When & where was first light and how can we look for it: introduction to conference and session 1

Other Conference Item

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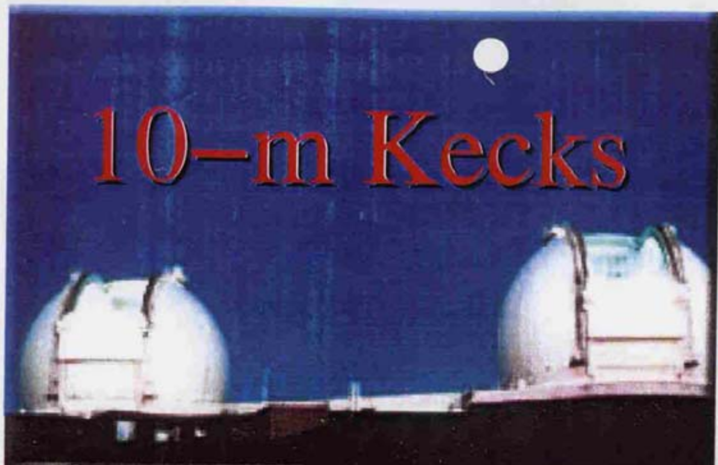
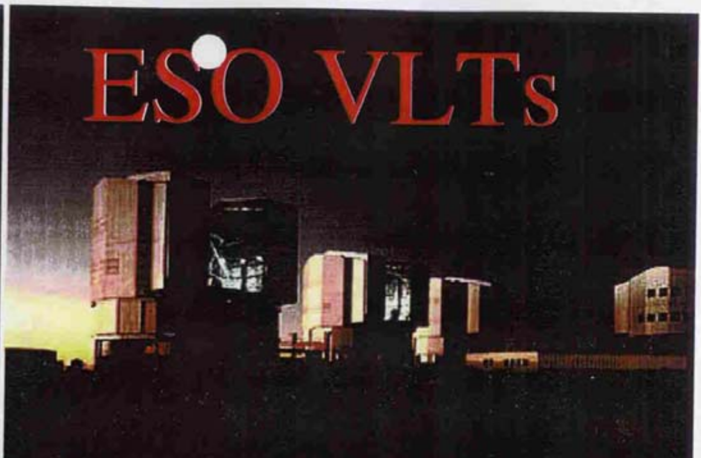
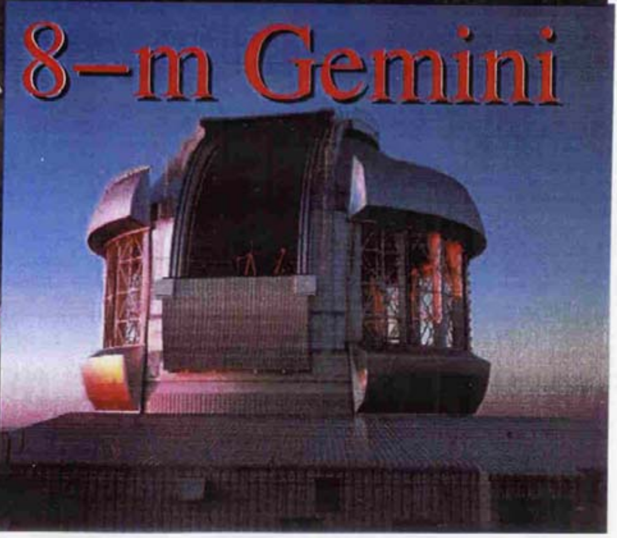


10–m Kecks

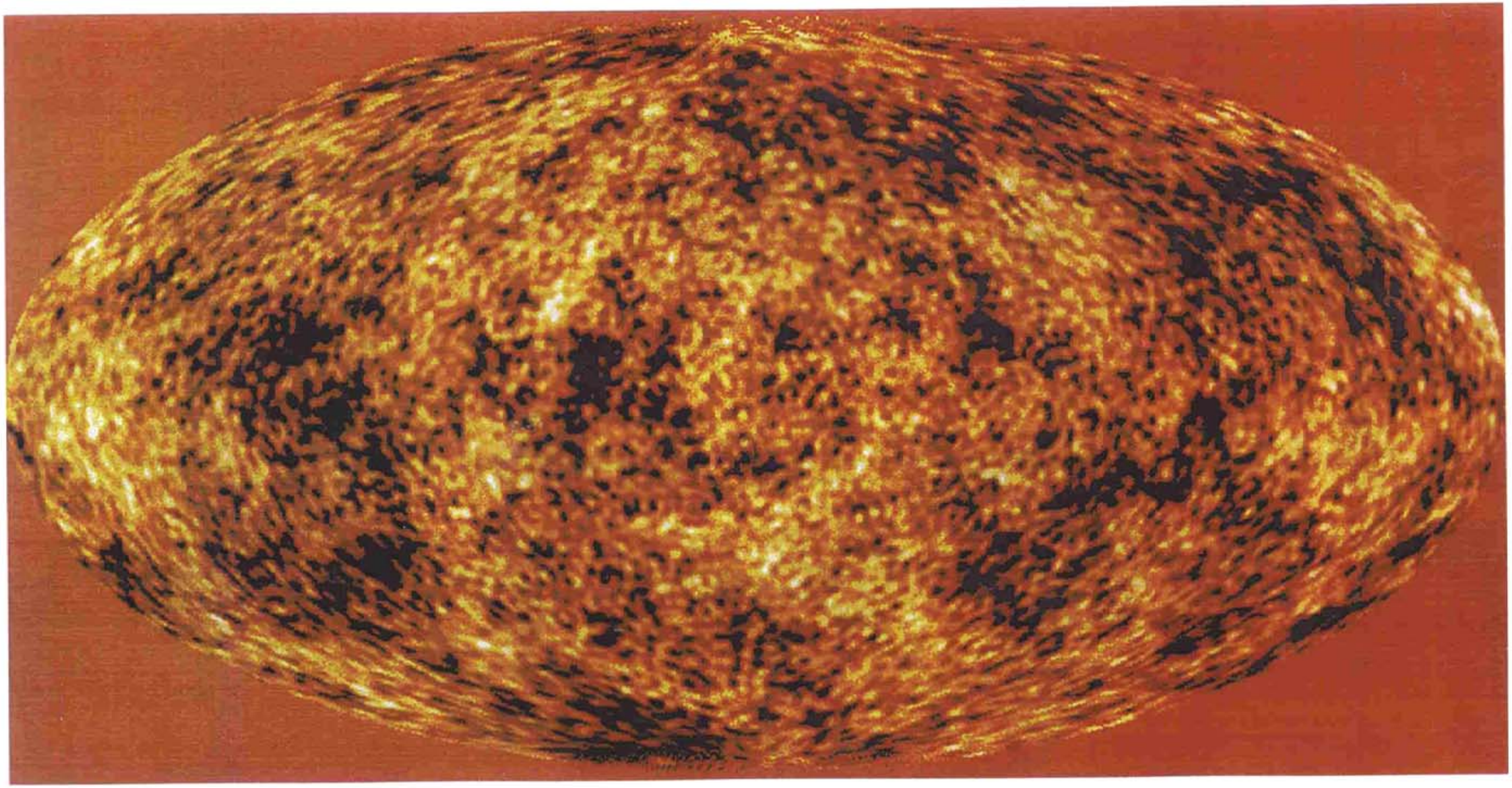


ESO VLTs

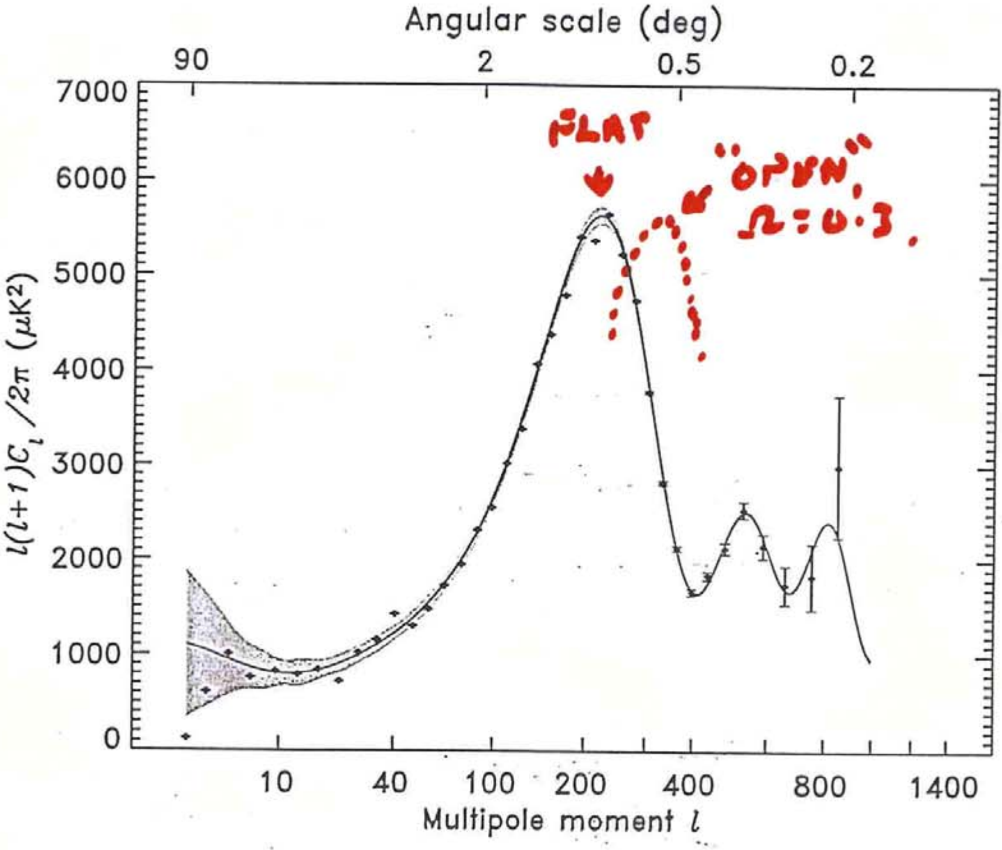
Photo©Neelon Crawford/Polar Fine Arts



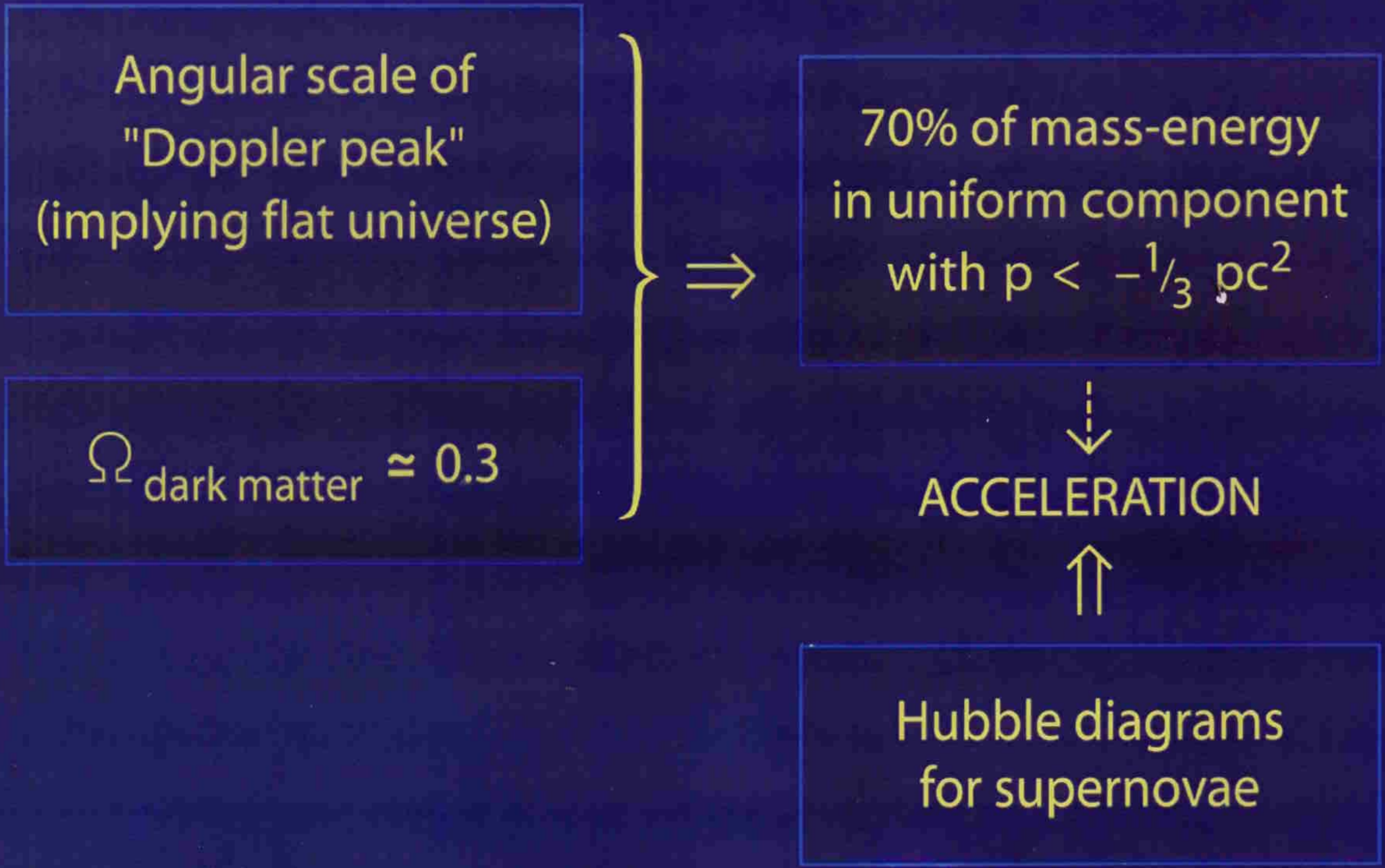
8–m Gemini



FIRST-YEAR "W-MAP" DATA



Hinshaw et al 2003



Angular scale of
"Doppler peak"
(implying flat universe)

$\Omega_{\text{dark matter}} \simeq 0.3$

$\Rightarrow$

70% of mass-energy
in uniform component
with $p < -{}^{1}\!/_{3}\,\rho c^2$

ACCELERATION

$\Uparrow$

Hubble diagrams
for supernovae

We live in a "flat" universe, in which the present-day mass-energy is made up of:

~ 5 % baryons

~ 25 % 'dark matter'

~ 70 % 'dark energy'
$(p < -\frac{1}{3}\rho c^2)$

Present-day structure seems to have evolved from initial 'curvature fluctuations' of amplitude $\sim 10^{-5}$

COSMIC BARYONS

- Stars and their remnants

(Gas in galaxies)

< 0.01

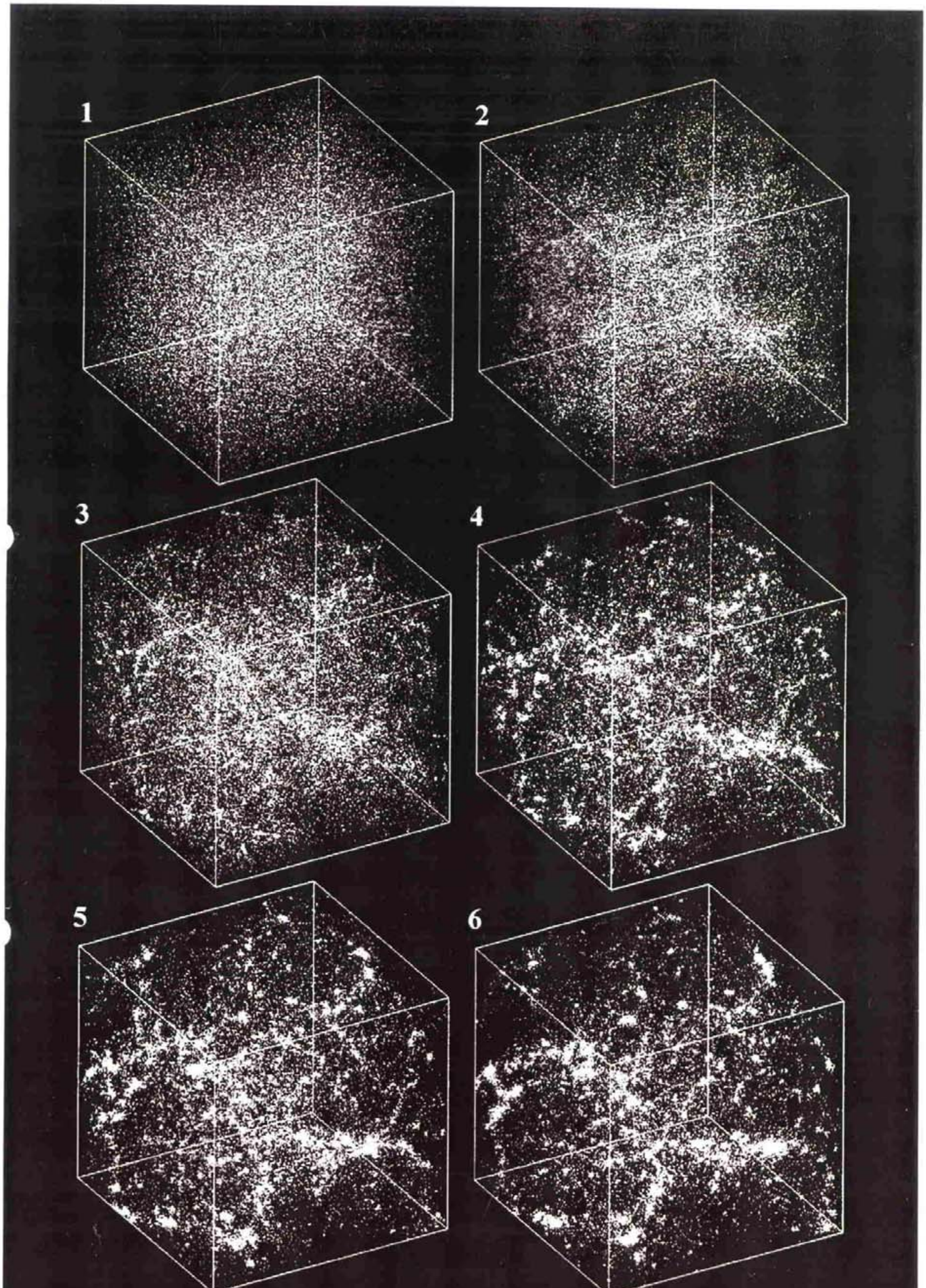
- Intergalactic gas:
  - Clouds and filaments
    ⇒ *Lyman alpha forest*
  - 'Warm' gas in groups of galaxies
    ⇒ *soft x-rays*

  Hot gas in clusters
    ⇒ *kev x-rays*
    S-Z effect

Big bang He and D abundances

$$\Omega_b \approx 0.02 \times h^{-2}$$

Limited scope for 'dark' baryons.



Schaye 2000

WHAT HAPPENS TO GAS IN DARK-MATTER HALOS?

How much gas falls in?

What is its angular momentum?

Can it cool?

Does cool gas make stars?

What parameters determine IMF?

How important is negative feedback from stellar winds and supernovae? (and from nucleus?)

How do mergers affect star formation, discs, etc?

What are the effects of cluster environment?

STRUCTURE FORMATION AND EVOLUTION: CAN THEY BE ADEQUATELY SIMULATED?

Gravitational effects

well enough

Gas dynamics (including shocks and radiative processes)

probably well enough

Early star formation

possibly well enough

Feedback from stars and AGNs

always a need (though one hopes diminishing) for parameter-fitting

Goal is to:

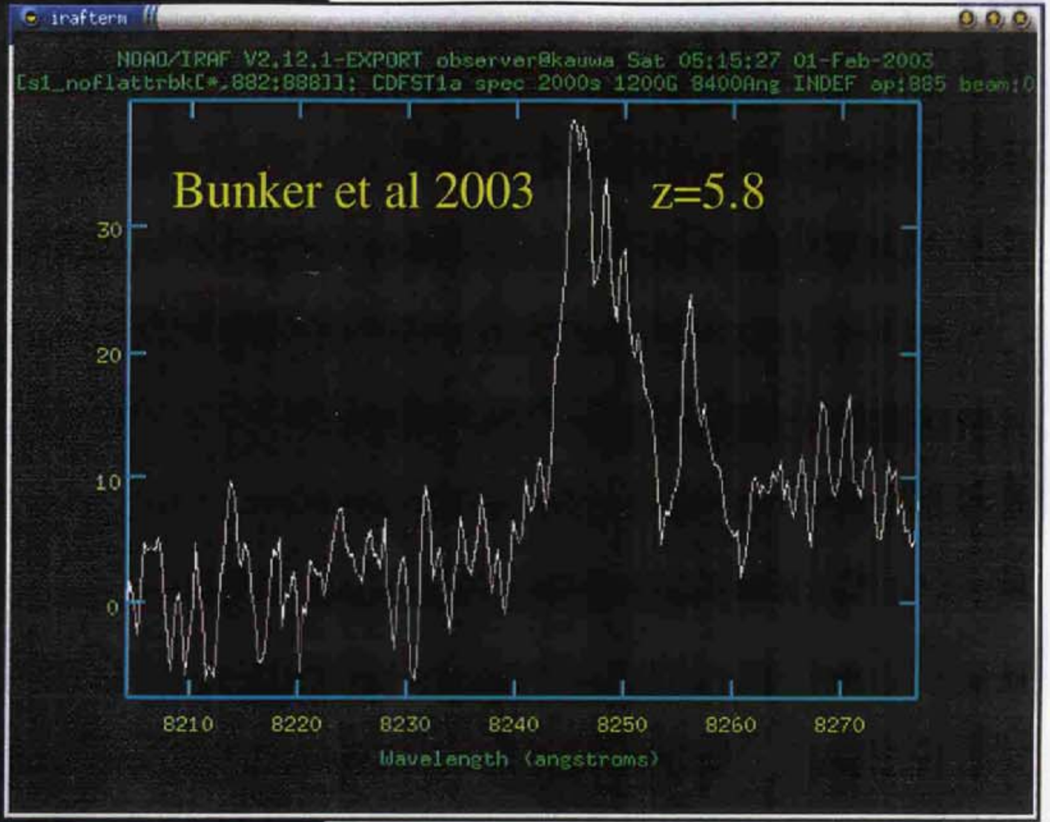
(1) Match luminosity functions, morphology statistics, clustering properties etc *at present epoch*

(2) Trace how these quantities have change with redshift, *back to largest possible z*

Rapid advances are due to :

- *LARGE-SCALE SURVEYS,*
- *POWER OF 8M-CLASS TELESCOPES.*

The Star Formation History of the Univese



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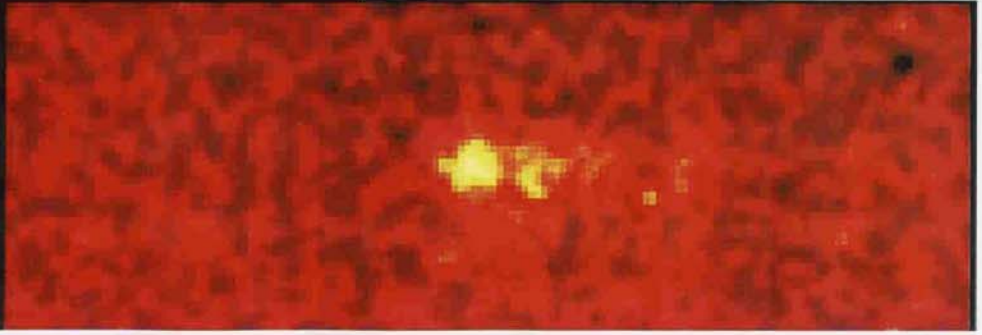


I–drops in the Chandra Deep Field South with HST/ACS
Elizabeth Stanway, Andrew Bunker, Richard McMahon
2003 (MNRAS)

ULTRA-HIGH REDSHIFT QUASARS

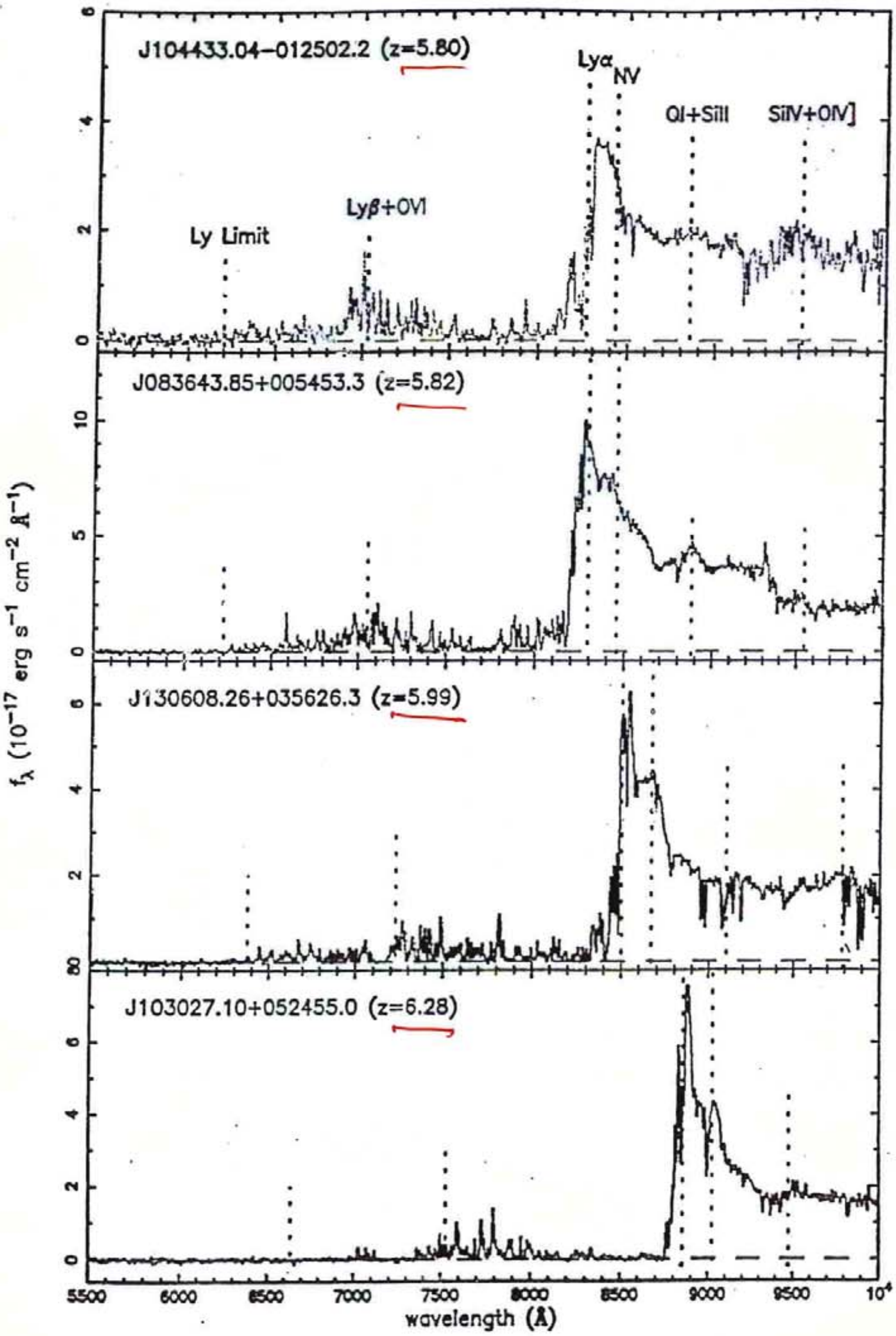
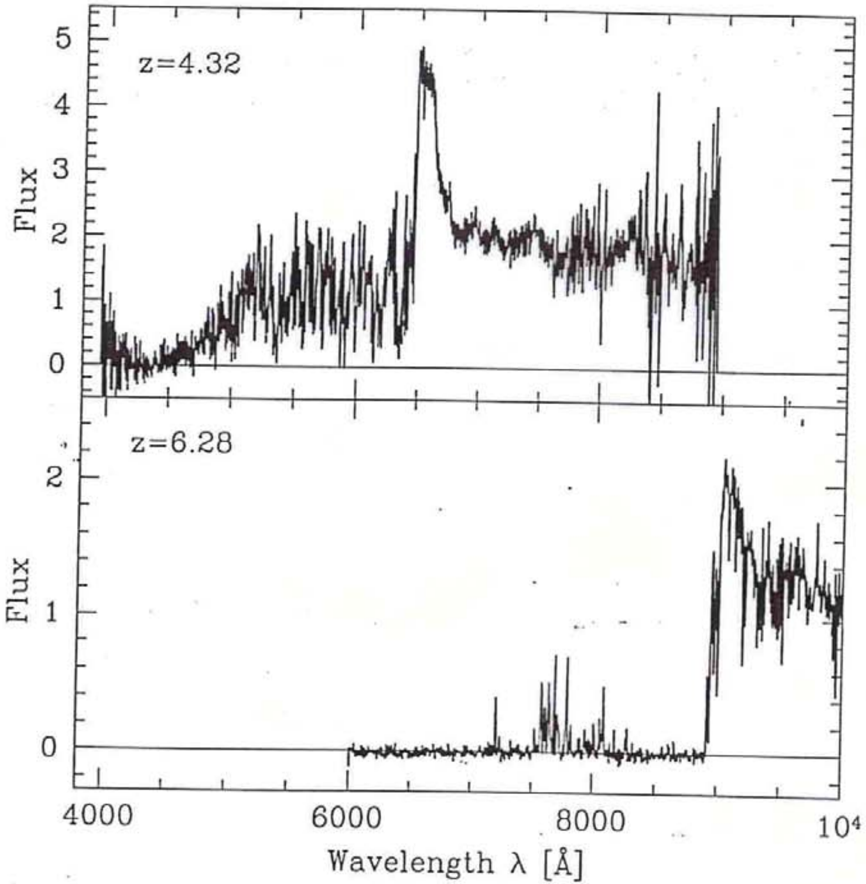


Figure 10: Optical spectra of four very-high redshift quasars

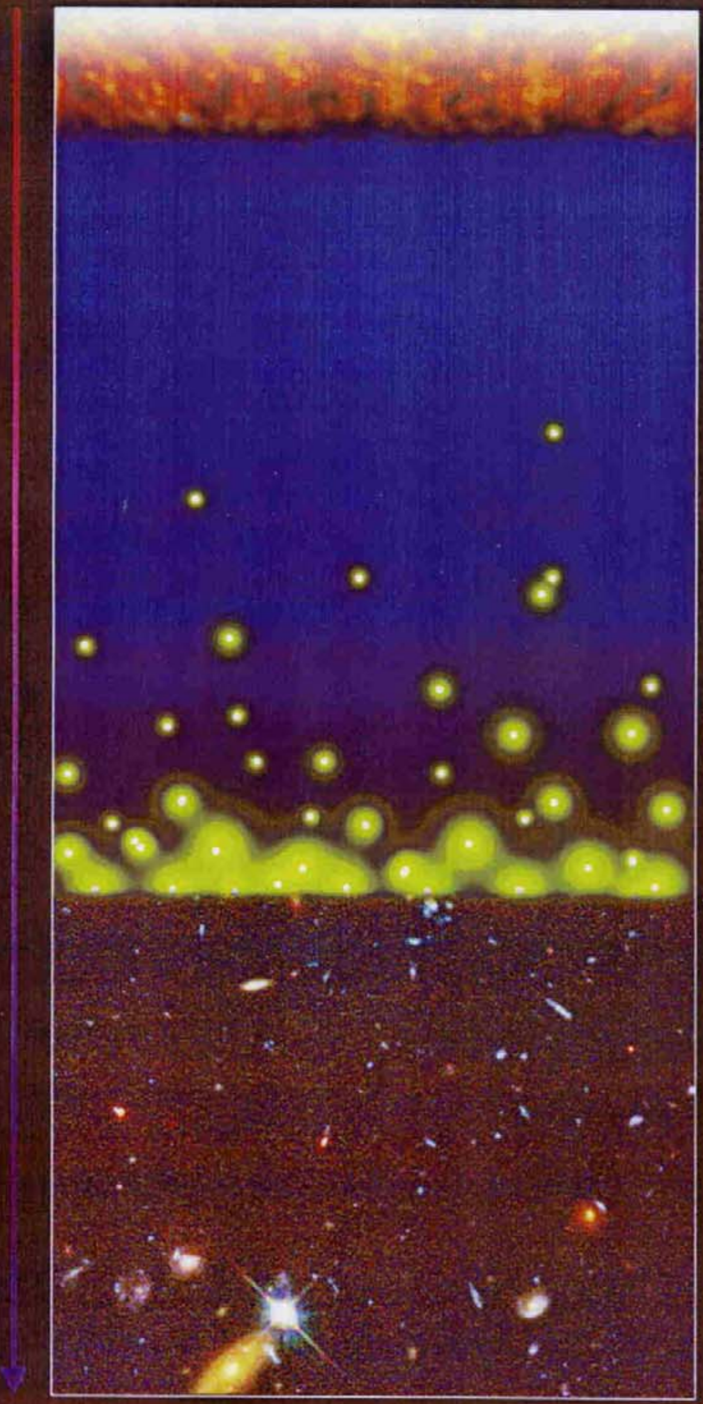
Becker et al (2001)
Fan et al (200



(Fan et al 2001, 2003)

What is the Reionization Era?

A Schematic Outline of the Cosmic History



Time since the Big Bang (years)

~ 300 thousand

~ 500 million

~ 1 billion

~ 9 billion

~ 13 billion

← The Big Bang

The Universe filled with ionized gas

← The Universe become neutral and opaque

The Dark Ages start

Galaxies and Quasars begin to form
The Reionization start

The Cosmic Renaissa
The Dark Ages end

← Reionization complete the Universe becomes transparent again

Galaxies evolve

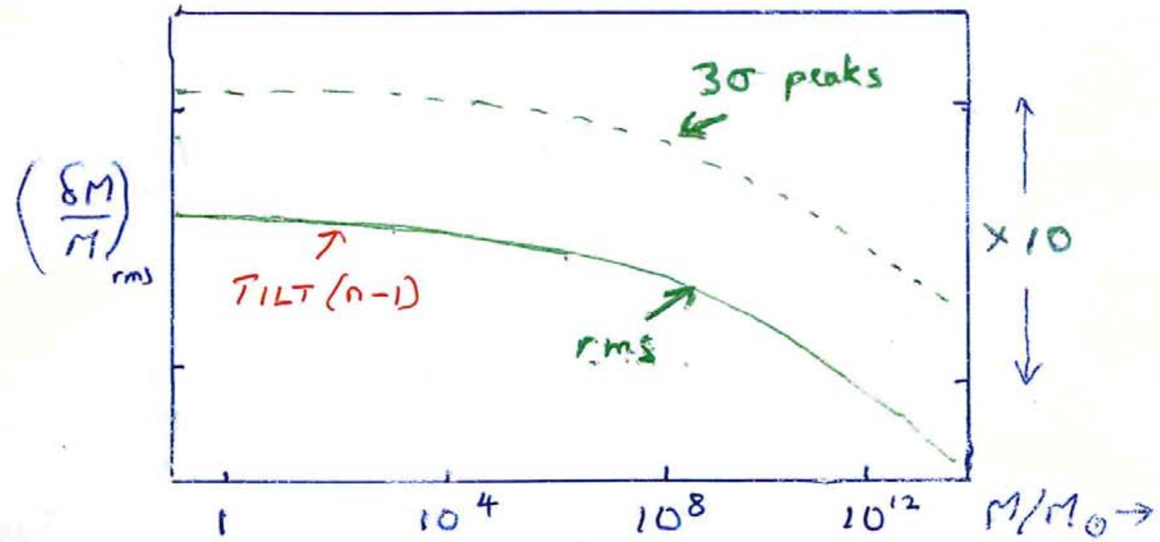
The Solar System forn

Today: Astronomers figure it all out!

S.G. Djorgovski et al. & Digital Media Center, Caltech

SMALL-SCALE STRUCTURE IN CDM

In "standard CDM" models, $\left(\frac{\delta M}{M}\right)_{rms}$ of form:



First non-linearities develop at $z \lesssim 30$ (from $\gtrsim 3\sigma$ peaks). Scale of structure in CDM builds up rapidly from $< 1\,\mathrm{M}_\odot$ to $\gtrsim 10^6\,\mathrm{M}_\odot$, with "crosstalk" between scales.

A dark-matter clump virialising at redshift z has:

$$T_{virial} = 10^4 \mu \left(\frac{M}{10^7\,\mathrm{M}_\odot}\right)^{\frac{2}{3}} \left(\frac{1+z}{20}\right) K.$$

$$V_{virial} = 13 \left(\frac{T_{virial}}{10^4 K}\right)^{\frac{1}{2}} \mu^{-\frac{1}{2}}\,\mathrm{km\ s}^{-1}$$

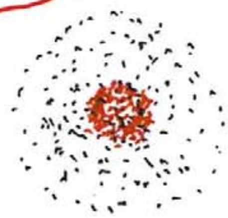
(μ is mean molecular weight)

FATE OF THE FIRST BOUND SYSTEM

$(z \simeq 20)$

$$\boxed{T_{\rm virial} \propto M^{2/3} (1+z)_{\rm coll}}$$

$10^4 M_\odot$

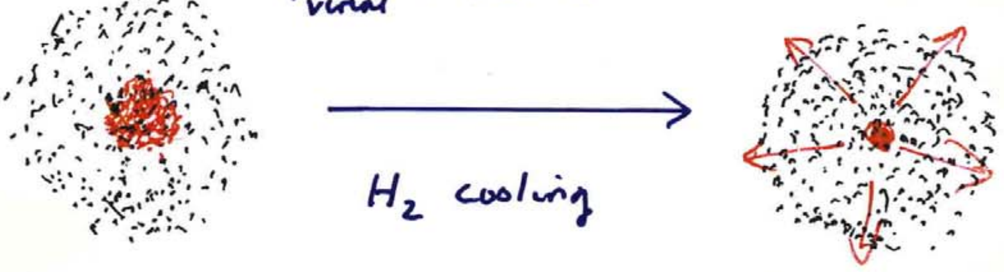


$T_{\rm virial} \simeq 50\,\rm K$

No cooling; no star formati

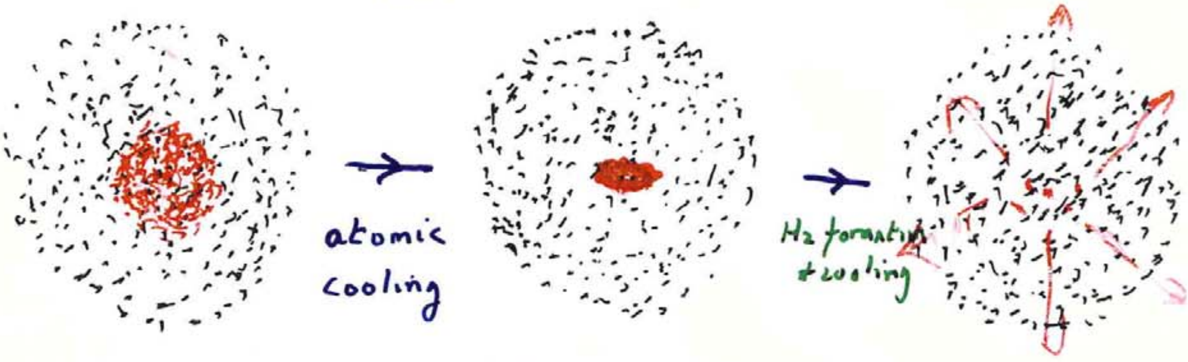
$10^6 M_\odot$

$T_{\rm virial} \simeq 10^3\,\rm K$



$10^8 M_\odot$

$T_{\rm virial} \simeq 20000\,\rm K$



FEEDBACK EFFECTS ON H_2 ABUNDANCE

1. Negative

Photodissociation by photons with

energy 11.5--13.5 ev *

* These propagate through neutral IGM.

2. Positive

X-rays and far UV raise n_e

and enhance formation via H^-

The ratio of positive/negative feedback depends on the ratio of 'quasar'/star contributions to the background before photoionization occurs.

Machacek, Bryan + Abel 2002

FIRST STARS contrasted with 'RECENT' STARS

Formation conditions

(i) Higher temperature in clouds
because:

No cooling due to heavy elements (or dust)

Ambient temperature of CMB is 2.73 $(1+z)$K

Since $M_{\text{Jeans}} \propto T^{\frac{3}{2}} \rho^{-\frac{1}{2}}$ this implies:

Higher masses for given ρ.

But higher T implies reduced opacity,
so ρ gets higher before radiation is trapped.

(ii) No dynamically-significant B-field (probably)

This tends to reduce characteristic masses

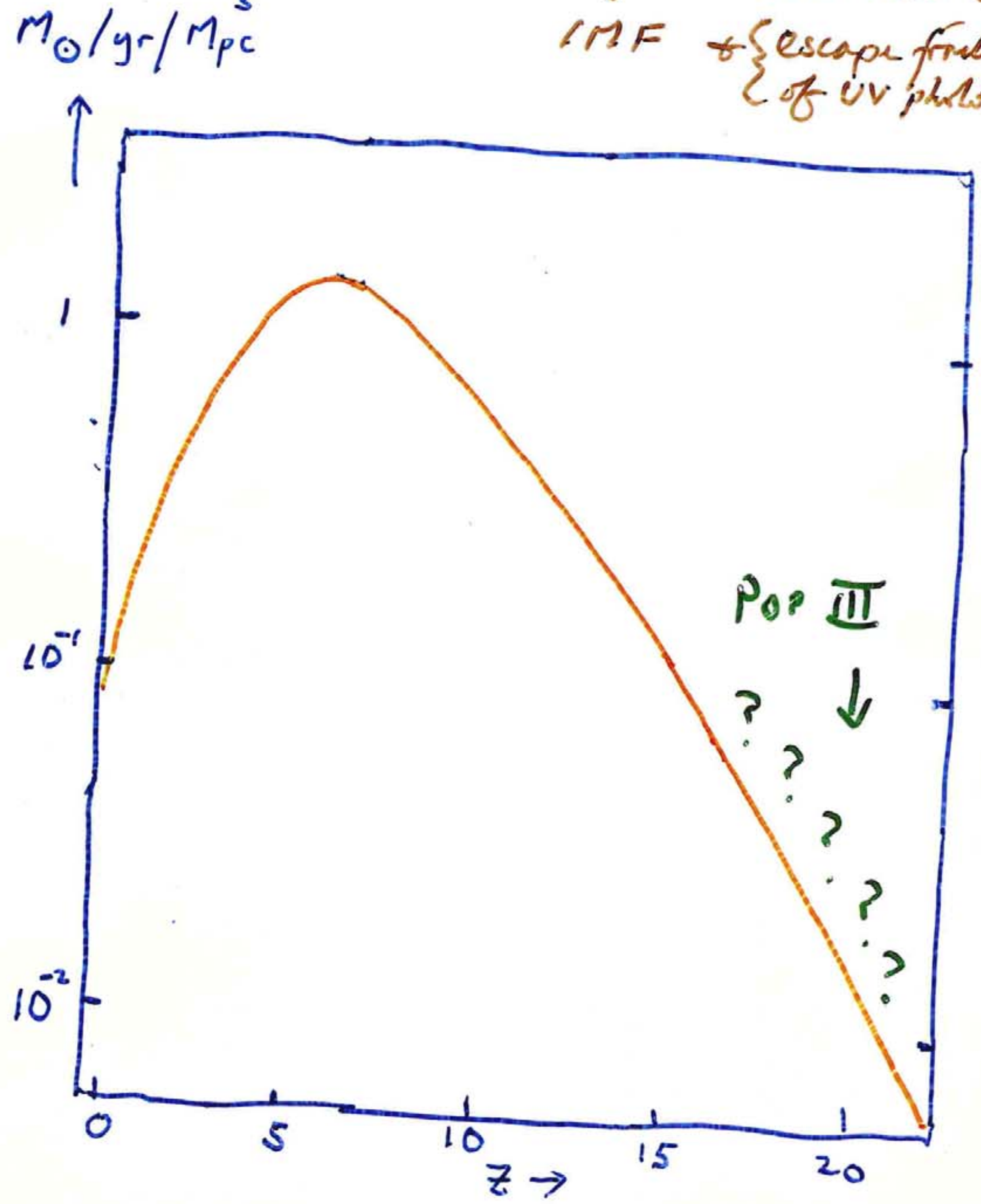
Net effect on IMF is NOT OBVIOUS!

Main sequence properties

No CNO cycle implies hotter centres
$\Rightarrow$ smaller radii
$\Rightarrow$ hotter surfaces
for given mass.

THEORETICAL STAR-FORMATION RATE

Ionization rate also depends on IMF + {escape fraction of UV photons}*



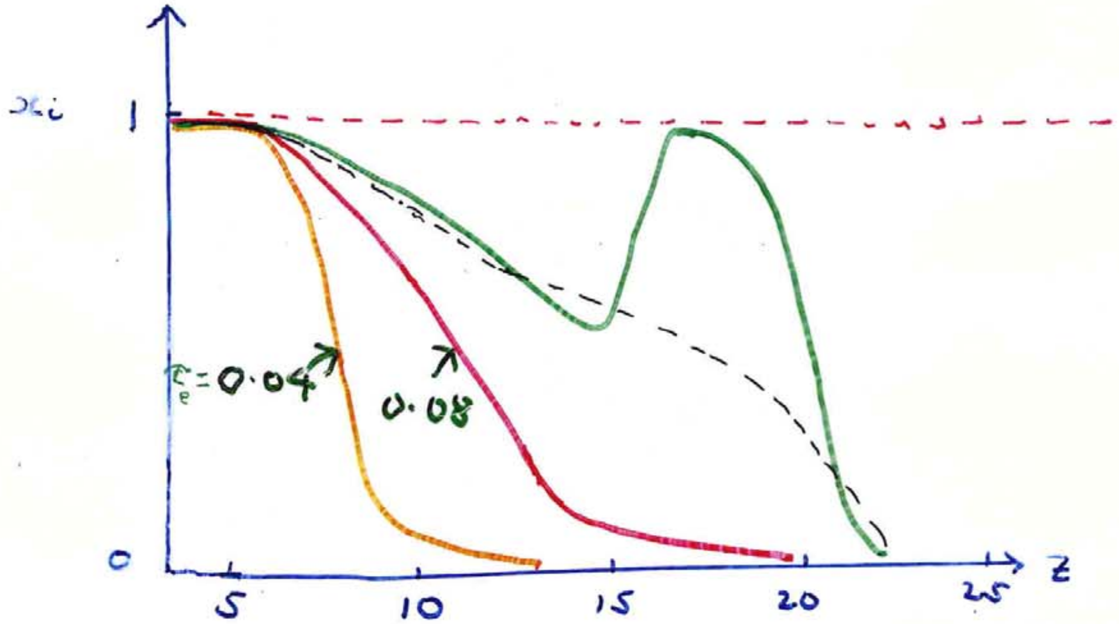
* depend on z

Hernquist & Springel 2002

PROBING IONIZATION HISTORY AT z > 6

QSO spectra tell us that H ionization is < 99.9% for z> 6.3. But at what z does it drop below 50%?
and when does it drop close to zero? *

Examples:



* In standard CDM models, no energy input at z > 30-40

Probes via:

- Detecting ultra-high z objects (small galaxies at z= 10, SN or gamma-ray bursts out to z>20)
- 21 cm line emission from inhomogeneous gas
- CMB fluctuations (especially polarisation at $\ell \lesssim 20$

IMPLICATIONS OF WMAP POLARIZATION DATA.

If $\tau \simeq 0.17$*

$$\left\{\begin{array}{l}\text{Number of photoionizations}\\ \text{per baryon}\end{array}\right\} \simeq 4 \left\{\begin{array}{r}\text{clumping factor}\\ \text{of ionized gas}\end{array}\right\}$$

To provide this level of early ionization, and yet have Gunn-Peterson absorption at z as low as 6, requires that UV photoionization cannot "track" star formation rate predicted by best-fit CDM models, but must be more efficient at $z \gtrsim 10$

But many (indeed most) scenarios predict more efficient ionization at high z.

No serious conflict**

* ± 0.04, and dependent on tilt n of fluctuation spectrum

**unless $n < 0.95$ (large tilt)

IONIZATION EFFICIENCY

UV (from hot stars)

Depends on:

(Proportion of baryons collapsing into minihalos.)

× (Fraction of baryons in minihalos that turns into stars)

× (UV emission per solar mass (function of IMF))

× (Fraction of UV that escapes star's dense environment.)

Ionization by X-rays *(From SN shells, accreting Pop III remnants or miniquasars)*

In comparision with UV:

--- more energy needed per (photo+secondary) ionization

---but escape into low-density IGM is guaranteed, so ionizations less quenched by recombinations.

21 cm RADIATION: A PROBE OF PARTIALLY-IONIZED GAS

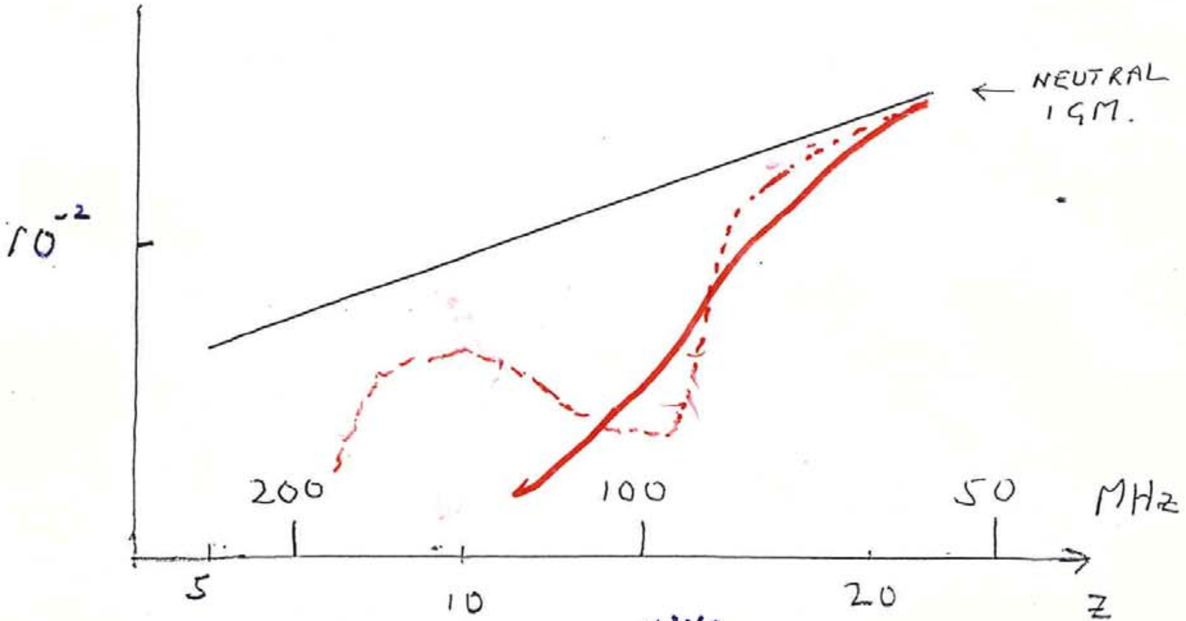
Fluctuation scale is

$$\max \begin{Bmatrix} \text{density-fluctuation scale} \\ \text{ionization scale} \end{Bmatrix}$$

[at high z (with no bright QSOs) density-fluctuation scale is larger]

21 cm emission tells us how the neutral fraction $(1 - x_e)$ changes with z.

$\langle \delta T_{21cm} \rangle$



Must wait for LOFAR and SKA

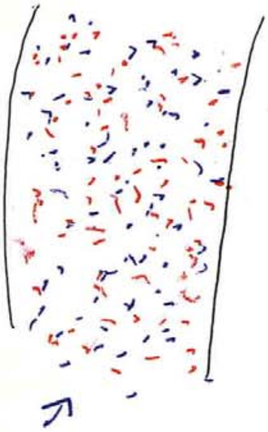
DISPERSAL & MIXING OF HEAVY ELEMENTS

Heavy elements are dispersed by SN-driven or wind-driven expulsion from sites of star formation.

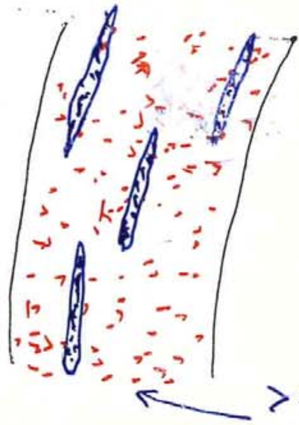
The enriched material may also carry magnetic flux (the 'seed field')

What fraction of cosmic volume gets contaminated at high z?

Does fine-grained mixing occur?



or



> solar abund in sheared remnants

10^{-3} solar abundance throughout cloud/filament

(testable by measuring thermal broading in quasar absorption lines)

INTERMEDIATE MASS HOLES AS POP III REMNANTS?

Black holes arise from:

'ordinary' very massive stars (He core mass up to 64 $M_\odot$)

and

VMOs with He core $\gtrsim$ 130 $M_\odot$

Cores in range 64-130 $M_\odot$ yield pair-instability SN

(e.g. Heger and Woosley 2001)

If most of ionizing UV at $z > 5$ comes from massive Pop III, then expect $\Omega \simeq 10^{-4}$ of baryons to be their remnants.

Do some merge, or accrete gas preferentially, to create $>10^6$ $M_\odot$ holes?

ARE SOME POP III REMNANTS THE PROGENITORS OF SUPERMASSIVE HOLES?

Via mergers?

It is not easy for a cluster of black holes to merge into single one.

Note: *one binary black hole with orbital speed* 10^4 *km/sec (separation* $10^3\ r_S$*) can store the entire binding energy of a cluster of 10000 holes with velocity dispersion 100 km/sec.*

Can other effects (eg dynamical friction on lighter objects, or gravitational radiation) get round this problem?*

Via accretion of gas if in favoured location?

Can a hole in dense environment swallow gas at a supercritical rate?

* If segregation and coalescence of massive stars occured in less than a stellar-evolution timescale, outcome could be a supermassive star (cf Quinlan and Shapiro 1993)

$M_h - \sigma$ RELATION FOR HOLES

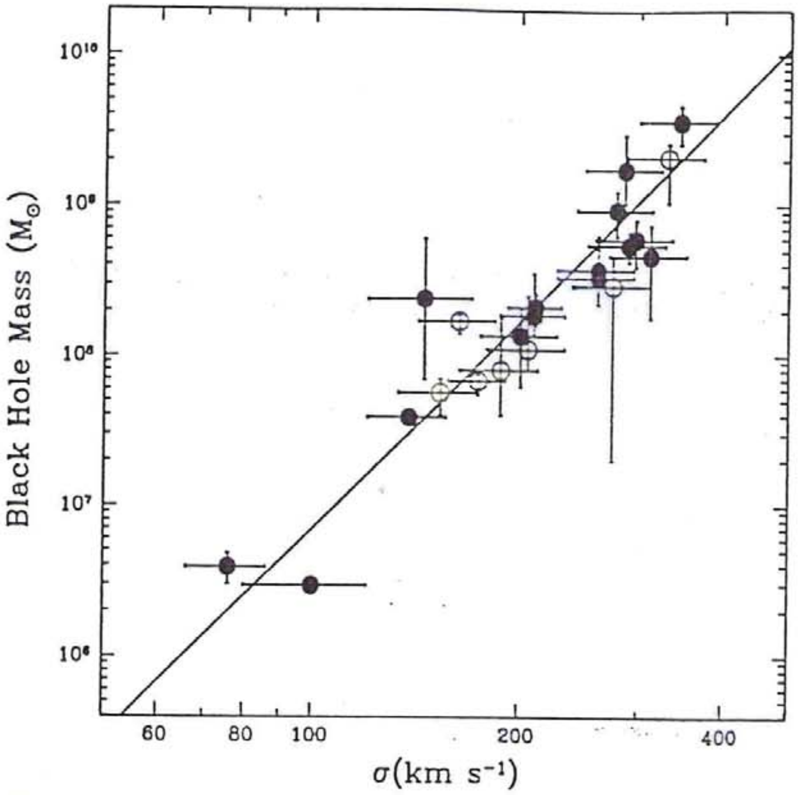


Fig. 2.— **Perfect correlation.** The mass of supermassive black holes as a function of the velocity dispersion of the stars in the host galaxy. Filled circles are from published data; open circles are based on unpublished analyses. The scatter of points about the best-fit line is fully consistent with that expected on the basis of measurement errors alone (shown by the error bars), implying that the underlying correlation is essentially perfect.

Ferrarese & Merritt
2002.

HOW MUCH SPIN?

Rapid spin* of hole would be expected if it:

- Resulted from merger of two comparable-mass holes ✱

or

- Formed (or gained the last $\gtrsim 1/2$ its mass) from coherently-spinning gas

Slow spin expected if it:

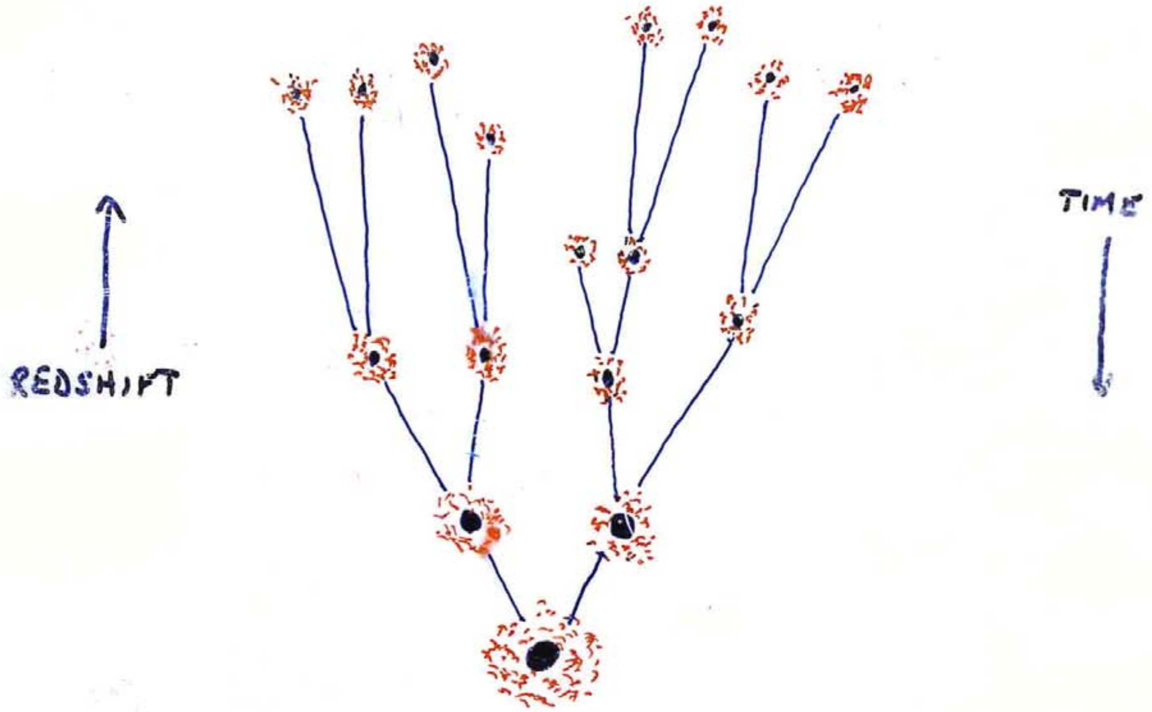
- Resulted from capture of randomly-orbiting smaller holes (or from capture of stars)

Rapid spin is a necessary requirement for Blandford-Znajek mechanism to be important.

✱ *Hole's spin need not be aligned with angular momentum in core of host galaxy*

or any other mechanism for tapping the hole spin energy)

MERGER HISTORY OF GALAXIES



In each merger, holes coalesce, and an episode of accretion occurs, giving rise to AGN phase.

(eg Kaufmann and Haehnelt 2000)

QUESTIONS:

How far down in mass does this process go?*
Do small halos (at high z) all contain black holes?

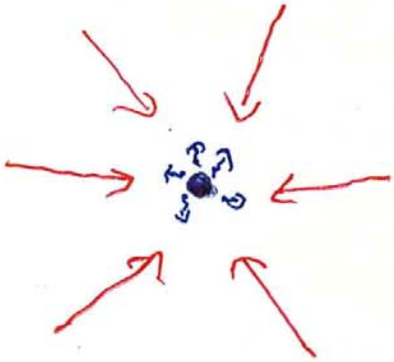
RELEVANT TO:

Faint end of quasar luminosity function
Extension of $M_h - \sigma_v$ relation to low σ_v.
Predicted LISA event rate
Link (if any) with Pop III remnants

* **Presence of black holes in all present-day galaxies need not require black holes in all precursors.** (Menou et al 2001))

FEEDBACK FROM AGN TO GALAXY

If AGN generates mechanical luminosity L_{Ed},
then the resultant outflow may exert negative feedback on infall in the entire galaxy



Dissipative formation of galaxy releases $\sim M_{gas}\,\sigma_*^2$,

in timescale R_{gas}/σ_* . (where $R_{gas} \simeq GM_{DM}/\sigma_*^2$)

i.e. power released by infall is $\sim(\sigma_*^5/G)(\underset{\underset{\sim 0.1}{\uparrow}}{M_{gas}}/M_{DM})$

$\Rightarrow \quad M_h \propto \sigma_*^5$

(yields approx 'Magorrian et al' relation)

$\Rightarrow$

Upper limit to hole mass in galaxy

Or

Upper limit to galaxy mass around given hole.

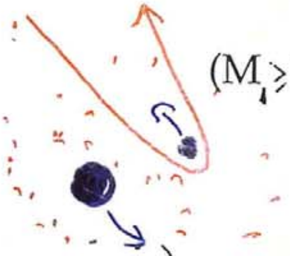
(Silk and Rees 1998
Fabian 1999, Blandford 1999)

STAGES IN MASSIVE BINARY COALESCENCE

1. *Dynamical Friction*

energy input $\gtrsim M_2 \sigma_*^2$
into stellar core

2. *Tight binary: 3-body interaction with stars*



$(M_1 \gtrsim M_2)$

timescale $\propto \left\{ \frac{1}{a} \times (\text{ loss cone factor}) \right\}$

$\Longrightarrow$ ejection of $\sim M_2 / m_*$ stars from core

3. *Gravitational radiation*

timescale $\propto a^4$

$\Longrightarrow \sim 0.1 M_2 c^2$ in gravitational waves

(very strong LISA signal!)

PROBES OF ULTRA-HIGH REDSHIFTS

Lyman-alpha emitting objects (a task for JWST?)

21 cm observations (LOFAR and SKA)

CMB parameter-fitting (Planck)

Supernovae/hypernovae

gamma-ray bursts (Swift)