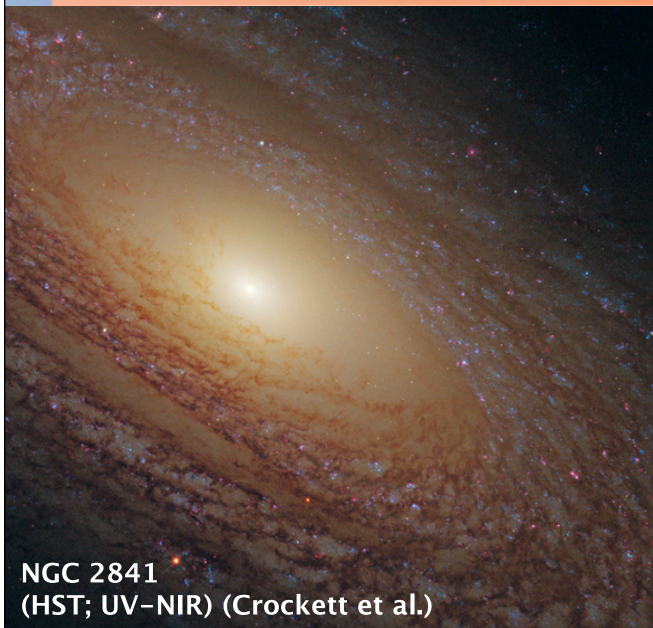
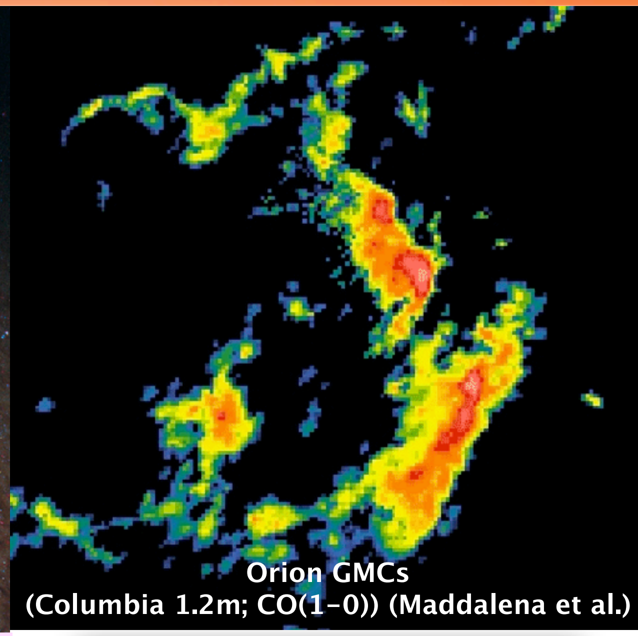
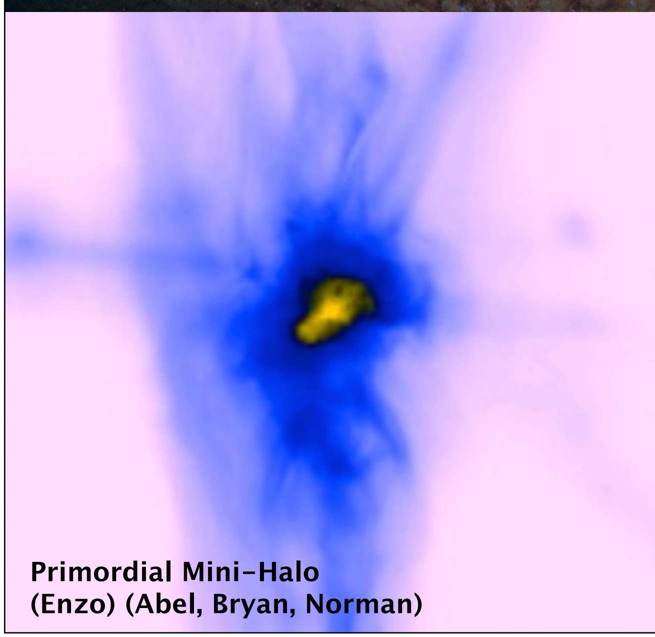
The Role of Star Formation on Galaxy Evolution

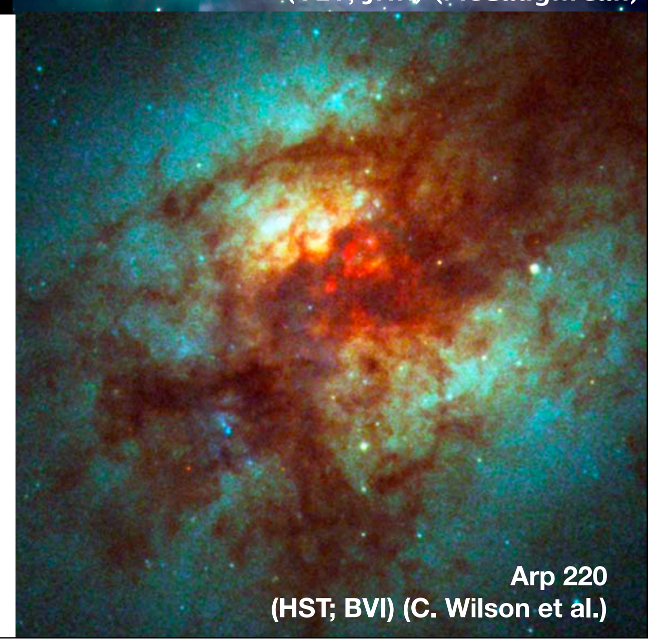

NGC 2841
(HST; UV-NIR) (Crockett et al.)


Orion GMCs
(Columbia 1.2m; CO(1-0)) (Maddalena et al.)

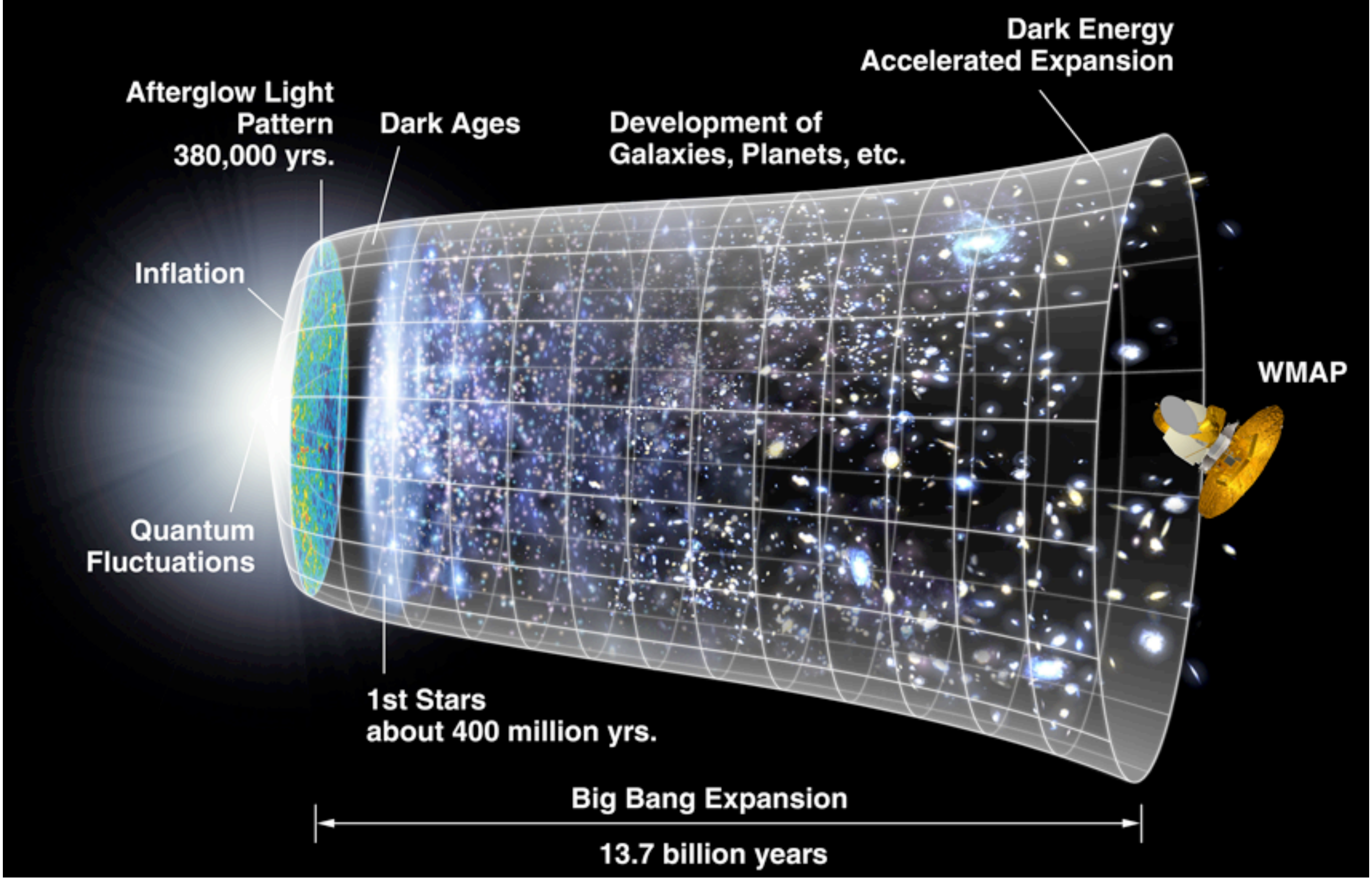

Orion Nebula Cluster
(VLT; JHK) (McCaughrean)


Primordial Mini-Halo
(Enzo) (Abel, Bryan, Norman)

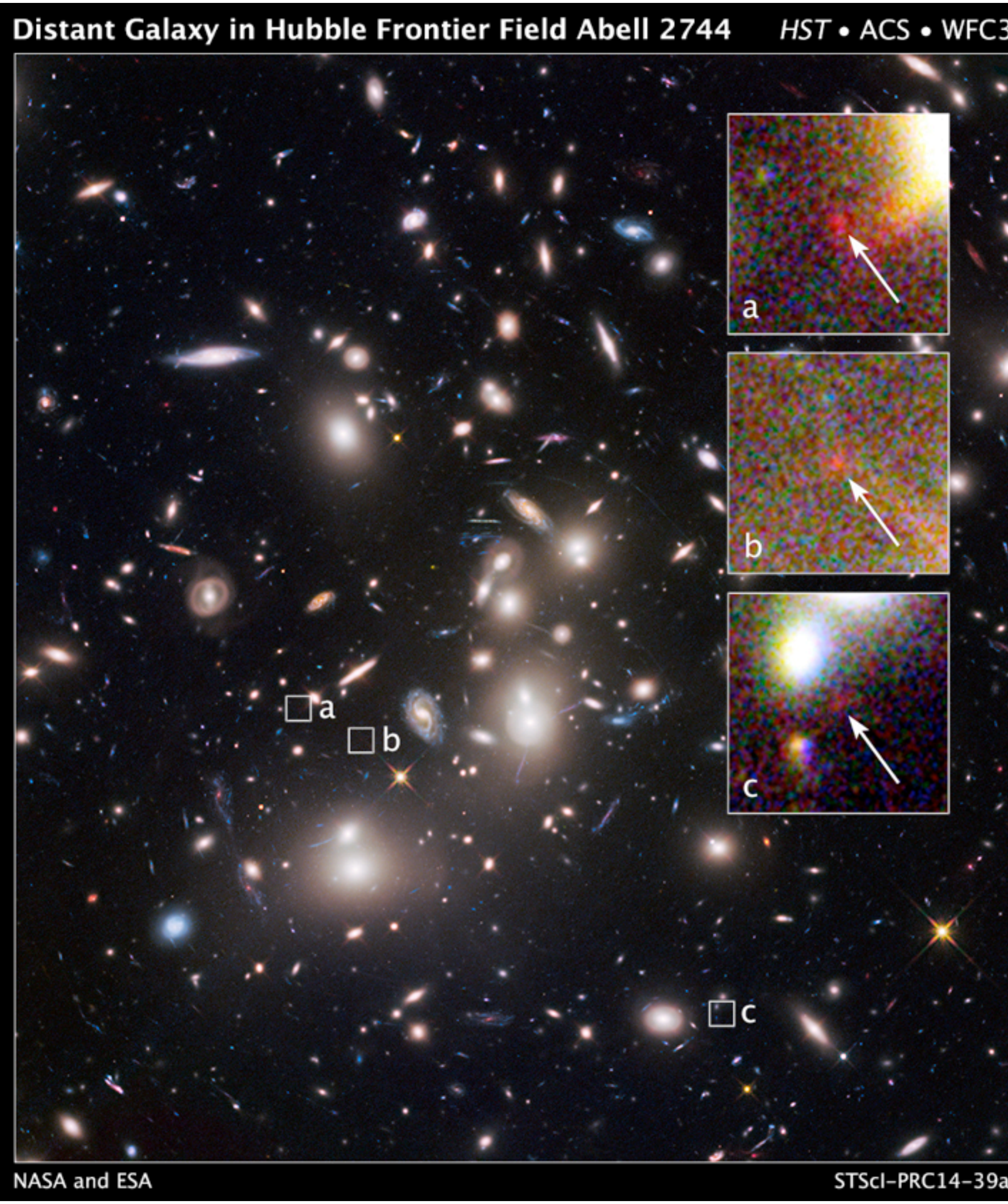
Jonathan Tan
(Univ. of Florida)
Nil Banik
Nicola Da Rio
Chutipong Suwannajak
Kei Tanaka
Ben Wu
Michael Butler (Zurich)
Adam Leroy (NRAO)
Chris McKee (UCB)
Thushara Pillai (MPIA)
Sven Van Loo (Leeds)


Arp 220
(HST; BVI) (C. Wilson et al.)

The Role of Star Formation on Galaxy Evolution

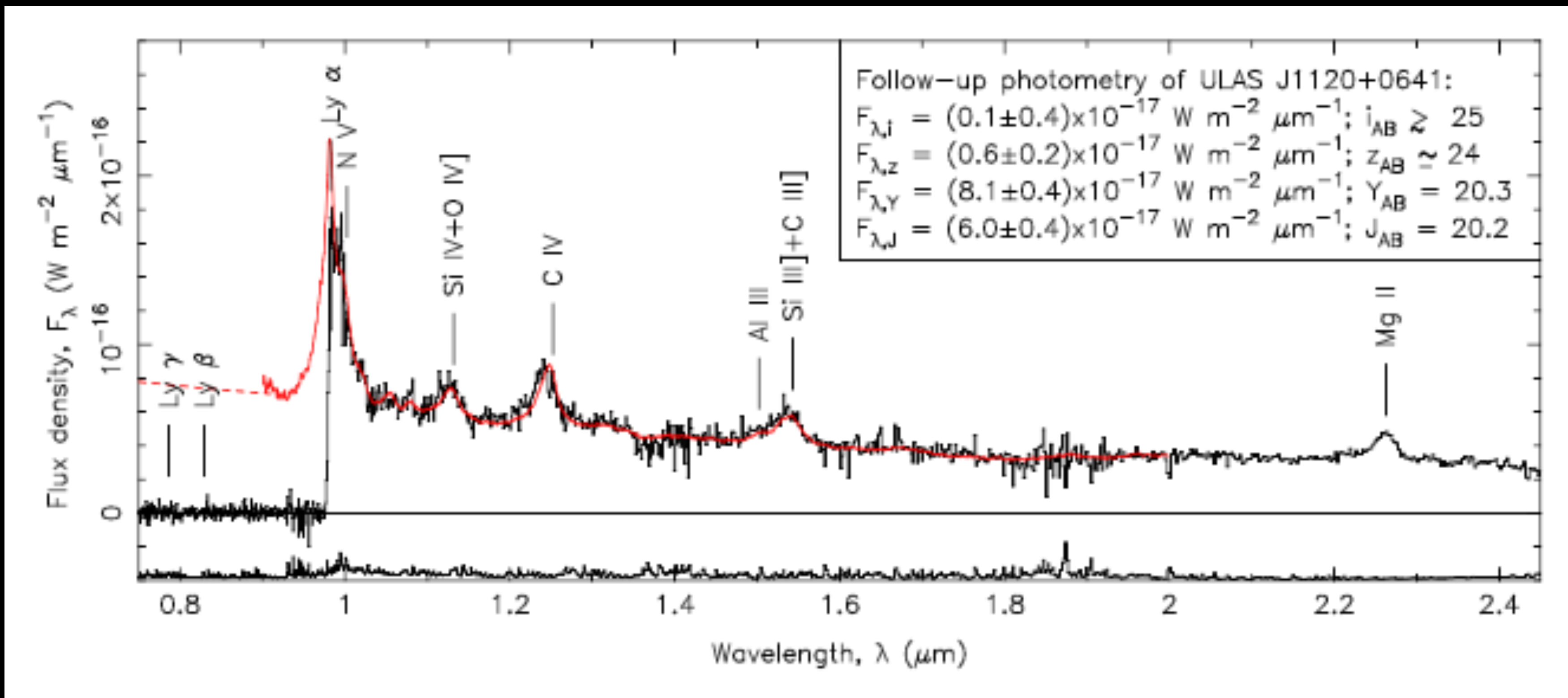


Galaxies at z ~ 8.5 - 12



e.g.,
Zitrin et al. (2014)
Coe et al. (2013)
Ellis et al. (2013)

Quasars at z ~ 6 - 7



z = 7.085, t = 770 Myr
ULAS J1120+0641
Mortlock et al. (2011)

Article Talk Read Edit

List of the most distant astronomical objects

From Wikipedia, the free encyclopedia

Most distant astronomical objects with spectroscopic redshift determinations

Name	Redshift (z)	Light travel distance§ (Gly)	Type	Notes
GRB 090423	z=8.2	13.035	Gamma-ray burst	[1][2]
z8 GND 5296	z=7.51	13.02	Galaxy	Confirmed Galaxy[3][4]
SXDF-NB1006-2	z=7.215	12.91	Galaxy	Galaxy[5][6]
GN-108036	z=7.213	12.91	Galaxy	Galaxy[6][7]
BDF-3299	z=7.109	12.9	Galaxy	[8]
ULAS J1120+0641	z=7.085	12.9[9]	Quasar	[10]
A1703 zD6	z=7.045	12.89	Galaxy	[6]
BDF-521	z=7.008	12.89	Galaxy	[8]
IOK-1	z=6.964	12.88	Galaxy	[6]
LAE J095950.99+021219.1	z=6.944		Galaxy	Lyman-alpha emitter — Faint Galaxy[11]

§ The tabulated distance is the light travel distance, which has no direct physical significance. See discussion at distance measures and Observable Universe

Wikipedia
The Free Encyclopedia

List of the most distant astronomical objects

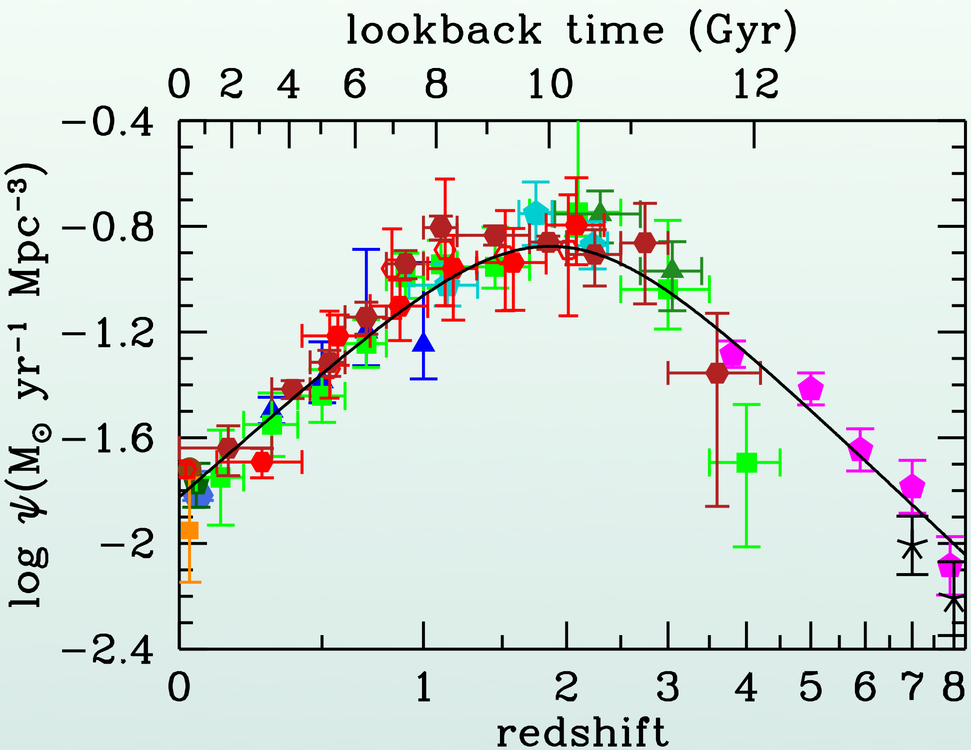
Notable candidates for most distant astronomical objects, based on photometric redshift estimates

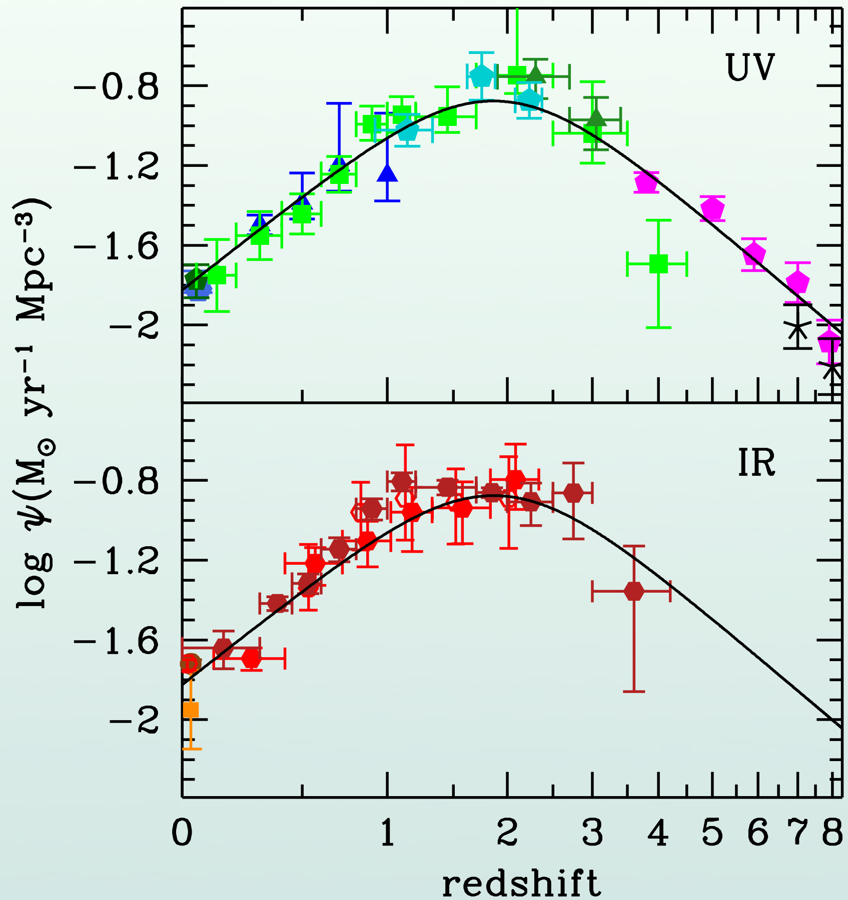
Name	Redshift (z)	Light travel distance§ (Gly)	Type	Notes
UDFj-39546284	z_p≈11.9?	13.37	Protogalaxy	This is a candidate protogalaxy,[13][14][15][16] although recent analyses have suggested it is likely to be a lower redshift source.[17][18]
MACS0647-JD	z_p≈10.8	13.3	Galaxy	Candidate most distant galaxy, which benefits by being magnified by the gravitational lensing effect of an intervening cluster of galaxies.[19][20]
MACS J1149-JD	z_p≈9.6	13.2[21]	Candidate galaxy or protogalaxy	[22]
GRB 090429B	z_p≈9.4	13.14[23]	Gamma-ray burst	[24] The photometric redshift in this instance has quite large uncertainty, with the lower limit for the redshift being z>7.
UDFy-33436598	z_p≈8.6		Candidate galaxy or protogalaxy	[25]
UDFy-38135539	z_p≈8.5		Candidate galaxy or protogalaxy	A spectroscopic redshift of z=8.55 was claimed for this source in 2010,[26] but has subsequently been shown to be mistaken.[27]
BoRG-58	z_p≈8		Cluster or protocluster	Protocluster candidate[28]
A1689-zD1	z_p≈7.6	13	Galaxy or protogalaxy	Galaxy[29]

§ The tabulated distance is the light travel distance, which has no direct physical significance. See discussion at distance measures and Observable Universe

This is an incomplete list that may never be able to satisfy particular standards for completeness. You can help by expanding it with entries that are reliably sourced.

Star Formation History





Madau & Dickinson (2014)

The Physics of Star Formation ... a complex, nonlinear process

- **Gravity vs "pressure support":** thermal, magnetic, turbulence, ram, radiation, cosmic rays. Also rotation/shear.

- **Evolution of pressure support:** Heating & cooling, generation (dynamo) & diffusion of B-fields, generation & decay of turbulence.

- **Chemical evolution** of dust & gas, affects heating/cooling & ionization fraction of HI/H_2.

- **Dynamical evolution** of binaries & clusters.

- **Stellar structure and evolution:** affects feedback and metal enrichment.

- **Feedback:** outflows/winds, dissociation/ionization, radiation pressure, supernovae.

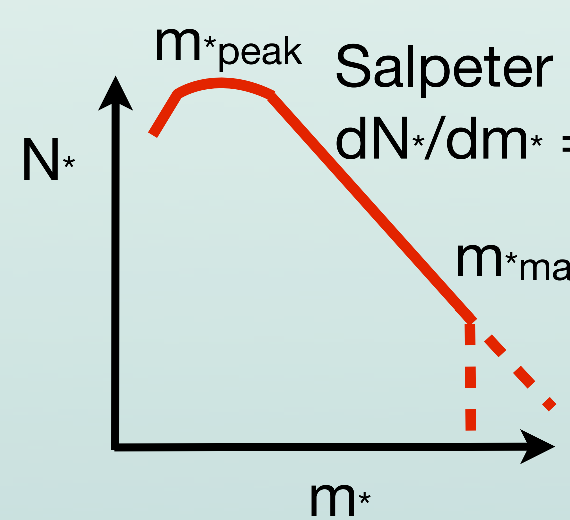
- **Uncertain initial/boundary conditions.**

- **Wide range of scales:** e.g., ~12 dex in space, time in a cluster; & multidimensional.

- **The need for sub-grid models in numerical simulations.**

Star Formation: Some Open Questions

- Causation: external triggering or spontaneous gravitational instability?
- Initial conditions: how close to equilibrium?
- Accretion mechanism: [turbulent/magnetic/thermal-pressure]-regulated fragmentation to form **cores** vs **competitive accretion / mergers**
- Timescale: fast or slow (# of dynamical times)?
- End result
  - Initial mass function (IMF)
  - Binary fraction and properties



Salpeter (1955)

$dN_*/dm_* = A\ m_*^{-2.35}$

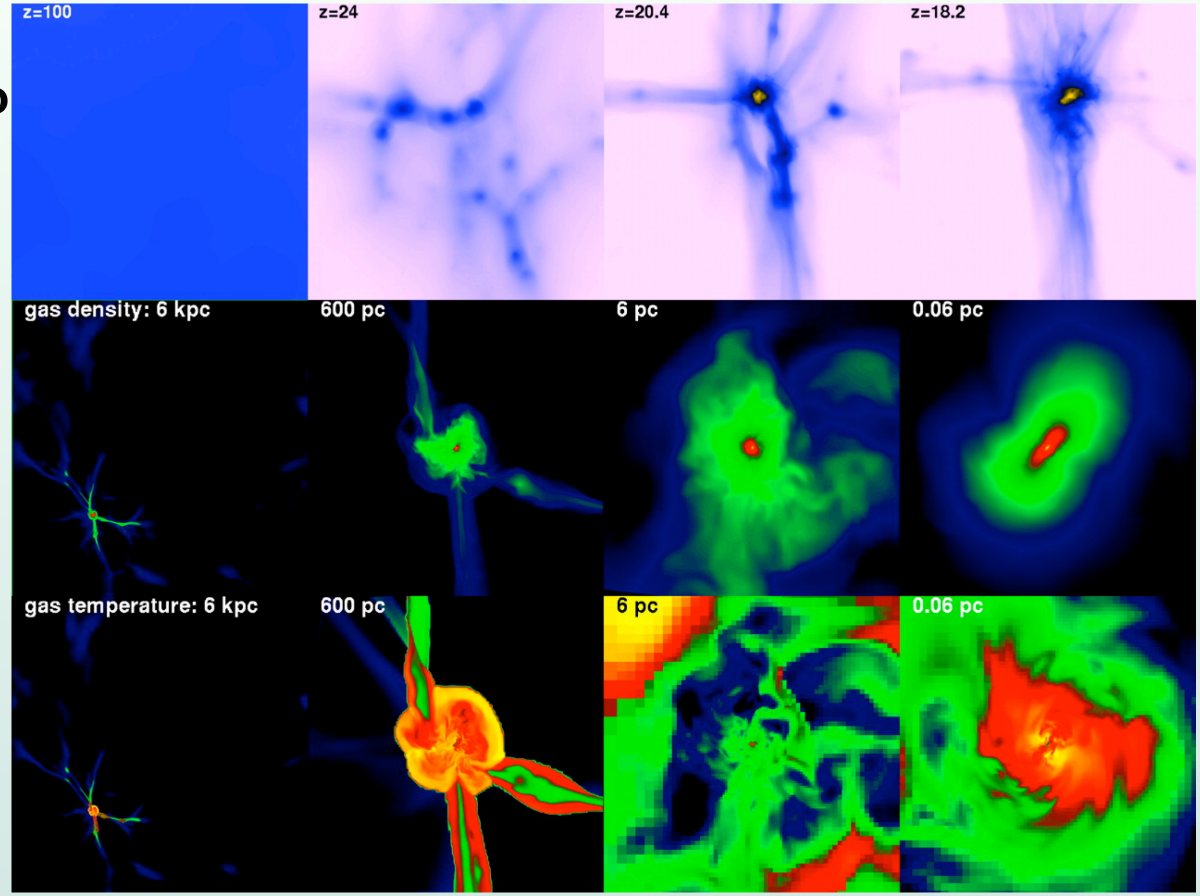
How do these properties vary with environment?

Galaxy Formation: Some Open Questions

- The first stars & galaxies: What were the masses of the first stars? How did they set the environment for first galaxy formation (radiation, mechanical and chemical)? IMF of early galaxies?
- Supermassive black holes: How do they form? How do they continue to accrete? Is this regulated by star formation? How does their feedback influence galaxy formation?
- Star formation “laws” in galactic disks: What physical mechanisms regulate global & local star formation rates in different galactic environments?
- Starbursts/AGN/low Z: How does the starburst/AGN/low Z environment affect the star formation process (e.g., IMF) and black hole fueling?

The First Stars

Abel, Bryan, Norman (2002)



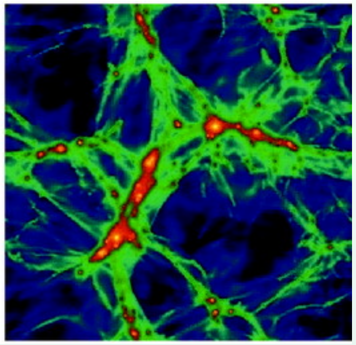
1. Form pre-galactic minihalo $\sim 10^6 M_\odot$ by $z \sim 20$

2. Form quasi-hydrostatic gas core inside halo: at $r \approx 10$pc: $M \approx 4000 M_\odot$, $n_H \approx 10$ cm^{-3}, $f_{H2} \approx 10^{-3}$, $T \sim> 200$K

3. Rapid 3-body H_2 formation at $n_H > \sim 10^{10}$cm^{-3}. Strong cooling -> supersonic inflow.

4. Form hydrostatic protostar: $n_H \approx 10^{17}$cm^{-3}, $T \approx 2000$ K: optically thick, adiabatic contraction -> protostar $m_* \approx 0.005 M_\odot$, $r_* \approx 14 R_\odot$ (Omukai & Nishi 1998). Simulations now reach stellar densities (e.g. Turk+; Greif+), but grind to a halt (short timesteps), still at small ($\ll M_\odot$) protostellar masses. Sometimes see binary fragmentation on larger scales (Turk et al. 2009, Susa et al. 2014).

Next need analytic & semi-analytic sub-grid model: when does accretion end?



Definitions

McKee & Tan (2008); O'Shea et al. (2008; First Stars III Conference Summary)

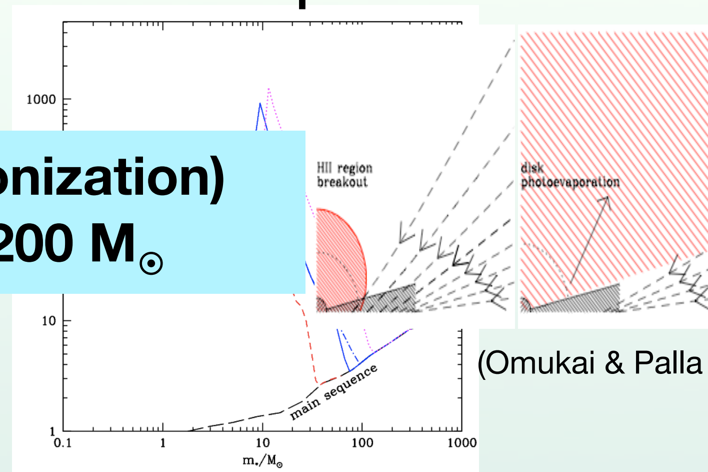
Population III
Stars having a metallicity so low ($Z<Z_{crit}$) it has no effect on their formation, i.e. negligible cooling ($\sim10^{-5}Z_{\odot}$), or their evolution ($\sim10^{-8}Z_{\odot}$).

Population III.1
The initial conditions for the formation of Population III.1 stars (halos) are determined solely by cosmological fluctuations.

Population III.2
The initial conditions for the formation of Population III.2 stars (halos) are significantly affected by other astrophysical sources (external to their halo).

Physical Processes in Pop III star formation

Protostellar feedback (ionization) halts accretion at ~100-200 $M_\odot$



(McKee & Tan 2008)

Protostellar Evolution (Omukai & Palla 2003; Tan & McKee 2004)

Magnetic Field Generation?

$$r_d = 3.44 \left(\frac{f_{\rm Kep}}{0.5}\right)^2 \epsilon_{*d}^{-9/7} \left(\frac{m_{*d}}{M_\odot}\right)^{9/7} K'^{-10/7}\ {\rm AU}.$$

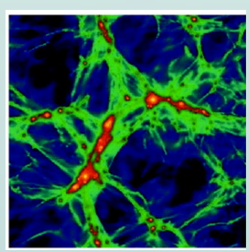
Rotation & Disk Structure; Fragmentation? (Tan & Blackman 2004)

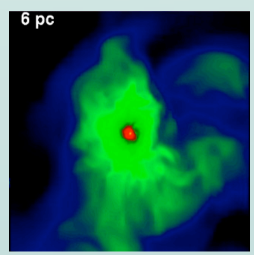
Dark Matter Annihilation Heating? (Spolyar et al. 2008; Natarajan, Tan, O'Shea 2009)

Accretion Rate $\dot{m}_* = 0.026 K'^{15/7} (m_*/M_\odot)^{-3/7} M_\odot yr^{-1}$ (Tan & McKee 2004)

Initial Conditions

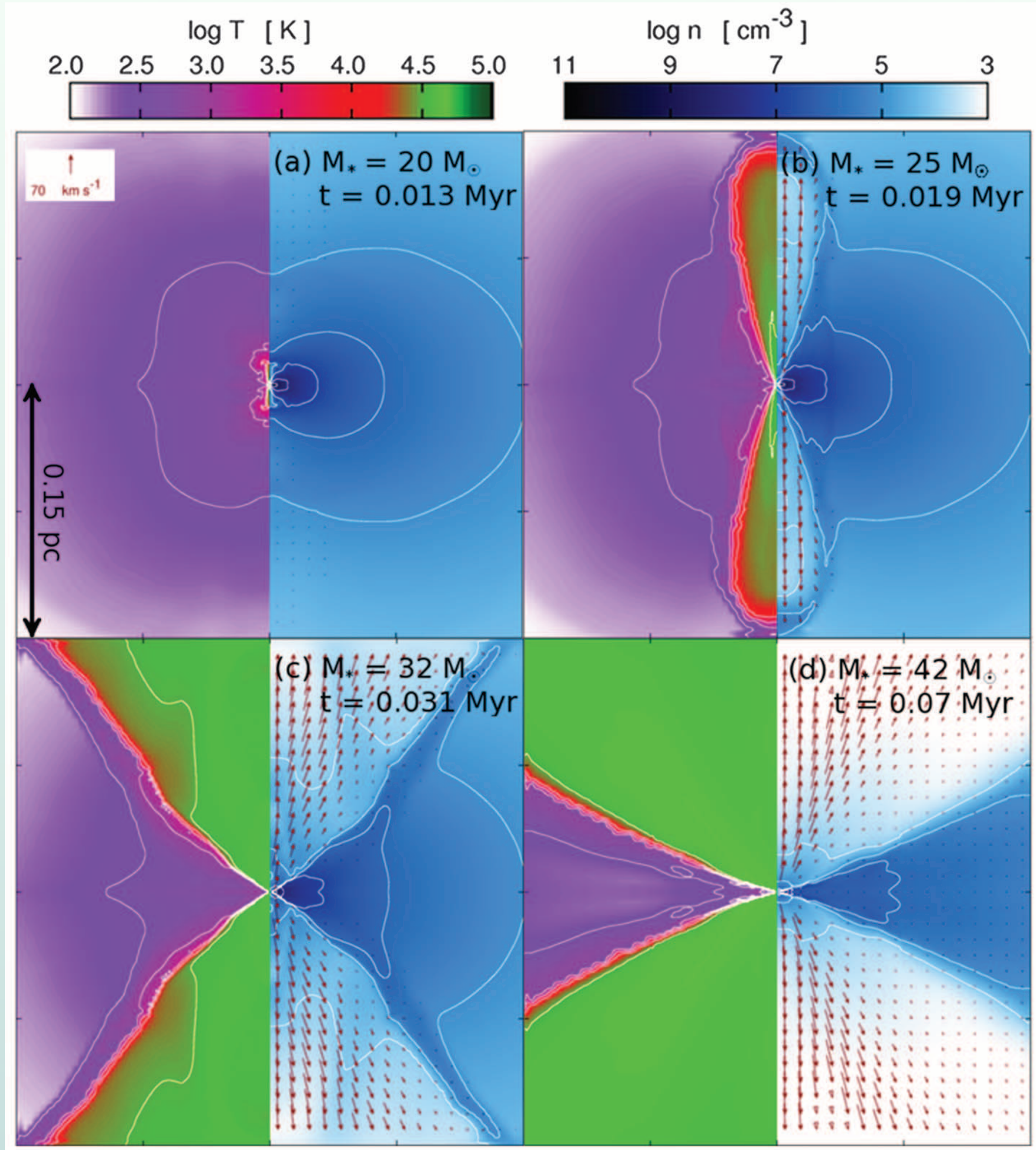
polytropic structure: $P = K\rho^\gamma$





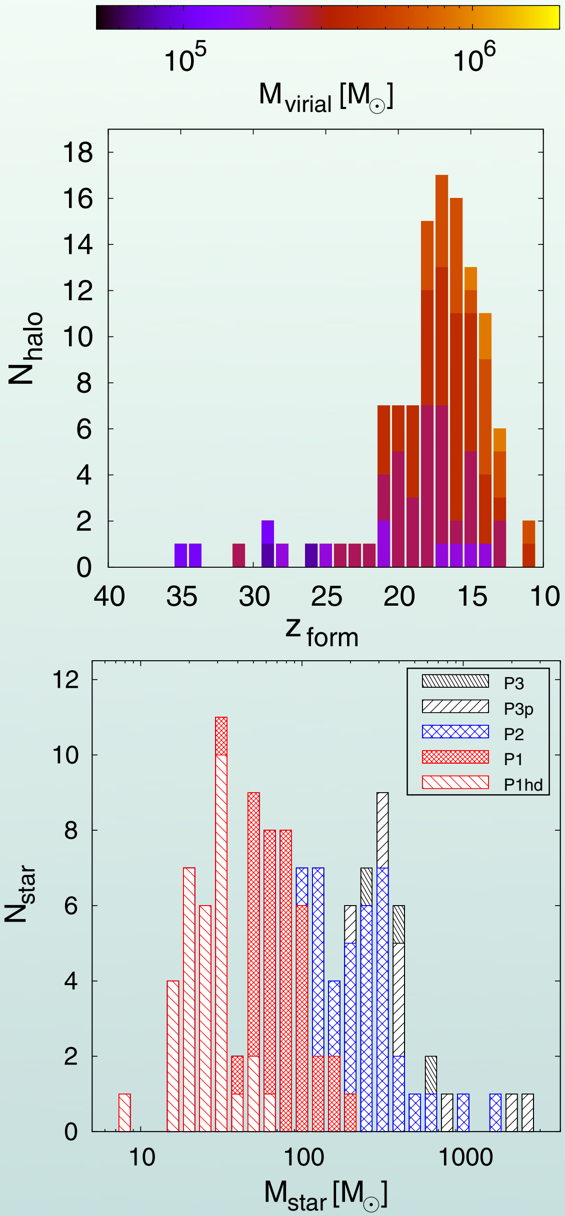
(Abel ea, Bromm ea, Yoshida ea, Omukai ea.)

Radiation-Hydro Simulations of Protostellar Feedback

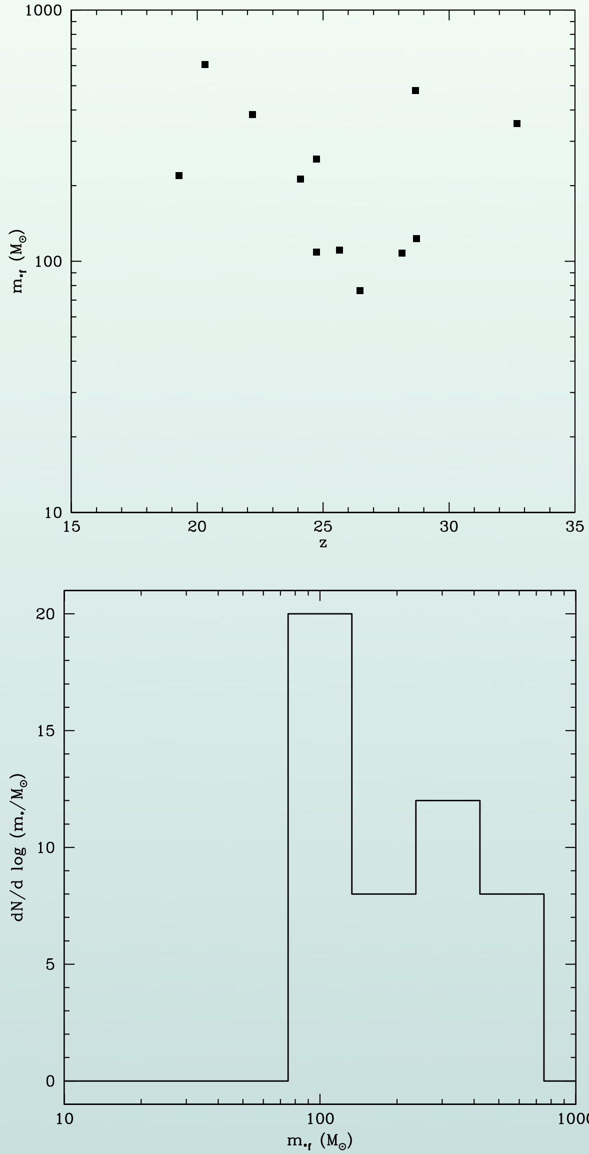


Hosokawa, Omukai, Yoshida, Yorke (2011)

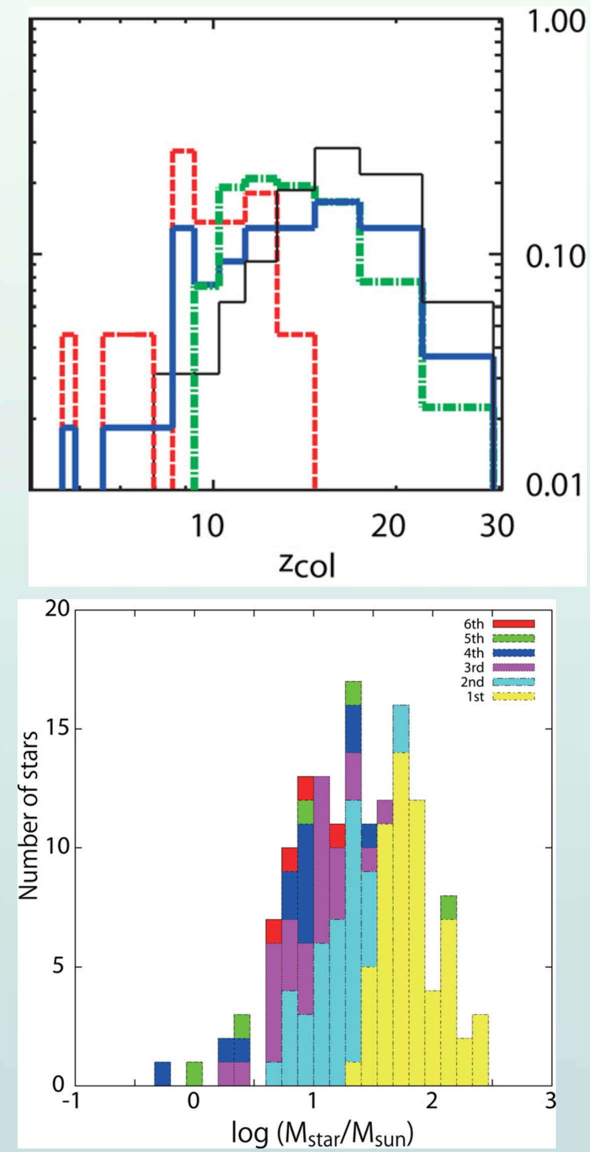
Populations of Pop III.1 stars



Hirano et al. (2014)



Tan et al. (2010)



Susa et al. (2014)

Some Pop III Questions

Fragmentation in minihalo and protostellar accretion disk?

- **"Low-fragmentation":** single stars/binaries/small-N (Turk et al. 2009; Hirano et al. 2014; Susa et al. 2014).
- **"High-fragmentation":** large numbers of Pop III stars, including low-mass (Greif et al. 2011; Clark et al. 2011).

Effect of WIMP DM annihilation? - perhaps can reduce fragmentation and make supermassive stars (Spolyar et al. 2008; Natarajan et al. 2009; Smith et al. 2012; Stacy et al. 2014)

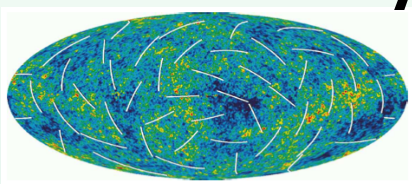
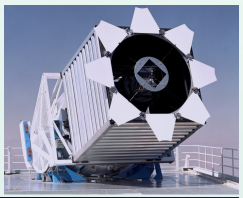
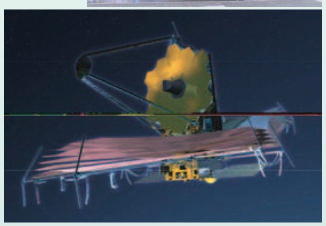
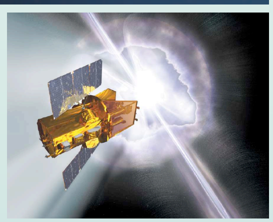
DM streaming lowers and delays Pop III SFR, by increasing required minihalo mass - (Tseliakhovich & Hirata 2010; Naoz et al. 2012)

Pop III.2 star formation: i.e., zero/negligible metallicity, but affected by astrophysical feedback. Thought to be of lower mass due to enhanced e- fraction -> larger H_2 abundance.

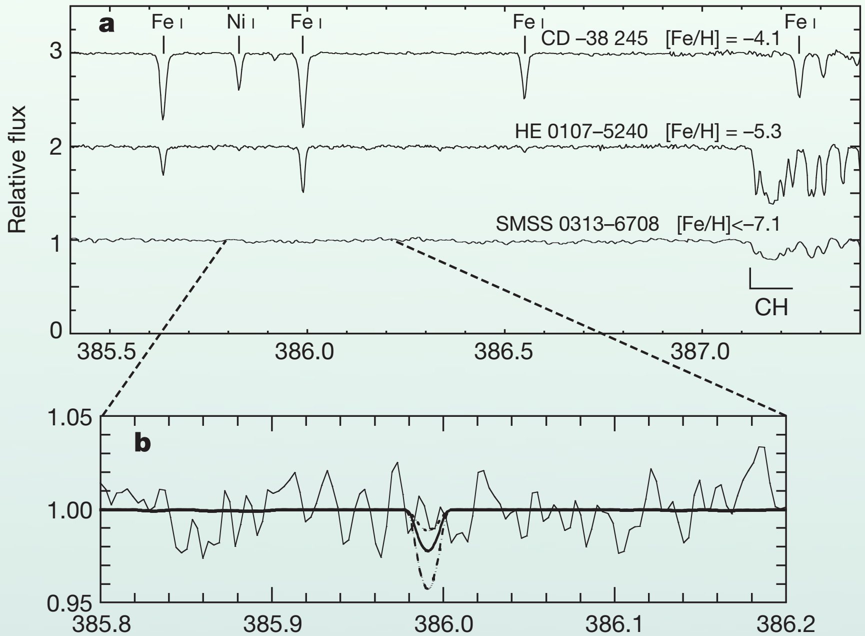
Relation to supermassive black hole formation, first galaxies, globular clusters? (review by Bromm 2013).

How reliable are Pop III stellar evolution & nucleosynthetic supernova yields? (Heger & Woosley 2002; Umeda & Nomoto 2002).

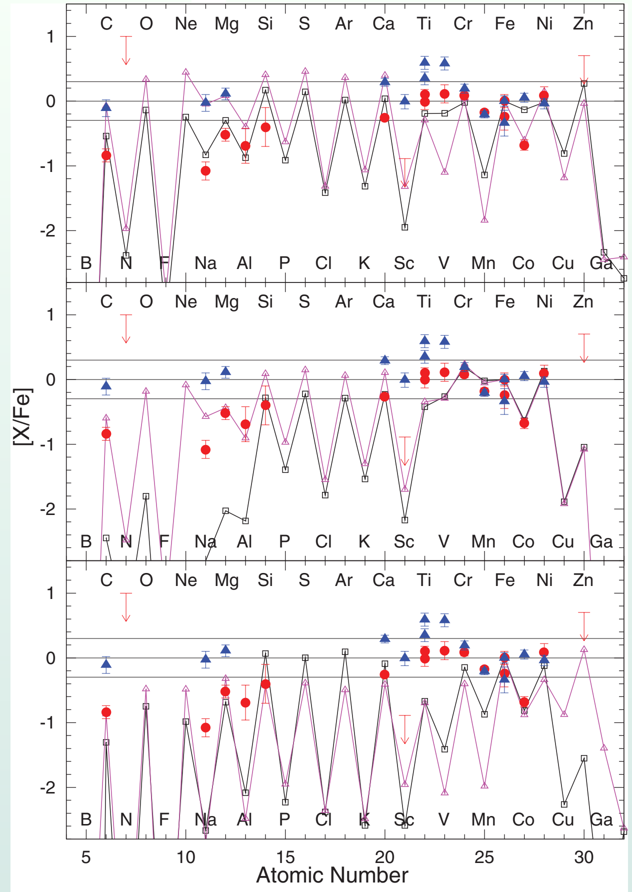
First Star Observables

Astrophysical Effects	Observations
 Reionization (H, He)	**CMB polarization** (WMAP Page et al. 07) **H 21cm** (LOFAR Morales & Hewitt 04)
 Metal Enrichment proto-galaxies and IGM	**Z of low Z halo stars** (Beers & Christlieb 05, Scannapieco et al. 2006; Meynet, Hirschi ea. 10) **Z of Lya forest?**(Schaye et al. 03 Norman et al. 04)
 Illumination	**NIR bkg. intensity** (Santos et al. 02; Fernandez & Komatsu 06; Matsumoto ea. 10) **NIR bkg. fluctuations** (Kashlinsky et al. 04)
 SN & GRBs?	**JWST** (Weinmann & Lilly 05) **SWIFT** (Bromm & Loeb 02; Tanvir ea 09)
Progenitors of Supermassive BHs? Early Galaxies?	**ULXs** (Mii & Totani 2005) **Quasars** (Mortlock et al. 2011) **NIR counts** (Stark et al. 07)

Metal-Poor Halo Stars



Very iron poor.
Enrichment from one low-energy SN?
m* ~ 60 M$_\odot$?
Keller et al. (2014)



CCSN 25M$_\odot$

Type Ia + CCSN

PISN M$_{He}$ = 140M$_\odot$

Low [C/Fe] & [Mg/Fe] and large odd-even effects: signature of PISN?
m* ~> 140 M$_\odot$?
Aoki et al. (2014)

Galactic Disks

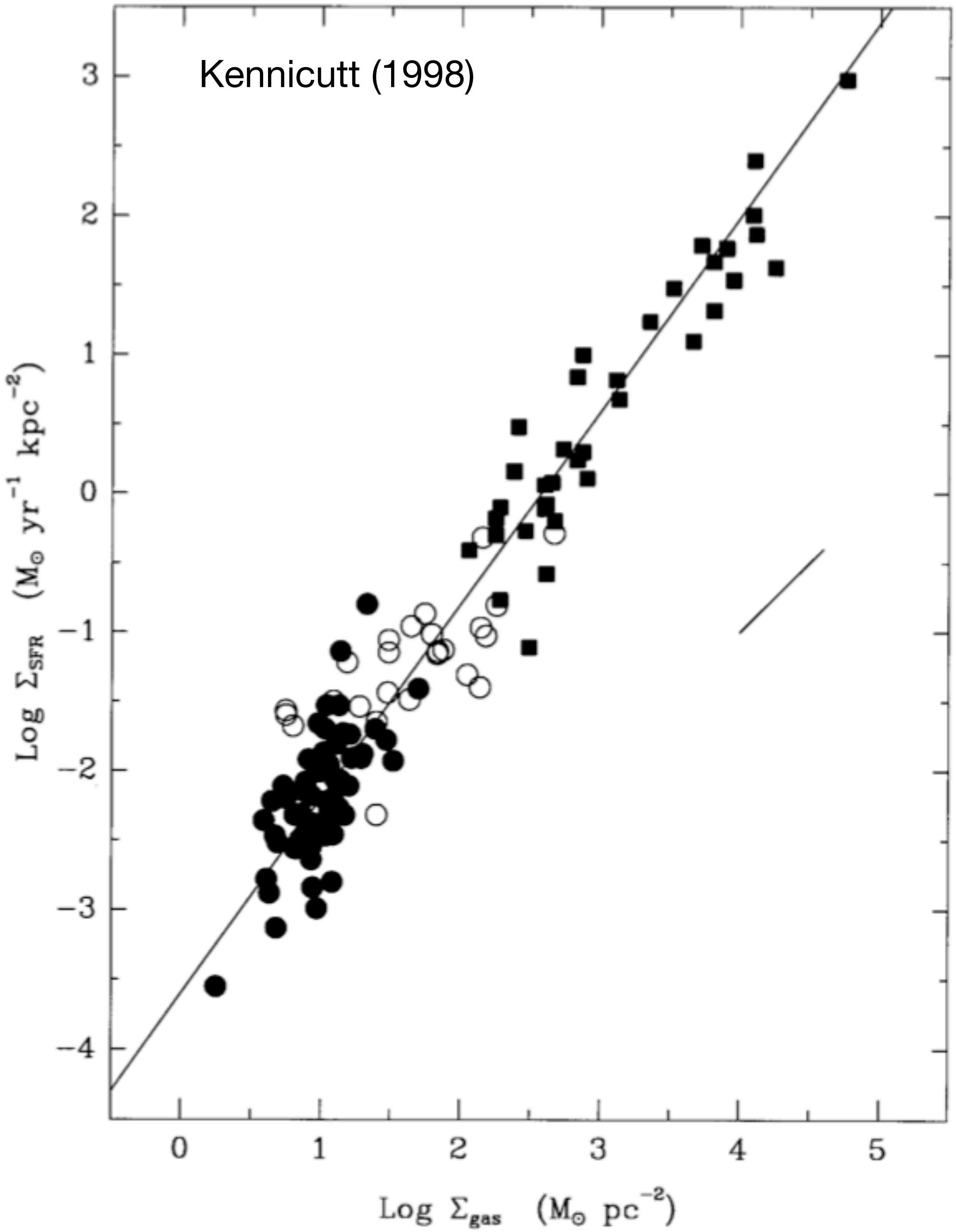
Quasi-equilibrium of SFR and ISM as modeling target
(in place of well-defined initial conditions)

Global galactic scales: Kennicutt-Schmidt (KS) Relation

Star Formation Rate per unit area of the disk, Σ_{SFR}, correlates with gas mass surface density, Σ_{gas}, (total H_2+HI and/or just H_2).

$$\Sigma_{SFR} = (2.5 \pm 0.7) \times 10^{-4}\left(\frac{\Sigma_{gas}}{1\, M_\odot\, \mathrm{pc}^{-2}}\right)^{1.4\pm0.15} M_\odot\, \mathrm{yr}^{-1}\, \mathrm{kpc}^{-2}$$

Also: Schmidt (1959), Wong & Blitz (2002), Boissier et al. (2003), Kennicutt et al. (2007), Leroy et al. (2008), Bigiel et al. (2008), Genzel et al. (2010)...



Global galactic scales (cont.): Dynamical KS Relation

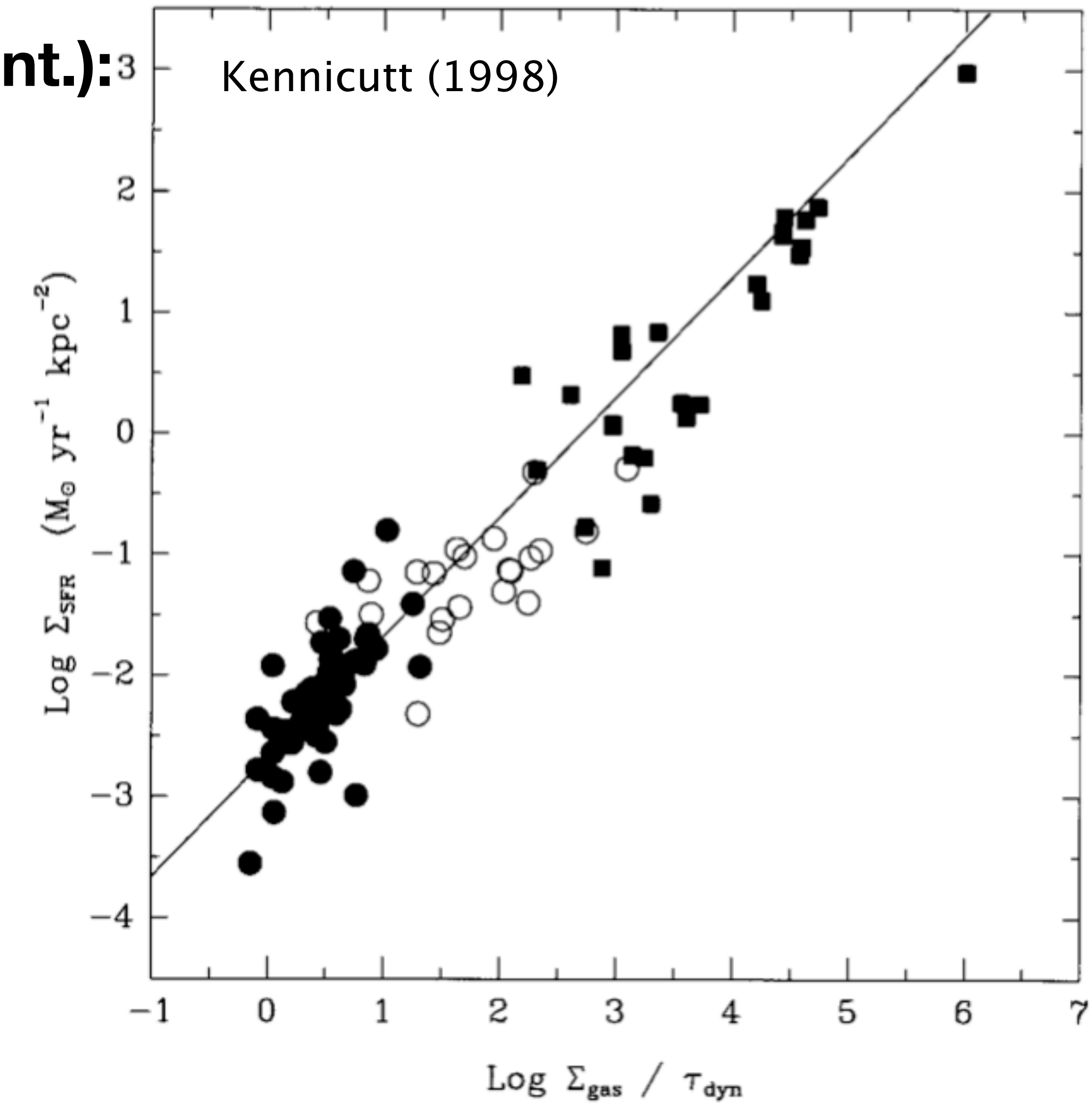
$\Sigma_{SFR} = \varepsilon_{orbit}\, \Sigma_{gas} / t_{orbit}$

$\propto\ \Sigma_{gas}\, \Omega$

$$\Sigma_{\rm SFR} \simeq 0.017 \Sigma_{\rm gas} \Omega_{\rm gas}$$

$\varepsilon_{orbit,outer} = 0.11$

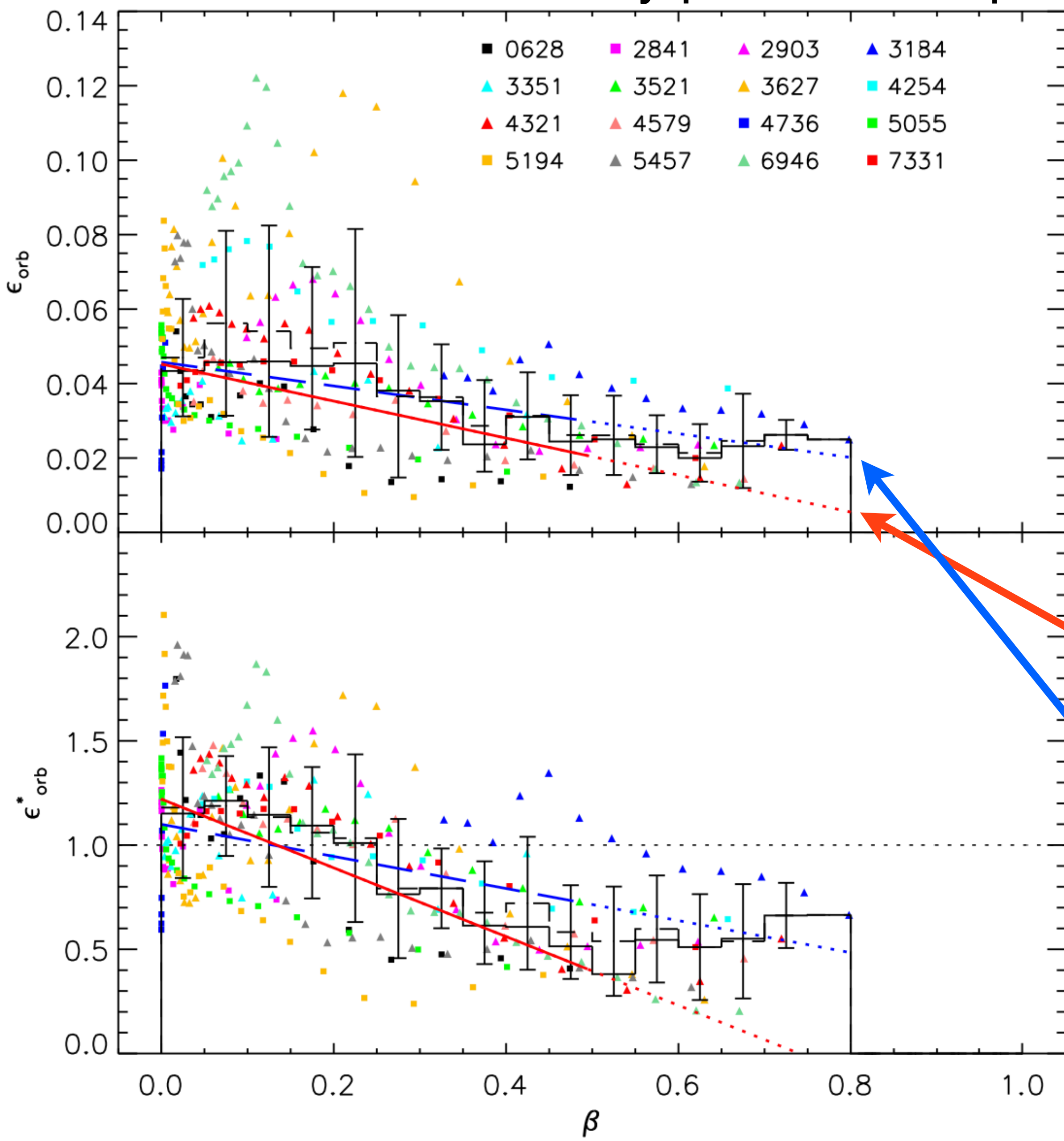
$\varepsilon_{orbit} = 0.04$
in H_2 dominated regions of 12 disk galaxies (Tan 2010; Leroy et al. 2008)



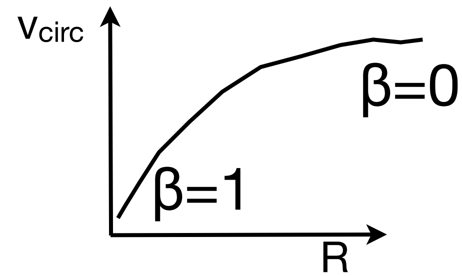
Test of SF Laws in Disk Galaxies II. Dependence on Dynamical Properties

Suwannajak, Tan, Leroy 2014

Star formation efficiency per orbit vs. β



$\beta \equiv d\ln v_{circ}/d\ln R$



16 disk galaxies, all with mean v_{circ}>100 km/s

Here we exclude r<1kpc

$$\epsilon_{orb} = \epsilon_{orb,0}(1 - \alpha_{CC}\beta)$$

α_{CC} = 1.1 ± 0.4

GMC collision theory predicts

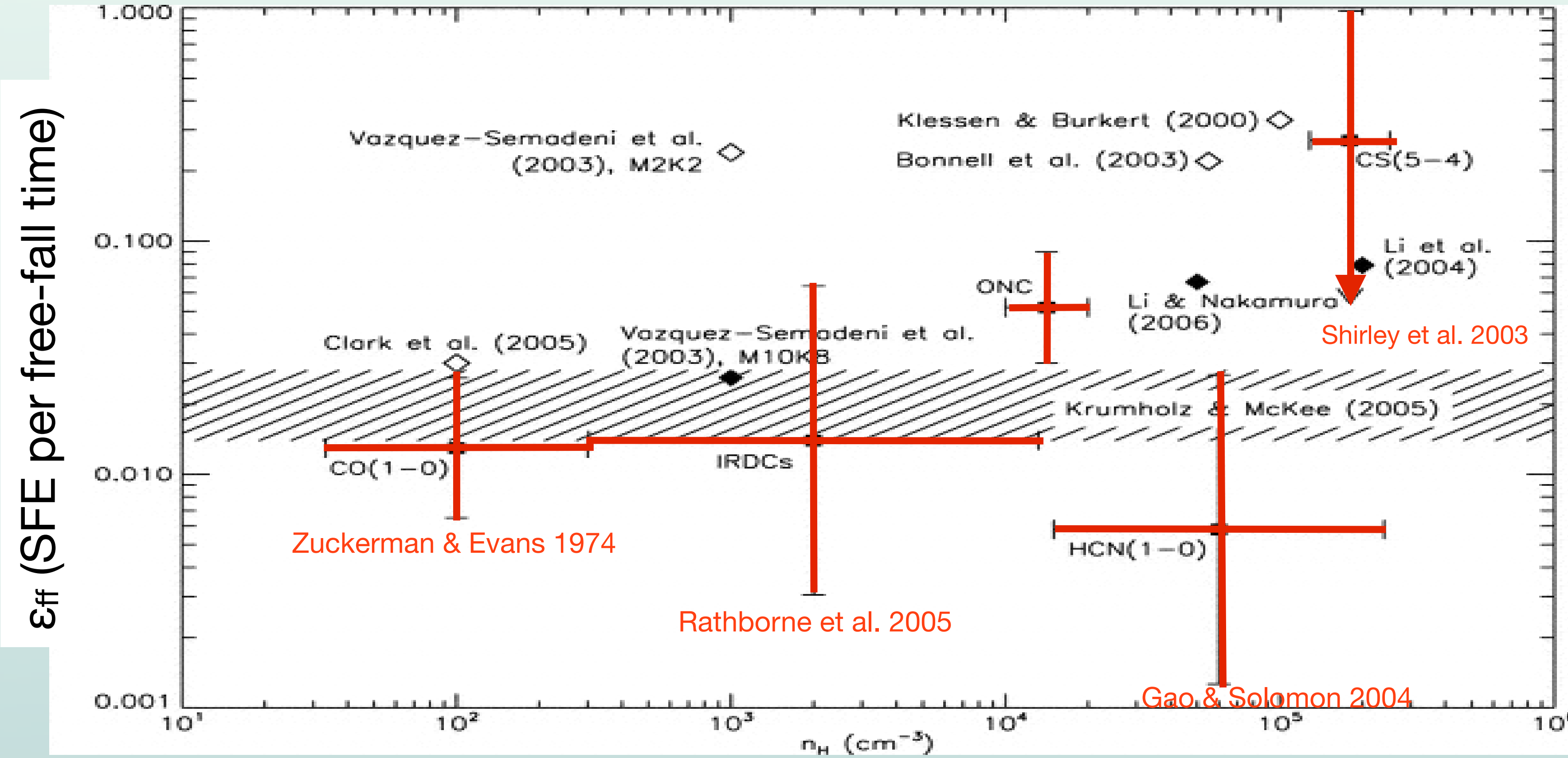
α_{CC} = 0.7

$$\Sigma_{sfr} = B_{CC}Q^{-1}\Sigma_g\Omega(1 - 0.7\beta)$$

Declining ϵ_{orb} with increasing β seen with high significance:
opposite to trend expected if formation of GMCs from diffuse ISM controls SFRs.

GMC & Clump scales:
Star Formation is Inefficient, Slow and Clustered

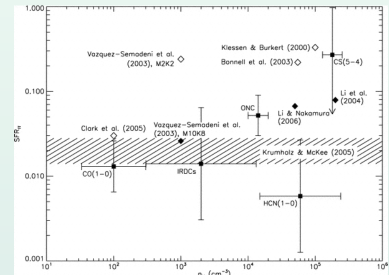
$\varepsilon_{ff} \sim 0.01$ in Galactic GMCs (Zuckerman & Evans 1974) and dense IRDCs (Krumholz & Tan 2007)



GMC & Clump scales:

Star Formation is Inefficient, Slow and Clustered

ϵ_{ff} ~ 0.01 in Galactic GMCs (Zuckerman & Evans 1974) and dense IRDCs (Krumholz & Tan 2007)

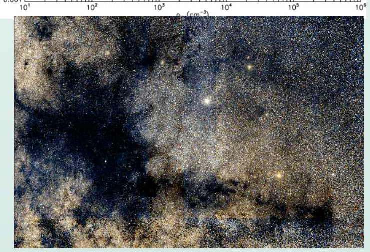


ϵ_{ff} << 0.01 in most gas in GMCs (A_V<10) (e.g. Lada et al. 2010)

Pipe Nebula with M_g~$10^4 M_\odot$ (Forbrich et al. 2009)

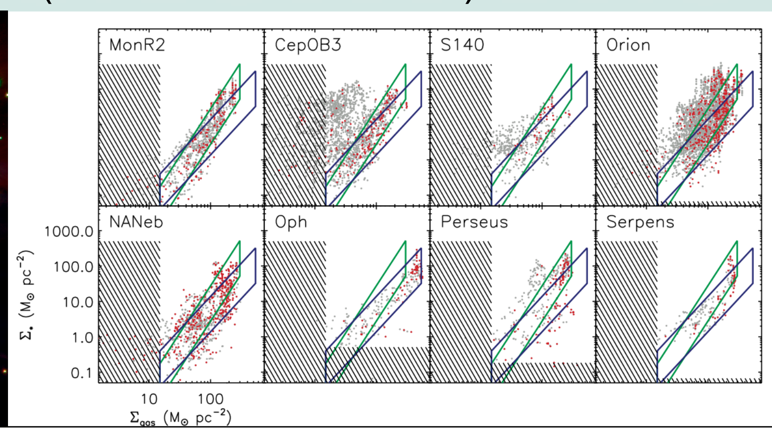
ϵ ~ 0.0006

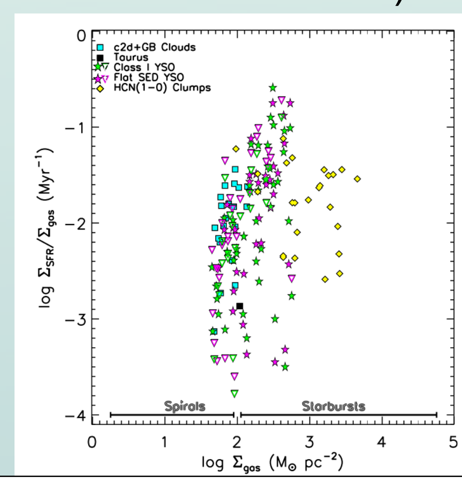
ϵ_{ff} ~ 0.0006 (assuming $t_{cloud}=1t_{ff}$)



SF Threshold ~100 $M_\odot$ pc^{-2} (A_V<4)? (Lada et al. 2010; Heiderman et al. 2010)

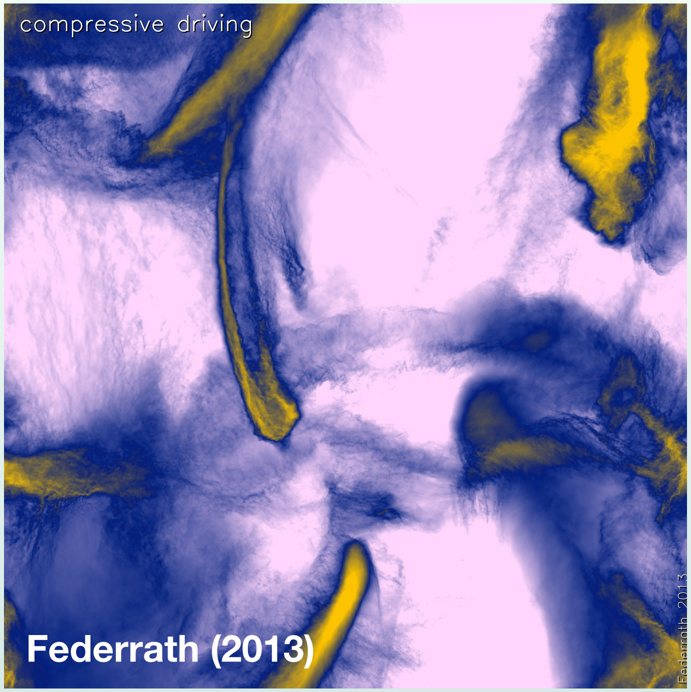
Or a more continuous transition? (Gutermuth et al. 2011)

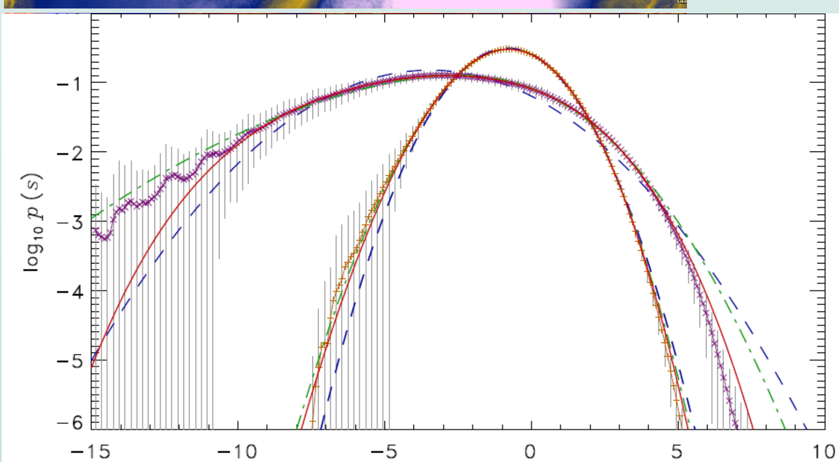




Turbulence

see, e.g., Padoan et al. (2014)





$$s \equiv \ln(\rho/\rho_0)$$

Driven supersonic turbulence in a periodic box.

4 main parameters:

- $\alpha_{vir} = 5\,\sigma_{v,1D}^2 R/(GM) \sim 2E_{kin}/E_{grav}$
- Sonic Mach no. $\mathcal{M}_s = \sigma_v / c_s$
- Turbulence driving parameter b (compressional: b=1; solenoidal: b=1/3)
- Alfven Mach no. $\mathcal{M}_A = \sigma_v / v_A = \sigma_v / (\langle B^2 \rangle / \langle 4\pi\rho \rangle)^{1/2}$ (or ratio of gas to magnetic pressure $\beta = 2c_s^2 / v_A^2 = 2\mathcal{M}_A^2/\mathcal{M}_s^2$)

Turbulence leads to a line-width vs. size relation: obs.: $\sigma_v \sim L^{0.5}$ (Larson 1981; Heyer & Brunt 2004)

Turbulence leads to ~log normal PDF of ρ

$$p_s\,\mathrm{d}s = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left[-\frac{(s - \langle s \rangle)^2}{2\sigma_s^2}\right] \mathrm{d}s$$

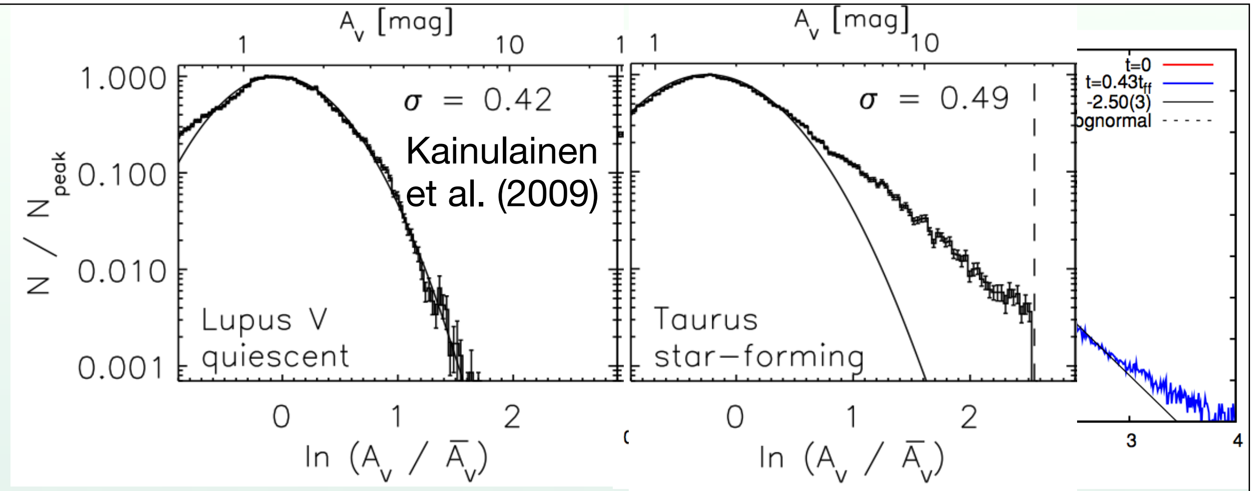
$$\sigma_s^2 = \ln\left[1 + b^2 \mathcal{M}_\mathrm{s}^2\right]$$

$$\sigma_s^2 = \ln\left[1 + b^2 \mathcal{M}_\mathrm{s}^2 \beta/(\beta + 1)\right]$$

Higher-order statistics can help find, e.g., $\mathcal{M}_A$, (Burkhart et al. 2009)

Turbulent SFR

Self-gravity leads to power-law tails in PDFs of ρ or Σ (e.g., Kritsuk et al. 2011). Such features are seen in star-forming GMCs.

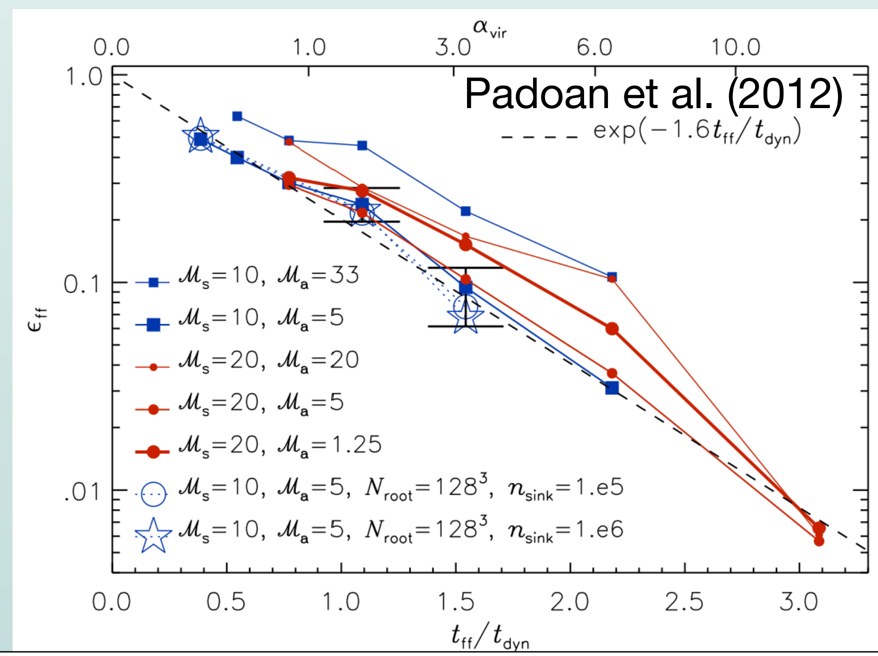


Star formation efficiency per free-fall time

$$\frac{\dot{M}_*(t)}{M_{\rm cl}(t)}\, t_{\rm ff,0} = \epsilon_{\rm ff} = \frac{\epsilon}{\phi_t}\int_{\widetilde{\rho}_{\rm crit}}^{\infty} \frac{t_{\rm ff,0}}{t_{\rm ff}(\widetilde{\rho})}\, p(\widetilde{\rho})\ {\rm d}\widetilde{\rho}$$

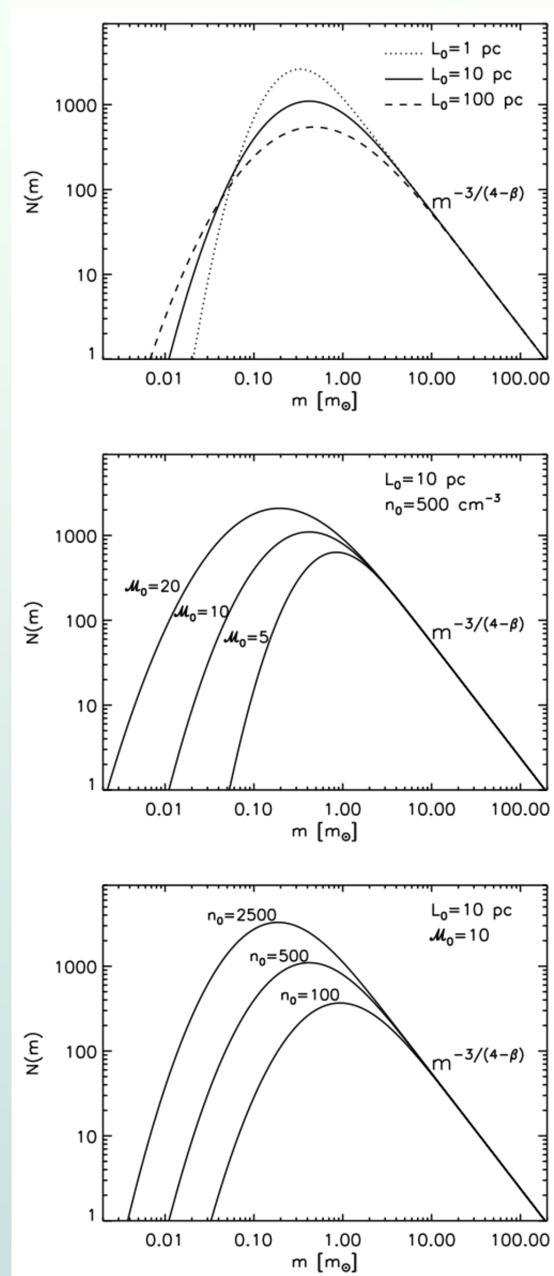
Krumholz & McKee (2005); Padoan & Nordlund (2011); Hennebelle & Chabrier (2011)

Numerically:
- threshold conditions for sink particle creation
- measure SFR as a function of α_{vir}, $\mathcal{M}_s$, b, $\mathcal{M}_A$



For ϵ_{ff}~0.01, requires α_{vir}~10

Turbulent Fragmentation & CMF/IMF



Padoan & Nordlund (2002)

- power spectrum of super-Alfvenic turbulence is a power-law, size of dense cores scales as thickness of post-shock gas.

Hennebelle & Chabrier (2008, 2009, 2011)

- turbulent support for massive cores
- but this predicts massive cores form from “low” density conditions

Hopkins (2012a,b,c, 2013)

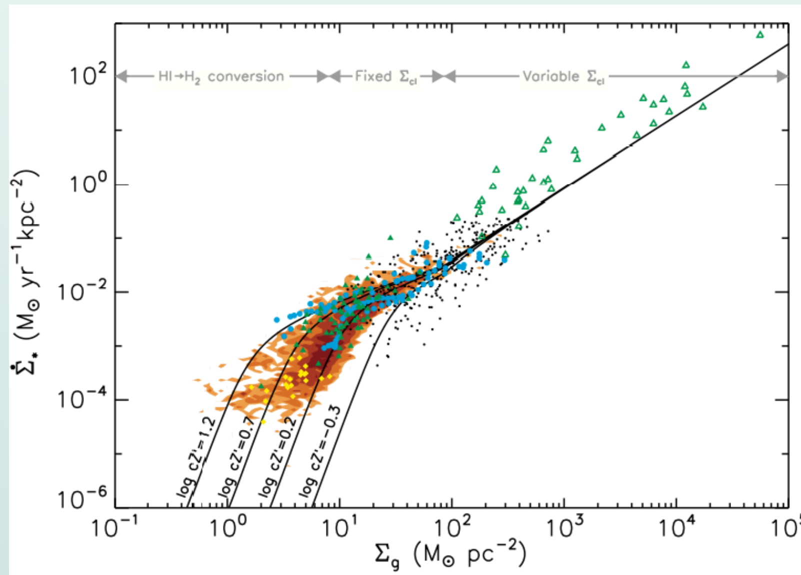
- Extended Press-Schechter for turbulent ISM

Application of Turbulence Models to Global SFRs

Krumholz & McKee (2005): GMCs are virialized and their surfaces in pressure equilibrium with Q~1 disk.

$$\Sigma_{\rm sfr} = A_{\rm KM} f_{\rm GMC} \phi_{\bar{P},6}^{0.34} Q_{1.5}^{-1.32} \Omega_0^{1.32} \Sigma_{g,2}^{0.68}$$

Krumholz, McKee & Tumlinson (2009): GMCs are virialized and their surfaces in pressure equilibrium with Q~1 disk for high Σ_g regime. Pressure set by internal feedback in low Σ_g regime.



$$\Sigma_{\rm sfr} = A_{\rm KMT} f_{\rm GMC} \Sigma_{g,2} \times \begin{cases} (\Sigma_g/85 M_\odot {\rm pc}^{-2})^{-0.33}, & \Sigma_g < 85\ M_\odot {\rm pc}^{-2} \\ (\Sigma_g/85 M_\odot {\rm pc}^{-2})^{0.33}, & \Sigma_g > 85\ M_\odot {\rm pc}^{-2} \end{cases}$$

See also Krumholz, Dekel & McKee (2012)

Potential Problems with Turbulence Models

1. Most results are for **hydrodynamic turbulence or ideal super-Alfvenic turbulence** (c.f., non self-gravitating simulations of, e.g., Falceta–Gonçalves et al. 2008; Burkhart et al. 2009; McKee et al. 2010; P-S Li et al. 2012).

2. Without continuous driving, **turbulence decays quickly** (Stone et al. 1998; Mac Low et al. 1998; c.f., Hansen et al. 2011). Is continually driven turbulence a realistic assumption for star-forming clouds? What processes dominate turbulent driving in GMCs, clumps, cores? See also **colliding HI flow models**: e.g., Heitsch et al. 2008, Vázquez-Semadeni et al. (2011), Chen & Ostriker (2014); **GMC Collision models** (Tan 2000; Tasker & Tan 2009); turbulence driven by **thermal instabilities**, e.g., Iwasaki & Inutsuka (2014); **supernova-driven** (e.g., Joung & Mac Low 2006).

3. Are **periodic boundary conditions** a reasonable assumption for simulations of GMCs, filaments, clumps, cores?

4. **Star formation thresholds** - choices of threshold densities for star formation / sink creation are quite arbitrary.

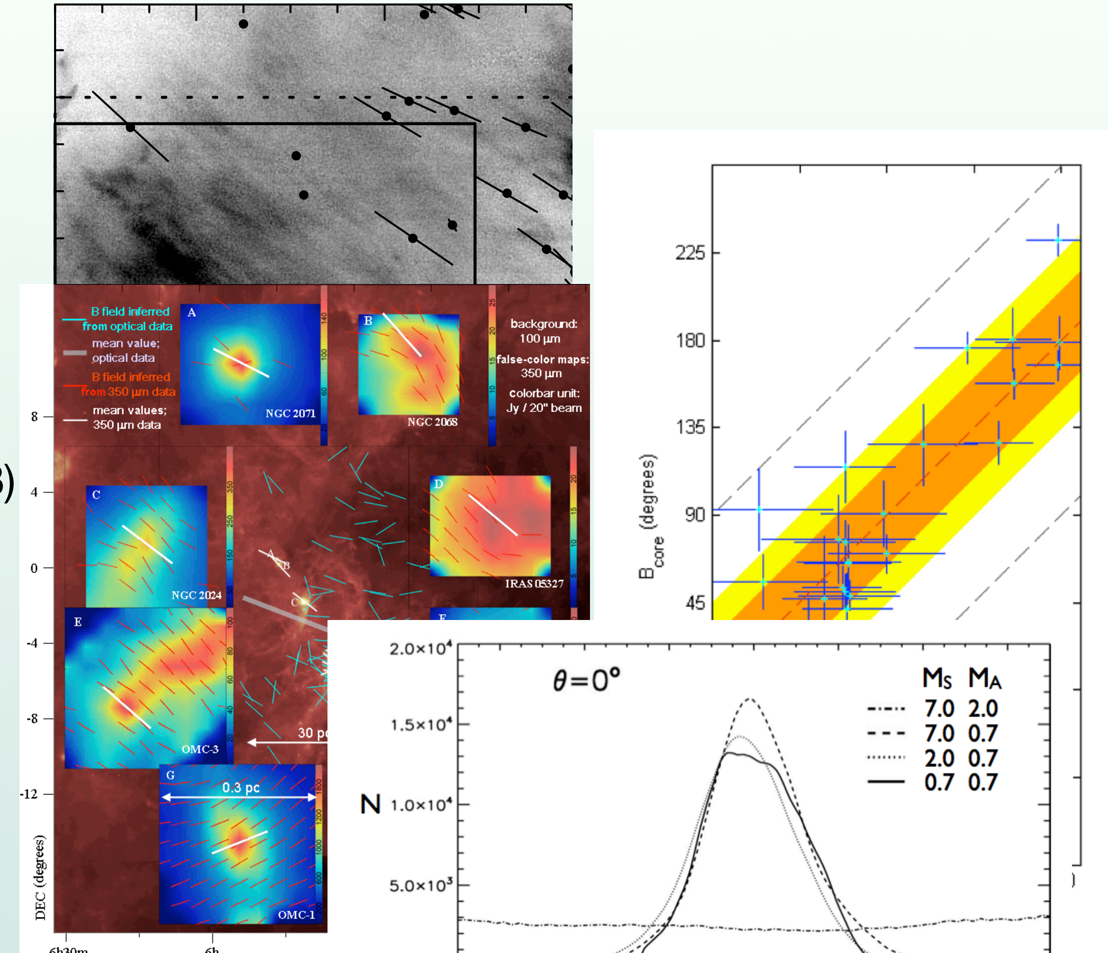
5. If star cluster formation is slow (Tan et al. 2006), then local regulation is via **outflow-driven feedback turbulence** (Nakamura & Li 2007, 2014) or **ionization-front-driven turbulence** (e.g., Walch et al. 2012, Dale et al. 2013).

Magnetic Fields

see, e.g., H-B Li et al. (2014), Crutcher (2012)

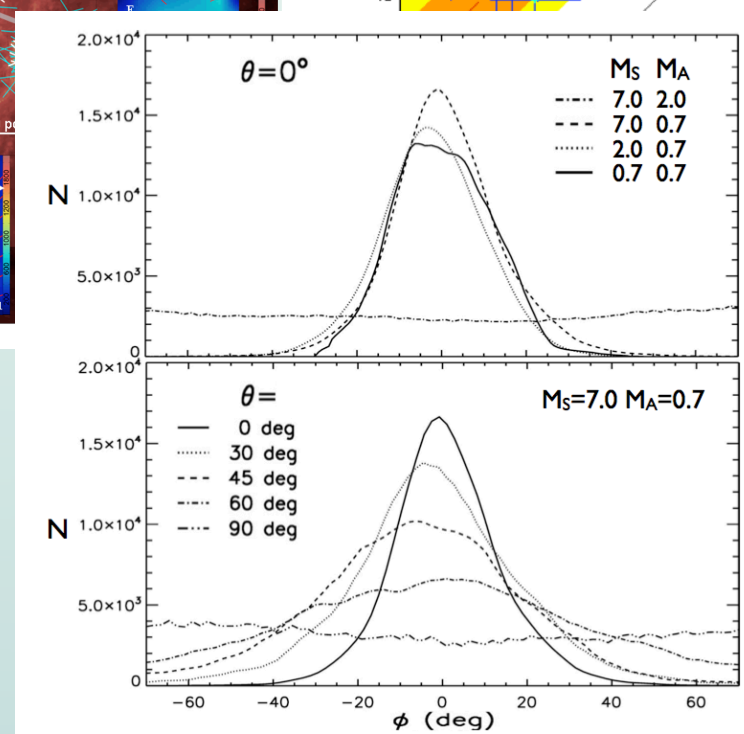
Ordered B-field vectors and elongated ^{12}CO emission velocity centroids in Taurus (Heyer et al. 2008)

Correlation of B-field vectors from ~100pc to <1pc scales (Hua-bai Li et al. 2009)



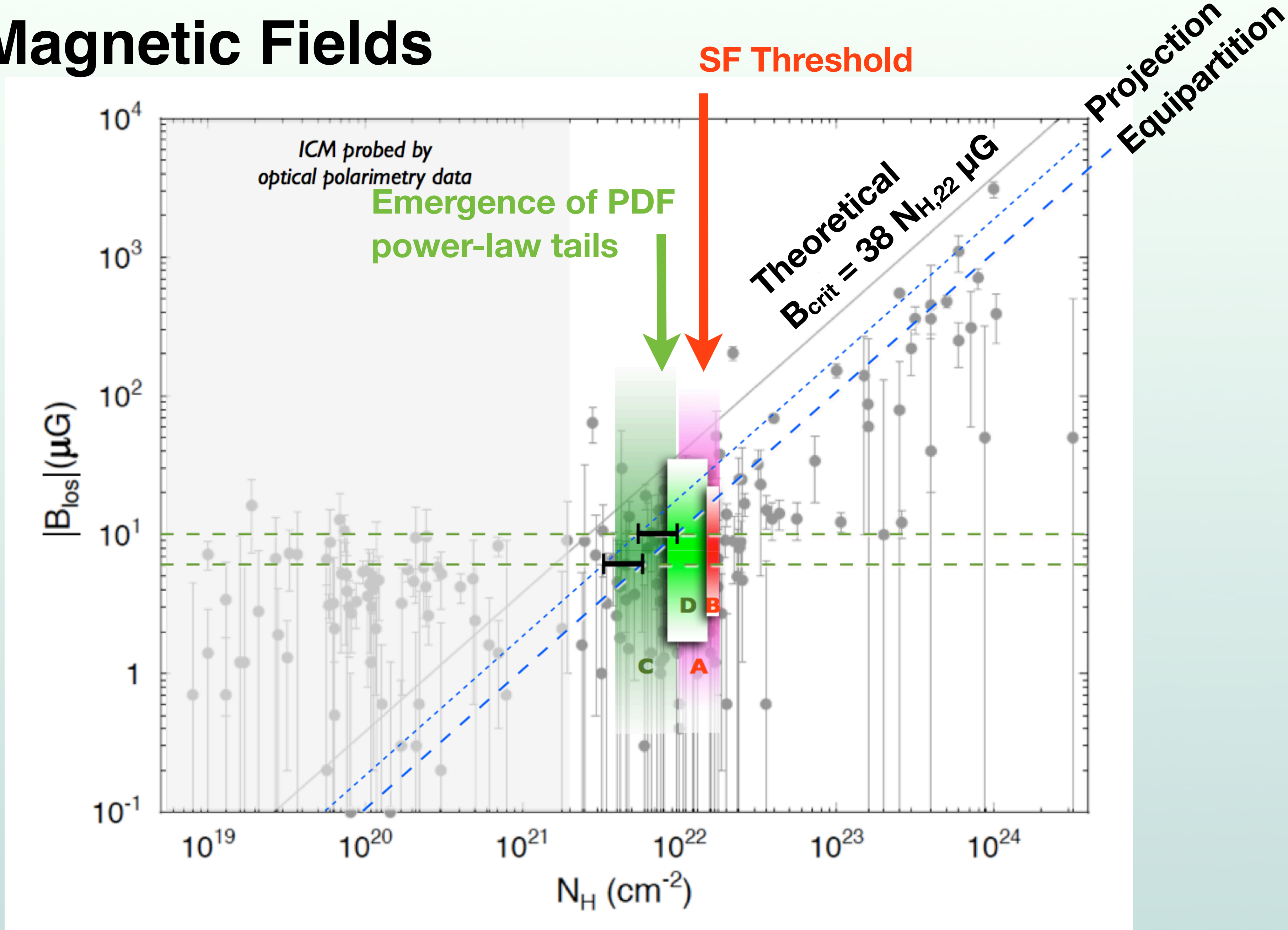
Comparison with simulated sub-mm polarization direction angle (φ) dispersion ->

Magnetic fields appear strong: $\mathcal{M}_A < 1$



Falceta–Gonçalves et al. (2008)

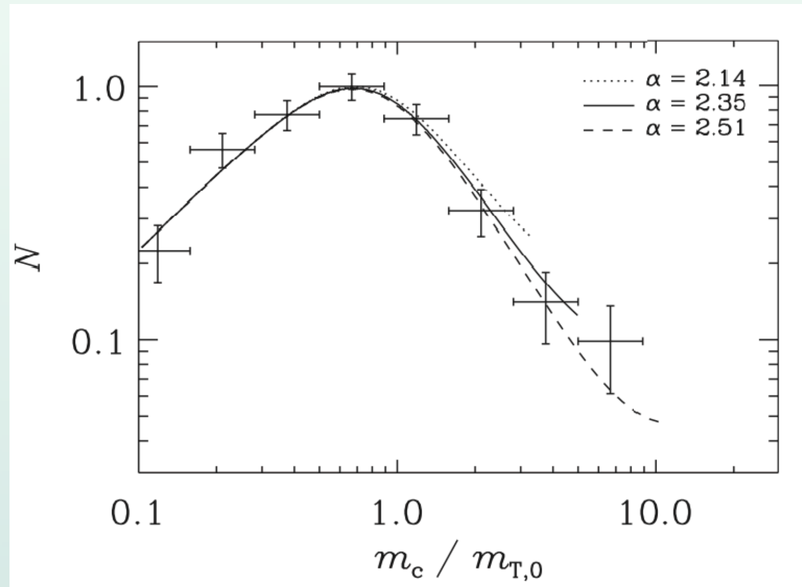
Magnetic Fields



H-B Li et al. (2014), adapted from Crutcher (2012)

Magnetic Fields

Ambipolar diffusion regulated model can also explain **CMF/IMF** (Kunz & Mouschovias 2009).

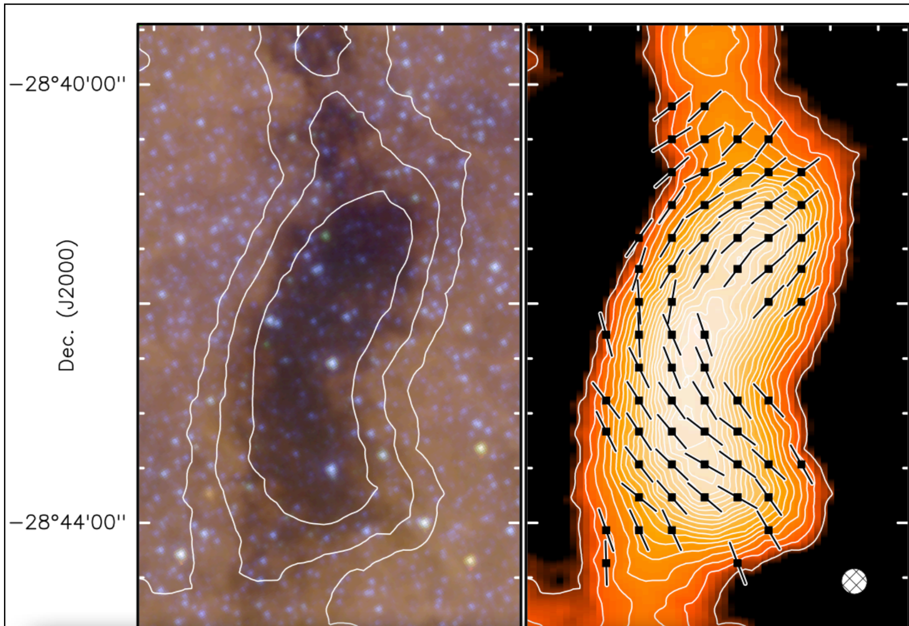


Ambipolar diffusion regulation can explain **star formation thresholds at A_V~8 mag** (McKee 1989).

But **turbulence-enhanced ambipolar diffusion** (Fatuzzo & Adams 2002) or **reconnection diffusion** (Lazarian et al. 2010) could be (more) important.

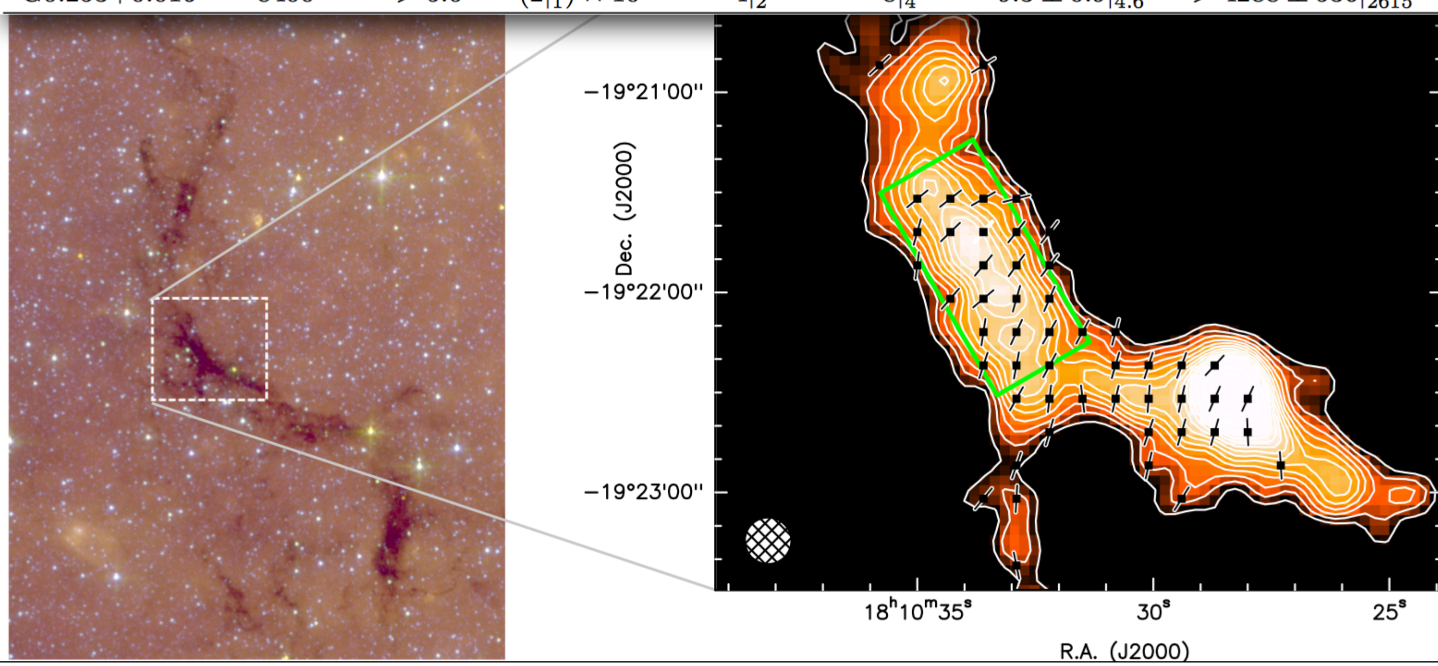
Strong B-fields in IRDCs

Pillai, Kauffman, Tan, Goldsmith, Carey, Menten (2014)



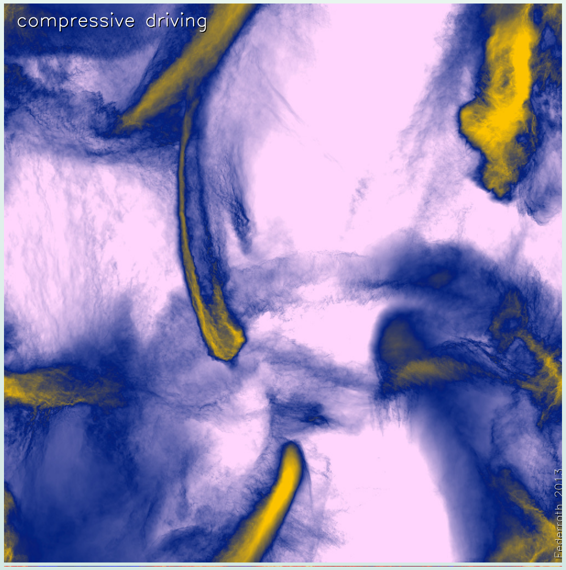
G0.253 - GC “Brick”
CSO,
350μm,
20”

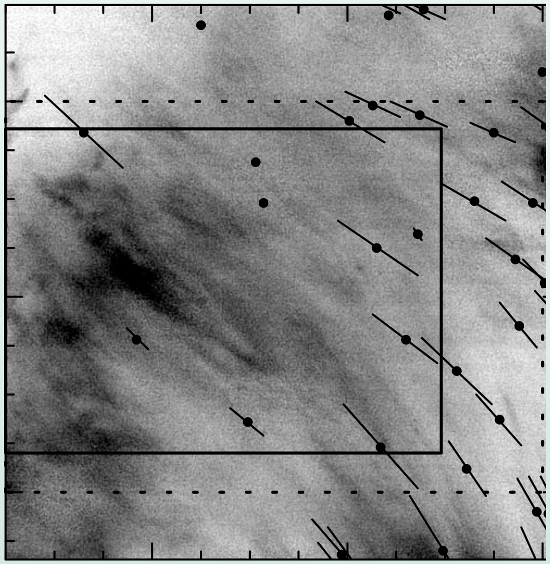
Source	Distance	σ_v	Mass	$\langle N_{\mathrm{H_2}} \rangle$	Density	σ_ϕ	$\mathrm{B_{tot}}$	$\mathcal{M}_\mathrm{A}$	$\frac{(M/\Phi_B)}{(M/\Phi_B)_{\mathrm{cr}}}$
	pc	$\mathrm{km\,s^{-1}}$	$\mathrm{M_\odot}$	$10^{23}\,\mathrm{cm^{-2}}$	$10^4\,\mathrm{cm^{-3}}$	deg.	μG		
G11.11−0.12[1]	3600	0.9 ± 0.1	$549\vert^{1098}_{275}$	$0.4\vert^{0.8}_{0.2}$	$3\vert^{6}_{2}$	$< 16.2 \pm 1.6$	$> 269 \pm 29\vert^{442}_{164}$	$< 0.8 \pm 0.1\vert^{1.2}_{0.5}$	$< 1.1 \pm 0.1\vert^{2.1}_{0.6}$
G0.253+0.016	8400	> 5.0	$(2\vert^{4}_{1}) \times 10^5$	$4\vert^{8}_{2}$	$8\vert^{16}_{4}$	$9.3 \pm 0.9\vert^{18.6}_{4.6}$	$> 4288 \pm 536\vert^{7033}_{2615}$	$< 0.4 \pm 0.1\vert^{0.7}_{0.3}$	$< 0.7 \pm 0.1\vert^{1.3}_{0.4}$



G11.11
JCMT,
850μm,
20”

So, are star formation rates controlled by turbulence, magnetic fields or something else?





What is the connection to global galactic dynamics?

Global Galaxy Simulations
I. Isolated galaxies

Some Global Isolated Galaxy Simulations

Dobbs (2008); Dobbs & Price (2008); Bonnell, Dobbs, Smith (2013)	SPH (zoom $0.16M_\odot$)	Spiral arm potential, B-fields	Sink particles
Hopkins, Quataert, Murray (2012); Hopkins (2013)	SPH (MW-like: $220M_\odot$)	Several galaxy types, DM, feedback	$n_{th}=10^3 cm^{-3}$ $\varepsilon_{ff}=0.015$
Wada, Baba, Saitoh (2011); Wada & Norman (2007)	SPH ($3200M_\odot$)	DM, feedback	$\varepsilon_{ff}=0.033$
Shetty & Ostriker (2008, 2012); Ostriker & Shetty (2011)	Grid: Zeus/Athena 2D; global & local	Feedback, fixed potential	$n_{th}=5x10^3 cm^{-3}$ $\varepsilon_{ff}=0.01$
Agertz et al. (2009, 2013) [see also Gnedin & Kratsov 2011]	AMR: RAMSES, 6 - 50pc	Fixed NFW potential, Feedback	$n_{th}=10^2 cm^{-3}$ $\varepsilon_{ff}=0.01$
Renaud et al. (2013)	RAMSES, 0.05pc	DM, feedback	$n_{th}=2x10^3 cm^{-3}$ $\varepsilon_{ff}=0.03$
Tasker & Tan (2009); Tasker (2011); Van Loo, Butler, Tan (2013) & Butler et al. (2014)	AMR: ENZO/MG, 8pc (global), 0.5-0.1pc (zoom)	Fixed, axisymmetric potential; No feedback, B-fields	$n_{th}=10^2 -10^6 cm^{-3}$ $\varepsilon_{ff}=0.02$

Setting up a galactic environment for GMCs

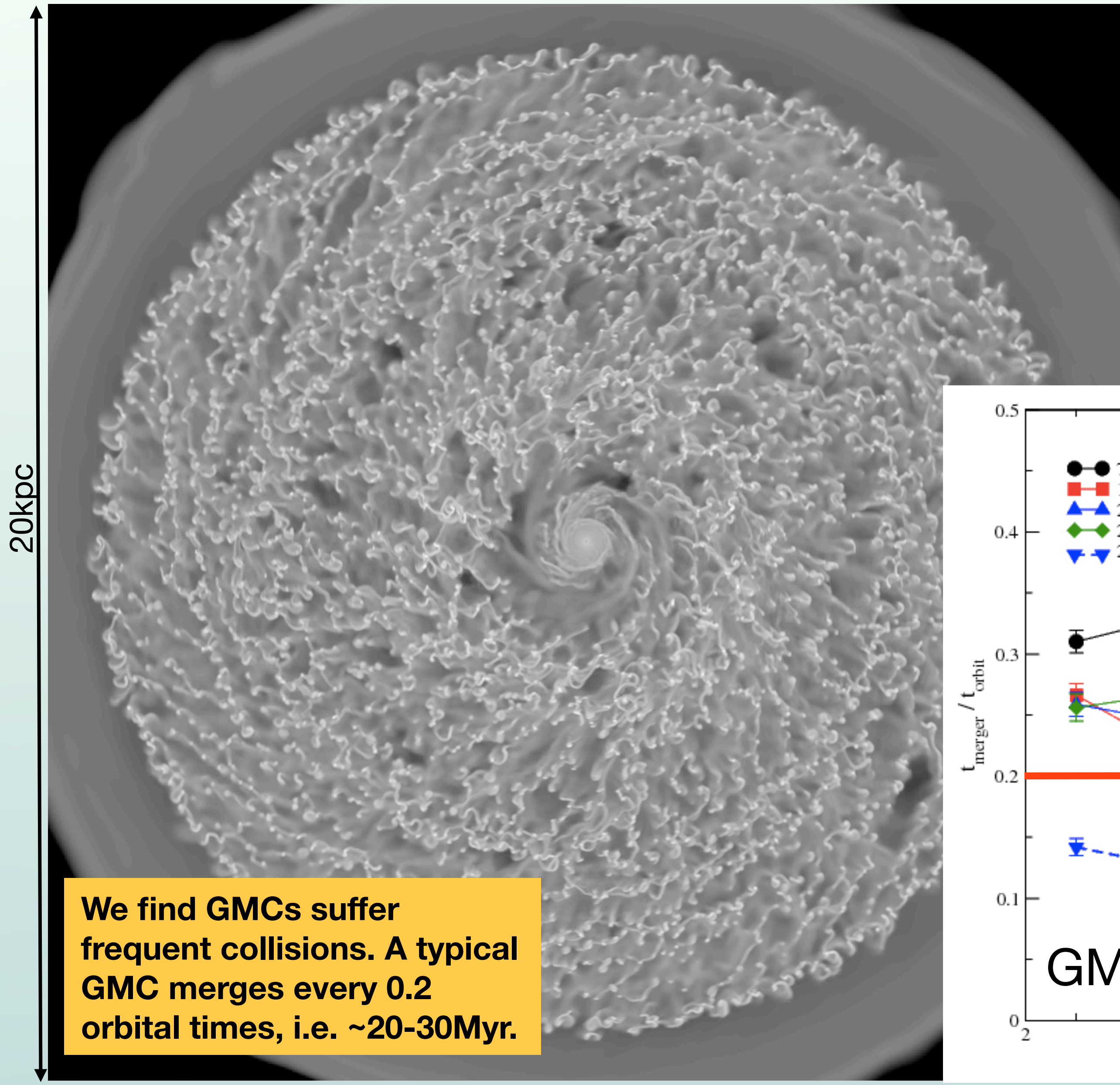
Tasker & Tan (2009) [see also Wada+; Dobbs+; Shetty & Ostriker; Renaud+]

ENZO AMR 3D Hydro
Atomic Cooling to 300K,
8pc resolution

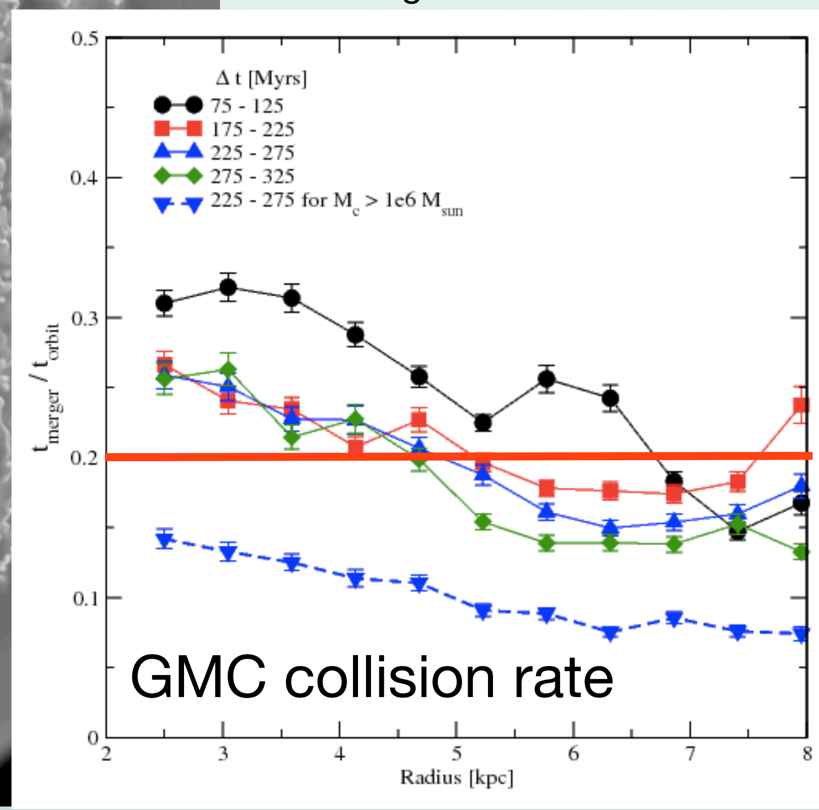
Flat rotation curve, axisymmetric fixed background potential (old stars & DM)

Q=1 (for σ=6km/s) from 2-10kpc

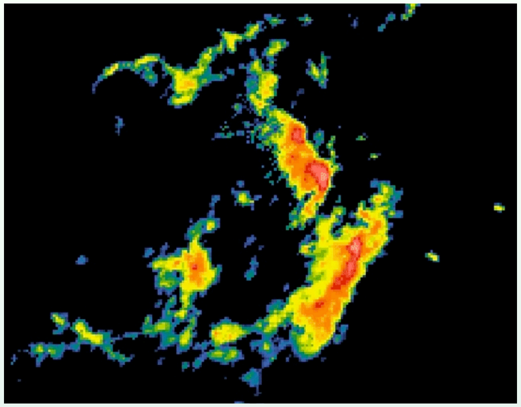
“GMCs” identified as regions with n_H>100cm^{-3}



We find GMCs suffer frequent collisions. A typical GMC merges every 0.2 orbital times, i.e. ~20-30Myr.



Implications of Frequent GMC Collisions



We find GMCs suffer frequent mergers.
A typical GMC merges every 0.2 orbital times,
i.e. ~20-30Myr.

1. Frequent mergers can explain the retrograde rotation of GMCs.

2. Frequent mergers can be an important source of turbulence in GMCs.

3. Frequent mergers can confuse virial parameter estimations

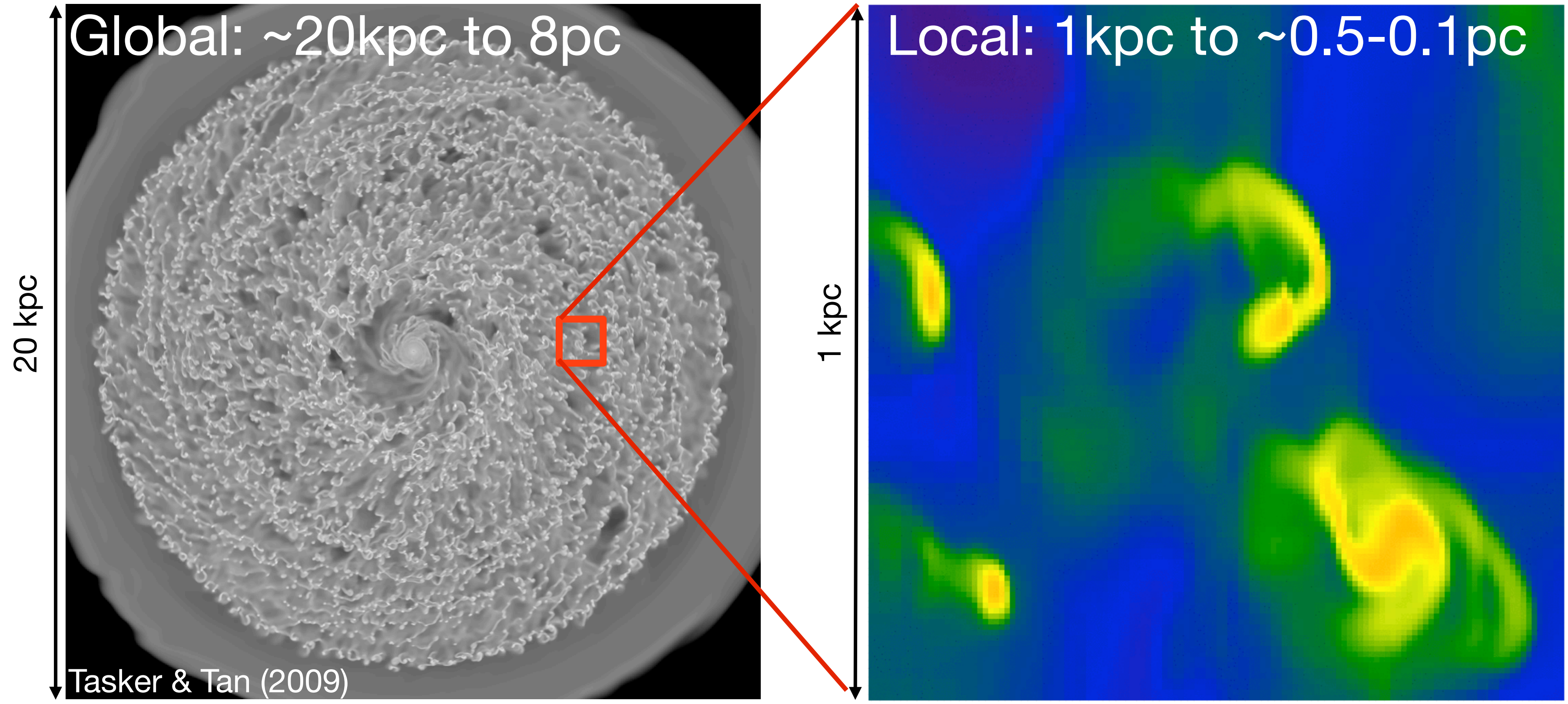
4. Frequent mergers redefine the notion of GMC lifetimes.

5. This process could trigger star formation and be the link between global galactic dynamics and star cluster formation.

But this scenario does require GMCs to be gravitationally bound and relatively long-lived.

Kiloparsec-scale simulations

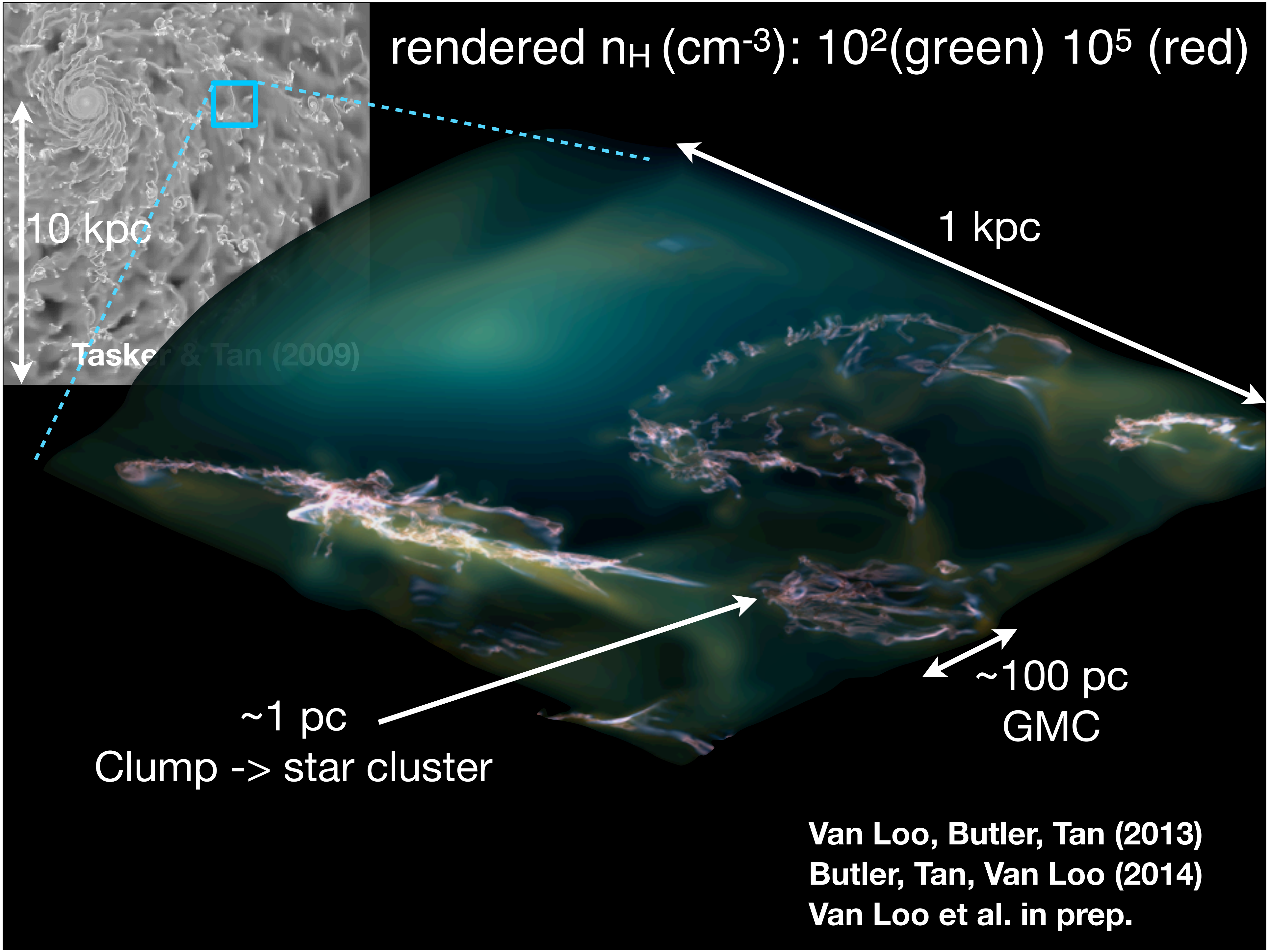
Van Loo, Butler, Tan (2013)



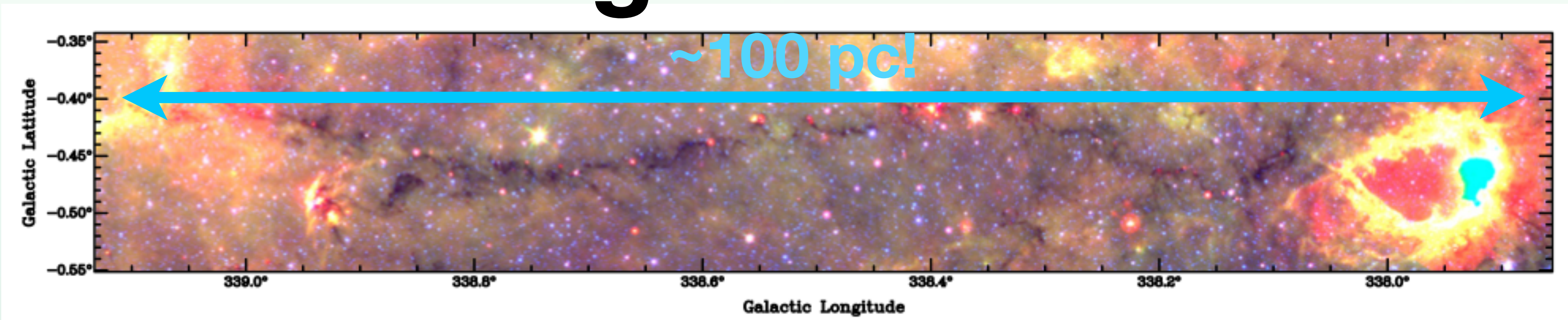
Enzo - (B=0)
- pseudo-shearing box
- extinction-dependent cooling and heating functions (Cloudy)
- run for 10 Myr

Star Particle Creation $\epsilon_{ff} = 0.02$

Cell Size (pc)	$n_{H,sf}$ (cm^{-3})	t_{ff} (yr)	Min. Cell Mass ($M_\odot$)	$M_{*,min}$ ($M_\odot$)
7.8	100	4.3×10^6	1640	1000[a]
0.49	10^5	1.4×10^5	400	100
0.125	10^6	4.3×10^4	63	10[b]


rendered n_H (cm^{-3}): 10^2(green) 10^5 (red)
10 kpc
Tasker & Tan (2009)
1 kpc
~100 pc
GMC
~1 pc
Clump -> star cluster
Van Loo, Butler, Tan (2013)
Butler, Tan, Van Loo (2014)
Van Loo et al. in prep.

Long Filaments



	length (pc)	mass ($10^5 M_\odot$)	m/l ($10^3 M_\odot$/pc)	dv/dr (km/s/pc)
Jackson et al. (2010)	80	4	~0.5(vir)	<0.09
Battersby & Bally (2012)	80	0.3-2	0.4-2.5	<0.05
Ragan et al. (2014)	110	0.09	0.08	0.06

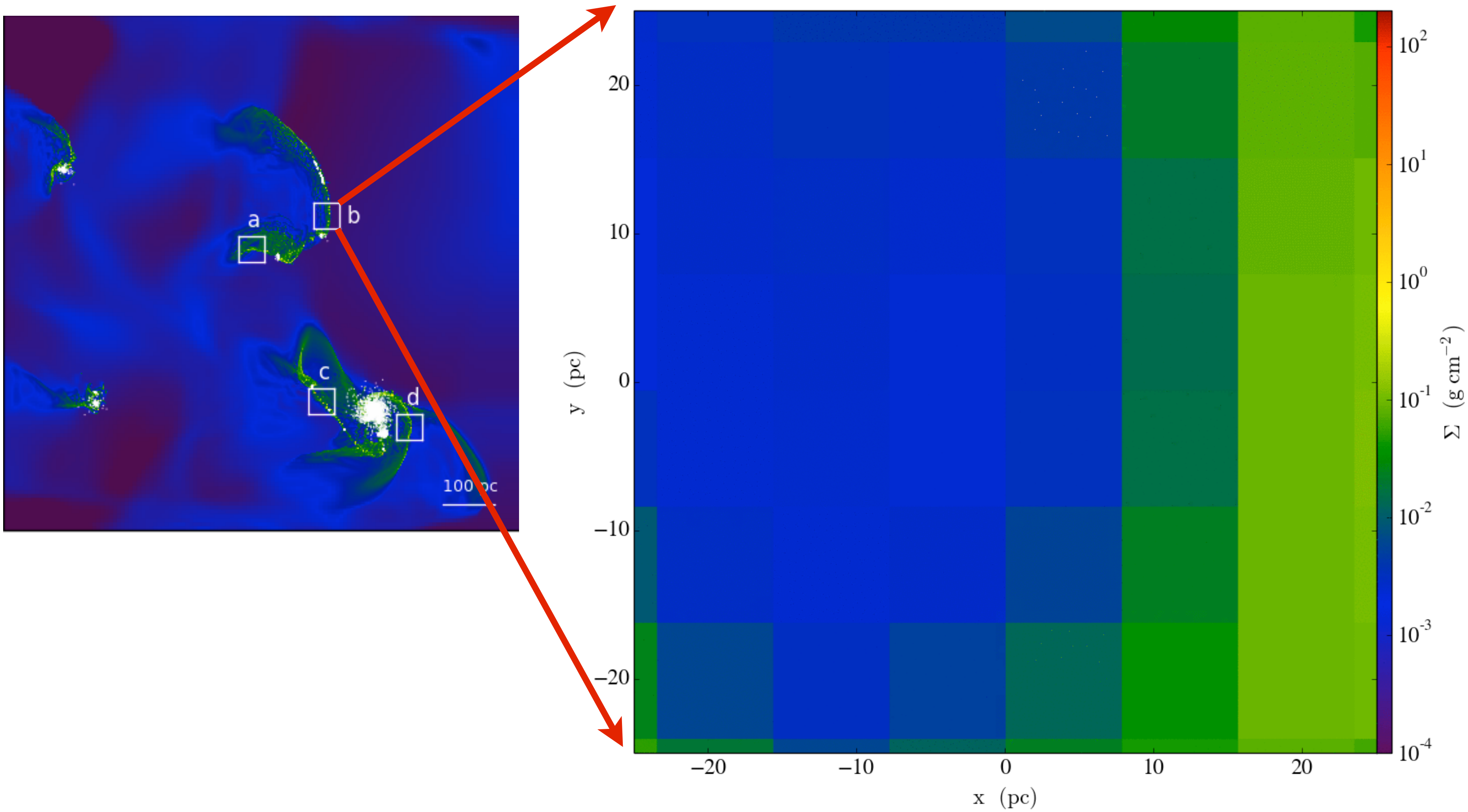
Regular clump spacing ~4pc

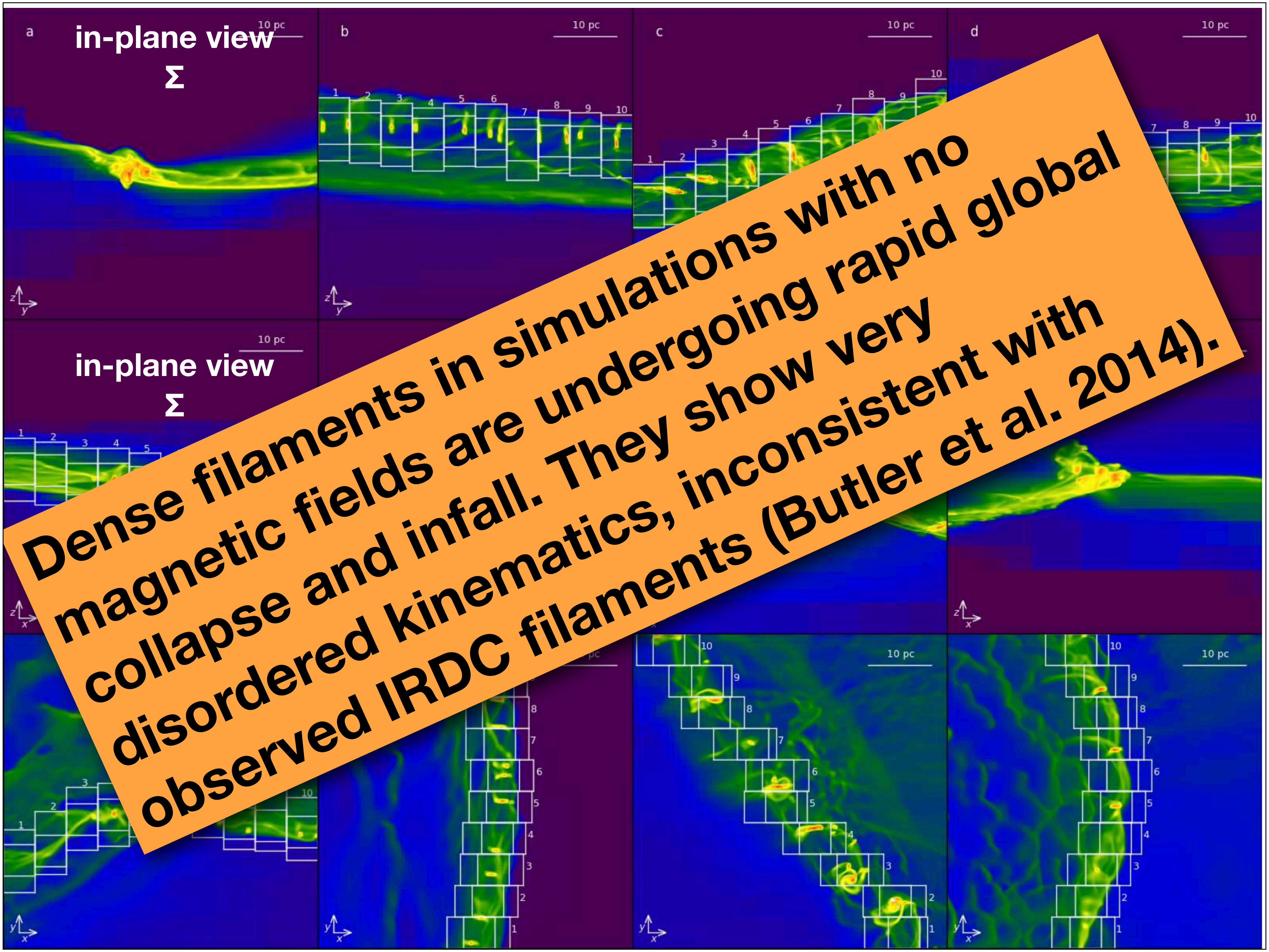
mean of 7 filaments

A challenge for turbulence/feedback models?

High Resolution (0.1pc) Hydro Results

Butler, Tan, Van Loo
(submitted; arXiv)



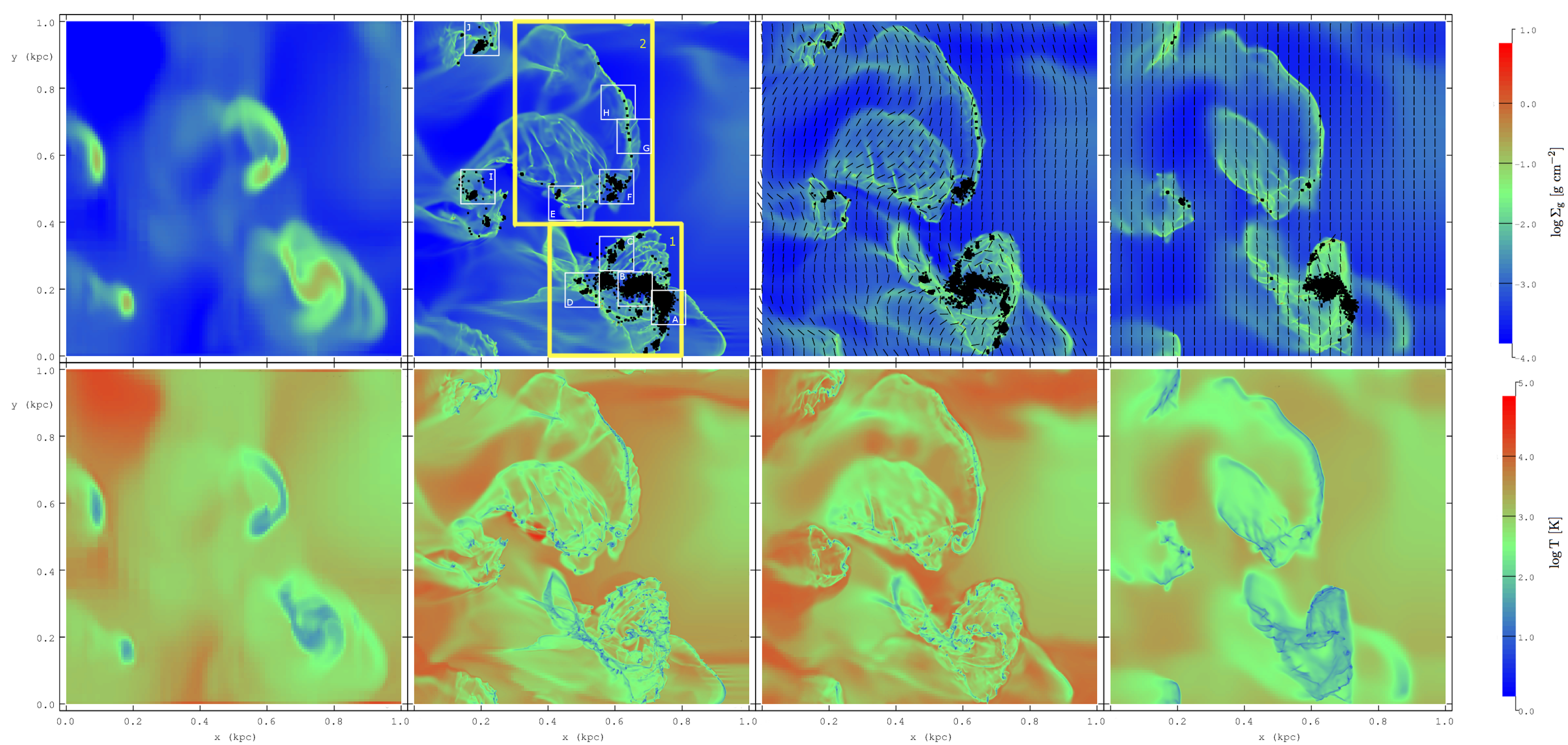

in-plane view
Σ
in-plane view
Σ
10 pc
a
b
c
d
Dense filaments in simulations with no magnetic fields are undergoing rapid global collapse and infall. They show very disordered kinematics, inconsistent with observed IRDC filaments (Butler et al. 2014).

Effects of Magnetic Fields

Initial Condition

t = 10 Myr

B=0 μG **B=10 μG** **B=80 μG**



Van Loo, Tan, Falle, in prep.

see also Pakmor, Marinacci & Springel (2014)

Effects of Feedback

e.g., Walch et al.: SILCC

The SILCC project

ISM-SPP

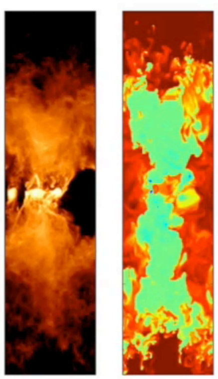
DFG Priority Program 1573

Interstellar Medium

SFB 956

Cologne | Bonn

The evolution of the Supernova-driven interstellar medium in a stratified galactic disk with Milky Way conditions: II. Peak placed Supernovae.

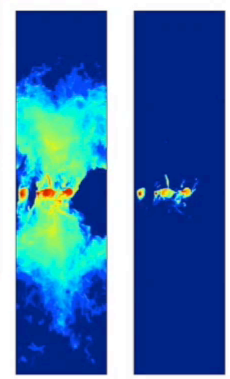


SILCC Collaboration

(1) Team University of Cologne: Stefanie Walch (PI)
(2) Team MPA Garching: Thorsten Naab, Philipp Girichidis, Andrea Gatto
(3) Team ITA Heidelberg: Simon Glover, Ralf Klessen, Christian Baczynski
(4) Team Czech Academy of Sciences: Richard Wünsch
(5) Team University of Zurich: Thomas Peters
(6) Team Cardiff University: Paul Clark (since May 2014)

Main parameters:

- Gas surface density = 10 $M_{\odot}/pc^2$
- Supernova rate = 15/Myr
- Supernova placement on density peaks



Global Galaxy Simulations
II. Cosmological zoom-in

Select cosmological volume to yield galaxy of given type, e.g. “MW-like”

(e.g., Steinmetz & Muller 1995; Navarro & Steinmetz 1997; Abadi et al. 2003; Governato et al. 2007; Agertz et al. 2011; Guedes et al. 2011)

Over-cooling problem

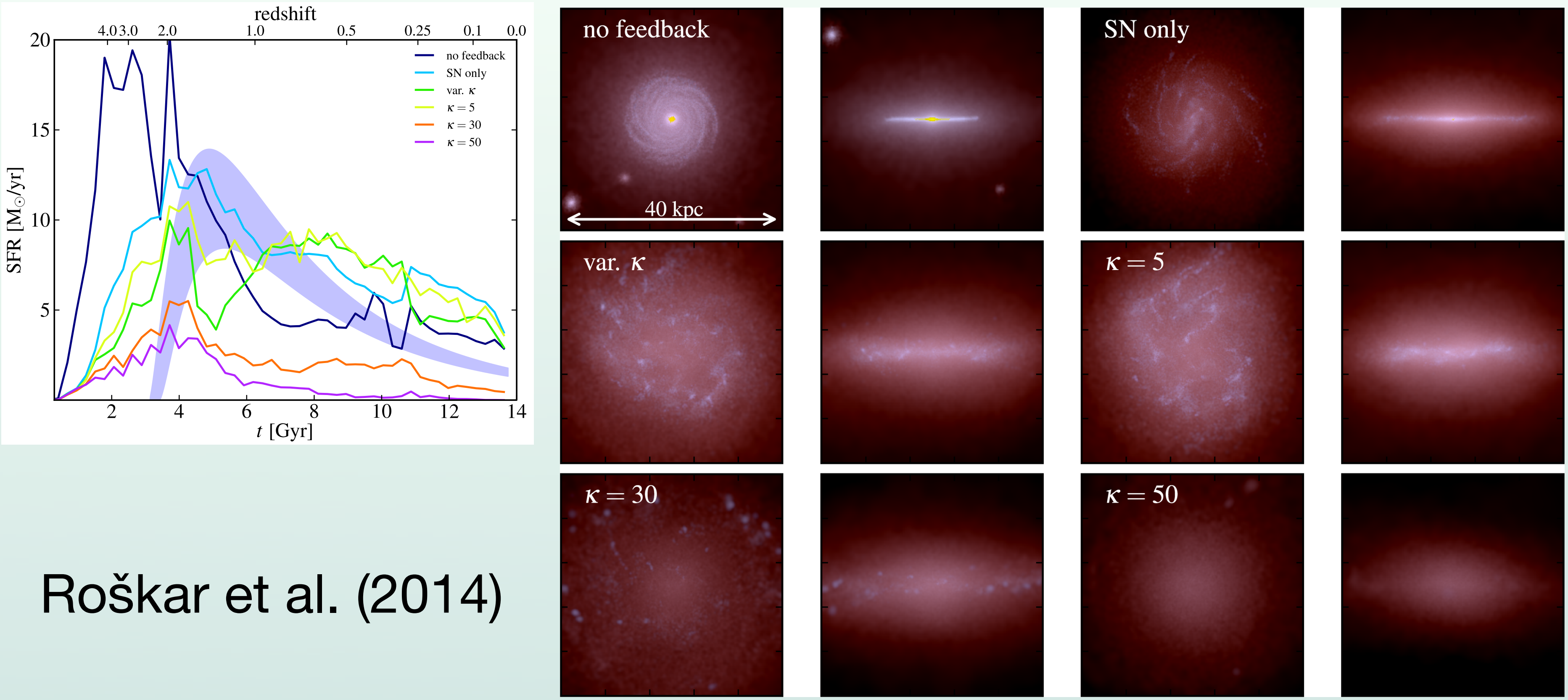
- too efficient star formation at early times

Angular momentum catastrophe

- ang. mom. loss during mergers, via dynamical friction: disks too small.

Problems “solved/addressed” by **increased resolution** and improved **sub-grid models for star formation & feedback**, including supernova, ionization and **radiation pressure**
(e.g., Murray et al. 2010; Hopkins et al. 2011; Brook et al. 2012; Stinson et al. 2013)

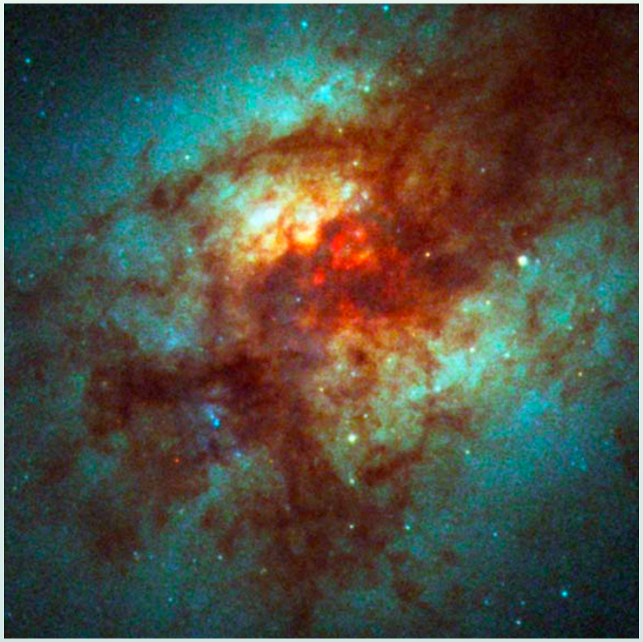
Radiative feedback & galactic disks



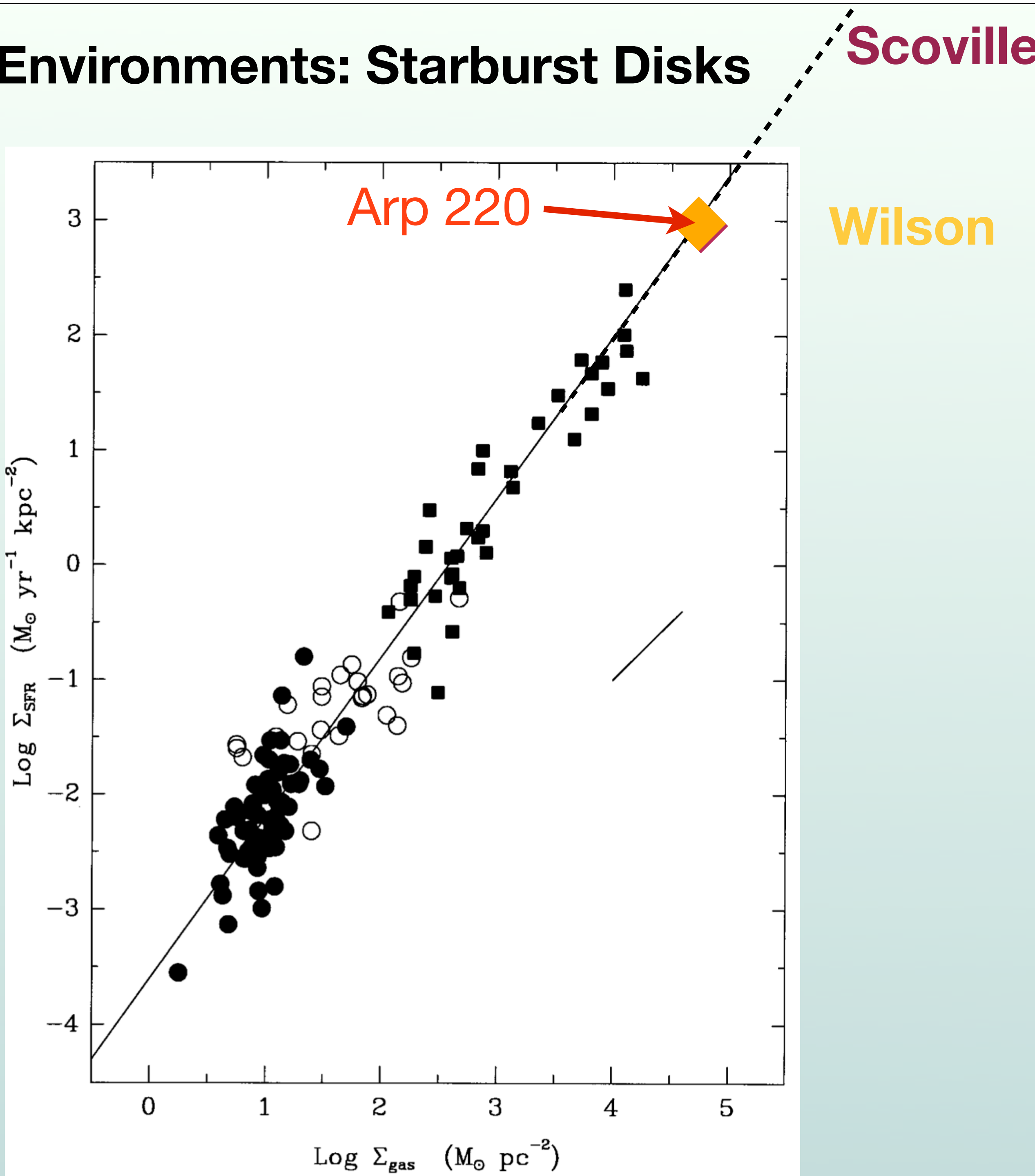
Roškar et al. (2014)

Strong radiative feedback (sub-grid scheme) can suppress early SF and eject sufficient baryons, but at the expense of thin-disk morphology.

Extreme Environments



Extreme Environments: Starburst Disks



Example of Arp 220

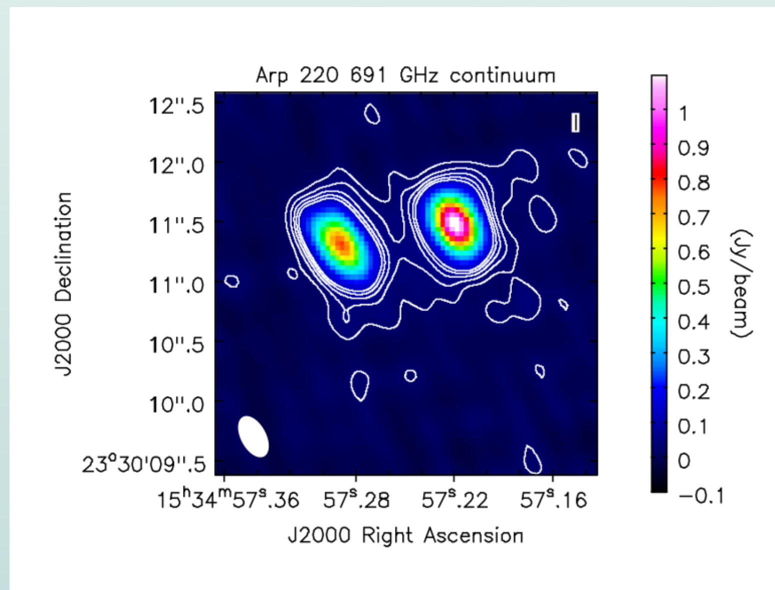
Kennicutt 1998	From Nick Scoville	Wilson et al. 2014
d ~= 75 Mpc		
D = 2”		
r = 365 pc	40 pc	(100, ~70) pc
$M_{gas} = 2.4 \times 10^{10}\ M_\odot$	$2 \times 10^{9}\ M_\odot$	$(1.1, 1.3) \times 10^{9}\ M_\odot$
$\Sigma_{gas} = 5.8 \times 10^{4}\ M_\odot\ pc^{-2}$	$4.0 \times 10^{5}\ M_\odot\ pc^{-2}$	$(0.54, 1.4) \times 10^{5}\ M_\odot\ pc^{-2}$
$L_{IR} = 2.3 \times 10^{12}\ L_\odot$	$1 \times 10^{12}\ L_\odot$	$(0.05, 0.6) \times 10^{12}\ L_\odot$
$SFR = 400\ M_\odot\ yr^{-1}$	$170\ M_\odot\ yr^{-1}$	$(9, 100)\ M_\odot\ yr^{-1}$
$\Sigma_{SFR} = 0.95 \times 10^{3}\ M_\odot\ yr^{-1}\ kpc^{-2}$	$35 \times 10^{3}\ M_\odot\ yr^{-1}\ kpc^{-2}$	$(0.3, 6.5) \times 10^{3}\ M_\odot\ yr^{-1}\ kpc^{-2}$

$v_{circ} = 370$ km/s

$\tau_{dyn} = 6 \times 10^{6}$ yr

$$\dot{\Sigma}_\star = \frac{\sqrt{2} f_g Q}{\epsilon\kappa c}\frac{\sigma^2}{r} \sim 400 f_{g_{0.5}} \sigma_{200}^2 Q r_{\rm kpc}^{-1}\kappa_1^{-1}\epsilon_3^{-1}\ M_\odot\ {\rm yr}^{-1}\ {\rm kpc}^{-2}$$

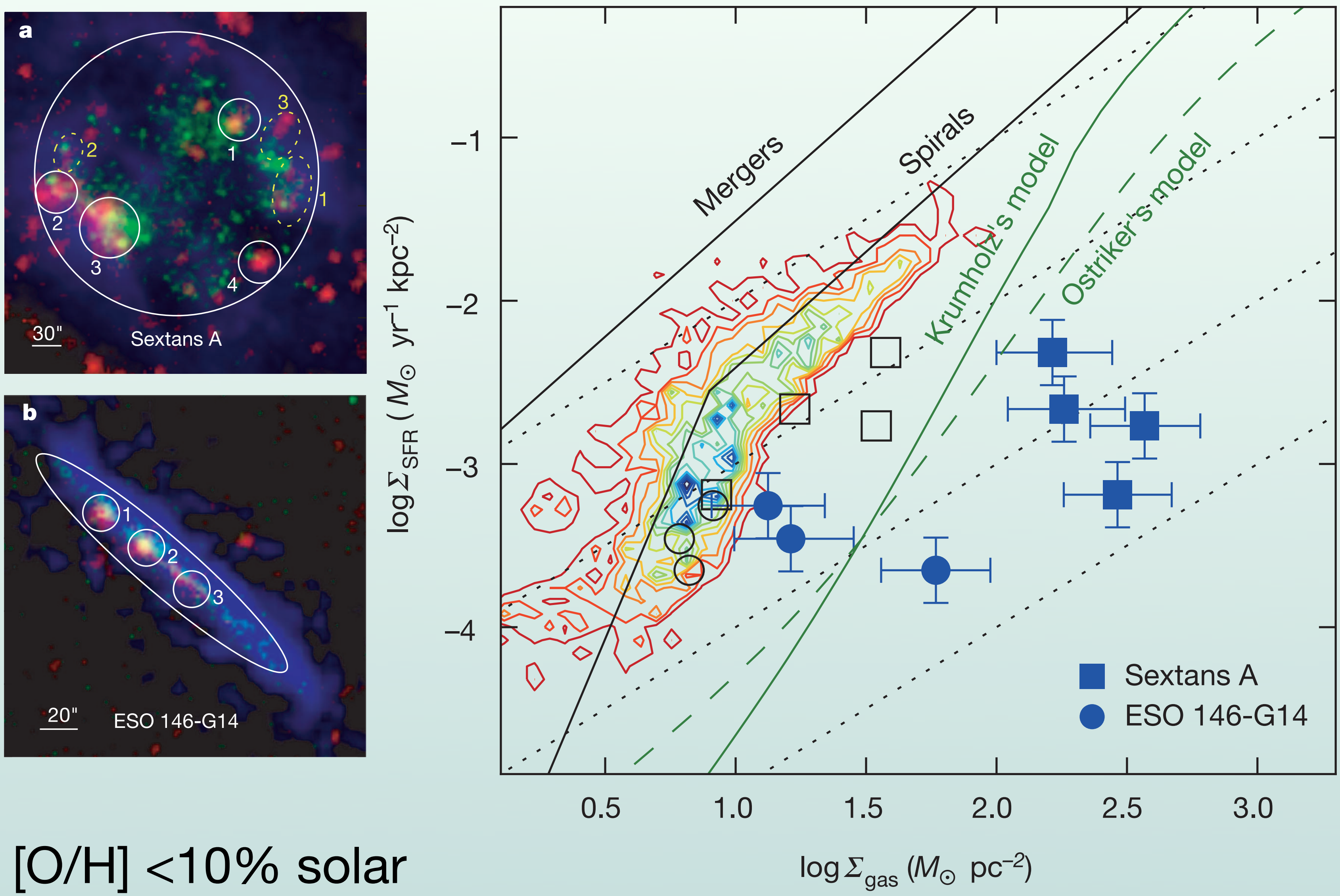
$$\frac{L}{M} = \frac{F}{\Sigma_{\rm tot}} = \frac{\pi Q G c f_g}{\sqrt{2}\kappa} = \frac{2\pi G c}{\kappa}\frac{h}{r} \sim 10^3 \frac{f_{g_{0.5}} Q}{\kappa_1}\ L_\odot\ M_\odot^{-1}.$$



Maximal starbursts due to radiation pressure?

(Scoville 2003; Thompson et al. 2005)

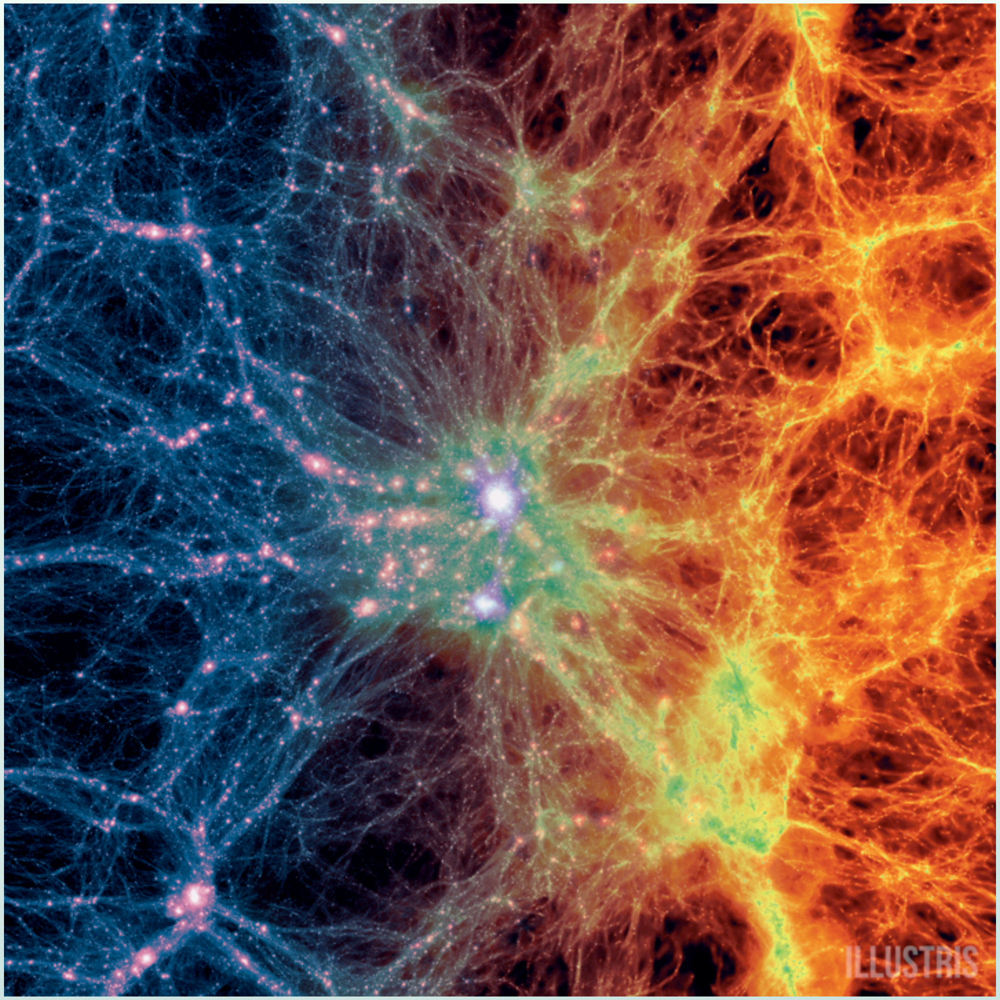
Extreme Environments: Low metallicity regions



[O/H] <10% solar

Shi, Armus, Helou et al. (2014)

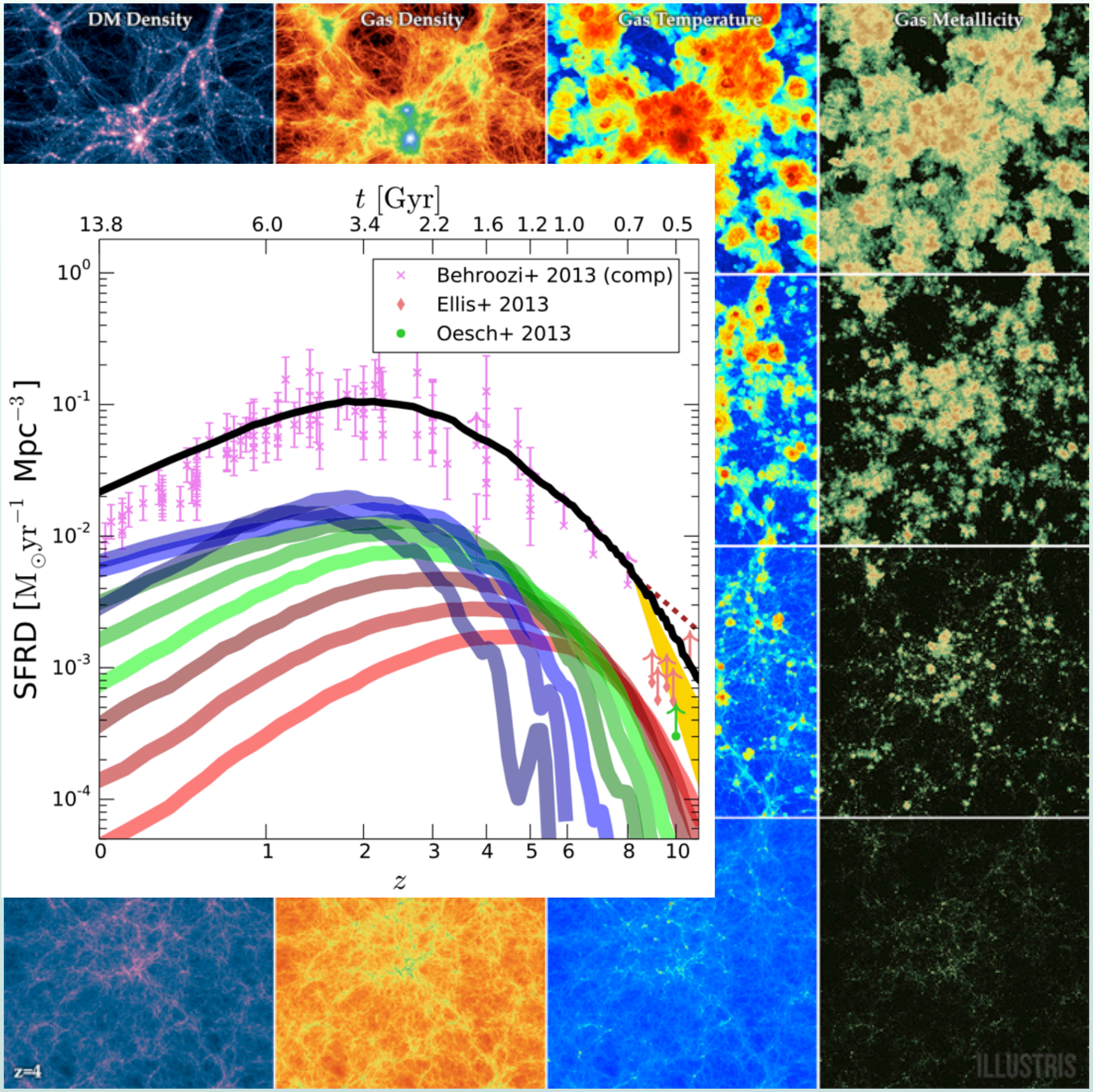
Galaxy Population Formation Simulations



Large cosmological volumes:

e.g., Illustris Simulation, ~(100Mpc)^3, Vogelsberger et al. (2014)

Galaxy Formation Simulations/Models



Included physics:

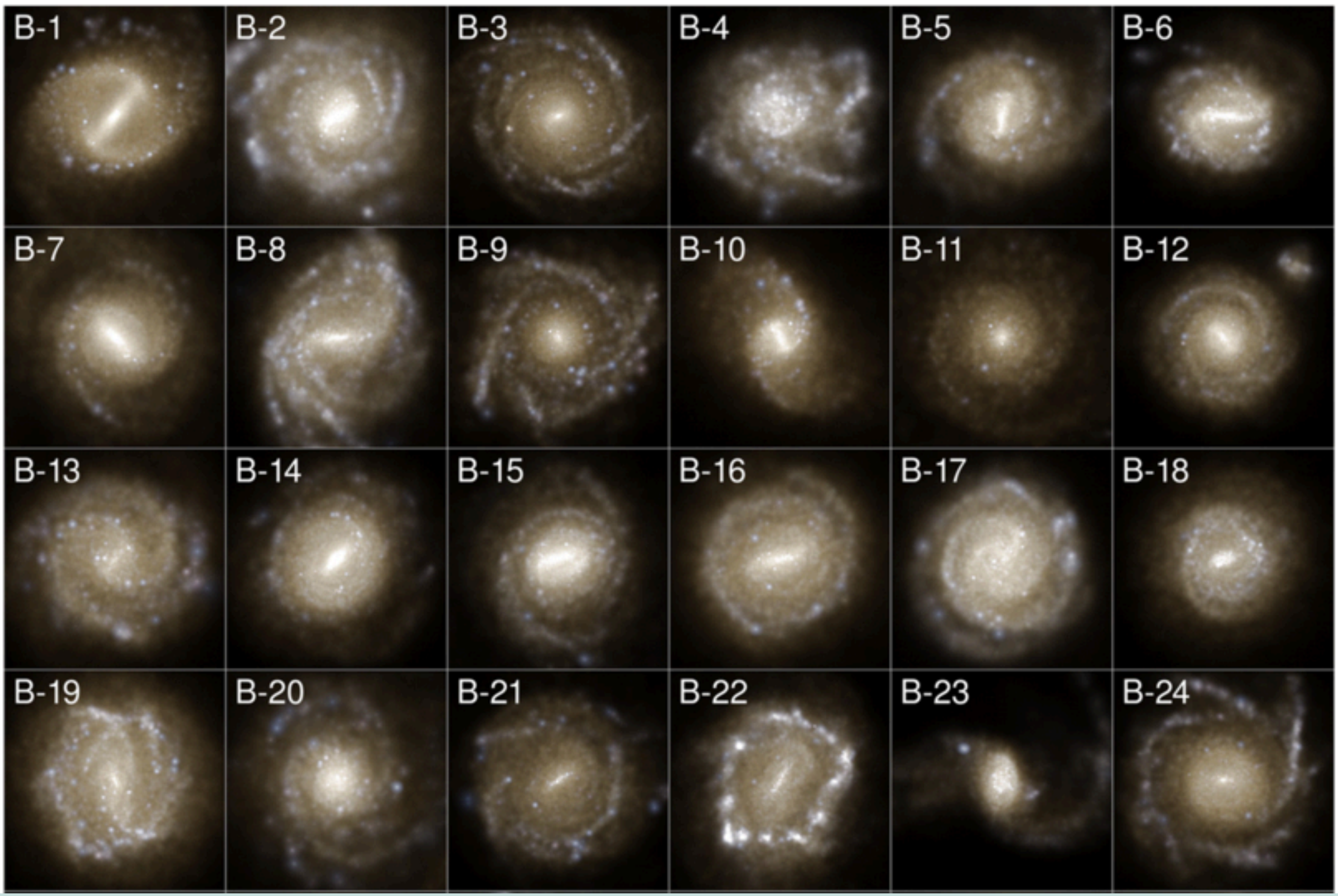
- primordial and metal-line cooling with self-shielding corrections
- stellar evolution
- stellar feedback
- gas recycling
- chemical enrichment
- supermassive black hole growth
- AGN feedback

Compare with:

- cosmic SFR density
- galaxy luminosity function
- Ω_{baryon} at z = 0
- galaxy morphologies with environment

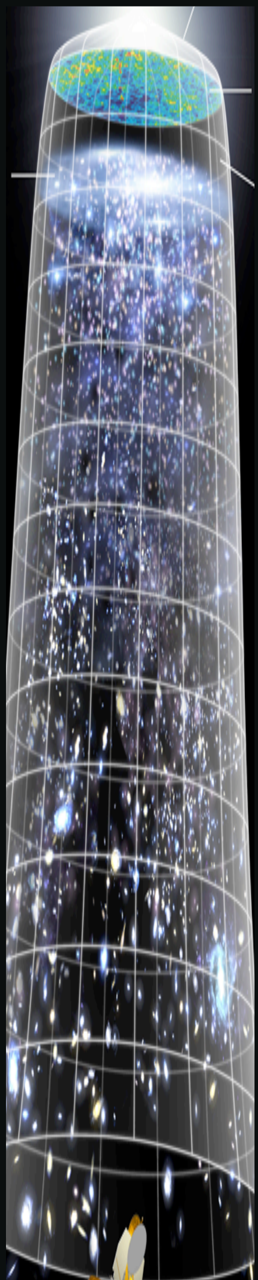
e.g., Illustris Simulation, Vogelsberger et al. (2014)

Galaxy Formation Simulations/Models



e.g., Illustris Simulation, Vogelsberger et al. (2014)

Conclusions: The Role of Star Formation on Galaxy Evolution



Star formation is complex and we struggle to understand even nearby systems: **Initial Conditions; Dependence on Sub-Grid Models; Connection to Observables.**

Pop III Star Formation has well-defined initial conditions. Latest results suggest very first stars (Pop III.1) are **massive ~10-100$M_{\odot}$**, but precise prediction is difficult and hard to test. Accurate modeling of subsequent generations is even more challenging (hopeless until we have better observational constraints?)

Disk Galaxy Star Formation is increasingly well observed, e.g., GMCs in nearby galaxies. Understanding the SFR, IMF and role of feedback are key problems.

Elements of sub-grid models: SFR are low: ϵ_{ff} ~ 0.01 above a threshold density

~~Stars form from Gas~~ **~~Stars form from Molecular Gas~~**

Stars form from Magnetically Moderately Supercritical Molecular Gas at A_V>10, mediated by Alfvénic or sub-Alfvénic turbulence and dynamically important large-scale B-fields.

Star formation localized in **~parsec-sized star clusters** but knows about **global disk timescales**. Shear mediated GMC collisions?

Important to have **observable simple test cases**, spanning a **range of environments: low metallicity; galactic centers; starbursts...**