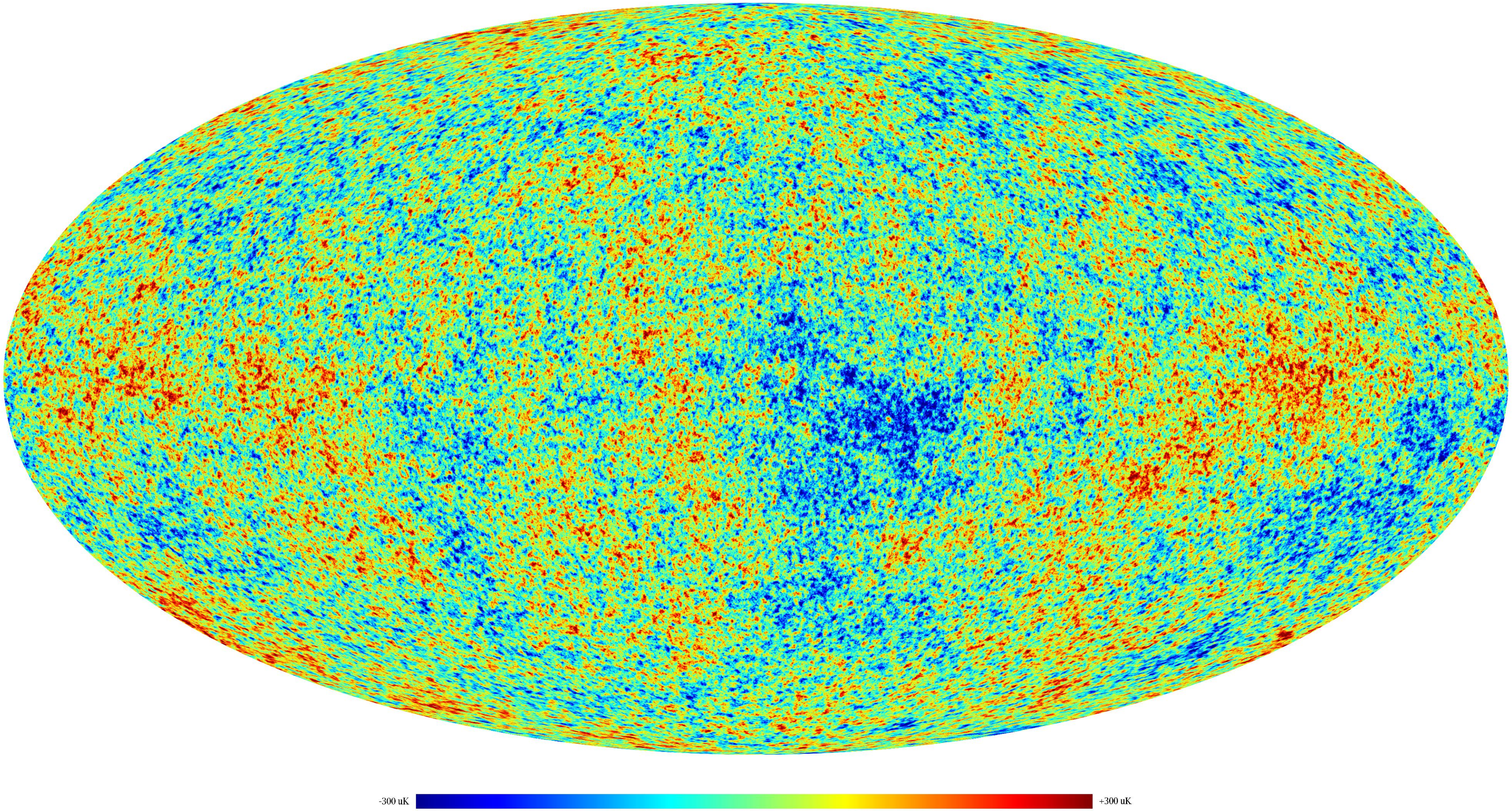
Did X-Ray Binaries Help Heat the Early Universe?

- Recombination
- The “Dark Ages”
- Star formation
- Dark matter
- First stars
- Reionization
- Spectral states of X-ray binaries
- X-ray binaries in blue compact dwarf galaxies

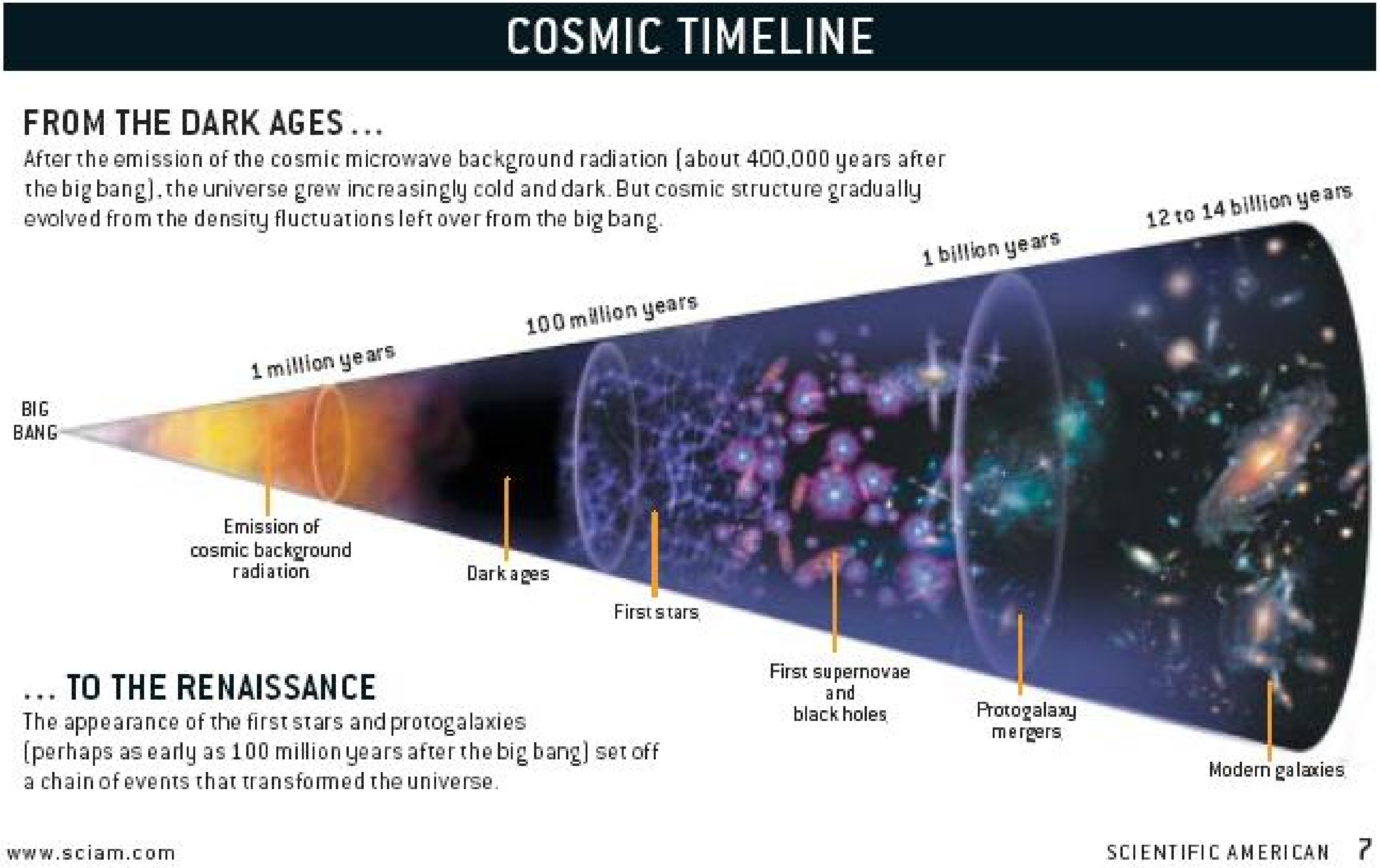
Cosmic Microave Background



- CMB is map of temperature of universe at 400,000 years old, is smooth to 1 part in 100,000.
- Temperature changes are caused by density changes.
- Density of universe at 400,000 years was very smooth.

Hubble eXtreme Deep Field

- In the Hubble XDF field we can see galaxies that are ten billion times dimmer than what the unaided human eye can see.
- The farthest galaxies in the picture are from when the universe was 500 million years old.
- At 500 million years, the universe is very lumpy, it is not smooth.
- How did the universe go from being smooth to lumpy?



COSMIC TIMELINE

FROM THE DARK AGES . . .

After the emission of the cosmic microwave background radiation (about 400,000 years after the big bang), the universe grew increasingly cold and dark. But cosmic structure gradually evolved from the density fluctuations left over from the big bang.

. . . TO THE RENAISSANCE

The appearance of the first stars and protogalaxies (perhaps as early as 100 million years after the big bang) set off a chain of events that transformed the universe.

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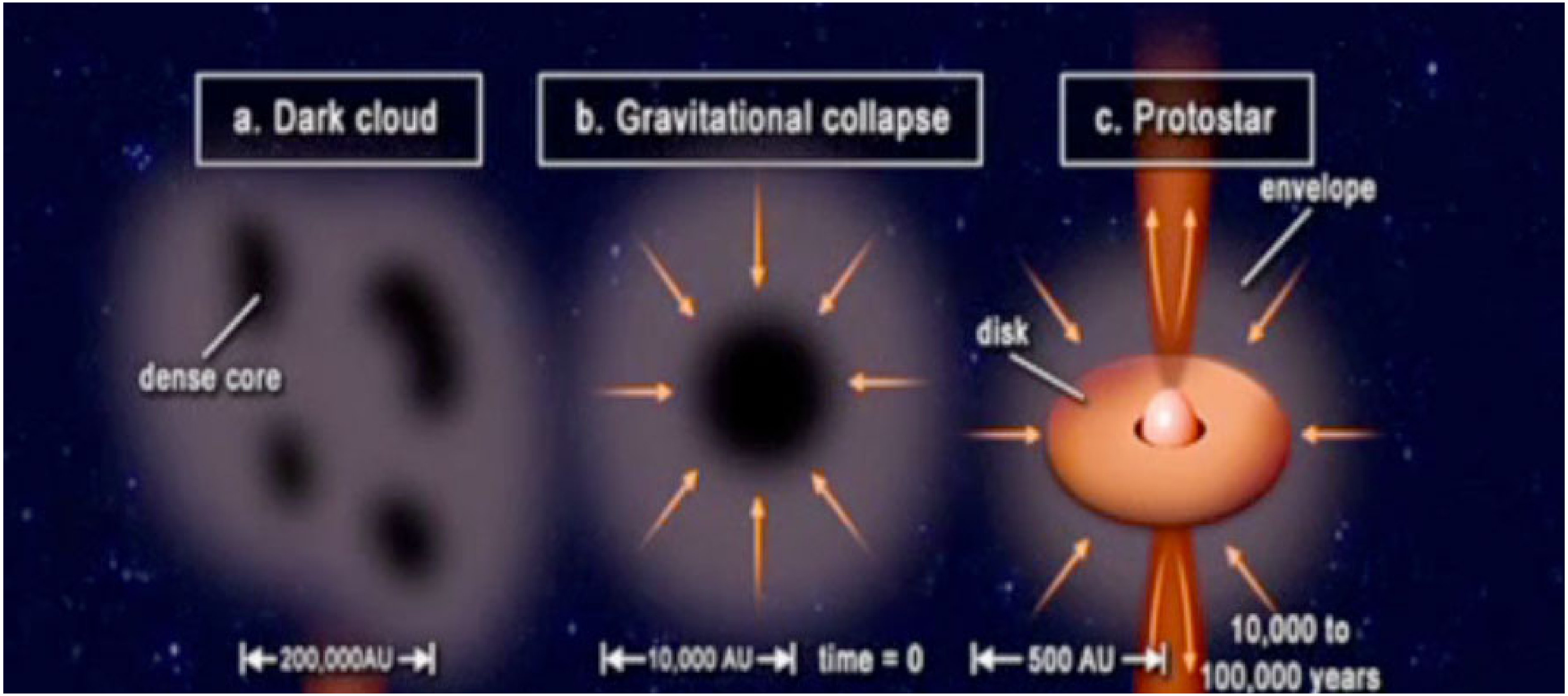
- Universe became transparent and neutral at recombination when CMB was produced.
- “Dark Ages” with no discrete light sources followed.
- First stars formed during the dark ages.

Star Formation

- Stars form in dense clouds of gas (NGC 3603)

Star Formation

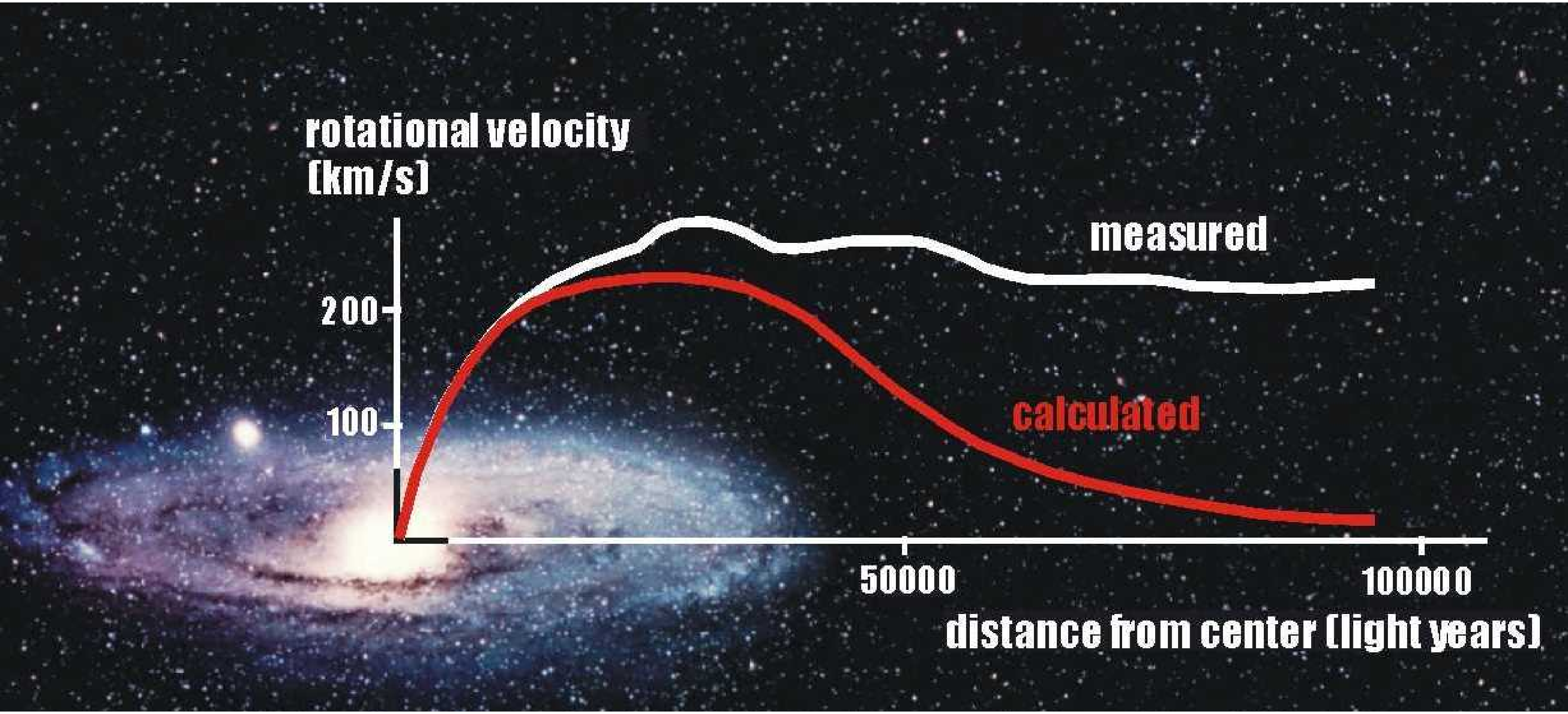


- Stars form around dense cores in gas clouds
- Gravity of dense core pulls in more gas
- Collapse of cloud feeds on itself until a star is born
- All astronomical structures form the same way – via gravity

First Stars

- First stars formed in the same way, around dense cores
- But there is a problem...
- The universe was very smooth, too smooth for the dense cores to be made of normal gas – stars would have formed too slowly and there would be too few.
- The dense cores were, instead, made of dark matter.

Dark Matter



- Our Sun orbits the Milky Way galaxy faster than it should.
- Dark matter, first suggested by Fritz Zwicky in the 1930s, keeps galaxies from flying apart.

First Stars

- First stars formed around concentrations of dark matter
- First stars formed before the first galaxies
- Stars formed in a roughly uniform distribution of gas – no galaxies or large scale structure

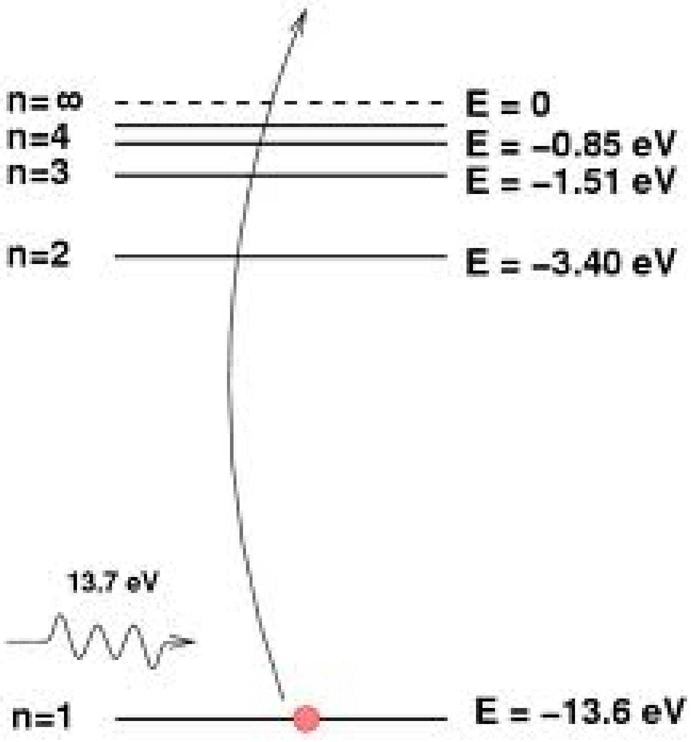
First Stars

- Jeans mass = mass needed for a gas cloud to collapse due to gravity at given temperature and pressure.
- At early times, the Jeans mass is modified by the expansion of the universe
- For $140 < z < 1000$, $M_J = 1.4\times10^5\ M_{\rm Sun}$ independent of z.
- For $z < 140$, $M_J = 5.7\times10^3\ M_{\rm Sun}\ [(1+z)/10]^{3/2}$
- Age of universe = 10 Myr at $z = 140$, = 500 My at $z = 10$

- These are small structures: 6000 to 140,000 $M_{\rm Sun}$

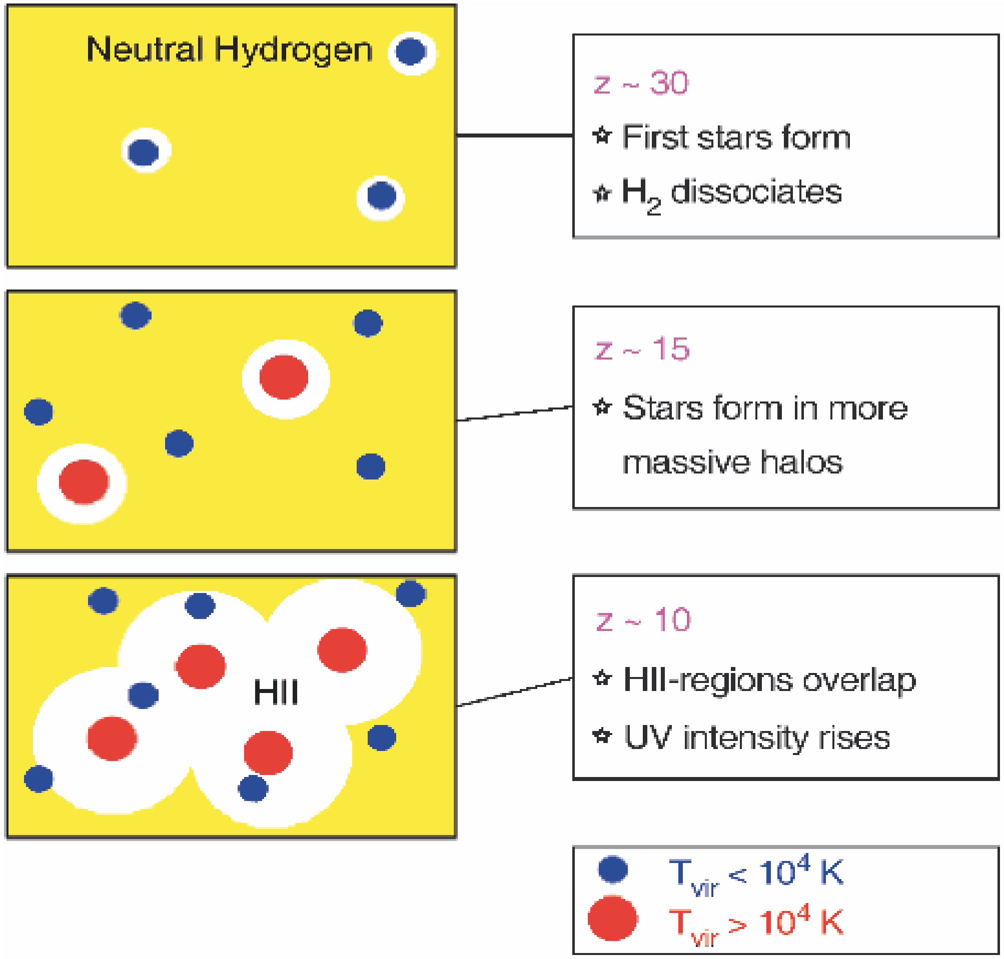
Reionization

- Neutral gas in between us and a distant object (like a quasar or galaxy) will produce absorption lines.
- Neutral hydrogen absorbs all photons with $E > 13.6$ eV, its ionization energy.
- If universe were still neutral, we could not see radiation with $\lambda < 91.2$ nm (in the rest frame) from distant galaxies.
- Universe became reionized at $z > 10$.
- Need UV or soft X-rays ($E > 13.6$ eV) to ionize H.



First Stars

- Primordial gas consisted of Hydrogen and Helium.
- A gas cloud must be sufficiently massive to collapse (above the Jeans mass), but also the cloud must be able to cool.
- Clouds cool by emitting radation.
- Atomic hydrogen emits radiation efficiently at $T > 10^4$ K.
- Molecular hydrogen emits radiation efficiently at $T > 10^3$ K.
- Other atoms and molecules emit radiation efficiently at much lower temperatures. Cooling for star formation occurring today is dominated by atoms/molecules other than H+He, what astronomers call metals.
- Because they cool only via H+He, the first stars were much more massive than stars found today, $M \sim 100\text{-}400\ M_{\text{Sun}}$.
- Massive stars are hotter, such massive stars emit copious UV.



$z \sim 30$

- ☆ First stars form
- ☆ H_2 dissociates

$z \sim 15$

- ☆ Stars form in more massive halos

$z \sim 10$

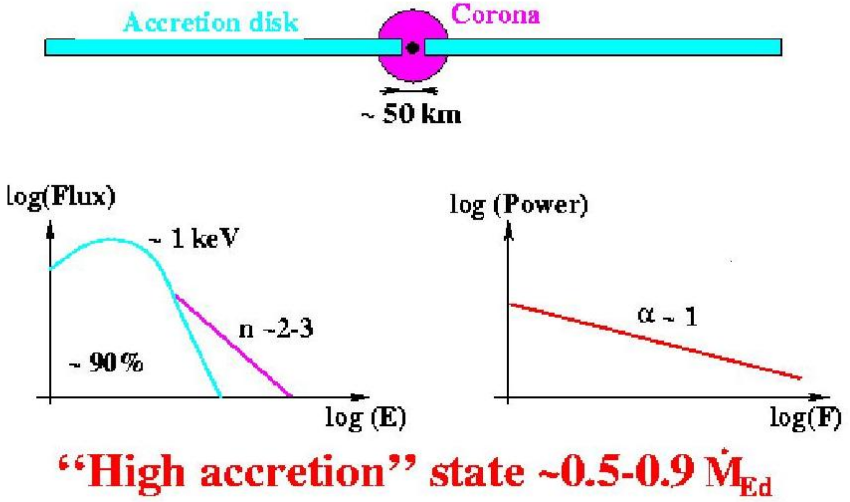
- ☆ HII-regions overlap
- ☆ UV intensity rises

● $T_{vir} < 10^4$ K

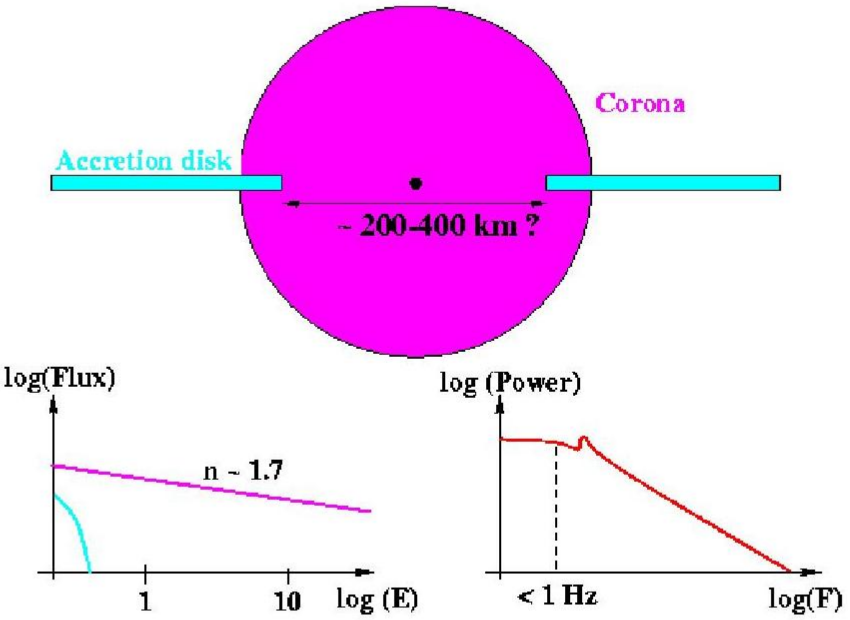
● $T_{vir} > 10^4$ K

- Pop III stars form in low mass halos, $T_{\text{vir}} \sim 3000$ K, $M \sim 10^4\ M_{\text{Sun}}$.
- Dissociate nearby H_2. Go supernova, enriching IGM with metals.
- Metals allow cooling at higher temperatures. Stars/galaxies form in higher mass halos.
- Fusion 7 MeV/proton, ionization 13.6 eV/proton, fuse $\sim 2\times10^{-6}$ of protons to reionize.

X-Ray Spectral States



“High accretion” state ~0.5-0.9 $\dot{M}_{Ed}$



“Low accretion”state ~ 0.01 $\dot{M}_{Ed}$

Emission consists of two components:

- Thermal emission from disk - multicolor blackbody
- Emission from corona - powerlaw or Comptonization

A State Transition of the Luminous X-ray Binary in the Low-Metallicity Blue Compact Dwarf Galaxy I Zw 18

Philip Kaaret (Iowa) and Hua Feng (Tsinghua)

Reionization

- Reionization is usually ascribed to UV from low metallicity and very massive stars, but there are issues with escape of UV from the host galaxies.
- The collapse of massive stars produces “compact objects”, black holes or neutron stars. If a compact object is in a binary with a gaseous star, then it can produce X-rays via accretion.
- Mirabel et al. (2011) suggested that X-ray binaries may have helped reionize the universe because soft X-rays are more penetrating than UV, but need enhanced XRB formation.

Is X-ray binary formation enhanced under the conditions found in the early galaxies?

BCDs are Analogs to Early Galaxies

I Zw 18 (HST, Aliosi)

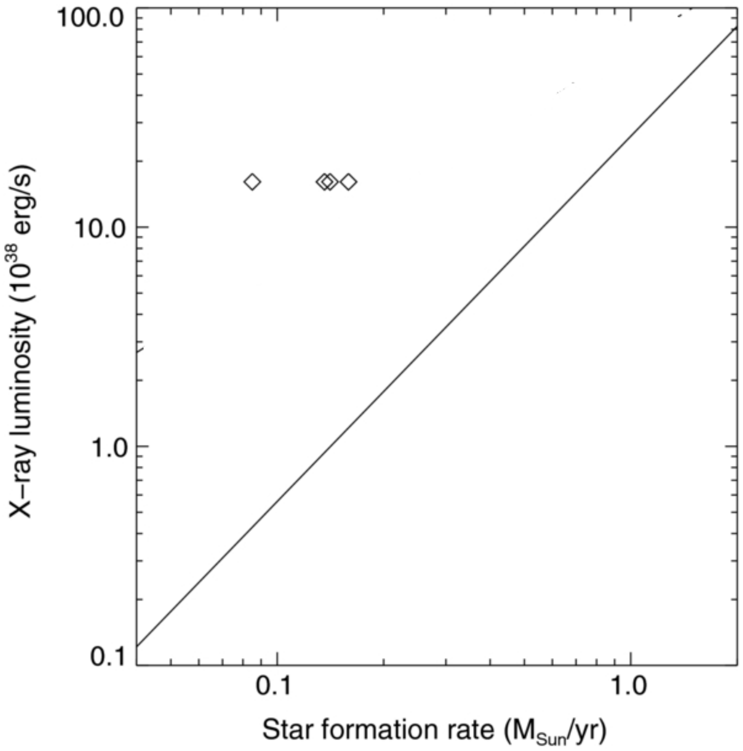
Blue Compact Dwarfs

- Large gas fraction
- Low metallicity (0.02 $Z_{\odot}$ for I Zw 18)
- Dominated by young stars
- Similar to early galaxies (lots of gas, few metals, young and massive stars)

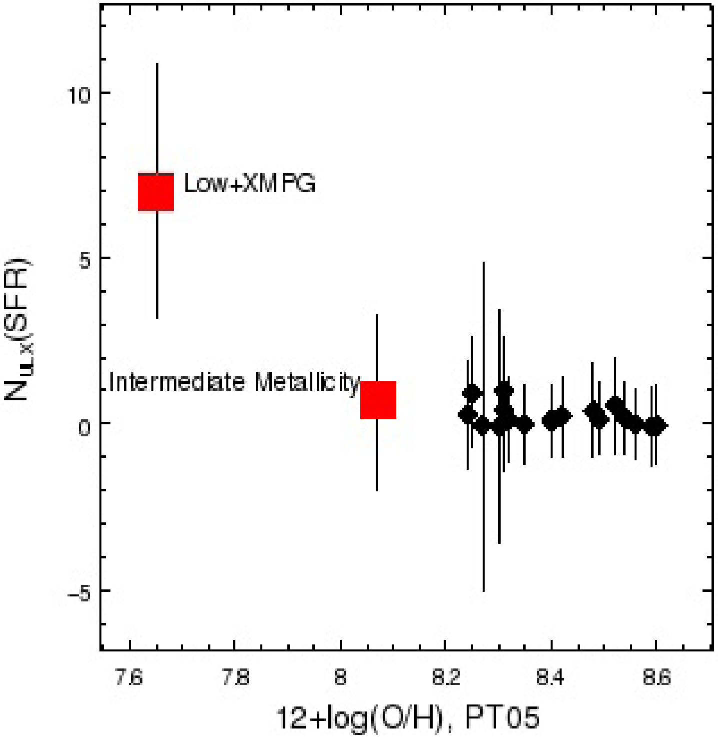
Is X-ray binary formation enhanced in BCDs?

XRBs at low metallicity

- X-ray binary production appears to be enhanced at low metallicity (Mapelli+ 2010, Kaaret+ 2011, Prestwich+ 2013).
- Provides support for theoretical predictions (Zampieri+ 2004, Dray 2006, Linden+ 2010, Fragos 2013).

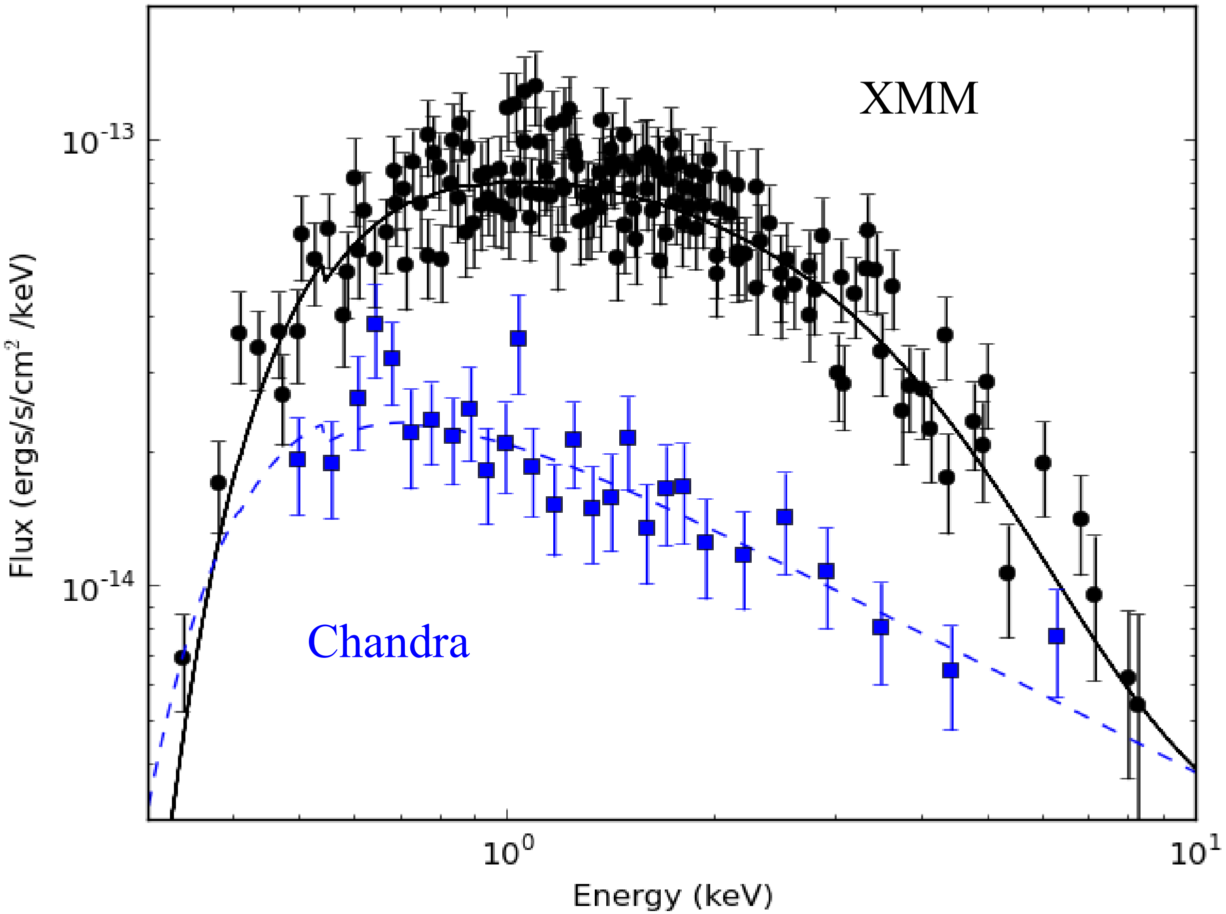


Kaaret, Schmitt, and Gorski 2011



Prestwich et al. 2013

X-Rays from I Zw 18



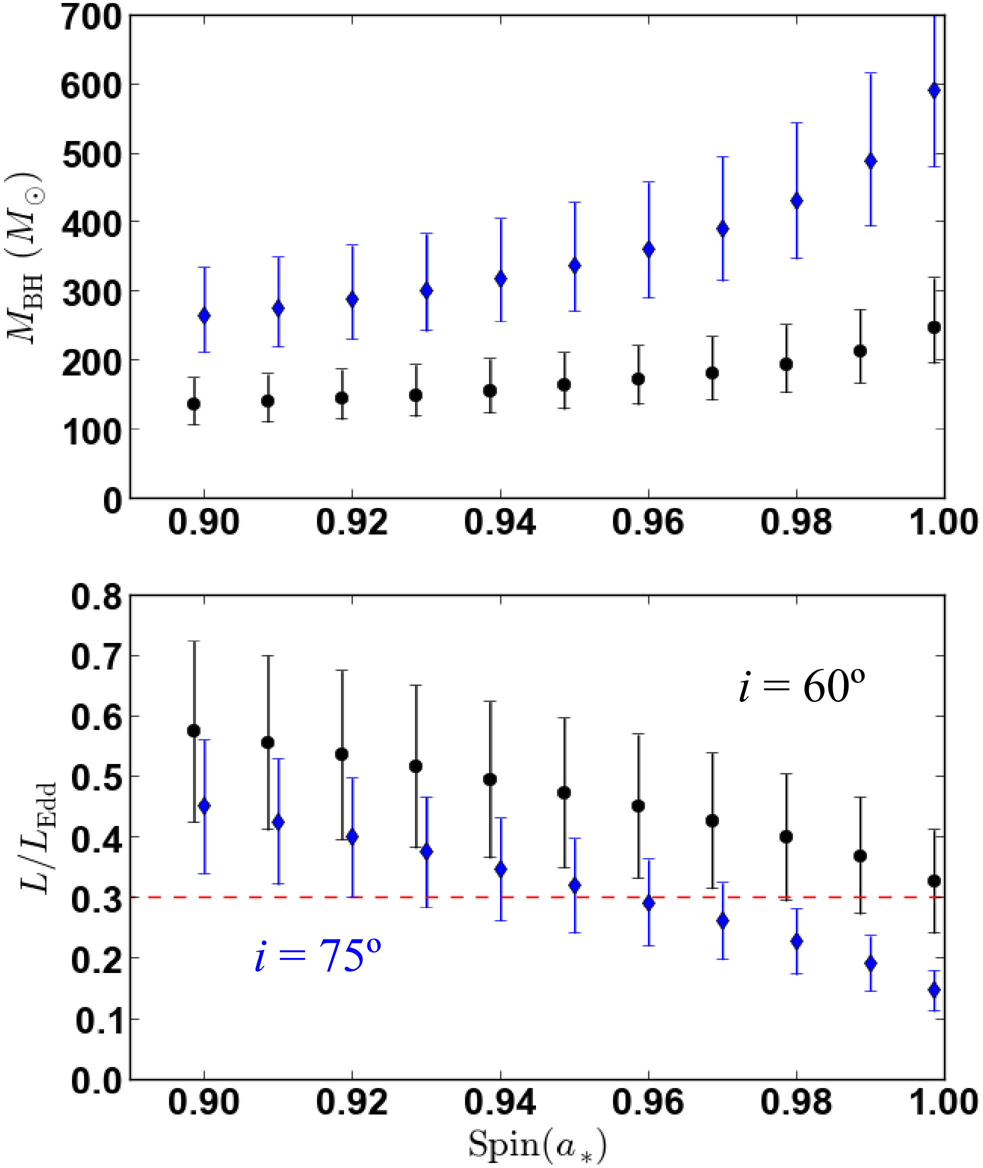
- **Low flux:** hard spectrum Γ = 1.9 ± 0.2, no evidence for curvature
- **High flux:** $L = 1\times10^{40}$ erg/s, disk makes 76% of flux (2-10 keV)
- States are similar to those of stellar-mass BH binaries
- ULXs spectra usually dominated by power-law/Comptonization, exceptions (M82 X-1, HLX-1) are good IMBH candidates
- Hard state luminosity suggests $M > 85\ M_\odot$

X-Ray Spectrum in Thermal State

- Thermal spectrum has temperature kT ~ 1 keV.

- Fits with simpl*kerrbb suggest rapidly rotating, massive black hole.

- Presence of an intermediate mass black hole in a BCD would be of great interest for supermassive black hole formation.



Conclusions

- The low-metallicity blue compact dwarf galaxy I Zw 18 contains an ultraluminous X-ray source.
- Its X-ray spectral states are similar to those of stellar-mass black hole binaries and suggest an unusually massive BH.
- X-ray binary production is enhanced at low metallicity. Thus, X-ray binaries may be important for reionization.
- X-ray study of analogs of early galaxies (BCDs, LBAs) is important to understand the thermal history of the universe and early galaxy formation.