Athena in the context of the multi-messenger era

Alexis Coleiro - APC / Université de Paris

Université de Paris

Outline

- Athena scientific goals and mission profile
- High-energy counterpart to NS-NS mergers
- High-energy counterparts of SMBH mergers / synergies with LISA
- Synergies with neutrino facilities & CTA

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https://arxiv.org/pdf/2110.15677.pdf

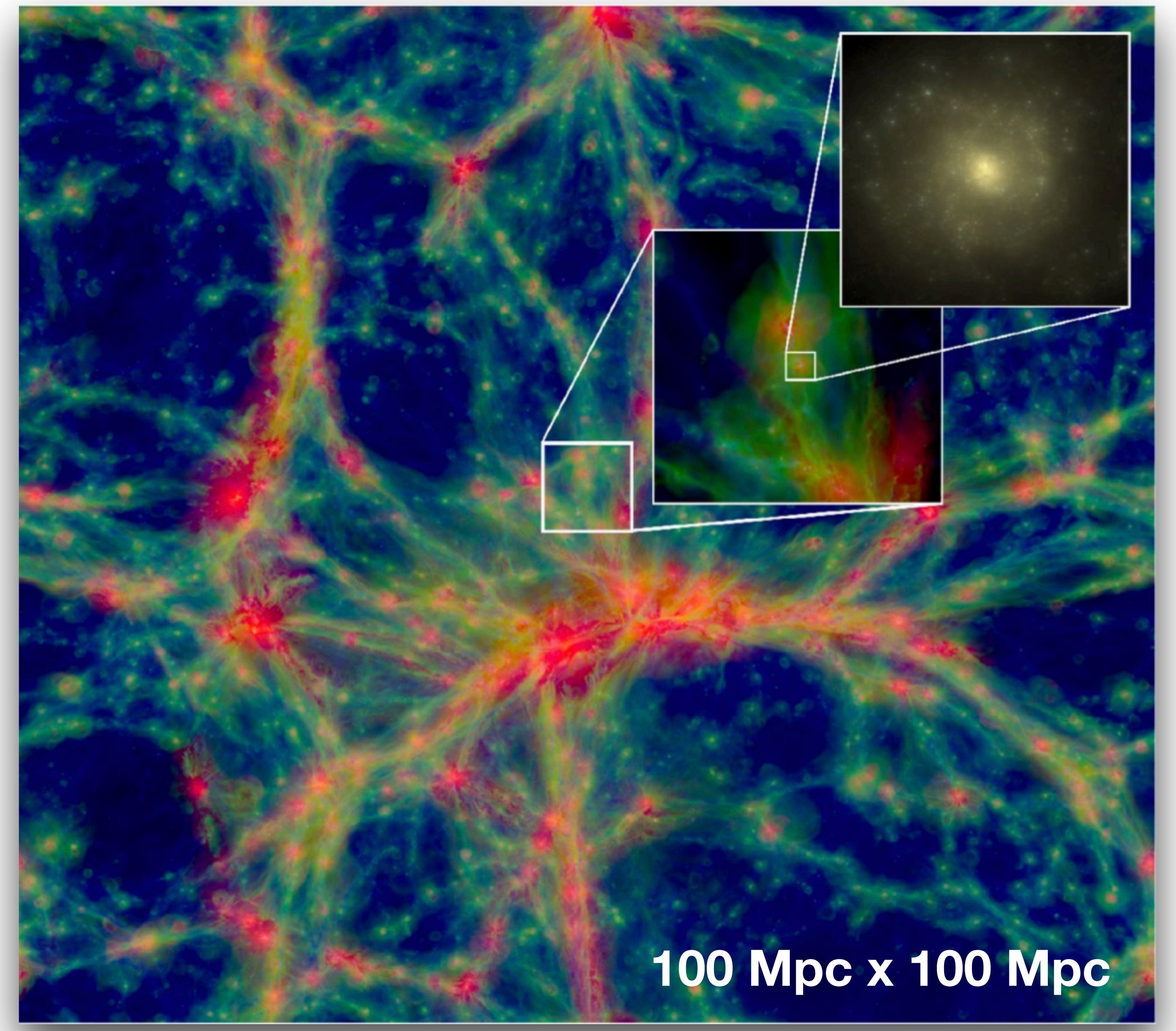
Scientific goals of ATHENA

- Athena selected in 2014 as next large mission of ESA's Cosmic Vision program
- Launch expected in 2033

- Key Questions:
  - **How does ordinary matter assemble into the large-scale structures we see today?**
  - **How do black holes grow and shape the Universe?**

- An observatory:
  - Observatory science across all corners of astrophysics
  - Fast ToO response (<4 hours) capability to study transient sources

- ~2/3rd of the time during nominal operations open to the community



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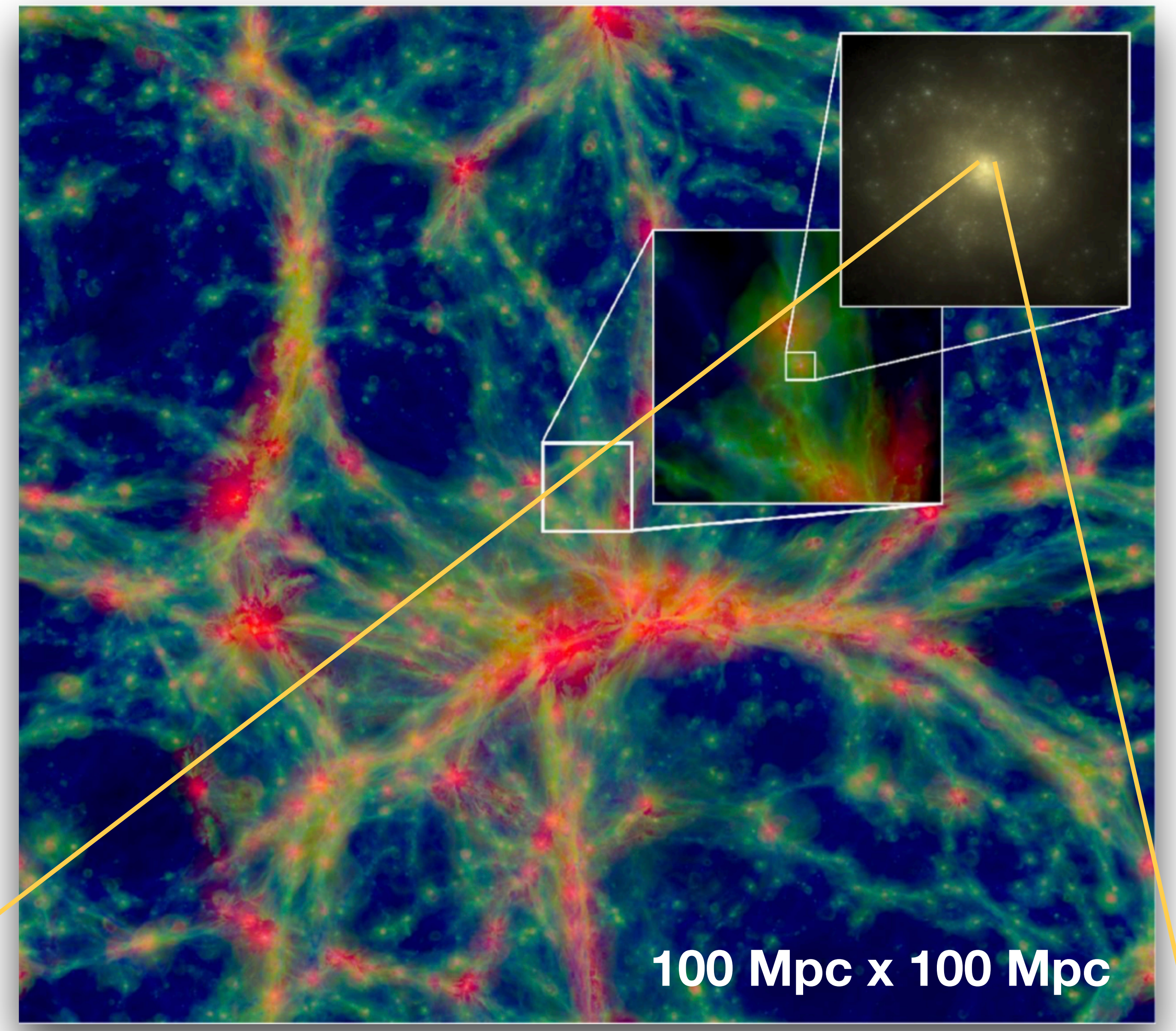

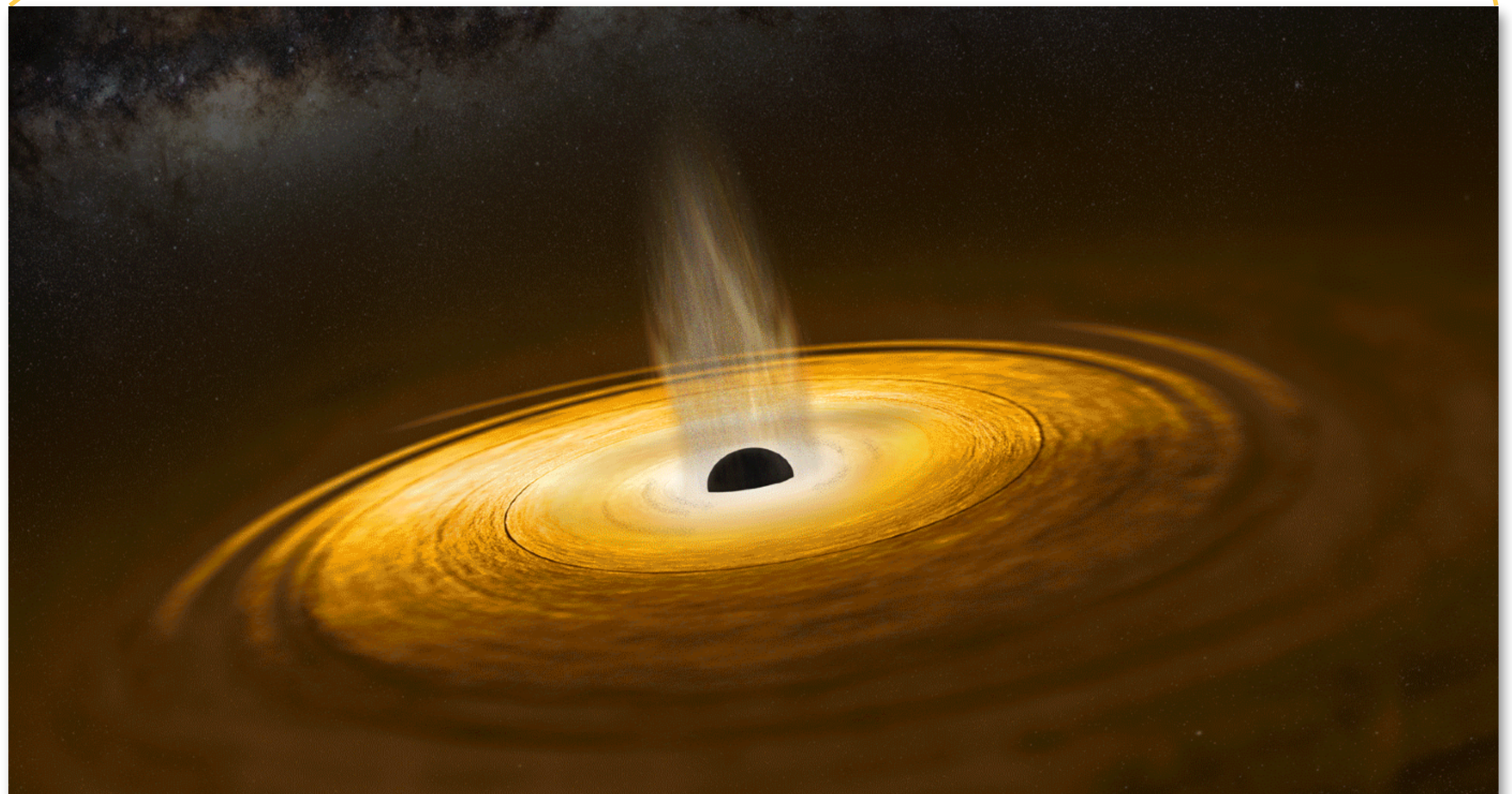

Supermassive black holes $> 10^6 M_\odot$

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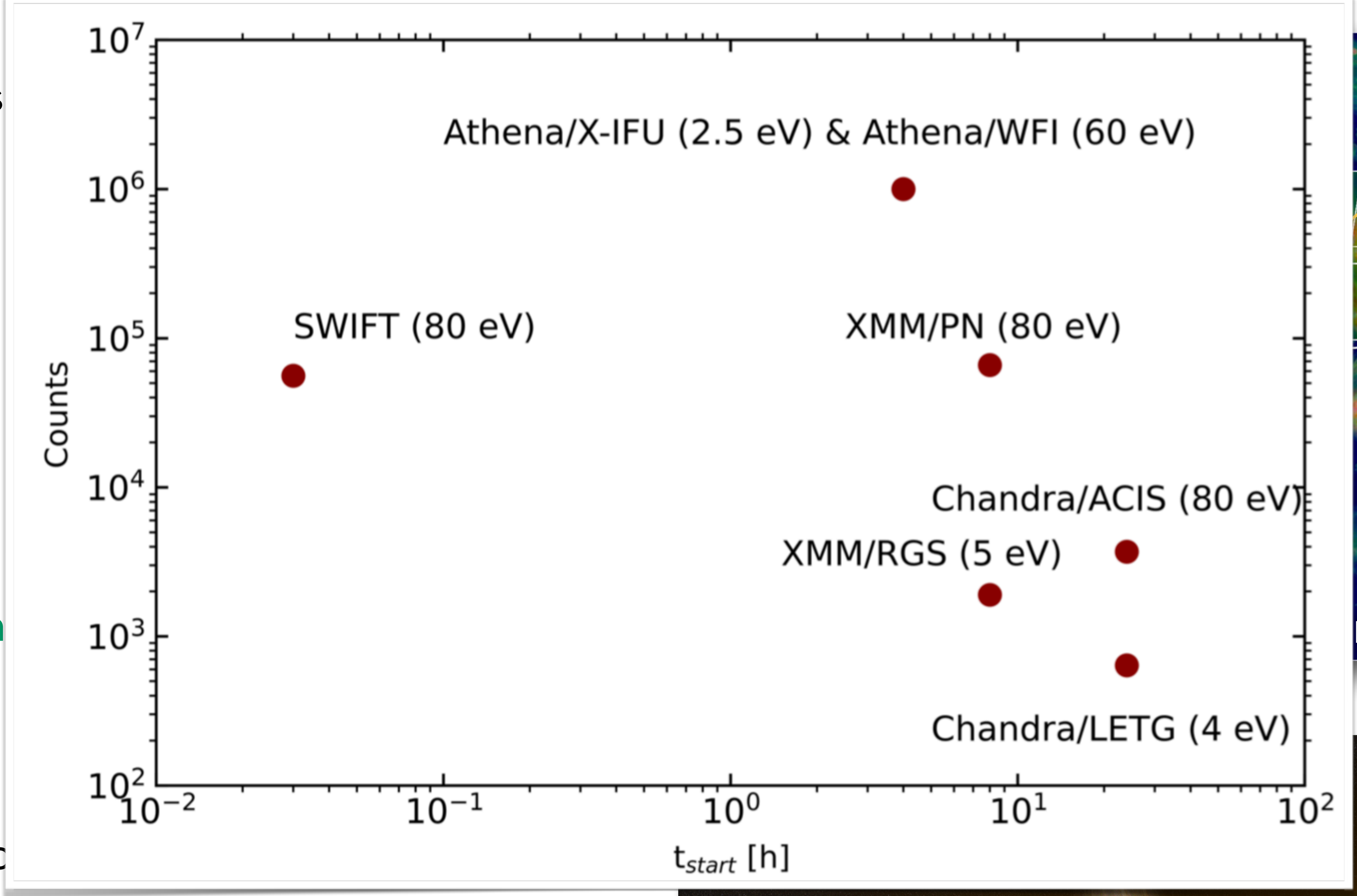
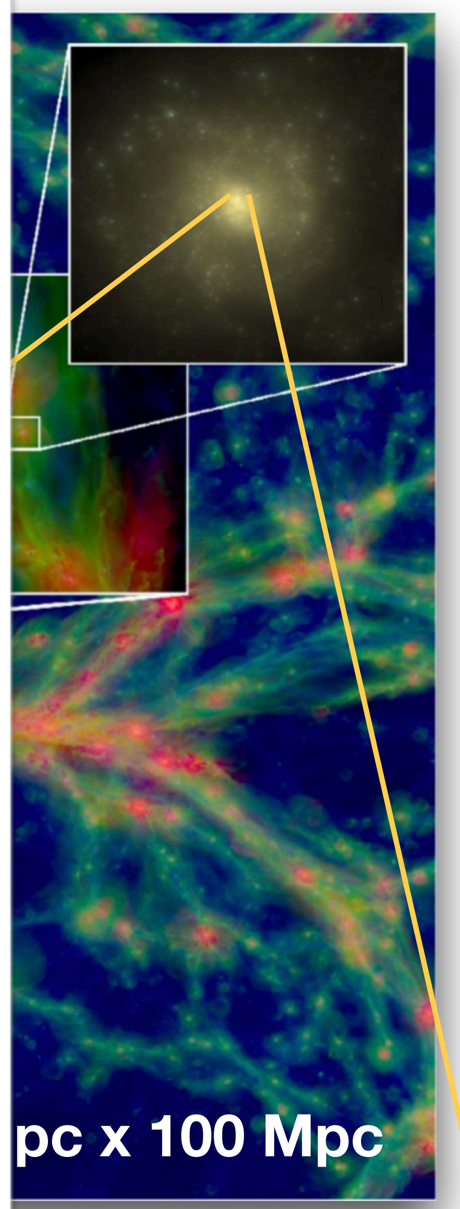
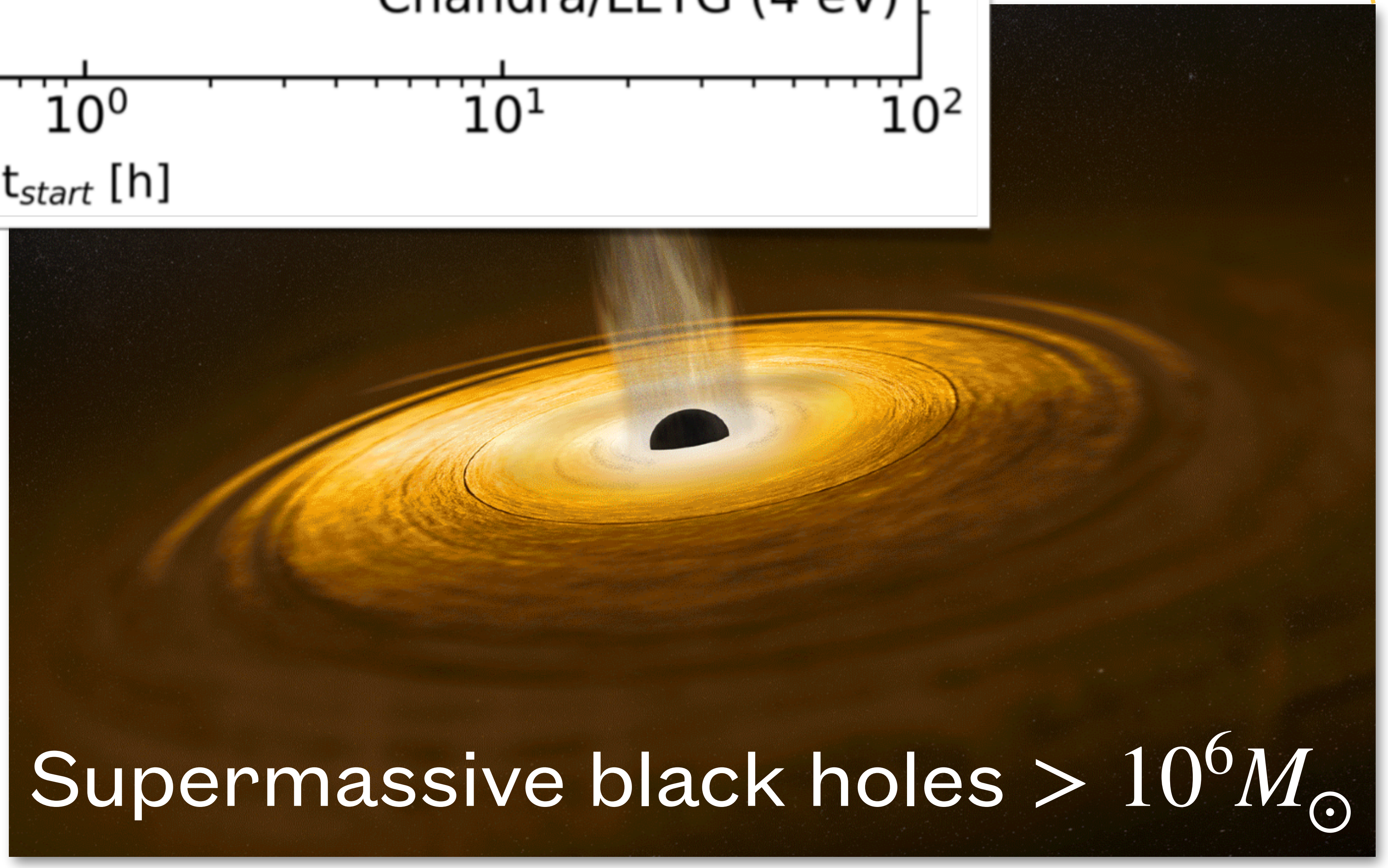
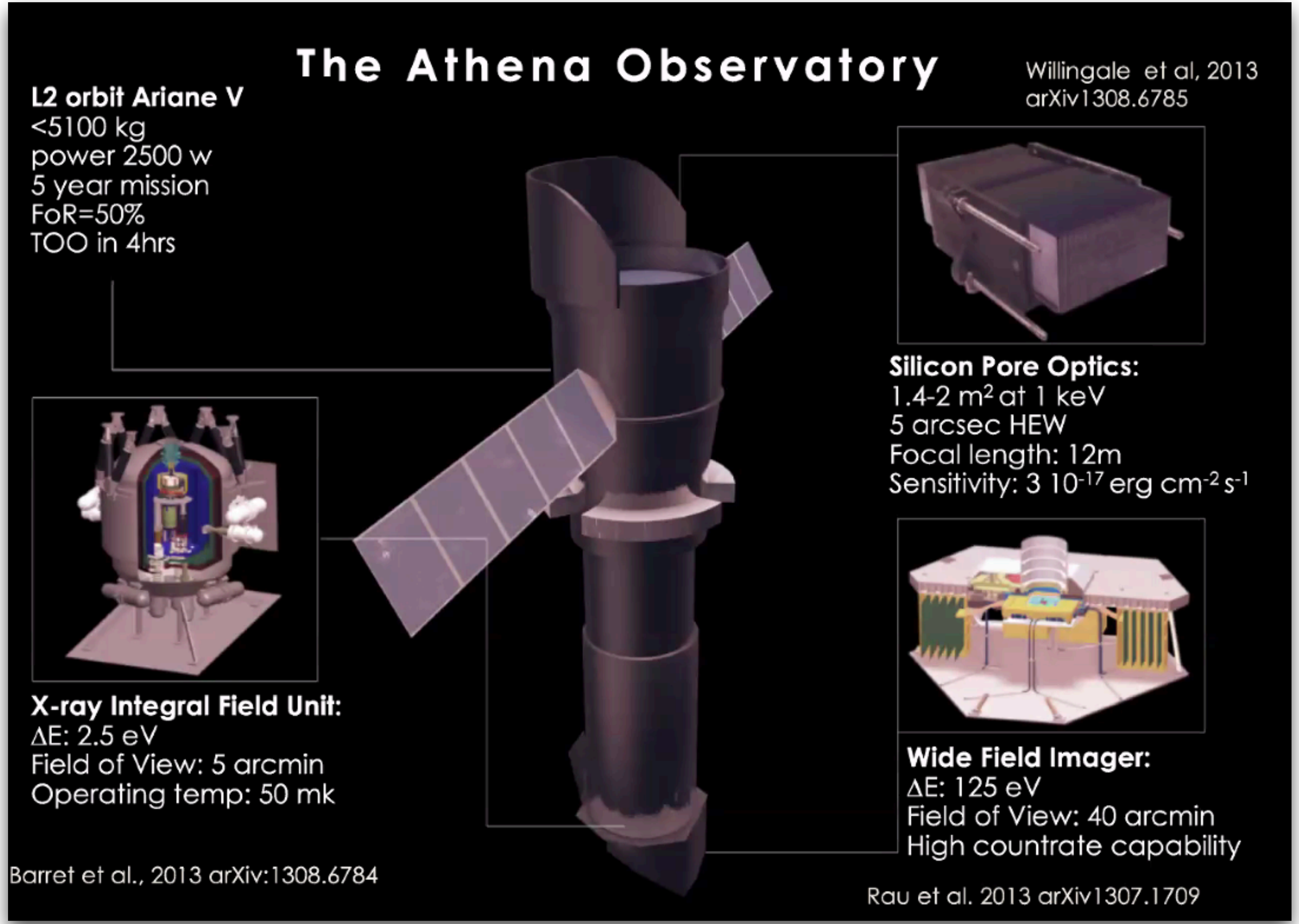
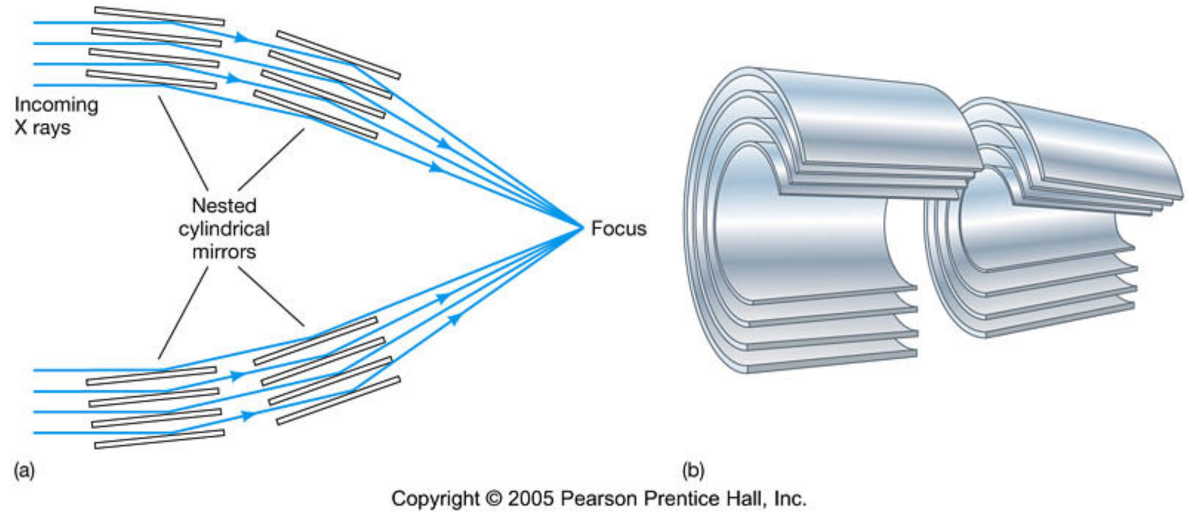


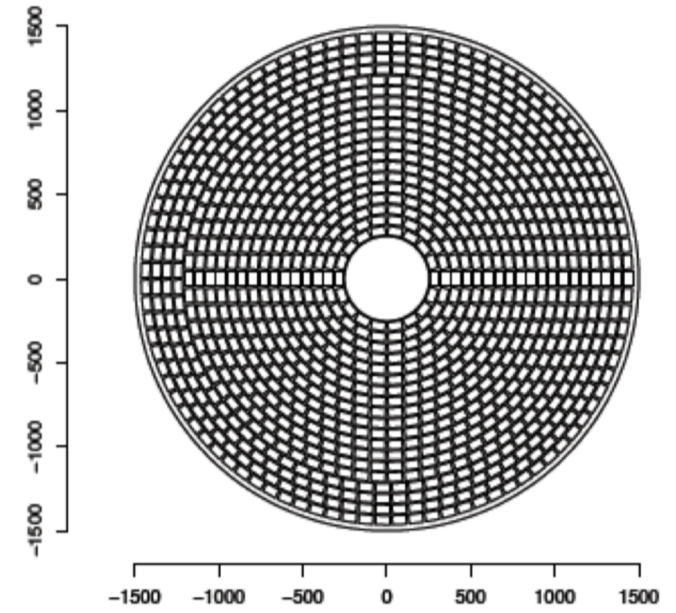


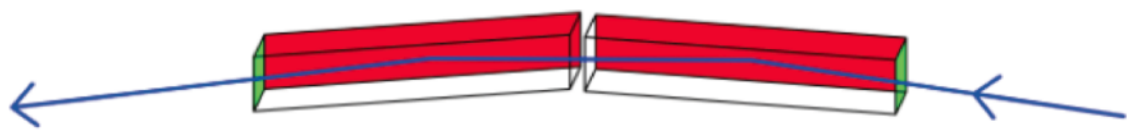


Mission profile

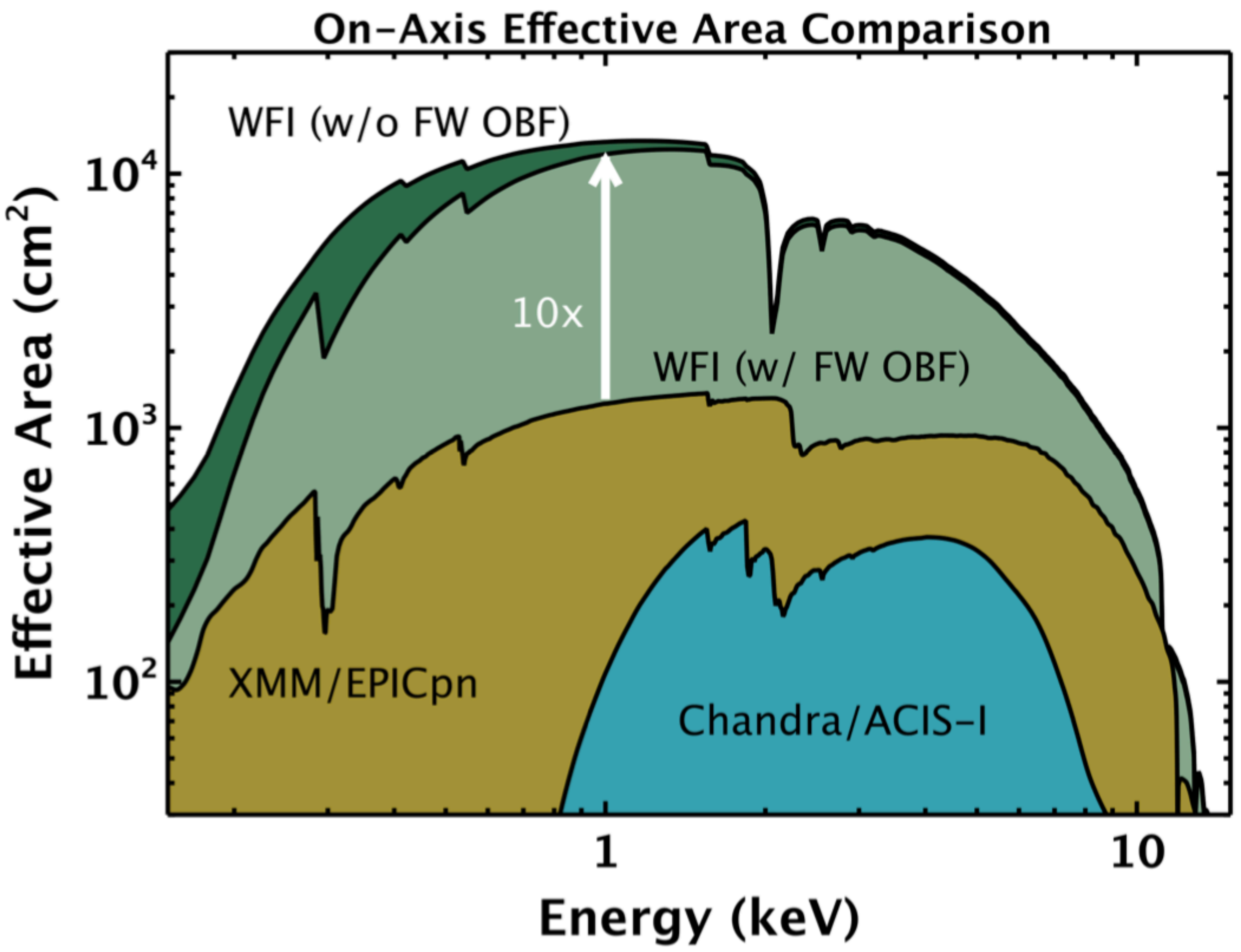


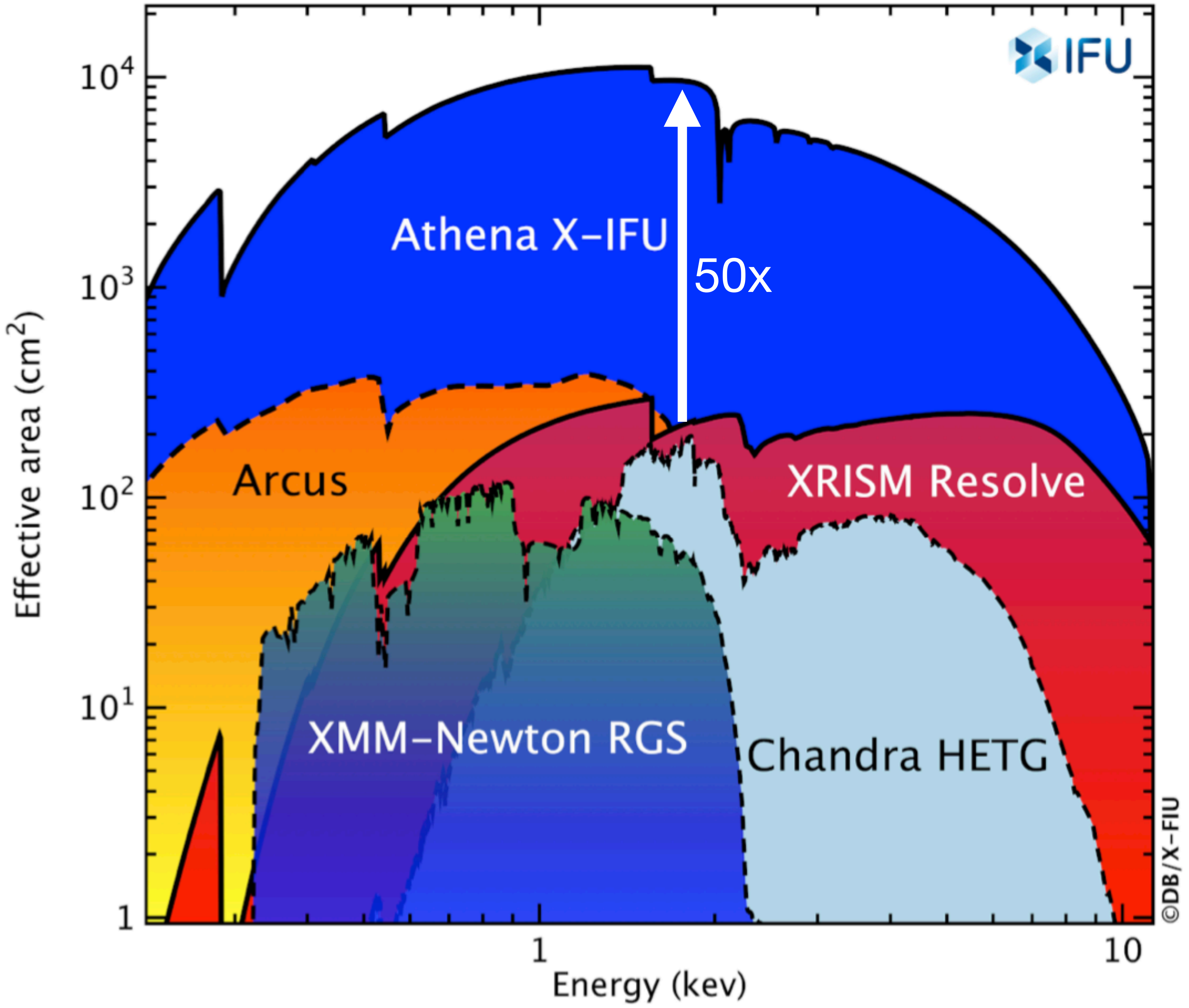




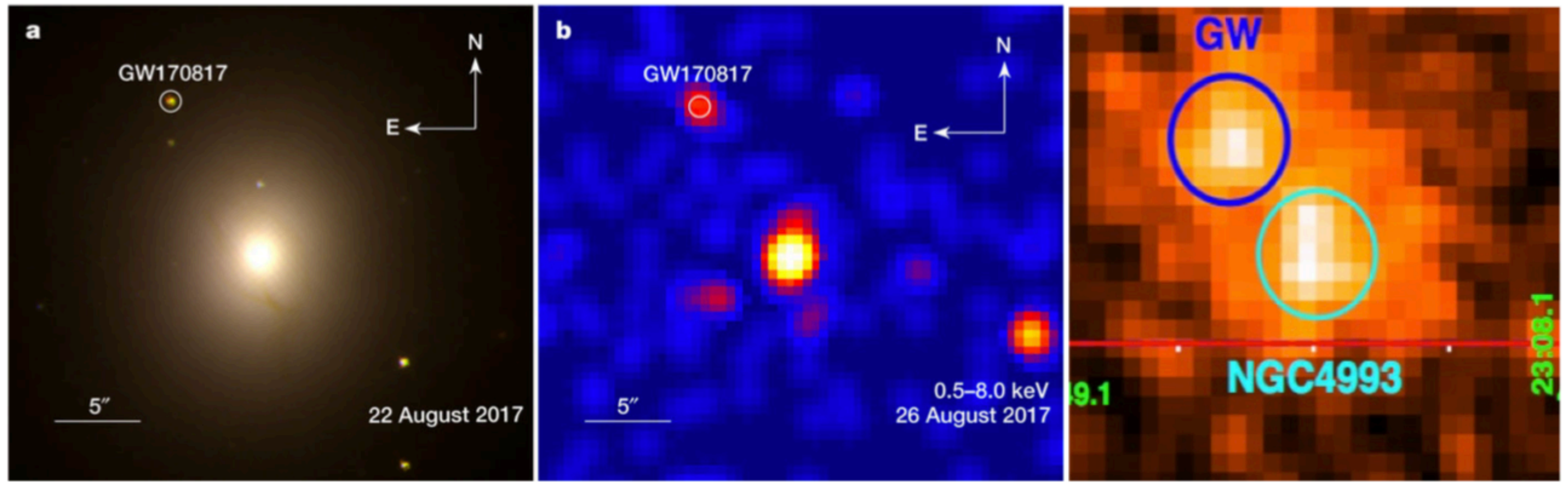


Athena: a large effective area mission





GRB and compact object mergers

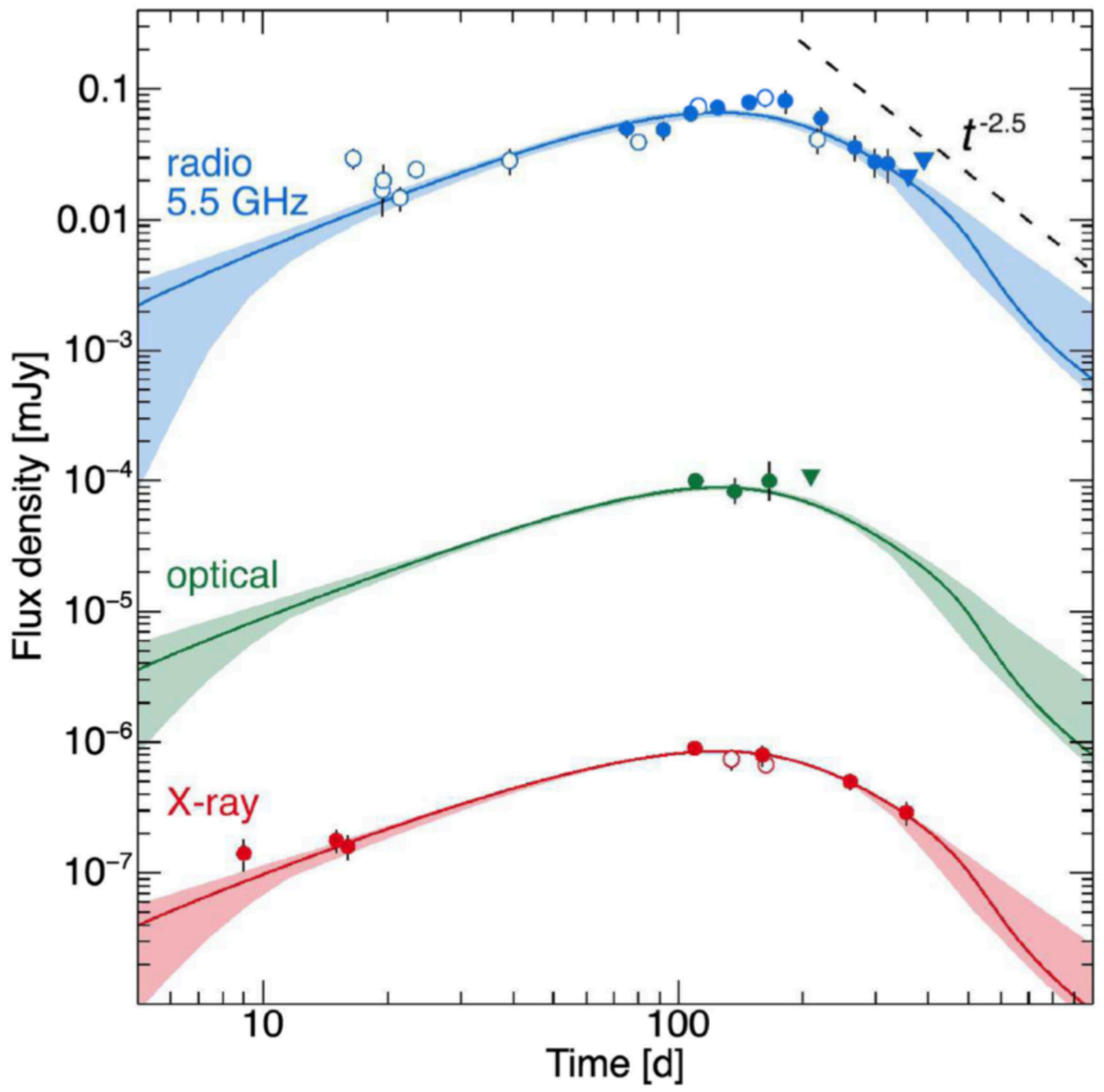


HST Chandra XMM-Newton

Troja, et al., Nature, 2017, 551, 71

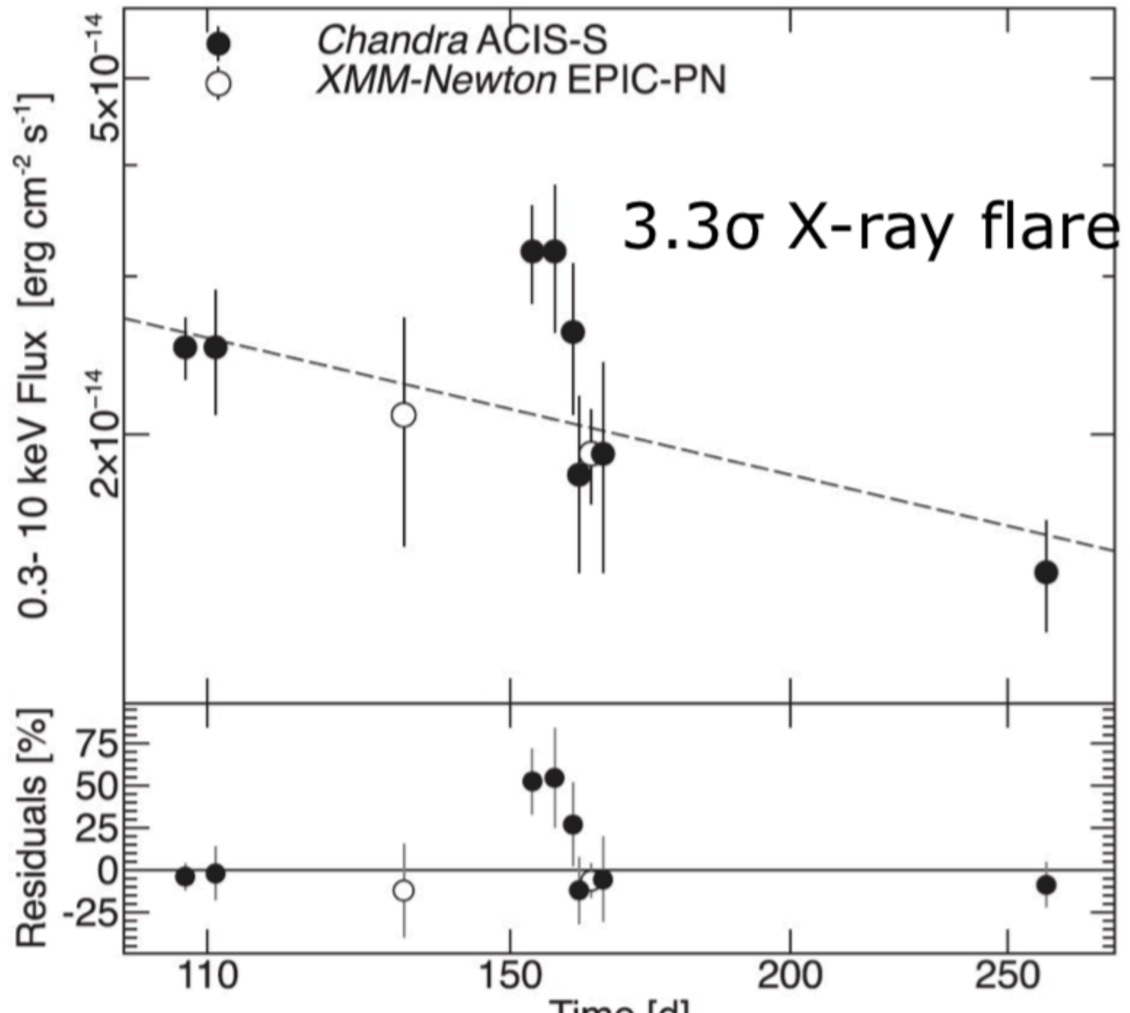
D'Avanzo, et al., 2018, A&A 613, L

Troja et al., 2018, MNRAS, 478, 18

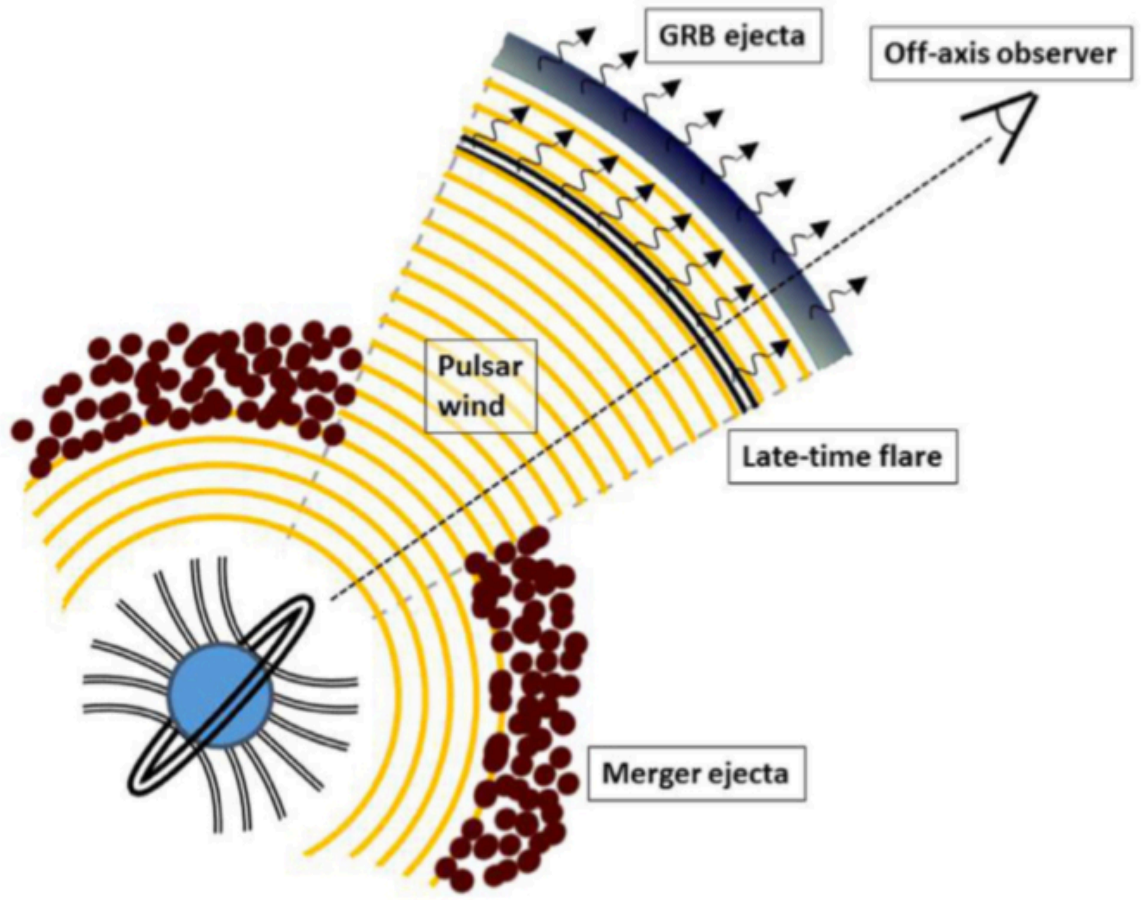


Troja et al., 2018, MNRAS 489

- X-ray counterpart consistent with a short GRB viewed off axis.
- X-ray lightcurve unveils dynamics and geometry of the ejecta and are crucial for modeling the system



Piro et al., 2019, MNRAS, 483, 1912



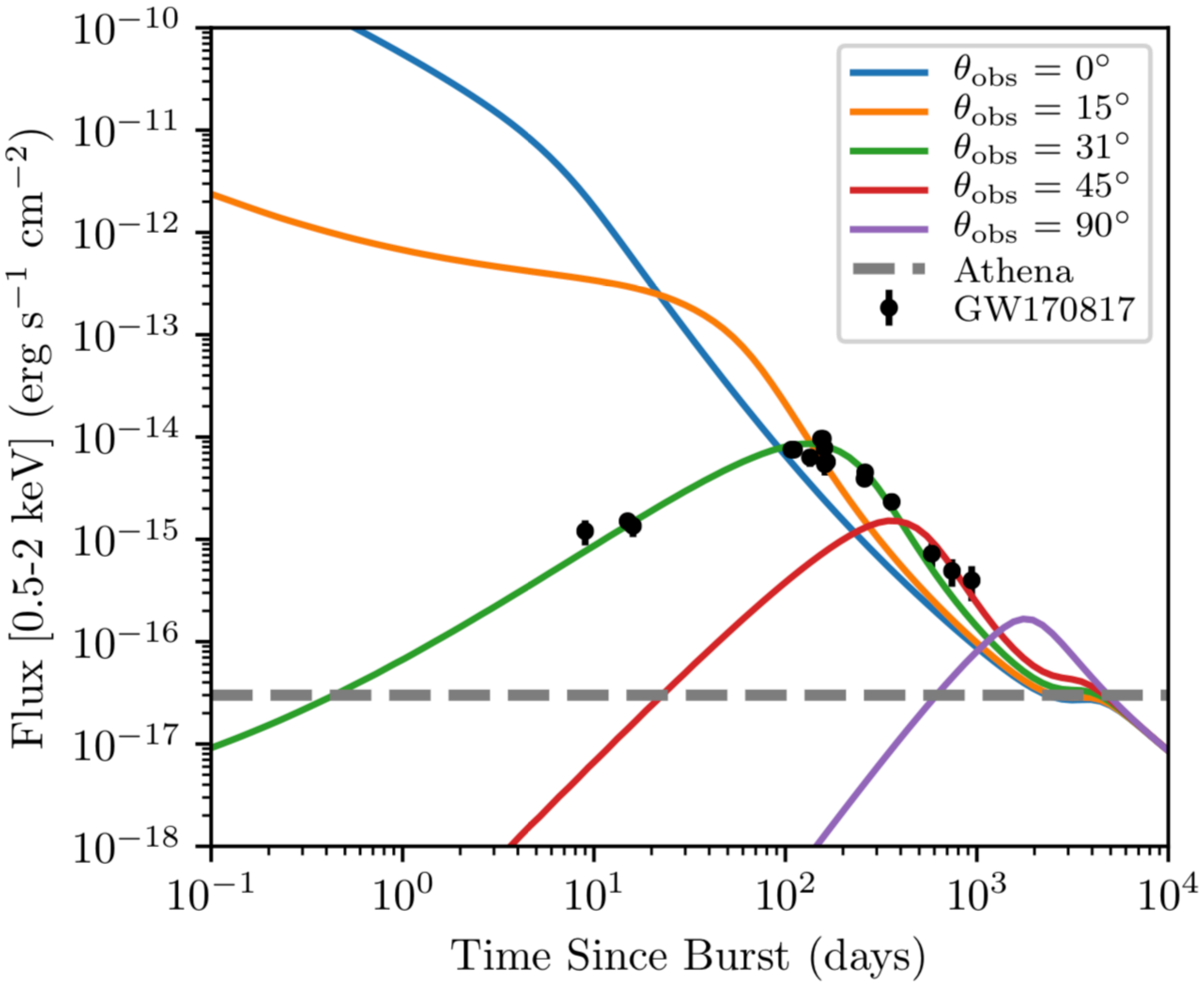
- Nature of the merger remnant ?
- X-ray observations could break the degeneracy between neutron star/magnetar and black hole
- A long-lived NS might affect X-ray emission either through X-ray flares of long-lasting X-ray plateau

GRB and compact object mergers

Predicted X-ray lightcurves of GW counterparts for different viewing angles, assuming standard afterglow at 41 Mpc

- X-ray probe:
  - Jet: GRB afterglow
  - Isotropic features: off-axis (orphan) afterglow and cocoon

- ATHENA will:
  - Probe a variety of viewing angles (population studies, jet structures, constraints on Hubble constant, …)
  - Constrain jet geometry and orientation
  - Probe the relation between jet's orientation (EM) and binary's inclination (GW)
  - Determine the rate of chocked jets/uncollimated sources
  - Break NS/BH remnant degeneracy



Troja et al., 2020, MNRAS, 498, 5643

Synergies with LISA: supermassive black hole mergers

- **LISA**: in operation in ~2030’
- Low frequency gravitational waves (0.1 mHz - 1 Hz)
- Monitoring of the distances between 3 spacecrafts
- Sky localization from 100 deg^2 to < 1 deg^2 (improves when the binary gets close to the merger)

- Unique opportunity to probe behaviors of matter in the variable space-time induced by the merging black holes

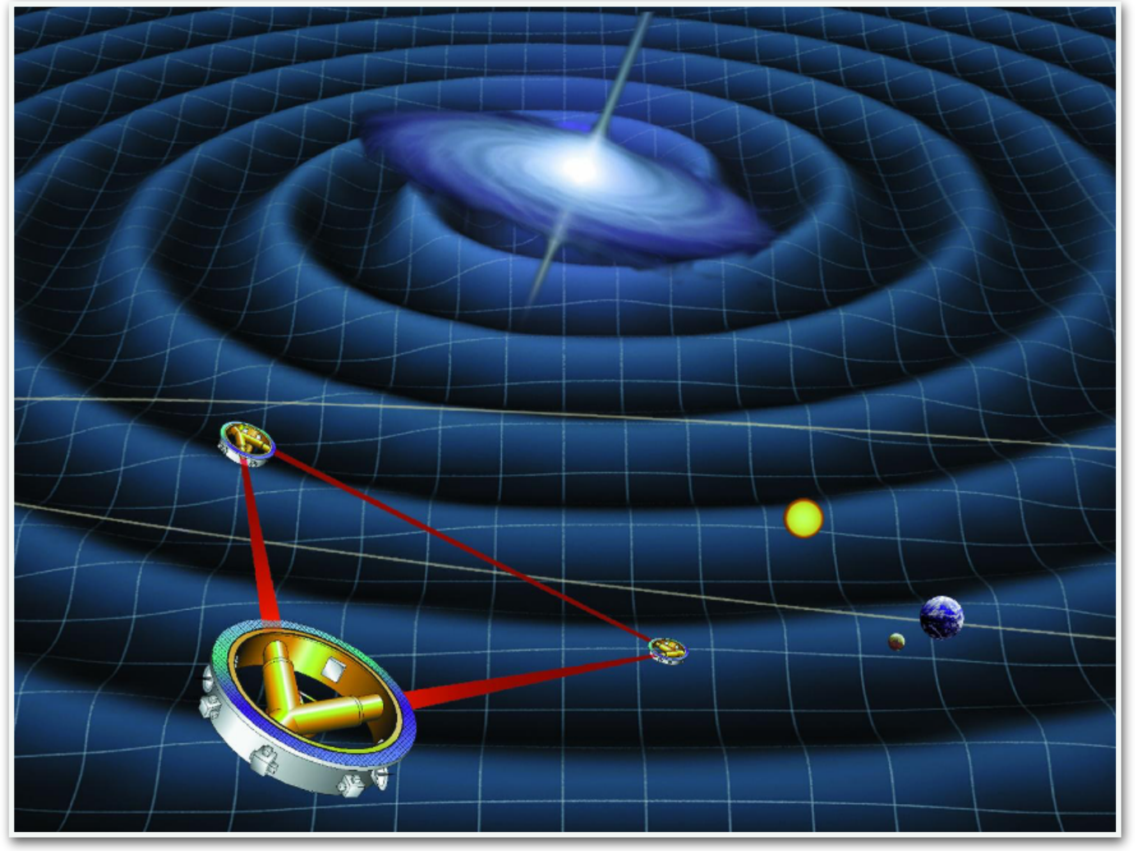
- Study speed of gravity (phase correlation of the GW and the X-ray time modulated signal)

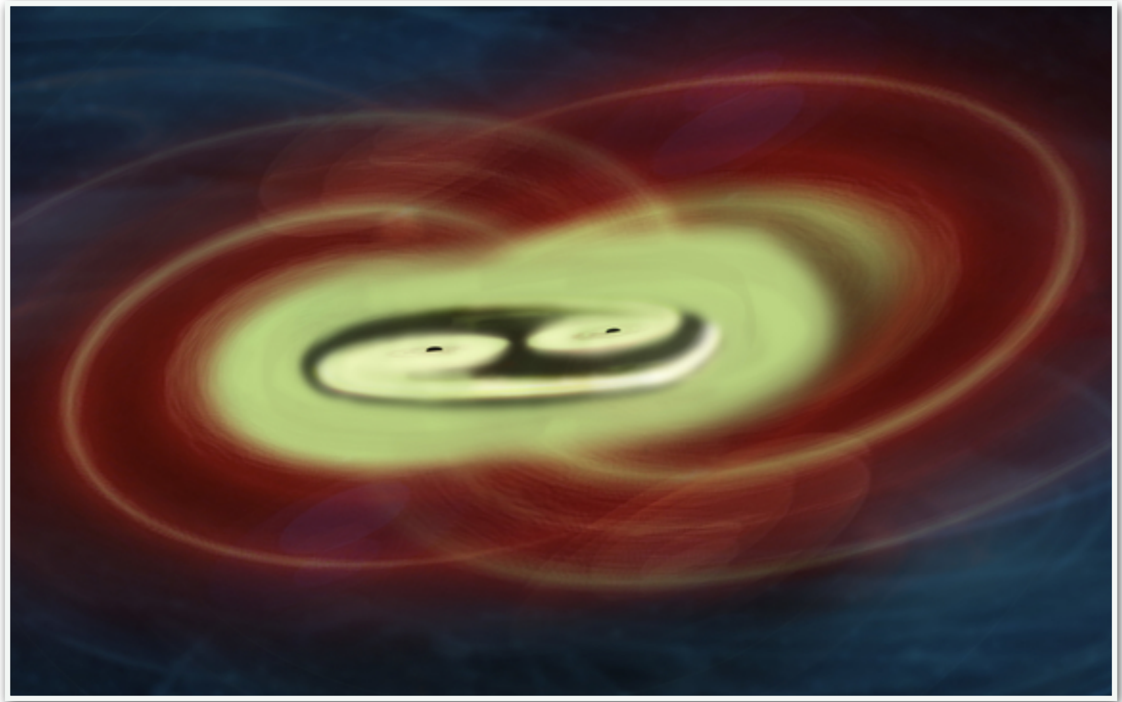
- Hubble constant measurement to $z \lesssim 2$ (GW give luminosity, EM provide redshift)

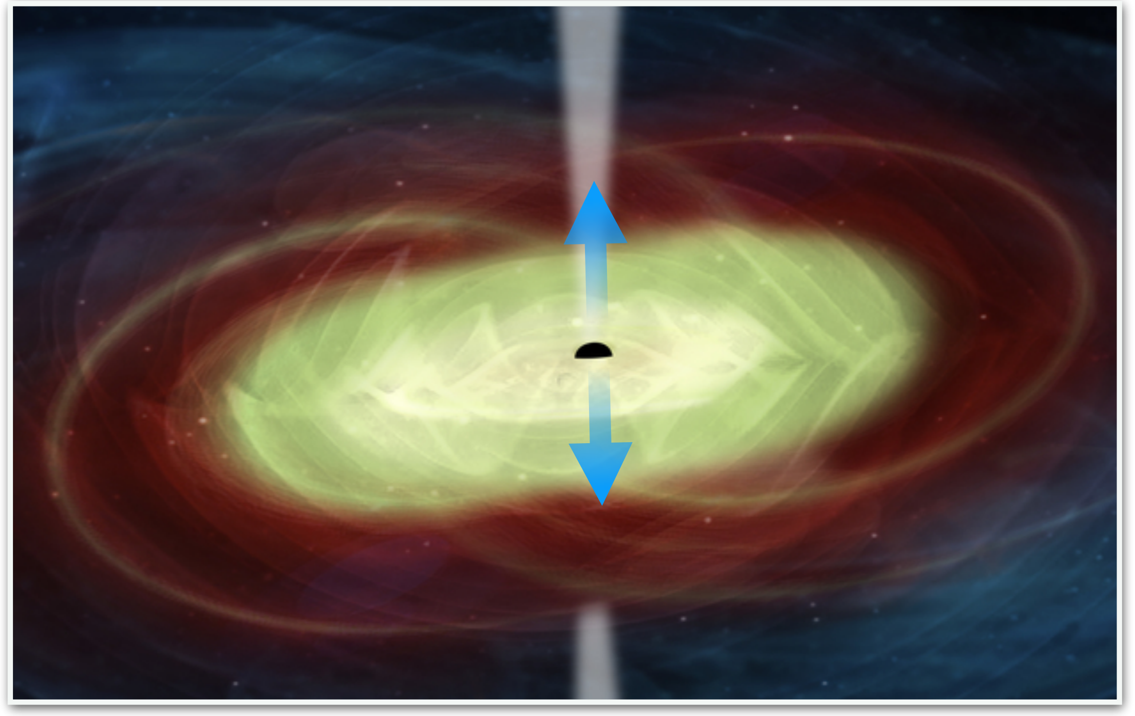
- Unique opportunity to probe AGN physics (onset of relativistic jets, formation of corona, …)

- Huge discovery space

- **Could ATHENA detect and follow-up counterparts to LISA mergers ?**

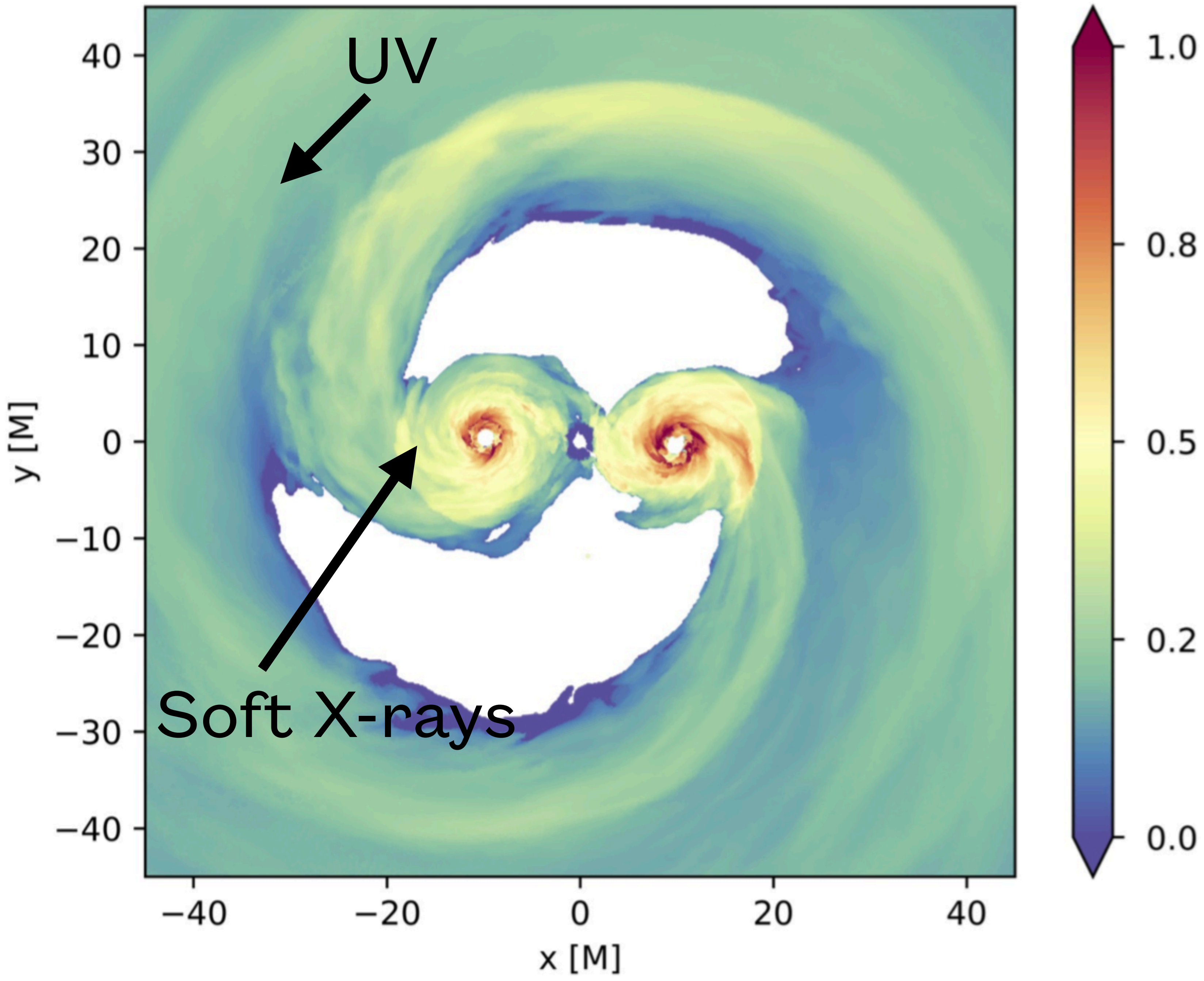




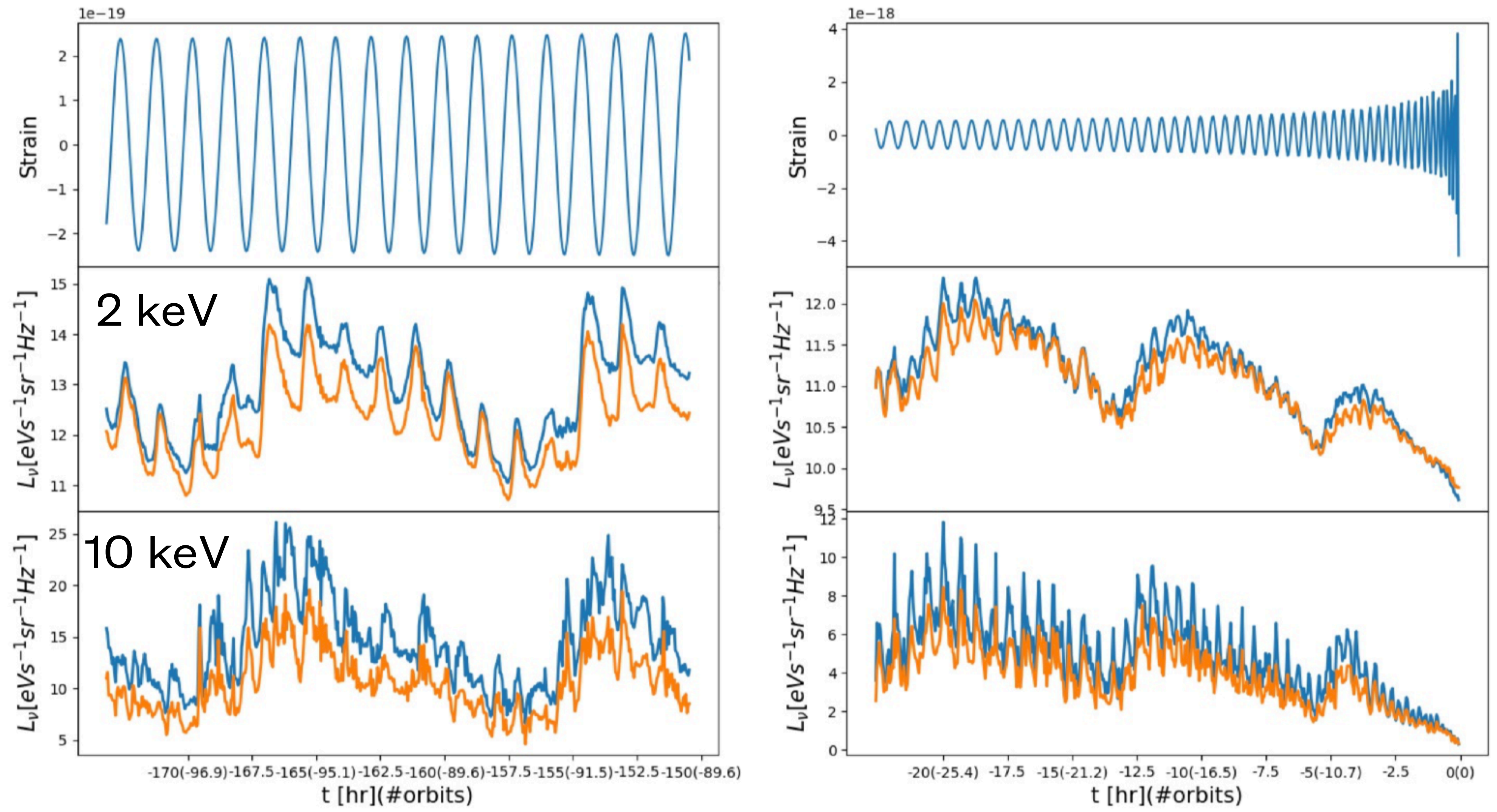


Synergies with LISA: supermassive black hole mergers

- LISA will detect mergers up to z~20
- Athena might detect in a few ks z<2 black holes (3/yr detected by LISA)
- **Challenge: distinguish mergers from isolated AGN**
- **X-ray emission during the late stages of the inspiral (days to hours before final merger) from:**
    - Circumbinary disc: X-ray emission in UV/soft x-rays (≤ 1keV)
    - Minidisks around BH: soft to hard X-ray emission (≥ 10 keV) from accretion coronae
- **X-ray emission might show clear modulation on timescales as short as a few hours** linked to orbital period and in-spiral (late) phases but a lot of unknowns (X-ray obscuration, modulation, …)
- **Key element:** sky localization by LISA (ideally 0.4 deg^2 a few hours prior to coalescence)
- Exact joint ATHENA/LISA observing strategies to be designed

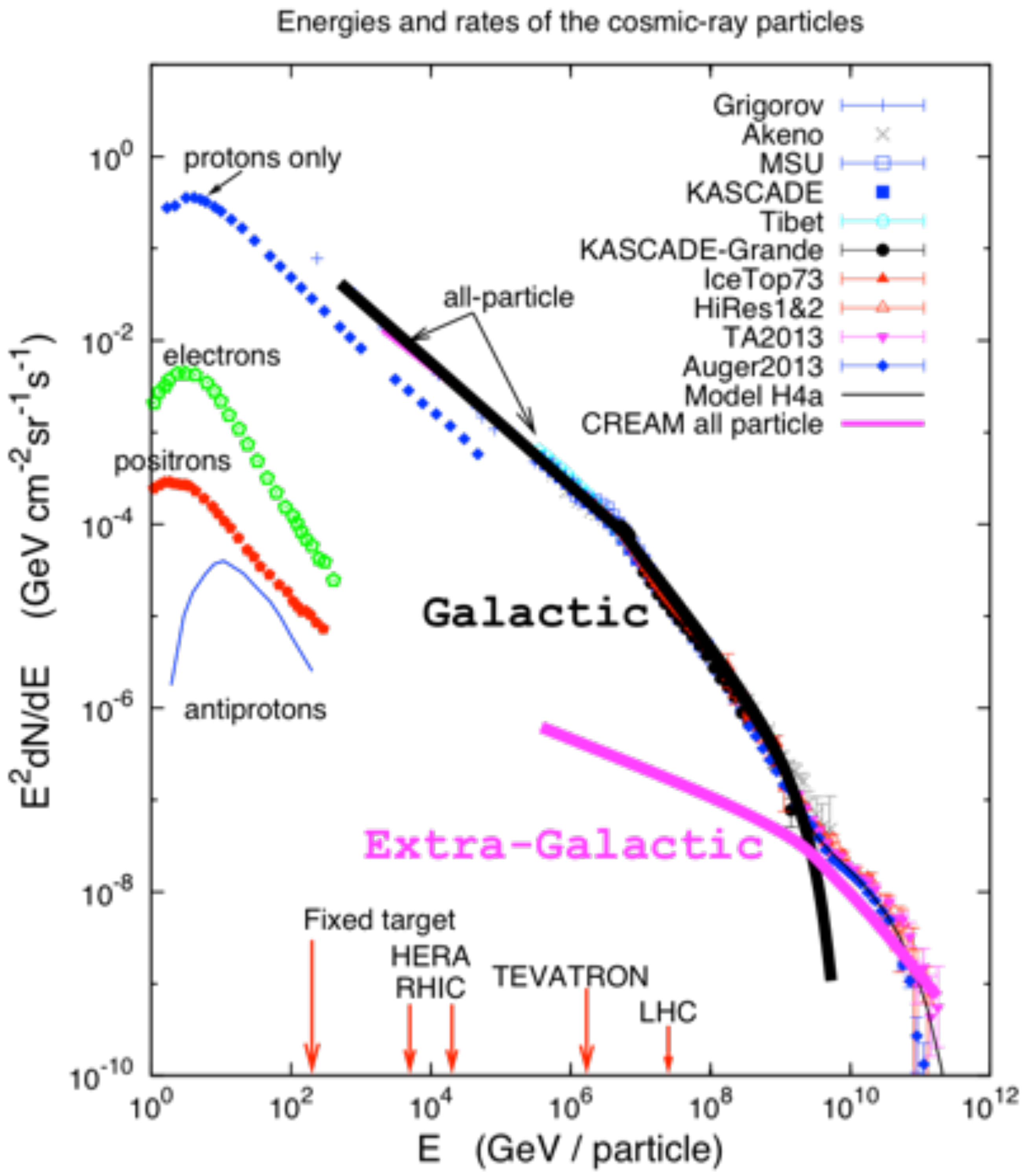


d'Ascoli et al., 2018

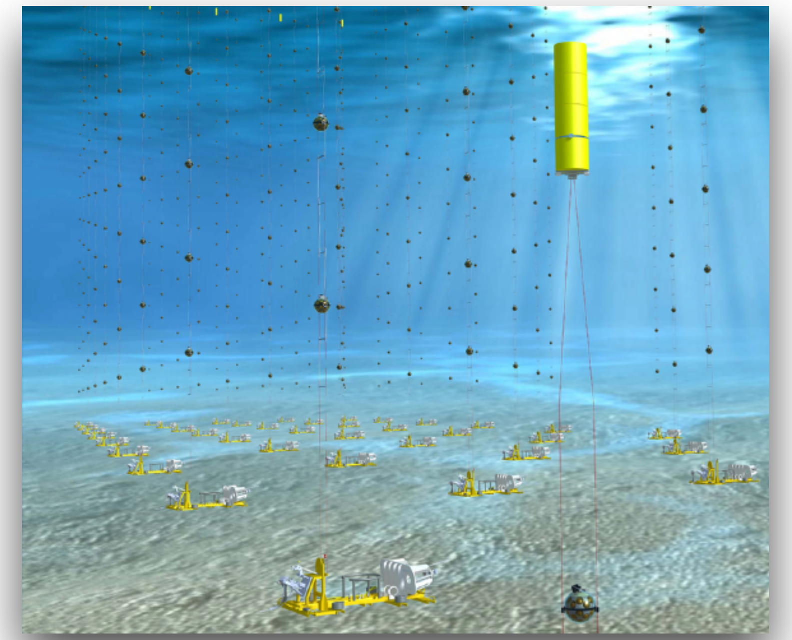


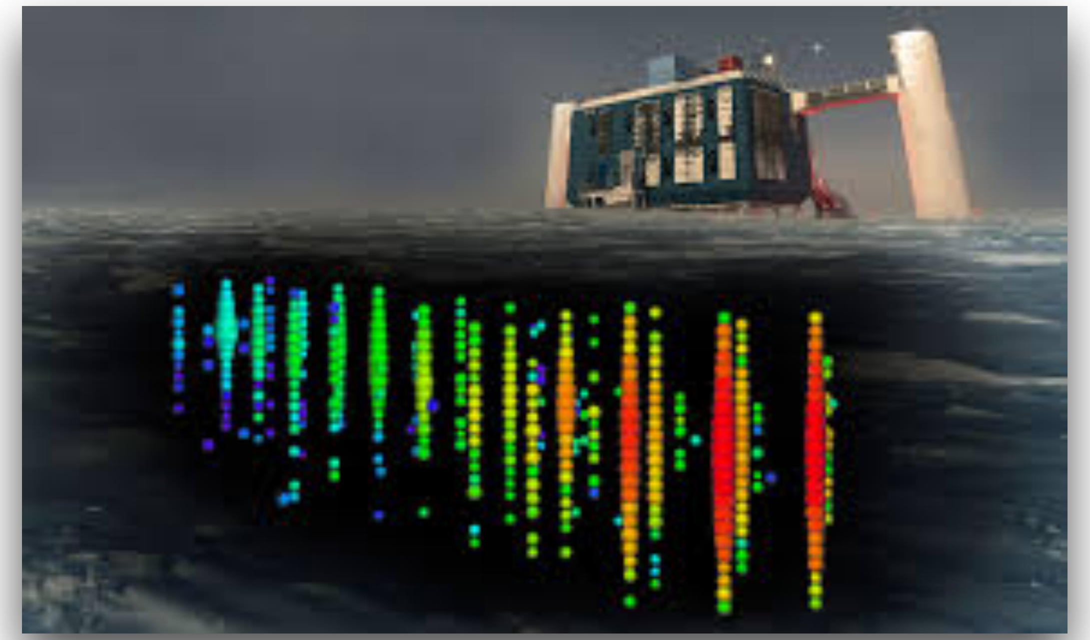
Tang, Y. et al., 2018, MNRAS 476

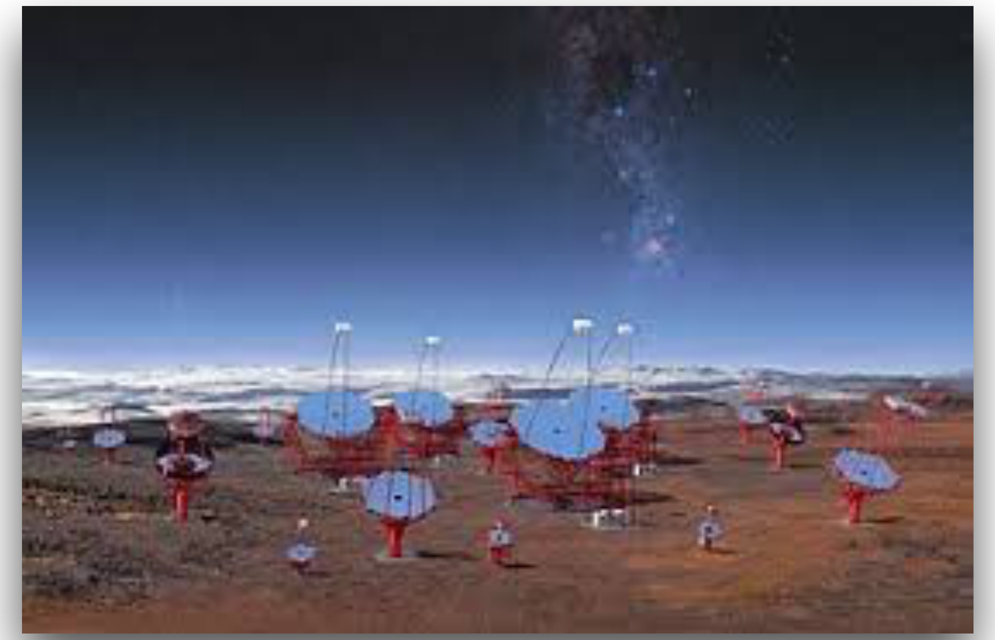
Particle/cosmic-ray acceleration in the Universe



- **Synergies with neutrino telescopes (KM3NeT, IceCube, Baïkal GVD) & CTA**
- Neutrinos are signature of accelerated relativistic hadrons
- X-ray / gamma-ray and neutrinos allow to disentangle non-thermal leptonic and hadronic populations to probe:
  - The origin of Galactic/extragalactic cosmic rays
  - The nature of relativistic jets in blazars
  - The ultra-fast outflows in AGN
  - Accretion shocks in cluster of galaxies
  - Sites of shock acceleration of Galactic cosmic rays (SNR, pulsars, PWN)







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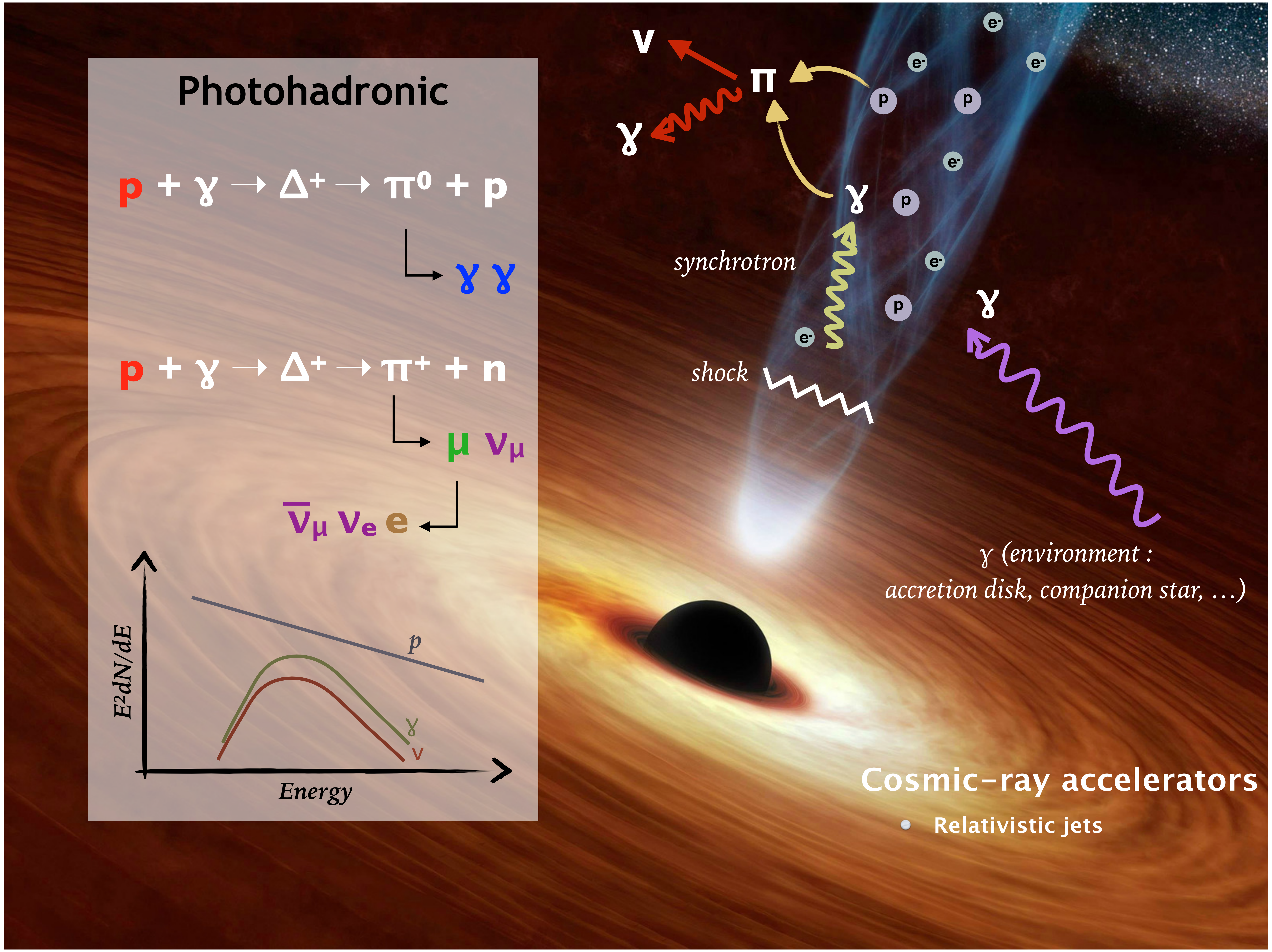
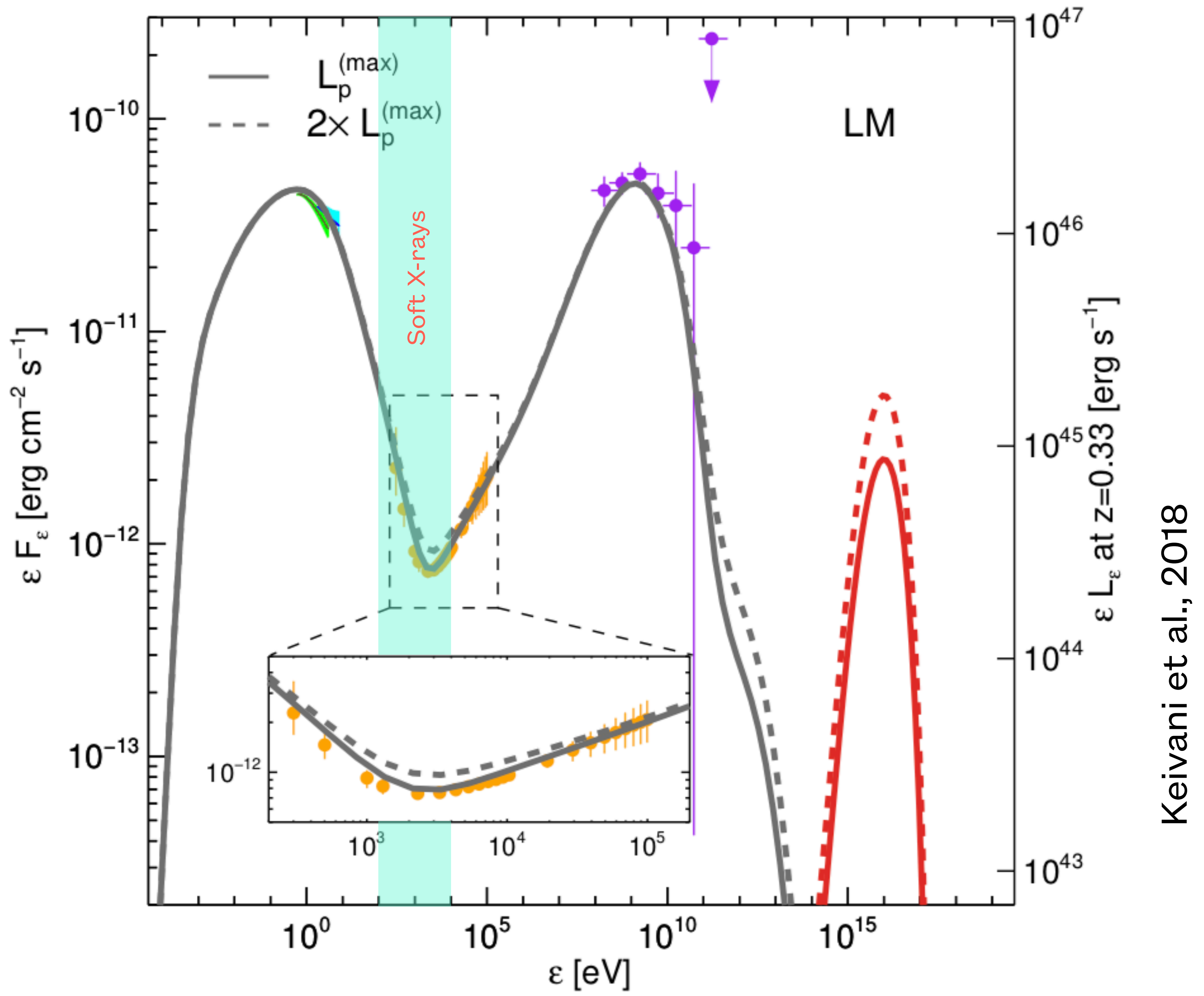


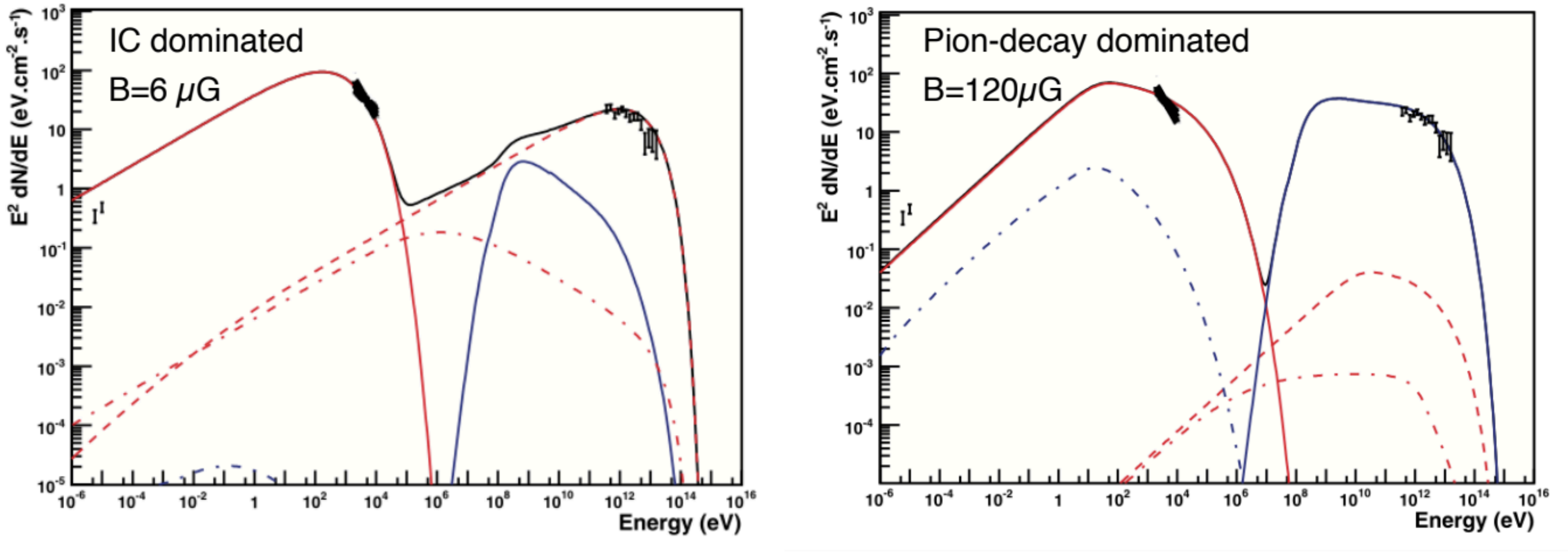
- Are the AGNs significant neutrino emitters ?
- Open question after the detection of an IceCube neutrino coincident with a gamma ray flare of TXS 0506+056 in 2017.
- X-rays can probe the local plasma and radiation energy densities, with which accelerated particles interact.

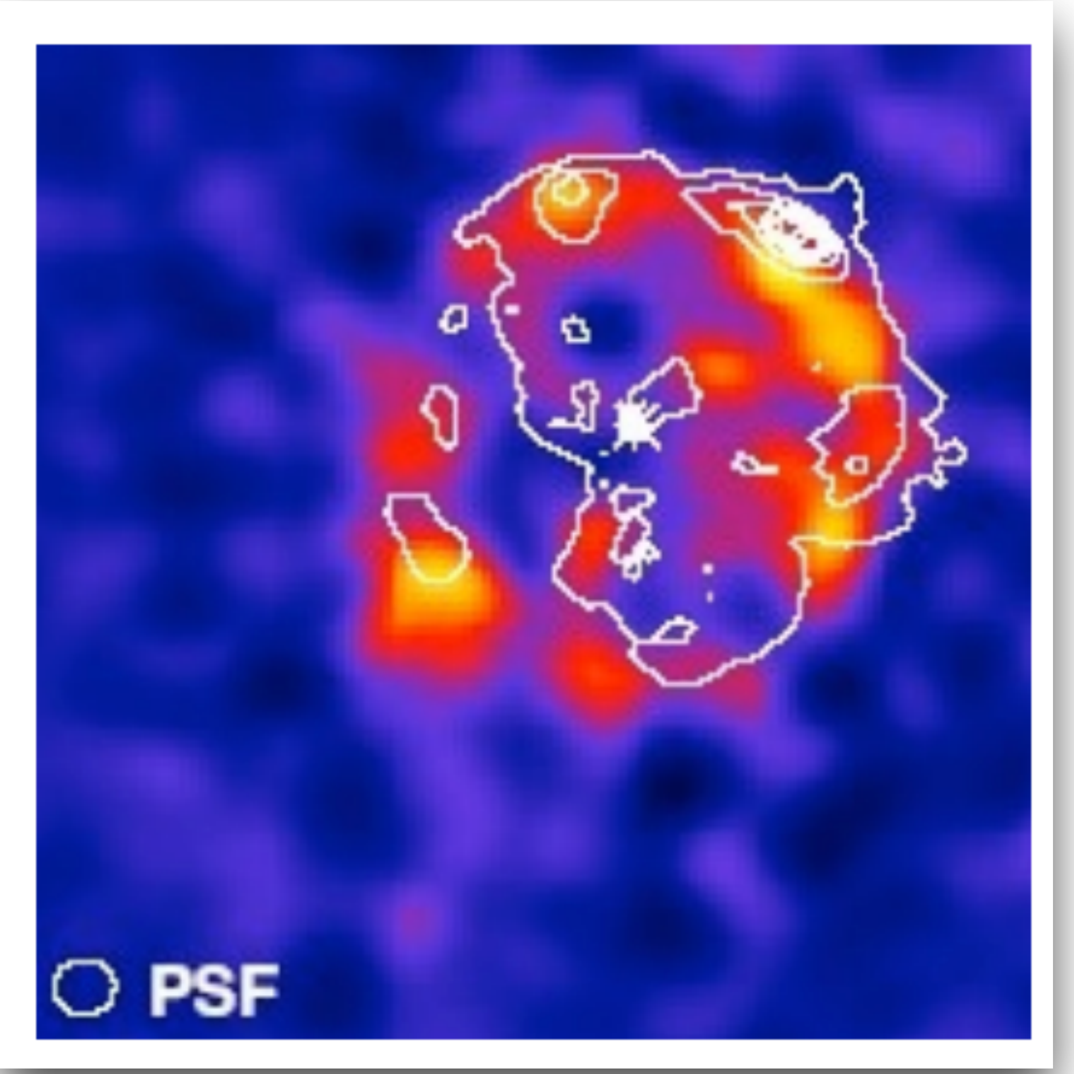


- Soft X-ray flux constrains hadronic component

Particle/cosmic-ray acceleration in the Universe

Supernova remnants: hadronic vs leptonic acceleration ?



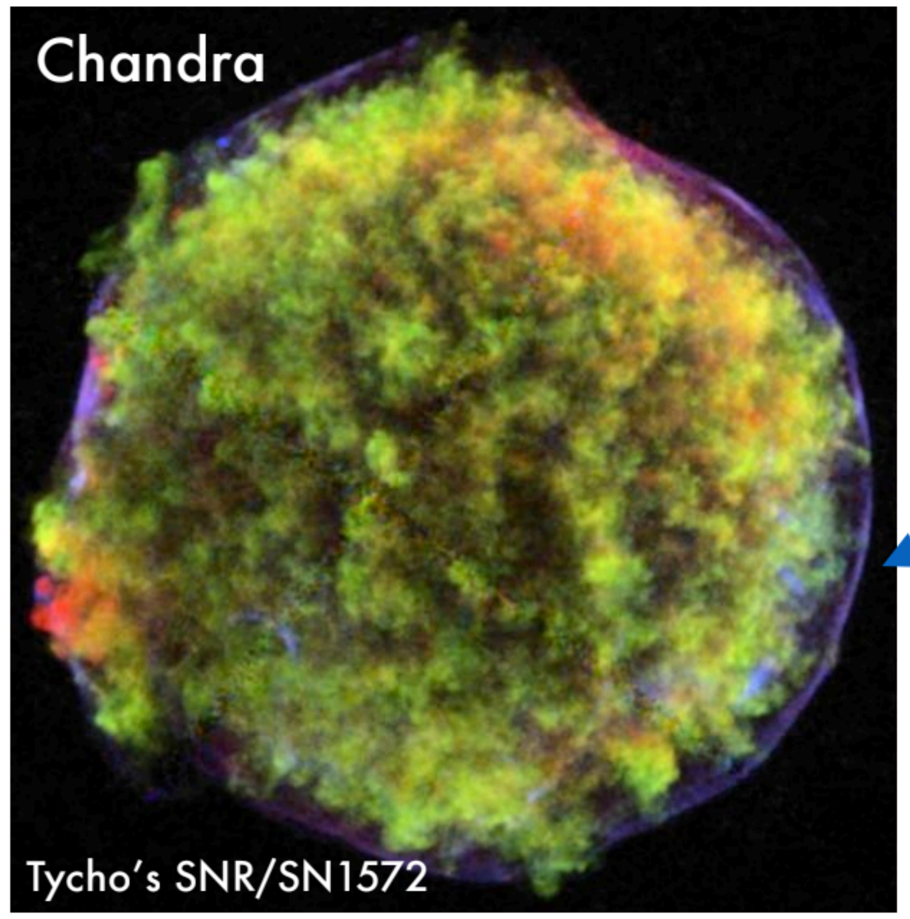


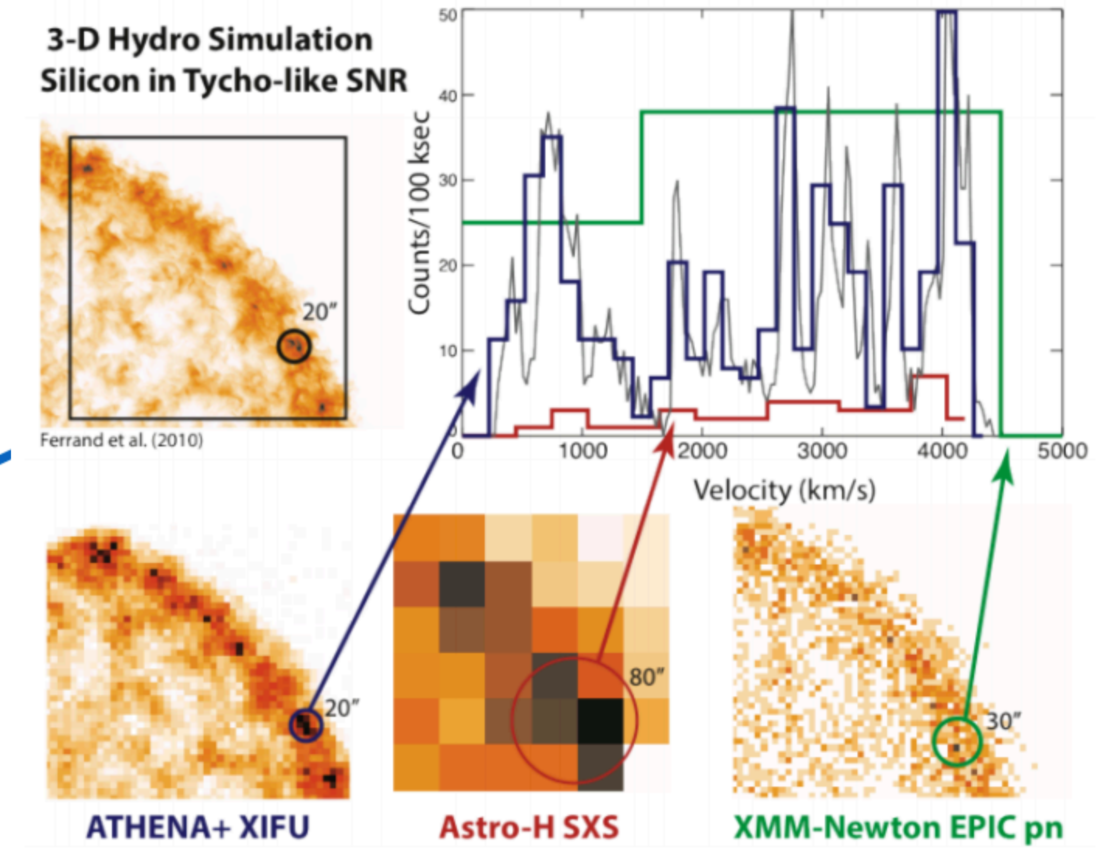
Leptons: synchrotron emission / hadronic: pion decay

Gamma-rays: not always possible to disentangle leptonic vs hadronic processes

Constrain hadronic processes:

- Need background density estimate → thermal X-ray observations
- Need magnetic field intensity → X-ray filament width
- Line broadening at the edge of the SNR: T_{ion} → cosmic ray acceleration efficiency





Decourchelle et al., 2013

Conclusions

- Athena will be an observatory impacting all fields of astronomy
- Over-performs any existing or planned X-ray mission
- Rapid ToO response and quick agility well tuned for multi-messenger astronomy
- NS-NS merger events (synergies with ground-based GW interferometers)
    - Detect jets at all orientation, determine demography of chocked jets and uncollimated sources
    - Constrain off-axis jet geometry
    - Constrain fundamental physics of particle-shock acceleration

- Synergies with neutrino telescopes and CTA
    - Disantangle leptonic vs hadronic populations in AGN relativistic jets and sites of cosmic-ray acceleration
- SMBH merger events (synergies with LISA)
    - Potentiality of studying the behavior of matter in variable space-time
    - Witness the post-merger onset of AGN activity (corona, jets, ...)
    - Huge discovery space ... but real challenge

More information at https://arxiv.org/pdf/2110.15677.pdf