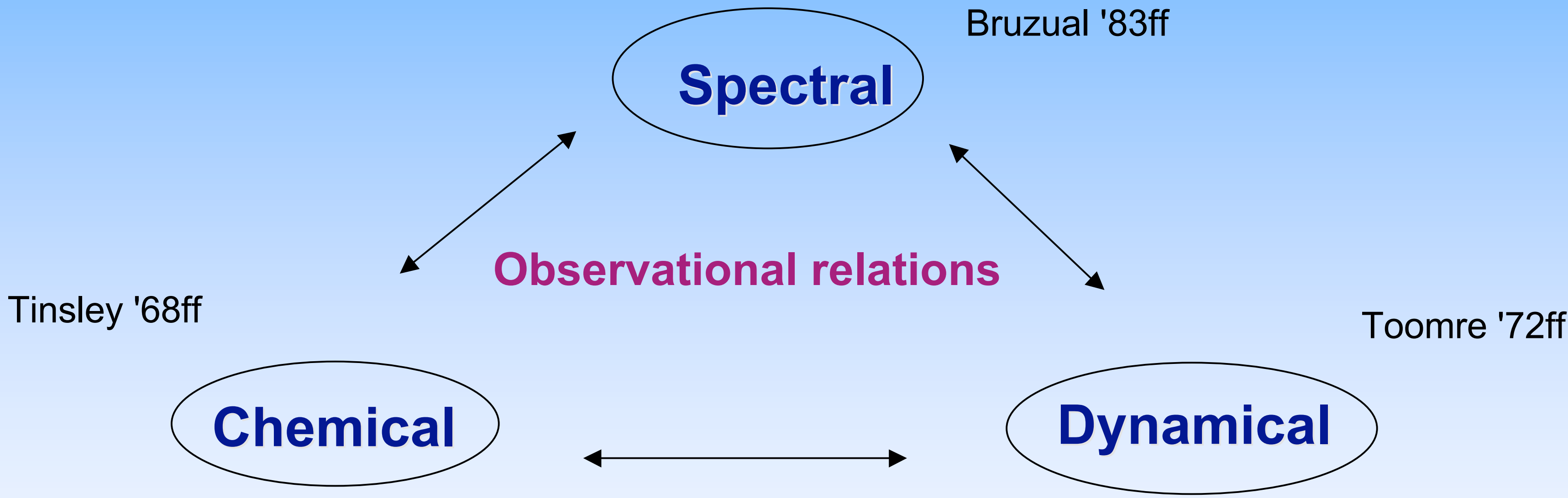
Dynamical Evolution of a Galaxies

= 3rd aspect of galaxy evolution



S : formation & evolution of stars +/- gas +/- dust
C : formation & nucleosynthesis of stars; infall/outflow of gas
D : internal & external gravitation, stars + gas + DM

Dynamical Evolution / Formation of Galaxies

Gravitation & Hydrodynamics :

Dark matter : semianalyt. / numer. N-body - dissipationsless
Stars : N-Body-Tree-Codes - collisionless
Gas : (Smooth Particle) Hydrodynamics - dissipative
(+ Tree-Codes)

+ Star Formation Criterium + Feedback

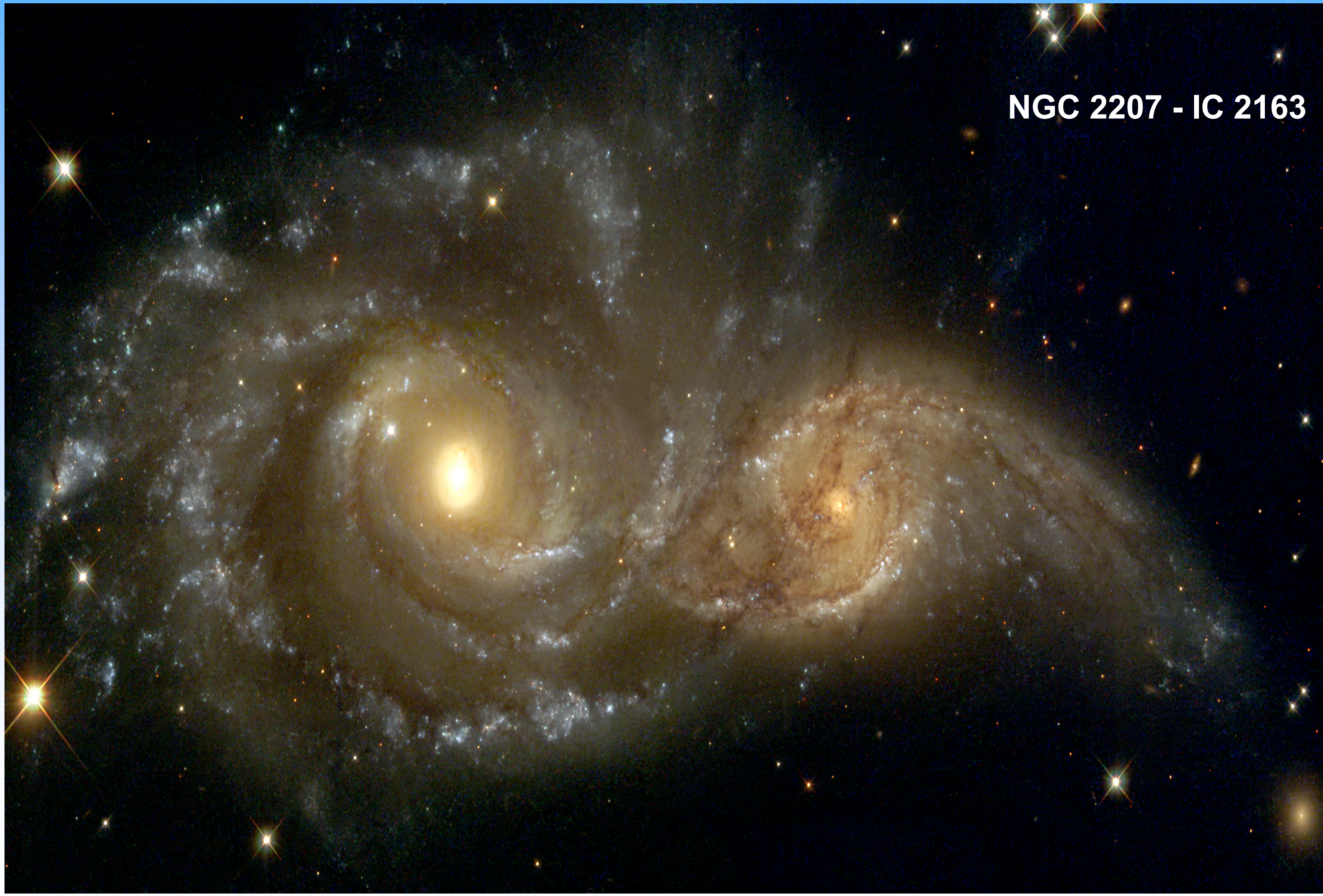
↓

(radiation, mechan. energy, mass, heavy elements)
from stars and AGB

➜ galaxy interactions

➜ galaxy formation

Galaxy – Galaxy Interactions



Galaxy Interactions

$$\langle \text{star} \leftrightarrow \text{star} \rangle \simeq 10^7 \langle \oslash_{\star} \rangle$$

$$\langle \text{galaxy} \leftrightarrow \text{galaxy} \rangle \simeq 40 \langle \oslash_{gal} \rangle$$

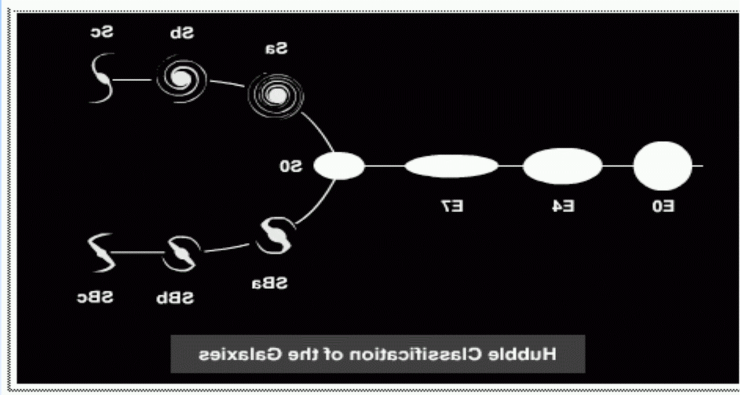
⇒ <1 major merger / galaxy / Hubble time>

+ many minor ones !

☛ Morphological transformation

spiral + spiral + starburst → E/S0

Sd + dwarf galaxy → Sb, Sa



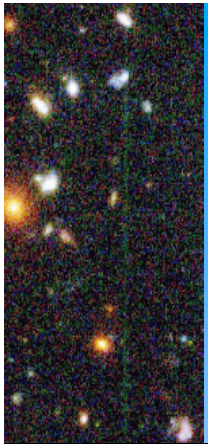
GALEV :

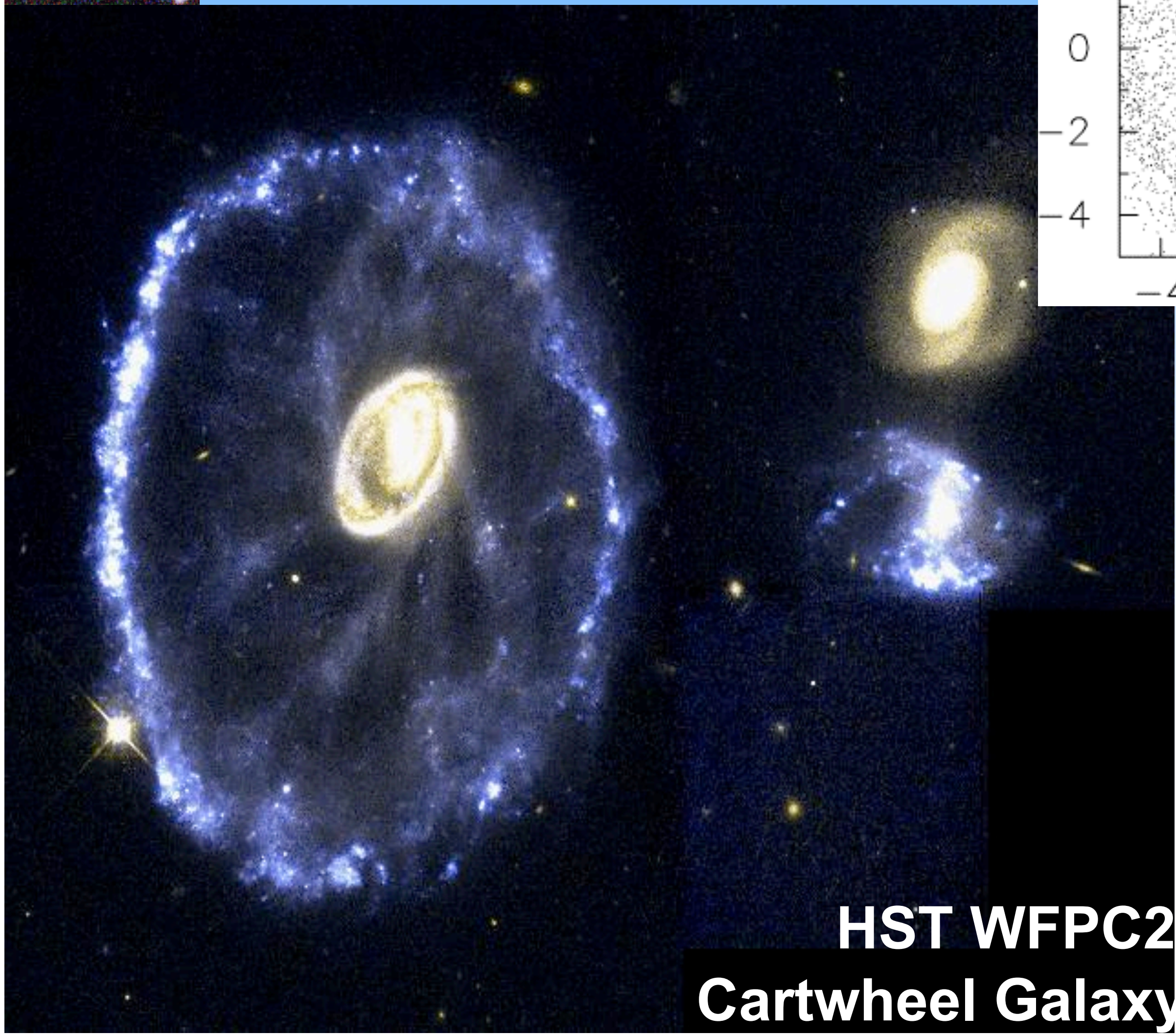
☛ Starbursts with extremely high star formation efficiencies η during interactions between gas-rich galaxies

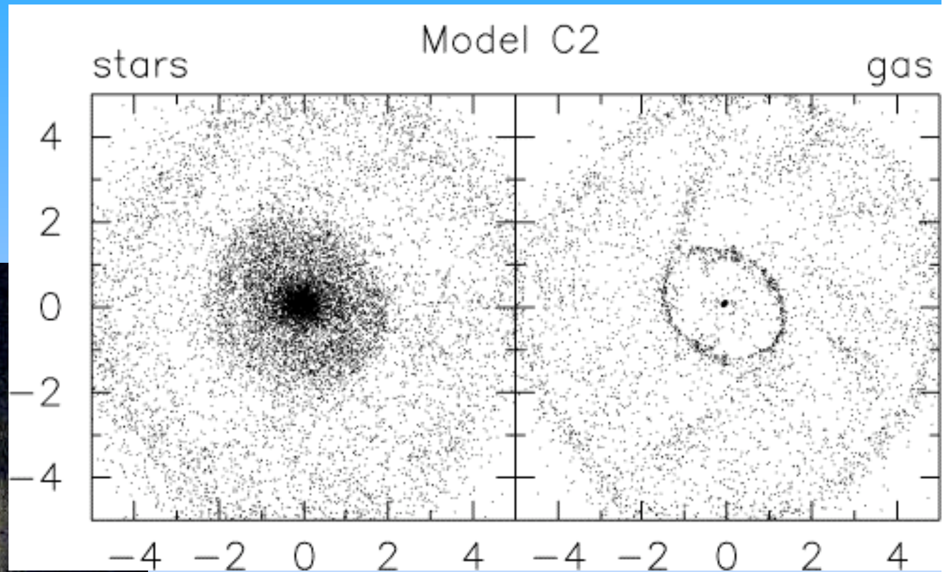
⇒ spectral transformation spiral + spiral + starburst → E

(FvA & Gerhard 1994a,b, FvA & Burkert 1995)

Galaxy Interactions

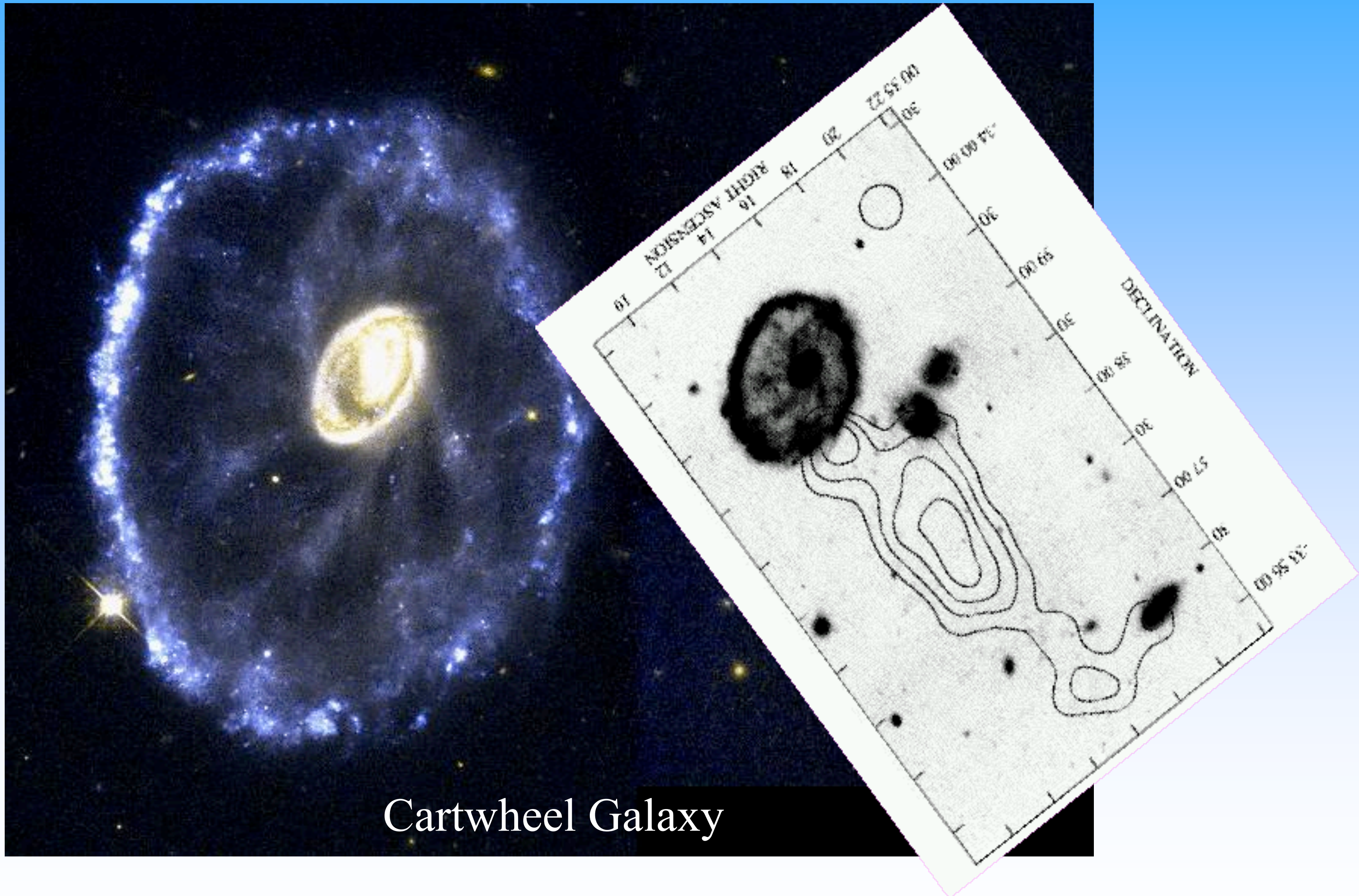






(Berentzen et al. 03)
GRAPE-3AF simulation

Galaxy Interactions



Cartwheel Galaxy

Galaxy Interactions

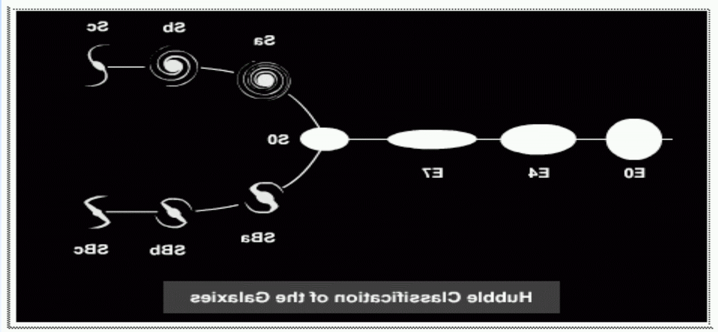
Arp's Atlas of Peculiar Galaxies : 1966

Toomre & Toomre 1972 ff : first numerical modelling of
disk – disk interactions : N-body (N=128 ...)

morphological transformation of disks ➜ spheroids

spiral + spiral ➜ “E”

spiral + dwarf ➜ spiral with bulge



Counterarguments :

* central densities too small
* GC specific frequencies too small

$T_{GC}:=N_{GC} / M_{gal}$

$<T_{GC}(E)> \sim 2 <T_{GC}(Sp)>$ (Ashman & Zepf 95)

Dynamical Models : Galaxy Interactions

Dynamical models 2008 :

N-body TREE Codes : stars + DM $N \sim 10^5 - 10^6$

disk + bulge + halo

SPH TREE Codes : gas (or Sticky Particles method)

➜ high gas concentrations towards centres

➜ central gas densities ~ stellar central densities of Es ✔

as observed in ULIRGs (= Ultraluminous IR Gals
= advanced stages of gas-rich mergers)

HI from beyond the optical radius brought into the galaxy/centre

Problems : shock resolution, molecular cloud structure,
multi-phase ISM, SF criterium/criteria, feedback

➜ formation of GCs in mergers : GC specific frequency ✔

Dynamical Models : Galaxy Interactions

Orbital parameters & galaxy properties :

global — nuclear starbursts — AGN fuelling
(e.g. Barnes & Hernquist 1992, Jogee 2005)

prograde encounters : global starbursts (? contracting ?)
retrograde -- " -- : nuclear starbursts & AGN fuelling

Consistent inclusion of SF, AGN formation/feeding and feed back from both still under construction

Dynamical Models :Galaxy Interactions

Dynamical models with gas :

Sp + Sp + starburst ➜ E 4

for 1:1 . . . 1:3 mergers with low gas content

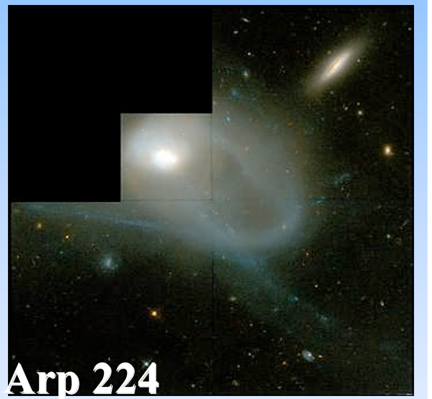
Sp + Sp + starburst ➜ S0

disk morphology + E kinematics

for 1:4 . . . 1:10 mergers

(Bournaud et al 2004)

observed e.g. in Arp 214 and Arp 224



(Jog & Chitre 2002)

Sp + Sp + starburst ➜ Sa

disk morphology + disk kinematics

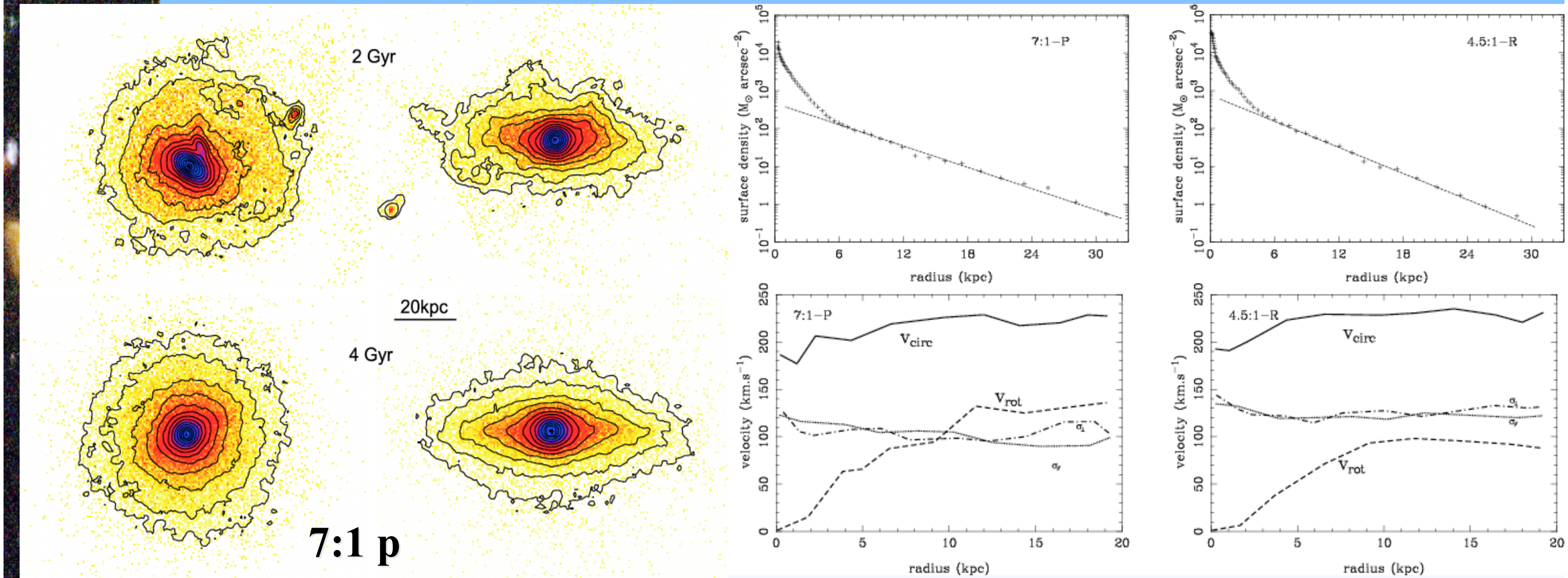
for 1:1 mergers with high gas content

(Springel & Hernquist 2005)

Dynamical Models :Galaxy Interactions

Sp + Sp + starburst ➔ S0

disk morphology + E kinematics

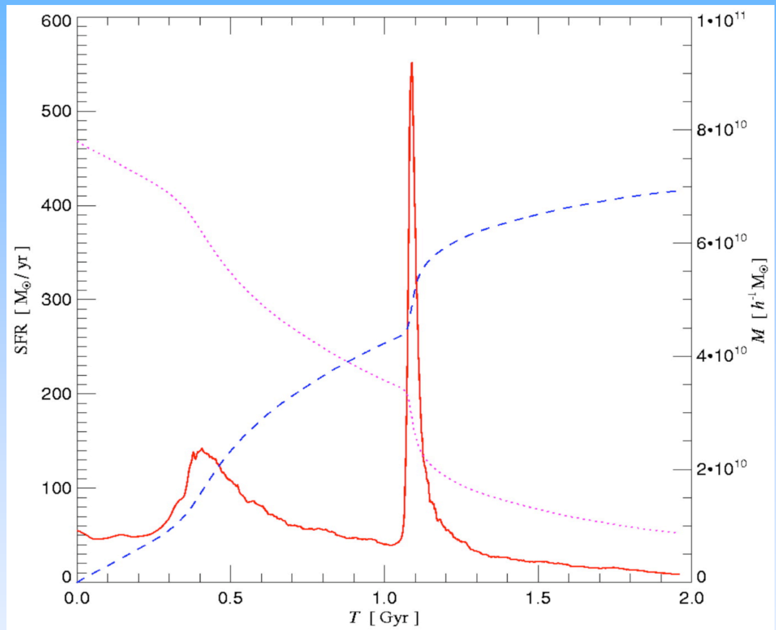


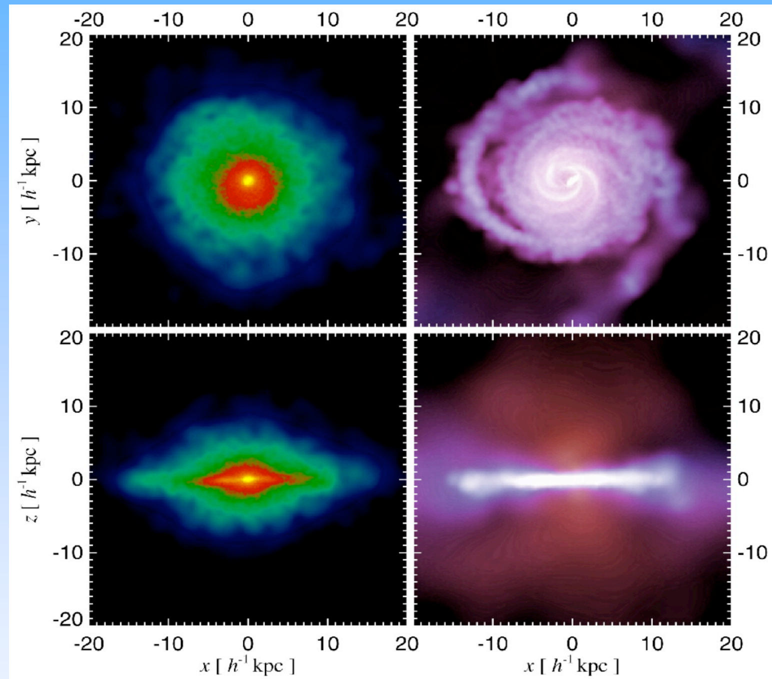
(Bournaud, Combes & Jog 2004)

Dynamical Models : Galaxy Interactions

Gas rich : Sp + Sp + starburst ➔ Sa

disk morphology + disk kinematics for young stars & gas





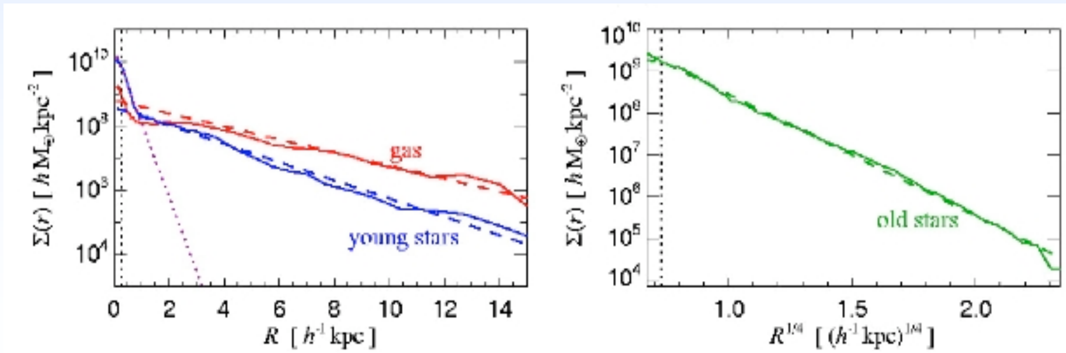
bulge = stars from 1. burst

disk rebuilt from gas

surviving strong burst

& subsequent SF

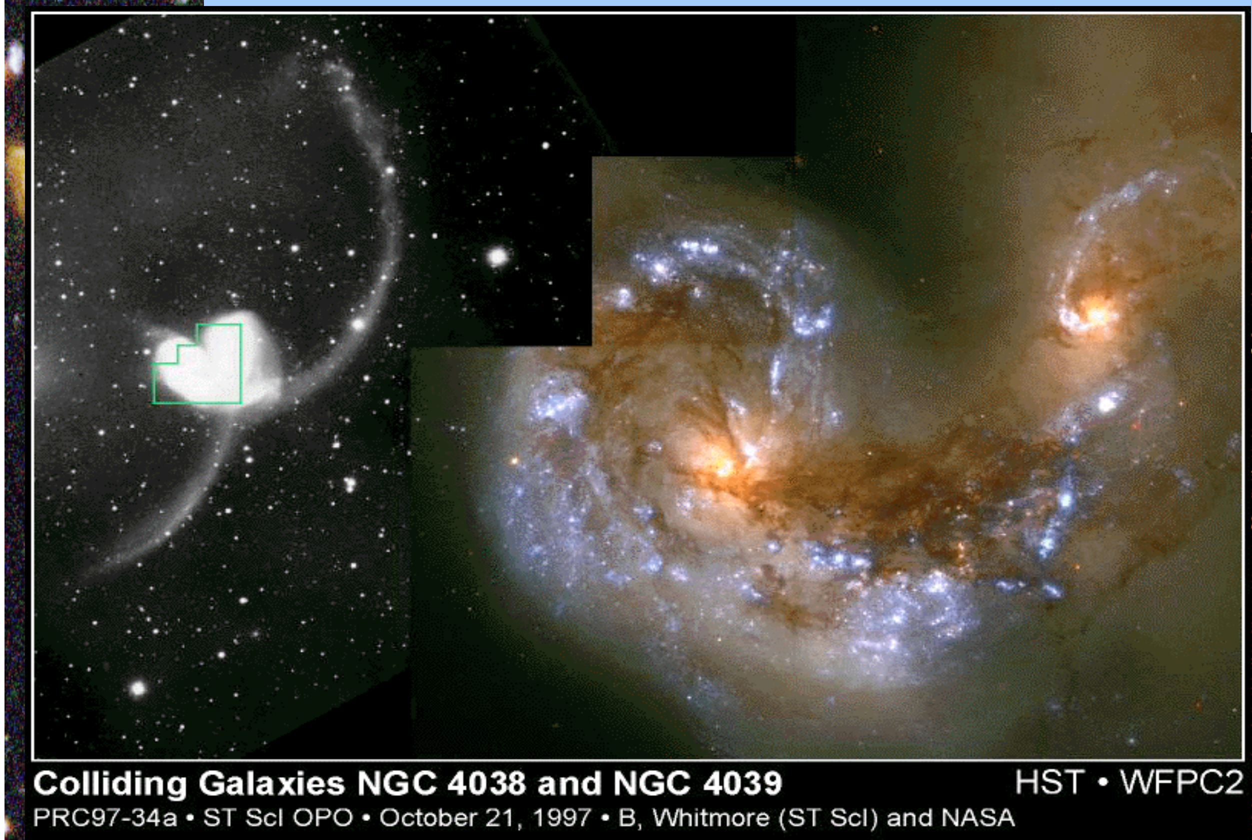
(Springel & Hernquist 2005)

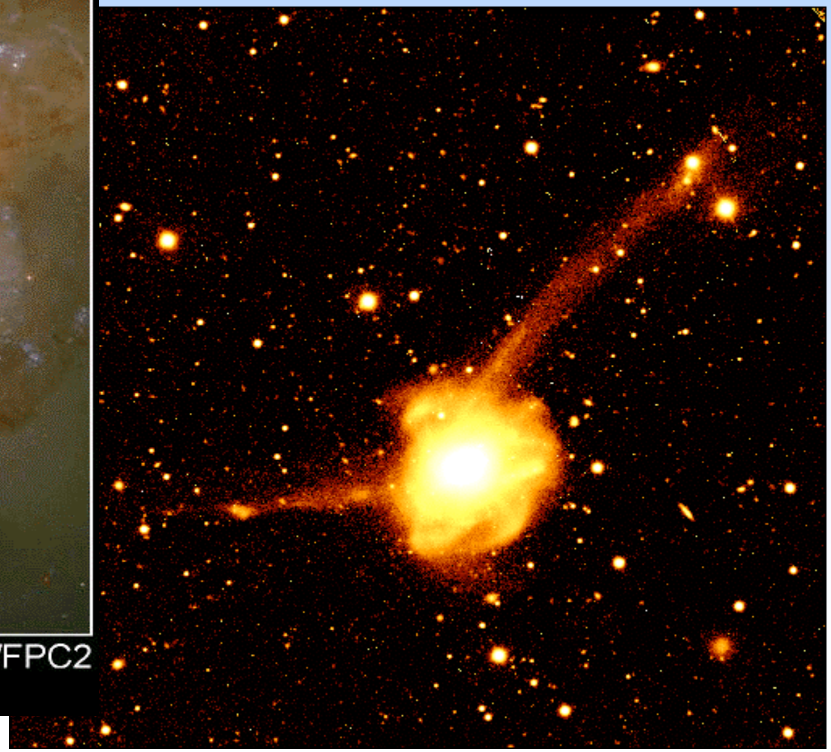


Interacting Galaxies & Mergers

Galaxy interactions/mergers trigger strong starbursts if 1 or 2 of the galaxies are gas-rich

e.g. spiral – spiral mergers (NGC 4038/39 = Antennae, NGC 7252, . . .)





Galaxy Interactions & Starbursts

Starbursts in giant interacting galaxies :

Evol. Synthesis modelling → SFR ~ 30 – 1000 $M_{\odot}$/yr,

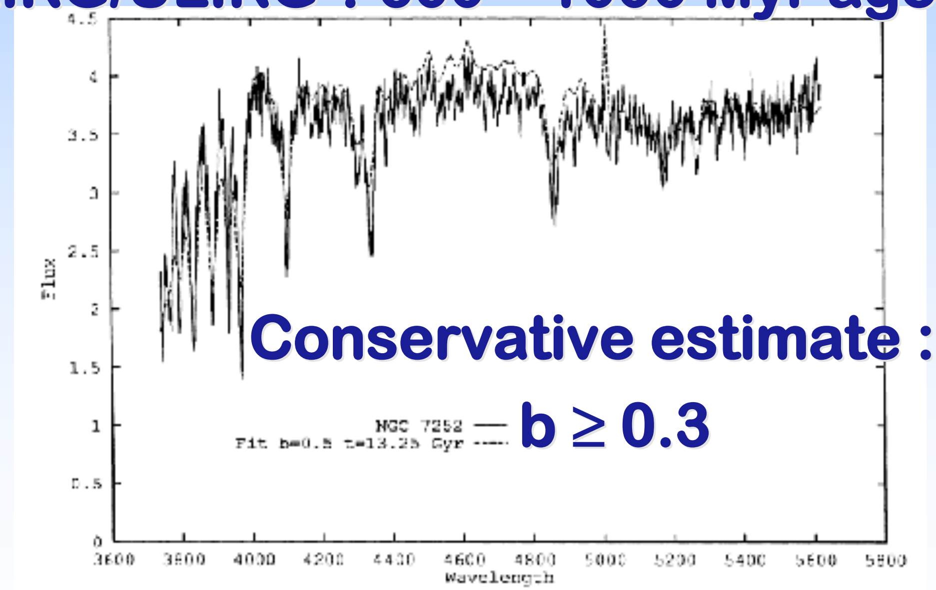
→ post - starbursts b~0.3 – 0.5 (FvA & Gerhard 1994a, b)

E.g. NGC 7252 : bright Sc-Sc Merger (HI in Tidal Tails)

Strong Balmer abs. lines --> Strong global starburst

R >10 kpc

LIRG/ULIRG ? 600 – 1000 Myr ago



Conservative estimate :

b ≥ 0.3

Star Formation Efficiency SFE := M_{stars} / M_{gas} ≥ 0.4 !

A model for NGC 7252

Start from broad band colours UBVRI :

comparison with model grid -> **box in parameter space**

Additional pieces of information:

length of tidal tails / typ. rotation velocity
~ dynam. age of interaction

HI in both tidal tails : 2 gas-rich spirals ~Sc

both tails of similar length : both spirals of sim. mass

very high luminosity : both Scs very bright

Within box of parameter space: detailed comparison with spectral properties

strong Balmer absorption lines : strong starburst
600 – 1000 Myr ago

metal lines : (0.5 – 1) $Z_{\odot}$

(Fritze – v. A. & Gerhard 1994a, b)

Galaxy Interactions & Starbursts

spectral modelling for NGC 7252 → residual SFR ~ 3 $M_{\odot}$/yr

powered by HI falling back from tidal tails (~50%) and

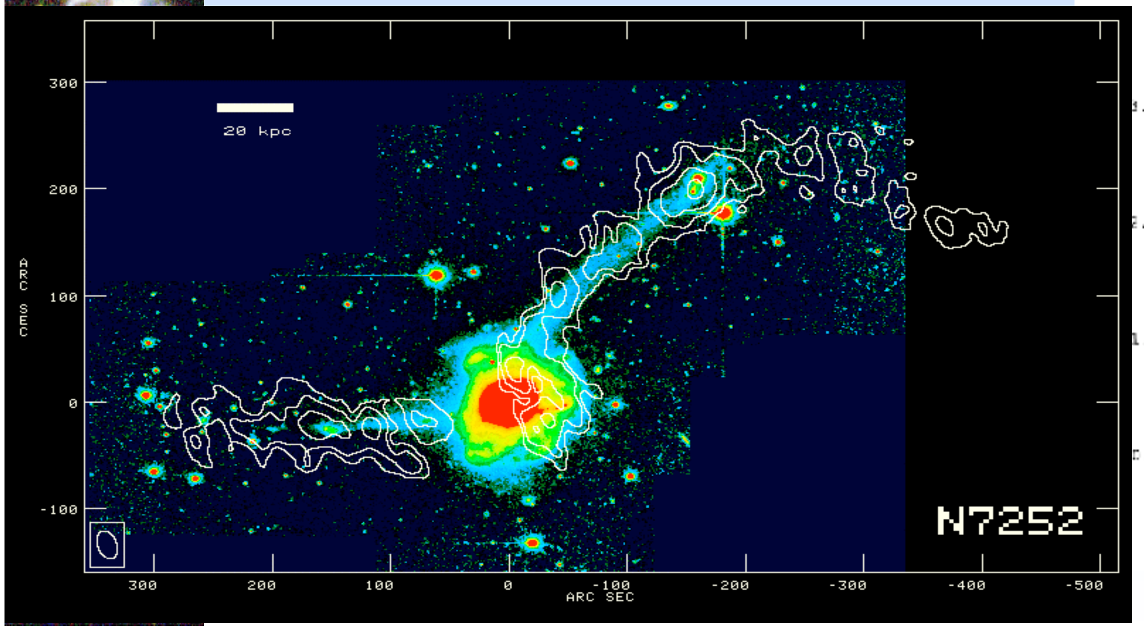
by gas restored from burst stars (~50%)

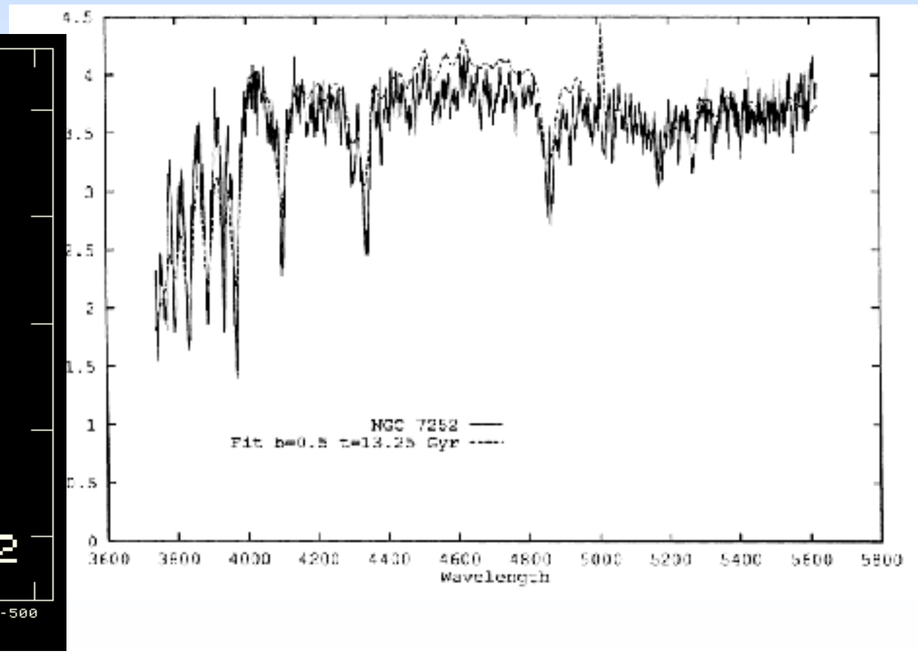
- emission component in Hβ absorption line
- IUE spectrum + ROSAT data

HI falling back from tails for >3 Gyr

➜ HI disk + SF ➜ stellar disk : S0 or Sa (spec + morph)

(Hibbard et al. 1997)





A model for NGC 7252

Future evolution :

will reach E/S0/Sa galaxy colours & spectra
within 3 – 5 Gyr depending on future SFR evolution

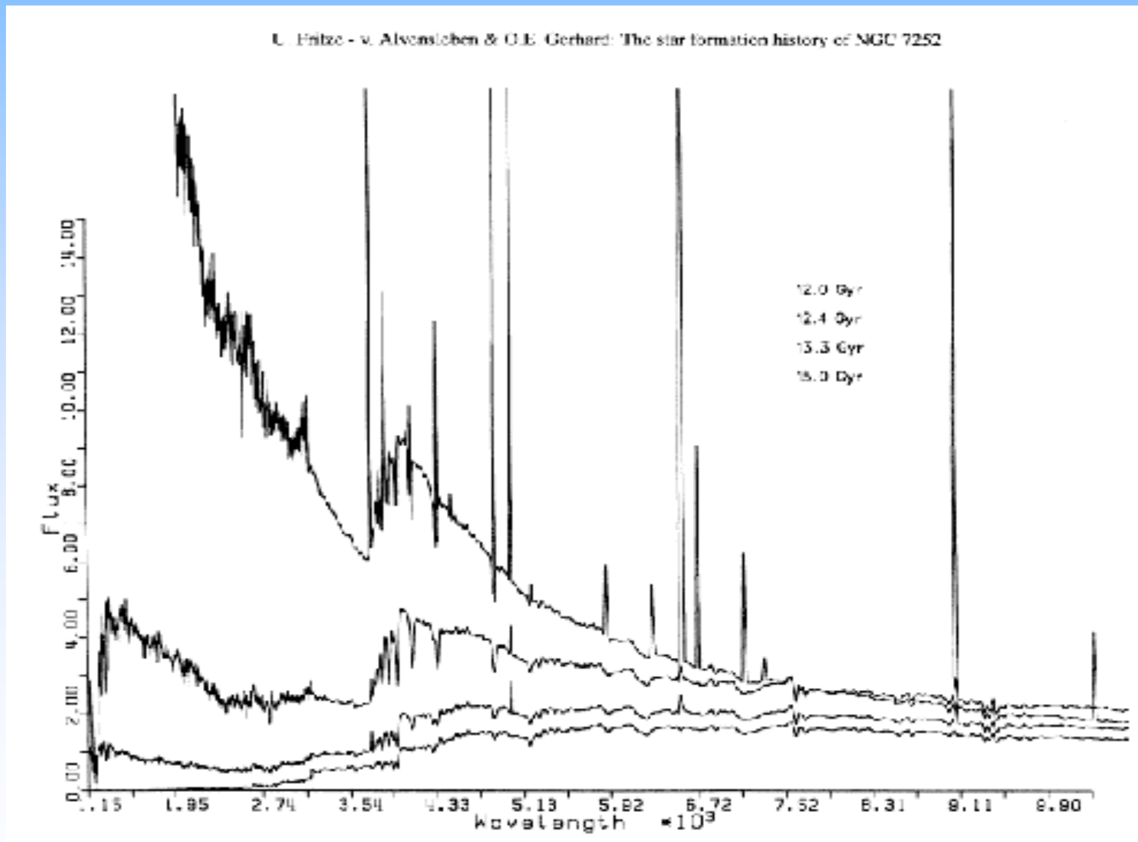


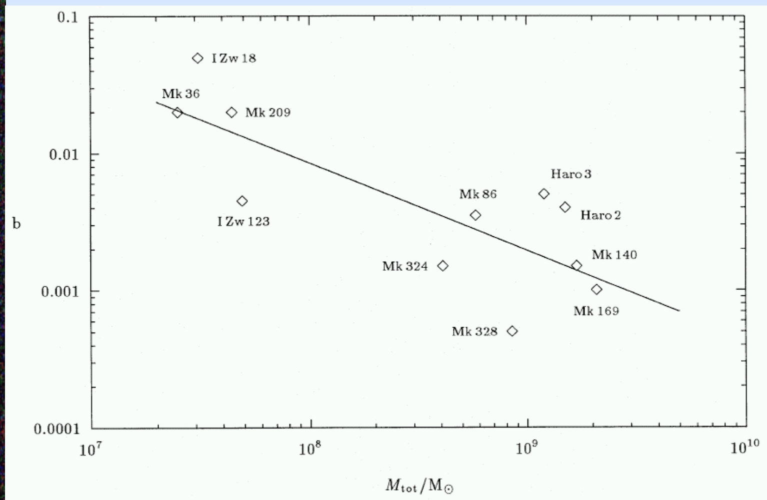
Fig. 2. Time evolution of our synthesized galaxy spectra from the UV to the NIR for our best fit model to NGC 7252

(Fritze – v. A. & Gerhard 1994 b)

Interacting Galaxies & Mergers

Burst strengths in isolated dwarf and interacting massive galaxies :

★ NGC 7252



(Krüger, FvA, Loose 1995)

can SF process be the same in isolated dwarf & major merger starbursts ?

Luminous InfraRed Galaxies (LIRGs) (e.g. Antennae)

$L_{FIR} \sim 10^{10} - 10^{11}\, L_{\odot}$

= global starbursts in giant gas-rich mergers

→ SFR ~ 30 . . . . 300 $M_{\odot}$/yr

Ultra Luminous InfraRed Galaxies (ULIRGs)

(e.g. Arp 220)

$L_{FIR} \sim L_{bol} \sim 10^{12} - 10^{13}\, L_{\odot}$ $A_V \sim 30$ mag

= nuclear starbursts in giant gas-rich mergers

→ SFR ~ 300 . . . . > 1000 $M_{\odot}$/yr

Star Formation Efficiencies

Star Formation Efficiency SFE := M_{stars} / M_{gas}

Global Scale

Spiral galaxies : SFE ~ 0.1 – 3 %

Irregular galaxies : SFE ~ 0.1 – 3 %

Starbursts in dwarf galaxies : SFE ~ 0.1 – 3 %

in giant interacting galaxies : SFE ~ 10 – 50 %

10-300 pc scale

Ultra Luminous IR Galaixes : ULIRGs : SFE ~ 30 – 90 %

Small Scale

Milky Way Molecular Clouds : SFE ~ M(MC core) / M(MC)

~ 0.1 – 3 %

Molecular Clouds & SF Processes

Normal galaxies (Spirals, Irrs) :

MC collapse → SFR

MC mass spectrum

= power law : m ~ -1.7 . . . . . -2

observed + okay w. supersonic turb.+gravity

≃ MC core mass spectrum

≃ open star cluster mass spectrum

Interacting galaxies :

MC – MC collisions enhanced → SFR ↗

MCs shock compressed by high ambient pressure

→ SFE ↗

$P_{ISM} \sim (3 – 4) \quad P_{MC}$ → SFE ~ 0.7 – 0.9 !

(Jog & Das 1992, 1996)

Molecular Cloud Structure

CO(1-0) traces molecular gas at n≥ 100 cm-3
HCN(1-0) traces molecular gas at n≥ 30000 cm-3
CS(1-0) traces molecular gas at n~100000 cm-3

Small Scale
Milky Way Molecular Clouds :

L(HCN,CS) / L(CO) ~ 0.1 – 3 %
~ M(MC core) / M(MC)

10-300 pc scale
Ultra Luminous IR Galaixes = massive gas-rich mergers :

L(HCN,CS) / L(CO) ~ 30 – 100 %
~ M(MC core) / M(MC)

Molecular Cloud structure in ULIRGs very different from Milky Way

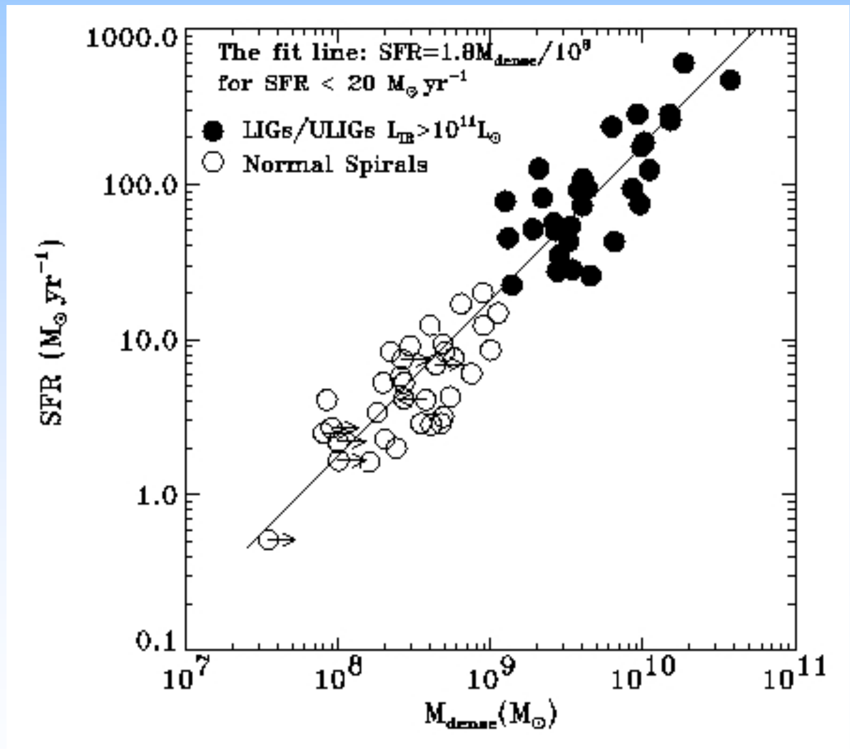
Can the SF process be the same ?

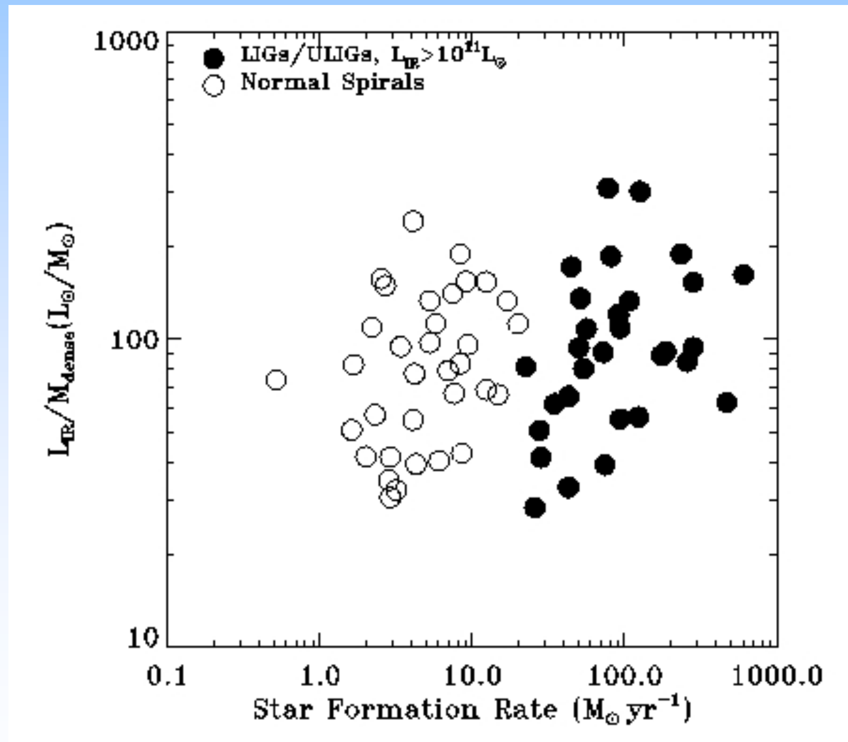
Molecular Cloud Structure & SF

For all galaxies (Spirals . . . ULIRGs) :

tight correlation SFR [L(FIR)] — M(MC cores)[L(HCN)]

SFR [L(FIR)] / M(MC cores)[L(HCN)] ~ const. =: SFE





(Gao & Solomon 2004, Solomon et al. 1992)

For all galaxies (BCDs . . . Spirals . . . ULIRGs) :

SFE ~ M(MC core) / M(MC)
~ L(HCN,CS) / L(CO)

Schmidt law (1959) : (Kennicutt 1998 :
SFR density ~ gas (HI) density ** n, n ~1.4)
SFR density ~ gas (CO) density ** n
n~1 for spirals . . . n~2 for ULIRGs
(over 5 orders in gas surface density & 6 orders in SFR density)

Schmidt law :
SFR density ~ gas (HCN,CS) density ** n
n=1 for all galaxies (spirals . . . ULIRGs)
(Gao & Solomon 2004)

Timescale & Efficiency for SF are set by transformation
low ➜ high density gas : HI, CO ➜ HCN, CS

➜ Importance of multi – phase ISM in dynam. models !

Starbursts in Interacting Galaxies

Pixel-by-pixel analyses of Tadpole & Mice galaxies

SF in these interacting & starburst galaxies is
star cluster formation to a large extent

70% of U - light is from star clusters
40% of I - light

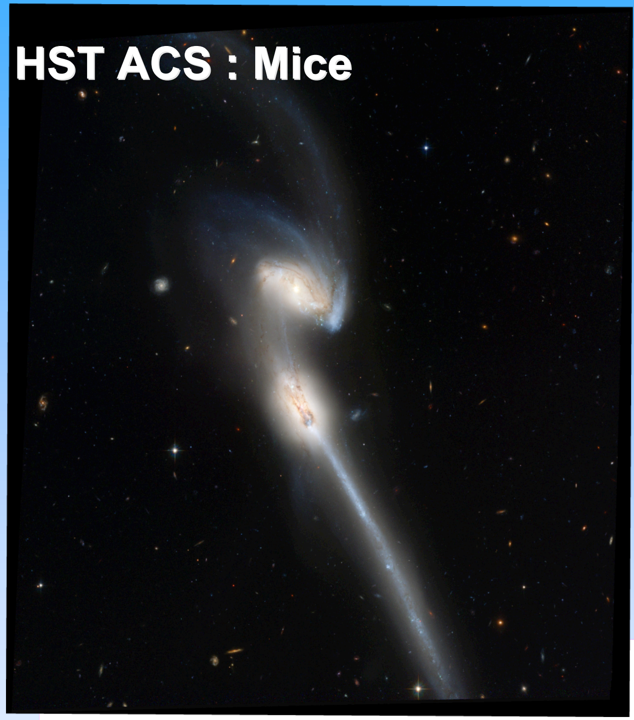
star cluster formation = dominant mode of SF

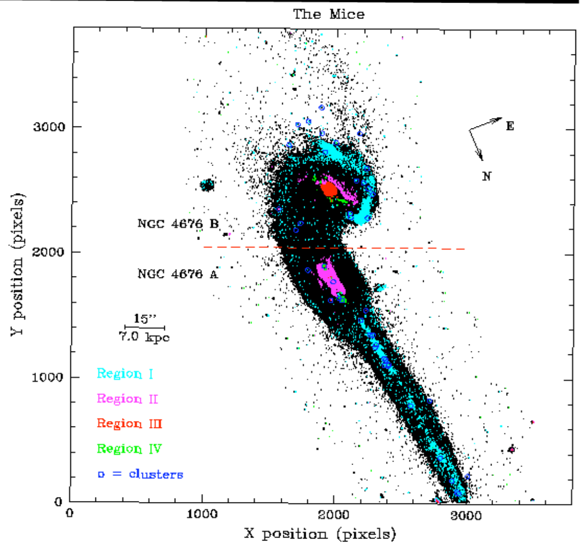
even in the expanding low-density tidal tails !

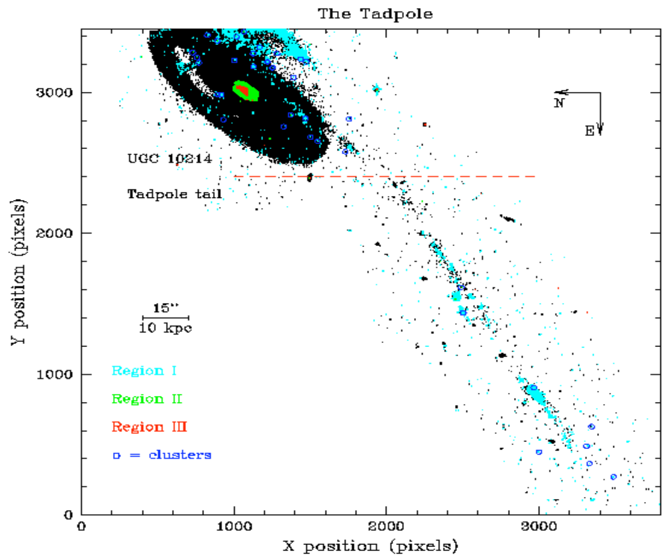
With SFR ↗ rel. amount of SF into star clusters ↗
rel. amount of SF into massive compact long-lived clusters ↗

Feedback from strongly clustered SF
≠ feedback from lower-level smooth SF

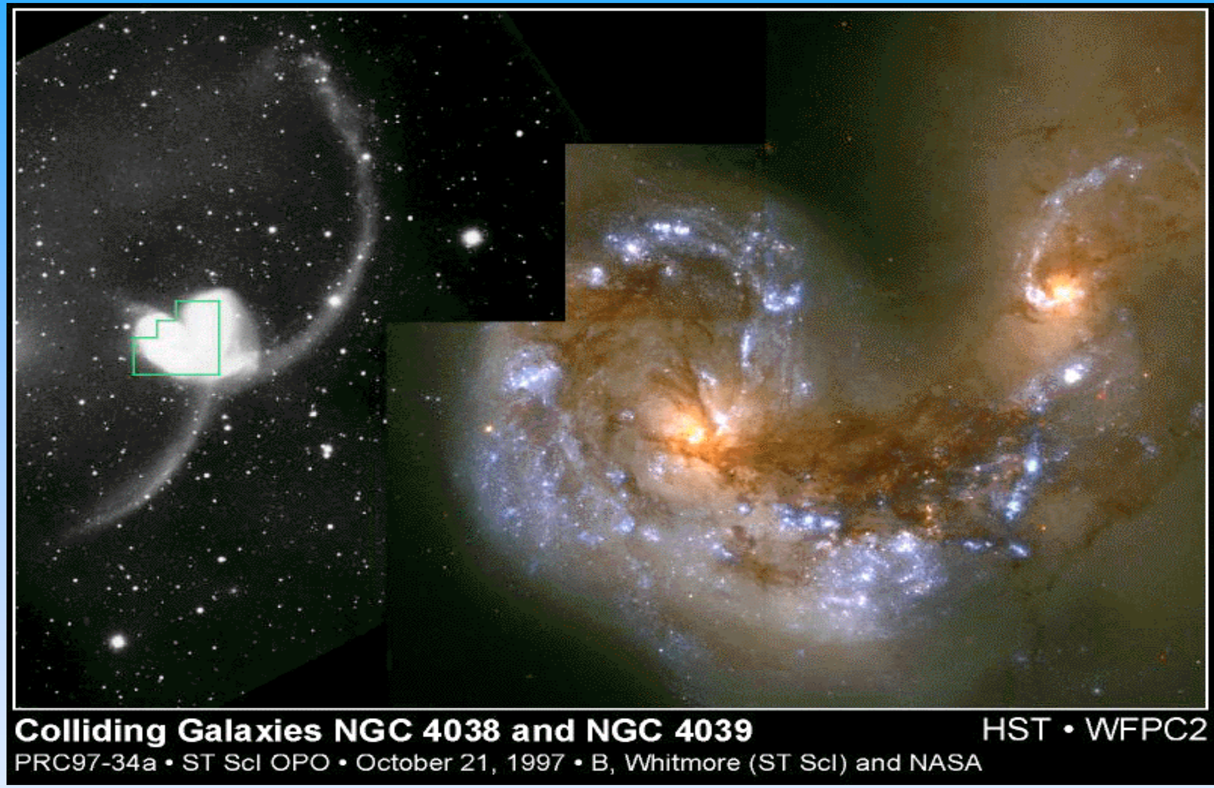
Starbursts in Interacting Galaxies
Pixel-by-pixel analyses







Galaxy Interactions & Cluster Formation



Strong starburst → formation of thousands of bright star clusters from gas pre-enriched in the spirals

high star formation efficiency → clusters strongly bound, long-lived proto-Globular Clusters!

(Burkert, Brown, Truran 96) $\eta \geq 10 - 30\ \%$: Globular Clusters

Secondary GCs = eternal tracers of violent SF epoch

Analysis of Star Cluster Systems : SSPs

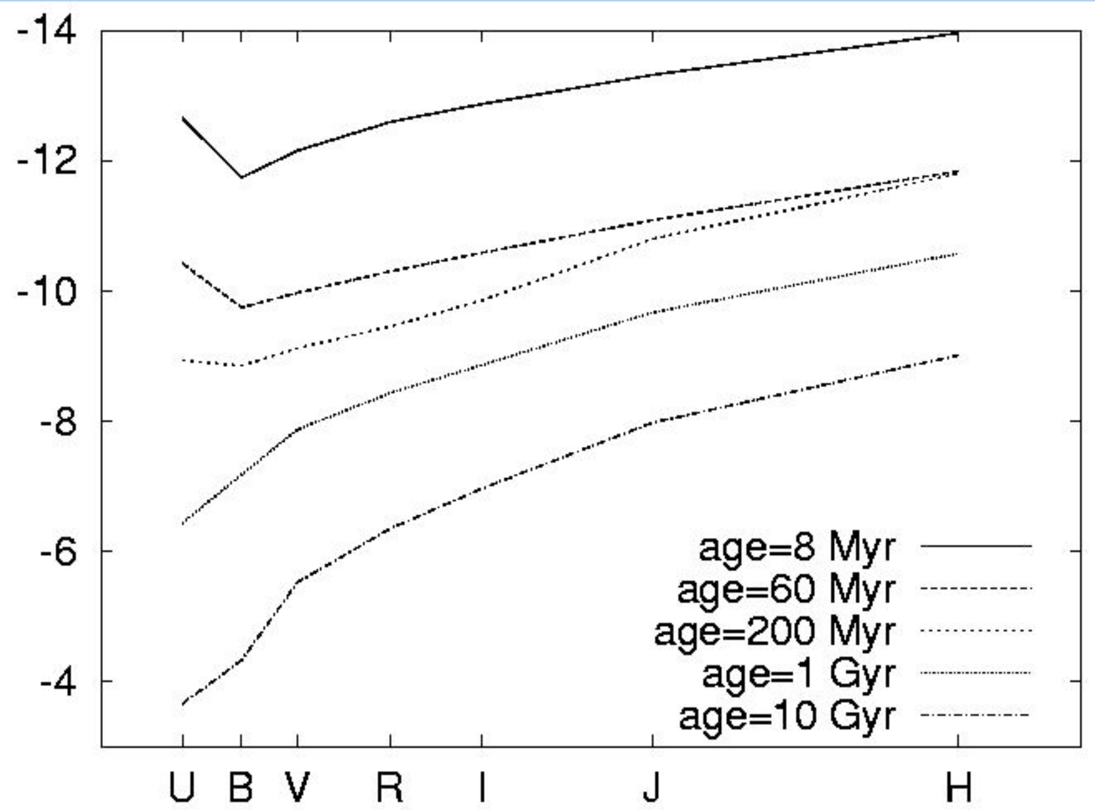
Grid of Spectral Energy Distributions

SSPs : 5 metallicities -1.7 ≤[Fe/H] ≤+0.4

4000 ages 4 Myr . . . . . 16 Gyr

20 extinction values 0 ≤ E(B-V) ≤ 1

(Starburst extinction law → Calzetti et al. 2000)



400.000

Spectral

Energy

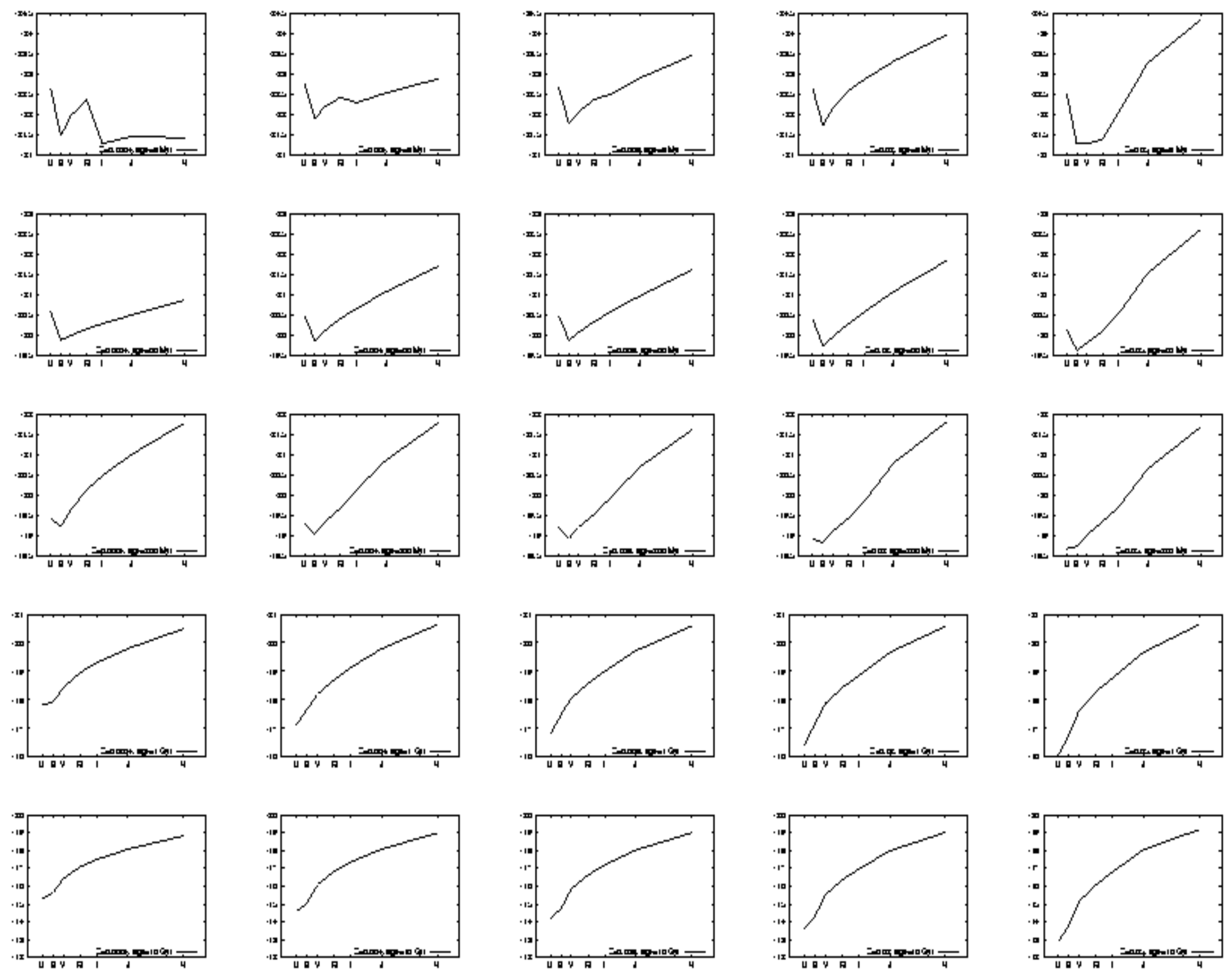
Distributions

e.g. $Z_{\odot}$, $E_{B-V} = 0$

↕ mass

Analysis of Star Cluster Systems

Multi–band photometry - Grid of Models (GALEV)



Z=0.0004 Z=0.004 Z=0.008 Z=0.02 Z=0.05

Spectral

Energy

Distributions

8 Myr

60 Myr

200 Myr

1 Gyr

10 Gyr

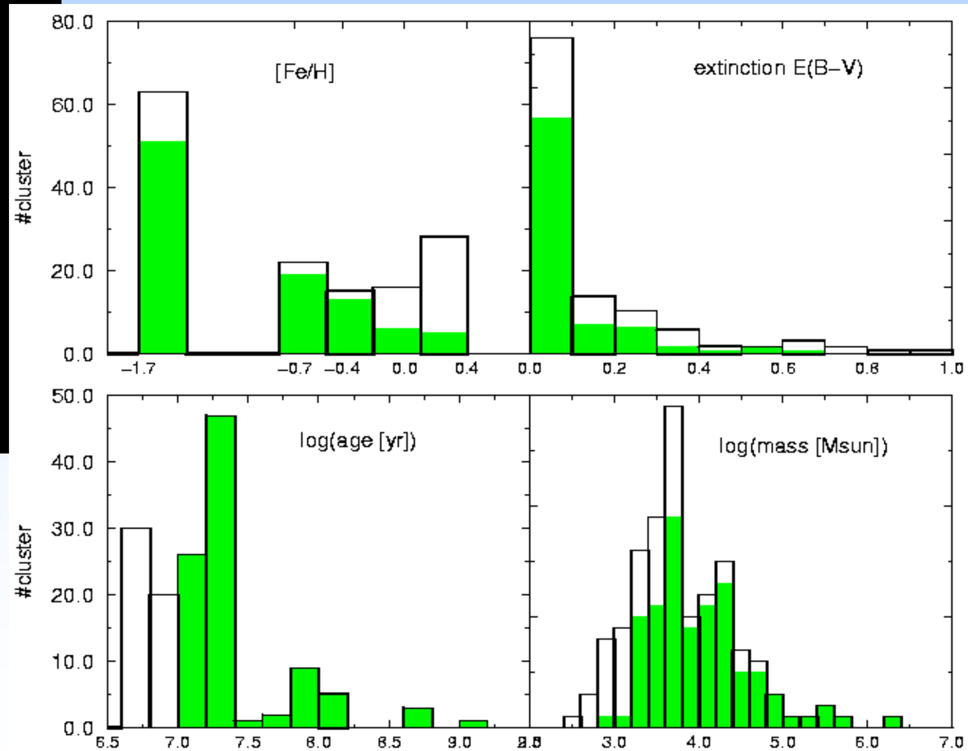
$E_{B-V}= 0$

Multi–band Photometry - Grid of Models

χ^2 method : AnalySED*

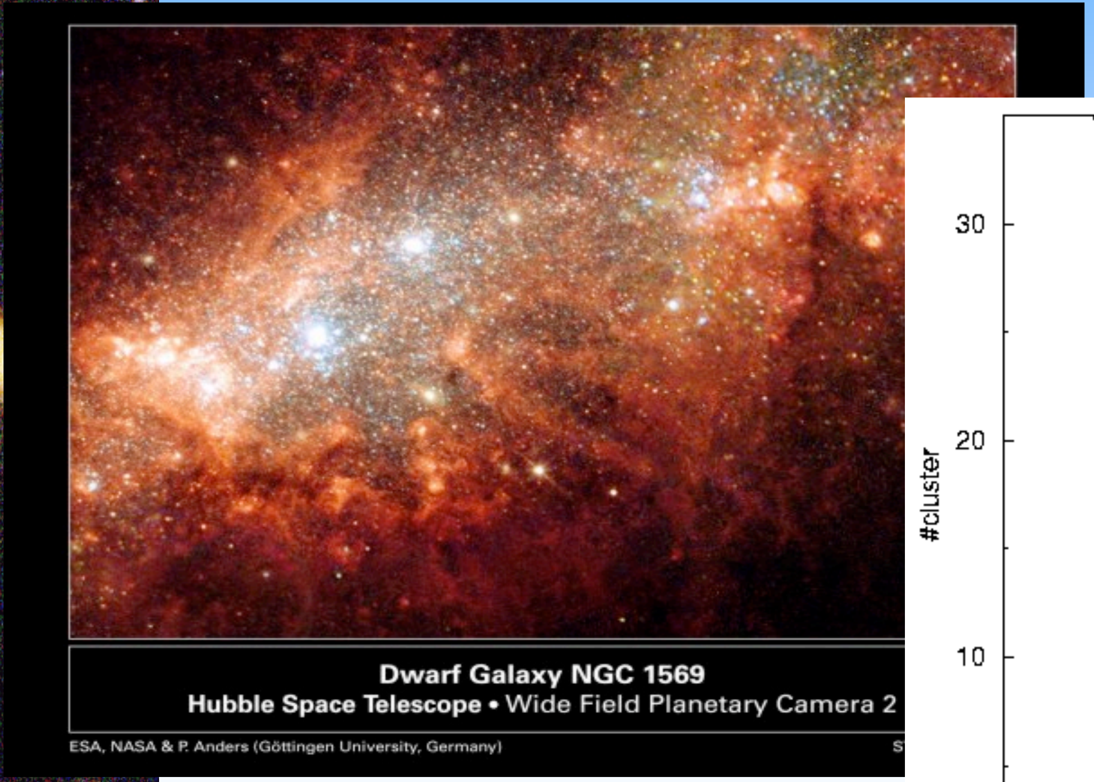
→ ages, metallicities, E(B-V) & masses ± 1σ ranges of all star clusters

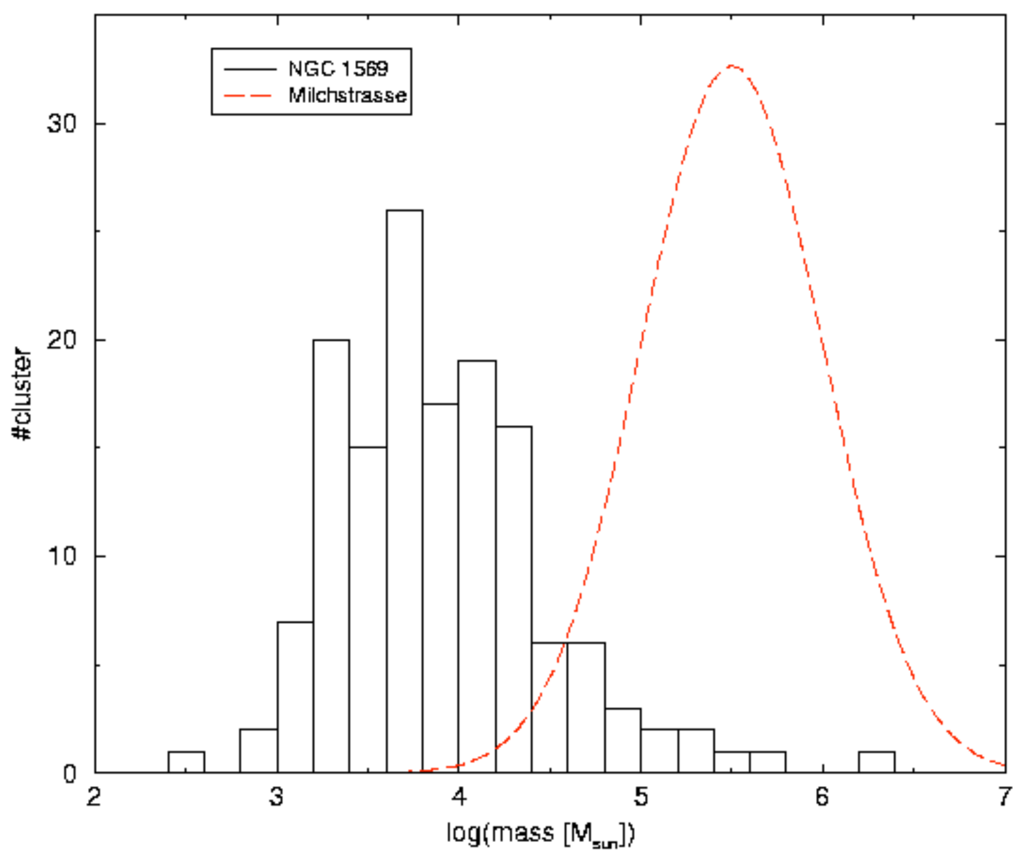
(Anders & FvA 03,
*Anders et al. 04a, b)



Analysis of Star Cluster Systems
Multi–band Photometry - Grid of Models

NGC 1569 dwarf starburst galaxy, 3 Super Star Clusters + 169 young star clusters, but only few with masses of Globular Clusters





(Anders & FvA 03, Anders et al. 04a, b)

Cosmological Importance of Galaxy Interactions & Starbursts

Hierarchical structure formation scenario :

Galaxies build up continuously from smaller building blocks ± starbursts !

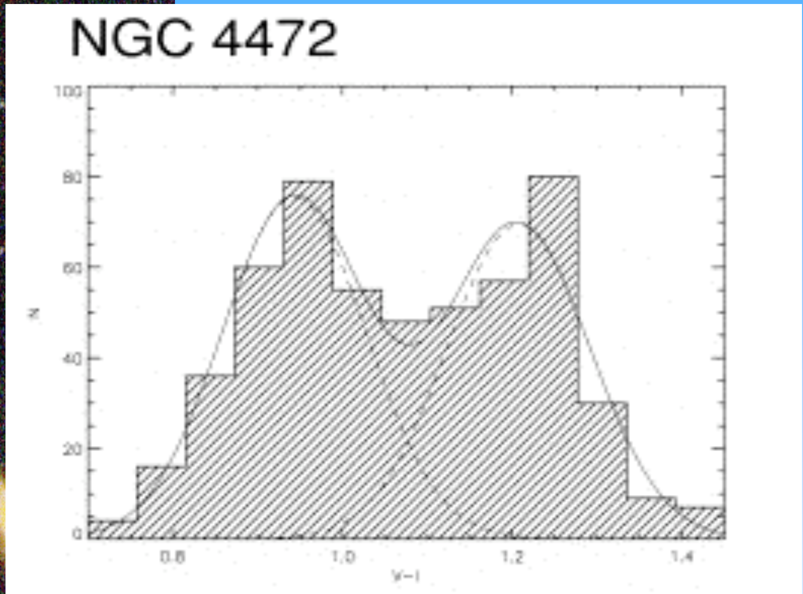
Galaxy interactions much more frequent in the past & much stronger, galaxies more gas-rich

Key role of (Globular) Clusters
= eternal tracers of violent star formation episodes

Cluster analysis 1-by-1 : age & metallicity distributions, much better than integrated light !
(FvA 98, 99, 04)

Multi-band Photometrie : HST, SALT (UBVRI+NIR)
Spectra : VLT, SALT out to d ~ 100 MLy

Age & Metallicity Distributions of Globular Clusters in E/SO Galaxies



Obs. : most show 2 color peaks

why 2 ?

optical colors ↔ age ± metallicity ?

degeneracy

blue peak: universal, old+metal poor ✔

red peak : variable, younger ± more metal rich ?

many different GC populations can hide within one optical colour peak (FvA 2004)

<V-I>red = 1.2 [Fe/H] = +0.4 age = 2.5 Gyr <V-K> = 3.6

<V-I>red = 1.2 [Fe/H] = - 0.4 age = 13 Gyr <V-K> = 3.0

Optical + NIR can tell the difference

(Kotulla+08a, b)

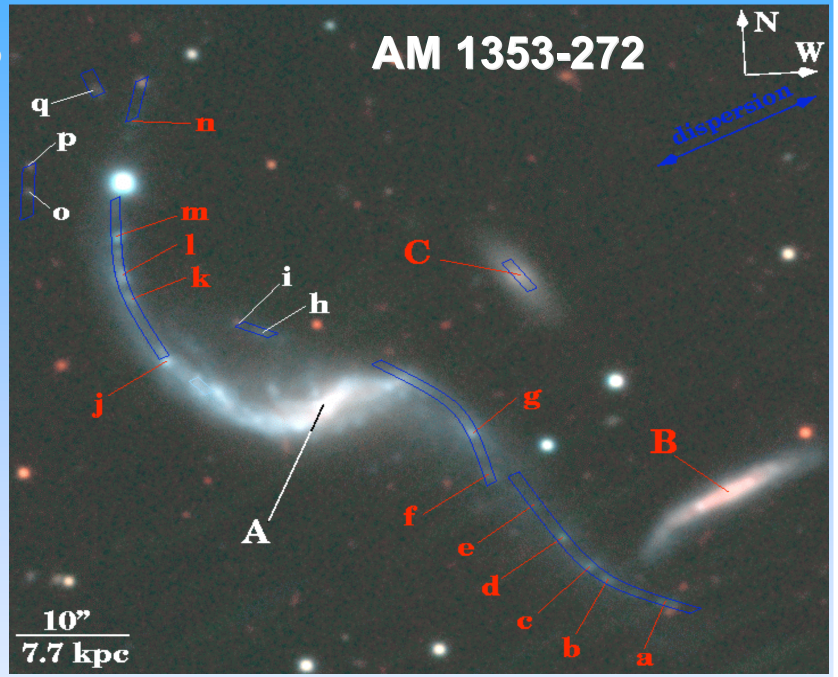
Formation of Tidal Dwarf Galaxies

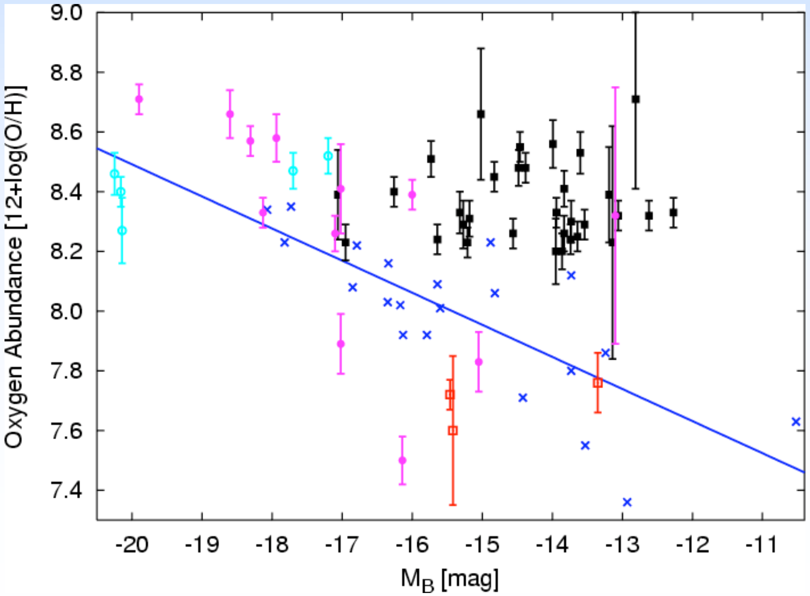
Gaseous / stellar condensations

→ **Tidal Dwarf Galaxies**
galaxy recycling

☛ galaxy formation in the **local** universe

☛ cosmological significance ! ?





Background objects

main I/A group members
and neighbors

confirmed TDG candidates

3 TDG candidates rejected :
not recycled objects

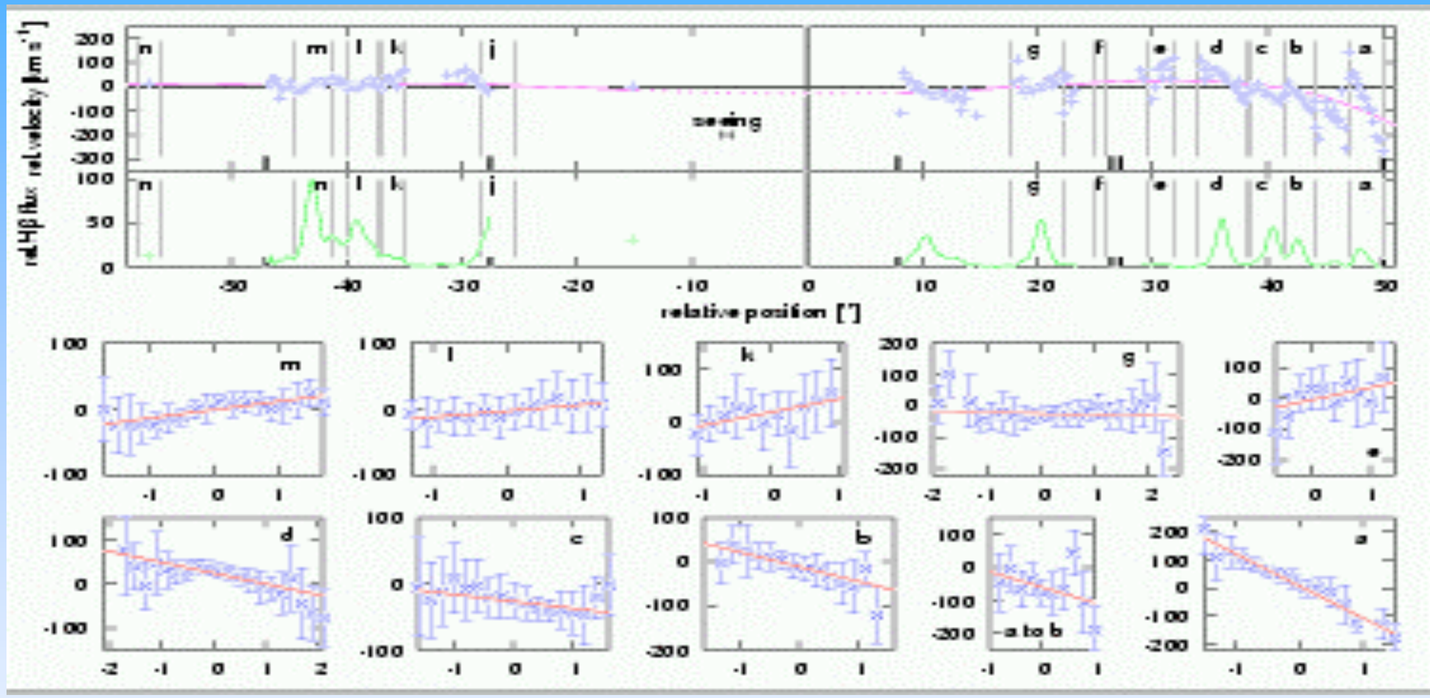
Local dwarf galaxies
(+ fitted relation)

VLT+FORS MOS

(Weilbacher, FvA, Duc 2000, 2001a, b, 2002, 2003)

Formation of Tidal Dwarf Galaxies

VLT+FORS MOS : kinematic independence ?



Velocity profiles : VLT FORS MOS (Weilbacher, FvA & Duc 2002)

- **significant velocity gradients** (> 2σ)
  in 7 TDG candidates in AM 1353-272
- **rotation and free fall**

→ **TDGs in formation**

Cosmo-Dynamical Evolution : The Millennium Simulation

Virgo Consortium MPA Garching

V. Springel et al. 2005

10^{10} particles in cube of (700 Mpc)^3
10 × more than previous simulations

> 1 month supercomputer CPU @ MPA Garching

DM, gas, stars, SF & feedback prescriptions
reconstruct evolutionary history
of 20 million galaxies from
ΛCDM primordial density fluctuation spectrum

Ω_Λ=0.7, Ω_{DM}=0.25, $\Omega_{gas/stars}$=0.05

vacuum energy density   Dark Matter

The Millennium Simulation

Starts from early density fluctuations :
random Gaussian field (CMB obs.: WMAP)
380 000 yr after Big Bang

temperature and density fluctuations ~ 10^{-5}

CDM : particles (?) that only interact gravitationally :
N-body system

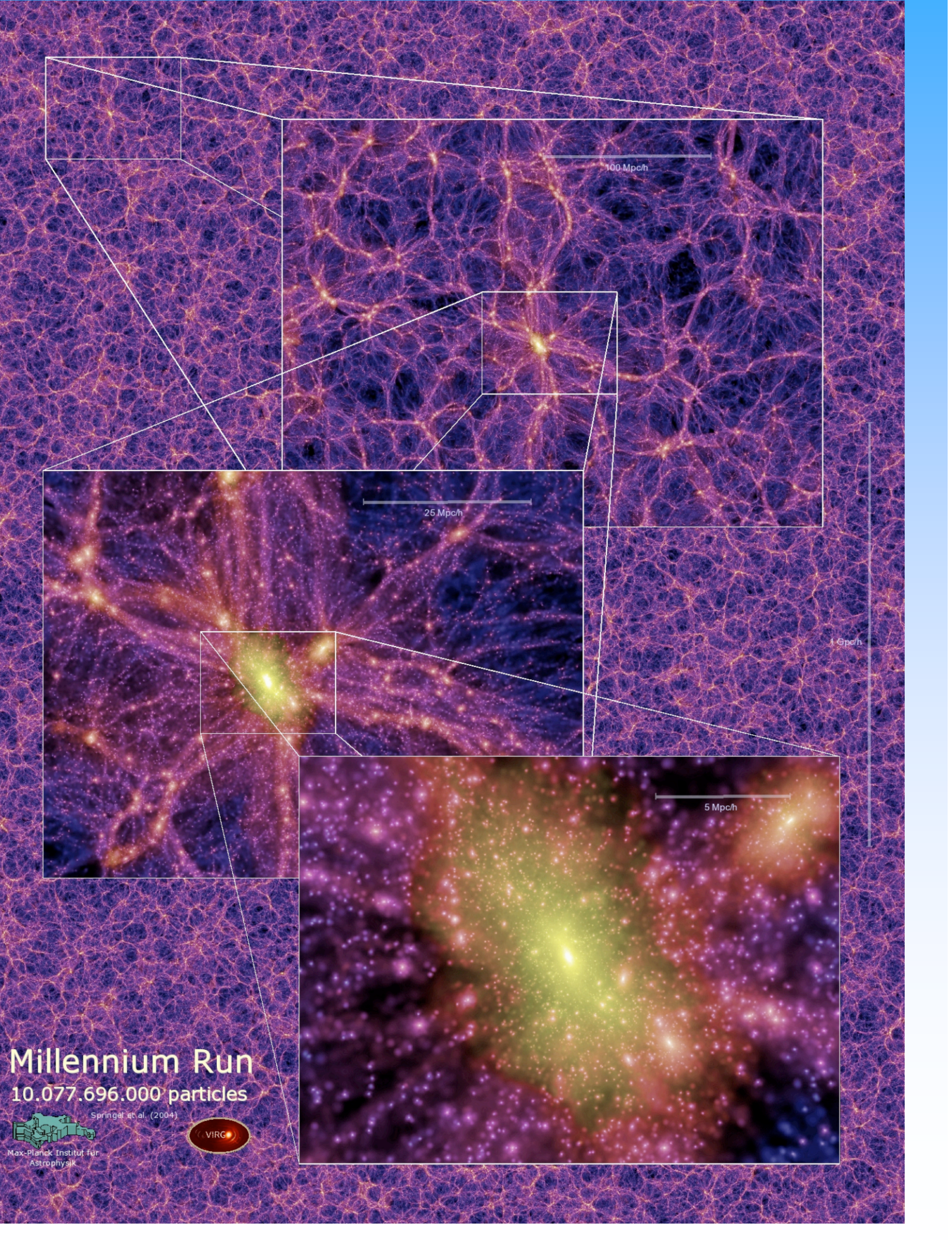
Tree – PM method for evaluation of grav. forces:
combination of hierarchical multipole expansion (=tree) algorithm & classical Fourier transform particle – mesh method

512 processor IBM p690 parallel computer, 1 TB of physical memory, 28 CPU days

mass resolution ~$1 \cdot 10^9\ M_\odot$

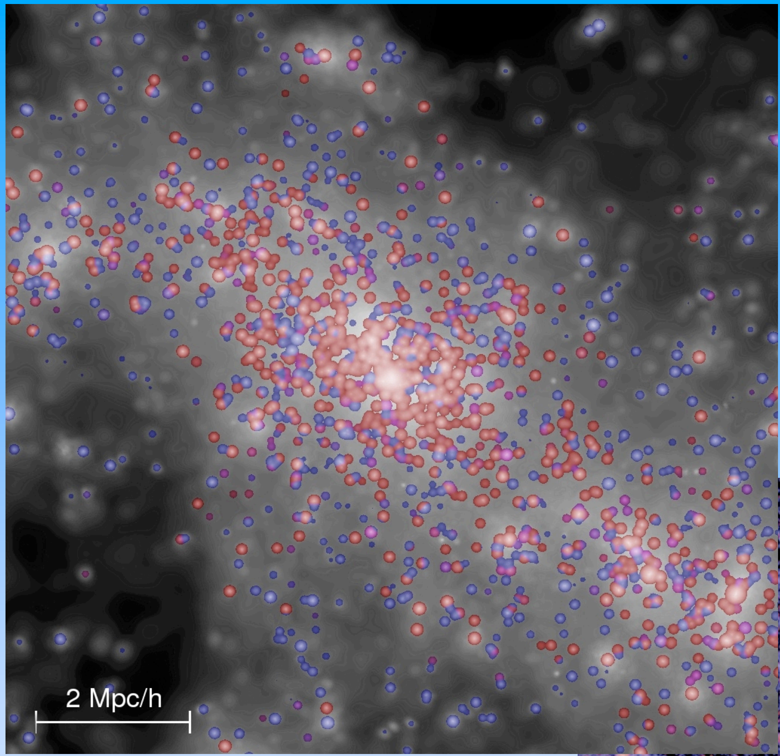
gas collapses inside potential wells of DM halos and forms stars

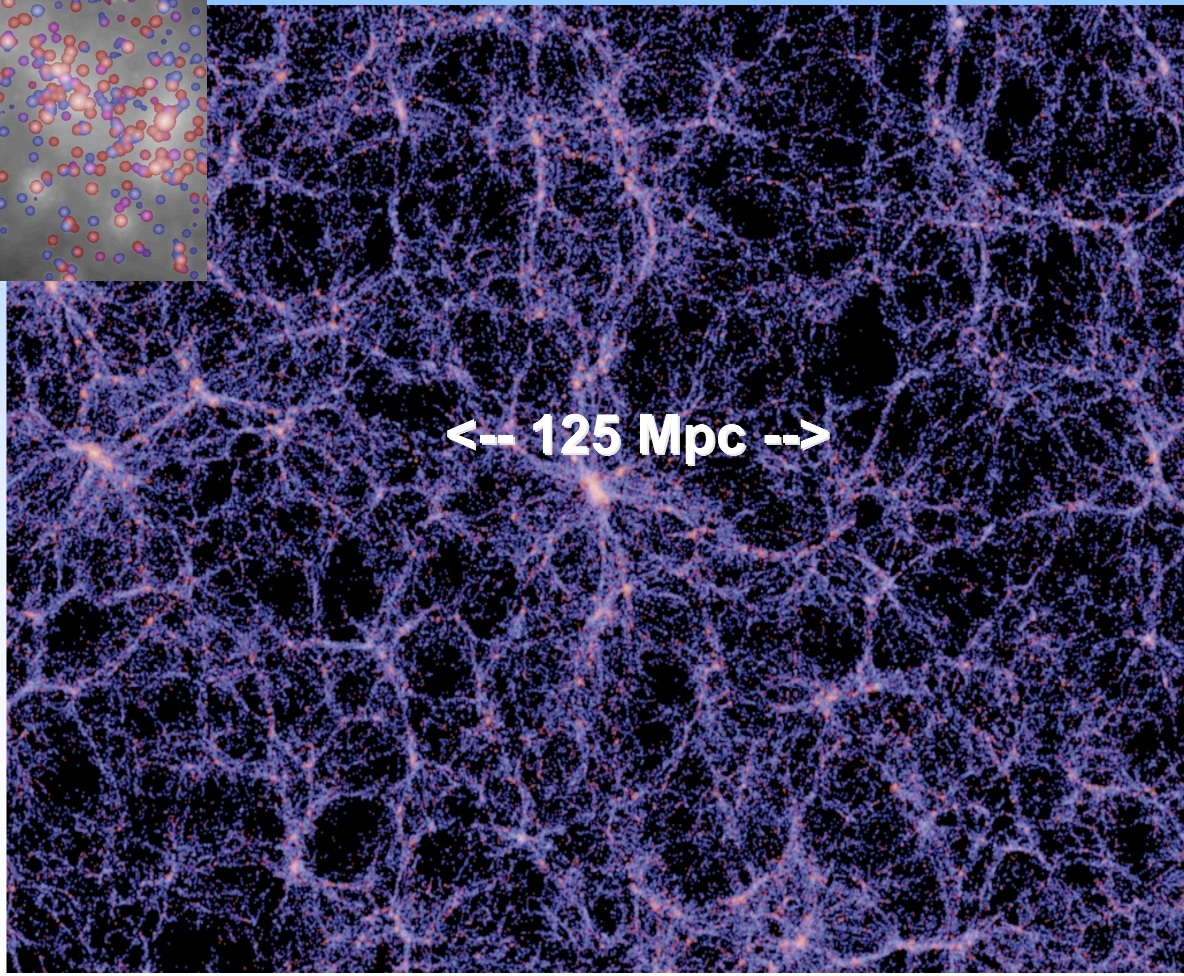
➜ www. mpa-garching.mpg.de/galform/presse/



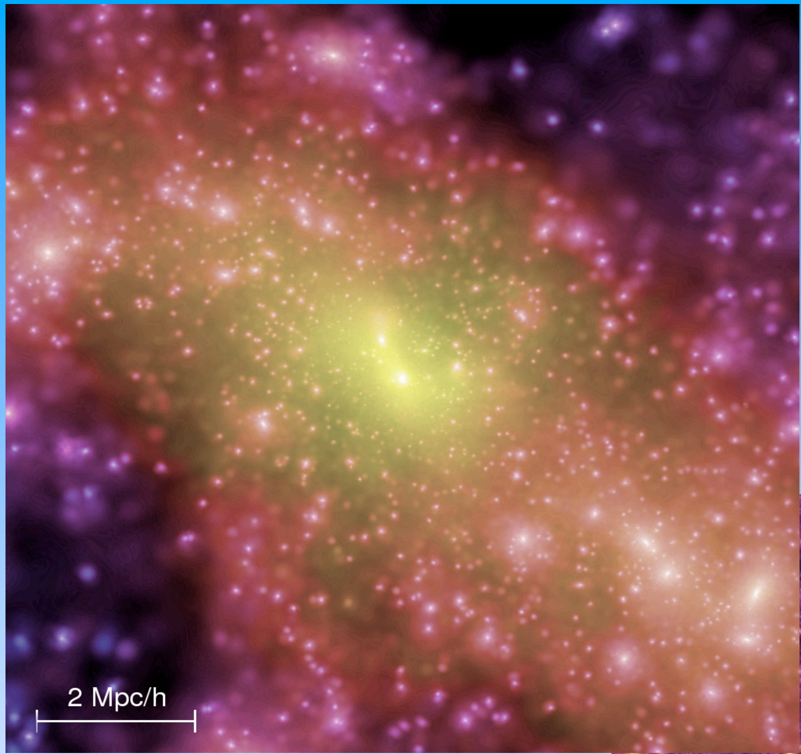
Galaxy Distribution

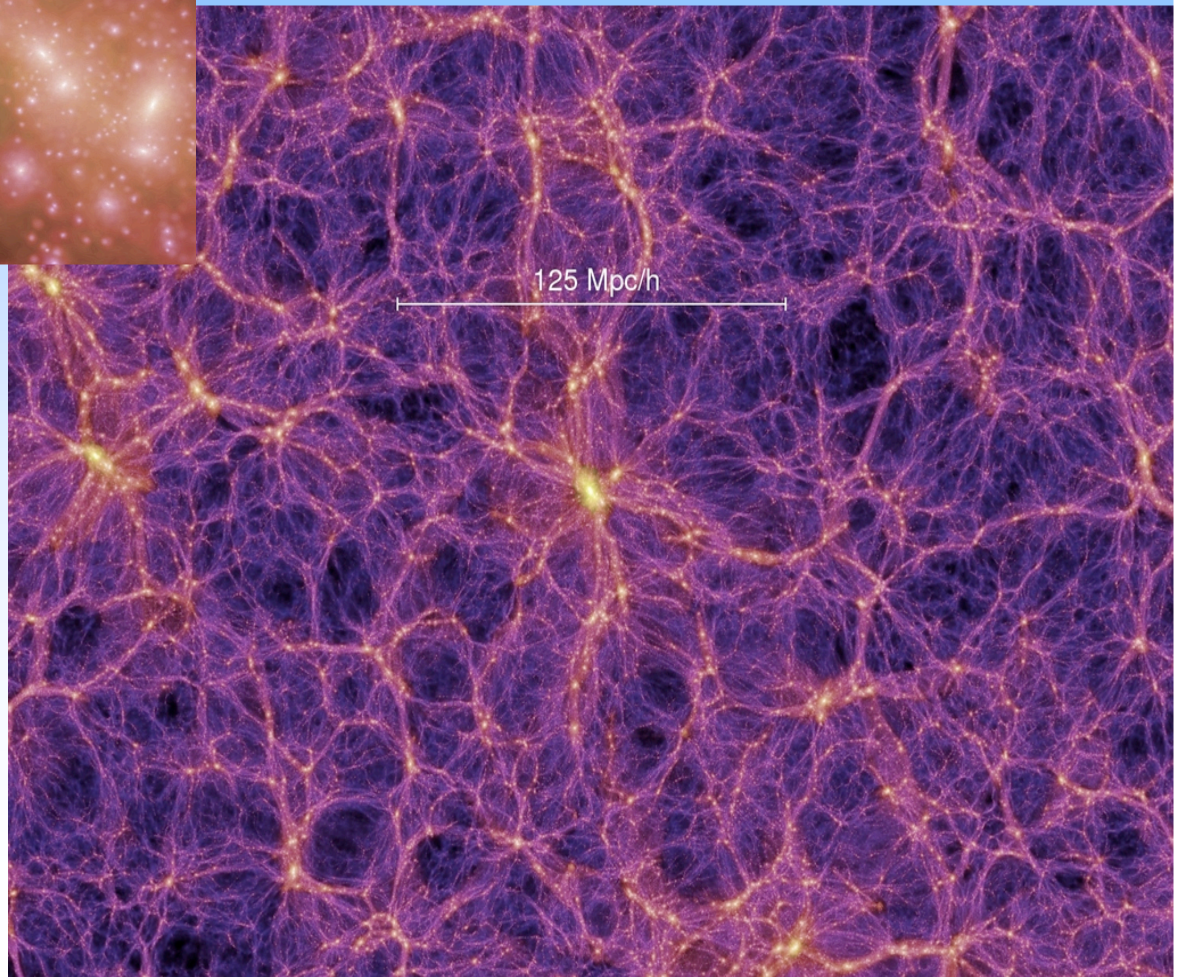
(luminous matter)



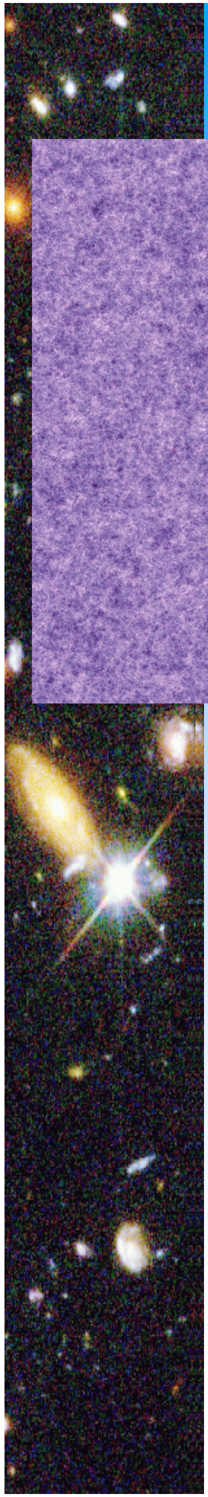


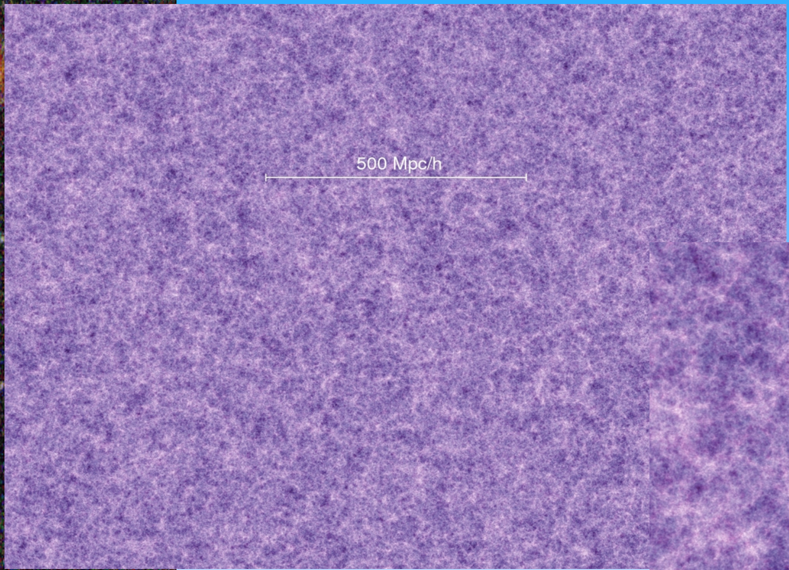
Dark Matter Distribution



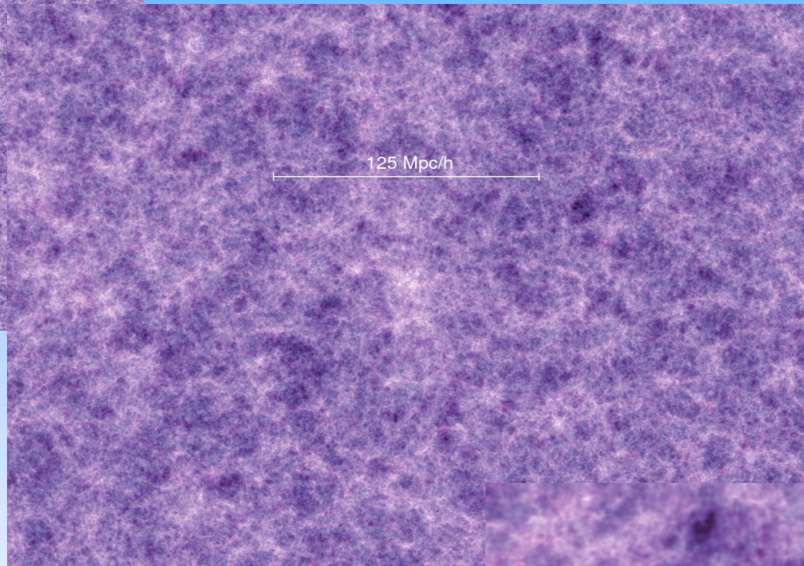


z=18 age=0.2 Gyr

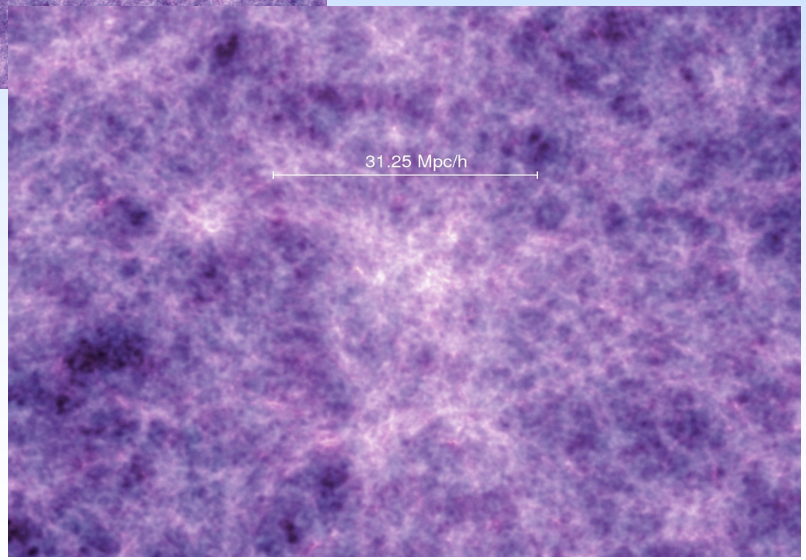




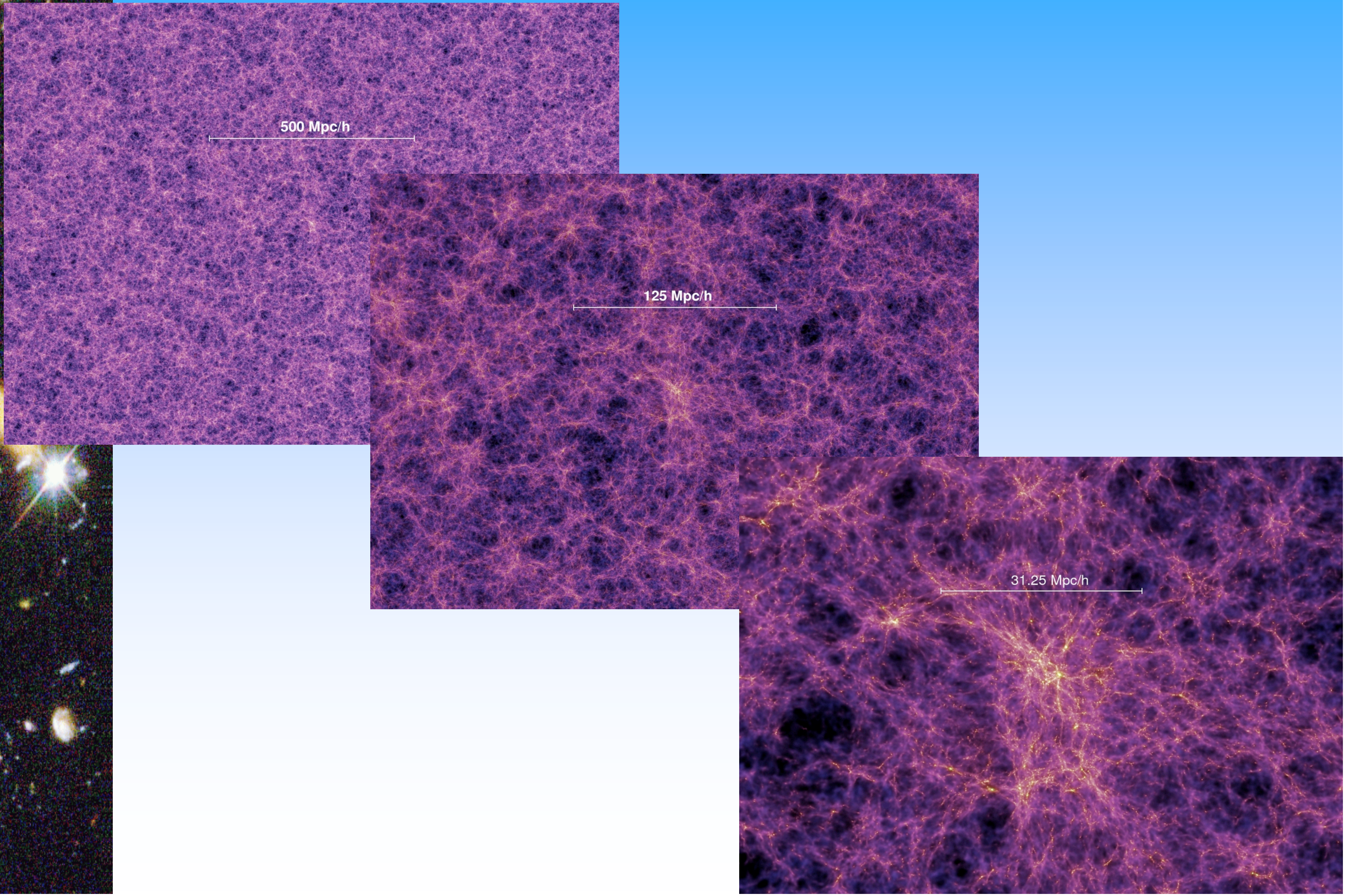
all slices are 15 Mpc thick



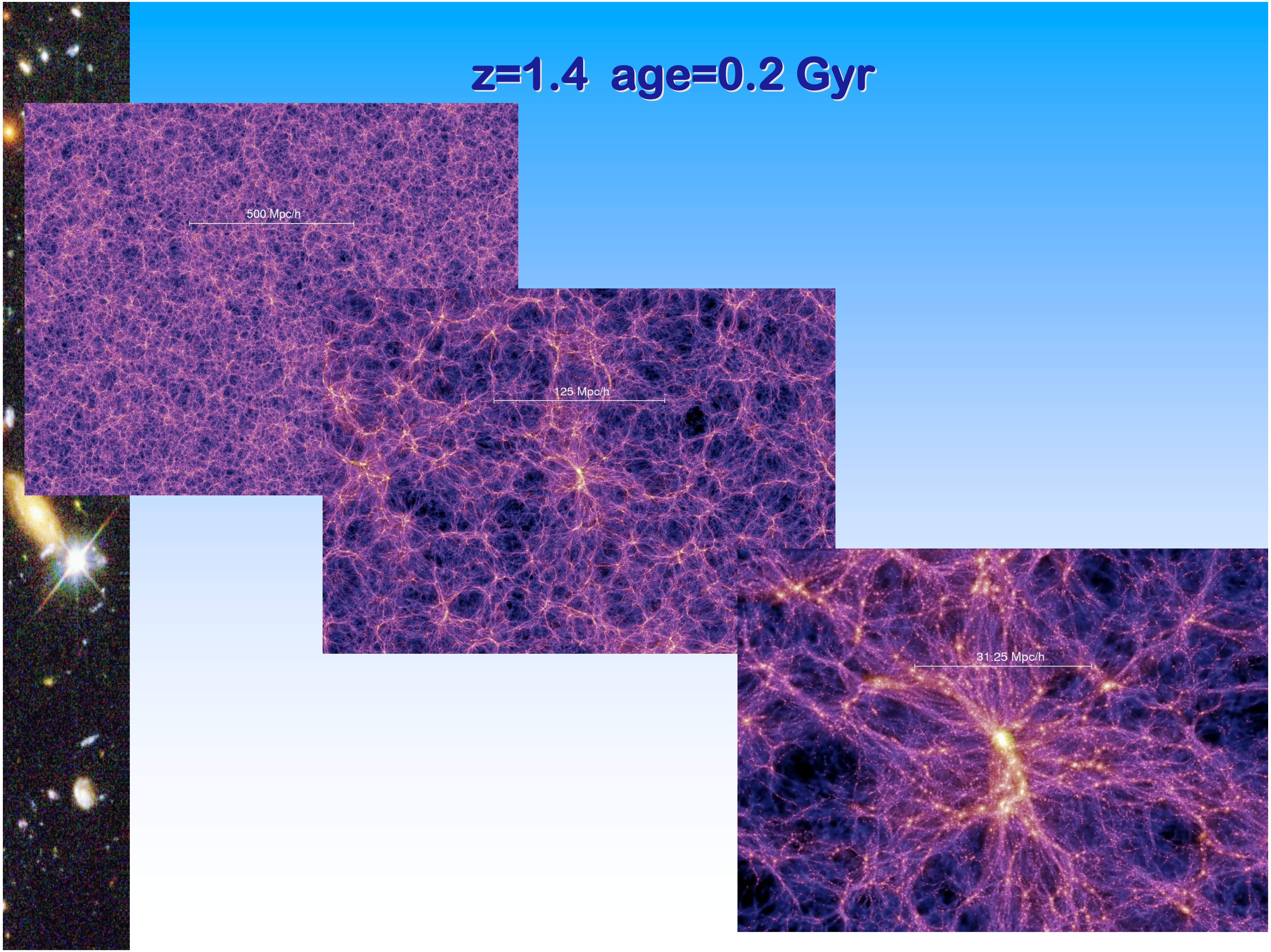
zoom in by factors 4



z=5.7 age=1 Gyr

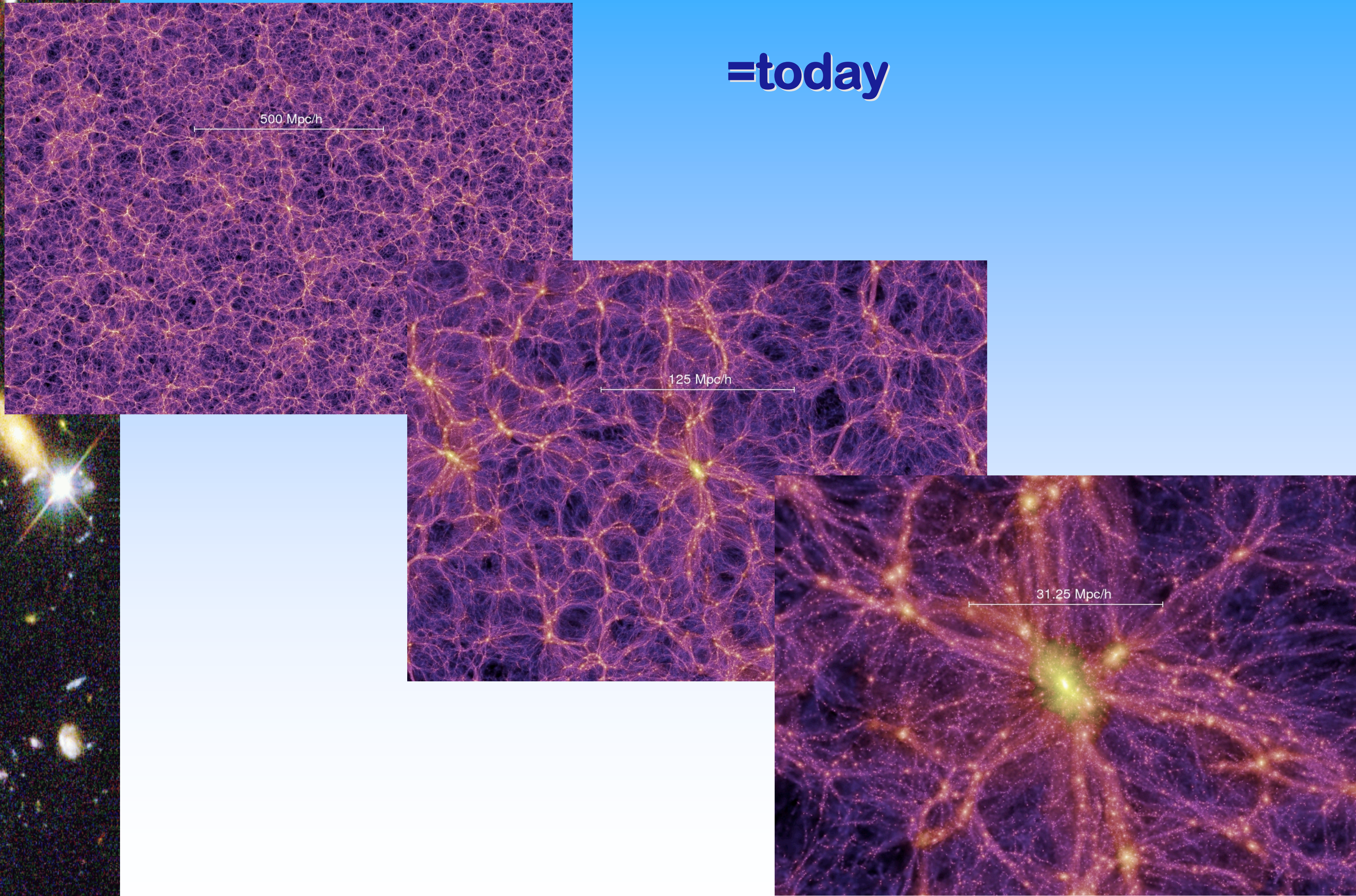


z=1.4 age=0.2 Gyr



z=0 age=13.6 Gyr

=today



The Millennium Simulation

☛ contains ~ $2 \cdot 10^6$ galaxies at z=0 with their full evolutionary histories

☛ allows to

★ follow groth of galaxies in mass and size
★ study clustering properties
★ black hole growth (via simplified prescriptions)

☛ shows a few very massive galaxies already at very high redshifts (z~5)

★ still needs to be fully exploited !

☛ made use of simplified & ad hoc assumptions for SF, AGN formation and AGN feedback

☛ detailed physical description still needs to be worked out

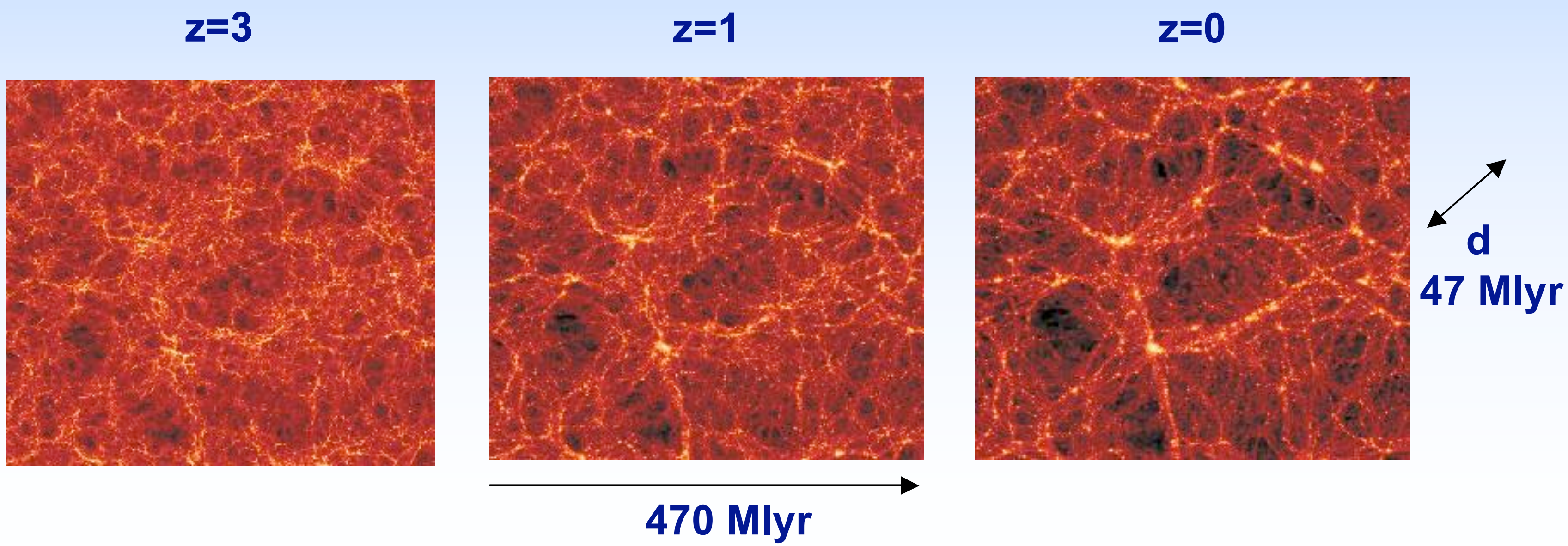
Formation & Dynamical Evolution of Galaxies

Coupling GALEV with a cosmological structure formation code
(Collab. with M. Steinmetz, AIP)

Primordial density fluctuation spectrum : Λ -Cold Dark Matter

GRAPE : N-body + SPH code

- **Dark Matter**
- **Gas** — **+ Bias + Star Formation + Feedback**
- **Stars** — **mass resolution 10^7 $M_\odot$**

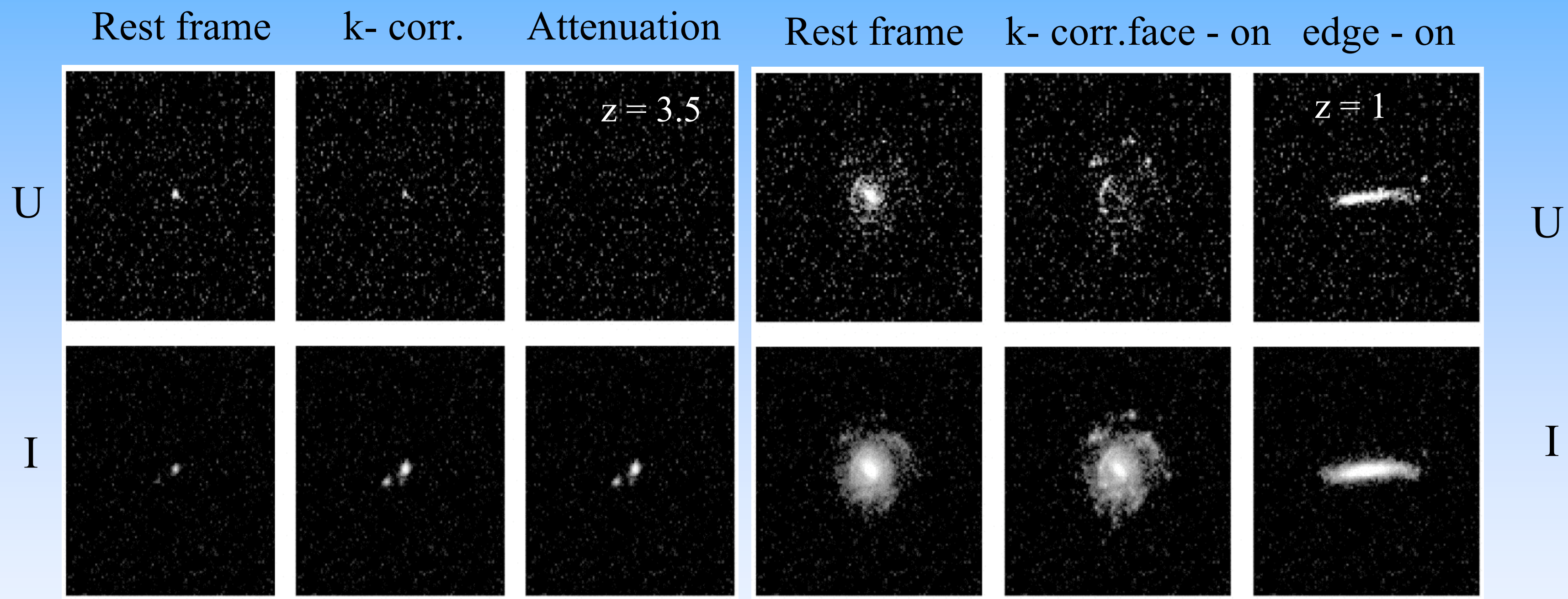


Formation & Dynamical Evolution of Galaxies

Zoom into subvolume with enhanced resolution

+ GALEV

→ artificial HST images of Milky Way type spiral



(Contardo, Steinmetz, FvA 1999)

Could not be continued to z=0 : disk too dense & compact

→ better resolution & better description for SF & feedback

“remedied” by Millennium run by ad hoc assumptions, justified a posteriori