# PHYS 2013, 2913, 2923
# Astrophysics & Cosmology

### Lectures 11-13

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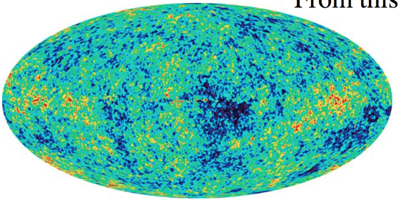
13 Lecture series: first 7 given by Celine
6 Lectures: Wednesday, Thursday (Zoom)
3 Tutorials: Tuesday (Zoom)
1 Assignment, 2 Quizzes, 1 Exam
**30 Oct – 20 Nov, 2020**

## Signposts – so where are we going with the lectures?

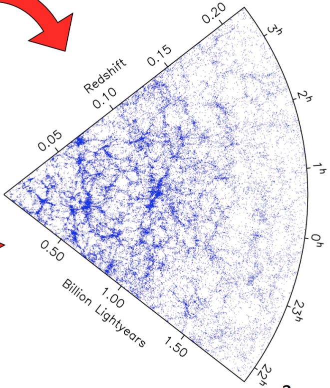
- Lectures 8-9 are about the main cosmological parameters and equations driving evolution, and the complex vacuum processes that get us from the Big Bang to a power spectrum of fluctuations, $P(k)$.
- The remaining lectures are about how we got from the first elements, the cosmic microwave background ($\delta \lesssim 10^{-5}$), and the first stars, to present day galaxies ($\delta \gtrsim 10^{2}$).
- Lectures 9-10 are about Big Bang nucleosynthesis, the creation of the first elements, and the Universal fog that came to be.
- Lectures 10-11 are about the cosmic microwave background and the onset of structure formation driven by dark matter.
- Lectures 12-13 are about the first stars, the formation of heavy elements, the first black holes, and the epoch of reionization when the fog lifted. We talk about how gas falls into galaxies and gets processed, and how galaxies evolve.

# Structure Formation and Evolution

From this ($\Delta\rho/\rho \sim 10^{-6}$)



to this
($\Delta\rho/\rho \sim 10^{+2}$)



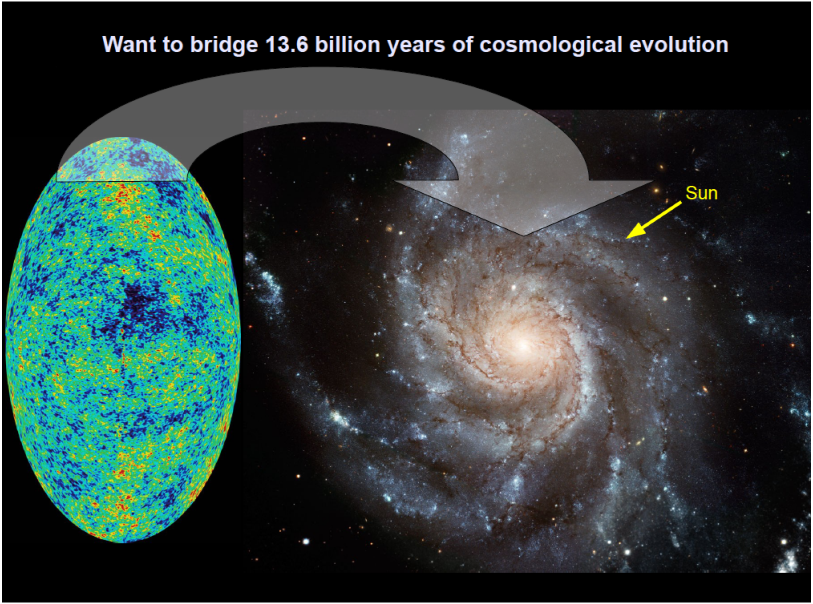

2

to this
($\Delta\rho/\rho \sim 10^{+6}$)

A human being represents $\Delta\rho/\rho \sim 10^{+30}$.

## From quantum fluctuations to galaxies - just extraordinary!

## Cosmological simulations: the non-linear regime, $z = 10000 \rightarrow 0$



# Cosmological simulations


**Currently the fastest supercomputers carry out about ~1 Petaflop, which are one thousand billion floating point operations per second**

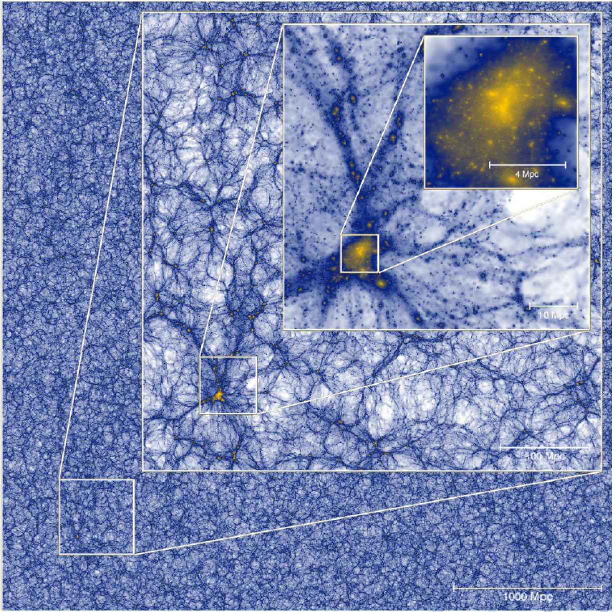
**JUGENE IN JUELICH**

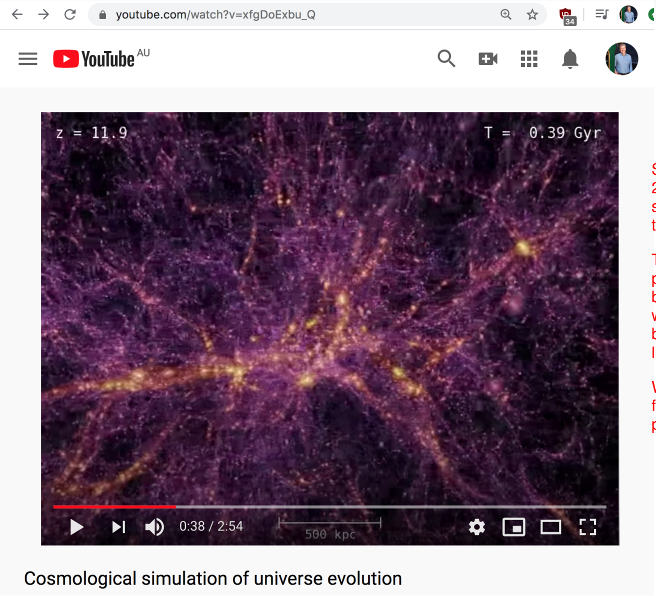
# Cosmological simulations: hierarchical web structure on huge scales, $z = 0$

**Millennium-XXL**

**303 billion particles**

Largest N-body simulation ever



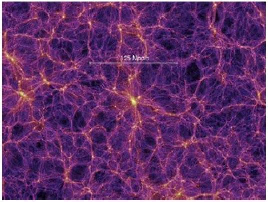



See Volker Springel's 2011 "dark sector only" simulation from $z = 50$ to today.

This is $\Lambda$CDM (WMAP parameters), so the best guide we have to what the true mass-bearing Universe looks like.

We are in a **co-moving** frame, i.e. universal expansion removed.

# Why are **cosmological simulations** of structure formation **useful for studying the dark universe**?




**Simulations are the theoretical tool of choice for calculations in the non-linear regime.**

**They connect the (simple) cosmological initial conditions with the (complex) present-day universe.**

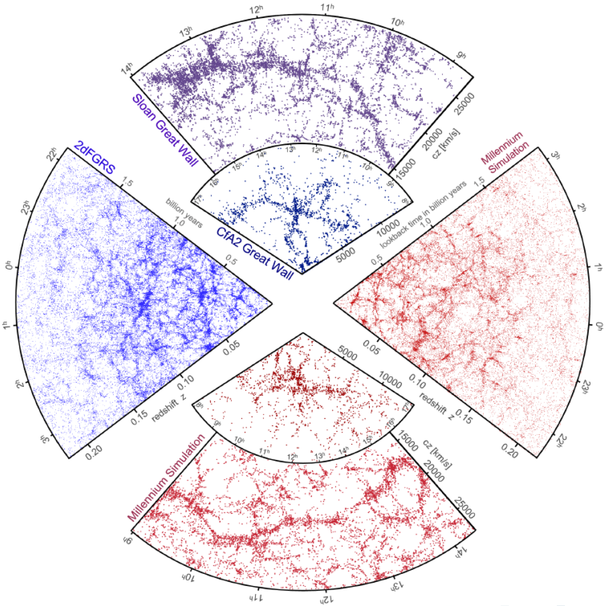
**Predictions from N-body simulations:**

- Abundance of objects (as a function of mass and time)
- Their spatial distribution
- Internal structure of halos (e.g. density profiles, spin)
- Mean formation epochs
- Merger rates
- Detailed dark matter distribution on large *and* fairly small scales
- Galaxy formation models
- Gravitational lensing
- Baryonic acoustic oscillations in the matter distribution
- Integrated Sachs-Wolfe effect
- Dark matter annihilation rate
- Morphology of large-scale structure (“cosmic web”)

# Cosmological simulations

Simulated and observed large-scale structure in the galaxy distribution

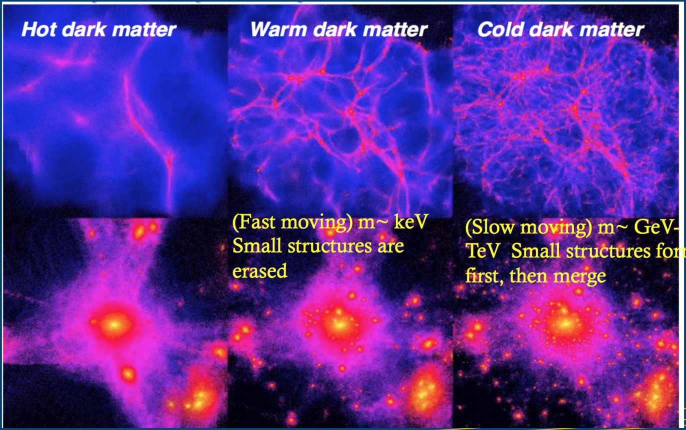
**MOCK PIE DIAGRAMS COMPARED TO SDSS, 2DFGRS, AND CFA-2**




Springel et al. (2006)

# Structure formation depends on DM type

**LCDM is the standard cosmological model** of structure formation , based on weakly Interacting massive particles (WIMPS), a.k.a. Cold dark matter (CDM)



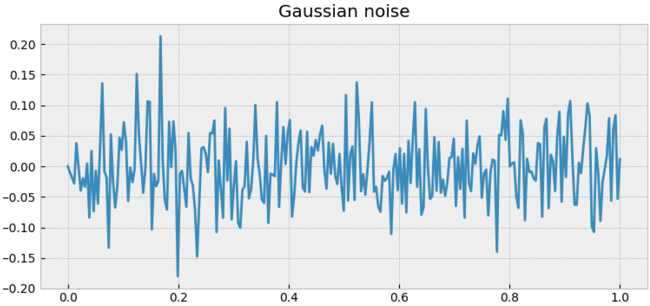



Credit: Ben Moore

## Overdensity, $\delta$

$$\delta(x) = \frac{\rho(x) - \bar{\rho}}{\bar{\rho}} = \frac{\rho(x) - \langle\rho\rangle}{\langle\rho\rangle} \tag{1}$$

dimensionless quantity $\delta(x)$
(we could have used $\varepsilon$)

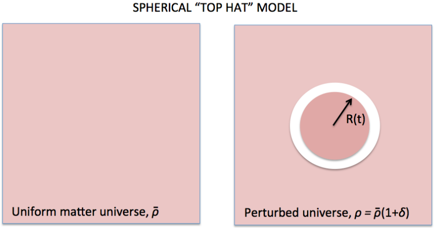


## Structure formation and gravitational instability

To study how mass-energy perturbations evolve, we use **linear perturbation theory** for as long as it holds, i.e. overdensity $\delta \ll 1$. On large cosmological scales, this works well until galaxies form. (In PHYS 4122, we investigate **non-linear dynamics** with new theory and simulations.) Since one part of $\rho$ cancels with differentiation,

$$\ddot{R} = -\frac{G}{R^2}\left(\frac{4\pi}{3}R^3\bar{\rho}\,\delta\right) \quad (2)$$

$$\frac{\ddot{R}}{R} = -\frac{4\pi G\bar{\rho}}{3}\delta(t) \quad (3)$$




This is a single equation with two unknowns $R(t)$ and $\delta(t)$. To solve, we need another, i.e. mass conservation:

$$M = \frac{4\pi}{3}\bar{\rho}[1+\delta(t)]R(t)^3 \quad (4)$$

that remains constant during collapse. Note

$$R(t) = R_0[1+\delta(t)]^{-1/3} \quad (5)$$

$$\approx R_0[1-\frac{1}{3}\delta(t)] \quad (6)$$

$$R_0 \equiv \left(\frac{3M}{4\pi\bar{\rho}}\right)^{1/3} = \text{constant} \quad (7)$$

## Structure formation and gravitational instability

So 2nd derivative & mass conservation,

$$\ddot{R} \approx -\frac{1}{3}R_0\ddot{\delta} \approx -\frac{1}{3}R\ddot{\delta} \tag{8}$$

$$\frac{\ddot{R}}{R} \approx -\frac{1}{3}\ddot{\delta} \tag{9}$$

Combining with (2),

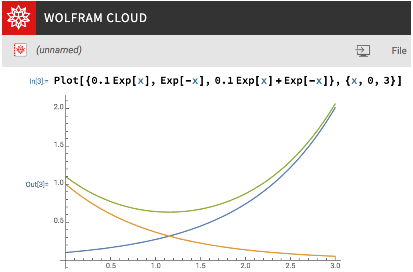
$$\ddot{\delta} = 4\pi G\bar{\rho}\delta \tag{10}$$

with the general solution (example on RHS):

$$\delta(t) = A_1 e^{t/t_{\rm dyn}} + A_2 e^{-t/t_{\rm dyn}} \tag{11}$$

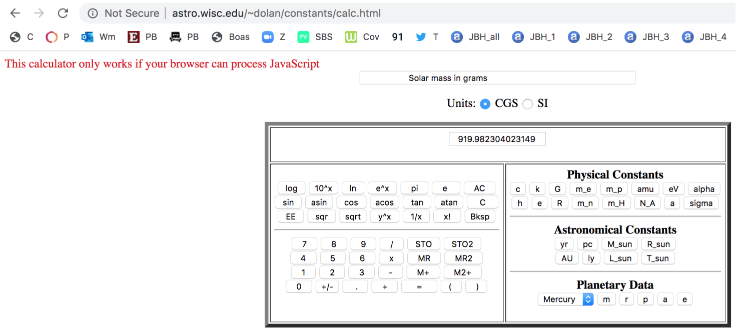
where $t_{\rm dyn}$ occurs often in astrophysics,

$$t_{\rm dyn} = \frac{1}{(4\pi G\bar{\rho})^{1/2}} = \left(\frac{c^2}{4\pi G\bar{\varepsilon}}\right)^{1/2} \tag{12}$$




The first term is for mean mass density, the second for mean energy density. E.g. if the Sun's energy turned off, it would collapse in $1/\sqrt{4\pi G\bar{\rho}_\odot} = \sqrt{R_\odot^3/3GM_\odot} = 920$ sec!

# Favourite calculator - how I solved the last problem




The Units switch above does not change the units of your calculation! It only specifies the units of the constants buttons for future entries!

| NAME | SYMBOL | NUMBER | CGS UNITS |
|---|---|---|---|
| Velocity of light | c | $2.998 \times 10^{10}$ | $cm\ s^{-1}$ |
| Planck constant | h | $6.626 \times 10^{-27}$ | erg s |
| Gravitational constant | G | $6.67 \times 10^{-8}$ | $cm^3\ g^{-1}\ s^{-2}$ |
| Electron charge | e | $4.803 \times 10^{-10}$ | esu |
| Mass of electron | m_e | $9.1096 \times 10^{-28}$ | g |
| Mass of proton | m_p | $1.6724 \times 10^{-24}$ | g |
| Mass of neutron | m_n | $1.6747 \times 10^{-24}$ | g |

## Jeans length, Jeans mass

Given the density, the runaway collapse time of the Earth's atmosphere at sea level is about 9 hours. Why does that not happen?

For a non-relativistic gas, the equation of state parameter

$$w = \frac{kT}{\mu c^2} \tag{13}$$

where $\mu$ is the mean mass per gas particle. In hydrostatic equilibrium, if the gas is squeezed, the pressure gradient works against the collapse. Perturbations travel at the sound speed, $c_s$, where

$$c_s = c\left(\frac{dP}{d\varepsilon}\right)^{1/2} = \sqrt{w} \cdot c \tag{14}$$

Over a region with diameter $R$, $\nabla P$ builds up in a time $t_{\rm cross} = R/c_s$. So to balance collapse, $t_{\rm cross} \leq t_{\rm dyn}$.

This leads us to a very important concept in astrophysics. The characteristic length limit that is stable through pressure against collapse, the **Jeans length**

$$\lambda_J \sim c_s t_{\rm dyn} \sim c_s \left(\frac{c^2}{G\bar{\varepsilon}}\right)^{1/2} \tag{15}$$

Overdense regions *larger* than $\lambda_J$ collapse; overdense regions *smaller* than $\lambda_J$ merely oscillate in density, i.e. stable sound waves going to and fro. For the Earth's atmosphere, $\lambda_J \sim 100,000$ km, far larger than the scale height, so nothing to worry about.

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## Energy, mass density fluctuations

Remember that we can talk interchangeably between mean energy ($\bar{\varepsilon}$) and mean mass ($\bar{\rho}$) density fluctuations (since $\bar{\varepsilon} = \bar{\rho} \cdot c^2$). At a given time $t$, the spatially averaged energy density is

$$\bar{\varepsilon}(t) = \frac{1}{V} \int_V \varepsilon(\vec{r}, t)\, d^3 r \tag{16}$$

where the volume $V$ is assumed to be at least the size of the biggest structure in the Universe at time $t$. The **overdensity** $\delta$ is a dimensionless density fluctuation,

$$\delta(\vec{r}, t) \equiv \frac{\varepsilon(\vec{r}, t) - \bar{\varepsilon}(t)}{\bar{\varepsilon}(t)} \tag{17}$$

- $\delta > 0$, overdense regions, e.g. filaments, sheets, groups, clusters
- $\delta < 0$, underdense regions, e.g. voids, voids within voids

special cases:

- $\delta \gtrsim 1$, non-linear regime (this is too difficult and needs a supercomputer)
- $\delta \ll 1$, linear regime (we work with theory as above and a supercomputer)
- $\delta = -1$, $\varepsilon = 0$ (the true void)

Using our earlier expression for the mean density in a flat Universe,

$$H^{-1} = \left(\frac{3c^2}{8\pi G\bar{\varepsilon}}\right)^{1/2} \tag{18}$$

i.e. the characteristic Hubble time for the Universe to expand. The same formula is comparable to the collapse time given the Universal density,

$$H^{-1} = \left(\frac{3}{2}\right)^{1/2} t_{\rm dyn} \approx 1.22\ t_{\rm dyn} \tag{19}$$

A more precise Jeans length is

$$\lambda_J = c_s \left(\frac{\pi c^2}{G\bar{\varepsilon}}\right)^{1/2} = 2\pi c_s\ t_{\rm dyn} = 2\pi \left(\frac{2}{3}\right)^{1/2} \frac{c_s}{H} \tag{20}$$

where the last expression is the Jeans length in an expanding flat Universe. Recall for a photon gas, $w = 1/3$, so that the sound speed $c_s = \sqrt{w}c = c/\sqrt{3} = 0.58c$.

$$\lambda_J = 2\pi \left(\frac{2}{3}\right)^{1/2} \sqrt{w}\frac{c}{H} \approx 3\frac{c}{H} \tag{21}$$

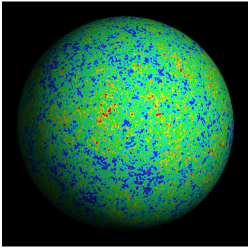
We can think of the very early Universe as filled only with radiation (baryons + dark matter emerging). It had perturbations $\lambda < \lambda_J$ but these were stable sound waves, hence the **cosmic microwave background.**

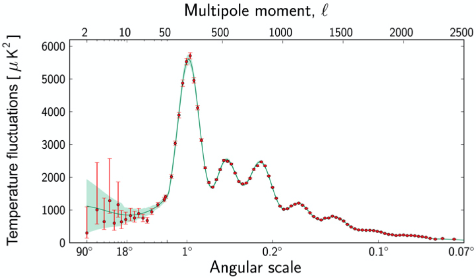
# Cosmic microwave background

Photons and baryons were co-mingled like a fluid and scattering off each other until $z_{\rm dec} = 1100$ about 400,000 yrs after the Big Bang, after which they become **decoupled** and go their separate way. The Jean's length of the photon-baryon fluid was about equal to the photon gas:

$$\lambda_{J,\rm dec} \approx \frac{3c}{H(z_{\rm dec})} \approx 0.6 \text{ Mpc} \approx 1.9 \times 10^{22} \text{ m} \tag{22}$$

The Hubble scale and the Jeans lengthscale are about $1^\circ$ and $3^\circ$ resp. on the CMB sky, about the size of the small blobs in the CMB map.



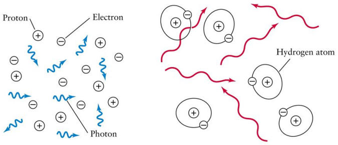



In PHYS 4122, we learn that the temperature fluctuations $\delta T/T = (1/3)\delta\Phi/c^2$ relate to mass-energy or potential gradient fluctuations via $\nabla^2(\delta\Phi) = (4\pi G/c^2)\delta\varepsilon$ – the **Sachs-Wolfe effect**. The Jeans mass in baryons over the Jeans volume is far too large ($M_J \sim 10^{19}$ M$_\odot$) and would take forever to collapse. Another problem is that **Silk damping** during the photon-baryon fluid phase (**radiation-matter equality**) smooths out the baryons. So how did we get to structure today?

There are two basic reasons. First, during radiation-matter equality, (dark) matter started to dominate the Universe. We believe this medium was unaffected by Silk damping, and continues to evolve for all time. Dark matter drives all structure formation. **Without dark matter, we would not exist**.

Secondly, after decoupling, photons and baryons behave as two separate gases and, for the baryons, the Jeans length drops by a factor of $10^5$, i.e. a Jeans mass of about $10^5$ $M_\odot$. This is about the mass of our smallest and most ancient dwarf galaxies, *a crucial step in the history of structure formation.* The evolution of dark matter mass is consistent with this story – the smallest structures collapse first, as we shall see.

**Recombination Epoch: Atom formation and radiation-mattter decoupling**



a Before recombination b After recombination

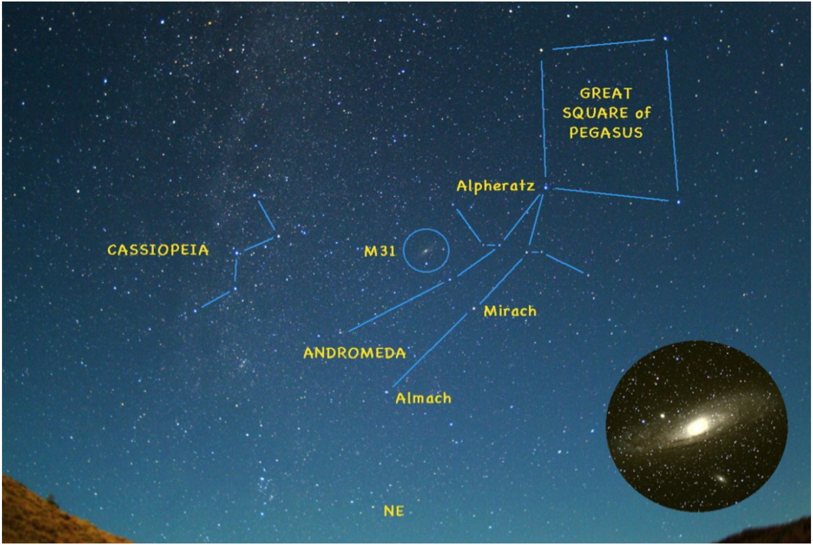
Table 9.1: Events in the early universe

| event | redshift | temperature (K) | time (megayears) |
|---|---|---|---|
| radiation-matter equality | 3570 | 9730 | 0.047 |
| recombination | 1370 | 3740 | 0.24 |
| photon decoupling | 1100 | 3000 | 0.35 |
| last scattering | 1100 | 3000 | 0.35 |

You can see how, in the early years, the expanding cooling Universe led to a changing equation of state - this was a critical epoch. At the moment, we only see back to right after decoupling, when photons and baryons went their separate way, and the CMB photons revealed the distribution of matter.

# My favourite dwarf galaxies: LMC and SMC

Our “Local Group” is dominated by us and Andromeda (M31), about the same size as us. It can be seen by eye on a dark site, easily with binoculars.

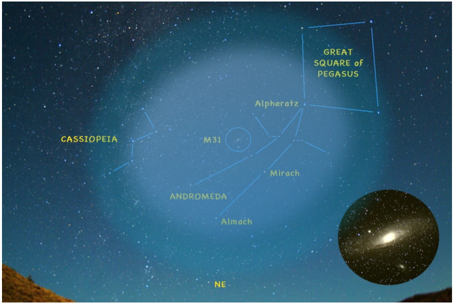


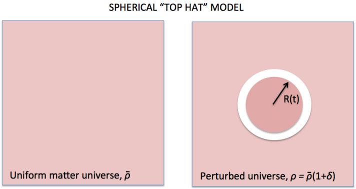
## Milky Way or M31 (Andromeda) expressed as an overdensity

The structure formation analysis + simulations above show that our dark halo is at least $10\times$ more massive in size and mass, compared to what we see. This makes our overdensity about $200\times$ the cosmic value, on average, i.e. $\delta \approx 200$ over sphere about $500 - 600$ kpc across.

This is a very lumpy object seen in dark matter (remember Springel's movie) that builds by accretion over 13 Gyr. I wonder if we'll ever be able to image the clumpy halo in detail?

Just imagine if we could "see" the dark matter surrounding M31 - it would be huge on the sky, many moons across...



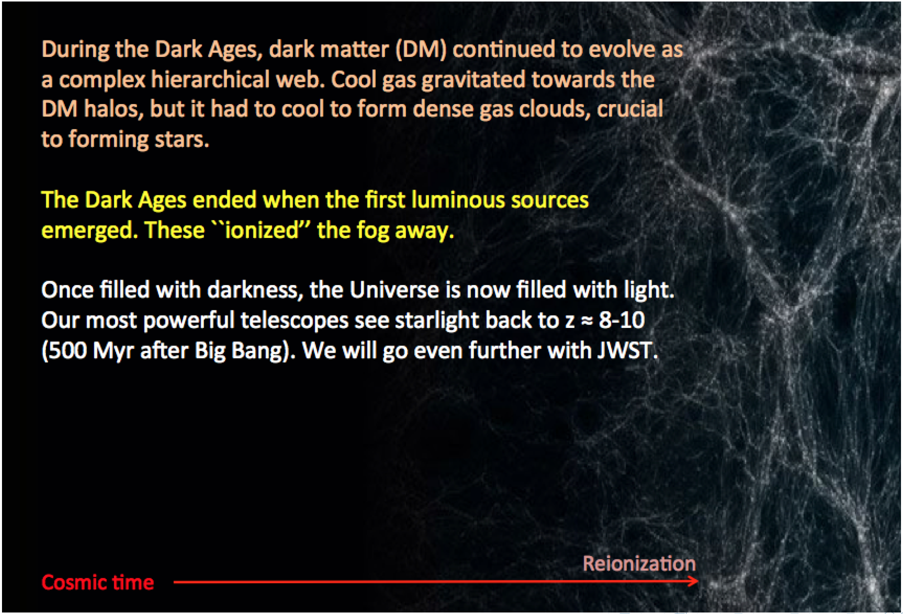



# Overview

Once again, in this last lecture, we cover these topics:

- Dark Ages
  - How did the Universe become neutral?
- First Stars & First Light
  - How did the first stars form?
- Reionization
- First Metals
- First Black Holes
- Golden Age
  - When did galaxy & black hole growth peak?
- Cosmic baryon evolution
  - Cosmic trends in stellar mass, metals, etc.
- Review

## The Universe after $z \approx 1100$ when baryons became important



# First light - how did the first stars form?

Key steps:

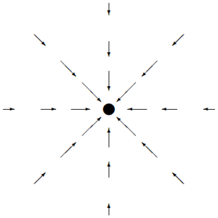
• Gas needs a dynamical time to gravitate towards potential wells, i.e. dark matter halos. But to stay bound to the halo, it needs to be cool enough. What is that criterion?

• Once bound to the halo, the gas needs to cool down even more to eventually collapse and form stars, i.e. Jeans mass. How can gas cool?

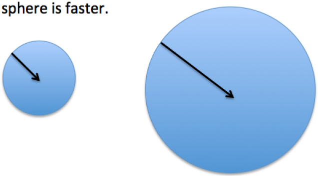
$$t_{\rm dyn} = \frac{1}{(4\pi G\bar{\rho})^{1/2}} = \left(\frac{c^2}{4\pi G\bar{\varepsilon}}\right)^{1/2} \tag{23}$$

The gas *does not stay cool* as it flows onto halos. Because it is a convergent flow by definition, the gas undergoes large-scale shocks as it collapses towards large-scale structure and massive halos. (We examine this in PHYS 4122.)

Shocks thermalize the gas to higher $T$. We have only recently found evidence for these diffuse, low density shocks outside galaxy groups and clusters. Since higher halo mass $M_{\rm vir}$ drives faster infall, and therefore shock heating, bigger halos must retain hotter gas.



Two equal density spheres with the same free-fall times because this depends on square root of density. But the collapse speed of the larger sphere is faster.



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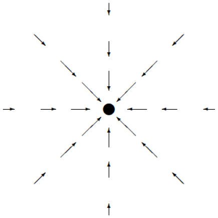

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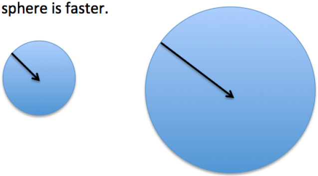


# How did the first stars form? contd.

How do we think about energetic particles being bound to a gravitating object? From Newton's laws:

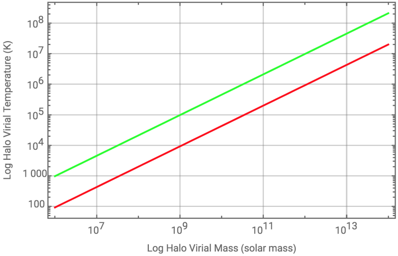
$$\frac{m}{R} \cdot v^2 = -\frac{m}{R} \cdot \frac{GM_{\mathrm{vir}}}{R} \tag{24}$$

For a particle with mass $m = \mu m_H$ (or equivalently density $\rho = n\mu m_H$, where $n$ is the number of protons or electrons per m$^3$), ionized gas can stay bound if its thermal energy $(3/2)nk_BT_e$ does not exceed the halo potential energy,

$$T_{\mathrm{vir}} = \frac{2}{3}\frac{GM_{\mathrm{vir}}}{R_{\mathrm{vir}}}\frac{\mu m_H}{k_B} \tag{25}$$

where $\mu$ is the mean molecular weight ($\mu \approx 0.6$ for a primordial H, He gas).

In the RHS plot, the red curve shows the equation above, and applies to $z \lesssim 1$). See how the smallest halos are cold, and massive groups are hot. But at $z \gtrsim 1$, the early halo gas runs hotter in an environment where there is external accretion shock pressure from the environment. Then we need a crude correction for redshift, i.e. $T'_{\mathrm{vir}} = T_{\mathrm{vir}}(1+z)$. That's shown in green for $z = 20$; the extension to highest masses can be ignored since few existed then.



## How did the first stars form? contd.

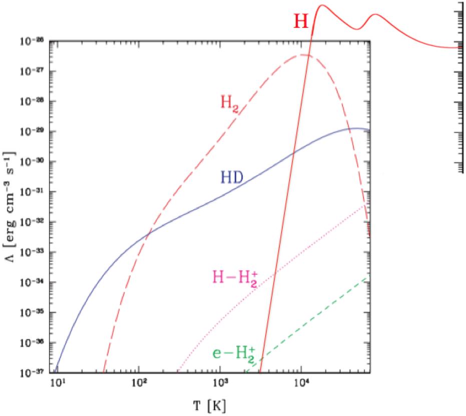
Now we are closer to answering this question. We still need a few things:

- How fast can the gas cool in the centres of halos?
    - Do we need any more ingredients to assist cooling?
- Which are the most likely halos that formed the first stars?
- Were these sufficiently widespread to ionize the Universe?

# Cooling down a primordial gas

**Cooling time.** Gas cools at a rate given by the **cooling function.** The thermal energy of the gas is converted into electronic transitions in atoms and molecules, since collisions push eletrons to higher orbits; photons emitted and escape into the Universe.

By $z = 20$, 180 Myr after the CMB era, the gas has cooled due to expansion by a factor of 50 and more molecule types form $-$ see list (Maio et al 2007). These give many more electronic transitions to allow gas to cool into haloes.



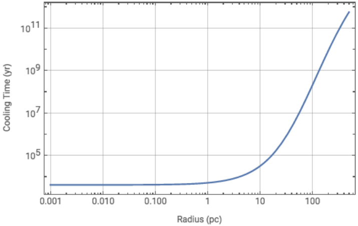

| Reactions | References for the rate coefficients |
|---|---|
| $H + e^- \rightarrow H^+ + 2e^-$ | A97/Y06 |
| $H^+ + e^- \rightarrow H + \gamma$ | A97/Y06 |
| $He + e^- \rightarrow He^+ + 2e^-$ | A97/Y06 |
| $He^+ + e^- \rightarrow He + \gamma$ | A97/Y06 |
| $He^+ + e^- \rightarrow He^{++} + 2e^-$ | A97/Y06 |
| $He^{++} + e^- \rightarrow He^+ + \gamma$ | A97/Y06 |
| $H + e^- \rightarrow H^- + \gamma$ | A97/Y06 |
| $H^- + H \rightarrow H_2 + e^-$ | A97/Y06 |
| $H + H^+ \rightarrow {H_2}^+ + \gamma$ | A97/Y06 |
| ${H_2}^+ + H \rightarrow H_2 + H^+$ | A97/Y06 |
| $H_2 + H \rightarrow 3H$ | A97 |
| $H_2 + H^+ \rightarrow {H_2}^+ + H$ | S04/Y06 |
| $H_2 + e^- \rightarrow 2H + e^-$ | ST99/GB03/Y06 |
| $H^- + e^- \rightarrow H + 2e^-$ | A97/Y06 |
| $H^- + H \rightarrow 2H + e^-$ | A97/Y06 |
| $H^- + H^+ \rightarrow 2H$ | P71/GP98/Y06 |
| $H^- + H^+ \rightarrow {H_2}^+ + e^-$ | SK87/Y06 |
| ${H_2}^+ + e^- \rightarrow 2H$ | GP98/Y06 |
| ${H_2}^+ + H^- \rightarrow H + H_2$ | A97/Y06 |
| $D + H_2 \rightarrow HD + H$ | WS02 |
| $D^+ + H_2 \rightarrow HD + H^+$ | WS02 |
| $HD + H \rightarrow D + H_2$ | SLP98 |
| $HD + H^+ \rightarrow D^+ + H_2$ | SLP98 |
| $H^+ + D \rightarrow H + D^+$ | S02 |
| $H + D^+ \rightarrow H^+ + D$ | S02 |
| $He + H^+ \rightarrow HeH^+ + \gamma$ | RD82, GP98 |
| $HeH^+ + H \rightarrow He + H_2^+$ | KAH79, GP98 |
| $HeH^+ + \gamma \rightarrow He + H^+$ | RD82, GP98 |

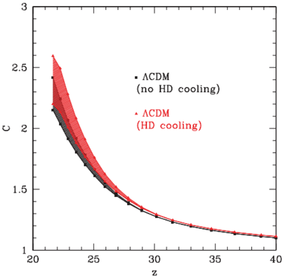
# Cooling down a primordial gas, contd.

So the **cooling time** is the gas energy density divided by the cooling rate,

$$t_{\rm cool} = \frac{3}{2}\frac{k_B T_e}{n_H \Lambda(T_e)} \qquad (26)$$

For $M_{\rm vir} = 10^6$ $M_\odot$ halo (3 slides ago), where $T_e = 10^3$ K, equation (8) gives RHS plot – short timescales at centre; impossible outer timescales.




Atmospheric clouds in warm air clump when they hit a cold front. Maio et al (2007) find that the clumping factor $C$ increases rapidly as gas cools by $z = 20$. These clumps make stars as simulations show us.

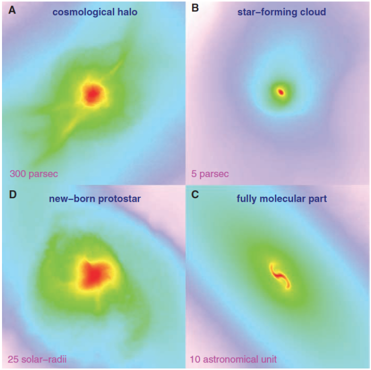
# "First star" simulations

We now have many of the ingredients we need. A decade ago, Naoki-san ran the best ever model of gas cooling in a $10^6$ M$_\odot$ halo, using all the reaction rates in Maio et al (2007), and resolving densities of $10^{20}$ cm$^{-3}$. Insane! A protostellar core (0.01 M$_\odot$) grows quickly, and this accretes more gas, growing to 10 M$_\odot$ in 1000 years.

## Protostar Formation in the Early Universe

Naoki Yoshida,[1]* Kazuyuki Omukai,[2] Lars Hernquist[3]

The nature of the first generation of stars in the universe remains largely unknown. Observations imply the existence of massive primordial stars early in the history of the universe, and the standard theory for the growth of cosmic structure predicts that structures grow hierarchically through gravitational instability. We have developed an ab initio computer simulation of the formation of primordial stars that follows the relevant atomic and molecular processes in a primordial gas in an expanding universe. The results show that primeval density fluctuations left over from the Big Bang can drive the formation of a tiny protostar with a mass 1% that of the Sun. The protostar is a seed for the subsequent formation of a massive primordial star.




Peak densities (red) are (A) $10^3$ cm$^{-3}$, (B) $10^6$ cm$^{-3}$, (C) $10^{19}$ cm$^{-3}$, (D) $10^{21}$ cm$^{-3}$.

The authors ran out of time but suspect the hot young star grew to $\gtrsim 300$ M$_\odot$ – huge!! The first stars were unique to their time, but why?? **See Naoki-san's movie here: www.youtube.com/watch?v=2COt_OTAENg&t=2s**

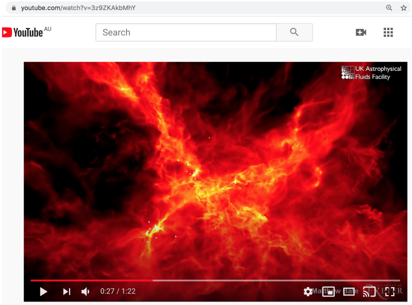
## How did the first stars form, contd.

The **Jeans mass,** $M_J$ is the critical mass above which gravity dominates. For perturbations below $M_J$, pressure dominates and perturbations expand when being compressed:

$$M_J = \left(\frac{5kT_{\text{gas}}}{GM}\right)^{3/2} \left(\frac{3}{4\pi\rho}\right)^{1/2} \tag{27}$$

The accretion rate of gas onto the core is thus $\dot{M} \approx M_J/t_{\text{collapse}}$. Since the collapse time $t_{\text{collapse}} \propto 1/\sqrt{\rho}$, then $\dot{M} \propto T_{\text{gas}}^{3/2}$. Since the first gas to form stars in the early Universe was warmer ($T \lesssim 200$ K) than today ($T_{\text{gas}} \sim 10$ K), the initial seeds could grow to much larger masses. Today, we don't have fast accretion shocks supplying extra pressure.

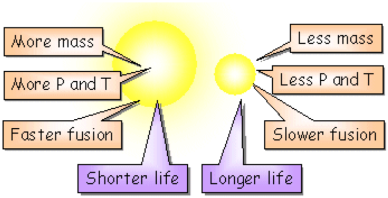
**A movie of star formation today.** The molecular cloud has $M = 500\ \mathrm{M}_\odot$, diameter about 1 parsec, $T_{\text{gas}} = 10$ K, $\mu = 2.46$, $t_{\text{collapse}} = 190,000$ years, total duration 300,000 years. $M_J$ is about the mass of the Sun, so lots of stars form in this cloud.



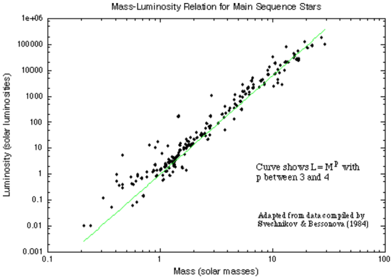
# High mass stars at any epoch live fast, die young

From the Hertzsprung-Russell diagram, we know $L_\star \propto M_\star^{3.5}$ (**mass-luminosity relation**). A star's luminosity $L_\star$ is from nuclear fusion, i.e. $E = fM_\star c^2$. The time on the main sequence is $t_{\rm MS} \sim M_\star/L_\star \sim M_\star^{-2.5}$.

This is all about a star's stability. A massive star has to run "hot" to self sustain. The stronger gravitational field drives higher $P_e$, $T_e$ and fusion reaction rates. This is needed to generate more radiation pressure on the upper layers to support them against collapse.

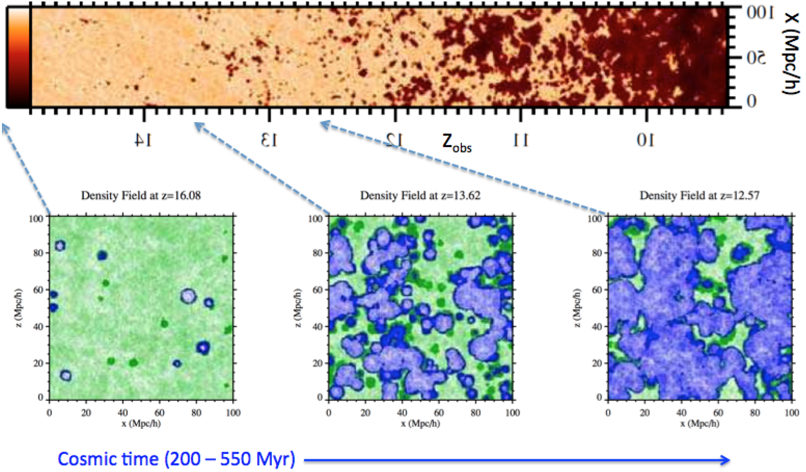



| Mass (Sun = 1) | Spectral Type | Luminosity (Sun = 1) | Main sequence lifetime (years) |
|---|---|---|---|
| 40 | O5 | 400,000 | 1 million |
| 15 | B0 | 13,000 | 10 million |
| 3.5 | A0 | 80 | 450 million |
| 1.7 | F0 | 6.4 | 3 billion |
| 1 | G2 | 1 | 10 billion |
| 0.8 | K0 | 0.46 | 17 billion |
| 0.5 | M0 | 0.08 | 56 billion |
| 0.1 | M7 | <0.0001 | >1 trillion |



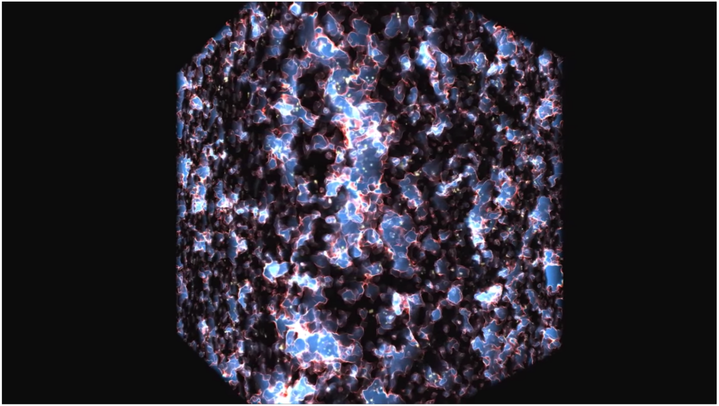

The table lists stars that we know of today $(z = 0)$. Another reason for the higher surface temperature of a massive star is the blackbody approximation, $L_\star \approx 4\pi R_\star^2 \sigma_S T_\star^4$.

## Reionization epoch, $10 < z < 20$?




We now watch a **cosmological simulation** to show how these massive, hot, young stars within rare overdensity peaks (halos) were able to boil off the H+He fog. Within a few million years, these stars produced the first metals and black hole seeds.

# The era of reionisation (simulation)



A simulation of the era of reionisation. When the Universe cooled down after the Big Bang, about 13.7 billion years ago, electrons and protons combined to form neutral hydrogen gas. This cool dark gas was the main constituent of the Universe during the so-called Dark Ages, when there were no luminous objects. This phase eventually ended when the first stars formed and their intense ultraviolet radiation slowly made the hydrogen fog transparent again by splitting the hydrogen atoms back into electrons and protons, a process known as reionisation. This epoch in the Universe's early history lasted from about 150 million to 800 million years after the Big Bang. This visualisation shows the progress of reionisation. Ionised regions are blue and translucent, ionisation fronts are red and white, and neutral regions are dark and opaque. See Alvarez et al. (2009) for more details on the simulations.

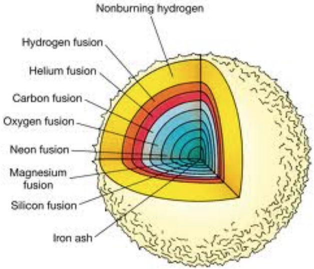
**Credit:** M. Alvarez (http://www.cita.utoronto.ca/~malvarez), R. Kaehler, and T. Abel

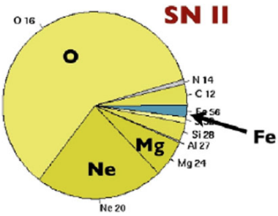
https://www.eso.org/public/usa/videos/eso1041d/?lang

# First stars and first metals

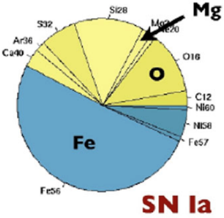
Nuclear fusion converts H→He, the H is used up, the core collapses to start He fusion, then He→CNO, and so on. Before the massive star explodes as a **supernova** (bottom RHS), it has layers (RHS) within. Most metal layers are ejected, some fall back onto the surviving nuclear object — **see bounce movie: www.youtube.com/watch?v=2UHS883_P60.**

The metals produced depend on the star's mass (bottom LHS). We don't know what the exact yields of the first stars are — exciting area of research constrained by the oldest (13+ Gyr) halo stars and LIGO gravitational wave observations.

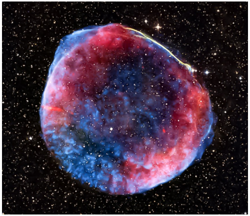



Star > 8 $M_\odot$ explodes as SN II

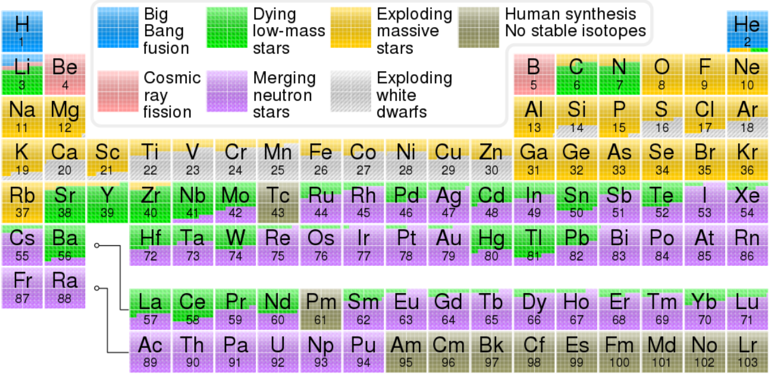


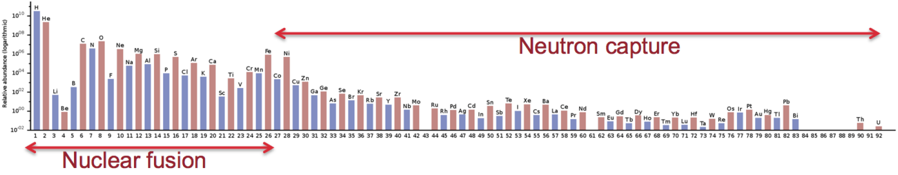

Low mass star feeding a WD which explodes as SN Ia



Explosion seen by Chinese scholars in 11th C., affected Earth's atmosphere, was same brightness as quarter moon!

# Element table, element fractions – snapshot in time



## First stars and black hole seeds

We know today that exploding stars create remnants, i.e. black holes, neutron stars. There are good reasons for believing the first stars seeded the first black holes. We need them to explain the hugely powerful **quasars** seen back to $z = 7.1$ (Mortlock et al 2011), 770 Myr after the Big Bang. But these are surely powered by **supermassive black holes** with masses $\sim 10^9$ M$_\odot$. How can something so massive grow so quickly?

A black-hole accretion disk converts accreting gas (rate = $\dot{m}$) to energy with a luminosity $L_\bullet = (\epsilon/0.1)\dot{m}c^2$. If we set this equal to $L_E$, this is the maximum rate we can grow a black hole, where the e-folding **Salpeter time** is easily shown to be

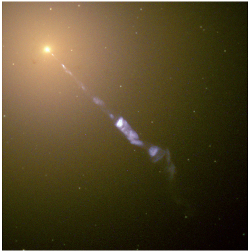
$$t_{\rm sal} = \frac{m_\bullet}{\dot{m}} = \frac{\epsilon\sigma_T c}{4\pi G m_H} \approx 47 \text{ Myr} \quad (28)$$

So if the first-star black-hole seed was $m_\bullet$, and the first stars appeared after 180 Myr, what was the mass of the seed?

$$m_\bullet \cdot e^N \sim 10^9 \text{ M}_\odot \quad (29)$$

The number of e-folding times is $N = (770 - 180)/45 = 13$, such that $m_\bullet \sim 2000\ M_\odot$. Really? *This seems way too high.* The first stars would need to be even more massive to leave this huge "seed" behind. Is there missing physics here? Are the first black-hole seeds formed in another fashion? This is a hot topic in astrophysics - we don't know the answer.

There are theorists who try to make weird **primordial black holes** using QM/QFT/GR and variations around inflation. I don't understand this work (yet).



Giant elliptical M87 with quasar-like nucleus driving a powerful jet. These were more common in the early Universe, but associated with rare density peaks even then. Very special maximum efficiency conditions were required to create these rare monsters.

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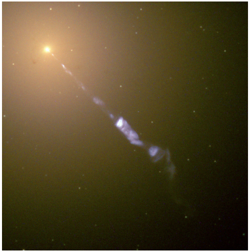

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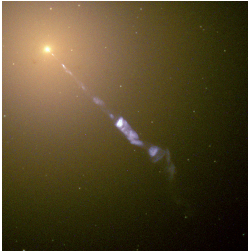

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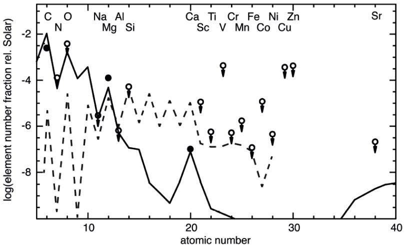
# Ancient stars in the Galactic halo: evidence of first black holes

After the terrible 2003 Canberra bush fires, Brian Schmidt (ANU VC) was able to build a small telescope called `SkyMapper` at the beautiful Siding Spring Observatory, NW New South Wales. This amazing little telescope initiated the discovery of the two most metal poor ([Fe/H] $<$ -6), most ancient stars (Keller et al 2014; Nordlander et al 2019). This metal content is like the Sun swallowing the Earth, and we can detect that!!

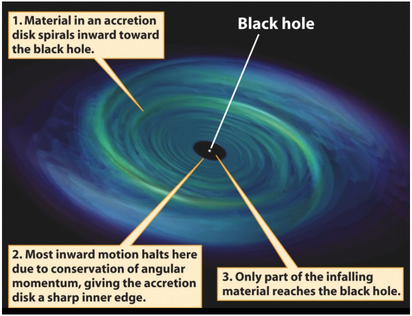
The oldest halo stars tell us of the state of metals in the first metal-enriched gas clouds 13.5$-$13 Gyr ago. We see evidence of **fallback** onto dense nuclear seeds (black holes mostly?). Remember the bouncing balls, where the lower ones ($\equiv$ lower gas layers) lost energy to the higher ones ($\equiv$ outer gas layers). The inner shells were made up of heavier elements. The bottom RHS plot shows that, cf. with no fallback models (dashed line), the heaviest metals are depleted. Where did they go? Fallback.

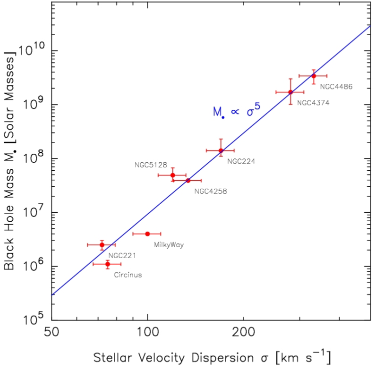


## Black holes – unseen monsters

Like dark matter, we don't see black holes, but we see the spectacular effects of the accretion disk spinning around the black hole. Black holes appear to be at the centres of all galaxies, and are likely to be the oldest structures (fossil relics) that began assembling in the early Universe after the first stars.

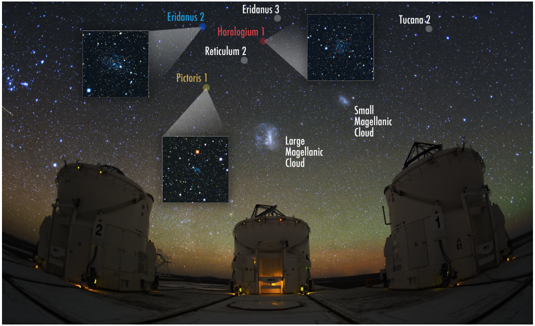
Over the past 20 years, an extraordinary correlation has been found (bottom RHS). The black-hole mass correlates with the galaxy's (spheroidal) mass. But a black hole is tiny, Solar-system size, and galaxies are huge, at least $10^8\times$ bigger in diameter.

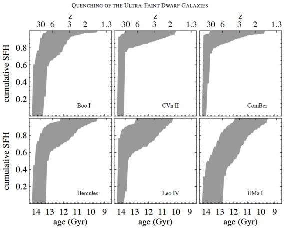


## Ancient dwarf galaxies – a tiny subset of the total CDM halos expected

Our Galactic halo has 60 orbiting dwarfs (to date), a few very massive like the Large Magellanic Cloud (LMC) with $M_{\rm tot} \sim 10^{10}$ $\mathrm{M}_\odot$. Most have far less mass down to $M_{\rm tot} \sim 10^6$ $\mathrm{M}_\odot$, e.g. the **ultra-faint dwarfs** (UFD). The LMC and SMC have stars forming today (e.g. 30 Doradus), but the UFDs are long dead. Examples are shown in the figure below.



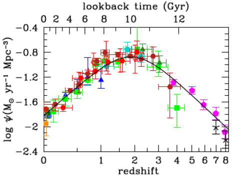



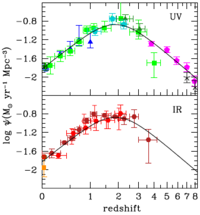

These UFDs sometimes only have $\sim 100$ stars. Because the halos are so small, even one supernova exploding can blow away most of the gas. Note how ancient they are (RHS plot; Brown et al 2014). Most of their stars were born about the time of reionization ($z = 10 - 20$). These first galaxies obviously were able to form *low mass stars*, which is necessary for the stars to survive 13 Gyr for us to see today. It was not only supermassive stars.

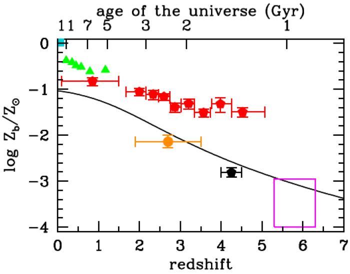
# The Golden Age, $5 < z < 1$ ($1 < t_{\mathrm{age}}/\mathrm{Gyr} < 5$)

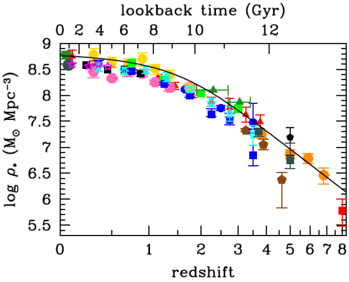
Madau & Dickinson (2014) review what we know about the star formation history of the Universe. **This is the key to understanding galaxy evolution.** The star formation rate $\psi$ (SFR) per comoving Mpc$^3$ per year went through a peak 10 Gyr ago. We see the same trend at all wavelengths.

Consistent with that, an increasing fraction of baryons $\rho_\star$ is locked up in stellar mass (bottom RHS), and the metal fraction $Z/Z_\odot$ is increasing also to $z = 0$ (bottom LHS).



# The Golden Age, $5 < z < 1$ $(1 < t_{\rm age}/{\rm Gyr} < 5)$

There was a lot more gas around in a much smaller Universe. Everything was happening then. See how black hole (accretion disc) activity also peaked then (bottom LHS). The star formation efficiency per unit mass $\psi/M$ (a meaure of SF efficiency) has been in decline ever since (bottom RHS), mostly because gas accretion has been drying up.

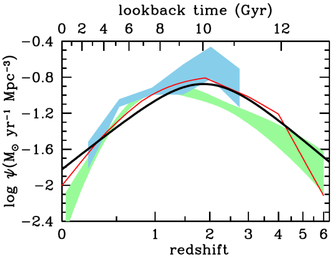



Figure 15: Comparison of the best-fit star formation history (*thick solid curve*) with the massive black hole accretion history from X-ray (Shankar et al. 2009, *red curve*; Aird et al. 2010, *light green shading*) and infrared (Delvecchio et al. 2014, *light blue shading*) data. The shading indicates the $\pm 1\sigma$ uncertainty range on the total bolometric luminosity density. The radiative efficiency has been set to the value $\epsilon = 0.1$. The comoving rates of black hole accretion have been scaled up by a factor of 3,300 to facilitate visual comparison to the star formation history.

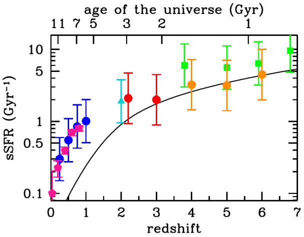
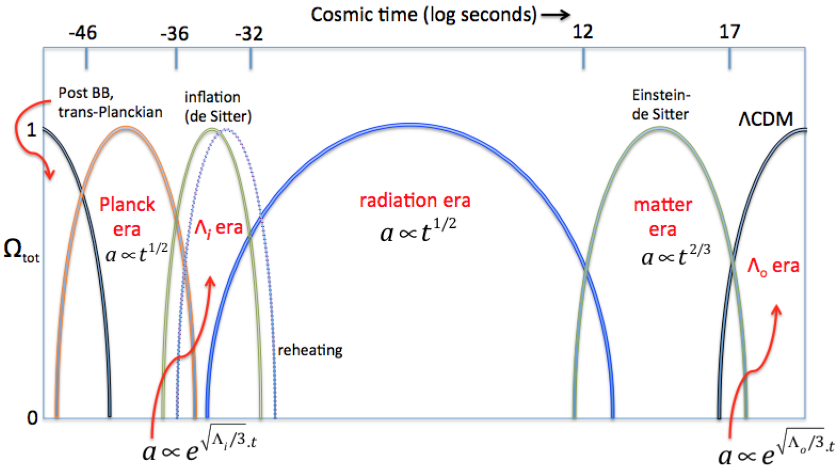



Figure 13: The mean specific star formation rate (sSFR$\equiv$ SFR$/M_*$) for galaxies with estimated stellar masses in the range $10^{9.4} - 10^{10}$ $M_\odot$. The values are taken from the literature: Damen et al. (2009) (*magenta pentagons*), Noeske et al. (2007) (*blue dots*), Daddi et al. (2007) (*cyan triangle*), Reddy et al. (2012) (*red dots*), Stark et al. (2013) (*green squares*), and González et al. (2012) (*orange dots*). The error bars correspond to systematic uncertainties. The González et al. (2012) and Stark et al. (2013) high-redshift points have been corrected upwards for the effect of optical emission lines on the derived stellar masses, using their "RSF with emission lines" model (González et al. 2012) and "fixed Hα EW" model (Stark et al. 2013). The curve shows the predictions from our best-fit SFH.

# Overview & revision

The Universe is a remarkable study that begins with physics we don't understand (trans-Planckian), moving through QFT (inflation), GR, particle physics, leptogenesis, baryogenesis, and astrophysics once matter takes over.




Remember that the Hubble parameter $H = \frac{\dot{a}}{a}$ so this has a different dependence in each era, declining overall like everything else, e.g. energy/matter (non-$\Lambda$) density declining like $a^{-3}$, temperature, pressure, etc. Note that during the $\Lambda$ eras, $H$ is a constant. Expanding universes have changing $a$ but not necessarily $H$.