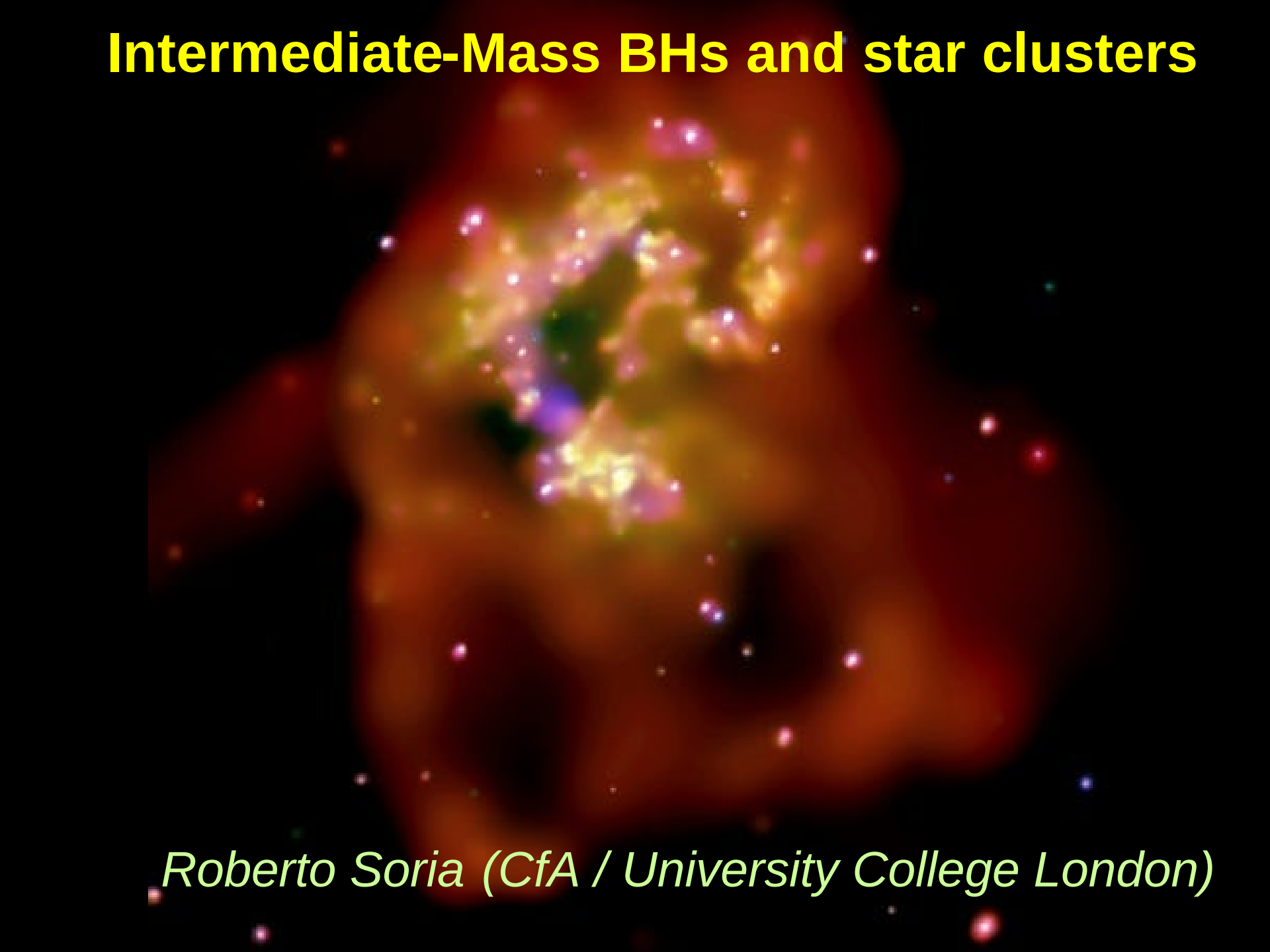
Intermediate-Mass BHs and star clusters



Roberto Soria (CfA / University College London)

Outline of this talk

Ultraluminous X-ray sources = accreting IMBHs?

What is the mass of the accreting BHs in ULXs?

From: luminosity
X-ray colors
other arguments

Star clusters/ULX associations?

Survival or dispersion of protoclusters

Implications for SMBH growth at high z

Seed IMBHs from early nuclear starburst or from mergers?

How to estimate the BH mass?

(Apparent isotropic) **Luminosity**

Mass inferred from the Eddington limit

(Model-fitted) **X-ray spectrum**

Mass inferred from the inner-disk temperature

X-ray timing (breaks, QPOs)

Mass inferred from the characteristic variability timescale
(only 2 or 3 ULXs have characteristic timescale)

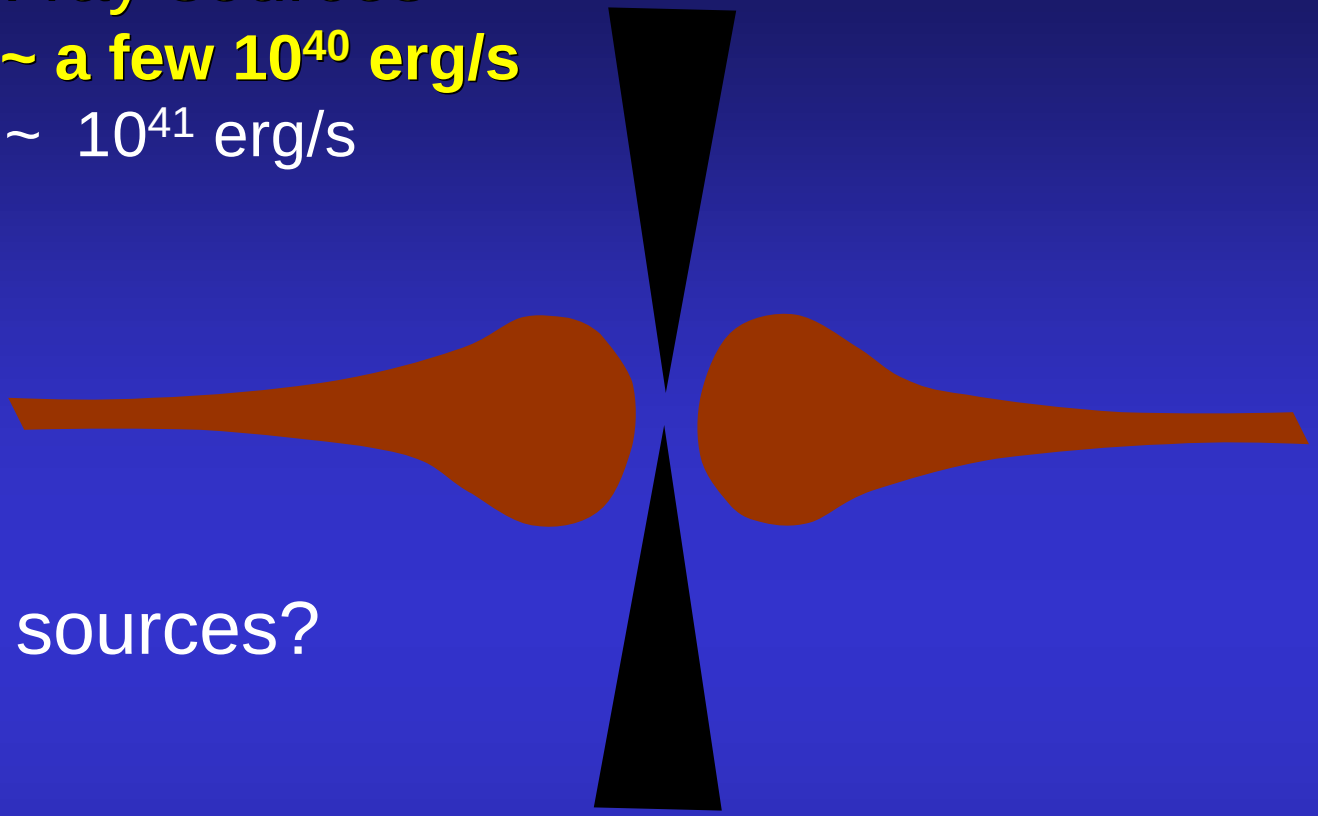
Optical spectroscopy (line profiles and shifts)

Direct measurement of the mass function and orbital parameters

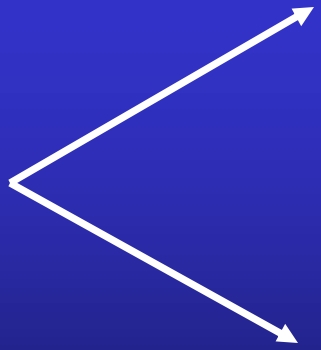
Ultraluminous X-ray sources

(isotropic) **L_x up to ~ a few 10^{40} erg/s**

(isotropic) L_{bol} up to ~ 10^{41} erg/s



beamed sources?



IMBHs with masses up to ~ a few 100 M_{sun} ?

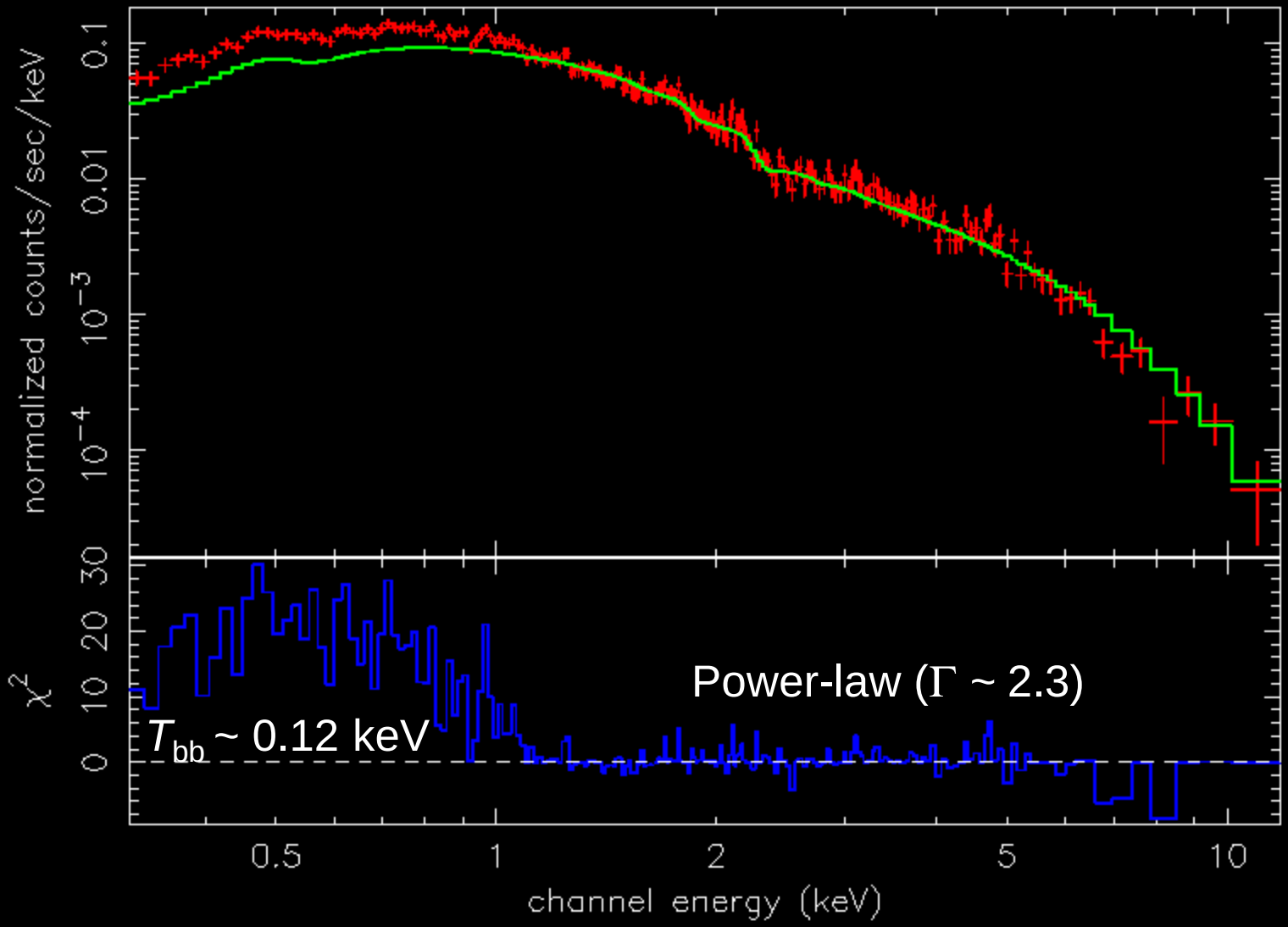
Eddington limit: $L = 1.3\ 10^{38}\ (M/M_{sun})$ erg/s

X-ray-spectrum argument for IMBHs

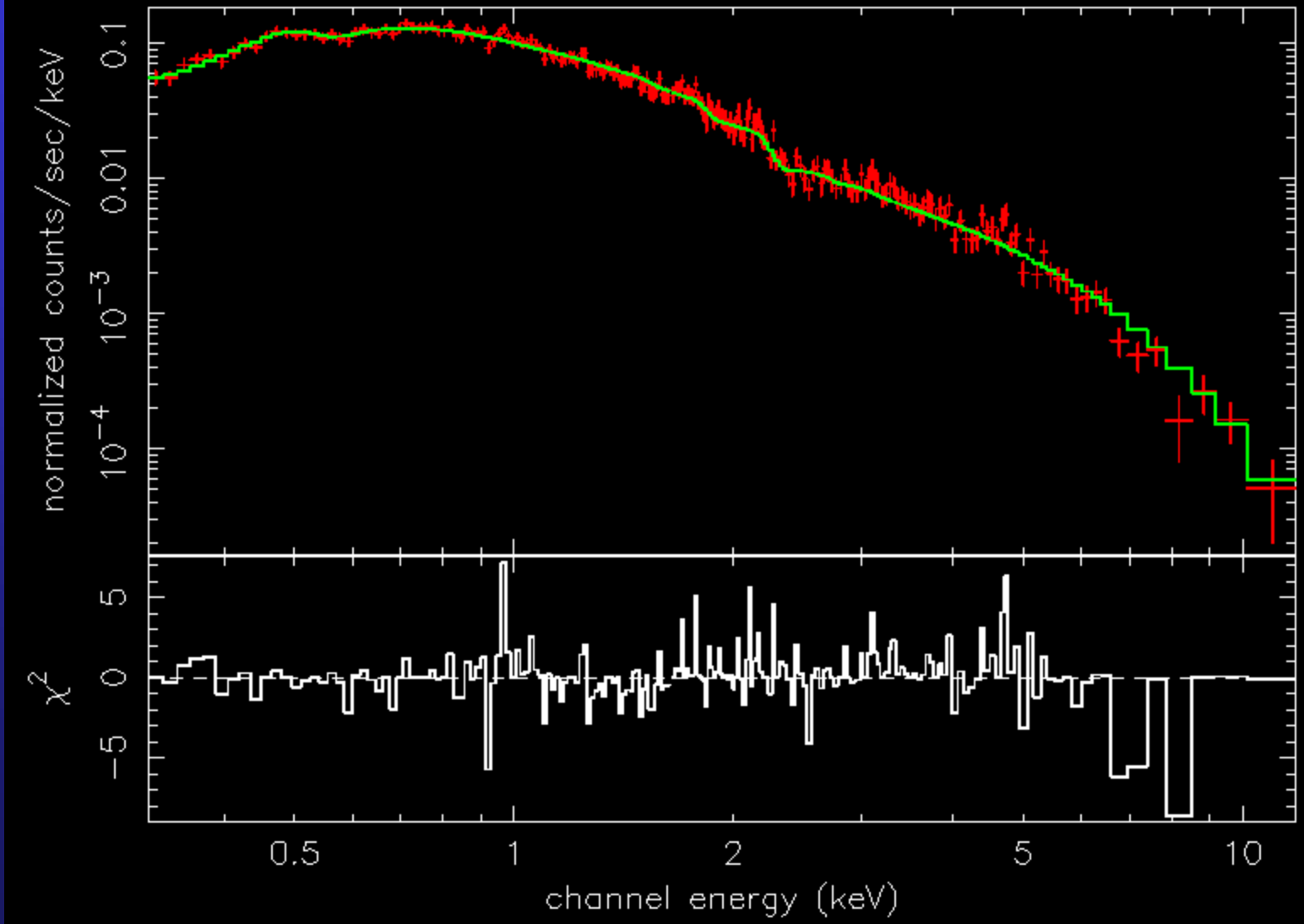
Standard, optically thick disk model:
for $L \sim L_{\mathrm{Edd}}$, $T_{in} \sim M^{-1/4}$

From *XMM* and *Chandra* observations:
$T_{in} \sim 0.1$—0.2 keV $\longrightarrow$ $M \sim 10^3$ --10^4 M_{sun}

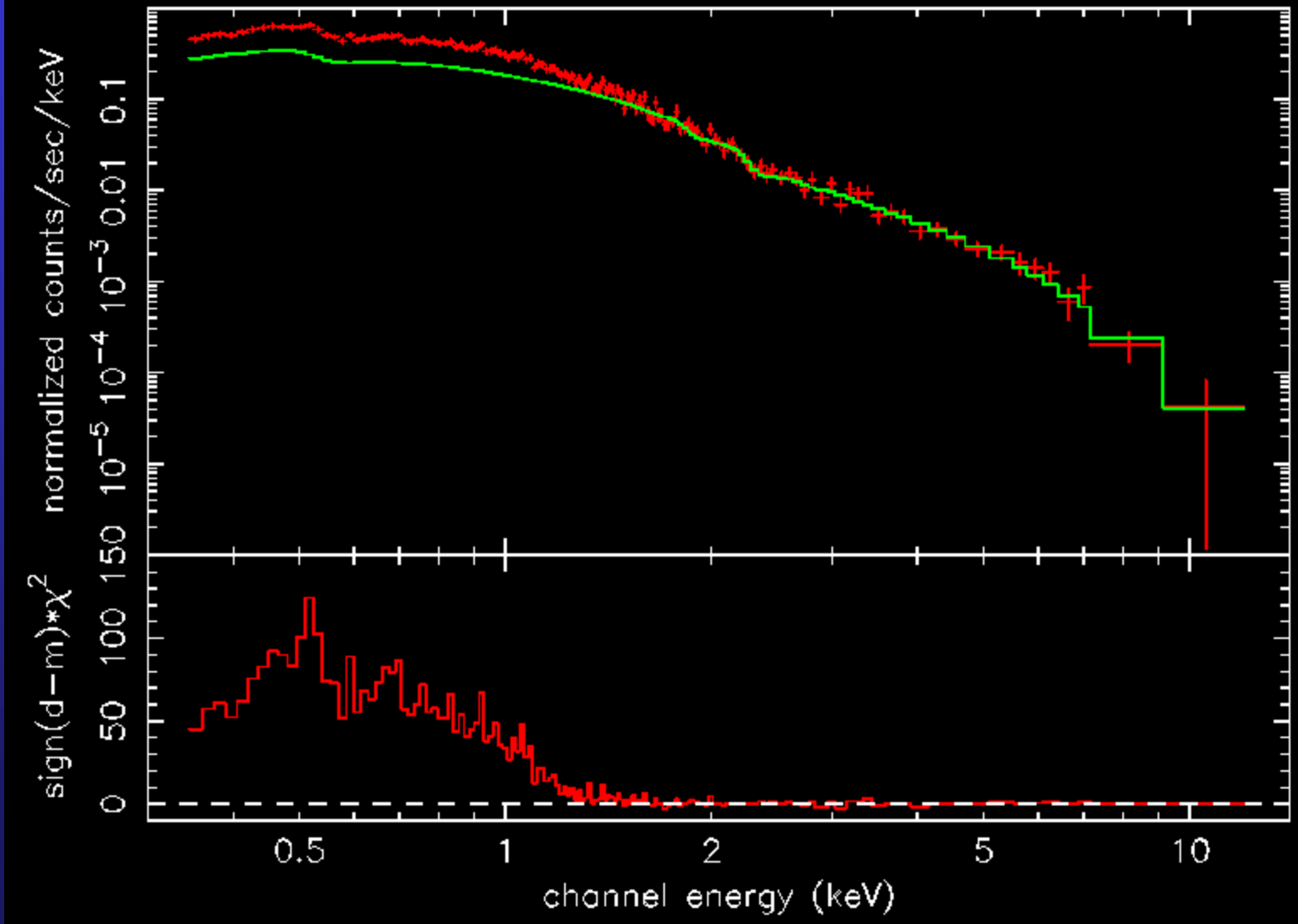
X-ray spectrum of NGC4559 X7 (*XMM*)



X-ray spectrum of NGC4559 X7 (*XMM*)

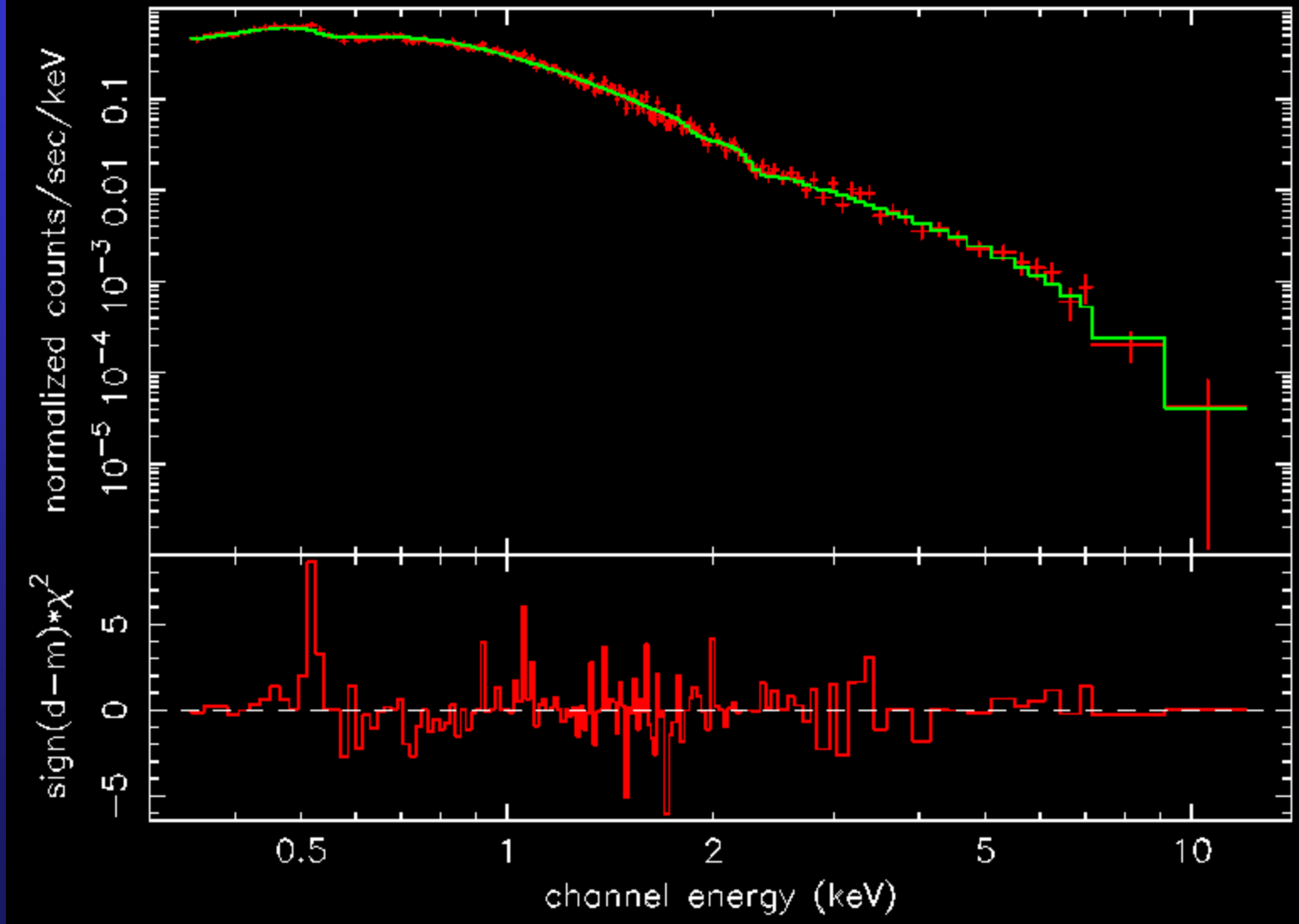


NGC5408 X-1

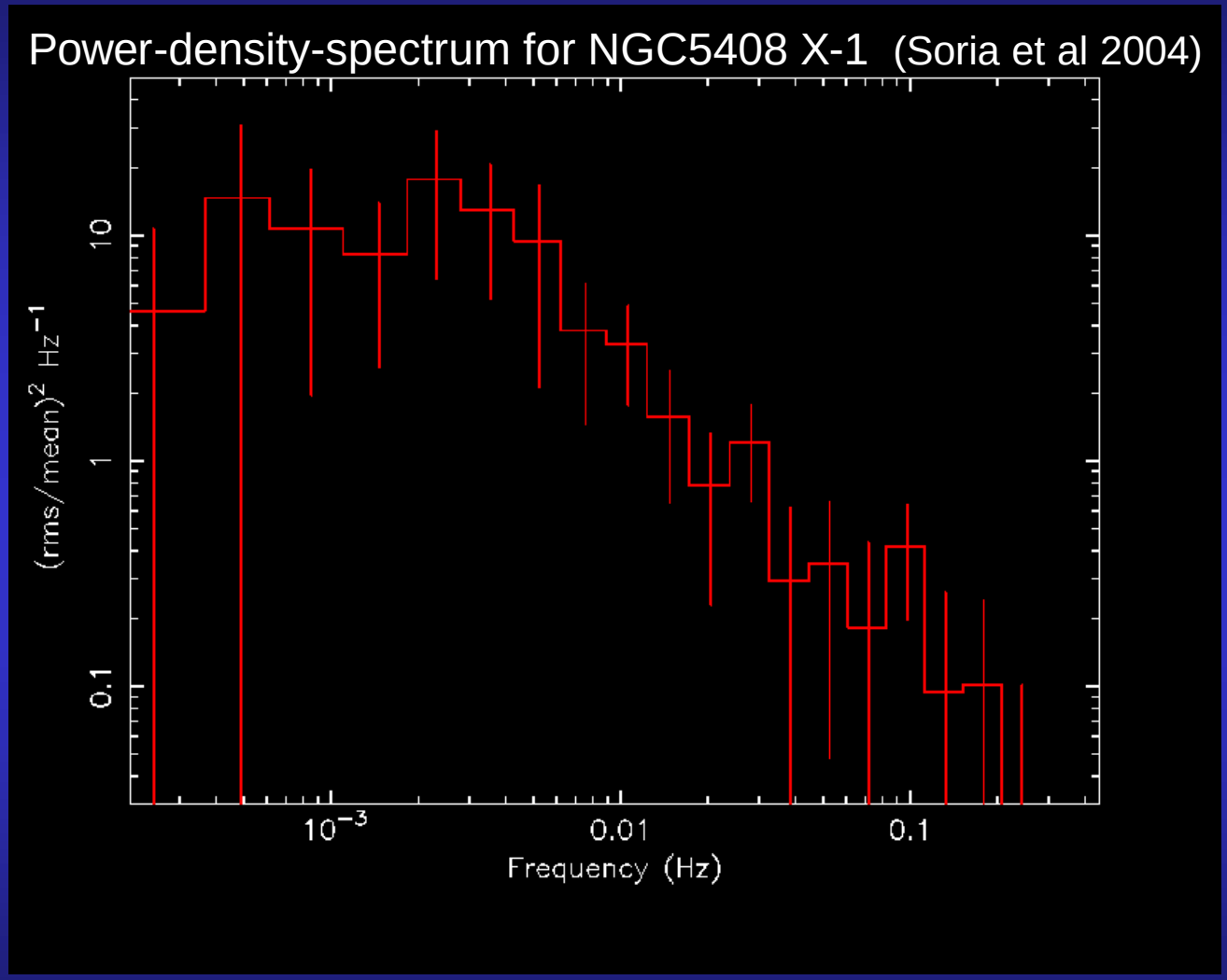

normalized counts/sec/keV
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
150
100
50
0
sign(d−m)*χ^2
0.5
1
2
5
10
channel energy (keV)

NGC5408 X-1

T_{bb} ~ 0.12 keV



X-ray-timing argument for IMBHs



Break frequency ~ $\nu_L^{1.65}$, $\nu_L \sim 1/M$ *(Titarchuk & Fiorito 2005)*

What is an “intermediate mass” BH?

Luminosity argument suggests

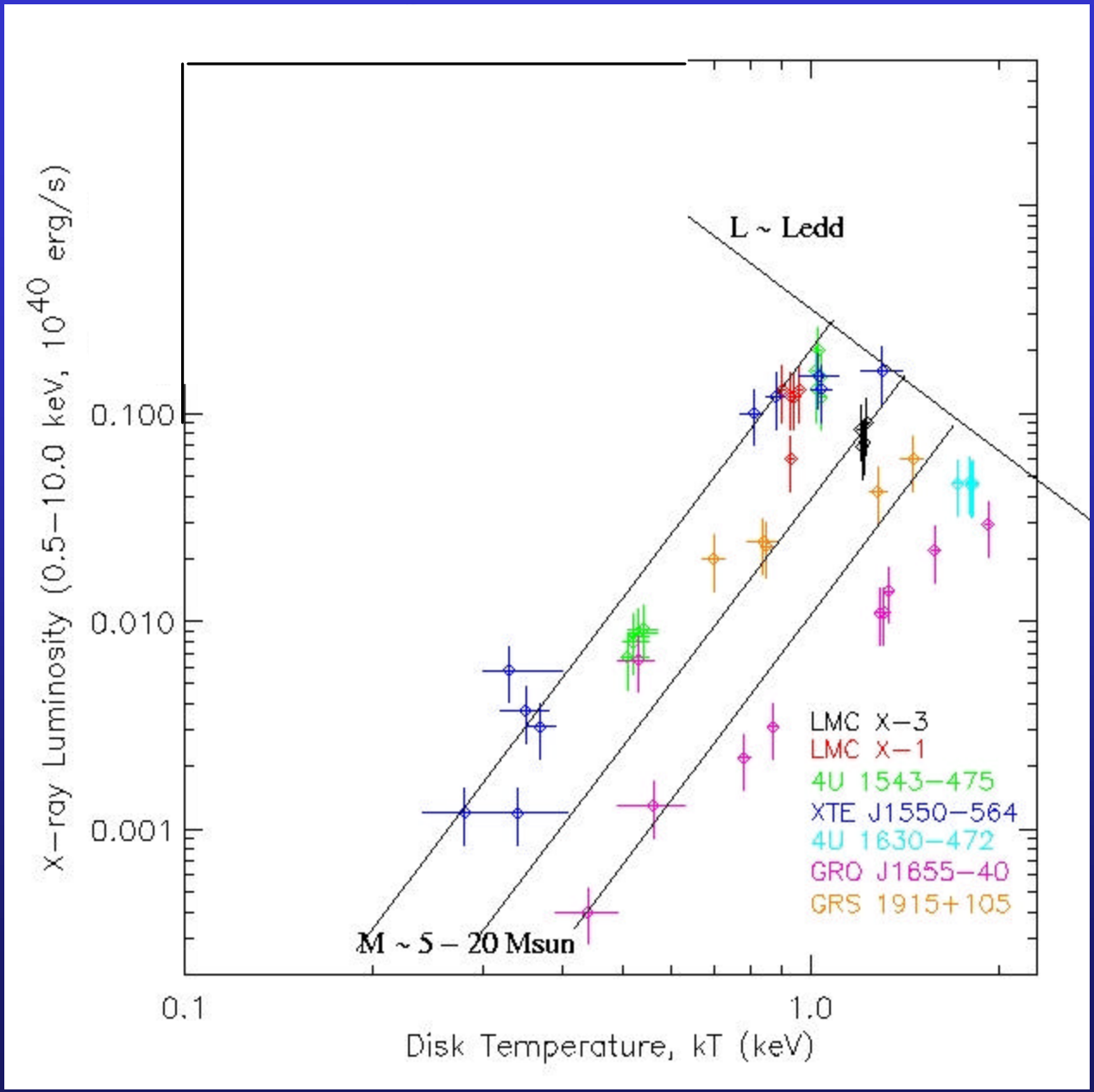
$M \sim 100\ M_{sun}$ *at* $L \sim L_{\mathrm{Edd}}$

Spectral argument suggests

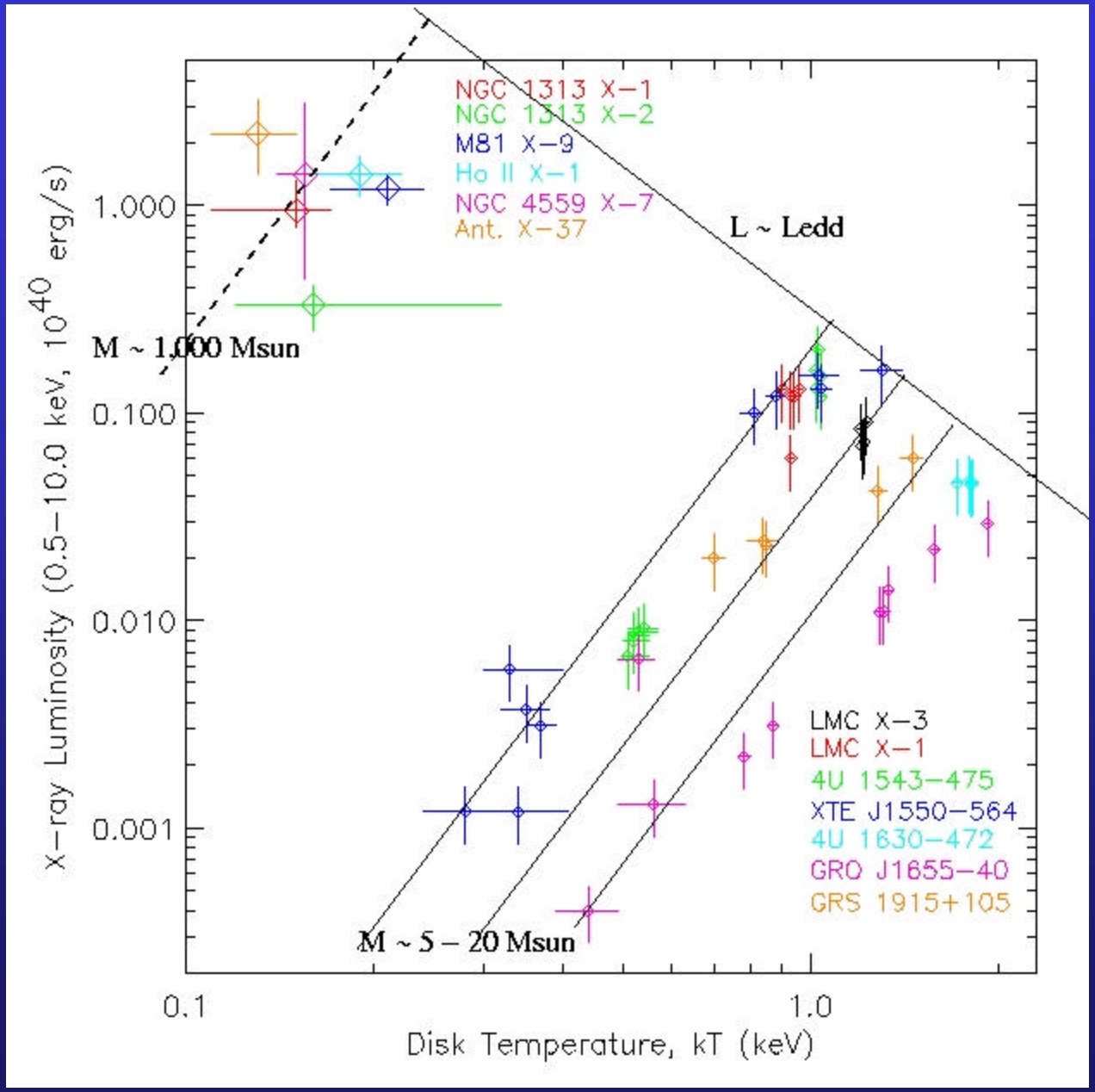
$M \sim 10^3$ --$10^4\ M_{sun}$ *at* $L \sim 0.1$—$0.01\ L_{\mathrm{Edd}}$

Are they consistent

- with each other?
- with *M* and *L* in stellar-mass BH?



(adapted from Miller et al 04)



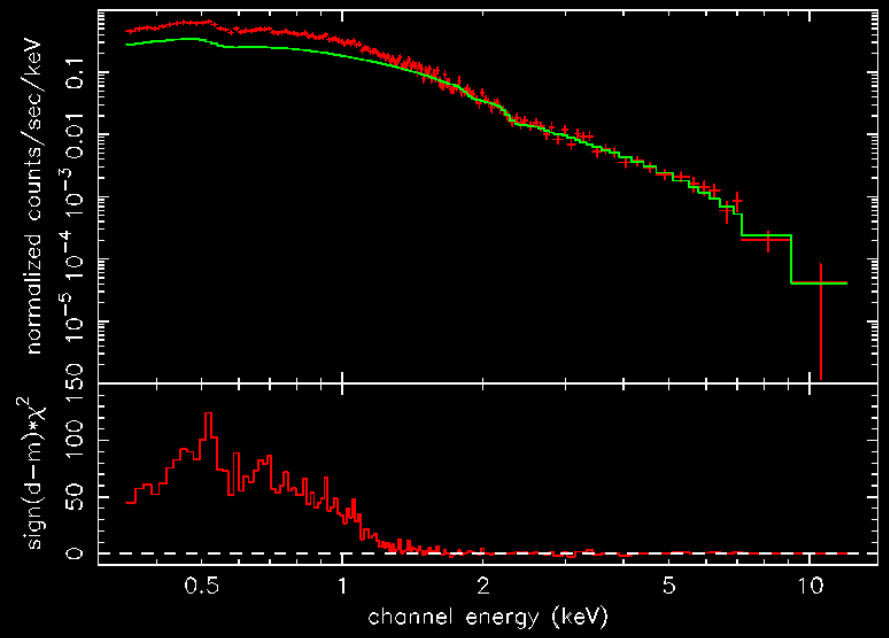
(adapted from Miller et al 04)

What is the “soft excess” at 0.15 keV?

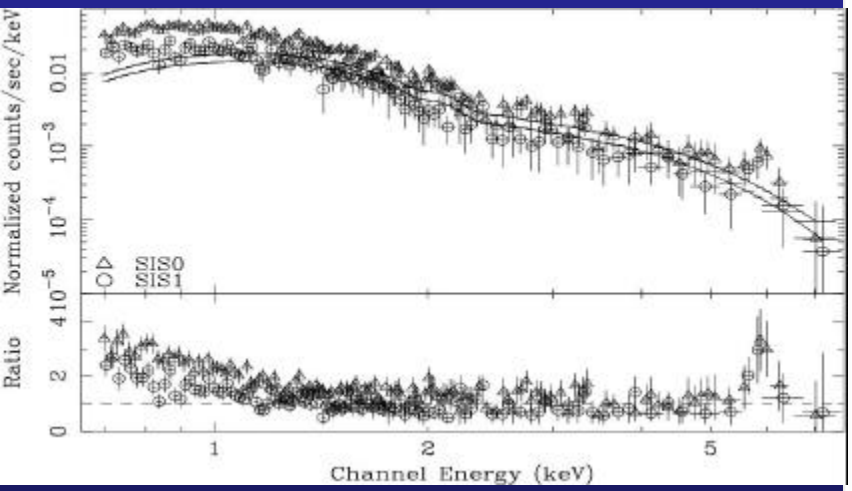
- Signature of the accretion disk?
  (if so, BH masses > 1000 M_{sun})
- Reprocessed component, downscattered in an outflow?
  (Titarchuk & Shrader 2005, Laming & Titarchuk 2004, King & Pounds 2003)
- Reflection component from ionized disk? (Ross & Fabian 2004)
- Fitting artifact due to absorption at 1 keV? (Gierlinski & Done 2004)
- Combination of reflection + wind absorption? (Chevallier et al 2005)

Similar problem for ULXs and many AGN

ULX in NGC 5408

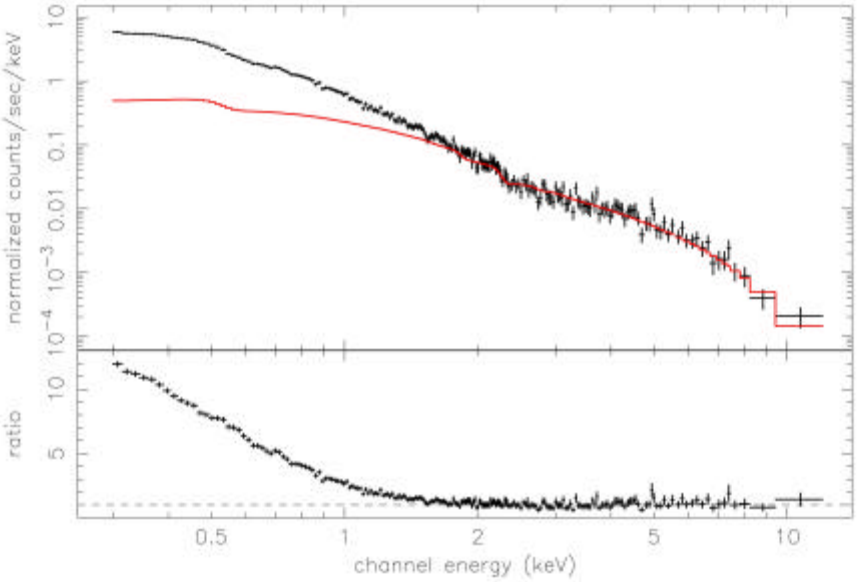


“Soft excess” in ULXs and AGN



(courtesy of Kajal Ghosh)

REJ1034 (Soria & Puchnarewicz 2003)



Personal bias:

Trust the luminosity distribution
more than spectral or timing arguments

We need BHs with M up to ~ 200 M_{sun} , not 5000 M_{sun}

Did ULXs form inside young star clusters?

How to form a 100 - 200 M_{sun} BH?

Big individual stellar progenitors

Mergers of smaller objects

- merging stellar-mass BHs
- merging smaller stars then forming a BH

Nuclear BHs of accreted dwarf galaxies

Most massive individual stars:

Today: Pistol star
initial mass ~ 200 M_{sun}
final core mass ~ 10 M_{sun}

At zero metallicity (z > 10):
Pop-III stars may have initial masses >~ 500 M_{sun}
and small wind losses

may produce massive BHs (Pop-III IMBHs)

Problems of Pop-III IMBH scenario for ULXs

Brightest ULXs in young star-forming environments

(some correlation with star formation)

Pop-III IMBHs need to capture a younger star
Capture rates too low?

Pop-III IMBHs may not even exist

(mass constraints from re-ionization and chemical enrichment)

Stellar merger model:
IMBH formation in a young super-star-cluster

Dynamical friction

10^6 M_{sun} cluster

Mass segregation
Runaway core-collapse

1000 M_{sun} BH

Stellar collisions/mergers in the core

Short-lived, very massive star (~1000 M_{sun})

Hypernova or direct collapse into IMBH

Numerical simulations by Portegies Zwart et al and by Gurkan, Rasio et al.

Formation of an IMBH in a young star cluster

Two necessary conditions

- Core collapse timescale < lifetime of the O stars

$t_{cc} <\sim 3$ Myr

$t_{cc} \sim 0.1 – 0.2\ t_{rh}$ (relaxation timescale)

$\longrightarrow\ t_{rh} <\sim 30$ Myr

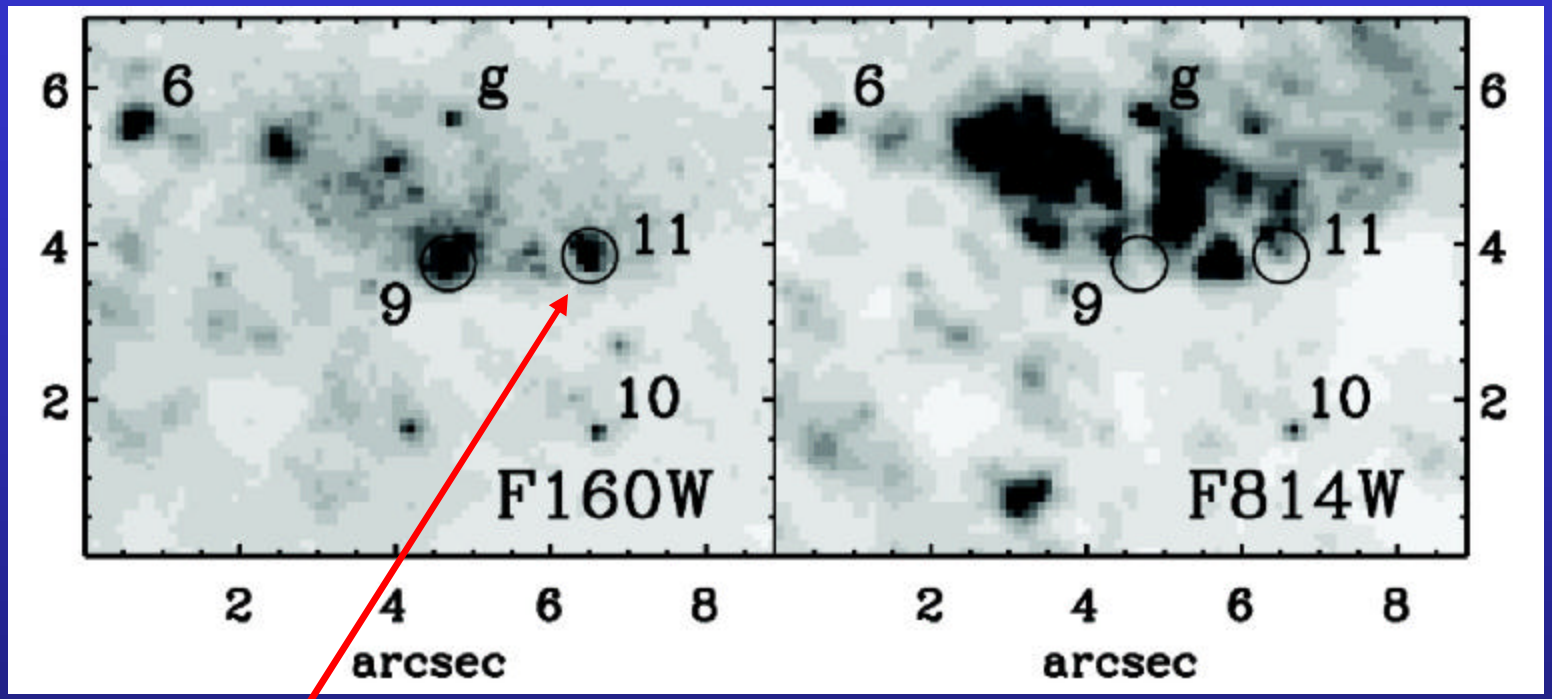
- Mass of the cluster $M_{cl} >\sim 10^5\ M_{sun}$

$M_{bh} \sim 0.001 – 0.002\ M_{cl}$

We need $M_{bh} >\sim 100\ M_{sun}$

Numerical simulations by Portegies Zwart et al and by Gurkan, Rasio et al.

Observational evidence for ULXs in clusters?



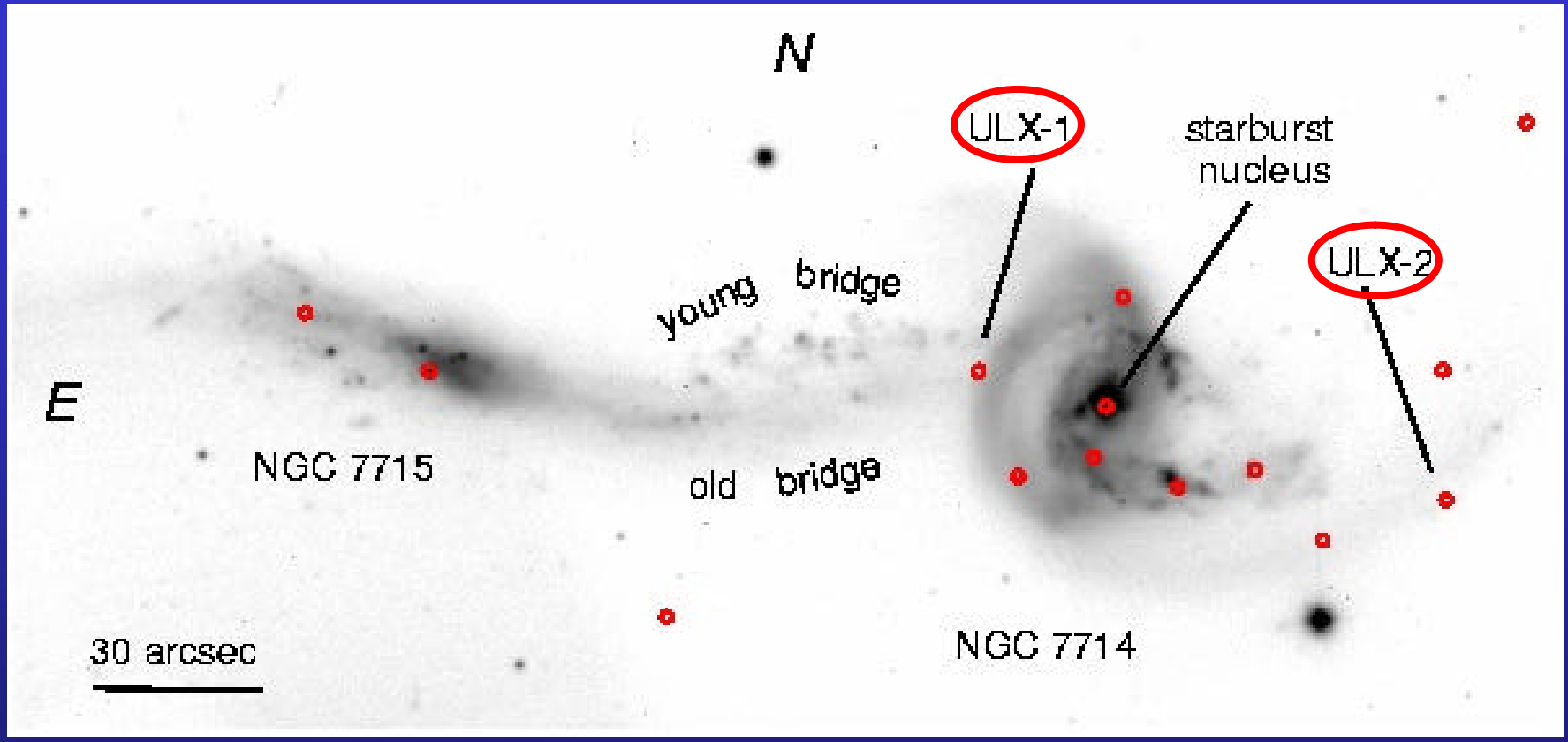
ULX in a young star cluster in M82

L_x varying from ~ 10^{39} to 10^{41} erg/s

M_{bh} ~ 1000 M_{sun} M_{cl} ~ 4 10^5 M_{sun}

Portegies Zwart et al, Nature, 2004

Not in clusters



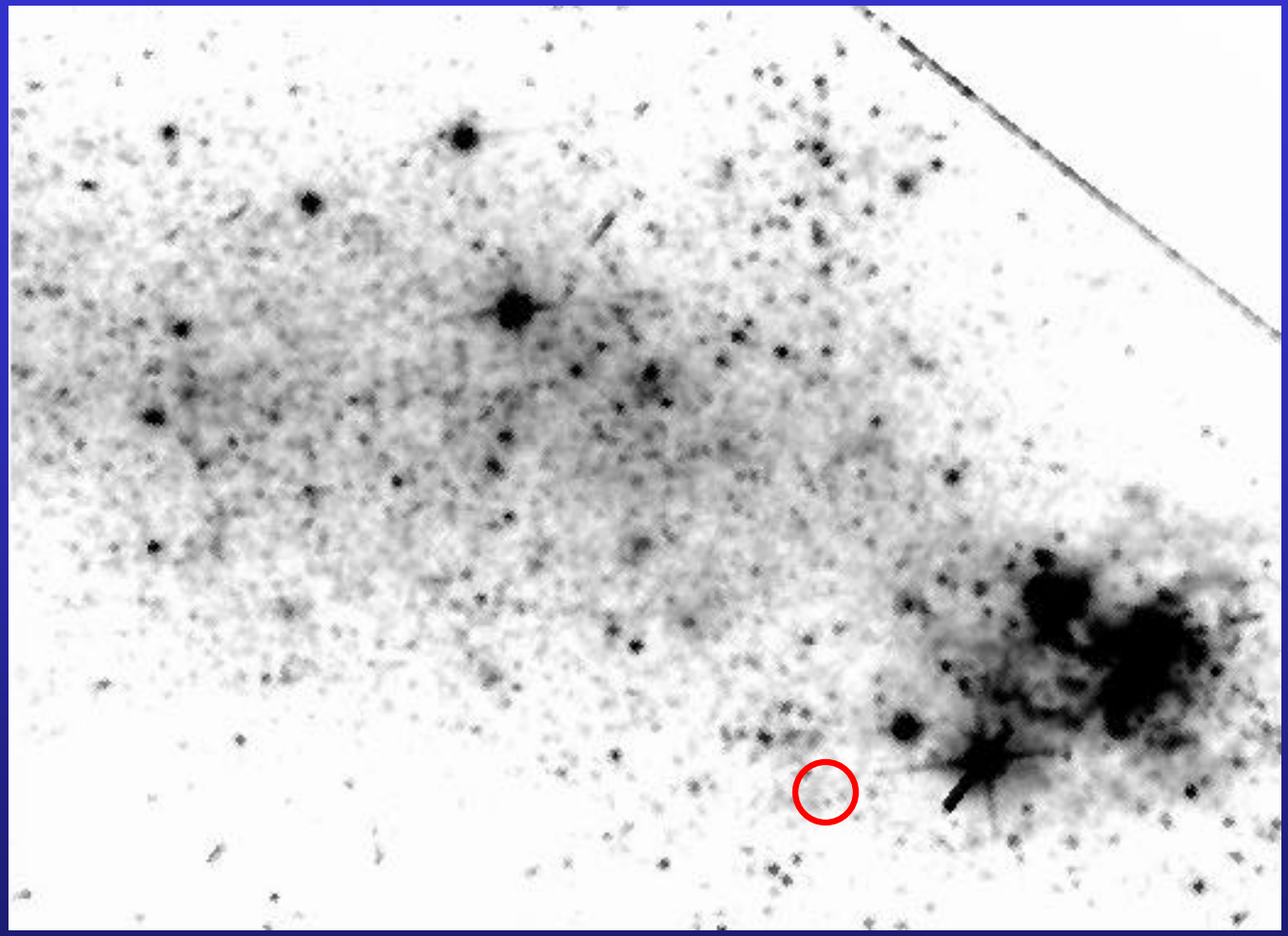
4 ULXs in the colliding galaxies NGC 7714 / 7715

with L_x ~ 2 – 8 10^{40} erg/s

2 are in clusters, 2 are not

Smith et al 2005, AJ, 129, 1350

Near clusters but not in one

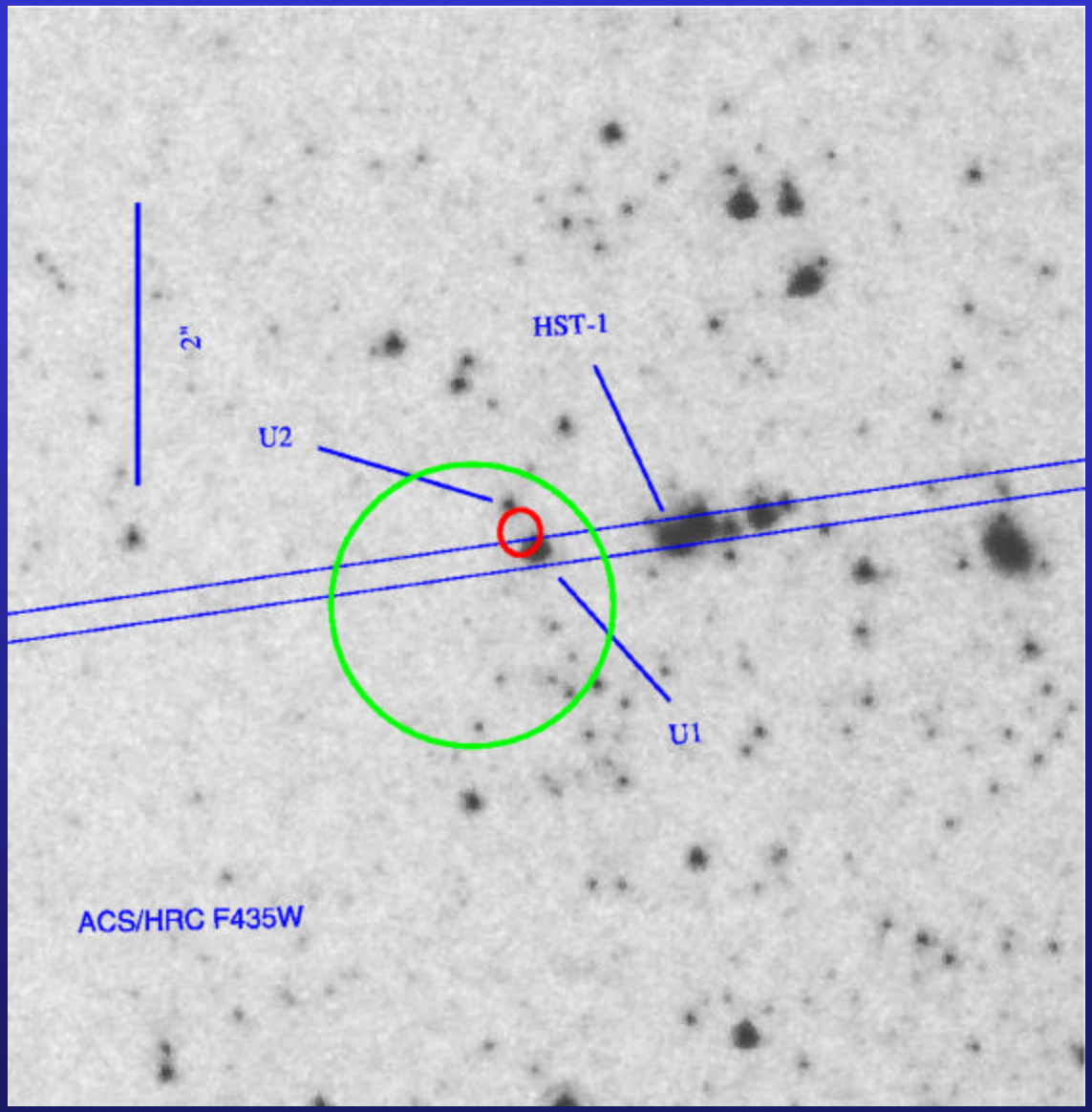


ULX in the starburst dwarf NGC 5408
with $L_x \sim 10^{40}$ erg/s

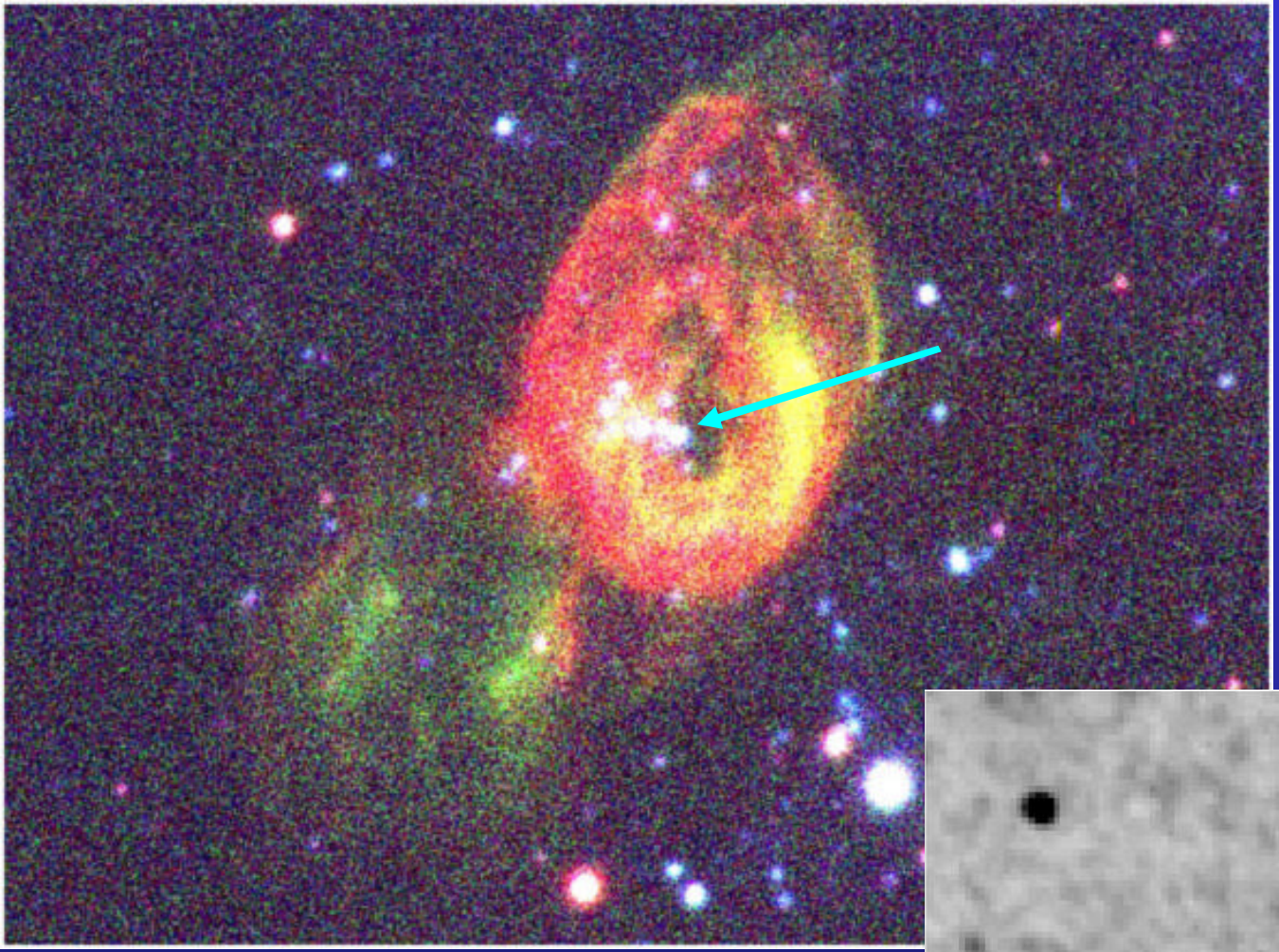
Near B stars but not in a cluster

Kaaret et al 2003
Soria et al 2004

Near OB stars but not in a super-star-cluster

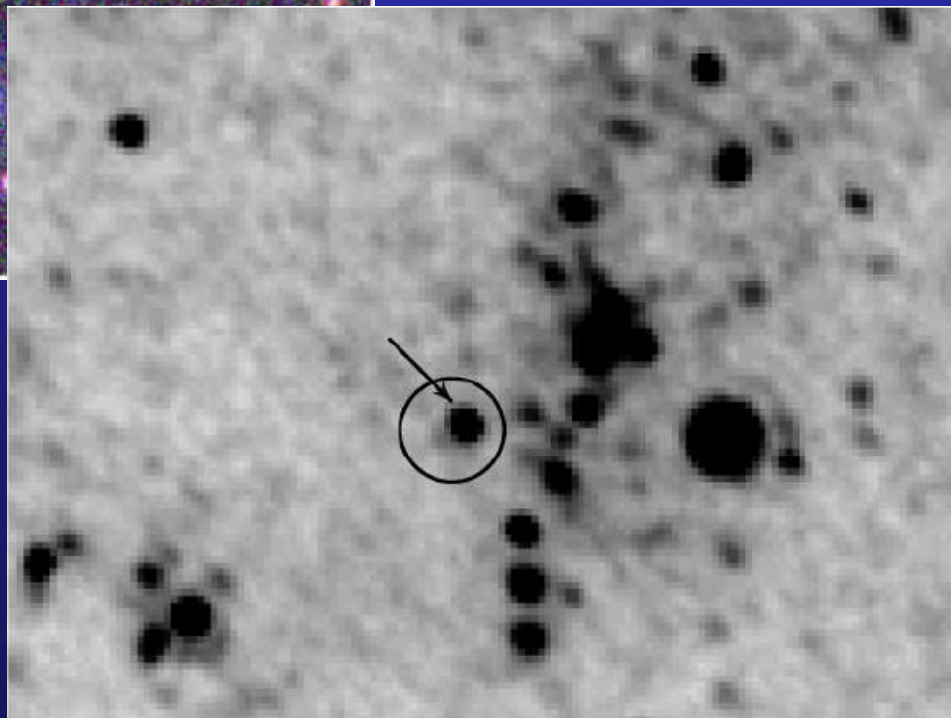


ULX in the dwarf galaxy NGC 5204 *Liu et al 2004*



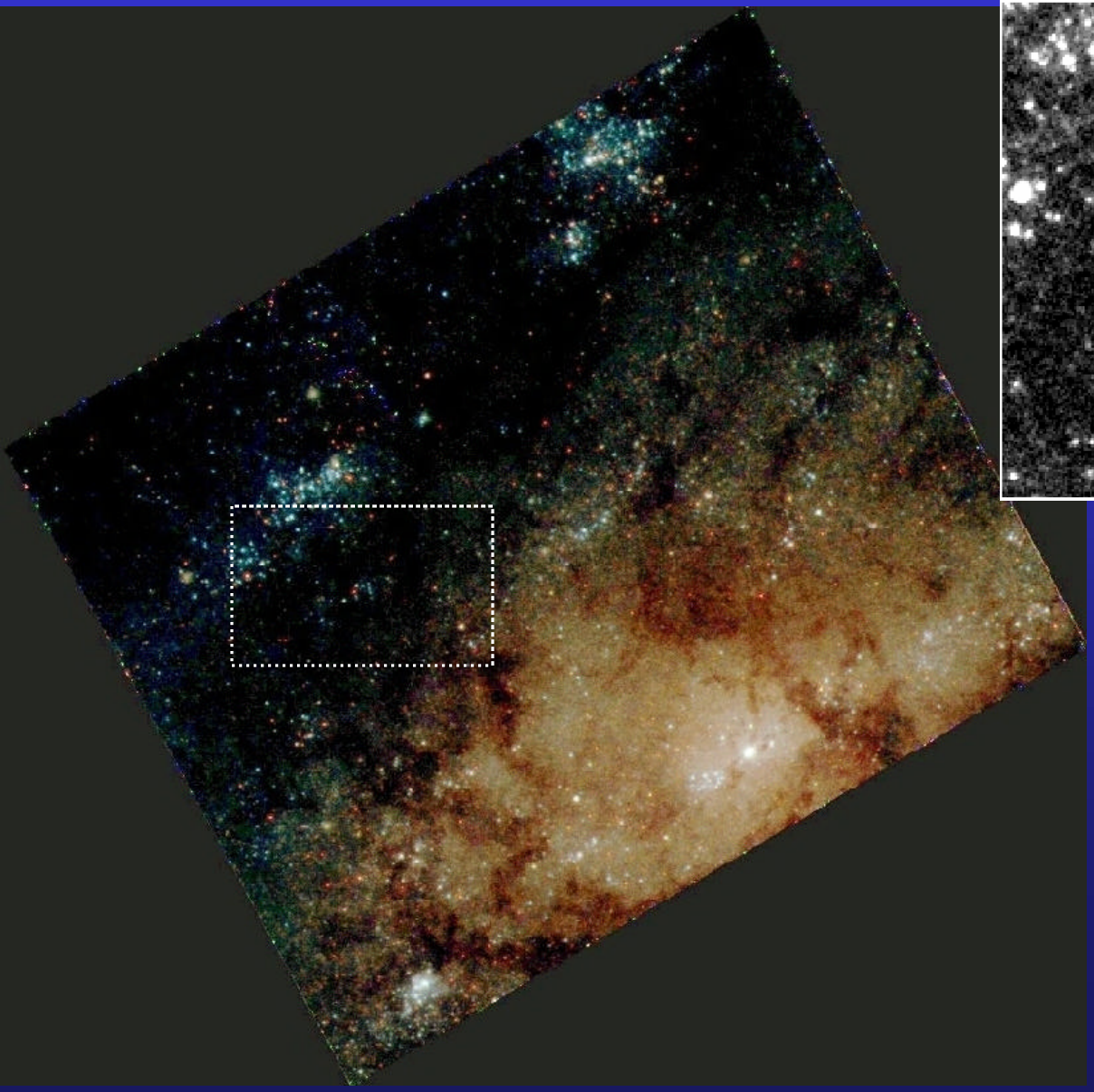
Holmberg IX
$L_x \sim 10^{40}$ erg/s

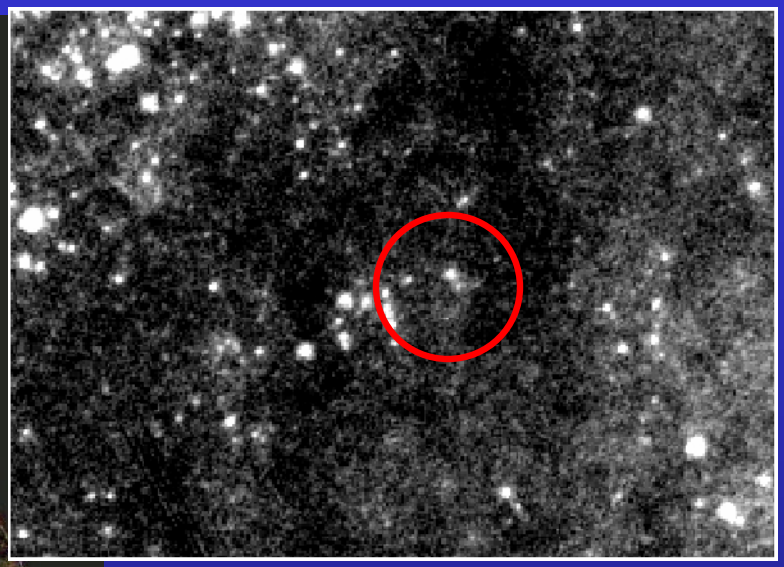
from M Pakull



NGC1313 X-2
$L_x \sim 10^{40}$ erg/s

NGC4559 X-10: near OB stars, no super cluster

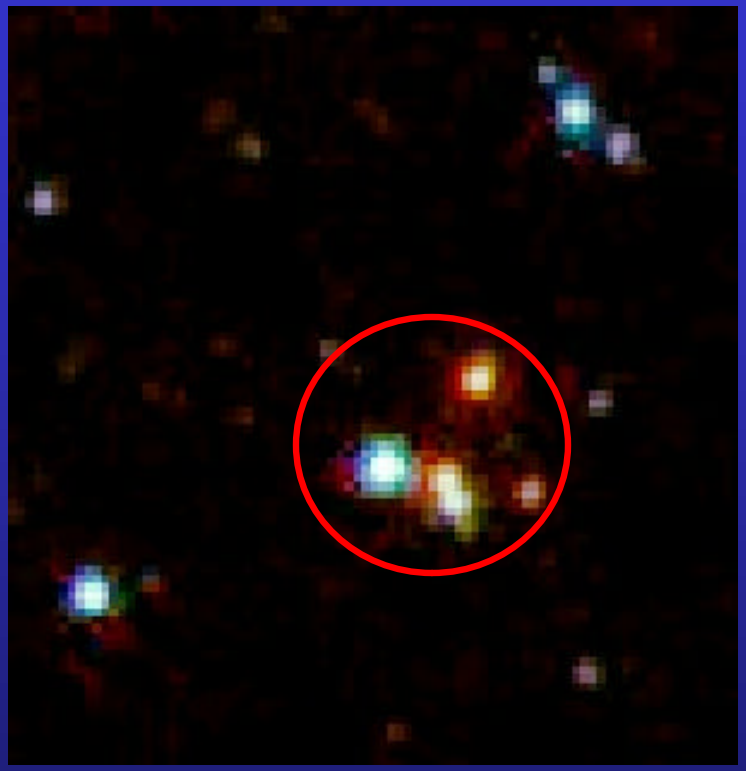




A few B stars
but no big clusters

Cropper et al 2005
Soria et al 2005

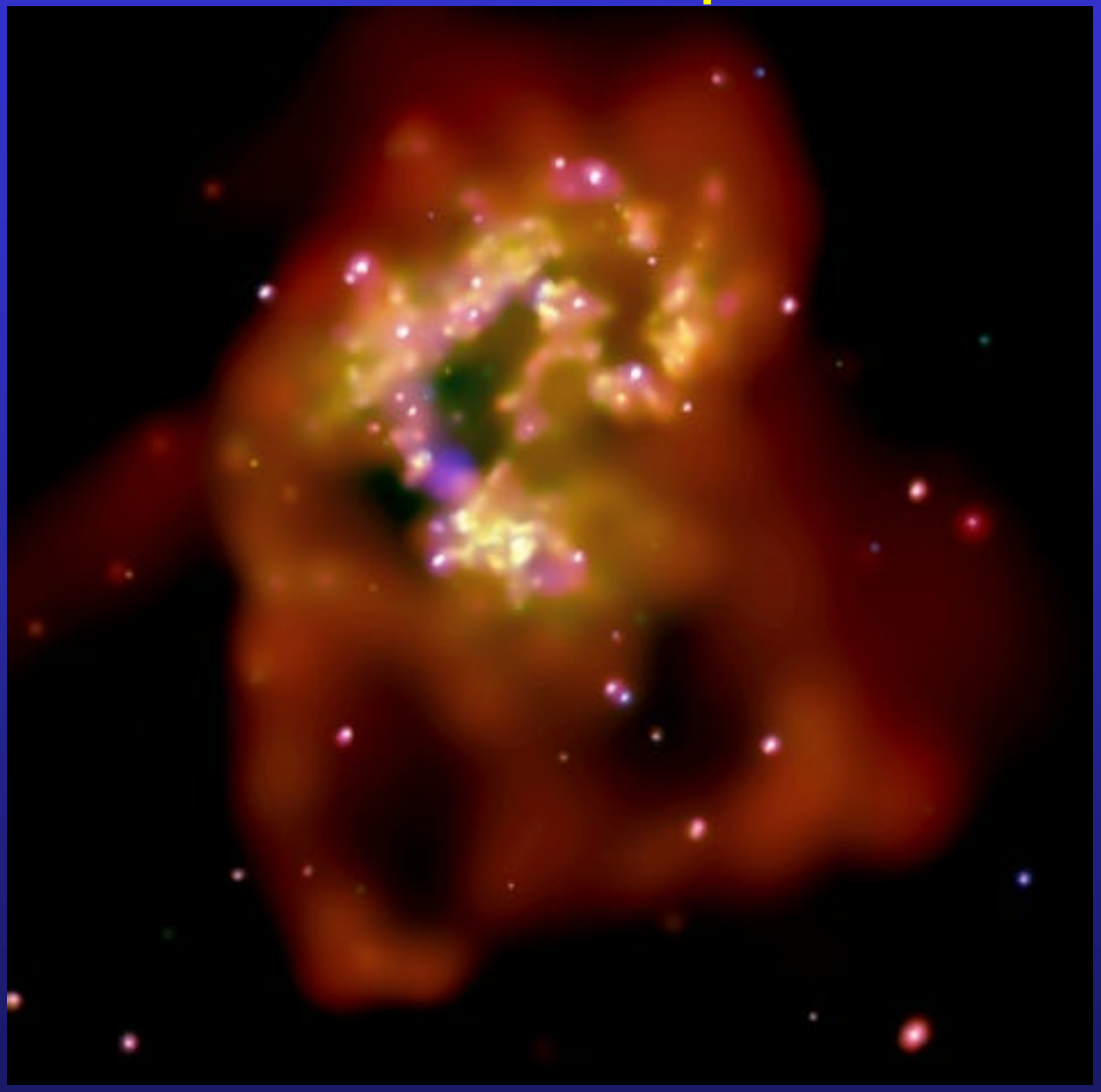
NGC4559 X-7: near OB stars, no super cluster



A few B stars
but no SSCs

Soria et al 2005

Antennae: lots of ULXs, displaced from clusters



ULXs are displaced from SSCs by ~ 100 – 300 pc

Zezas, Fabbiano et al 2002

Swartz et al 2006, in preparation:
Determine fraction of ULXs in clusters

Survey of > 100 candidate ULXs

Estimate and throw out background AGN

Classify ULXs in young clusters, old clusters, or field

Why are most ULXs not inside super clusters?

Were they ejected?

Inconsistent with IMBH, would require low BH mass
(eg, Zezas et al 2002; Belczynski et al 2005)

Have their parent clusters dispersed?

Tidal disruption: always too slow (>~ 50 Myr)
SN disruption: perhaps….but there are *no signs of the dispersed super clusters*

How to form a 100 - 200 M_{sun} BH?

Individual stellar progenitors (Pop-III)

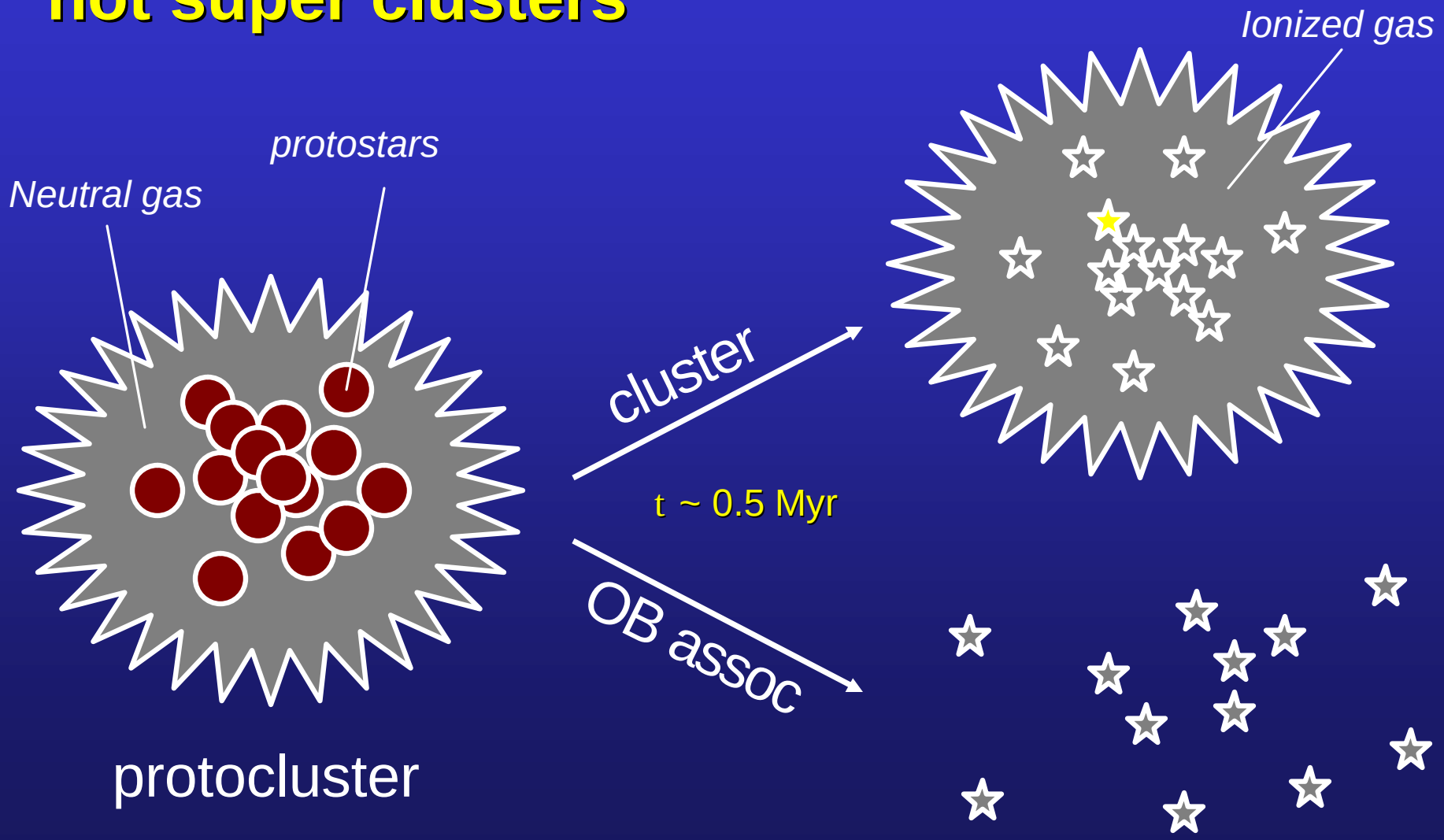
Nuclear BHs of accreted dwarf galaxies

Mergers of stellar-mass BHs in old clusters

Mergers of O stars in young super clusters

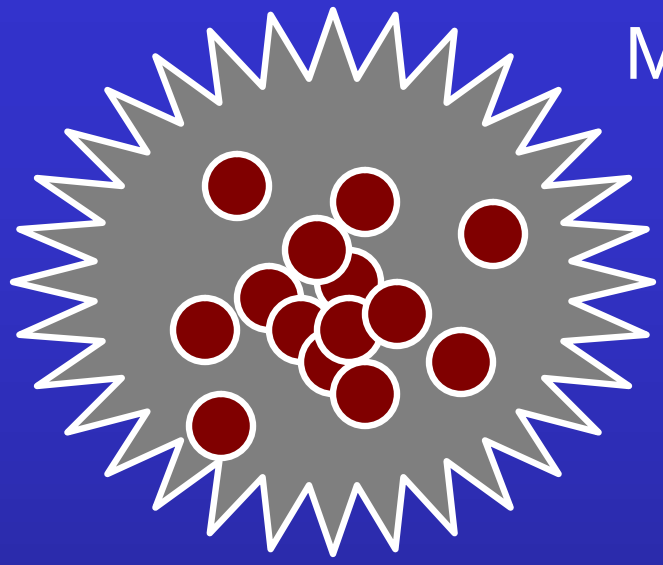
Suggestion:

IMBHs formed in smaller proto-clusters, not super clusters



(eg, Kroupa & Boily, 2002-2004; Geyer & Burkert 2001)

σ_h < 10 km/s



M ~ $10^{3.5}$ -- 10^5 M_{sun}

Ideal conditions for

- forming BHs with M ~ 30 -- 200 M_{sun}
- dispersing the protocluster

Dense proto-clusters ideal for coalescence

Elmegreen & Shadmehri (2003)
Bally & Zinnecker (2005)

Stellar captures and mergers are favoured by proto-stellar disks / envelopes

- Larger cross section
  R (protostar) >~ 100 AU >~ 10^{15} cm
  R (O-star) ~ 10^{12} cm
- Envelopes help losing ang momentum
- Continuing accretion hardens binaries

Collisional rates enhanced at high density and low velocity dispersion (gravitational focussing)

Mid-size proto-clusters are very fragile:

$M \sim 10^{3.5}$ -- 10^{5} M_{sun}

$\sigma_h < 10$ km/s

They may evaporate "explosively"

when proto-stars ⟶ stars,
on a timescale $\tau \sim 0.5$ - 1 Myr

when a few massive stars
coalesce in their core
(⟶ merger-induced outflows)

Massive proto-stellar mergers

→ Explosive expulsion of gas

→ proto-cluster disruption

Merger of 100 + 100 M_{sun} stars releases ~ 10^{51} erg *(Bally & Zinnecker 2005)*

Binding energy of gas in a 10^5 M_{sun} cluster ~ a few 10^{50} -- 10^{51} erg

Single SN releases ~ 10^{51} erg

Two regimes for coalescence + IMBH formation?

$M <\sim 10^5 M_{sun}$
$\sigma_h < 10$ km/s
$t_{cc} <\sim 0.5$ Myr

IMBH formation
in unbound proto-cluster

ULX in a sparse OB assoc
(size >~ 100 pc)

$M >\sim 10^{5.5} M_{sun}$
$\sigma_h >\sim 10$ km/s
$t_{cc} <\sim 3$ Myr

IMBH formation
in bound cluster

ULX in a cluster
(size <~ 3 pc)

Additional advantage of the proto-cluster scenario

Same physical process that creates massive [O + O] binaries, progenitors of BH HMXBs

↓

ULXs in spiral galaxies = high-luminosity end of HMXBs (recall Lum Function from Doug's talk)

IN SUMMARY: protocluster scenario may explain:

formation of BHs with $M \sim 100\ M_{sun}$

why they are no longer in a cluster after ~ 10 Myr (why some are surrounded by gas nebula)?

why ULX population looks like tail end of HMXBs

Brightest ULXs formed in young proto-clusters in the local Universe

Natural outcome of clustered star formation: don’t need old Pop-III remnants

and in the early Universe?

IMBHs as seeds for SMBHs at z >~ 6

Hierarchical mergers + accretion *(models by Volonteri et al)*

Galaxy merger / satellite accretion

Star formation
and/or starburst

Infall of seed Pop-III IMBHs
from halo & satellite galaxies

Some IMBHs
sink to center

↓

Merge into SMBH

↓

Gas accretion

Some IMBHs left
wandering across galaxy

IMBHs as seeds for SMBHs at z >~ 6

Galaxy merger / satellite accretion

↓

Nuclear starburst

↓

IMBHs formed in nuclear starburst

(reach galactic center on shorter timescale)

↓

Merge into SMBH

↓

Gas accretion

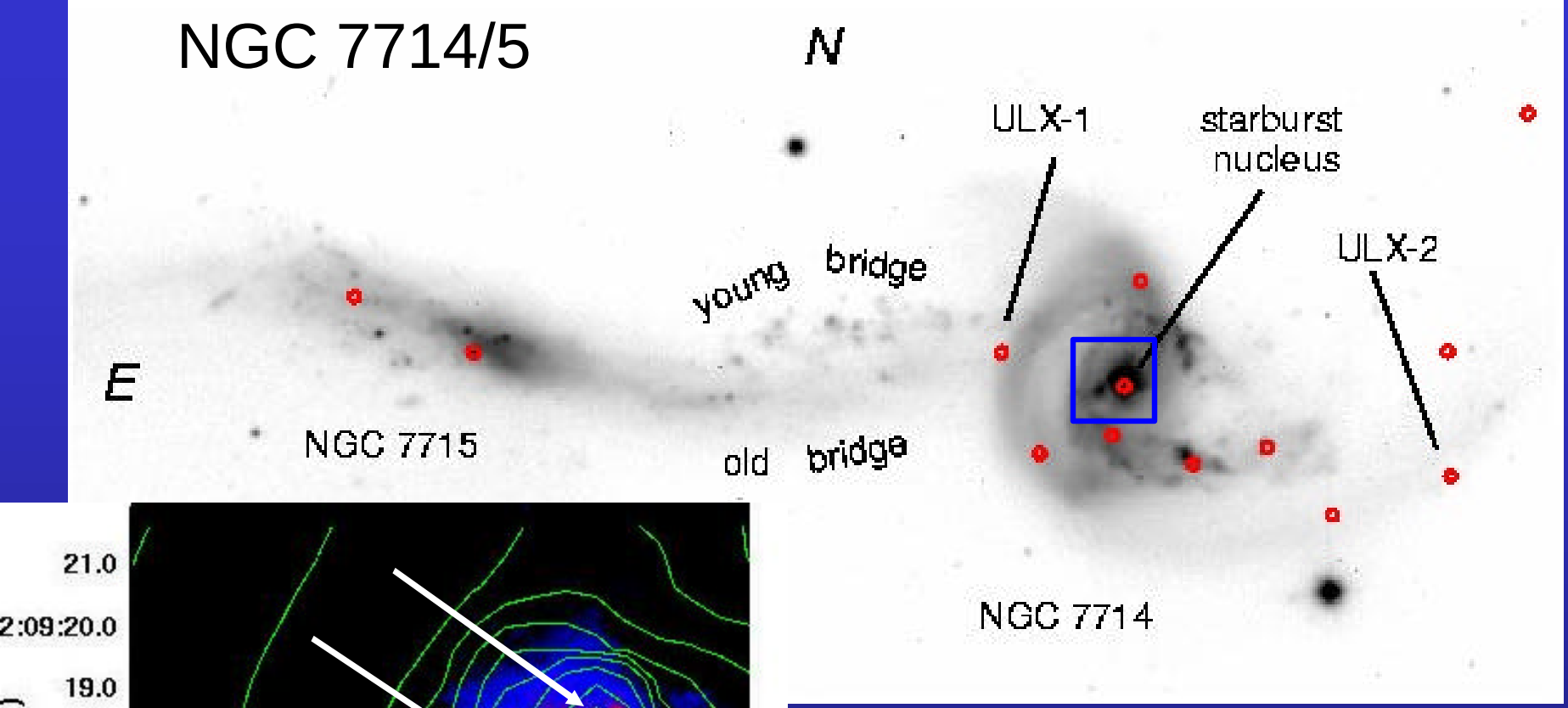
Main differences

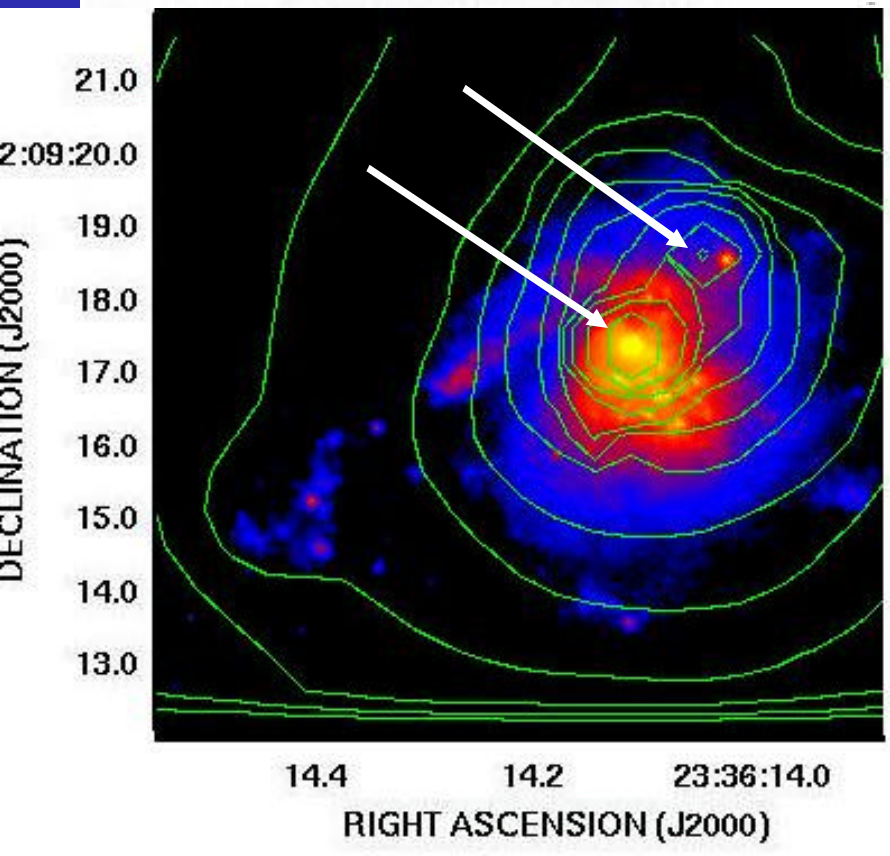
- Seed IMBHs from Pop-II, clustered star-formation in galactic nuclei, not from Pop-III halo stars

- Shorter dynamical timescale
  for seed IMBHs to sink and merge

- Don’t need actual satellite mergings,
  just tidal interactions → gas inflow → starburst

NGC 7714/5





Early phase of assembly of an SMBH from IMBHs in a nuclear starburst?

(Smith et al 2004)

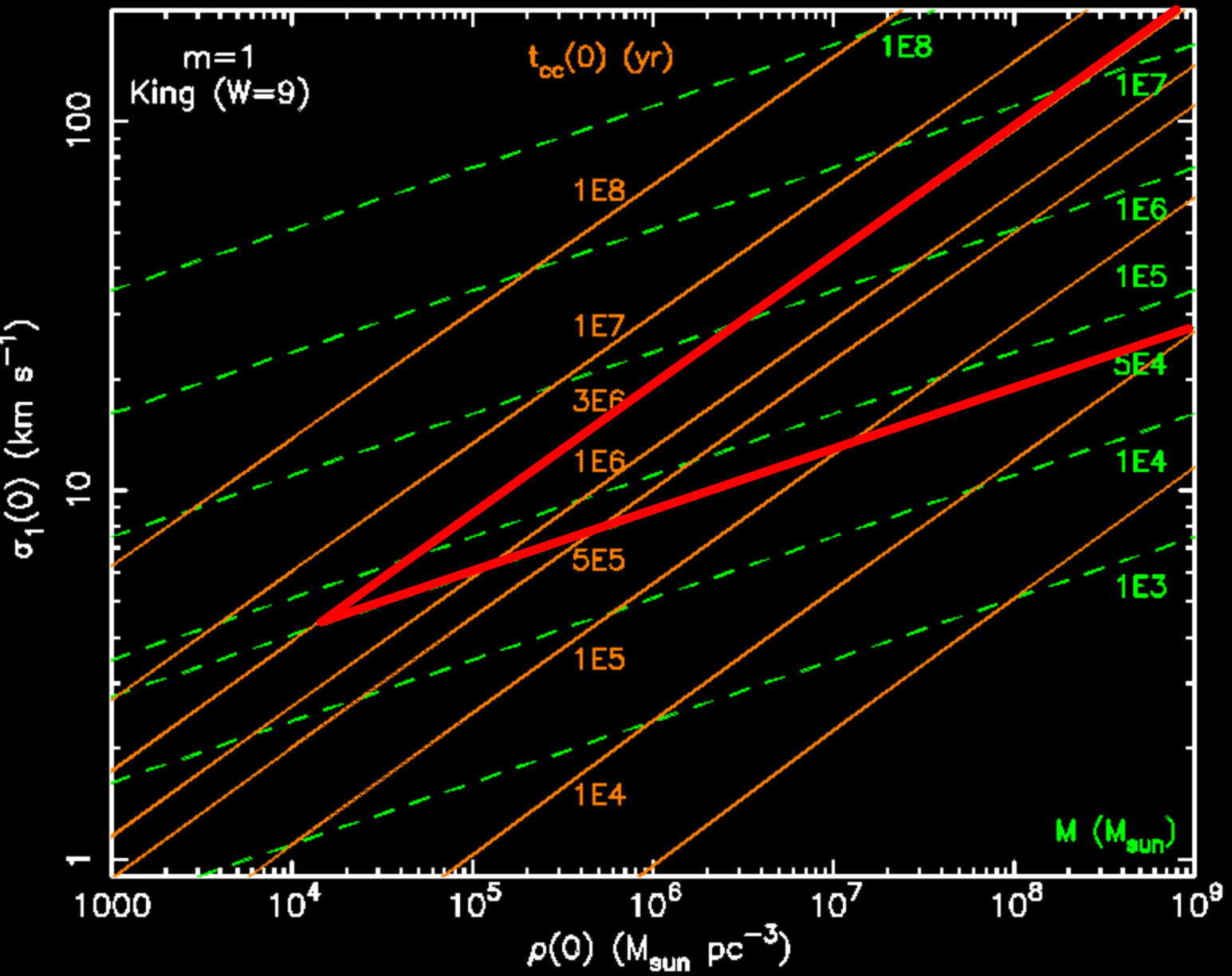
Summary: we speculate that:

Most ULXs could be BHs with $M \sim 30$ -- $200\ M_{sun}$ formed in medium-size, dense proto-clusters, via merger of a few massive proto-stars

↘ Essentially same process that forms HMXBs, normal outcome of clustered star formation

SMBHs assembled from Pop-II seed BHs (during massive nuclear starbursts at $3 \lesssim z \lesssim 10$) not from Pop-III BHs sinking down from the halo

Parameter space for IMBH formation from core collapse



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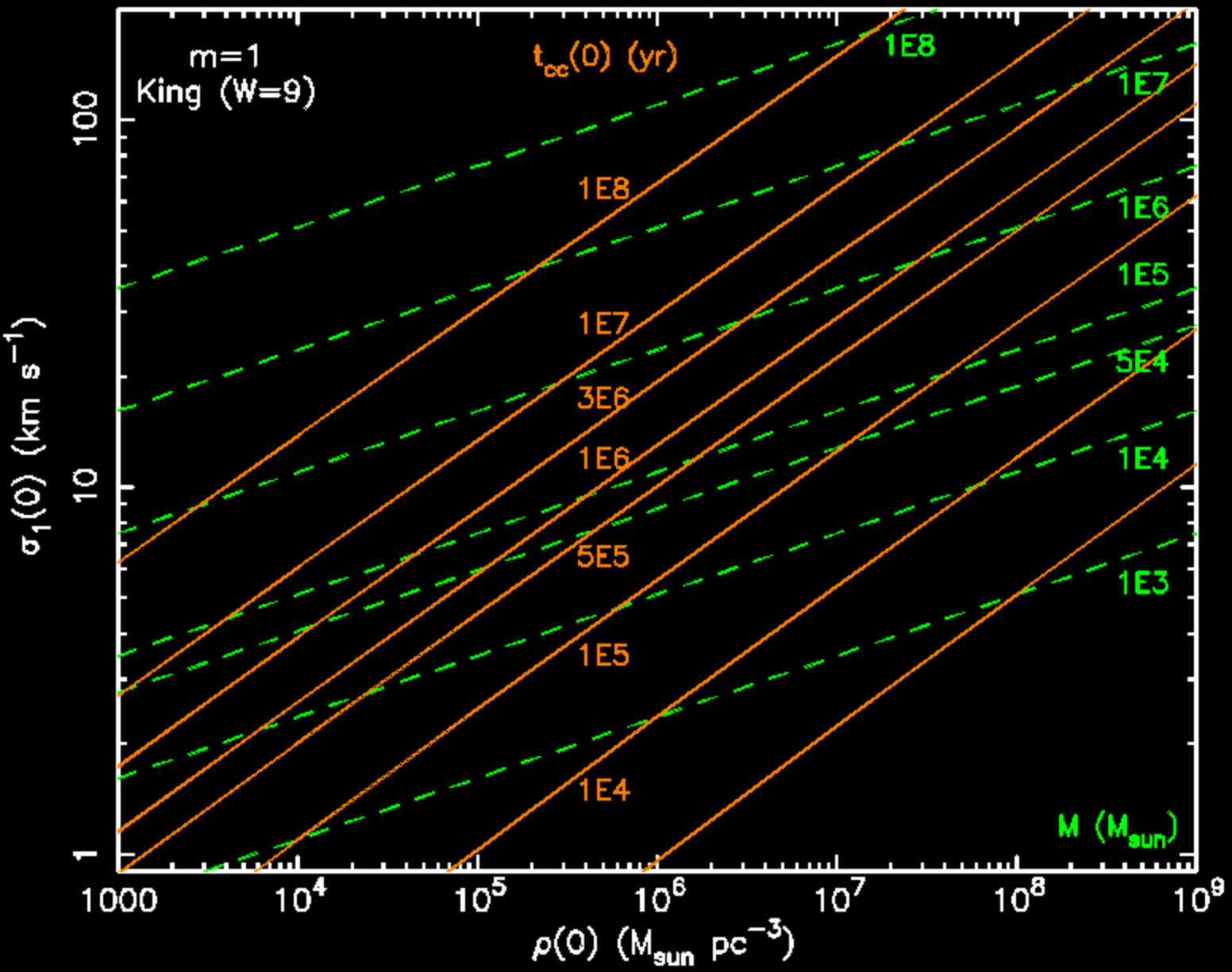

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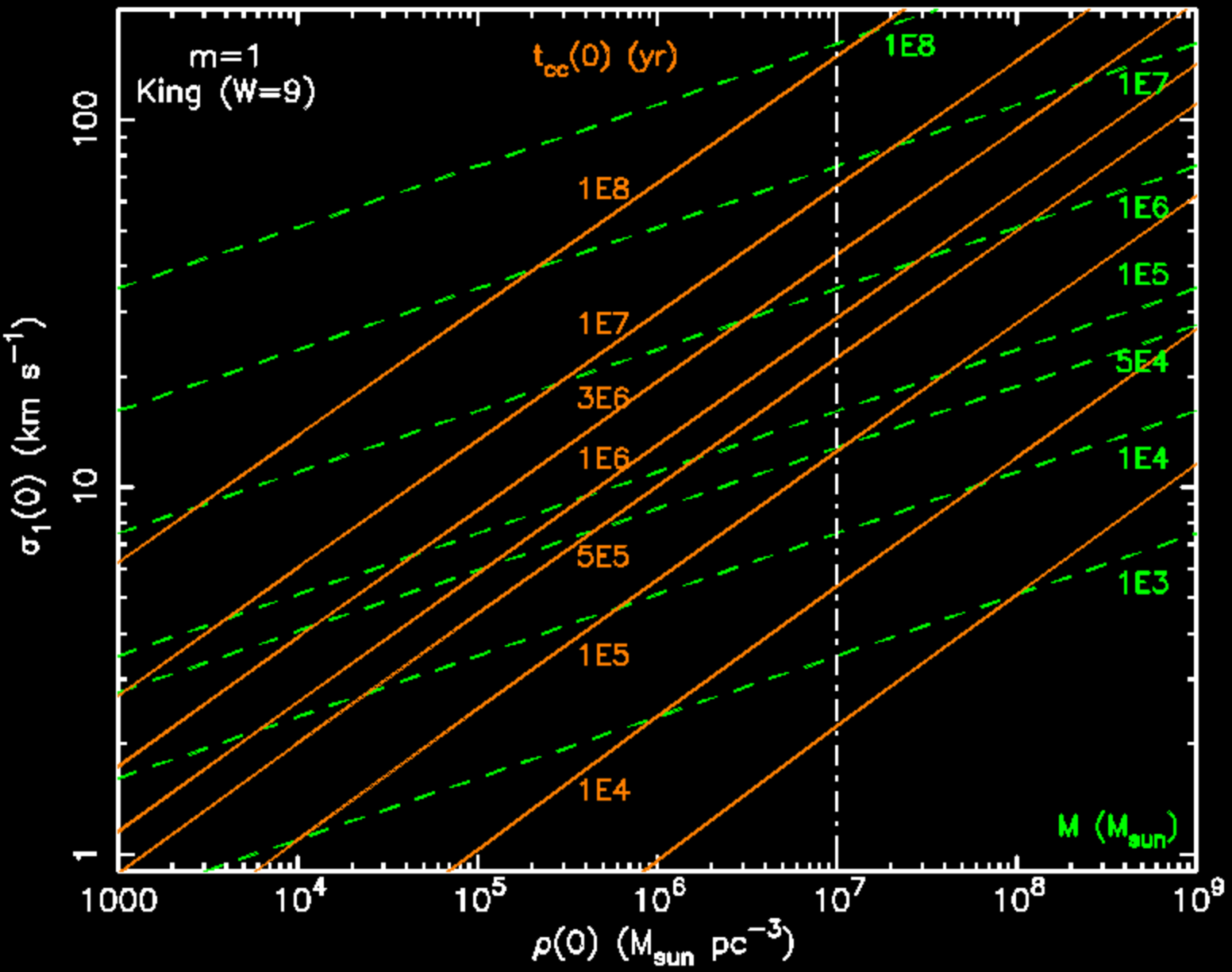

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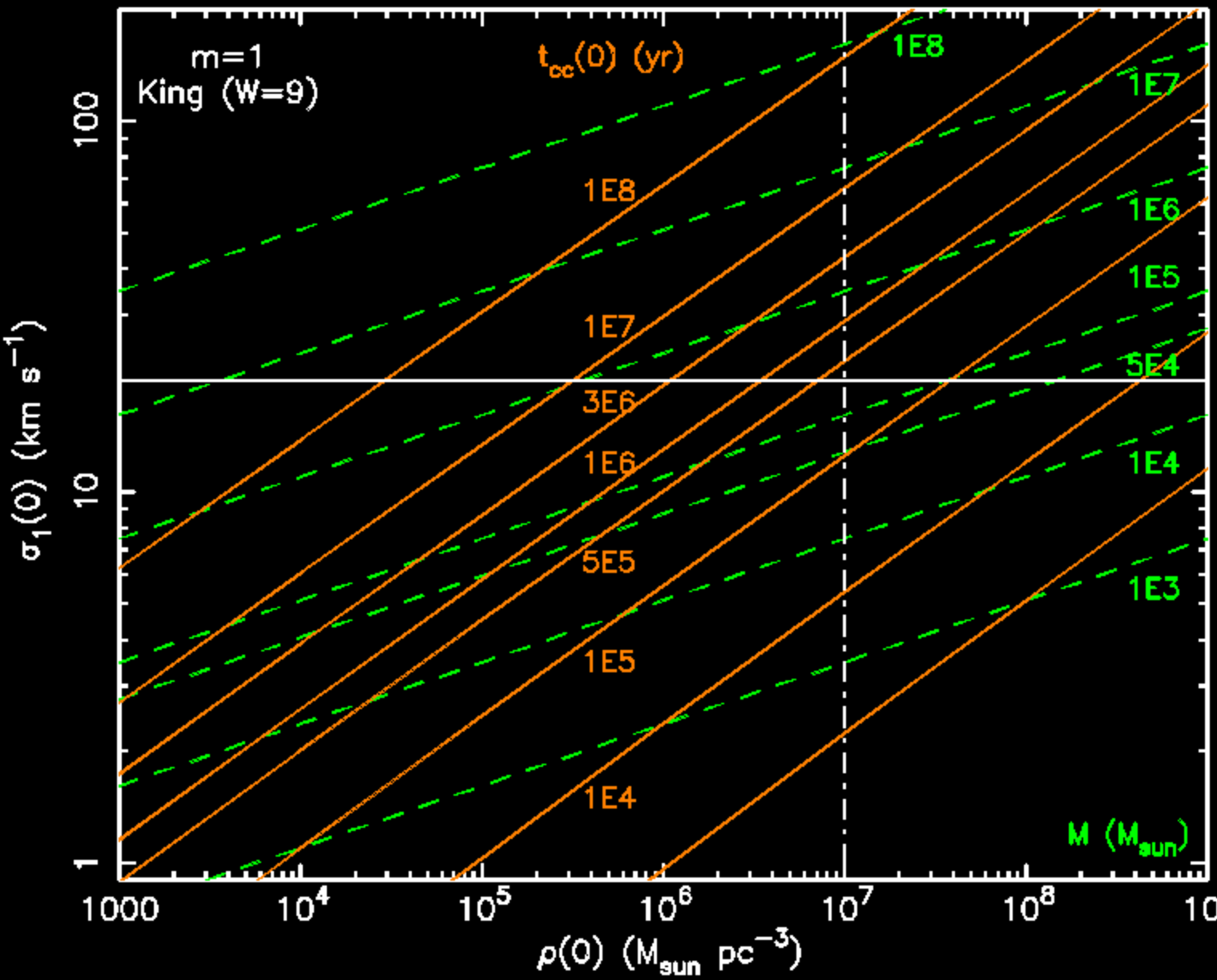

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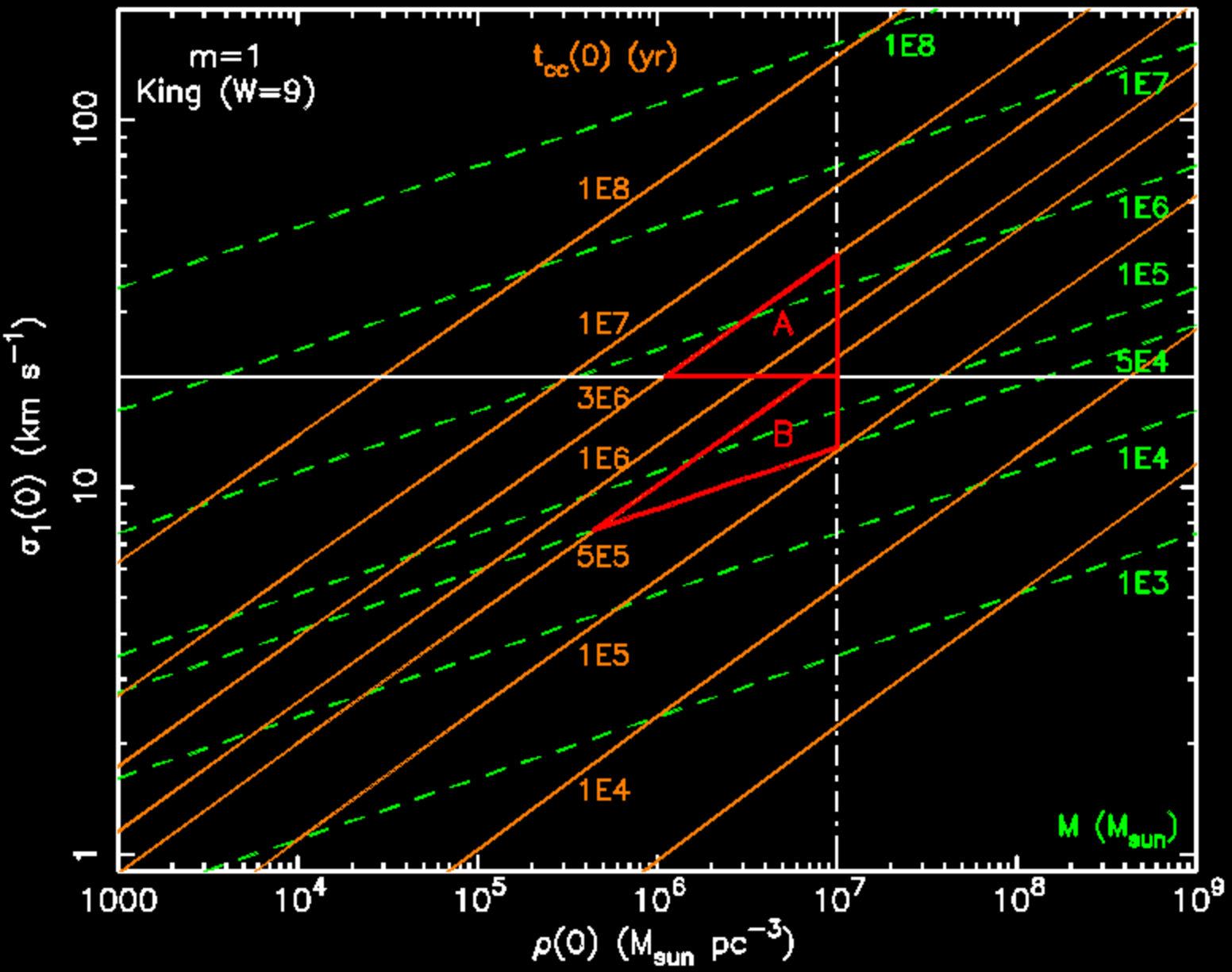

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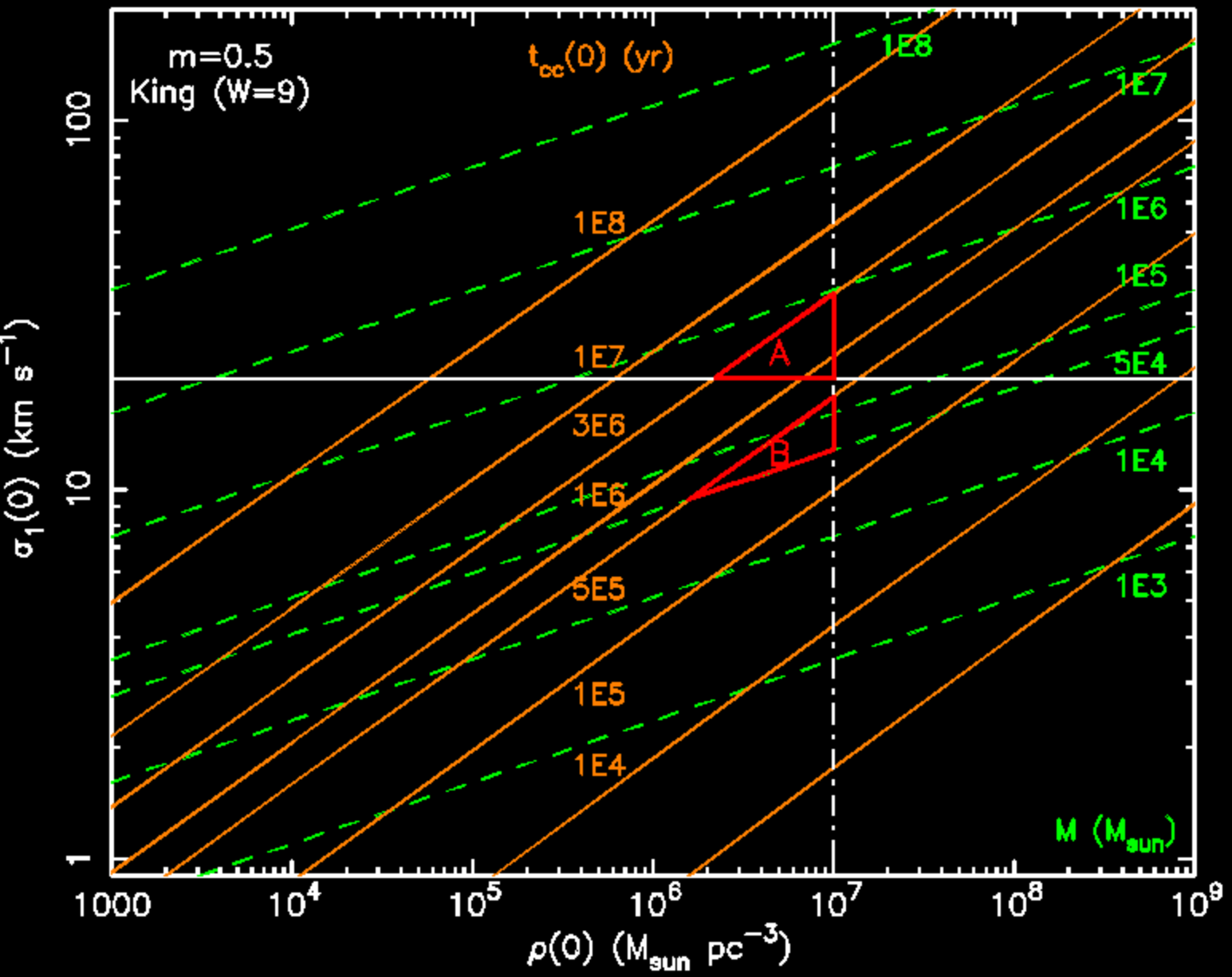

Parameter space for IMBH formation from core collapse