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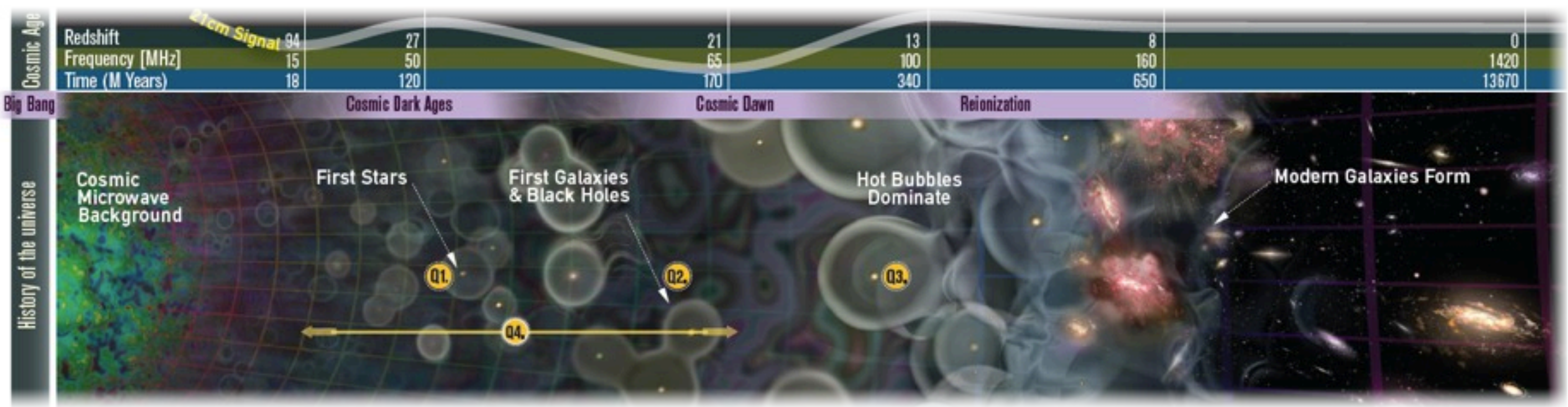
kapteyn instituut

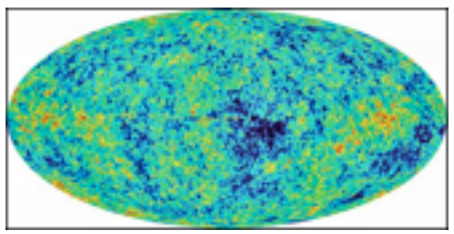
Discovering the Sky at the Longest Wavelengths - EoR & Dark Ages



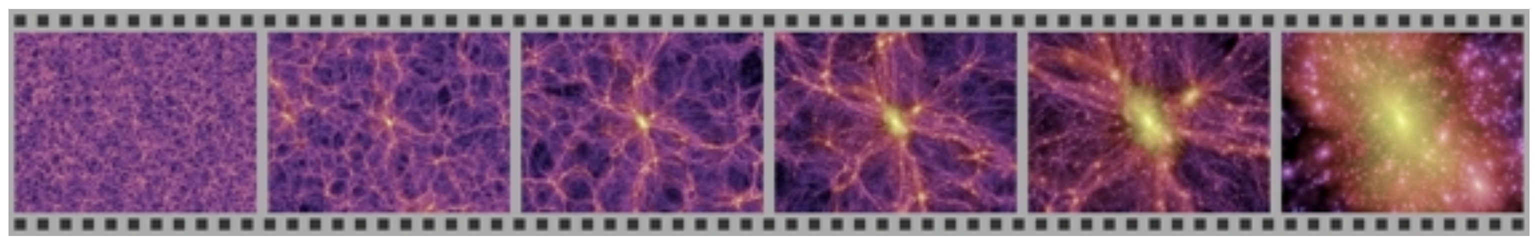
Prof. Léon Koopmans
(Kapteyn Astronomical Institute)

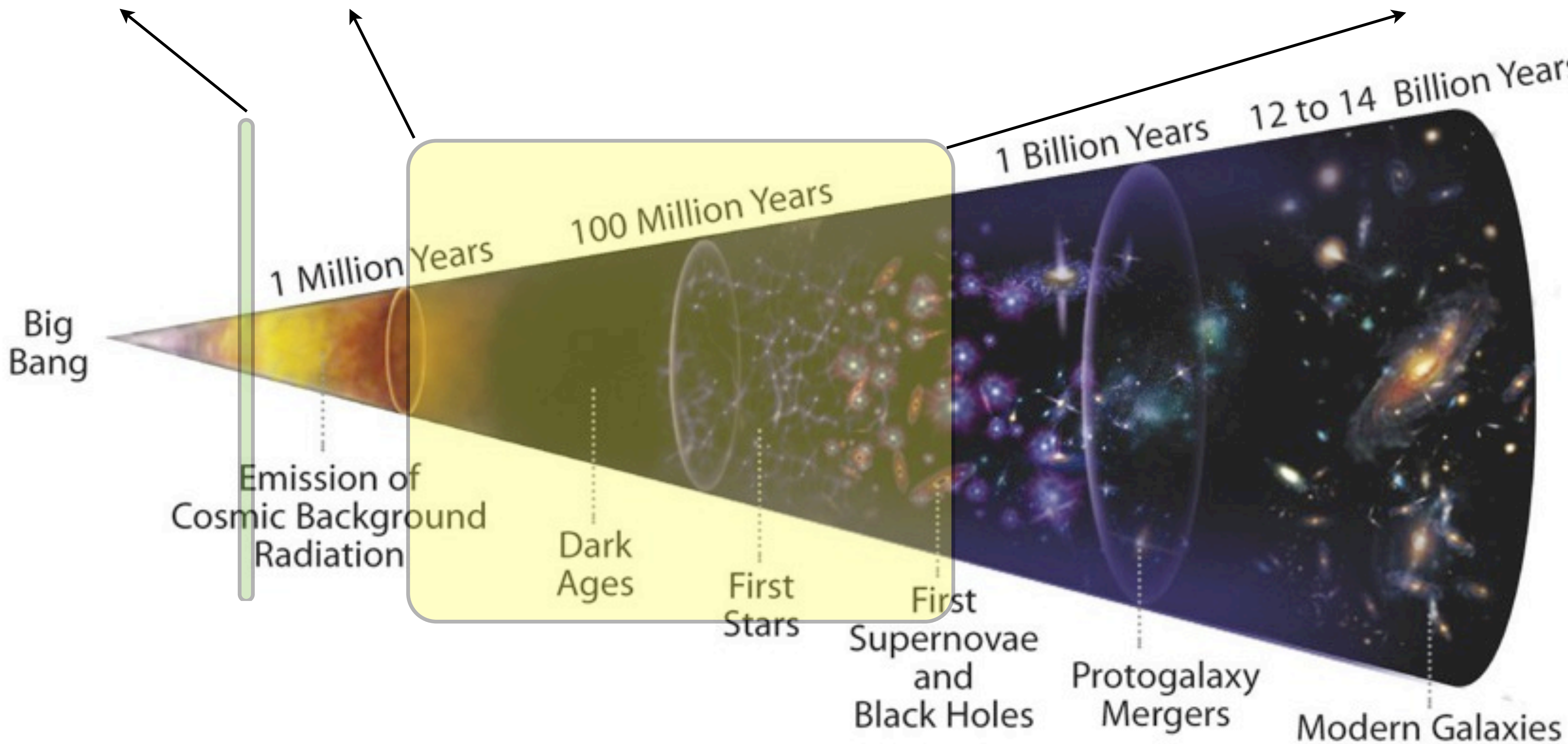
Dark Ages versus the CMB

CMB traces a single moment of the Universe. ~400,000 yrs

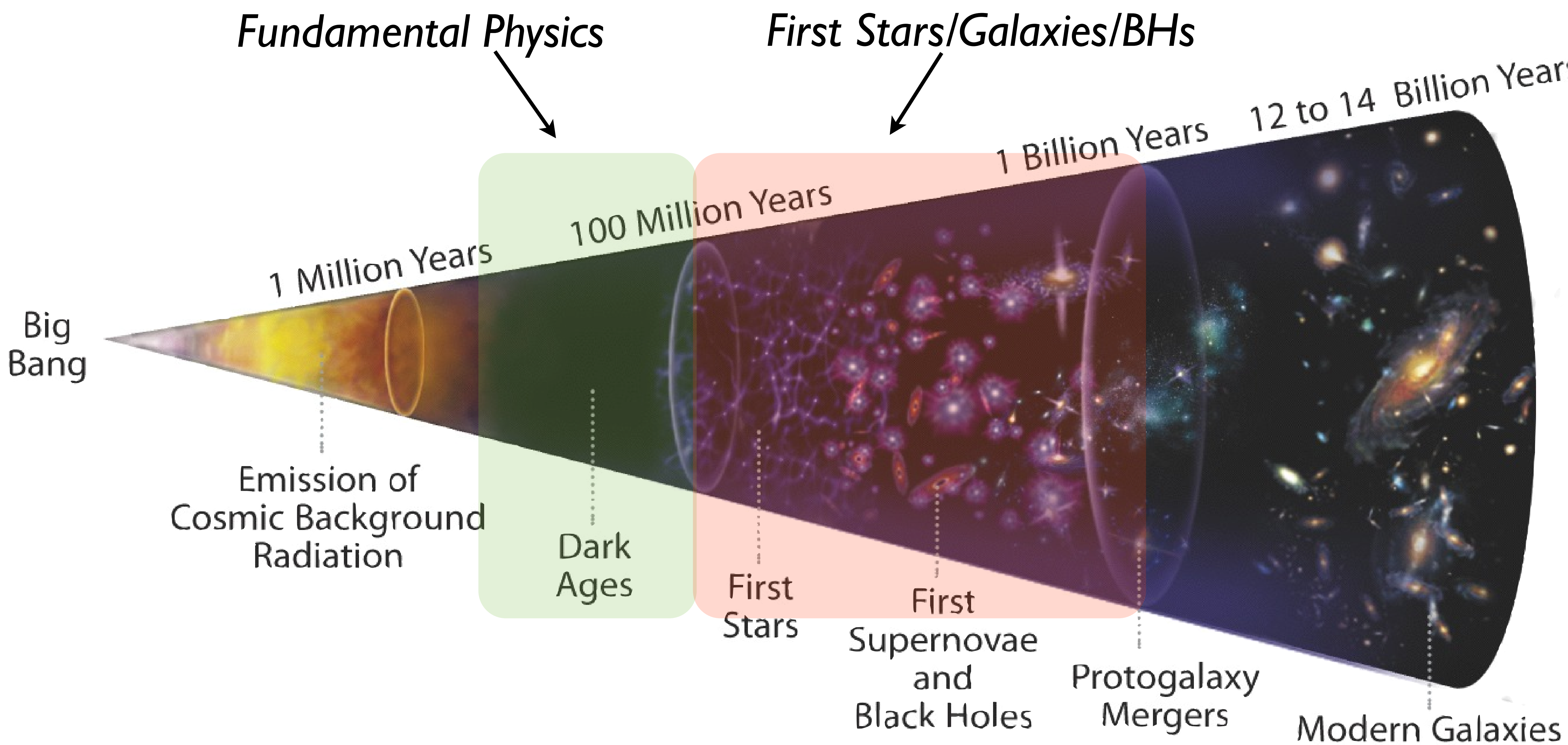


HI absorption from the Dark Ages traces an evolving "movie" of structure formation.





Cosmic Dawn and the Epoch of Reionization



After recombination, neutral hydrogen follows dark matter ("Dark Ages") and eventually forms the first non-linear structures, stars/mini-quasars that reionize hydrogen again ("Cosmic Dawn/Epoch of Reionization")

Studying the Global History of Hydrogen

DSL

Space

Ground

Dark Ages:

- z>200: spin temperature is coupled to the CMB and no HI signal is observed
- z=200-50: HI is seen in absorption against the CMB because spin temperature T_s couples to the gas kinetically and is lower than T_{CMB}; HI T_b fluctuations are sourced by density fluctuations

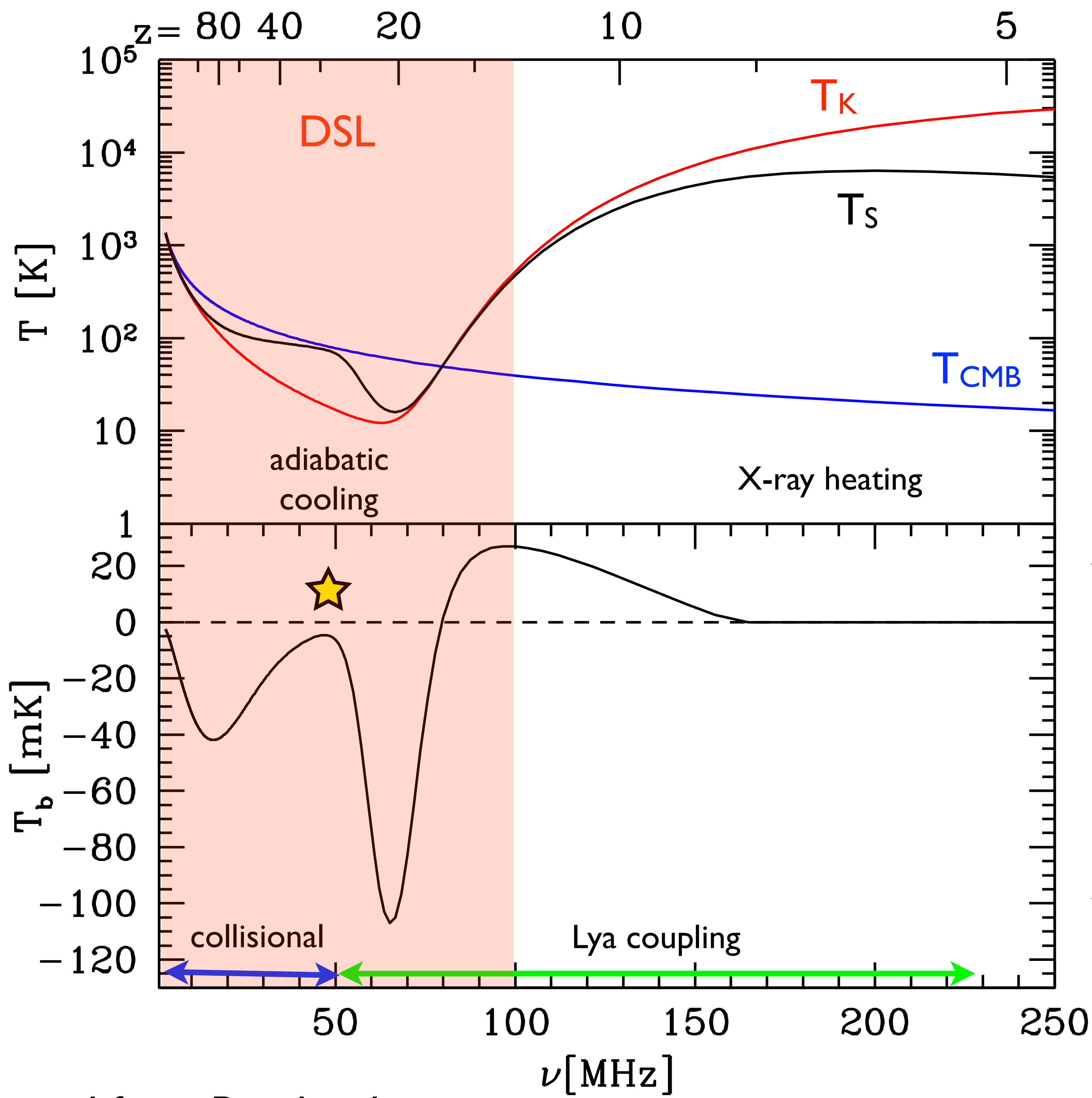
Cosmic Dawn:

- z~40: Kinetic coupling of T_s to T_{kin} becomes ineffective and T_s couples again to T_{CMB}; First sources (e.g. stars) appear and effect the gas through Lyα (Wouthuysen-Field effect) and X-ray heating.
- z~20: These effects couple T_s to T_{kin} again and HI is seen in absorption. Fluctuations are source by density and Lyα/X-ray flux fluctuations. After sufficient heating HI is seen in emission.

Reionization:

- z=15-6: Sources continue increasing and start ionizing the surrounding medium

The Global Signal of Neutral Hydrogen



Adapted from Pritchard

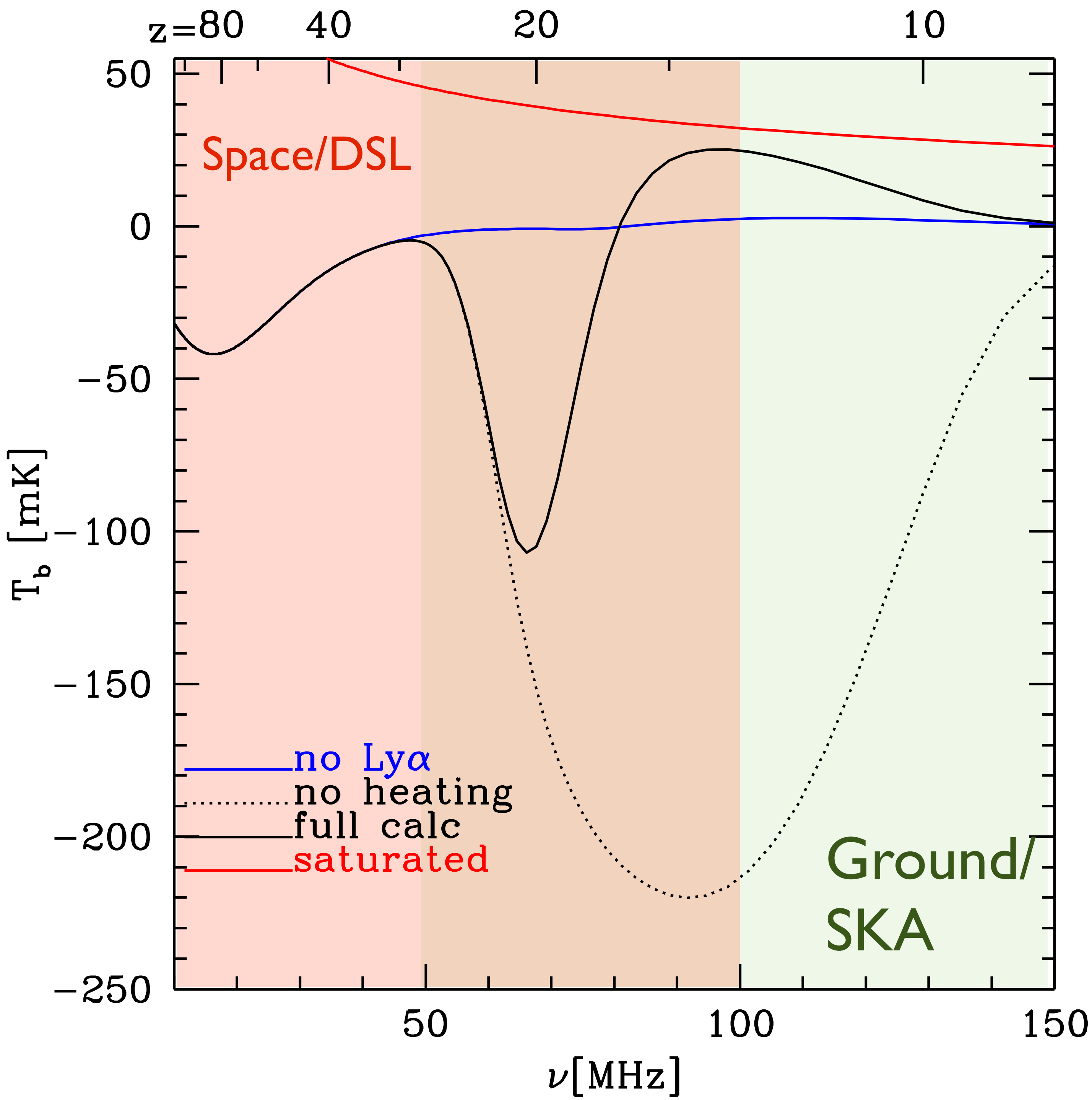
Main processes:

1) Collisional coupling
2) Lyα coupling
3) X-ray heating
4) Photo-ionization

Signal strength is roughly between -100 to +30mK.

But, foregrounds vary from 10^3 to 10^5 K @ z=15 to z=100.

The Global Signal of Neutral Hydrogen



Adapted from Pritchard

The physical processes during the Dark Ages, Cosmic Dawn and EoR are poorly known.

Whereas SKA can study the CD/EoR, the Dark Ages & early Cosmic Dawn at z>27, can only be studied with the other instruments: e.g. DSL

DSL covers the redshift range of the Cosmic Dawn and Dark Ages.

DSL: Required S/N

For a filled antenna/dish/dipoles, the sensitivity per BW and integration time is given by:

$$\delta T = \frac{T_{\rm sys}}{\sqrt{\Delta\nu t_{\rm int}}}$$

The Galactic FG dominates T_{sys} at low frequencies, for e.g. LOFAR:

$$T_{\rm sys} = 140 + 60 \left(\frac{\nu}{300\ {\rm MHz}}\right)^{-2.55}\ {\rm Kelvin}$$

The constant is the receiver temperature, which in general is negligible at low radio frequencies (<10% of T_{sky} for DSL).

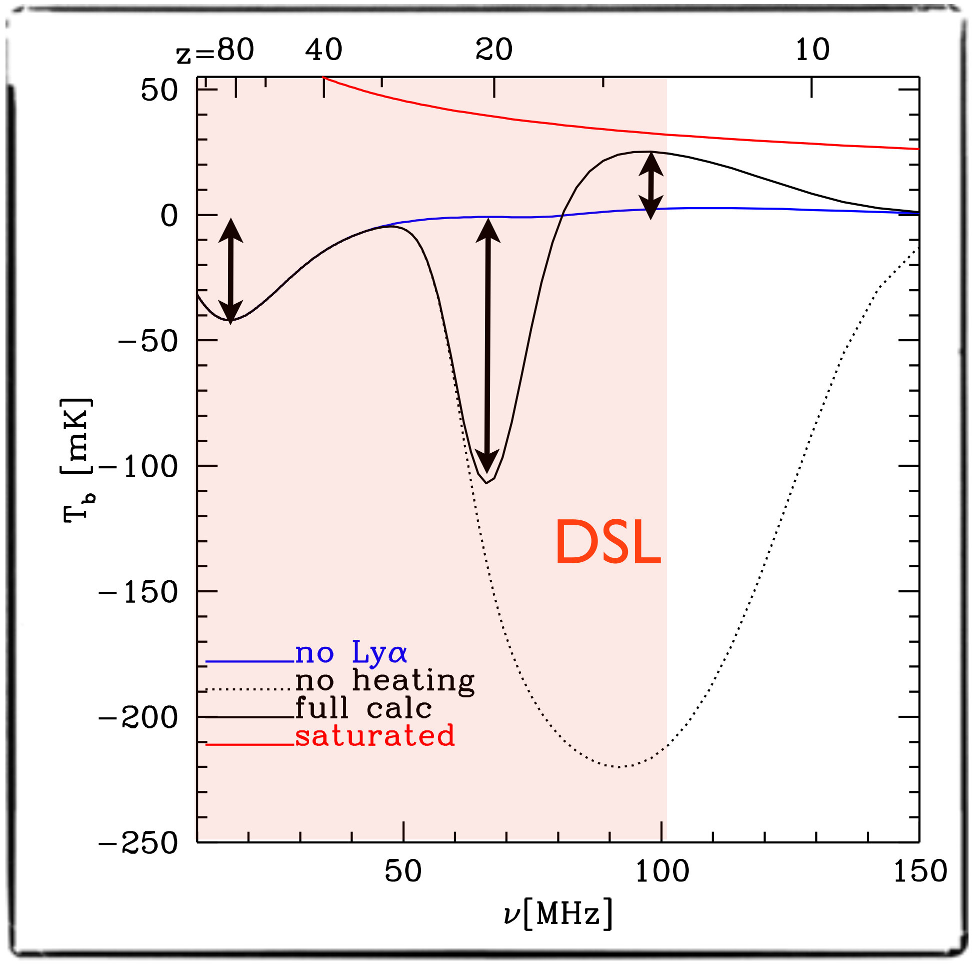
DSL: Required S/N

At ν~70/20 MHz, the system temp. $T_{sys} \sim T_{sky} \sim$ 2500/60000 K. One needs to reach ~10/5 mK for a 10-σ detection of a -100/-50 mK signal

The integration times can be approximated as follows:

$$t_{\rm int} = 17~{\rm hr} \times \left(\frac{\nu}{70~{\rm MHz}}\right)^{-5.1} \left(\frac{\Delta\nu}{1~{\rm MHz}}\right)^{-1} \left(\frac{\delta T}{10~{\rm mK}}\right)^{-2}$$

$$t_{\rm int} = 170~{\rm day} \times \left(\frac{\nu}{20~{\rm MHz}}\right)^{-5.1} \left(\frac{\Delta\nu}{10~{\rm MHz}}\right)^{-1} \left(\frac{\delta T}{5~{\rm mK}}\right)^{-2}$$



Hence if the width of the signal exceed ~1/10 MHz, one can reach ~10/5 mK in t_{int} less than one day/year, but the required spectral DR ~ 10^7 needs an extremely accurate band-pass calibration. This is one of the major challenges of ALL (ground/space based) low-frequency global-signal experiments.

The Global Signal of Neutral Hydrogen

	Name	Freq. Range	Instrument
Ground	LOFAR	10/30-80 MHz	Ground Interf.
Ground	LEDA	20-80 MHz	Ground Interf.
Ground	EDGES	90-205 MHz	Single Dipole
Ground	CORE	50-250 MHz	Dual Dipole
Space	DARE	40-120 MHz	Moon-orbiting Two Dipoles
Space	DSL	0.3-100 MHz [?]	Lunar/Space(L2)

Specs	Earth	Lunar/Space(L2) Orbit	Pros for going to Lunar/Space(L2) orbit
Sensitivity	Thermal level can be reached	Thermal levels can be reached	No ionospheric cutoff below 5-10 MHz
Di/tripole time dependent gain variations	Slow variations with temperature and humidity.	Relatively stable, but relatively unimportant in signal detection.	Space environment (T_{sys}) is more stable.
Ionosphere Refraction/ diffraction	Refraction, diffraction and absorption	None	No effects of the ionosphere
Radio Frequency Interference	Severe, but manageable above 30 MHz with high time/freq. resolution in (semi)remote areas. Self-RFI might be issue.	Very low levels, but possibly -80dB needed around z=80. Self-RFI has to be suppressed.	Far less RFI if shielded from the Earth. High time-freq. resolution might be critical though (1s-1kHz).
Sky*Beam model variations	Causes frequency variations in the dynamic spectrum. Mitigated through combination with interferometry.	Use sky models extrapolated to low frequencies. Lunar environment might change the beam.	Interferometric cross-checks, but time-variations are small, because the sky rotates slowly in the beam.
Bandpass gain variations	Noise loads required, but receiver noise (after LNA) might be the limiting factor.	Noise loads required. Understanding of receiver noise is also required.	Similar as on Earth.

Conclusions

(1) To observe the Dark Ages and (early; z>30) Cosmic Dawn, a space mission is needed with several years lifetime (long integrations).

(2) The 21-cm signal is the only known observable from the Dark Ages and probes the physics of the Universe just after recombination.

(3) Only the global 21-cm signal can (currently) be observed. It requires an extremely accurate (1:10^{6-7}) bandpass calibration, which can only be reached in space (w/stable environment, no ionosphere, RFI shielding).

(4) DSL can detect a signal from the Dark Ages in ~170/$\sqrt{N}$ days (N being the number of independent receivers), but the frequency coverage should be from few MHz go up to ~100MHz to cover the full 21-cm spectrum from the Dark Ages up to the EoR.

High-risk high-gain science: DSL specs closely match a global CD/EoR science case, if bandpass calibration to 1:10^7 can be achieved over ~10-100MHz for one or more receivers. It fits inside the mission lifetime. Long baselines can help spectral calibration and control spectral leakage.