Gas accretion in spirals & ellipticals: theory & observations

Carlos S. Frenk
Institute for Computational Cosmology, Durham

University of Durham

The galaxy baryon budget in a ΛCDM universe

From Simon White's talk yesterday:

- The total amount of baryons associated with halos of galaxies is > 5 times the observed stars and gas at all redshifts

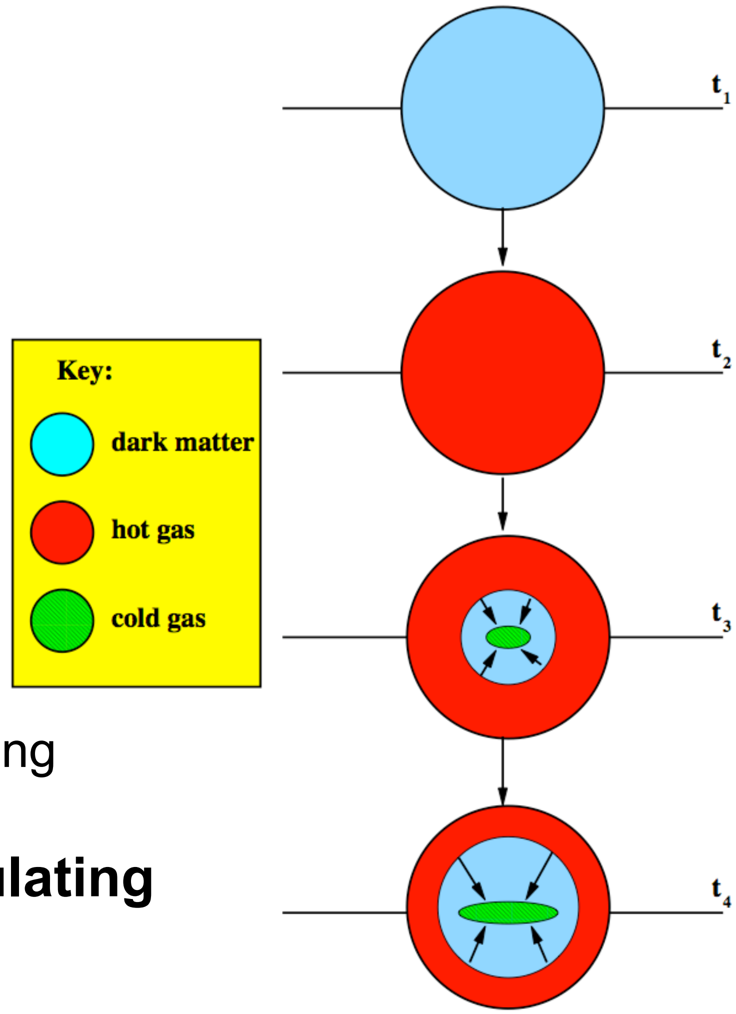
- These baryons should have accreted onto all but the smallest galaxy/halo systems as their halos grew

Where are these baryons?

A simple picture of disc galaxy formation in CDM

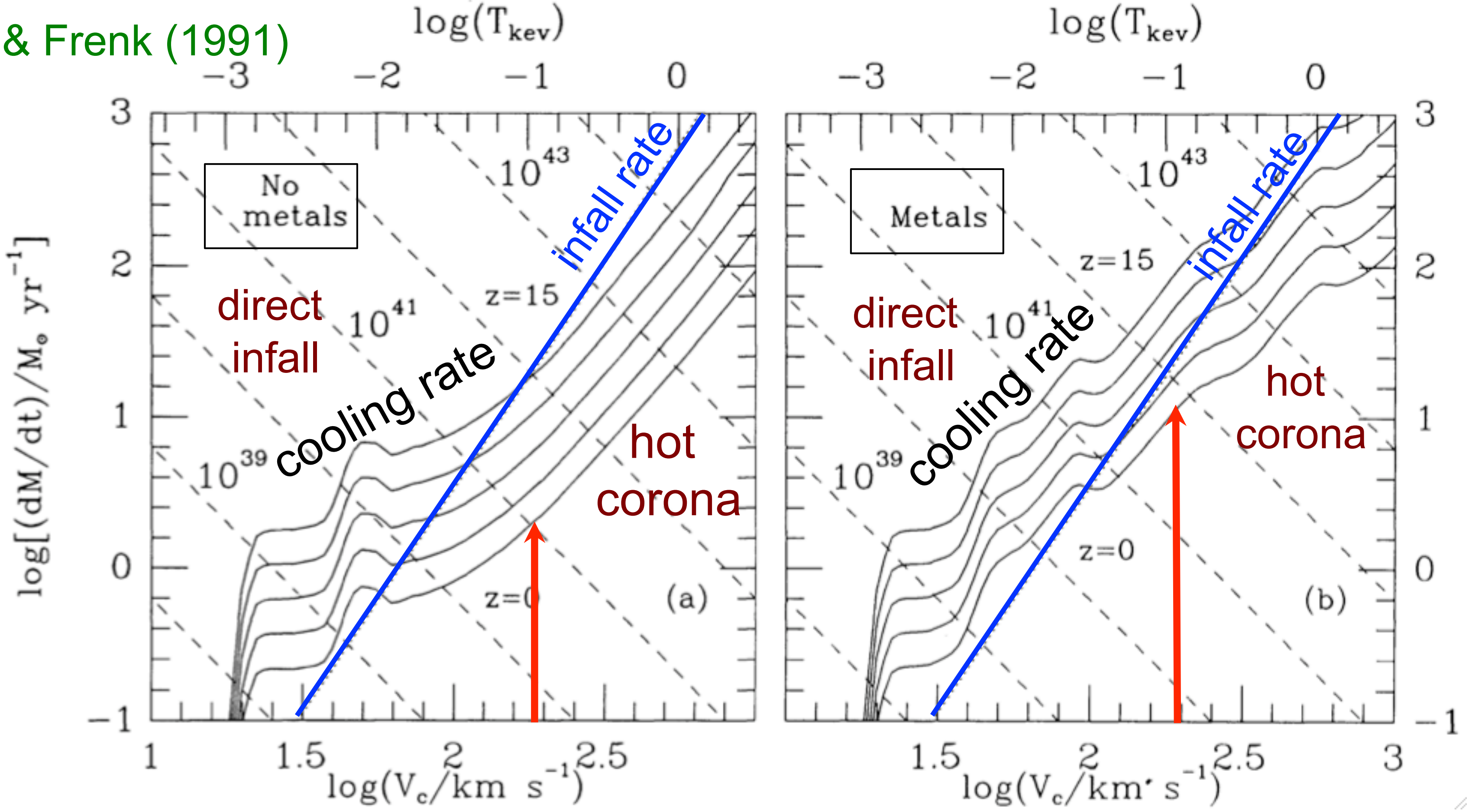
White & Frenk '91

- **Gas accreted onto dark matter halo**
  - Has cosmic baryon fraction
  - Is shocked
- **Gas cools radiatively**
  - If $t_{cool} < t_{dyn}$ gas infalls directly
  - If $t_{cool} > t_{dyn}$ gas forms hot atmosphere:
    - at virial temperature (~10^6 K for MW)
    - distributed like dark matter
  - Cooled gas forms rotationally supported disc
  - Stars condense out of cold gas
  - Some gas returned to hot corona by SN heating
- **In large galaxies, process is self-regulating**
  - Disk continues to grow in spirals & ellipticals
  - Cooling gas emits x-rays



Galaxy formation in a cold dark matter universe

White & Frenk (1991)



For Milky Way analogues, predict:

- kT~0.1 keV (soft X-ray)
- 10^{41}-10^{42} erg/s for $v_c \sim 220$ kms^{-1} at z=0

…detectable with *ROSAT, XMM, Chandra*

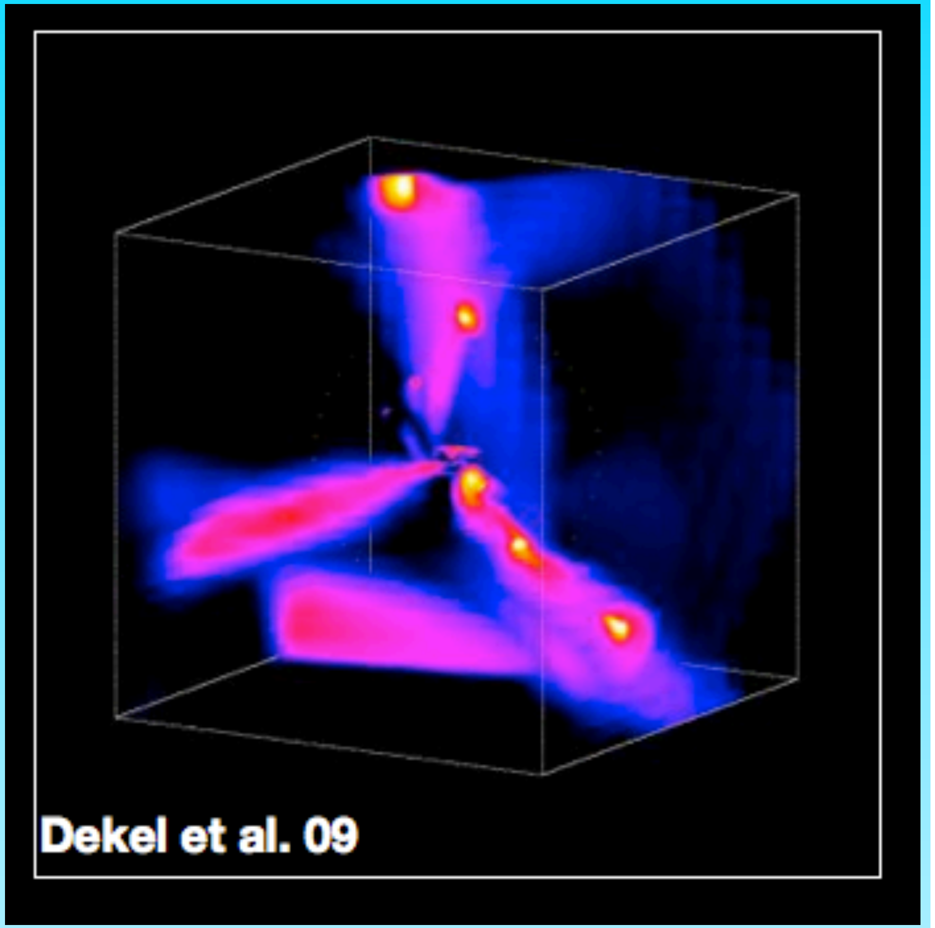
Institute for Computational Cosmology

"Cold flows"

In SPH sims, cold gas delivered into central parts by filaments

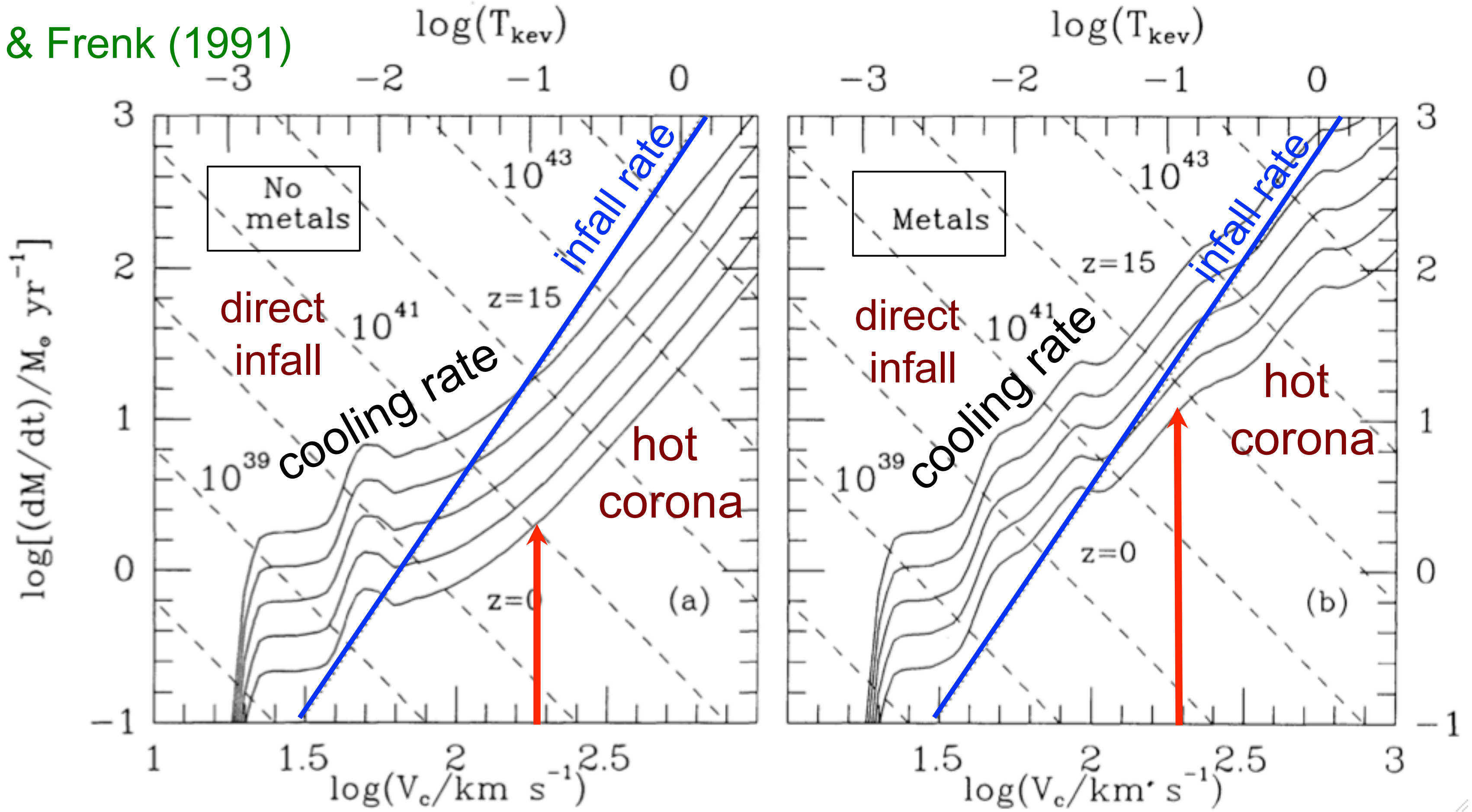
Katz et al. '03, Keres et al. '05

WF '91 theory includes rapidly cooling gas ($t_{cool} < t_{dyn}$) but assumes spherical symmetry



Galaxy formation in a cold dark matter universe

White & Frenk (1991)

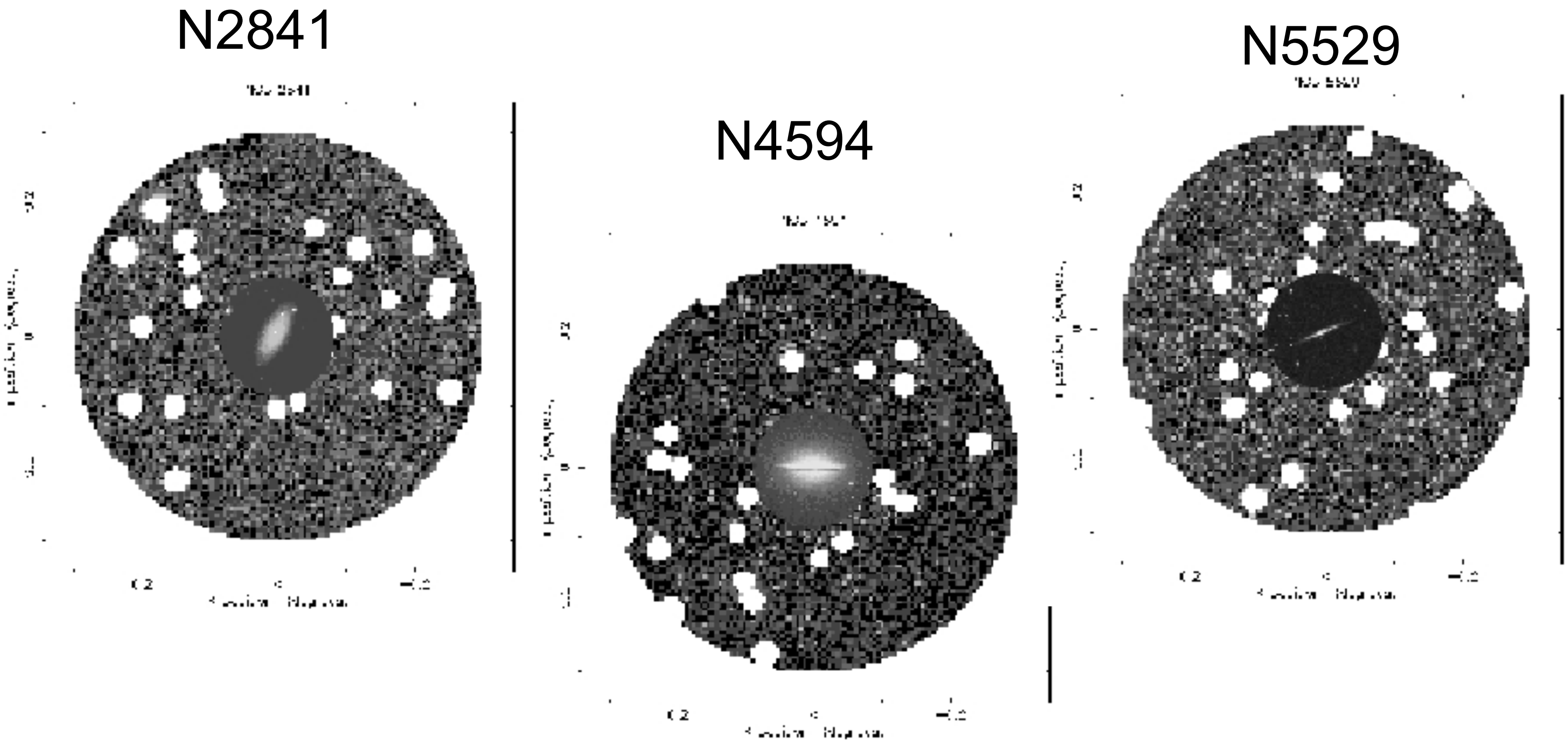


For Milky Way analogues, predict:

- kT~0.1 keV (soft X-ray)
- 10^{41}-10^{42} erg/s for $v_c \sim 220$ kms^{-1} at z=0

…detectable with *ROSAT, XMM, Chandra*

Looking for X-rays form spirals with ROSAT



Upper limit: (10-100) x below theoretical predictions

Benson, Bower, Frenk & White ‘00

A problem for CDM galaxy formation theory!

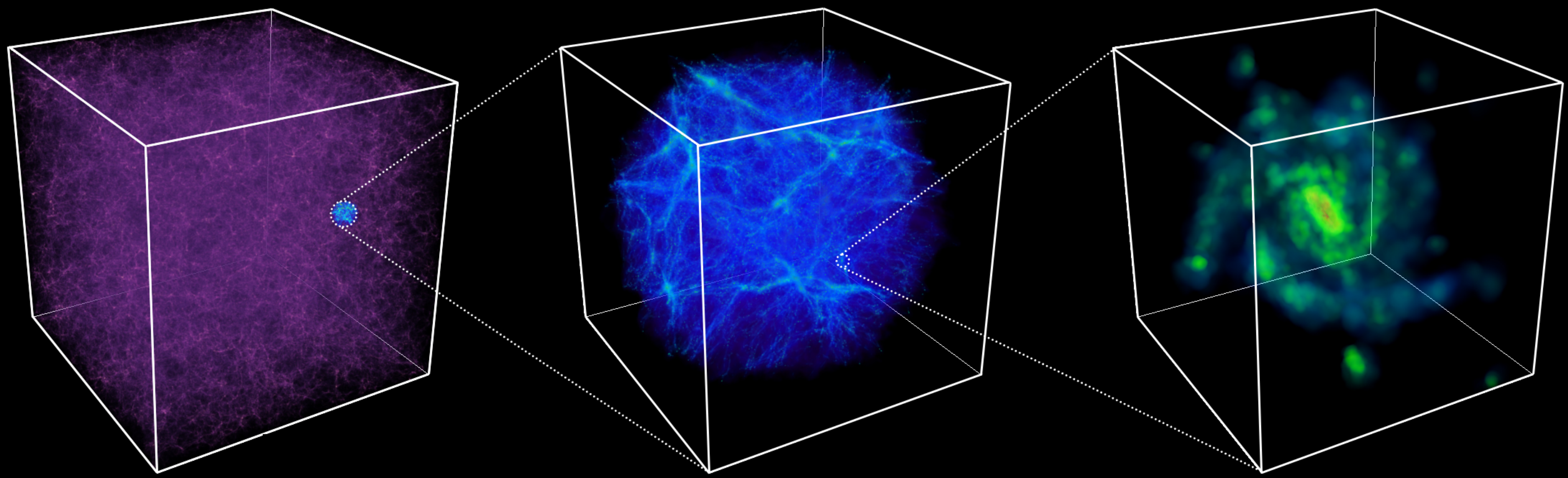
XMM/Chandra → several detections of X-rays from halos of spirals

… but L_X is (10-100) x below theoretical predictions

Where did WF91 go wrong?

→ Check with hydro simulations

Galaxies-Intergalactic Medium Interaction Calculation



Millennium Simulation
L = 500 Mpc/h

GIMIC region (1 of 5)
r ~ 20 Mpc/h

GIMIC galaxy
ε = 500 pc/h

- ``Resimulation” of 5 regions from the Millennium simulation including baryons
- Covering whole range of environments (voids --> clusters)
- OWLS code: SPH, cooling, SF, feedback, chemodynamics
- m_{gas} ~10^6 M_{sun}/h, L* galaxies resolved with 10^5 particles
- Runs to z=0

Crain et al. (2009)

University of Durham

The OWLS code

Gadget-3 (Virgo consortium)

- Gas cooling → including 11 metals, external UV background
- Star formation (Schmidt law)
- Stellar evolution → inc SN Type II & Ia and release of 11 metals
- SN driven galactic winds
- NO black holes or AGN feedback → important for $M_h > 10^{13} M_o$

X-ray coronae in simulations of disc galaxy formation

Robert A. Crain, Ian G. McCarthy, Carlos S. Frenk, Tom Theuns & Joop Schaye

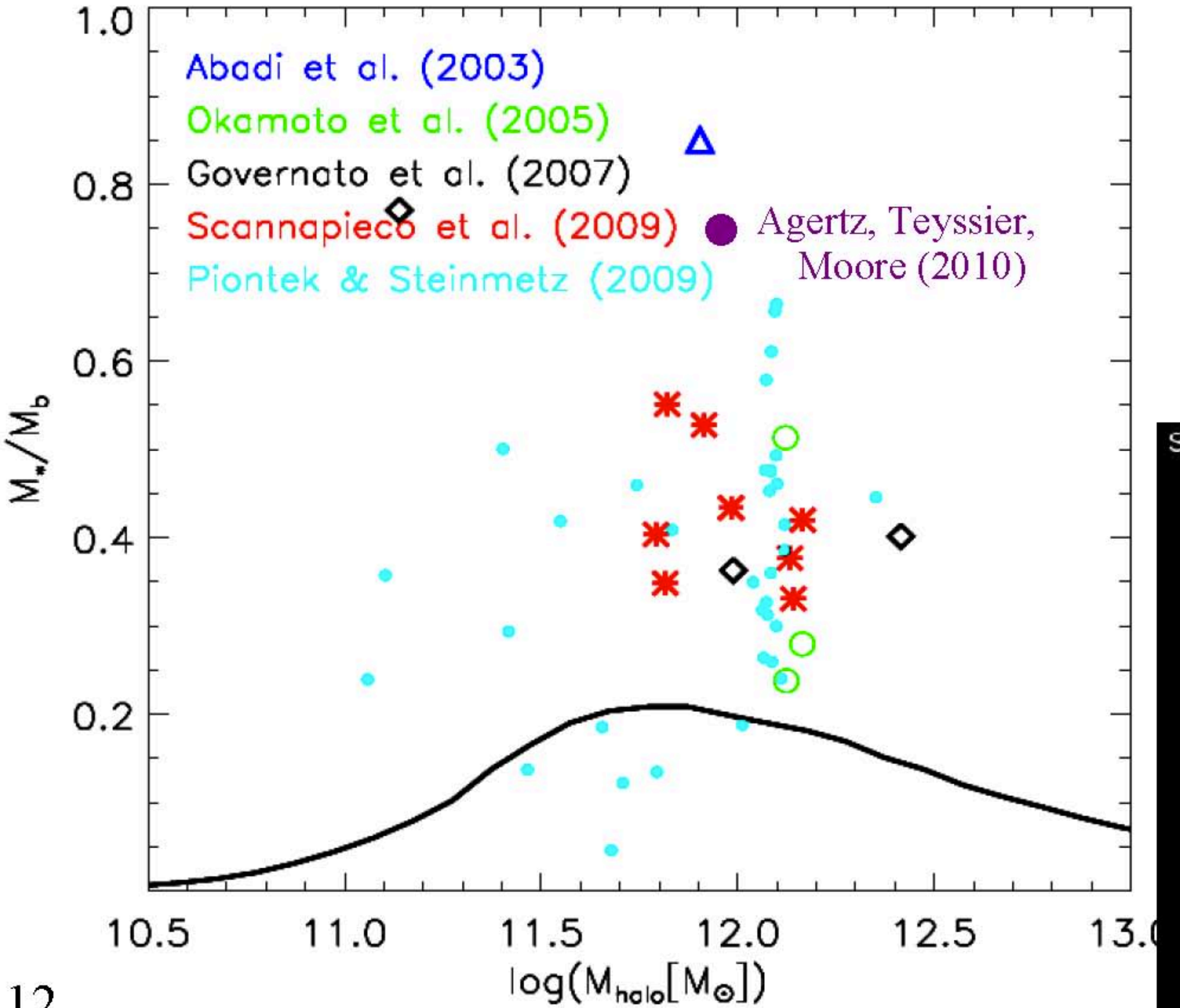
Galaxies in GIMIC

Are these simulations reliable?

Two problems with cosmological simulations:

- Too many stars are formed
- Difficult to make disk galaxies

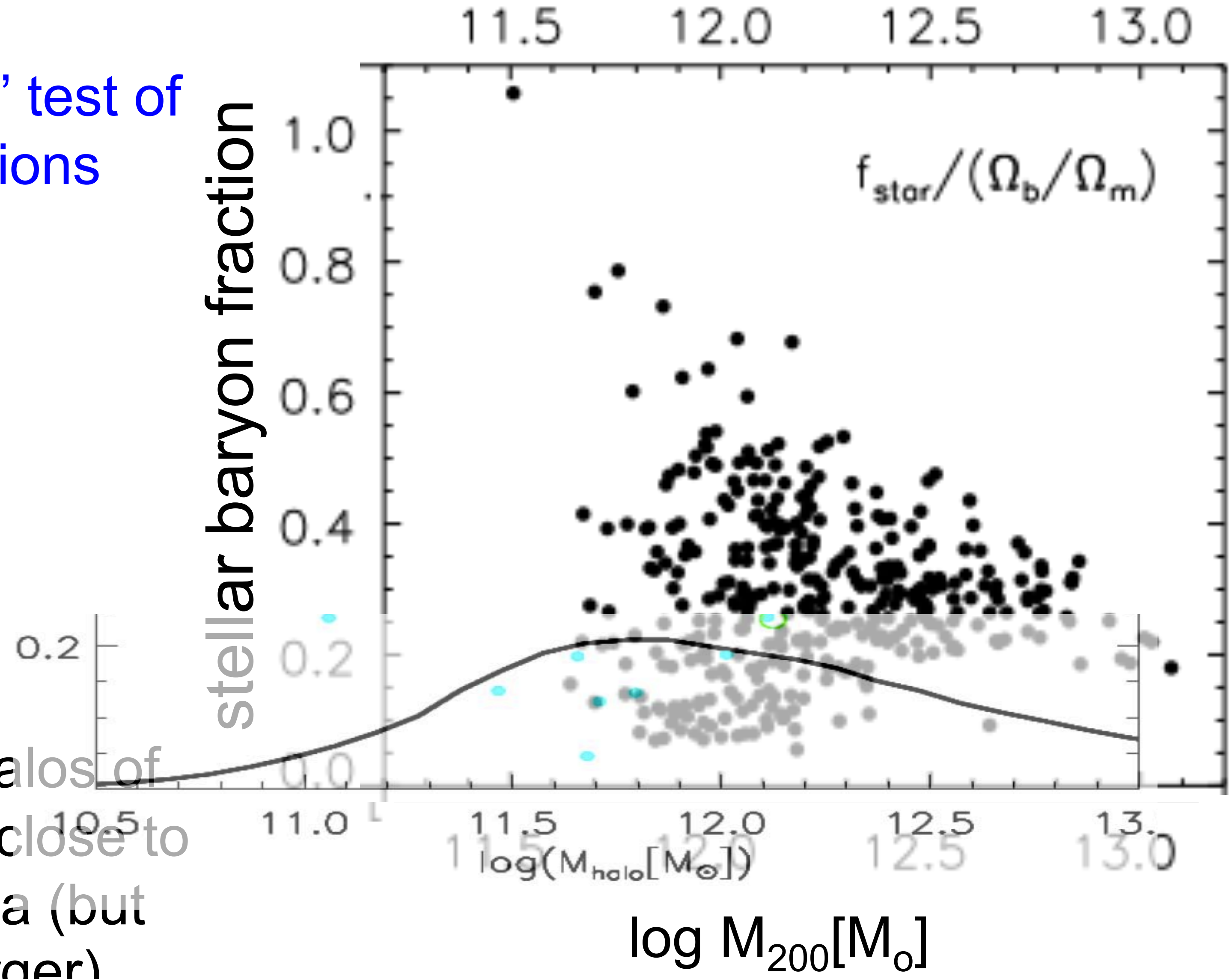
"Successful" simulations fail to match this...



Guo et al 2010

Disk galaxies in GIMIC

The "Guo-White" test of SPH simulations



Gimic gals in halos of $M<10^{12.5}$ M_o are close to Guo-White data (but scatter is larger)

Crain et al. '10

Galaxies in GIMIC

Are these simulations reliable?

Two problems with cosmological simulations:

- Too many stars are formed
- Difficult to make disk galaxies

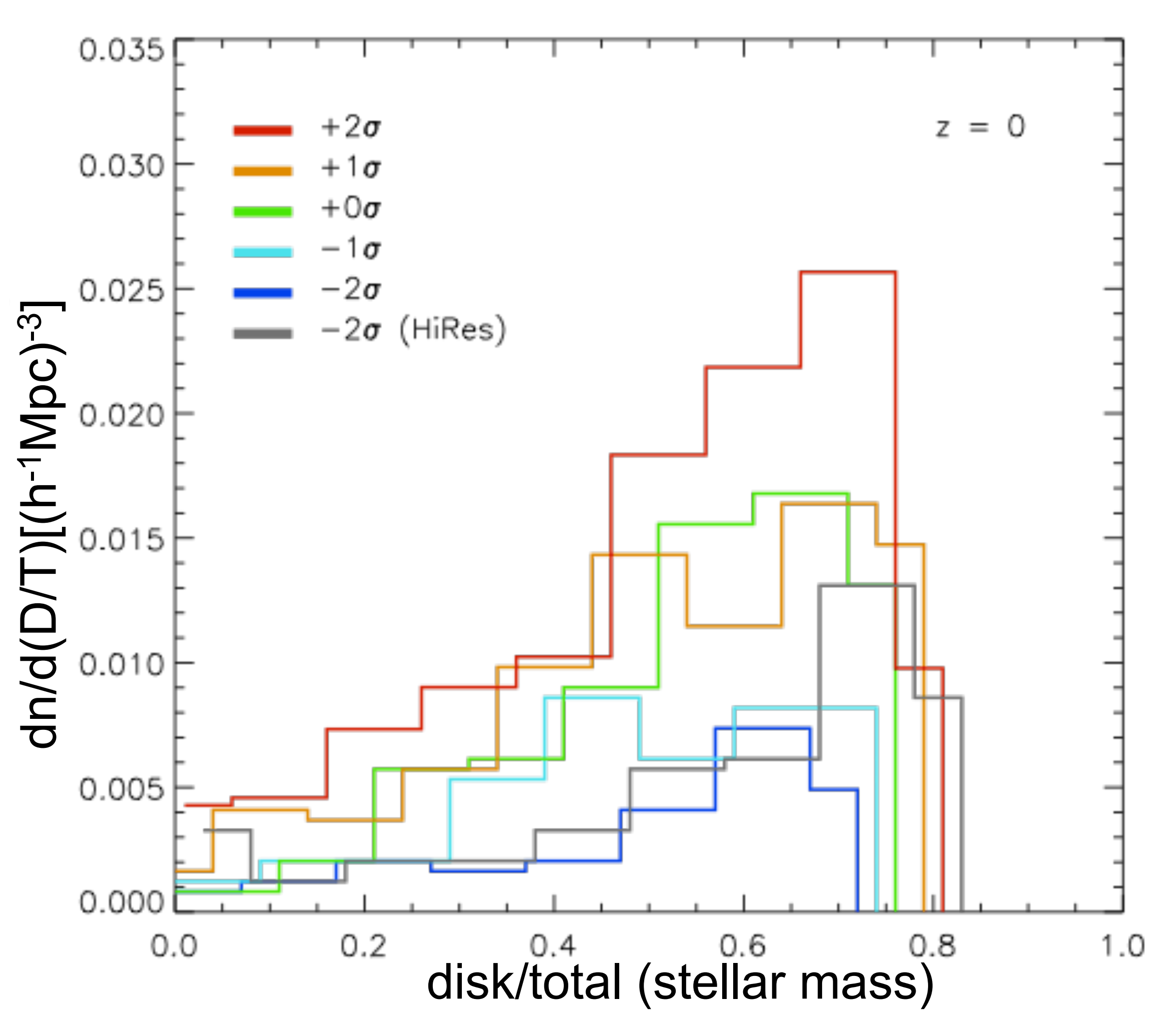
Disk galaxies in GIMIC

1267 galaxies, $M_* > 10^{10}$ M_o

Realistic distribution of D/T stellar mass ratio (50% with D/T>0.5) !

Select:

- Isolated central galaxies
- $10^{10} < M_\star < 10^{11.5}$ M_o
- D/T > 0.3
- 500 well-resolved 'Milky Ways'



Crain et al. '10

Institute for Computational Cosmology

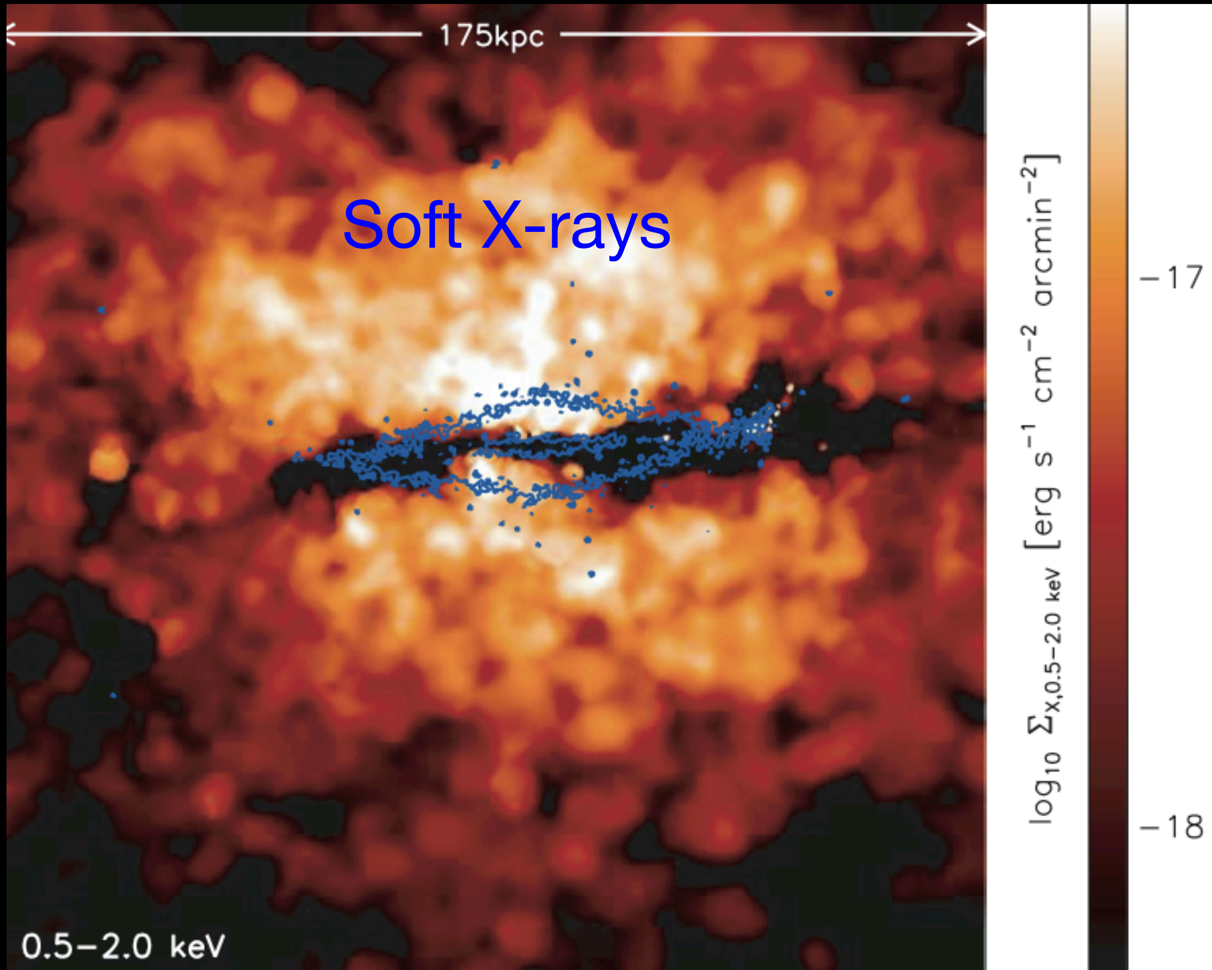
Simulations of galaxy formation and the real world

with
Rob Crain (Swinburne)
Ian McCarthy (Cambridge),
Tom Theuns (Durham),
Joop Schaye (Leiden).

Crain etal ‘10

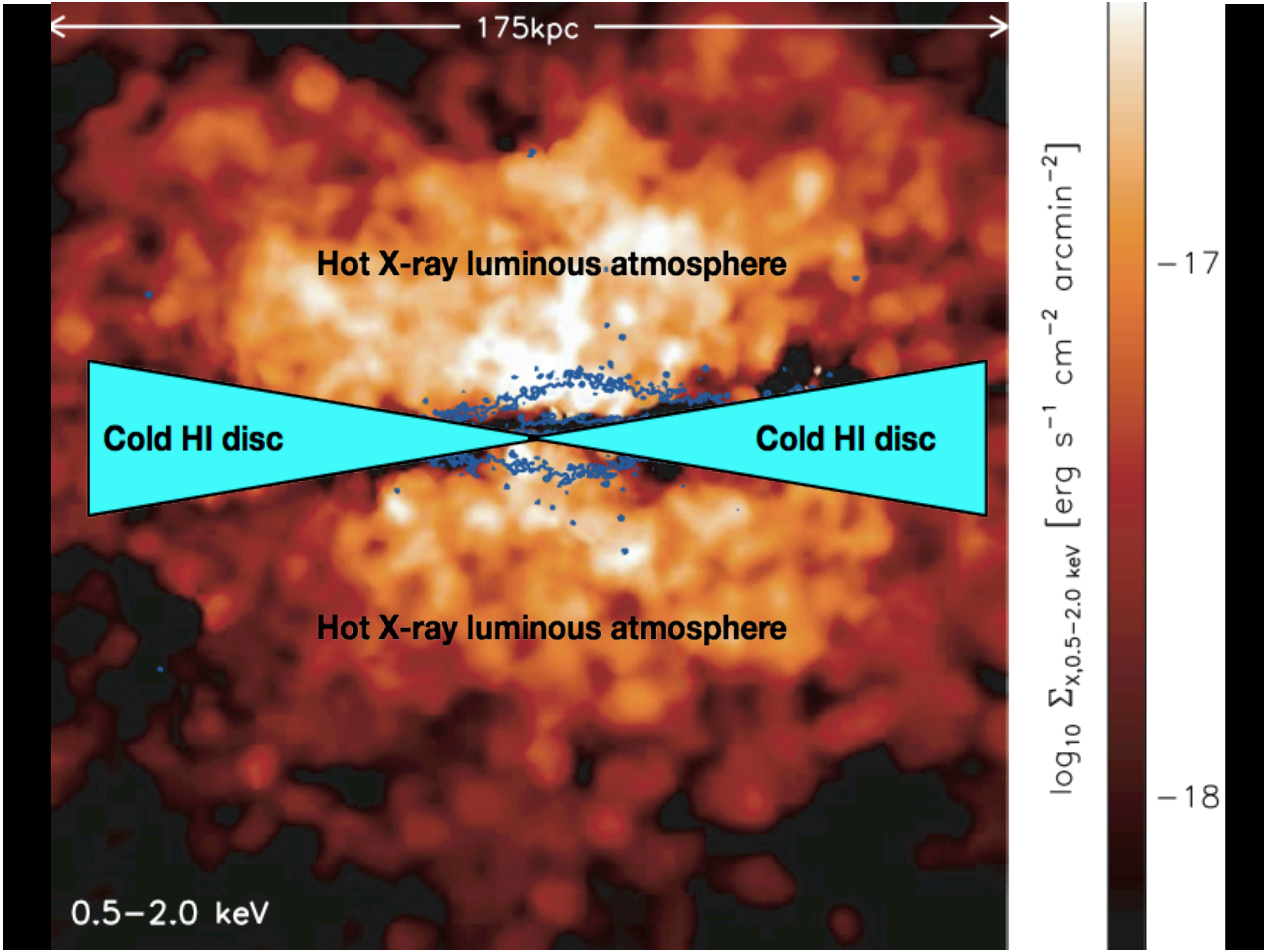
Hydro simulation: gas density and OVIII flux

A GIMIC galaxy in X-rays and K-band light



Crain et al '10

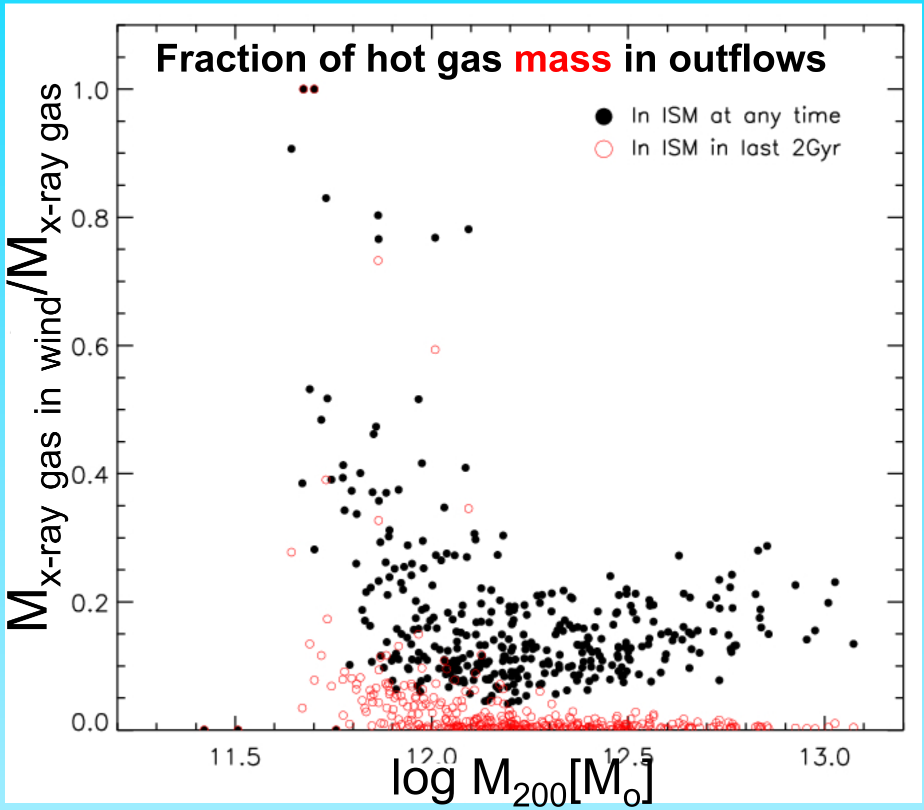
- Soft X-ray luminosity: APEC Extra-planar, bound gas at T > 20,000 K; H, He & 9 metals
- K-band luminosity: star particles treated as SSP+ GALAXEV (B&C'03)

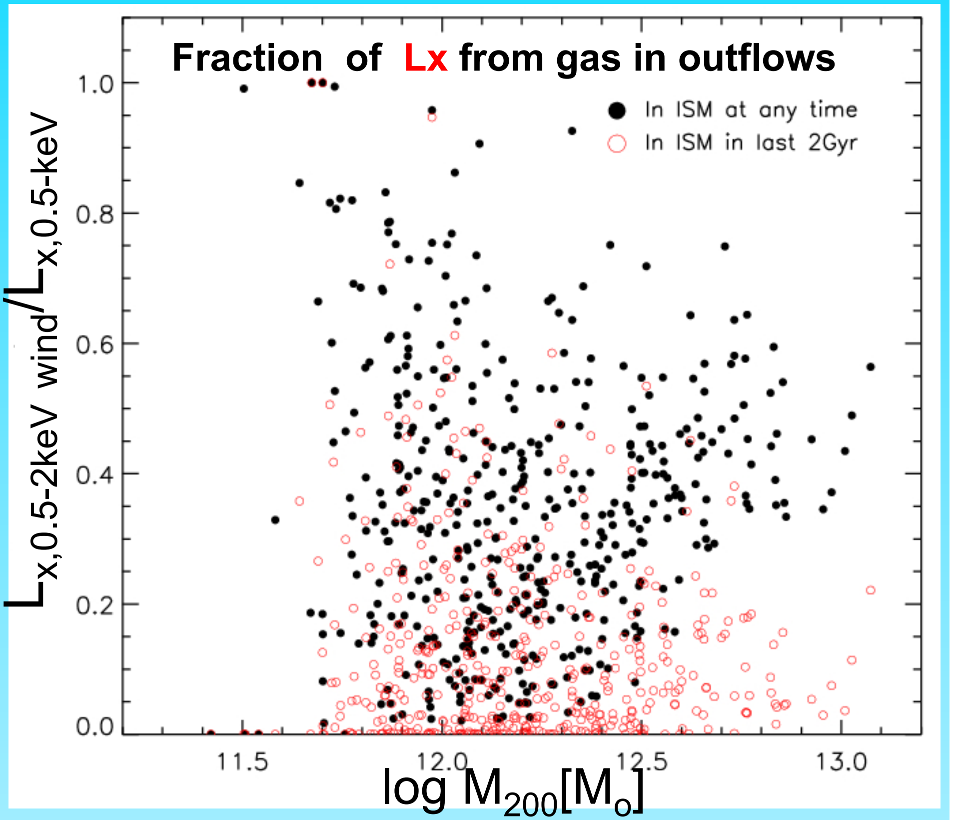


175kpc
Hot X-ray luminous atmosphere
Cold HI disc
Cold HI disc
Hot X-ray luminous atmosphere
0.5–2.0 keV
−17
−18
log10 Σ X,0.5–2.0 keV [erg s^-1 cm^-2 arcmin^-2]

University of Durham

X-rays: inflow or outflow?





- Little X-ray emiiting gas (by mass) is in outflows. Mass dominated by hydrostatic corona
- Sub-dominant outflows contribute disproportionately to L_X

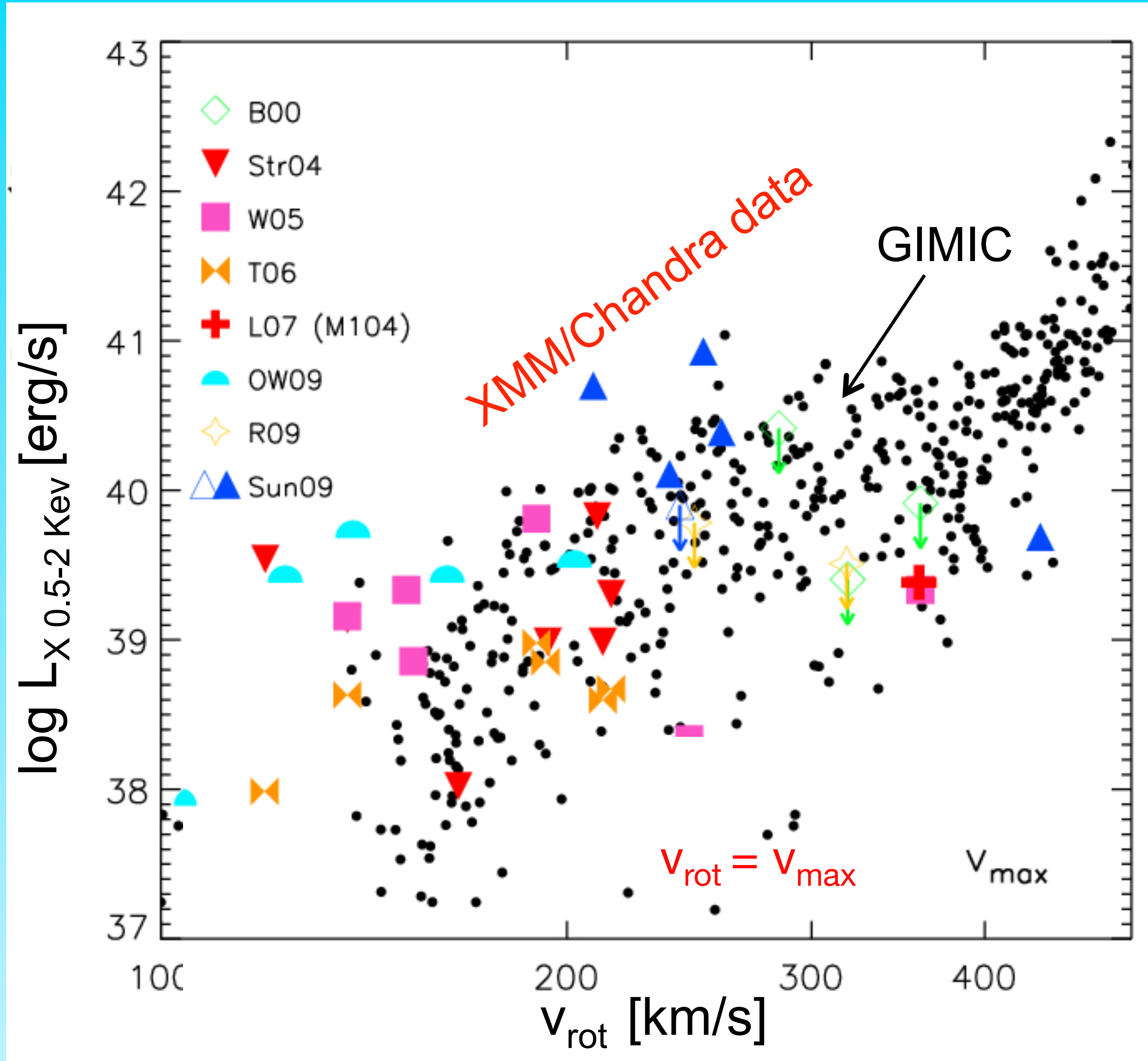
X-ray flux dominated by low surface brightness cooling flow gas, but SN outflows contribute disproportionally because they come from dense, metal-rich central parts

X-ray luminosity – disc velocity

University of Durham

Data for:

- edge-on spirals
- binaries subtracted
- extraplanar emission



- Assume $v_{rot} = v_{max}$
- Simulations agree with observations!

Crain et al. '10

X-ray luminosity – disc velocity

Simulations and data match!

In sims most X-ray emission due to gas cooling from hot corona

… at (10-100) lower L_X than predicted by WF '91

Detection of a Hot Gaseous Halo Around the Giant Spiral Galaxy NGC 1961

Michael E. Anderson[1], Joel N. Bregman[1]

... found diffuse emission that appears to extend to 40-50 kpc. We fit β-models to the emission, and estimate a hot halo mass within 50 kpc of $5 \times 10^9 M_\odot$. When this profile is extrapolated to 500 kpc (the approximate virial radius), the implied hot halo mass is $1 - 3 \times 10^{11} M_\odot$. These mass estimates

Detection of a Hot Gaseous Halo Around the Giant Spiral Galaxy NGC 1961

Michael E. Anderson[1], Joel N. Bregman[1]

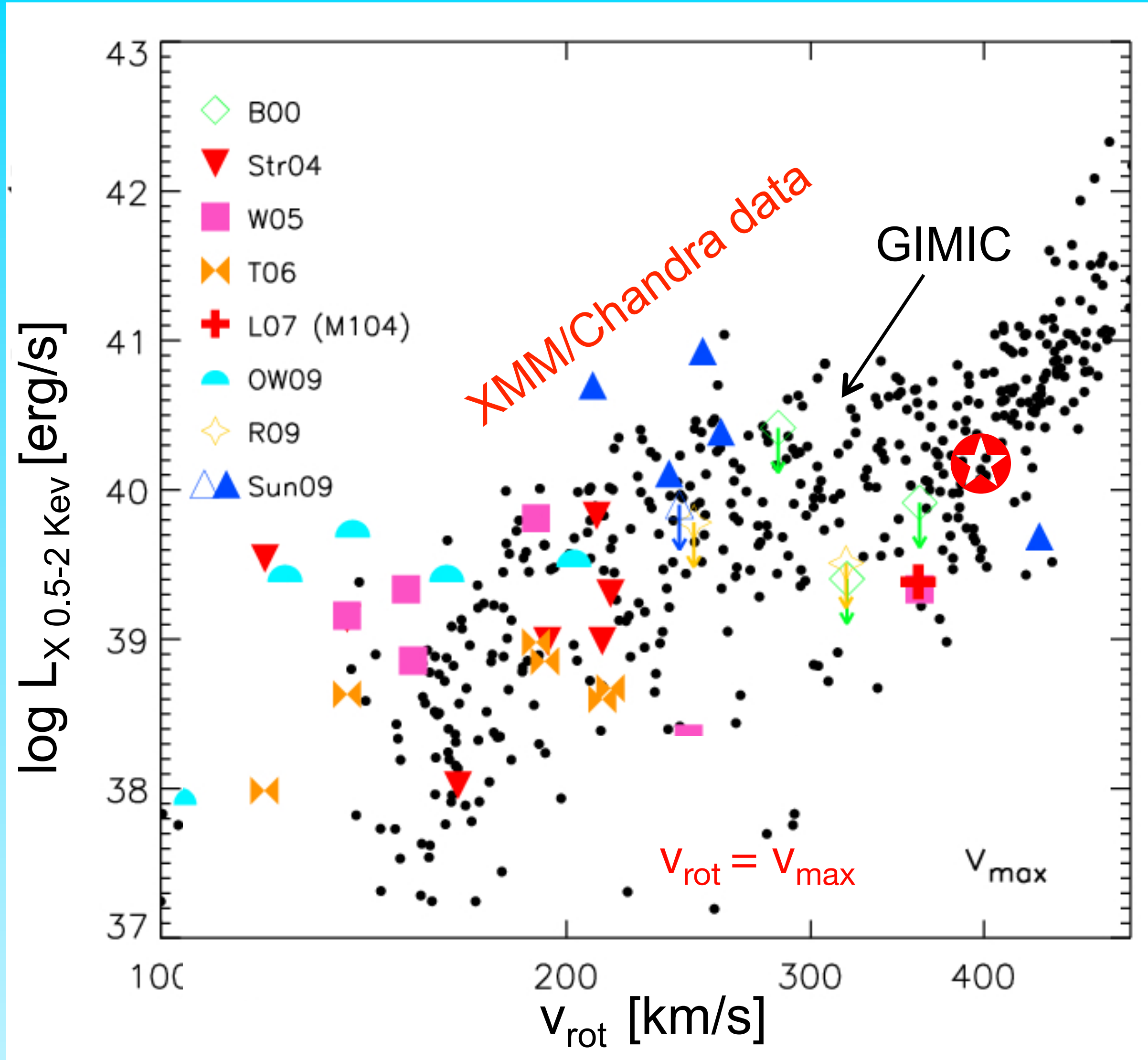
A recent paper (Crain et al. 2010b) attributes these detections of extended emission to galactic coronae, instead of the standard explanation of the emission as a fountain or a wind originating from within the galaxy. This interpretation is in disagreement with the standard understanding of galactic fountains in spiral galaxies, but regardless of interpretation it still is true that no hot halo has been detected around a disk galaxy at a radius of more than a few kpc.

X-ray luminosity – disc velocity

University of Durham

Data for:

- edge-on spirals
- binaries subtracted
- extraplanar emission



- Assume $v_{rot} = v_{max}$
- Simulations agree with observations!

Crain, McCarthy et al. '10

University of Durham

Winds/fountains *vs* accretion

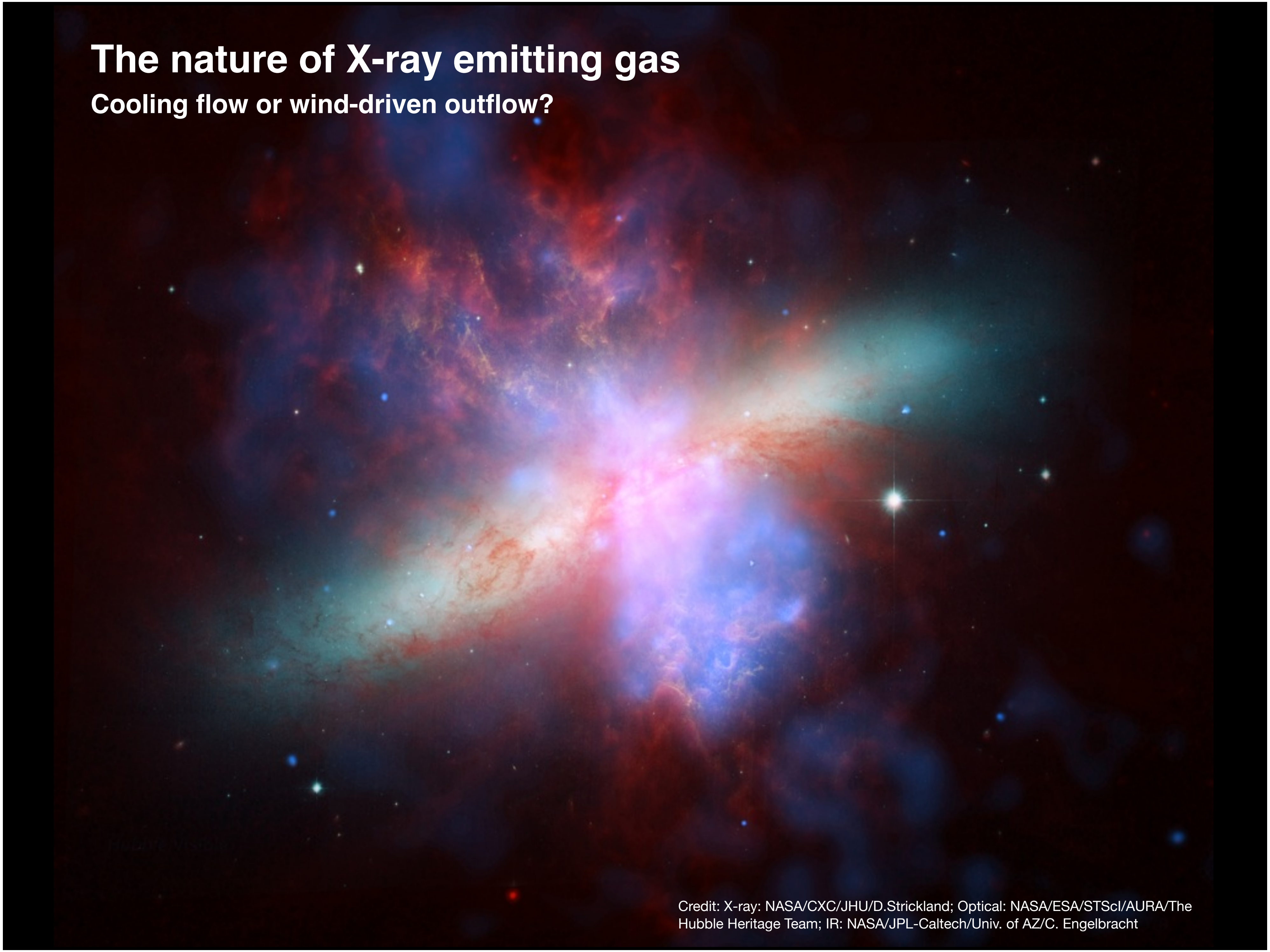
Reasons for the:

"standard explanation of the emission as a fountain or originating from within the galaxy" (Anderson & Bregman '11)

- Correlation between L_X and SFR, $\dot{M}_*$
- Correlation between L_X and stellar mass, L_K

The nature of X-ray emitting gas

Cooling flow or wind-driven outflow?



Credit: X-ray: NASA/CXC/JHU/D.Strickland; Optical: NASA/ESA/STScI/AURA/The Hubble Heritage Team; IR: NASA/JPL-Caltech/Univ. of AZ/C. Engelbracht

University of Durham

Winds/fountains *vs* accretion

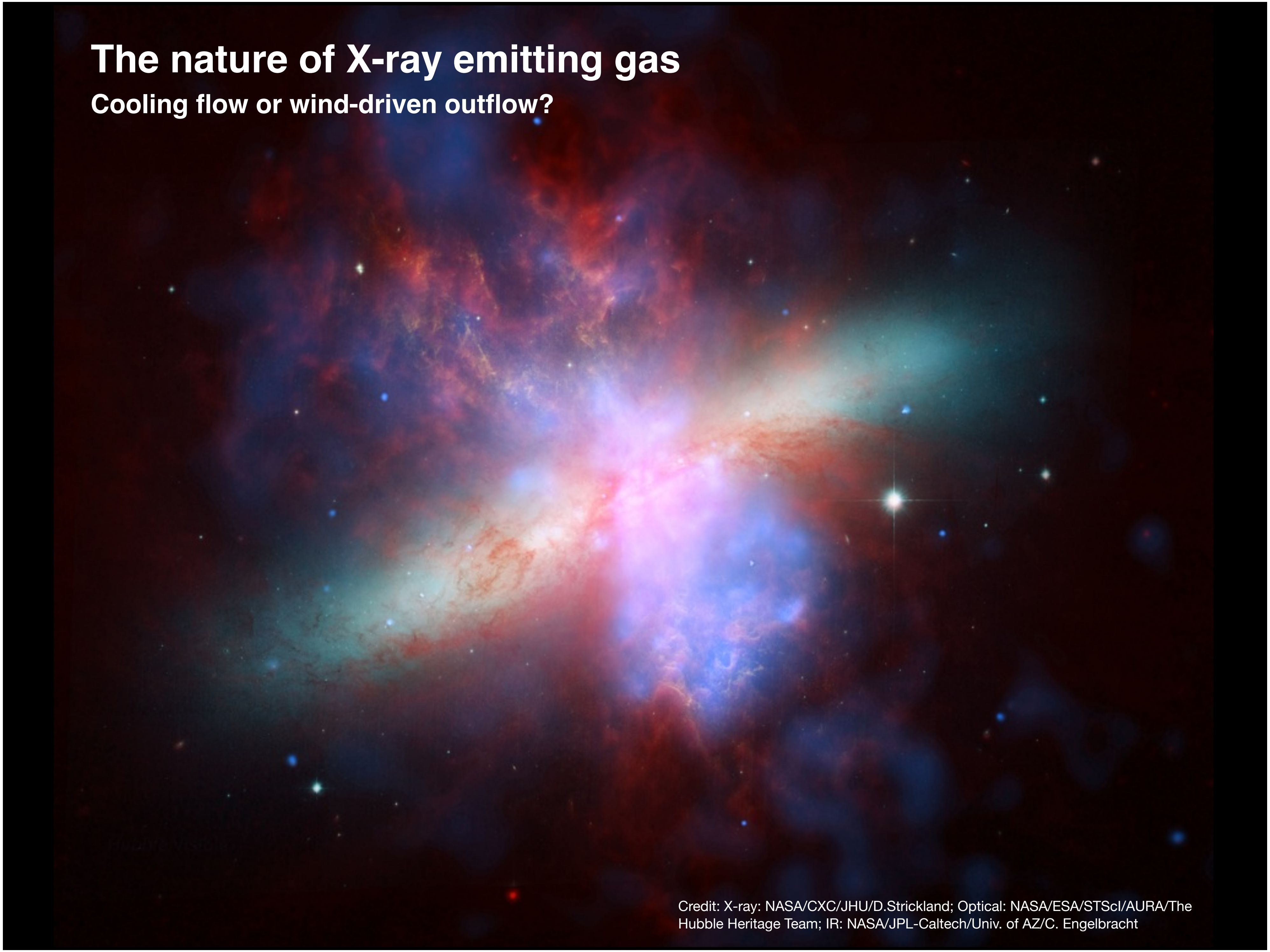
Reasons for the:

"standard explanation of the emission as a fountain or originating from within the galaxy" (Anderson & Bregman '11)

- Correlation between L_X and SFR, $\dot{M}_*$
- Correlation between L_X and stellar mass, L_K
- M82

The nature of X-ray emitting gas

Cooling flow or wind-driven outflow?

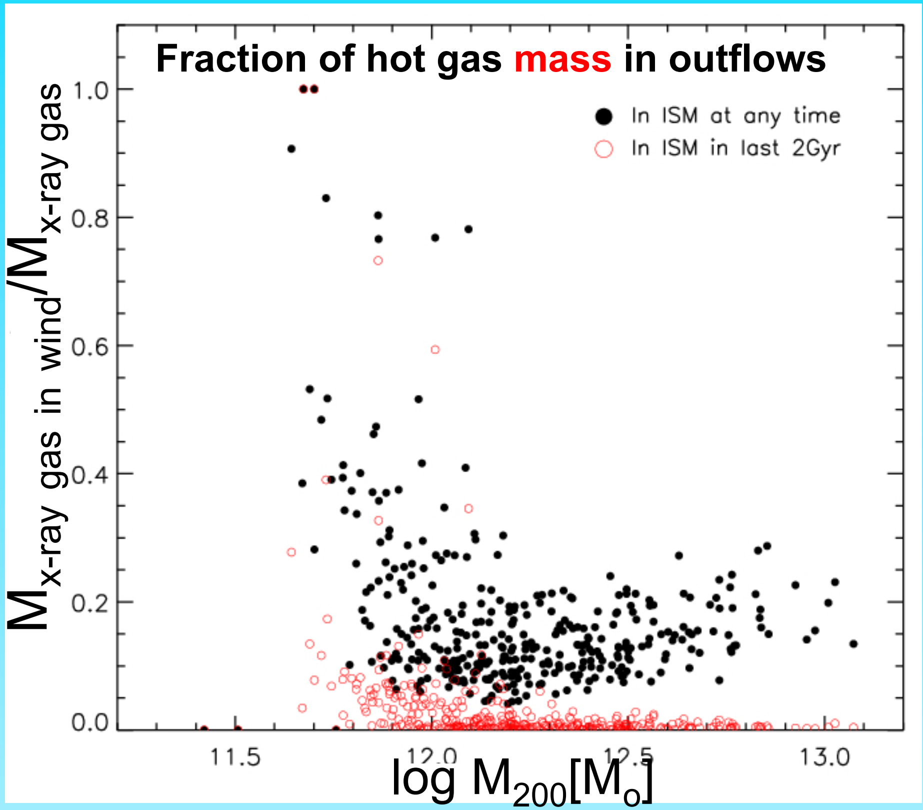


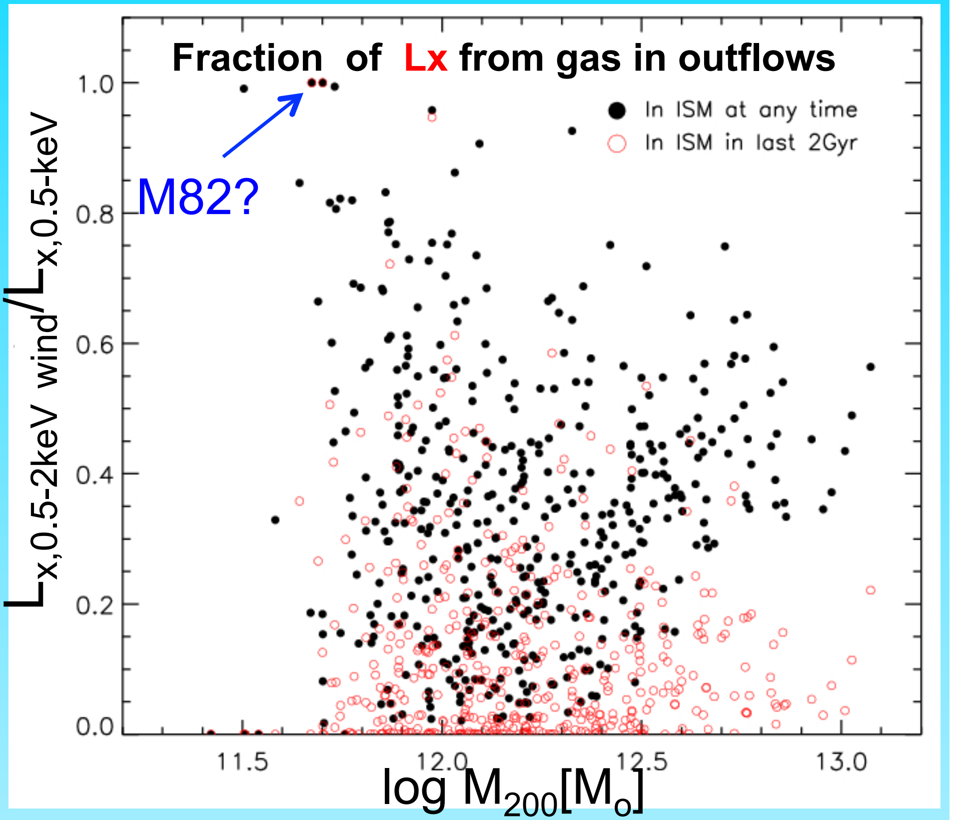
Credit: X-ray: NASA/CXC/JHU/D.Strickland; Optical: NASA/ESA/STScI/AURA/The Hubble Heritage Team; IR: NASA/JPL-Caltech/Univ. of AZ/C. Engelbracht

M82 is not a good test of WF91

University of Durham

X-rays: inflow or outflow?





- Little X-ray emiiting gas (by mass) is in outflows. Mass dominated by hydrostatic corona
- Sub-dominant outflows contribute disproportionately to L_X

X-ray flux dominated by low surface brightness cooling flow gas, but SN outflows contribute disproportionally because they come from dense, metal-rich central parts

Winds/fountains *vs* accretion

Reasons for the:

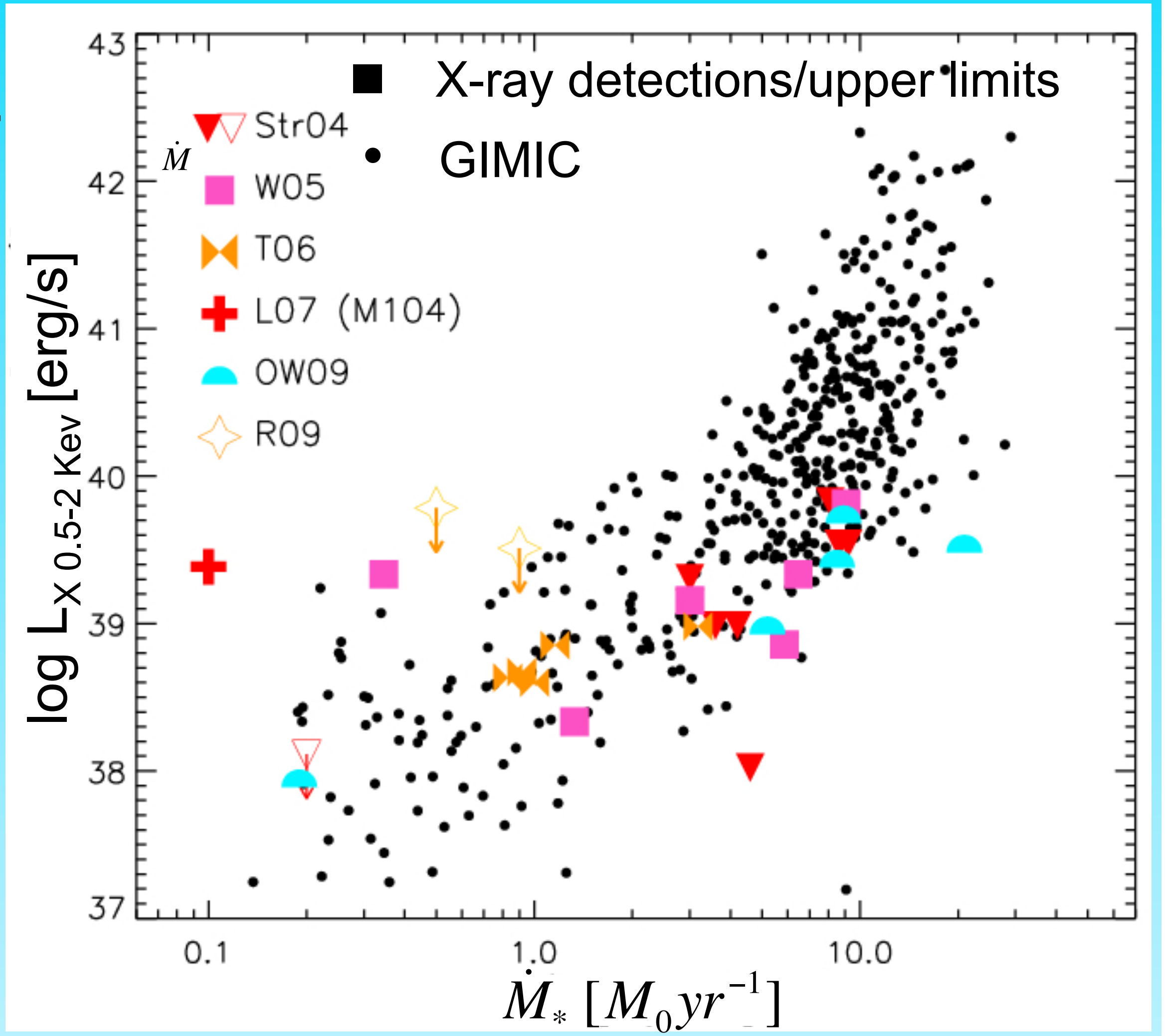
"standard explanation of the emission as a fountain or originating from within the galaxy" (Anderson & Bregman '11)

- Correlation between L_X and SFR, $\dot{M}_*$
- Correlation between L_X and stellar mass, L_K
- M82

L_X vs stellar K-band luminosity

University of Durham

- Data shows weak $L_X - \dot{M}_*$ reln.
- Simulations and data match!



Obs:: Benson+ 00, Strickland+ 04, Wang 05, Tullmann+06, Li, Wang & Hameed 07, Owen & Warwick 09, Rasmussen+ 09,Sun+09

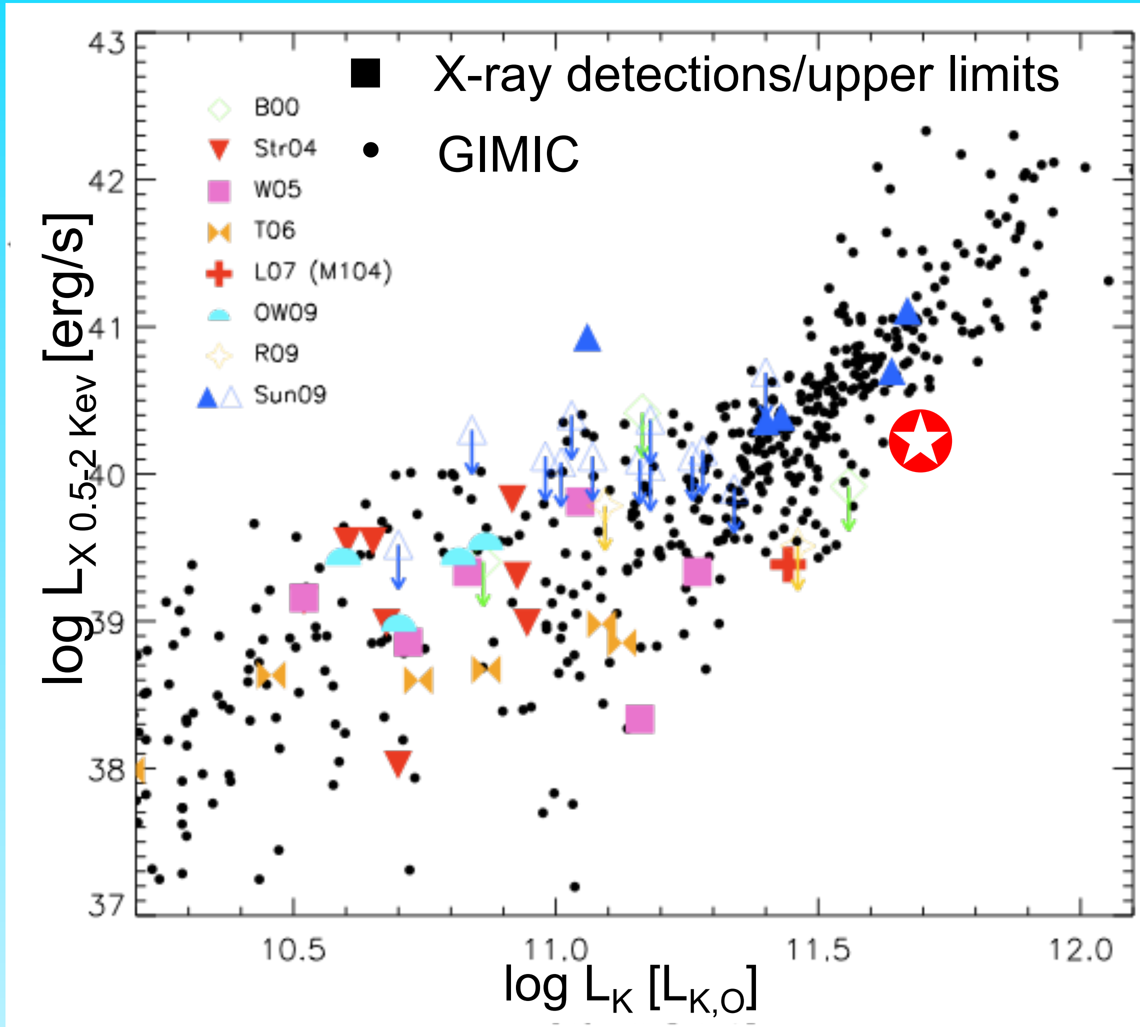
Crain, McCarthy et al. '10

Institute for Computational Cosmology

University of Durham

L_X vs stellar K-band luminosity

- L_X – L_K correlation
- Simulations and data match!
- Increased scatter at L_K<3x10L_o



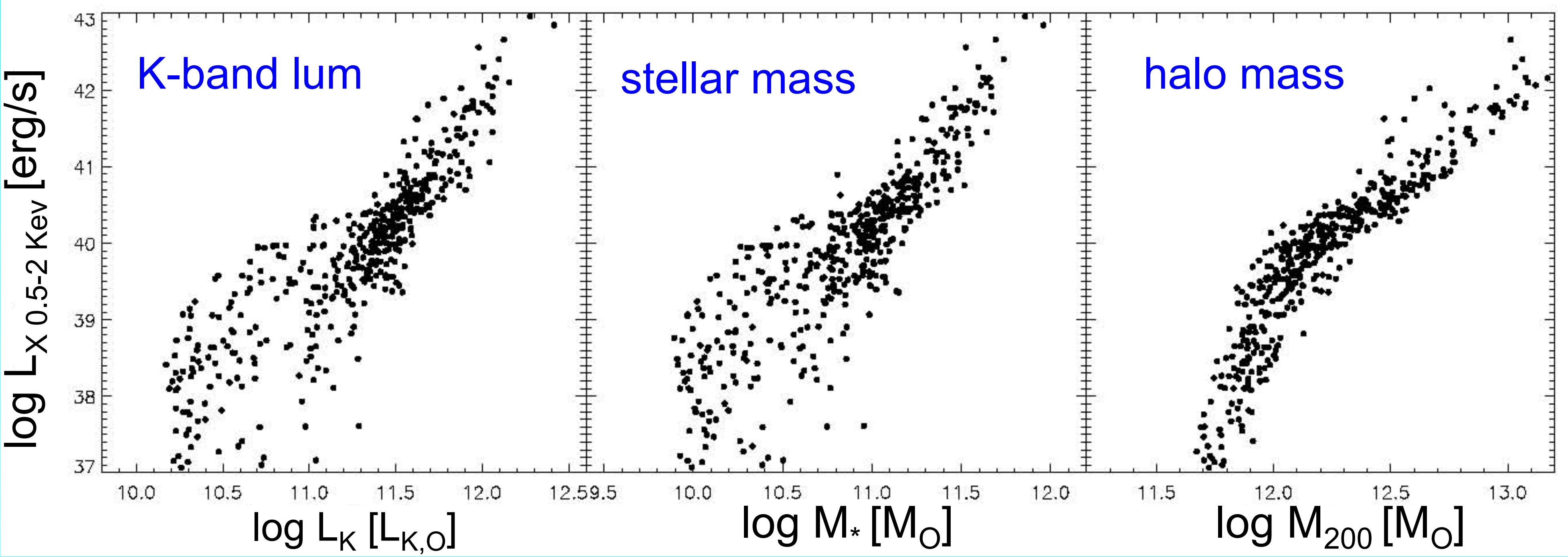
Obs:: Benson+ 00, Strickland+ 04, Wang 05, Tullmann+06, Li, Wang & Hameed 07, Owen & Warwick 09, Rasmussen+ 09,Sun+09

Crain, McCarthy et al. '10

Institute for Computational Cosmology

L_X vs stellar K-band luminosity

University of Durham



L_X, $\dot{M}_*$, M_*, L_K all depend on M_{200}!

… and this is why L_X correlates with $\dot{M}_*$, L_K, etc

University of Durham

A problem for CDM galaxy formation theory!

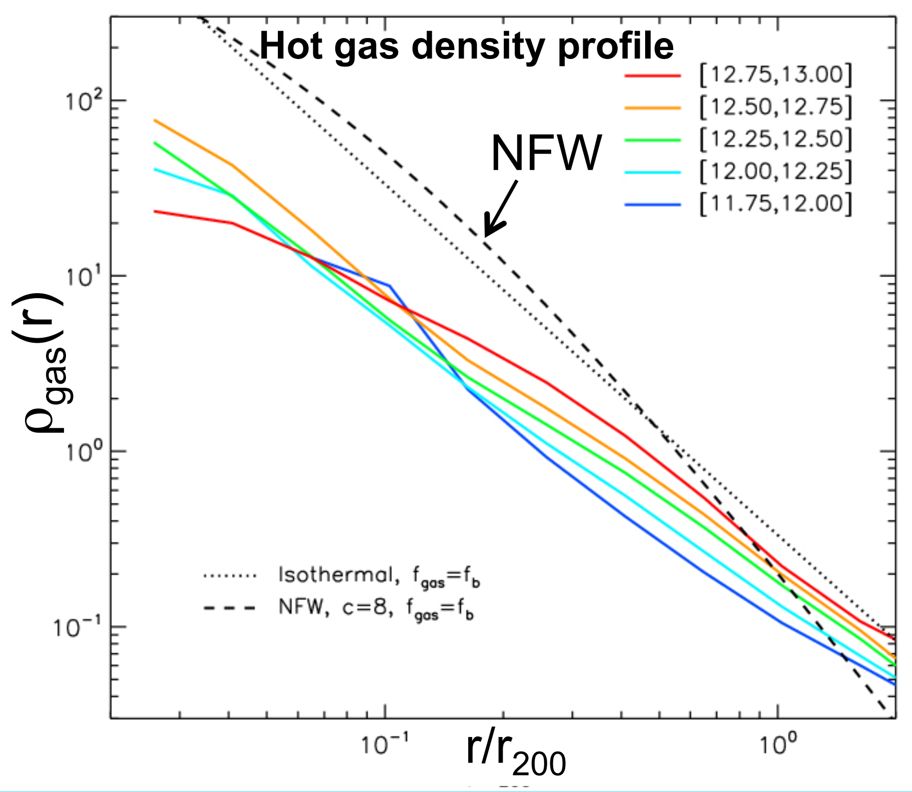
XMM/Chandra → several detections of X-rays from halos of spirals

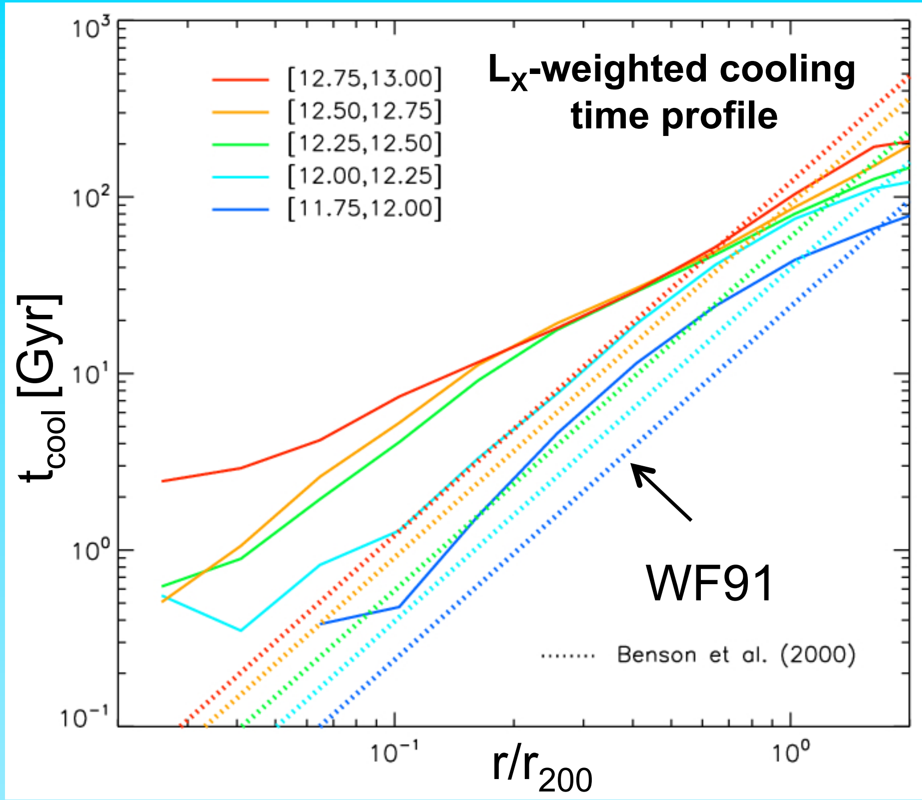
… but L_X is (10-100) x below theoretical predictions

Where did WF91 go wrong?

University of Durham

The state of halo gas





Cooling/star formation & SN feedback reduce the central density of hot gas. Entropy injection increases t_{cool} w.r.t. analytic model.

Suppression of L_X by x(10-100) relative to WF'91

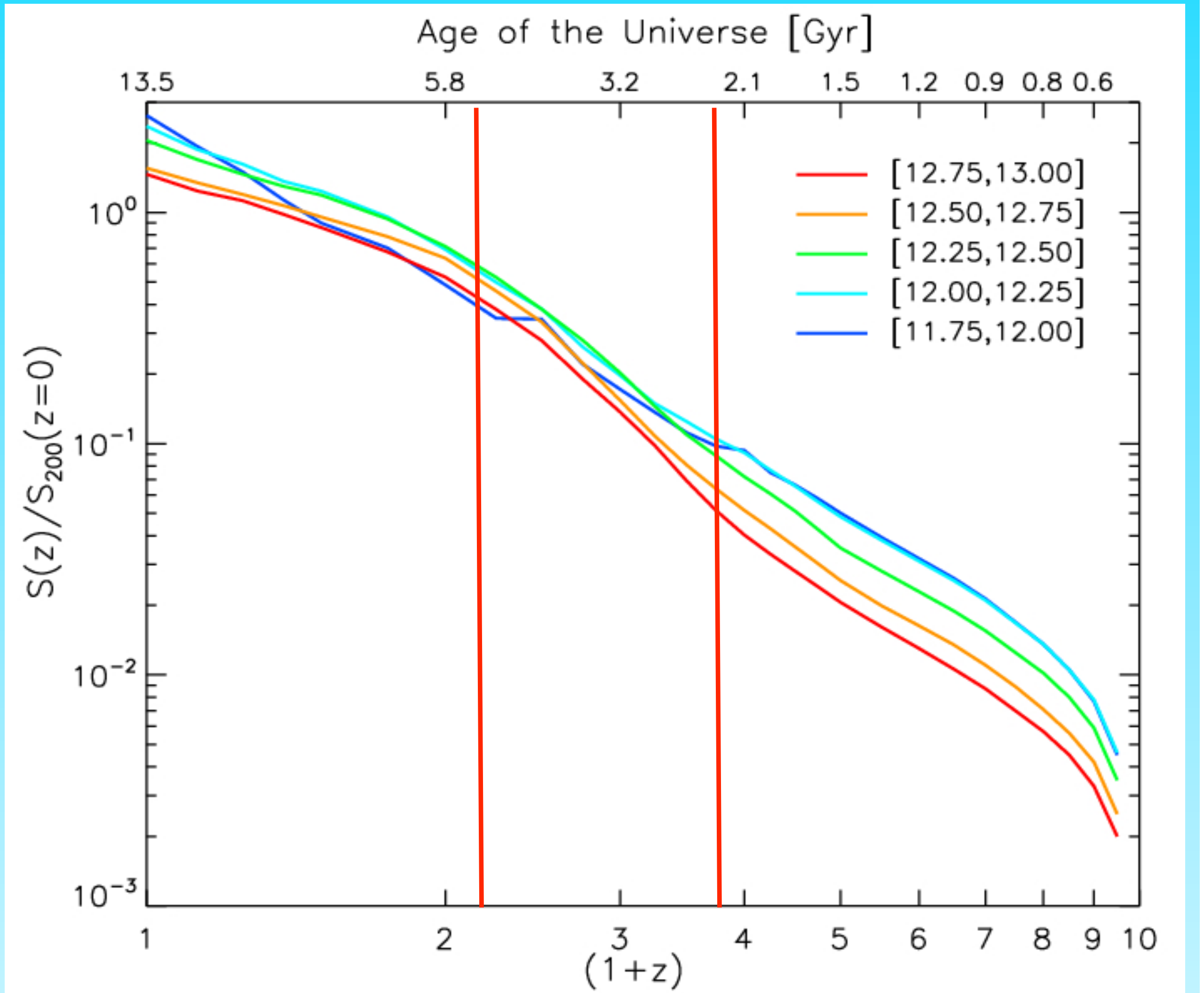
Institute for Computational Cosmology

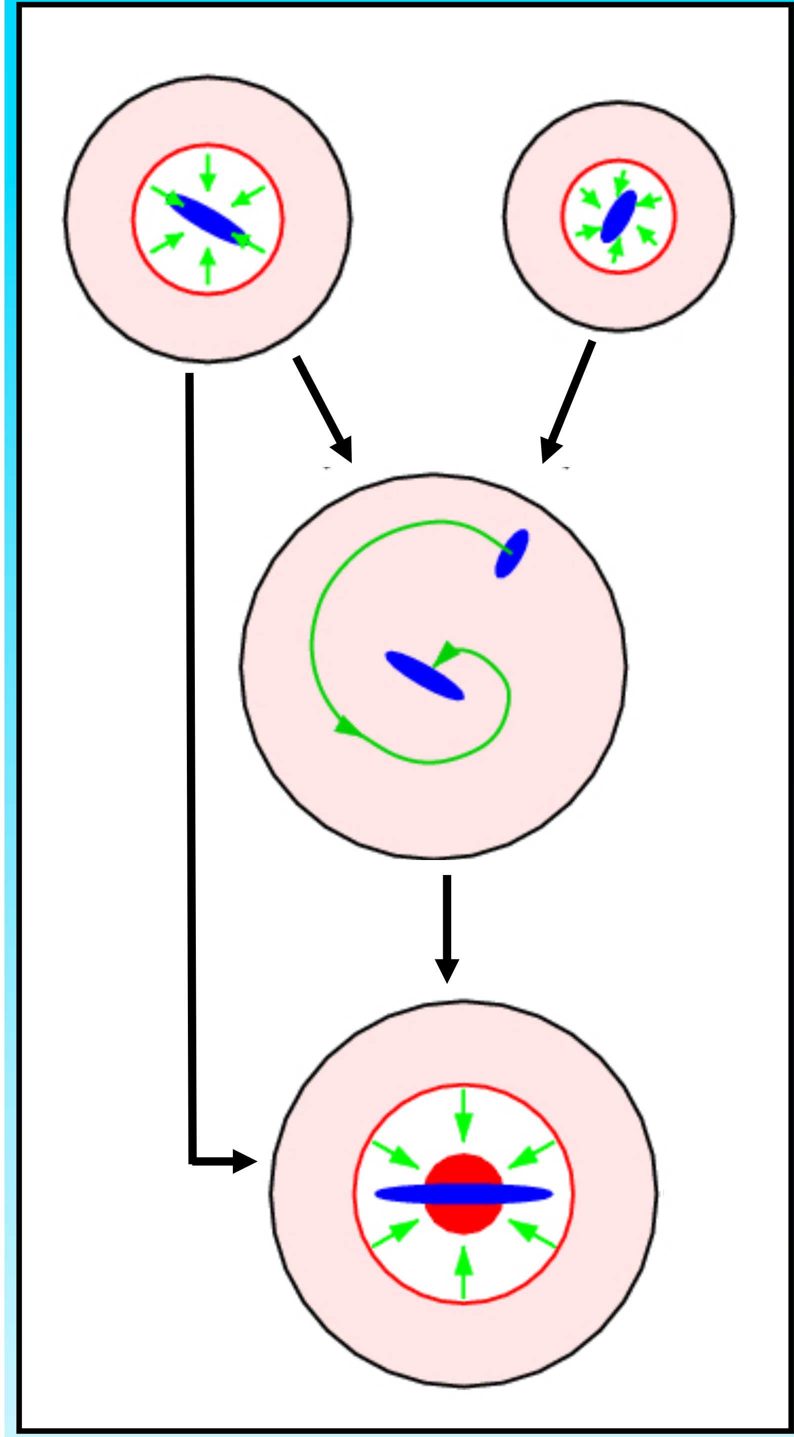
The evolution of halo gas

University of Durham

Entropy evolution

Rapid entropy injection at z~1-3, during peak of star formation





Galaxy formation: the basics

- Infalling gas shock-heated to T_{vir}
- Gas cools radiatively onto central galaxy and forms disk, conserving J

  → $r_{disk} \sim \lambda_h r_{cool}$
- Stars form in disk
- And give rise to feedback effects
- Satellite sinks by dynamical friction and merges onto central galaxy
- Mergers trigger central starburst
- In major mergers, stellar disks → spheroids
- New disk may form by gas accretion

X-rays for galaxy halos: spirals

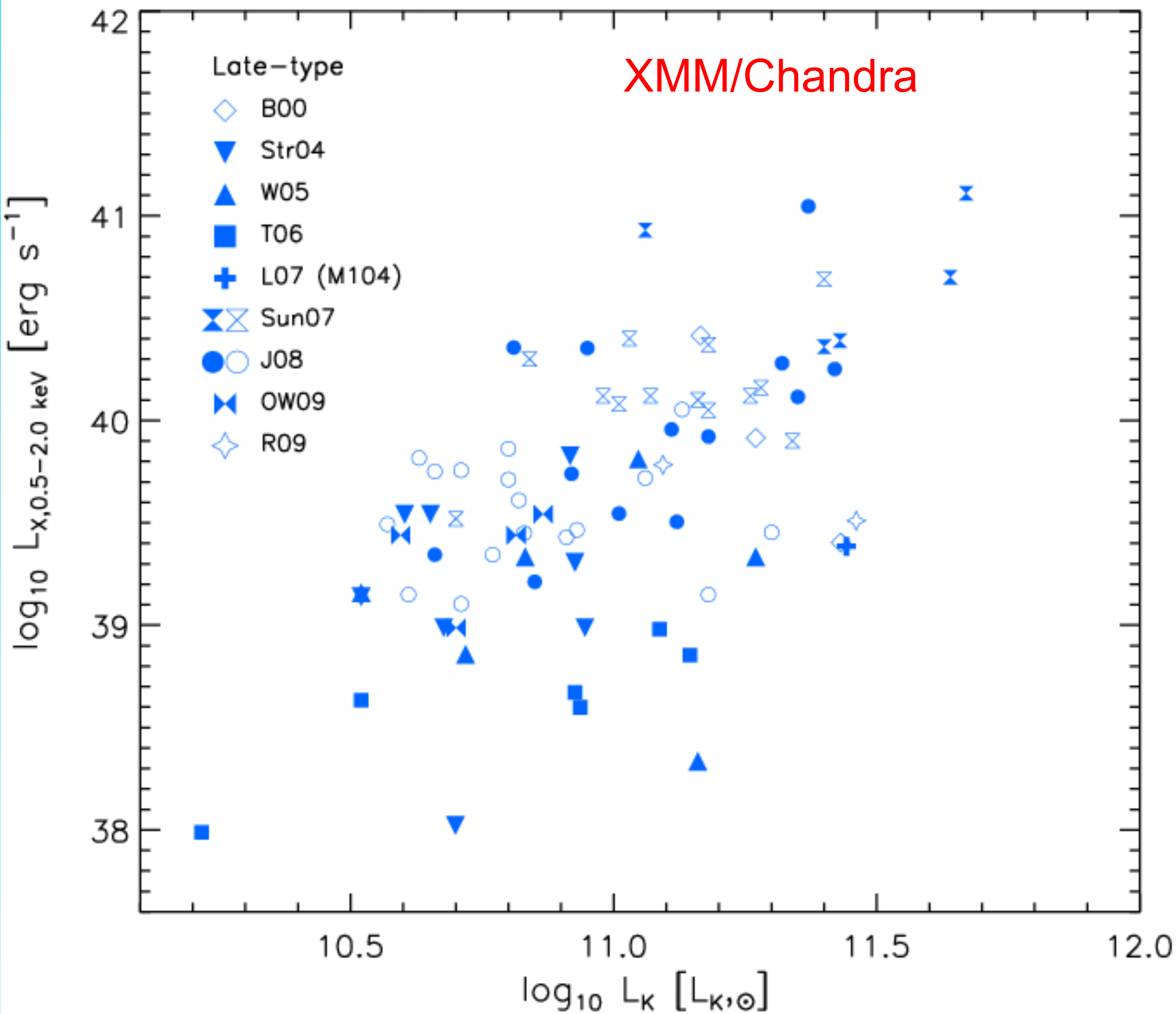
University of Durham

XMM/Chandra

Spirals

$L_{X(0.5\text{-}2KeV)}$ *vs* L_K

(exc binaries)



X-rays for galaxy halos: ellipticals

University of Durham

XMM/Chandra

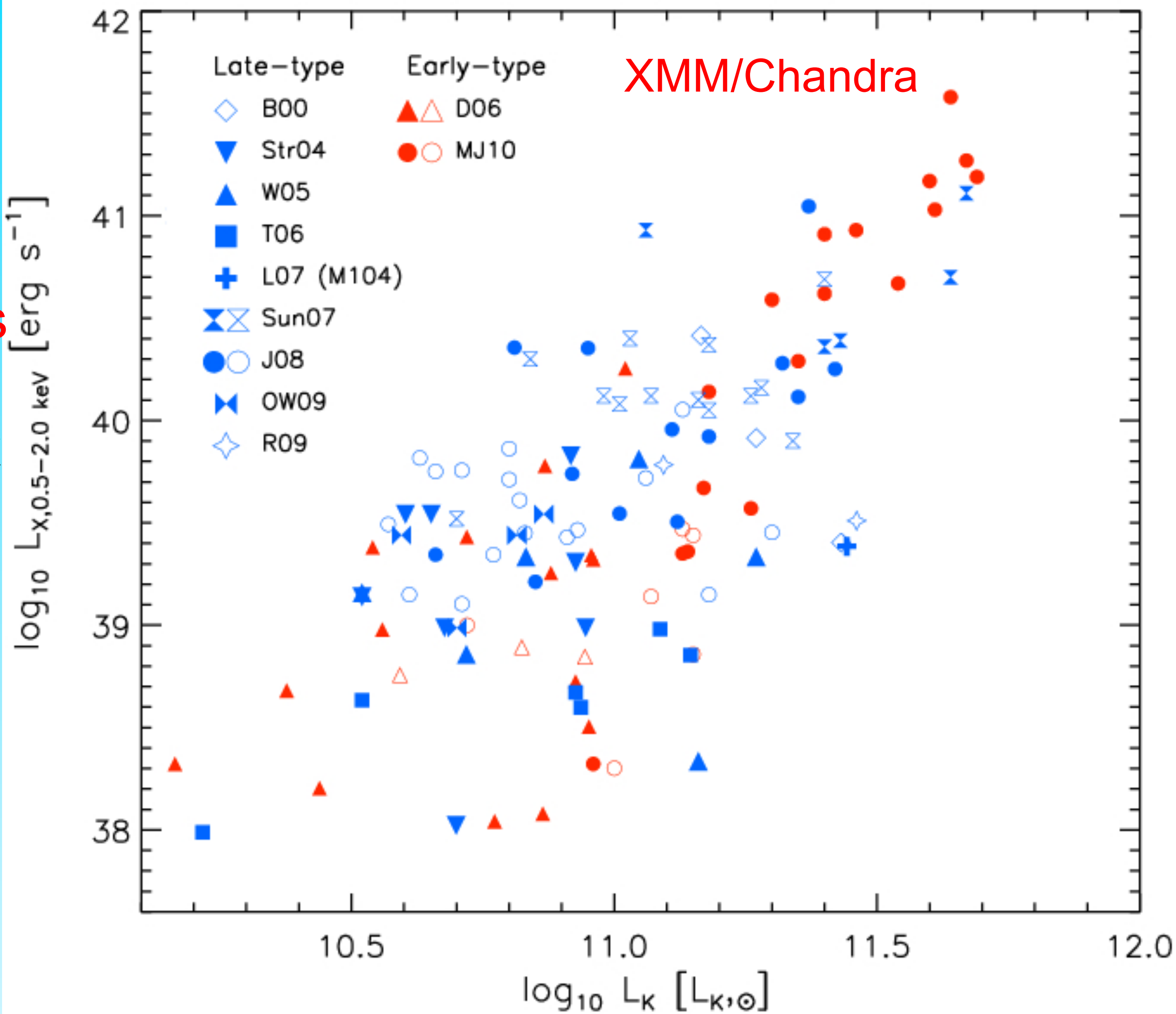
Spirals / Ellipticals

$L_{X(0.5\text{-}2KeV)}$ *vs* L_K

(exc binaries)

Same location!

Same physics?



X-rays for galaxy halos: ellipticals

University of Durham

XMM/Chandra

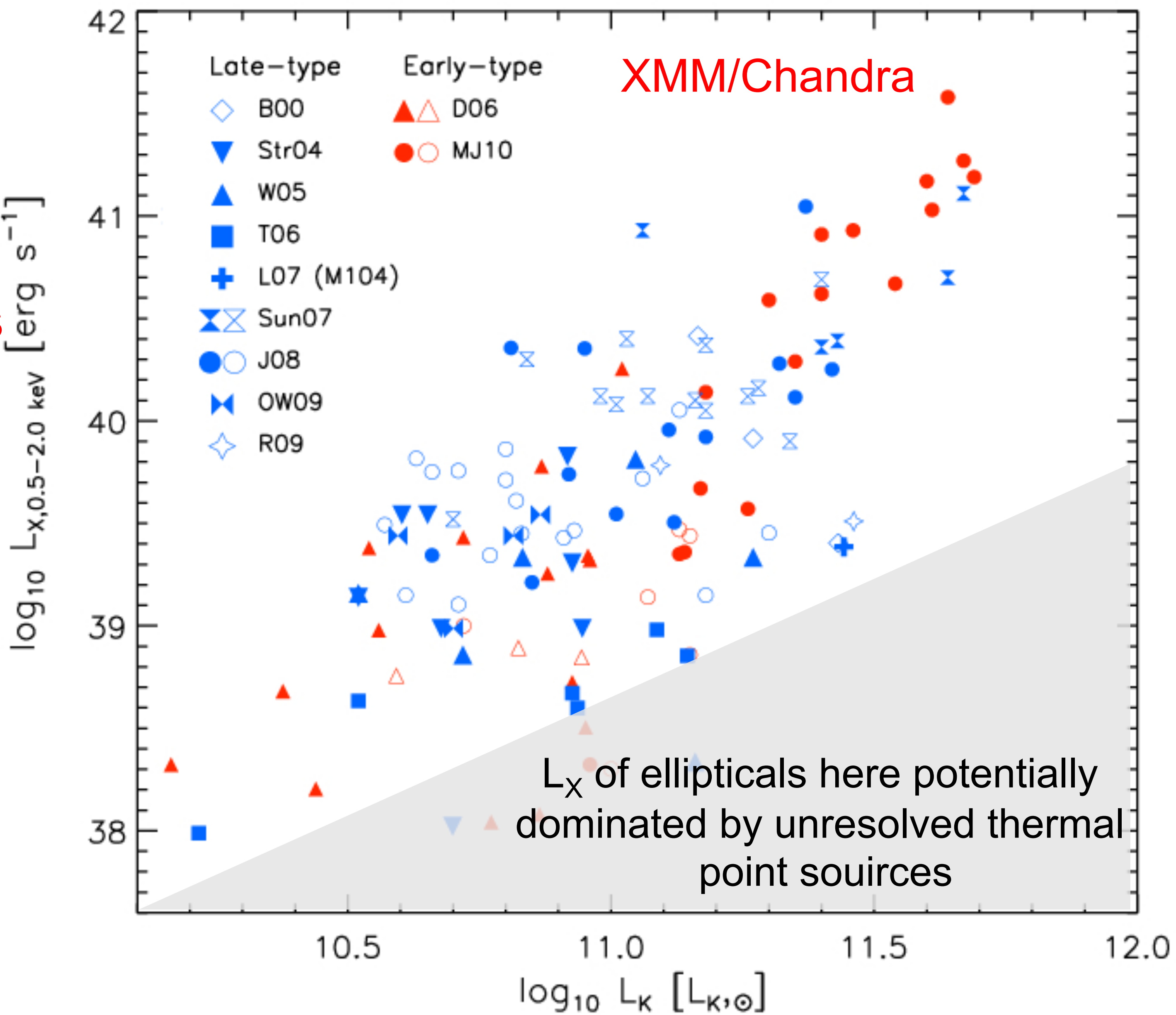
Spirals / Ellipticals

$L_{X(0.5\text{-}2KeV)}$ *vs* $\overline{L_K}$

(exc binaries)

Same location!

Same physics?



X-rays for galaxy halos: S+E

University of Durham

XMM/Chandra

and

GIMIC

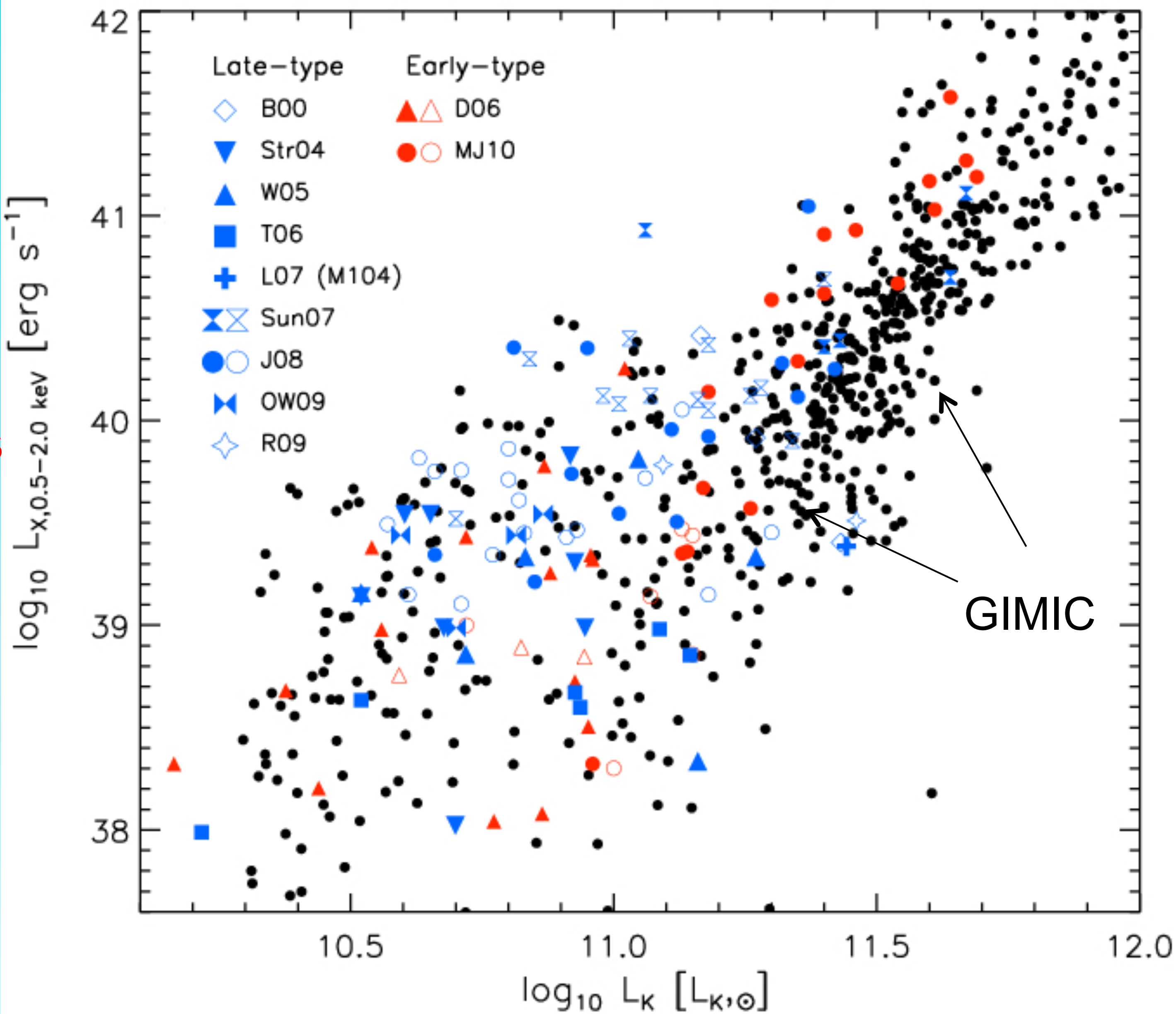
Spirals / Ellipticals

$L_{X(0.5\text{-}2KeV)}$ *vs* L_K

Same location!

Same physics?

Emission from hot corona!



X-rays: from galaxies to clusters

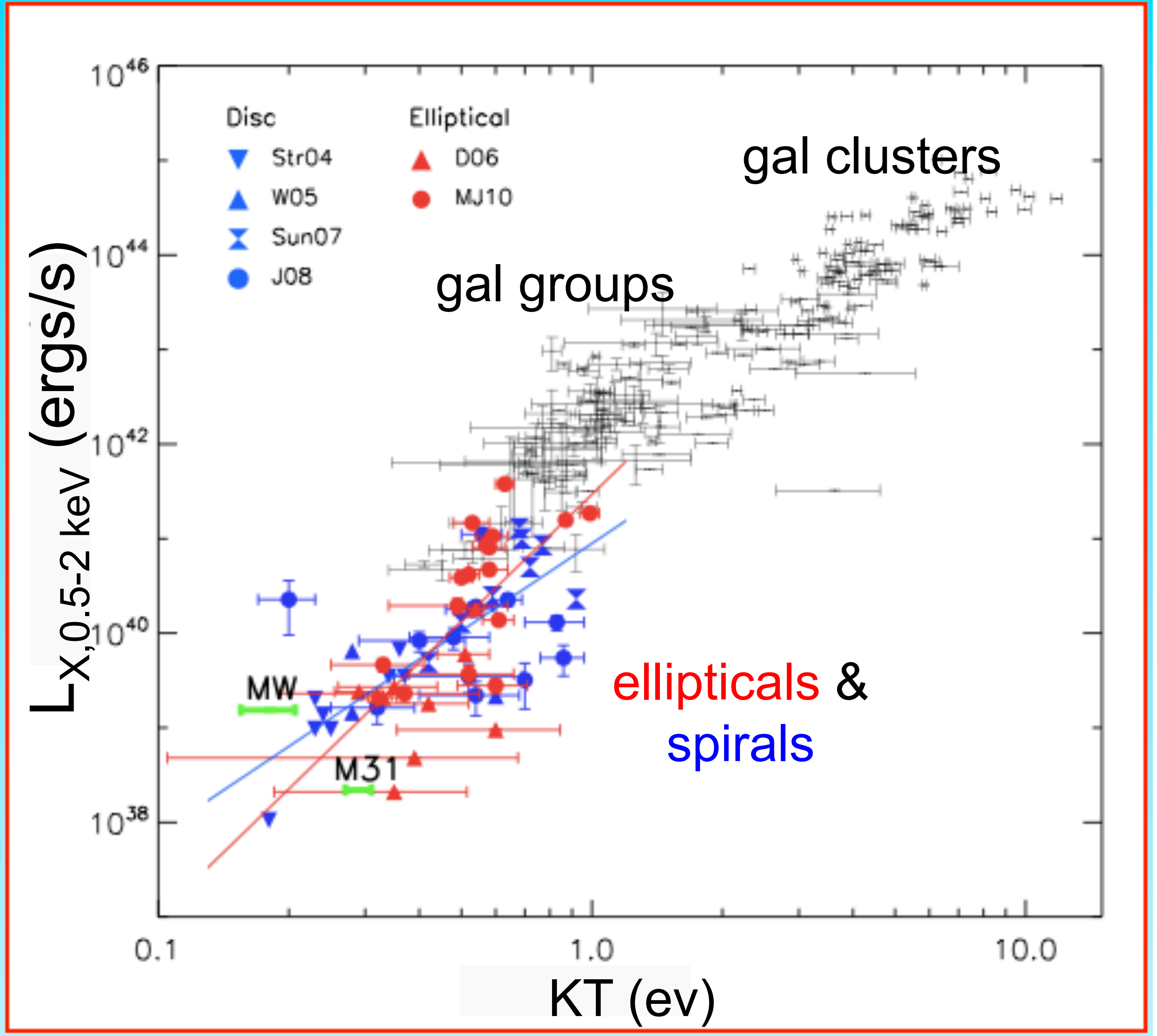
University of Durham

Clusters, groups, spirals, ellipticals all lie on a single L_X-T_X relation!

Over 5 decades in L_X

→ Same physics?

Break may be due to transition from baryonically closed to baryonically open halos



McCarthy et al ‘11

Institute for Computational Cosmology

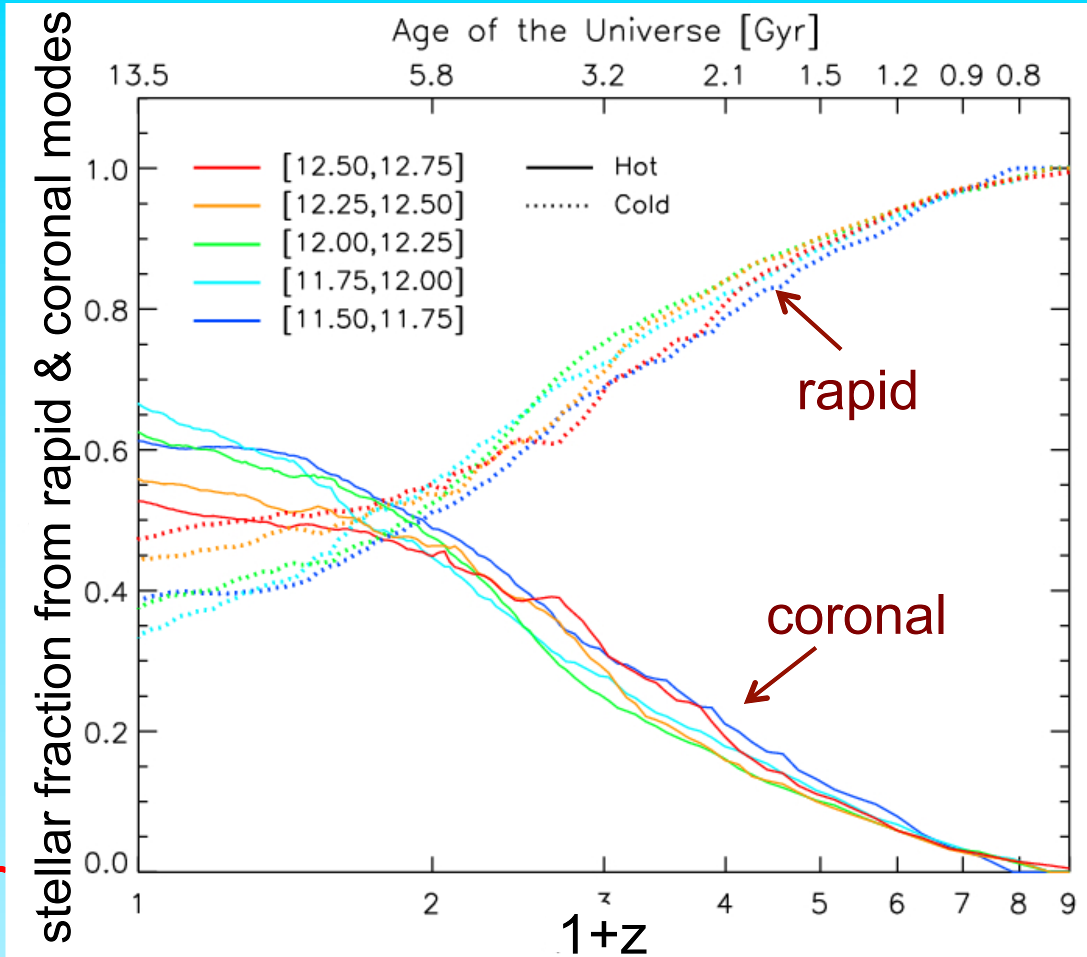
What fuels star formation in disks?

University of Durham

Distinguish gas accreted with short and long t_{cool} as:

- "Rapid mode": $T_{max} > 10^5$K
- "Coronal mode": $T_{max} < 10^5$K

- Rapid mode dominates z<1
- For $M_{halo} \sim 10^{12}$Mo, 2/3 of star formed from coronal mode



Crain, McCarthy, Frenk et al. '10

Institute for Computational Cosmology

University of Durham

Conclusions

- Hot X-ray emitting halos: key prediction of CDM gal. form. theory
- Observed halos around spirals: (10-100)x fainter than predicted
- GIMC simulations give low L_X in agreement with obs because:
  - Baryon content reduced by star formation and winds
  - Gas much less concentrated than DM due to SN feedback (entropy raised at z~1-3)
- X-rays dominated by cooling from hot quasistatic corona
- < 30% of X-rays come from winds (which are disproportionally bright)
- Sims agree with obs. scaling relns: $L_X - v_{rot}$, $L_X - L_K$, $L_X - \dot{M}_*$
- Ellipticals have similar X-ray properties to spirals
- Spirals & ellipticals follow same $L_X - T_X$ rel. as groups & clusters

The baryon content of gal halos

University of Durham

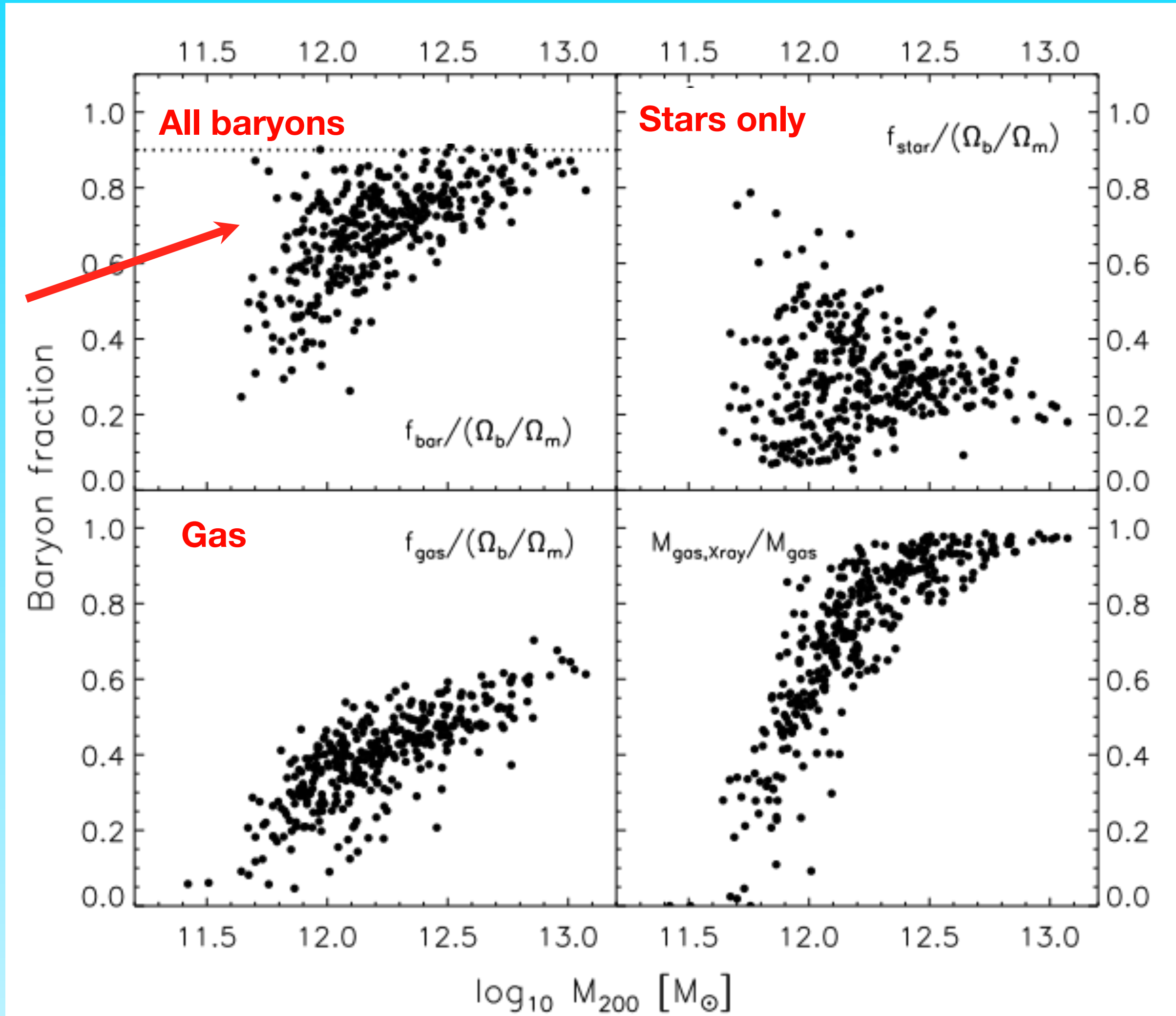
ICC

Baryon fractions

Suppressed below 90% of cosmic by SF & winds

For $M_{halo} < 10^{12}\ M_o$
f_b~0.5 of cosmic

→ Low f_b contributes to low L_X



Crain, McCarthy et al. '10