Gamma
FIRST PERUGIA Gravi γ Wave WORKSHOP
MULTI FREQUENCY TO MULTI MESSENGER
THE NEW SIGHT OF THE UNIVERSE

PERUGIA - ITALY
Rocca di Sant'Apollinare
2019 May 16-17
Aula Magna San Pietro
Public event: 2019 May 18

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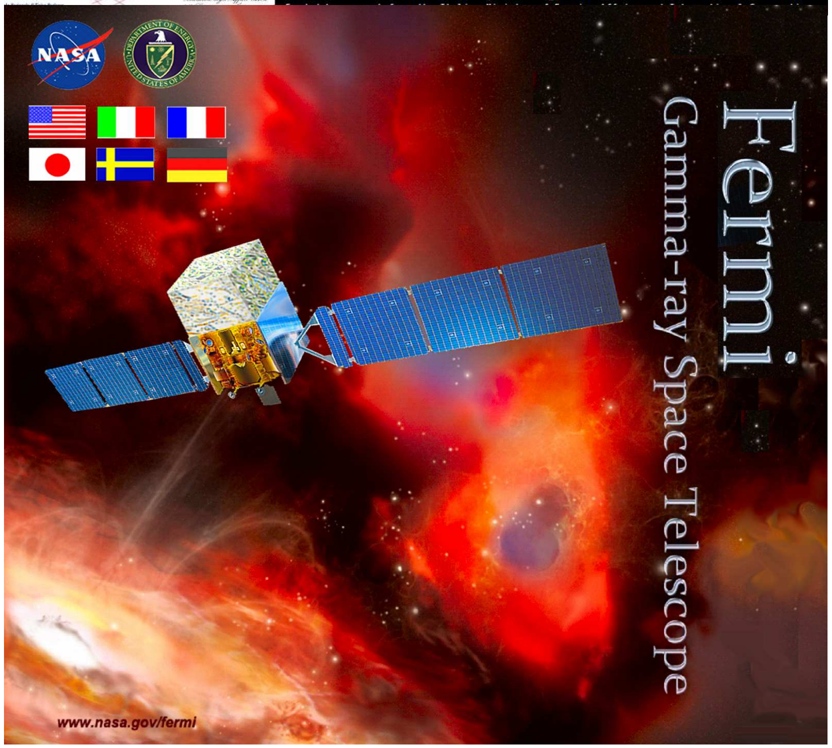

Binary supermassive black holes and gamma-ray blazars

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On behalf of the Fermi LAT Collaboration

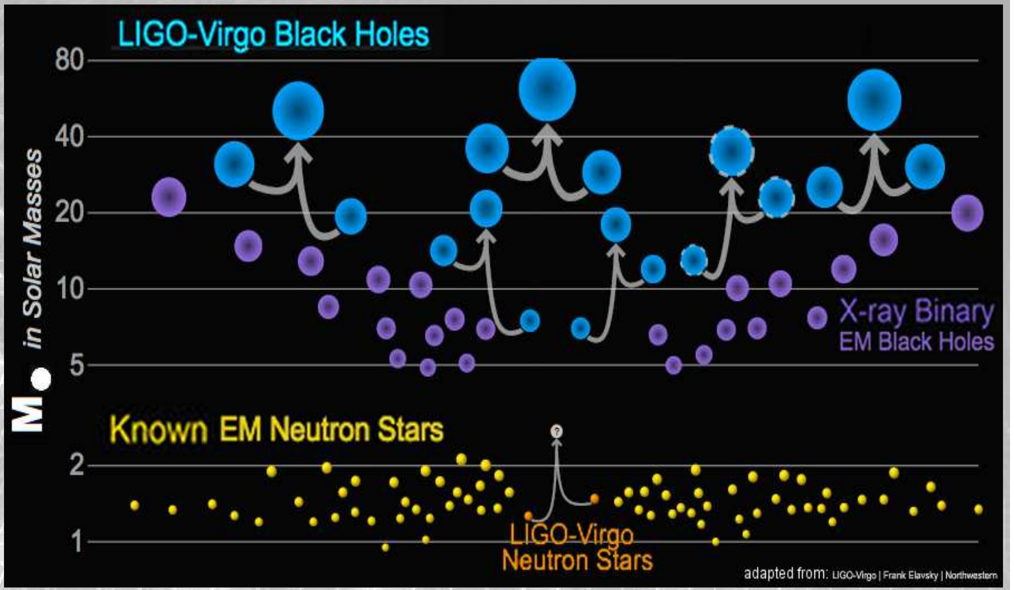
Istituto Nazionale di Fisica Nucleare

1st Perugia Gravi-Gamma Wave Workshop
Multi-frequency to Multi-mesenger the New Sight of the Universe
May 16-18 2019, R.St. Apollinare & Perugia, Italy

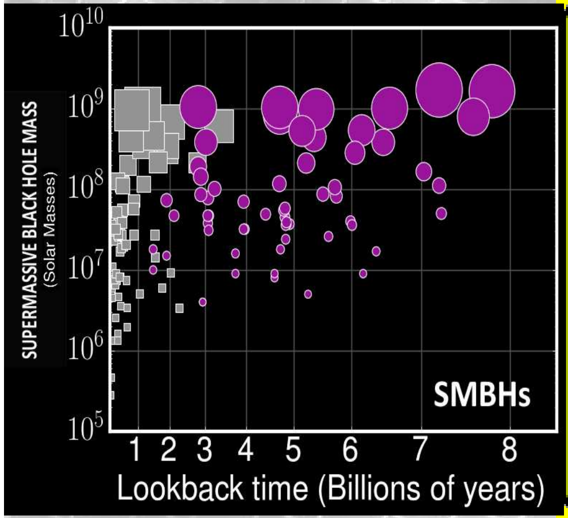
Black holes: stellar (BH) /supermassive (SMBH)

Black holes (BHs): the early fathers

1783 John Michell, 1796 Pierre-Simon de Laplace; 1915 Albert Einstein; 1916 Karl Schwarzschild and Sir Arthur Eddington; 1918 H. Reissner and G. Nordstrøm, 1923 George Birkhoff, 1930 Subrahmanyan Chandrasekhar, 1931 Lev Davidovic Landau, 1934 Walter Baade and Fritz Zwicky, 1933 Georges Lemaitre and Howard Percy Robertson, 1939 Robert Oppenheimer, Hartland Snyder and George Volkoff. 1960s Yakov Zel'dovic, George Wheeler, David Finkelstein, Martin Kruskal, George Szekeres. 1963 Roy Kerr, 1964 Roger Penrose, 1965 Ezra Newman, 1967 Werner Israel, 1968 Brandon Carter, 1971 Edwin Salpeter, 1972 Stephen Hawking, George Ellis, James Bardeen, Brandon Carter, Jacob Bekenstein...



adapted from: LIGO-Virgo | Frank Elavsky | Northwestern



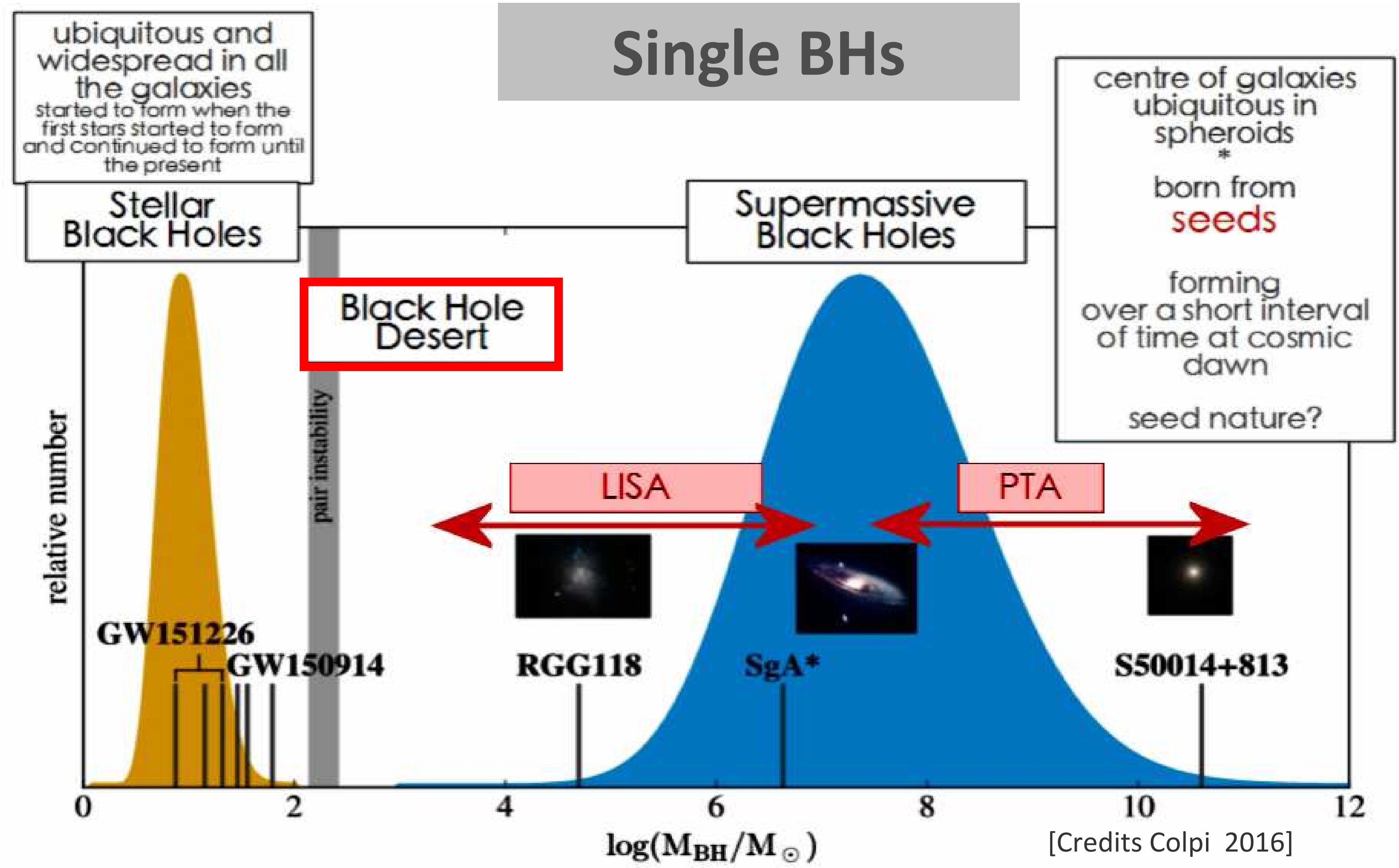
SMBH Mysteries

- How are MBHs born and how do they grow?
- How efficiently do MBHs merge and how does this affect their galaxy hosts?
- What are the demographics of MBHs in the Universe?

Solving SMBH Mysteries

- LISA will measure the masses and spins of coalescing MBHs to a few % accuracy in $10^4 - 10^7\,M_\odot$ binaries out to $z \sim 20$.
- GWs will unveil the MBH growth via mergers, and their accretion history via mass and spin measurements.
- GWs will shed light on the co-evolution of galaxies and MBHs.

BHs: two flavors



Single BHs

ubiquitous and widespread in all the galaxies
started to form when the first stars started to form and continued to form until the present

Stellar Black Holes

Black Hole Desert

Supermassive Black Holes

centre of galaxies ubiquitous in spheroids
*
born from **seeds**

forming over a short interval of time at cosmic dawn

seed nature?

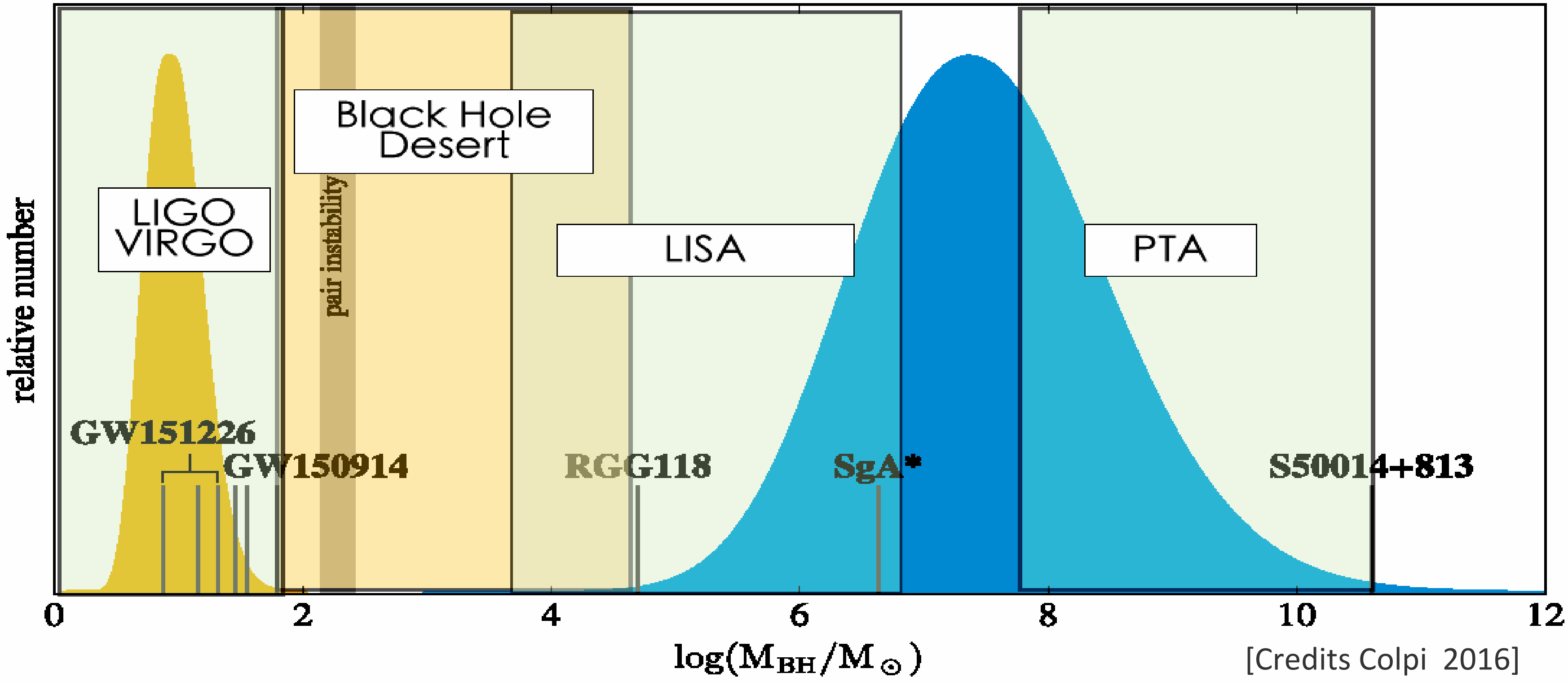
[Credits Colpi 2016]

BHs: two flavors

- is the “black hole desert" inhabited by black holes which we still do not detect ?
- is there a natural real genetic divide ?
- is the desert consequent to the "migration" of seeds into the domain of the massives ?
- is the desert populated by transition objects (from clustering/aggregation/accretion of stellar objects as single building blocks ?

☐ Binary black holes: → the gravitational waves universe

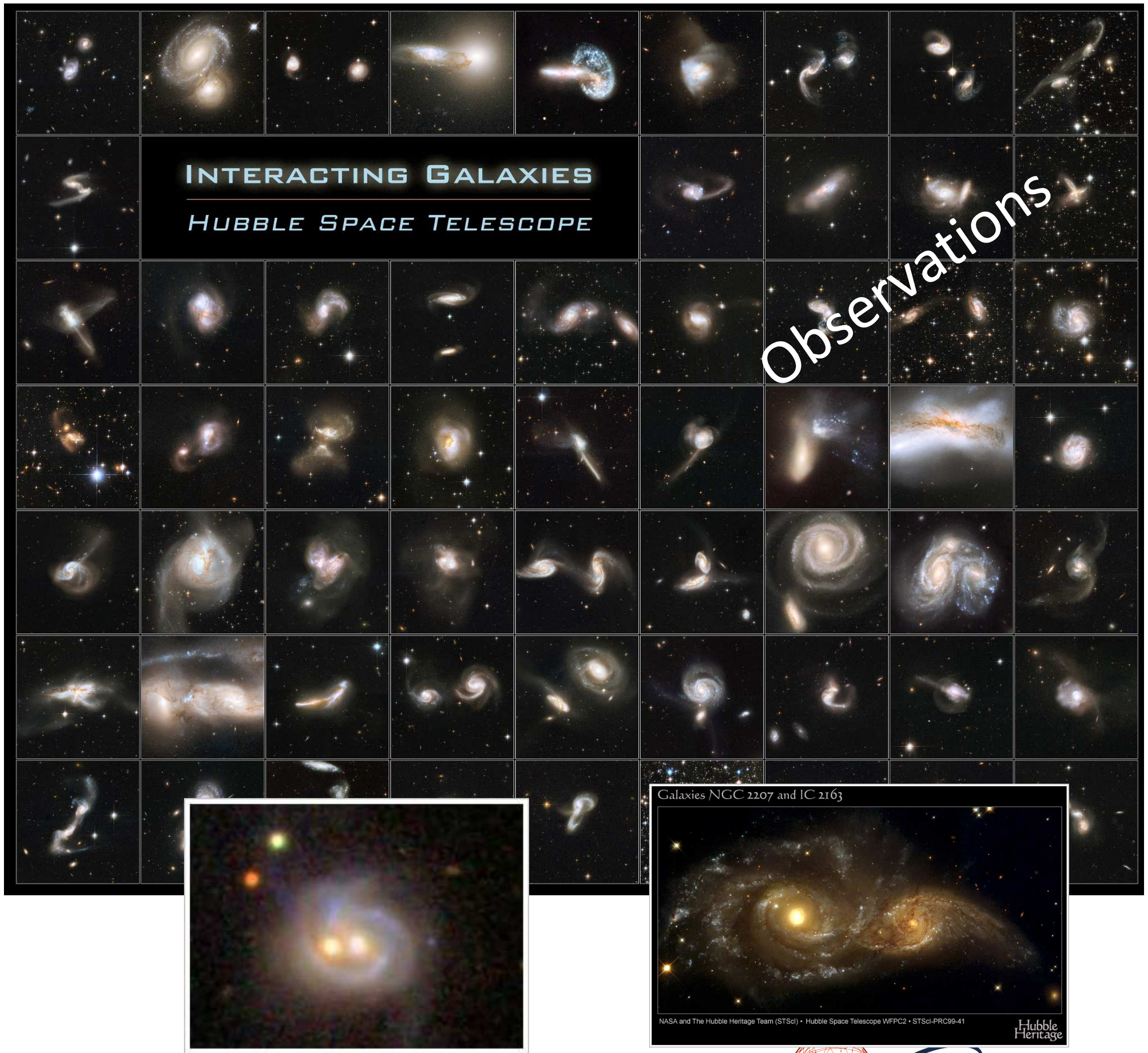
Binary BHs

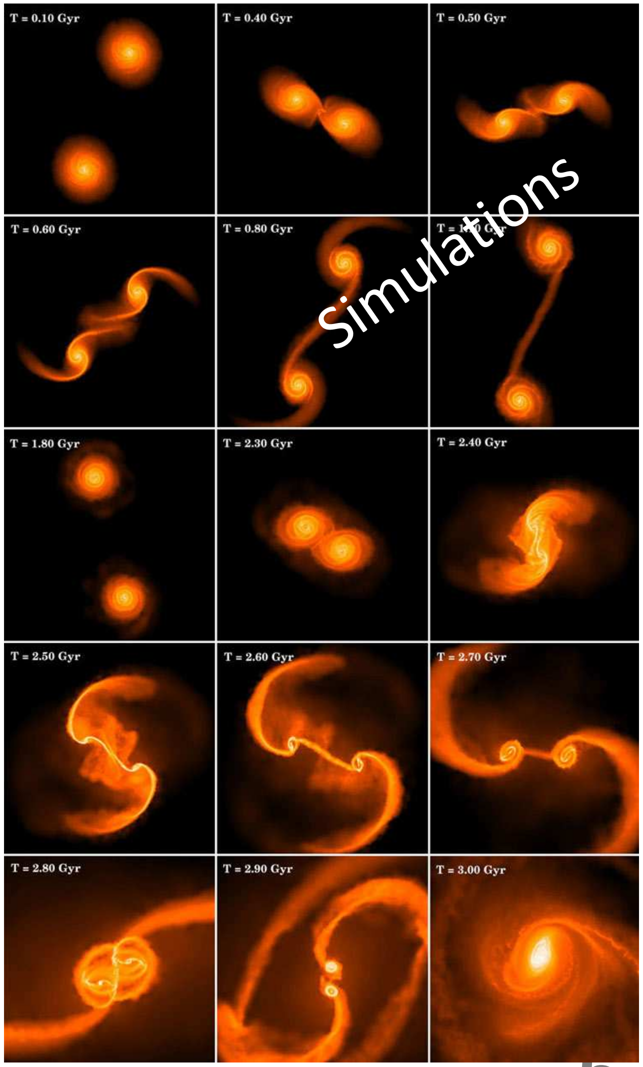


[Credits Colpi 2016]

Galaxy encounters/mergers

- ❑History of the Universe: hierarchical structure formation, galaxy mergers, SMBH pairs and SMBH binaries.



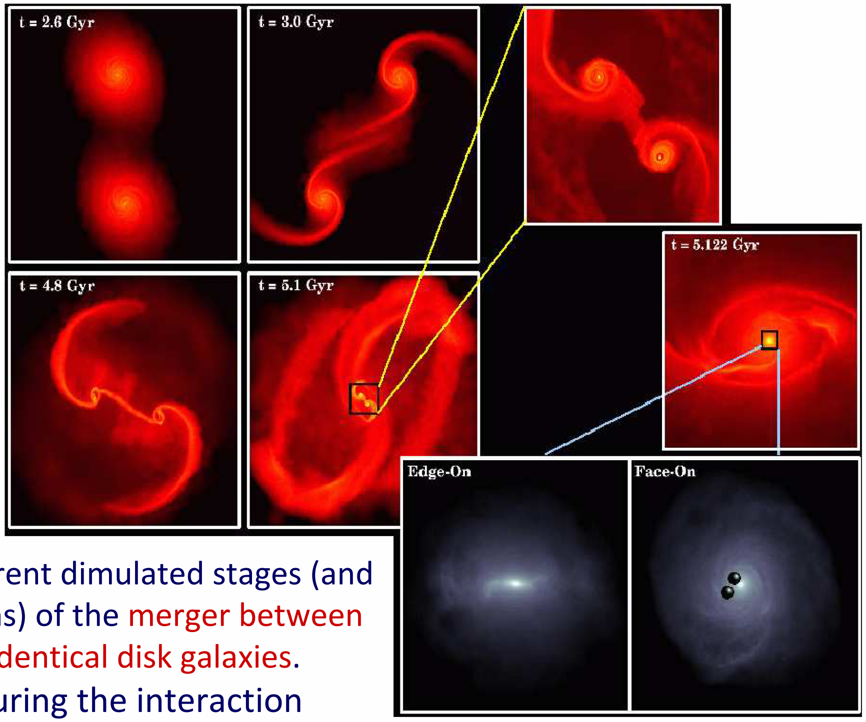


Supermassive BHs pairs/binary

❑ Supermassive black holes (SMBHs) are a ubiquitous component of the nuclei of galaxies and AGN. Following the merger of two massive galaxies, a SMBH binary will form, shrink due to stellar or gas dynamical processes and ultimately coalesce by emitting a burst of gravitational waves.

❑ Close (sub-pc systems) binary SMBHs → indirect searches:

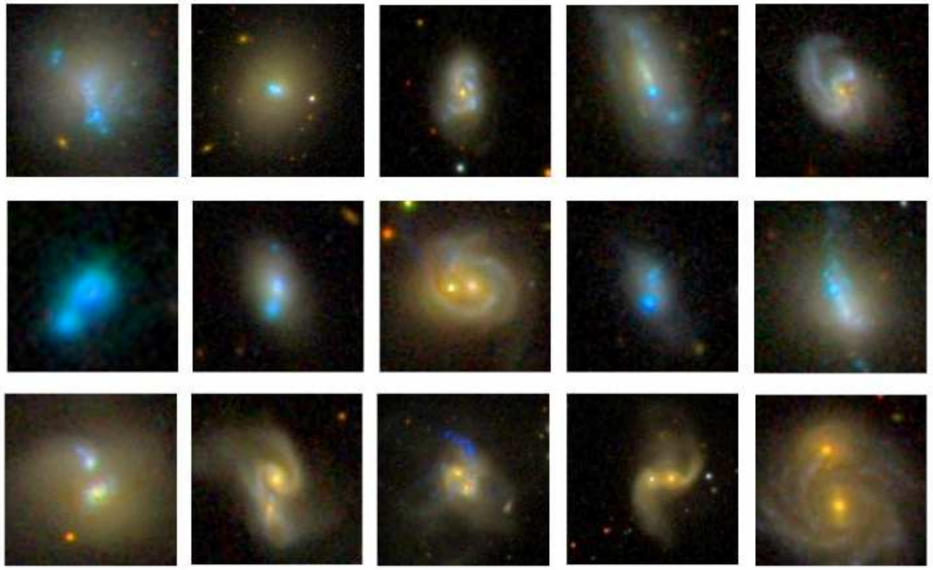
- Double or asymmetric spectral lines (but Liu+2015).
- Helical, distorted jets; tidal disruption events (TDE) as dips in light curves.
- Periodic/quasi-periodic oscillations (long-living) in flux light curves.



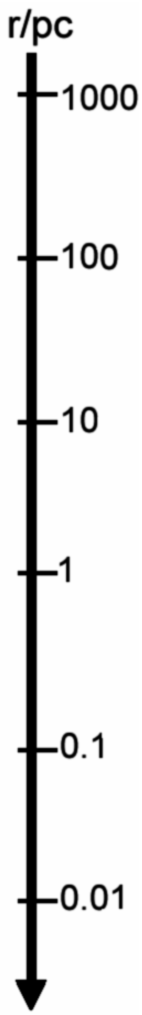
Different dimulated stages (and zooms) of the merger between two identical disk galaxies.

❑ During the interaction tidal forces tear the galactic disks apart, generating spectacular tidal tails and plumes.

❑ Simulations: two SMBHs form an eccentric binary in the disk in less than a million years as a result of the gravitational drag from the gas rather than from the stars . [Mayer et al. 2007].



Supermassive BHs pairs/binaries



Observational evidence for SMBH pairs and gravitationally bound binary systems:

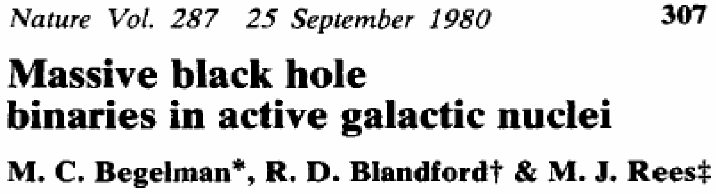
☐ quasar pairs, AGN in clusters of galaxies

☐ pairs of active galaxies, interacting galaxies in early phase of interaction/merging (double-peaked narrow optical emission lines, if both galaxies have NLR)

☐ SMBH pairs in "single" galaxies and advanced mergers, kpc/100-pc scales (ex.: two accreting SMBHs spatially resolved, often heavily obscured --> X-ray/radio observations)

☐ spatially unresolved binary-SMBHs candidates (1. pseudo/quasi/semi-periodic signals in radio/optical flux light curves; 2. pc-scale spatial radio-structures distorted/helical-patterns in jets; 3. double-peaked broad lines)

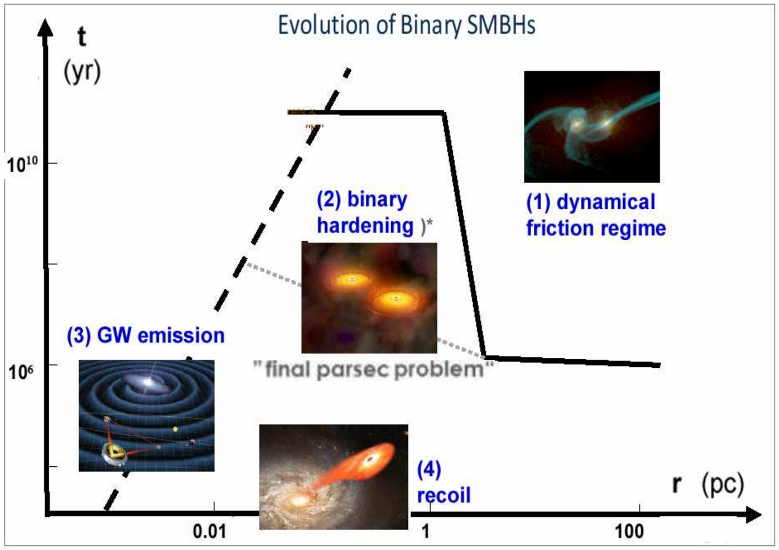
☐ a few post-merger candidates (X-shaped radio sources, galaxies with central light deficits, double-double radio sources, recoiling SMBHs)



Nature Vol. 287 25 September 1980 307

Massive black hole binaries in active galactic nuclei

M. C. Begelman*, R. D. Blandford† & M. J. Rees‡



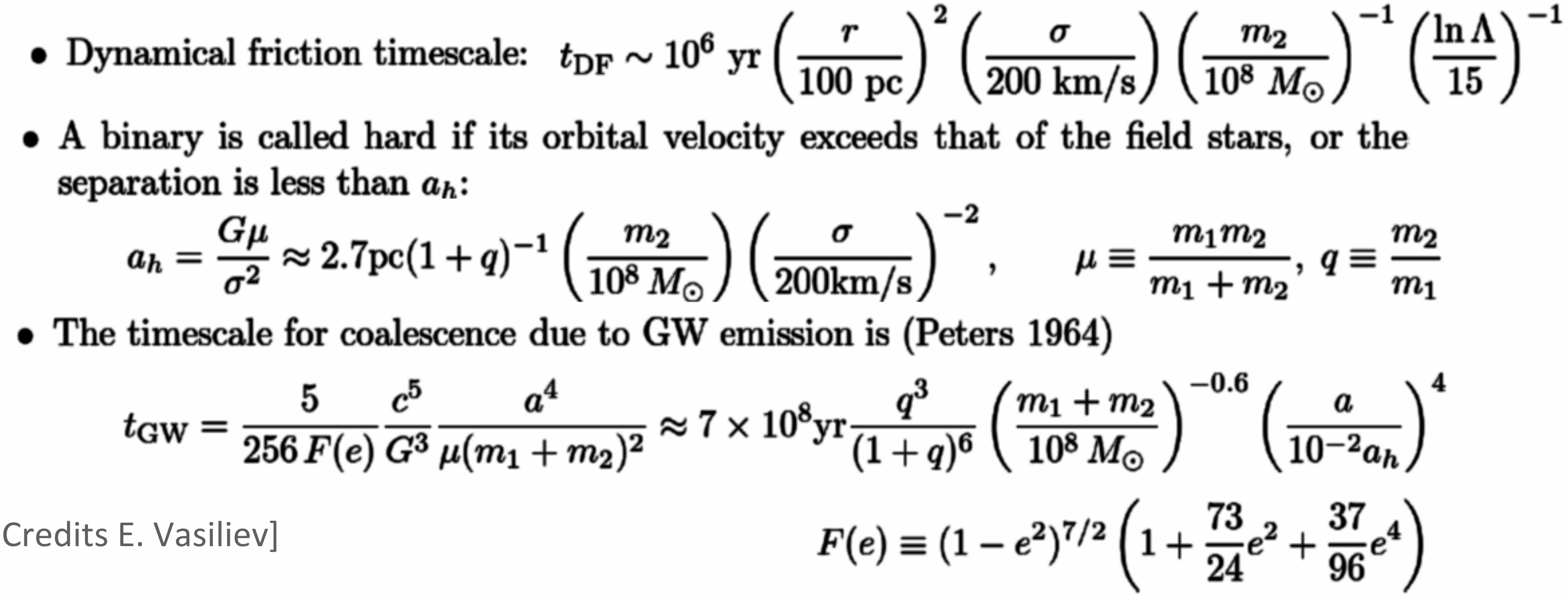
[Credits S. Komossa 2014] Komossa et al.

- Galaxy mergers. Sites of major BH growth & feedback processes.
- Coalescing binary SMBHs. Powerful emitters of GWs and e.m. radiation.
- GW recoil. SMBHs oscillate about galaxy cores or even escape.

Evolution and timescales of binary SMBHs

Little evidence for widespread binary SMBHs → they need to merge rather efficiently. Merger is a natural way of producing SMBHs from smaller seeds.

❑ Merger of two galaxies creates a common nucleus; dynamical friction rapidly brings two black holes together to form a gravitationally bound binary (r~10 pc).
❑ Three-body interaction of binary with stars of galactic nucleus ejects most stars from the vicinity of the binary by the slingshot effect; a "mass deficit" is created and the binary becomes "hard" (r~1 pc).
❑ The binary further shrinks by scattering off stars that continue to flow into the "loss cone", due to two-body relaxation or other factors.
❑ As the separation reaches 0.01 pc, GW emission becomes dominant in carrying away the energy.
❑ Reaching a few Schwarzschild radii (~10^–5 pc), the binary finally merges.



- **Dynamical friction timescale:** $t_{\rm DF} \sim 10^6\ {\rm yr} \left(\frac{r}{100\ {\rm pc}}\right)^2 \left(\frac{\sigma}{200\ {\rm km/s}}\right) \left(\frac{m_2}{10^8\ M_\odot}\right)^{-1} \left(\frac{\ln\Lambda}{15}\right)^{-1}$
- A binary is called hard if its orbital velocity exceeds that of the field stars, or the separation is less than a_h:

$$a_h = \frac{G\mu}{\sigma^2} \approx 2.7{\rm pc}(1+q)^{-1} \left(\frac{m_2}{10^8\ M_\odot}\right) \left(\frac{\sigma}{200{\rm km/s}}\right)^{-2}, \qquad \mu \equiv \frac{m_1 m_2}{m_1+m_2},\ q \equiv \frac{m_2}{m_1}$$

- The timescale for coalescence due to GW emission is (Peters 1964)

$$t_{\rm GW} = \frac{5}{256\,F(e)}\,\frac{c^5}{G^3}\,\frac{a^4}{\mu(m_1+m_2)^2} \approx 7\times10^8{\rm yr}\,\frac{q^3}{(1+q)^6}\left(\frac{m_1+m_2}{10^8\ M_\odot}\right)^{-0.6}\left(\frac{a}{10^{-2}a_h}\right)^4$$

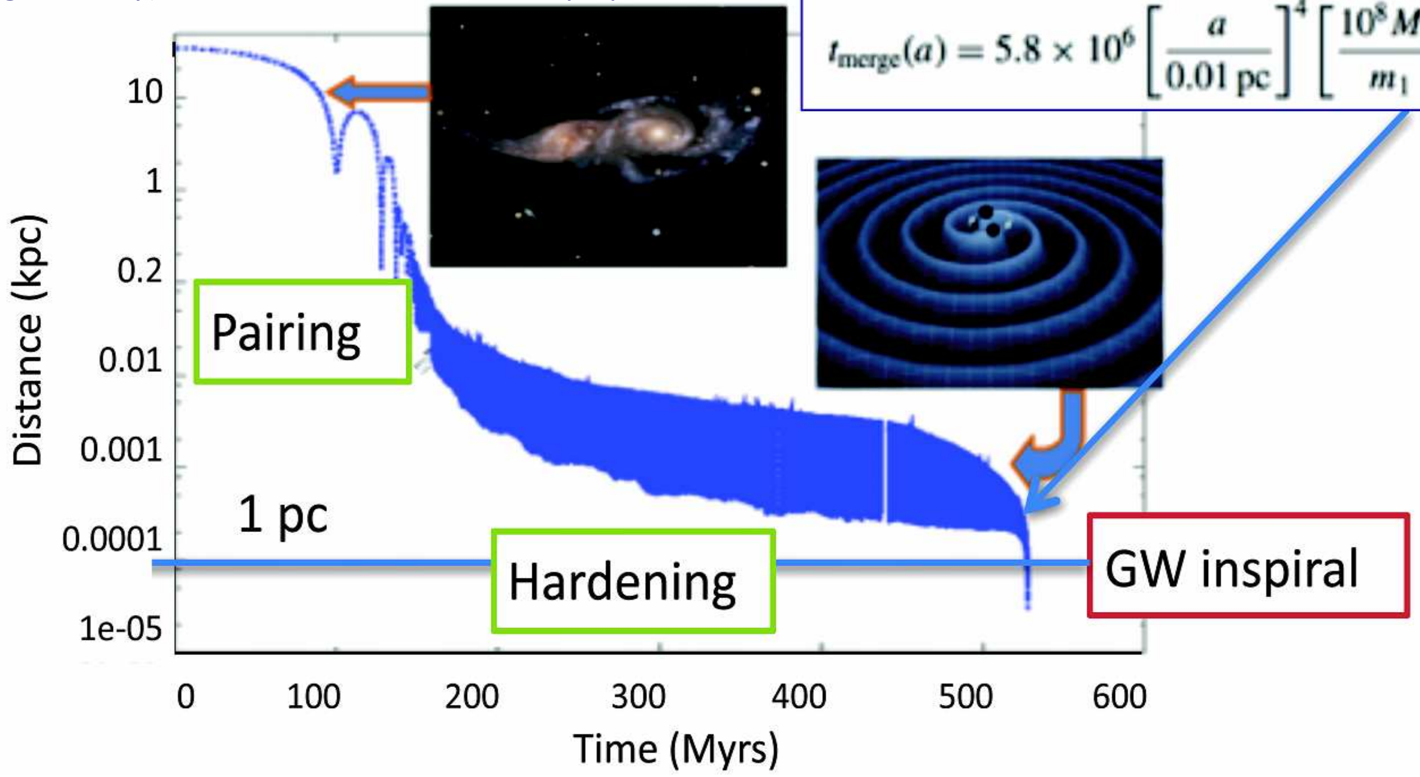
$$F(e) \equiv (1-e^2)^{7/2}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)$$

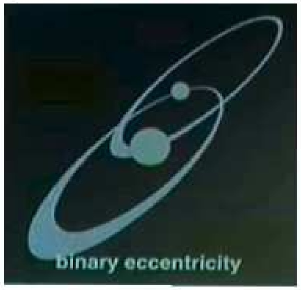
[Credits E. Vasiliev]

Supermassive BHs pairs/binaries

❑ Observational evidence is important to solve the theoretical “final parsec problem” in GR (solved by non spherical geometry). There is also the final 0.1 pc problem.

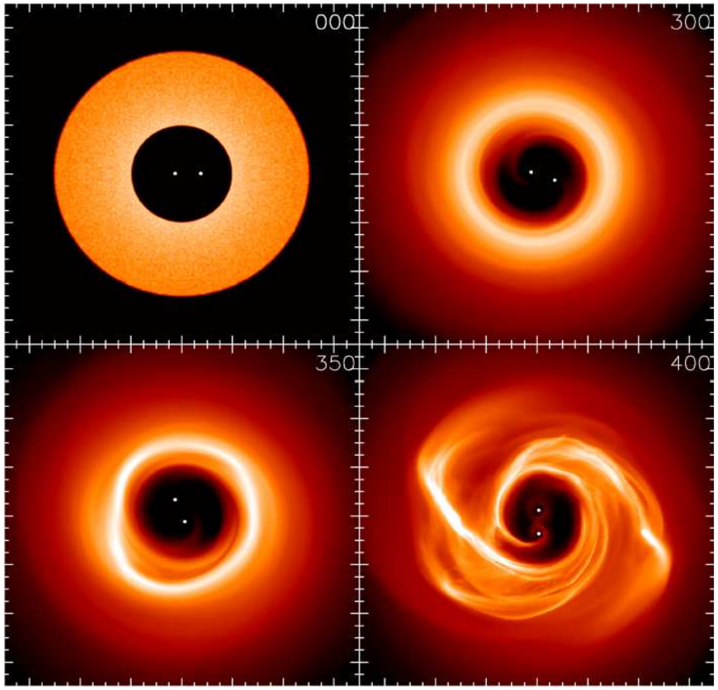
$$t_{\rm merge}(a) = 5.8 \times 10^6 \left[\frac{a}{0.01\,{\rm pc}}\right]^4 \left[\frac{10^8 M_\odot}{m_1}\right]^3 \frac{m_1^2}{m_2(m_1+m_2)}\ {\rm yr}$$





Timescale from two galaxy merger to their central SMBH merger in the range 10^8-10^9 years

Within the last parsec



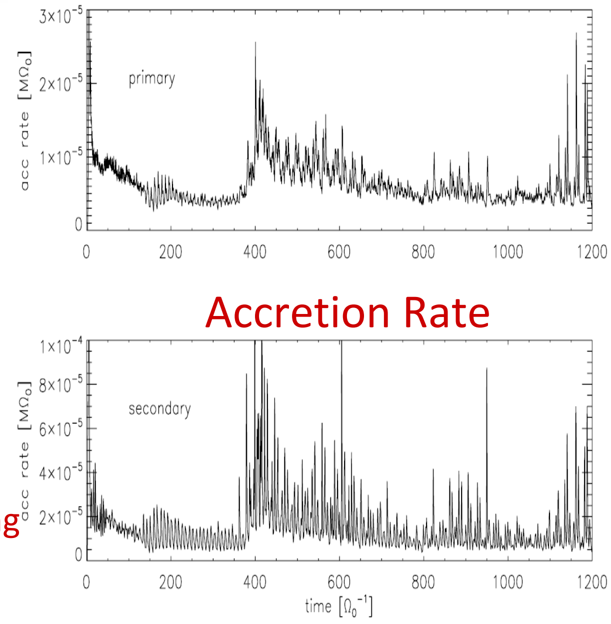
❑*Thin* gaseous disk
❑Disk *aligns* with binary plane
❑Binary evacuates *cavity*
❑*Viscous* decay
("Type II migration"):
- secondary dominated;
- disk dominated

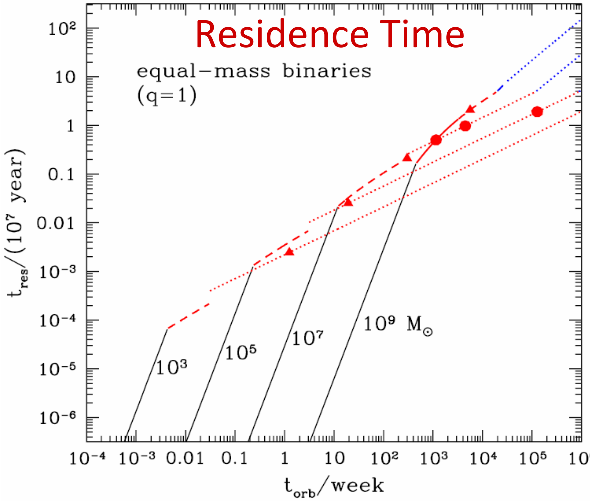
❑ *Gravitational Wave* driven evolution

Example of requirements for large optical surveys dedicated to finding optically periodic variable AGN/quasars:

❑ ≥ 100 sources @ tvars≤ 1 year ;
≥ 5 sources @ tvars≤ 20 weeks;
❑ wide surveys best to probe GW-decay
❑ Assume: • f_Edd= 0.3;
• f_var = 0.1 ; • tQ = 10^7 years

❑ Look for week/month/ year periodic variability
❑Look for spectral features ~ several x 1,000 km/s


Accretion Rate


Residence Time

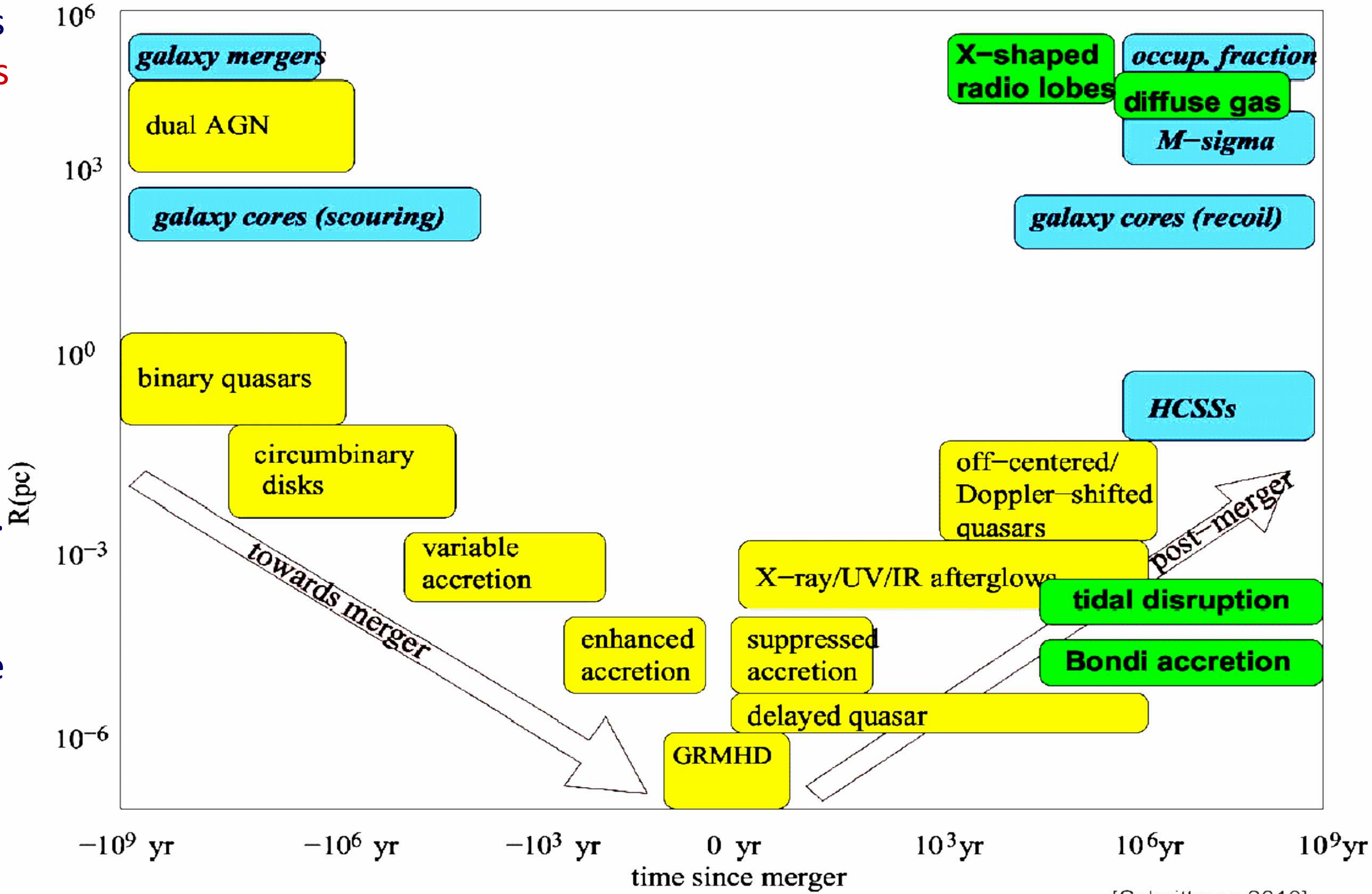
Detecting decaying binary SMBHs.
Optimistic Assumptions:
❑ binary is producing *bright emission* (~30% L_edd)
❑non-negligible fraction (~10%) of this emission is *variable*
❑clearly identifiable *period* t_var~ t_orbit
❑in-spiraling binary = periodically variable quasar
Identifying such binaries statistically?
❑ *fraction of quasars* with period t_var = (1+z) t_orb , f_var = t_res / t_Q

SMBH binaries, astrophysical phenomenology and GWs

GWs frequency domains probed by LISA and PTAs and expected GW signals from binary IMBHs/SMBHs.

- ❑ Nano-Hz GW regime: superposition of signals coming from many stationary sources (stochastic background).
- ❑ Milli-Hz GW regime: extreme-mass ratio inspirals (EMRI) at a rate of few events per year; Intermediate-mass (but do exist?) BHs.

Micro/Nano-Hz GW regime:
SMBH binaries.



[Schnittman 2013]

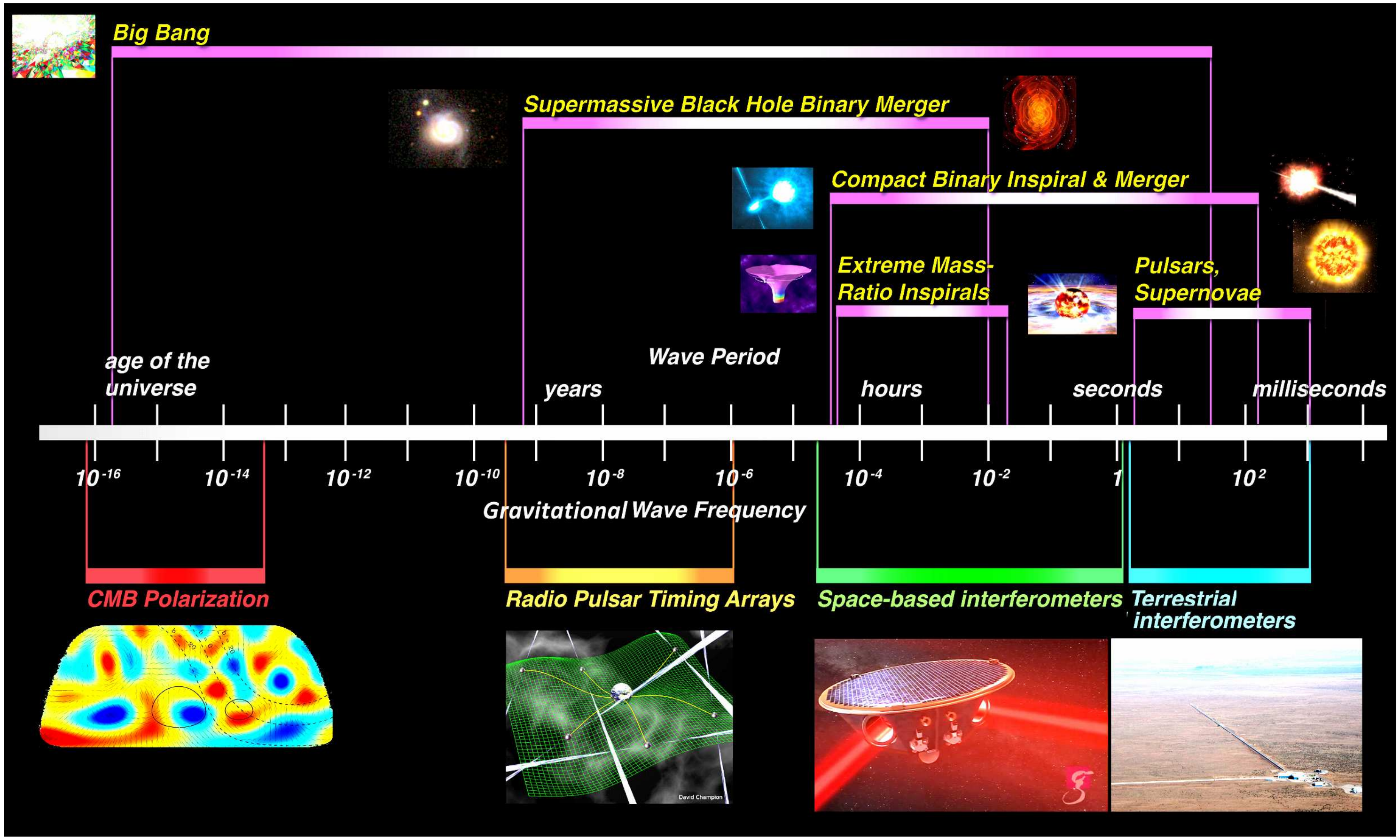
Selection of potential EM sources for astrophysical manifestations/signals of binary SMBH mergers, sorted by timescale, typical size of emission region, and physical mechanism (blue/italic = stellar; yellow/times-roman = accretion disc; green/bold = diffuse gas/miscellaneous). The evolution of the merger proceeds from the upper-left through the lower-center, to the upper-right [Schnittman 2013].

SMBH binaries and GWs

Instruments capable of detecting gravitational waves (GWs) and their sources in next years:

- ground-based interferometers like aLIGO, aVIRGO, KAGRA, Geo600, etc.;
- Pulsar Timing Arrays (PTAs)
- Square Kilometer Array (SKA);
- LISA space mission,
- the 3rd gen. Einstein GW Telescope.

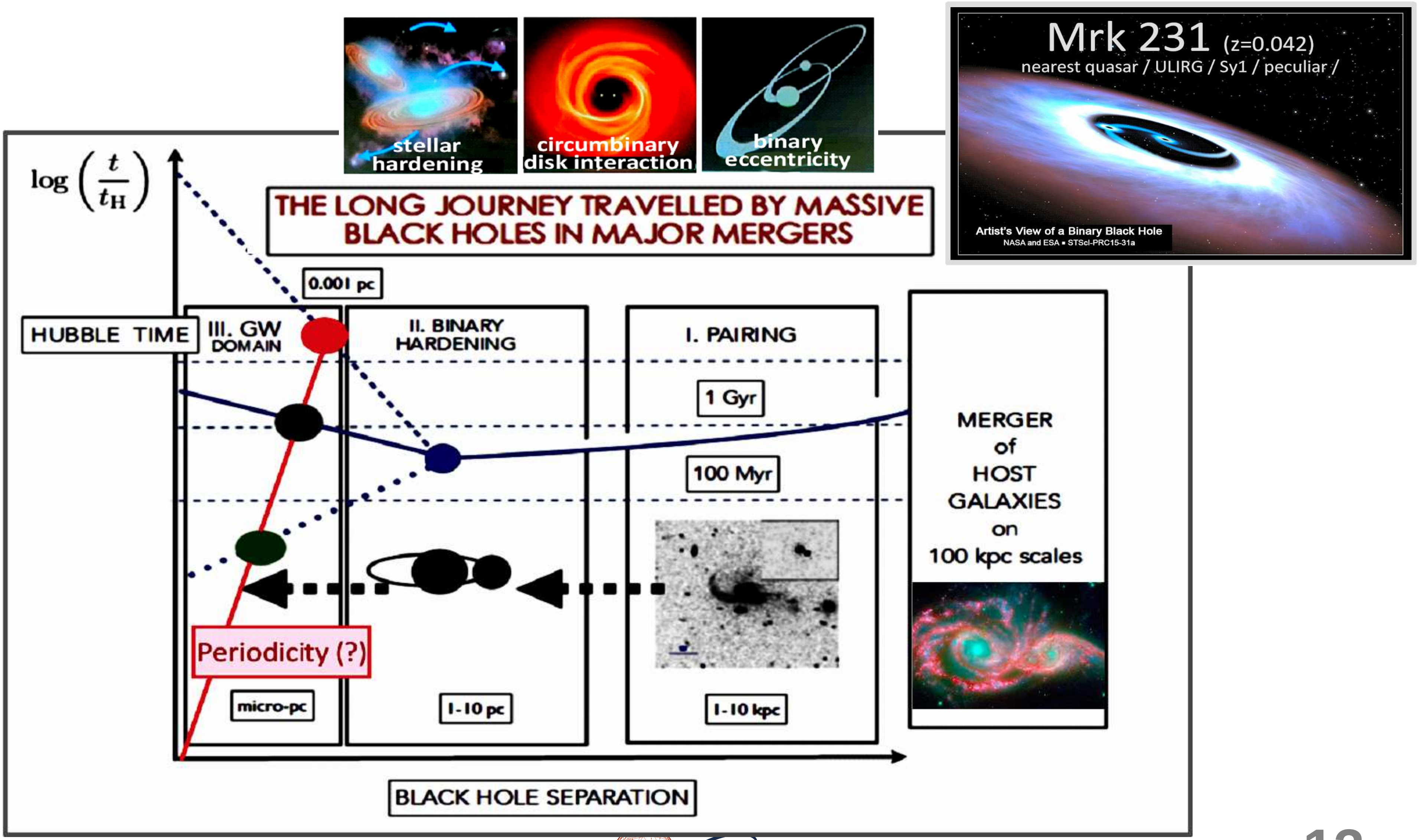
Also binary IMBHs & SMBHs



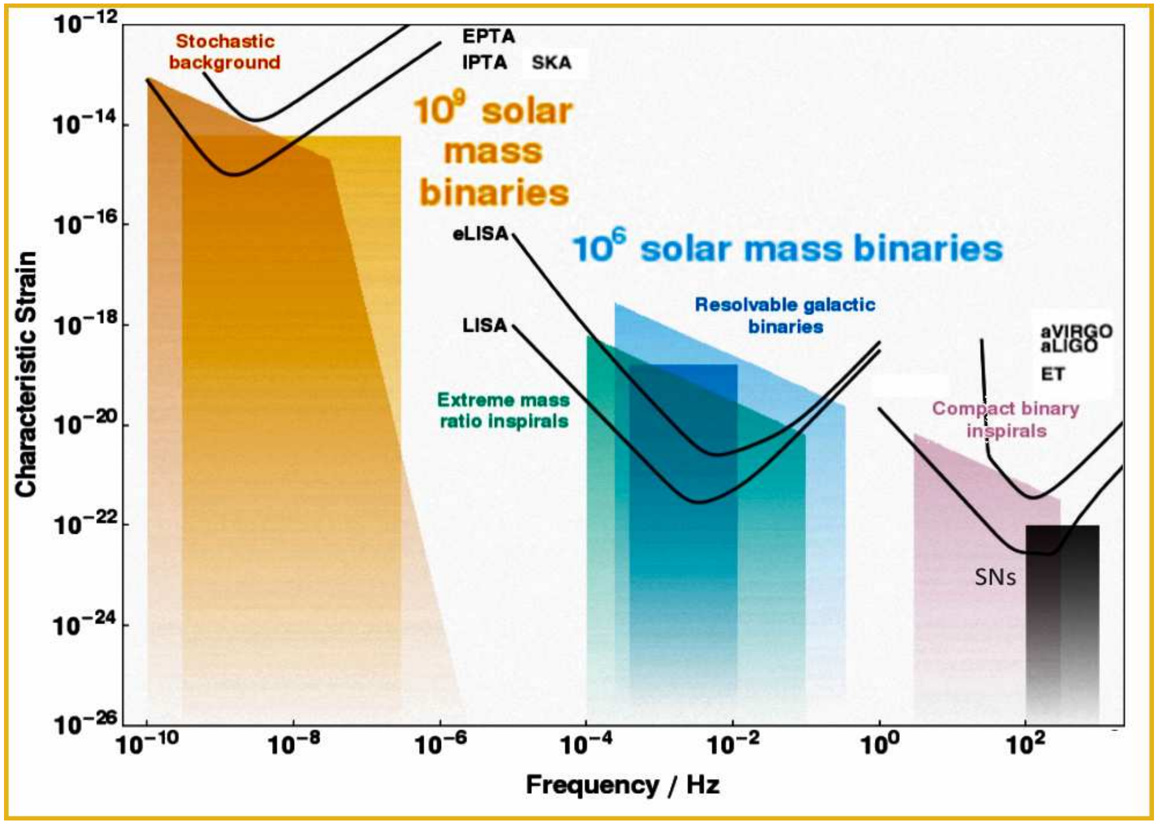
❑ Binary intermediate-mass black hole (IMBH) binaries with BH masses between 10^4 Msun and 10^7 Msun and extreme / intermediate mass ratio inspirals (EMRI/IMRI) are expected to be detected by LISA. Ability to explore for the first time the low-mass end of the SMBHs hole population at cosmic times as early as redshift >8.

❑ Ultra-low GW frequency domain (nHz) is probed by Pulsar Timing Arrays → possibly binary SMBHs (>10^7 Msun).

SMBH binaries and GWs



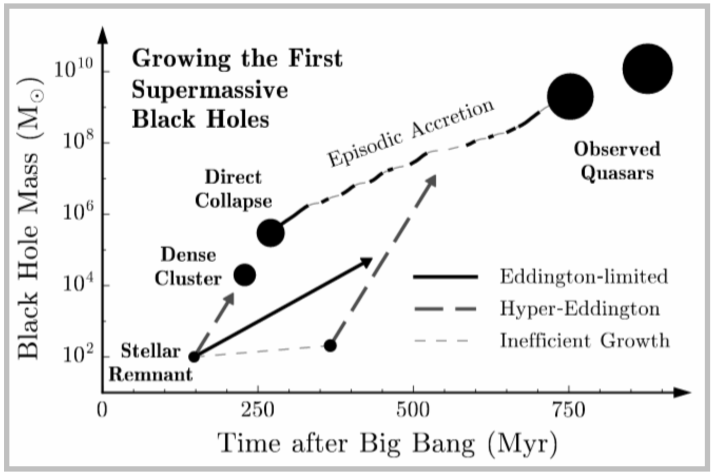
SMBH binaries and GWs: LISA and PTAs



❑ Pulsar timing arrays (PTAs) started to place constraints on galaxy merger history from limits on the stochastic Gravitational Wave (GW) background.

❑ Coalescing binary SMBHs → loudest sources of very-low frequency (micro-Hz to nano-Hz) GWs in the universe. Subsequent GW recoil has potential astrophysical implications (SMBHs oscillate/even escape).

❑ Importance of accretion, merging and stellar captures in BH mass growing and on the BH spin history.



❑ Possibilities for future GW astronomy: new research window on structure formation and galaxy mergers, direct detection of coalescing binary SMBHs, high-precision measurements of SMBHs masses and spins, constraints on SMBHs formation and evolution.

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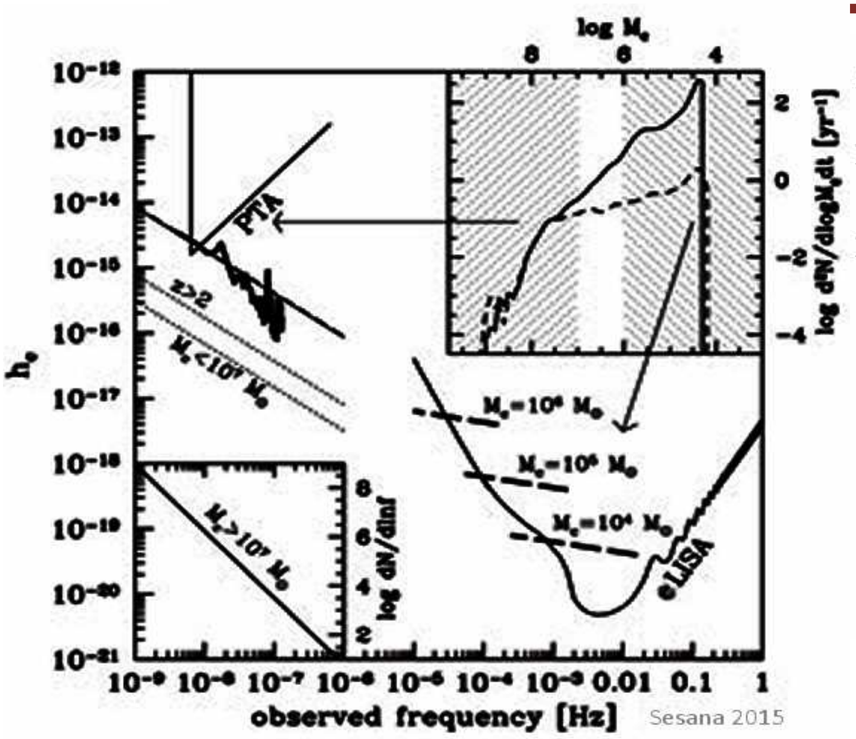
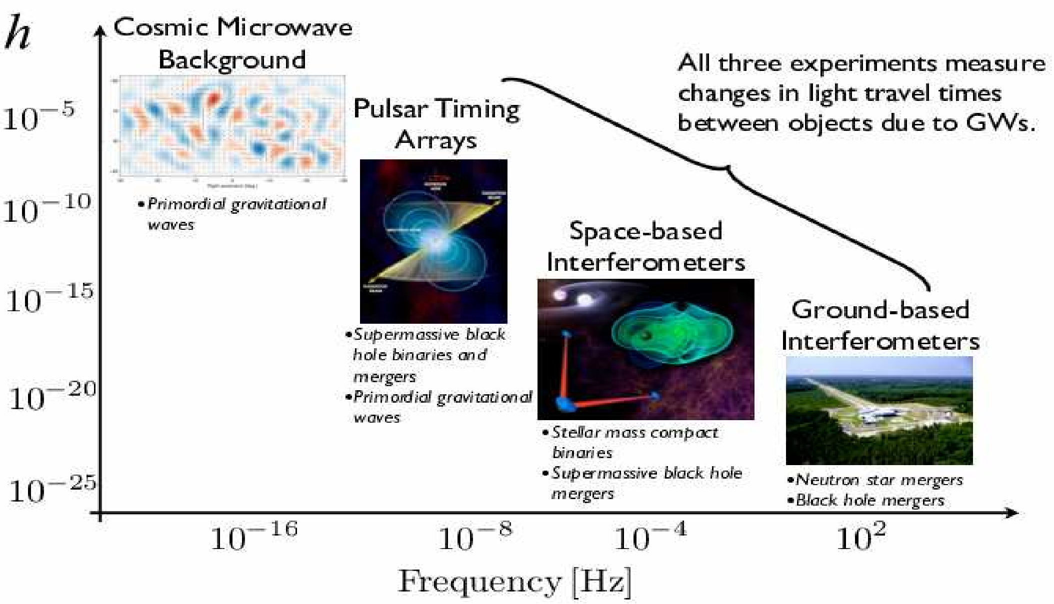
SMBH binaries and GWs: LISA and PTAs/SKA



Sesana 2015



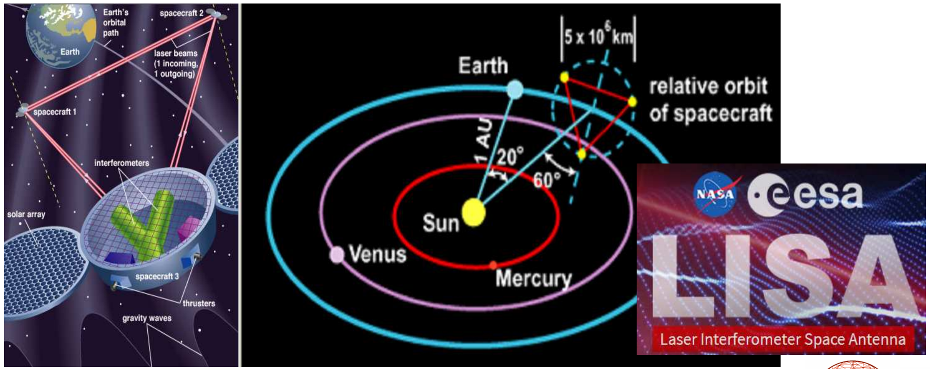
All three experiments measure changes in light travel times between objects due to GWs.

Cosmic Microwave Background
- *Primordial gravitational waves*

Pulsar Timing Arrays
- *Supermassive black hole binaries and mergers*
- *Primordial gravitational waves*

Space-based Interferometers
- *Stellar mass compact binaries*
- *Supermassive black hole mergers*

Ground-based Interferometers
- *Neutron star mergers*
- *Black hole mergers*

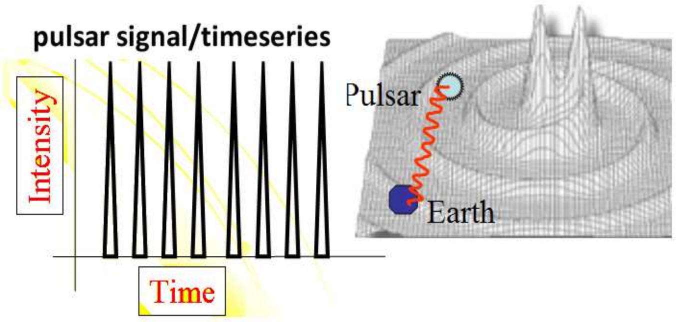


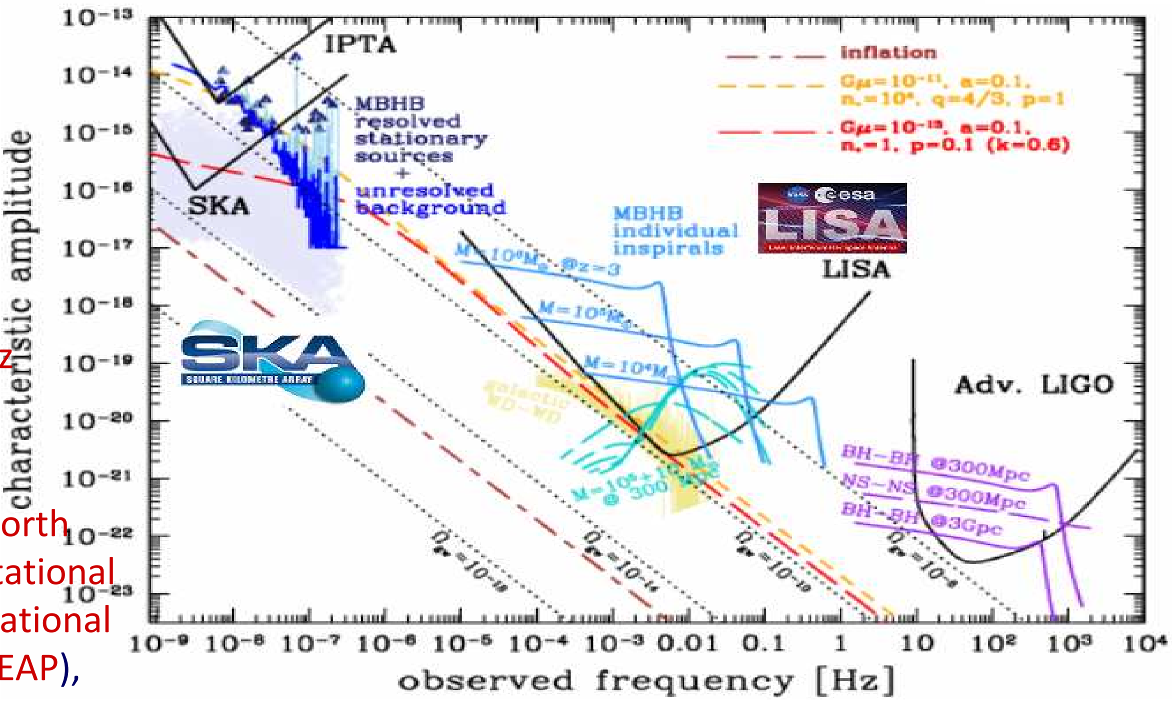
SKA TELESCOPE

SQUARE KILOMETRE ARRAY

Exploring the Universe with the world's largest radio telescope

SMBH binaries and GWs: PTAs and SKA

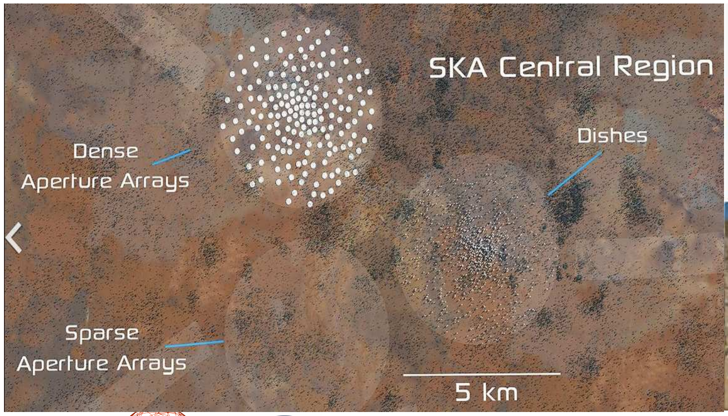




- ❑ Binary SMBHs emit GWs in the nanohertz to millihertz band, and indirect detection possible with PTAs

- ❑ Current PTAs are (European PTA EPTA, North American Nanohertz Observatory for Gravitational Waves NANOGrav, Parkes PTA PPTA, International PTA IPTA, Large Eurpean Array for Pulsars LEAP), future and larger international PTAs and the future SKA project.

- ❑ Cureent PTAs efforts will form the basis for detailed studies of GW and GW sources by the future high-sensitivity SKA project.

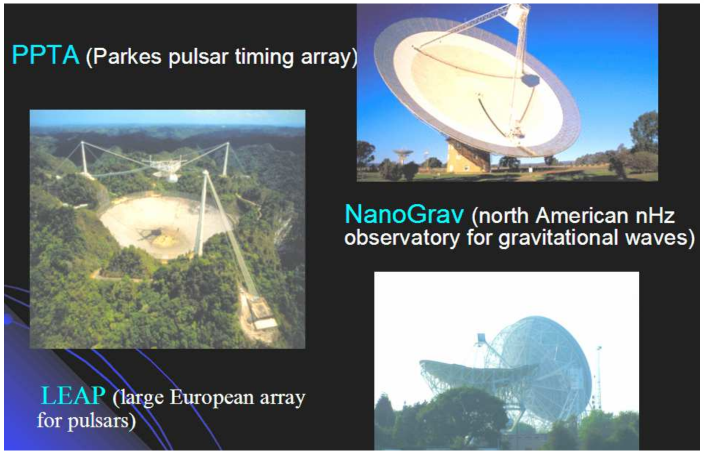


SMBH binaries and GWs: PTAs

EPTA

NANOGrav

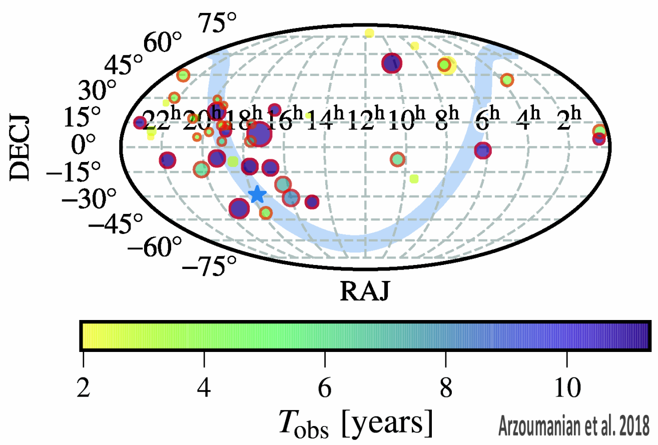
PPTA


PPTA (Parkes pulsar timing array)

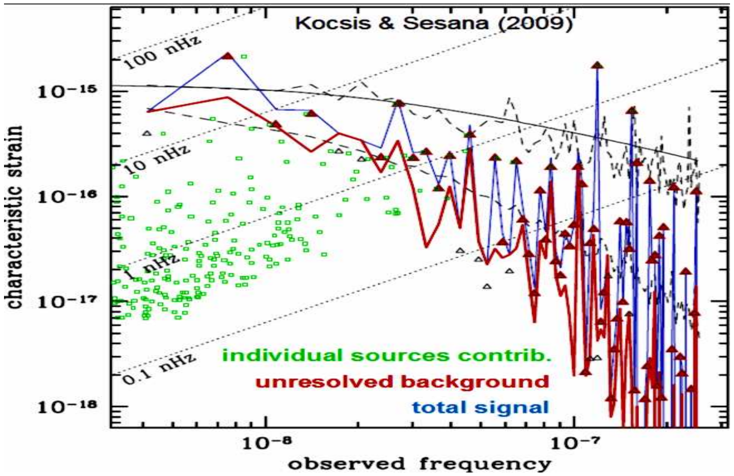
NanoGrav (north American nHz observatory for gravitational waves)

LEAP (large European array for pulsars)

45 pulsars in the NANOGrav 11-year dataset



Arzoumanian et al. 2018



☐ Most likely source of GWs detectable by PTAs is a stochastic background (GWB) from binary SMBHs in cores of distant galaxies/AGN.

☐ Observed pulsar periods are modulated by low frequency GWs traversing our Galaxy. GWs passing over pulsars are uncorrelated. GWs passing over Earth produce a correlated signal in the terrestrial time of arrival (TOA) residuals for al pulsars.

☐ With observations of a few pulsars we can only put a limit on the strength of the stochastic GW background.

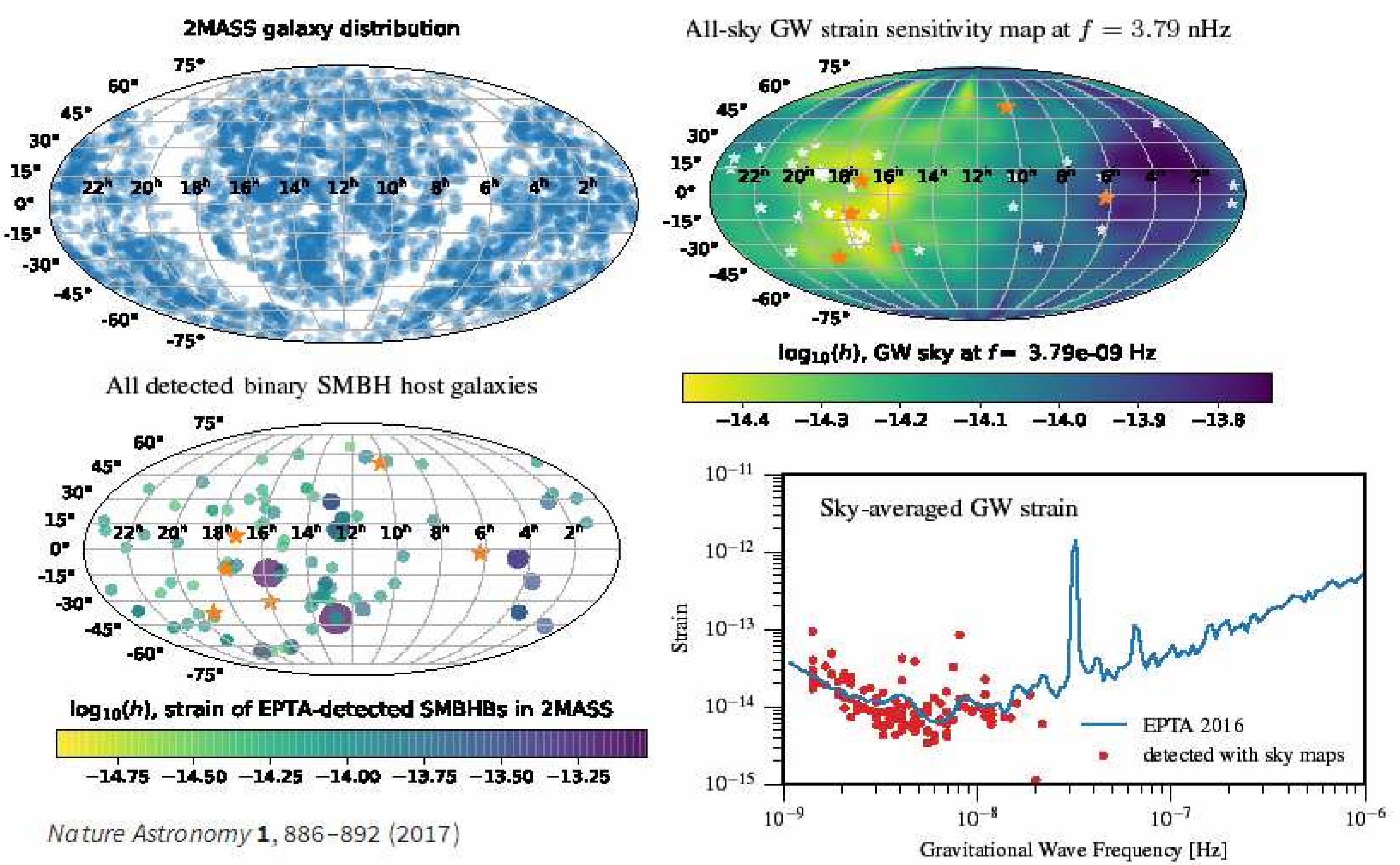
☐ Best limits are obtained for GW frequencies of about 1/D where D is the time duration of the time range of the data collected.

☐Accretion gas suppresses the stochastic background and individually resolvable sources remain.

☐ First detection likely will requires a observations of some dozen of "good" pulsars over a >15 years observations timescale.

SMBH binaries and GWs: PTAs

☐Estimations and studies with simulations and construction of realistic GW skies and future international PTAs and SKA projections, using IPTA pulsars with their real noise properties, and galaxies from the 2 Micron All Sky Survey (2MASS) together with galaxy merger rates from the “Illustris” merger trees simulation predictions:



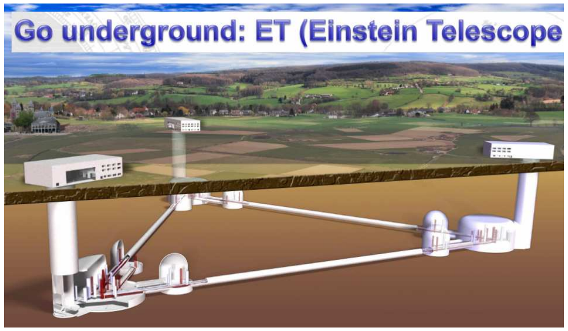
Nature Astronomy **1**, 886–892 (2017)

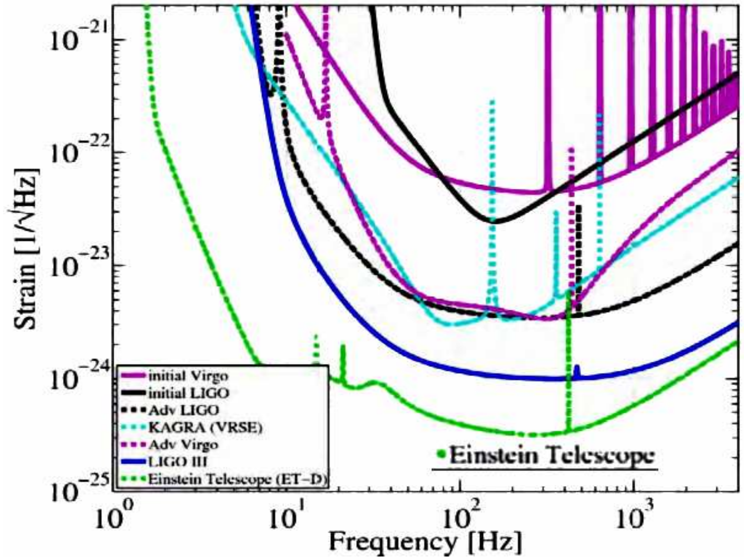
→ the probability of each 2MASS galaxy to contain a binary SMBH emitting GWs in the PTA band (i.e. GW frequency > 1 Nano-Hz) gives <1% of GW skies realization having galaxies hosting detectable binary SMBHs.

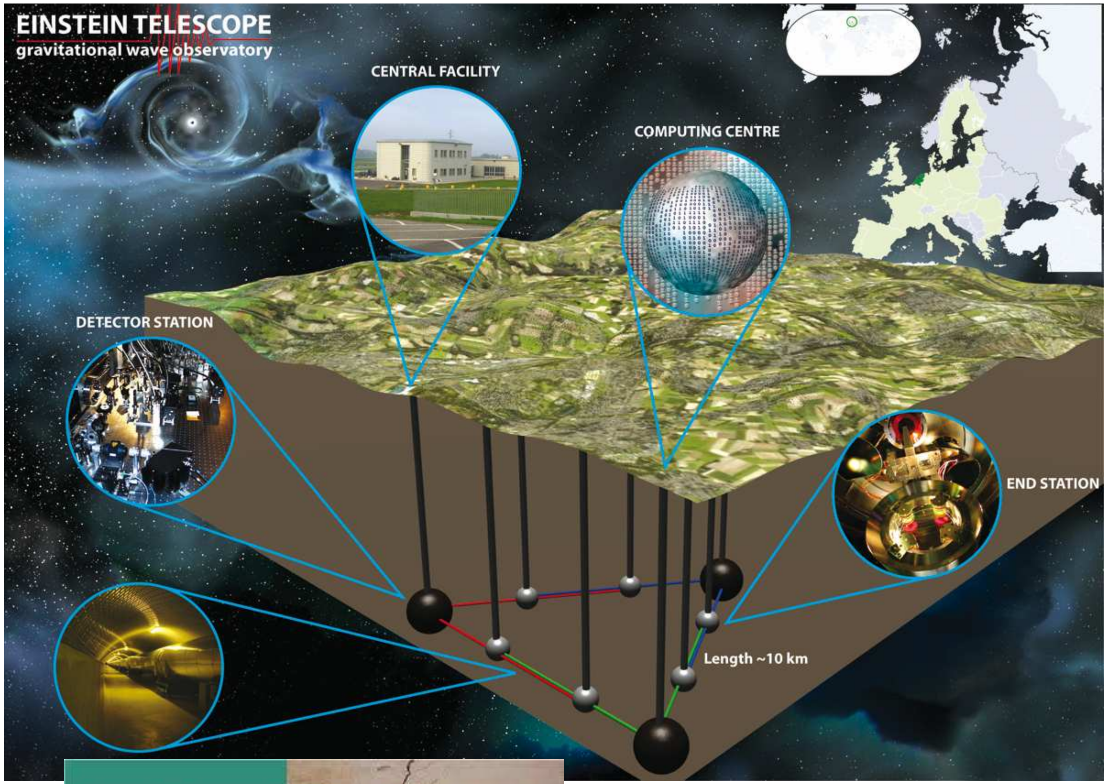
→ about 90 2MASS galaxies expected to host detectable binary SMBHs, and <10 galaxies expected to host stalled binary SMBHs that do not overcome the final parsec problem and will never merge.

[Mingareli+ 2017, Nature Astron. 1, 886]

GW 3rd Generation Einstein Telescope







- ☐ GW 3rd Generation Einstein Telescope (ET) facility has 3 detectors, configured in a triangular topology, and each detector consists of 2 interferometers. The 10 km arms of the observatory are housed underground to suppress seismic and gravity-gradient noise. Optical components are placed in an ultra-high vacuum and cryogenic environment. The ET observatory is a large leap in sensitivity.

ET and SMBH ?? – Expl.1: Kozai-Lidov catalyst

The hierarchical triple body post-Newtonian GR approximation has useful applications to a variety of systems from astronautics of solar system probes, planetary solar system dynamics, and stellar scales to supermassive black holes scales.

❑ The secular Kozai-Lidov mechanism (also known as effect, oscillations, resonance, oscillation) is a dynamical phenomenon affecting the orbit of a binary system perturbed by a distant third body under certain conditions. For example the Kozai-Lidov resonance is particularly important for the shaping of the orbits of irregular satellites of planets.

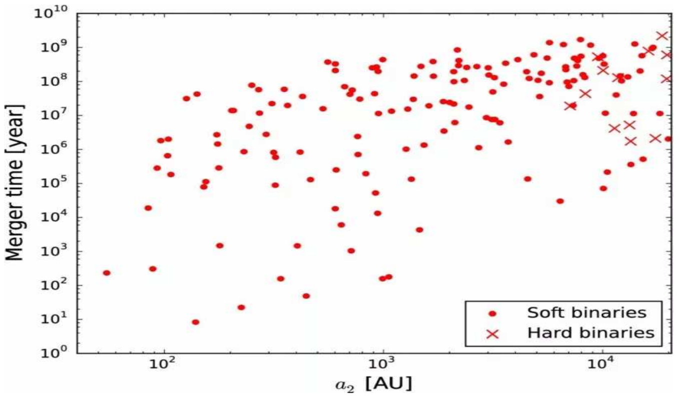
❑ Environment near the central SMBHs of an AGN has large number of stars and compact objects (BH-BH/BH-NS/NS-NS b

$$T_{\rm Kozai} = 2\pi \frac{\sqrt{GM}}{Gm_2}\frac{a_2^3}{a^{3/2}}\left(1-e_2^2\right)^{3/2} = \frac{M}{m_2}\frac{P_2^2}{P}\left(1-e_2^2\right)^{3/2}$$

❑ Secular Kozai precession of eccentricities and inclinations evolves such binaries due to the perturbation by the SMBH.

→ binaries in this SMBH environment inspiral and coalesce at timescales <<Hubble_time (and much shorter than similar binaries which do not reside near a SMBH).

→ SMBHs serve as catalyst for the inspiral and coalescence of compact-objects binaries.



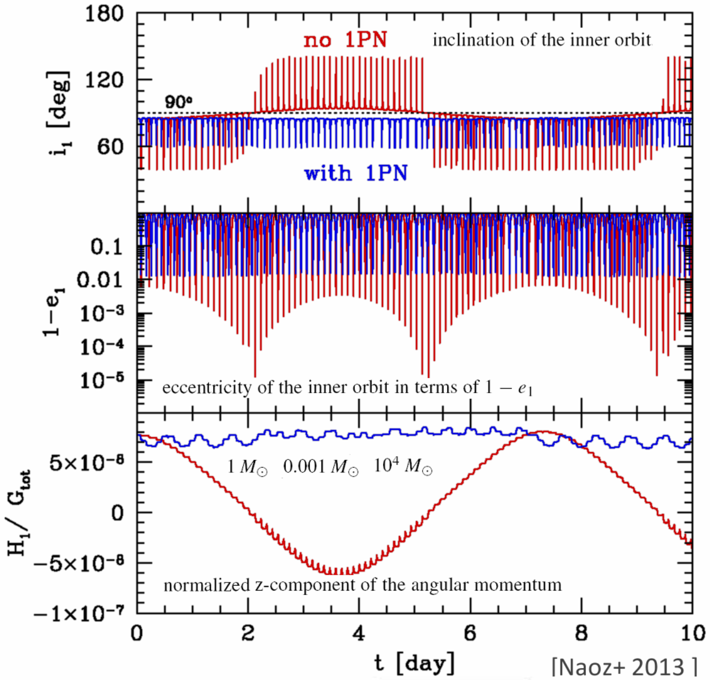
❑ BH-BH binaries in galactic nuclei with quadrupole and octupole-level secular perturbations, general relativistic precession, and high-frequency gravitational wave emission.

❑ A possible (new) science case for the next ground based GWs observatory: the Einstein Telescope (ET).

Kozai-Lidov resonance: PN theory + 3-body system

❑ Expansion of the first-order post-Newtonian Hamiltonian to leading-order + hierarchical three-body problem → Kozai-Lidov mechanism [Kozai 1962, Lidov 1962]: a highly inclined perturber can produce large-amplitude oscillations in the eccentricity and inclination of the three-body system.
It is a resonant-like eccentricity excitation.

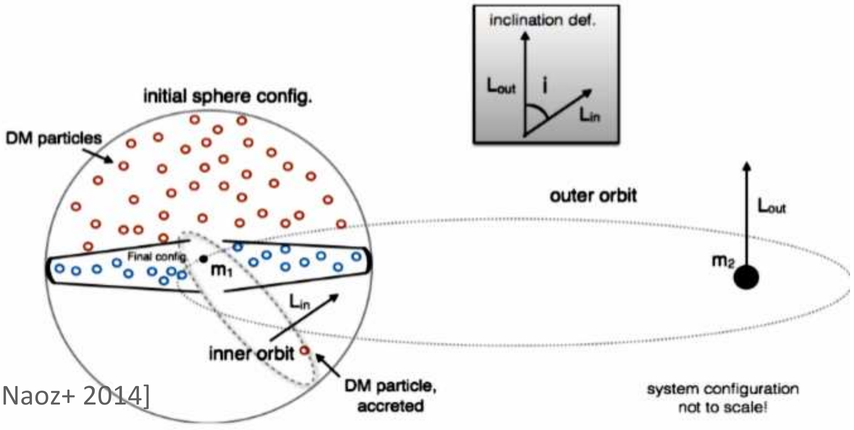
❑ Kozai–Lidov resonance is a secular (coherent and long interaction compared to orbital period) effect common in hierarchical triple systems but absent from two-body dynamics. It has been suggested to play an important role in both the growth of BHs at the centers of dense stellar clusters and the formation of short period BH X-ray binaries [Miller & Hamilton 2002, Ivanova+ 2010, Naoz+ 2013].



[Naoz+ 2013]

❑ GWs emitted during Kozai–Lidov-induced, highly eccentri orbits of compact, star-mass system, binaries might be detectable by 2nd and 3rd order (ET) ground-based GW antennas. [Armitage & Natarajan 2005, Sesana+ 2010].

❑ Dark Matter could form torii around SMBHs via the eccentric Kozai-Lidov mechanism [Naoz+ 2014]



[Naoz+ 2014]

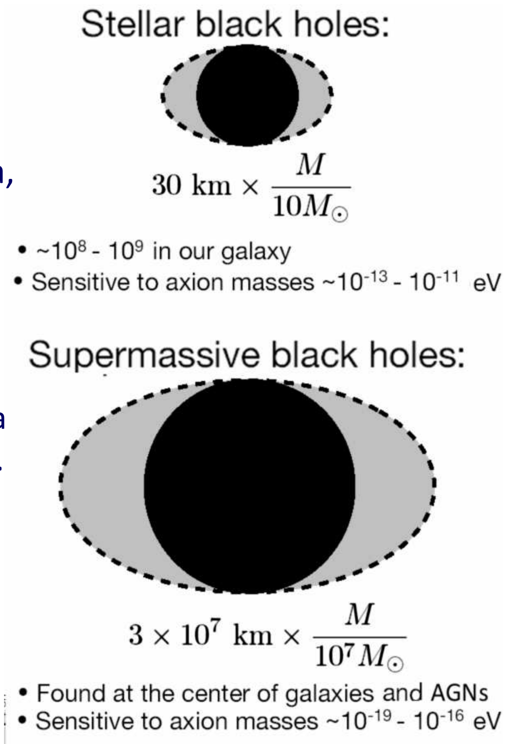
ET and SMBH ?? – Expl.2: Axionic SMBHs

❑ Quantum chromo dynamics (QCD) axion is one of the best hyphotetical particle motivated beyond standard model of particle physics, solving the strong-CP problem by making the QCD theta angle a dynamical field.

❑ It is a Pseudo-Goldstone boson with mass and couplings fixed by the decay constant f_a, very weakly interacting and with large Compton wavelength.

❑ Black holes can be used as natural cosmic axion particle detectors because the BH size is similar to the axion Compton wavelength, and the strong gravity regime.

❑ Hairy (axionic) black hole "Gravitational Atom": In analogy with the Hydrogen atom of quantum mechanics, axions and axion-like particles (ALPs) clouds gravitationally bind around a BH and occupy the quantum states characterized by the usual atomic quantum numbers, n, l, m. Fine-structure constant and quantized energy levels for hairy (axionic) BH gravitational atom!



Stellar black holes:
- ~10^{8} - 10^{9} in our galaxy
- Sensitive to axion masses ~10^{-13} - 10^{-11} eV

Supermassive black holes:
- Found at the center of galaxies and AGNs
- Sensitive to axion masses ~10^{-19} - 10^{-16} eV

LIGO/Virgo → discovery of GWs from BH-BH, NS-NS merger events.
These "hydrogen atom" (elementary piece) of gravity

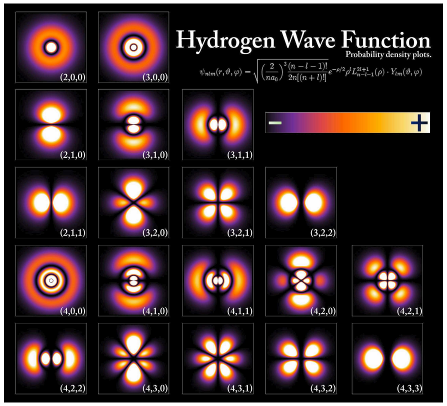
❑ BUT: are they BHs? And, in case, are they Kerr BHs? Are they no-hairy BHs of GR ?

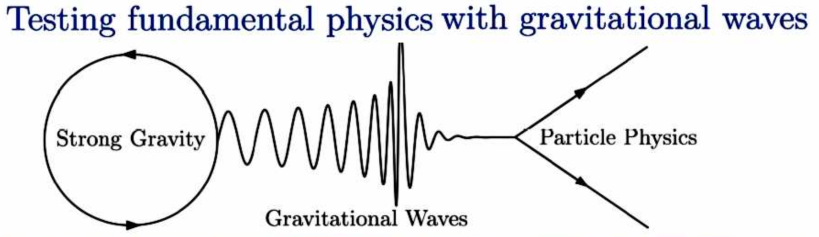
❑ Tests of GR at extreme is similar to tests of nuclear physics at extreme?

❑ Other GW sources besides binaries of BHs and NSs ?

❑ Signatures of dark matter in GWs?

❑ Inspiral-merger-ringdown phases in current merger GWs bursts can provide complementary diagnostics too.

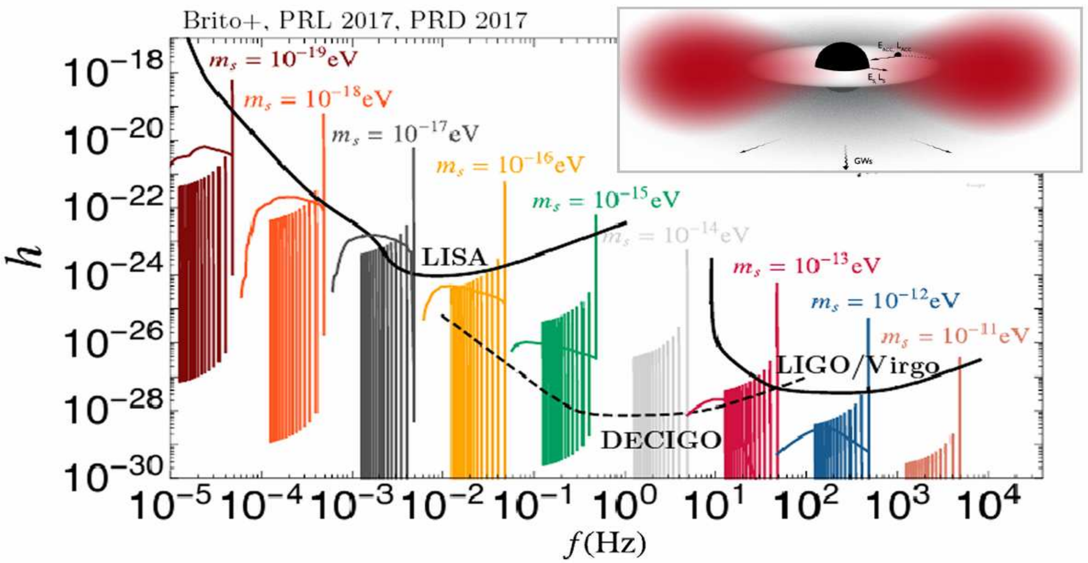


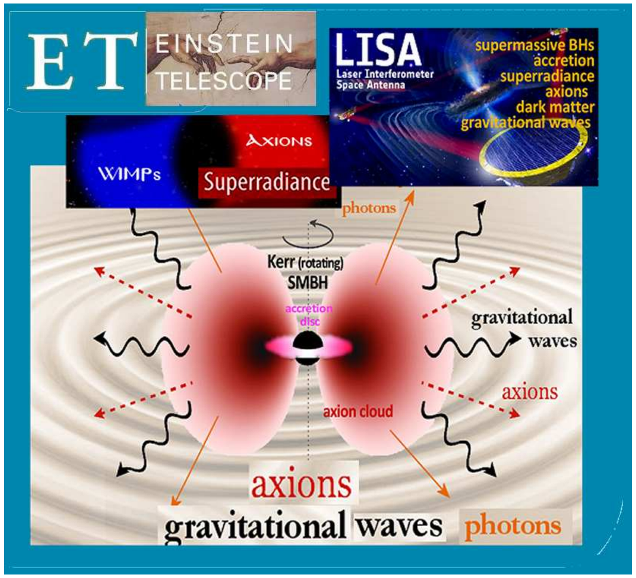


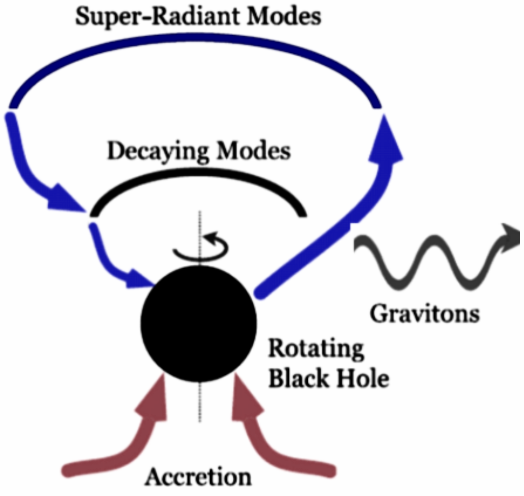
ET and SMBH ?? – Expl.2: Axionic SMBHs

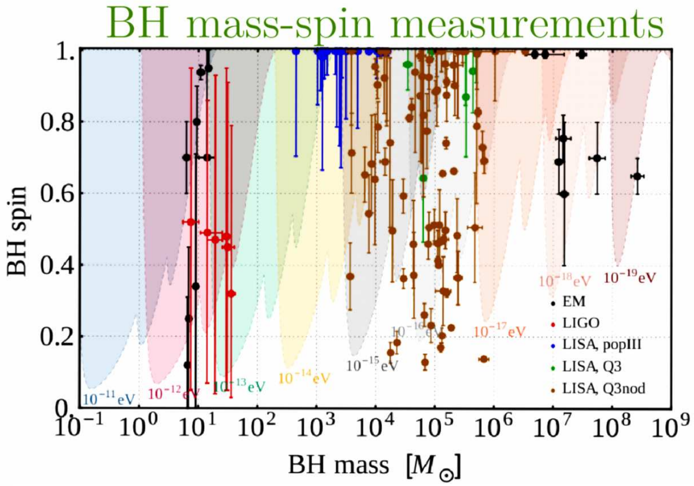
❑ Spinning (Kerr) BHs are unstable against gravitationally bound ultralight boson fields, through superradiance phenomenon [Arvanitaki+ 2012, Cardoso+ 2015] (the Penrose 1969 process in classical physics).

❑ These "hairy" axionic BHs/SMBHs are continuous GW source at a GW frequency given by the axion mass.
→ Expected GW periodic signals from axions in BHs/SMBHs !


Brito+, PRL 2017, PRD 2017






BH mass-spin measurements

ET and SMBH ?? – Expl.3: SMBHs high-freq. tails

SMBH GWs can leak to higher GWs frequencies (>1 Hz) of interest for detection by ground-based GW antennas?.

❑ If the high-frequency spectral tail asymptotes to h(f) are proportional to f^−a (a <=2) then the spectral amplitude is a constant or increasing function of the mass M at a fixed frequency f>>c^3/GM.
This will happen if the time-domain waveform or its derivative exhibits a discontinuity.

❑ Some possible physics processes which may generate high-frequency GWs signals from SMBHs at the center of AGN (>1Hz GWs direct emitter or GW-perturbing signals):

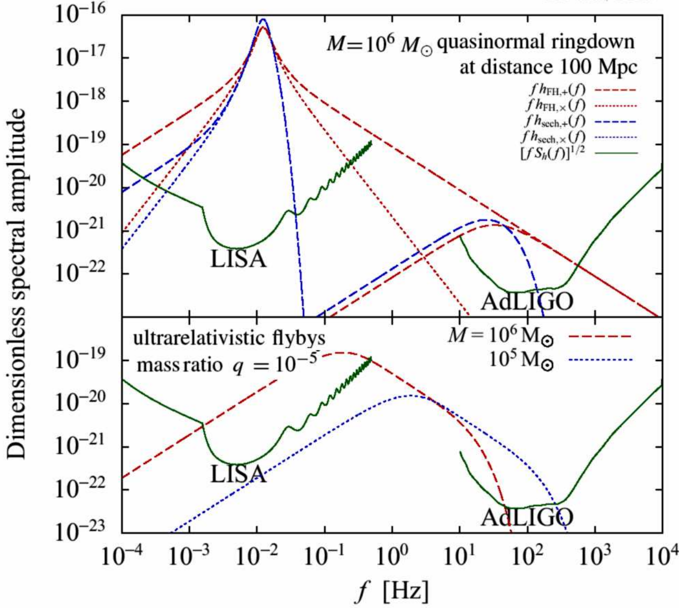
- (1) gravitational bremsstrahlung of ultrarelativistic objects in the vicinity of an SMBH at the center of an AGN;
- (2) ringdown modes excited by an external process that has a high-frequency component or terminates abruptly;
- (3) gravitational lensing echoes and diffraction.

❑ Known strong gravitational lensed AGN (a few Fermi LAT gamma-ray blazars are gravitationally lensed too) can imply echoes and diffraction of inspiraling stellar mass binaries in the AGN with a signal delays from of a few to days. → lensed primary signal and GW echo both amplified if the binary is within a ~10 deg (r/100M)^−1/2 cone behind the SMBH (r dystance form the SMBH,) [Kocsis 2013].

❑ ET could provide observational constraints on the event rates of such sources independent of their origin. These potential sources have also a well-defined GW broadband spectral shape, h(f) proportional to f^−1 / f^−2, allowing the development of optimal search algorithms.

❑ These signals may be distinguished from instrumental glitches if they show up coincidentally in all of the different instruments in a detector network (two LIGO, Virgo, Kagra, ET) with a consistent spectral amplitude.

Kocsis, 2013



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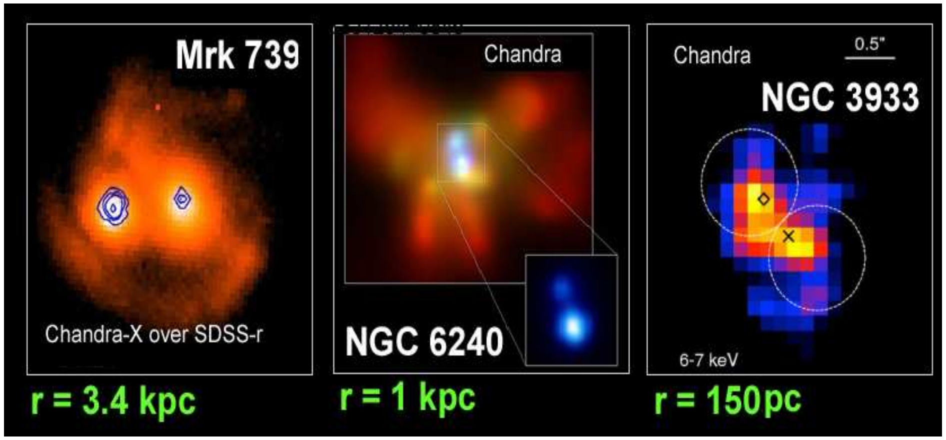
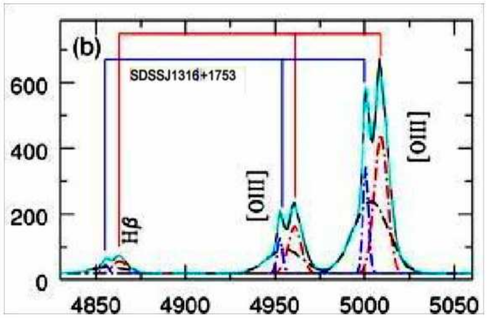
Observational evidence for SMBHs pairs/binaries

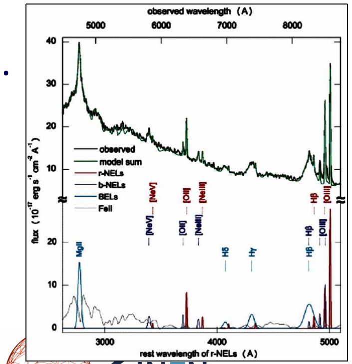
❑ Pair of accreting SMBH in "single" galaxies (spatially resolved 10-pc to 100-pc): NGC 6240; 4C+37.11 , NGC 3933, LBQS 0103-2753, Mkn 739, ESO 509-IG 066…

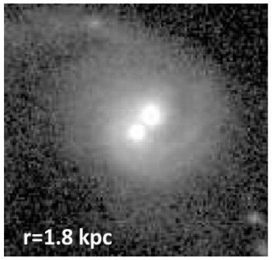


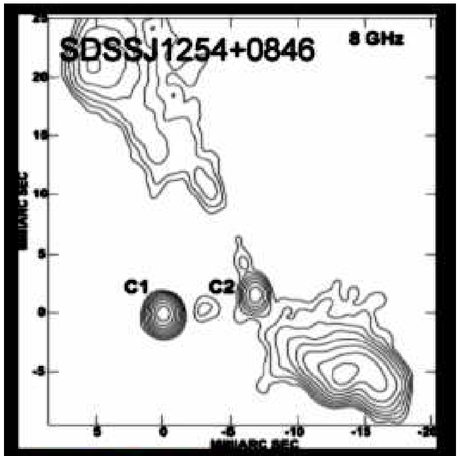
❑ Spatially unresolved (close if <0.1pc) binary SMBHs:

- from claims of quasi-periodic variability signatures: OJ 287, PG 1302-102, 3C 345, PSO J334.2028+01.4075, AO 0235+16, 3C 273, etc... (still very debated topic).
- from observed helical distorted radio jets (jet-emitting 2ndary SMBH orbiting primary, precession, jet reorientation in X-shaped radio galaxies): 3C 345, NRAO 530/PKS 1730-13, 3C 120, 3C 66B, Mkn 501, etc...
- from observed double-peaked broad lines: SDSS J0927+2943, SDSS J1316-1753, SDSS J150243.1+111557, PG 1302-102 (non-double but asymmetric). Only small fraction of all "double-peakers" are good candidates; only a few confirmed as "detections".
- other evidences: some candidate TDEs (SDSS J120136.02+300305.5), recoils (anisotropic emission of GWs from coalescing binary SMBHs leads to recoil of the newly formed single SMBH) and more exotic ones.



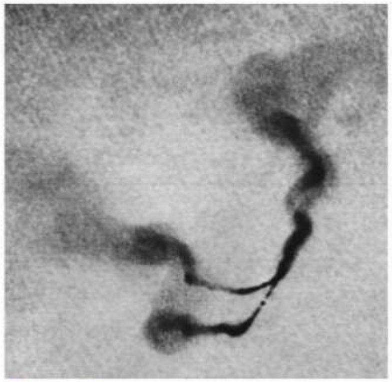




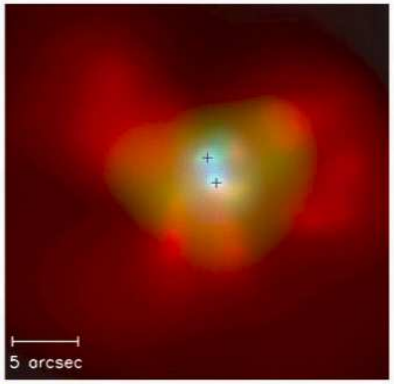


r = 7 pc
radio galaxy, z=0.06
two radio cores C1,C2
compact, variable & flat-spectrum
→ true nuclei

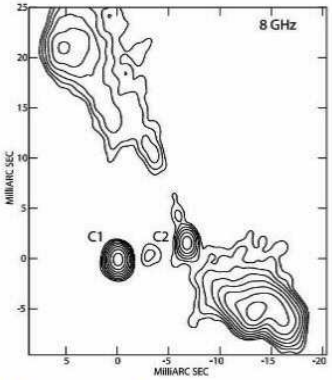
Observational evidence for SMBHs pairs/binaries



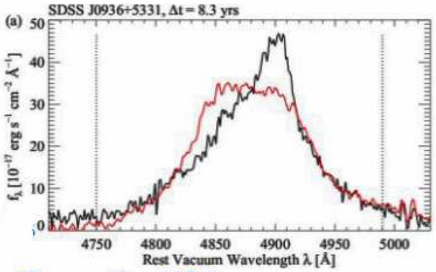
Dual jets (3C 75, a~7kpc)
[Owen+ 1985]



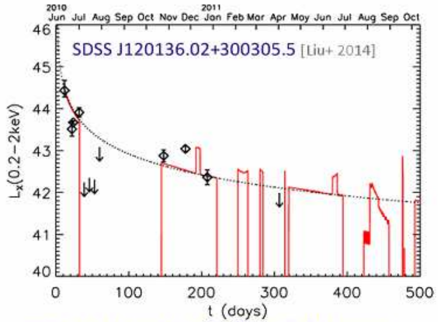
Dual X-ray sources
(NGC 6240, a ~ 1.5 kpc) [Komossa+ 2003]



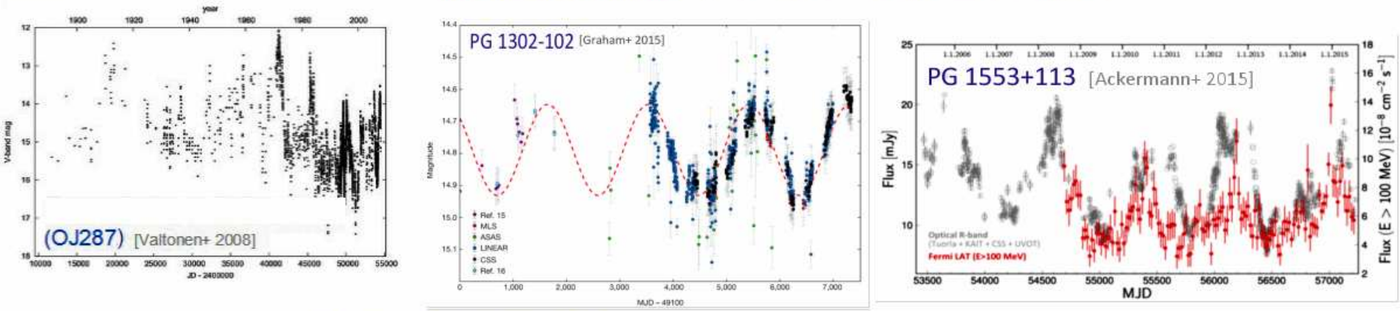
Binary radio sources
(0402+379, a ~ 7pc) [Owen+ 1985]



Kinematic shift in
multi-epoch observations
[Liu+ 2013]



TDE events and dips in X-ray light curves



Quasi periodicity in light curves (still controversial topic)

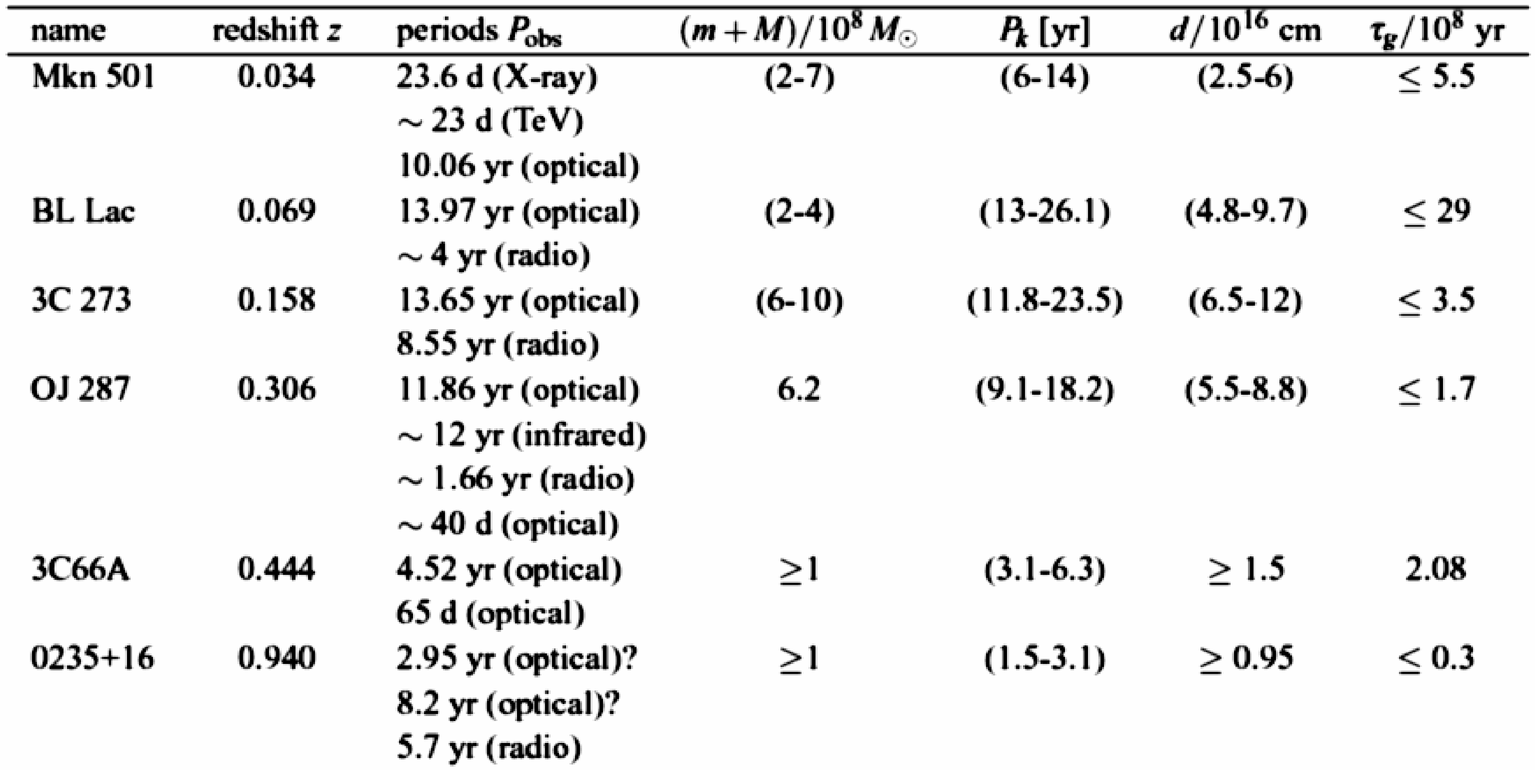
❑ Many binary SMBHs candidates but few non-controversial confirmations! Why so few ?
Large distances (difficult to resolve). Perhaps obscured. Need to distinguish other phenomena (in-jet knots, lensing, ...). In close pairs most current methods require at least one SMBH to be active (many may not be).

❑ Perhaps the greatest challenge is to identify the inactive binary SMBHs which might be the most abundant, but are also the most difficult to identify. Most binary SMBHs may form quiescently either in gas-poor or minor galaxy mergers without driving AGN activities.

Possible quasi-periodic signatures in blazars

☐ Long-term radio/optical light curves of blazars → possible periods several years (OJ 287, PG 1302-102, CGRaBS J1359+401, 3C 345, PSO J334.2028+01.4075, AO 0235+16, 3C 273, TXS 0059+581, BL Lac...)

☐ Short-term optical/X-ray/TeV light curves of blazars → possible periods of several tens of days (Mkn 501, Mkn 421, PKS 2155-304, 3C 66A, S5 0716+714 , OJ 287, Sy 1 KUG 1031+398/RX J1034.6+3938…)



name	redshift z	periods $P_{\rm obs}$	$(m+M)/10^8\,M_\odot$	P_k [yr]	$d/10^{16}$ cm	$\tau_g/10^8$ yr
Mkn 501	0.034	23.6 d (X-ray) $\sim$ 23 d (TeV) 10.06 yr (optical)	(2-7)	(6-14)	(2.5-6)	≤ 5.5
BL Lac	0.069	13.97 yr (optical) $\sim$ 4 yr (radio)	(2-4)	(13-26.1)	(4.8-9.7)	≤ 29
3C 273	0.158	13.65 yr (optical) 8.55 yr (radio)	(6-10)	(11.8-23.5)	(6.5-12)	≤ 3.5
OJ 287	0.306	11.86 yr (optical) $\sim$ 12 yr (infrared) $\sim$ 1.66 yr (radio) $\sim$ 40 d (optical)	6.2	(9.1-18.2)	(5.5-8.8)	≤ 1.7
3C66A	0.444	4.52 yr (optical) 65 d (optical)	≥ 1	(3.1-6.3)	≥ 1.5	2.08
0235+16	0.940	2.95 yr (optical)? 8.2 yr (optical)? 5.7 yr (radio)	≥ 1	(1.5-3.1)	≥ 0.95	≤ 0.3

Candidate BSMBHs in literature based on some reported quasi-periodicity evidence. Associated gravitational lifetime tg is estimated for mass ratios m/M > 1/100 [Rieger 2008, 2007].

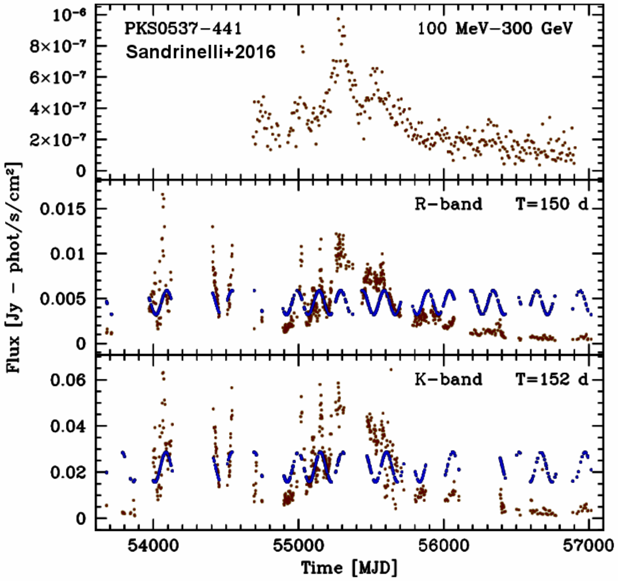
Periodicity in blazars: some problems

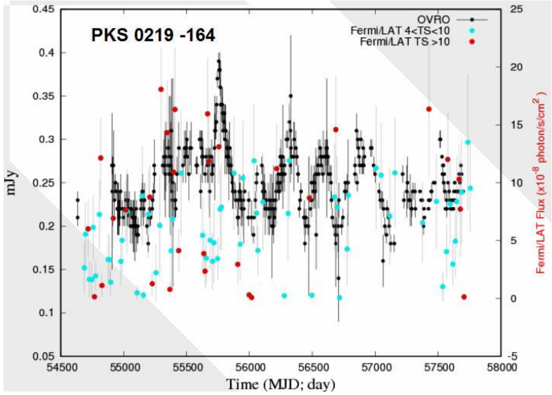
☐ Problem: single band light curves. Too strong claim to argue for unresolved close (<0.1 pc) BSMBH system based on periodicity in 1 single energy band. To observe multifrequency quasi-periodicy and cross-correlations can support the claim. To observe helical pc-scale radio-jet patterns and observe periodical polarization patterns can support the claim.

☐ Problem: single portion of the light curve ("cherry pick" of data). The full time interval of the available data must be considered and analyzed (not only the one portion that conveniently shows a periodicity). Periods that are intrinsically transient (do not last more than a few cycles) are not a result on "periodicity".

☐ Problem: data gaps (especially optical light curves). How gaps influence our analysis results?

☐ Problem: quality of the light curve and significance of the period. To be convinced the light curves and fit would have to be comparable to what we see in X-ray binaries but in most cases they are not (very different samplings, gaps, errors, dispersion/confusion resulting from heterogeneity of different instruments/telescopes…).





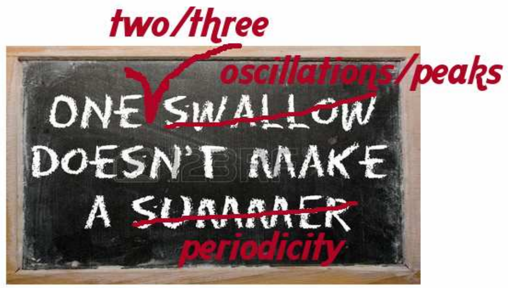
Periodicity in blazars: red-noise problem

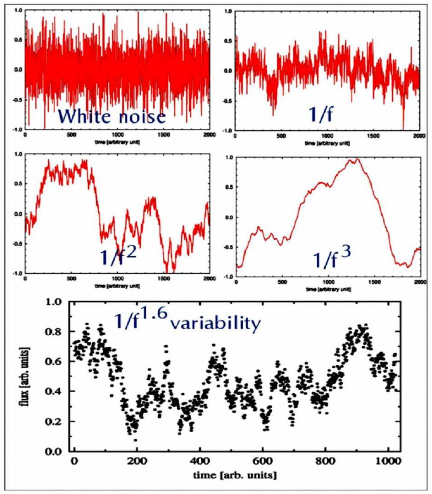
Periodicity → binaries

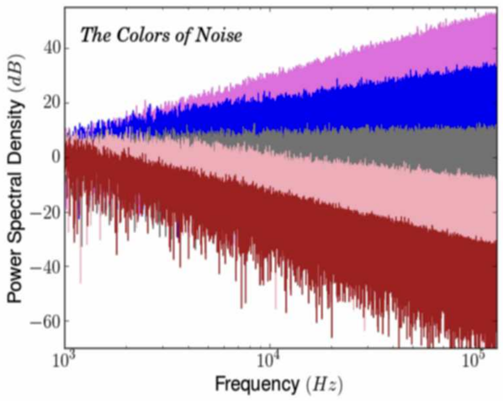
- Sillanpää+1988
- Lehto&Valtonen 1996
- Raiteri+2001
- Fan et al. 2002
- Rieger 2004
- Liu et al. 2006
- Valtonen et al. 2008
- Sandrinelli et al. 2014
- Graham+2015
- Ackermann et al. 2015
- Valtonen et al. 2016

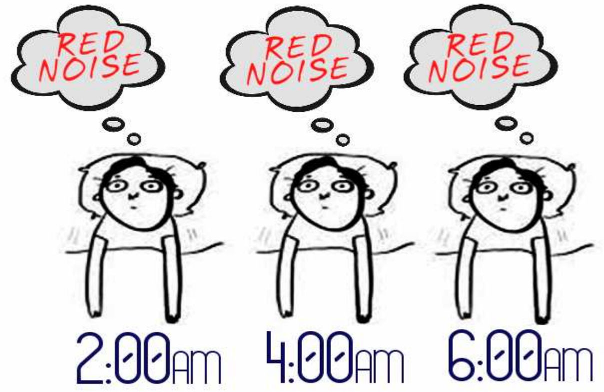
☐Problem: red-noise. The periodicity significance is difficult to assess given the usually limited length of the light curves. Red-noise, i.e. random and relatively enhanced low-frequency fluctuations (Brownian noise) over intervals comparable to the sample length, hinders the evaluation of significance. Essentially stochastic variability can build red noise and it can show up and mimic a misinterpreted periodic trend.
(...*one swallow does not a summer make*!
... *red-noise keeps you awake during the night*!). Simulations can help.

☐ Problem: when blazar luminosities range over maybe 4–5 orders of magnitude, why do claimed periods all have similar time scales of a few years (1–25 years) ? If real this is puzzling.





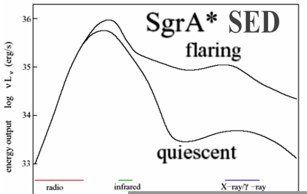


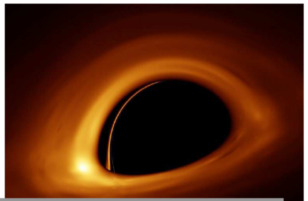


red-noise keeps you awake during the night !

One example: 20-min QPO in Sgr A* vs red-noise

❑ Claims for near-IR and X-ray wavelengths quasi-periodic oscillation (QPO) signal with 20-minute period reported in light curves of Sgr A* since 2003 (hot spots Keplerian orbits at ISCO, rotational modulations of accretion instabilities).





nature
International journal of science

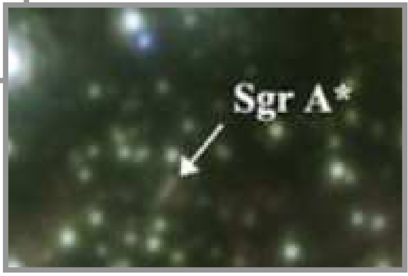
Letter | Published: 30 October 2003

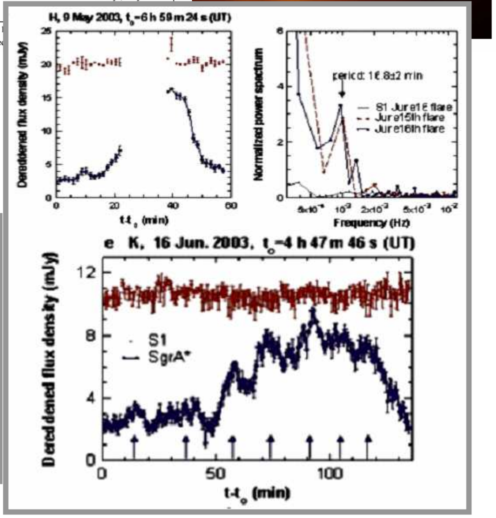
Near-infrared flares from accreting gas around the supermassive black hole at the Galactic Centre

R. Genzel, R. Schödel, T. Ott, A. Eckart, T. Alexander, F. Lacombe, D. Rouan & B. Aschenbach

Nature **425**, 934–937 (30 October 2003)

Genzel+ 2003;
Aschenbach+ 2004;
Eckart+ 2006;
Meyer+ 2006;
Trippe+ 2007;
Falanga+ 2007;
…etc.

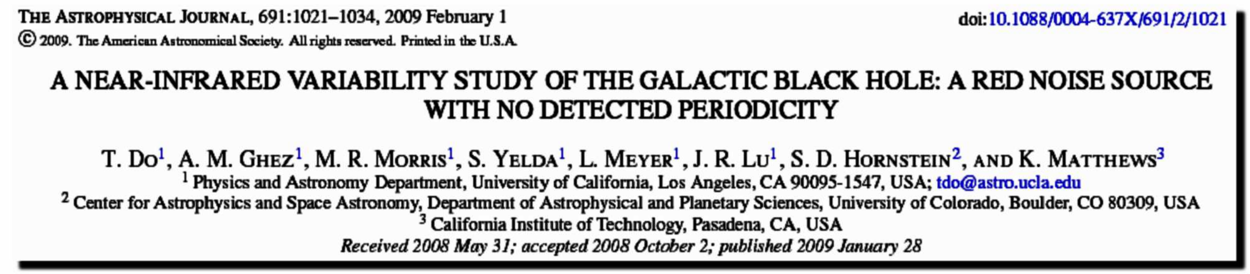




❑ Sgr A* near-IR periodicity disproved six years later: relatively short observation time baselines; only a few clamined-period oscillations; low amplitude oscillations; not rigorous assessment of statistical significance.

→ Oscillations entirely consistent with models based on correlated noise (power density spectra, PDS, 1/f^a with slopes a between 2.0 and 3.0) .

→ i.e. realizations purely ascribed to RED NOISE).



The Astrophysical Journal, 691:1021–1034, 2009 February 1 doi:10.1088/0004-637X/691/2/1021

A NEAR-INFRARED VARIABILITY STUDY OF THE GALACTIC BLACK HOLE: A RED NOISE SOURCE WITH NO DETECTED PERIODICITY

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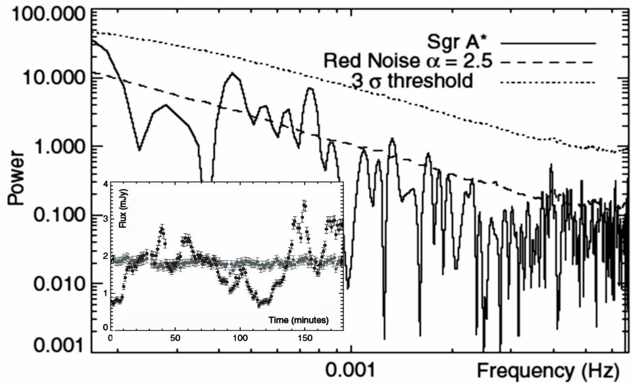
Received 2008 May 31; accepted 2008 October 2; published 2009 January 28

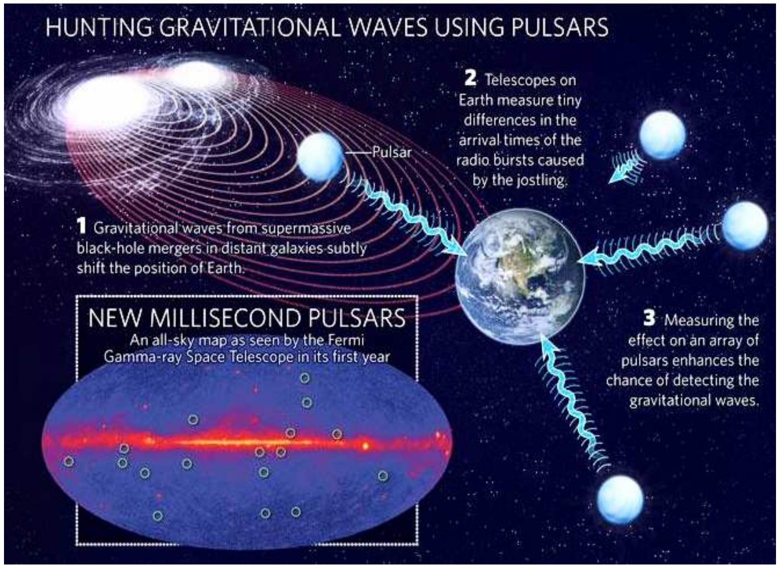


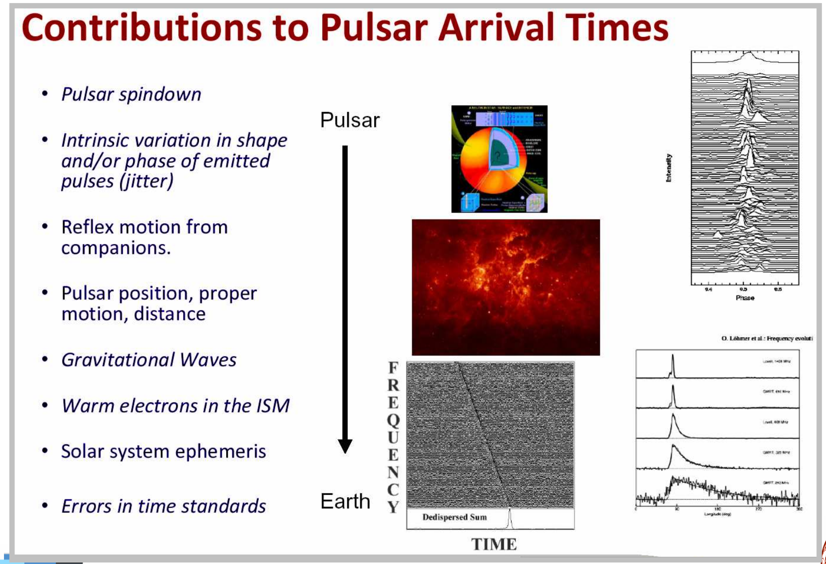
Second example: red noise in PTAs data

❑ Sensitivity of pulsar timing arrays (PTA) to gravitational waves limited by timing red noise (stochastic wandering of pulse arrival times has a red spectrum). Red timing noise spectrum plateaus below some critical frequency (Lasky et al. 2015, MNRAS, 449, 3293).

❑ Red noise in PTA data:

- Most young pulsars show intrinsic red spin noise
- Rotation instabilities ?
- Magnetospheric torque changes ?
- Open question: is this a generic property of MSPs too ?
- Can have similar spectral properties to GW bursts
  → need to, at least, model the presence of red noise in datasets
- Triage bad pulsars



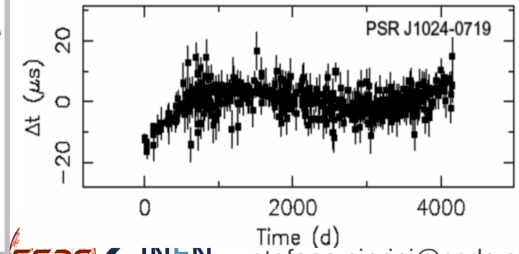


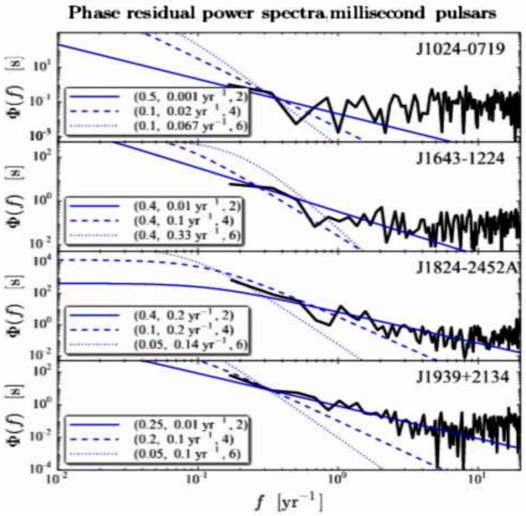
Contributions to Pulsar Arrival Times

- *Pulsar spindown*
- *Intrinsic variation in shape and/or phase of emitted pulses (jitter)*
- Reflex motion from companions.
- Pulsar position, proper motion, distance
- *Gravitational Waves*
- *Warm electrons in the ISM*
- Solar system ephemeris
- *Errors in time standards*

❑ Largest red-noise signal in data set are the variations in dispersion measure

→ need to remove red noise signal without removing red signal associated with a GW burst.



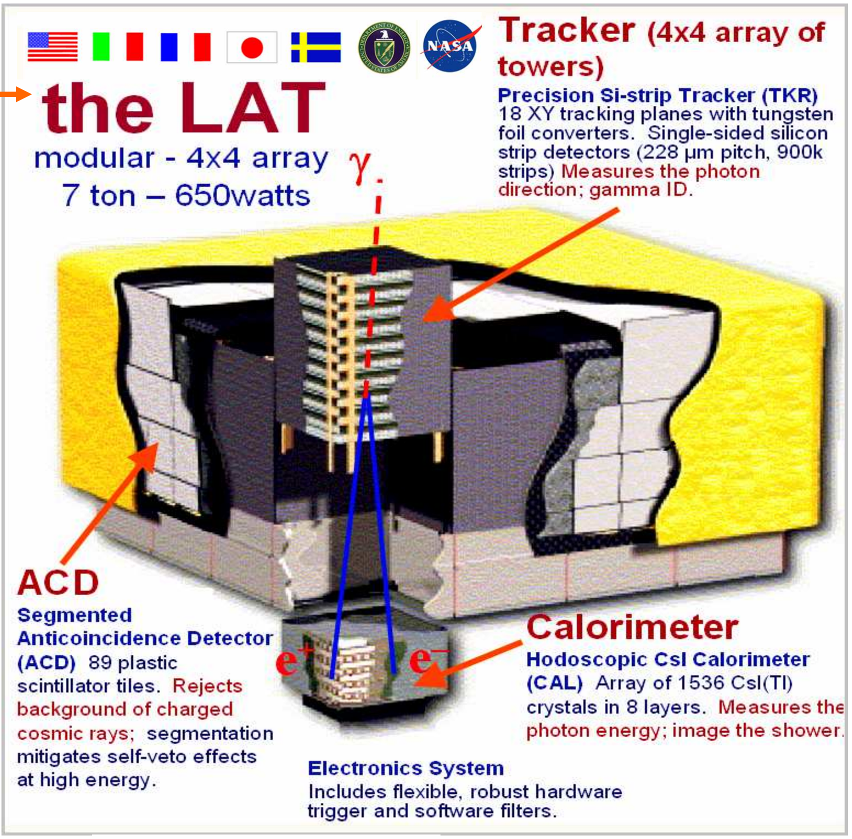


10 years of *Fermi* Gamma-ray Space Telescope

Fermi (formerly GLAST): two Instruments

The Large Area Telescope (LAT)
20 MeV - 300 GeV
>2.5 sr FoV

The Burst Monitor (GBM)
8 keV – 40 MeV
9.5 sr FoV



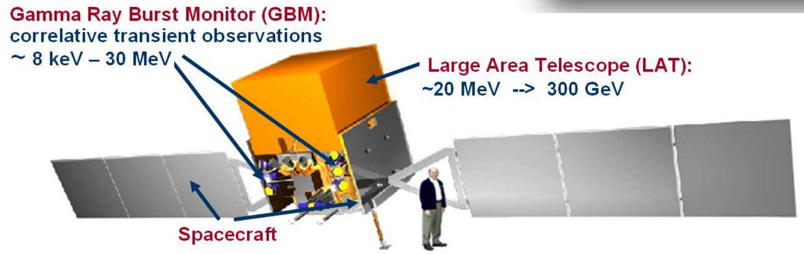
the LAT
modular - 4x4 array
7 ton – 650watts

Tracker (4x4 array of towers)
Precision Si-strip Tracker (TKR) 18 XY tracking planes with tungsten foil converters. Single-sided silicon strip detectors (228 µm pitch, 900k strips) Measures the photon direction; gamma ID.

ACD
Segmented Anticoincidence Detector (ACD) 89 plastic scintillator tiles. Rejects background of charged cosmic rays; segmentation mitigates self-veto effects at high energy.

Calorimeter
Hodoscopic CsI Calorimeter (CAL) Array of 1536 CsI(Tl) crystals in 8 layers. Measures the photon energy; image the shower.

Electronics System
Includes flexible, robust hardware trigger and software filters.

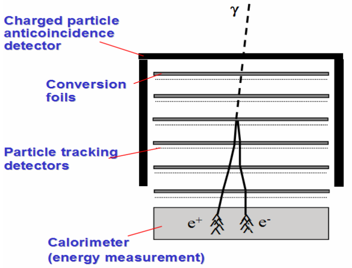


Gamma Ray Burst Monitor (GBM): correlative transient observations
~ 8 keV – 30 MeV

Large Area Telescope (LAT):
~20 MeV --> 300 GeV

Spacecraft

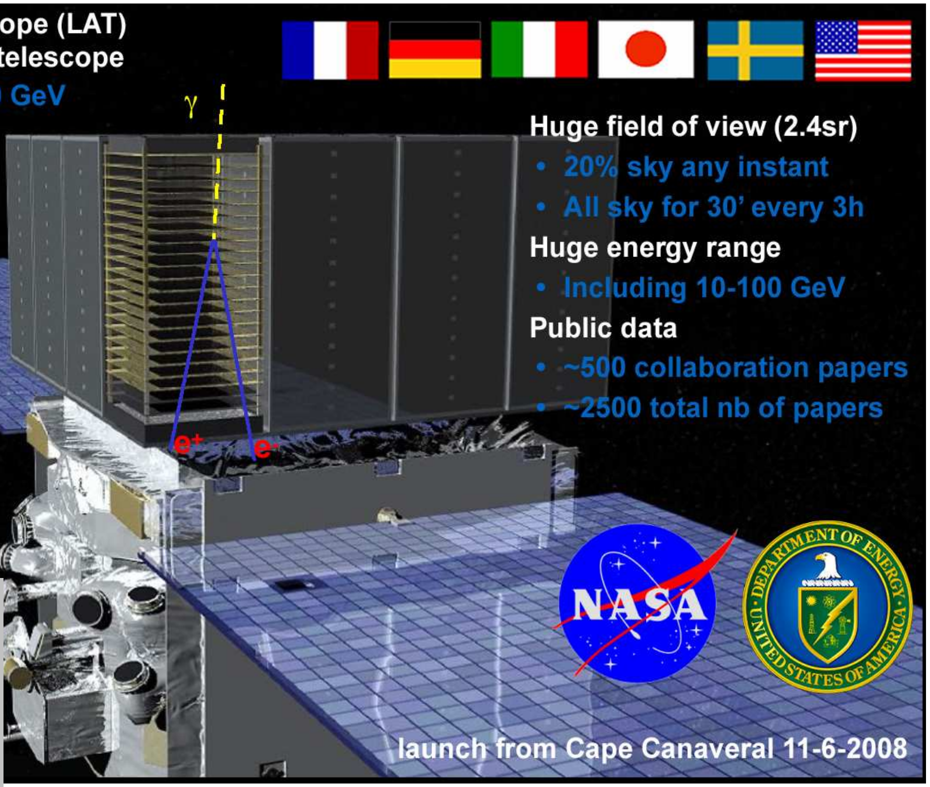
International and interagency collaboration between NASA and DOE in USA and agencies in France, Germany, Italy, Japan and Sweden



stefano.ciprini@ssdc.asi.it - SSDC & INFN Rome

10 years of *Fermi* Gamma-ray Space Telescope

Large Area Telescope (LAT)
- pair conversion telescope
- 20 MeV – > 300 GeV



Huge field of view (2.4sr)
- 20% sky any instant
- All sky for 30' every 3h

Huge energy range
- Including 10-100 GeV

Public data
- ~500 collaboration papers
- ~2500 total nb of papers

Gamma-ray Burst Monitor (GBM) - counters
- 8 keV – 40 MeV

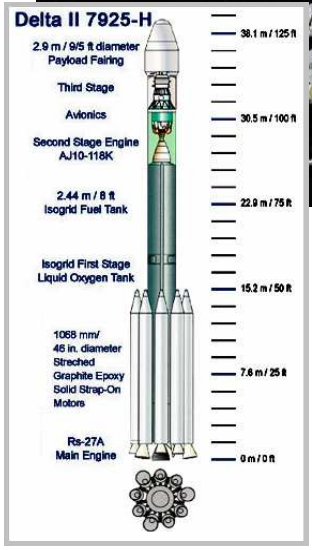
launch from Cape Canaveral 11-6-2008

❑ Gamma-rays cover a huge swath of the e.m. spectrum
❑ The gamma-ray sky is relatively poorly studied
❑ HE (GeV) gamma-rays probe the non-thermal universe
❑ Extreme environments hosting powerful cosmic particle acceleration
❑ Galactic/Extragalactic multimessen. physics, transients, variability
❑ More: dark matter, Solar sci., TGFs…

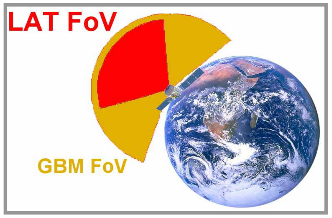
❑ Enhanced multi-messenger/multi-wavelength opportunities.
❑ Fermi unique all-sky monitor in a broad energy range (unique survey at GeV photon energy band).

Celebrating 10 Years of Fermi
June 11, 2018

❑ **Launched** 11 june 2008, Delta II Rocket, circular orbit, 565km altitude, 25.6 deg inclination.
Operations. Primary mode: all-sky survey with scan of the entire sky for 30min every 3 hours. Autonomous Repoint Request (ARR). Target of Opportunity (ToO). Huge field of view (2.4sr).

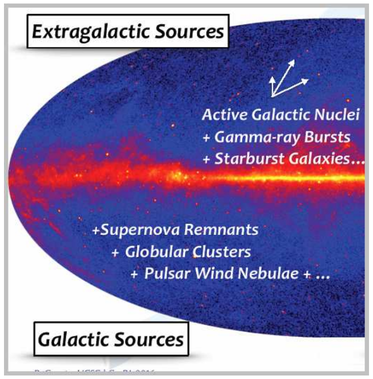


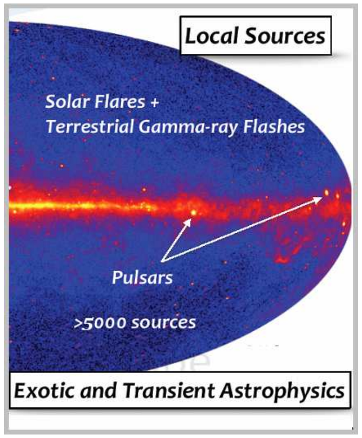
- **Large effective area**
- **Good angular resolution**
- **Huge energy range**
- **Wide field of view**



Mission to study cosmic particle accelerators in energy, time, sky position/distribution, distance

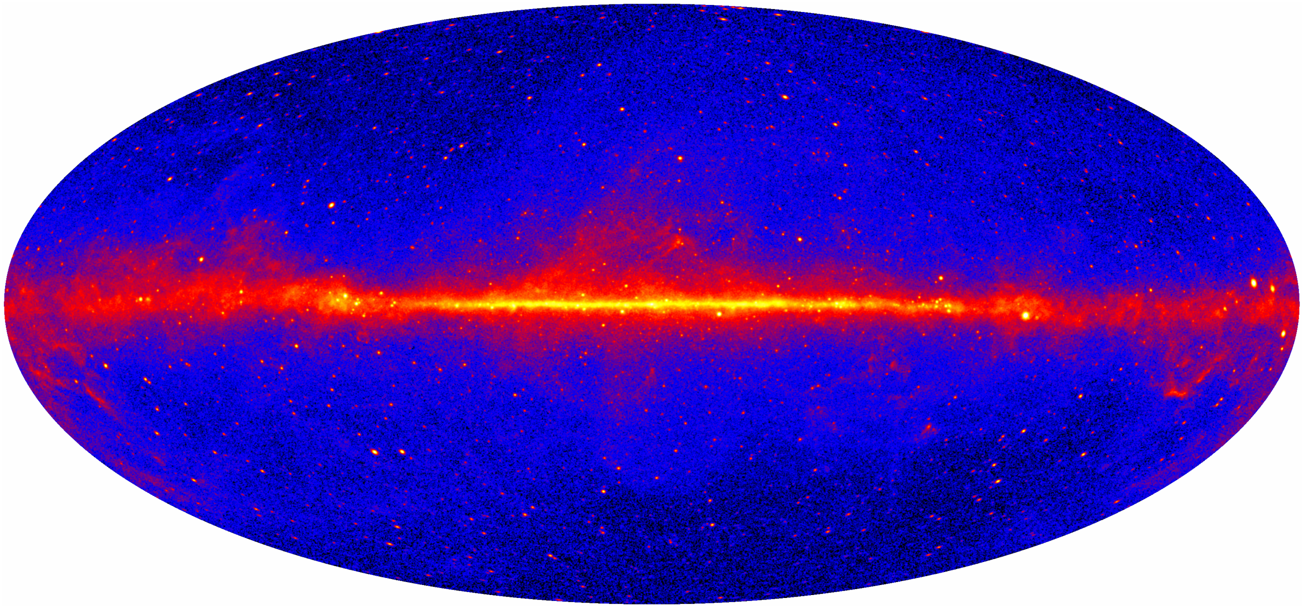
10-year E>1 GeV gamma-ray sky

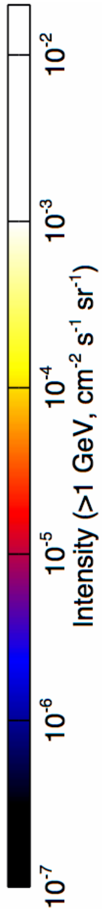




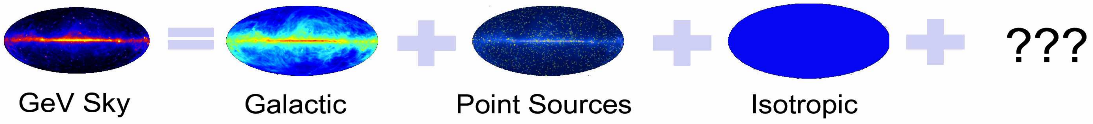
All-sky SURVEY:

uniformity, sensitivity depth, diffuse emission science, populations studies, serendipity, variability monitor, transients search, cross-correlation, cross-match, time domain science, multifrequency astronomy, multi-messenger astroparticle physics





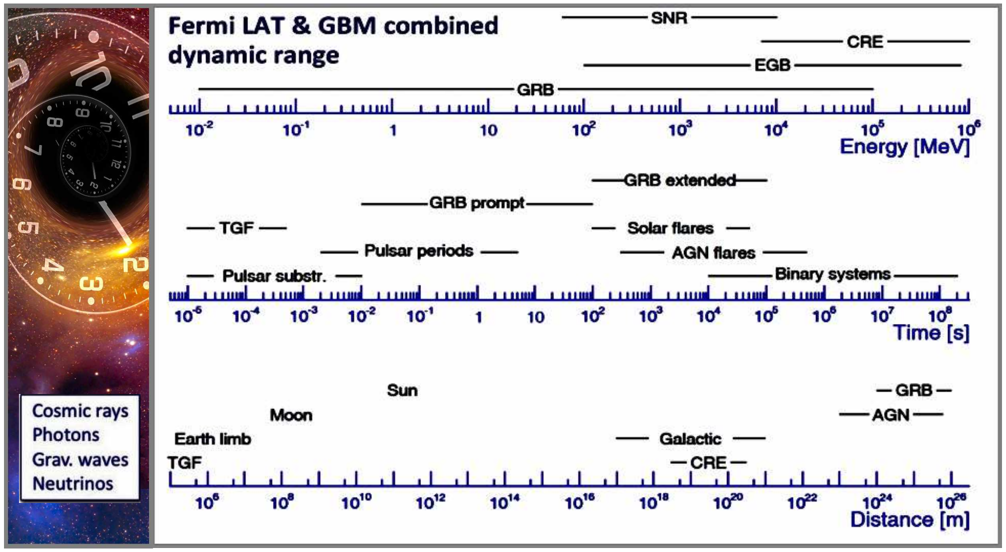
10-year (August 4, 2008 - August 4, 2018) gamma-ray intensity all-sky image obtained by the Fermi LAT.
Pass 8 Source class PSF3 event type data, intensity units, E>1 GeV, 100 deg zenith angle limit, Galactic coordinates, Hammer-Aitoff projection and logarithmic scaling. *Credits NASA/DOE/Fermi-LAT Collaboration.*

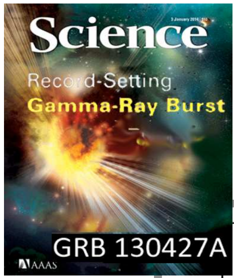


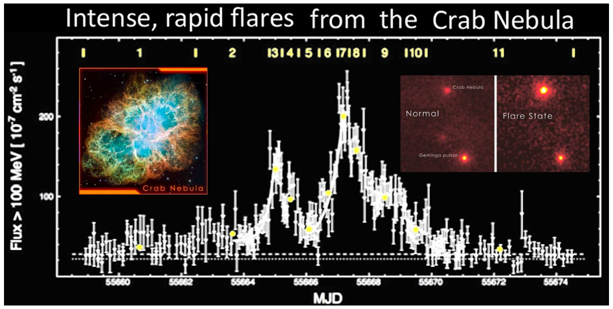
stefano.ciprini@ssdc.asi.it - SSDC & INFN Rome

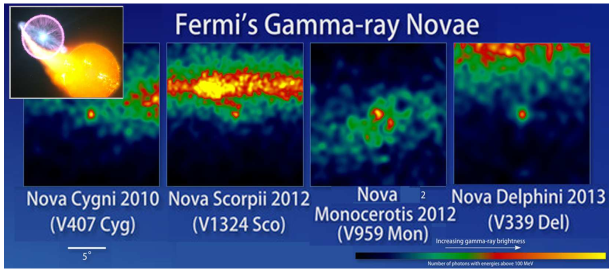
Fermi: all-sky survey & time-domain monitor

ALL-SKY + ALL-TIMES (spatial SURVEY + TIME-DOMAIN monitor + depth in z)
mission for the HE Universe, exploring gamma-ray timescales from millisec to years.

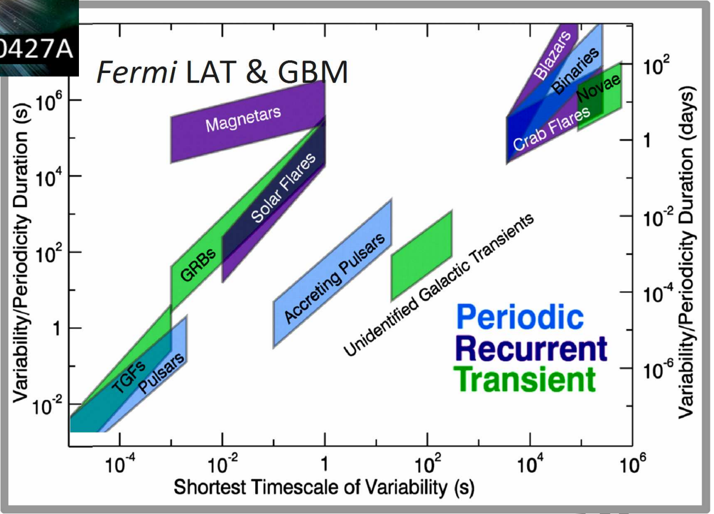


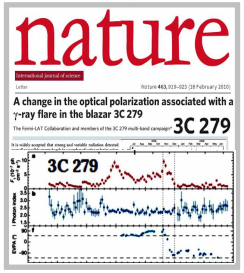






- ❑ Fermi LAT+GBM wide FoV and continuous survey → excellent to “catch” GRBs, AGN/blazars flares, glitches, galactic transients, novae, SNs, solar flares, TGFs; to search for neutrinos ,UHECRs, gravitational waves e.m. counterparts, DM non-steady emission; to monitor the variable HE sky (SERENDIPITY).




nature

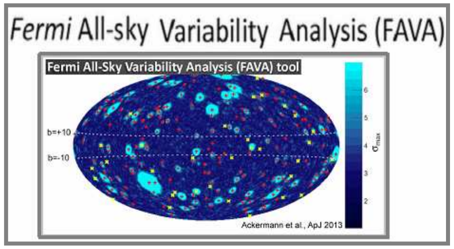
International journal of science

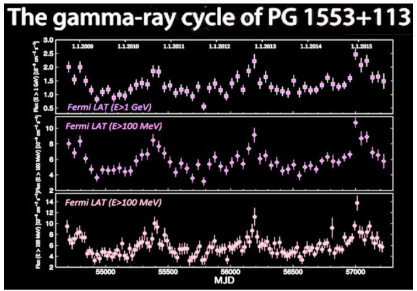
Letter — *Nature* **463**, 919–923 (18 February 2010)

A change in the optical polarization associated with a γ-ray flare in the blazar 3C 279

The Fermi-LAT Collaboration and members of the 3C 279 multi-band campaign*

3C 279

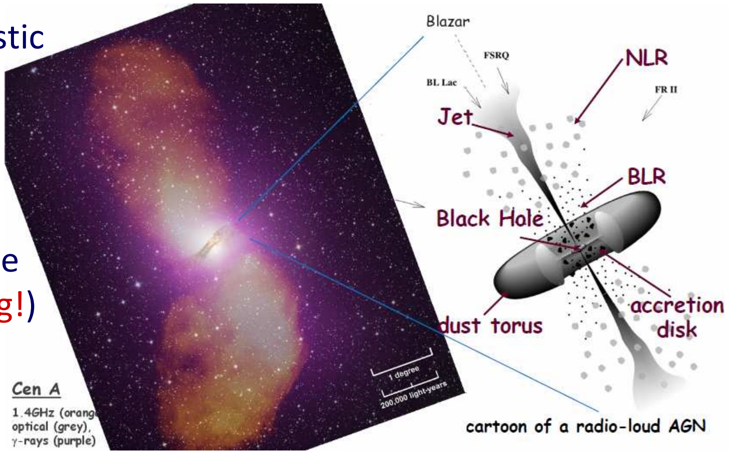




Blazars: supermassive BHs with beamed jets

❑ "Blazar": phenomenological term (obs. characteristics). They are relativistic cosmic particle accelerators (extragalactic particle beams/beacons), having jets pointing directly at us, with appearance in radio, optical, X-rays.

❑ The most variable AGN (emission lines in strength, continuum levels in flux brightness) → variability over all energy bands (radio to GeV-TeV gamma rays) and time scales is a defining property of blazars (and a promise to understand them). Erratic/aperiodic/stochastic variability (it is not boring!)



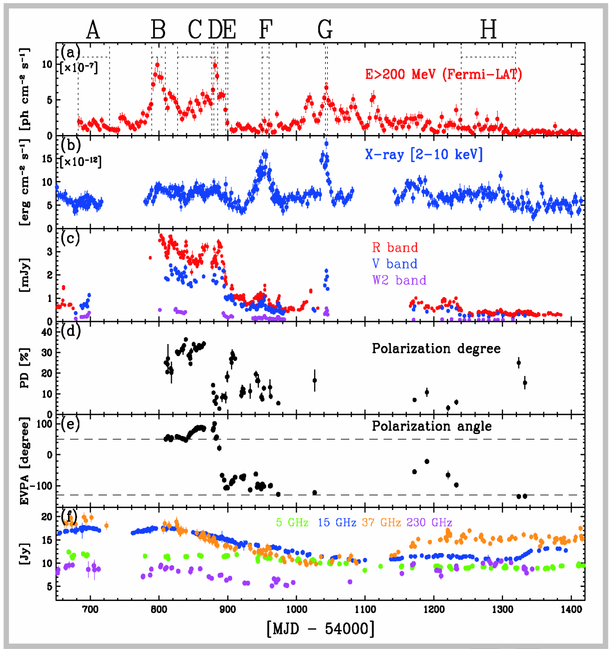
Cen A

1.4GHz (orange), optical (grey), γ-rays (purple)

cartoon of a radio-loud AGN

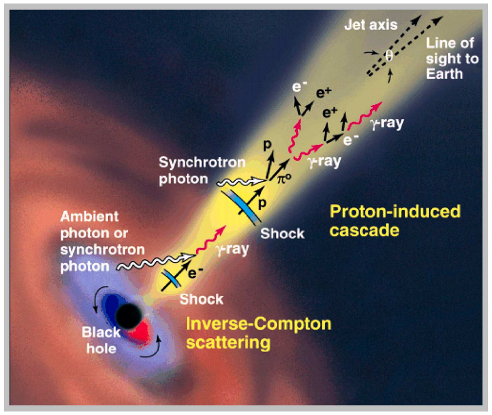
❑ Relativistic motion of jet components Doppler-boosts emission in the direction of motion. Here misaligned-blazars, are types of radio galaxies.

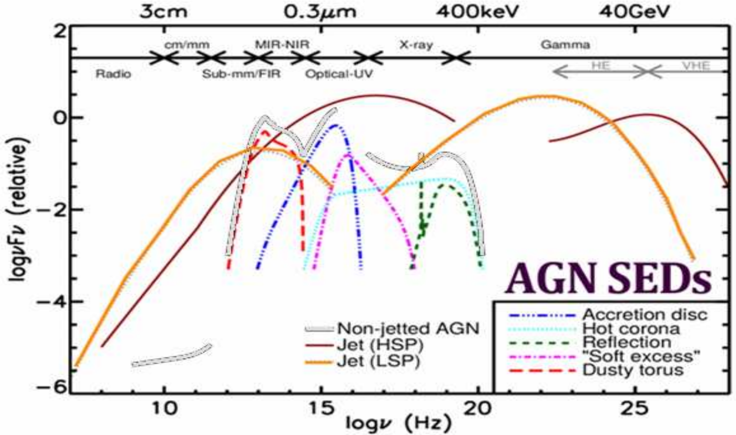
❑ Bright inverse Compton peak in SEDs in addition to synchrotron peak.



❑ Prominent point sources, dominating the census, in the gamma-ray sky. Compact radio sources (not always resolved). Polarization in radio/optical.

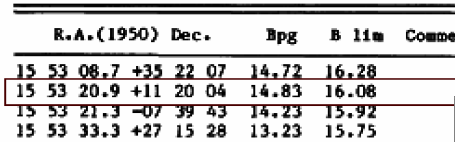
❑ "Extremely rich , multifrequency, data sets on blazars (intensive and extensive observing campaigns/monitor, flux/structure/polarization/spectral/temporal data).



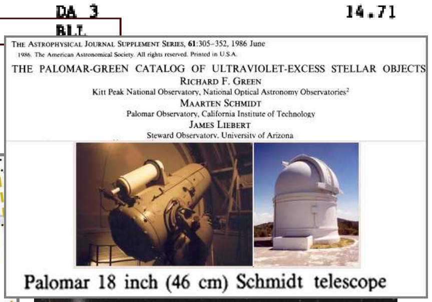


The blazar PG 1553+113 (a.k.a. 1ES 1553+113)

- ☐ PG 1553+113 (a.k.a. 1ES 1553+113): optically/X-ray selected BL Lac object (Green+ 1986; Falomo & Treves 1990).
- ☐ X-ray counterpart discovered by the Einstein Observatory (1ES catalog, in 1981 March 12, 3.3ksec, 1.27 cts/s). Observations by XMM, Chandra, Suzaku, Swift, etc. Chandra. Warm-hot intergal. medium (Nicastro+ 2013).
- ☐ Redshift constraints: 0.39 < z < 0.62 (Danforth+ 2010, Aliu+ 2015). Further estimation z=0.49+/-0.04 (Abramowski+ 2015).
- ☐ VHE (E>100GeV) gamma-ray emission discovered independently by H.E.S.S. (Aharonian+ 2006), and by MAGIC (Albert+ 2007; Aleksic+ 2012).
- ☐ PG 1553+113 plausible counterpart with IceCube event ID 17 (Padovani & Resconi 2014).
- ☐ Fermi LAT 3FGL catalog (3FGL 1555.7+1111): power-law, hard spectral photon index (1.604+/-0.025) and F(E>100MeV) =(1.32+/-0.03)X10^-8 ph cm^-2 s^-1). Variable source.
- ☐ Many spectral/SED studies (LAT data + MAGIC /H.E.S.S./VERITAS data). Dominant non-thermal in-jet emission.



R.A.(1950)	Dec.	Bpg	B lim	Comment	Class	B	U-B	B-V	v
15 53 08.7	+35 22 07	14.72	16.28		DA 3				14.71
15 53 20.9	+11 20 04	14.83	16.08		BLL				
15 53 21.3	-07 39 43	14.23	15.92						
15 53 33.3	+27 15 28	13.23	15.75						



The Astrophysical Journal Supplement Series, 61:305–352, 1986 June

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THE PALOMAR-GREEN CATALOG OF ULTRAVIOLET-EXCESS STELLAR OBJECTS

Richard F. Green

Kitt Peak National Observatory, National Optical Astronomy Observatories[2]

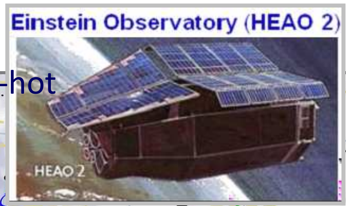
Maarten Schmidt

Palomar Observatory, California Institute of Technology

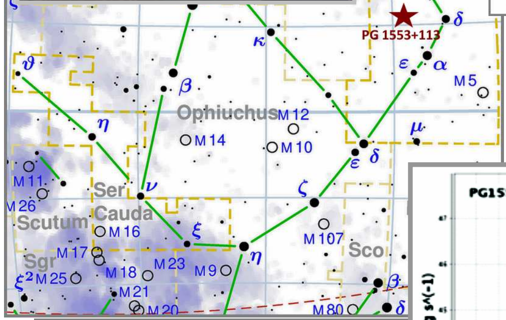
James Liebert

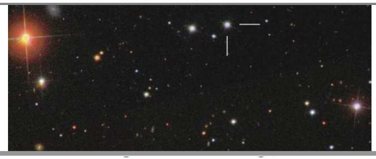
Steward Observatory, University of Arizona

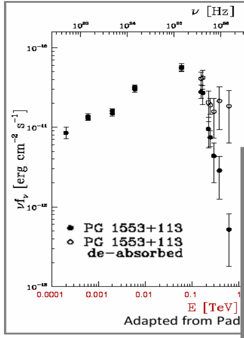
Palomar 18 inch (46 cm) Schmidt telescope



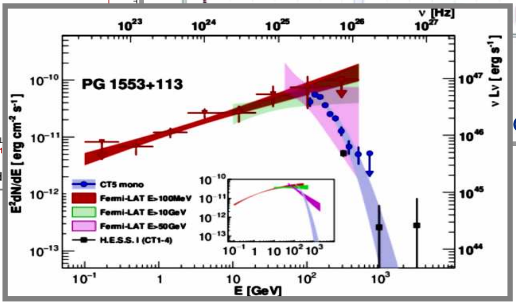
Einstein Observatory (HEAO 2)

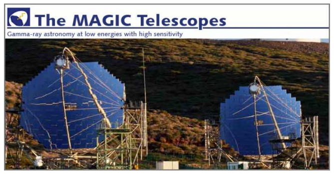




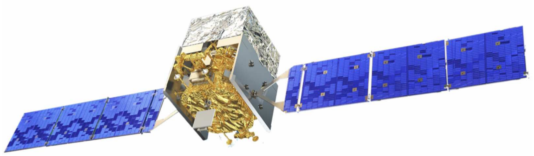


Adapted from Pad





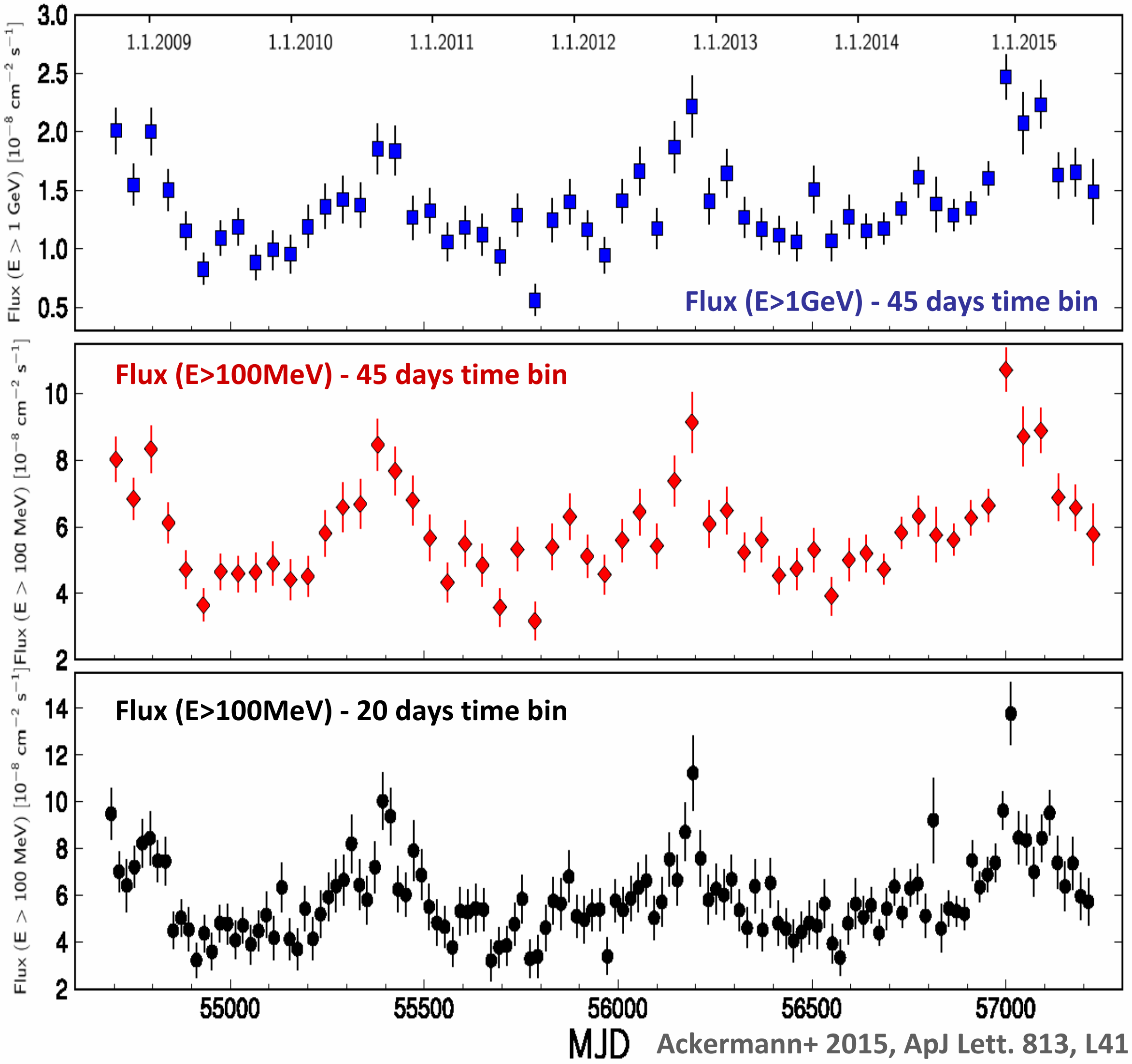
Recap: the 6.9-year Fermi LAT gamma-ray light curves



- ❑ [Ackermann+ 2015, ApJ L., LAT paper]: *Fermi* LAT gamma-ray flux (E>100MeV and E>1GeV) light curves of PG 1553+113 based on Pass 8 dataset up to July 19, 2015, produced in regular/large-size time bins of 45-day and 20-day bins.

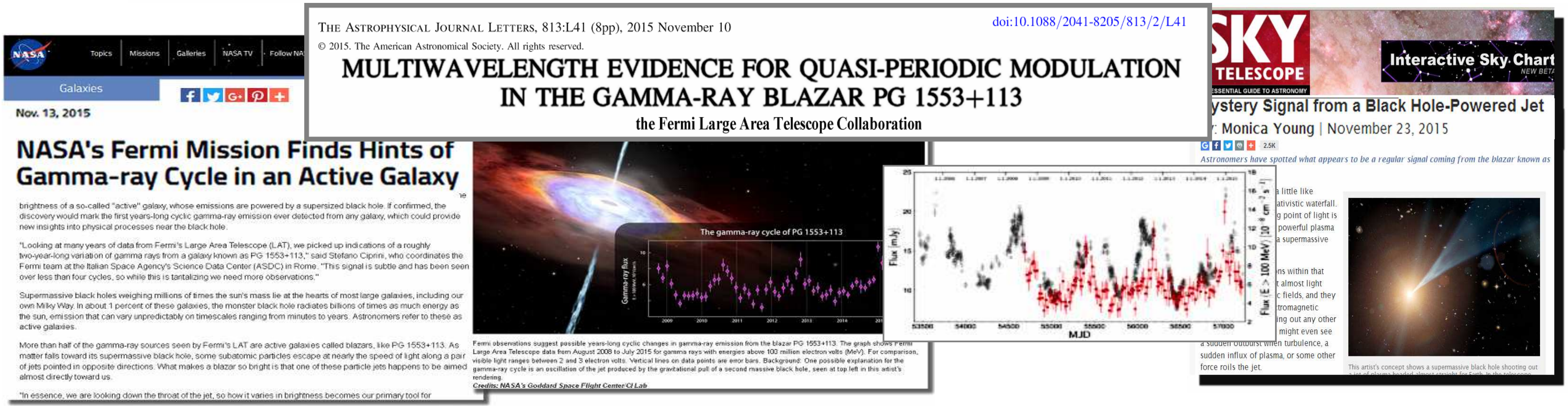
- ❑ A long-term oscillating trend visually evident. Sinusoidal modulation (using magnitude log-flux scale). Quasi regular periodicity in 3.5 cycles. Significance still marginal against red-noise but strengthened by MW cross-correlations. Similar oscillatory trend in optical data.

➔ Deterministic prediction (valid in long-lived coherence hypothesis): next quasi-periodic GeV peaks were foreseen around 2017 and 2019.



Ackermann+ 2015, ApJ Lett. 813, L41

Recap: the discovery and the LAT 2015 paper



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Galaxies

Nov. 13, 2015

NASA's Fermi Mission Finds Hints of Gamma-ray Cycle in an Active Galaxy

brightness of a so-called "active" galaxy, whose emissions are powered by a supersized black hole. If confirmed, the discovery would mark the first years-long cyclic gamma-ray emission ever detected from any galaxy, which could provide new insights into physical processes near the black hole.

"Looking at many years of data from Fermi's Large Area Telescope (LAT), we picked up indications of a roughly two-year-long variation of gamma rays from a galaxy known as PG 1553+113," said Stefano Ciprini, who coordinates the Fermi team at the Italian Space Agency's Science Data Center (ASDC) in Rome. "This signal is subtle and has been seen over less than four cycles, so while this is tantalizing we need more observations."

Supermassive black holes weighing millions of times the sun's mass lie at the hearts of most large galaxies, including our own Milky Way. In about 1 percent of these galaxies, the monster black hole radiates billions of times as much energy as the sun, emission that can vary unpredictably on timescales ranging from minutes to years. Astronomers refer to these as active galaxies.

More than half of the gamma-ray sources seen by Fermi's LAT are active galaxies called blazars, like PG 1553+113. As matter falls toward its supermassive black hole, some subatomic particles escape at nearly the speed of light along a pair of jets pointed in opposite directions. What makes a blazar so bright is that one of these particle jets happens to be aimed almost directly toward us.

"In essence, we are looking down the throat of the jet, so how it varies in brightness becomes our primary tool for

The Astrophysical Journal Letters, 813:L41 (8pp), 2015 November 10 doi:10.1088/2041-8205/813/2/L41

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MULTIWAVELENGTH EVIDENCE FOR QUASI-PERIODIC MODULATION IN THE GAMMA-RAY BLAZAR PG 1553+113

the Fermi Large Area Telescope Collaboration

Fermi observations suggest possible years-long cyclic changes in gamma-ray emission from the blazar PG 1553+113. The graph shows Fermi Large Area Telescope data from August 2008 to July 2015 for gamma rays with energies above 100 million electron volts (MeV). For comparison, visible light ranges between 2 and 3 electron volts. Vertical lines on data points are error bars. Background: One possible explanation for the gamma-ray cycle is an oscillation of the jet produced by the gravitational pull of a second massive black hole, seen at top left in this artist's rendering.

Credits: NASA's Goddard Space Flight Center/CI Lab

SKY TELESCOPE

ESSENTIAL GUIDE TO ASTRONOMY

Interactive Sky Chart NEW BETA

ystery Signal from a Black Hole-Powered Jet

: Monica Young | November 23, 2015

Astronomers have spotted what appears to be a regular signal coming from the blazar known as

a little like ativistic waterfall. g point of light is powerful plasma a supermassive

ns within that t almost light c fields, and they tromagnetic ing out any other might even see a sudden outburst when turbulence, a sudden influx of plasma, or some other force roils the jet.

This artist's concept shows a supermassive black hole shooting out

- ❑ Time signal: serendipitous discovery, based on light curves, with analysis and research led by **Sara Cutini** (INFN Perugia, was SSDC) that saw in 2014 the gamma-ray long-term oscillation using large time bins in LAT data, and by **S. Ciprini** (INFN TorVergata+Perugia & SSDC) with first variability timing analysis, discussion and paper handling. → First joint (shy) talk based on Pass7 data on Sept. 2014 at LAT Coll. Meeting in Montpellier, France.

- ❑ Soon fundamental contribution by our friend **S. Larsson** (KTH Royal Inst. Tech. Stockholm & Dalarna U.): complementary and also critical cross-check variability timing analysis and cross correlation analysis.

- ❑ Main contribute in the paper then by **D.J. Thompson** (NASA GSFC).

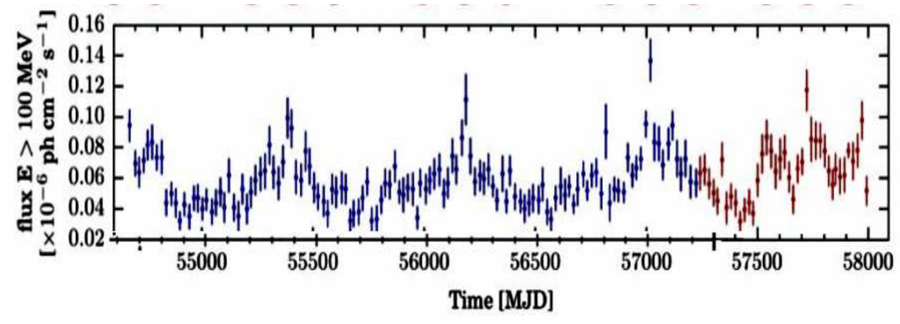
- ❑ Contributions to parts of analysis also by **R. Corbet** and **W. Max-Moerbeck**.

- ❑ Discussion contributions by many. External multifrequency data contributors. **E. Lindfors**, **T. Readhead** leaders for optical/radio data, **M. Perri** leader for Swift XRT and UVOT data).

- ❑ Target initially triggered by **A. Stamerra** (now MAGIC co-spokeperson), that asked to Sara Cutini in 2014 to produce LAT SEDs data for high/low states of a few MAGIC TeV blazars (also PG 1553+113) → serendipitous discovery during the work for identification of high/low states.

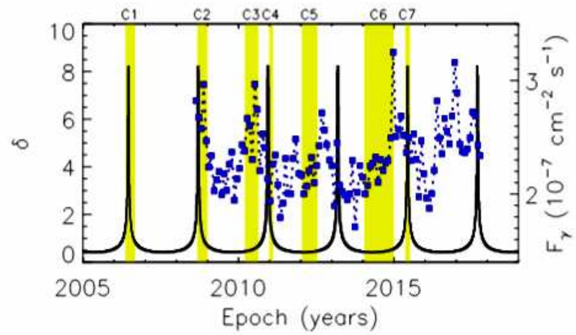
LAT ApJ 2015 paper: follow-up interest and papers

Interest by the external scientific community in this [Ackermann+ 2015, ApJ] LAT paper → follow-up works & tests/models all in the binary SMBH scenario and addition of a 1 or 2 year data baseline.



Examples:

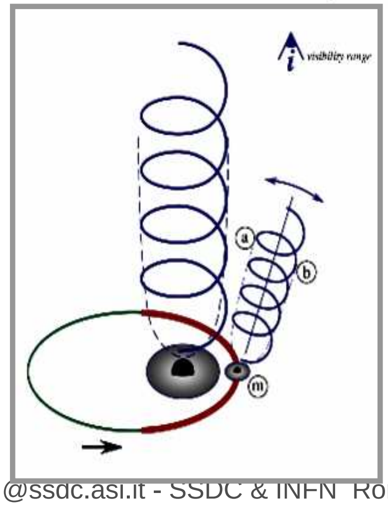
☐ [Tavani+ 2018]:
2016-2017 data added and claim for a Jan. 2017 new gamma-ray peak fitting the 2.2-year modulation. Binary SMBHs dynamics (about 10^8 and 10^7 Msun. BH masses). Periodic stresses of the main BH jet triggering MHD-kinetic tearing instabilities. Magnetic reconnections and acceleration of electrons producing synchrotron emission and inverse Compton emission in GeV gamma rays.

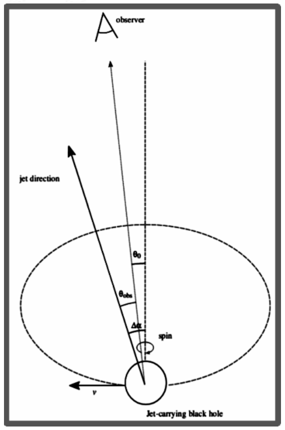


☐ [Caproni+ 2017]:
Binary SMBH model with main relativistic jet that is steadily precessing in time.

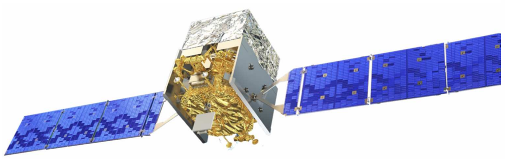
☐ [Sandrinelli+ 2018]:
Binary SMBH model & relativistic jet instabilities both probable. Binary SMBHs model in tension with very low freq. gravitational wave background currently measured by Pulsar Timing Arrays. General difficulties in associating quasi-periodicities of BL Lac objects to binary SMBH systems.

☐ [Sobacchi+ 2017]:
Binary SMBH model with an imprint of the secondary SMBH orbital speed on its jet. Jet preferably carried by (secondary) SMBH.



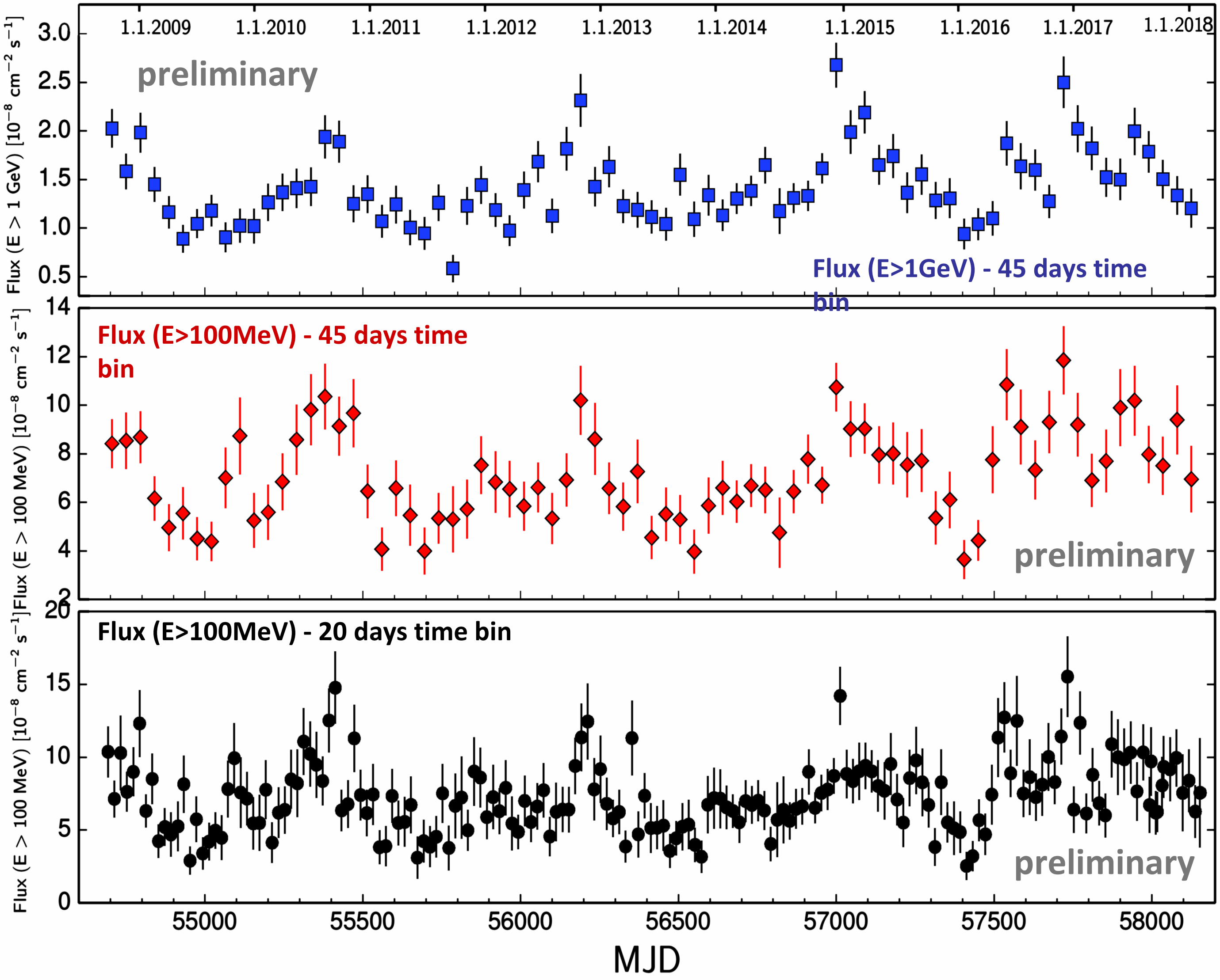


9.5-year LAT gamma-ray flux light curves

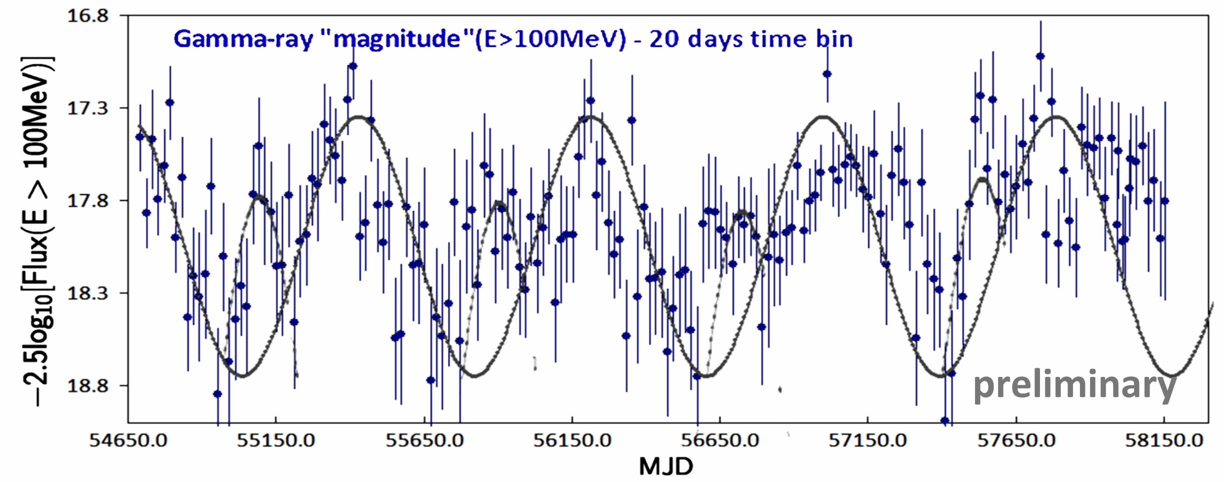


- ❑ *Fermi* LAT gamma-ray flux (E>100MeV and E>1GeV) light curves (lc) of PG 1553+113 Pass 8 dataset up to Jan. 2018 (full 10.8-year baseline in the paper in preparation).
- ❑ Regular/large-size time bins of 45-day and 20-day bin size. Temporal analysis cross-checks on adaptive bin and aperture photometry lcs.
- ❑ Long-term oscillating trend visually evident but a more noisy appearance. Predicted oscillation maximum is observed.

→ Periodicity in 4.5 cycles.



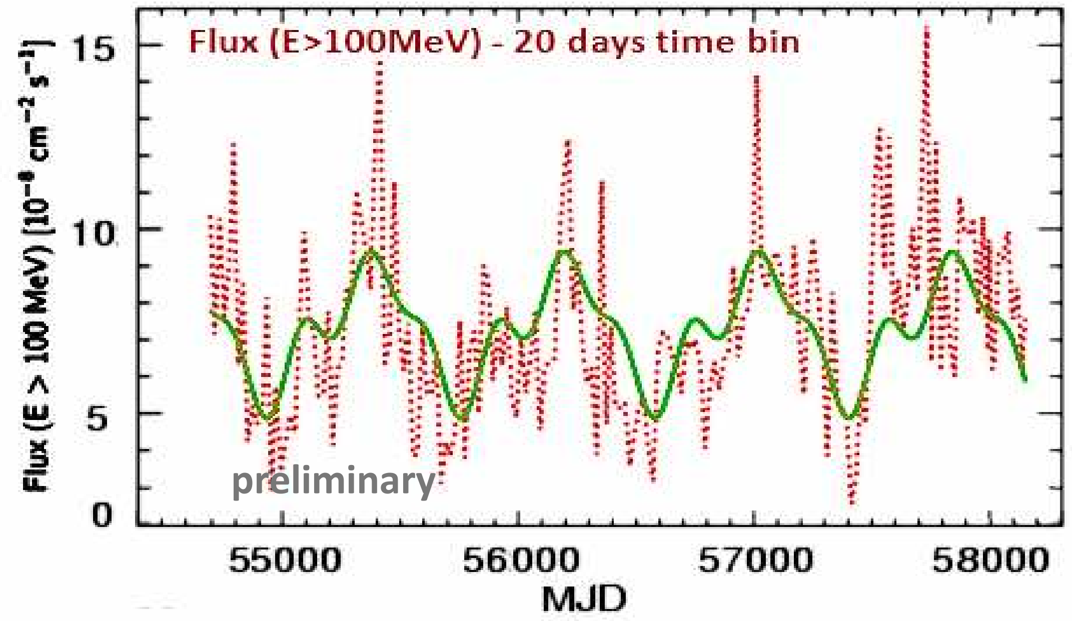
9.5-year LAT gamma-ray light curves

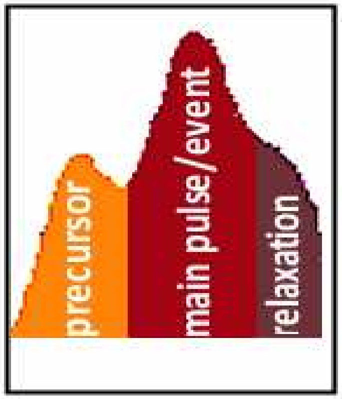


- ☐ 9.5-year LAT gamma-ray flux light curve of PG1553+113 (E>100MeV 20-day bin) reported in log10 Y-scale ("magnitude"). A strict single-pulse sinusoidal curve (P=2.18y) curve is superposed.

- ☐ 9.5-year LAT gamma-ray flux (E>100MeV 20-day bin) light curve of PG 1553+113.

The light curve is fitted (green curve) with a coherent pulse consisting of 4 Fourier components.

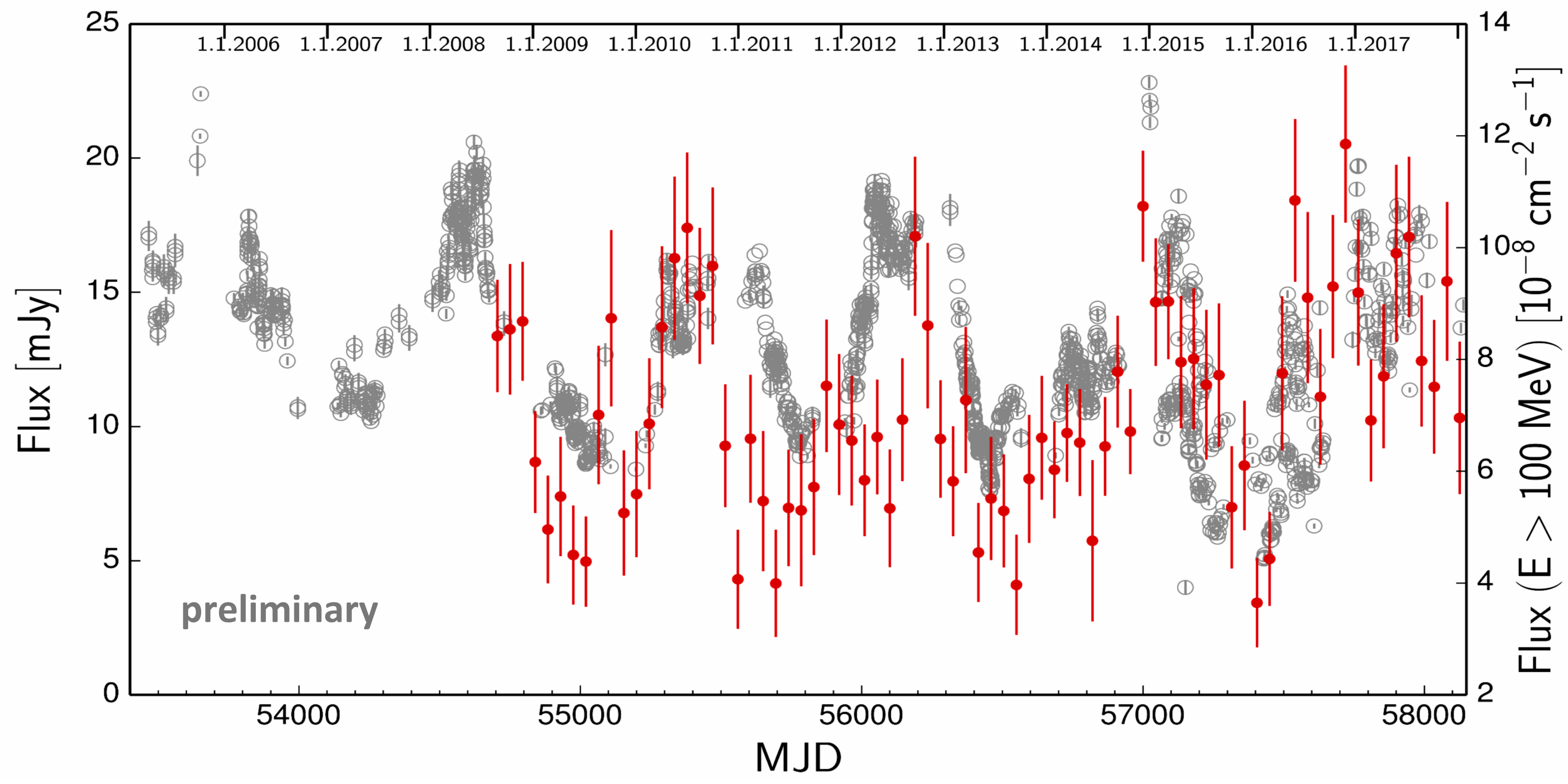




Gamma-ray overlapped optical light curves

- ❑ 9.5-year LAT gamma-ray flux (E>100MeV 20-day bin) light curve of PG 1553+113 (red datapoints).
- ❑ 12.5-year optical (R-band) light curve of PG 1553+113 (grey datapoints).

Collected from: Tuorla+KVA monitor program data + Catalina CSS archive data + KAIT monitor data + Swift UVOT data. Swift dedicated program on PG 1553+113 since 2015.



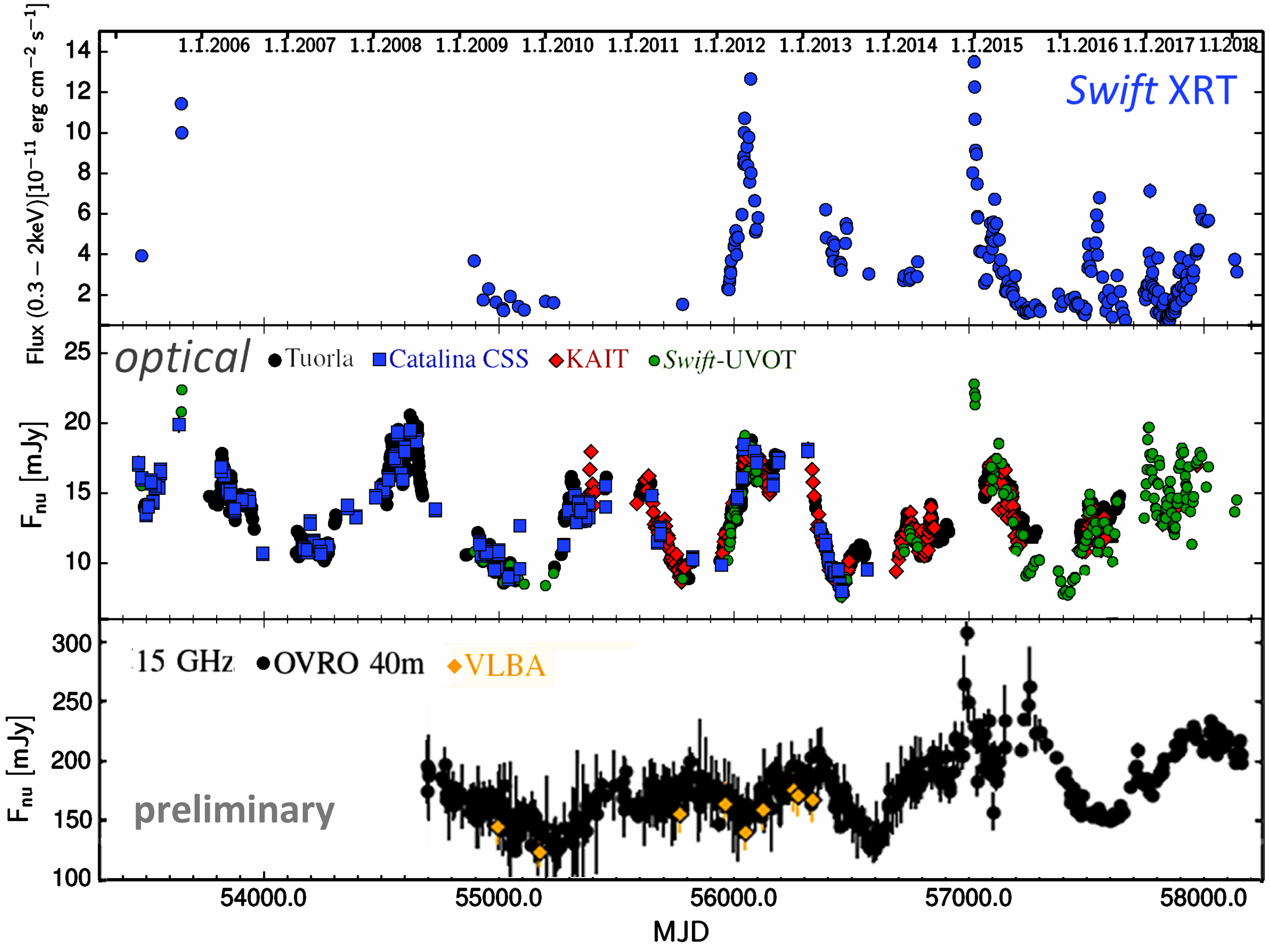
Radio/optical/X-ray light curves

Multifrequency flux light curves built at: X-ray, optical (R and V bands) and radio (15 GHz) band.

➔X-ray data obtained with Swift-XRT (thanks to past MW campaigns and dedicated follow-up program on PG 1553+113 started on Dec.2014).

➔ Long-term Rossi-XTE (ASM) and Swift-BAT also under re-analysis (but poor statistics and noisy).

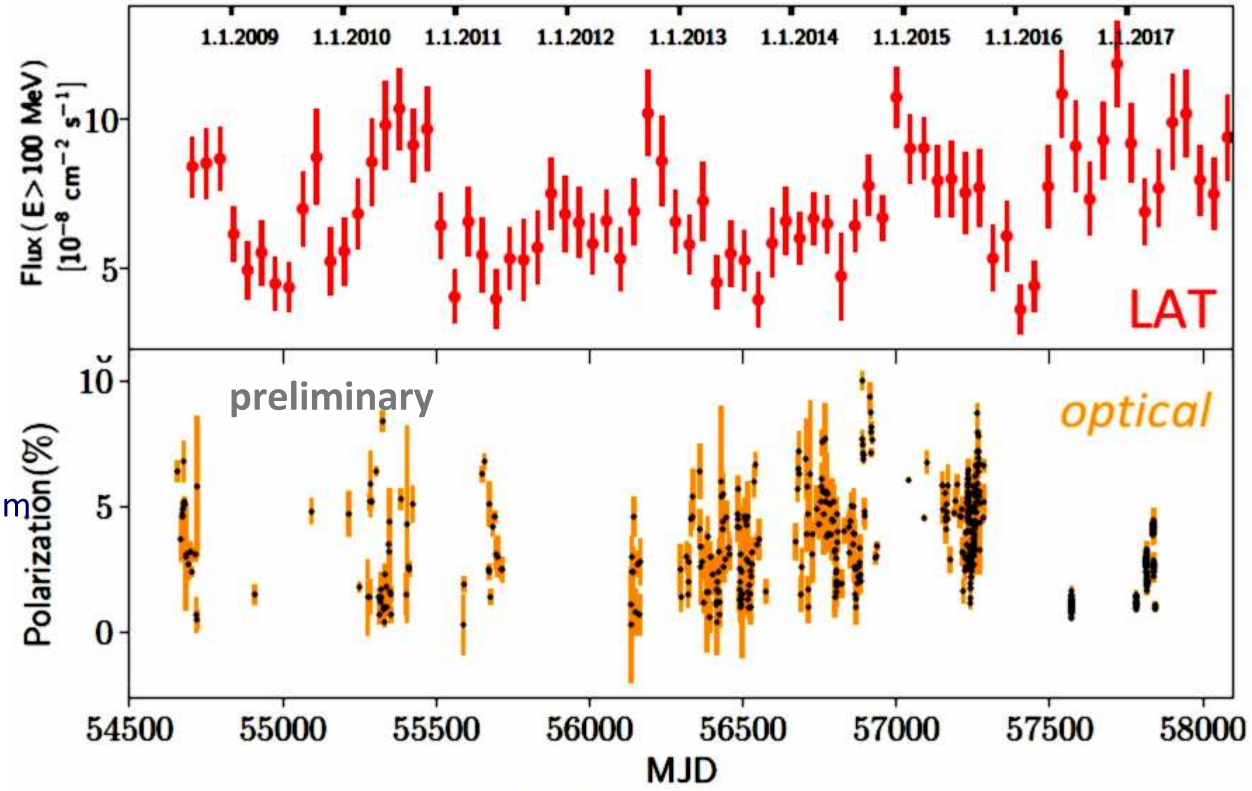
➔ Optical band is assembled with Tuorla monitoring program, with Katzman Automatic Imaging Telescope (KAIT) monitoring data Catalina Sky Survey (CSS) data and a dedicated follow-up program of *Swift*-UVOT.

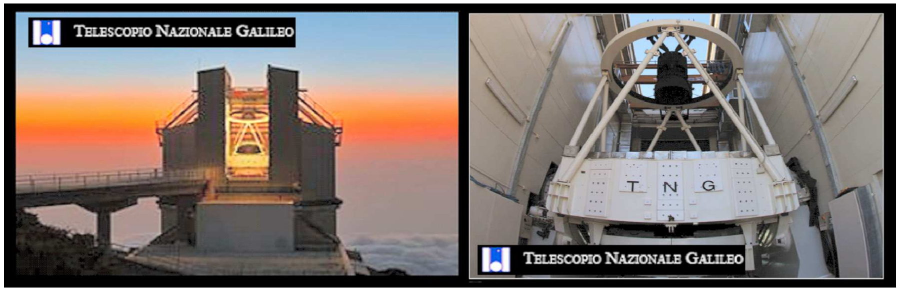


➔ Radio band at 15 GHz is assembled with 40m Owens Valley Radio Observatory (OVRO) with blazar monitoring program supporting *Fermi* (Richards+ 2011) and Monitoring Of Jets in Active galactic nuclei with VLBA Experiments (MOJAVE, Lister+ 2009)

Optical polarization degree light curve

- ❑ LAT 45-day bin gamma-ray (E>100 MeV) flux light curve compared to 10-year optical polarization data.
- ❑ Optical polarization degree data collected mainly from KANATA telescope, Japan.
- ❑ Some data added from Raiteri+ 2016 (Crimean Obs. in Russia, Lulin Obs. in Taiwan, Skinakas Obs. in Crete Greece, St. Petersburg obs. in Russia).
- ❑ More (short term) data from our program at the Italian 3.6m INAF-TNG telescope in La Palma, Canary Islands (DOLORES and PAOLO instruments).
- ❑ Preliminary, optical polarization degree appear related to short term, erratic in-jet, optical flaring activity.





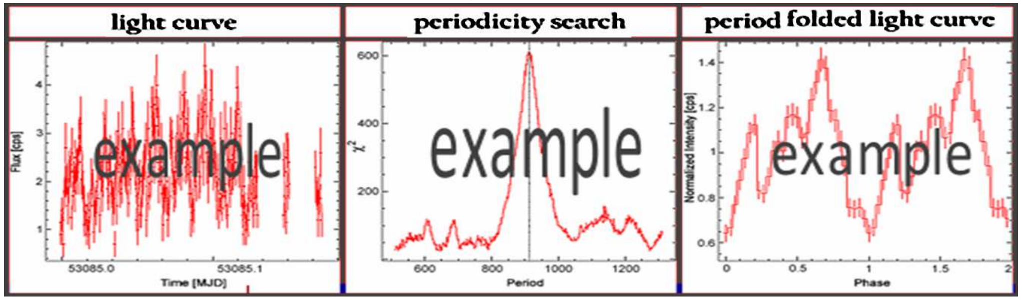
Higashi-Hiroshima Observatory

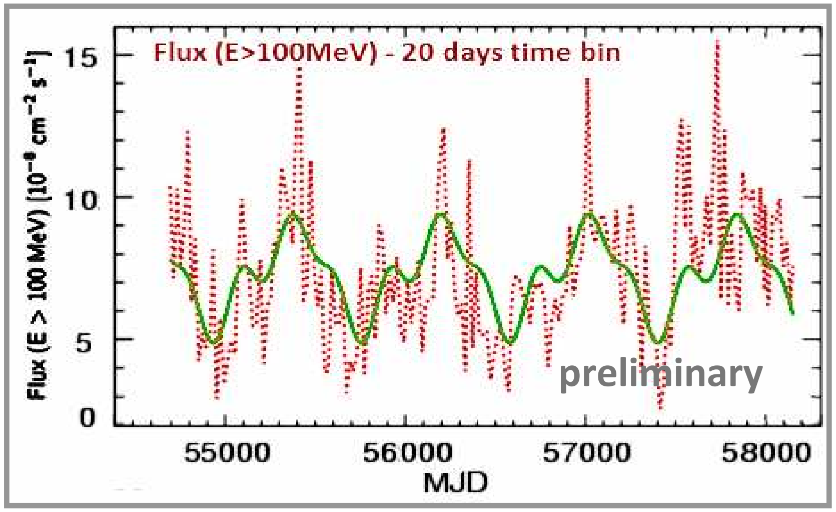
KANATA optical and NIR telescope

KANATA 1.5-m Optical and Near-Infrared telescope

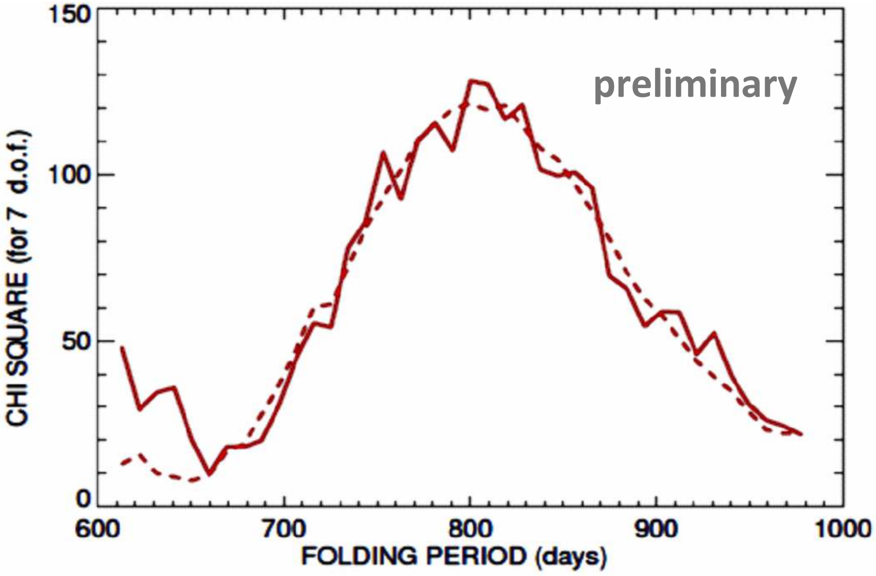
Temporal variability analysis: epoch folding

A classical 3-step "how-to" periodicity:





Pulse shape analysis (flux E>100 MeV 20-day bin)



Epoch folded light curve (flux E>100 MeV 20-day bin)

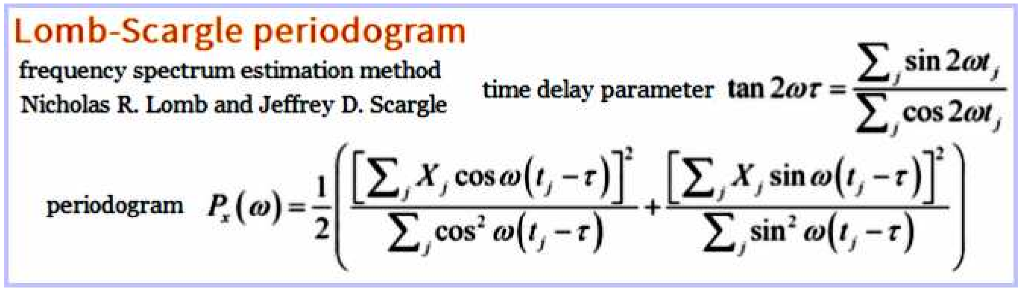
❑ 1) The epoch folding / pulse shape analysis.

- The driving method in presence of a mostly regular sampling and coherent sinusoidal oscillations.
- Analysis based on period-folded and pulse shape light curve (4 Fourier components).
- Power is confirmed at a gamma-ray characteristic periodical timescale of 2.2+/-0.2 years in all the 9.5-year LAT gamma-ray light curves.

Temporal variability analysis: further methods

☐ 2) FSSC at GSFC web: direct discrete Fourier transform and power density spectra (PDS) using a gross 30-day bin aperture photometry technique, confirms the same 2.2-year timescale.

☐ 3) Lomb-Scargle algorithm PDS periodogram (LSP), also compared to the wavelet epoch-average spectrum.



Lomb-Scargle periodogram

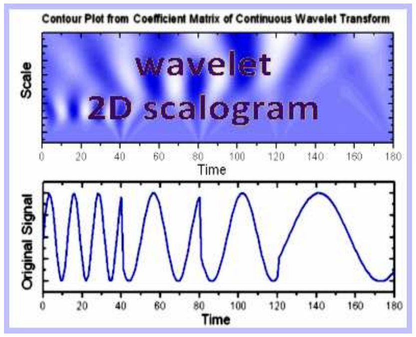
frequency spectrum estimation method
Nicholas R. Lomb and Jeffrey D. Scargle

time delay parameter $\tan 2\omega\tau = \frac{\sum_j \sin 2\omega t_j}{\sum_j \cos 2\omega t_j}$

periodogram $P_x(\omega) = \frac{1}{2}\left(\frac{\left[\sum_j X_j \cos\omega(t_j-\tau)\right]^2}{\sum_j \cos^2\omega(t_j-\tau)} + \frac{\left[\sum_j X_j \sin\omega(t_j-\tau)\right]^2}{\sum_j \sin^2\omega(t_j-\tau)} \right)$

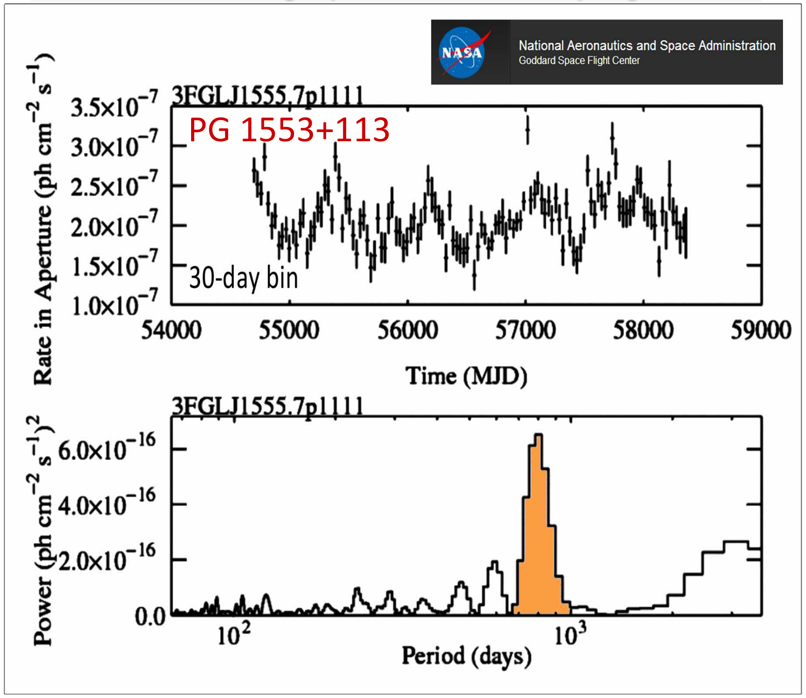
☐ 4) More methods (also for cross-check): discrete autocorrelation function DACF, structure function SF, phase dispersion minimization PDM, etc.)

☐ 5) Continuous Wavelet Transform (Morlet-mother waveform). Coherent gamma-ray signal peak along all the light curve epochs.



☐ 6) Two approaches for signal significance estimation against the red-noise. (quantitative analysis in progress on the 10 year dataset, for the paper).

LAT 3FGL Catalog Aperture Photometry Lightcurves



Public discrete FFT PDS using aperture photometry counts and exposure weighted light curve at FSSC-GSFC website (suitable for quicklook inspection of gross features). Not suitable for scientific analysis and publications (not background subtracted, contaminated by nearby sources photons in the aperture).

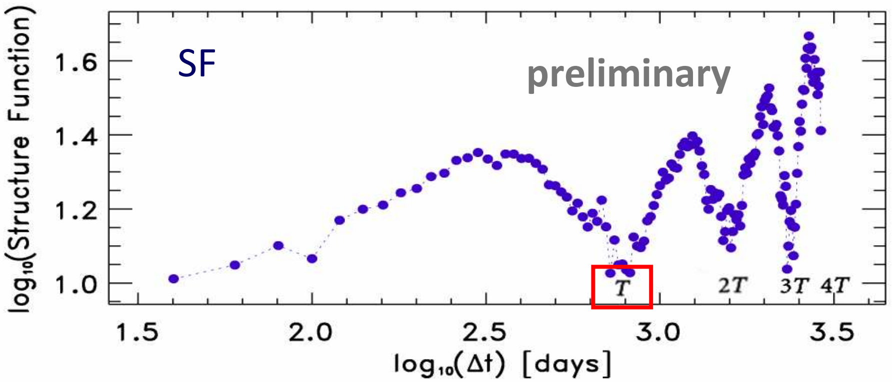
Credits [Robin Corbet, NASA GSFC]

stefano.ciprini@ssdc.asi.it - SSDC & INFN Rome

Structure Function and Discr. AutoCorr. Function

- ☐ Cross checks with further analysis methods and functions of the LAT 20-day bin, gamma-ray (E>100 MeV) light curve of PG 1553+113 are consistent with quasi-periodicity signal of T=2.2 years period.

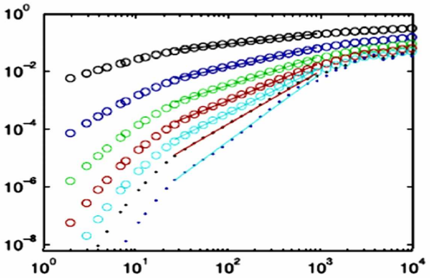
1st order Structure Function (SF) plot

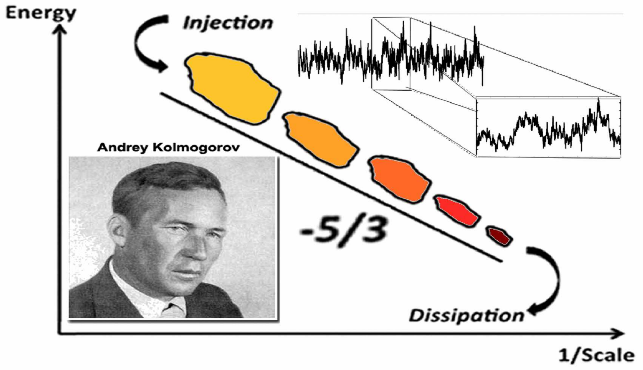


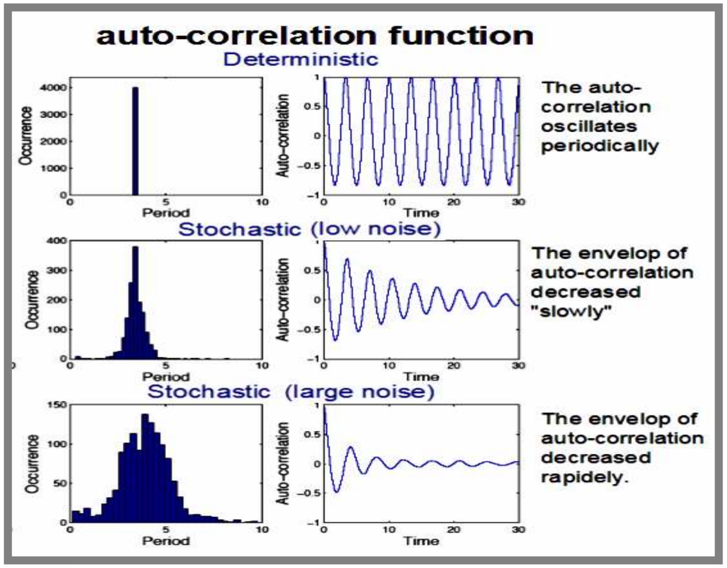
Kolmogorov structure function

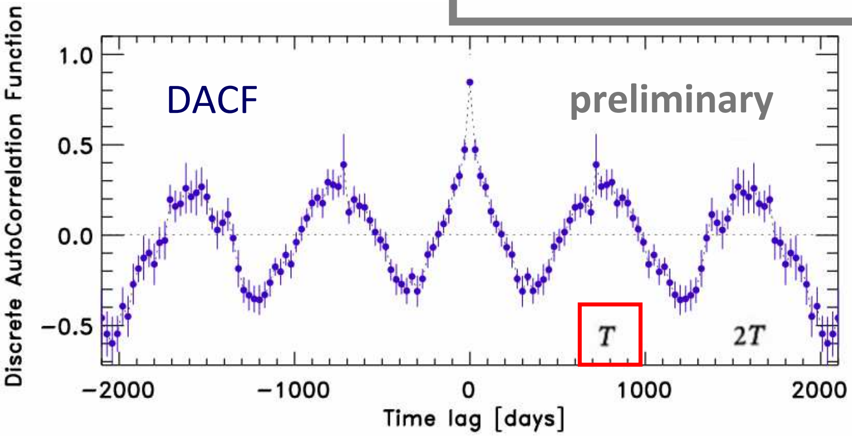
"studying the structure of turbulence"

Turbulence = the last unsolved problem of classical physics







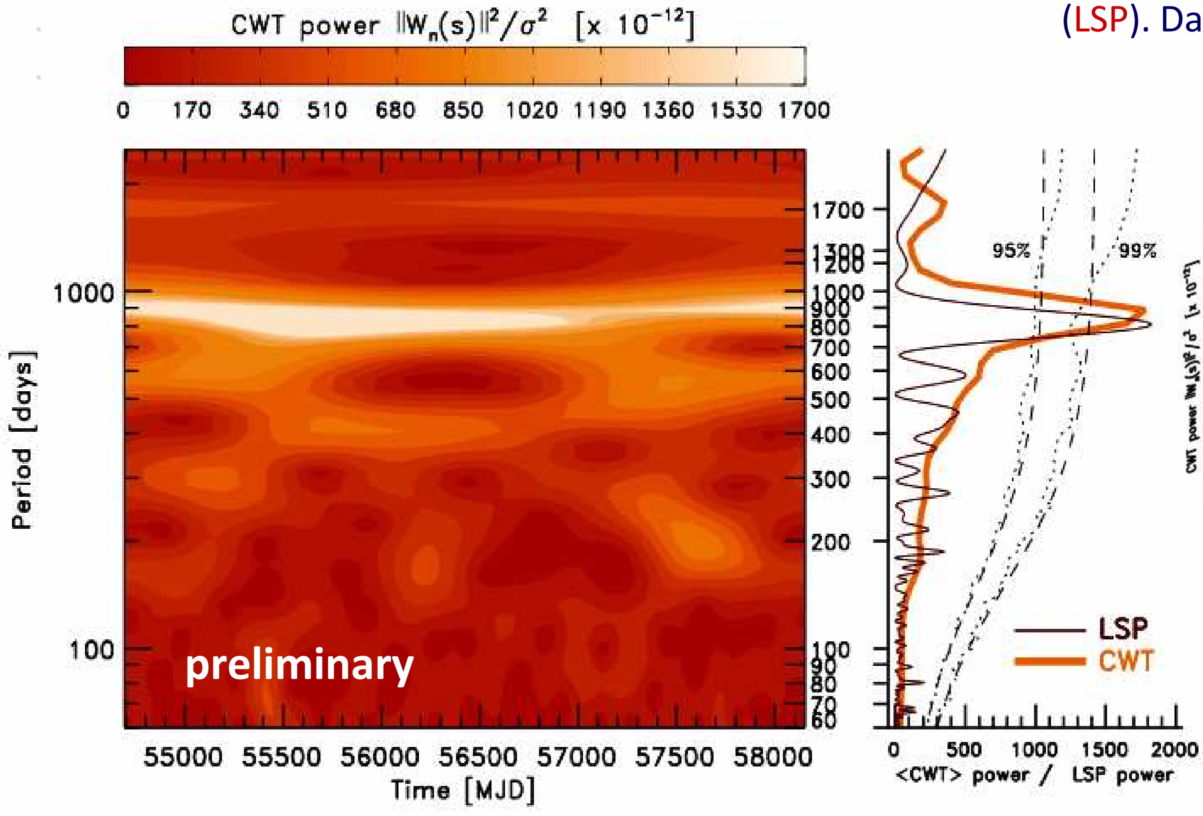


Discrete Auto-Correlation function (DACF) plot

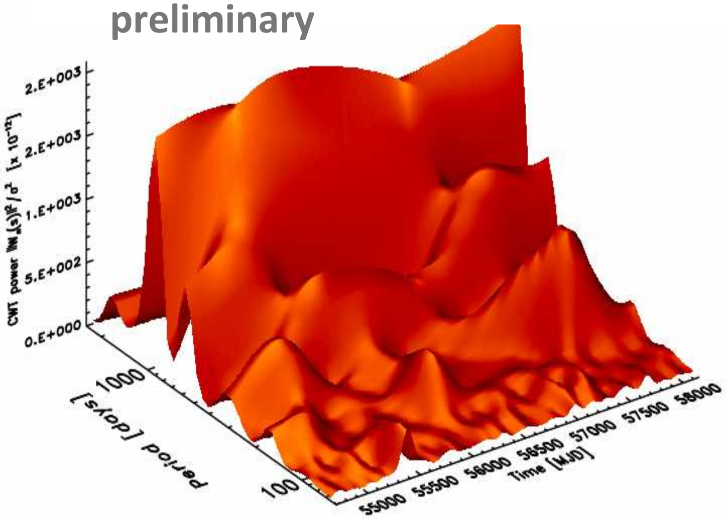
Gamma-ray light curve: wavelets and LSP

❑ 2D plane contour plot of the continuous wavelet transform (CWT, i.e. a 2D power density spectrum), a.k.a. wavelet scalogram, of the 9.5-year, 20-day bin, LAT gamma-ray (E>100 MeV) light curve of PG 1553+113.

❑ Morlet mother function (filled color contour). The right side panel shows the 1D smoothed (all-time-epoch-averaged) power spectrum of the CWT scalogram. A signal power peak is in agreement with the 2.2 year value found with epoch fold/pulse shape analysis. This right side panel also include the Lomb-scargle Periodogram (LSP). Dashed lines depict increasing levels of confidence against red noise.



preliminary

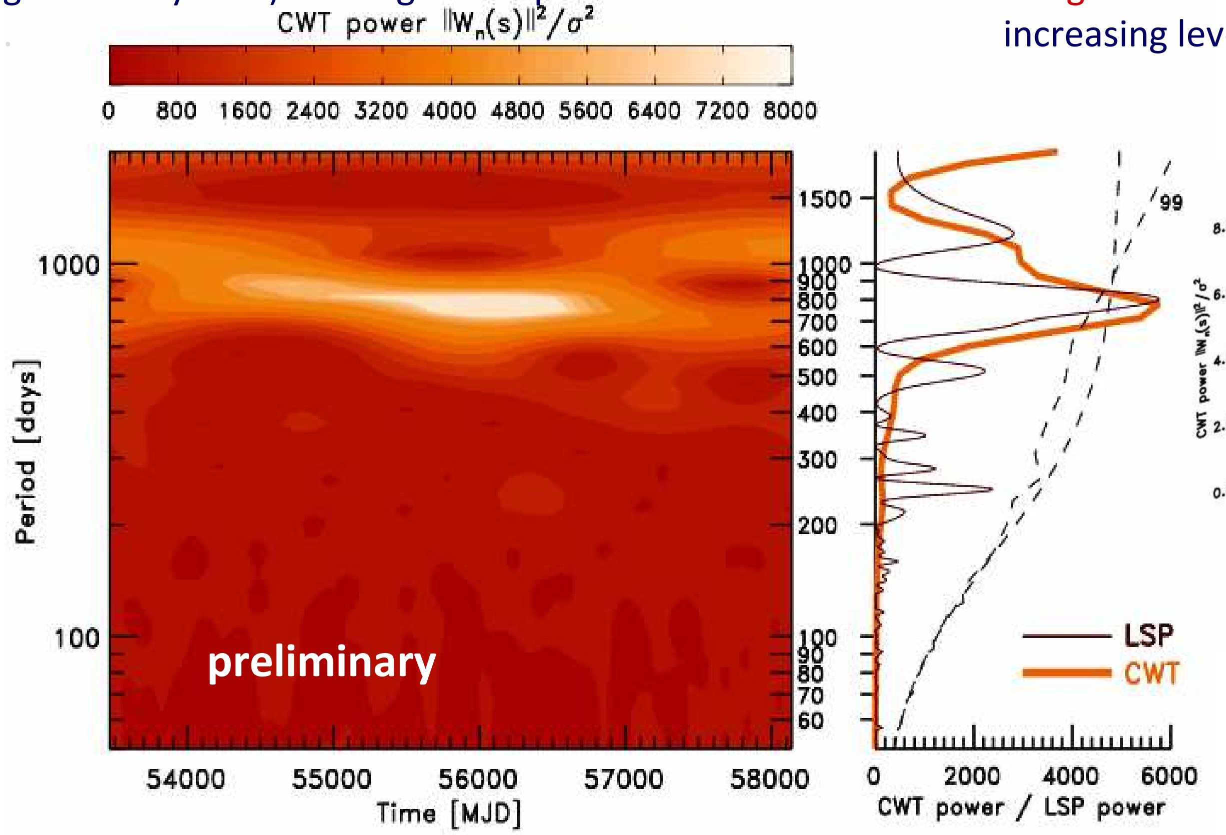


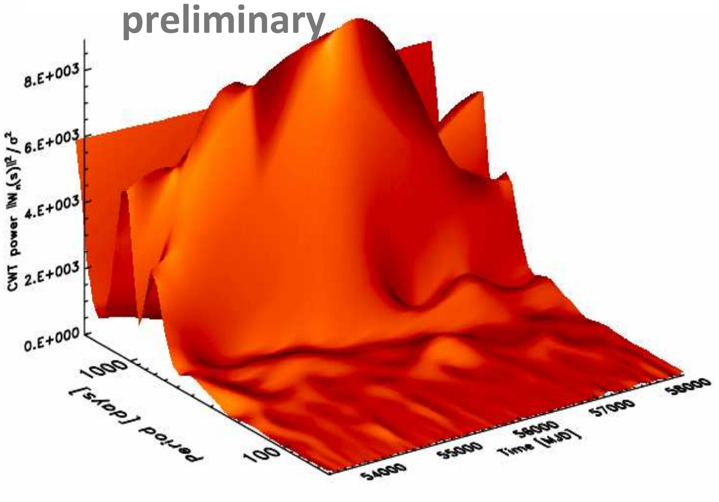
The same CWT scalogram in a 3D surface representation.

Optical lc wavelet and LSP analysis

❑ 2D plane contour plot of the continuous wavelet transform (CWT, i.e. a 2D power density spectrum), a.k.a. wavelet scalogram, of the about 13-year, optical, unevenly sampled, light curve of PG 1553+113.

❑ Morlet mother function (filled color contour). The right side panel shows the 1D smoothed (all-time-epoch-averaged) power spectrum of the CWT scalogram. A signal power peak is at 2.2-year value (the same of the gamma-ray data). This right side panel also include the Lomb-scargle Periodogram (LSP). Dashed lines depict increasing levels of confidence against red noise.





The same CWT scalogram in a 3D surface representation.

PG 1553+113: cross-correlation analysis

Cross-correlation analysis. Important diagnostic for multifrequency periodicity analysis in AGNs/blazars.

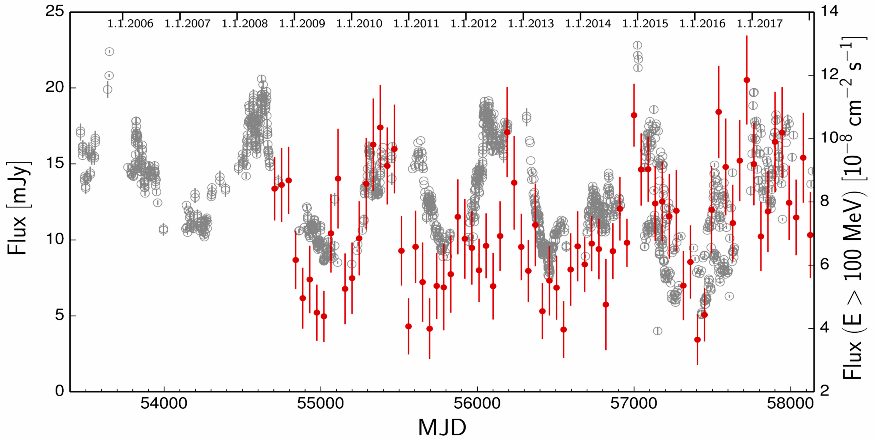
❑ Optical-gamma-ray cross-correlation (unbinned unevenly-sampled and large-gapped optical light curve opposed vs the uninterrupted and regular 45-day bin (E>1GeV) LAT gamma-ray light curve) supports the periodicity because:

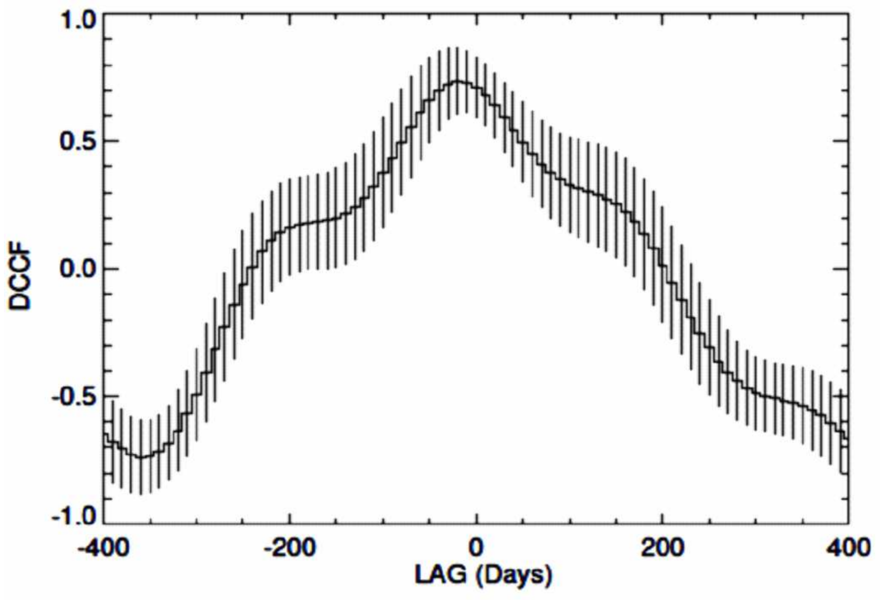
1) the optical covers additional time epochs, a bit more backwards in time

2) the optical-gamma energy bands can be described with similar periodicity plus erratic faster variations (in-jet flaring plus usual blazar variability and/or measurements noise). But optical/gamma noise and sampling different → found similar quasi periodicity strengthen its reality.

❑ Significance of the gamma-ray-optical cross-correlation preliminary estimated to be >95%.

Strong cross-correlation with time lag consistent with zero lag (-16+/-27 days) → strengthens the fact the periodicity is real and possibly coherent.





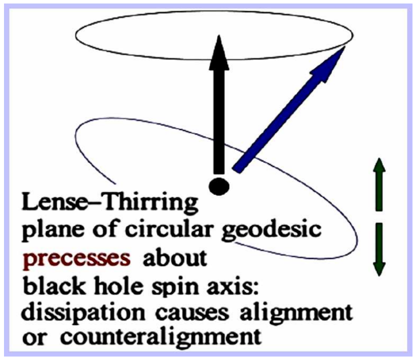
Open astrophysical scenarios for PG 1553+113

❑ Jet wobbling/precession/rotation/nutation on parsec scales (…but 2-years is a too short timescale?). Non-ballistic (→components) helical motion travel time effects can lead to observed time shortening effects.

❑ Curvature and helical-like structure of the relativistic jet, and/or of the radiating in-jet components. Such features can results in differential Doppler beaming magnification changing periodically, with oscillations of the angle of sight and the observed radiation boosting. A whole jet structure/geometry and/or in-jet localized components.

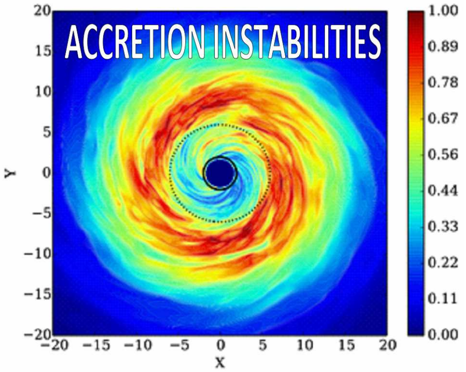
❑Alternatively disc-jet connection and symbiosis with induced quasi-periodical triggers and ejections.

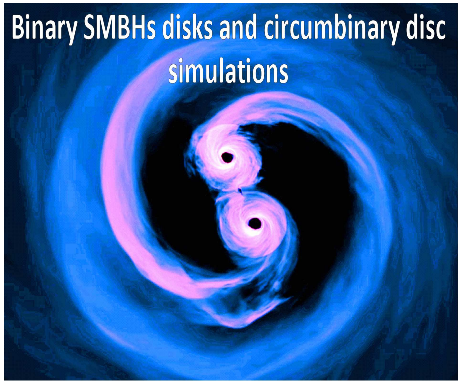
- Warped disks; accretion perturbations; periodically intermittent supply of plasma in the jet funnel; MHD/magneto-rotational instabilities in relativistic magnetized accretion disks, MHD stresses with magnetic reconnection (intrinsic to material of accretion disk or jet itself).
- These can be well consinstent with tidal/efficiency/ perturbations and MHD-tearing instabilities given by a close BH companion, i.e. a sub-parsec (<10^18 cm) binary, gravitationally bound, supermassive black hole system (SMBHs).

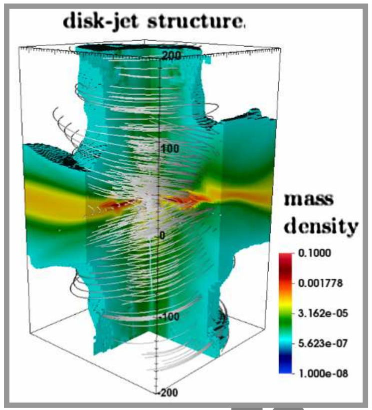


❑ Physical origin of jet wobbling is in changes in direction at the jet nozzle:

- by accretion disk precession, Lense-Thirring (rotational dragging in GR) precession, orbital Keplerian motion of the accretion system with jet nutation (rocking, nodding) in a binary SMBHs scenario,
- by periodic perturbations, warps, stresses to accretion disc again in a binary SMBHs scenario.







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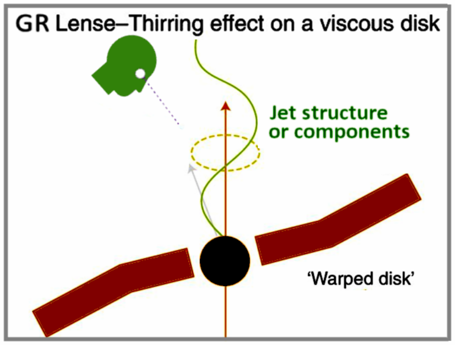
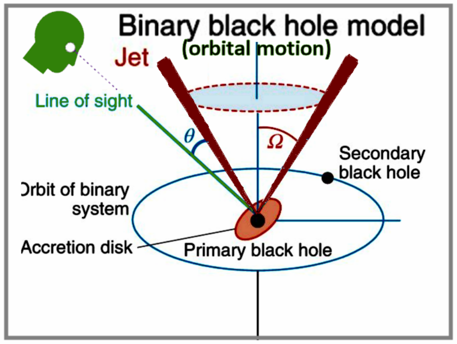
Open astrophysical scenarios for PG 1553+113

☐ Pulsational accretion flow instabilities, approximating periodic behavior, are able to explain periodic modulations in the energy outflow efficiency.
Magnetically arrested and magnetically dominated accretion flows (MDAFs) could be suitable regimes for radiatively inefficient of TeV BL Lac objects like PG 1553+113 (Fragile & Meier 2009), characterized by advection-dominated accretion flows and subluminal, turbulent, and peculiar radio kinematics.

☐ Similar mechanims to low-frequency QPO of Galactic high-mass binaries (Fender & Belloni 2004, King et al. 2013). PG 1553+113 has a low accretion rate. QPO Lense-Thirring precession requires inner accretion flow forms a geometrically thick torus rather than a standard thin disk as the latter warps (Bardeen-Petterson effect) rather than precesses (Ingram et al. 2009). ADAF-disks anyway can give precessing jets.

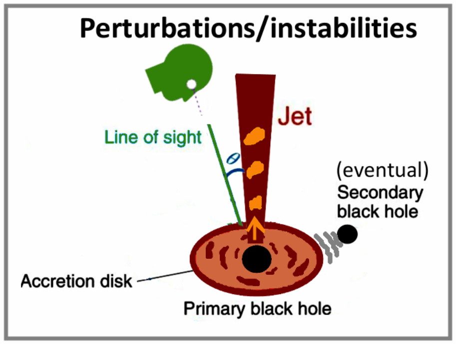
☐ Lense-Thirring precession could affect the jet direction, giving the QPO.


GR Lense–Thirring effect on a viscous disk


Binary black hole model (orbital motion)

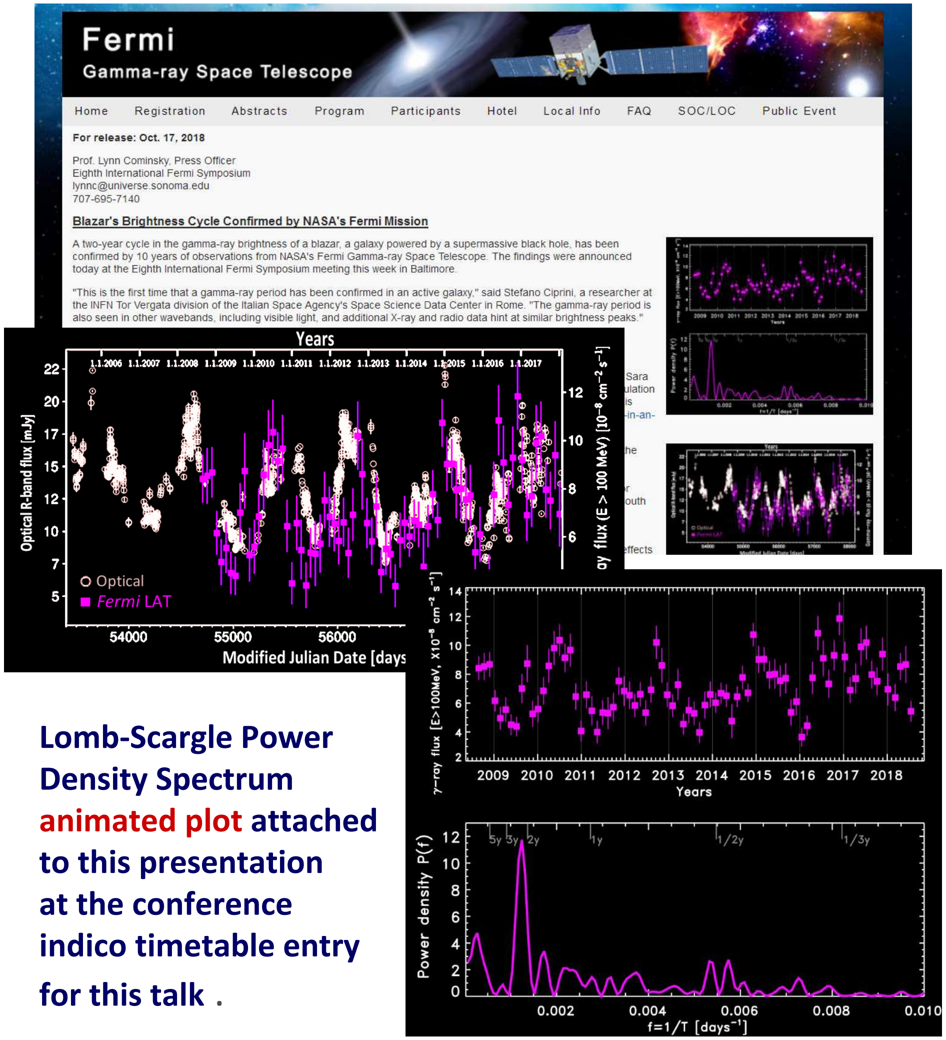
☐ Binary, gravitationally bound, SMBH system (total mass of 1.6X10^8 Msun, milliparsec separation, early inspiral nano-Hz gravitational-wave driven regime. Keplerian binary orbital motion with periodic accretion perturbations or jet nutation.

- Disk evolution accelerated onto a binary SMBH system, as shown by simulations. Probability of observing such a GW-driven milli-pc system (mass ratios 0.1–0.01, and lifetime 10^5−10^6 years) might be small.
- About current PTAs nano-Hz GW detection limits we would better aim to have millisec pulsars timing constrains/detections from Square Kilometer Array.
- Event Horizon Telescope, EHT, (too distant ?); LISA (too very-low frequency GWs ?).


Perturbations/instabilities

PG 1553+113 gamma-ray light curve fourier power spectrum animation plot and a recent 3D GR+MHD simulation

NASA-GSFC + Fermi LAT Press Release of Oct. 17, 2018



For release: Oct. 17, 2018

Prof. Lynn Cominsky, Press Officer
Eighth International Fermi Symposium
lynnc@universe.sonoma.edu
707-695-7140

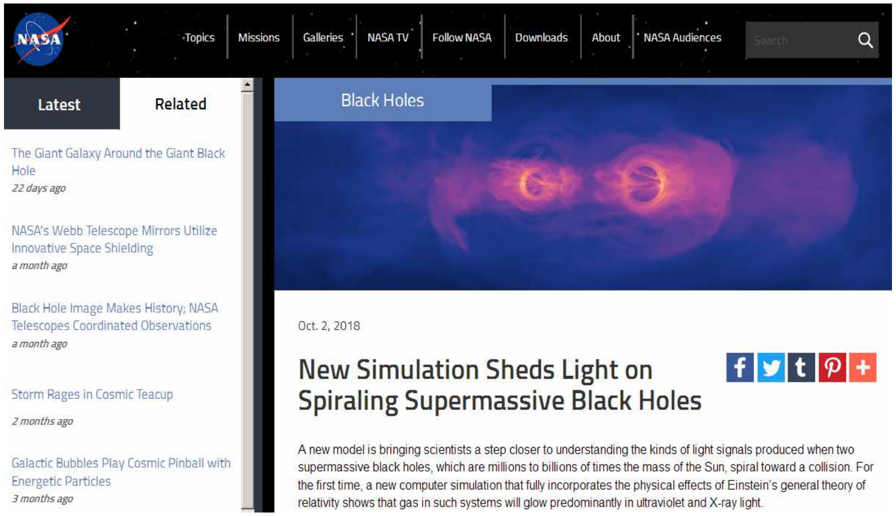
Blazar's Brightness Cycle Confirmed by NASA's Fermi Mission

A two-year cycle in the gamma-ray brightness of a blazar, a galaxy powered by a supermassive black hole, has been confirmed by 10 years of observations from NASA's Fermi Gamma-ray Space Telescope. The findings were announced today at the Eighth International Fermi Symposium meeting this week in Baltimore.

"This is the first time that a gamma-ray period has been confirmed in an active galaxy," said Stefano Ciprini, a researcher at the INFN Tor Vergata division of the Italian Space Agency's Space Science Data Center in Rome. "The gamma-ray period is also seen in other wavebands, including visible light, and additional X-ray and radio data hint at similar brightness peaks."

Lomb-Scargle Power Density Spectrum animated plot attached to this presentation at the conference indico timetable entry for this talk .

NASA General Press Release Oct. 2, 2018



The Giant Galaxy Around the Giant Black Hole
22 days ago

NASA's Webb Telescope Mirrors Utilize Innovative Space Shielding
a month ago

Black Hole Image Makes History; NASA Telescopes Coordinated Observations
a month ago

Storm Rages in Cosmic Teacup
2 months ago

Galactic Bubbles Play Cosmic Pinball with Energetic Particles
3 months ago

Oct. 2, 2018

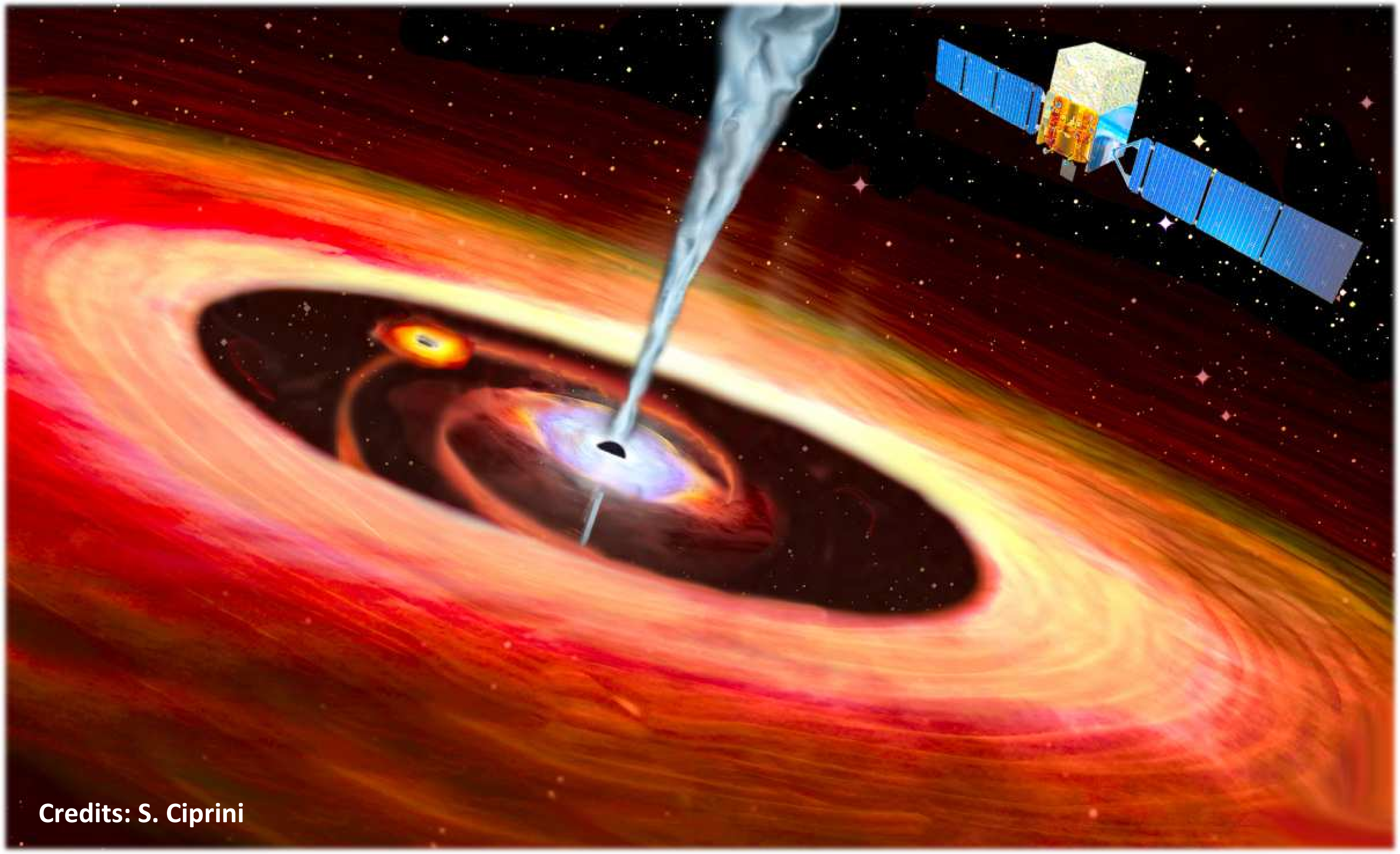
New Simulation Sheds Light on Spiraling Supermassive Black Holes

A new model is bringing scientists a step closer to understanding the kinds of light signals produced when two supermassive black holes, which are millions to billions of times the mass of the Sun, spiral toward a collision. For the first time, a new computer simulation that fully incorporates the physical effects of Einstein's general theory of relativity shows that gas in such systems will glow predominantly in ultraviolet and X-ray light.

New computer simulation that fully incorporates 3D General Relativity magneto-hydrodynamics showing gas in a binary supermassive black hole system at only 40 orbits from merging and glowing predominantly in ultraviolet and X-ray light [d'Ascoli+2018, ApJ, 865, 140].
Data reported in Bowen+ [2018] produced by Harm3d code [Noble+ 2009] are used for detailed predictions of both the spectrum and the time-dependence of the light emitted.

Simulation movie attached to this presentation at the conference indico timetable entry for this talk .

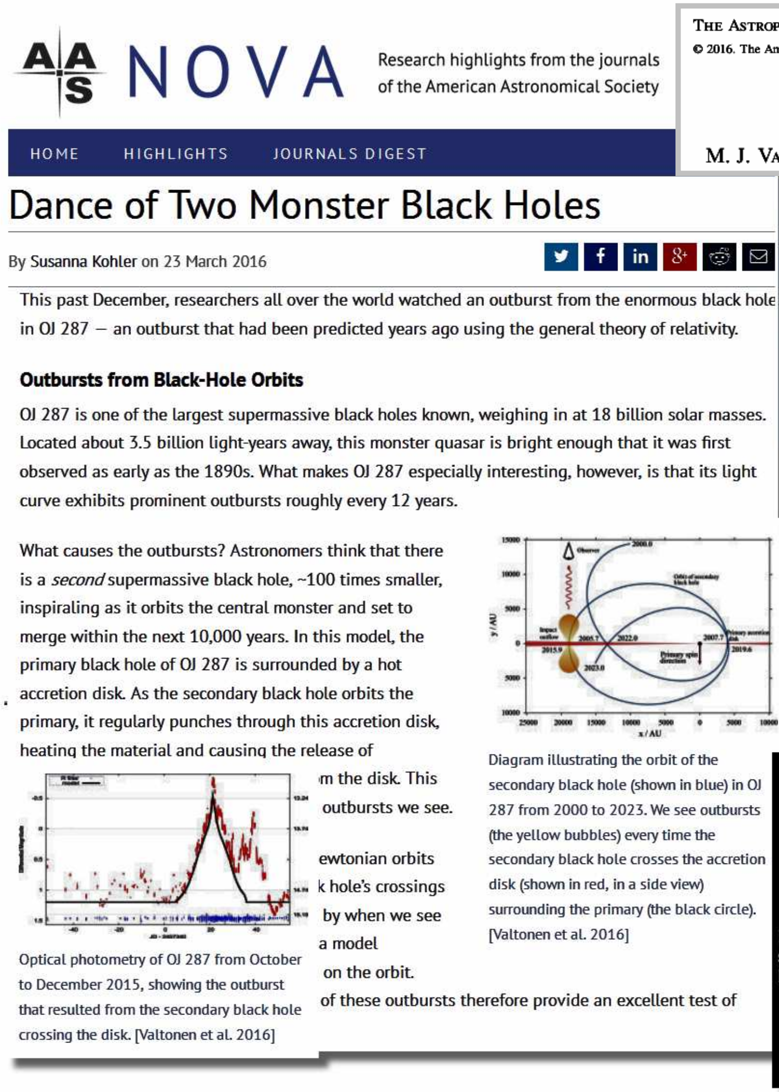
A “sexy” hypothesis and cartoon for PG 1553+113



Credits: S. Ciprini

stefano.ciprini@ssdc.asi.it - SSDC & INFN Rome

Another source OJ 287 (but longer period 12-years)



Dance of Two Monster Black Holes

By Susanna Kohler on 23 March 2016

This past December, researchers all over the world watched an outburst from the enormous black hole in OJ 287 — an outburst that had been predicted years ago using the general theory of relativity.

Outbursts from Black-Hole Orbits

OJ 287 is one of the largest supermassive black holes known, weighing in at 18 billion solar masses. Located about 3.5 billion light-years away, this monster quasar is bright enough that it was first observed as early as the 1890s. What makes OJ 287 especially interesting, however, is that its light curve exhibits prominent outbursts roughly every 12 years.

What causes the outbursts? Astronomers think that there is a *second* supermassive black hole, ~100 times smaller, inspiraling as it orbits the central monster and set to merge within the next 10,000 years. In this model, the primary black hole of OJ 287 is surrounded by a hot accretion disk. As the secondary black hole orbits the primary, it regularly punches through this accretion disk, heating the material and causing the release of

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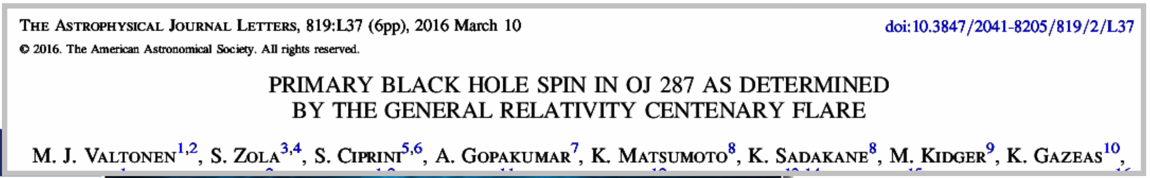
Diagram illustrating the orbit of the secondary black hole (shown in blue) in OJ 287 from 2000 to 2023. We see outbursts (the yellow bubbles) every time the secondary black hole crosses the accretion disk (shown in red, in a side view) surrounding the primary (the black circle). [Valtonen et al. 2016]

Optical photometry of OJ 287 from October to December 2015, showing the outburst that resulted from the secondary black hole crossing the disk. [Valtonen et al. 2016]



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PRIMARY BLACK HOLE SPIN IN OJ 287 AS DETERMINED BY THE GENERAL RELATIVITY CENTENARY FLARE

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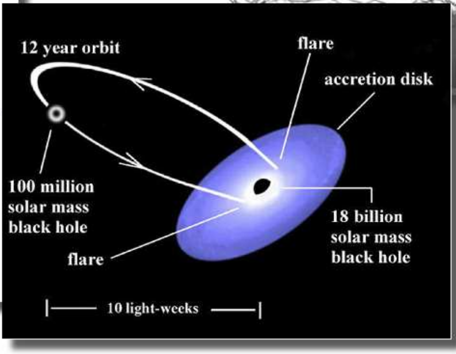
Artist's impression of a quasar. In the quasar OJ 287, a secondary supermassive black hole orbits the primary, occasionally punching through the accretion disk surrounding the primary. [ESO/M. Kommesser]



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Valtonen, Zola, Ciprini, Gopakumar, et al. 2016, ApJ Lett, 819, 37

Conclusions

❑ Time to consider supermassive BHs (SMBHs) in the search for (micro/nano-Hz) GWs.
→ Next prospects for SKA, future international PTAs projects, LISA (this for the lower mass population <10^6_Msun).

❑ Possible (more or less exotic) effects at high frequency GWs (> 1 Hz) of supermassive BHs (→ potential interest for the high-sensitivity Einstein Telescope).

❑ Astrophysical direct evidence for sub-pc spatially unresolved binary-SMBHs candidates (quasi periodic signals, pc-scale distorted radio-structures/helical-patterns in jets, double-peaked broad lines, etc.) is an interesting and debated topic.

❑ Blazar periodicity in blazar light curves is not a trivial problem and data analysis. Strong claims needs strong evidence. Multifrequency cross-correlations and polarization data are important. Beware of sparse data, systematics, and the ubiquitous red-noise.

❑ Periodicity can be also explained by a variety of mechanisms different by a binary SMBH system.

❑Discovery of about 2-year gamma-ray (and optical) periodicity in PG 1553+113 seems coherent and maintained also in the 10 year *Fermi* LAT dataset, with improving significance.

❑ Importance of astrophysical knowledge about the universal accretion phenomenon in classical astrophysics. It provides a useful contribution also to accreting SMBH physics in AGN, to jets physics, and to GW and multimessenger particle physics.

❑ SMBHs are tantaslizing: multifrequency + multimessenger particle (VHE/UHE neutrinos, UHE CRs, MeV-GeV-TeV gamma rays) + gravitational waves + axions (dark matter) cosmic laboratories. .