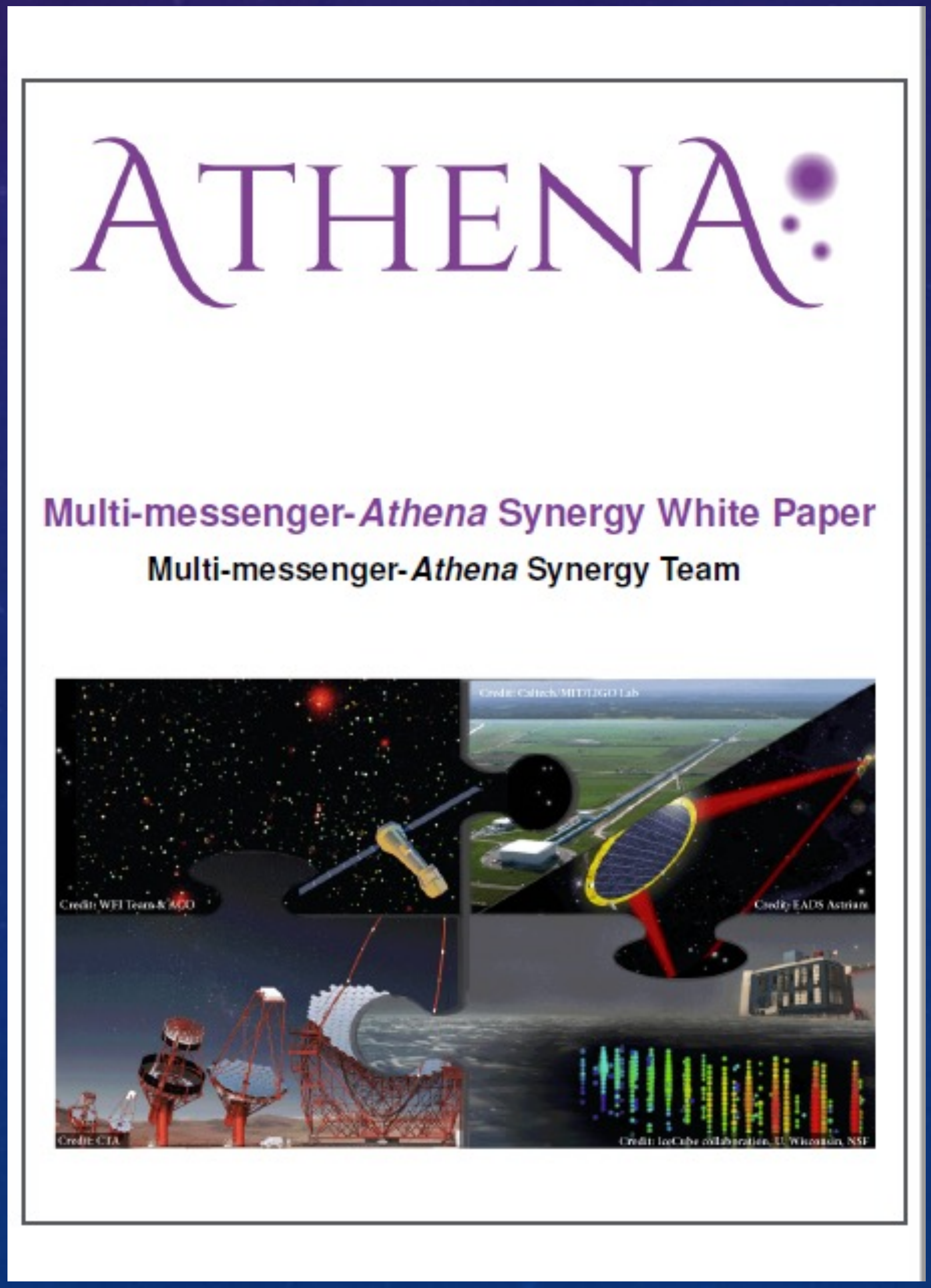
MULTI-MESSENGER SCIENCE WITH ATHENA AND FUTURE MULTI-MESSENGER OBSERVATORIES

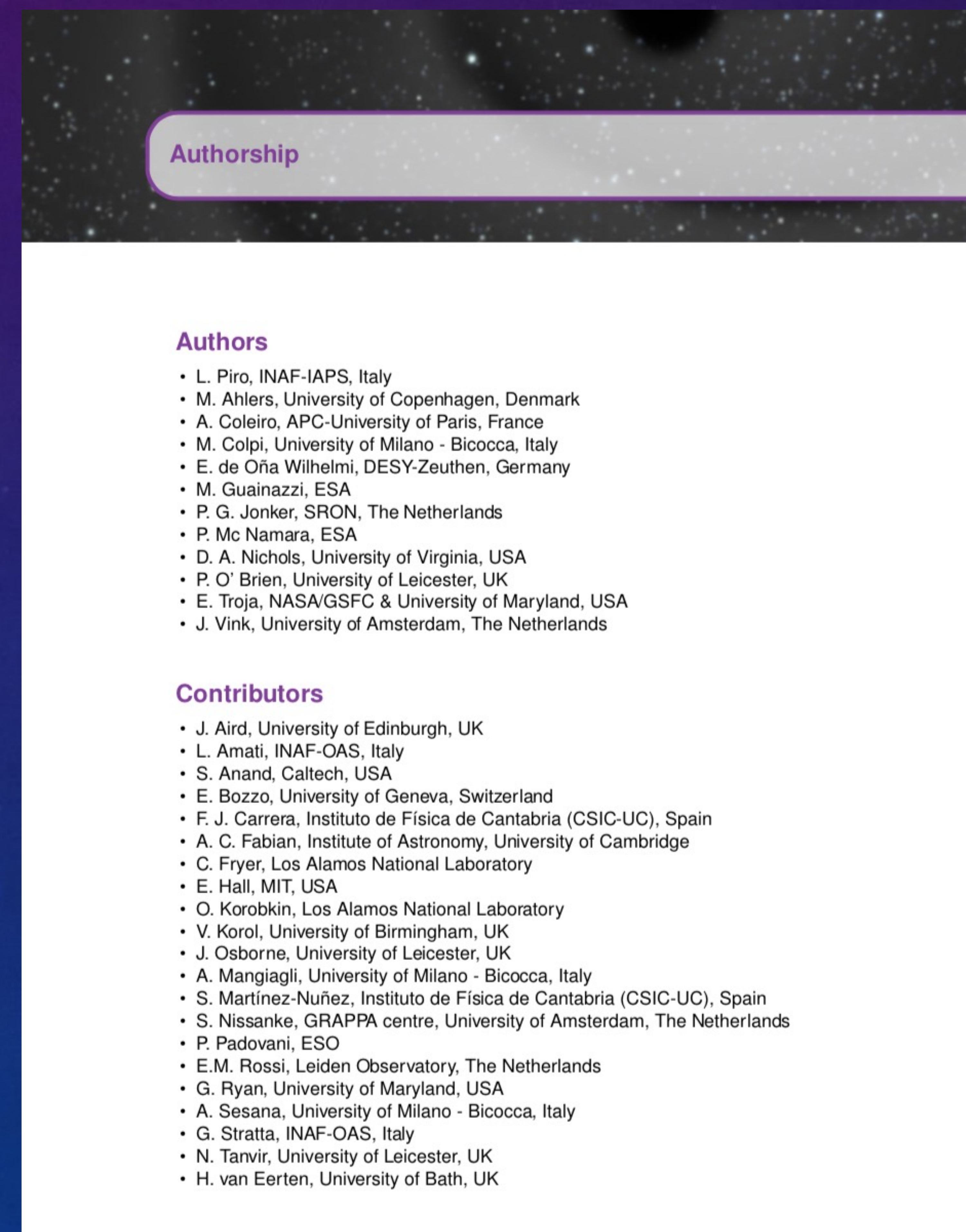


LUIGI PIRO

INAF/IAPS

THE ATHENA MULTI-MESSENGER SYNERGY WHITE PAPER

- Scientific synergies between the Athena and Gravitational Waves, neutrinos, high energy and Gamma Ray Burst transient facilities that will be operational contemporary to Athena.
- Outline the observing strategy to successfully implement the synergy science goals
- Each facility (incl Athena): contact person + experts
  - **A& ground based GW, AVirgo/Aligo and future facilties (ET, CE,..)**
  - **A& LISA**
  - **A& ν's and HE (ICECUBE, KM3Net, CTA)**
  - A& Transient Universe experiments a la Theseus
- Piro et al 2021: arxiv:2110.15677, Exp.Astron, 2022



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RECENT DEVELOPMENTS ON ATHENA

- Revision of the Large Mission program after ESA exec proposal at June SPC due to current cost estimation of Athena (1.9Be end of phase B1) and LISA (1.5 Be end of phase A) :
- Both missions to comply with an indicative cost-cap of 1.3Beuro each
- Athena instruments successufully went through SRR
- (New)Athena to run a design-to-cost study, aiming at retaining the ambition as a flagship mission and departing as little as possible from the current configuration but with the expectation of significant reduction in the complexity and performance
- Involving ESA, Athena Instrument Consortia and Athena science redefinition team (open call)
- ESA-Athena Instrument Consortia KO meeting: Sept.22
- Mission re-design by 2023, followed by Delta phase A-B1
- Exisiting science drivers and the new prospects of Multimessenger Science, based on planned performances, provide a crucial reference to steer the study

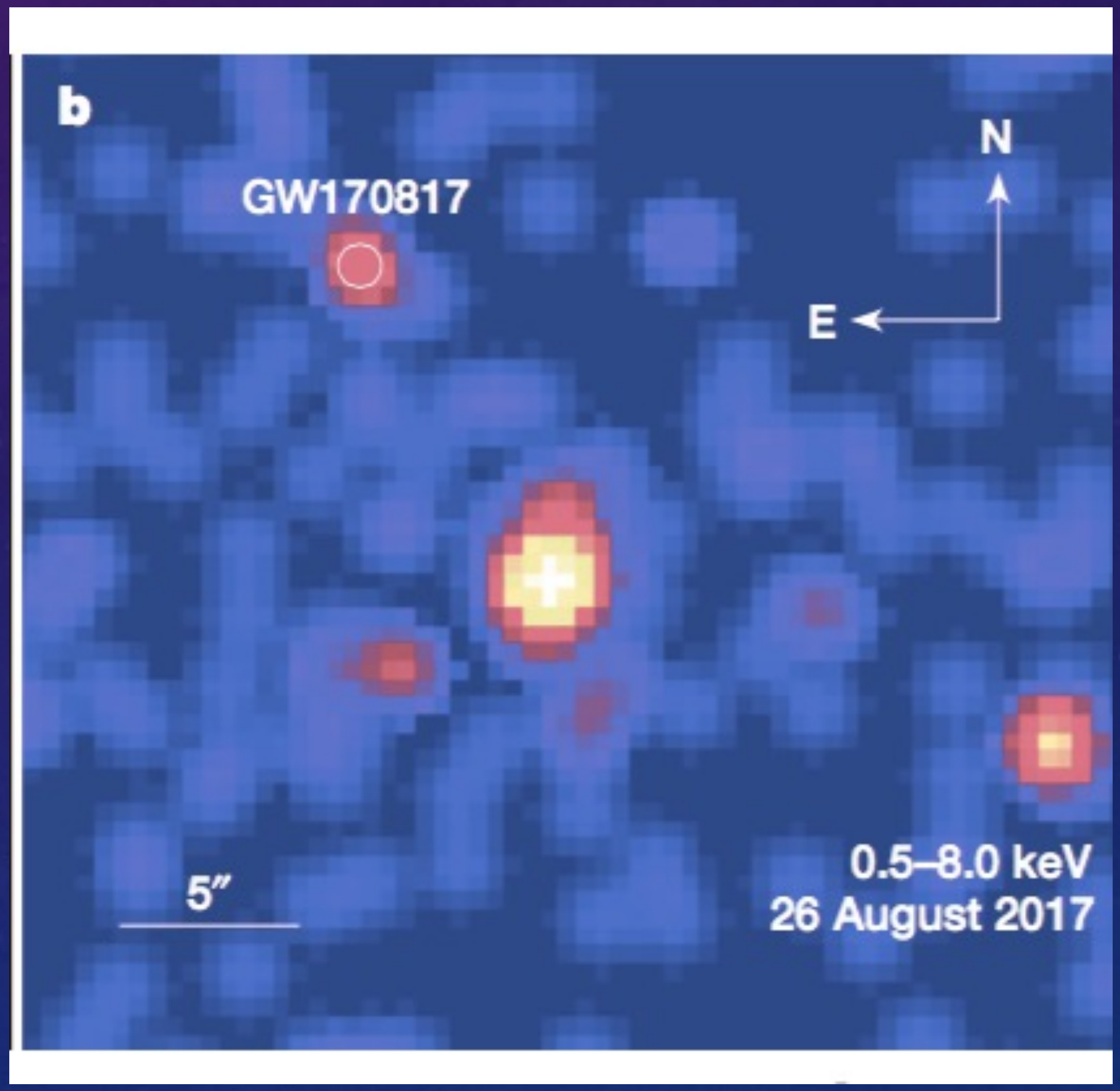
ATHENA AS A MULTIMESSENGER TOOL

- Energetic phenomena explosions, accelerations sites, transients
- Athena assets:
  - 10-100 fewer field sources than at lower frequencies
  - Wide field (0.4 sq.degree) (+mosaic/raster scan)
  - arcsec imaging (location accuracy 1arcsec)
  - sensitivity down to few 10^{-17} erg/cm2/s
  - Integral field spectroscopy with high spectral resolution (R=1000@2.5keV)
  - Fast Too (4hrs) , large FoR(>50%)

ATHENA AND GROUND-BASED GW INTERFEROMETERS

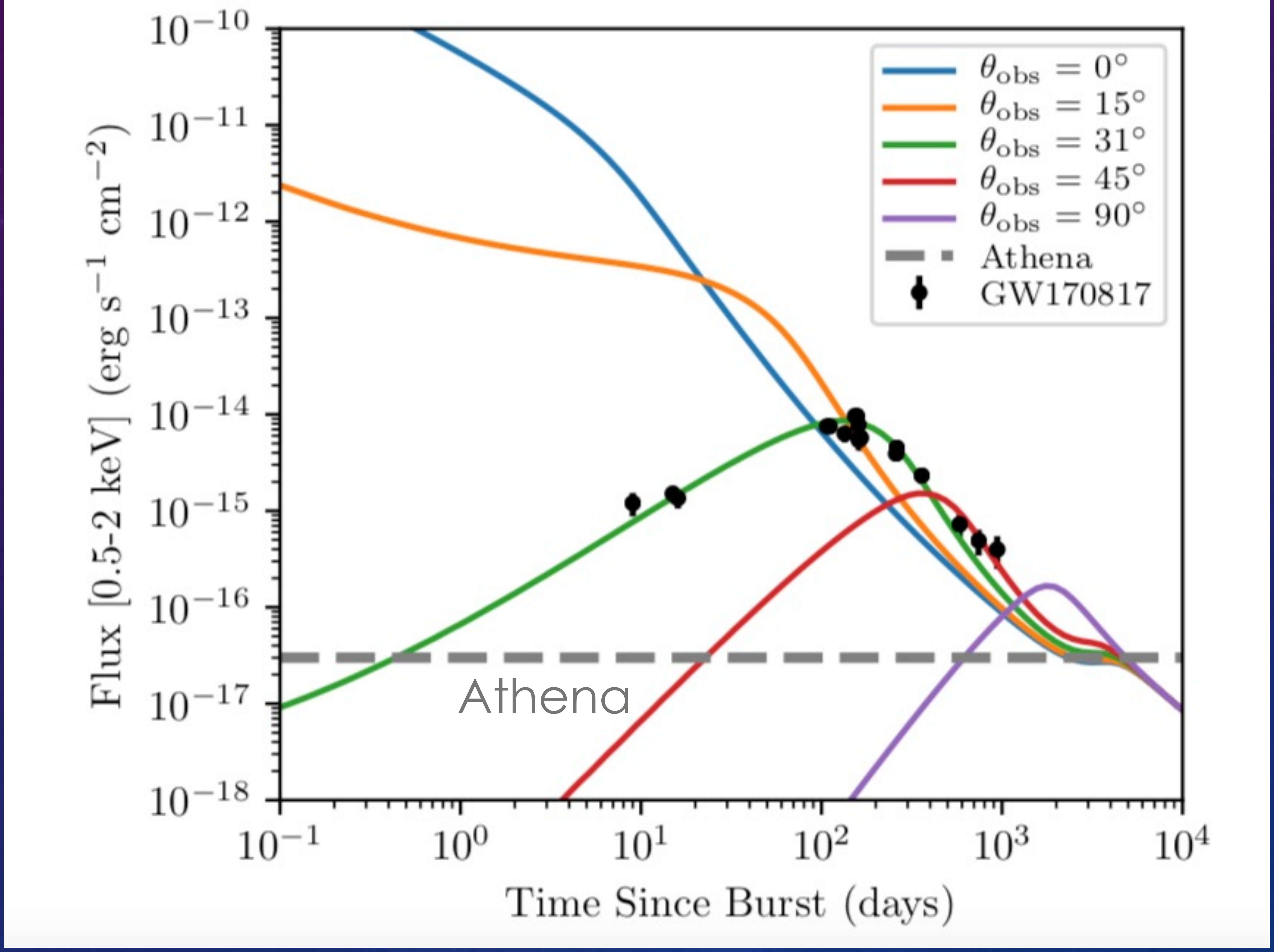
- Synergy science themes
  - **Jet physics and accretion power**
  - Formation and evolution of black holes,
  - NS EOS
  - Acceleration processes
  - **How did intermediate- and high-Z elements form**
- Class of Sources
  - Binary stellar mergers (BNS, BBH, NS-BH)

Discovery image of GW170817 with Chandra



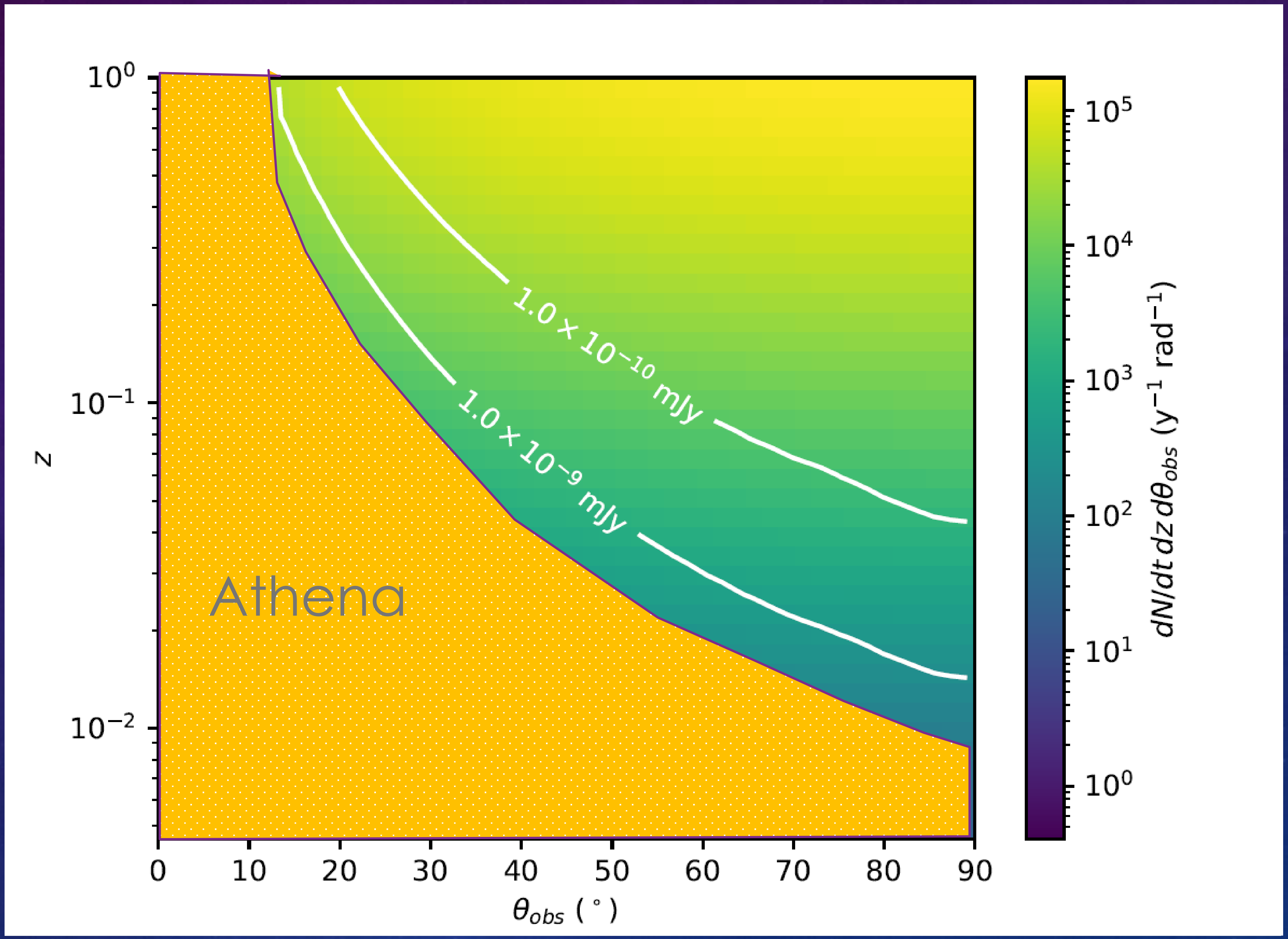
Troja, Piro, van Eerten+ Nature, 2017

EXTENDING THE EM HORIZON OF GW MERGERS WITH ATHENA



GW170817-like

EXTENDING THE EM HORIZON OF JETS FROM GW MERGERS

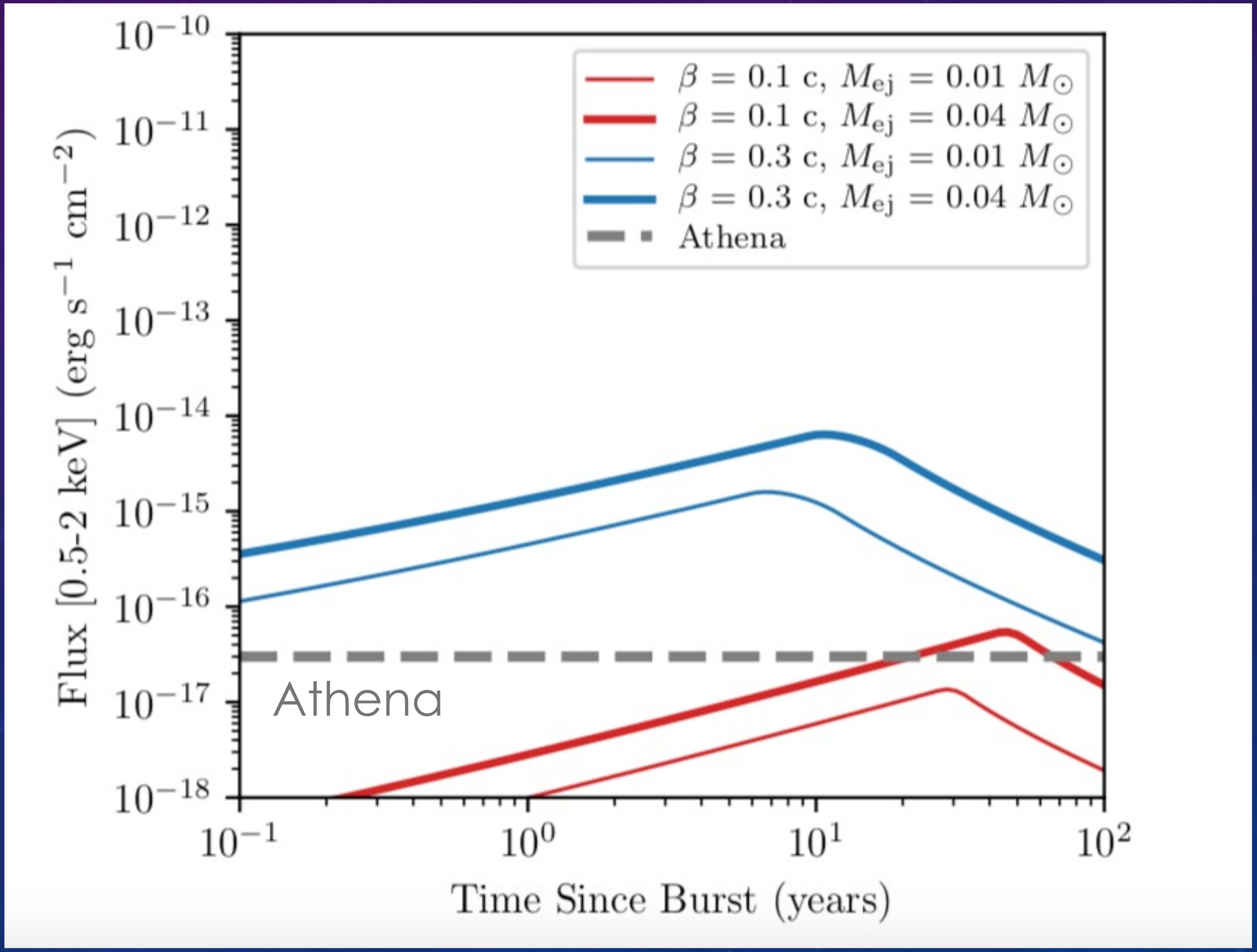


GW170817-like upto 35 deg for z<0.1 and 15 deg for z<1

LATE-TIME X-RAY KILONOVA

- Mass and velocity of ejecta and launching mechanisms (dynamical, wind from AD)
- Constraints on r-process material
- Additional energization by magnetar

Afterglow from interaction of kilonova ejecta with environment



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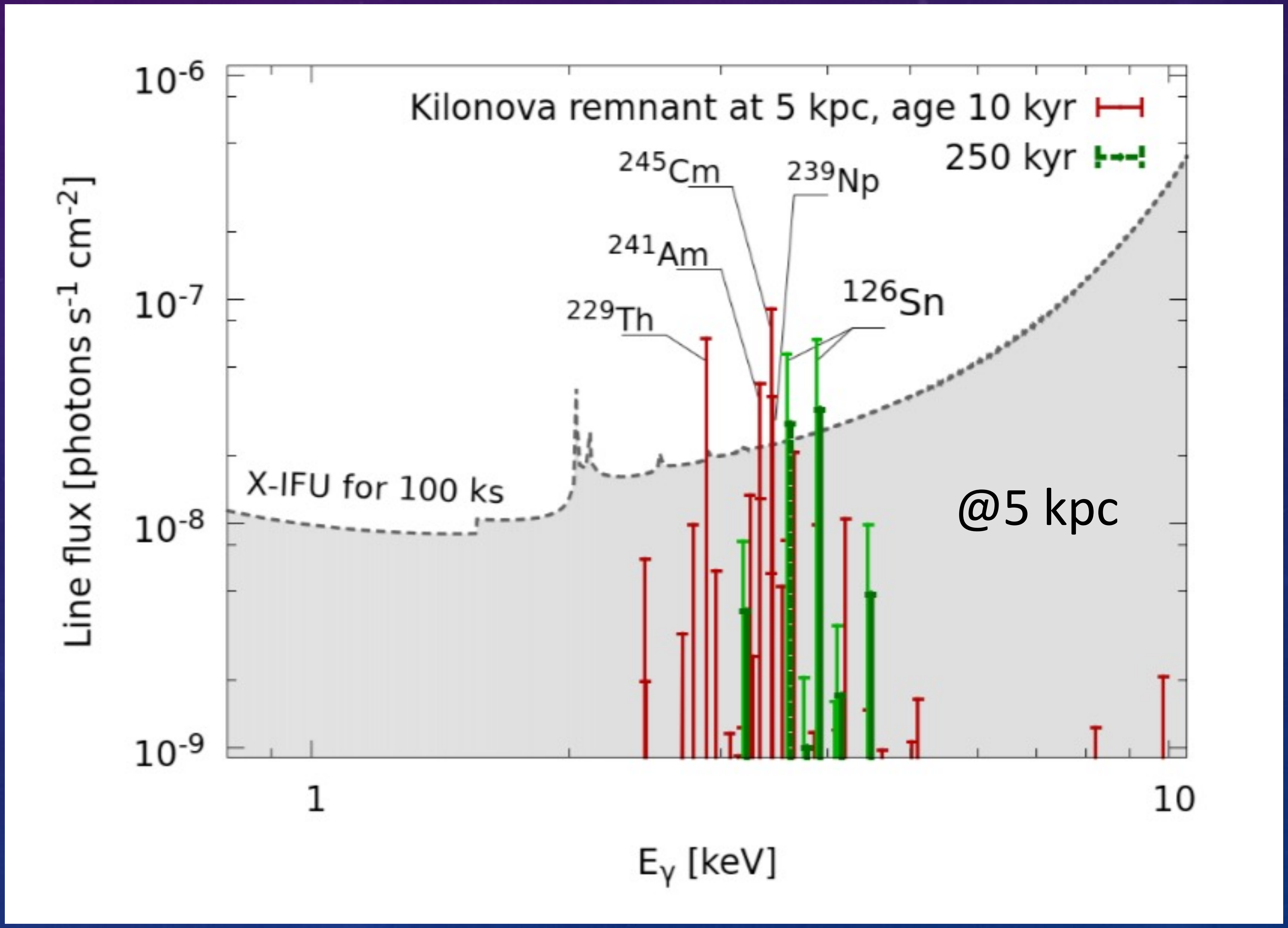
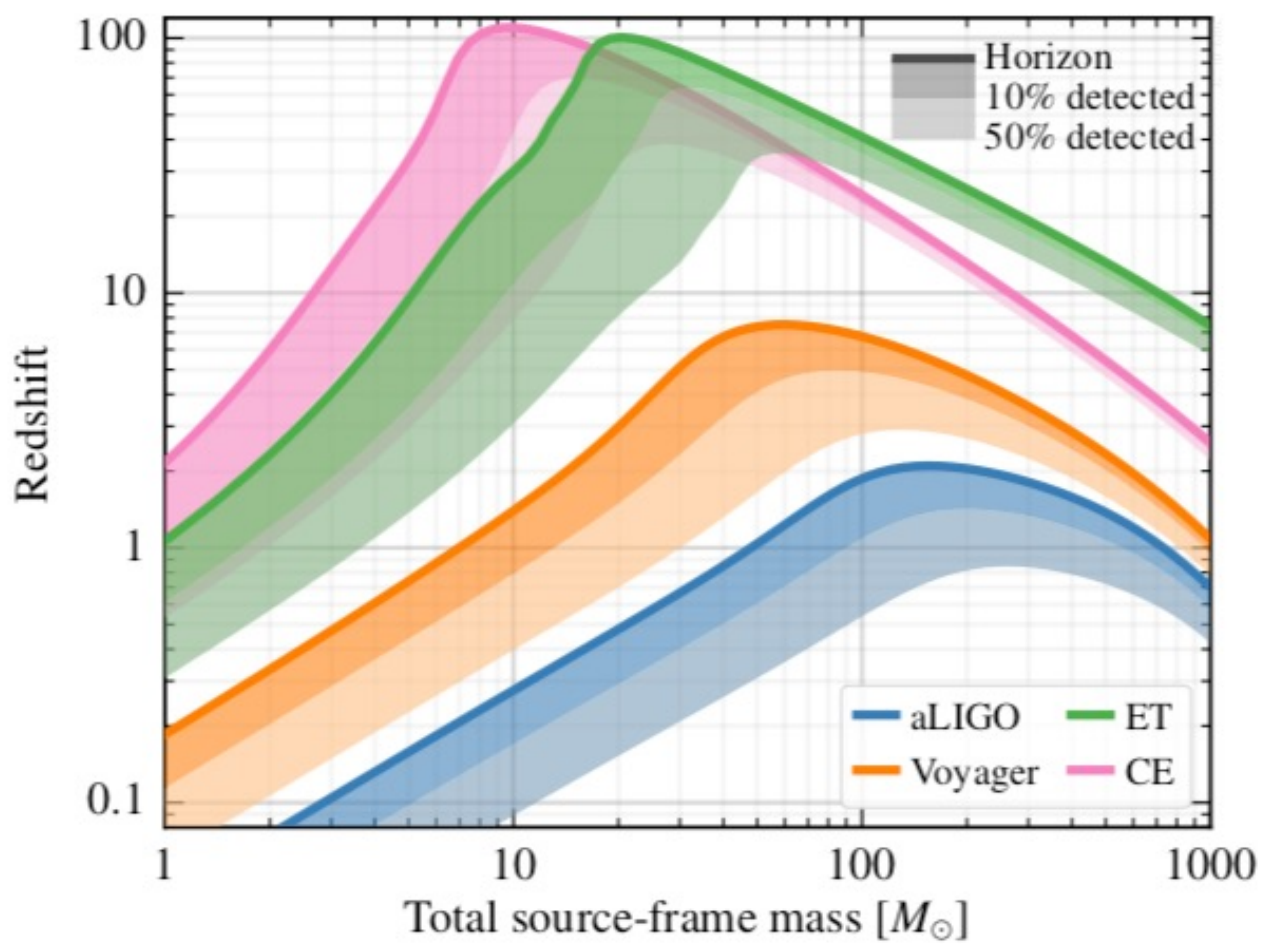
X-RAY KILONOVA REMNANTS

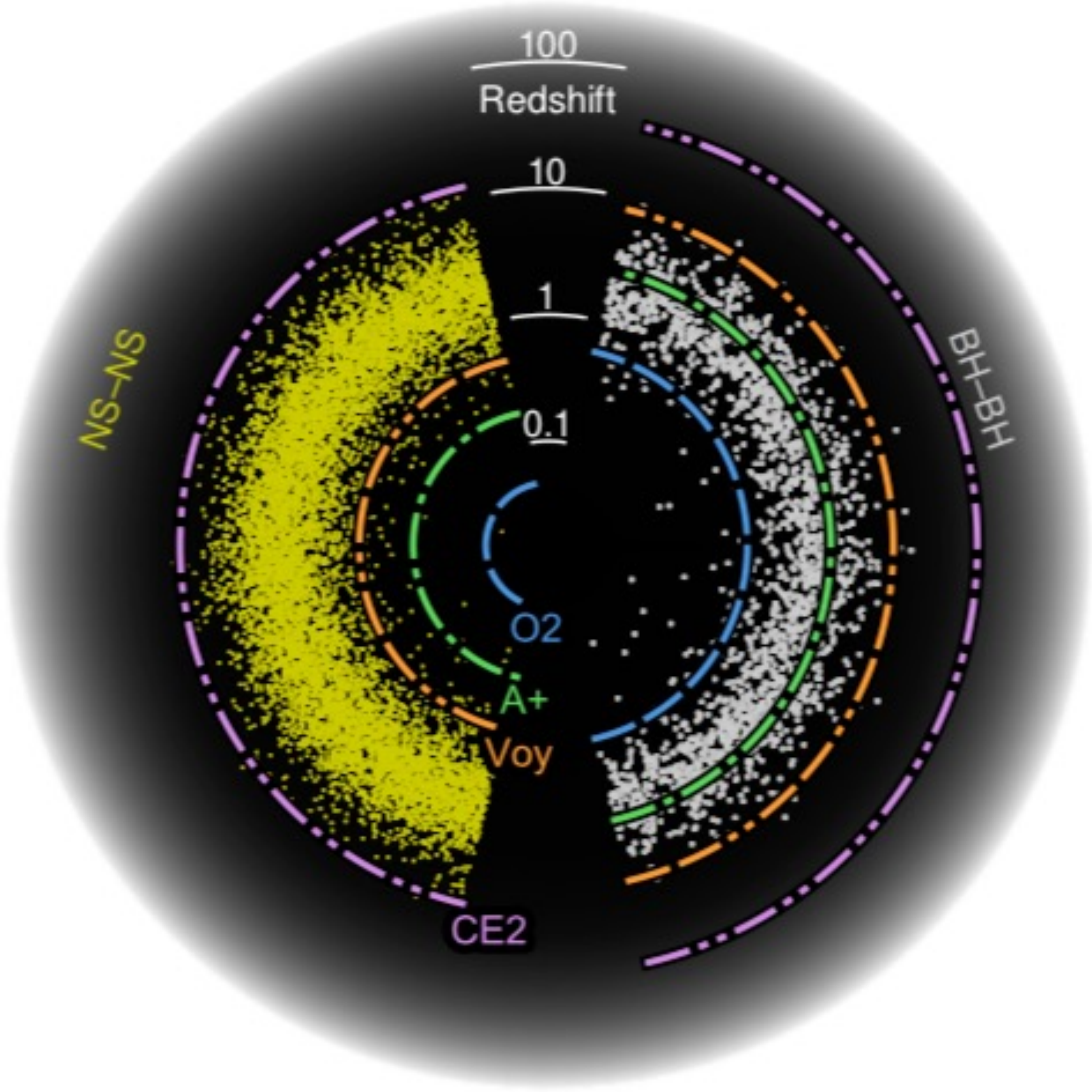
Line emission from radioactivity from r-process isotopes:

- Amount/composition of ejecta
- Constraints on nuclear physics models of r-process

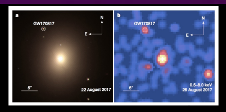


HORIZON AND RATES OF GW INTERFEROMETERS





Network	N(detected) [yr^{-1}]	Median loc. [sq.deg]	N(<1 sq.deg.) [yr^{-1}]	N(<10 sq.deg.) [yr^{-1}]	N(<100 sq.deg.) [yr^{-1}]
HLVKI	15	7	0	15	15
3Voyager	800	20	5	170	770
1ET+2Voyager	6,100	21	20	960	6,100
1ET+2CE	320,000	12	4,500	130,000	310,000



OBSERVING STRATEGY

- Population of NS-NS and NS-BH in the parameters space:
  - Inclination angle (dependance of jet model/structure)
  - Spin of the final object (relevant e.g. for jet launching/energy extraction)
  - Spin of the initial BH (fo BH-NS, drives the mass of kilonova ejecta)

Athena (WFI&XIFU) sample of light curves (and spectra) of 40 events

- Late-time kilonova/magnetar emission
  - Athena XIFU sample of 10 mergers localized in the >2020 by GW+EM (expected >40)
  - Potential kilonova remnants (radio candidate, SN126 features in SNR)
- Early kilonova
  - Athena (WFI) Sample of ~ 10 events
  - Fast TOOs

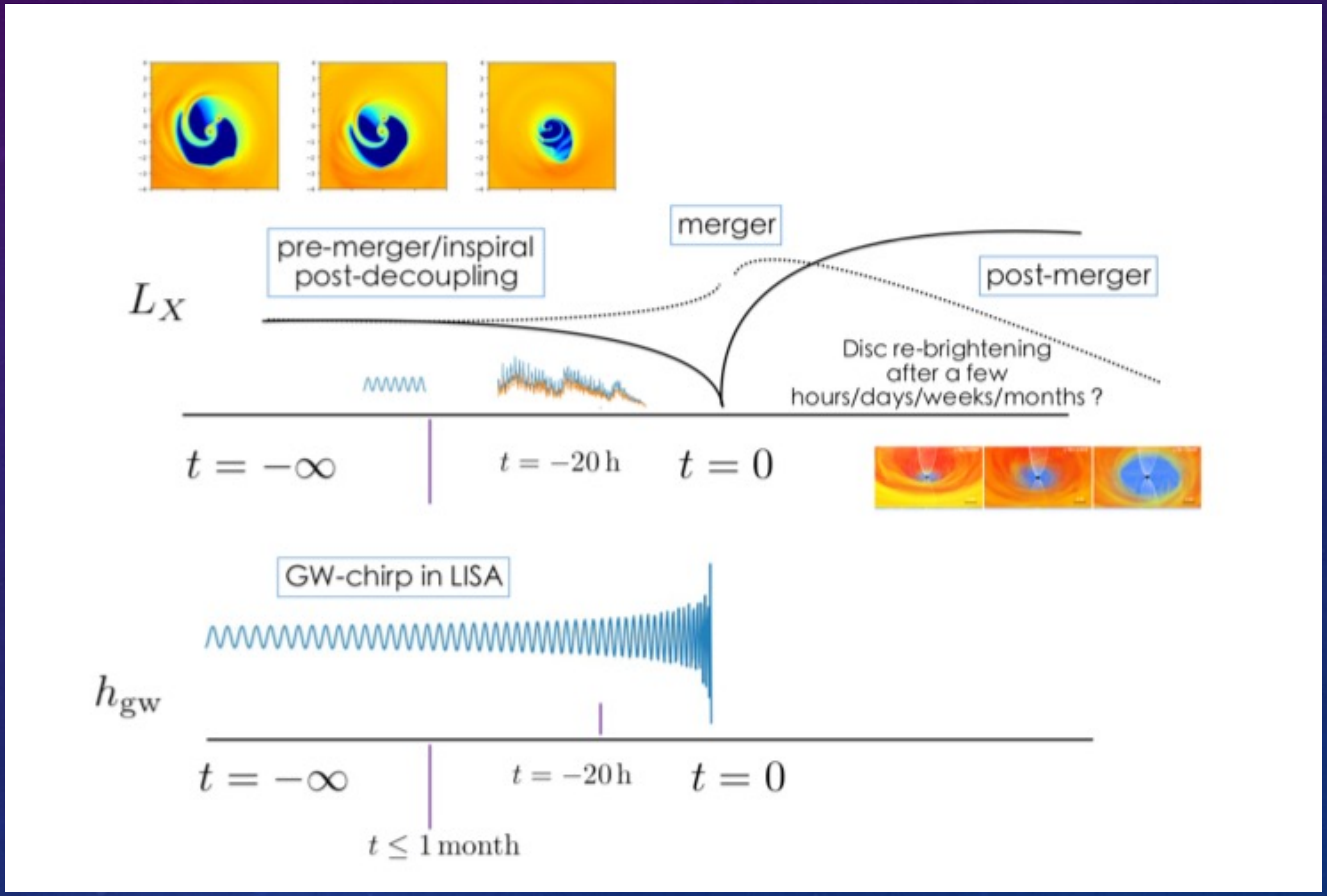
ATHENA AND LISA

- Synergy science themes
  - **Accretion flows, formation of X-ray corona and jet launching around newly formed horizons**
  - Testing General Relativity as theory of gravity and measuring the speed of GWs and dispersion properties *(GW and EM chirp)*
  - Enhancement of the cosmic distance scale using GW sources as standard sirens
- Sources
  - **Super Massive (binary) BH mergers (SMBHM) in gas-rich environments**
  - Extreme mass ratio inspirals (EMRIs) where a stellar black hole is skinning the horizon of a large black hole surrounded by an AGN disc
  - Coalescence of stellar mass binary BHs
  - Interacting double white dwarf and accreting binary systems

X-RAY AND GW TIMELINE OF SMBHM

X-ray emission based on theory, widespread range of prediction

- Premerger: Gas accretion (modulated): X-ray precursor
- Post-merger: formation of hot corona, launch of jet



RATES AND JOINT ATHENA-LISA OBSERVATIONS

- SMBHB binary by LISA: 10 to 300 in 4 years
- Athena exploratory sample: error box & X-ray flux by Athena=> z<1-2 for mass 10^5-10^7 Msun: a few

Table 3.1: Observational-based predicted number of expected SMBH merging events visible by *Athena* and LISA over 5 years.

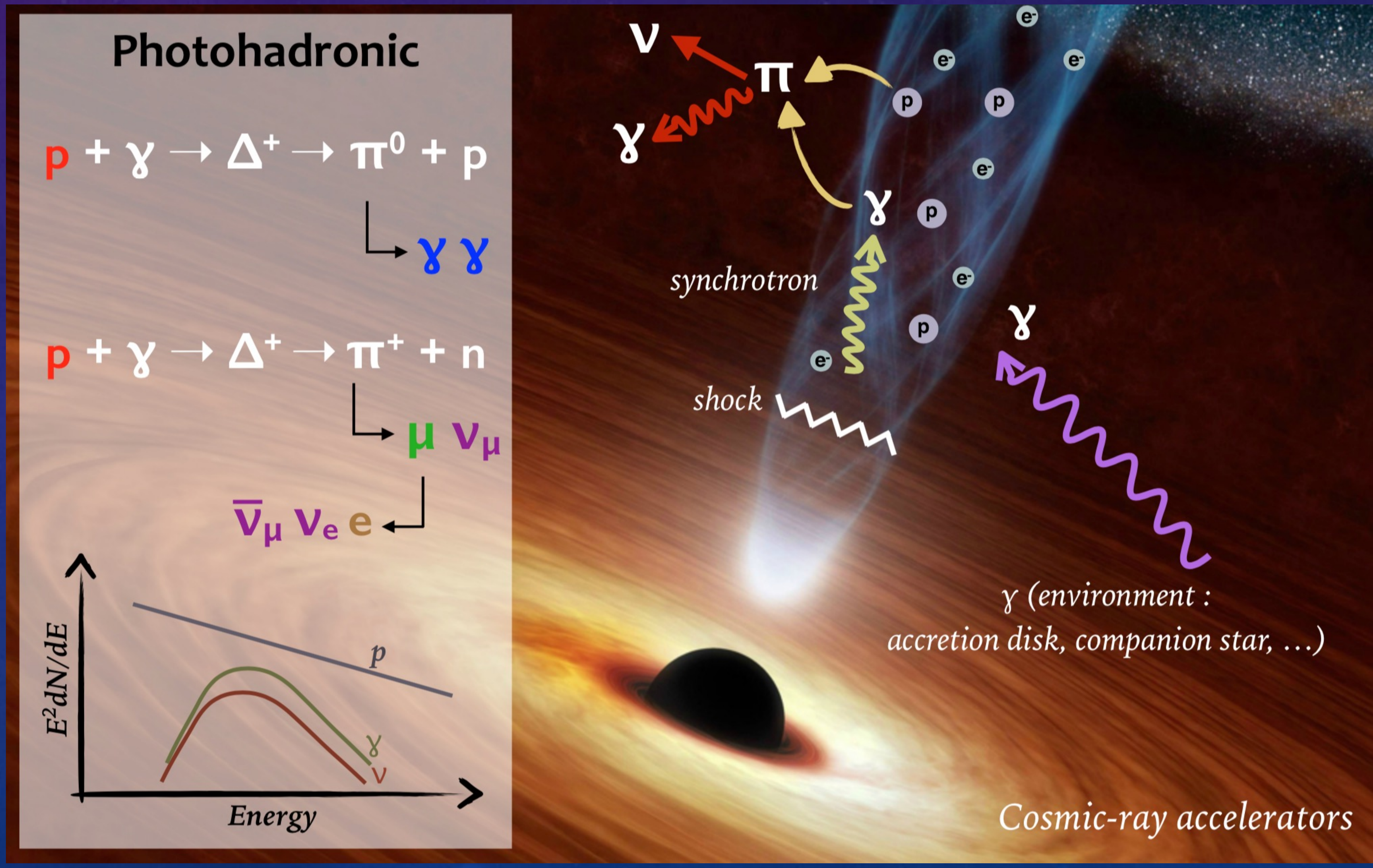
	$M=10^6\ M_\odot$	$M=10^7\ M_\odot$
$z = 1$	1.5	0.5
$z = 2$	12	1.2

Table 3.2: Fluxes(0.5-2 keV) in cgs units and exposure times (in brackets, units of ks) to detect a X-ray unobscured AGN at the Eddington limit with the current configuration of the *Athena* mirror+WFI.

	$M=10^5\ M_\odot$	$M=10^6\ M_\odot$	$M=10^7\ M_\odot$
$z = 1$	5.3×10^{-17} (250 ks)	5.3×10^{-16} (7 ks)	5.3×10^{-15} (<1 ks)
$z = 2$	1.1×10^{-17} ($\gtrsim$1 Ms)	1.1×10^{-16} (70 ks)	1.1×10^{-15} (3 ks)

ATHENA, VHE AND NEUTRINO OBSERVATORIES

- Overaching theme: Cosmic Accelerators and Origin of Cosmic Rays
  - Hadronic vs Leptonic
- Sources (shock sites):
  - Blazars
  - SNR
  - Sne (ν's from CC)
  - Pulsar/PWN
  - GRBs
  - Starburst galaxies
  - Clusters as CR reservoirs
  -



ROLE OF X-RAY OBSERVATIONS WITH ATHENA

- Constrain the hadronic vs leptonic origin of the gamma-ray component => Same acceleretion process for hadrons and leptons. X-ray counterpart of CR: Synchroton from accelerated electrons (spectra, imaging)
- Enable conversion of neutrino and/or gamma-ray luminosity into a total energy budget of CR=> X-ray thermal emission => density and composition (high-res spectra, imaging, w.p.r.t. to Synchrotron-dominated regions)
- Measure the efficiency of CR acceleration in the source=> ion temperature is a proxy => high-resolution spectral of the thermal line broadening (hundreds km/s to separate bulk motions)

OBSERVING STRATEGY

- Athena science theme (Hot and Energetic Universe) includes several sources that are promising sites of particle acceleration targeted by VHE and neutrino telescopes (simultaneous obs not requested)
- Follow-up of new sources found by CTA (galactic and extragalactic survey): imaging and spectra with AThena
- TOO observations of neutrino alerts (about 10 per year) and CTA transients (e.g. VHE from GRBs, upto 2/year).

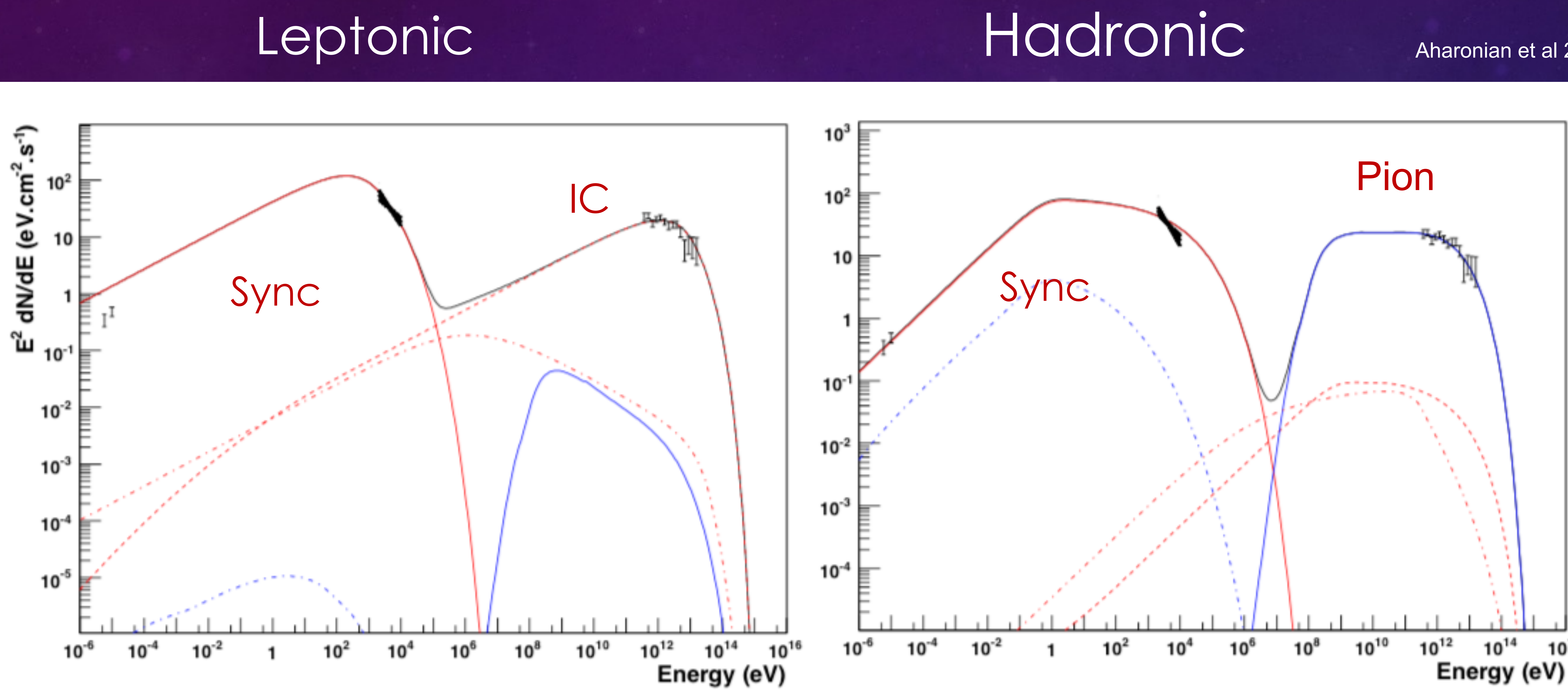
CONCLUSIONS

- Athena observational capabilities well suited to Multimessenger window
- Joint study specifically devoted to Athena, Advanced LIGO, Virgo, and 3G (ET,CE), LISA, CTA, KM3Net, ICECUBE in a White paper:
  - Several exciting science themes, boosting the scientific return
  - Preliminary Observational strategy (including discovery/explorative observations)
- Multimessenger synergies as presented here expected to be a key driver in the redefinition of (New)Athena

BACK UP SLIDES

AN EXAMPLE OF A SNR

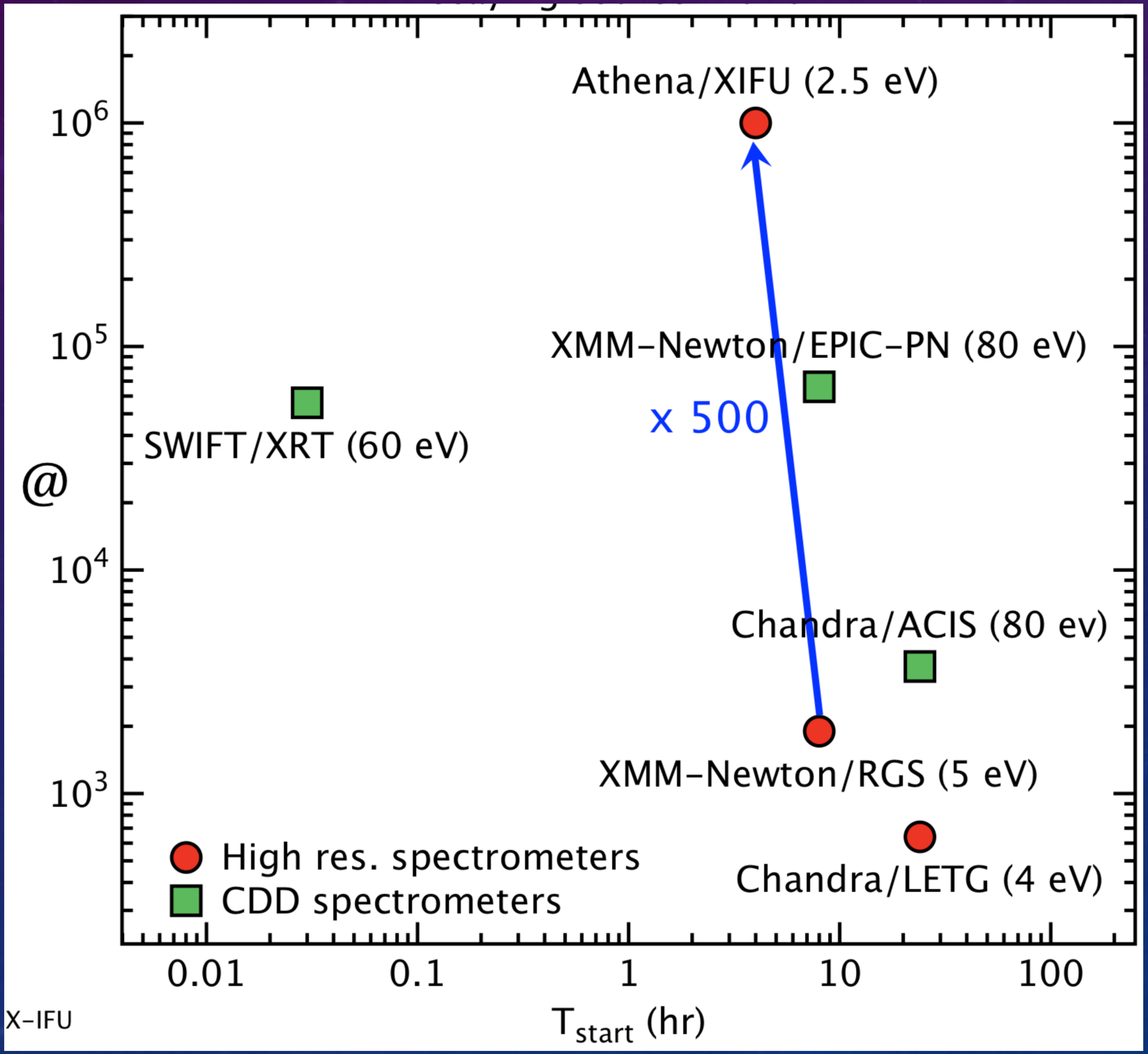
Aharonian et al 2017



In addition: high spectral resolution by *Athena* of the thermal X-ray component, if present (like in SNR), helps in assessing the energy content of the hadronic component, by measuring the density and ion temperature, a proxy of CR acceleration efficiency.

Athena TOO

enabling high spectral resolution and high sensitivity in the Transient Universe



- Afterglow of mid-bright GRB observed for 50 ksec

X-RAY KILONOVA REMNANTS

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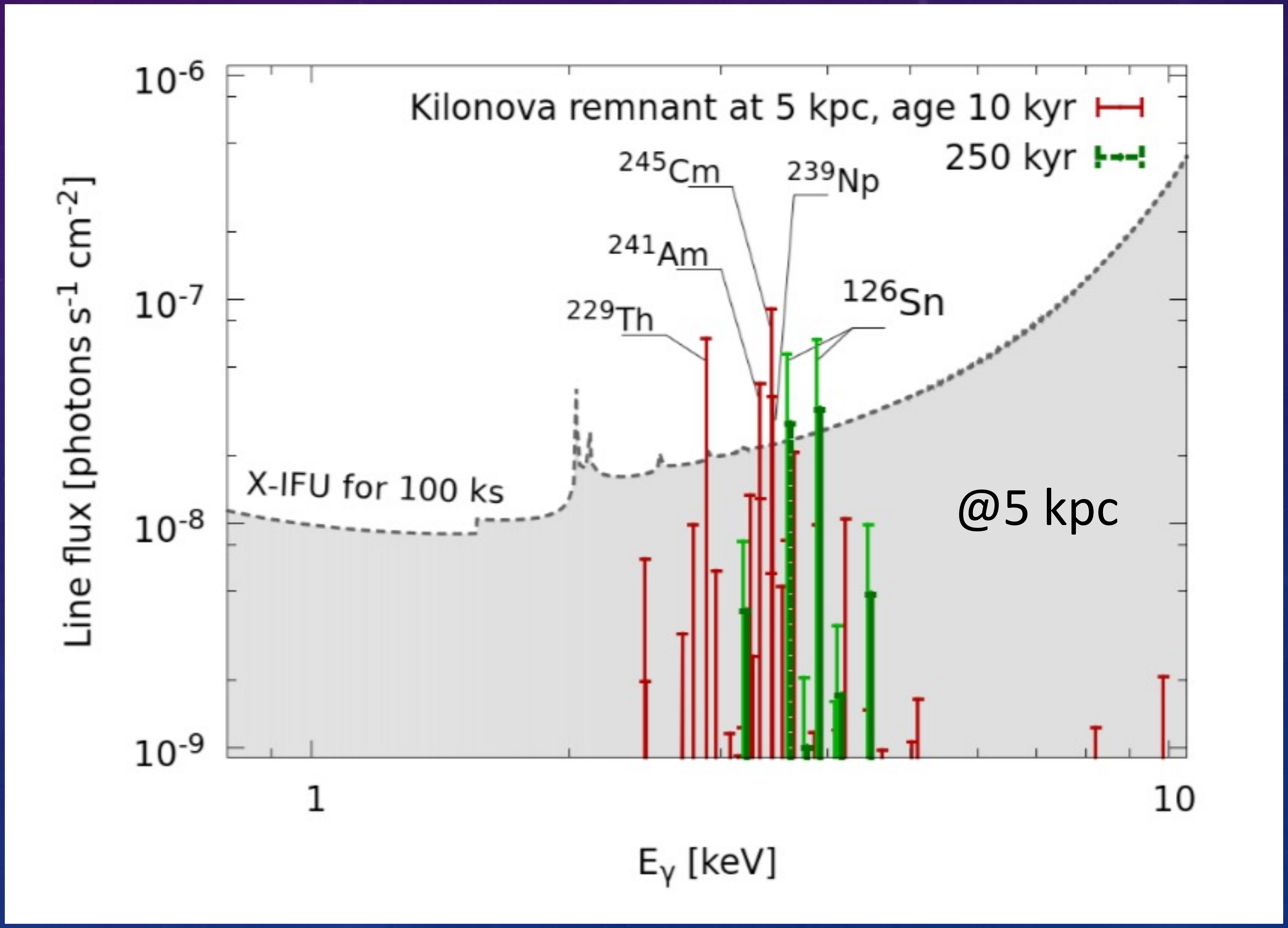
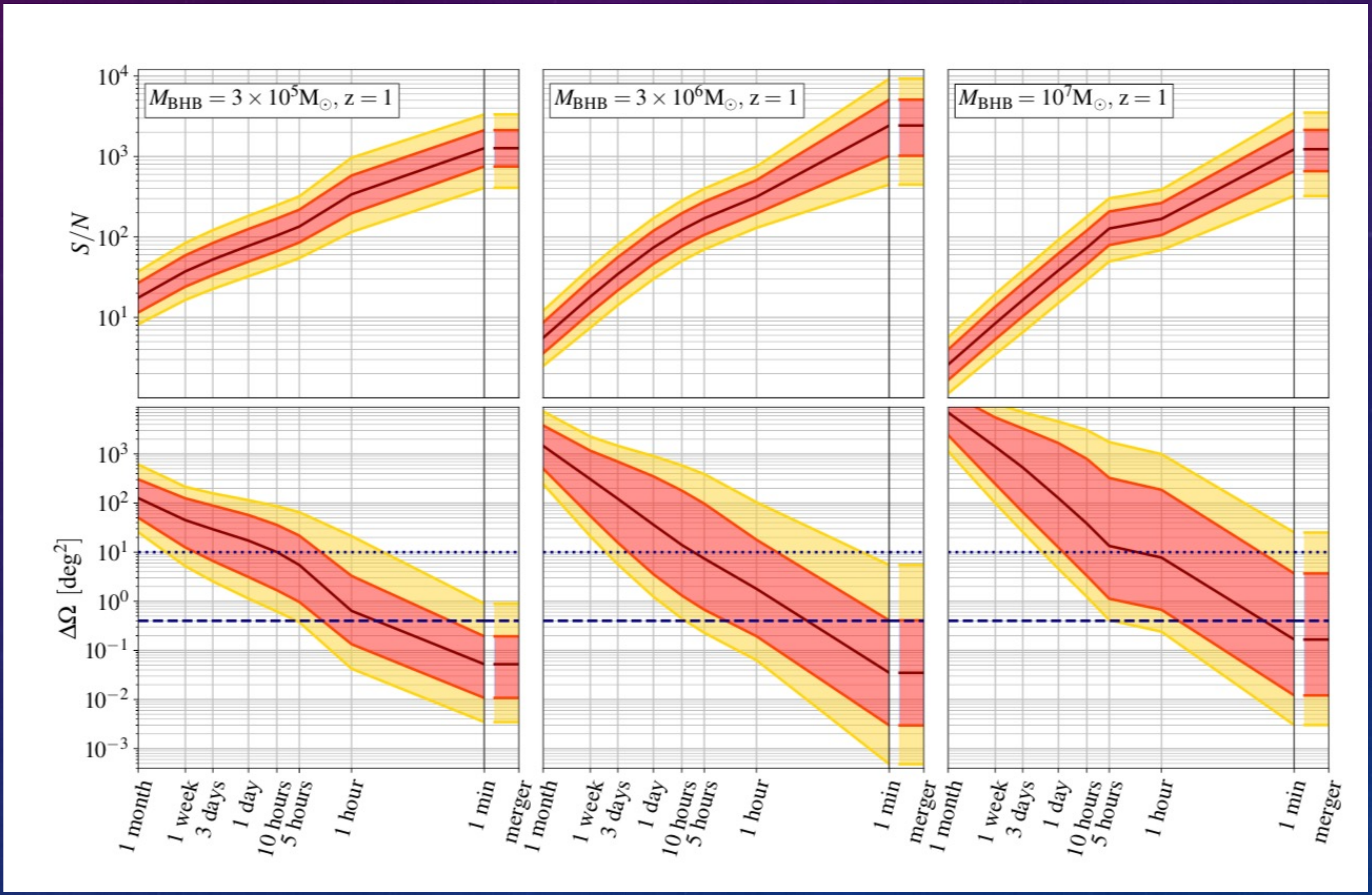


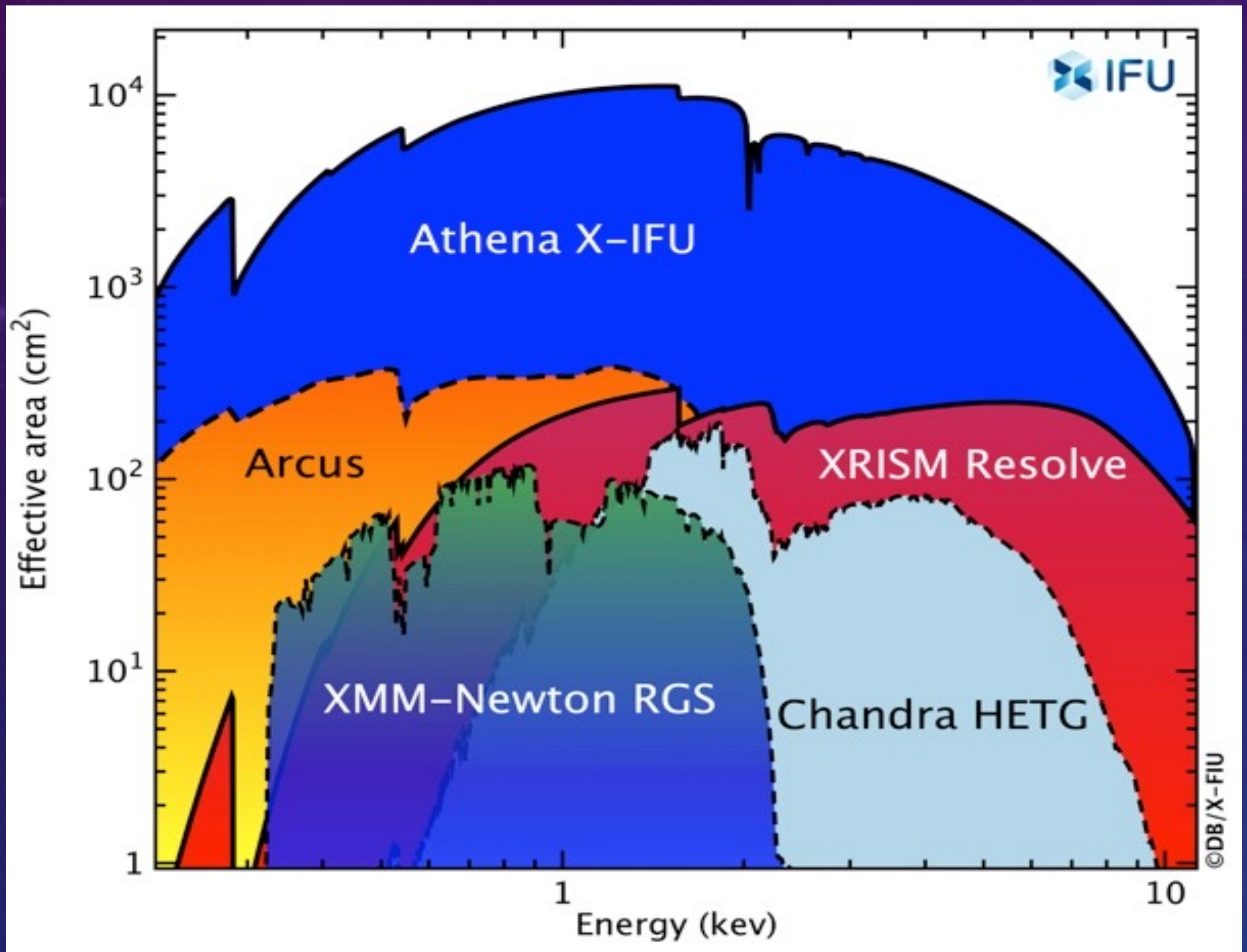
LISA LOCALISATIONS OF SMBBH

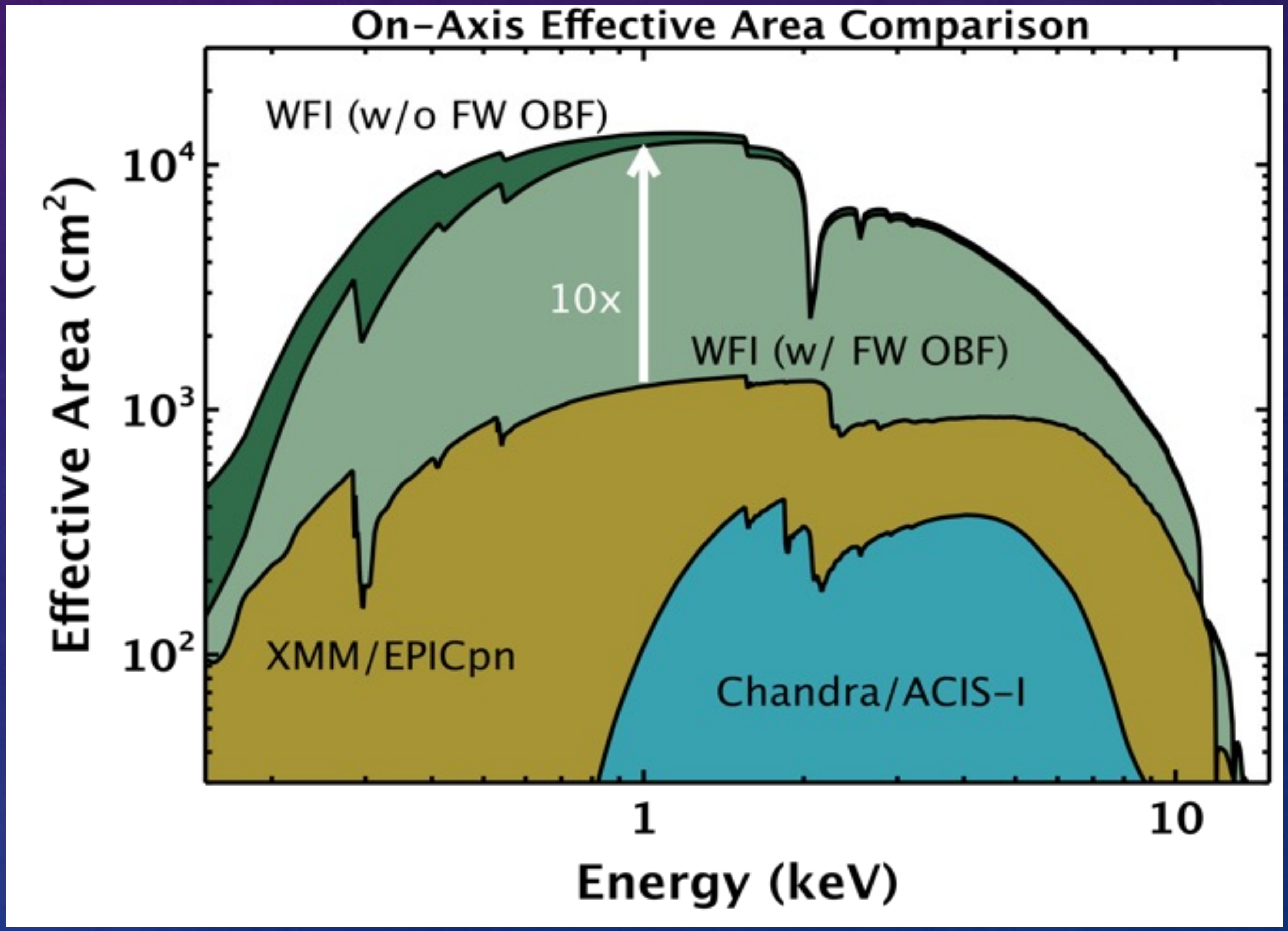


Athena raster scan

Athena WFI

ATHENA EFFECTIVE AREA

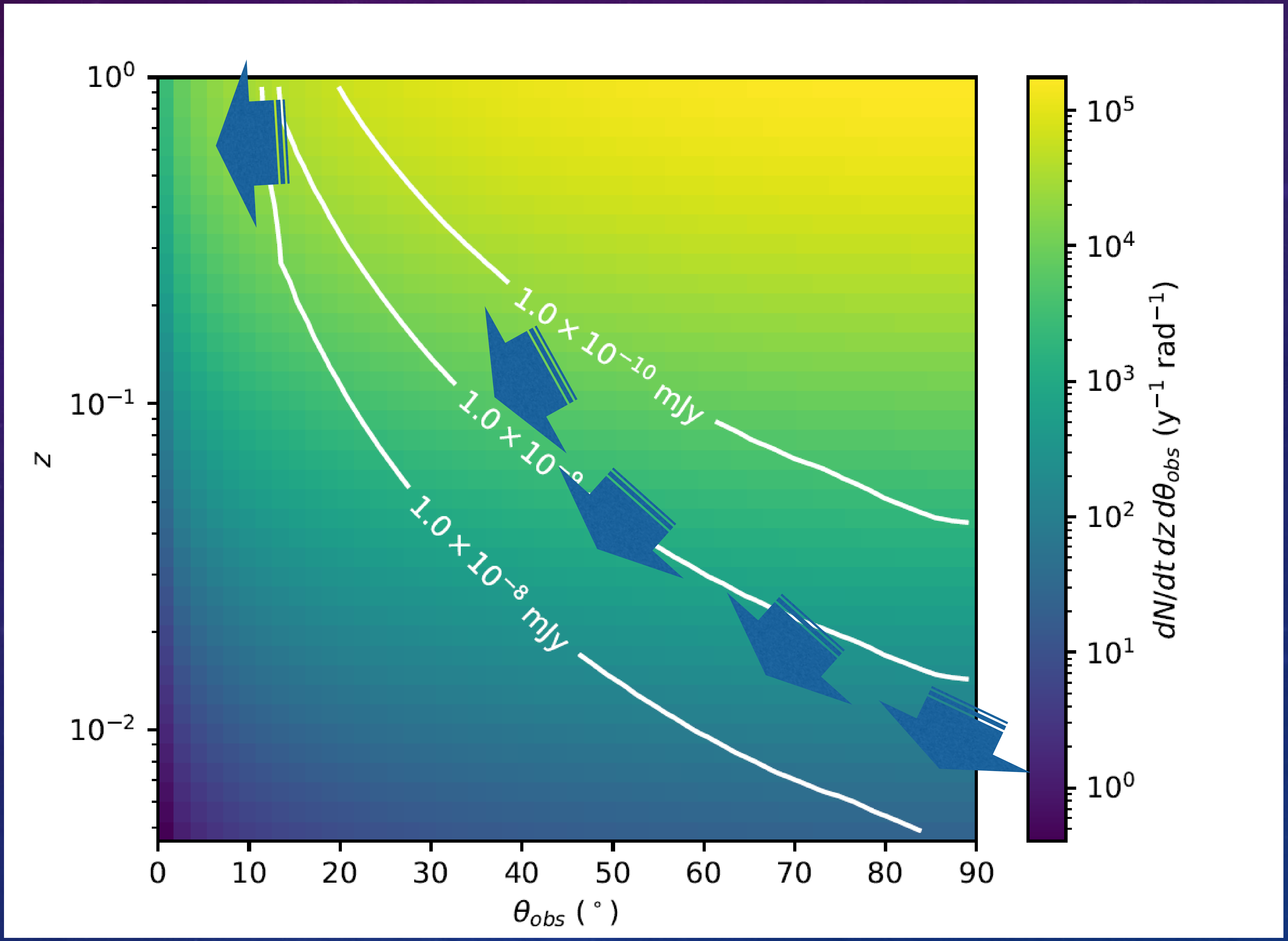




VHE AND NEUTRINO SYNERGY BY ATHENA/X-RAY OBSERVATIONS

- Source identification
- Determine what the radiation mechanism is:
  - pion decay (hadronic) → need local density estimate (e.g in SNR from X-ray)
  - Proton sync (hadronic) vs IC (leptonic)
  - inverse Compton (leptonic) → need local radiation field and B-field (synchrotron) Lsyn/LIC ≈ UB/Urad
  - bremsstrahlung (leptonic) → need local density estimate + B-field (synchrotron)
- Determine how particles are accelerated:
  - First order Fermi acceleration (shocks)
  - → study in detail in radio,optical, X-rays (velocity, ion temperature (line broadening) and get acceleration efficiency;
  - Second order Fermi acceleration (turbulence) → line broadening

EXTENDING THE EM HORIZON OF JETS FROM GW MERGERS



GW170817-like upto 40 deg for 2G and 15 deg for 3G