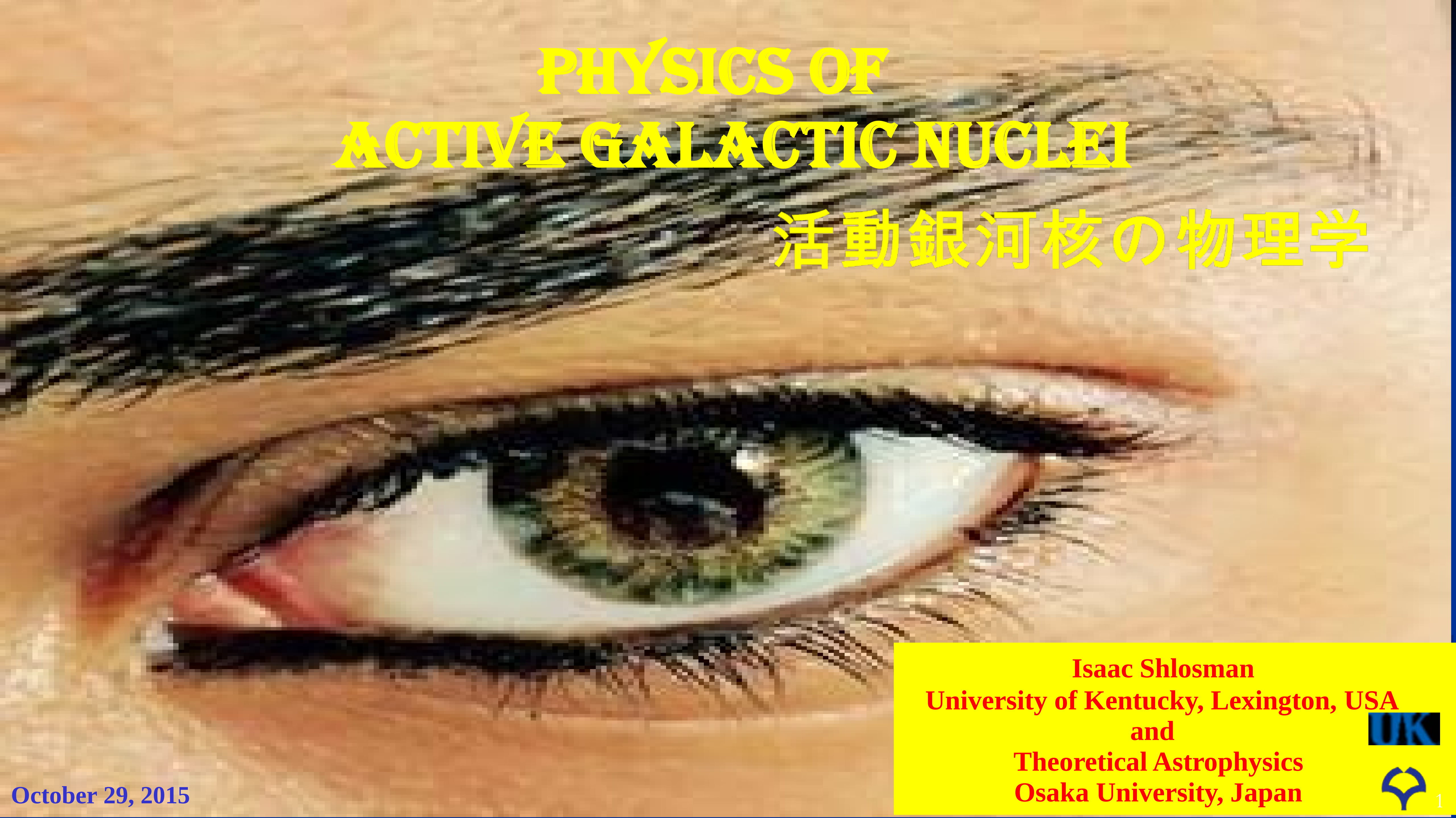


Physics of Active Galactic Nuclei

活動銀河核の物理学

Isaac Shlosman
University of Kentucky, Lexington, USA
and
Theoretical Astrophysics
Osaka University, Japan

October 29, 2015

Physics of Active Galactic Nuclei

活動銀河核の物理学

- History, Taxonomy and Detection
- Supermassive Black Holes and Accretion Processes
- AGN: Inflows and Outflows
- AGN and Host Galaxies: Fueling and Feedback
- Formation and Evolution of AGN

LECTURE 4
AGN AND HOST GALAXIES: FUELING AND FEEDBACK

AGN host galaxy morphology

AGN environment

Fueling: external versus internal sources
smooth accretion: cosmology?
angular momentum problem

Feedback: radiation, mechanical

Coexistence: supermassive black holes and their host galaxies

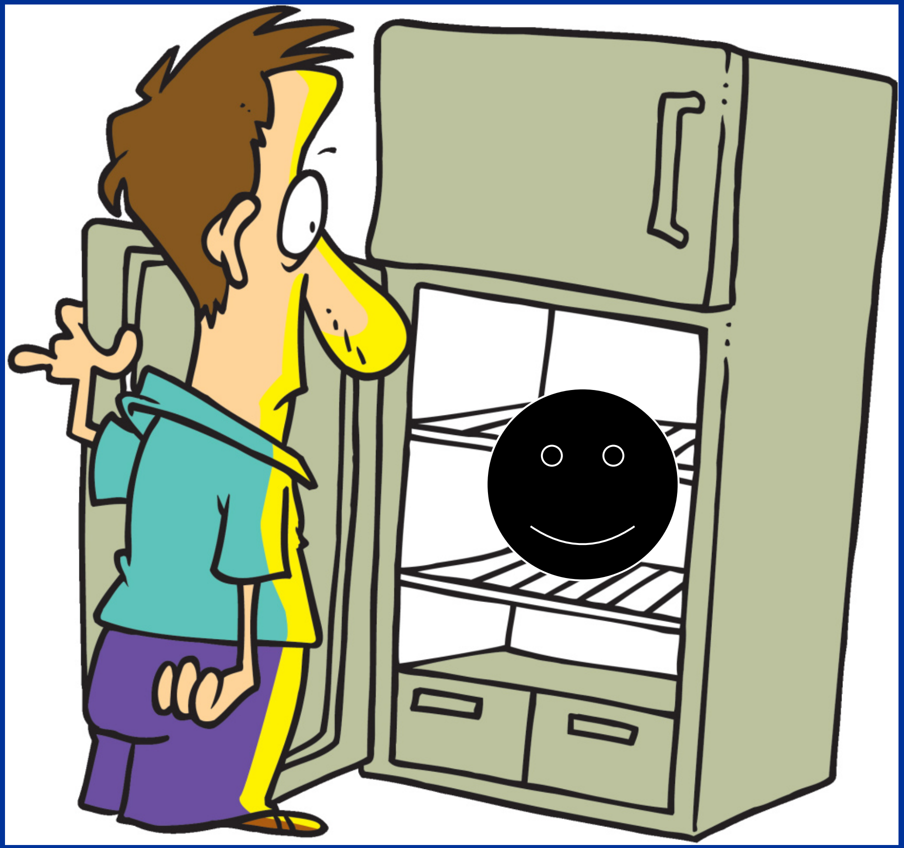
AGN and HOST GALAXIES: FUELING and FEEDBACK

Active Galactic Nuclei : live in galaxies! No isolated AGN!

This means, AGN evolution can be affected by galaxies, and, in return, they can affect evolution of galaxies → feedback

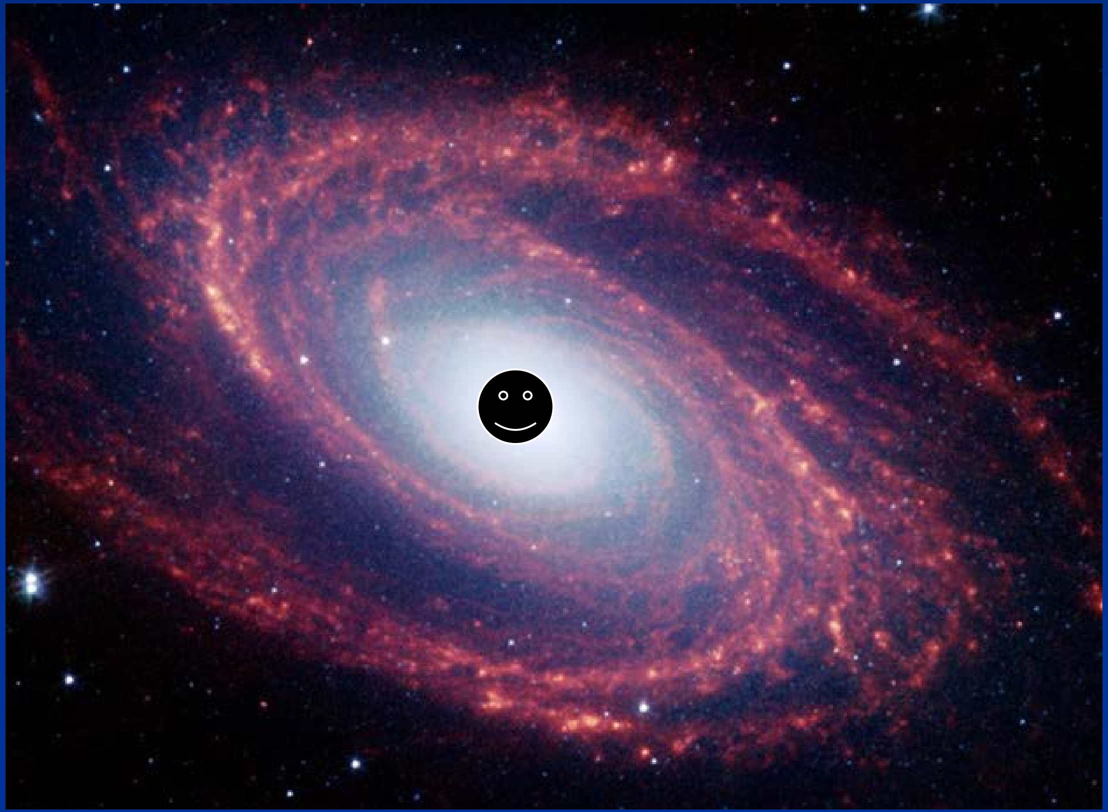
WHAT BRINGS FOOD TO YOUR TABLE?

What Feeds AGN?

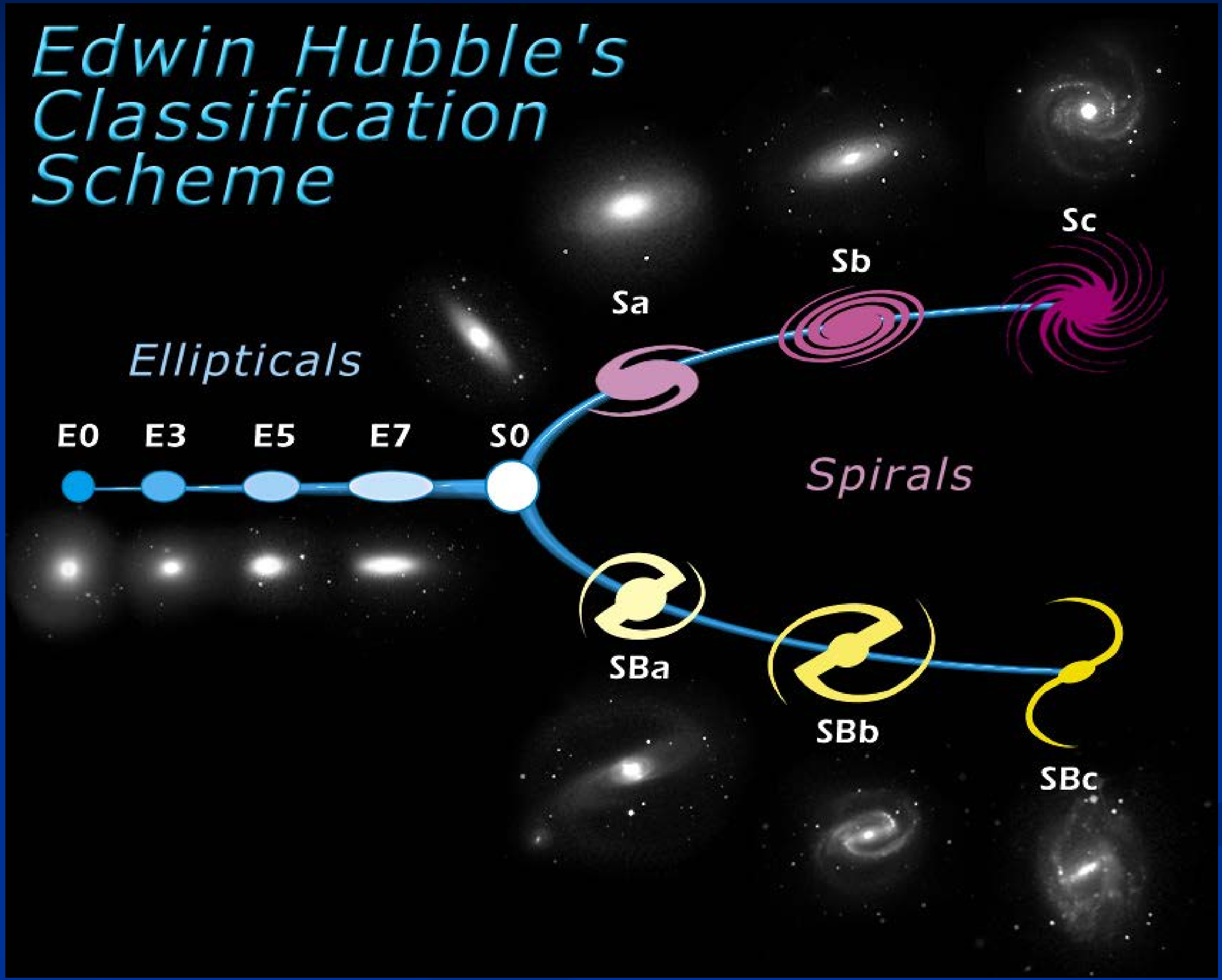


HOST GALAXIES OF AGN

Where do AGN live?



Do AGN galaxies are special?



WHERE DO AGN LIVE?

In galactic centers → why?

they been born there
WHY?

SMBH was born there

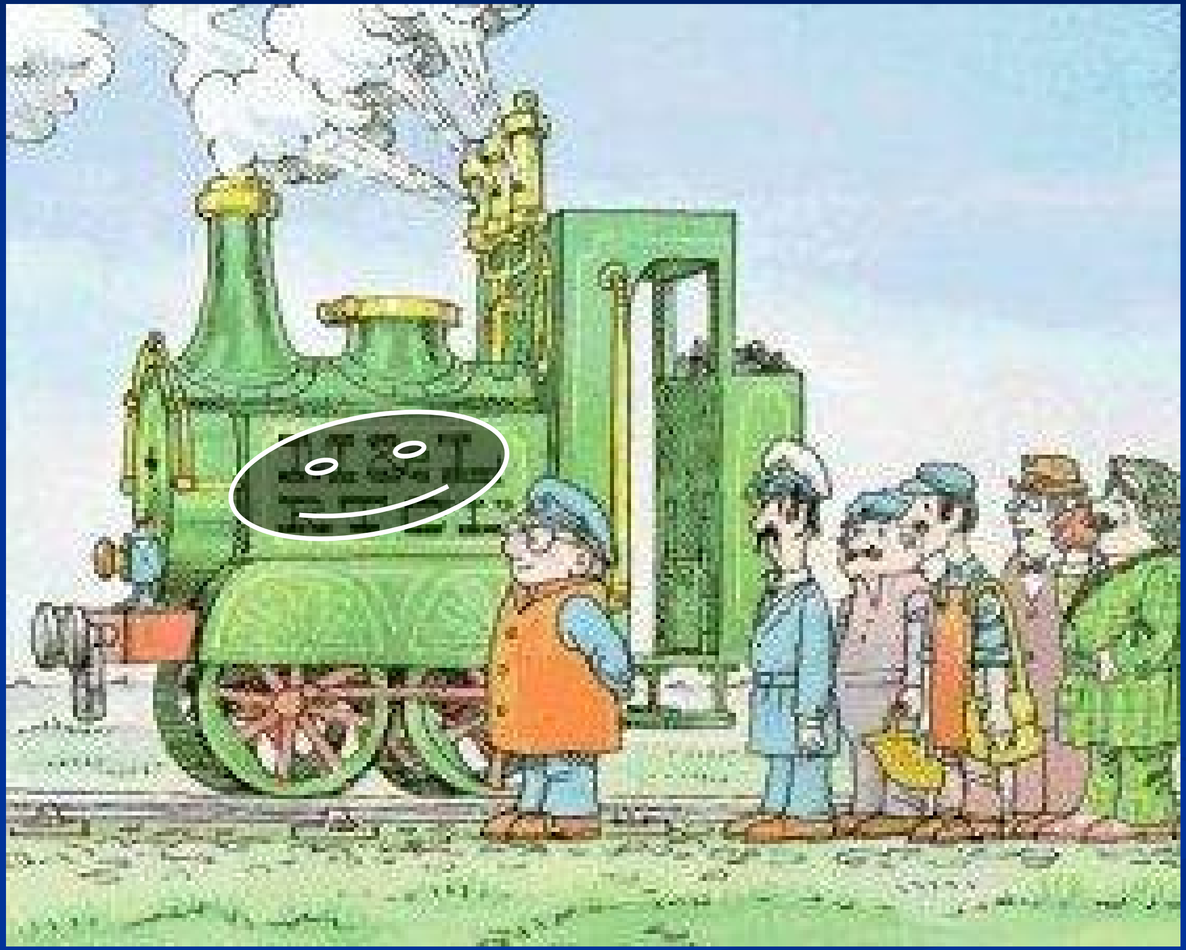
plenty of food!

they migrated there
HOW?

galaxy mergers

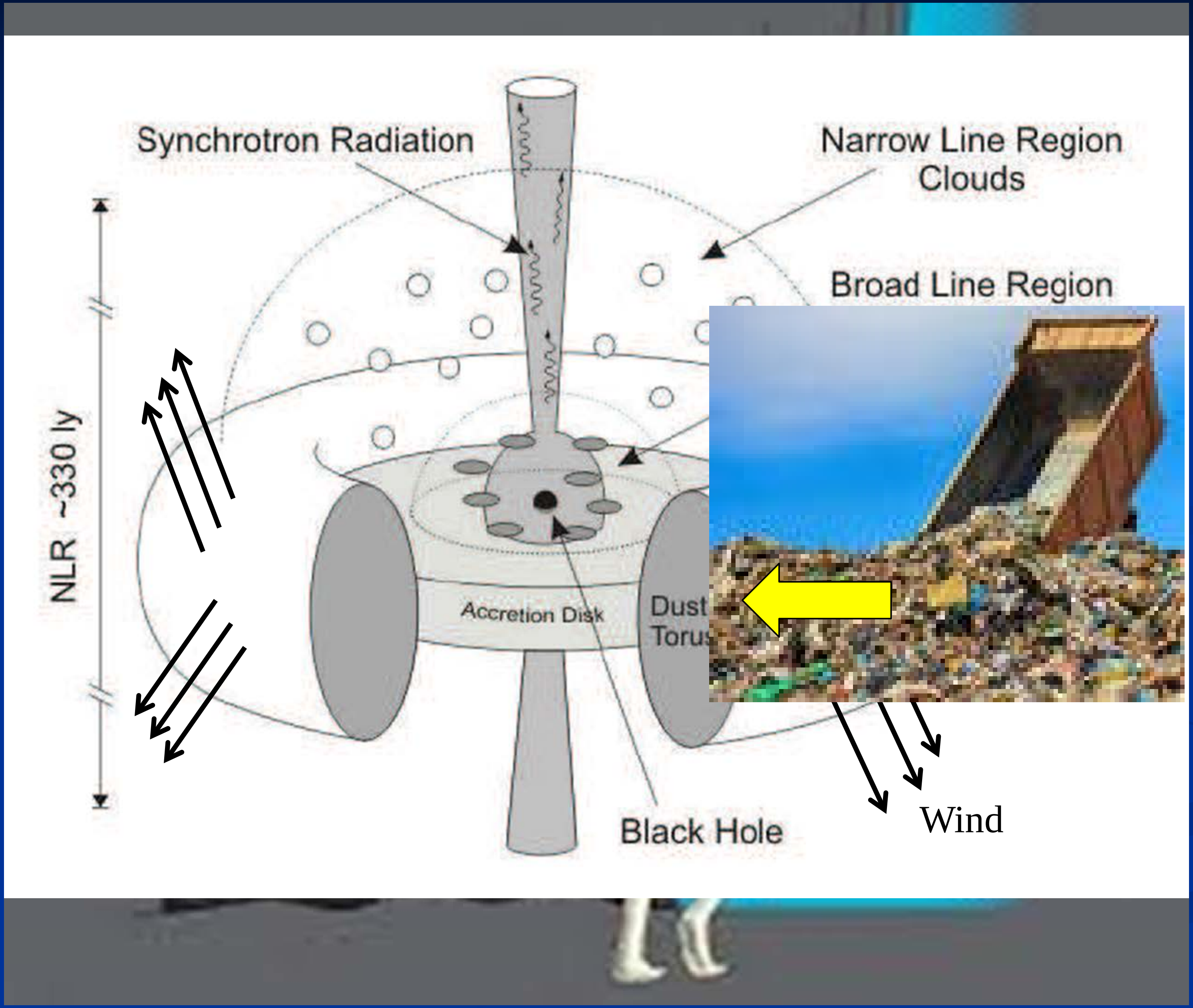
what else could we do?
(and there is plenty
of food there!)

THE CENTRAL ENGINE OF AGN



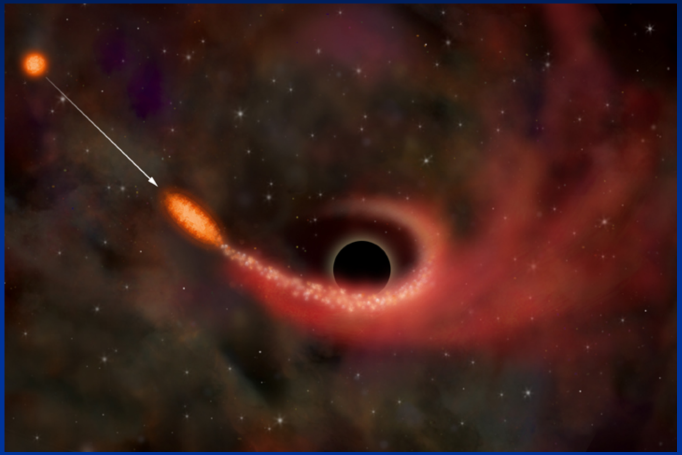
Supermassive black holes (SMBHs)

THE CENTRAL ENGINE: THE VIEW

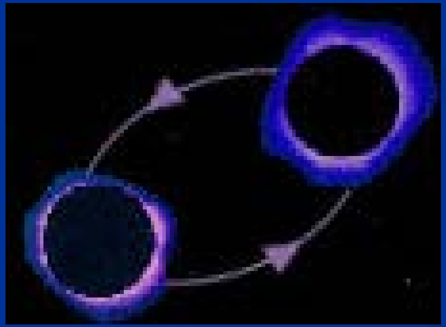


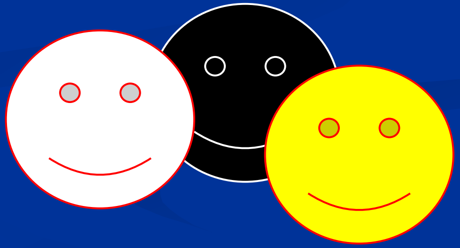
WHAT DO AGN EAT?

stars: whole and
digested

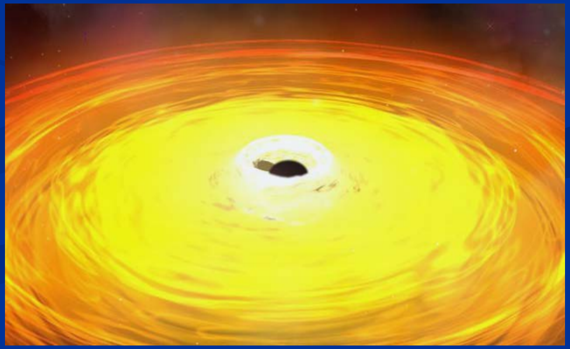


compact objects:
white dwarfs
neutron stars
BHs, SMBHs





gas, gas clouds: gas accretion



Black holes eat everything

REVIEW ARTICLE

The fuelling of active galactic nuclei

Isaac Shlosman, Mitchell C. Begelman & Julian Frank

We review accretion mechanisms for powering the central engines of active galactic nuclei (AGN) and possible sources of fuel. Local sources, such as dense star clusters, require extreme set of parameters. Instead we argue that the interstellar matter in the main body of the host galaxy is channelled towards the centre and address the problem of angular momentum transport. Thin accretion disks are not a viable means of delivering fuel to luminous AGN on scales much larger than a parsec because of the long inflow time and effects of self-gravity. There are also serious obstacles to maintaining and regulating geometrically thick, hot accretion flows. We emphasize the role of non-axisymmetric perturbations of the gravitational potential on galactic scales and their triggers: galaxy interactions and internal self-gravitational instabilities. We outline a unified model for fuelling AGN, in which the inflow on large scales is driven by gravitational torques, and on small scales forms a mildly self-gravitating disk of clouds with inflow driven by magnetic torques or cloud–cloud collisions.

THE term 'active galactic nucleus' refers to nuclei that exhibit an anomalous energy output, compared to that expected from a 'normal' mixture of stars and gas. It is usually reserved for

the largest scales (beyond a few tens of parsecs) inflow is likely to be driven by gravitational torques. We discuss how each of these mechanisms contributes to the fuelling, and how an epi-

AGN FUEL SOURCES

❖ Tidal disruption events (TDEs): stellar disruptions by SMBHs

When a wandering star finds itself within

$$R_p \leq R_t \sim \left(\frac{M_{\rm BH}}{\rm M_*}\right)^{1/3} R_*$$

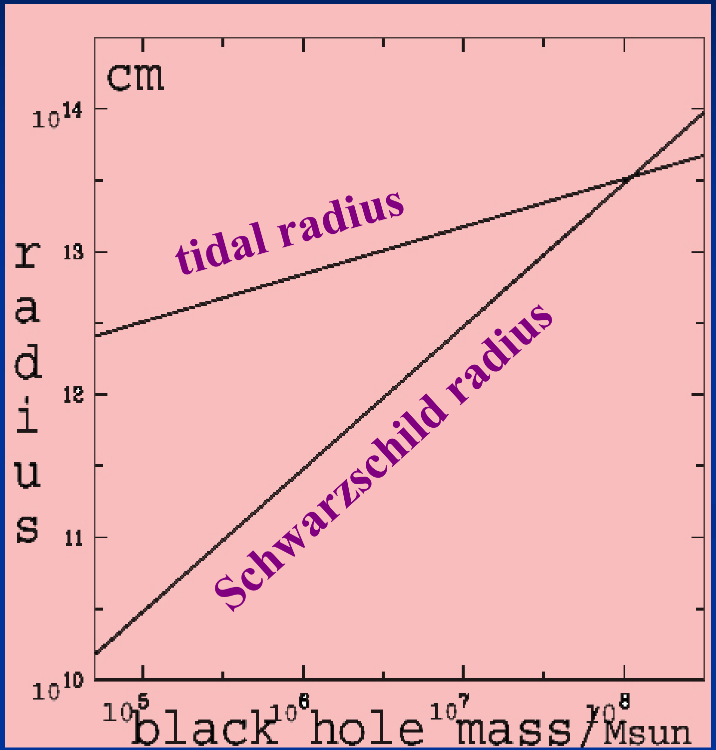
it is tidally disrupted

For solar type star

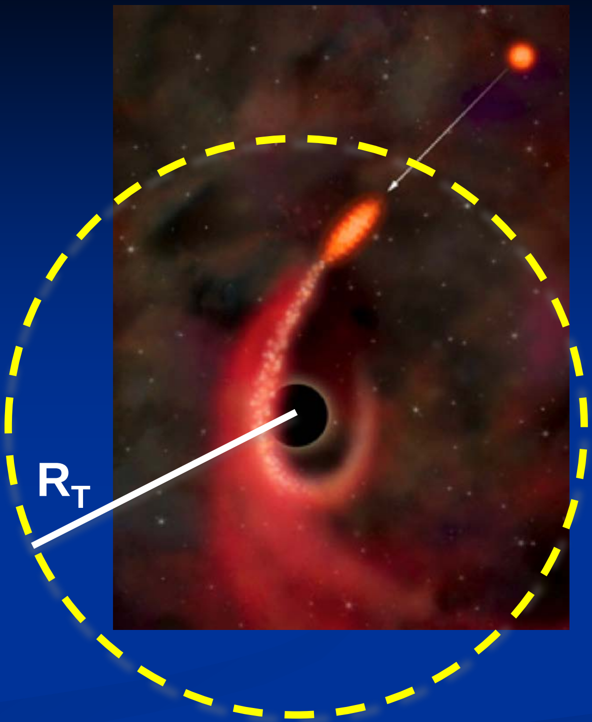
$$R_t \geq R_s = \frac{2GM_{\rm BH}}{c^2}, \;\; \text{for } M_{\rm BH} \leq 10^8 M_\odot$$

Rate of TDEs ~ 10^{-4}-10^{-5} $yr^{-1}gal^{-1}$

(e.g. Magorrian & Tremaine 1999)



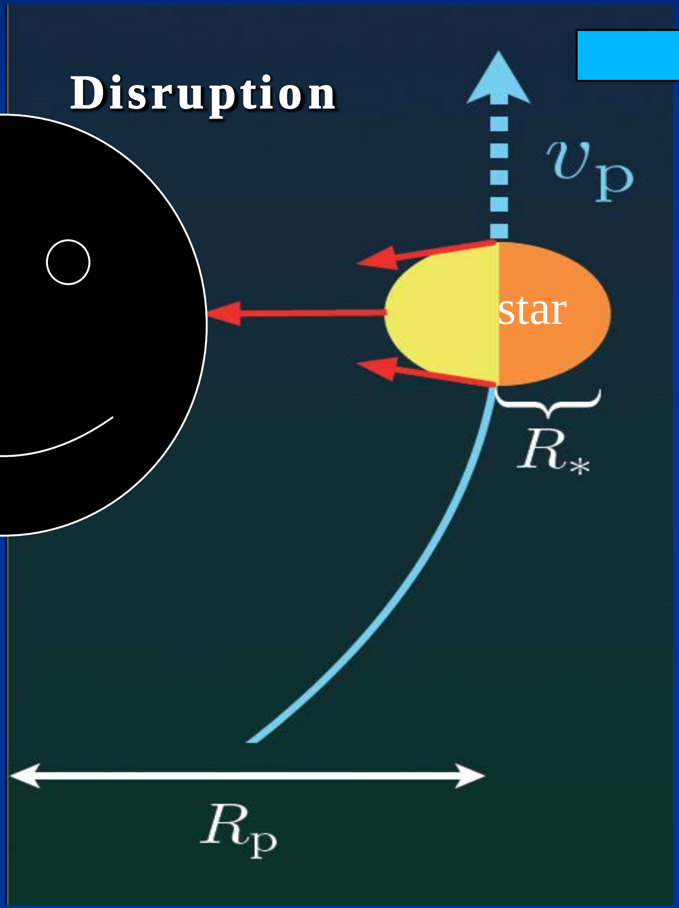
star is ripped apart once the BH's tidal forces exceed the selfgravity of the star

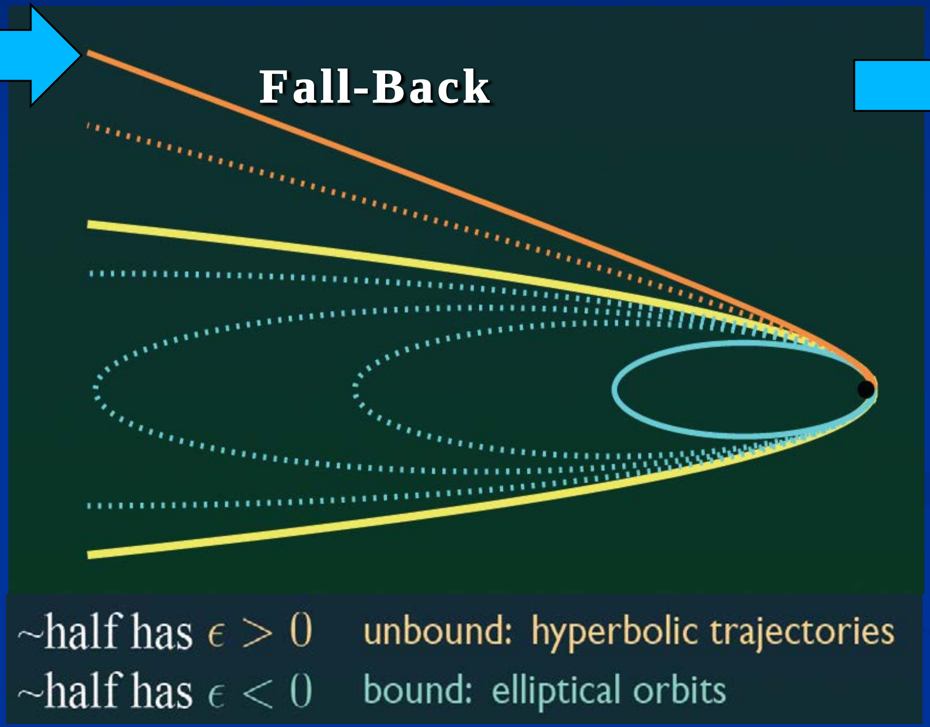


AGN FUEL SOURCES

❖ Tidal disruption events (TDEs): stellar disrruptions by SMBHs

(Rees 1988; Phinney 1989; Evans & Kochanek 1989)



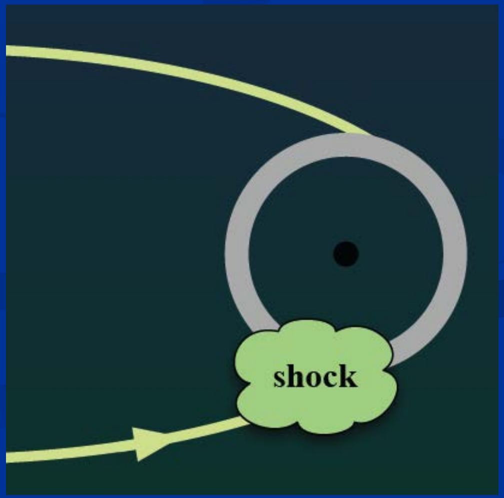


After passing nozzle, gas collides with incoming part of itself (GR precession)
→ shock
Keeps hitting itself as it orbits around the SMBH shrinks
→ orbit circularization

Circularization and Accretion

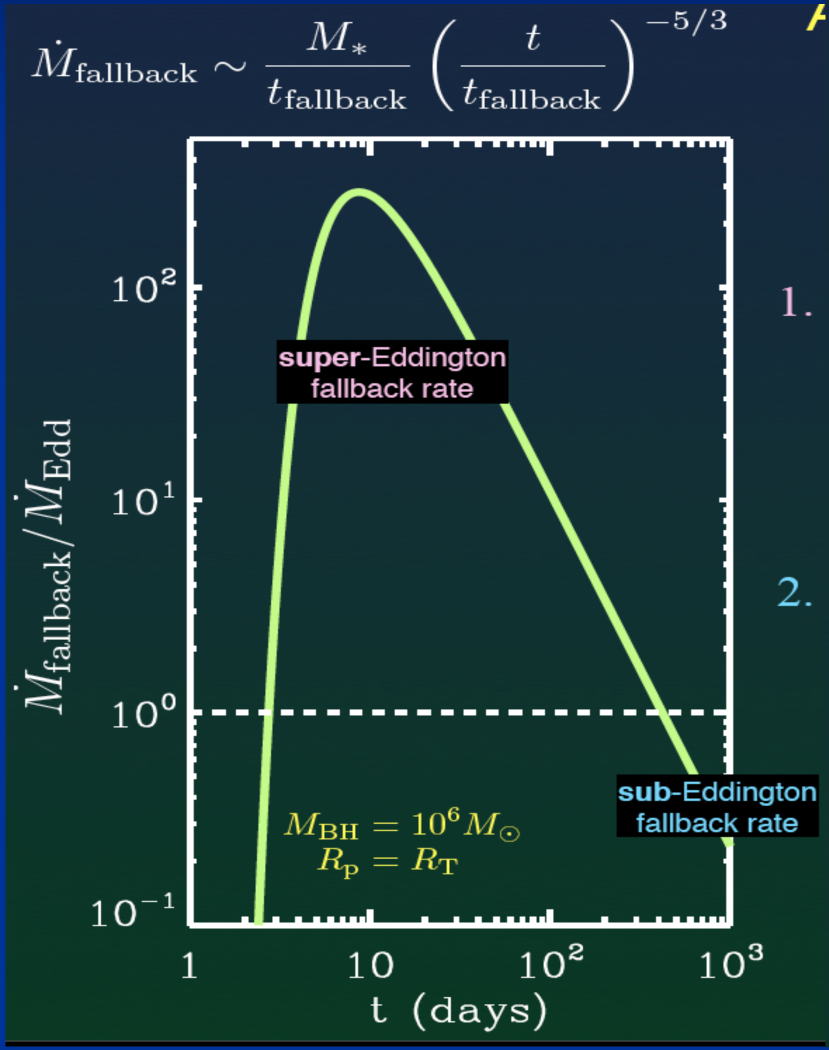
$$\dot{M}_{fallback} \sim \frac{M_*}{t_{fallback}}\left(\frac{t}{t_{fallback}}\right)^{-5/3}$$

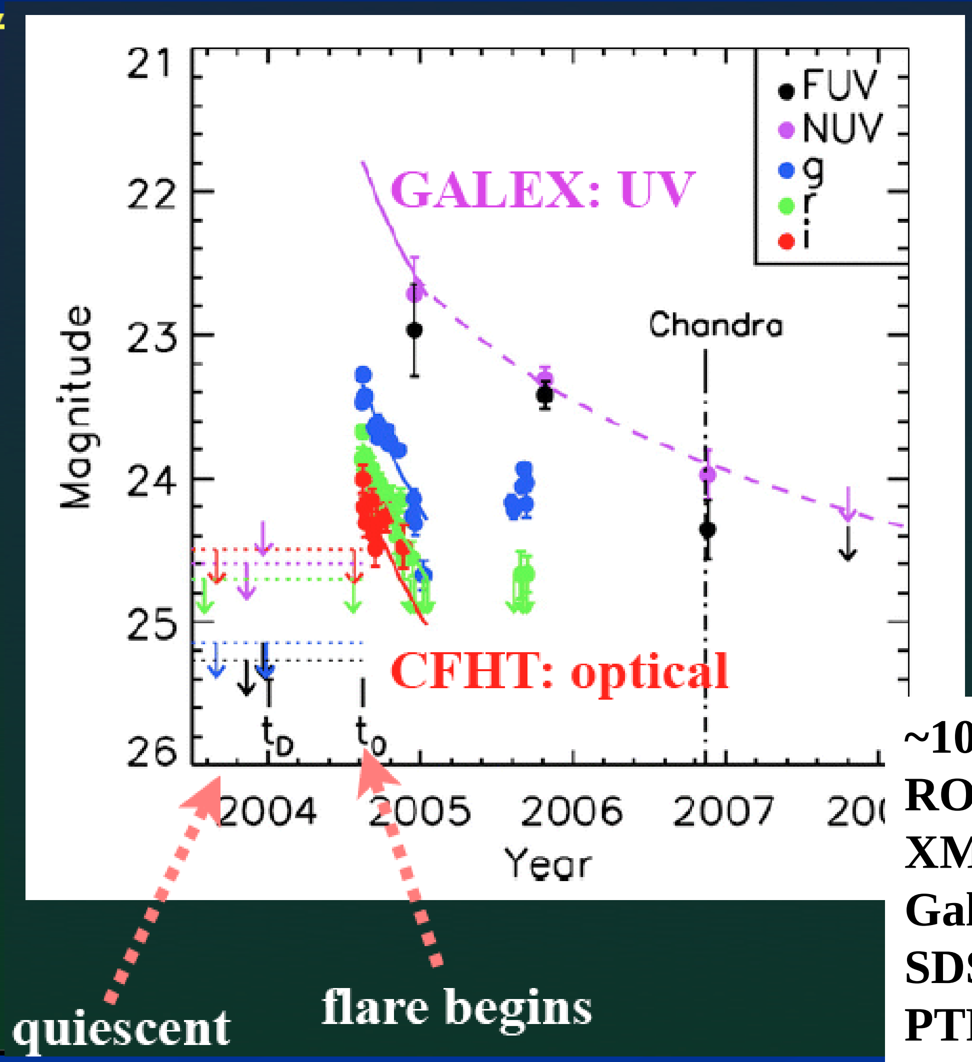
$$t_{fallback} \sim days$$



AGN FUEL SOURCES

❖ Tidal disruption events (TDEs): post-disruption "flares" in UV/optical/X-ray bands



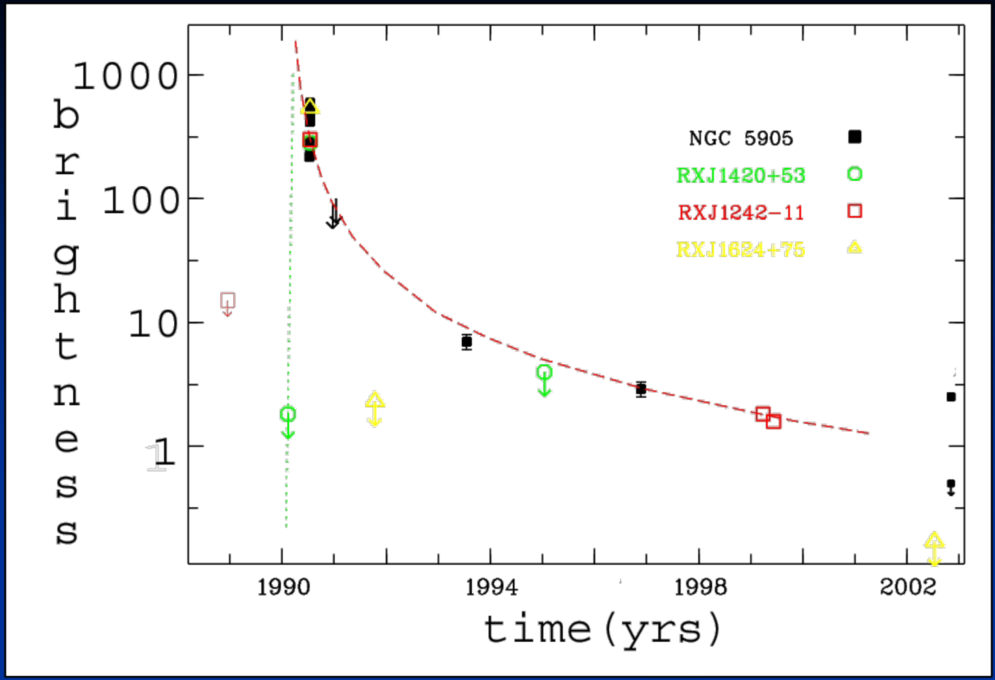


Gezari et al. 2008

~10 Candidate Detections so far by
ROSAT All-Sky Survey (Komossa 2002)
XMM Slew Survey (Esquej et al. 2007)
Galex Deep Imaging (Gezari et al. 2009)
SDSS Stripe 82 (van Velzen et al. 2010)
PTF (Cenko et al. 2010)

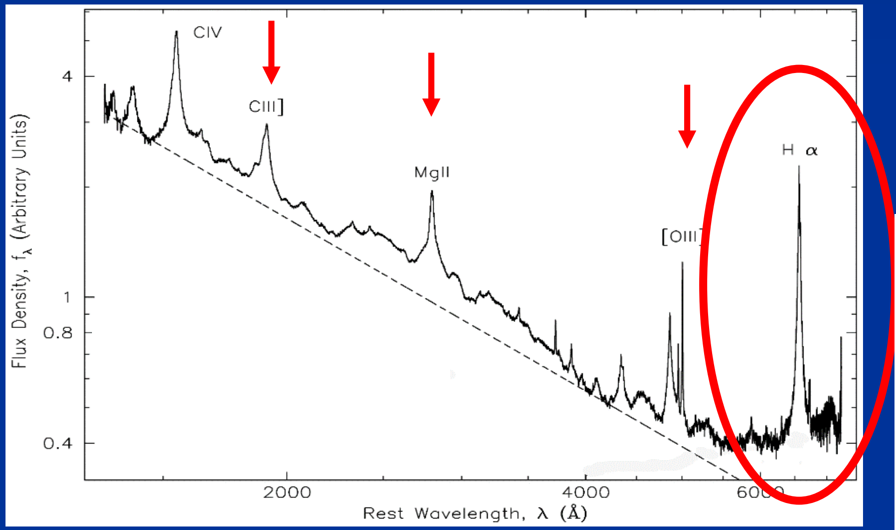
AGN FUEL SOURCES

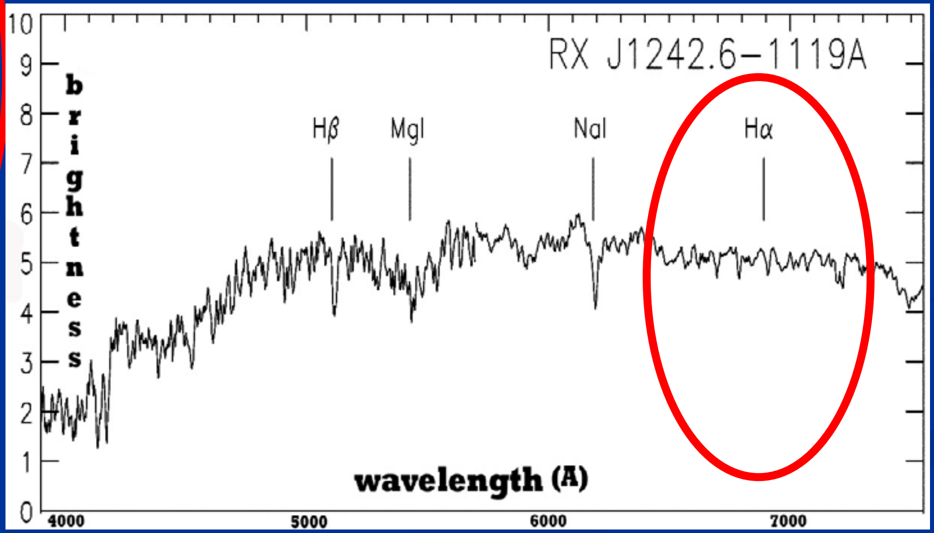
- TDEs: detected X-ray flares



Enormously powerful outburst of X-ray radiation from several galaxies

Normal, inconspicuous, non-active galaxies





X-rays dropped by factors up to 6000, years after the peak

AGN FUEL SOURCES

Swift J1644+57 gone MAD: the case for dynamically-important magnetic flux threading the black hole in a jetted tidal disruption event

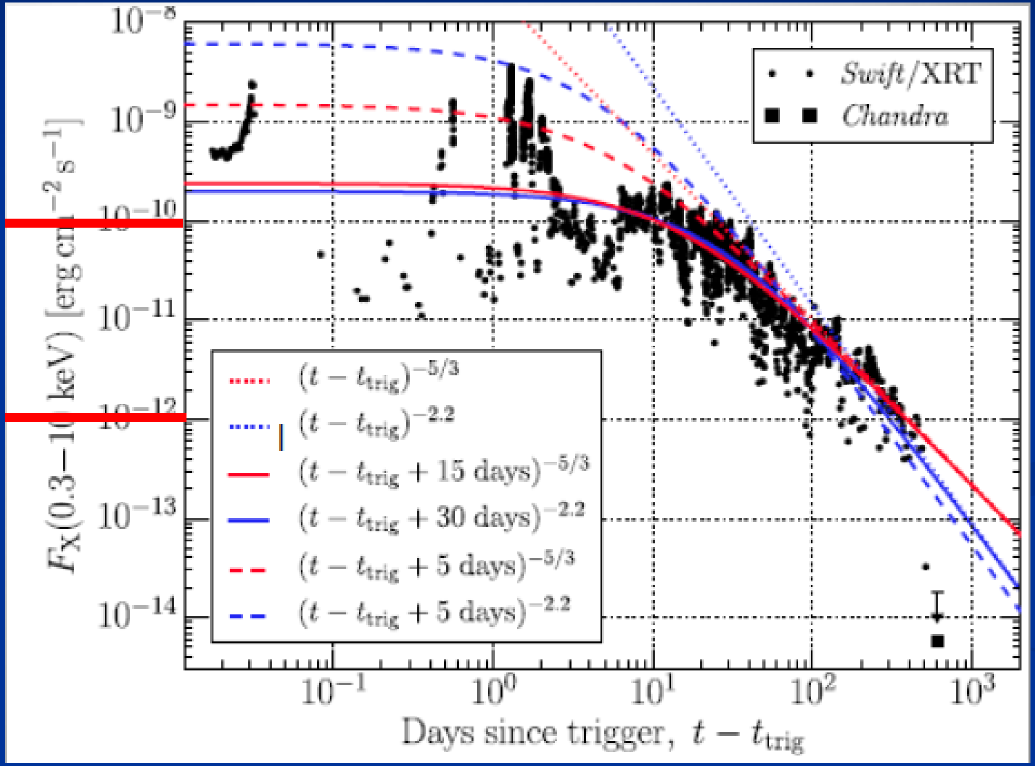
Alexander Tchekhovskoy[1★], Brian D. Metzger[2], Dimitrios Giannios[3], and Luke Z. Kelley[4]

❖ TDEs: detected X-ray flares

Super-Eddington TDE Swift J1644+57

~100 L_E

~L_E



Tchekhovskoy et al. (2014)

X-ray curve measured by Swift and Chandra.

$L \sim 2\times10^{47}$ erg/s

$M_\bullet \sim 10^6 M_\odot$

→ Swift + Chandra light curves

→ L corrected for beaming

→ Radio "re-brightening after ~ 4 months

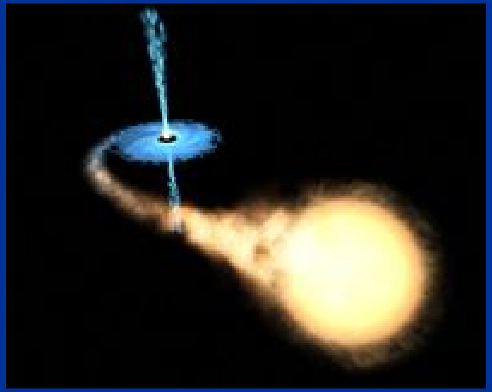
BY-PRODUCTS OF TDEs IN AGN

❖ Tidal disruption events (TDEs): jets?

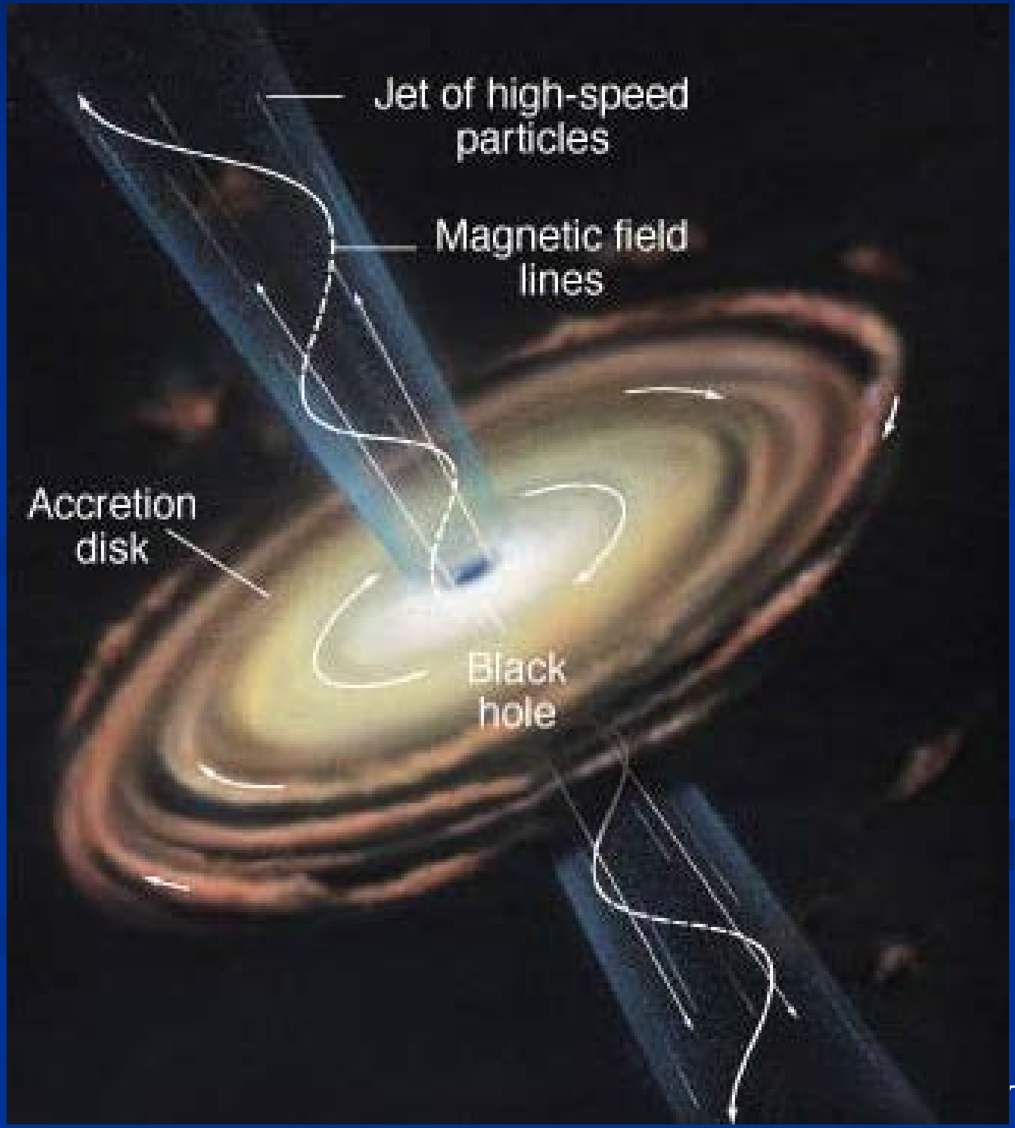
Where there is an accretion onto BHs → there are jets

A substantial fraction of gravitational (accretion) energy may be channeled into relativistic jets
→ non-thermal signatures from TDEs

jets in galactic centers

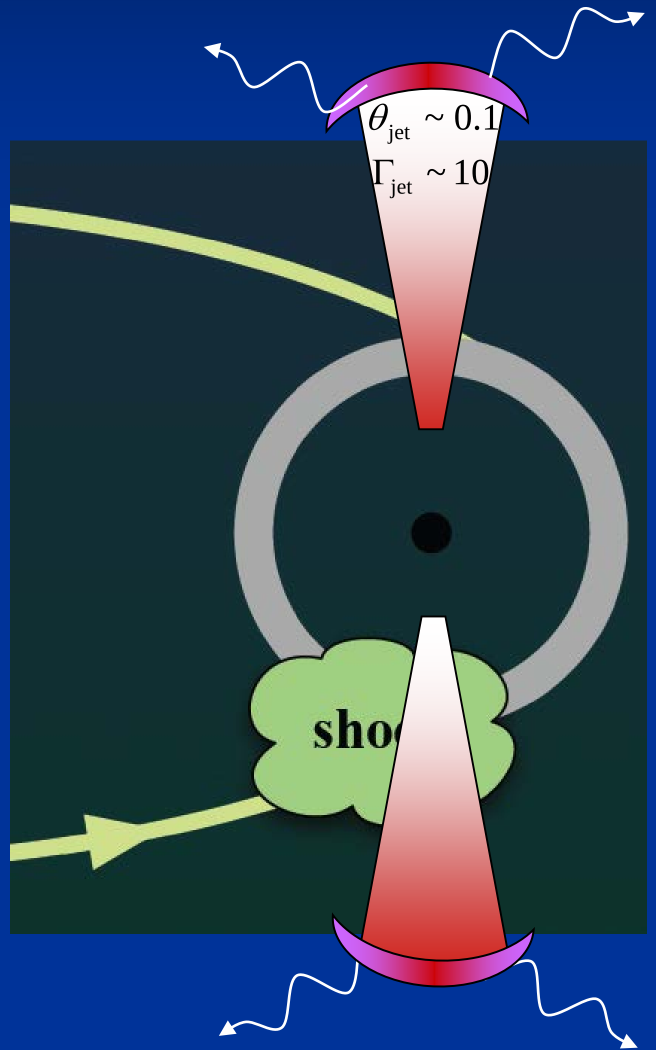


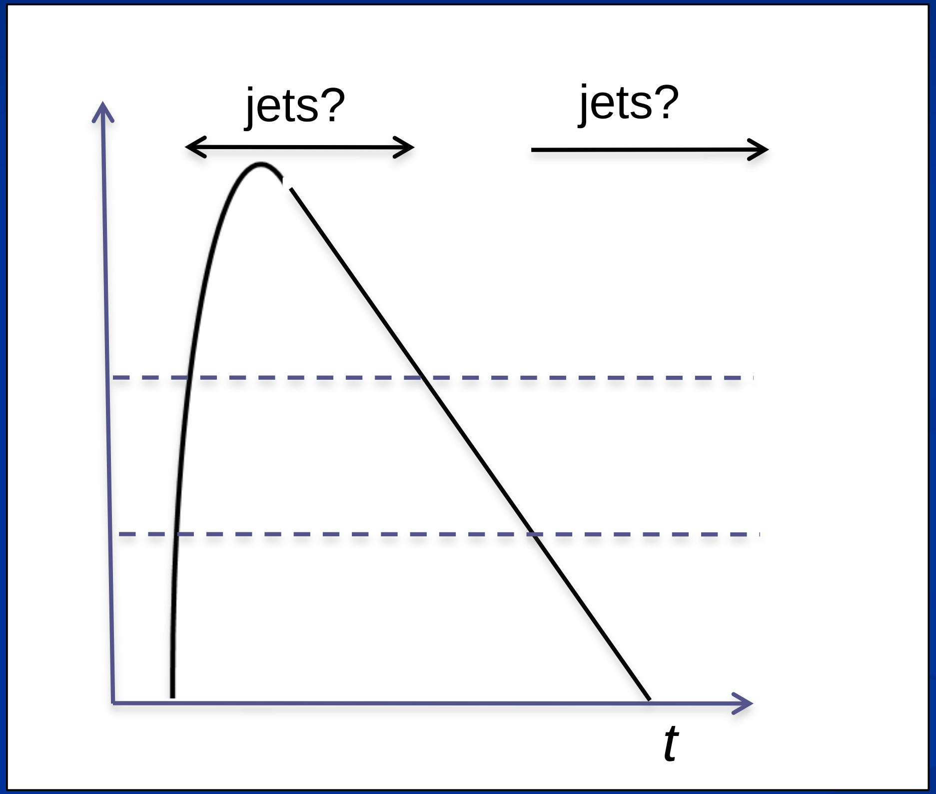
stellar binaries



BY-PRODUCTS OF TDEs IN AGN

Tidal disruption events (TDEs): radio-transients → jets? (Giannios & Metzger 2011)



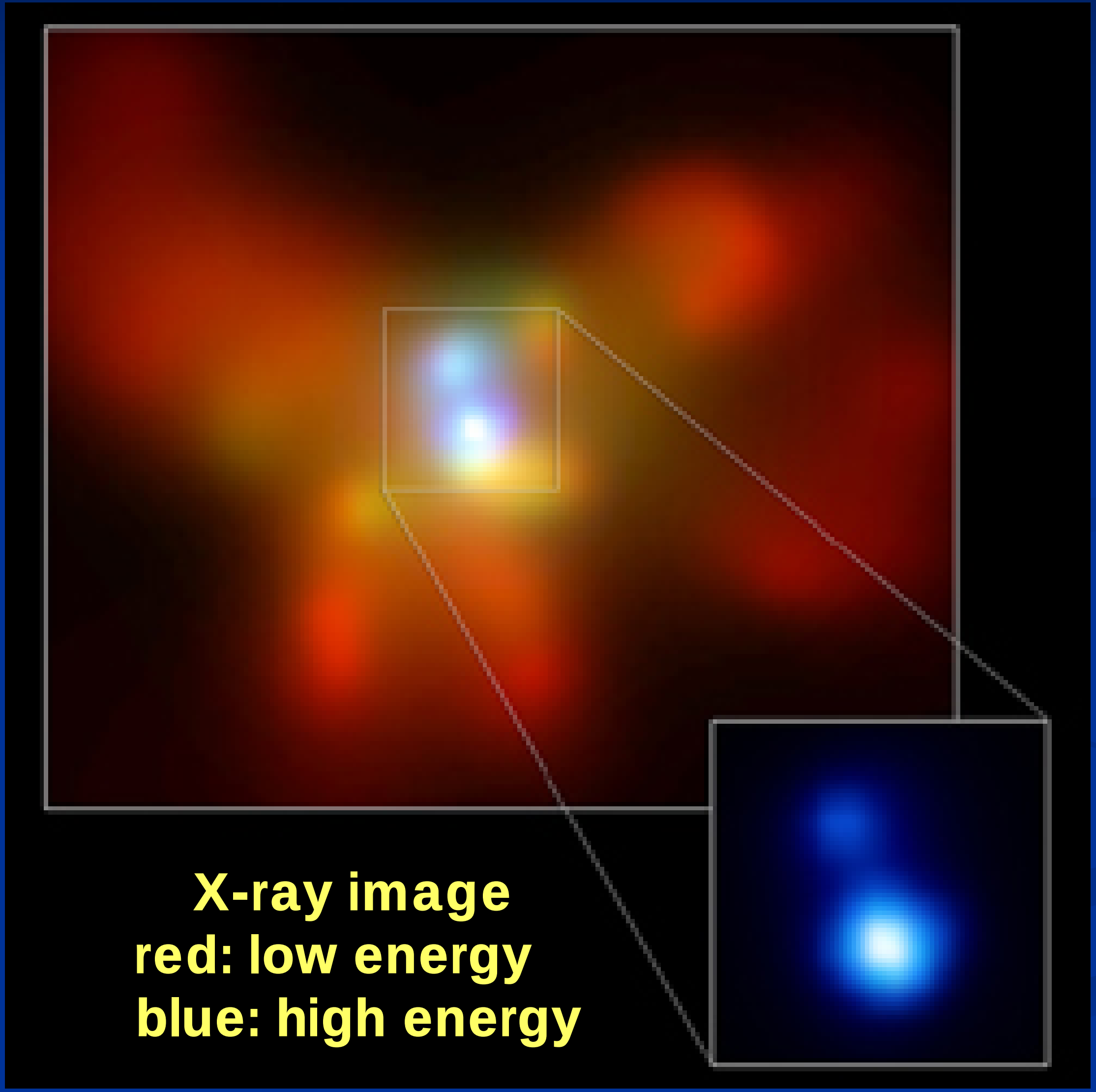


energy released $E_{\rm rel} \sim 0.1 M_{acc} c^2 \sim 10^{53}\,{\rm erg}$

energy in jets $E_{\rm jet} \sim \varepsilon_{\rm jet} E_{\rm rel} \sim 10^{51} \frac{\varepsilon_{\rm jet}}{0.01}\,{\rm erg}$

AGN FROM GALAXY MERGERS

❖ Galaxy mergers → SMBHs mergers → SMBH pairs → NGC 6240



When galaxies merge
→ their SMBHs merge
→ gravitational torques
→ gas channeling inward

Does this means AGN are only triggered in mergers? → No !

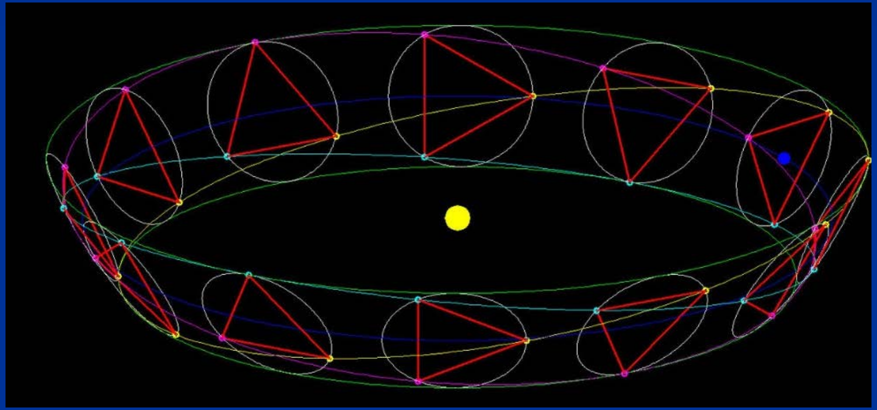
Maybe 20 % are,
what about the rest?

AGN FROM GALAXY MERGERS

❖ Galaxy mergers → SMBH mergers → detection

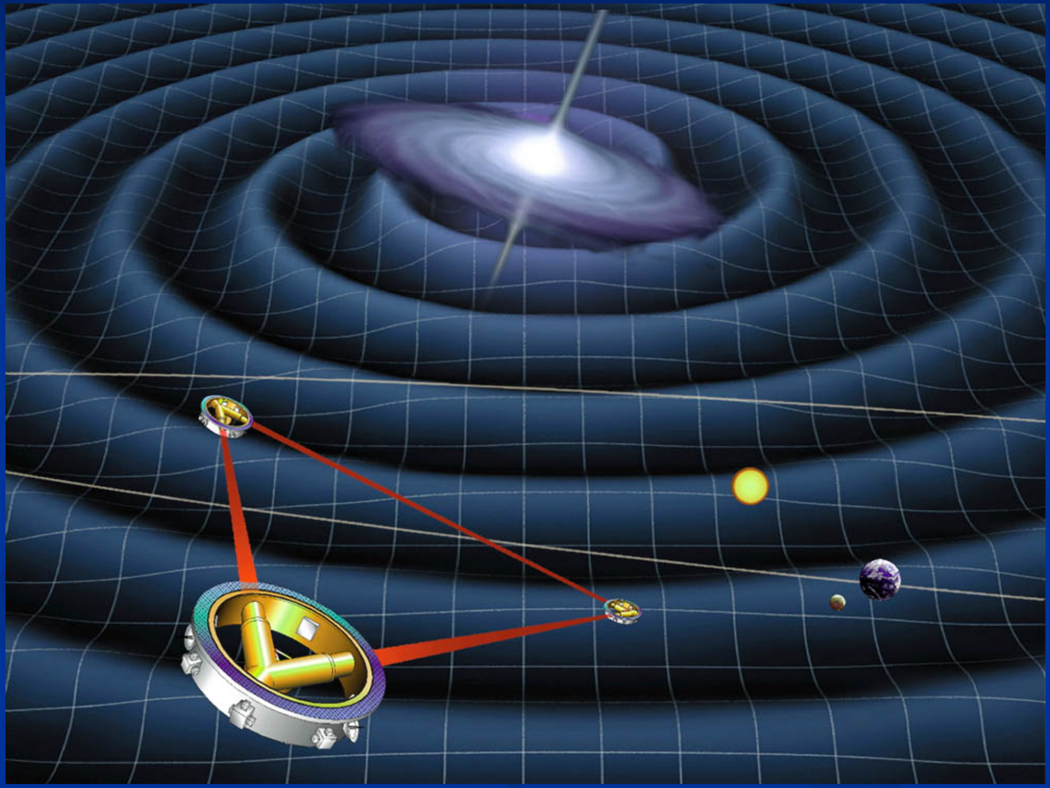
Future prospects:

detection of gravitational waves from the merging black holes



LISA configuration

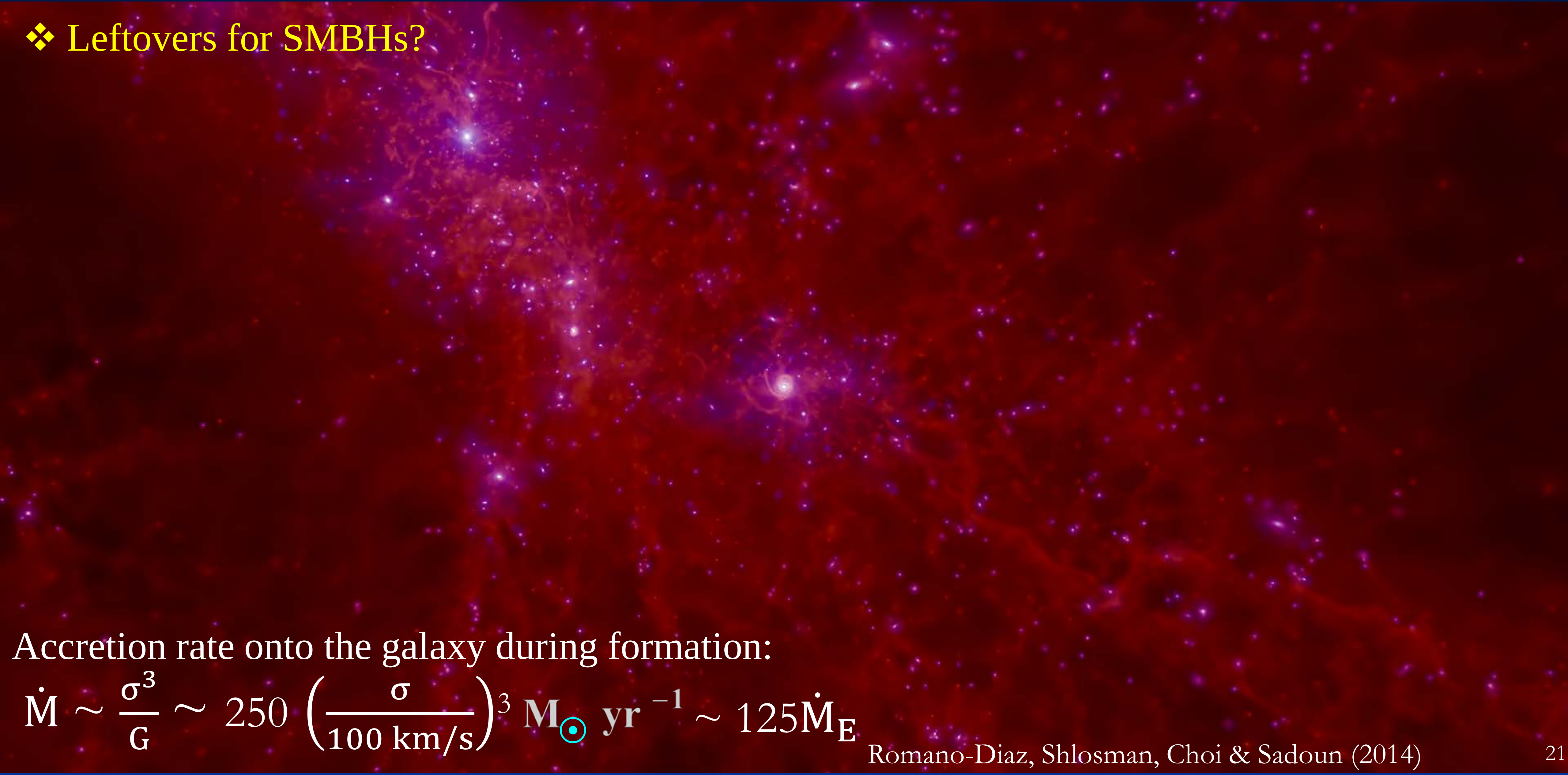
LIGO Hanford beam tube



gravitational waves from merging SMBHs: to be detected by LIGO and LISA

ACCRETION ONTO GALAXIES

- Leftovers for SMBHs?

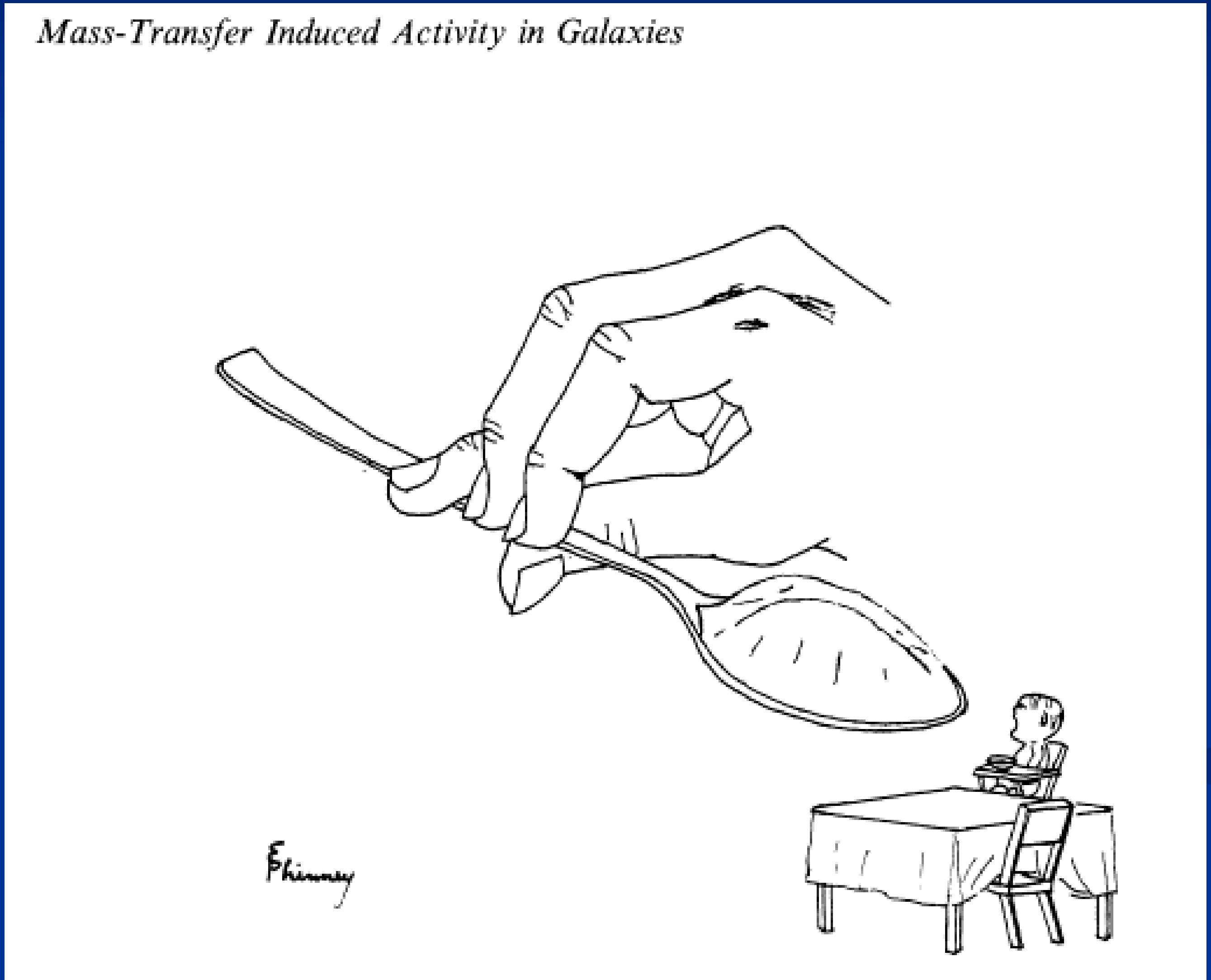


Accretion rate onto the galaxy during formation:

$$\dot{M} \sim \frac{\sigma^3}{G} \sim 250 \left(\frac{\sigma}{100\ \mathrm{km/s}}\right)^3 M_\odot\ \mathrm{yr}^{-1} \sim 125\dot{M}_E$$

Romano-Diaz, Shlosman, Choi & Sadoun (2014)

Too Little Food is Bad,
Too Much Food is Worse



ACCRETION ONTO GALAXIES

- How to get the gas to the center: feeding the SMBHs

Using galactic morphology and gravitational torques

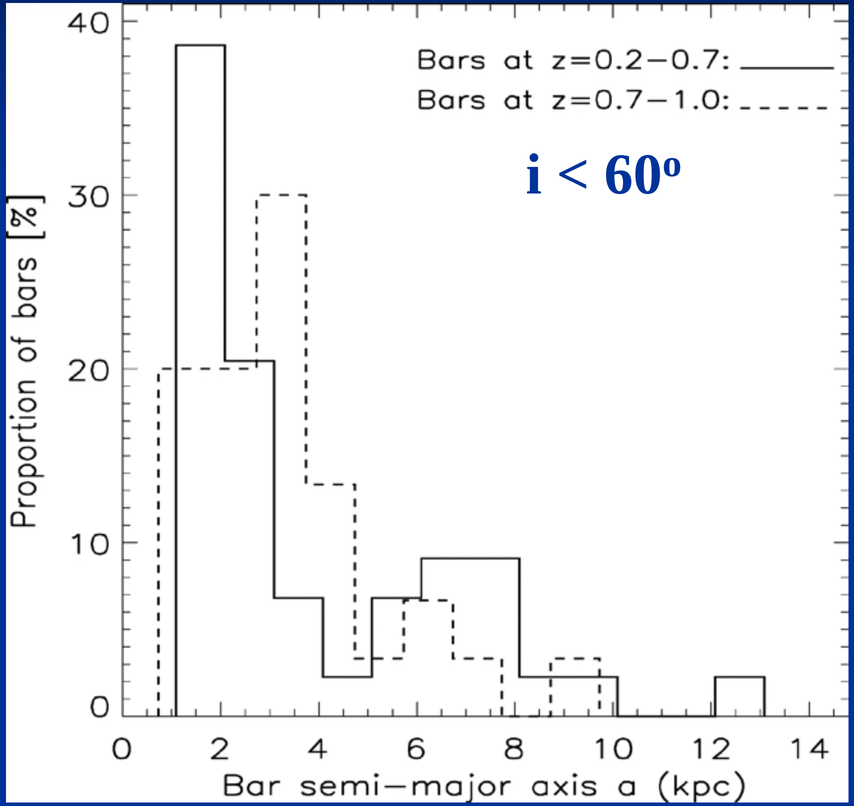
Bars are strong, stable, bi-symmetric perturbations of axial symmetry:

$F_\varphi / F_r \sim 100\ \%$

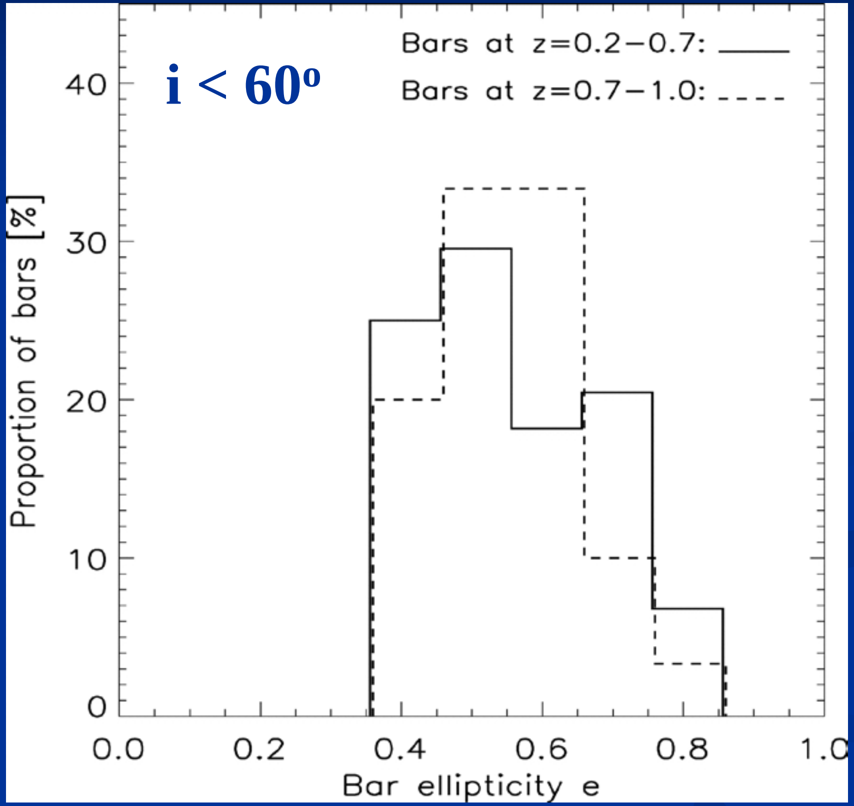
bars trap stellar (or gas) orbits: they are self-gravitating

WHAT and WHERE ARE BARS?

➢Bar fraction with z



➢Bar strength with z



GEMS: GOODS (HST)
+ COMBO-17

(Jogee, Barazza, Rix, Shlosman & GOODS Team 2004)

Large (a>1.2 kpc) strong (e>0.4) bars: no evolution with z: $30\% \pm 6\%$

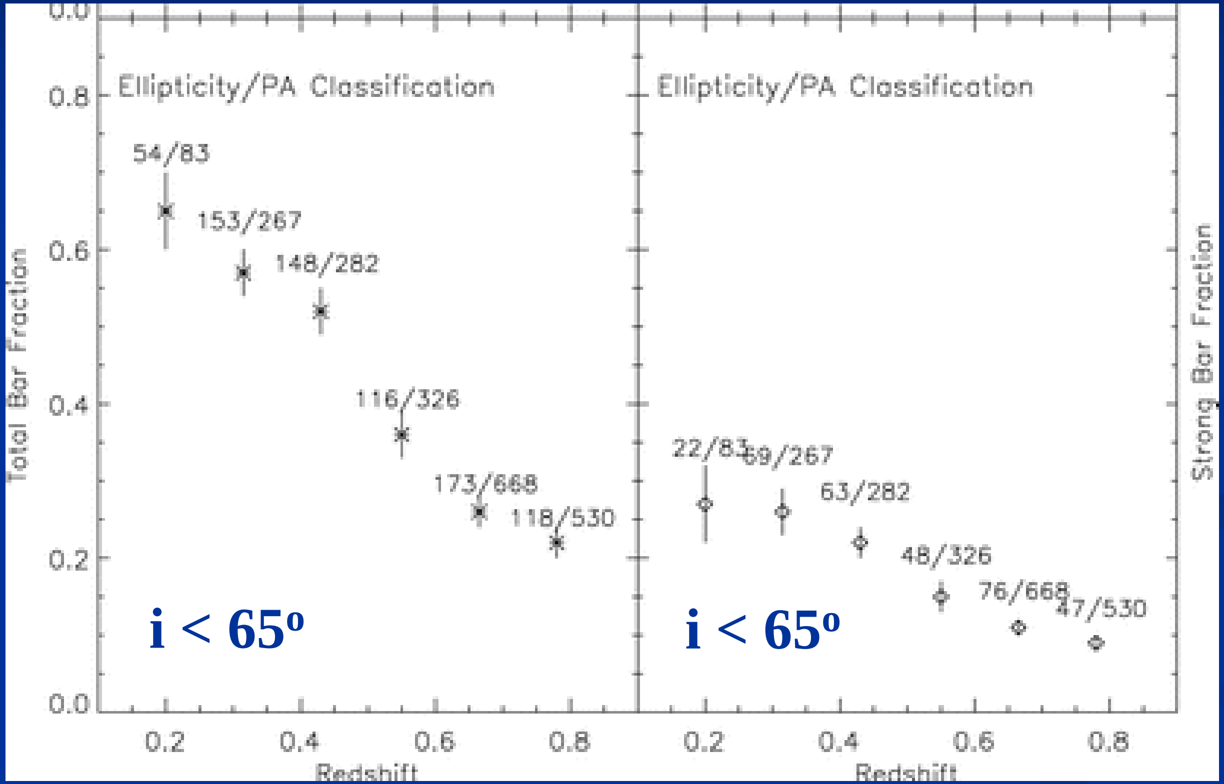
WHAT and WHERE ARE BARS?

➢ **Bar fraction with z:**

COSMOS survey (Sheth et al. 2008)

Large (a > 2 kpc) bars in massive disk galaxies: constant with z,

In low-mass blue spirals decline for z > 0.3



weak bars | strong bars

Overall: **Jogee et al. (2004) and Sheth et al. (2008)**
→ weak decline of ~2 between z~0.2-1

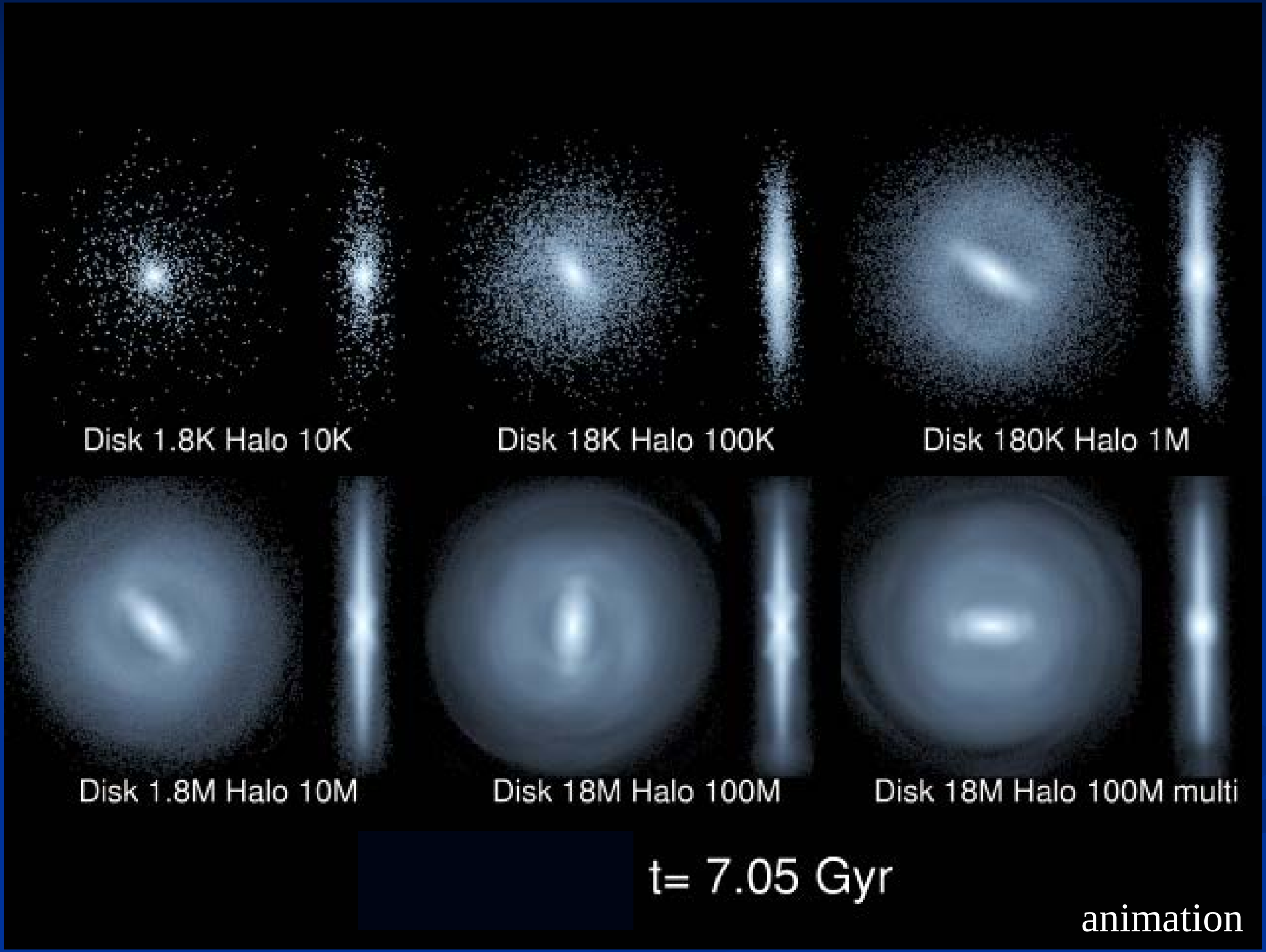
THE ORIGIN OF BARS?

Stellar bars forming as
a result of the bar instability?

Numerical convergence study:

DM halo: N=10K → 10^8→10^{10}

Disk: N=1.8K → 1.8 x 10^7

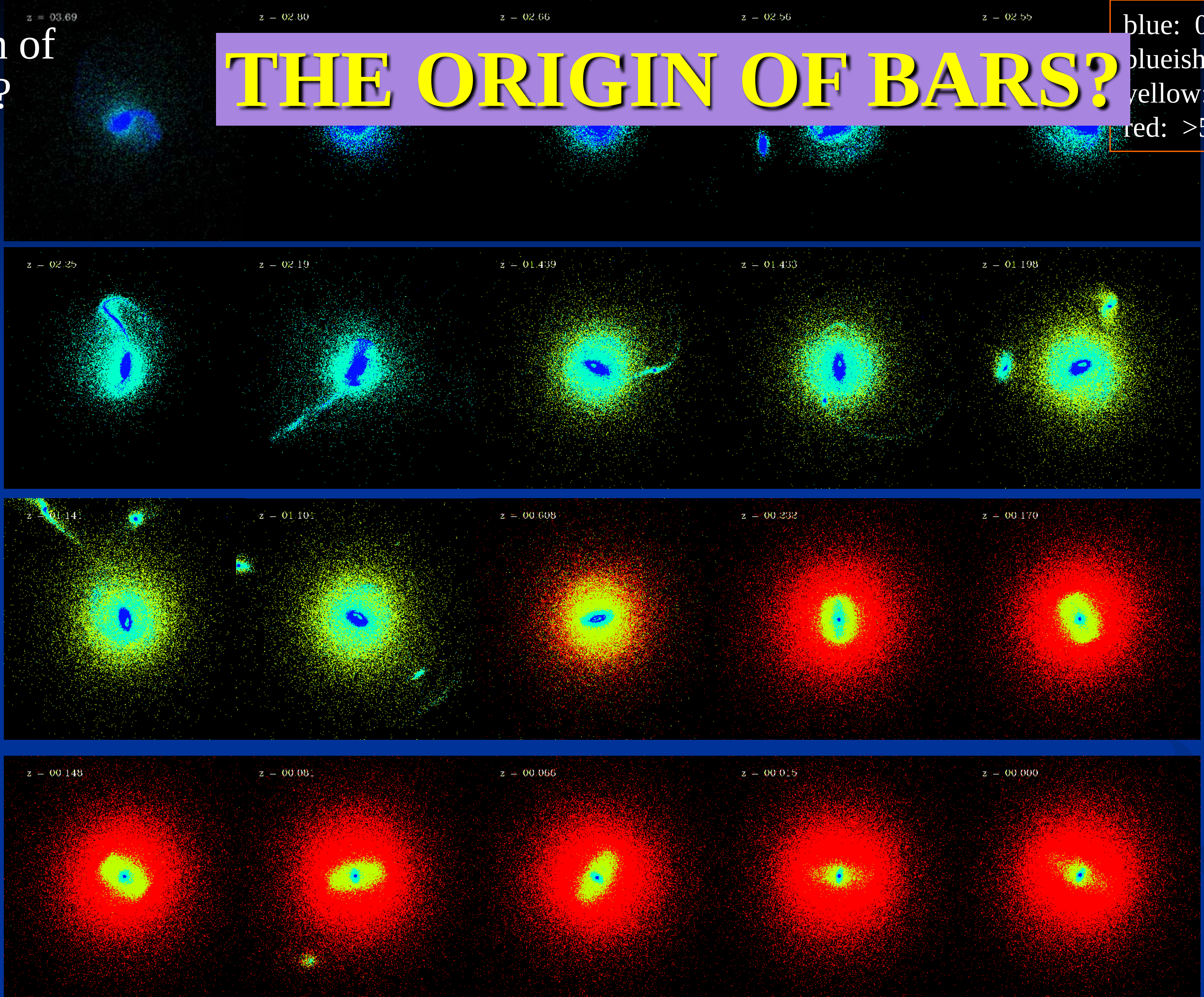


Dubinski, Berentzen & Shlosman (2009)

THE ORIGIN OF BARS?

Tidal origin of stellar bars?

blue: 0-0.2 Gyr
blueish: 0.2-2 Gyr
yellow: 2-5 Gyr
red: >5 Gyr

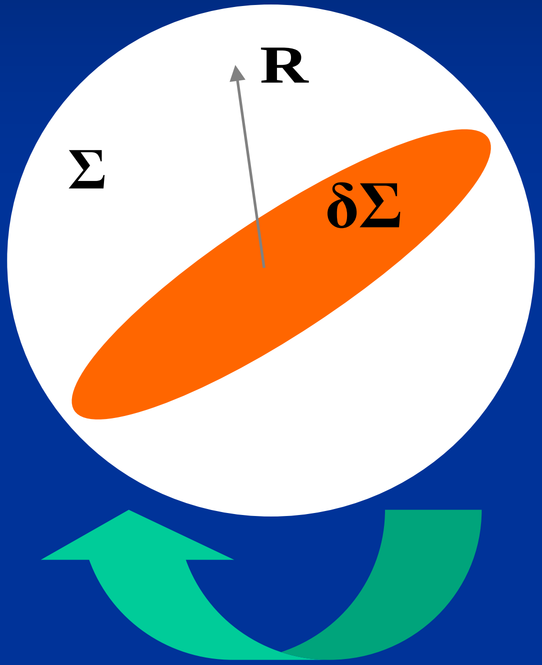


Romano-Diaz et al. (2008)

WHAT BARS CAN DO?

- Gravitational torques

disk M_d inside spherical DM halo M_h subject to m=2 perturbation:



$T \sim G(\delta\Sigma)^2 R^3$ **torque from the perturbation**

$J(<R) \sim R^3 \Sigma v_\varphi$ **angular momentum in the disk**

$\tau_J \sim J/T \sim (M_h/M_d)(\Sigma/\delta\Sigma)^2 \tau_{dyn}$ ***J*-loss timescale**

$\Sigma/\delta\Sigma \sim 0.01$ **spiral arm**

$\Sigma/\delta\Sigma \sim 1$ **bar**

effective gravitational viscosity:

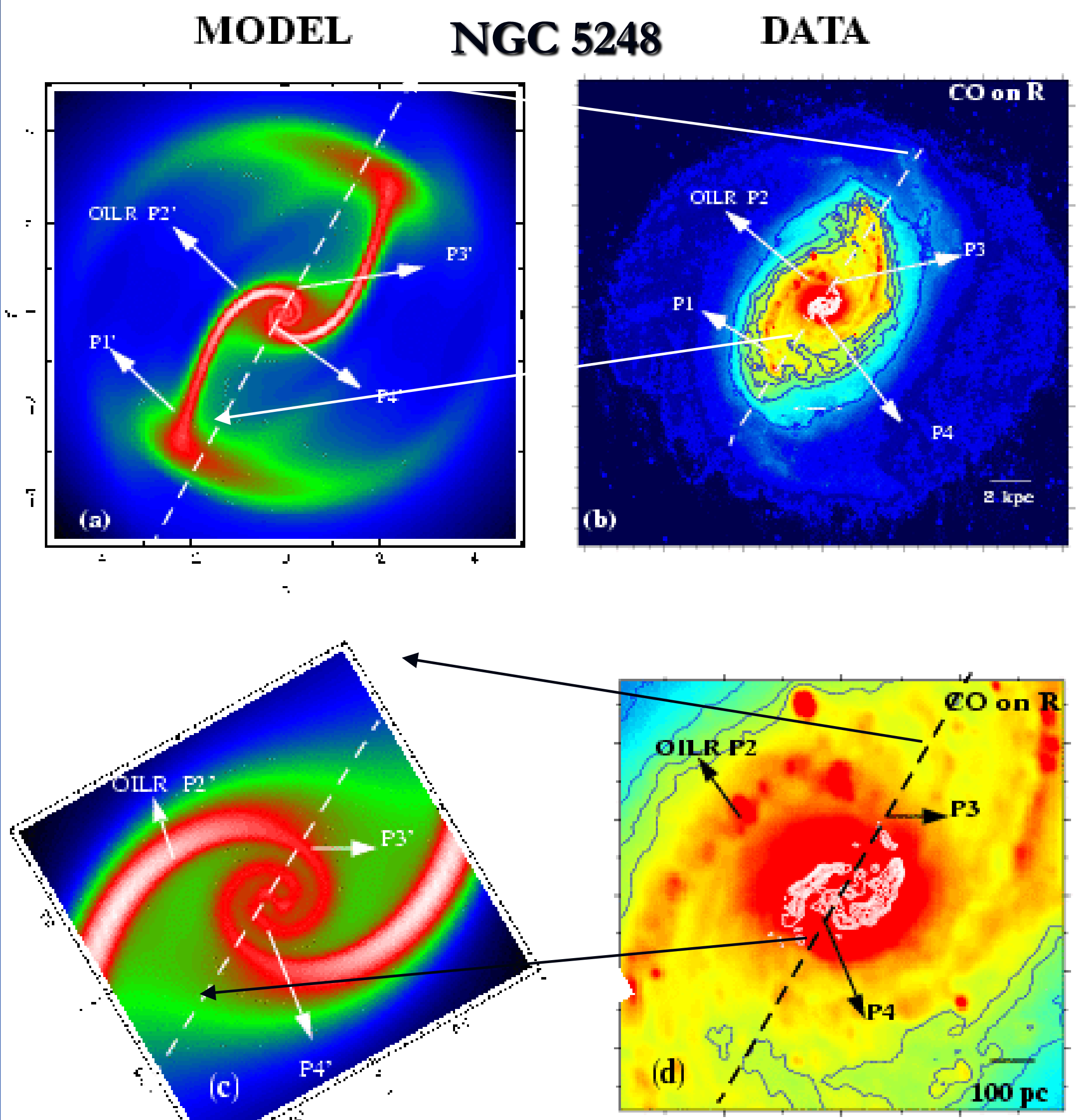
$\lambda_{max} \sim G\Sigma/\Omega^2$ → $\nu_{eff} \sim \lambda_{max}/t_{orb}$

if gas present → torque from stars on gas:

$$\text{torque} = -\left[\int_0^{2\pi}\int_0^{\infty} \Sigma^a(r,\phi)\frac{\partial\Phi^a_{gas}(r,\phi)}{\partial\phi}\right] r\,dr\,d\phi,$$

WHAT BARS CAN DO?

- Bars drain angular momentum from the gas



Jogee et al. (2002)

gas inflow

nuclear starbursts
at ~ 1 kpc

growing bulge:
exponential n < 2,
in contrast to
"classical" bulge
with n > 2

•fueling SMBH ?
(SFB89; Englmaier & Shlosman 04)

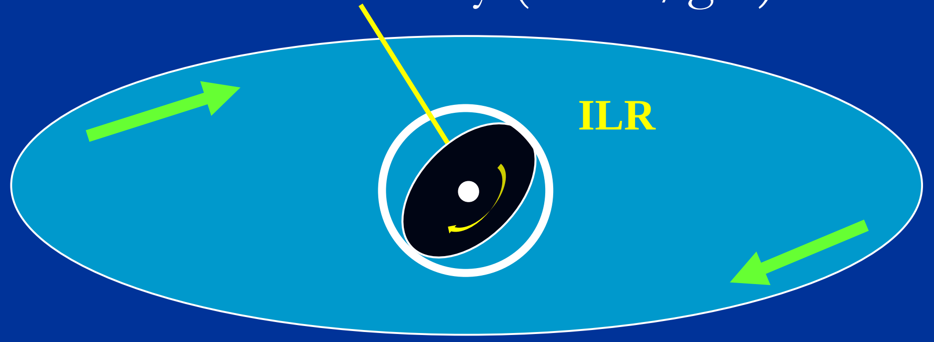
WHAT BARS CAN DO?

- **Nested bars:** bars-in-bars mechanism

theoretical perspective

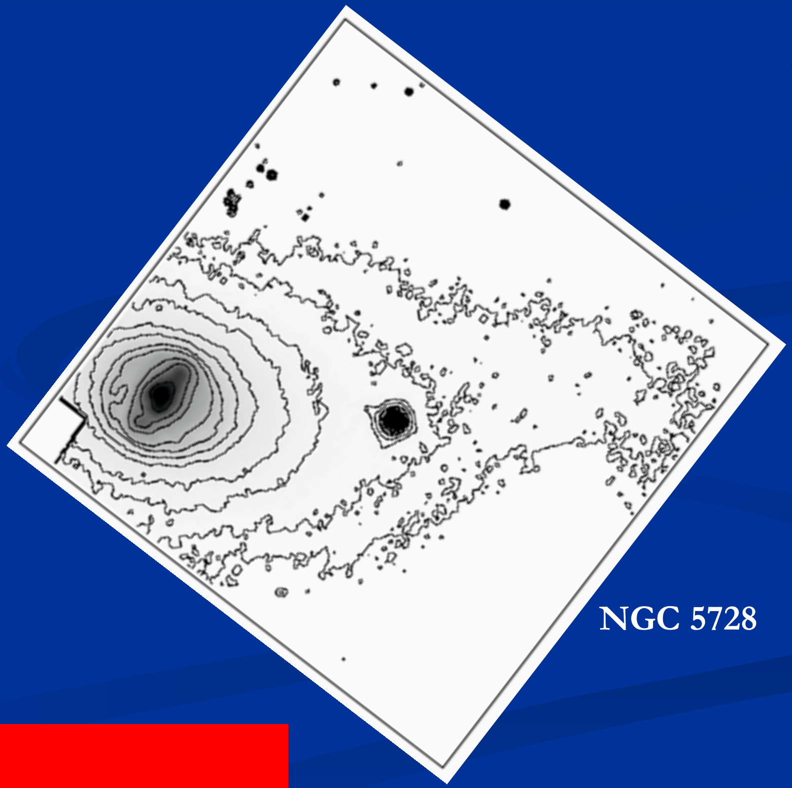
How do nested bars form?
Are nuclear bars secondary and triggered by the gas inflow?

secondary (stellar/gas) bar



primary (stellar/gas) bar

(Shlosman, Begelman & Frank 1988/1989/1990)

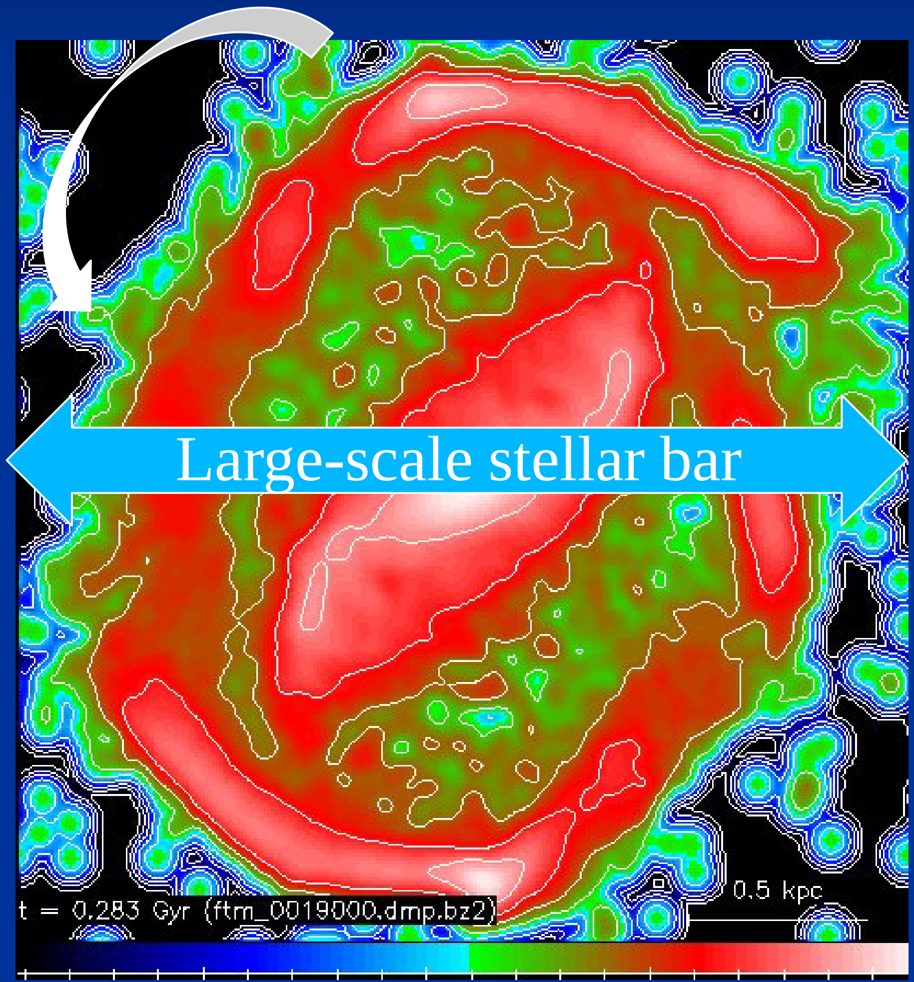


NGC 5728

Can be in dynamically coupled (co-rotating) and decoupled (tumbling with different speeds) states

GAS INFLOW WITH NESTED BARS

- Nested bars: inner gas bar
- → avalanche type inflow



Dynamical Decoupling of Nested Bars: Self-Gravitating Gaseous Nuclear Bars

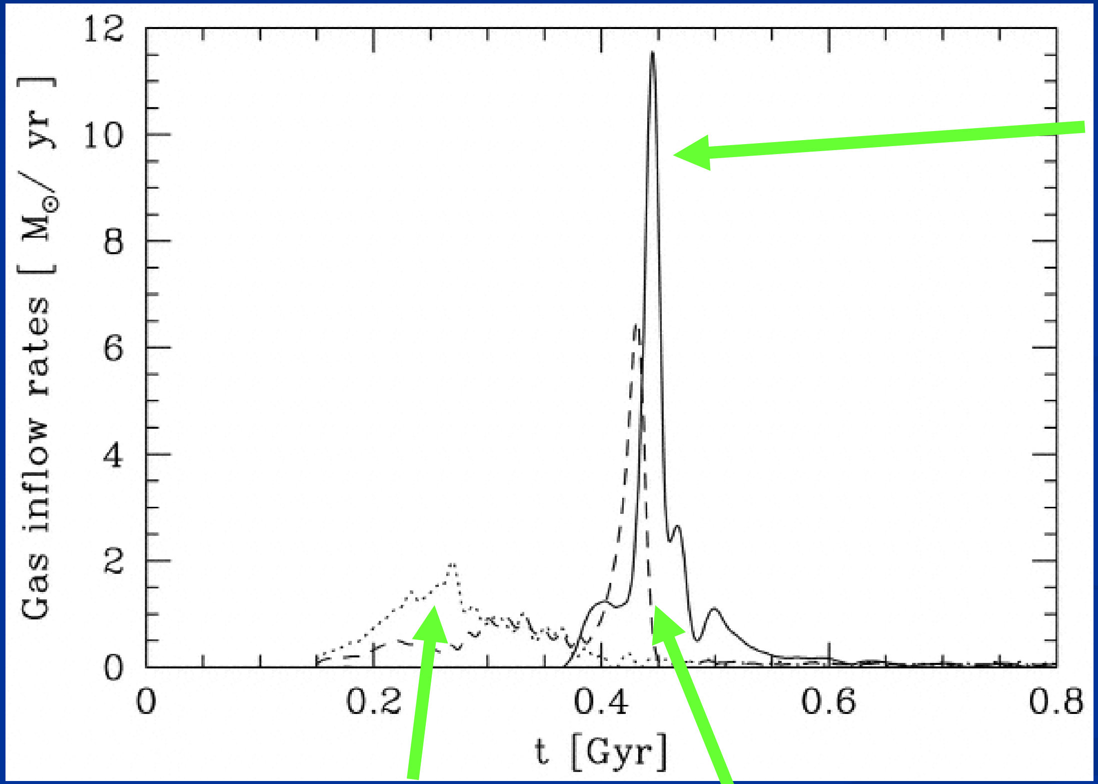
Peter Englmaier
Astronomisches Institut
Uni Basel, Switzerland

Isaac Shlosman
University of Kentucky
USA

ApJ Letter 2004

GAS INFLOW WITH NESTED BARS

- Nested bars: inflow rates



Englmaier & Shlosman (2004)

WHAT BARS CAN DO?

- Bars – the universal channel used by nature to get rid of angular momentum in order to reach lower energy configuration

Bars → prime internal drivers of dynamical and secular evolution in galaxies and fueling various processes

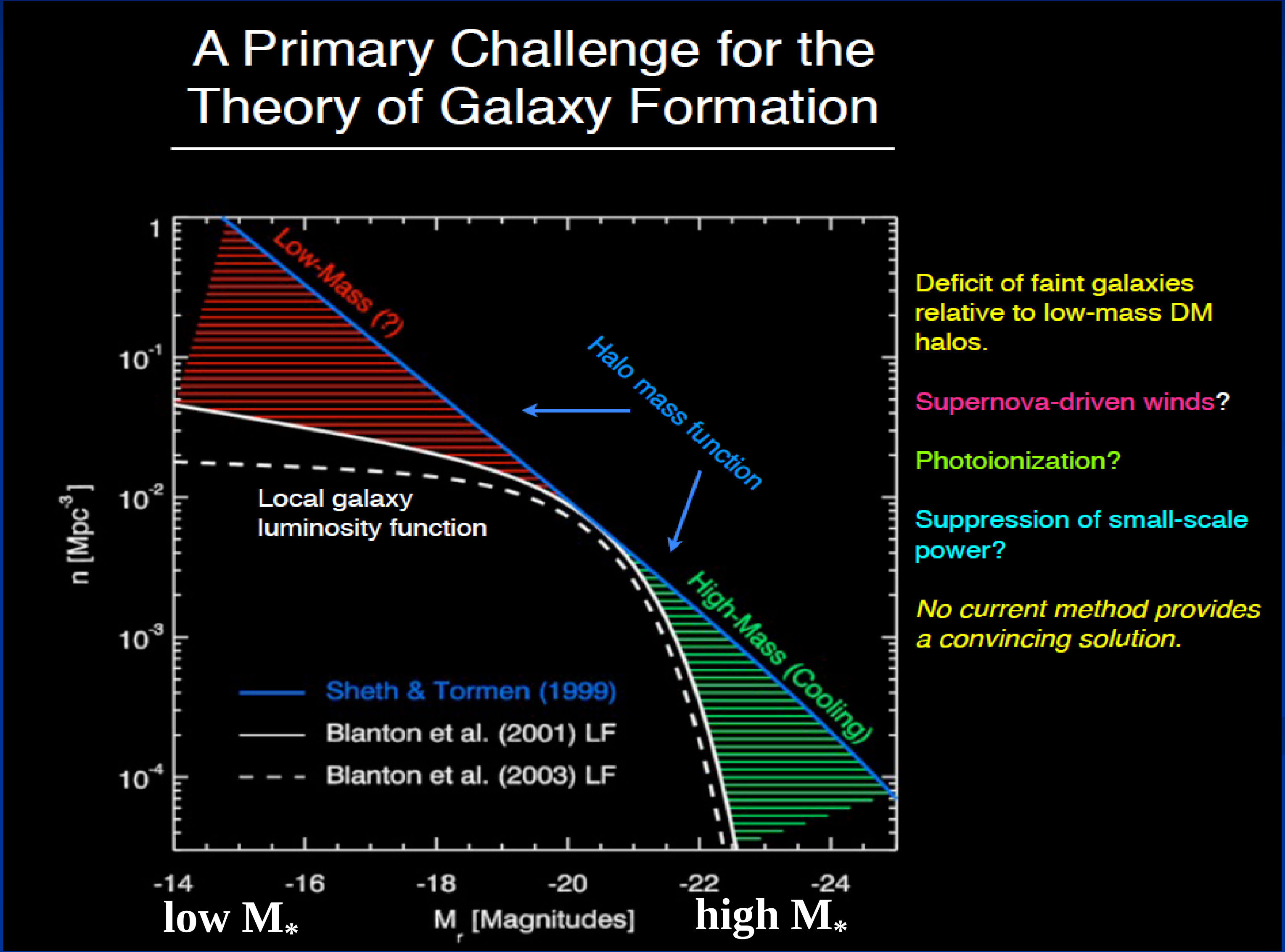
AGN FEEDBACK

❖ AGN energy input: reducing star formation rate

Galaxy luminosity function (LF) differs from dark matter halo luminosity function for low-mass and high-mass galaxies

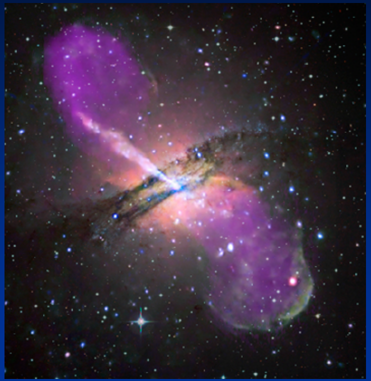
Supernova feedback

AGN feedback



AGN FEEDBACK

❖ Radiative energy input: driving winds



Ionizes the host ISM and cluster IGM
→ decreasing star formation

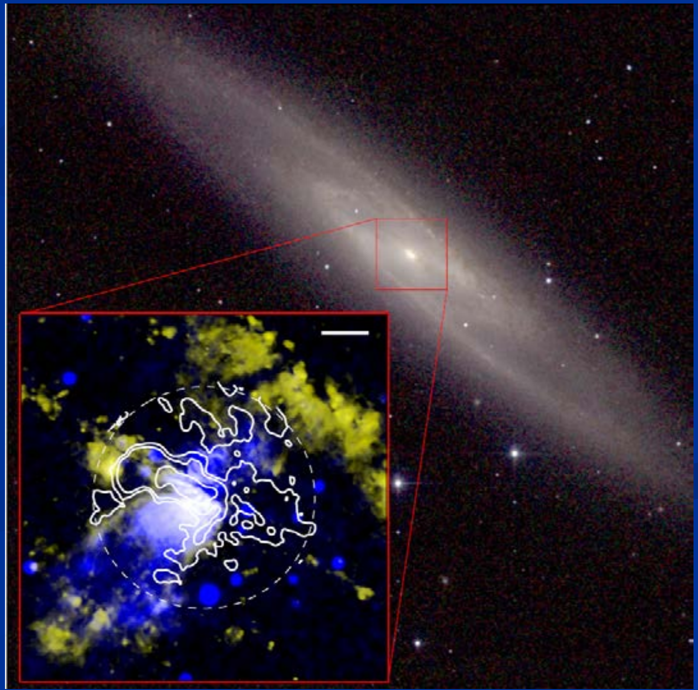
Multiwavelength view of the starburst galaxy M82. Yellow-green/optical HST; orange → 10^4 K *H* gas; red/Spitzer→ cold gas/dust; blue/Chandra

This negative feedback affects the galaxy luminosity function (LF), especially the high end

chandra

It drives galoactic winds and expels the chemically-enriched material into IGM

Comparable mechanical energy frpm AGN jets in clusters of galaxies

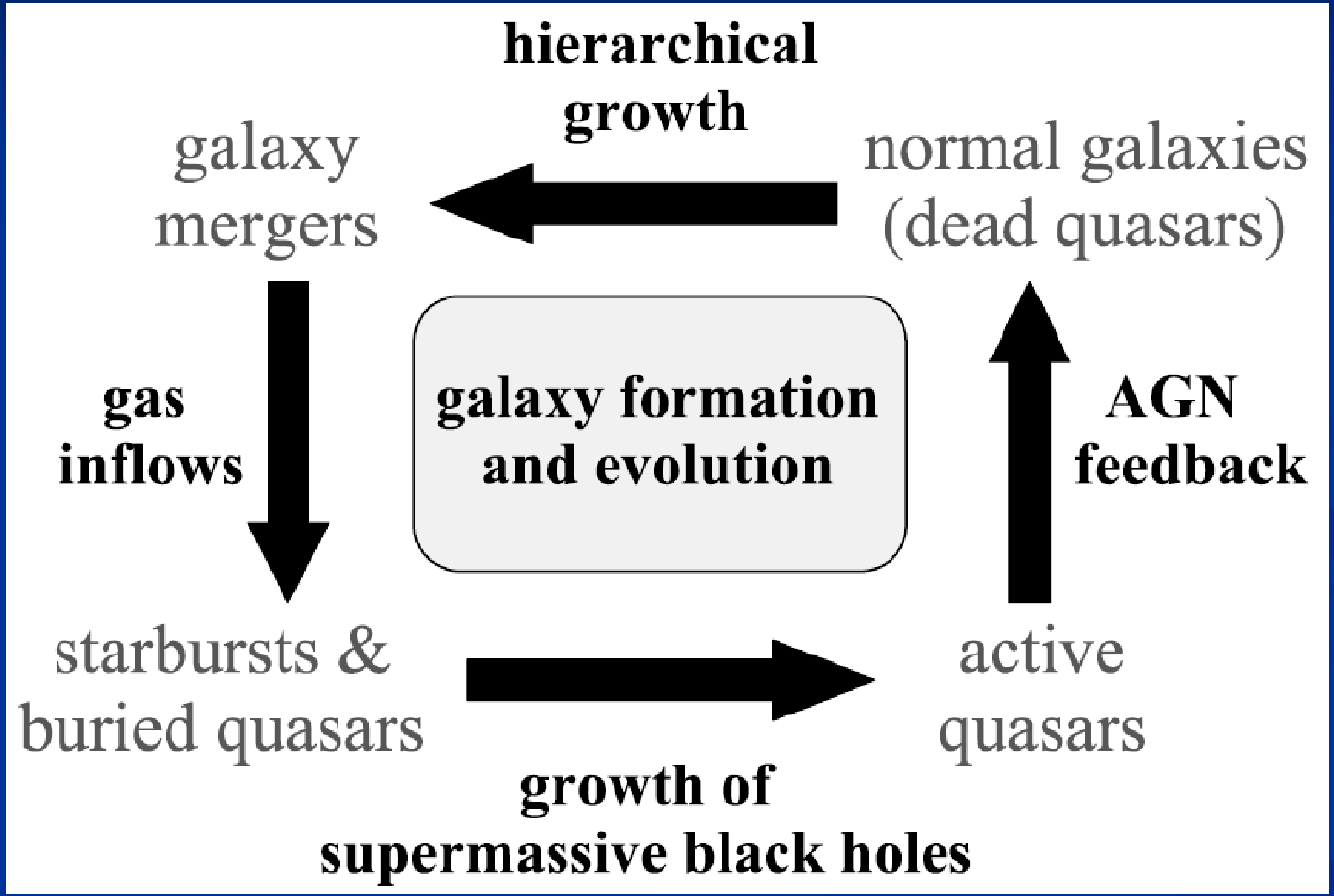


NGC 253: warm and hot wind by ALMA and galalactic disk by 2MASS JHK image

$$E_{AGN} \sim L_{AGN}\, t_{AGN} \sim 10^{12} L_{\odot}\; 10^{7}\ \mathrm{yr} \sim 10^{60}\ \mathrm{erg}$$

$$E_{bind.gal.} \sim M_{gal}\, V_{gal}^{2} \sim 10^{12}\, M_{\odot}\, (200\ \mathrm{km/s})^{2} \sim 10^{60}\ \mathrm{erg}$$

AGN AND SUPERNOVA FEEDBACK



AGN FEEDBACK

- Observational challenges

Feedback on galaxy clusters scales is more easily observable (larger physical scales, denser atmospheres, brighter diffuse emission from the hot gas in the X-rays)

Feedback on galactic scale is hard to resolve

Galaxies experience most of their growth at earlier times than clusters (in a hierarchical Universe)

Dust extinction in the region of interest obscure both AGN and star-formation

CONCLUSIONS TO TALK 4

- Accretion on SMBHs involves a wide variety of processes → from tidal disruption of stars to smooth accretion from gaseous disks
- Different accretion rates and mechanisms result in different energy-to-radiation conversion efficiencies → but we still don't know where is the main reservoir of fuel that powers AGN
- Accretion onto SMBHs is associated with various types of mass and energy ejection: radiation, mechanical energy, accretion disk winds, etc. → this provides a powerful feedback to evolution of stars, galaxies and galaxy clusters
- Presence and properties of SMBHs are intimately linked to the formation and evolution of galaxies in the universe. Two processes long predicted by theory recently observed:
  - Disruption of stars by SMBHs at centers of several galaxies → appear as spectacular X-ray flares, abd provide completely independent route to find and study BHs and their environment
  - Active pairs of SMBHs, merging BHs in nearby galaxies have been detected
- Two main ingredients for AGN phenomenon: SMBHs and fuel delivery mechanism (internal and external) → these machanisms are based on gravitational and magnetic torques