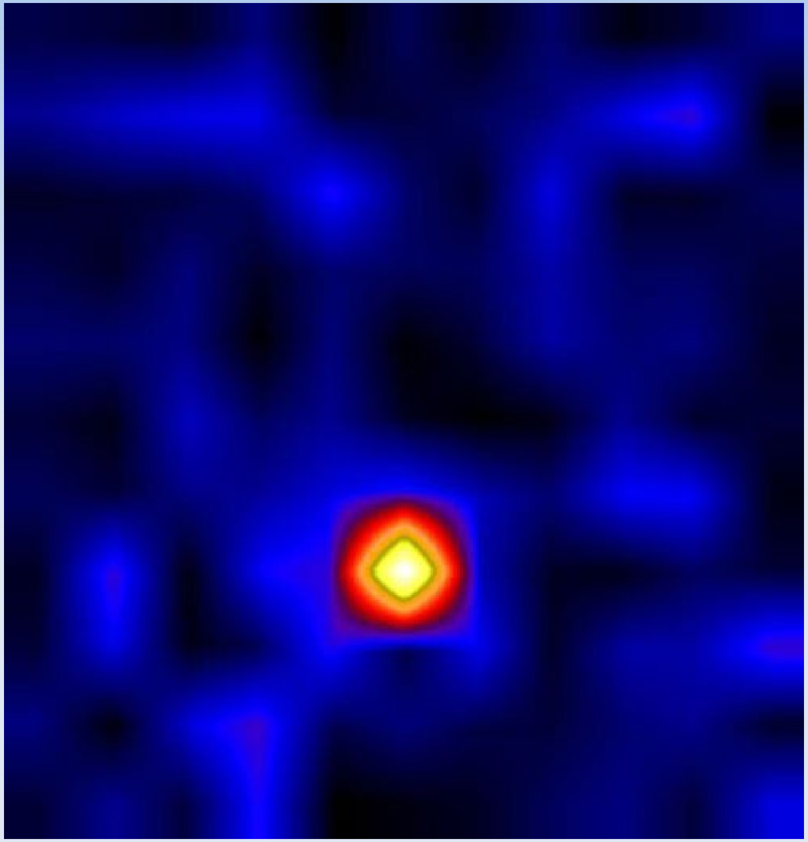
Compact Stars



Lecture 14

Summary of the previous lecture

- I presented supernova classification, and core-collapse supernova mechanism.
- Supernova type I b/c and II are massive star’s core-collapses. Supernova Ia are thermonuclear explosions of a white dwarf.
- I also talked about supernovae Ia and cosmology. Their observations may be relevant to probe the high-redshift Universe.

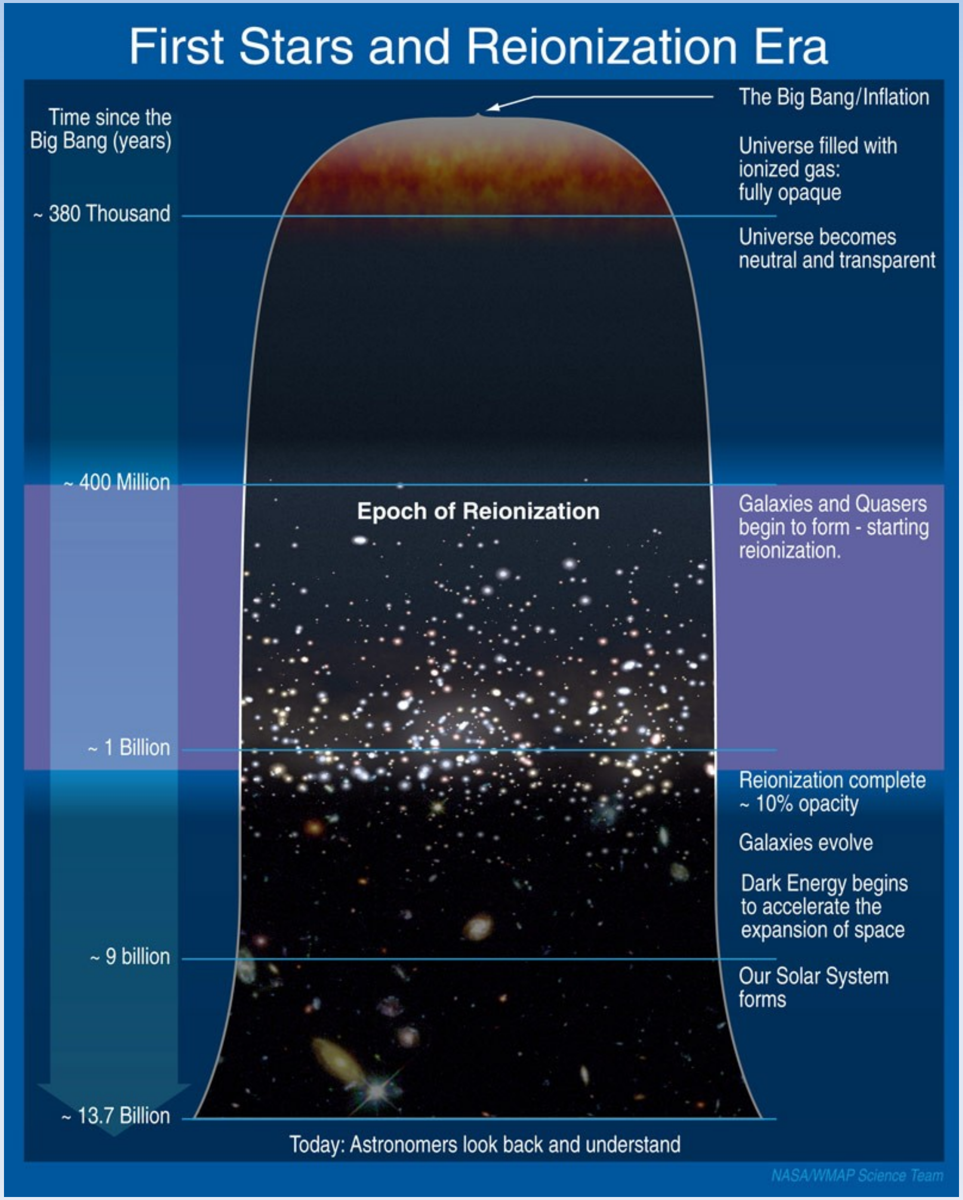
Today: last few topics

- Reionisation.
- Luminosity function of quasars, Soltan argument
- Mass – velocity dispersion for supermassive black holes
- Intermediate mass black holes
- Mass gap between X-ray and GW data for black holes
- Primordial black holes, evaporation, Hawking radiation

Transitions of gas in the Universe

- Recombination of Hydrogen in the Universe occurred about 379 000 years after Big Bang ($z=1080$)
- Temperature was low enouh to recombine electrons and protons into Hydrogen atoms. Photon absorption due to scattering off free electrons decreased and Universe became transparent.
- About 150 million years after Big Bang ($20>z>6$) first structures formed and their radiation re-ionized Hydrogen in the intergalactic gas again.
- Because of cosmic expansion, electron scatterings were less frequent and Universe remained transparent

Universe timeline



First Stars and Reionization Era

NASA/WMAP Science Team

Gunn-Peterson effect

- The reionisation of the intergalactic medium by first quasars occurred around redhift z~6. This is proved by the Gunn-Peterson absorption feature by neutral H, seen in the spectra of distant sources.
- Absorption of quasar light at wavelengths of Lymann-alpha transition of Hydrogen is stretched, due to redshift effect. Instead of sharp absorption lines, a broad feature called „trough” is seen.
- Predicted by Gunn & Peterson (1965)

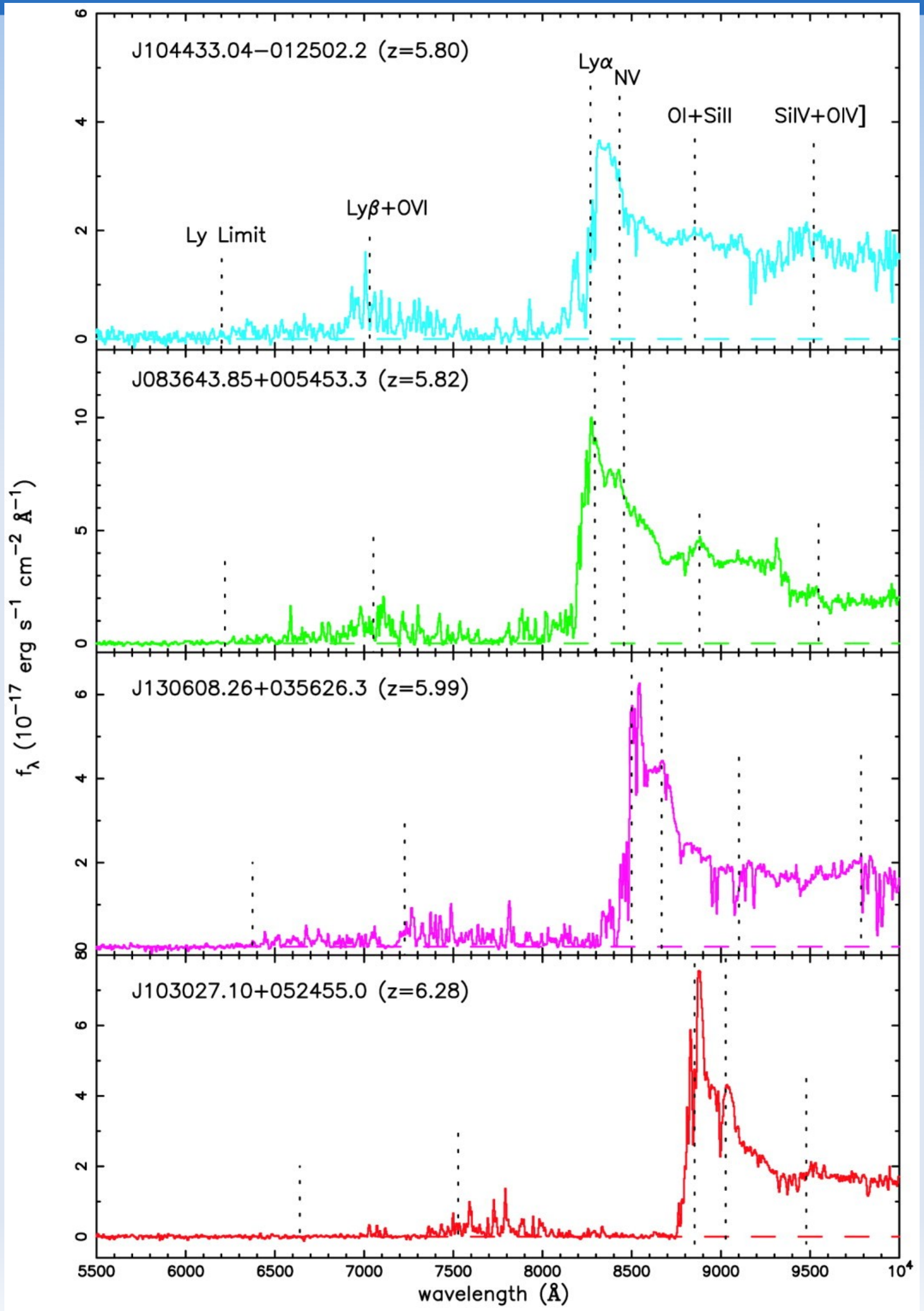
SDSS quasars spectra

Optical spectra of quasars with $z>5$ from Keck, discovered in the Sloan Digital Sky Survey.

To $z\sim5.7$, the Lyα absorption evolves as expected from an extrapolation from lower redshifts.

However, in the highest-redshift object, SDSS J103027.10+052455.0 ($z=6.28$), the average transmitted flux is 0.0038+/-0.0026 times that of the continuum level over 8450 Å$<\lambda<$8710 Å ($5.95<z_{abs}<6.16$), consistent with zero flux.

Becker et al. (2001)

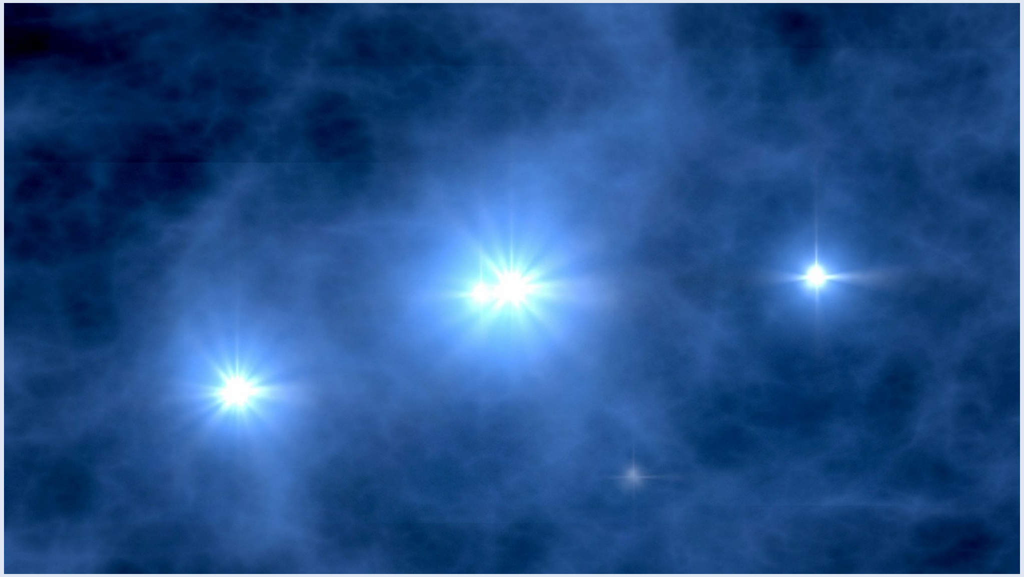


Evidence for reionisation

- The discovery of the trough in a $z = 6.28$ quasar, and the absence of the trough in quasars detected at redshifts just below $z = 6$ presented strong evidence for the Hydrogen in the universe having undergone a transition from neutral to ionized around $z = 6$.
- Despite the fact that the ratio of neutral hydrogen to ionized hydrogen may not have been particularly high, the low flux observed past the Lyman-alpha limit indicates that the universe was in the final stages of reionization.

Energy sources

- Primary candidates for ionisation are all sources which produce a significant amount of energy in the ultraviolet and above.
  - Quasars
  - Population III stars
  - Dwarf galaxies



Luminosity function

- Luminosity function gives the number of objects of a given luminosity per its interval (e.g. Schechter 1976)

$$\Phi(L)dL=\Phi_0\left(\frac{L}{L_0}\right)^{\alpha}\exp\left(\frac{-L}{L_0}\right)dL$$

- The light density in the Universe is then

$$J=\int_0^{\infty} L\,\Phi(L)\,dL$$

- From observed number of quasars at various redshifts, we may calculate integrated light density due to quasar radiation.
- This ‘Soltan argument’ gives the mass density in SMBHs per Mpc^3 which is estimated at 5x10^5 M$_{\text{Sun}}$.

Soltan argumennt

- In 1969, Lynden-Bell suggested that 10^{10} „dead quasars" exist in the universe
- Theory outlined by Andrzej Soltan (1982), took into accunt quasar luminosity function
- If the quasars are powered by accretion onto a supermassive black holes, then there is a connection between the black hole masses and quasars luminosity
- Luminosity of accreting quasar:

$$\boxed{L = \epsilon \dot{M} c^2}$$

- Integrating the luminosity function of observed quasars, we obtain the estimate for mass contained in the supermassive black holes via accretion. Lower bound of 10^{-10} erg/m^3 resulted in 10^{14} Solar mass per Gpc^3.

Black Hole demographics

- Measurements of the QSO luminosity function from the 2dF QSO Survey (0.3 < z < 2.3, Boyle et al. 2000) and the Sloan Digital Sky Survey (3.0 < z < 5.0, Fan et al. 2001), were used to update Soltan's results.
- The cumulative mass density in SBHs which power QSO activity can be expressed as:

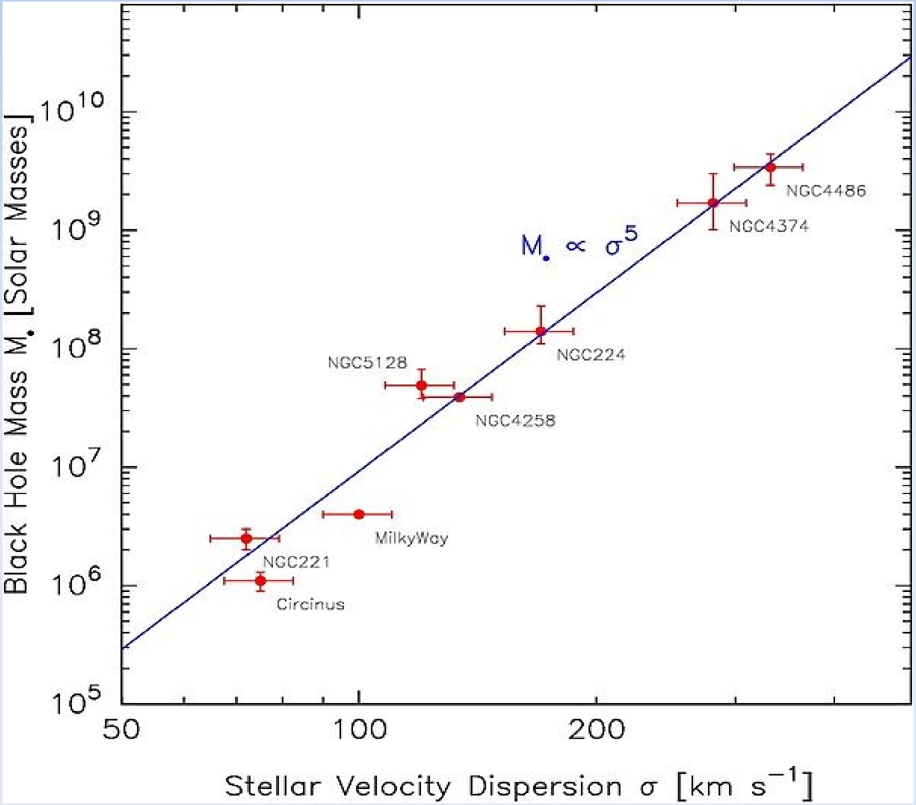
$$\rho_{QSO} = \frac{K_{bol}}{\epsilon c^2} \int_o^\infty \int_L^\infty \frac{L' \Phi(L', z)}{H_0 (1+z) \sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda}} \, dz \, dL'$$

where the mass accretion rate is $K_{bol}\, \epsilon^{-1}\, c^{-2}$, with K_{bol} the bolometric correction (Elvis et al. 1986), and ϵ is the energy conversion coefficient, ~ 0.1.

M81: bulge

M-sigma relation

- Empirical correlation between the stellar velocity dispersion of a galaxy bulge and the mass of the supermassive black hole at the galaxy's center.
- First shown by Ferrarese & Merritt (2000).
- Interpreted to imply a mechanical feedback between the growth of a BH and bulge (Silk & Rees 1998; King 2003)



Current estimates for the black hole density

- Sołtan argument made a reasonable case that supermassive black holes were at one time ultraluminous quasars.
- The first estimates of the mass density in supermassive black holes were 5-10 times higher than Sołtan's estimate. This was resolved in 2000 via the discovery of the M–sigma relation.
- As of 2008, the best constraints for the supermassive black hole mass per Mpc^3 in the local universe derived from the Sołtan argument is between $2 - 5 \times 10^5$ solar masses.

Salpeter time

- Massive stars as well as many quasars radiate close to the Eddington luminosity.
- This is yielding a minimum lifetime of star. (Lower-mass stars radiate less than at Eddington rate and last longer than this).
- The resulting characteristic ”Salpeter time” is:

$$\boxed{t_S = \epsilon\ c\ \sigma_T/(4\ \pi\ G\ m_p) = 4\text{x}10^8\ \epsilon\ [\text{yrs}]}$$

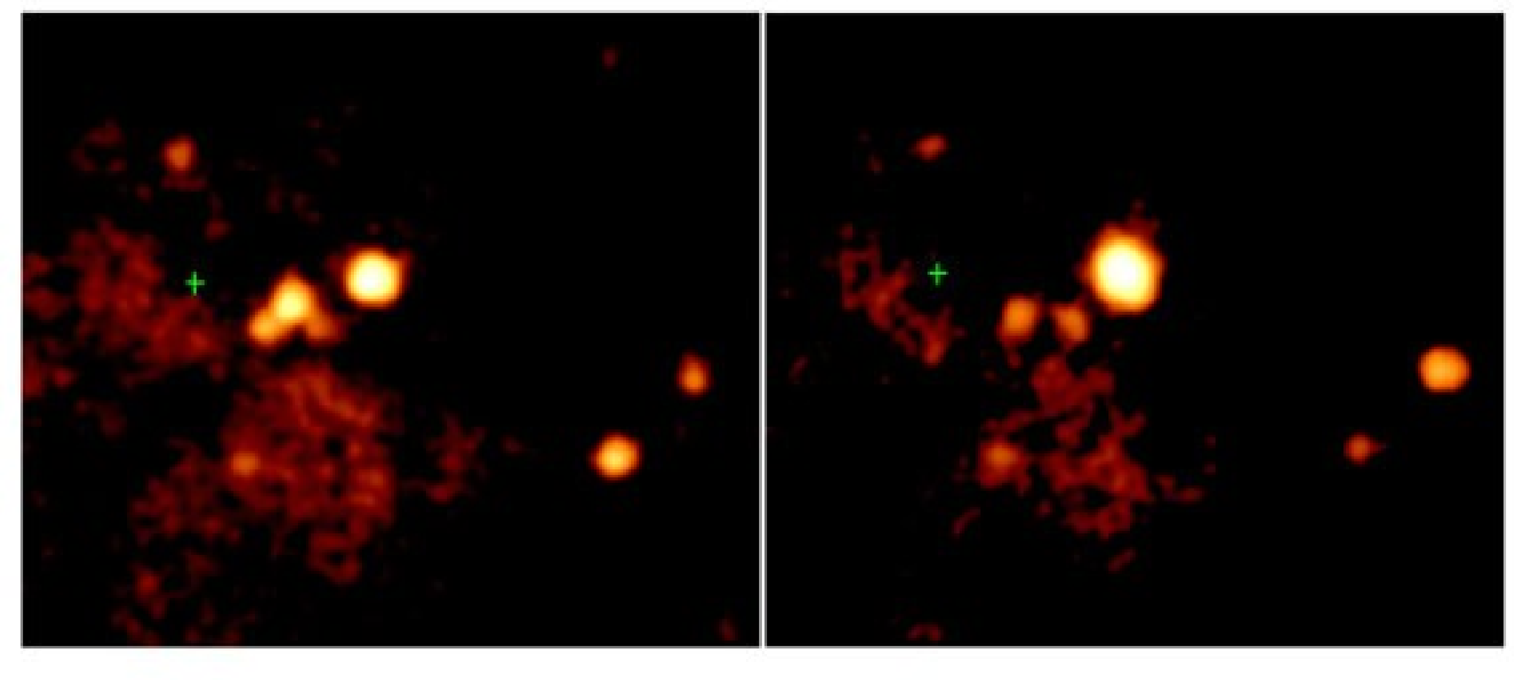
- The mass growth rate of a black hole accreting at M_{Edd} is exponential with an e-folding timescale t_S (efficiency for quasars is $\epsilon \sim 0.1$).

Intermediate mass black holes

- ULX are the ultraluminous X-ray sources, whose bolometric luminosities exceed the Eddington limit for a stellar mass BH, if the radiation is isotropic.
- Their accreting black hole should have a mass 100-10000 Solar masses.

M 82 X-1, Chandra image (cross marks the galaxy's center).

The source luminosity is ~10^{41} ergs/s (Matsumoto et al. 2001)



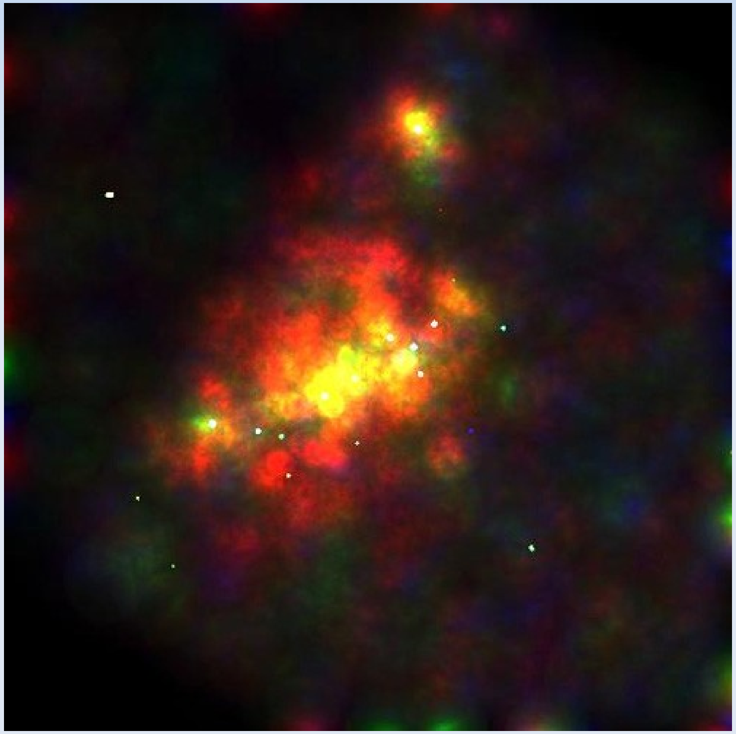
ULX’s

The Milky Way has not been shown to contain a ULX, although SS 433 may be a possible source.

The main interest in ULXs stems from their luminosity exceeding the Eddington luminosity of neutron stars and even stellar black holes.

It is not known what powers ULXs.

Models include beamed emission of stellar mass objects, accreting intermediate-mass BHs, and super-Eddington emission.



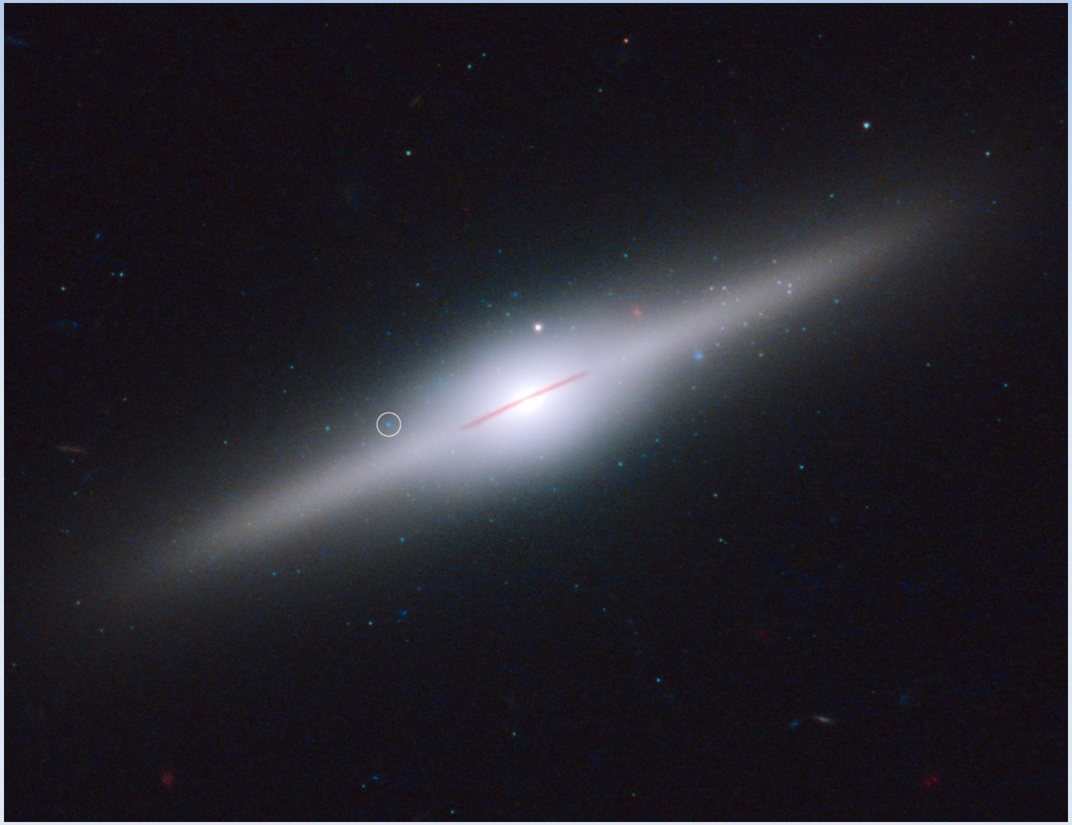
Intermediate mass BH

- Stellar black holes are formed as a collapse of massive star
- Supermassive black holes are found in quasars
- The ‘mass gap’ between 10-20 M_{sun} and 10^5-10^9 M_{sun} seemed unfilled…

HLX-1

Hyper-Luminous X-ray source 1, commonly known as HLX-1, is an intermediate-mass black hole candidate, located in the lenticular galaxy

ESO 243-49 about 290 million light-years from Earth

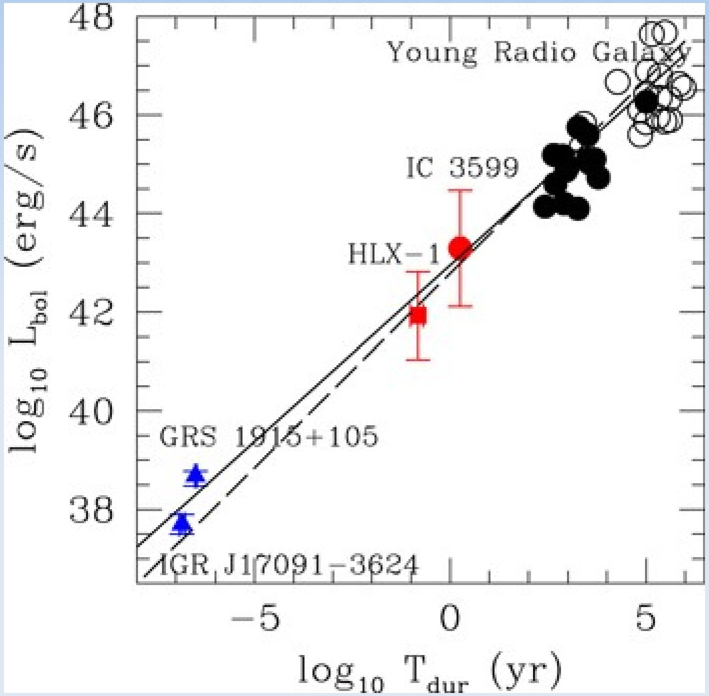


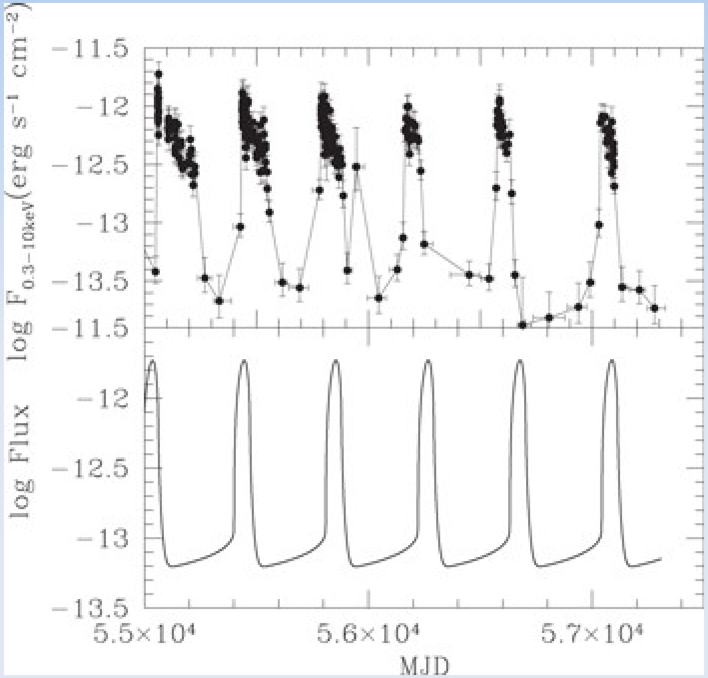
ESO 243-49 (center) with HLX-1 (circled)

HLX-1

- The hyperluminous X-ray source HLX-1 in the galaxy ESO 243-49, is currently the best intermediate-mass black hole (BH) candidate. It has luminosity of 10^{42} erg/s in X-rays (Webb et al. 2010)
- Source displays spectral transitions similar to those observed in Galactic BH binaries, but with a luminosity 100-1000 times higher.
- Data from Swift, XMM-Newton, and Chandra fit the BH mass range $\sim 2 \times 10^4 M_{Sun}$ and the $L_X \sim T^4$ relation .
- "Plateaus" in the accretion rate could be evidence that enhanced mass-transfer rate is the driving outburst mechanism in HLX-1 (Godet at al. 2012).
- The source luminosity is determined by distance estimate. The HST parallax measurement might be wrong and maybe the source is a stellar-mass object ?

HLX-1 mass estimate from variability cycles





Left: correlation between the bolometric luminosity and the outburst duration for different-scale BHs. The black filled and empty circles represent the GPS and CSS sources, respectively, from Czerny et al. (2009)

Right: Figure shows observational light curve of HLX-1 (top panel) and modeled light curve of accretion disk (bottom). Fit from Wu et al. (2016), used the BH mass of log(M_{BH})=5.1

ULX alternative explanation

- Another explanation is that the Ultra-Luminous X-ray sources are in fact stellar mass black holes with a beamed emission (so called microquasars), viewed pole-on.
- Or the accretion rate is supercritical.
- Different estimates of mass are made from the observed QPO oscillation frequency (Dewangan et al. 2005)

BHs in Globular clusters

In the cores of GCs, the evidence for IMBH comes from the stellar velocity distribution, the surface density profile, and, for very deep observations, the mass-segregation profile near the cluster center.

Constraints on central IMBH masses, require the use of detailed cluster dynamical models.

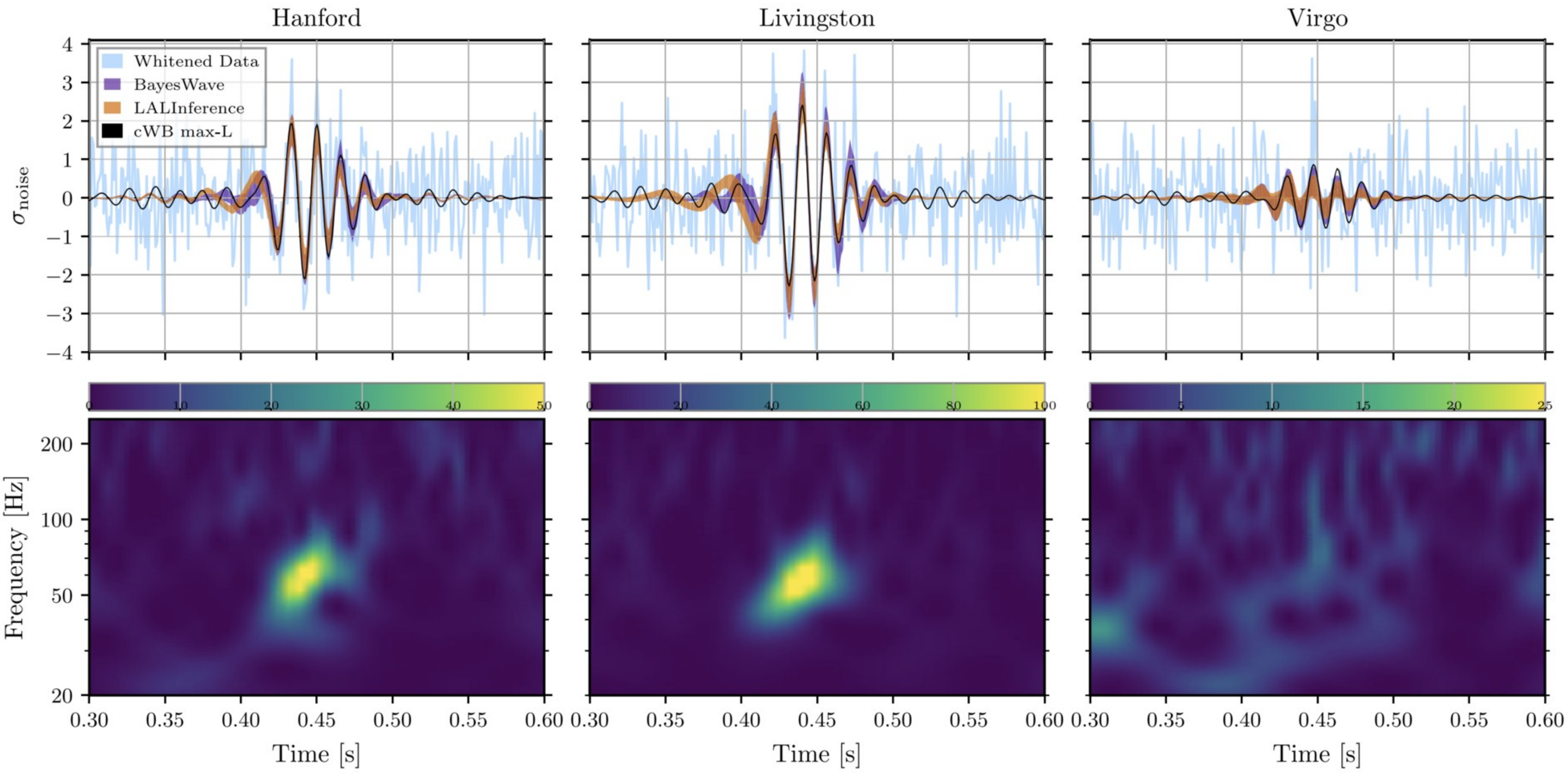
globular star cluster Omega Centauri (NGC 5139)

Models are built on Monte Carlo simulations of stellar interactions within the cluster environment.

Where are IMBHs formed?

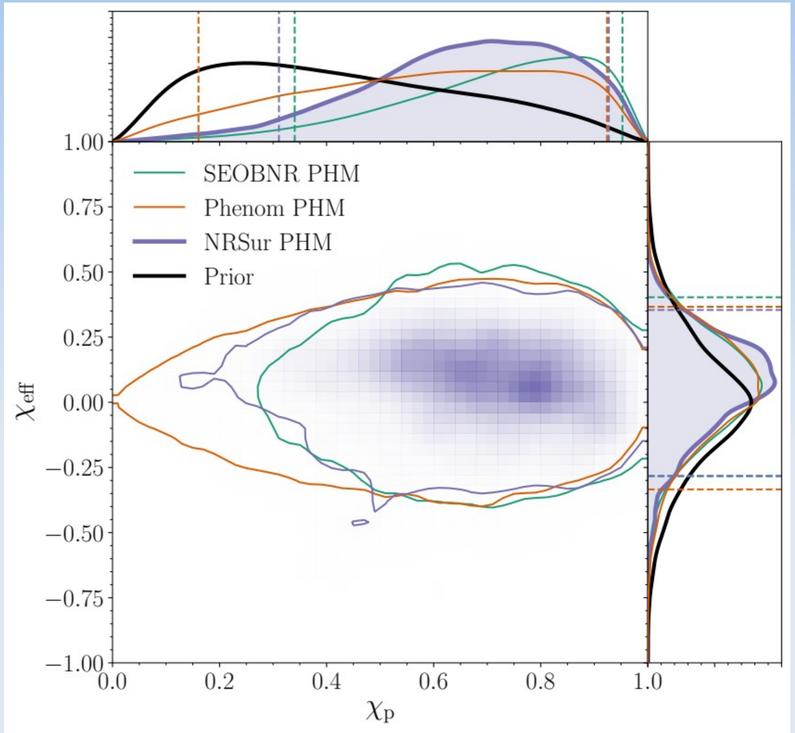
- Intermediate-mass black holes are typically defined as having masses between 100 and 100,000 MSun.
- Massive black holes should grow from these smaller black holes. However, we have never found one, they are the missing link in the black hole spectrum.
- GW190521 changes this, at 142^{+28}_{-16} the merger remnant is without doubt an intermediate-mass black hole.

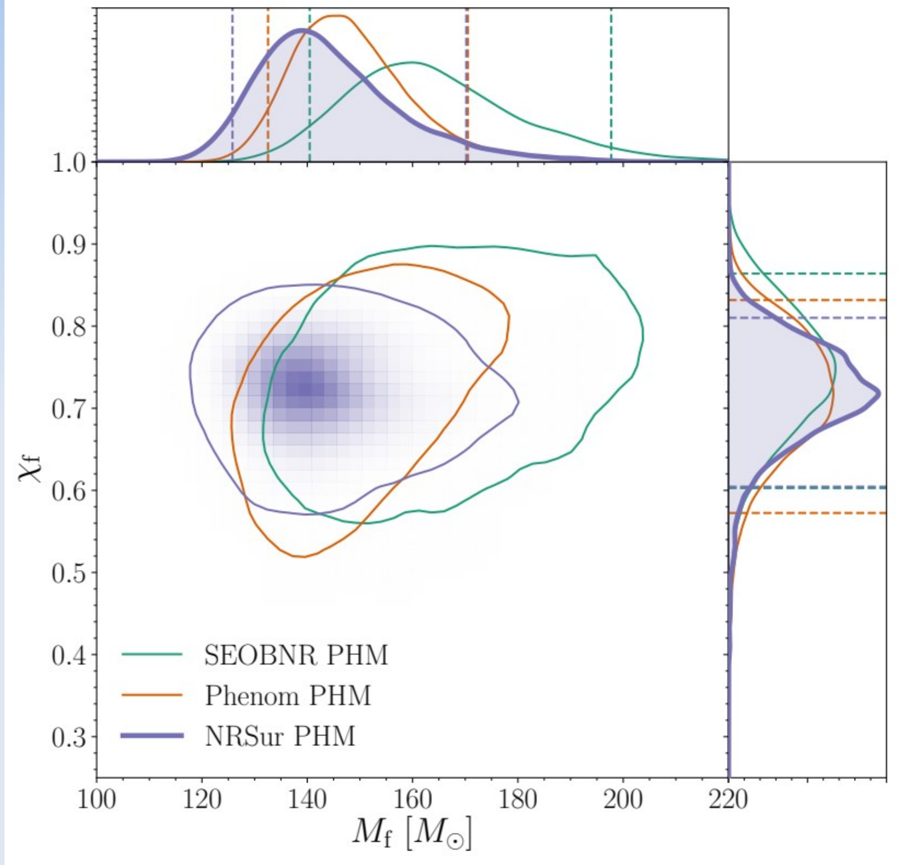
GW 190521 discovery



At 85 and 66 solar masses respectively, the two black holes comprising this merger are the largest progenitor masses observed to date.The resulting black hole had a mass equivalent to 142 times that of the Sun, making this the first clear detection of an intermediate-mass black hole. The remaining 9 solar masses were radiated away as energy in the form of gravitational waves.

150 Msun binary black hole merger GW190521





The large black hole masses extremely difficult to explain.

The mass estimates may be different if the binary was eccentric, and if the final spin precesses. Ringdown waveform analysis allowed to estimate precession probability

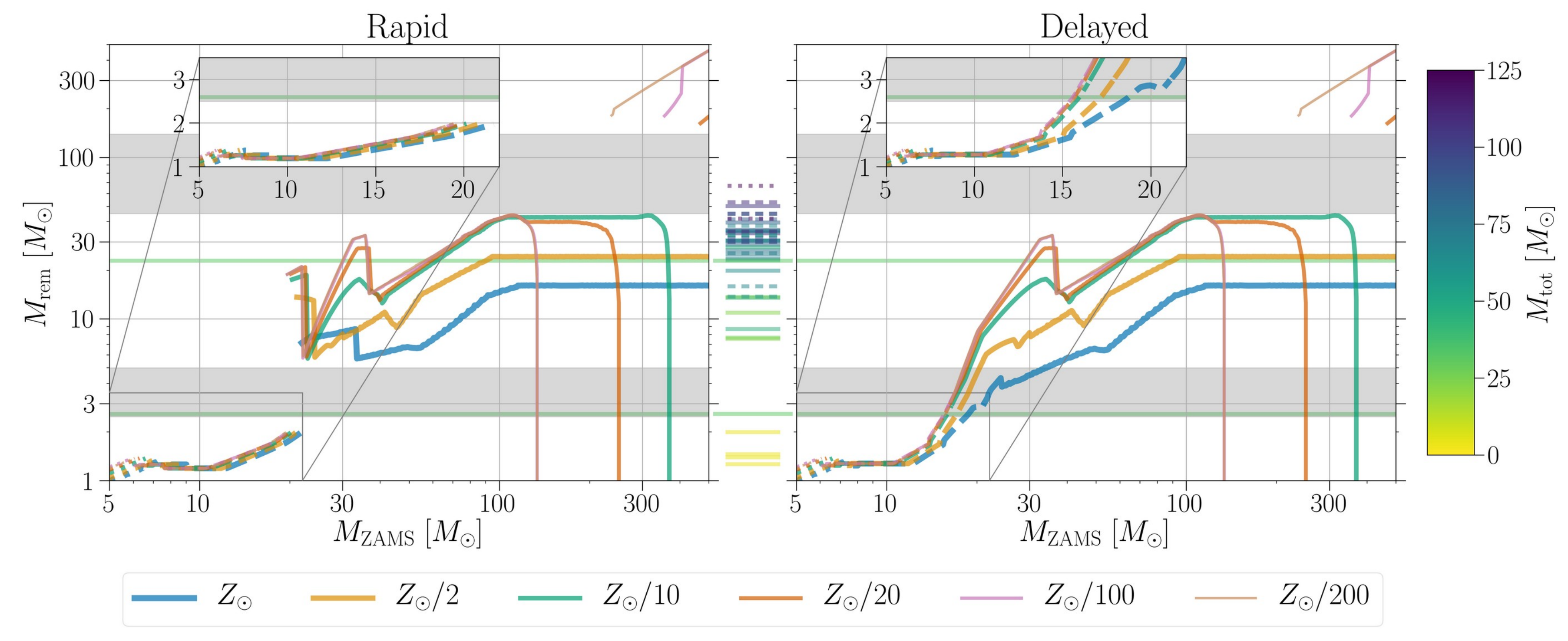
Estimated mass and spin for the final black hole. We show results several different waveform models and use the numerical relativity surrogate (NRSur PHM) as our best results. The two-dimensional shows the 90% probability contour. The dotted lines in one-dimensional plots the symmetric 90% credible interval.

Astrophys. J. Lett. 900, L13 (2020)

Pair Instability supernova

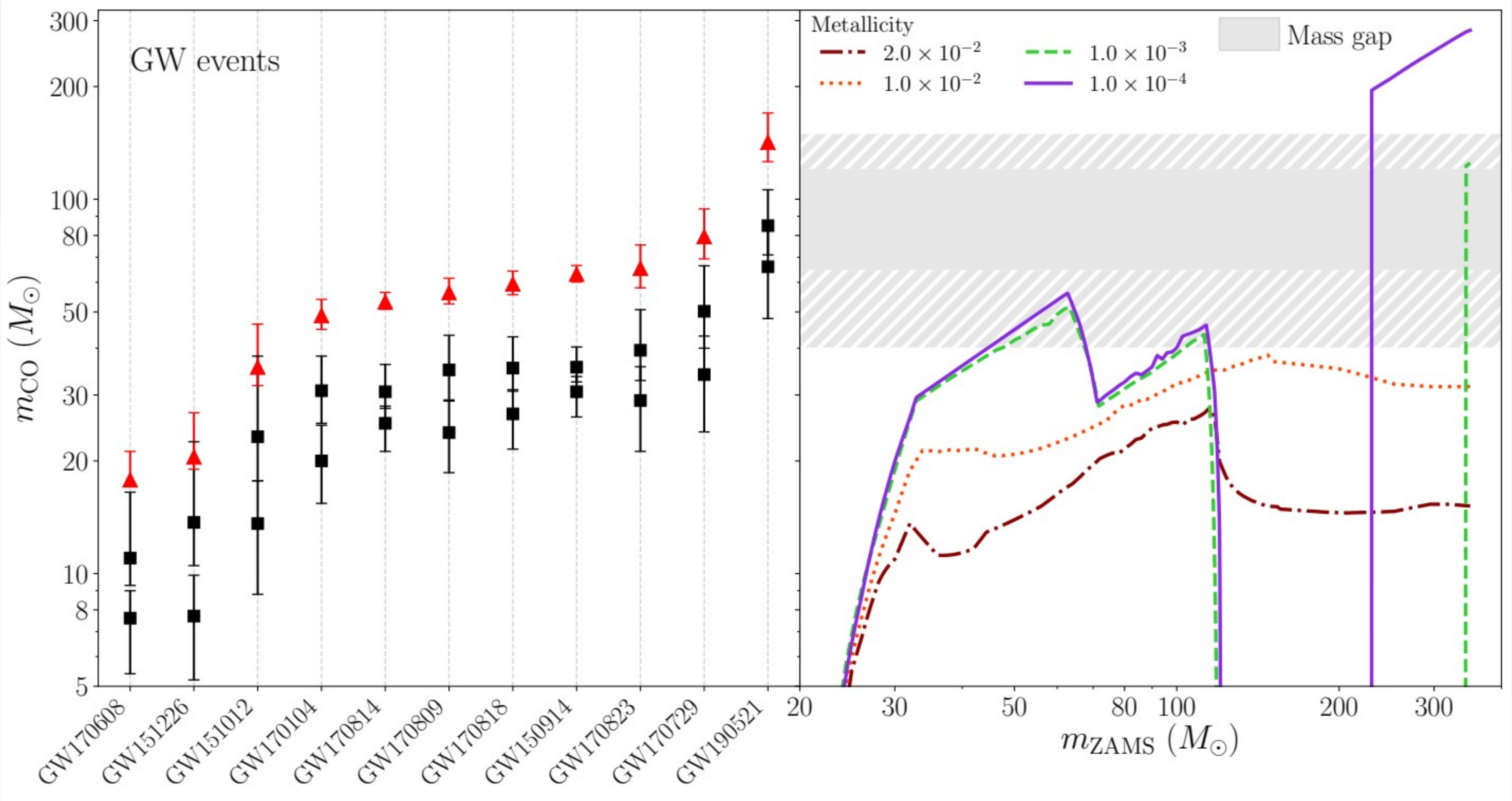
- When the cores of stars become hotter tham $3x10^9$ K, the photons bouncing around inside the core become energetic enough to produce e^+-e^- pairs
- Radiation pressure is reduced and star begins to collapse. Explosive reactions are triggered
- Stars with he cores of 30-65 M_{Sun} undergo cyclic pair-instability collapse and explosion – final BH mass is smaller
- Stars with cores 65-130 M_{Sun} will be completely destroyed by pair instability and no compact remnant is left

Remnant mass as function of metallicity



Remnant (white dwarf, neutron star or black hole) mass for different initial (zero age main sequence) stellar masses. The two panels are for two different supernova models. The grey bars indicate potential mass gaps: the lower core collapse mass gap (only predicted by the Rapid model) and the upper pair-instability mass gap. The tick marks in the middle are various claimed gravitational-wave source, colour-coded by the total mass of the binary (Zevin et al. 2020).

Mass gap


GW events
$m_{\rm CO}\ (M_\odot)$
300
200
100
80
50
30
20
10
8
5
GW170608
GW151226
GW151012
GW170104
GW170814
GW170809
GW170818
GW150914
GW170823
GW170729
GW190521
Metallicity
2.0×10^{-2}
1.0×10^{-2}
1.0×10^{-3}
1.0×10^{-4}
Mass gap
20
30
50
80
100
200
300
$m_{\rm ZAMS}\ (M_\odot)$

Possibilities to fill mass gap

- Super-efficient accretion from the companion grows the black hole
- Helium core is in fact below the pair instability treshold, but the envelope is ‘oversized’, i.e. captured from a companion star
- Massive BBH binary formed by dynamical capture in dense star cluster, from two components that are results of mergers themselves (hierarchical mergers)
- Accretion inside an AGN disk
- The massive black holes did not form is stars but were primordial

Break

Primordial black holes

- Primodrial black holes formed in the early Universe, from the primordial density fluctuations, in the regions of density excess
- The mass of a primordial black hole depends on time, when it formed in the early Universe (B. Carr, astro-ph/0511743).
- If density of the black hole, $\rho_{BH}=M/(4/3\ \pi\ R^3)$, where R its Schwarzschild radius, then M(time) is given by the critical density in the expanding Universe, with ρ_{crit} scaling as t^{-2}.

Mass of primordial black hole

- For the flat universe with dust (pressureless) equation of state in cosmological model:

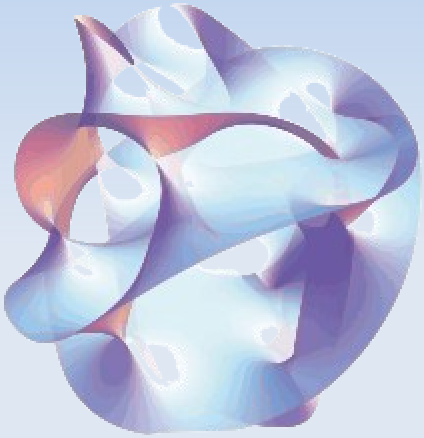
$$\boxed{M(t)=\frac{3c^3t}{4G}}$$

- In case of flat model with relativistic EoS:

$$\boxed{M(t)\approx\frac{c^3t}{G}=10^{15}\left(\frac{t}{10^{-23}s}\right)[g]}$$

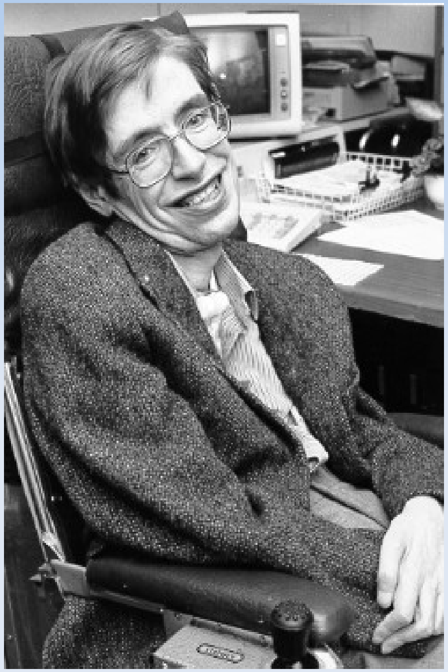
- The holes which formed at Planck era (10^{-43} s) could have 10^{-5} g. Those formed at t=1 s have 10^5 Solar mass.

How they could form



- Primordial density fluctuation, which prevents a small region against expansion
- Phase transition, when a local ‘softening’ of the equation of state occurs and pressure drops
- In the string theory, some strings may cross with themselves and form „loops”. If the loop size is less than the Schwarzschild radius, the black hole may form.

Hawking radiation



- Stephen Hawking studied the quantum properties of black holes. In 1974, he showed that the black hole can emit particles, which Compton wavelength is less than its Schwarzschild radius.
- This is analogous to the virtual electron-positron pair production in the stron electric field. They are created in vacuum, where the separation of charges is at least equal to the Compton wavelength:

  $eE\lambda > 2\ m_e\ c^2$ (E-field intensity, e-electron charge, m_e- electron mass)

Black hole thermodynamics

- The temperature of Hawking radiation is inversely proportional to the mass of the hole:

$$\boxed{T=\frac{hc^{3}}{8\pi G\,M\,k}=6\,x\,10^{-8}\left(\frac{M_{BH}}{M_{Sun}}\right)^{-1}[K]}$$

- The rate of its thermal radiation:

$$\boxed{\frac{dE}{dt}=\frac{d}{dt}(M\,c^{2})=-4\,\pi\,R_{Schw}^{2}\,\sigma T^{4}}$$

- The time, after which the black hole with initial mass M_{BH} will completely evaporate, is given by integrating its rate, from M_{BH} to 0 , and time from 0 to t_{max}. Finally

$$\boxed{t_{max}=const\,M^{3}=10^{64}\left(\frac{M_{BH}}{M_{Sun}}\right)^{3}[yrs]}$$

Until now, t=13.6 Gyrs, only the black holes with mass less than 10^{15} g could have evaporated. They must be formed then until 10^{-23} seconds after Big Bang.

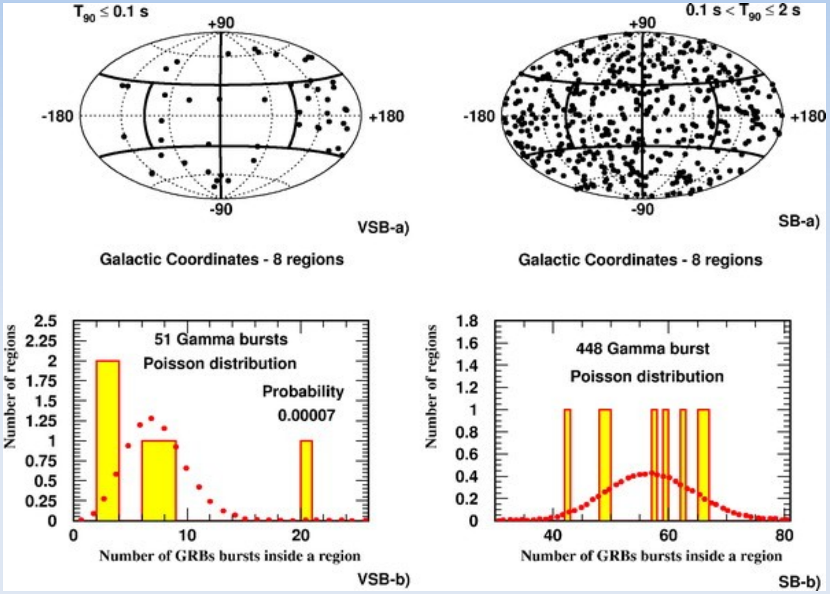
Number of primordial black holes

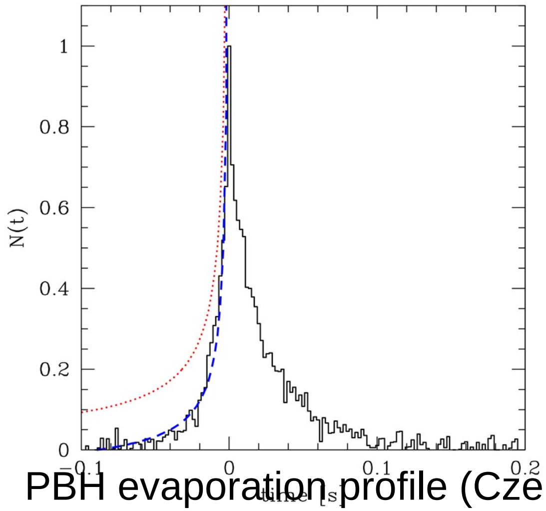
- The black holes which evaporate now, can produce thermal radiation of energy around kT=100 MeV.
- The observed intensity of background gamma-ray radiation may constrain the number density of mini-black holes in the Universe (F. Halzen et al., 1991, Nature, 353, 807)
- The inferred number is less than 10^{-8} of the critical density needed to „close” the Universe.

Role of primordial BHs

- They are not numerous enough to contribute significantly to the dark matter content of the Universe
- They could be source of subtle gravitational effects: lensing, gravitational waves
- In the early universe, they could affect the processes of nucleosynthesis, bariogenesis, be the source of neutrinos and gravitinos
- They are interesting for the quantum-gravity theory, as they could be potentially produced at energies above TeV range in large hadron colliders.
- Speculative works investigate the role of PBHs in the changing gravitational constant.
- Now they can contribute to gamma ray background, and potentially weak gamma ray bursts.

Hypothesis of very Short GRBs from PBHs





- PBH evaporation profile (Czerny, Cline, AJ, et al. 2011)

- Cline et al. (2005). The sky was divided into eight equal regions. In the case of an isotropic distribution, the number of bursts in each region should be described by the Poisson distribution.
- Figure shows BATSE GRB events (1991 April 4–2000 May 26). Angular distribution of the GRBs in Galactic coordinates and the corresponding histograms, in comparison with Poisson distribution predictions for two different T_{90} ranges (filled circles).

PBH fireball and cosmic rays

- Depending on mass, PBH can emit mass-less particles (photons, neutrinos, gravitons, $M>10^{17}$ g), or electrons, or muons.
- For $10^{14}<M<10^{15}$ g, the emitted muons, will decay into electrons and neutrinos
- For smaller mass, even hadrons might be emitted, but as a stream of free quark-gluon plasma, with E=200-300 GeV
- These hadrons then decay to pions, after collision with interstellar medium. They can produce foton-electron ‘showers’ in the Earth atmosphere, detectable with Cherenkov detectors

H.E.S.S. detector

High Energy Stereoscopic System (H.E.S.S.) is a system of imaging atmospheric Cherenkov telescopes (IACTs) for the investigation of cosmic gamma rays in the photon energy range of 0.03 to 100 TeV. The acronym was chosen in honour of Victor Hess, who was the first to observe cosmic rays. Telescope is located in Namibia, and went into operation in 2002.

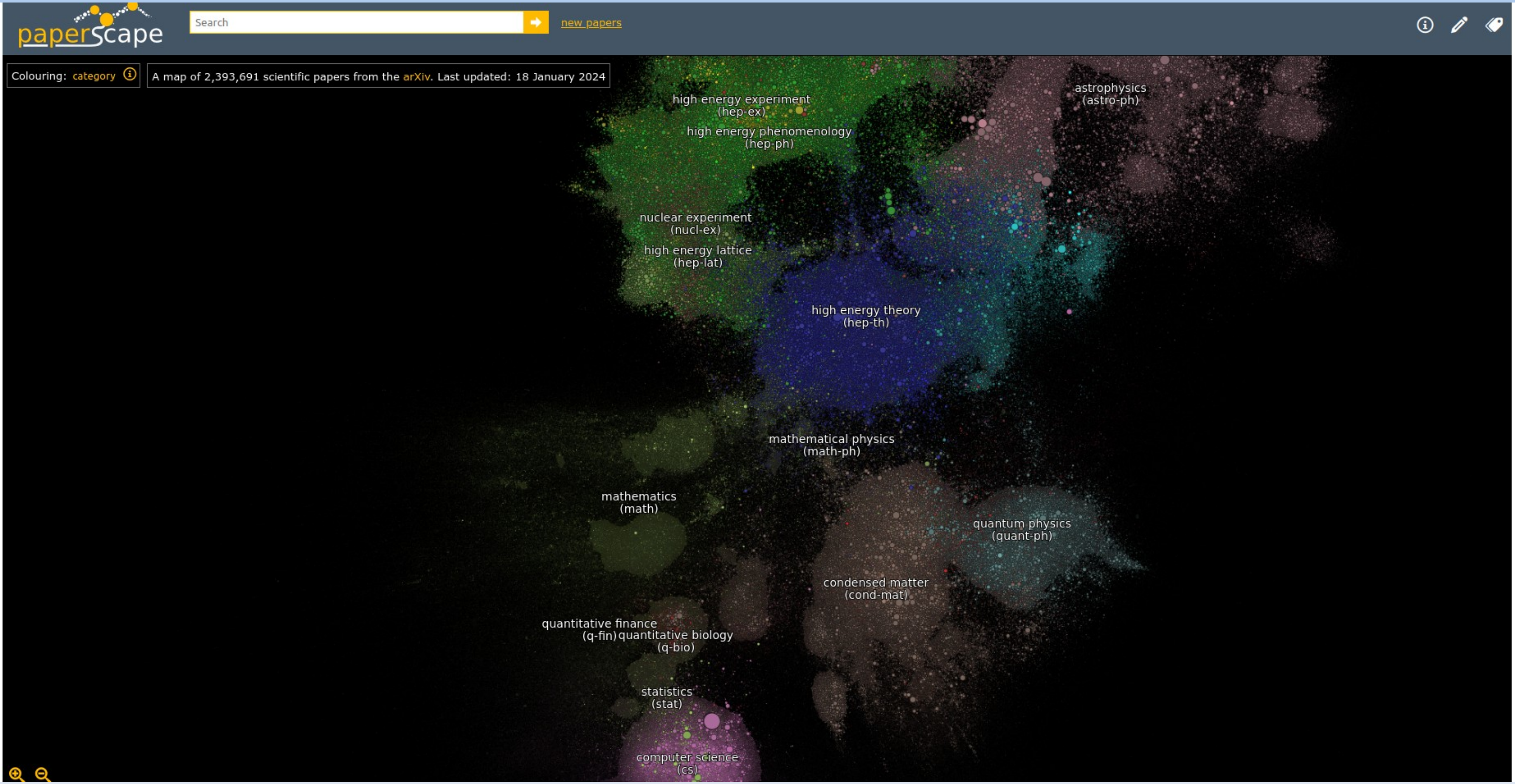
LSST telescope

Vera C. Rubin Observatory is a brand new astronomical facility on top of Cerro Pachón ridge in Chile. Rubin Observatory will conduct a ten-year survey of the Southern Hemisphere sky (referred to as the Legacy Survey of Space and Time, or LSST) with the goal of answering some of scientists' biggest questions about the Universe.

Rubin Observatory is under construction, with expected completion in 2024

https://www.lsst.org/

Scientific Universe



Colouring: category

A map of 2,393,691 scientific papers from the arXiv. Last updated: 18 January 2024