Extreme universe from 1963 to 2017

Sigma Xi, Albuquerque NM, May 15, 2017
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Abstract

In 1963 numerous researchers, including Maarten Schmidt and Alan Sandage, realized that **Quasars** were at cosmological distances and thus have some extreme energy source. In 1966 Halton Arp published a "**catalog of peculiar galaxies**" which were extreme in appearance (now understood to be dominated by interacting (colliding) galaxies).   In 1967 **pulsars** were discovered by Jocelyn Bell (and Anthony Hewish) and in 1969 **gamma-ray bursts** by the Vela military satellites (but classified until 1973). In 1969 pulsars were proposed by Thomas Gold to be rapidly rotating neutron stars which, due to their extreme magnetic fields and high rotational speed, would emit radiation similar to a rotating beacon. Finally in 1997 gamma-ray bursts were found to be at cosmological distances requiring some extreme energy source. Today the High Altitude Water Cherenkov (HAWC) observatory, located on the flanks of the Sierra Negra volcano near Puebla, Mexico at an altitude of 4100 meters (13,500 feet) observes the gamma-ray sky at extreme (TeV, *i.e.* a trillion electron volt) energies.   Curiously most HAWC sources find their ancestry in the extreme universe that began to blossom approximately 50 years ago.

Cambridge radio surveys

After WWII, Martin Ryle, Antony Hewish and colleagues of the Cavendish Astrophysics Group developed a series of radio interferometers. By the late 1950s the 'One-Mile' and later '5 km' effective aperture telescopes, at the Mullard Radio Astronomy Observatory, were used to map the radio sky, producing the famous Cambridge 2C and 3C surveys of **radio-loud** sources.

Cambridge 3C survey follow-up

The Cambridge 3C catalog has been the basis of many optical and radio studies to understand the *physics* of these **radio-loud** sources.

In 1963, an identification of the radio source 3C 48 with a “<u>star-like</u>” optical object was published by Allan Sandage and Thomas A. Matthews. However the spectrum of the faint <u>*blue star*</u> contained many unknown broad emission lines.

Cambridge 3C survey follow-up

Aside: to link the 3C 48 radio source with an optical object required improved position information. This was Matthews' roll using the Owen's Valley Radio Observatory interferometer … seen in this period photo.

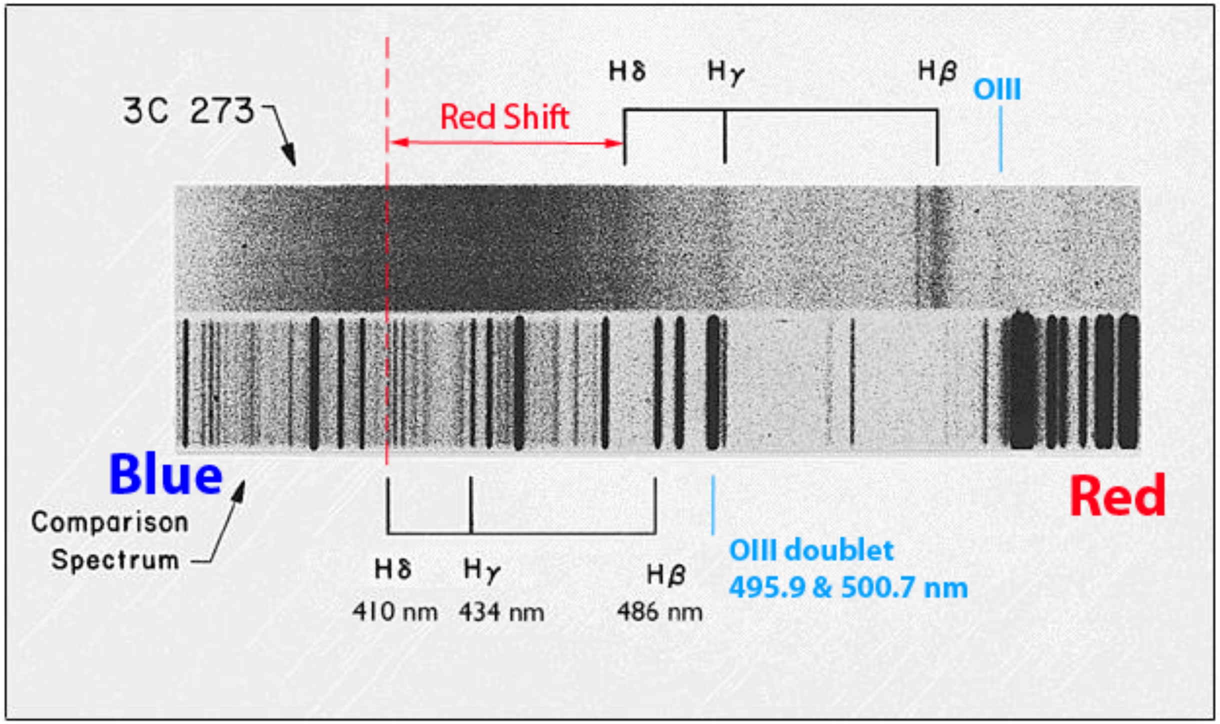
[…radio source positions were accurate up to 10-seconds of arc (Jesse Greenstein {1961})]

Cambridge 3C survey follow-up

In 1962/3 a breakthrough was achieved. The location of another radio source, 3C 273, was pinpointed. This allowed Maarten Schmidt to optically identify the object and obtain an optical spectrum using the 200-inch Hale Telescope on Mount Palomar. Curiously this spectrum revealed the same *strange emission lines* as 3C 48.

3C 273 “strange spectrum” understood

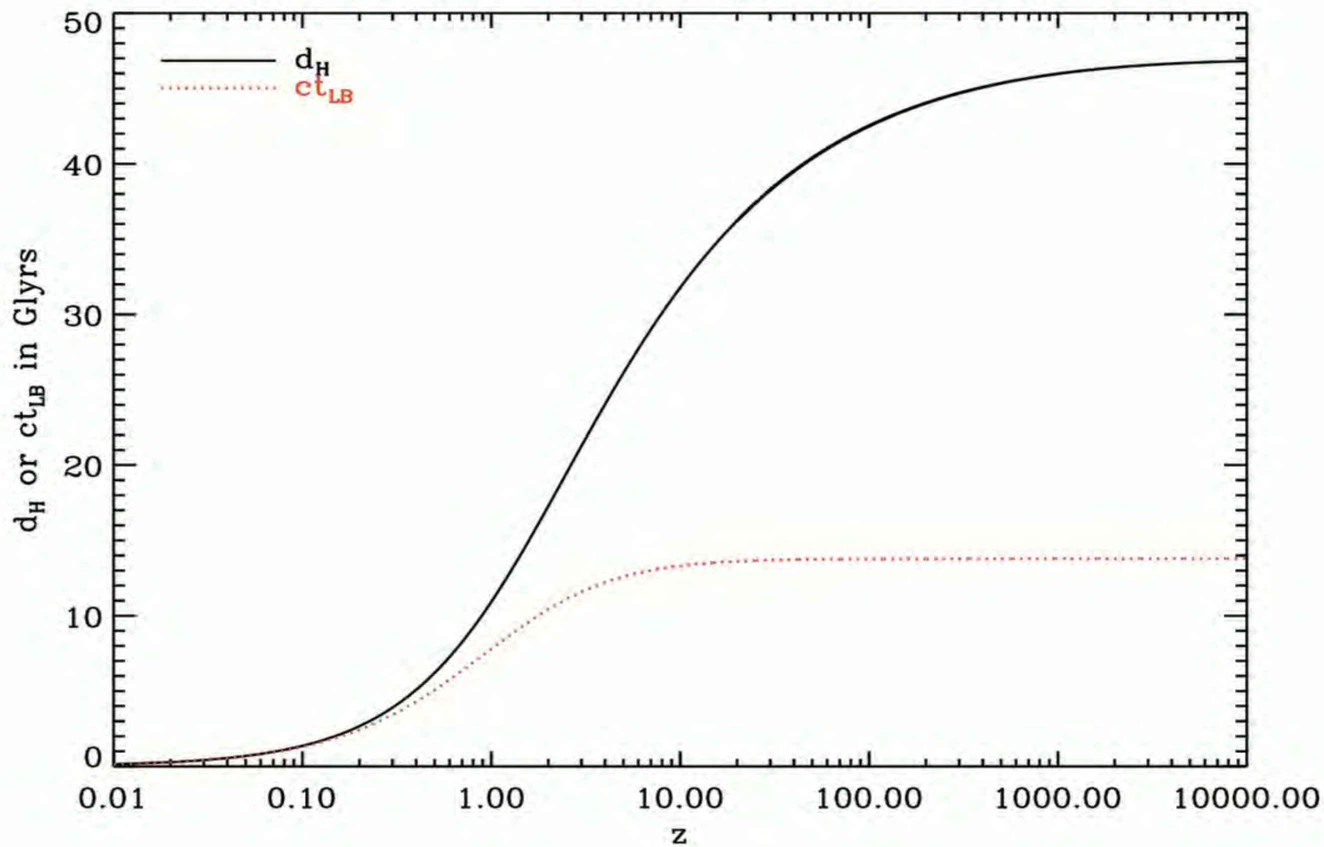
Schmidt realized that 3C 273 *strange emission lines* were actually spectral lines of hydrogen **redshifted** by 15.8 percent. We now interpret this as a **cosmological redshift**: the wavelength of the emitted radiation is lengthened due to the expansion of the Universe! The universe has grown by 1.158x since this light was emitted. This same analysis for 3C 48 showed that the universe had grown by 1.365x since its observed light was emitted!



Universe distance : redshift relationship

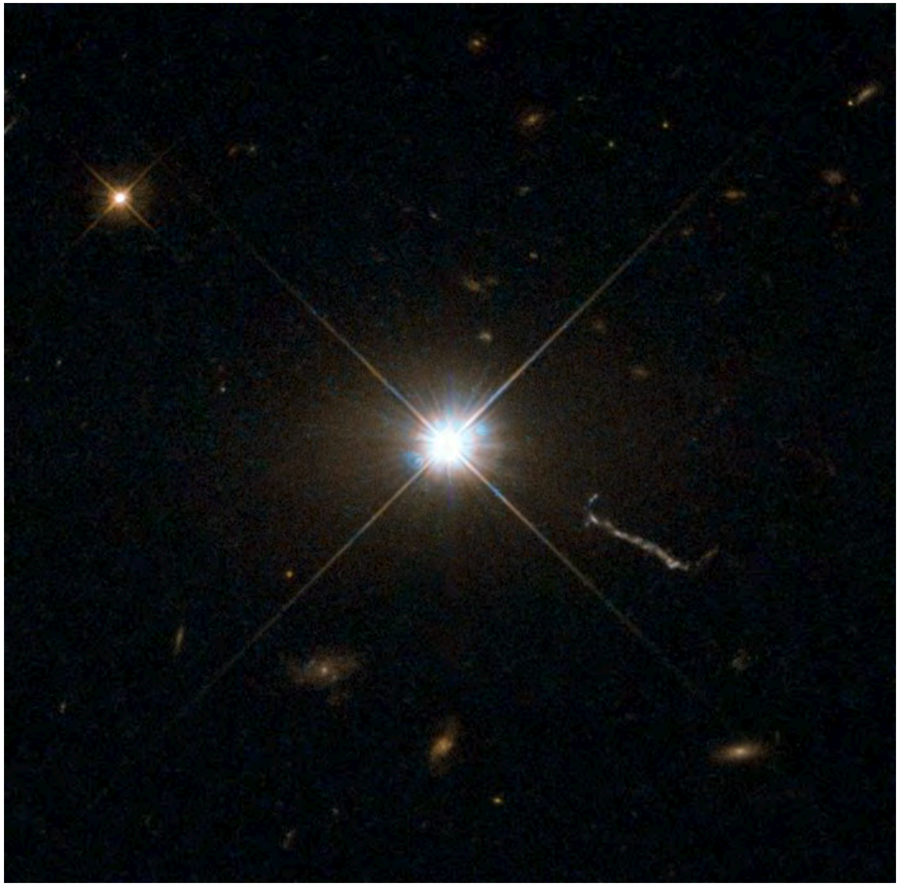
Cosmology can relate the universe expansion scale factor: 1+**z,** where **z** is the source **redshift**, to the light travel time (see red dotted line in the plot). For 3C 273 z=0.158 tells us that the light travel time is 2.44 billion years! [For 3C 48 z=0.365 tells us the light travel time is 3.9 billion years!]

For comparison it takes 26 thousand years for light travel from the center of the Milky Way galaxy to Earth and 2.5 million years for light travel from the nearby Andromeda galaxy to Earth!



Quasars: new physics and universe probe!

If 3C 48 and 3C 273 are at extreme distances how can they be so luminous? [Recall that the apparent brightness of all light sources decreases as **1/distance²**.]

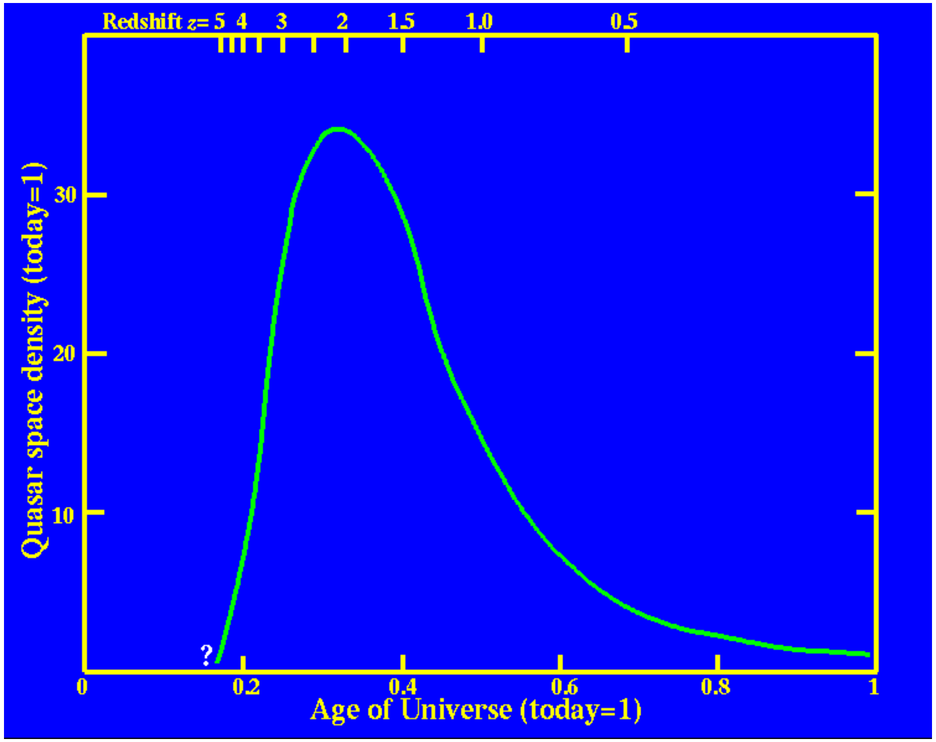


Curiously images of these sources, on right is a modern Hubble Space Telescope image of 3C 273, often appear star-like.

These objects, now called quasi-stellar objects or **Quasars,** are our first examples of the ***extreme universe.***

Quasars: new physics and universe probe!

The probable importance of **Quasars** was recognized immediately. The extremely high luminosities of these objects implied physical extremes that were not found elsewhere in the nearby Universe. The high luminosities of **Quasars** also imply that they might serve as important cosmological probes, since they could in principle be detected and identified at very large distances.

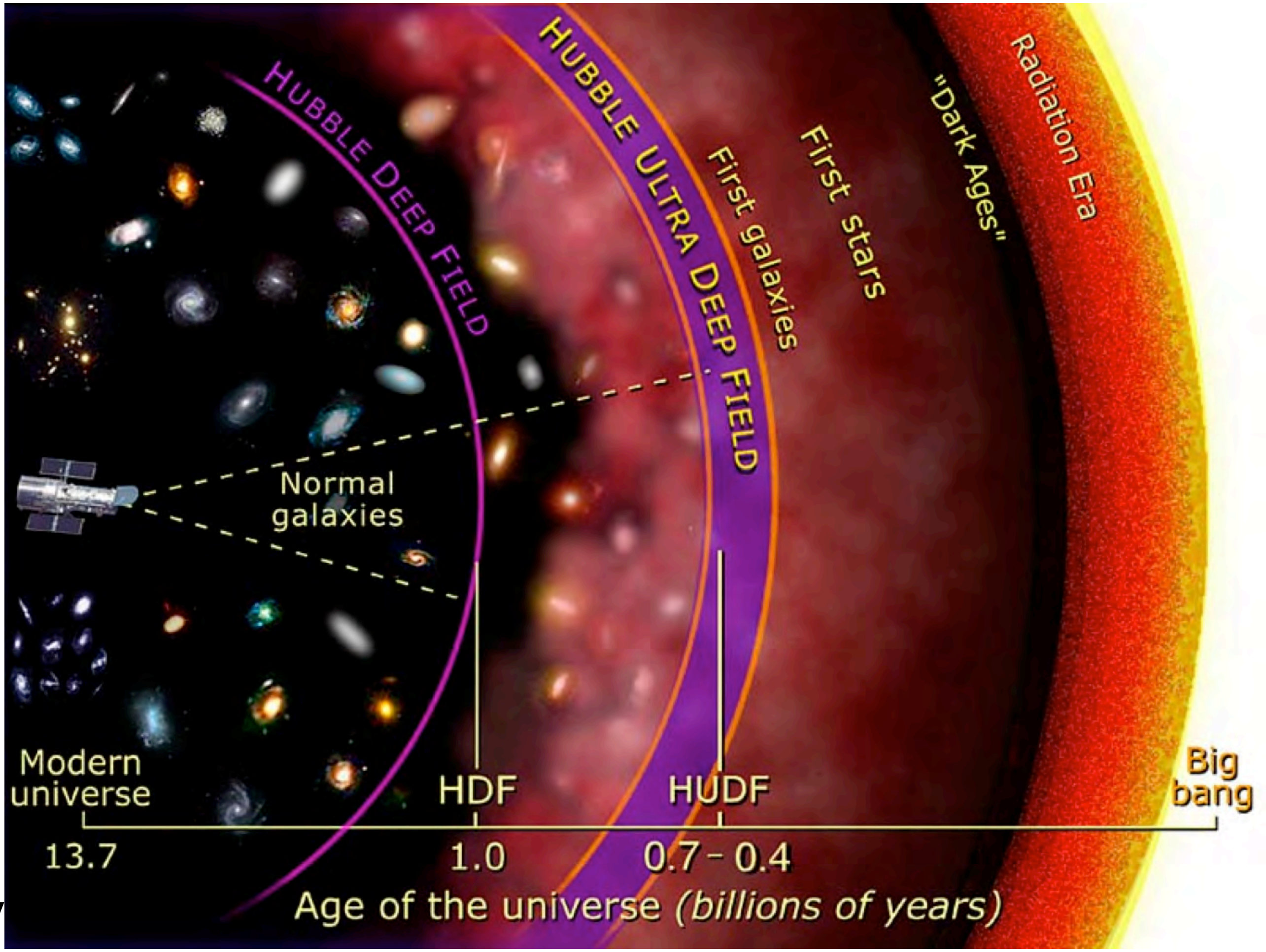


Curiously **Quasars** are not uniformly distributed: the “comoving number density” of **Quasars** peaks at a redshift of about **z**=2.0 (*viz.* 10.4 billion years ago) **…** Why a “peak”? Why then?

Quasars: new physics and universe probe!

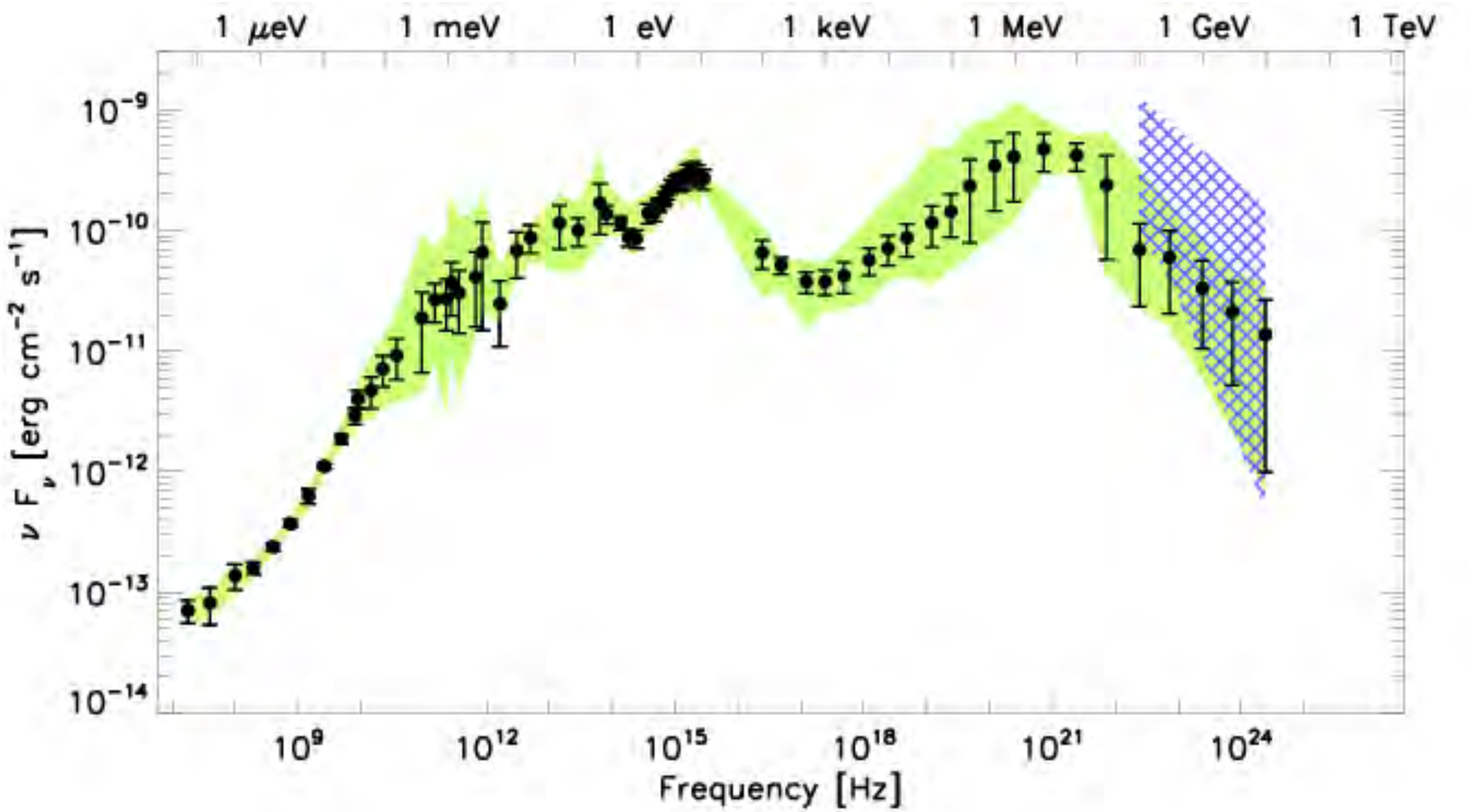
In this cartoon of the Universe, the Big Bang was 13.7 billion years ago. Light from the currently most distant known **Quasar** started to us 12.9 billion years ago or about 0.8 billion years after the Big Bang; a little less distant than the most remote sources imaged by the Hubble Space Telescope!

And the peak number density of **Quasars** was 10.4 billion years ago or About 3.3 billion years after the Big Bang … by which time most galaxies look *"normal", i.e.* similar to those today



Quasars: new physics and universe probe!

We now know that **Quasar** "light" emission is extreme in many ways. *E.G.*: the distribution of radiated energy VS frequency (or energy) for 3C 273 extends from radio (millionth of an eV) to gamma-ray (almost a TeV) energies!

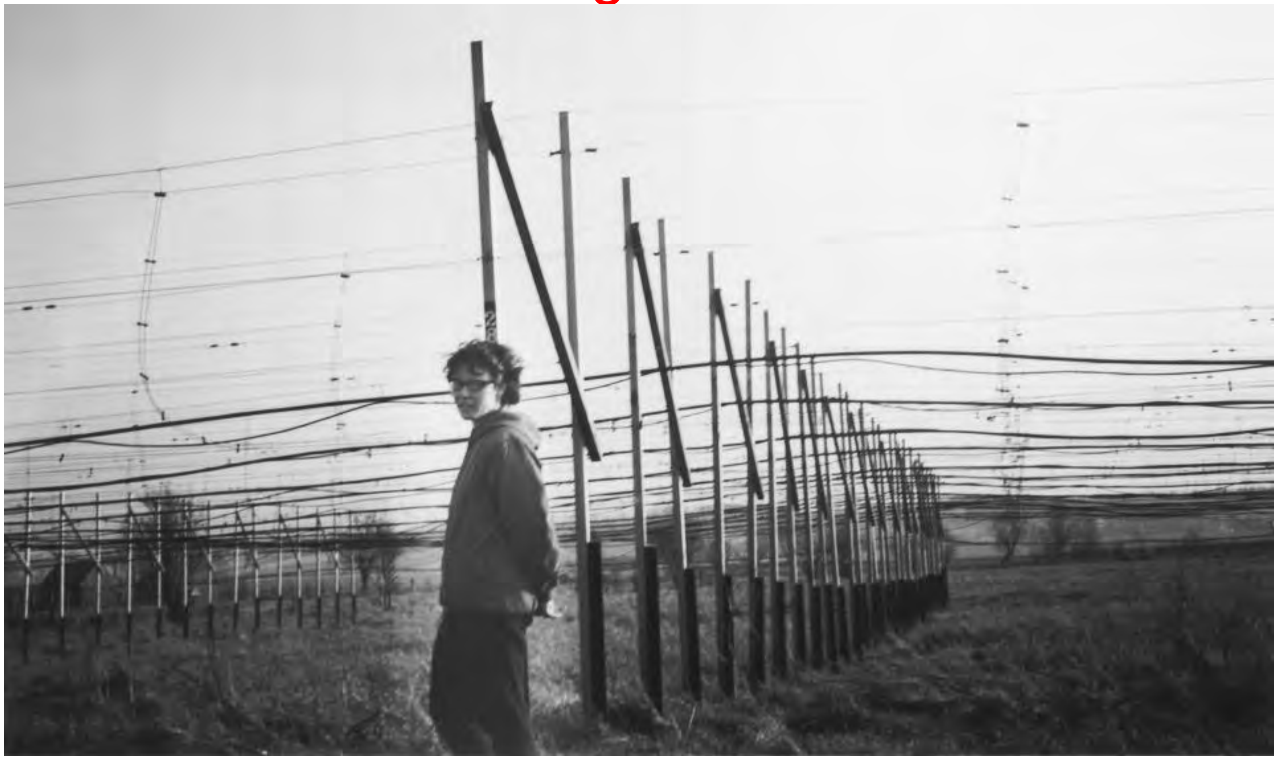


The hunt to find Quasars

By 1964, a number of radio **Quasars** were known and some of these radio sources were **point-like**, *i.e.* had small angular sizes. Anthony Hewish showed that **point-like** radio sources would twinkle as the radio waves were slightly modified by small inhomogeneities in the ionised plasma (the solar wind) flowing out from the Sun. Hewish realised that a large, low-frequency array dedicated to the measurement of the twinkling of compact radio sources would provide a new approach to finding **Quasars**.

The hunt to find Quasars

In 1965, Hewish designed a large array and was awarded a grant of £17,286 to construct it. **Jocelyn Bell** joined the 4.5 acre array project as a graduate student in October 1965. The telescope, a phased array of dipoles, was commissioned during July 1967 and observed the sky (from declination -10-deg to 50-deg) every four days. A key aspect of the array was that it had to be possible to measure the fractional twinkling of the radio sources in real time.



The hunt to find Quasars

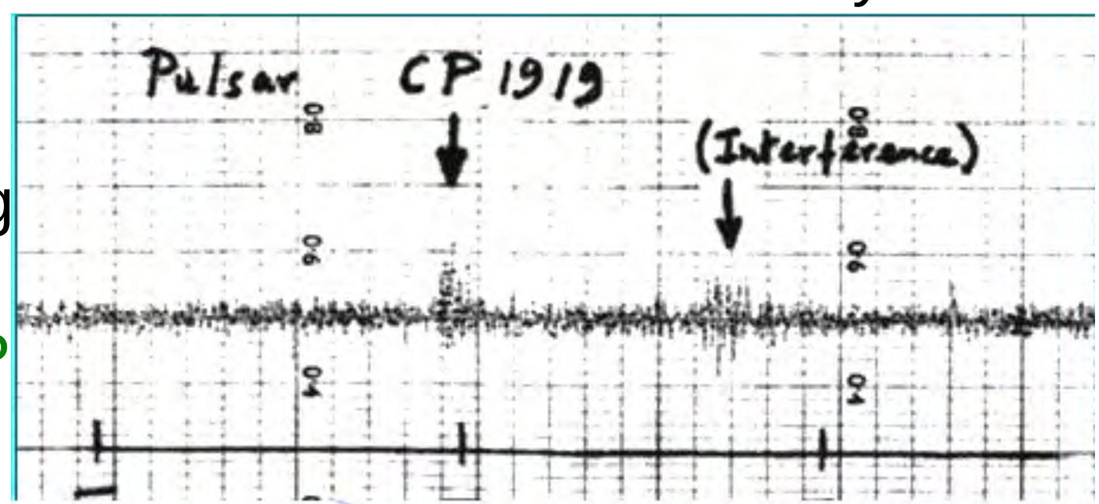
Bell recalls: The array was configured with four beams. The output appeared on four 3-track pen recorders, and produced 96 feet of chart paper every day (1'/hour/beam). The charts were analyzed by-hand by me. We decided initially not to computerize the output: because until we were familiar with the behavior of our telescope and receivers we thought it better to inspect the data visually and because a human can recognize signals of different character whereas it is difficult to program a computer to do so.

The hunt to find Quasars

Bell recalls: After the first few hundred feet of chart analysis I could recognize the twinkling sources, and I could recognize radio interference (noise). Six or eight weeks after starting the survey I became aware that on occasions there was a bit of "scruff" on the records, which did not look exactly like a twinkling source, and yet did not look exactly like man-made interference either. Furthermore I realized that we had seen "the scruff" previously on the same part of the records — *i.e.* from the same patch of sky (right ascension 1919) [in constellation Velpecula].

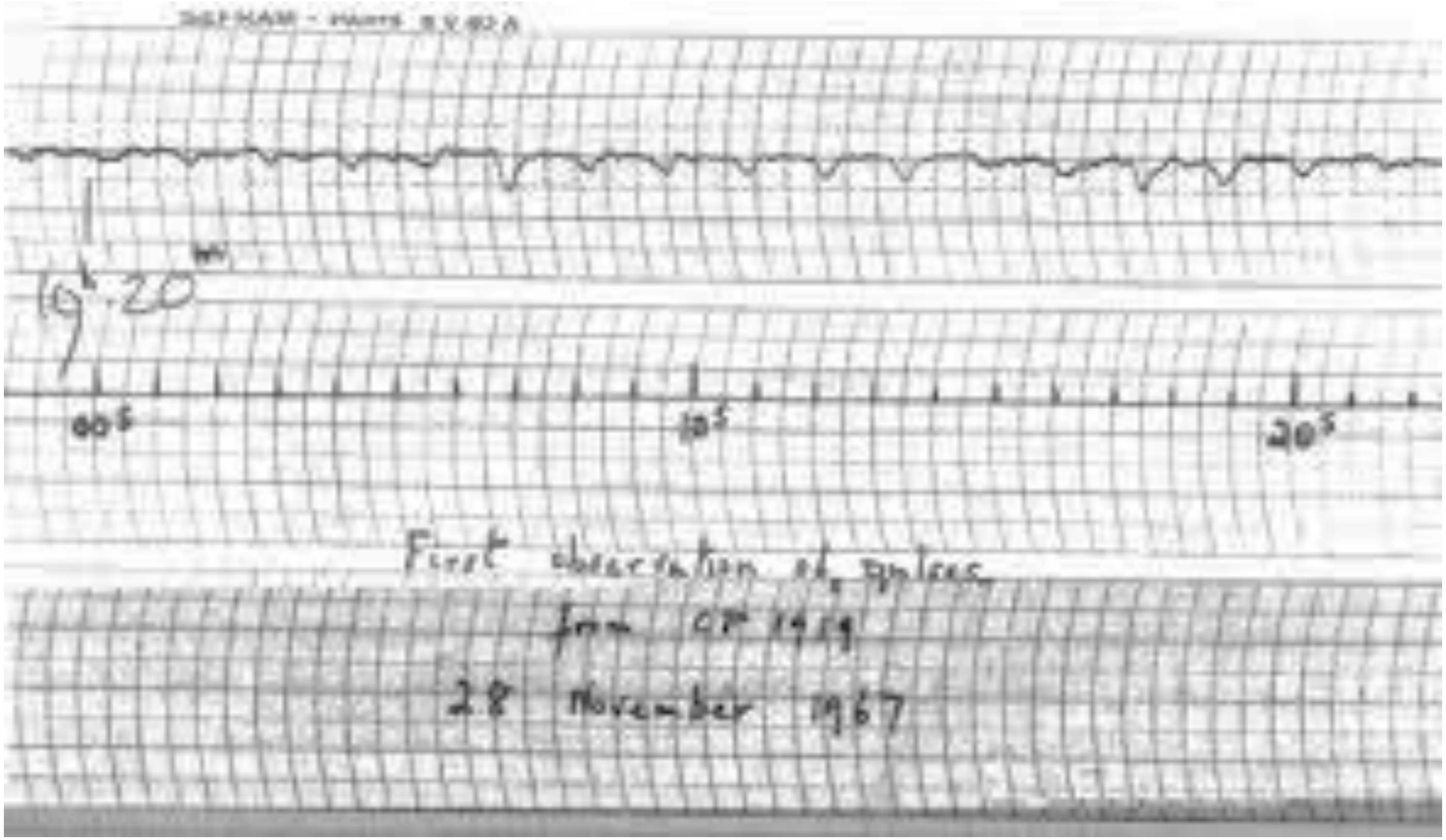
The hunt to find “the scruff”

Bell recalls: The source was transiting during the night — a time when solar-wind twinkling should be at a minimum, and one idea we had was that it was a point source. So we decided that it deserved closer inspection, and that this would involve making faster chart recordings as it transited. Towards the end of October ‘67 when we had finished doing some special tests on 3C 273, and when we had at last our full complement of receivers and recorders, I started going out to the observatory each day to make the fast recordings. They were useless. For weeks I recorded nothing but receiver noise. Then one day I skipped the observations to go to a lecture, and next day on my normal recording I saw that “the scruff” had been there. [What does CP stand for?]



The hunt to find the "scruff"

Bell recalls: A few days after that at the end of November '67 I got it on the fast recording. As the chart flowed under the pen I could see that the signal was a series of pulses, and my suspicion that they were equally spaced was confirmed as soon as I got the chart off the recorder. They were 1 1/3 seconds apart.

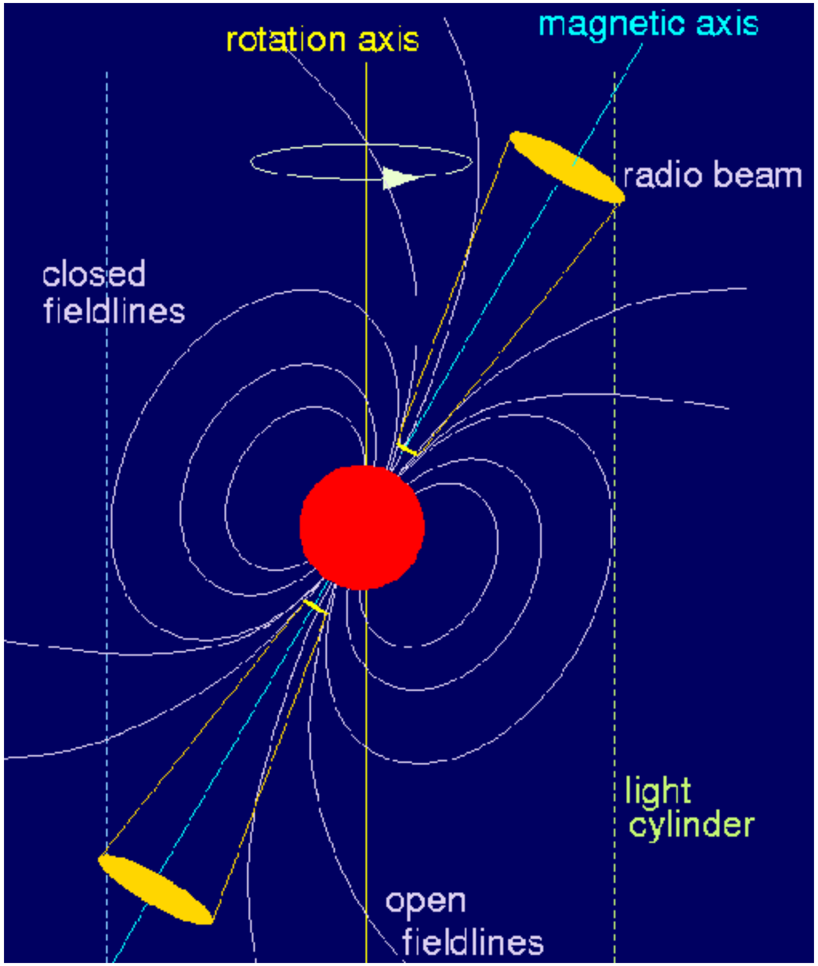


From “scruff” to pulsar

Bell recalls: Some days later I was analyzing a recording of a completely <u>different part of the sky</u>, I thought I saw some “scruff”. I rapidly checked through previous recordings of that part of the sky, and on occasions there was “scruff” there …

Ultimately the 1968 Nature papers of Hewish, Bell, et al reported 4 <u>rapidly pulsing radio sources</u>.

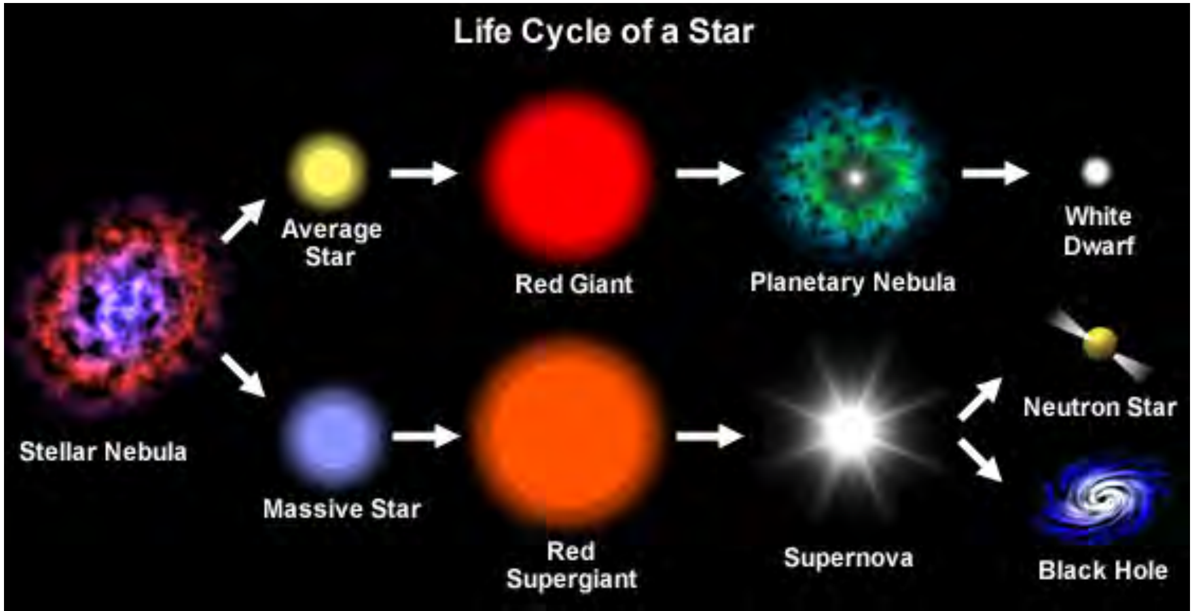
Thomas Gold’s 1969 Nature paper proposed *Rotating* ***Neutron Stars*** *as the Origin of the Pulsing Radio Sources …*



From “scruff” to pulsar to neutron star

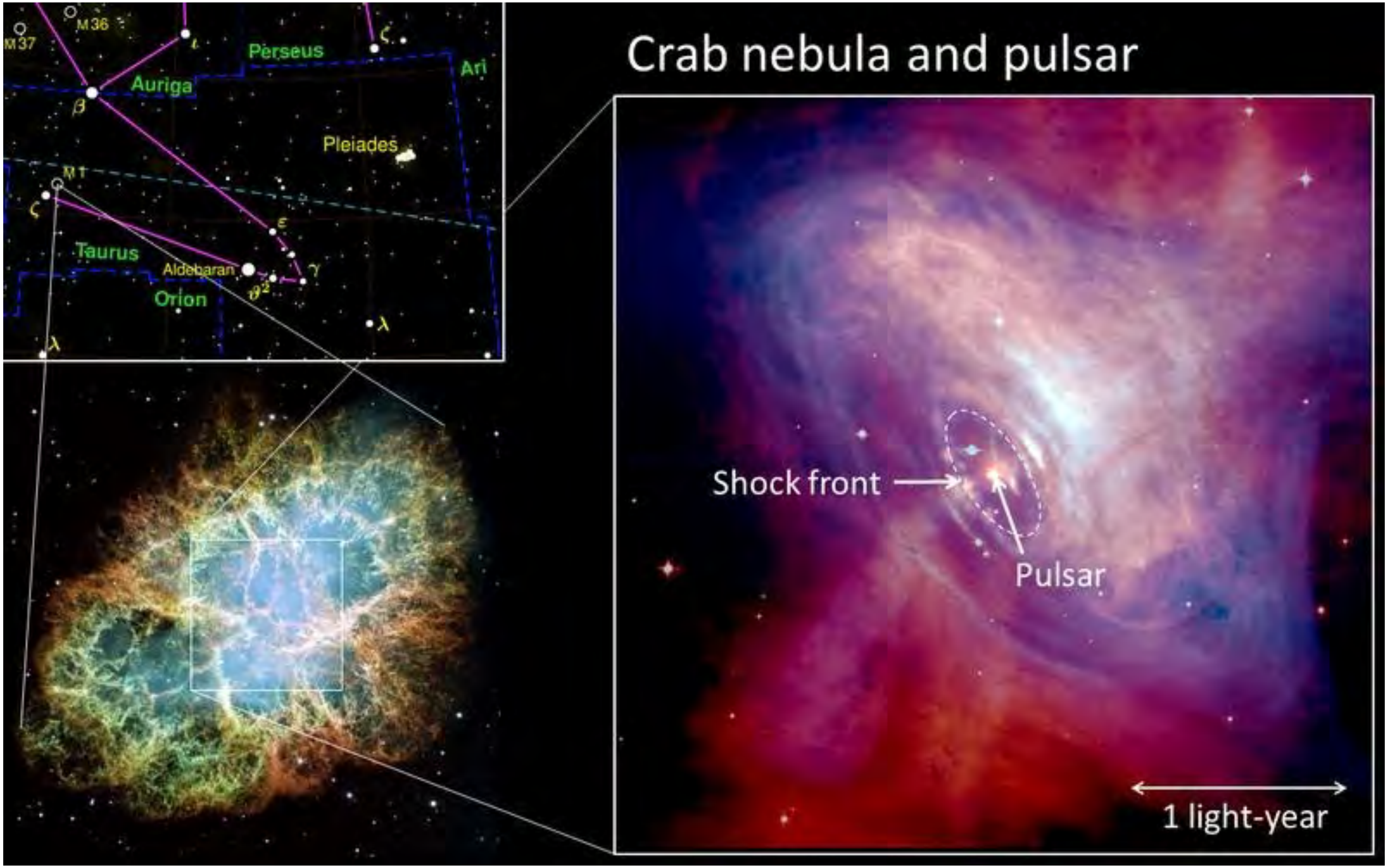
Aftermath: In 1968 Bell earned her PhD -- pulsars appeared in the appendix of her dissertation. In 1974 Hewish and Ryle received the Nobel Prize for the discovery of pulsars. **Hmmm.**

Curiously **neutron stars** had been proposed as early as 1934 (Baade and Zwicky) but had to wait 34 years for evidence of their existence. They have masses of about 1 to 3 solar masses and radii of about 10km. They form in the “death” of 10 ~ 30 solar mass stars as ***core collapse* supernovas**.



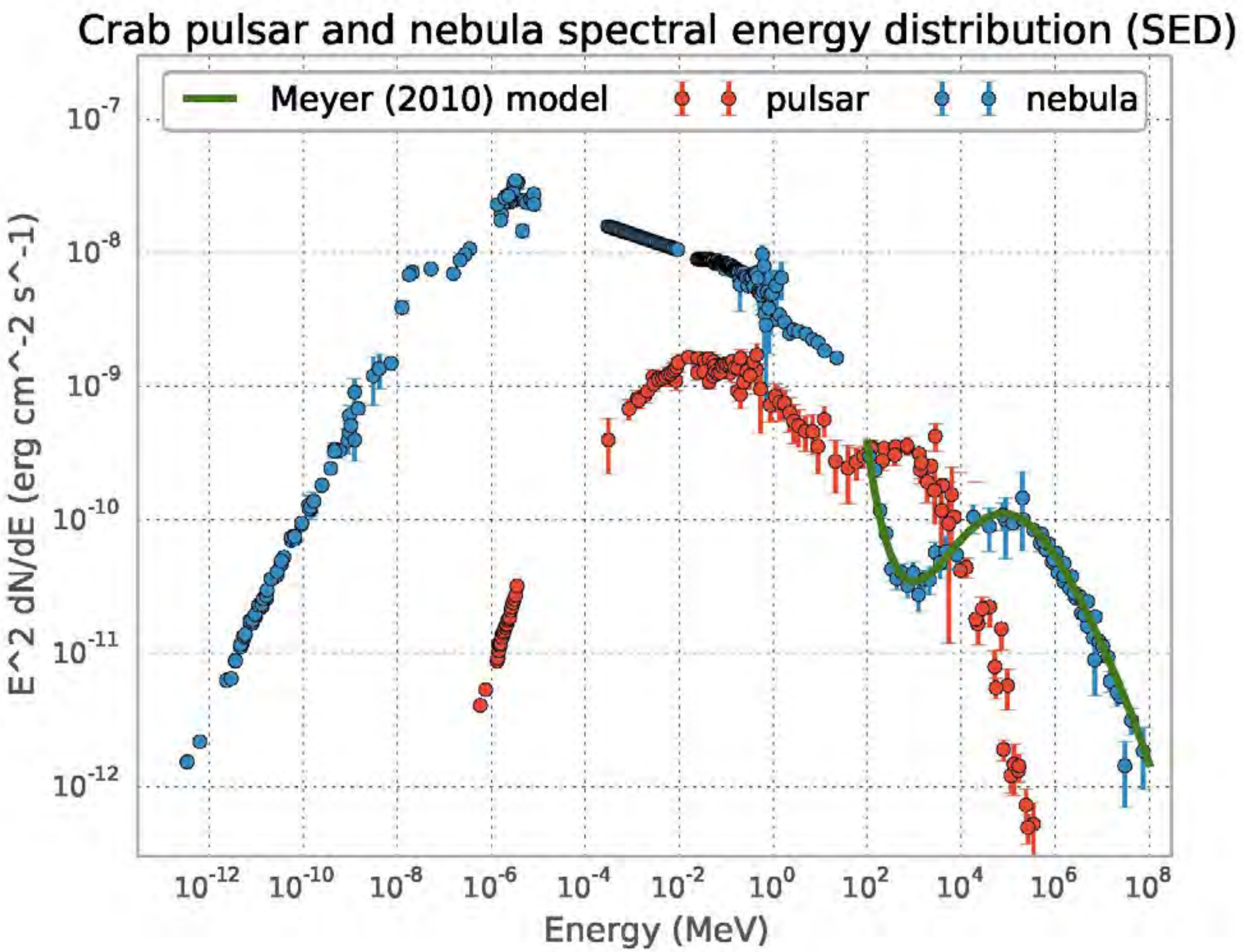
Now there are lots of pulsars

Fast forward to today. One of the most well known pulsars is the “Crab pulsar” remnant of a supernova in 1054!



Now there are lots of pulsars

Fast forward to today. What is interesting is that the Crab (nebula + pulsar), like Quasars, radiates "light" from radio to gamma-ray energies! These objects: super-nova remnants and pulsars, are our second example of the ***extreme universe.***



Arp: peculiar galaxies

Quasars and pulsars oh my! Was this evidence for a new ***extreme universe***?

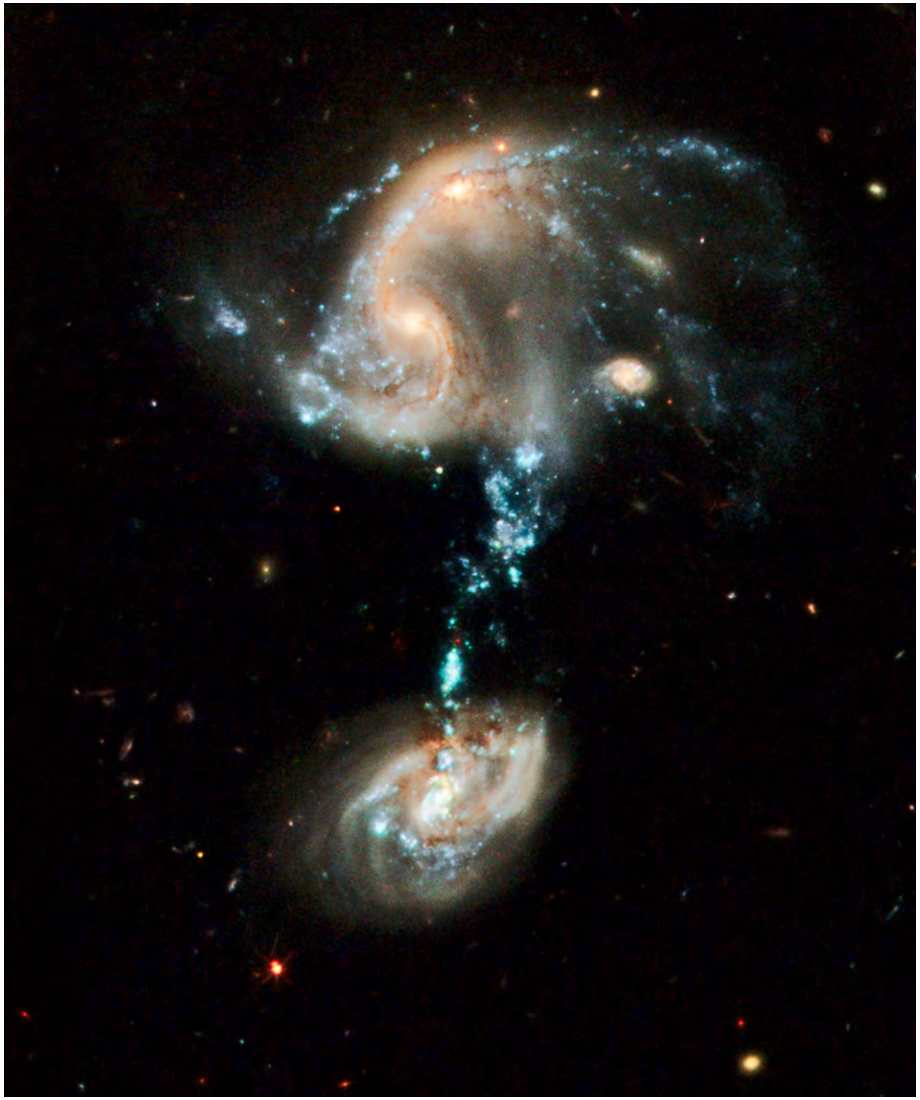
In 1968, Halton Arp showed images from his 1966 catalog: "Atlas of Peculiar Galaxies" at an astronomy symposium at the U. of Toronto where I was a graduate student. Many images, such as this one, were wild and wondrous! Are these additional evidence for the ***extreme universe***?

Arp: peculiar galaxies

Arp, a staff member at the Palomar Observatory, had focused on several topics including galaxies which showed: unusual, or perturbed arms, or filamentary extensions. These were sampled with high-resolution photographs from the 200” Hale telescope.

Arp: peculiar galaxies

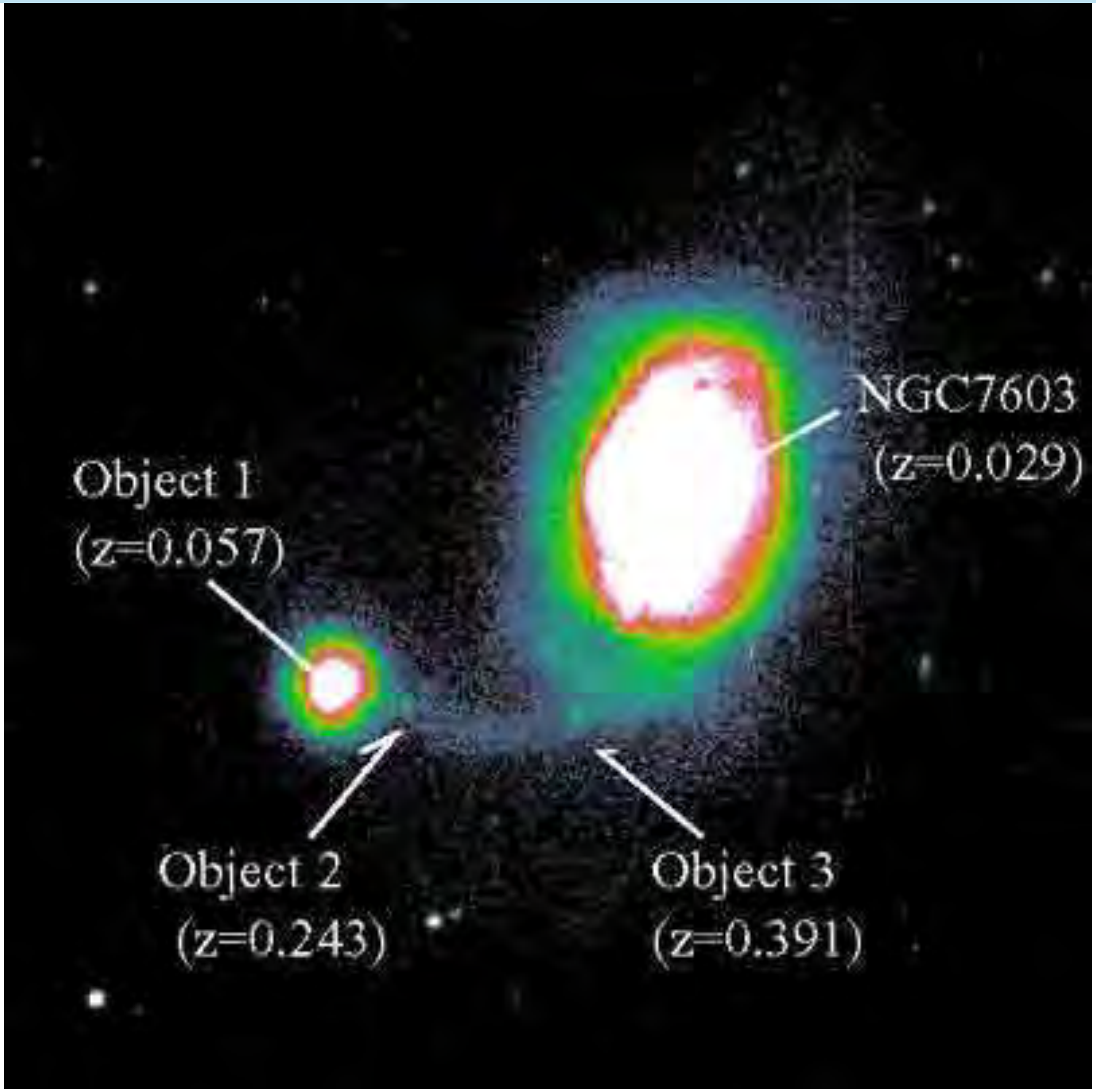
Many of his images showed what appeared to be streams, or material-flow, linking the objects (galaxies).



Arp: peculiar galaxies

Notable: a few of Arp's images appeared to show streams, or material-flow, linking sources at <u>very different red shifts</u>!

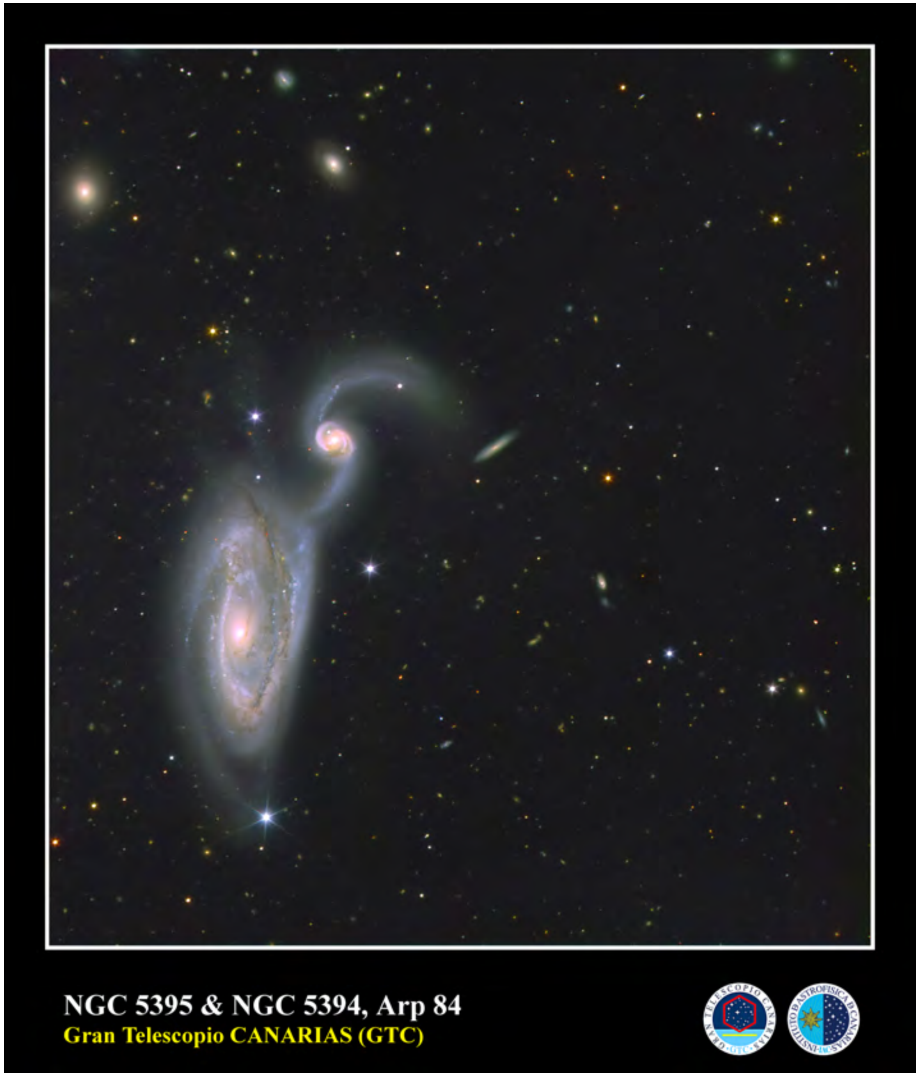
Based on these *pairings* Arp challenged the assignment of redshifts and the related expansion of the universe in his 1973 book: *The Redshift Controversy*.



Today Arp's controversial *pairings* are believed to be from chance overlaps …

Arp: peculiar galaxies

So: in the end probably no *extreme universe* in Arp's peculiar galaxies … BUT the images themselves are timeless!



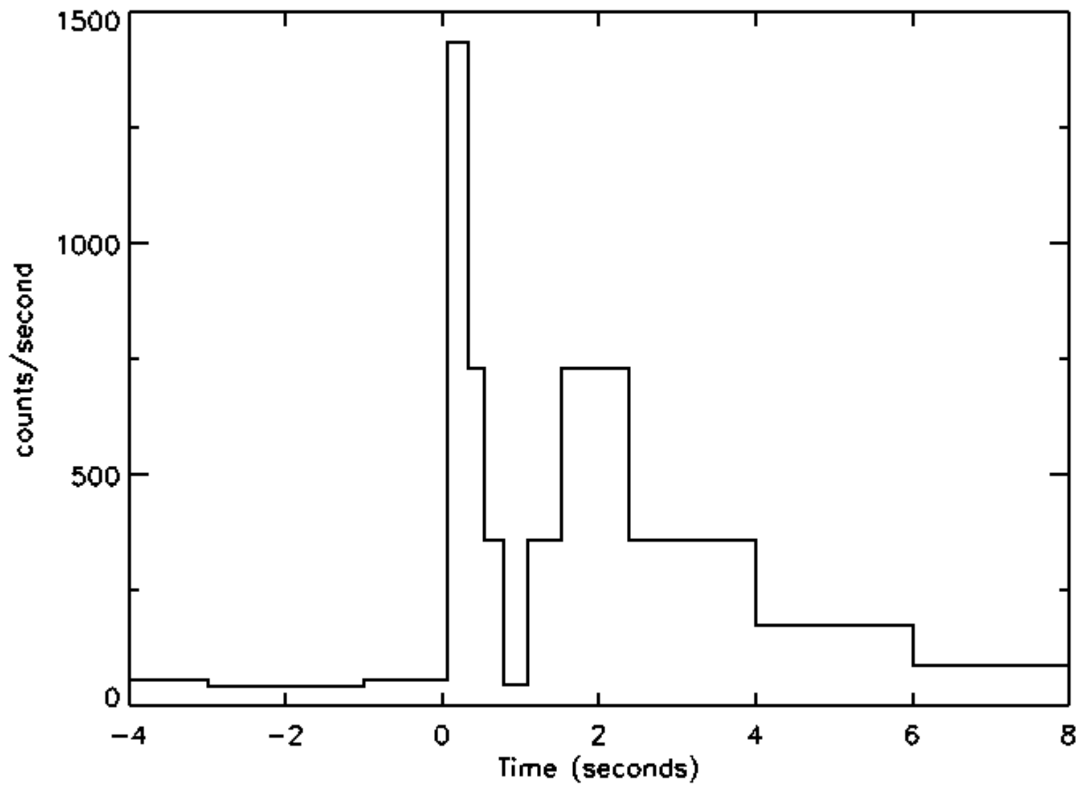
Vela monitoring → gamma-ray bursts

Vela was the name of a group of satellites developed at Los Alamos and Sandia Laboratories to monitor compliance by the Soviet Union with the 1963 Partial Test Ban Treaty. Vela started in 1959 as a small-budget research program.

The original Vela satellites were equipped with 12 external X-ray detectors and 18 internal neutron and gamma-ray detectors. They were equipped with solar panels generating 90 watts. They were launched in pairs (as shown in the artist sketch).

Vela monitoring → gamma-ray bursts

On July 2, 1967, at 14:19 UTC, the Vela 4 and Vela 3 satellites detected a flash of gamma radiation that were unlike any known nuclear weapons signatures. Nuclear bombs produce a very brief, intense burst of gamma rays: less than one millionth of a second. The radiation then steadily fades as the unstable nuclei decay. The signal detected by the Vela satellites had neither the intense initial flash nor the gradual fading, but instead there were two distinct peaks in the light curve. Uncertain of what had happened, but not considering the matter particularly urgent, the data were filed for future study.

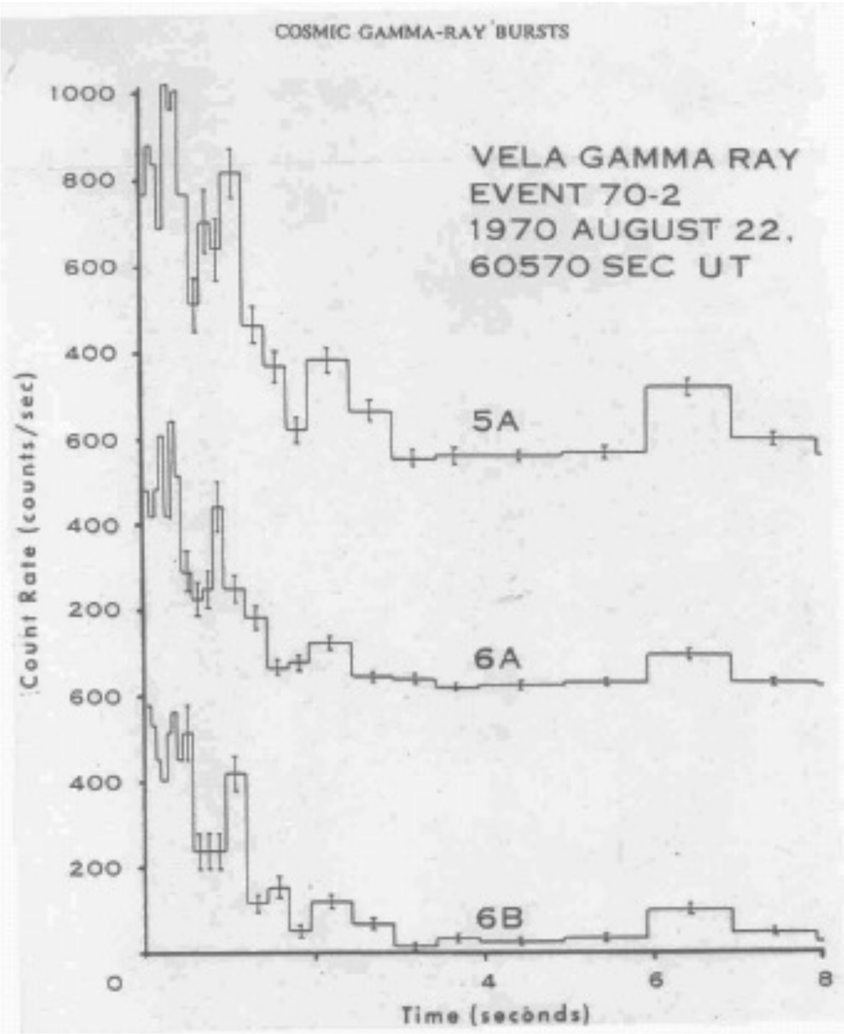


Vela monitoring → gamma-ray bursts

Vela 5 was launched on May 23, 1969. With sensitivity and time resolution significantly more accurate than on Vela 4, the Los Alamos team expected these new satellites to detect more gamma-ray bursts. They found twelve events which did not coincide with any solar flares or supernovas. Some of the new detections also showed the same double-peak pattern that had been observed by Vela 4.

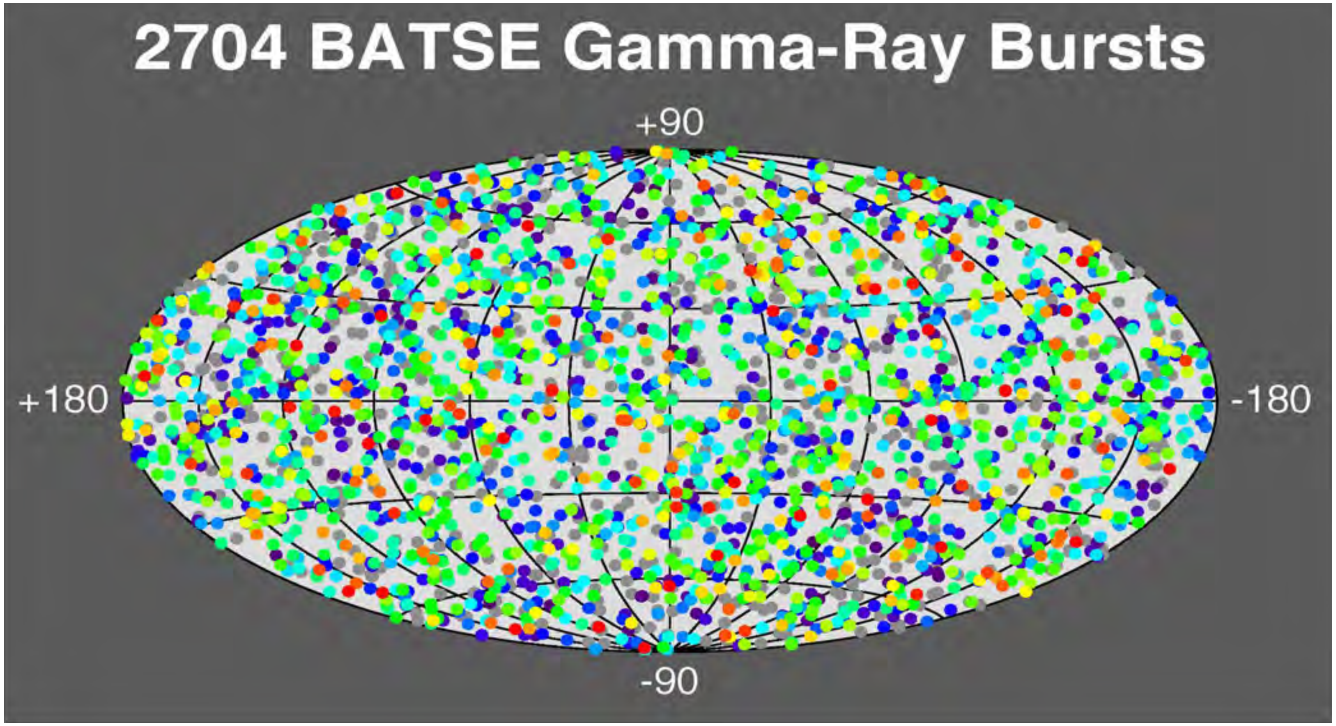
Vela monitoring → gamma-ray bursts

Vela 6 satellites were launched on April 8, 1970, with the intention of determining the direction from which the gamma rays were arriving. The Vela 6 satellite orbits were chosen to be as far away from Vela 5 as possible, generally on the order of 10,000 km apart. This separation meant that, despite gamma rays traveling at the speed of light, a signal would be detected at slightly different times by different satellites. By analyzing the arrival times, Klebesadel and his Los Alamos team successfully traced sixteen gamma-ray bursts.



Vela monitoring → gamma-ray bursts

The random distribution of bursts across the sky made it clear that the bursts were not coming from the sun, moon, or other planets in our solar system. In 1973, Ray Klebesadel, Roy Olson, and Ian Strong of the Los Alamos Scientific Laboratory published *"Observations of Gamma-Ray Bursts of Cosmic Origin".* Today the uniform distribution of Gamma Ray Bursts exclude our galaxy and support an extra-galactic origin.



Vela monitoring → gamma-ray bursts

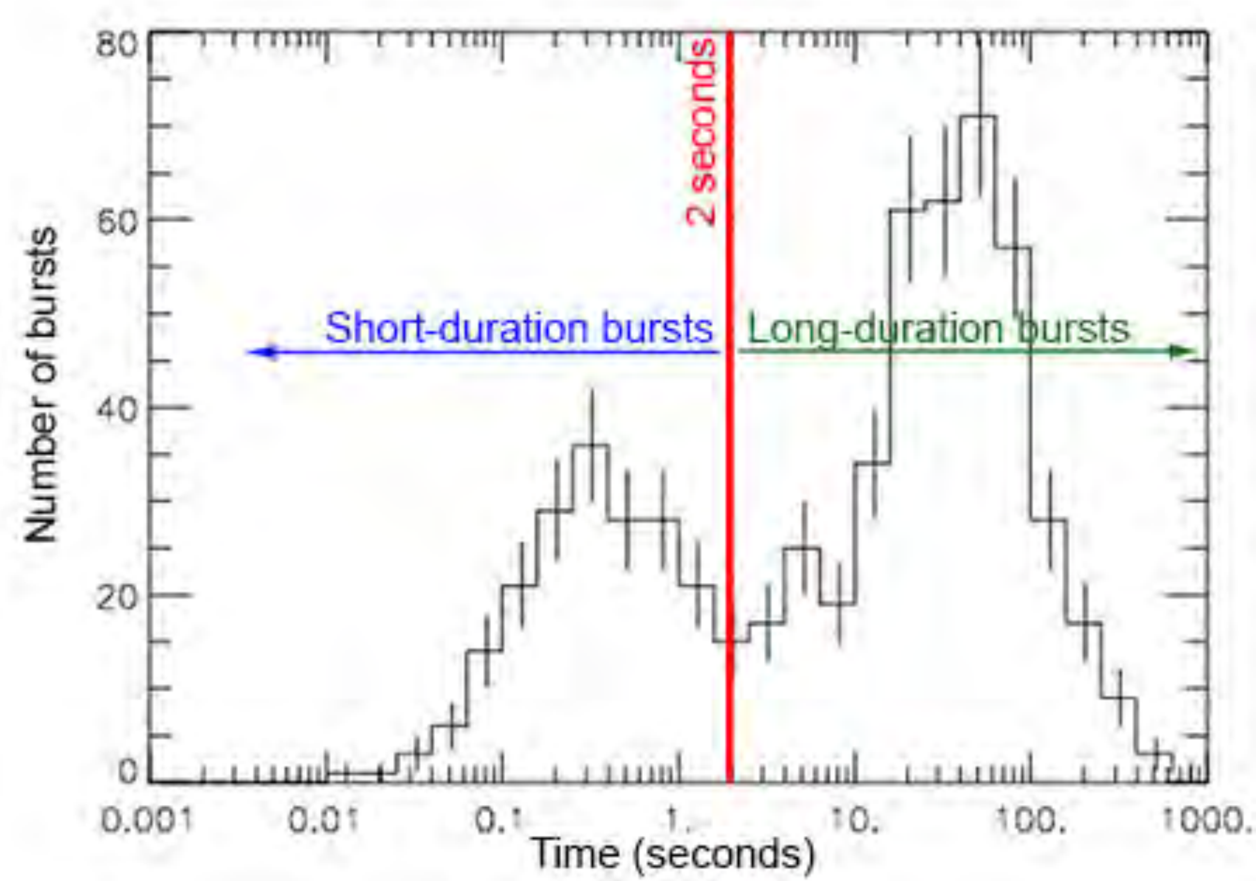
24 years later: in 1997 a gamma-ray burst (GRB 970508) was localized in time for optical follow-up. By comparing photographs of the error box taken on May 8 and 9, 1997 (the day of the event and the day after), one object was found to have increased in brightness. Between May 10 and 11, Charles Steidel recorded the spectrum of the variable object from the Keck Observatory. Mark Metzger analyzed the spectrum and determined a redshift of z>=0.835, placing the burst at a distance of at least 6.6 billion light years! Whoa … that is extra-galactic!

Fortunately his source was also observed by Dale Frail with the VLA providing additional details on the *extreme* nature of this burst.

Vela monitoring → gamma-ray bursts

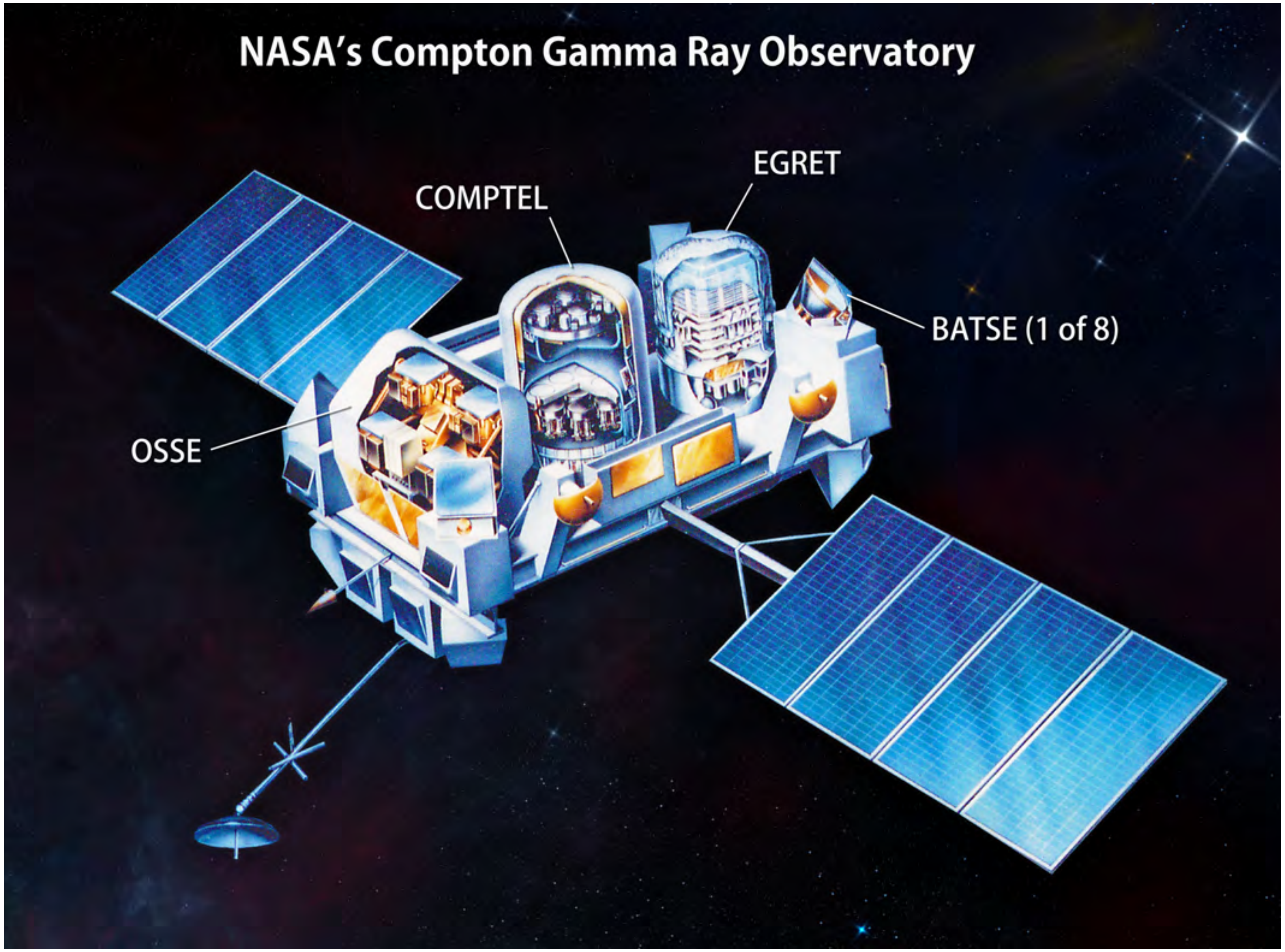
Since then: we now know that gamma-ray bursts (GRBs) fall into a least two classes: **short** and **long**. Curiously the **long** bursts **may** bring us "full cycle" back to "core collapse supernovas" **…** when for "many many" solar mass stars this results in a remnant (central) **black hole** [*versus* a neutron star].

The extreme luminosities and high energy (gamma ray) emissions of gamma-ray bursts make them our third example of the ***extreme universe.***



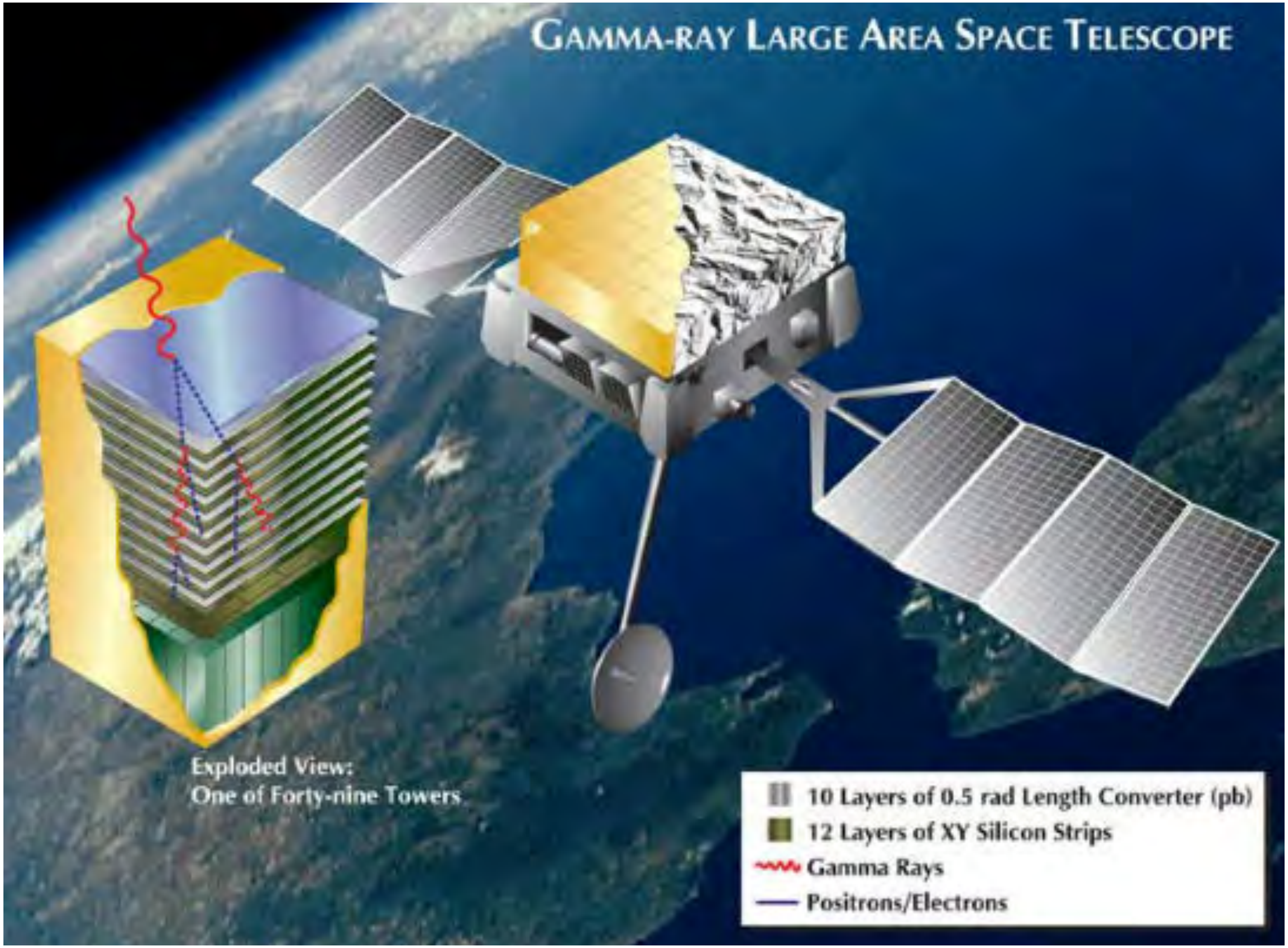
Vela → next generation gamma ray satellites

The **Compton Gamma Ray Observatory** (**CGRO**) was a space observatory detecting light from 20 keV (X-rays) to 20 GeV (gamma rays) from 1991 to 2000 (forced crash after gyro failure).



Vela → next generation gamma ray satellites

The **Fermi Gamma Ray Observatory** was launched June 11, 2008. The Large Area Telescope (LAT) is sensitive to gamma rays from 20 MeV to 300 GeV.

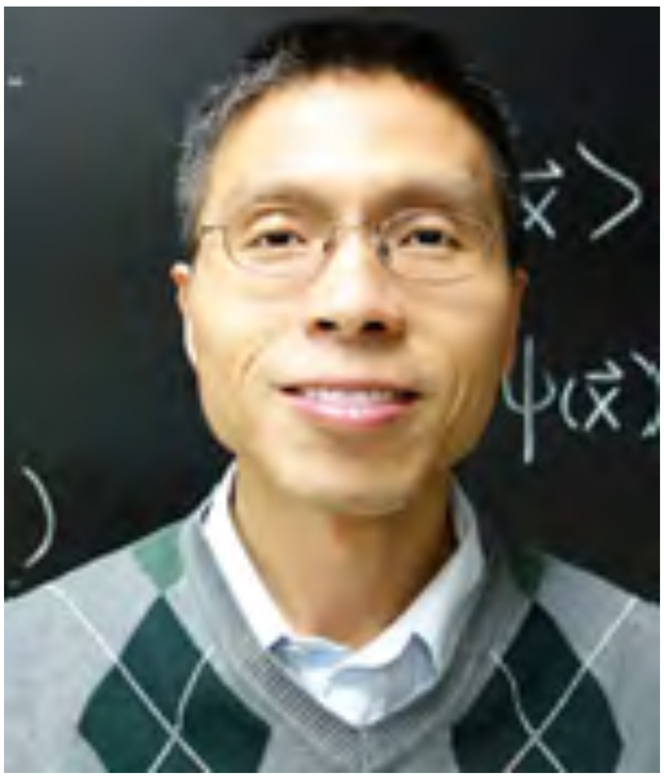


Studying the extreme universe at UNM

To be strictly honest: Googling "*Extreme Universe*" you might get a different take on all of this. For example: you would learn that it is also a universe inhabited by comic super-heros … Do only I find a strange resemblance between Prophet and Hewish!?

Studying the extreme universe at UNM

To be strictly honest: a number of my faculty colleagues also study the extreme universe and/or are super-heros including: Huaiyu Duan (neutron star and super nova neutrino theory) and Gregory Taylor (gamma-ray bursts and super massive black holes):



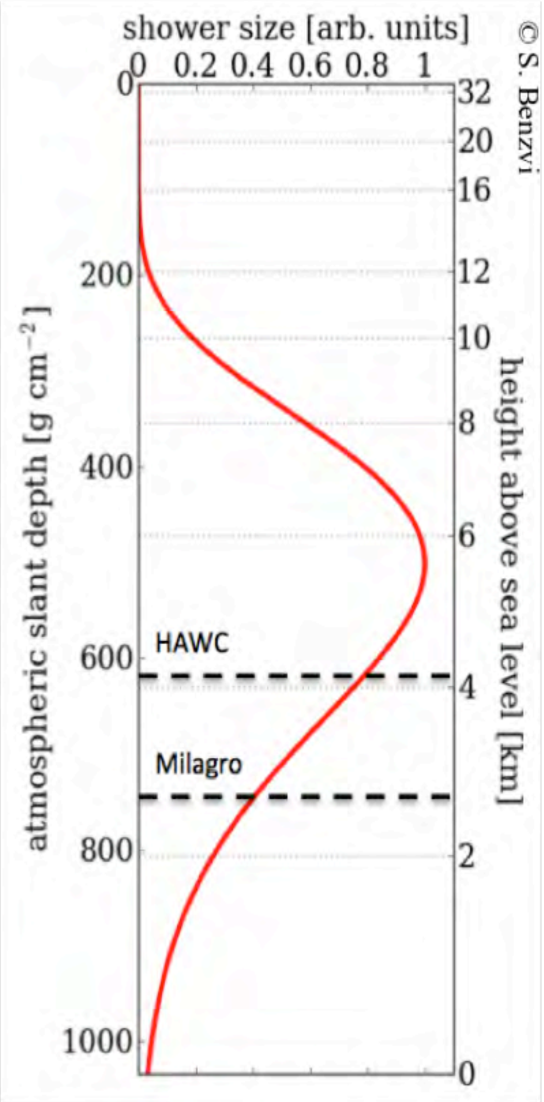
Studying the extreme universe at UNM

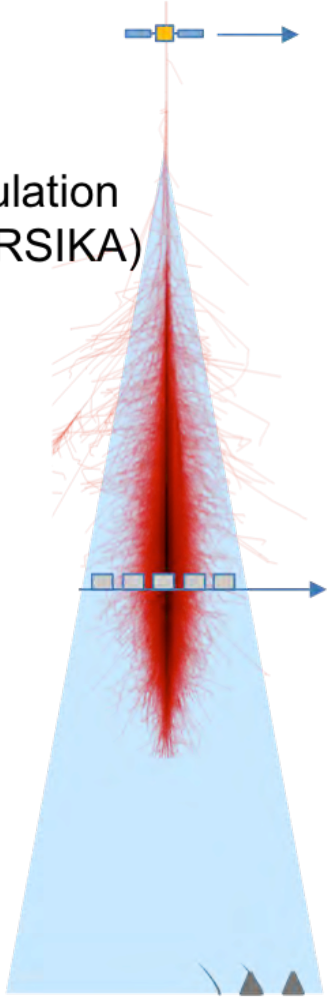
The *Extreme Universe* is characterized by:

- amazingly luminous sources
- “light” emitted from radio (micro-eV) to gamma-ray (TeV) energies
- Time-variable sources (pulsars, gamma-ray bursts, curiously Quasars also show brightness variations)
- Other (more technical issues: jets, broad emission lines, …)

In recent years I have studied the *Extreme Universe* with experiments designed to measure: the highest energy cosmic rays and currently the highest energy (astro-physical) gamma-rays. The latter experiment is called the High Altitude Water Cherenkov, HAWC, observatory. [Don’t forget to ask: why high altitude, why water, and why Cherenkov?]

HAWC: at TeV energies use the atmosphere!





Wide Field of View, Continuous Operations

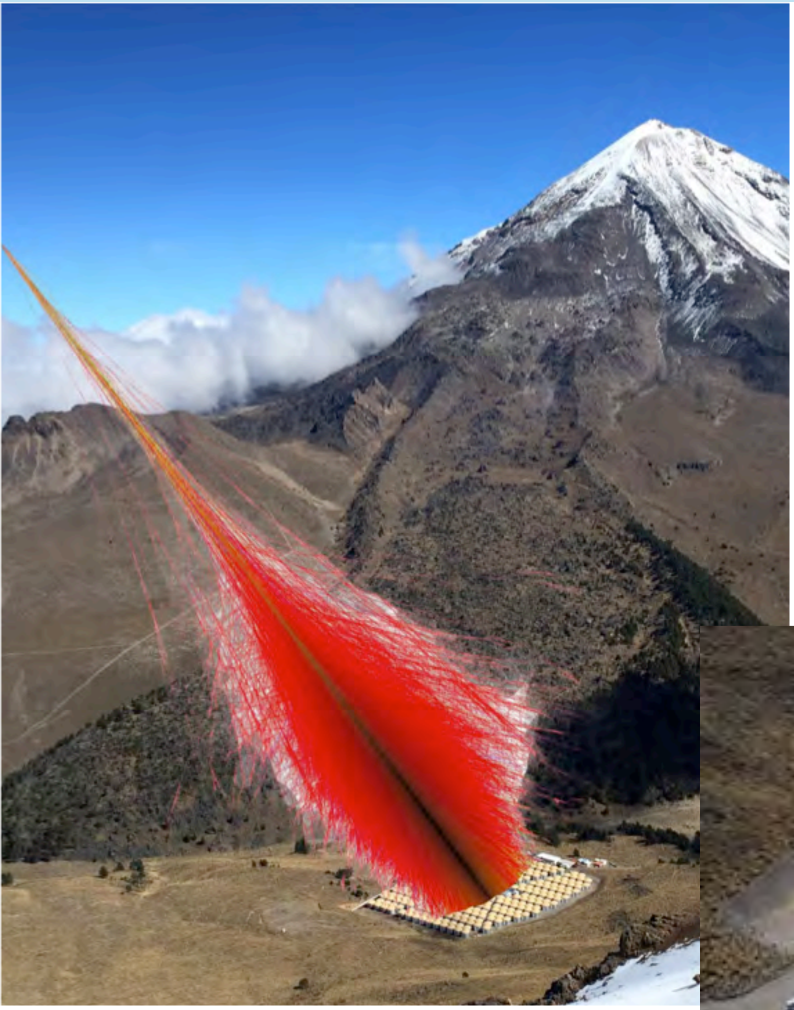
Satellite Detector

Extensive Air Shower (EAS) Detector

TeV Sensitivity

Imaging Atmospheric Cherenkov Telescope (IACT)

HAWC: an array of large water tanks

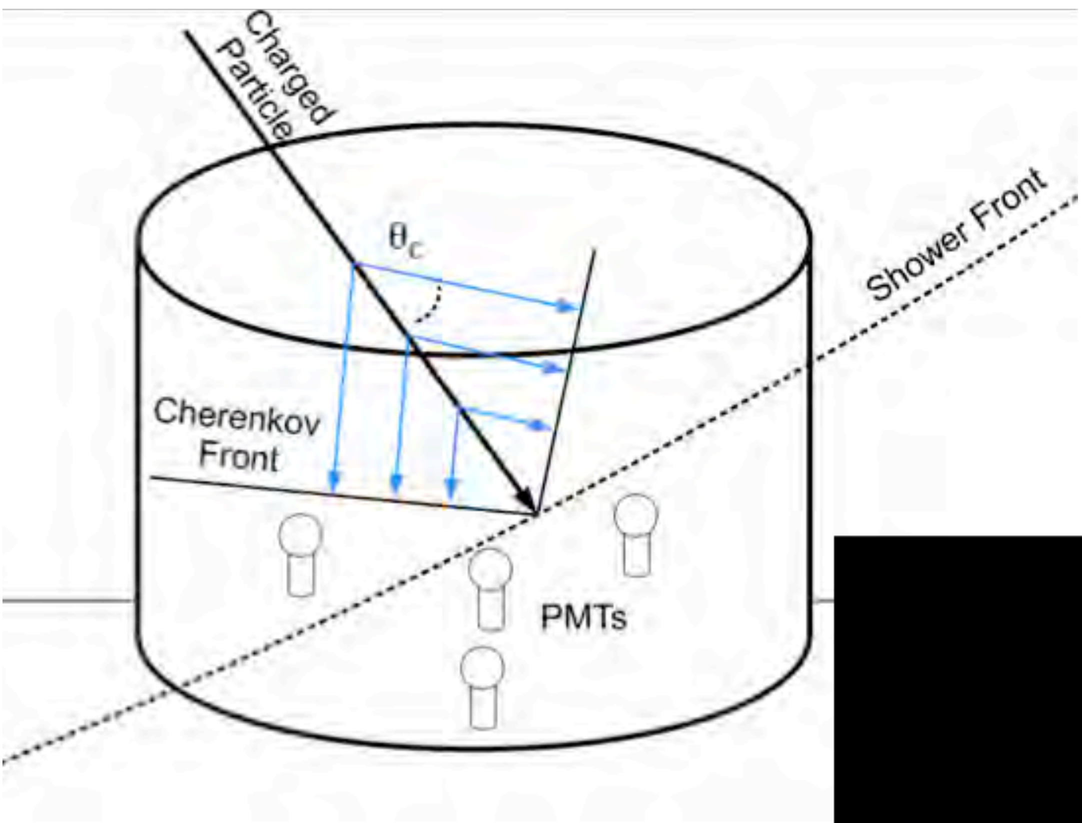


HAWC is an array of 300 huge water tanks sited at 4100m elevation next to the 3rd highest peak in North America!

Curiously HAWC, and the radio array used to discover pulsars, are essentially the same size.

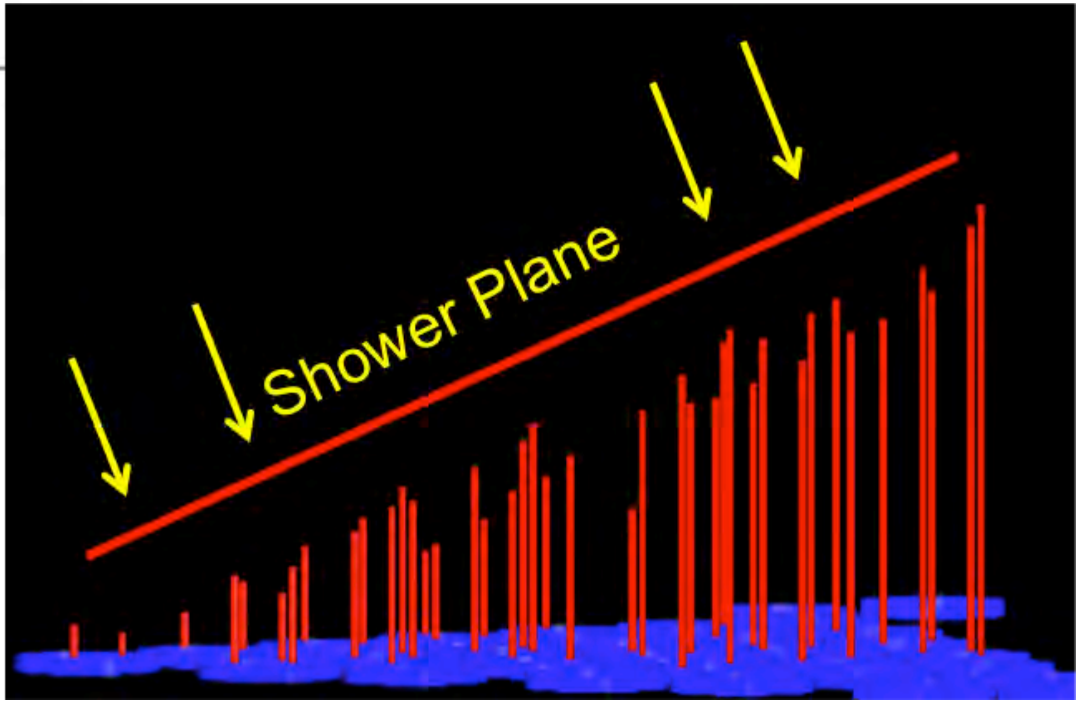
HAWC: sometimes its winter even in Mexico

HAWC: times tell us the shower direction

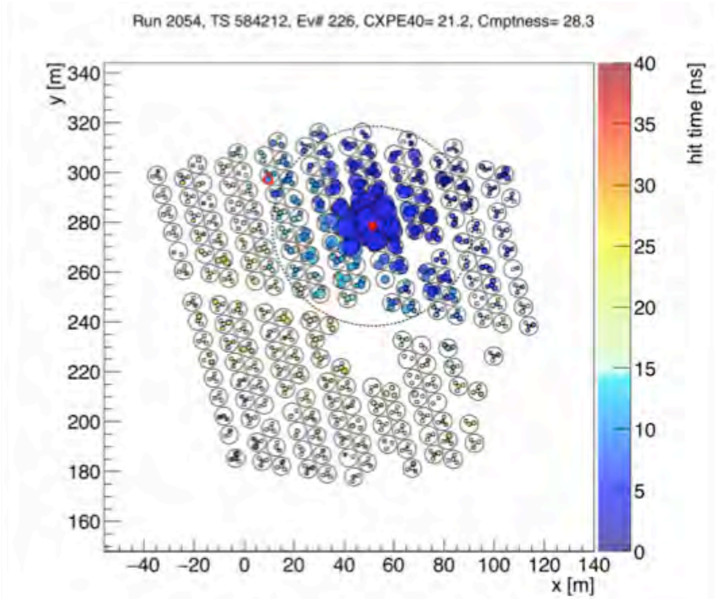


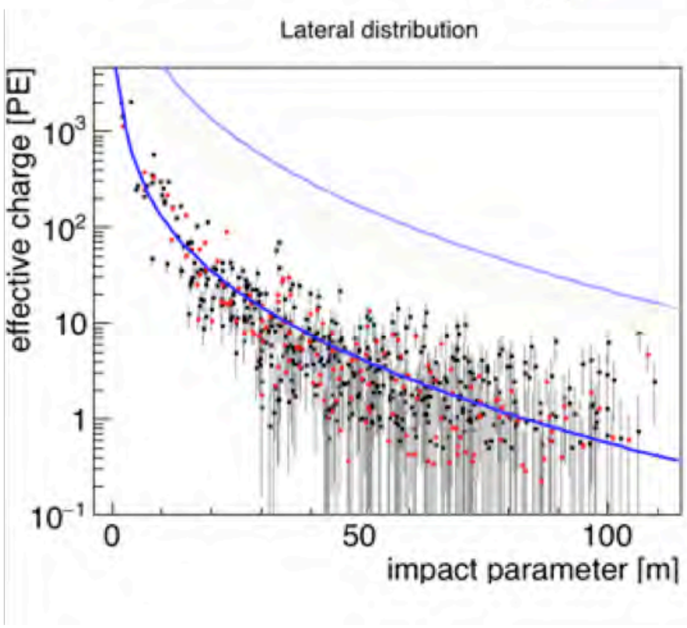
HAWC pointing accuracy varies from about 1-deg (near threshold) to about 0.1-deg for the highest energy gamma-rays.

For reference, angular size of the moon is 0.5-deg.



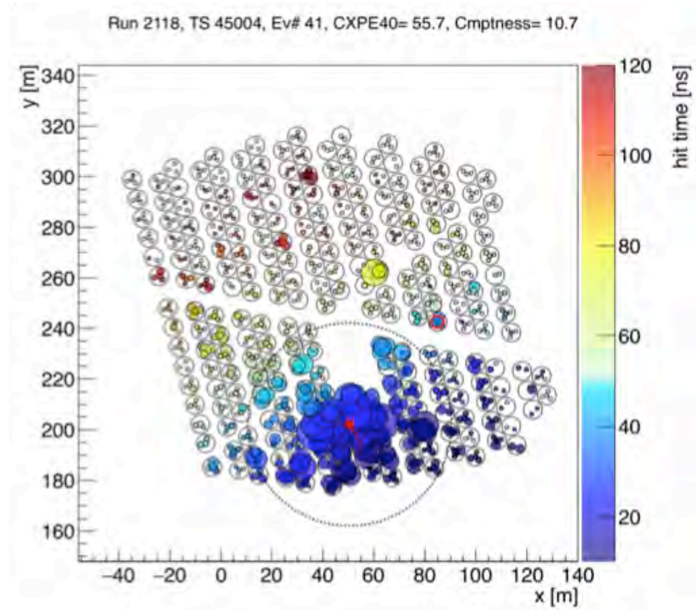
HAWC: what do events look like?

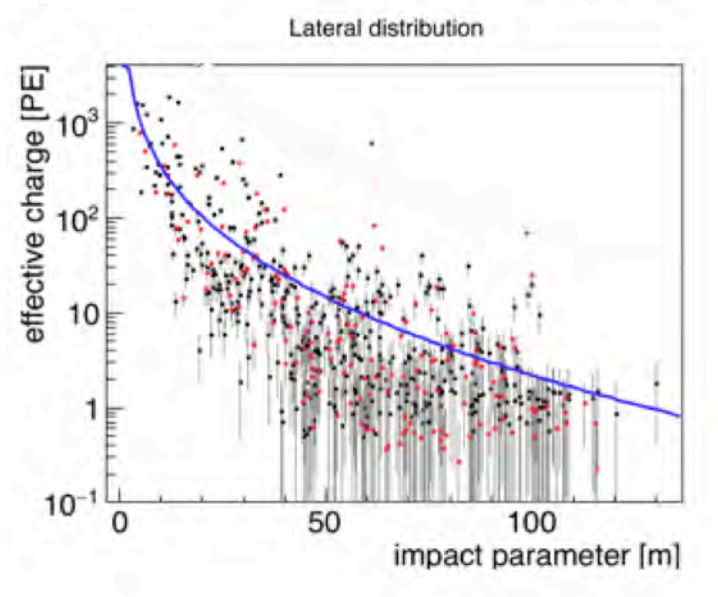




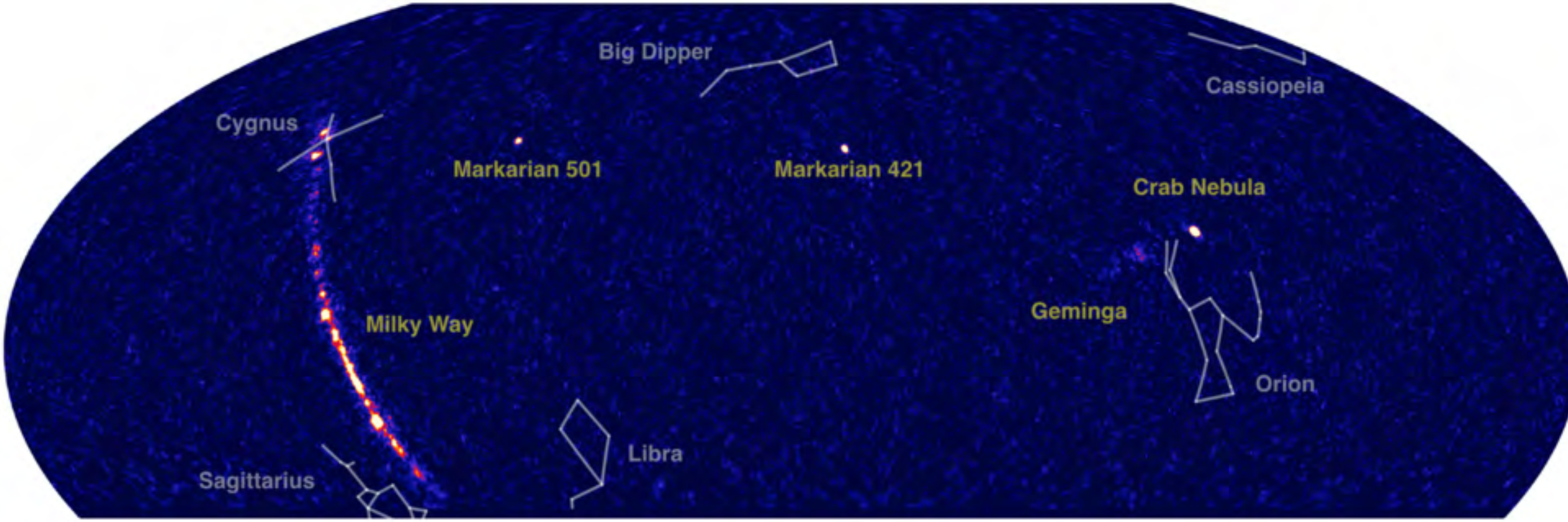
Gamma-ray events (left) are more *uniform* than cosmic ray (back ground) events (right).

Too detailed but this is how we separate gammas from CRs.





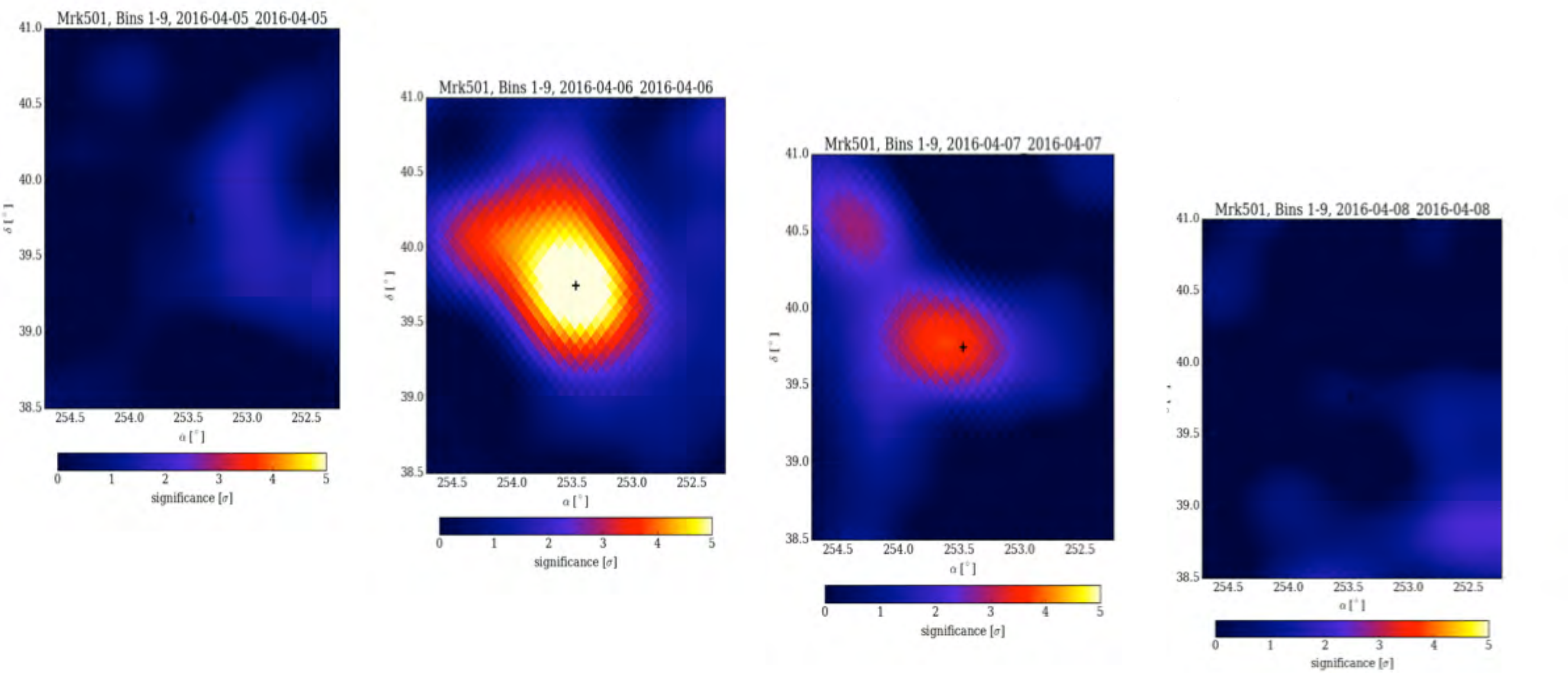
HAWC: map of the TeV gamma-ray sky



The analysis of the first 507 days of data identified 39 sources; the majority were in the plane of the Milky Way. So far: 7 have been associated with pulsars, 2 with super-nova remnants and 2 with Quasar-like sources.

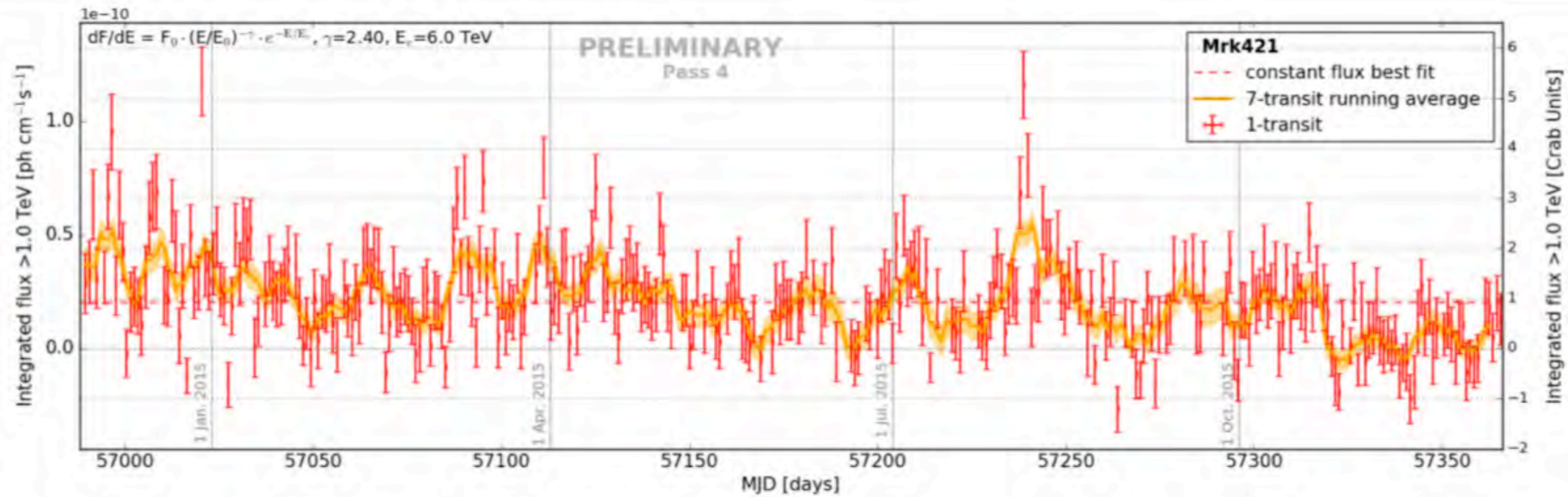
UNM Research Assistant Professor Robert Lauer leads the study of the 2 Quasar-like sources named Markarian (Mrk) 421 and Mrk 501.

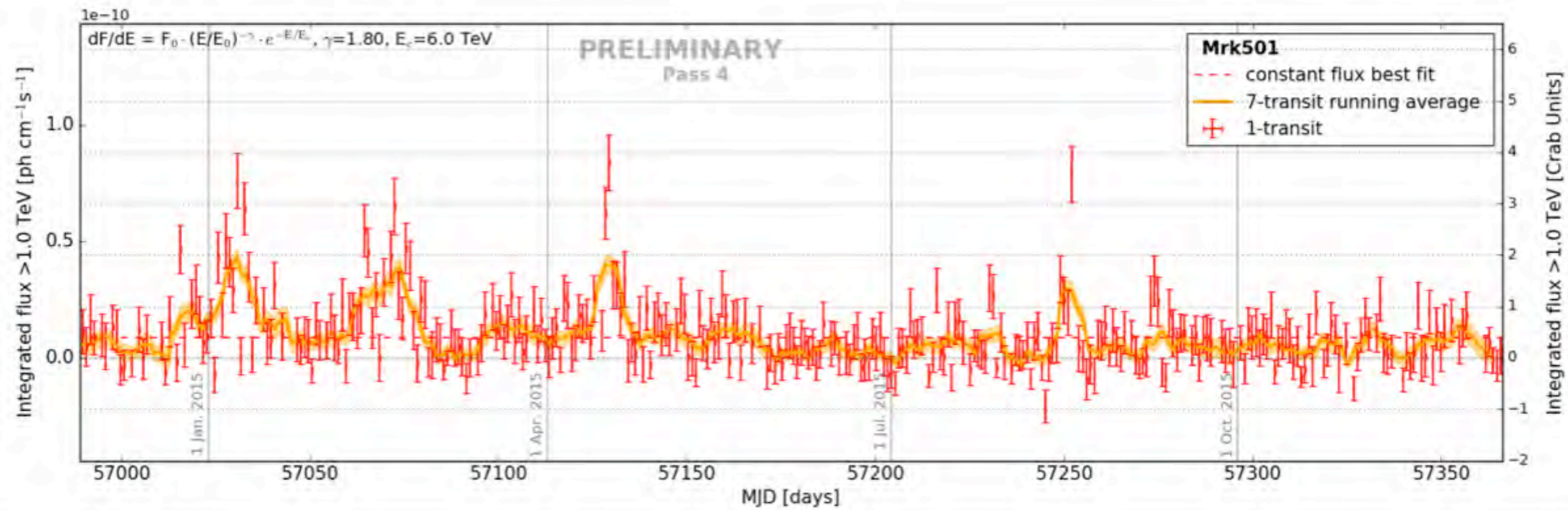
HAWC: Mrk 501 varies greatly in brightness



The “*HAWC sky images*” are made one event at a time … just as telescope images are made one photon at a time! These show the resulting *HAWC sky images* centered on Mrk 501 on April 5, 6, 7 and 8 of 2016. Note: each image is from a source *transit*, similar to the transit scans (to search for Quasars) used by the radio array that discovered pulsars.

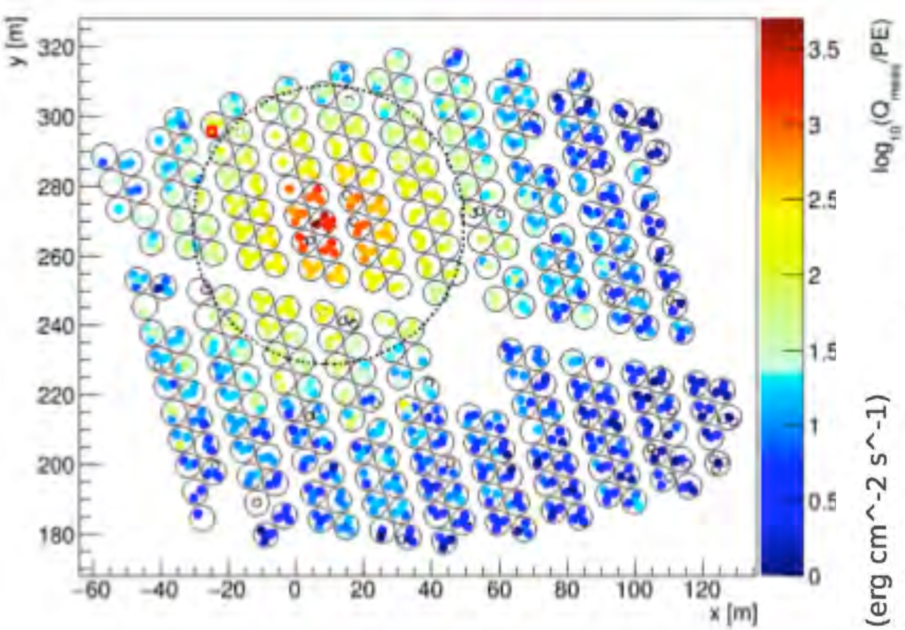
HAWC: monitors Mrk 421 and 501 every day!

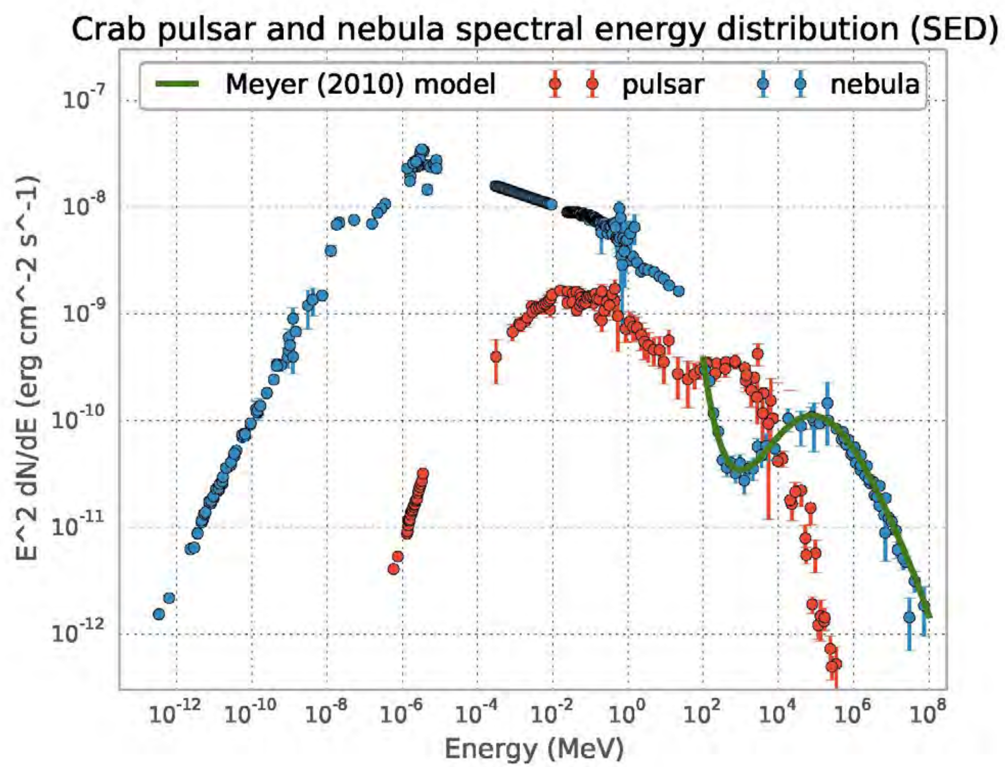




HAWC: brightest source is the Crab …

HAWC measurements of gamma-rays from the Crab (nebula) find events, like this one with an estimated energy of 60 TeV, that are nearly “*off-scale*” based on previous measurements **…**



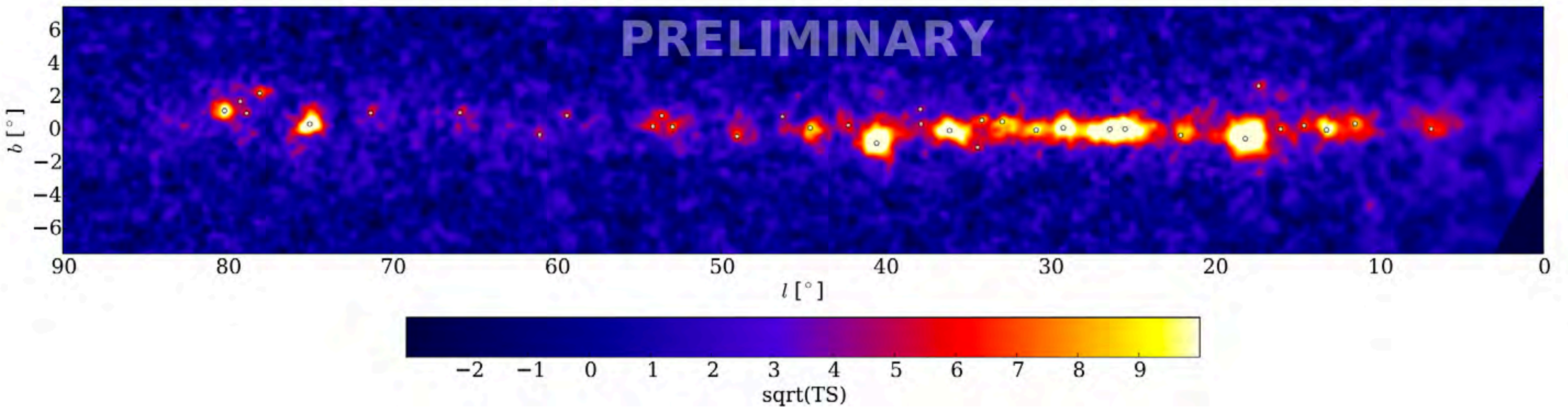


Next step, spectral analysis (for all HAWC sources) to identify possible maximum source (cutoff) energies.

HAWC: view back after leaving the site

HAWC: soon to be released

And it is possible that the HAWC (galactic) source catalog:



may soon be available for those with questionably discerning taste …

Was the universe *extreme* enough?

While often extreme in luminosity and range of photon-energies and time-variability, the universe is never in bad taste!

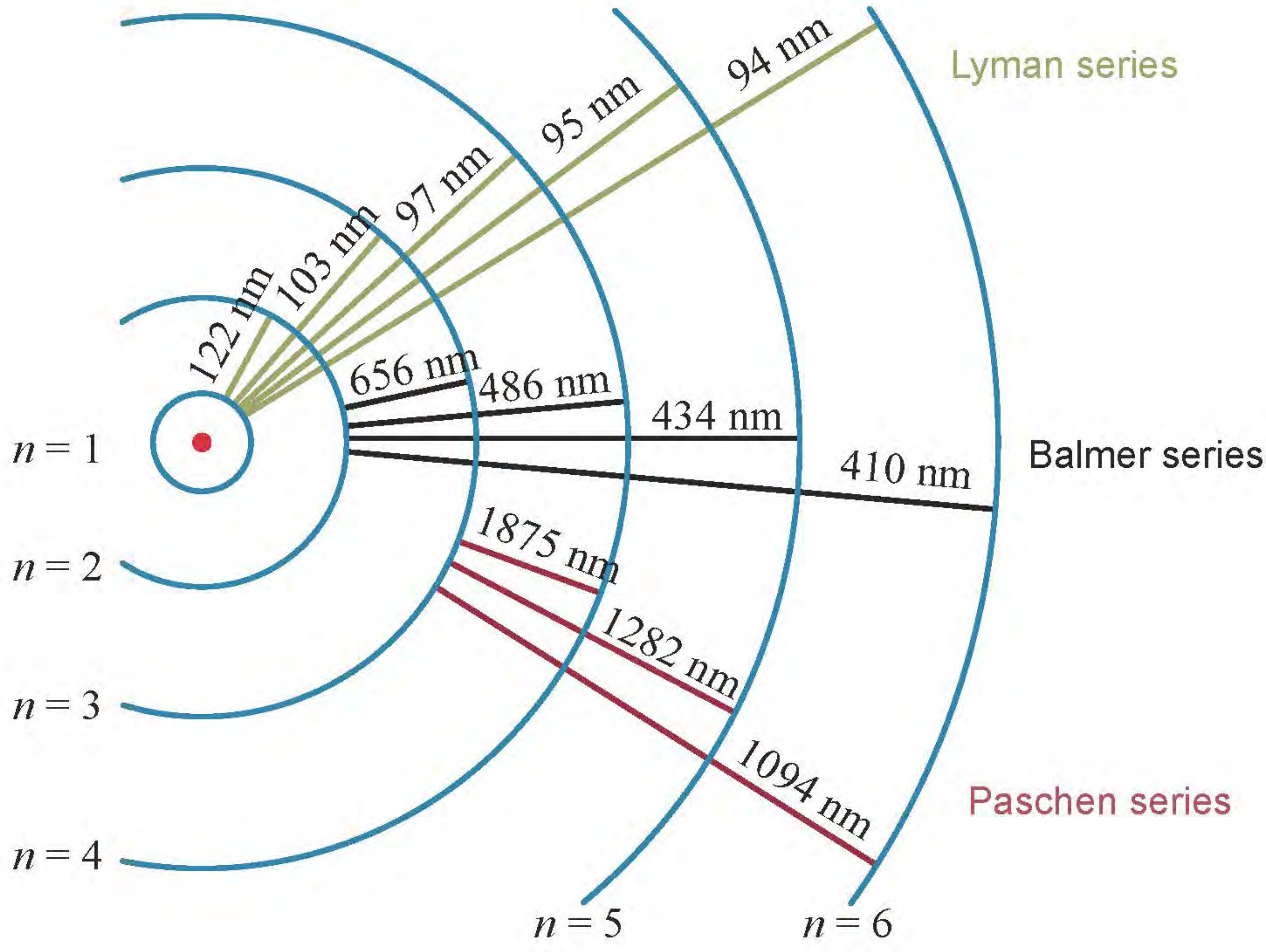
And has your sense of the *extreme universe* expanded your view of the universe?   What is your 1+**z** factor?

Thanks … an *extreme* pleasure!

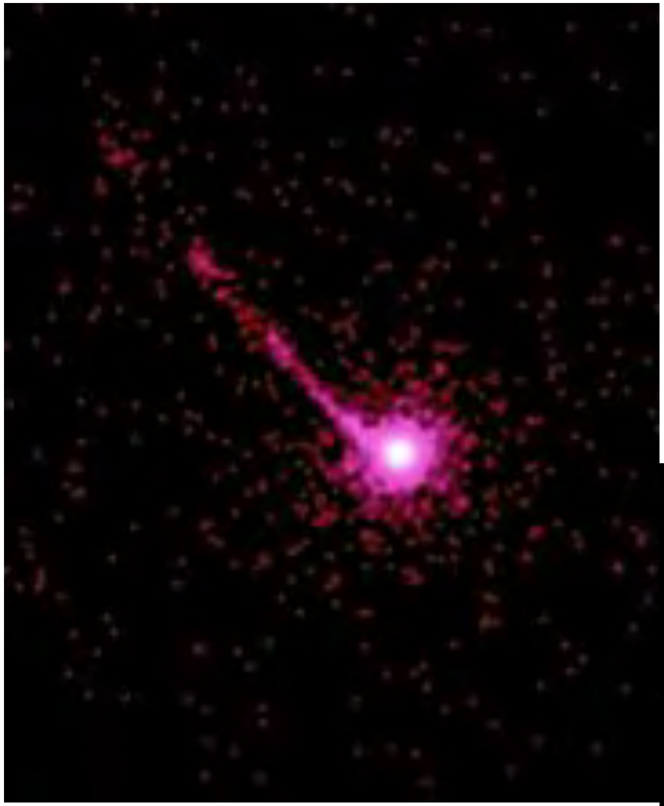
Why science teachers are not asked to monitor recess.

Backup slides

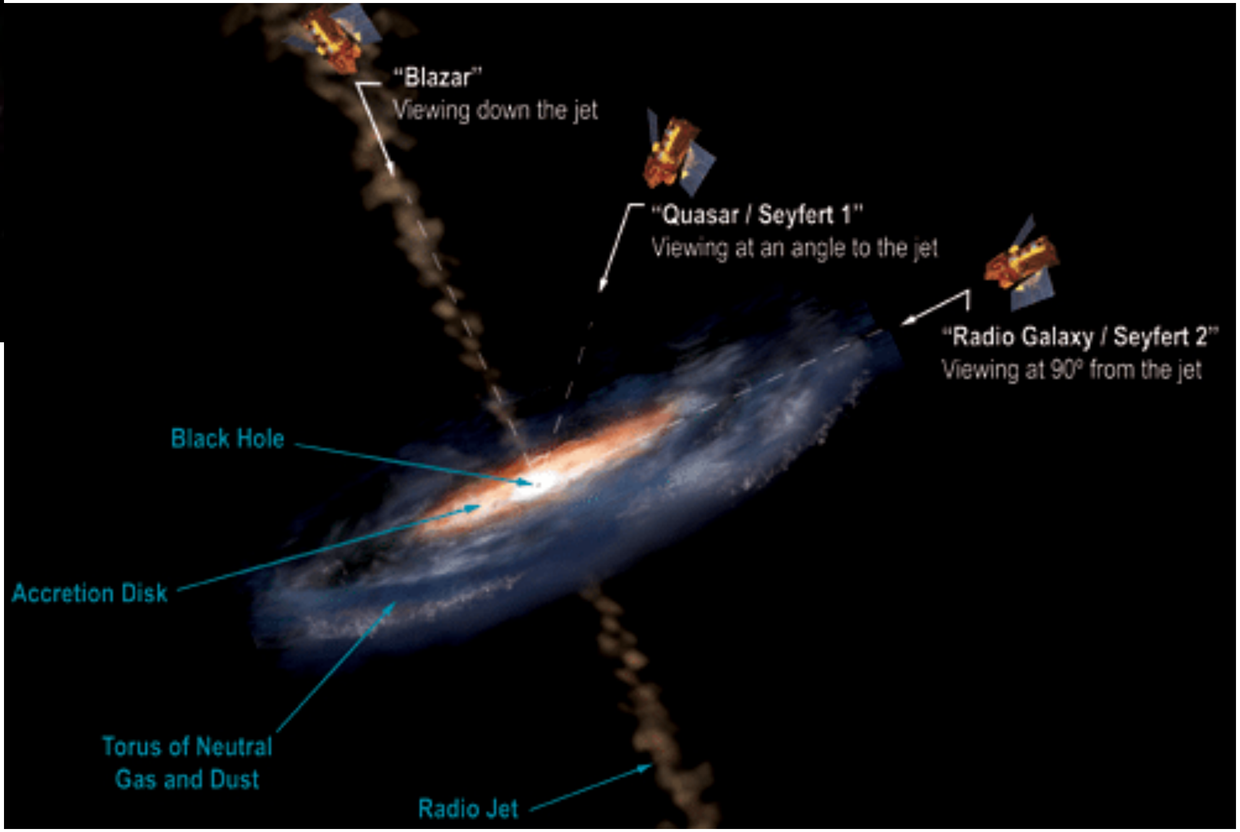
Hydrogen spectral transitions



Possible model for Quasars



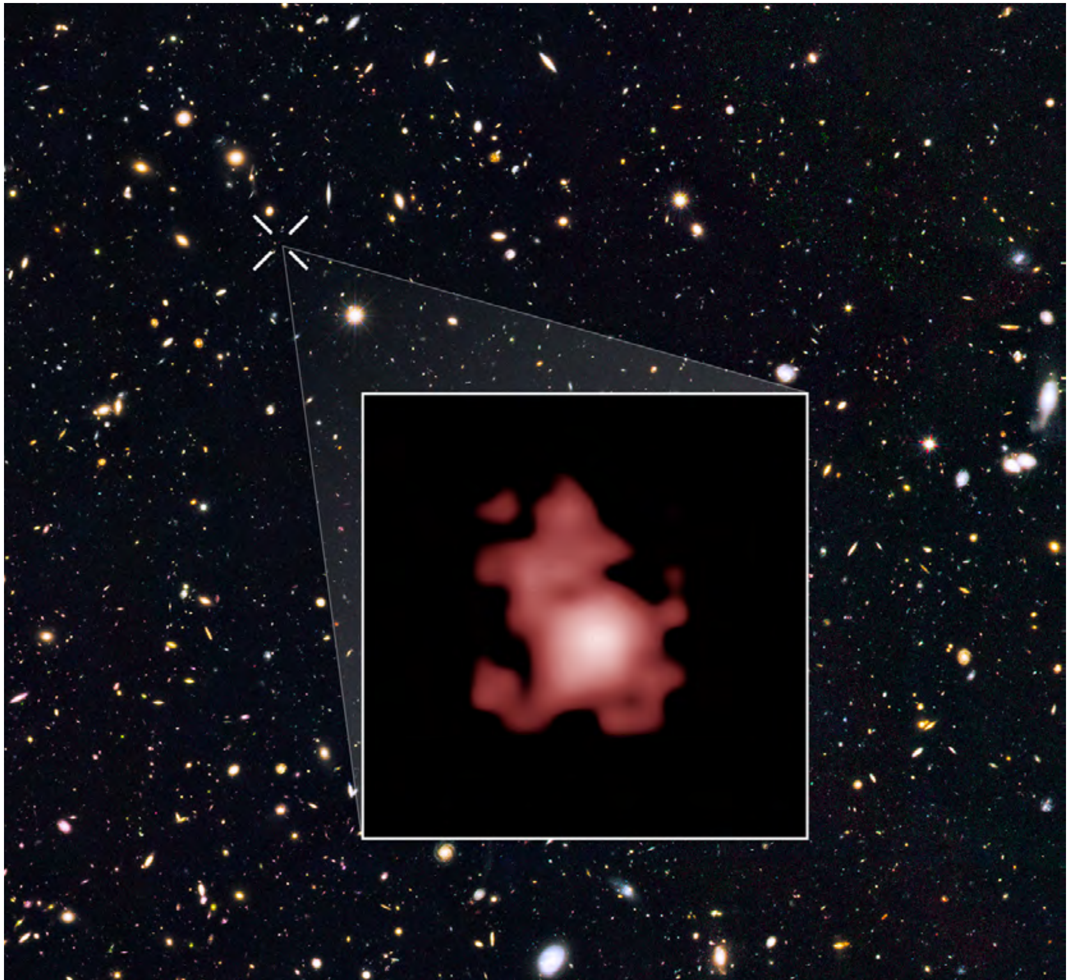
Quasars are thought to be super-massive Black Holes in a period of “peak” mass acquisition …
(Top left): X-ray image of Quasar
(Bottom right): artist sketch of typical model of super-massive Black Holes



Quasars: new physics and universe probe!

[Light from the currently most distant known **Quasar** started to us 12.9 billion years ago or about 0.8 billion years after the Big Bang.   Today it appears as a mere red dot in the telescope image … not shown.]   The most remote source imaged by the Hubble Space Telescope →

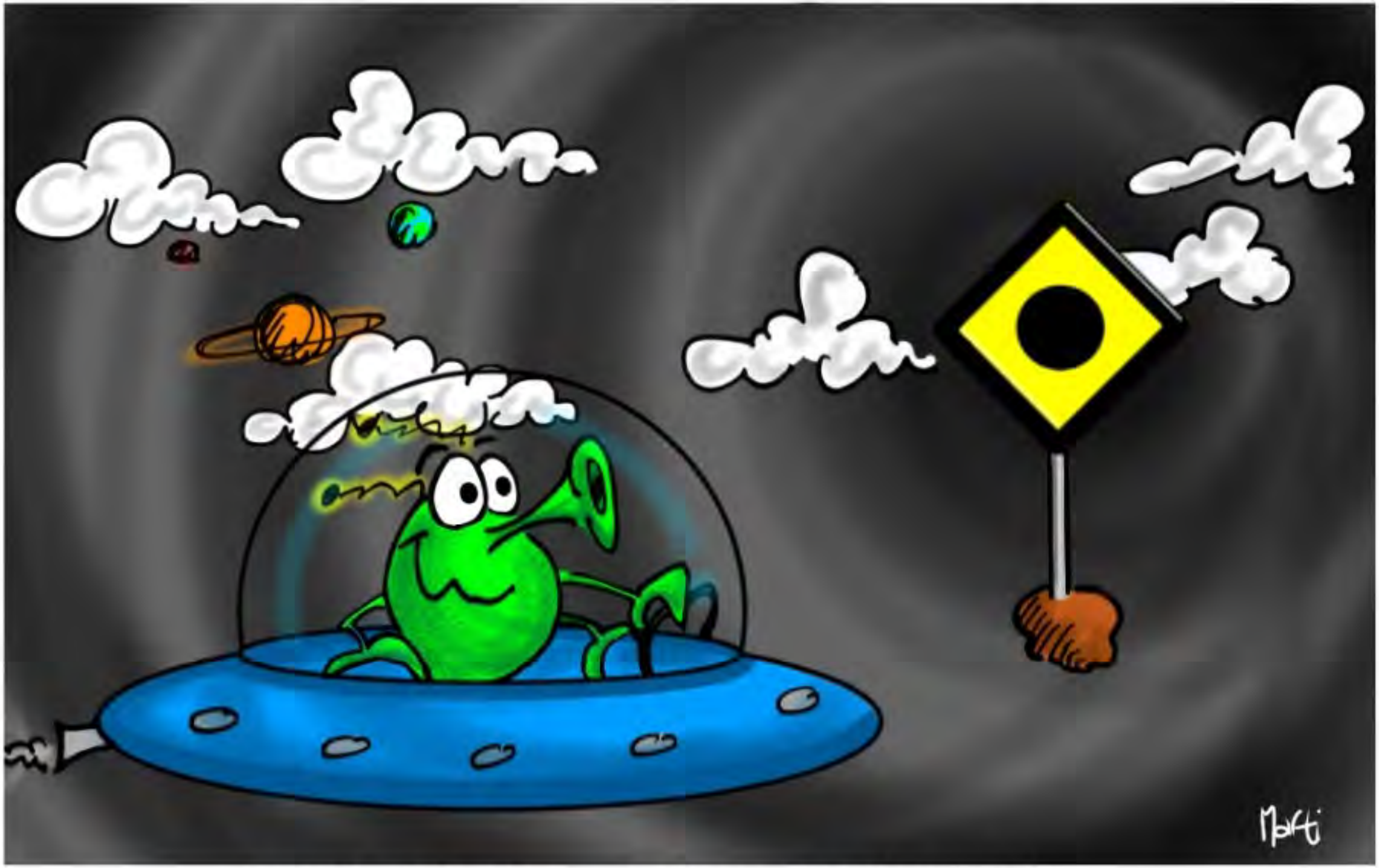
is a galaxy (but not [also] a Quasar). Light from this galaxy started to us 13.3 billion years ago or about 0.4 billion years after the Big Bang! It is also red and curiously more *irregular* than “modern” galaxies.



Black Holes … but are they real?

A black hole - a tremendous creation
Its physics defies imagination
Time and space it can bend
Wow! I can't comprehend
The gravity of this situation

The international sign for a “Black Hole”



Ben, the little alien man, observed the hazard sign, warning him of a possible black hole ahead.

Black Hole rules of thumb …

What happens in a Black Hole stays in the Black Hole.

Once you go Black you never go back.

Black Hole *extremely bad* jokes?

What’s the difference between the Federal Deficit and a Black Hole?
The event horizon.

A star walks into a black hole... but it doesn't seem concerned.
The black hole turns to the star and says, "Sir, I don't think you understand the gravity of this situation.”

What did the two black holes say when they collided?
Nothing, they just waved.

When did star production peak?

Quasar number density lies in between “new” and “old” star models …