A sample of good miliparsec separation massive black hole binaries

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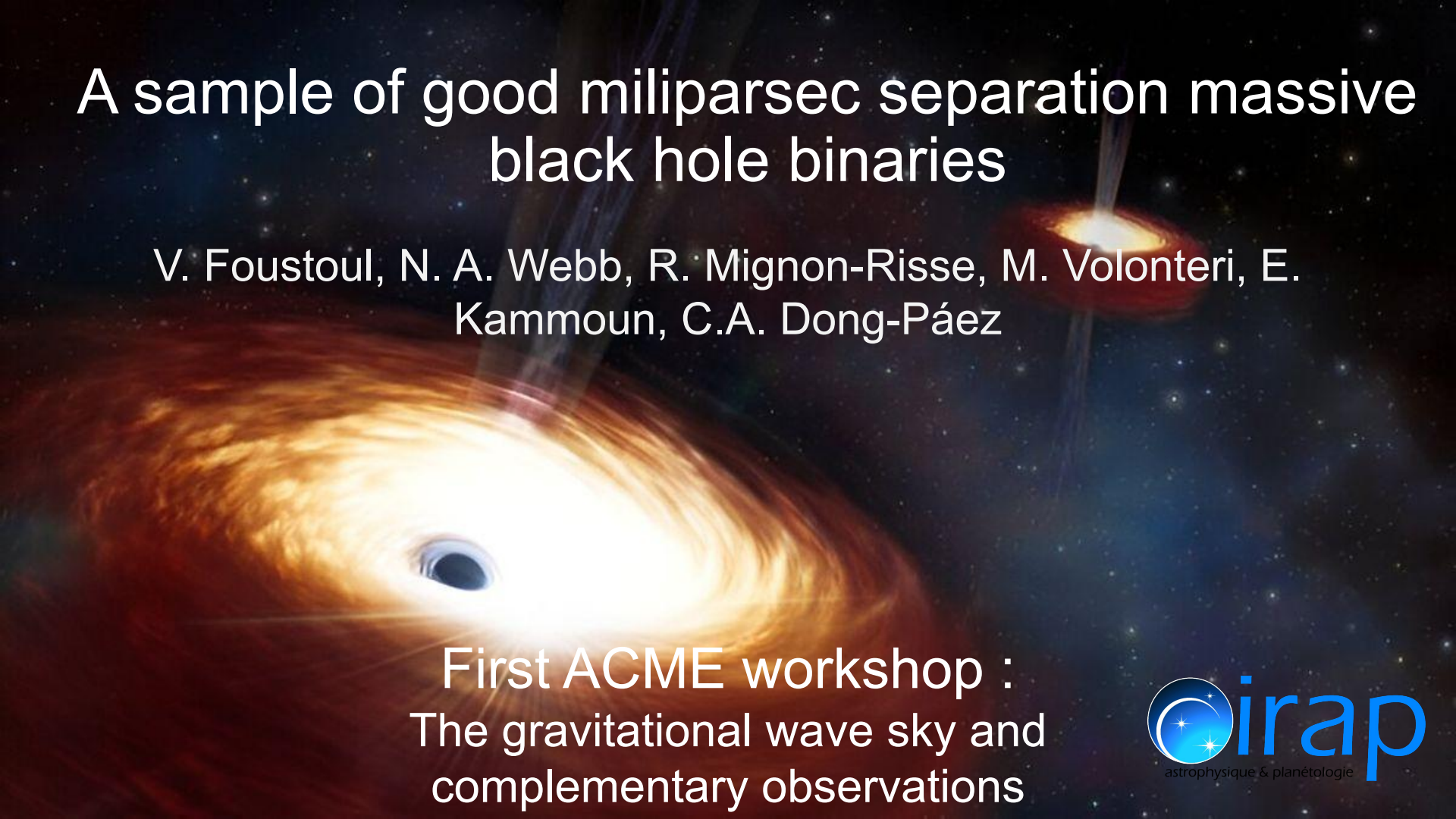
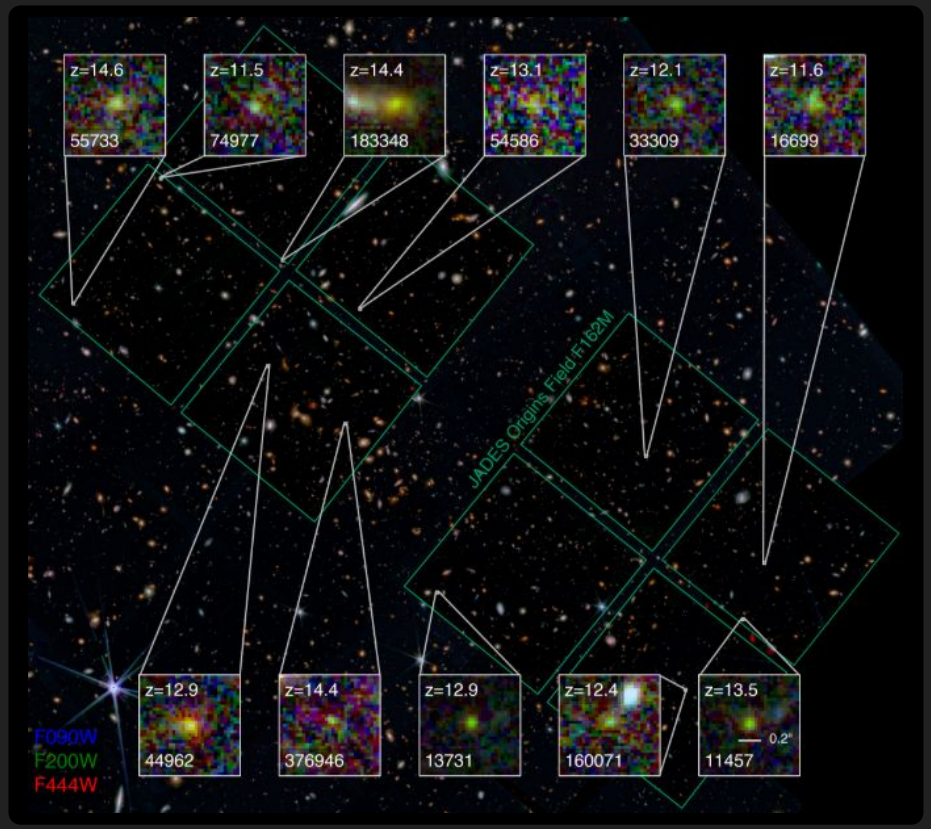


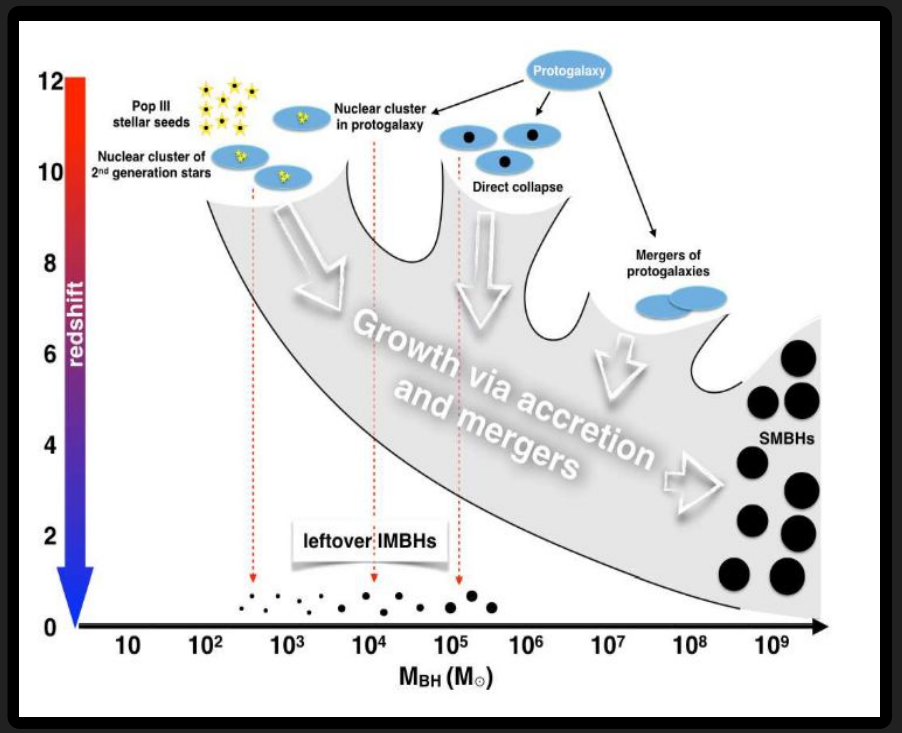
First ACME workshop :
The gravitational wave sky and complementary observations

irap
astrophysique & planétologie

Supermassive Black holes (SMBHs)



High-z galaxy candidates from JADES Origin Field (Robertson et al. 2023)

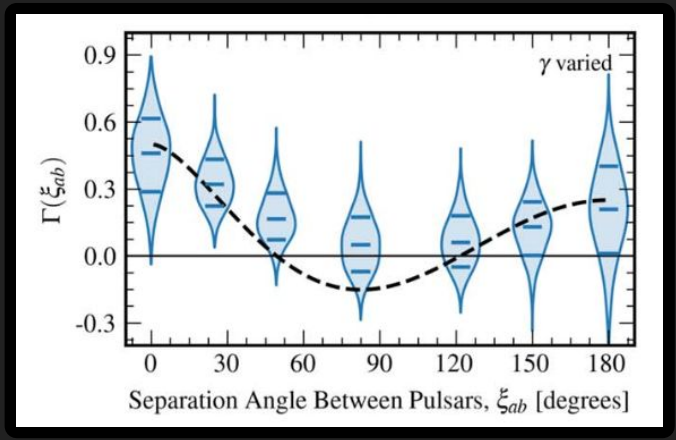


SMBHs possible formation and evolution channels (Mezcua 2017)

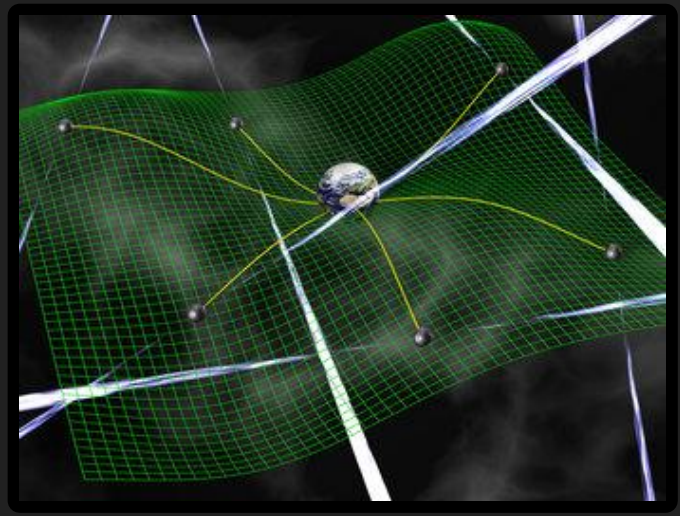
Pulsar Timing Array (PTA)

- Pulsar Timing Array (PTA) :
  - Frequency : nHz

$M > 10^8 M_\odot$

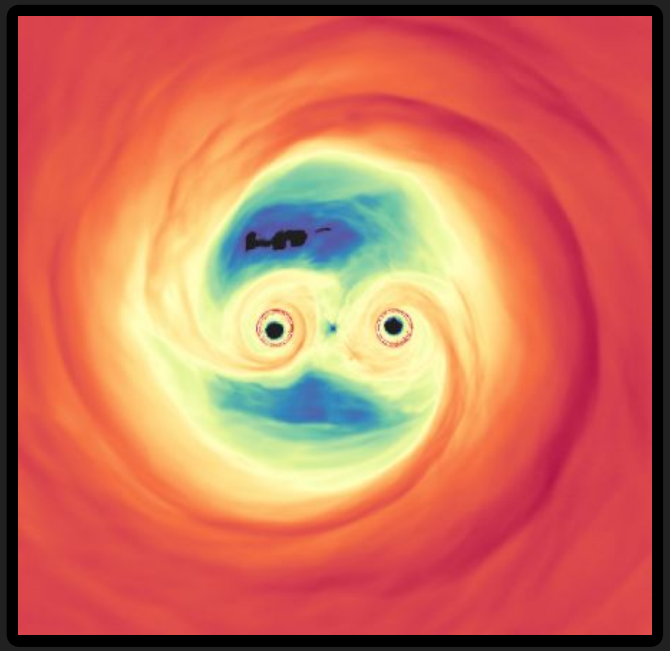


NANOGrav interpulsar correlation curve (Agazie et al, 2023)



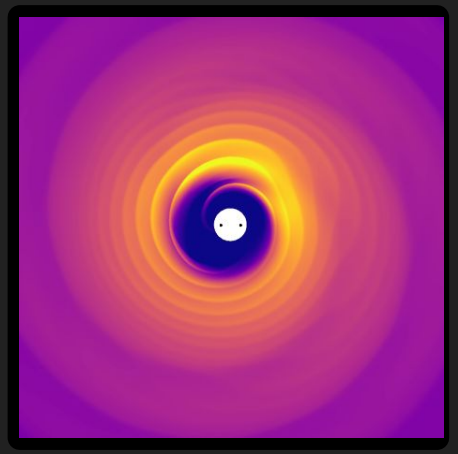
Artist view of Pulsars arrays (credit : Max Planck Institute for Radio Astronomy)

Massive black hole binary (MBHB) geometry



MBH Binary system (D'Ascoli et al, 2018)

- System separated into three parts :
  - Circumbinary disc
  - Accretion streams
  - Mini-discs

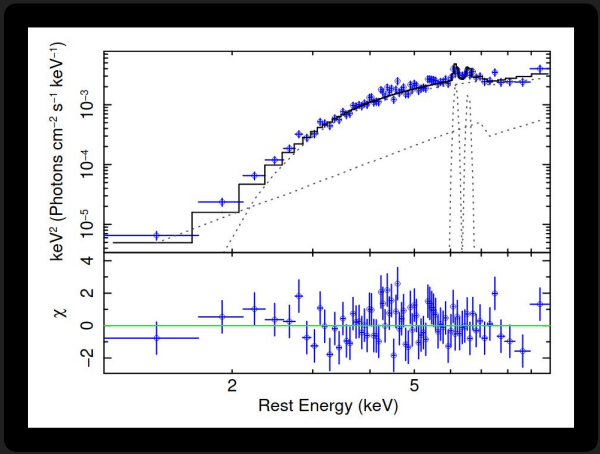


Variability coming from multiple origins

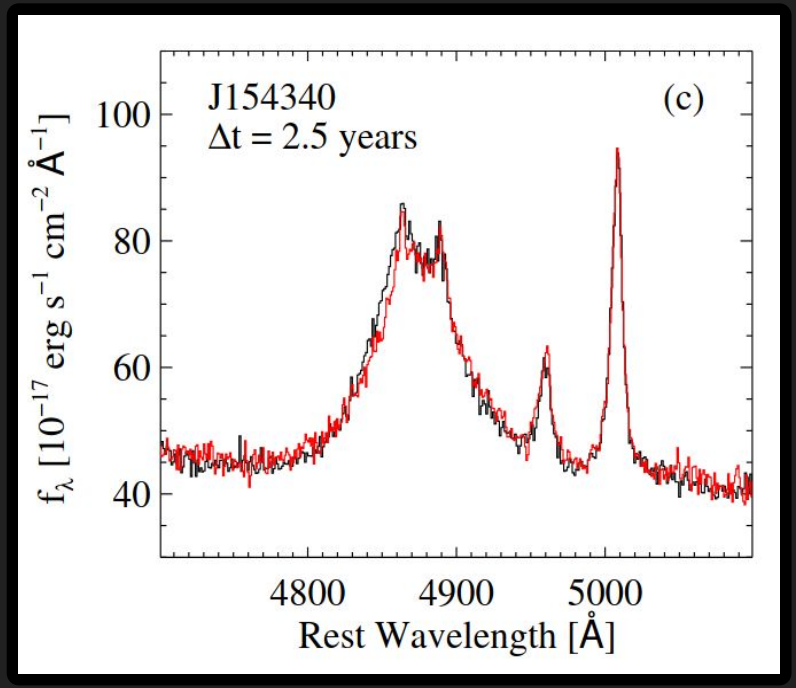
Density map in an equal mass MBHB (Mignon-Risse, Varnière, Casse, 2023)

Electromagnetic signatures from MBHB

- Asymmetries in emission line profiles
- Systematic and monotonic changes in profile shape

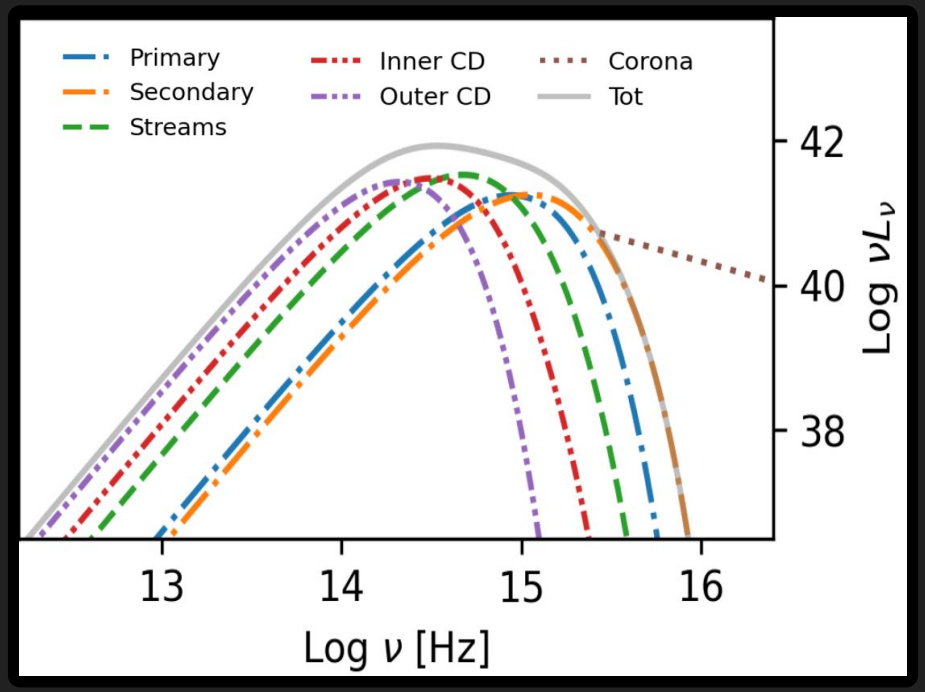


Double peaked Fe Kα emission line in sub-pc MBHB candidate (Severgnini et al, 2015)

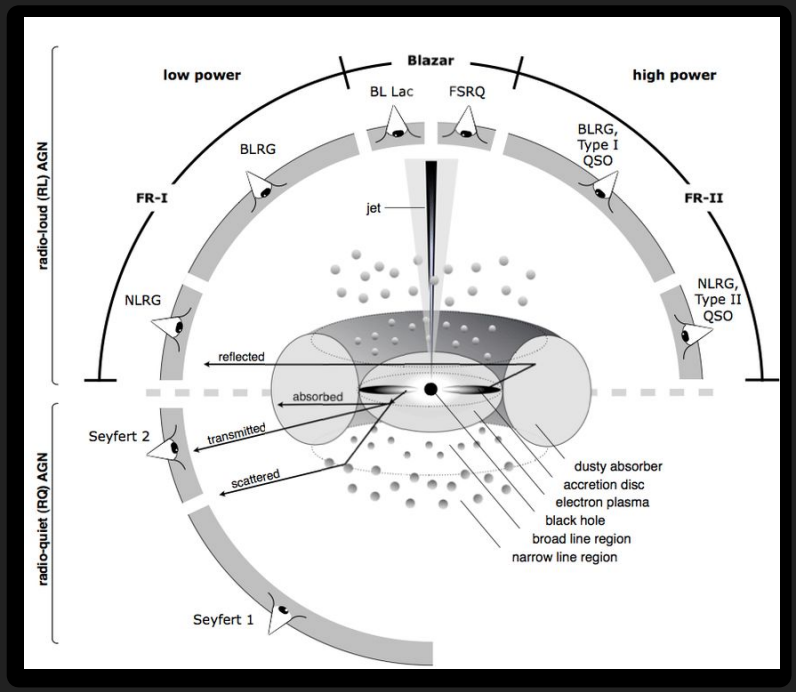


Radial velocity variations in the shape of broad Hβ line (Runnoe et al, 2016)

X-ray emission from MBHB

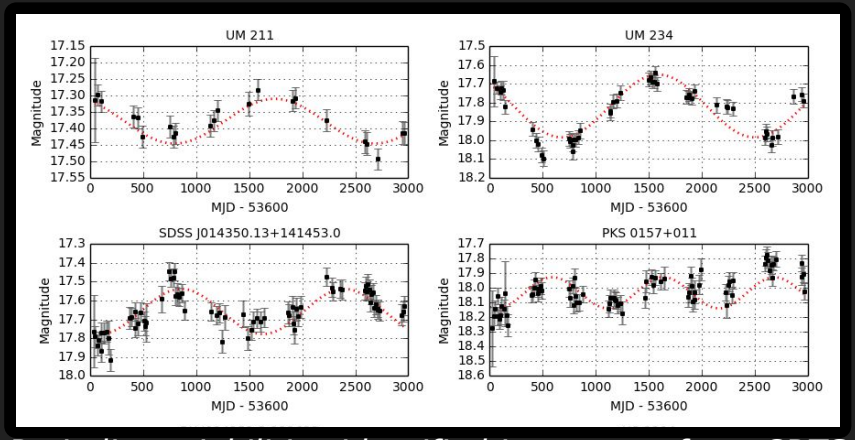


MBHB expected X-ray spectra (Cocchiararo et al, 2024)



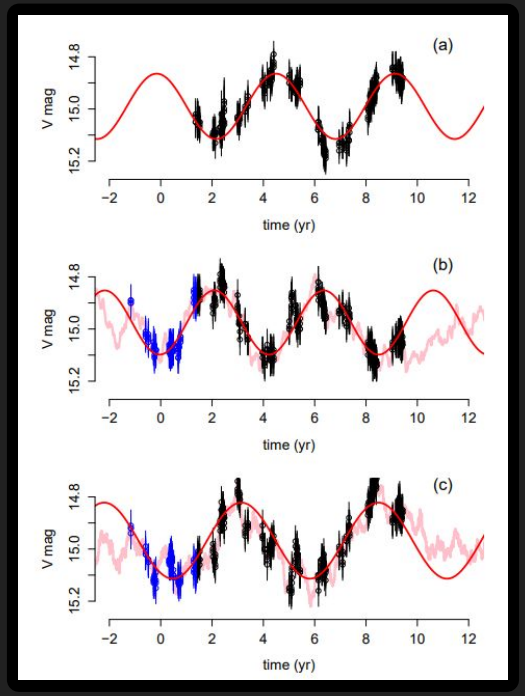
AGN unified model (Beckmann and Shrader, 2012)

Search for close MBHBs



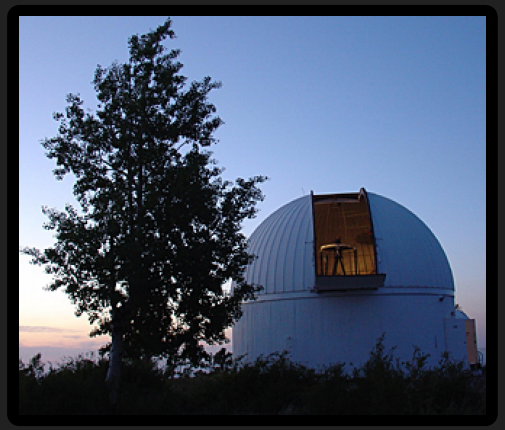
Periodic variabilities identified in quasars from CRTS survey (Graham et al, 2015b)

- 111 candidates identified in Graham et al, 2015



(a) CRTS lightcurve of candidate PG 1302-102
(b) bending power-law spectrum lightcurve
(c) damped random walk lightcurve
(Vaughan et al, 2016)

Optical catalogs



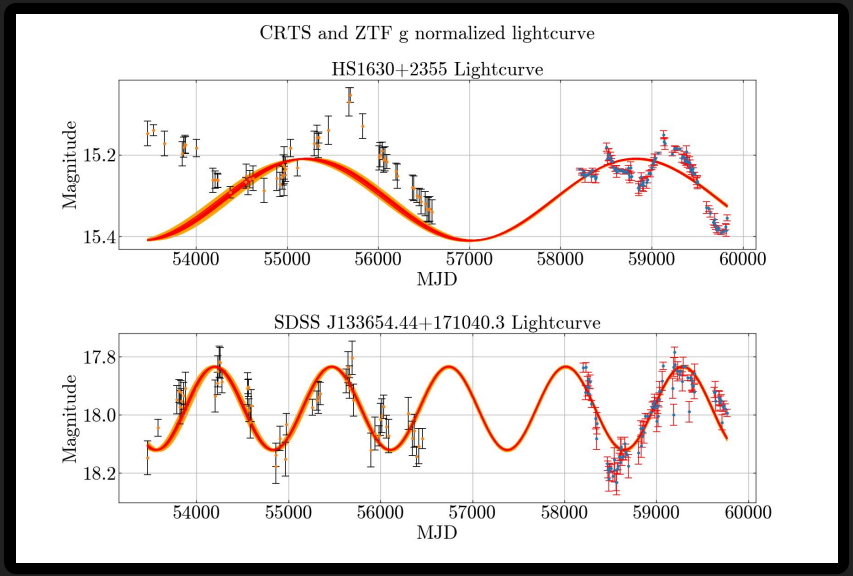
Catalina Sky Survey (Credit: University of Arizona)

- Catalina Real-Time Transient Survey (CRTS) optical catalog :
  - Mt Lemmon Survey
  - Catalina Sky Survey
  - Siding Spring Survey
- Observations : ~2005-2015 in V band
- ~ 500 million objects

- Zwicky Transient Facility (ZTF) :
  - Palomar observatory
- Observations : ~2017 - ongoing in r, g and i filters
- ~ 7 billion sources

Palomar observatory (Credit: Caltech)

Searching for periods

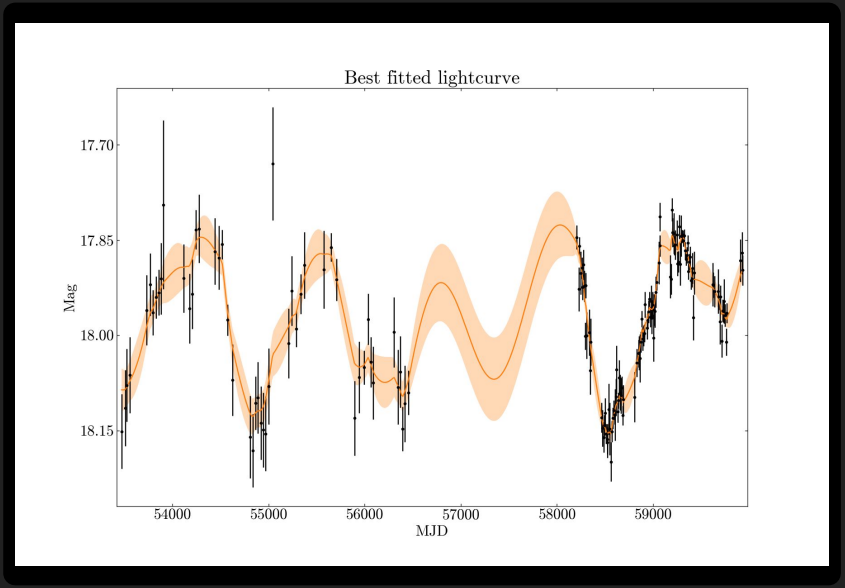


HS1630+2355 and SDSS J133654.44+171040.3 CRTS (black) and ZTF (red) optical lightcurve

- Fitted CRTS and ZTF combined optical lightcurve
- Confirmed the periodicity for 26 candidates from Graham et al, 2015b and found 10 candidates from Chen et al, 2020
- Find same periods with Generalised Lomb Scargle periodogram

Red noise

- Modelled DRW using Gaussian Processes
- Find similar periods
- Computed Bayes factor between DRW and DRW+sine modulation



SDSS J133654.44+171040.3 CRTS and ZTF optical lightcurve fitted with a sine + red noise model

Red noise

- Modelled DRW using Gaussian Processes
- Find similar periods
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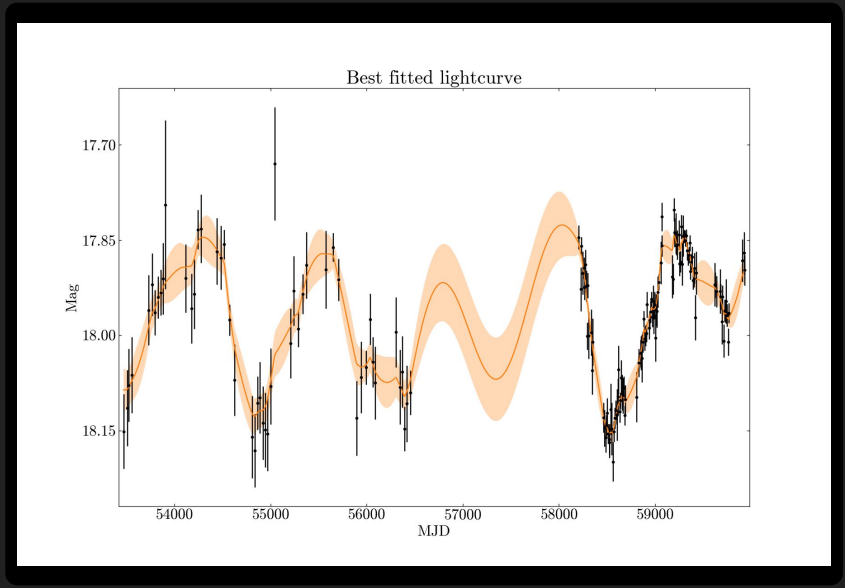
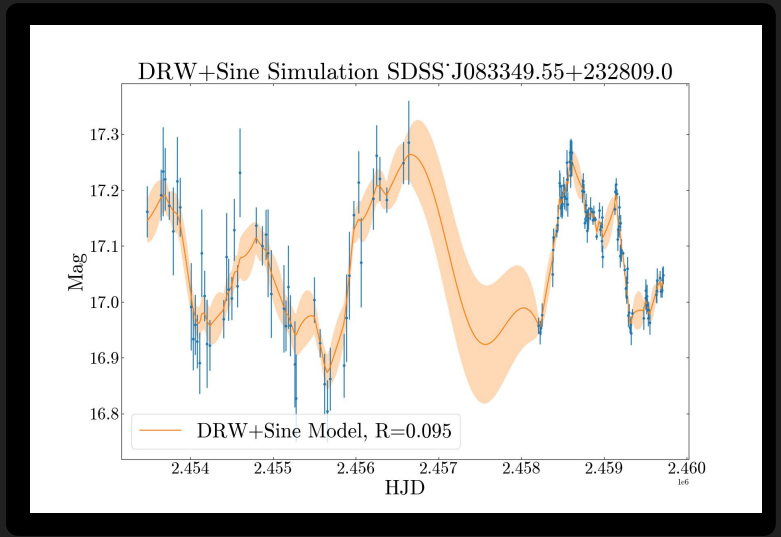
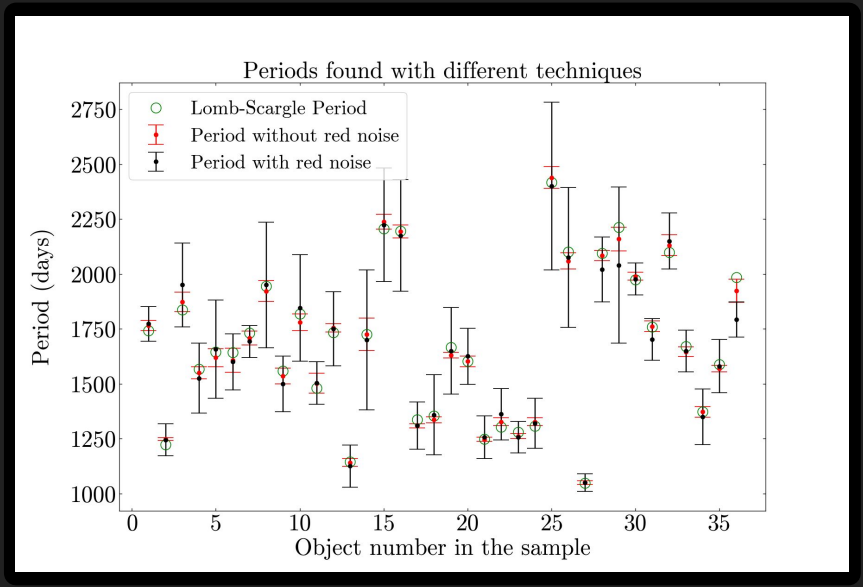


SDSS J133654.44+171040.3 CRTS and ZTF optical lightcurve fitted with a sine + red noise model

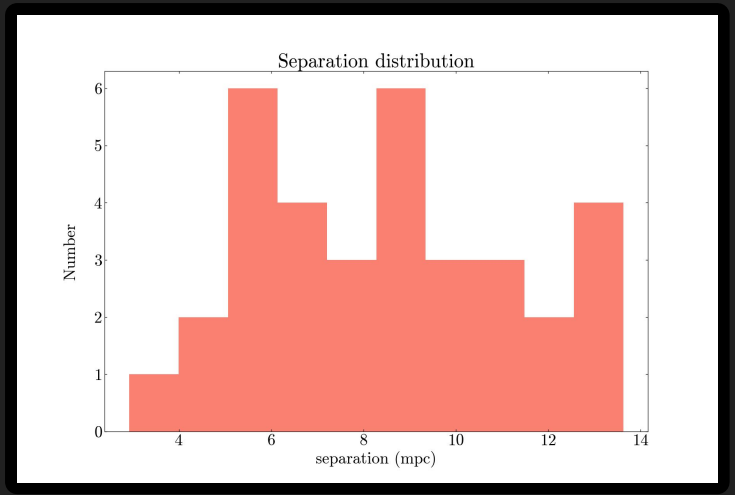


Results



Periods found with different techniques (Lomb-Scargle, Sinusoidal function, Sinusoidal + red noise model)

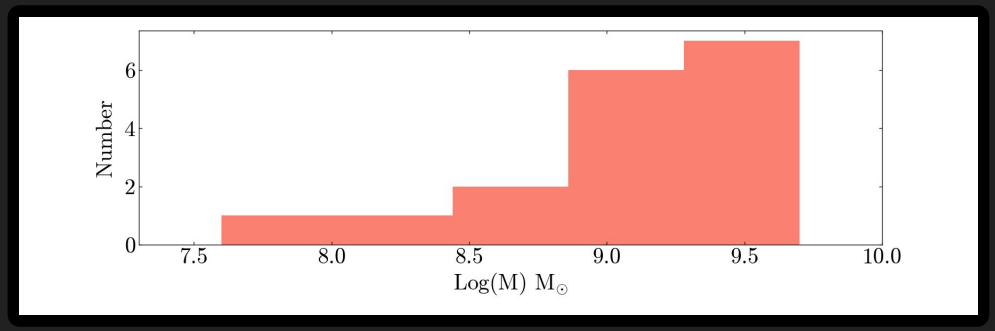
- Found 36 MBHBs candidates with reliable periods, showing between 3 to 5 cycles
- Refuted 58 sources previously proposed as candidates



Orbital separation distribution for an orbital origin of the variability

Expected number of binaries

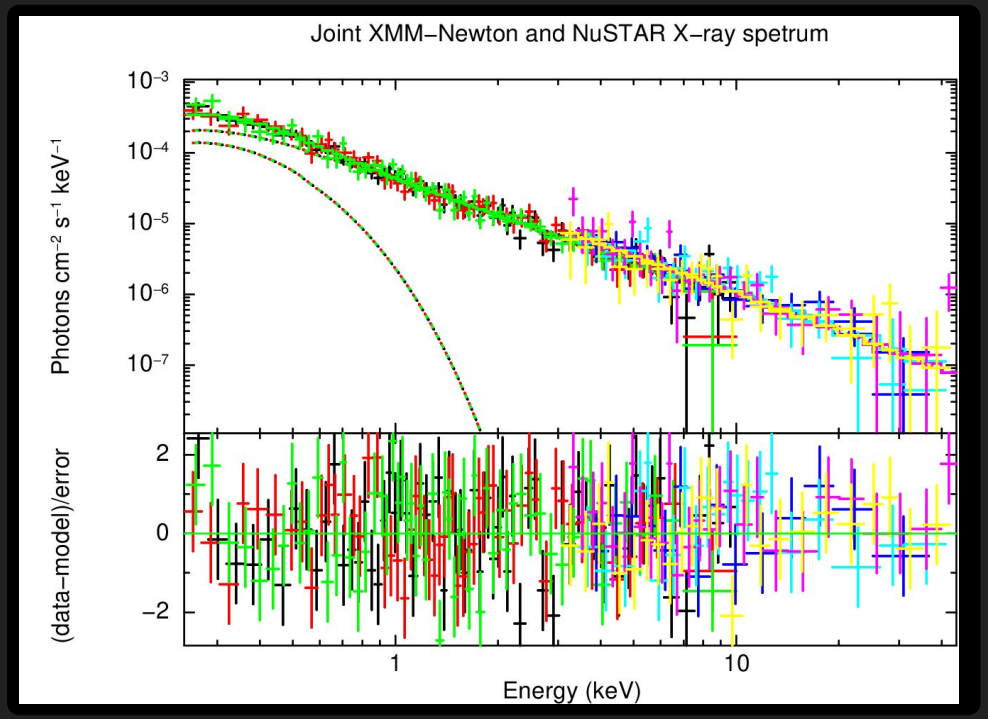
- Computed expected number of binaries at z<1 considering homogeneous distribution of binaries in Universe
- Expect around 21 sub-parsec separation binaries at z<1
- Compatible with predictions, for example Volonteri et al, 2009



Histogram representing mass distribution of proposed MBBHs candidates

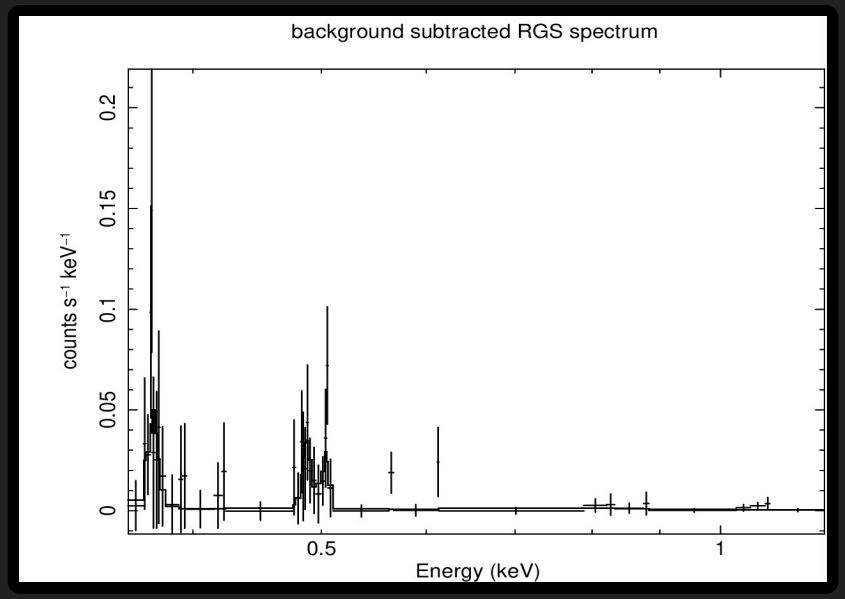
Joint XMM-Newton and NuSTAR observation

- J133654+171040
- Redshift : 1.23
- X-ray spectra model : Thermal disc + powerlaw
- Negligible absorption
- Typical type-I AGN X-ray spectra



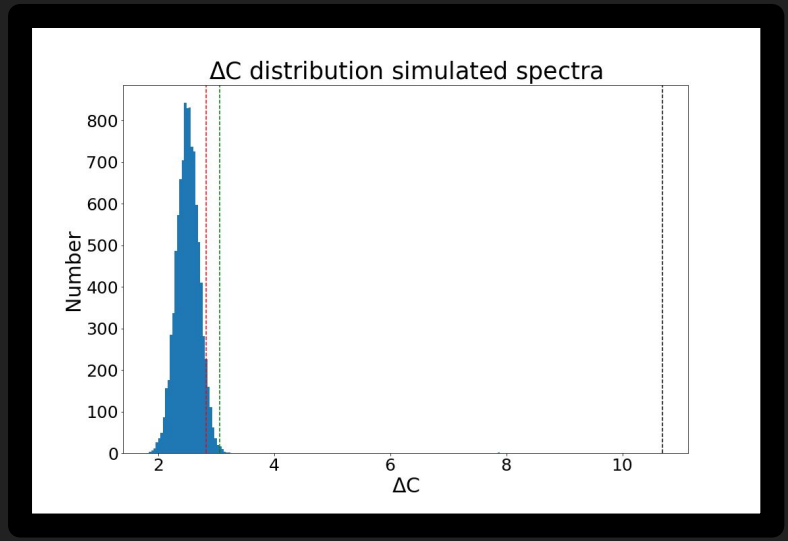
Joint XMM-Newton and NuSTAR X-ray spectra of J133654+171040

Joint XMM-Newton and NuSTAR observation



XMM-Newton background subtracted high resolution RGS spectrum

- Identify three emission lines : 0.37, 0.48 and 0.50 keV
- Fe L-shell transitions in source frame : 2nd AGN : Type-II ?



Conclusion and future work

- Identifying mergers will help understand their importance in SMBH evolution
- We propose a sample of 36 sub-parsec separation MBHBs candidates
- Our results are commensurate with simulations (masses and numbers, Foustoul et al. 2025a, submitted)
- Some of our sources ($z<1$) may be detectable by PTA
- Joint X-ray observation of one candidate shows evidence for a possible binary of type-I and type-II AGN (Foustoul et al. 2025b, in prep)
- The Vera C. Rubin observatory will be useful to find lower mass candidates