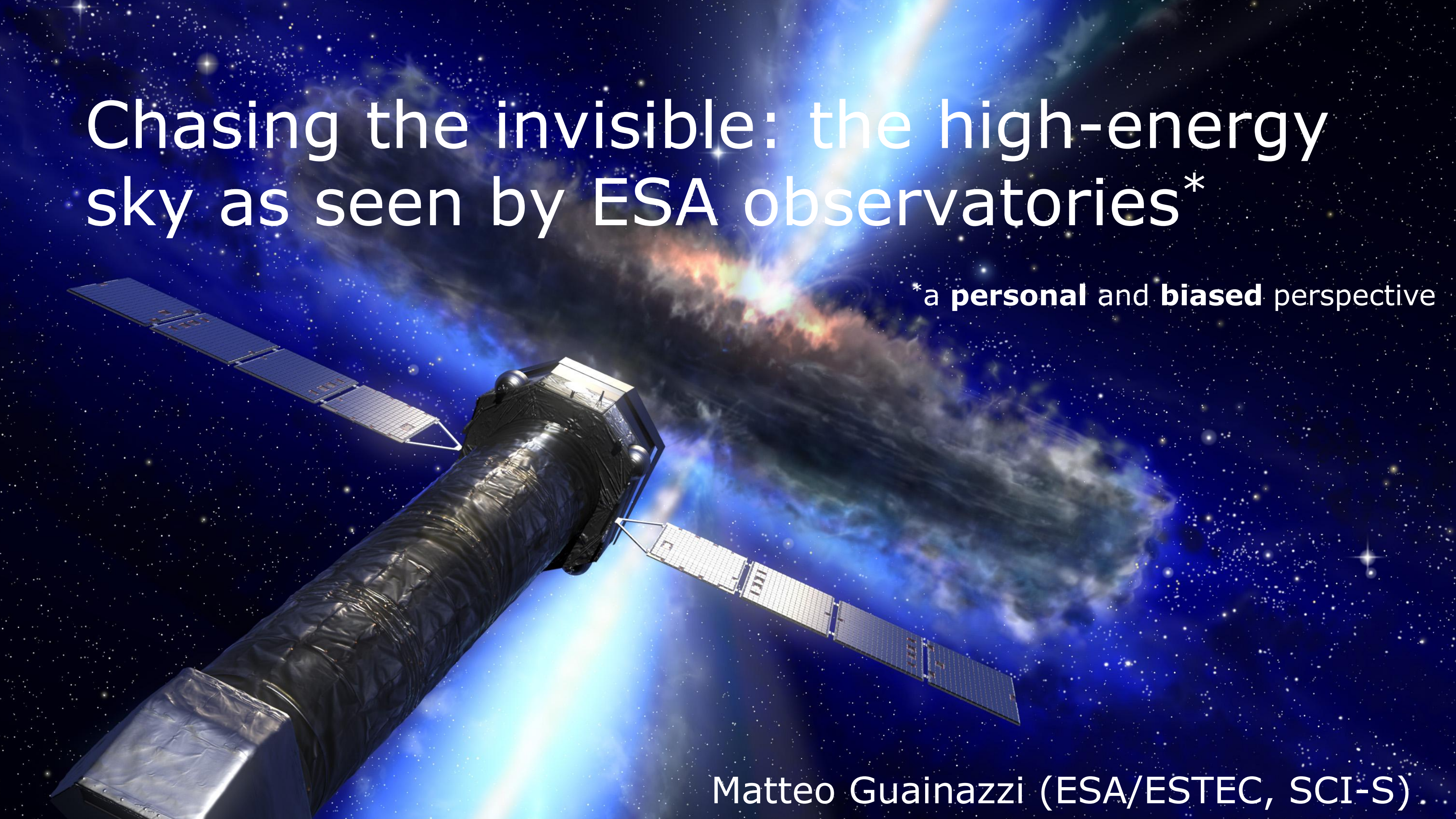
Chasing the invisible: the high-energy sky as seen by ESA observatories*

*a **personal** and **biased** perspective



Matteo Guainazzi (ESA/ESTEC, SCI-S)

“The Hot and Energetic Universe”

ESA Cosmic Vision program questions:

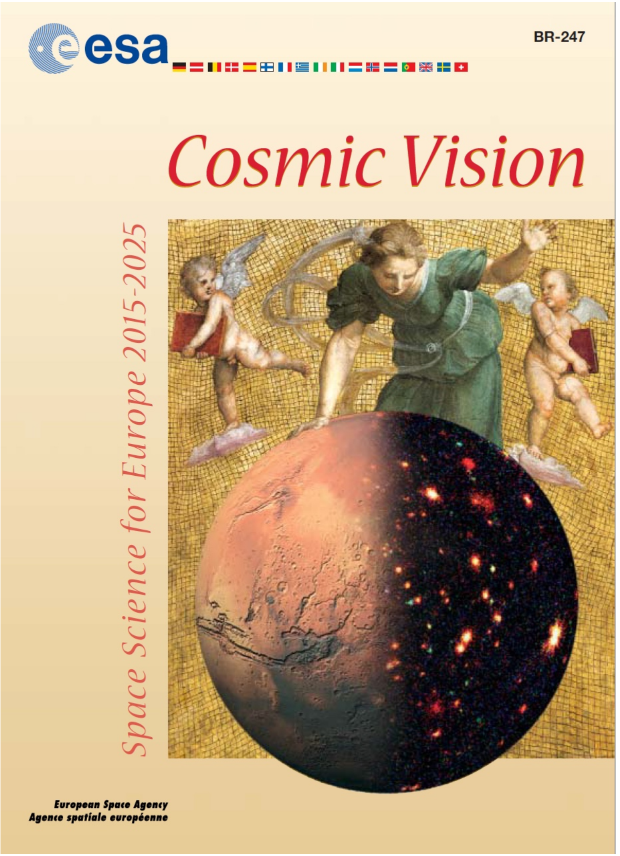
1. What are the conditions for planet formation and the emergence of life?
2. How does the Solar System work?
3. What are the fundamental physical laws of the Universe?
4. How did the Universe originate and what is it made of?

How did the Universe originate and what is it made of?

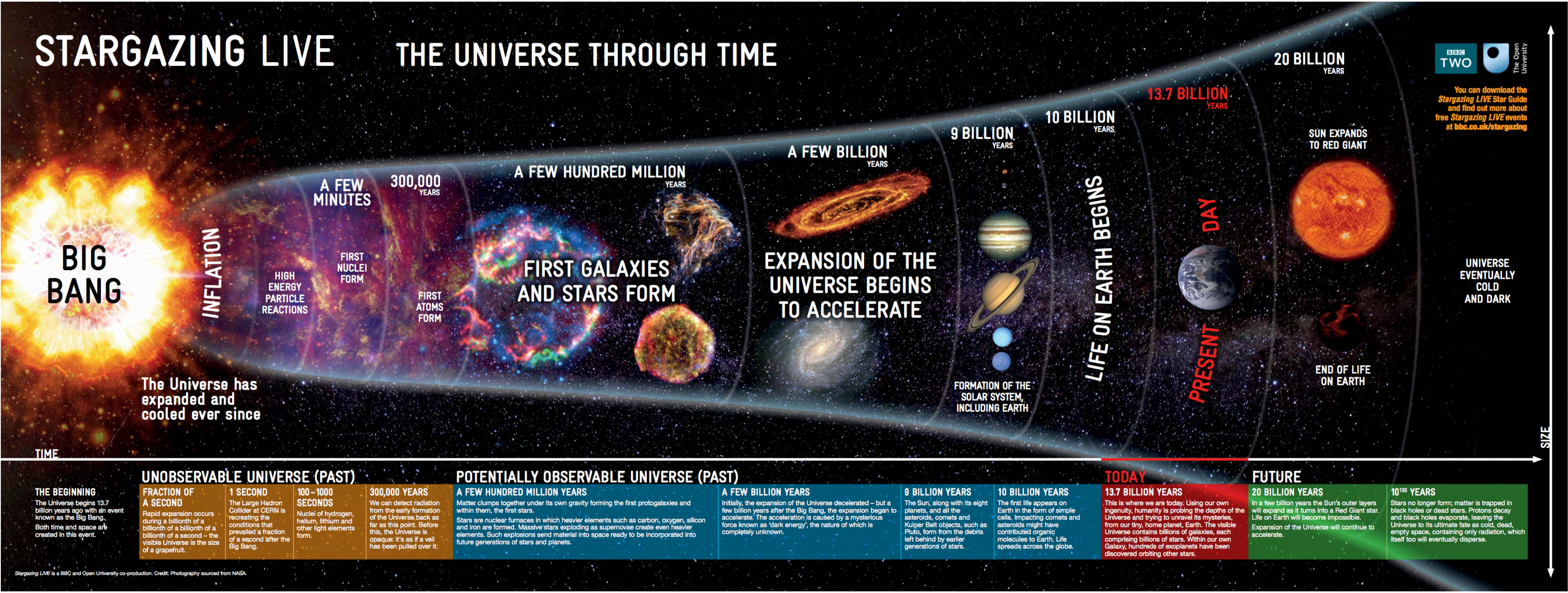
“The hot and Energetic Universe” science theme:

1. How does ordinary matter assemble in the large-scale structures?
2. How do black holes grow and shape galaxies?

Leading to the selection of a new large X-ray observatory: Athena



A short summary of the history of the Universe



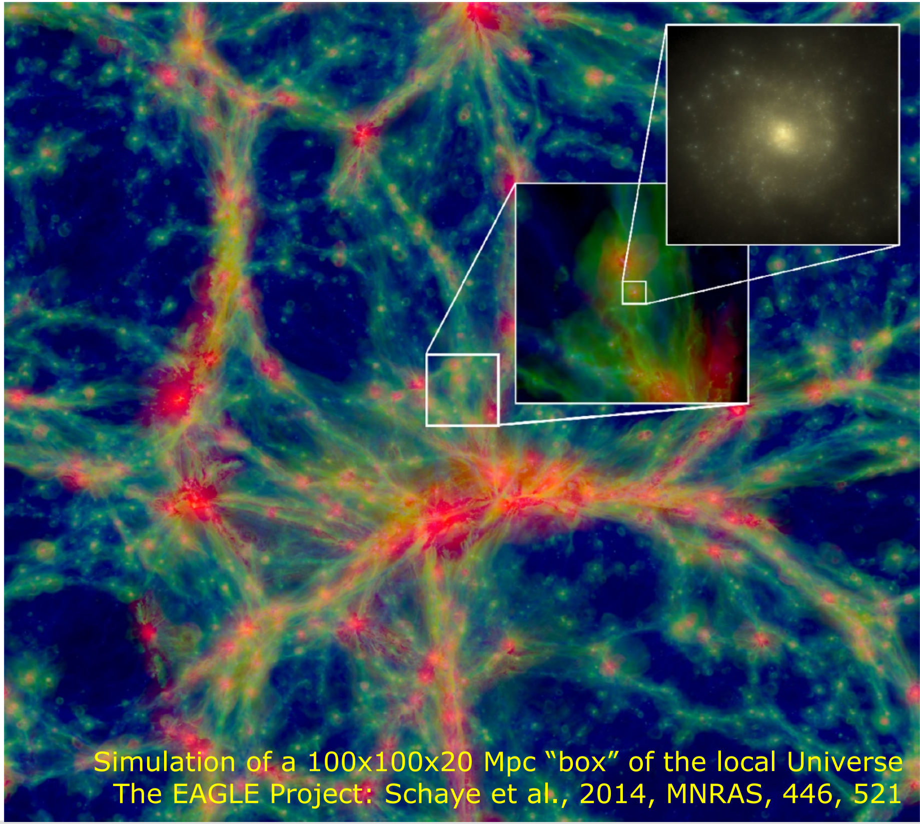
Courtesy: The Open University and BBC

The ”Cosmic Web”

- The Universe is not homogeneous: we *do* see planets, moon, stars…
- Simulations suggest that on scales ~1 Gpc hot gas is distributed in filaments: the “**cosmic web**”
- The gas is so hot, that it emits primarily very energetic radiation: UV, X-rays …
- At the nodes of this web, huge clustering of galaxies

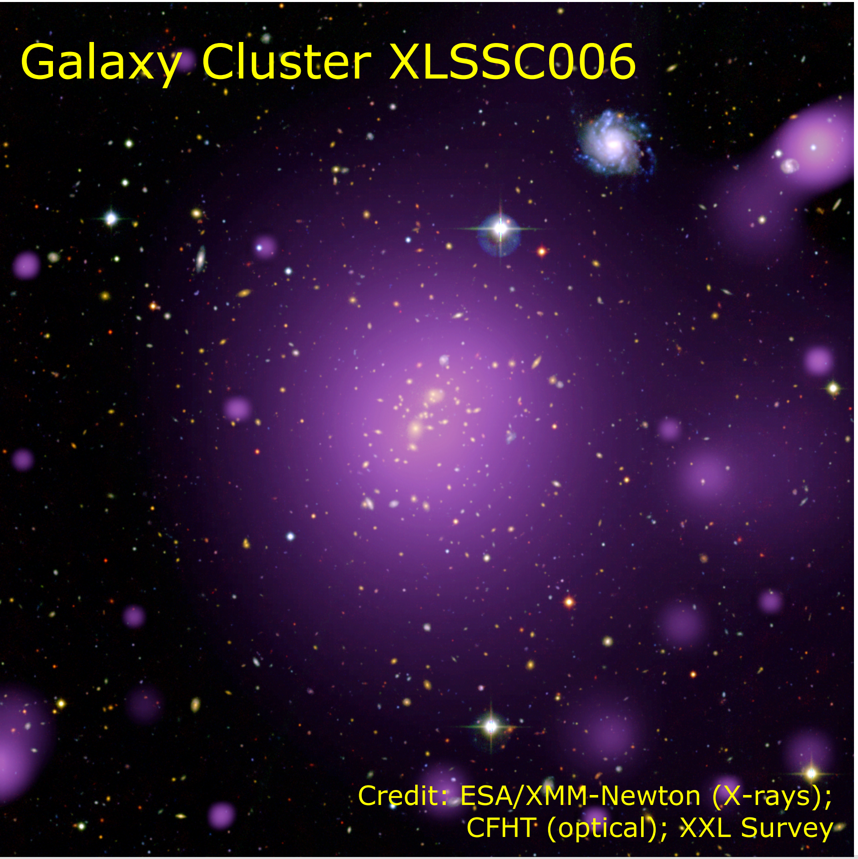
1 Gpc ~ 3×10^{22} km

$T<10^{4.5}$ $10^{4.5}\leq T\leq 10^{5.5}$ $T>10^{5.5}$ K



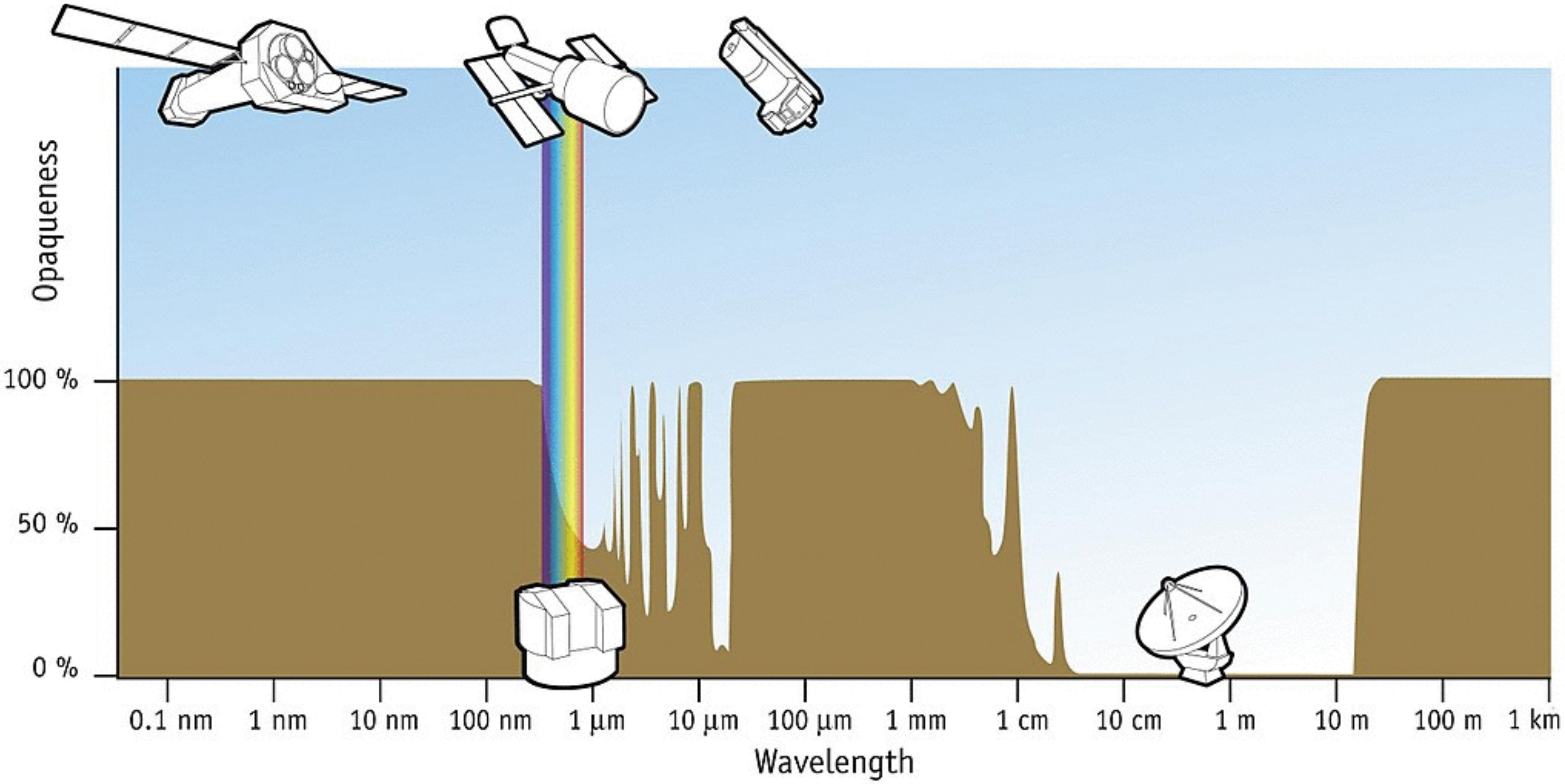
Simulation of a 100x100x20 Mpc “box” of the local Universe
The EAGLE Project: Schaye et al., 2014, MNRAS, 446, 521

A typical Galaxy Cluster



- Galaxy Clusters are the largest gravitationally-bound structures in the Universe
- Optical (white/yellow): galaxies
- X-rays (purple glow): T≥10^6 K gas
- Invisible: dark matter (85% of the total mass in the cluster)
- We need all wavelengths for a complete view of the Universe!

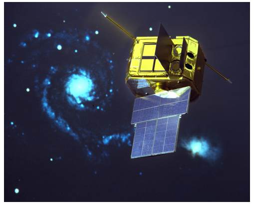
The (X-ray) need to go to space



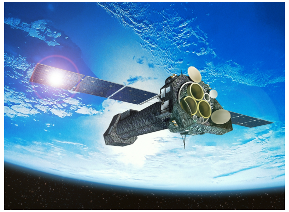
ESA high-energy observatories

http://sci.esa.int/athena/60759-history-of-x-ray-astronomy-in-europe-from-exosat-to-athena/

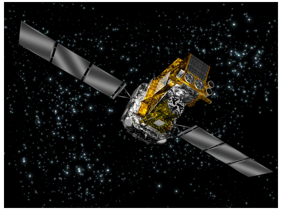
EXOSAT (1983-1986)



XMM-Newton (1999-)



INTEGRAL (2002-)

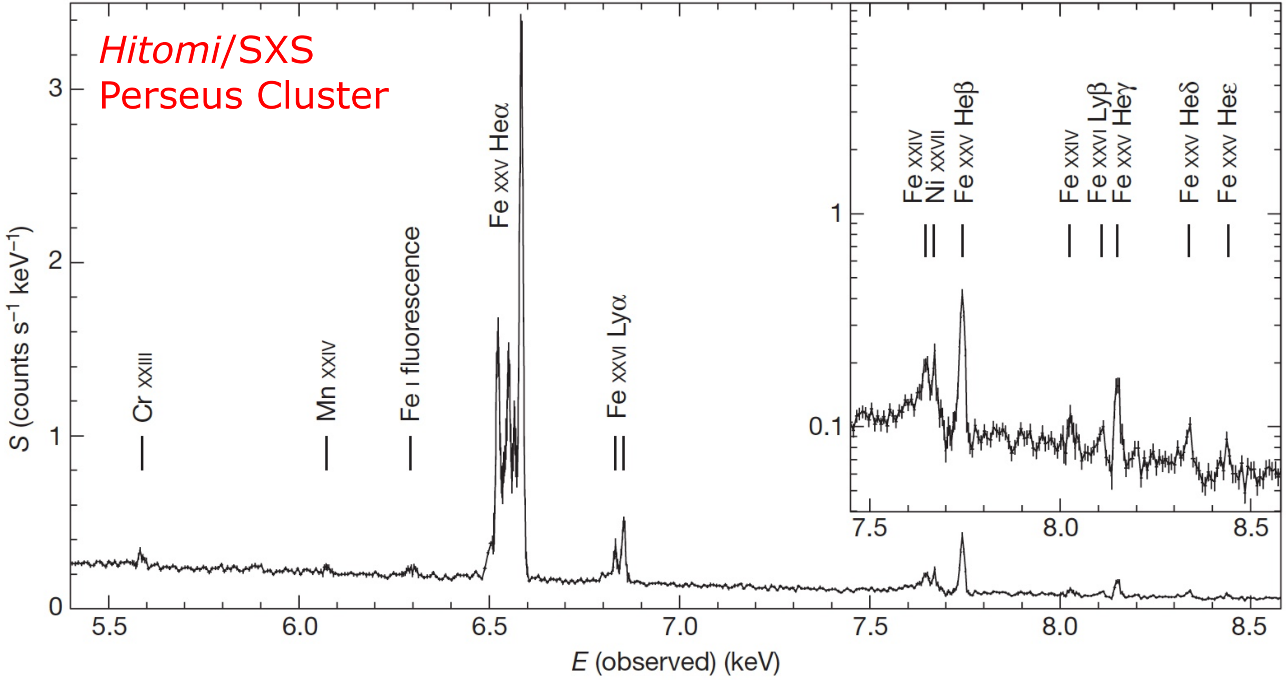


Accurate timing
Moderate resolution spectroscopy

γ-ray imaging and spectroscopy
Complementary X-ray and optical monitors

Spectro-imaging capabilities at CCD resolution
High-resolution spectroscopy in the soft X-ray band
Complementary optical photometry

The X-ray spectrum of a galaxy cluster

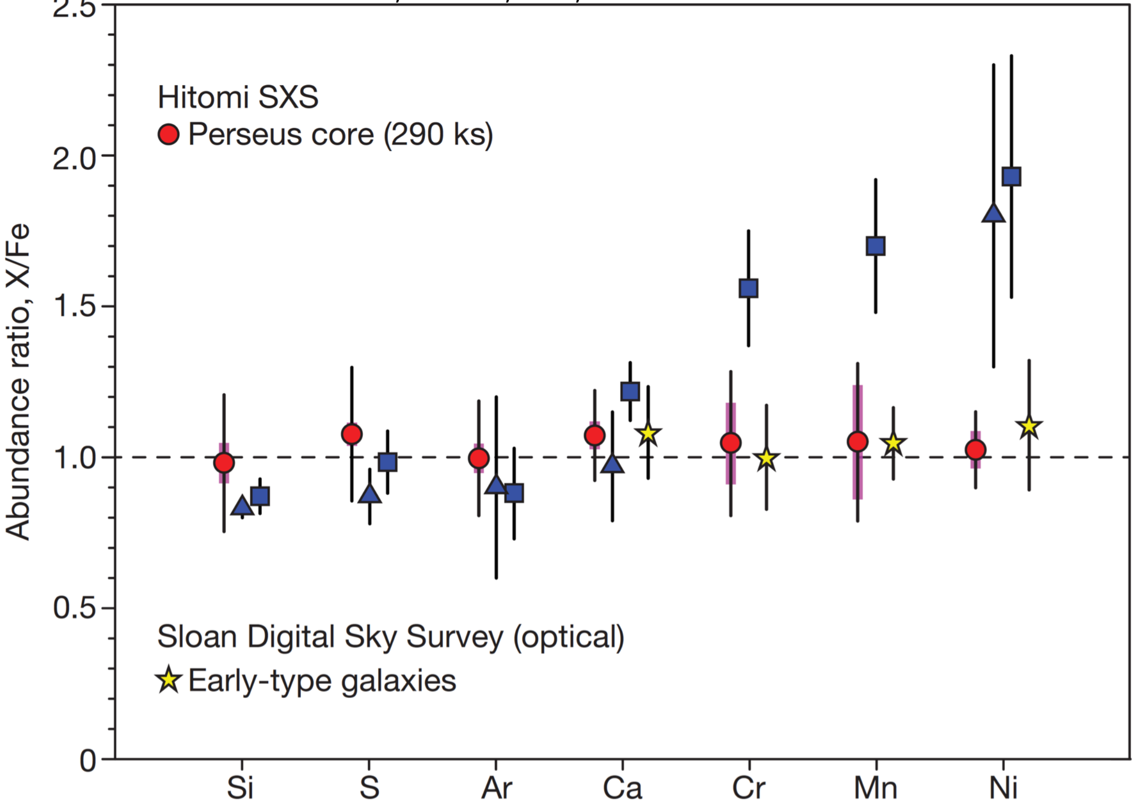


- *Hitomi* (ひとみ): JAXA mission with NASA and ESA participation
- Lost in 2016 after 6 weeks of operation ☹
- But, before that, measured the most accurate spectrum of a galaxy cluster ever

Hitomi Collaboration, Nature, 446, 521

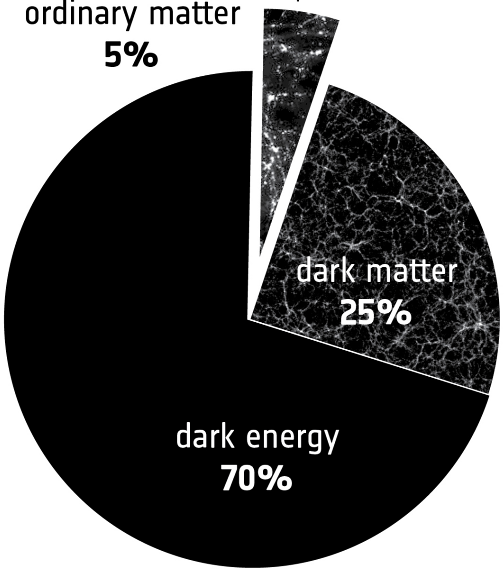
Cosmic "metallicity" (= chemistry)

Hitomi Collaboration, Nature, 551, 478



- Weak emission lines of Si, S, Ar, Ca, Cr, Mn, Ni
- The abundances (red points) reflect the cosmological history of metal production
- The Perseus chemical composition is the same as in the Sun environs (dashed line)
- [The blue points are older, less accurate measurements: science progresses!]

Missing baryon problem



Nicastro et al., **2017**, AN, 338. 281

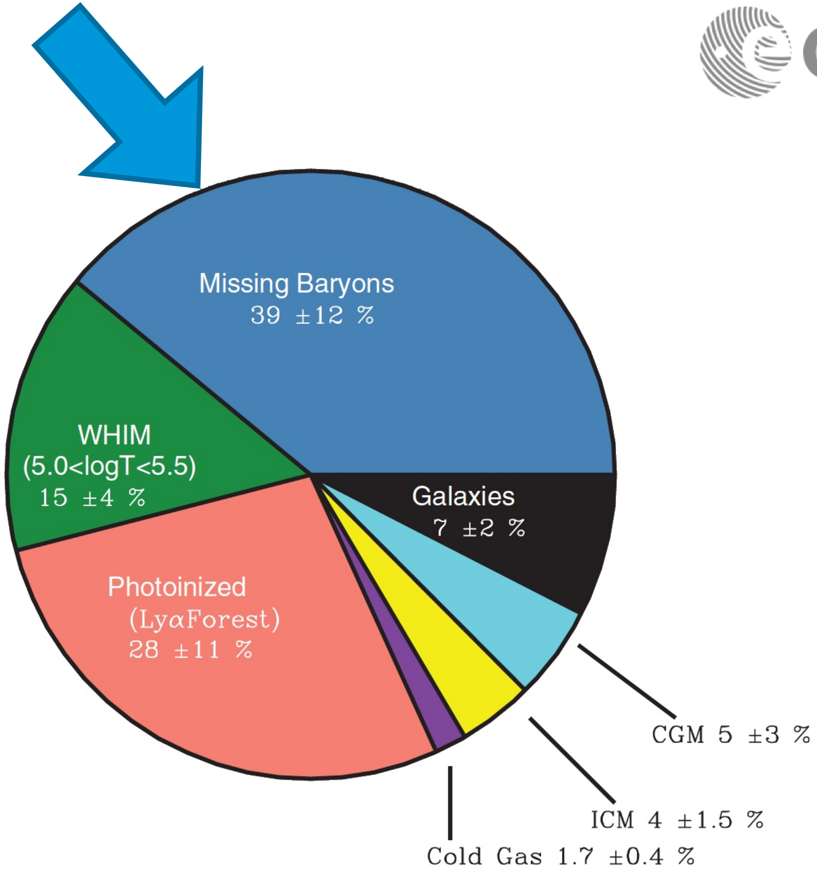
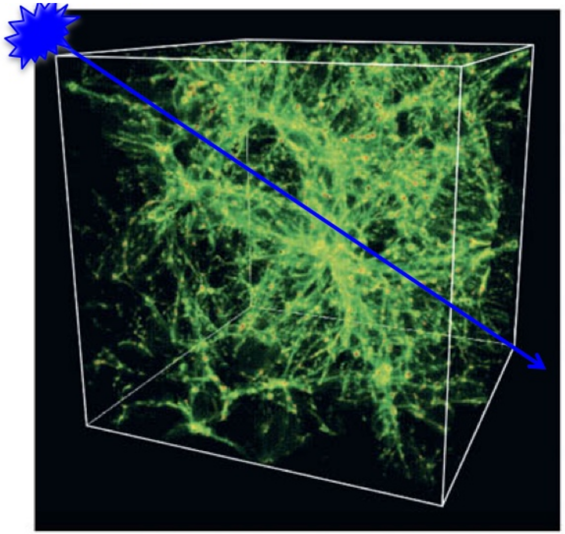
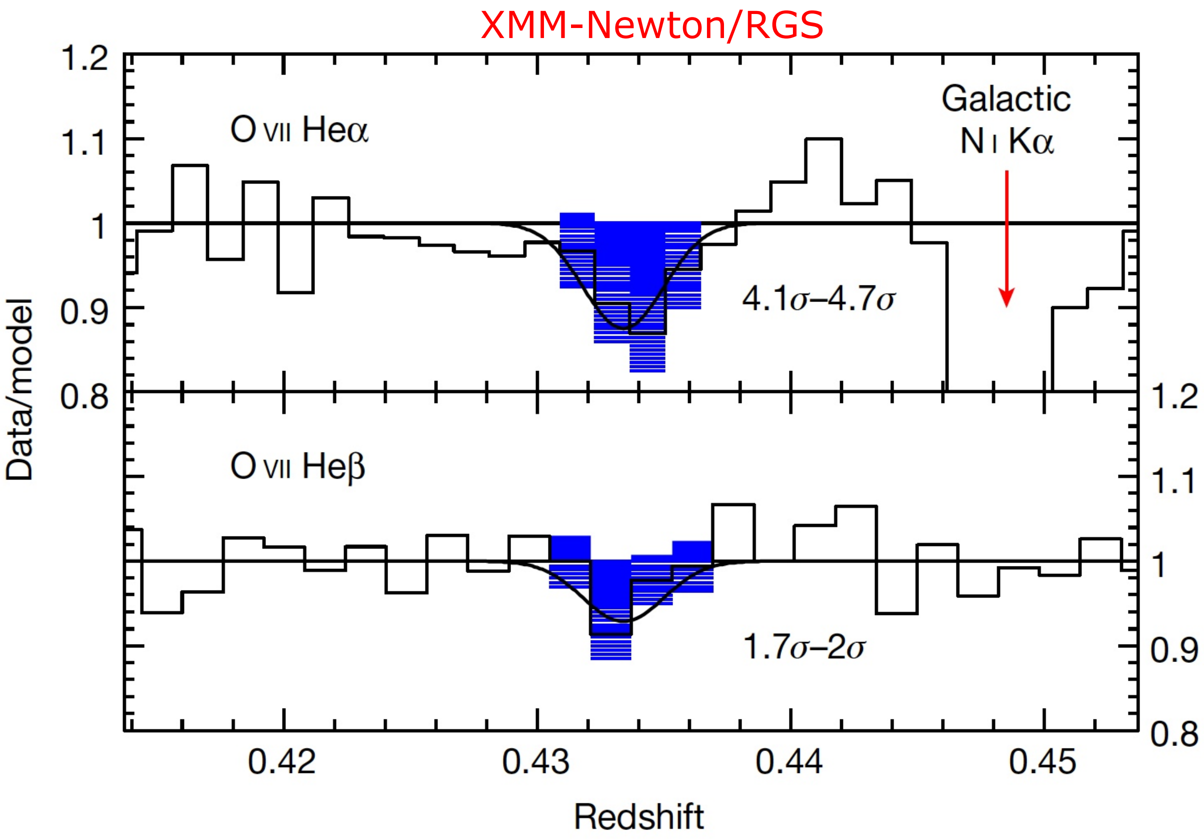


FIGURE 1 Baryon budget in the Universe, at $z = 0$. The actual percentage of baryons still missing (blue slice) could be as high as $\simeq 50\%$. The

”Warm Hot Intergalactic Medium” (WHIM)

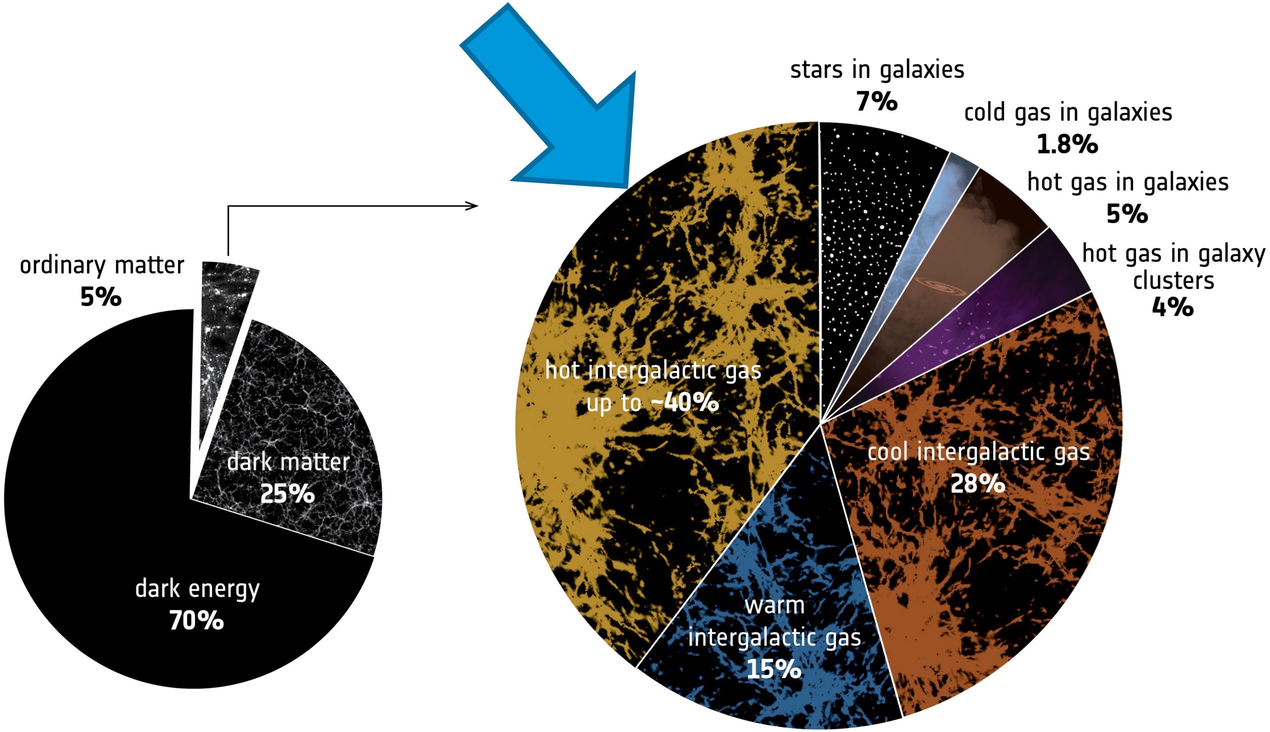
Search for absorption lines produced by the hot gas in the cosmic filaments against a bright background source





Nicastro et al., **2018**, Nature, 558, 406

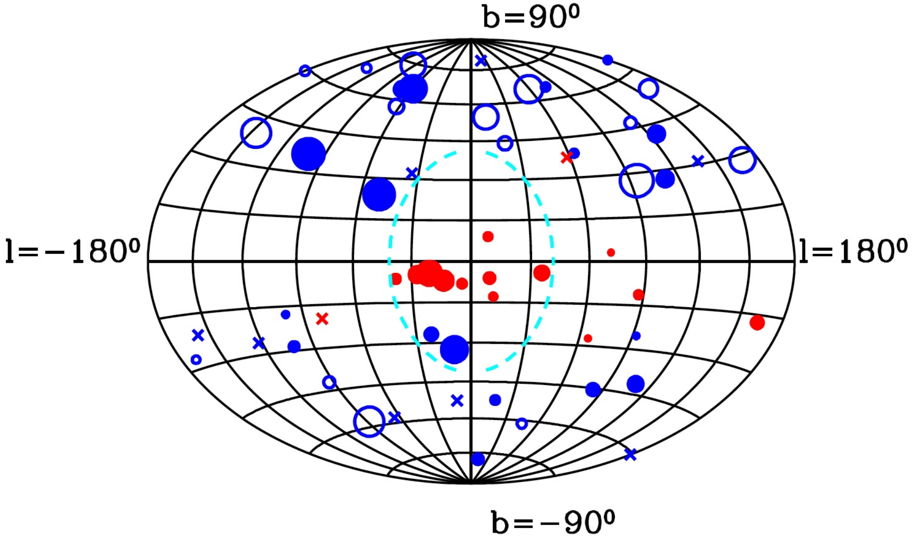
Missing baryon problem: solution



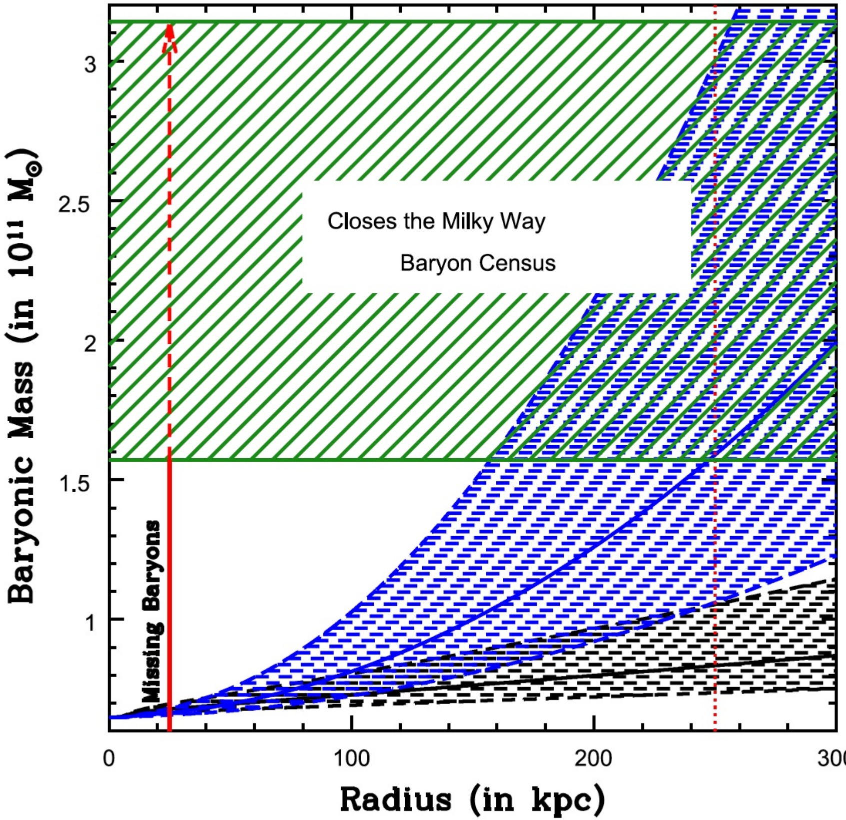
The missing baryons in the Universe have been eventually found!

Similar problem for the Galactic baryons solved!

The celestial sphere in Galactic coordinates



Points: Detection of hot gas around our Galaxy via Oxygen absorption line by XMM-Newton/RGS



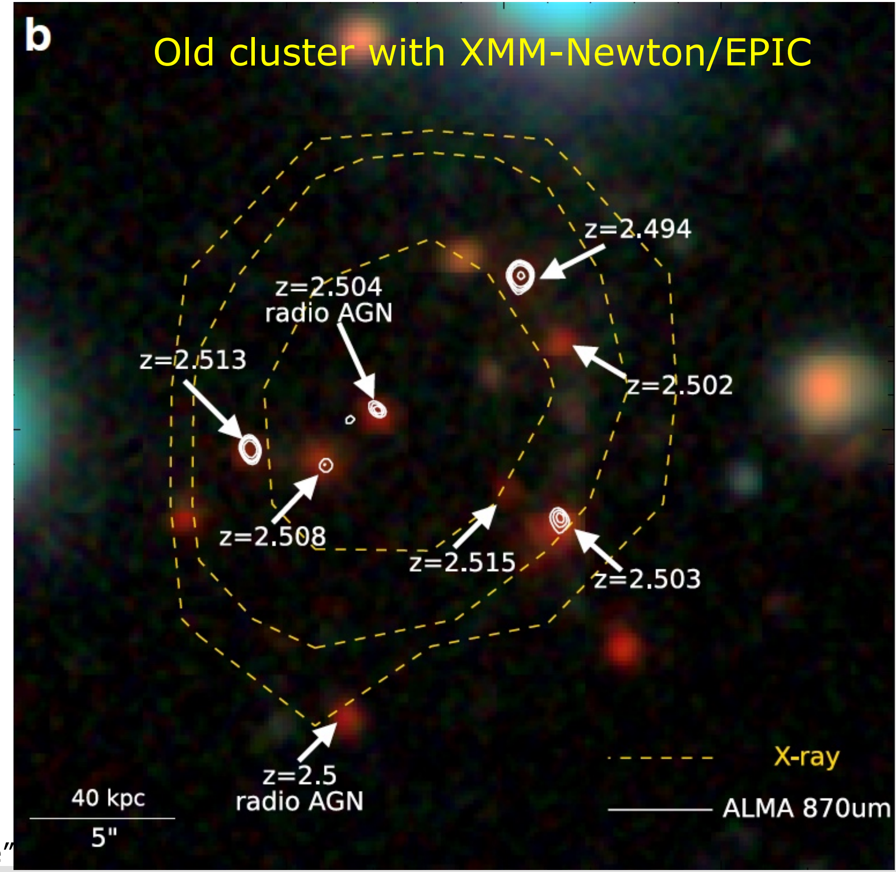
Nicastro et al., 2018, ApJ, 828, L12

Clusters up to very high-redshift

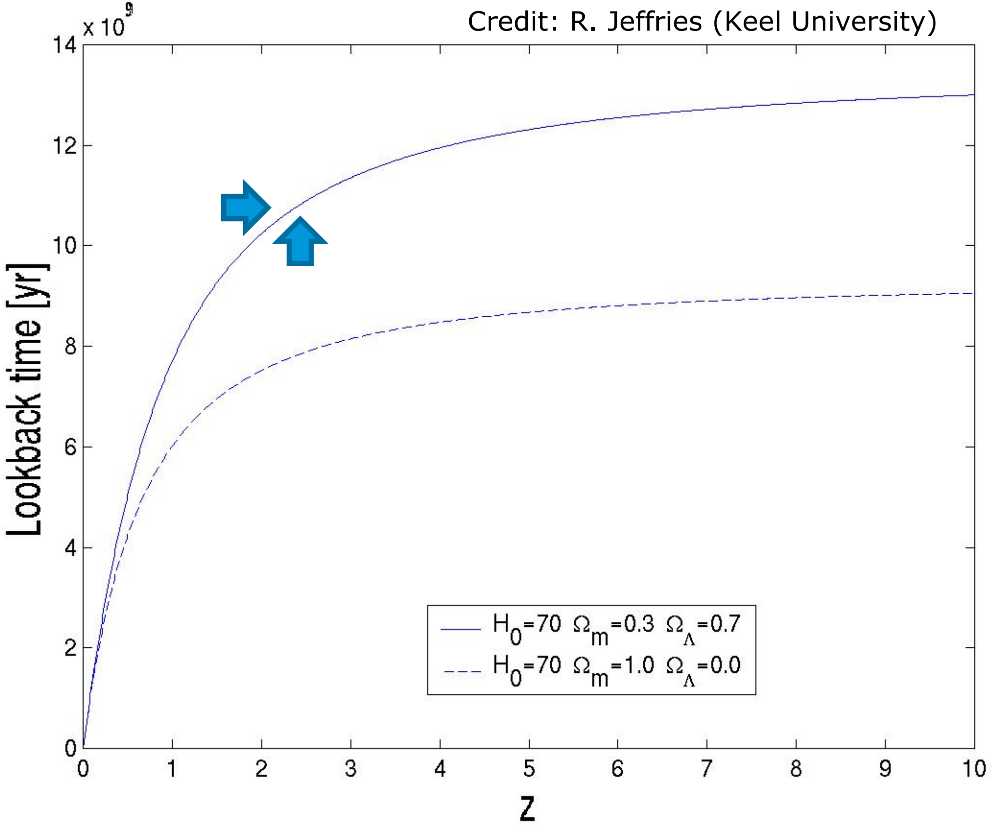
- Galaxy clusters probe "cosmology" (*i.e.* Universe history and evolution)
- The mass distribution vs. time depends on the Universe density, acceleration history etc. etc.
- We can measure the mass via X-rays
- The oldest cluster known:
  - Redshift (z) ≈2.506
  - Mass $\geq 10^{11}\ M_{sun}$
  - Produces 3400 M_{sun}/year of new stars

"Redshift" is a measure of the distance/look-back/time"

Wang et al, 2016, ApJ



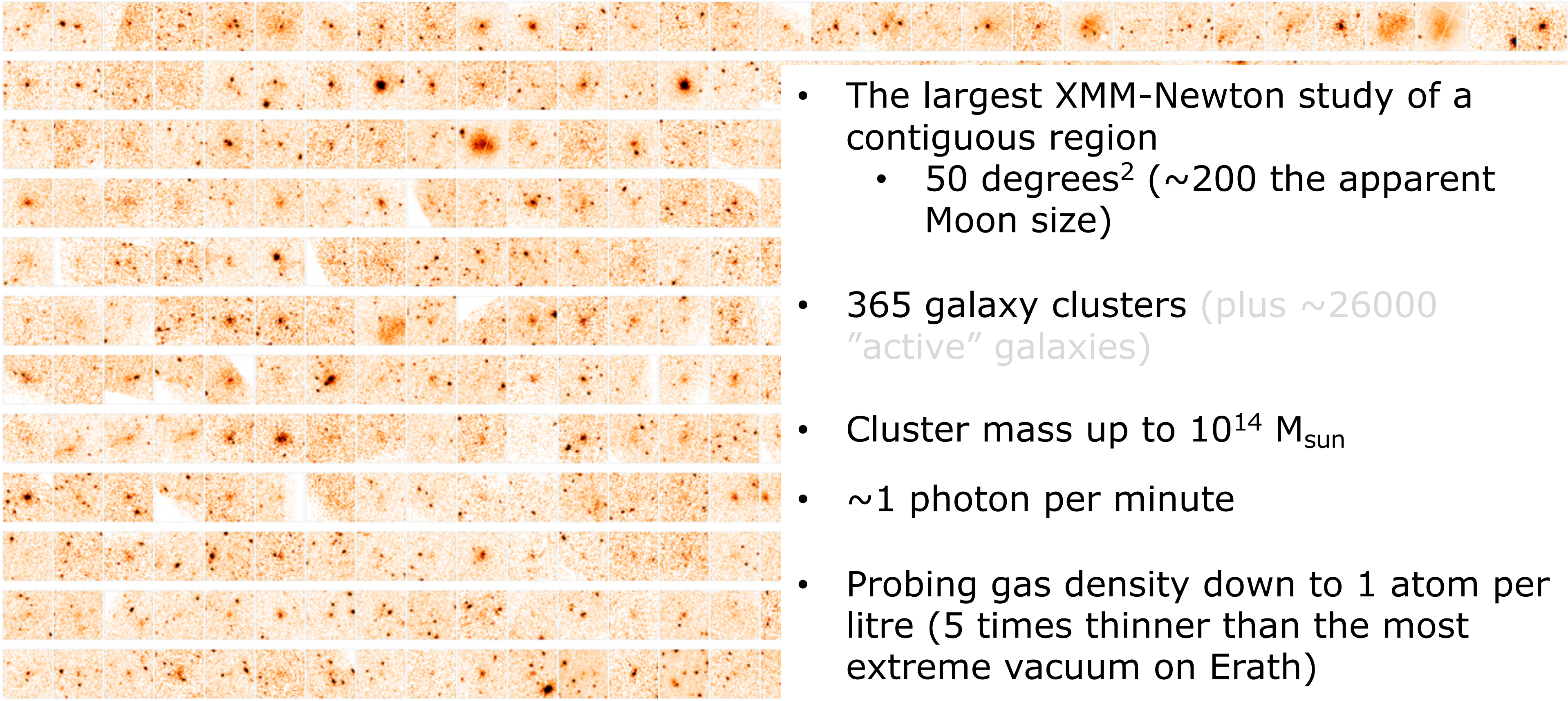
Redshift vs. distance/look-back-time



- Distant galaxies apparently move away from us
- The farther, the more their light is (apparently!) less energetic (red-shifted)
- The relation depends on models (“cosmology”)
- z=2.5 ⇒ ~20% of the age of the Universe

XXL Survey (X3)

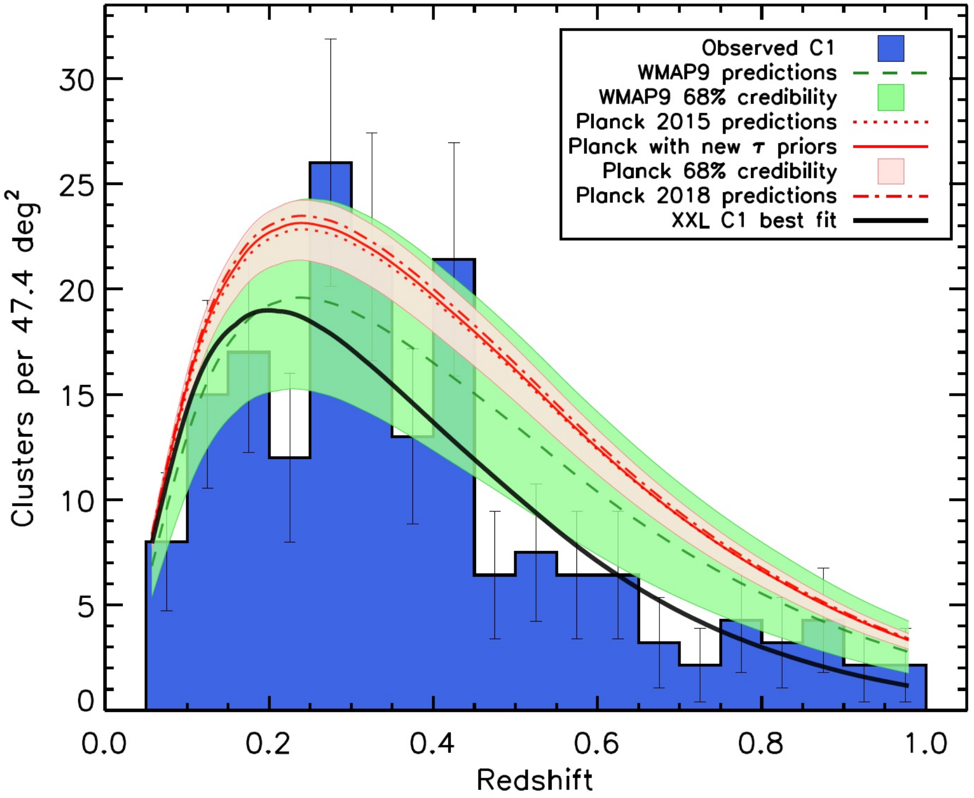
Credit: ESA/XMM-Newton/XXL Survey

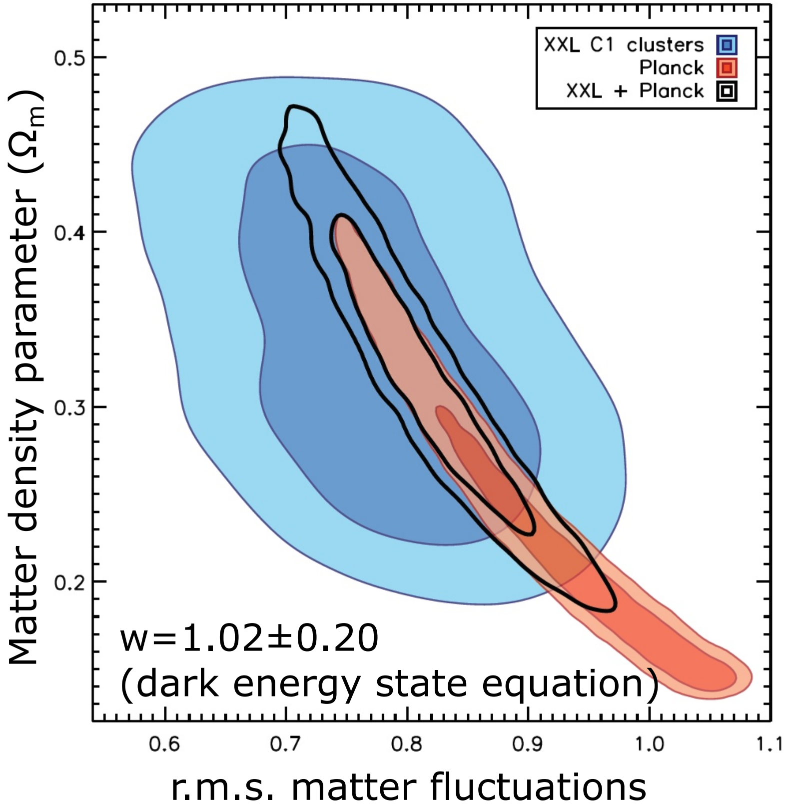


- The largest XMM-Newton study of a contiguous region
  - 50 degrees^2 (~200 the apparent Moon size)
- 365 galaxy clusters (plus ~26000 "active" galaxies)
- Cluster mass up to 10^{14} M_{sun}
- ~1 photon per minute
- Probing gas density down to 1 atom per litre (5 times thinner than the most extreme vacuum on Erath)

Cosmology with galaxy clusters

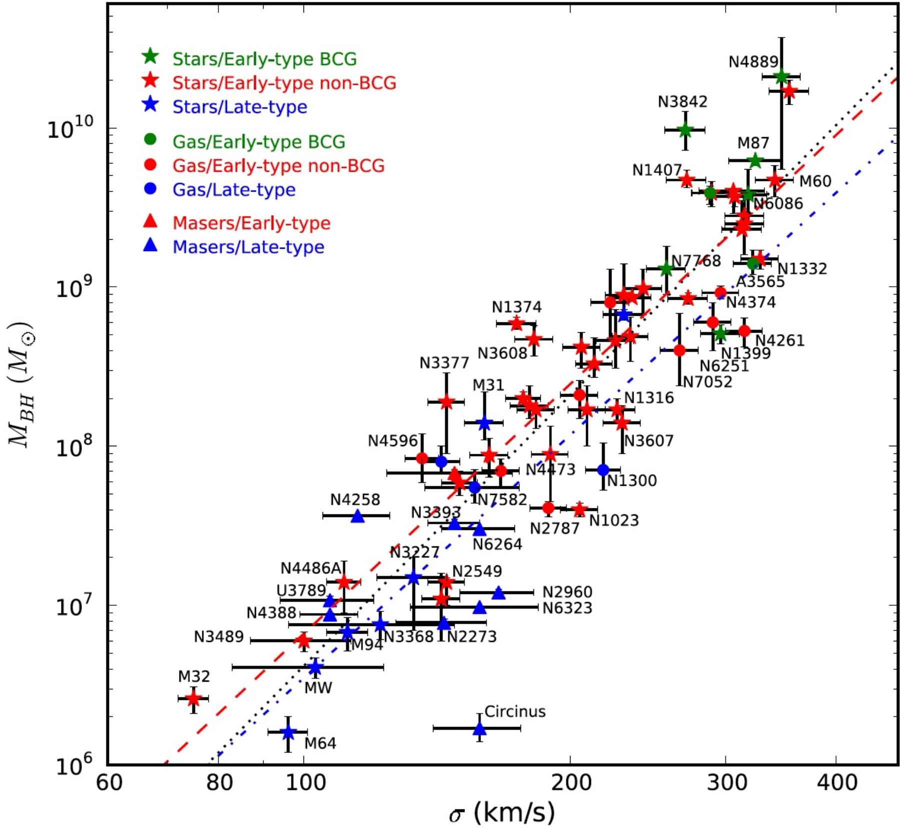
Pacaud et al., 2018, A&A, 620,10





Black hole mass vs. galaxy bulge

Mcconnell & Ma, 2013, ApJ, 764, 184



- Most galaxies host a very massive black hole in their core
- The black hole mass and the mass of the galaxy bulge are correlated
- No direct gravitational effect
- Hypothesis: the black hole regulates the star formation in the host galaxy (“feedback”)
- However, “black holes” are black …

Stars orbiting a dark spot in the centre of our Galaxy

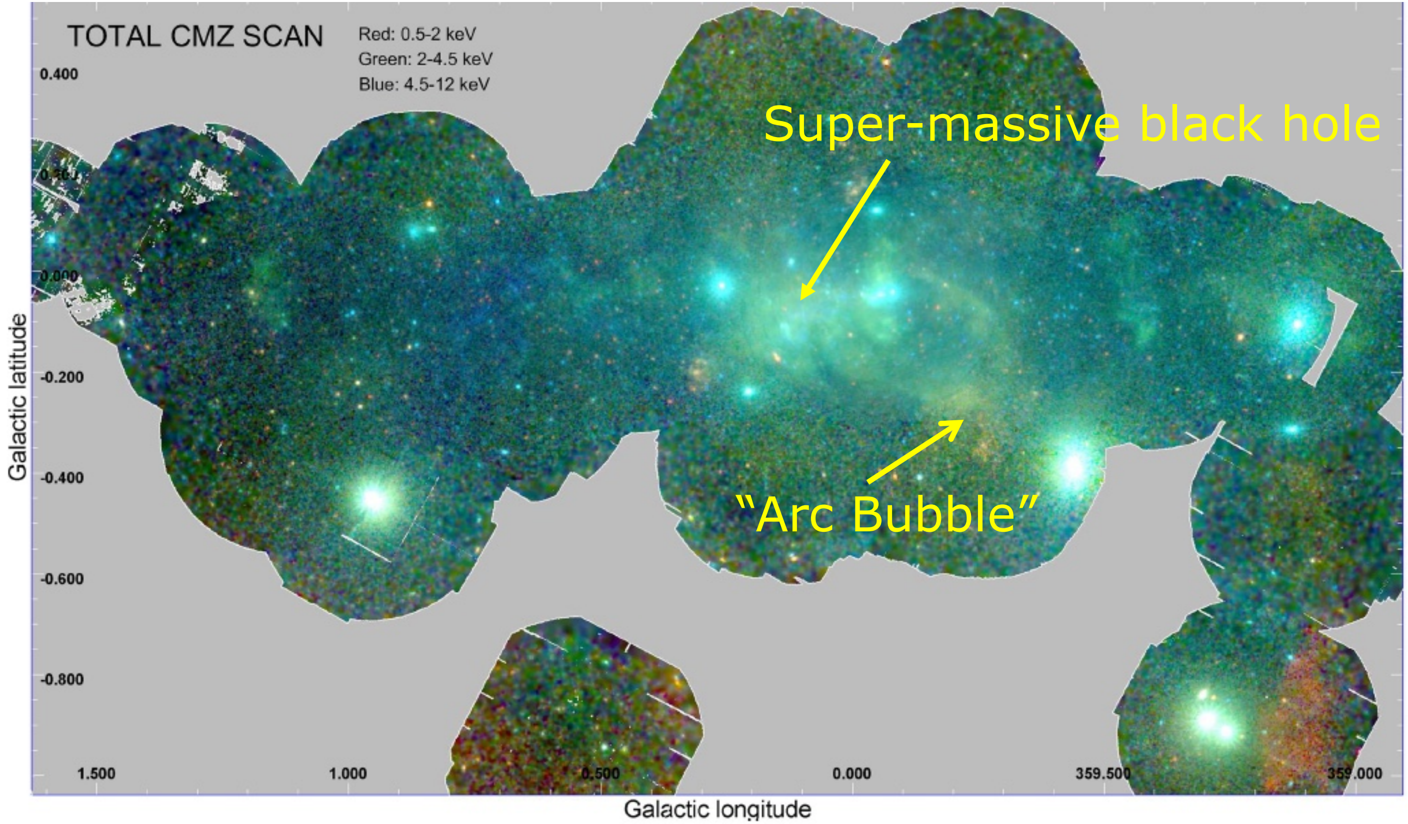
Super-massive black hole, ~4×10^6 M_{Sun}

Credit: ESO/NACO-VLT

SgrA*: the centre of our own Galaxy

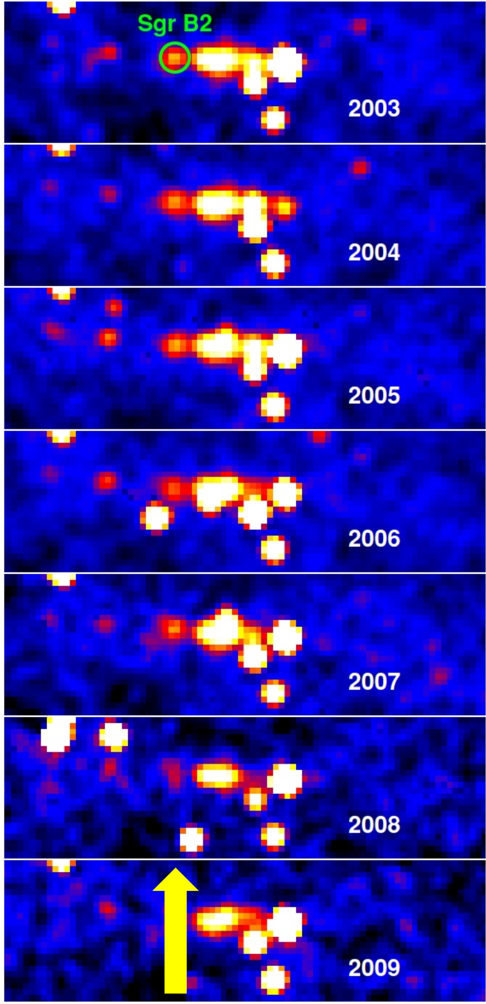
- XMM-Newton/EPIC image of the centre of our galaxy
- Lost of bright and powerful sources but …
- … no current trace of the black hole!

Ponti et al., 2015, MNRAS, 453, 152



Prior phases of Milky Way activity – Sgr B2

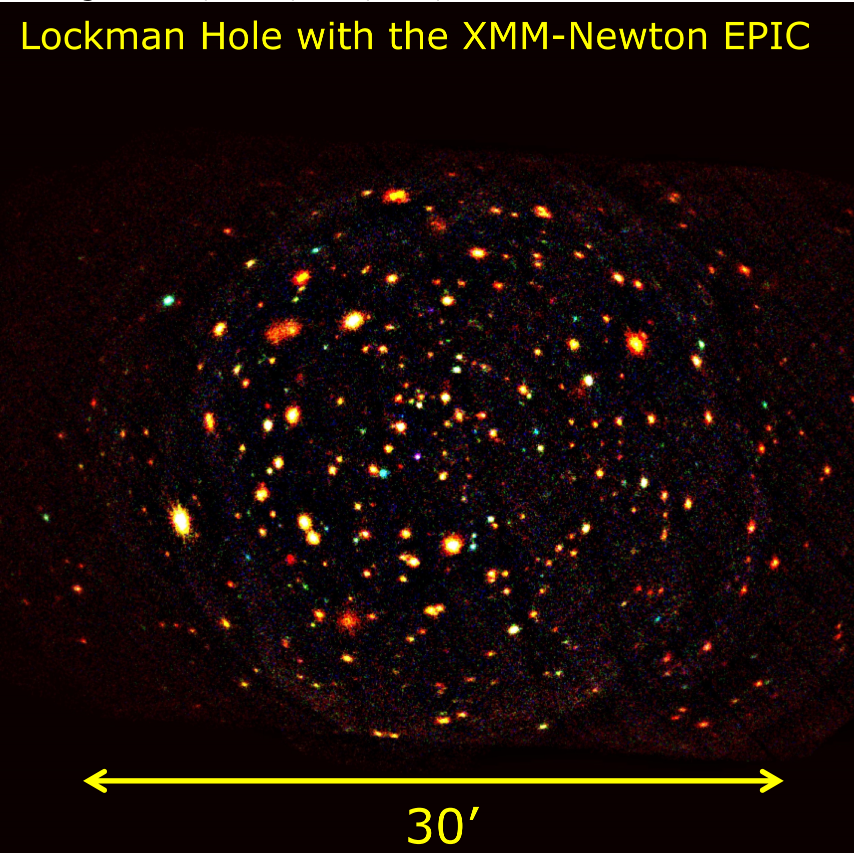
- GC image by INTEGRAL IBIS/ISGRI (20-40 keV)
    - More difficult to get sharp images above 10 keV (but we have started now)
- Brightening and fading of a hard X-ray source (follow the yellow arrow)
- Echo of a phase of past activity of the black hole in the Milky Way
- ~100000 times brighter than now, ~100 years ago



Terrier et al., 2010, ApJ, 719, 413

Lockman Hole: a typical AGN "deep field"

Hasinger et al., 2001, A&A, 365, 45



- Deep image with XMM-Newton imaging instrument
- ≥100 sources in a patch as big as the size of the Moon on the sky vault
- In ~20 years of operations, XMM-Newton has discovered almost half million of unknown sources like these
- Most of them are galaxies with a black hole at the centre
  - Active Galactic Nuclei

Active Galactic Nuclei (AGN)

- Galaxies hosting a supermassive black hole at their centre
- ~10% of total galaxies
- Matter acquires relativistic velocities and million K temperatures ⇒ X-rays
- Most common constituent of the X-ray sky

AGN: accretion and ejection

Credit: ESA/ATG Medialab

AGN “feedback”

Where the wind is located

Gas covering

Gas radial velocity

$$\dot{M}_{\rm out} = 4\pi r N_{\rm H} \underbrace{\mu m_p}_{\text{Average particle mass}} C_g v_r$$

pi

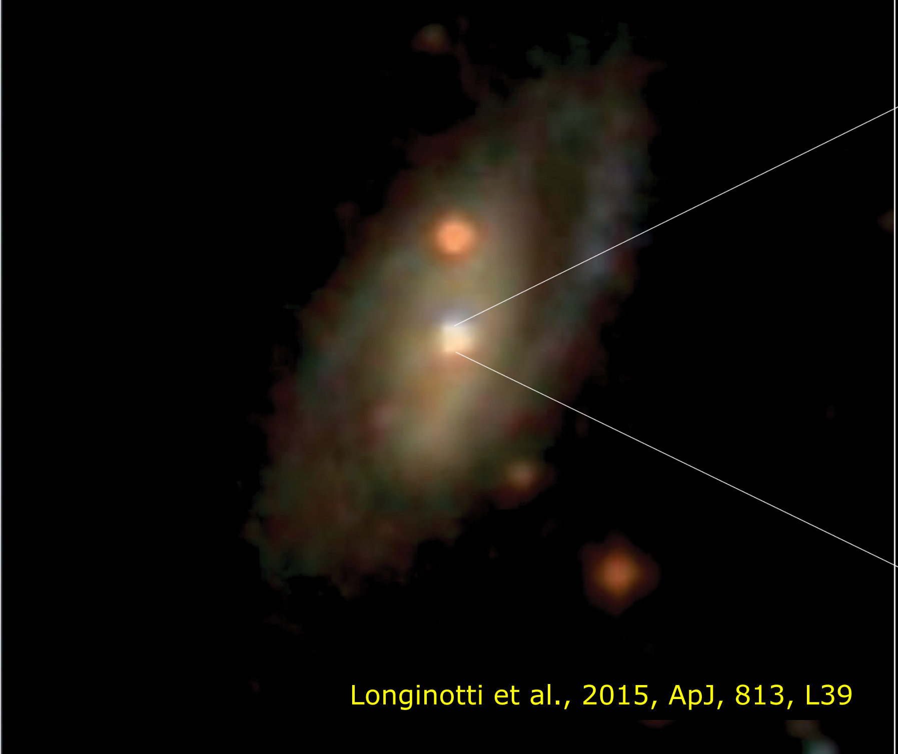
Mass outflow rate

Gas density along the line-of-sight

Once the mass rate is know, the kinetic energy rate is: $\dot{E}_{\rm K} = L_{\rm KE} = \frac{1}{2}\dot{M}_{\rm out}\, v_{\rm out}^2$

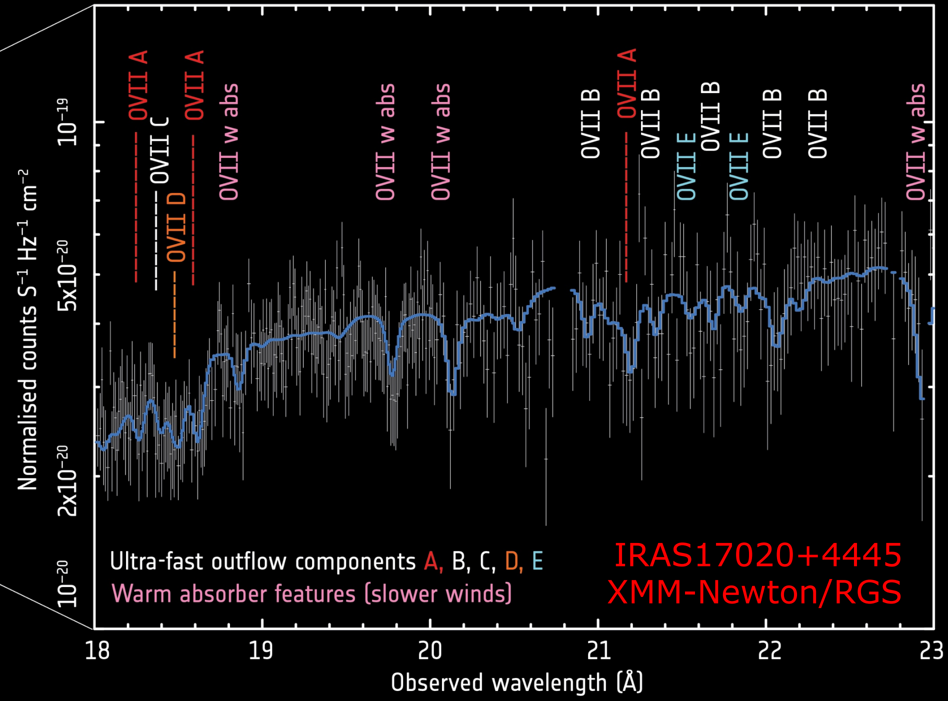
AGN feedback in a "twin" of the Milky Way

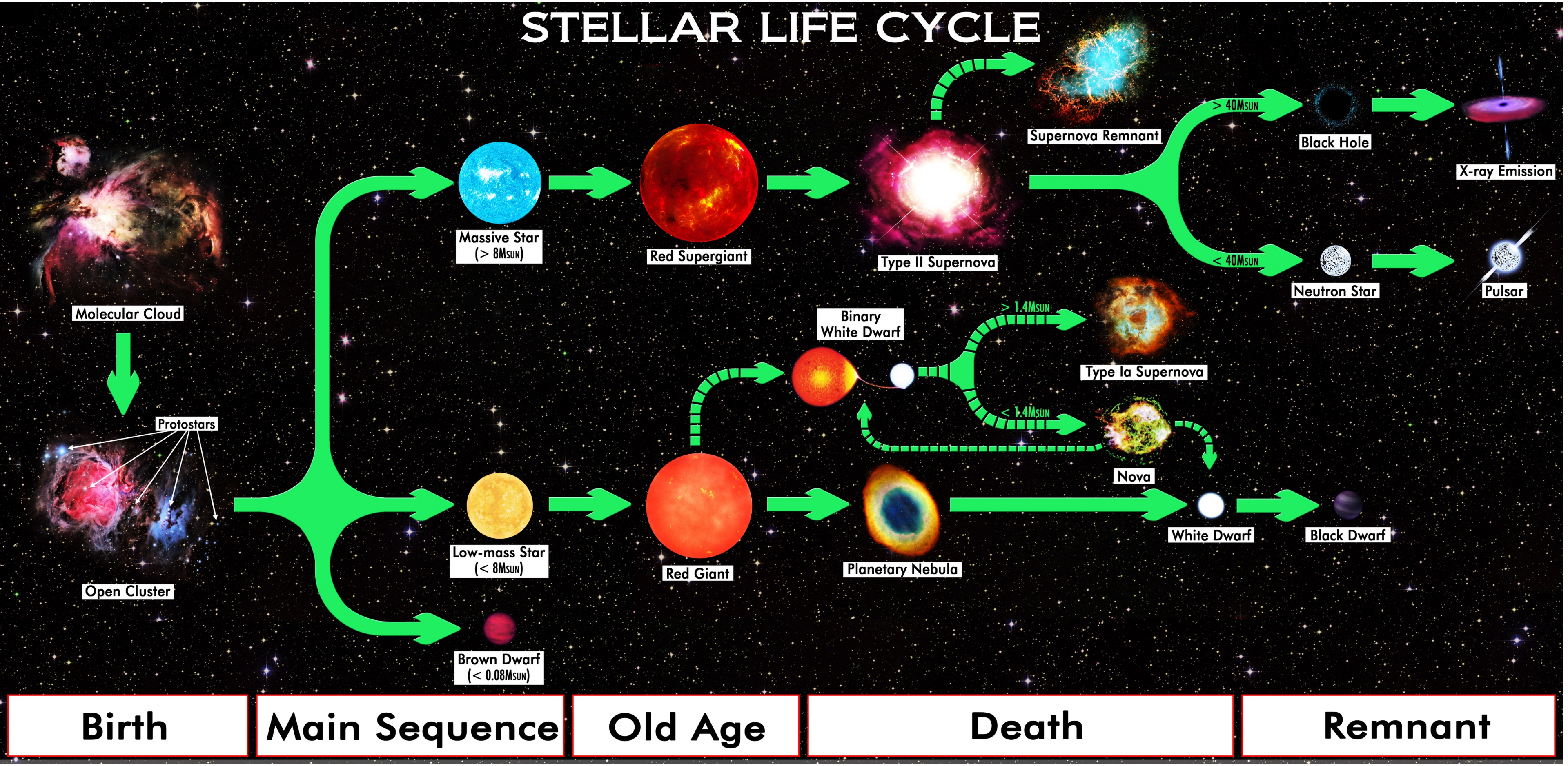
This galaxy is very similar to the Milky Way
But hosts a super-massive *active* black hole



Longinotti et al., 2015, ApJ, 813, L39

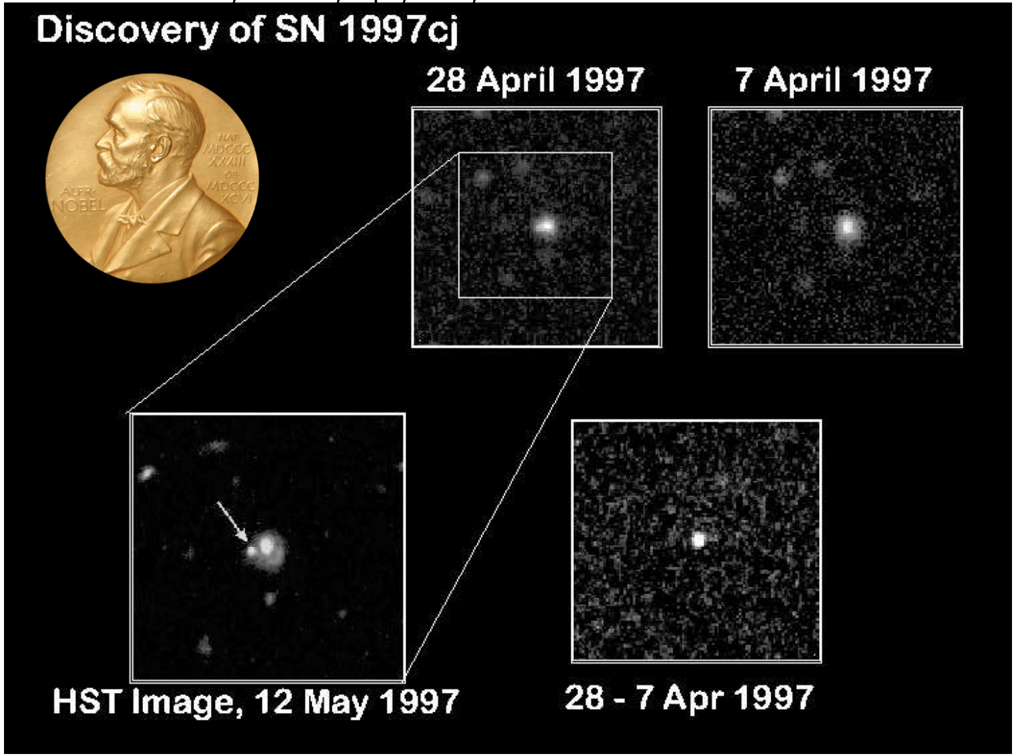
The BH spits out ~25% of the Sun mass in hot gas with a velocity ~10% of the speed of light

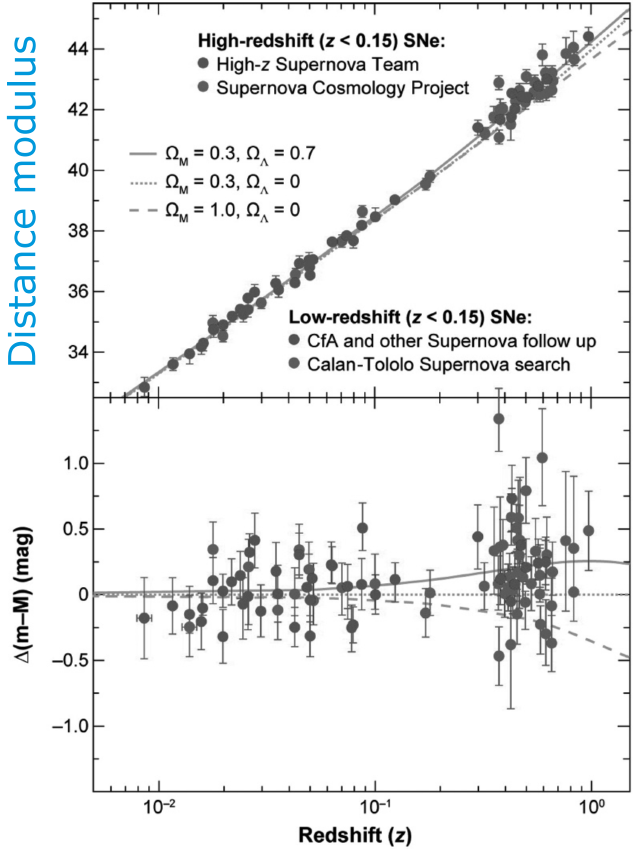



STELLAR LIFE CYCLE
Molecular Cloud
Protostars
Open Cluster
Massive Star
(> $8M_{SUN}$)
Low-mass Star
(< $8M_{SUN}$)
Brown Dwarf
(< $0.08M_{SUN}$)
Red Supergiant
Red Giant
Type II Supernova
Supernova Remnant
> $40M_{SUN}$
< $40M_{SUN}$
Black Hole
X-ray Emission
Neutron Star
Pulsar
Binary
White Dwarf
> $1.4M_{SUN}$
< $1.4M_{SUN}$
Type Ia Supernova
Nova
Planetary Nebula
White Dwarf
Black Dwarf
Birth
Main Sequence
Old Age
Death
Remnant

Cosmology with SuperNovae (SNe) Ia

Perlmutter et al., 19998, ApJ, 517, 565

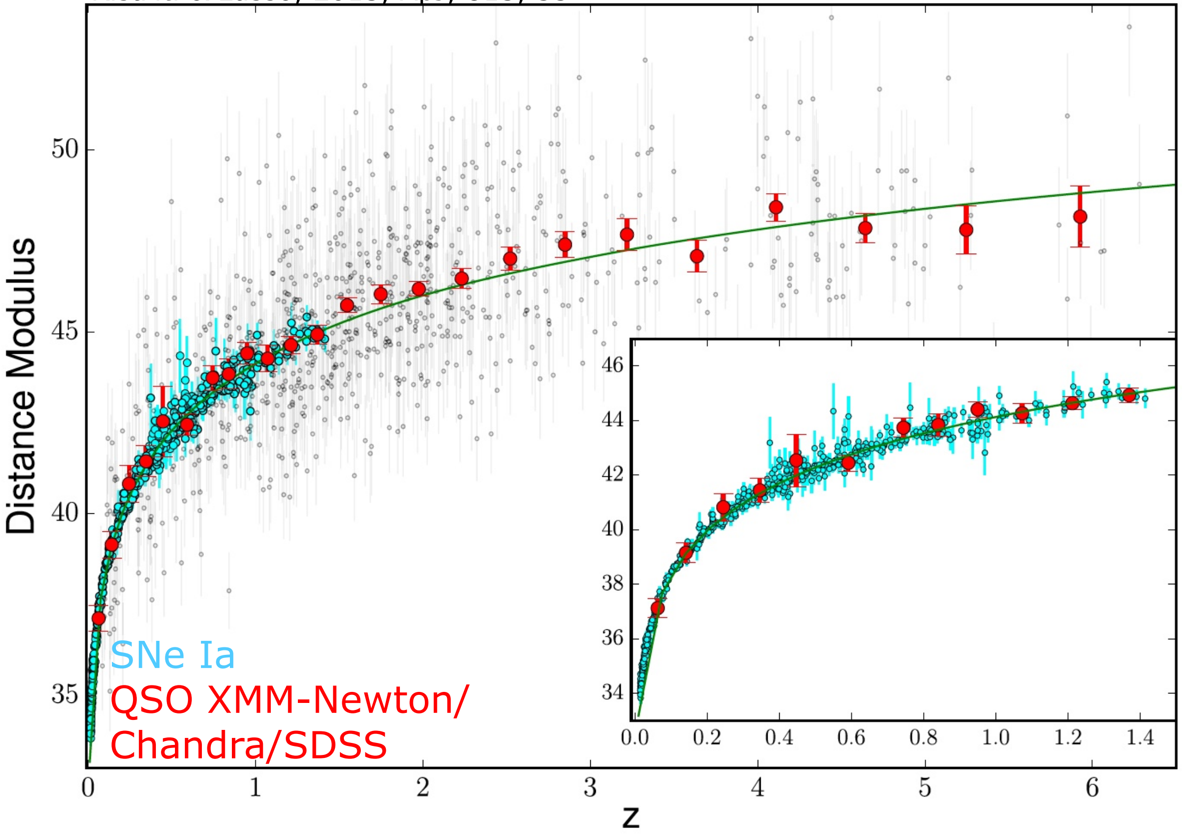




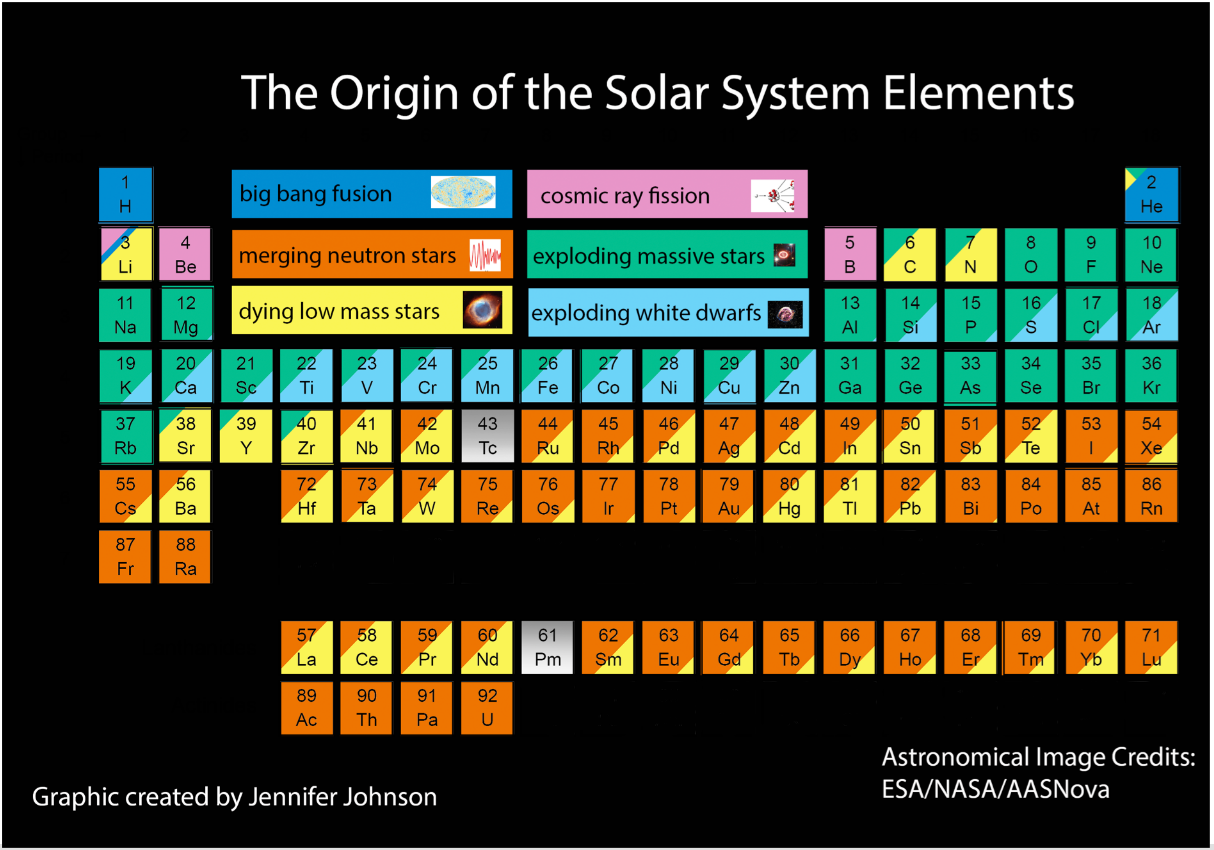
Cosmology with AGN

- Cosmology with SNe is limited to z≤1.5
- The ratio of UV to X-ray luminosity in AGN is correlated with the UV luminosity
- Hence, quasars (strong AGN) can be used as “standard candles”
- Extension to z~6 possible

Risaliti & Lusso, 2015, ApJ, 815, 33



Supernovae as cosmic factories



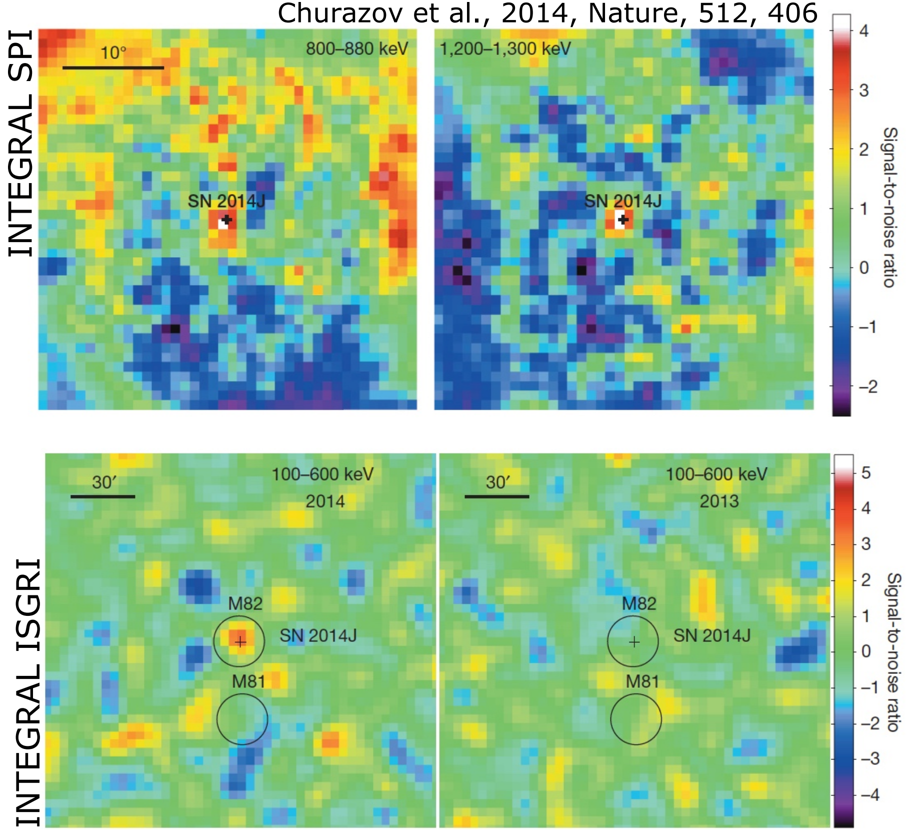
- SNe Ia are created by the explosion of White Dwarfs
- They produce elements from Si (Z=14) to Zn (Z=30)
- Some of these elements create lines in γ-rays

[White Dwarf = Hot core of the star after the exhaustion of the nuclear fuel]

Supernovae as factories of elements

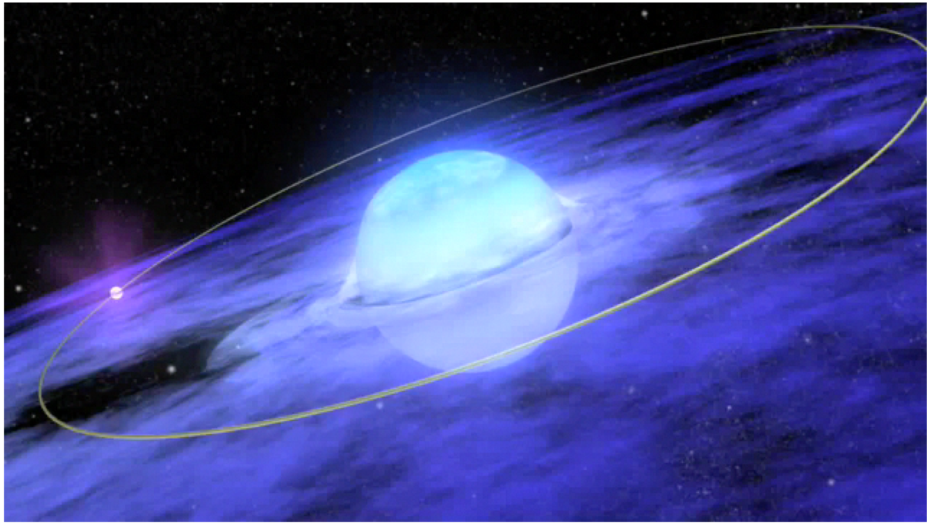
- A new supernova exploded in a nearby galaxy (M82) in 2014: SN2014J
- A new source appeared at the energy of two ^{56}Co lines, and γ-ray continuum
- Products of the β-decay of ^{56}Ni
- In the explosion, 0.6±0.1 solar masses of ^{56}Ni were generated

Churazov et al., 2014, Nature, 512, 406

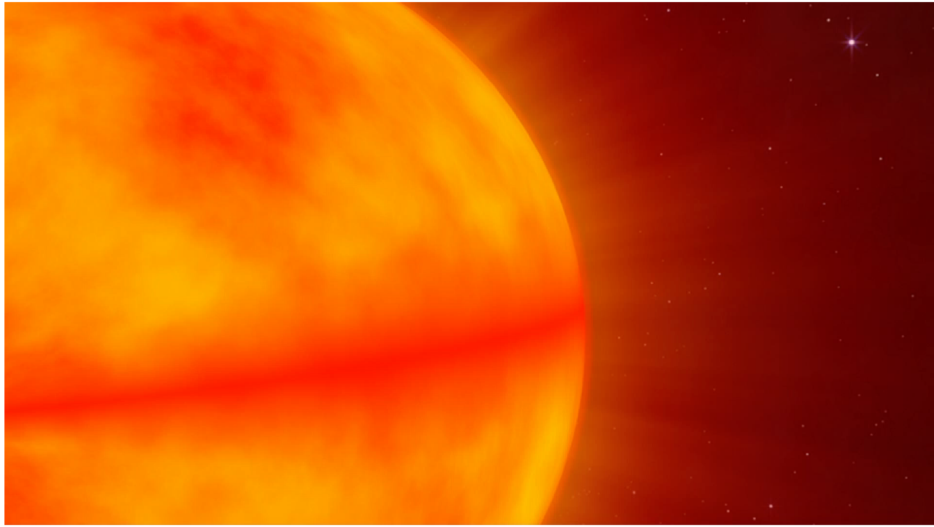


X-ray binaries

Hot star + neutron star (wind-fed)



Sun-like star + black hole (disk-fed)

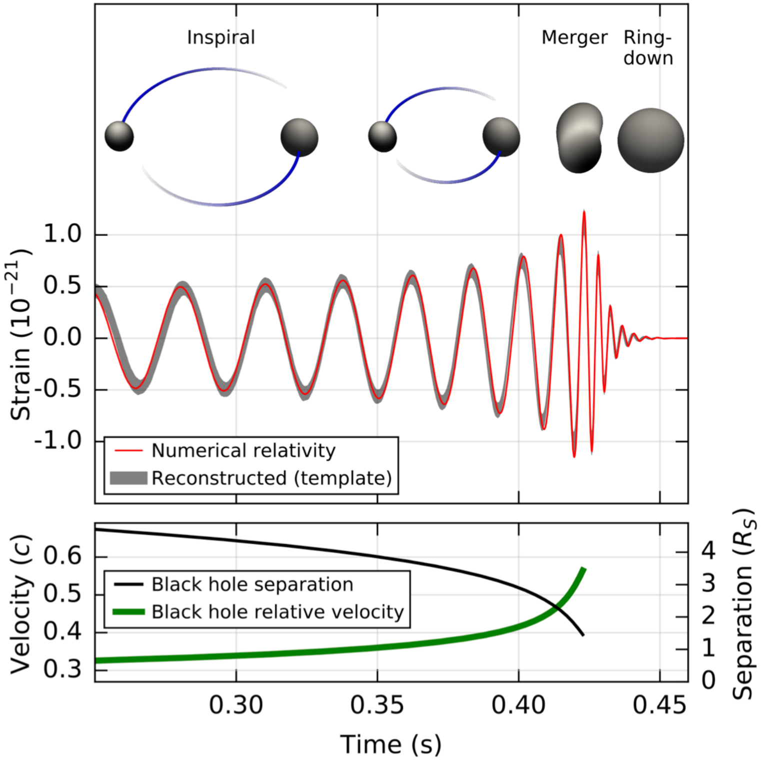


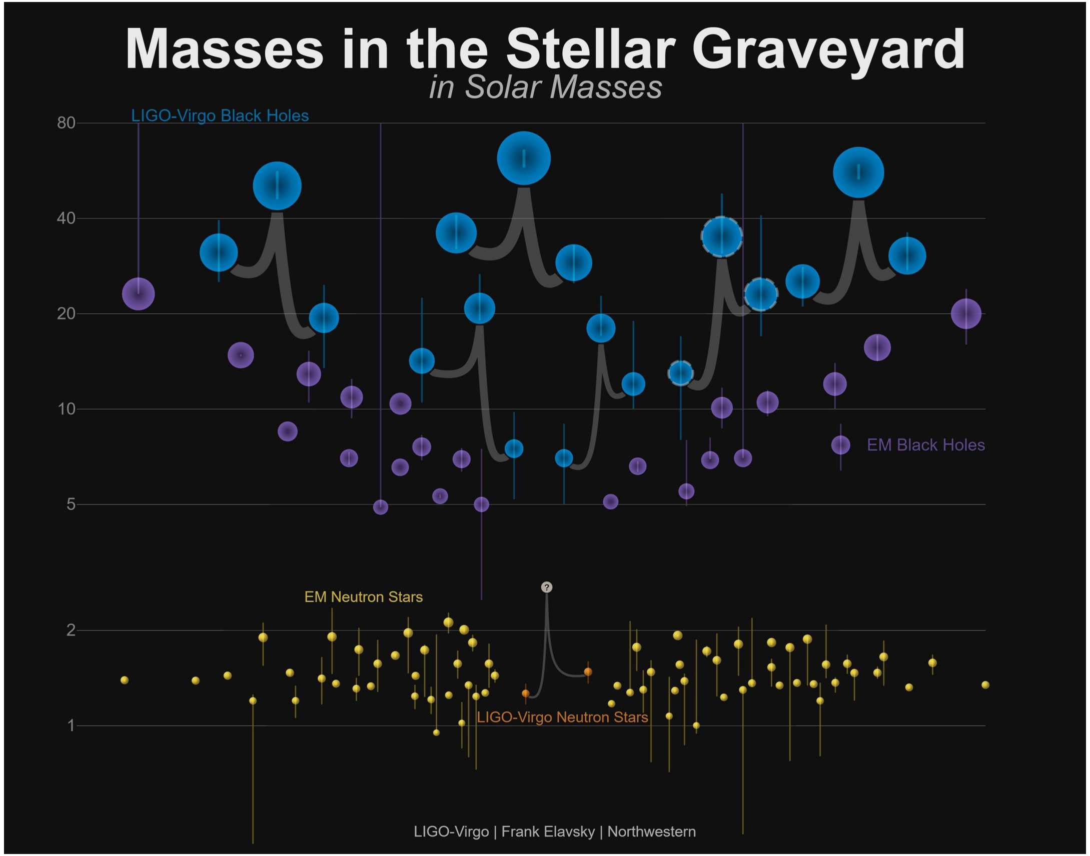
Credit: NASA Goddard

Both systems emit copiously X- and γ-rays

Gravitational waves from BH-BH merger

Abbott et al., 2015, Ph.Rev.Lett., 116, 061102



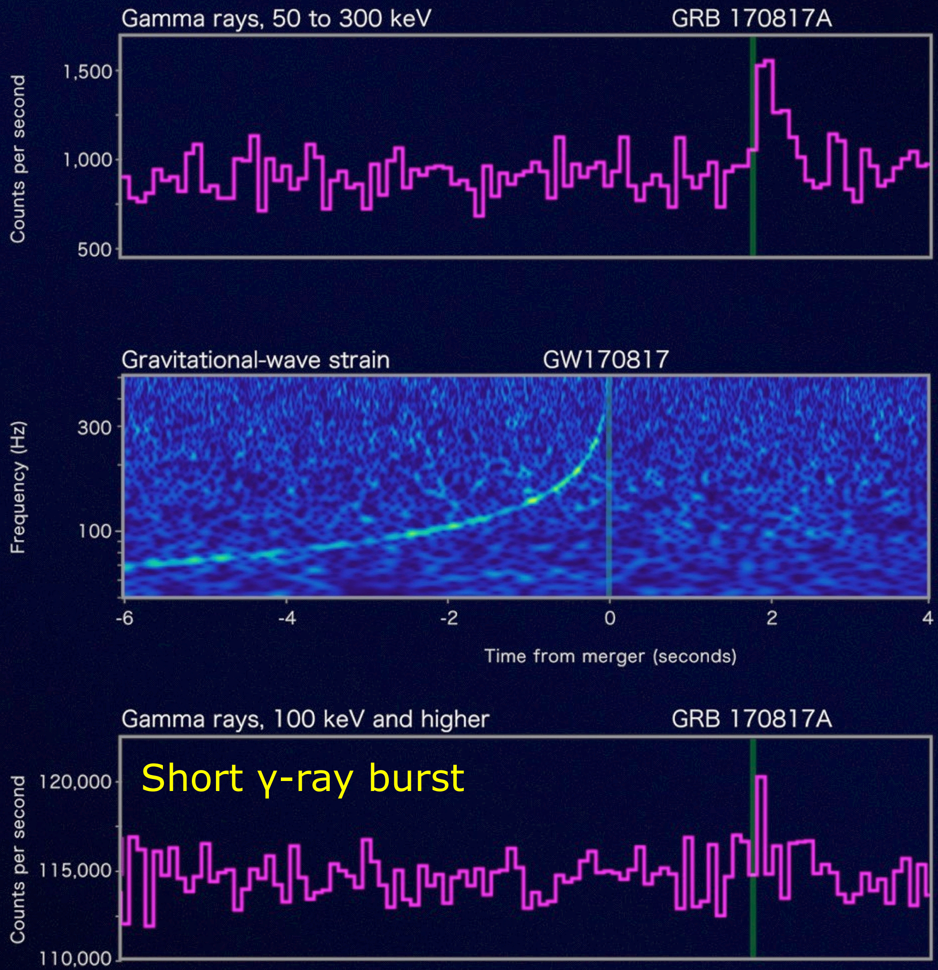


Credit: NASA's Goddard Space Flight Center, Caltech/MIT/LIGO Lab and ESA

Fermi

LIGO-Virgo

INTEGRAL



Electromagnetic X-ray counterparts

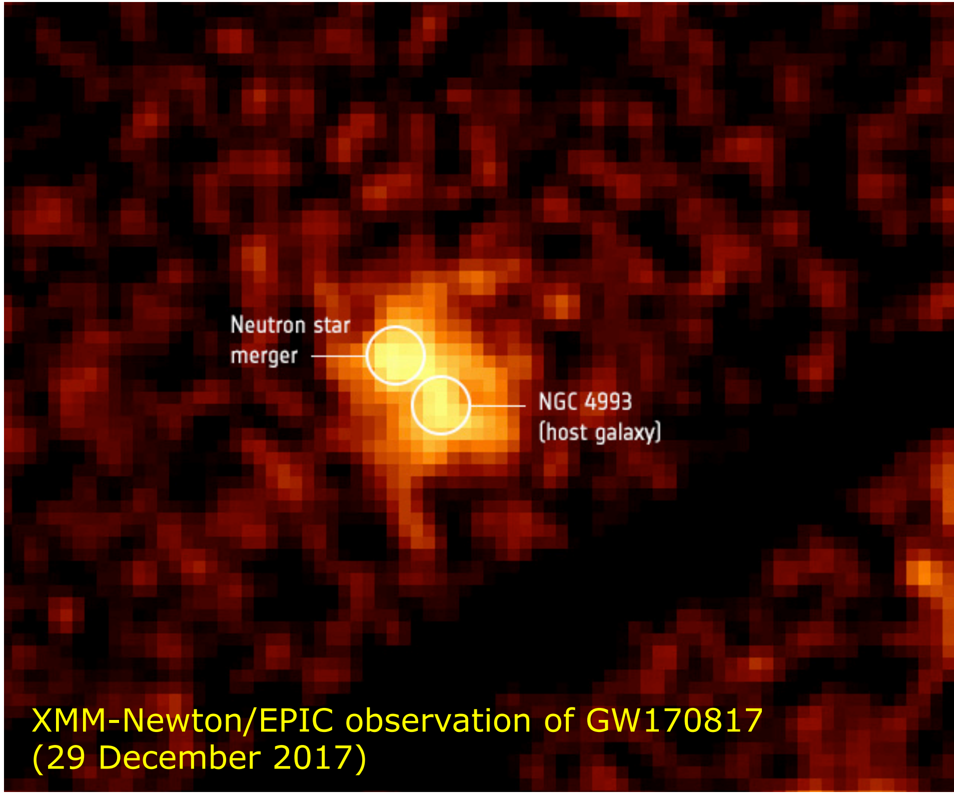
- Discovery of the electromagnetic counterpart marks the beginning of the "multi-messenger astrophysics"

- Neutron star merger is the progenitor of short γ-ray bursts

- Later (~2 weeks) X-ray afterglow

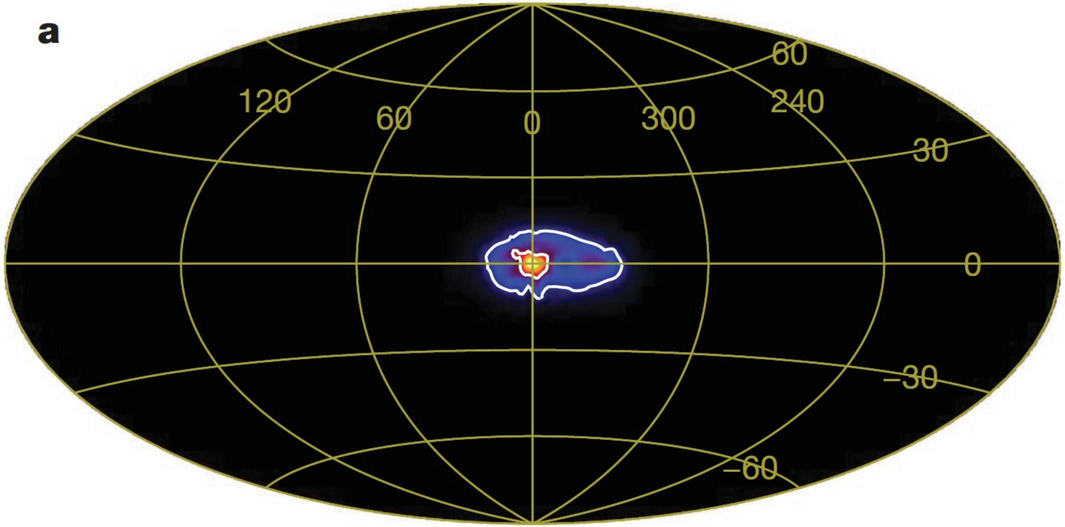
- Off-axis jet interacting with the post-merger winds and ejecta

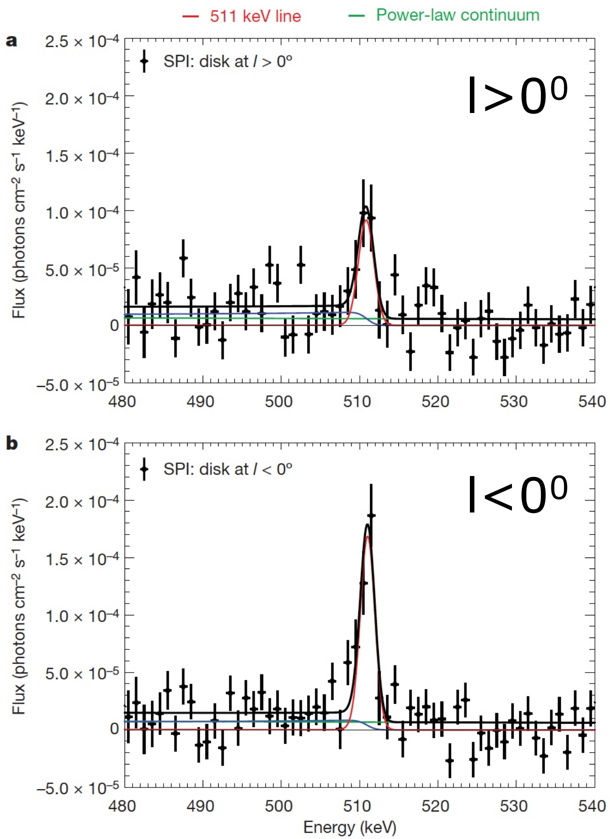
D'Avanzo et al., 2018, A&A, 613, L1



e+-e- annihilation in X-ray binaries

INTEGRAL/SPI image of the 511 keV line in Galactic coordinates: electron-positron annihilation

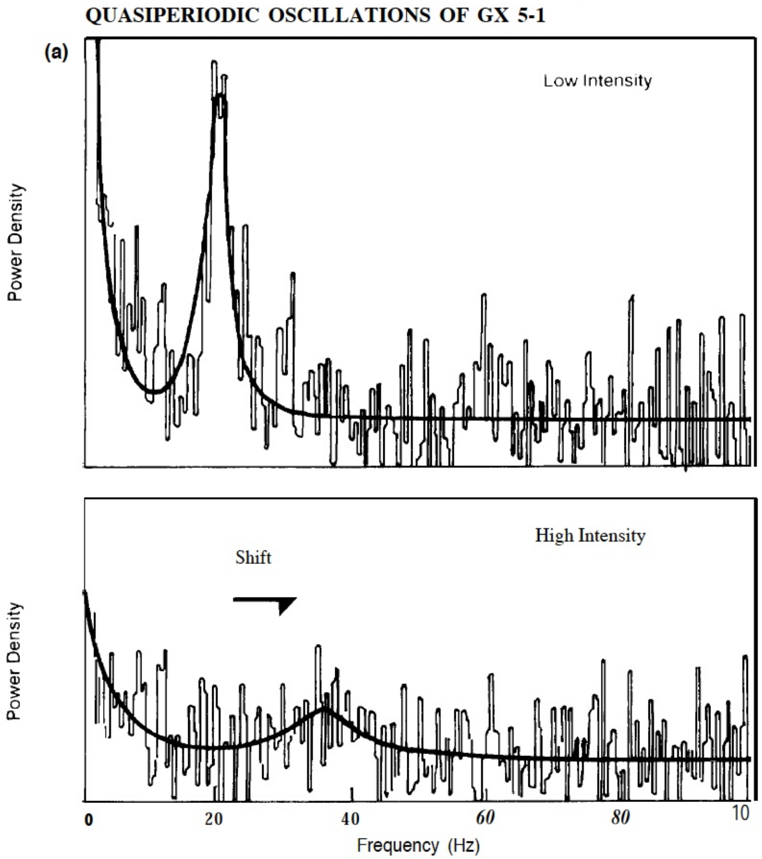




Weidenspointner et al., 2008, Nature, 451, 159

Similar to the distribution of Low Mass X-ray Binaries

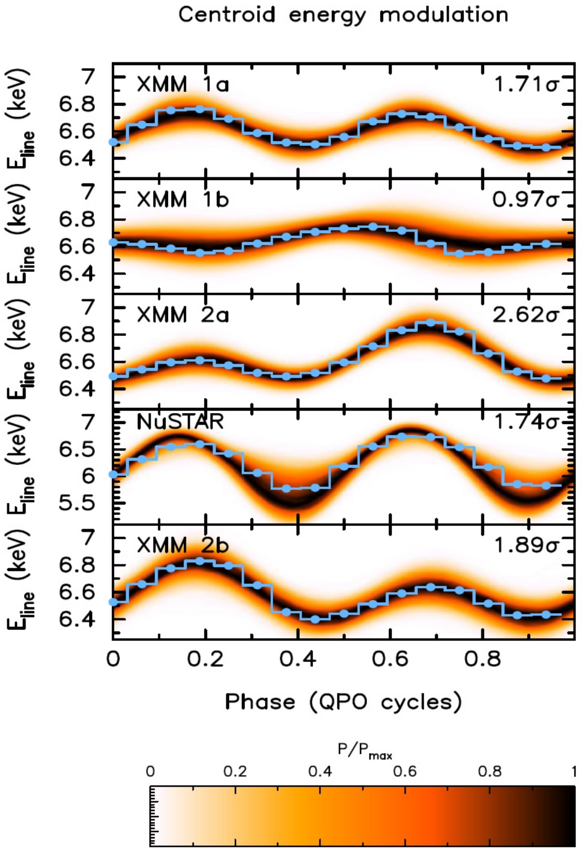
Quasi Period Oscillations in binaries



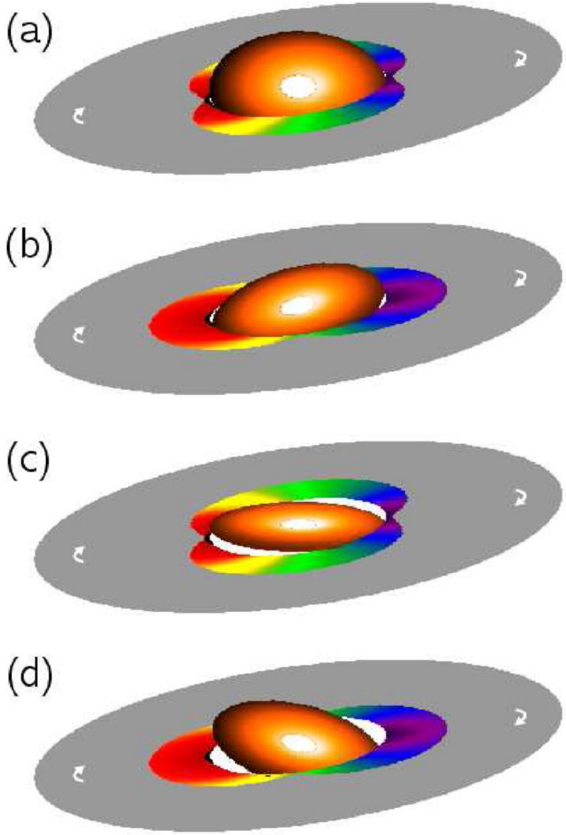
- One the main discoveries by EXOSAT
- Quasi-periodic features in the Fourier spectrum of X-ray bright sources in the bulge of our Galaxy
- At the time of my Ph.D., we thought we understood them …
- … but just a few years ago there were no less of 12 theories fitting the data equally well

van der Klis et al., 1985, Nature, 316, 225

Testing predictions of General Relativity with XRB



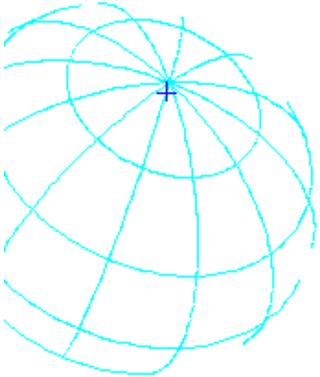
- The X-ray spectrum of H1743-322 is modulated at the QPO frequency
- Precession of the innermost part of the disk close to a black hole
- Matter flows through a space-time dragged by the black hole potential
- "Lense-Thirring effect": prediction of Einstein's relativity!



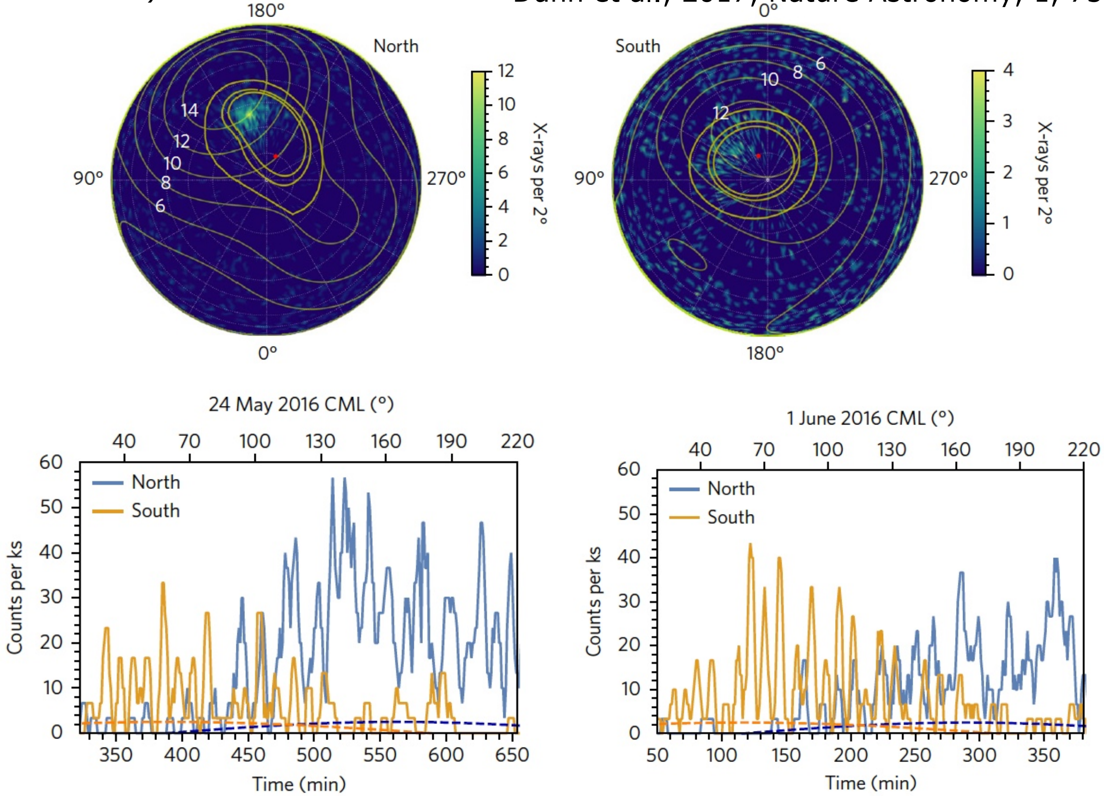
Ingram et al., 2016, MNRAS, 461, 1967

Earth and Jupiter auroras

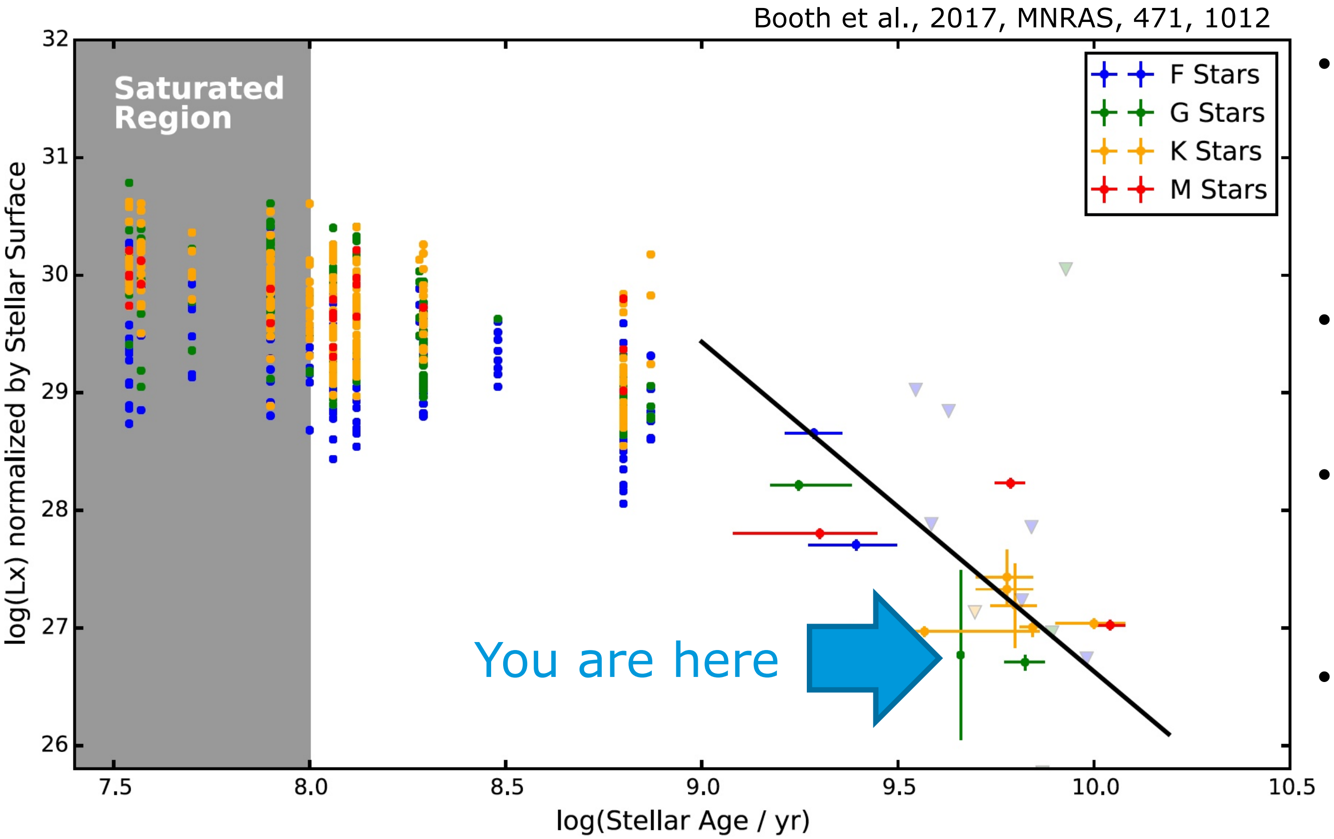
ESA/Integral/E.Churazov (IKI/MPA)/M.Türler (ISDC/Univ. of Geneva)



Dunn et al., 2017, Nature Astronomy, 1, 758



Habitability of Earth-like planets

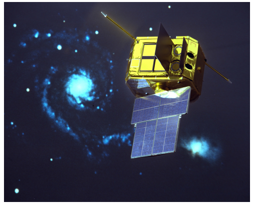


- Faster-than-expected decay of the X-ray activity in Sun-like stars
- X-rays from *Chandra* and XMM-Newton
- Star ages determined from pulsation (COROT/Kepler)
- Potential good news for habitability of planets around such stars

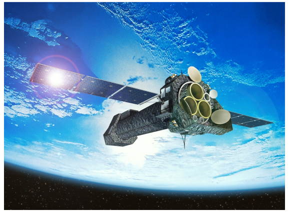
ESA high-energy observatories

http://sci.esa.int/athena/60759-history-of-x-ray-astronomy-in-europe-from-exosat-to-athena/

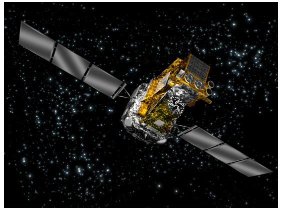
EXOSAT (1983-1986)



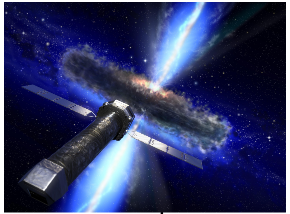
XMM-Newton (1999-)



INTEGRAL (2002-)



Athena (~2030s-)



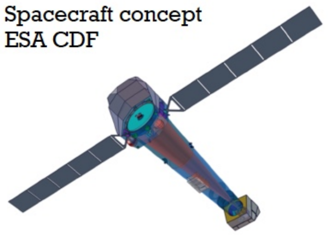
Accurate timing
Moderate resolution spectroscopy

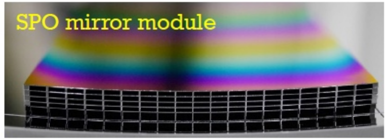
γ-ray imaging and spectroscopy
Complementary X-ray and optical monitors

Spectro-imaging capabilities at CCD resolution
High-resolution spectroscopy in the soft X-ray band
Complementary optical photometry

Big, powerful, sharp!

Athena: mission profile

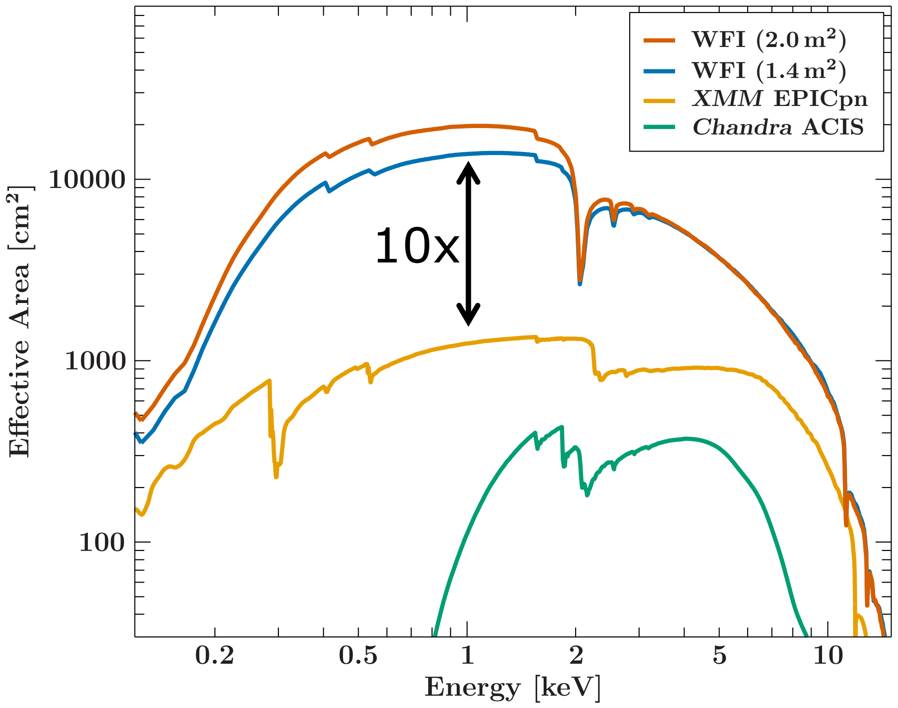




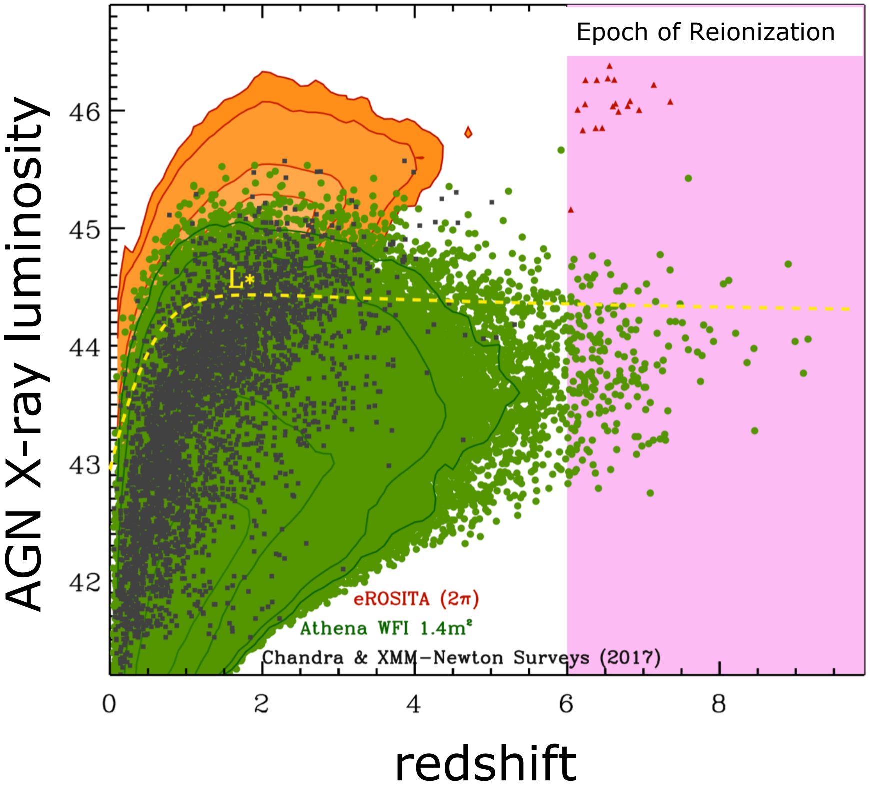
- Single telescope, Silicon Pore Optics (**SPO**) technology, 12 m focal length, 5″ HEW (req.), ≥1.4 m^2 area@1 keV, 0.25 m^2 @6 keV
- **WFI** (Active Pixel Sensor Si detector): wide-field (40′x40′) spectral-imaging, CCD-like energy resolution (120-150 eV @6 keV)
- **X-IFU** (cryogenic imaging spectrometer): 2.5 eV energy resolution, 5′ effective diameter field-of-view, ~5″ pixel size
- Count rates capabilities: >1 Crab (WFI)/~1 Crab (30% throughput) X-IFU (increased thanks to defocusing capabilities)
- ≥4 hours response with a ~50% efficiency to observe a ToO in a random position in the sky
- Launch early 2030, Ariane 6.4, L2 halo orbit (TBC)
- Nominal life-time 4 years + extensions
- **Observatory**! ~2/3rd of the observing time open via proposals

Athena survey performance

Credit: A.Rau (MPE)

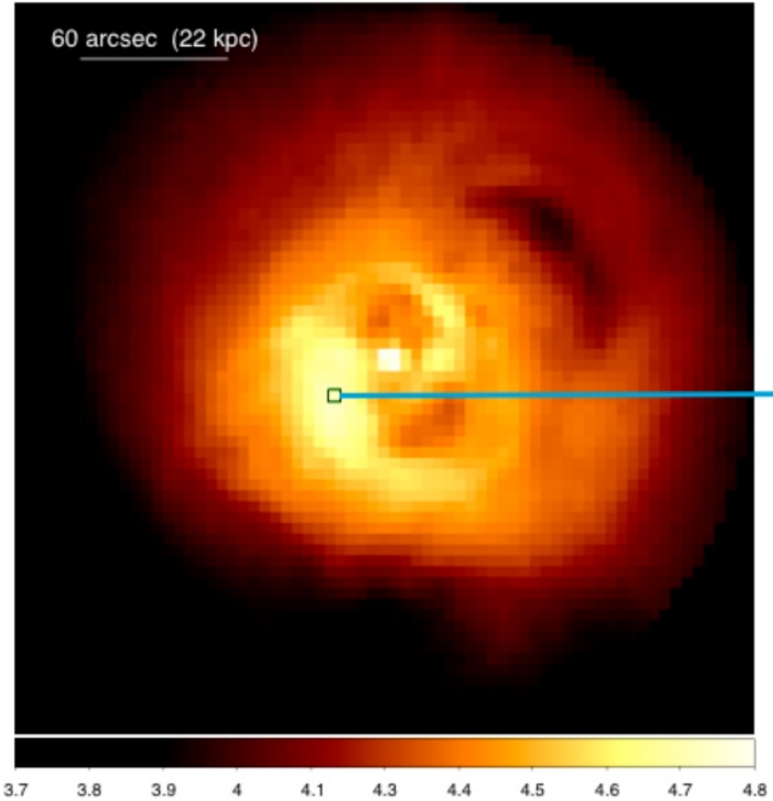


Credit: J.Aird (IoA)

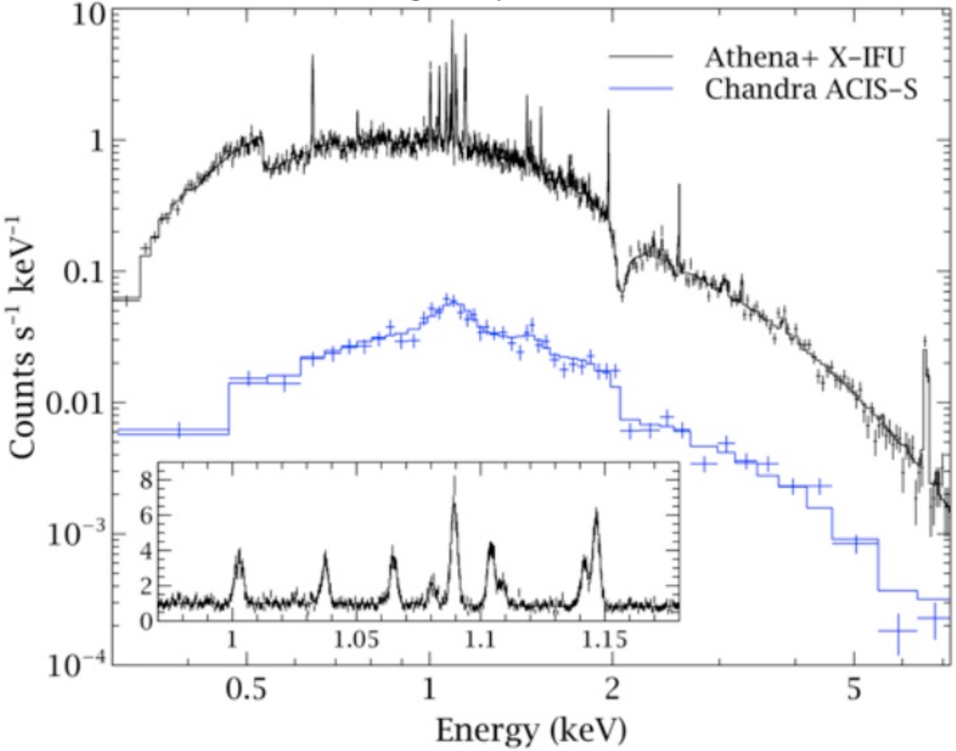


Athena spectroscopic performance

Nandra et al., 2013, The Hot and Energetic Universe WP



Sensitivity to lines ≥10-70x better then any existing, or planned missions



Summary

- X- and γ-ray astronomy investigate energetic phenomena in the Universe:
    - formation and evolution of the hot (~10^6 K) gas "cosmic web"
    - cosmological evolution of the chemistry in the Universe
    - formation and evolution of super-massive black holes and galaxies
    - behavior of matter in the strong-field regime of General Relativity
    - final stages of stellar evolution (neutron stars, black holes)
    - even solar system objects, and Earth-like planets habitability
- Europe and ESA's (open!) observatories have been playing a leading role
- INTEGRAL and XMM-Newton healthily operating during almost 2 decades,
    - Produce >1 paper/day on the above topics, and on many more!
- The future will be even brighter thanks to **Athena** (→ talk by Dr. Didier Barret)