GALACTIC INFLOWS & OUTFLOWS

(OBSERVATIONS)

Santiago GARCIA-BURILLO

Observatorio Astronómico Nacional (OAN)-Spain

With many contributions from...:

...F.Combes, A.Usero, S.Aalto, M.Krips, S.Viti, A.Alonso-Herrero, L.Hunt, E.Schinnerer, A.Baker, F. Boone, V.Casasola, L.Colina, F.Costagliola, A .Eckart, A.Fuente, C.Henkel, A.Labiano, S.Martin, I.Marquez, S.Muller, P.Planesas, C.Ramos-Almeida, B. Emonts, A. Arribas, M. Villar-Martin, M.Spaans, L.Tacconi, P.van der Werf.

OUTLINE

- Molecular inflows in (nearby) galaxies

  -Gravitational instabilities and angular momentum transport
  -AGN fueling problem

- Molecular outflows in (nearby) galaxies

  -SF/AGN feedback in...

  Starbursts
  Seyferts
  Radiogalaxies
  QSOs/ULIRGs

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BARS: ENGINES OF SECULAR EVOLUTION

- Barred galaxies show a higher concentration of molecular gas compared to non-barred systems on ~1 kpc scales
(e.g., Sakamoto+99)

- Bars + interactions trigger SF
(e.g., Ellison+11)

- But there is no strong correlation between bars and AGN activity at z=0
(e.g., Knapen+00, Cardamone+11)

AGN Feeding in Nearby Galaxies

Search of a 'universal' feeding agent in low-L AGN is tricky:

- Bars, bars within bars, m=1 modes, warps, nuclear spirals,winds from stars...
- Fueling efficiency of these mechanisms (based on models) unclear.
- Sometimes gas gets stopped in a 'cul de sac'.

- ***Complications in low L AGNs (Seyferts, LINERs):***
  - AGN duty cycle shorter than lifetime of feeding mechanism?
  - Several mechanisms at work with different time-scales?

Models' predictions still controversial.

Picture drawn from observations?:

Look at 'real' galaxies on 'critical scales'...

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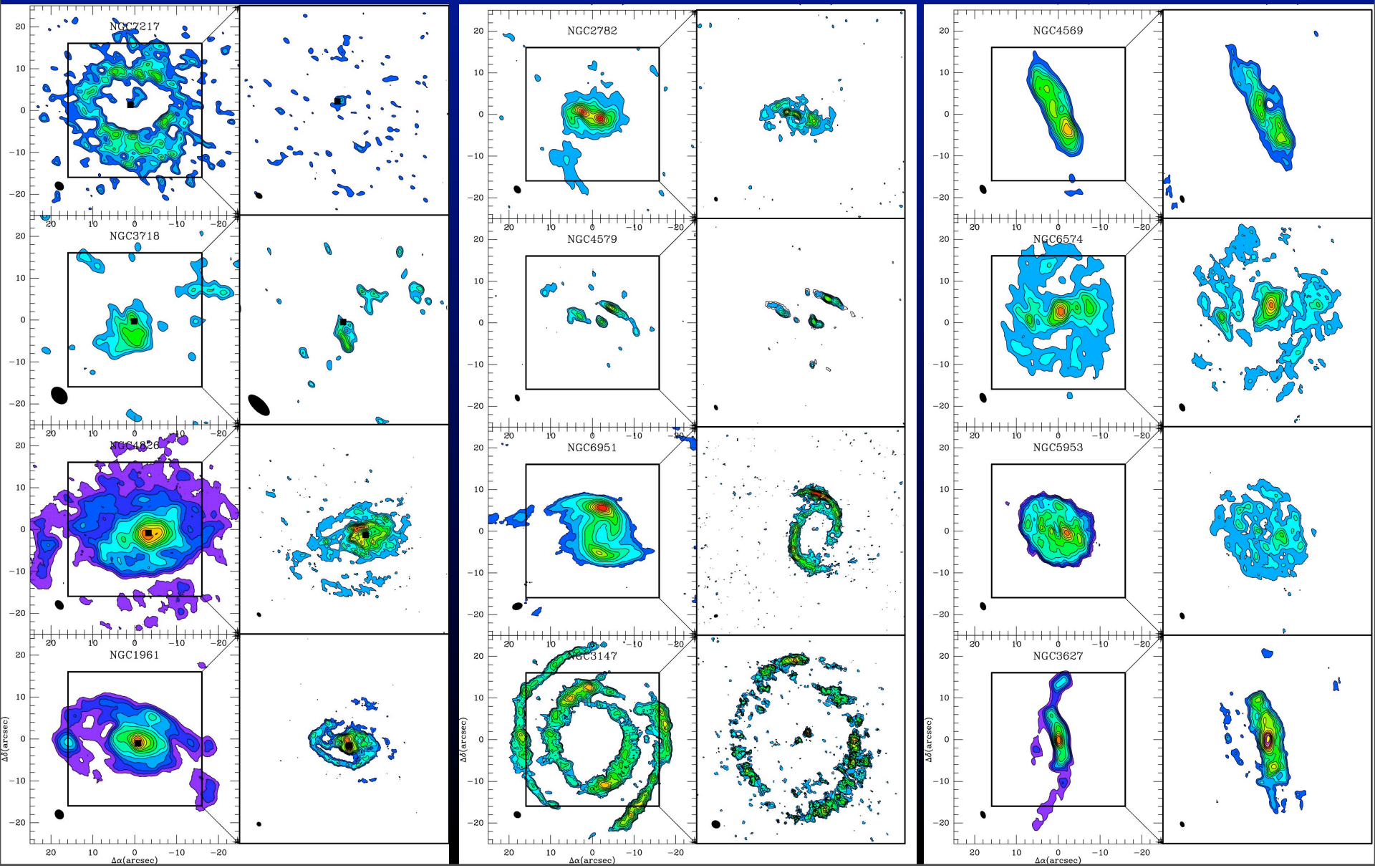
NUGA: CO survey of 25 LLAGN with IRAM interferometer

Probing critical scales for L transfer (<10-100pc) (D~5-30Mpc)

High-spatial resolution (0.5"-1") and high dynamic range CO images of 25 nearby AGN

CO Images of NUGA

García-Burillo+2003,2005,2009, 2012; Combes+2004,2009; Krips+2005,2006,2007; Boone+2007, Lindt-Krieg+2008; Hunt+2008, Casasola+2008, 2010,2011; van der Laan et al 2011



Tracking down AGN Feeding

García-Burillo+2005

CO maps: tracking down 'ongoing' feeding

High sensitivity/resolution --->detailed study of distribution and kinematics of gas

Stellar potentials: gravity torque maps

NIR images->potential

CO maps->gas distribution

→ Gravity torques t(r) exerted by stellar potential on gas.

Looking for the feeding agent in the stellar potential…..

Torque budget t(r) on the gas determined by stellar potential

'Smoking Guns' : t<0

García-Burillo & Combes 2012

- ~1/3 LLAGNs analyzed show **t(r) <0** down to **r < 25-100 pc**

Dynamical decoupling of embedded structures

Nuclear bars - within - bars/ovals: *e.g.; NGC2782 (Hunt+2008)*
Nuclear ovals - within -bars: *e.g.; NGC4579 (García-Burillo+2009)*

ILR-free large-scale bars *e.g.; NGC3627 (Casasola+2011)*

'Smoking Guns' : t<0

NGC4579 *García-Burillo+2009*

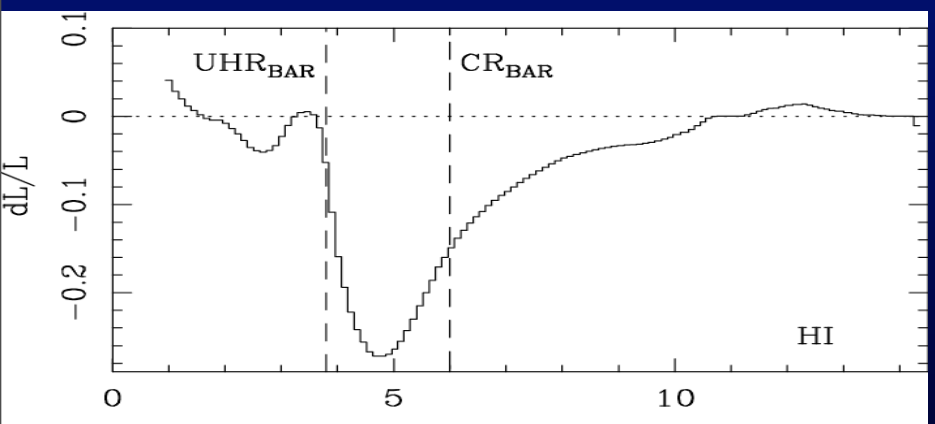
Gravity torque feeding budget in NGC4579: clues to **bar evolution**

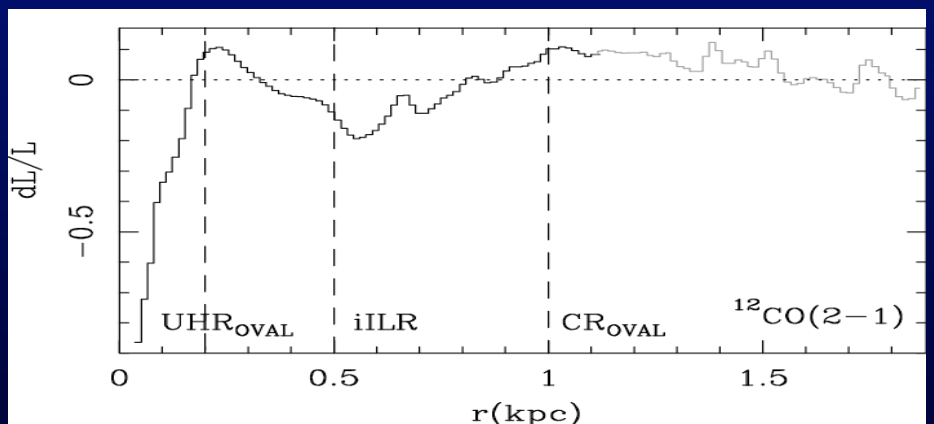
Negative torques due to BAR from OLR to UHR: corotation barrier overcome!

Negative torques inside IILR of BAR due to decoupled OVAL

HI

CO 2 - 1





The 'evolved' bar + weak OVAL in NGC4579 favor accretion down to ~ 50pc

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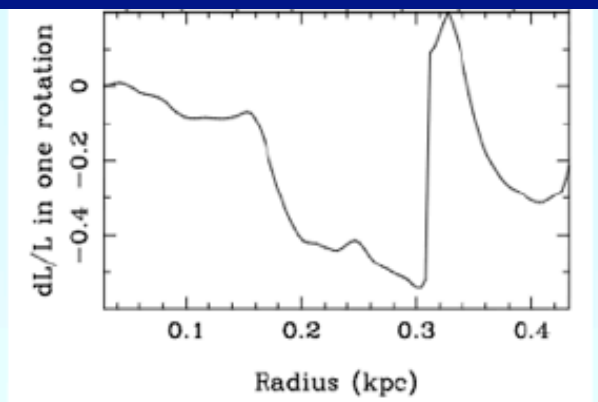
'Smoking Guns' : t<0

NGC1566

Combes+2014

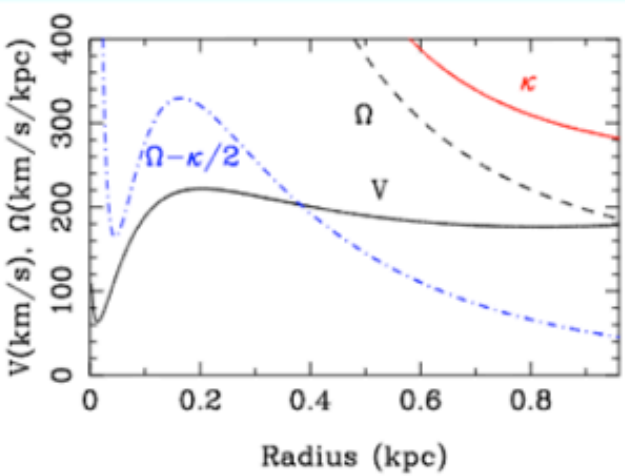
Gravity torque budget t(r)



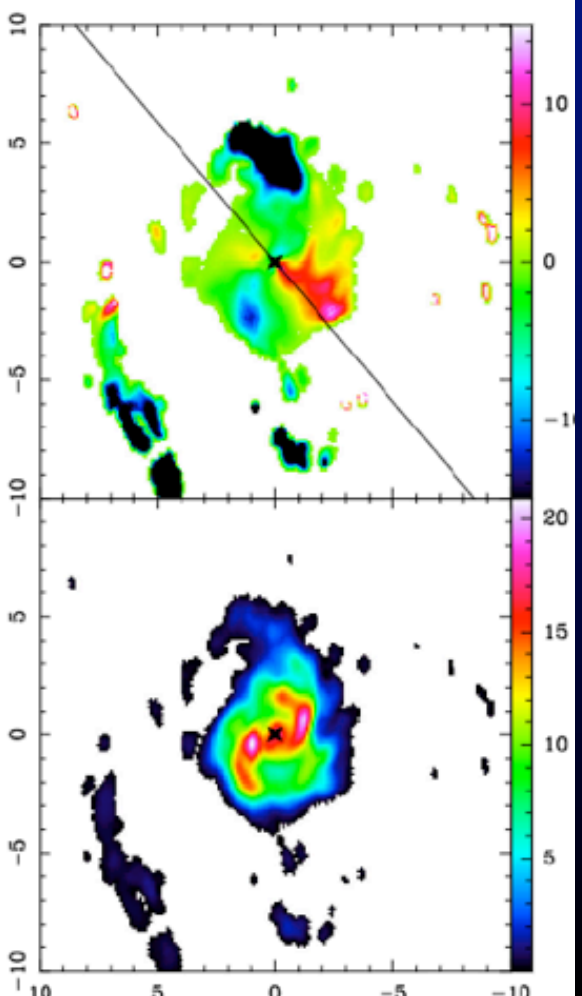
Gas is driven inwards

Trailing spiral inside the ILR ring of the bar

BH influence on the dynamics



ALMA CO 3-2 map



A 'Puzzling' Torque Budget

García-Burillo & Combes 2012

✸ ~2/3 LLAGNs analyzed show **t(r) > 0 at r ≤ 300 pc**

➡ 'Non-cooperative' embedded structures

Nuclear bars - within - bars: *e.g.; NGC4321 (Garcia-Burillo+2005; Haan+2009)*
Nuclear ovals - within -bars: *e.g.; NGC6951 (García-Burillo+2005; Haan+2009; van der Laan +2011)*

➡ Featureless axisymmetric potentials

e.g.; NGC4826 (Garcia-Burillo+2003)
NGC7217 (Combes+2004; Haan+2009)
NGC5953 (Casasola+2010)

A 'Puzzling' Torque Budget

- ~2/3 LLAGNs analyzed show **t(r) > 0 at r ≤ 300 pc**

→ Stellar potential `inefficient' to drain angular momentum 'at present'

- How to solve the feeding 'puzzle'…?

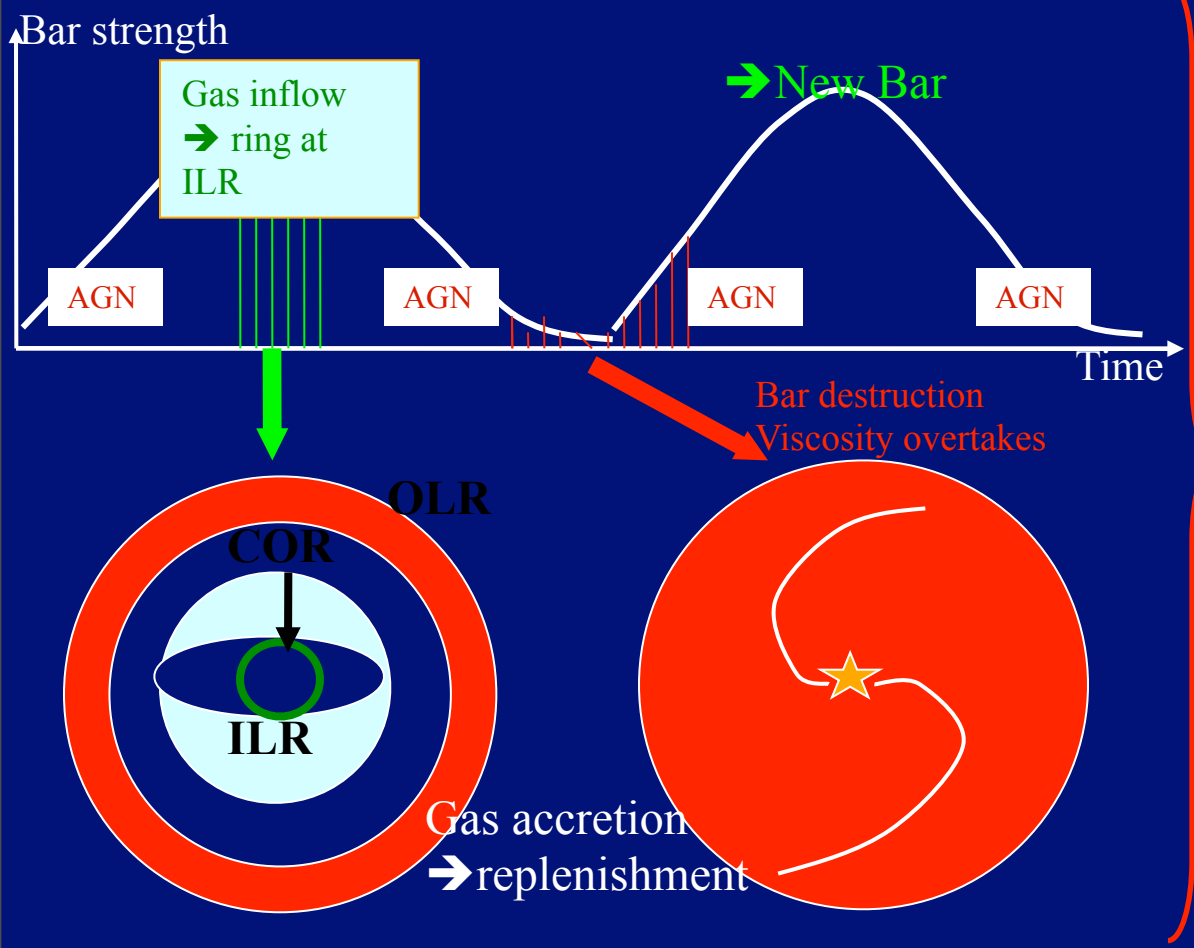
→ Gravity torques assisted by ***other mechanisms***?

→ A ***short-lived*** (< 10^7 yrs) feeding ***agent*** in stellar potential?: 'smoking gun' evidence of feeding elusive

AGN Feeding and `Evolving´ Bars

García-Burillo+2005

* Several (~3-4) bar episodes develop in a galaxy life-time: bars self-destroy through angular momentum exchange with gas *(Combes 2004, Bournaud+2005)*



* Bars create rings, but subsequent destruction allows for disk replenishment and **AGN** phases.

*Gravity torques and viscosity produce ~2-4 AGN phases per bar cycle

*Diversity of morphologies in NUGA maps supports this view

A 'Puzzling' Torque Budget

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Conclusions - I: INFLOWS

Large-scale (primary) bars / interactions drive gas inflow down to scales ~ a few 100pc-1kpc

No universal pattern on scales probed by NUGA (~10pc -a few 100 pc) (nuclei have their various ways...)

Gas flows reveal large-scale and embedded m=2, m=1 instabilities

Gravity torque maps: gas stalled in rings most of the time

Only ~1/3 NUGAs show negative torques down to ~50pc

Fueling mechanisms related to bar cycles:

Secular evolution and dynamical decoupling are key

Scales <1pc-10 pc? :viscosity, dynamical friction, m=1, warps, ... (e.g. M31)

More observations to confirm predictions of num. simulations.!

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Molecular outflows in (nearby) galaxies

-SF/AGN feedback in...

Starbursts
Seyferts
Radiogalaxies
QSOs/ULIRGs

OUTFLOWS

- Negative feedback from SF /AGN activity required to stop galaxy mass overgrowth, explain M_{BH}-M_{bulge} correlation and bimodal color distribution in galaxies

e.g.,Fabian 99;Kauffman+03;Murray+05;di Matteo+05;Hopkins+05,+12;Perez-González+08,Kormendy & Ho+13

- Mounting evidence of massive gas outflows detected in SF-galaxies/AGNs/ mergers at different redshifts

Outflows regulate fueling of SF and BH growth: baryons escape from disk to thick disks, halos, CGM and even IGM...

e.g., Heckman+90;Rupke+05+13;Veilleux+05,+13;Arribas+08,+14;Sturm+11;Feruglio+10,+12,+15;Aalto +12,+15;Alexander+10;Morganti+03, +13;Maiolino+12;Cicone+14;Dasyra & Combes+12; Combes+13;Walter +02;Alatalo+11,+14; Garcia-Burillo+01,+14

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-Gas outflows are multi-phase with large variance of properties: ionized, atomic and molecular. What is the most relevant phase?

-What drives (molecular) outflows? SF? AGN? a combination thereof?

-Physical framework to explain outflows: radiation pressure? winds? jets?

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-Outflow Mass/Energy/Momentum budget

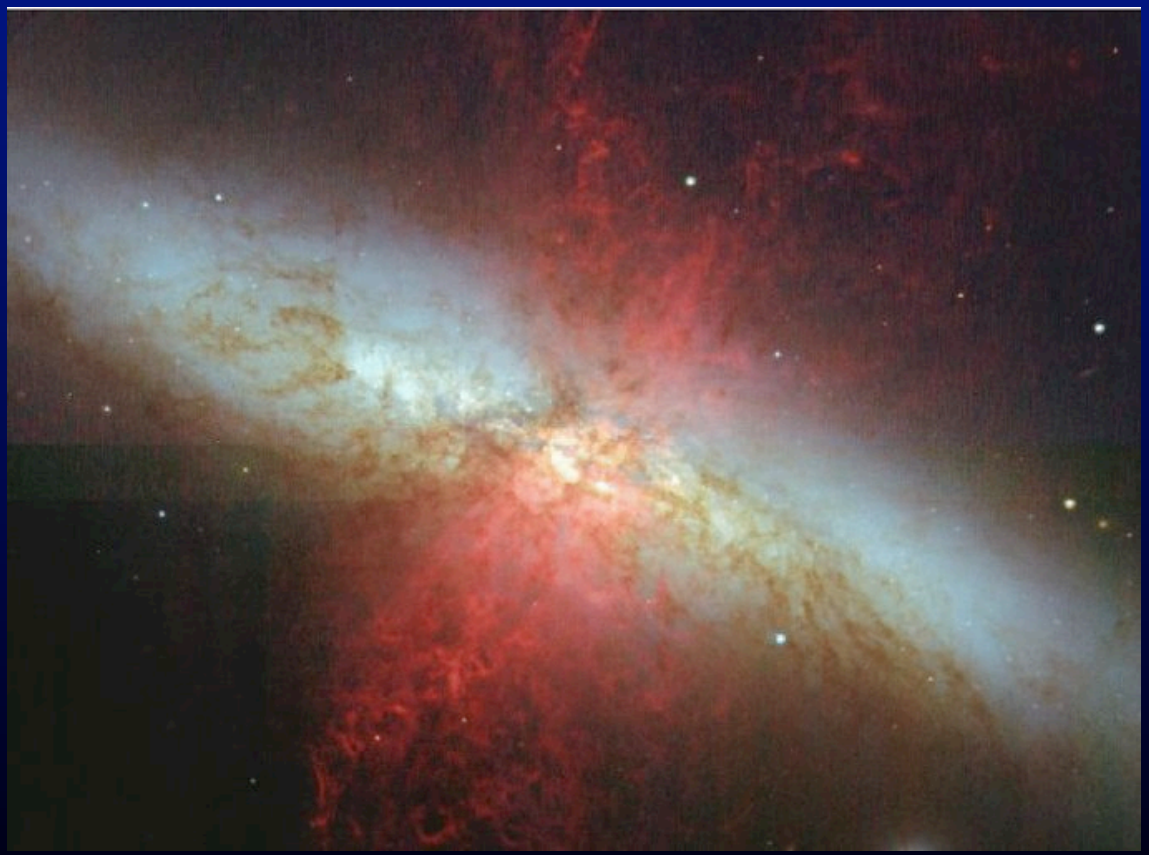
dM/dt ? L_{kin}? dP/dt?

-Inflow *vs* Outflow: (pseudo) equilibrium, self-regulation?

Molecular Outflows: starbursts

Bland+1998, Yun+1998, Martin 1998, Sakai & Madore+2001, Garcia-Burillo+2001, Walter+2002, Alonso-Herrero+2003, Veilleux+2009, Contursi+2013, Salas+2014

M82



-Strongly interacting SB

-Ionized/atomic/molecular outflow driven by SF: SN explosions

-Gas outflow perpendicular to galaxy disk

-v_{max} close to v_{escape}

-Significant fraction (0.1) of gas injected from disk into halo/IGM on T~10 Myr

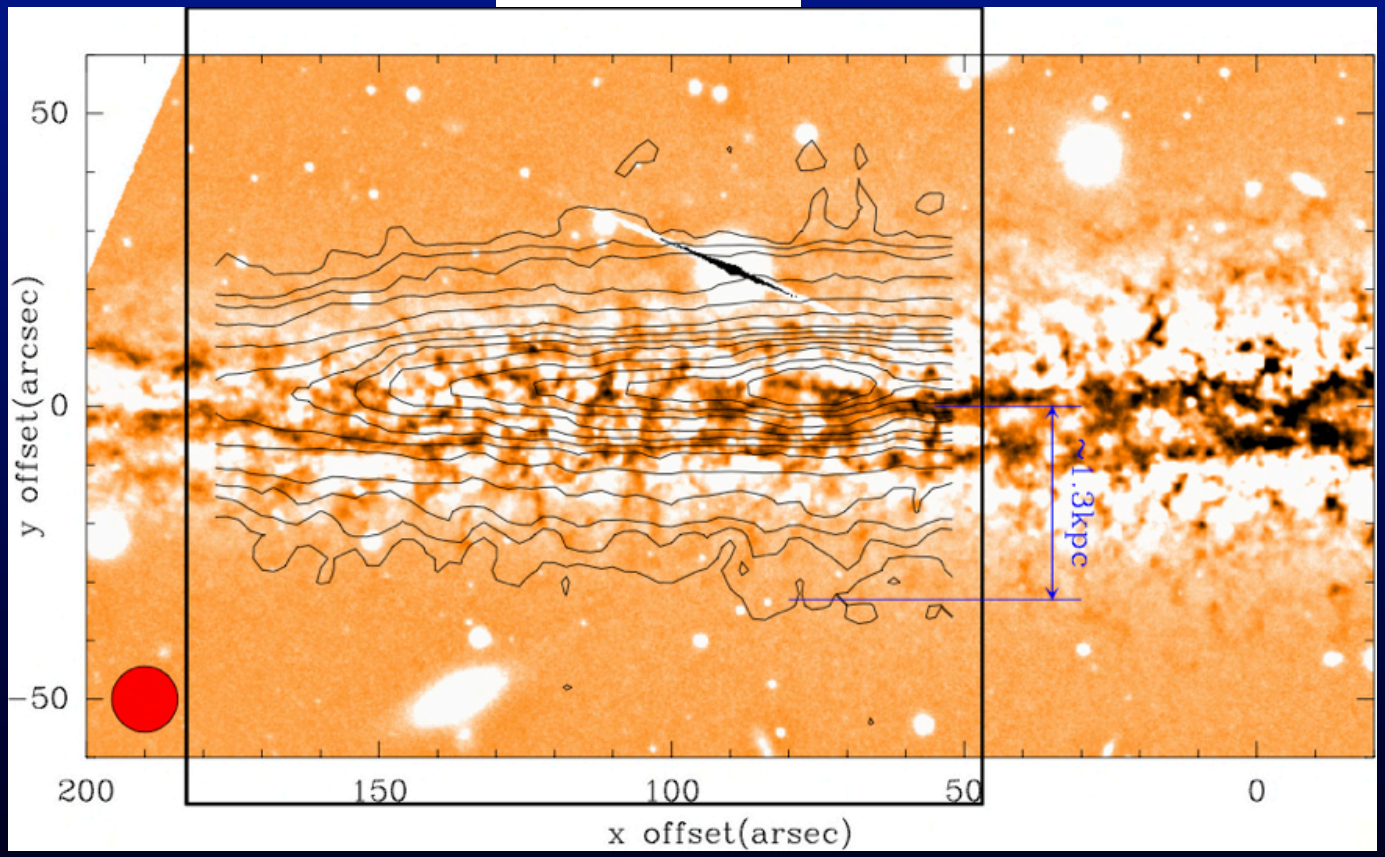
Molecular outflow: $dM_{out}/dt = 30\ M_{sun}/yr \sim 3$ x SFR → **outflow can quench SF**

Molecular 'thick' Disks:

NORMAL GALAXIES

García-Burillo et al. 2015, in prep

NGC891



CO(2-1)
30m map on USM optical image

Molecular thick disk: CO emission up to z~1.3 kpc, M_{thick}~20% of total mass if X_{CO} ~MW

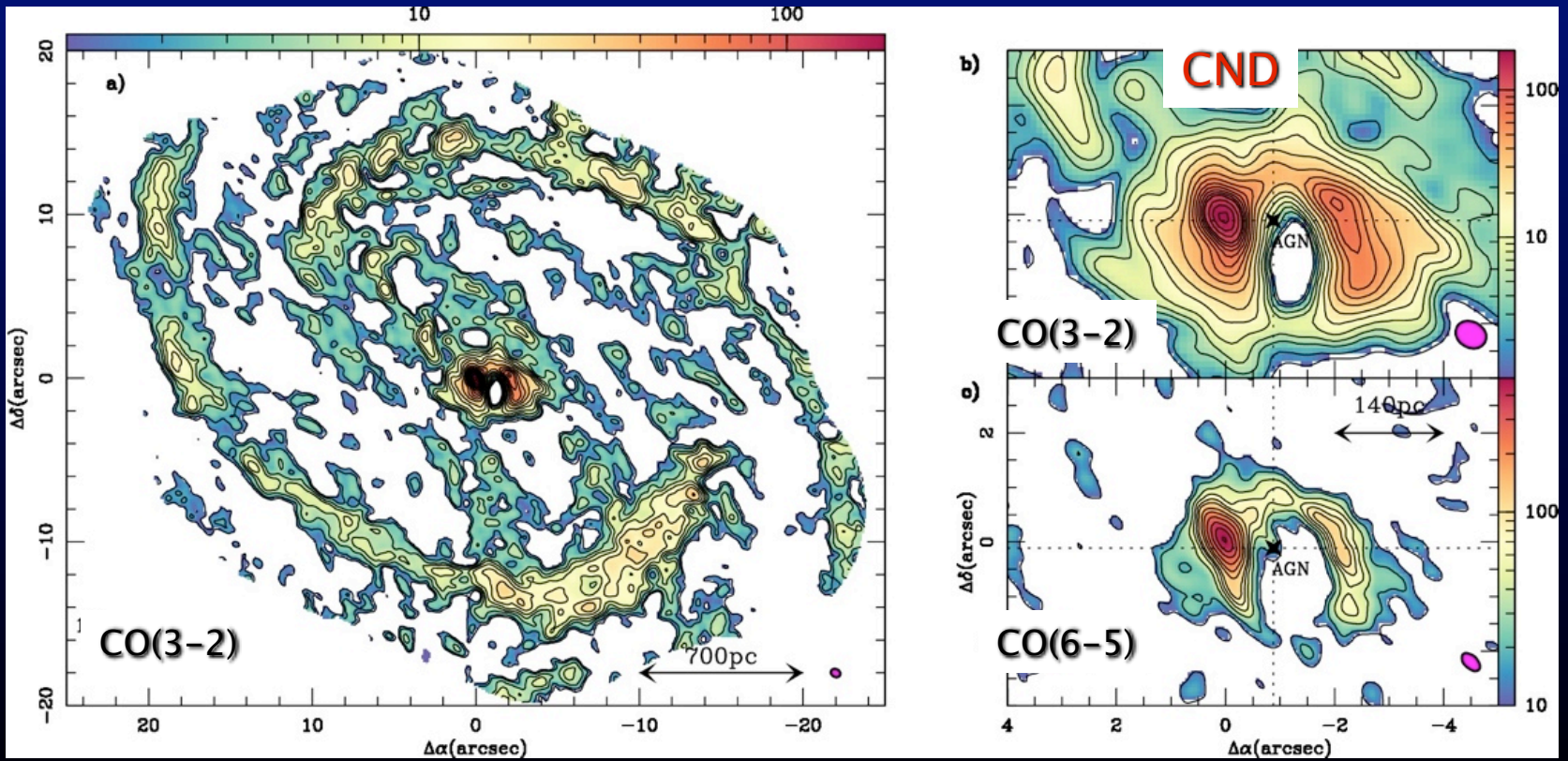
Molecular Outflows: Seyferts

García-Burillo+2014

-CO (3-2) and (6-5) ALMA maps at 0.3”-0.5” (20-35pc) resolution. **Dynamic range: >200 !**

-CO traces SB pseudo-ring at r~1 kpc, BAR, CND and interarm emission.

-Molecular gas at CND: off-centered r~200pc ring around AGN (similar to NIR H_2 map).

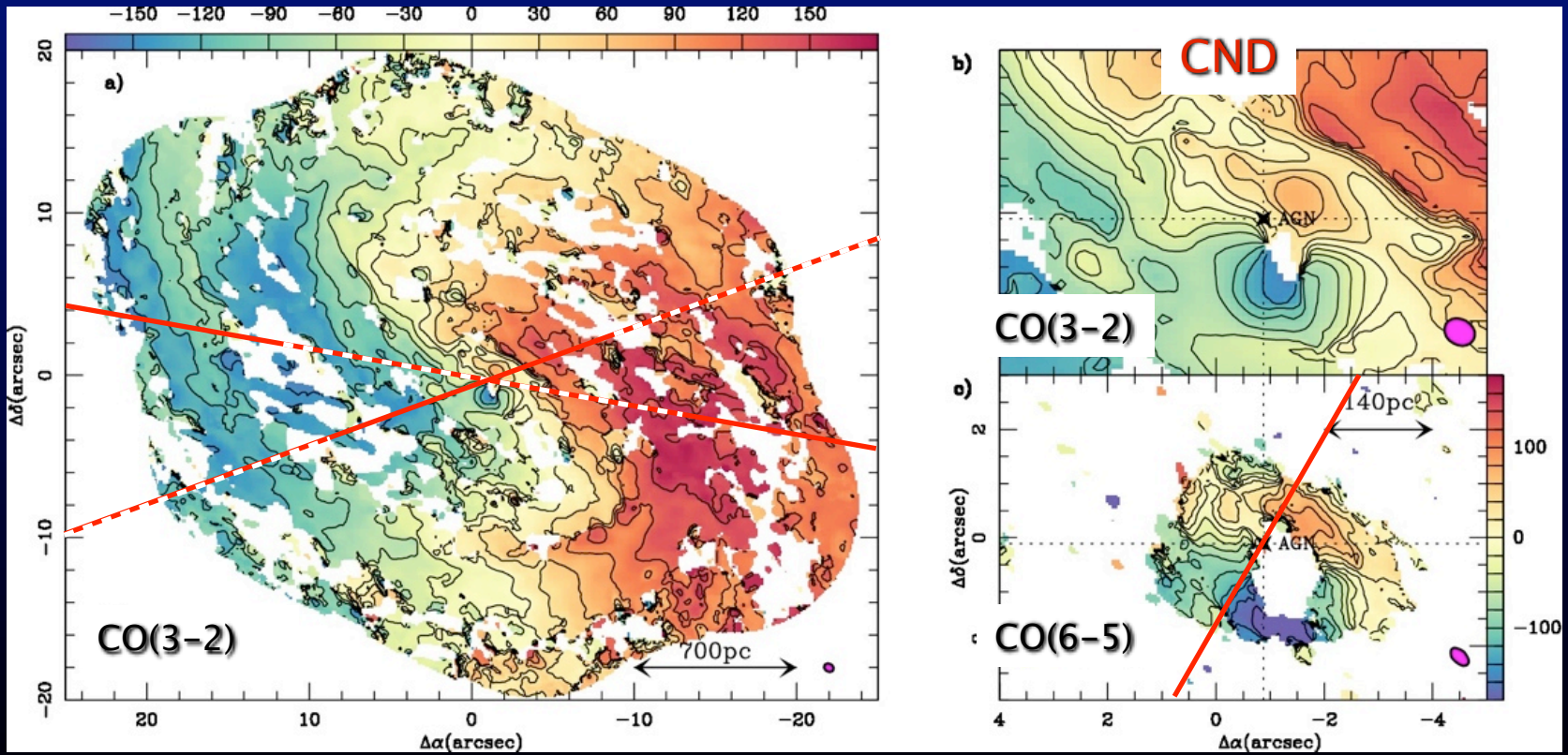


The NGC1068 Outflow seen by ALMA

García-Burillo+2014

-Modeled rotating pattern (PA~289º) perturbed on large scales by streaming motions in spiral +bar

-Strong tilt (ΔPA~70º) of isovelocities in CND betrays kinematic decoupling close to the AGN



CO isovelocities

The NGC1068 Outflow seen by ALMA

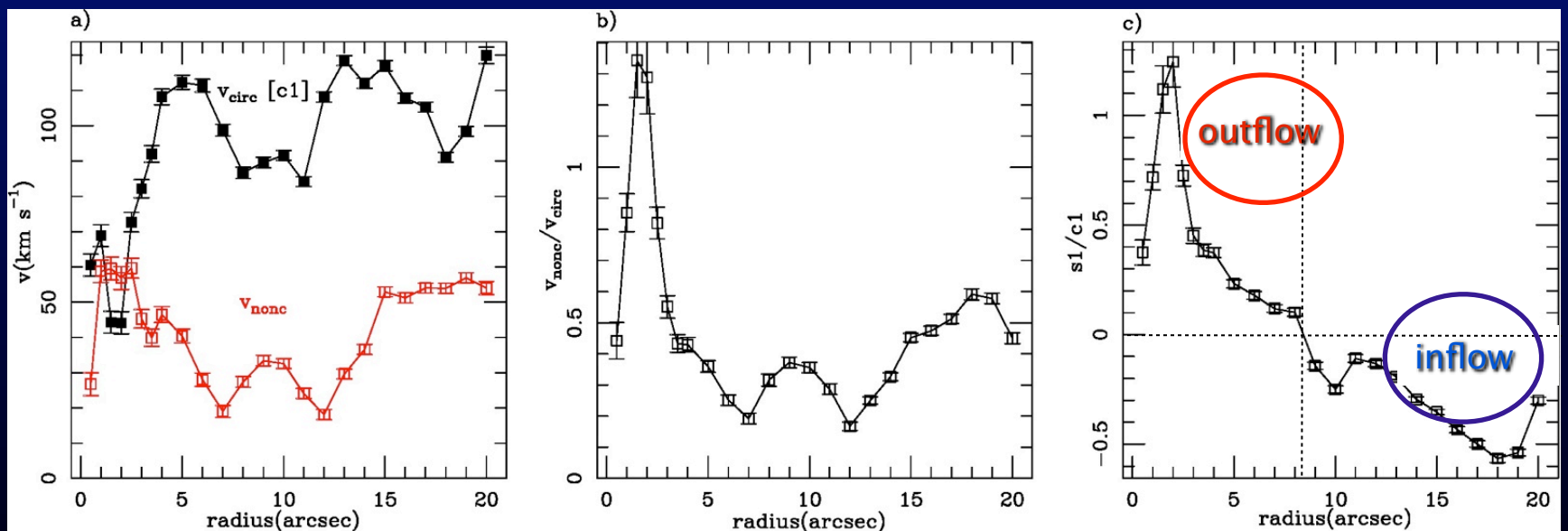
García-Burillo+2014

-Fourier decomposition of velocity field shows strong non-circular motions in the CND:

$v_{nonc} \sim v_{circ}$ at r <2" (150pc)

-Outward radial motions (s1) ~ circular velocity (c1): a **molecular outflow** at the CND

s1/c1>0.5 at r<3" (200pc)



Inflow and outflow coexist in different regions

The NGC1068 Outflow seen by ALMA

García-Burillo+2014

-Outflow detected in all **dense** gas tracers imaged by ALMA:

-Outflow is **coplanar**

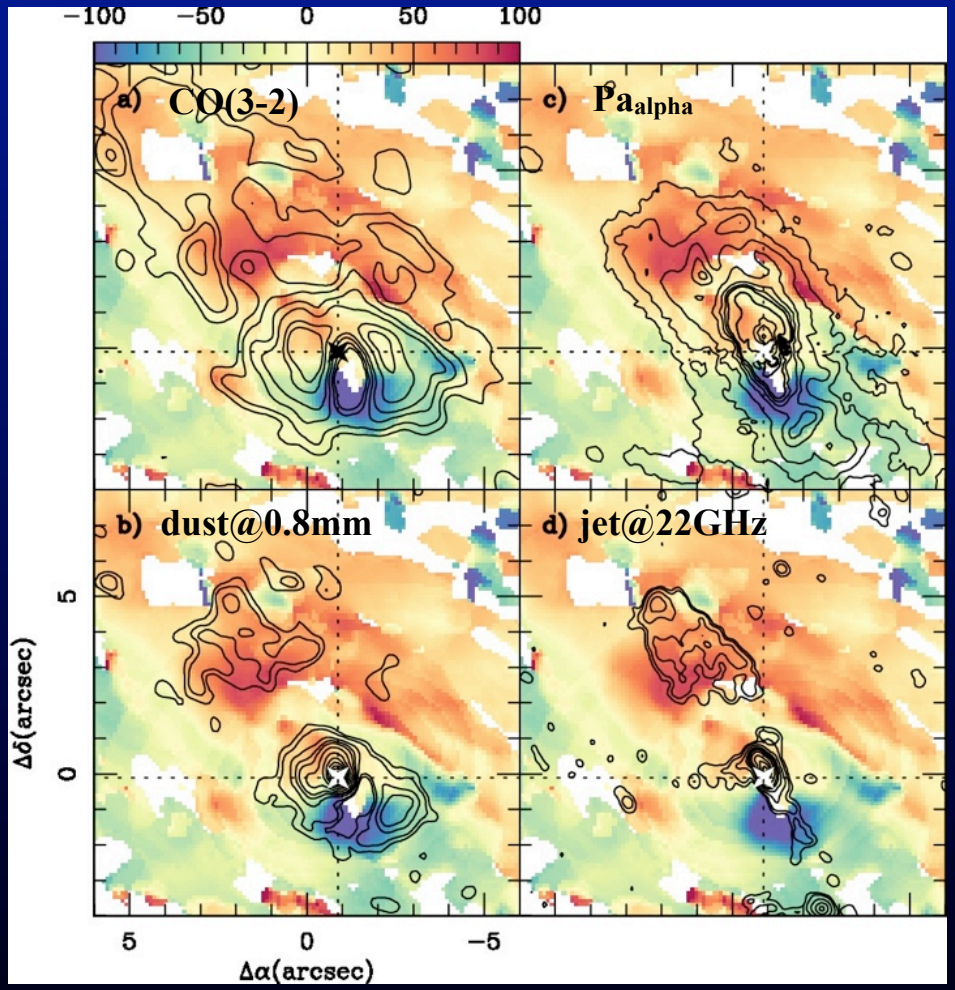
~50% of molecular gas in CND involved in outflow (motions outside virial range):

$M_{out} \sim 1.8 \times 10^7 M_{sun}$
$T_{depl} \sim 1$ Myr

-**dM/dt~60 M⊙/yr** ...similar to other low-L AGNs *(Alatalo+10; Aalto+12; Combes+13)*

dM/dt ? L_{kin}? dP/dt?

color= CO residual vel. field in CND



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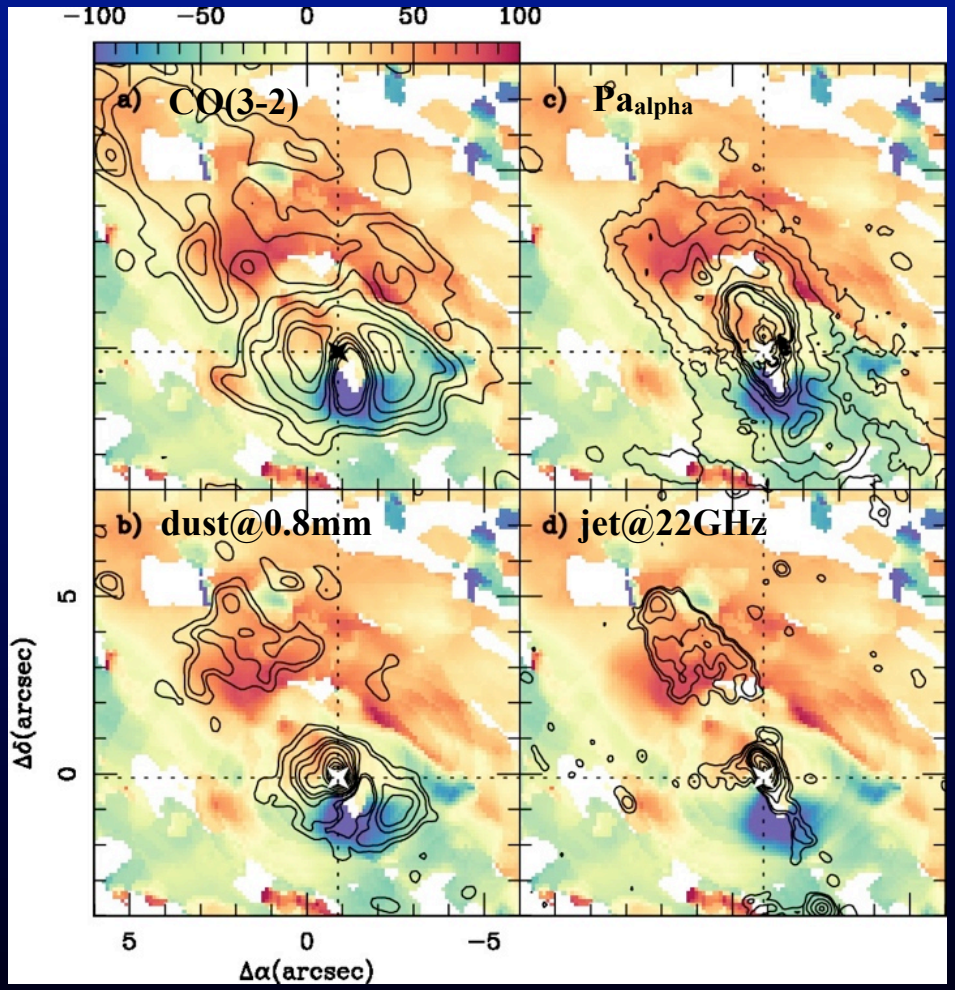

→ **AGN (not SF!) can drive the outflow by radiation pressure, winds or jets**

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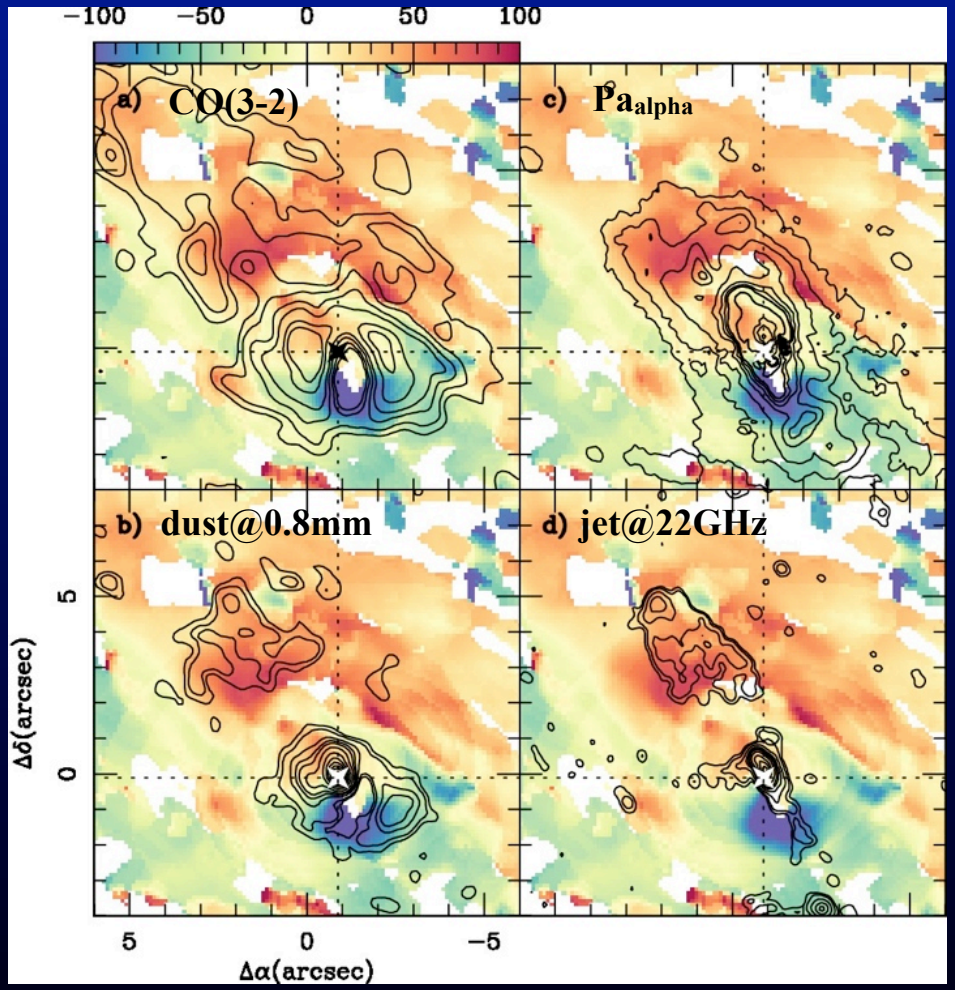
-Close spatial association between ionized-gas nebula / jet and CO outflow velocities.

color= CO residual vel. field in CND



→ Molecular outflow regulates SF and AGN fueling: 'self-regulation'

The NGC1068 Outflow seen by ALMA

García-Burillo+2014

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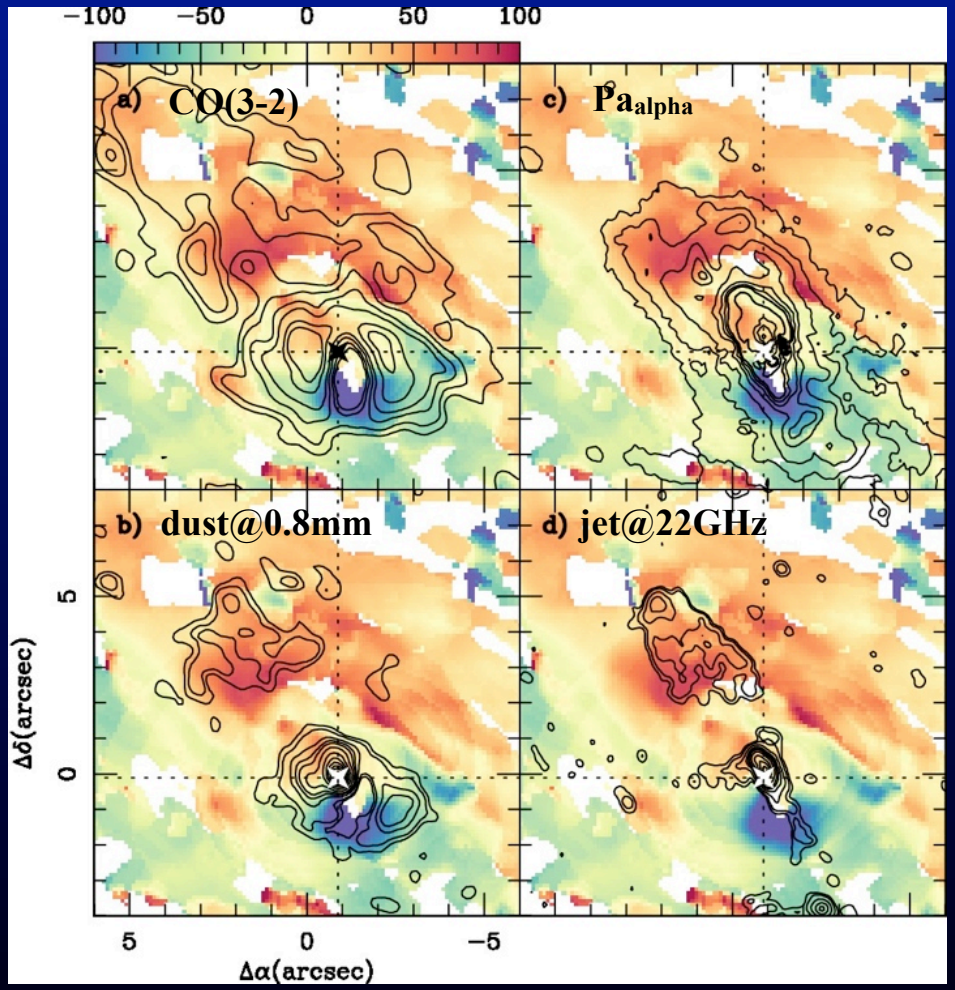


-No inflow *close to the 'torus'??*

Higher resolution (<0.1"=a few pc) key to deriving fueling budget at r <40 pc and resolve/isolate torus.

...waiting for Cycle-2 observations

MOLECULAR OUTFLOWS: RADIOGALAXIES

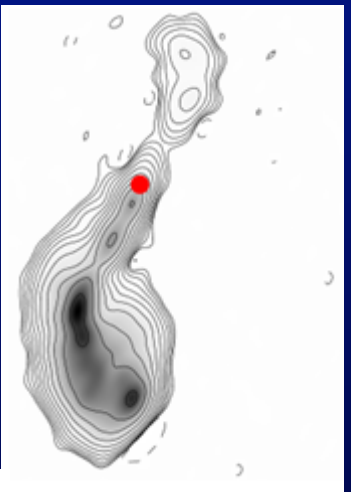
4C12.50

Dasyra & Combes 2011, 2012, Morganti+2005, 2013, Guillard+2012

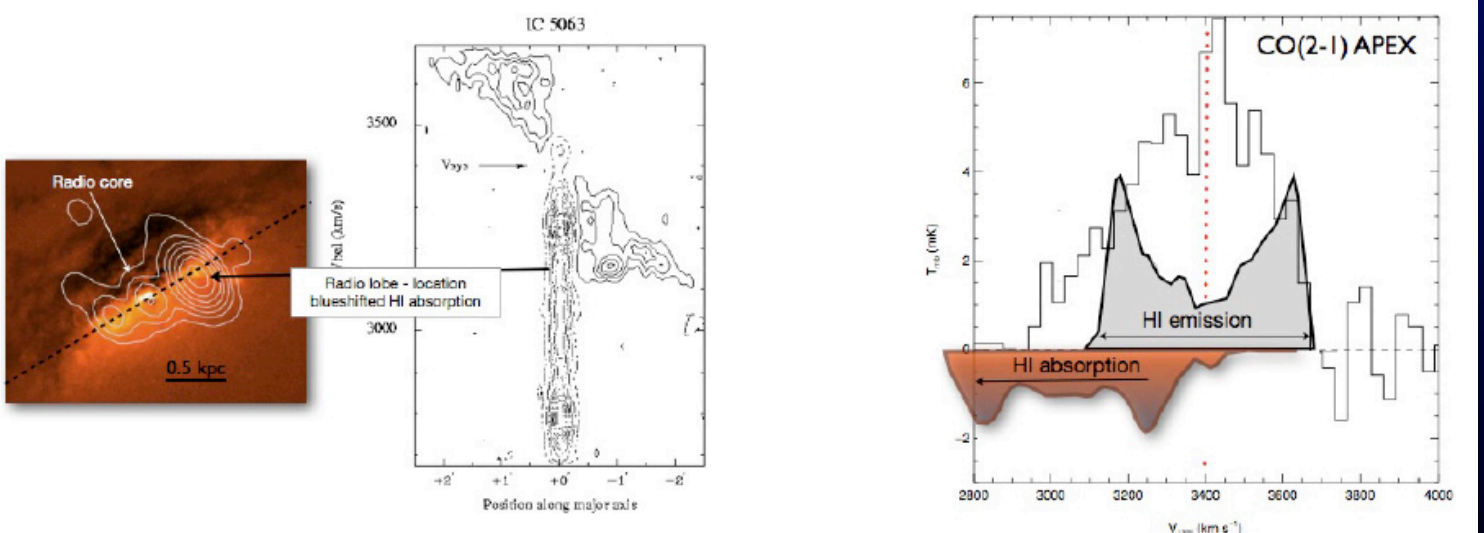
H_2 outflows and bright H_2 emission in RGs (shocks?)

4C12.50 SFR ~400-1000 Mo/yr Outflow ~130 Mo/yr

Young, restarted radio loud AGN
The HI+CO outflow is located 100 pc from the nucleus where the radio jet interacts with the ISM



A&A 552, L4 (2013)



IC5603

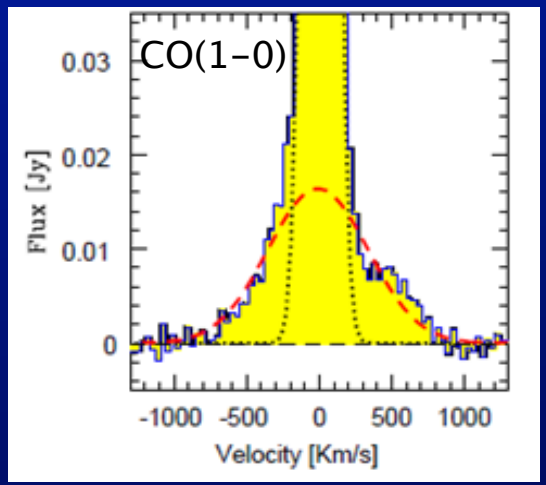
Morganti+2013, 2015, Dasyra+2015

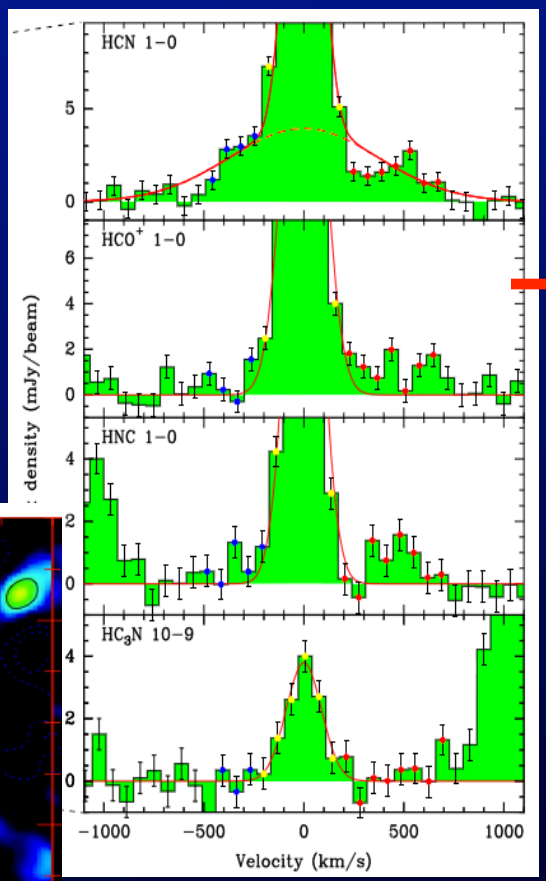
→Radio-mode AGN feedback is very efficient!

Molecular Outflows: ULIRGs

Mrk231 *Feruglio+2010, 2012, 2015; Aalto+2012, 2015*

SFR ~200 Mo/yr Outflow ~1000 Mo/yr ->AGN driven

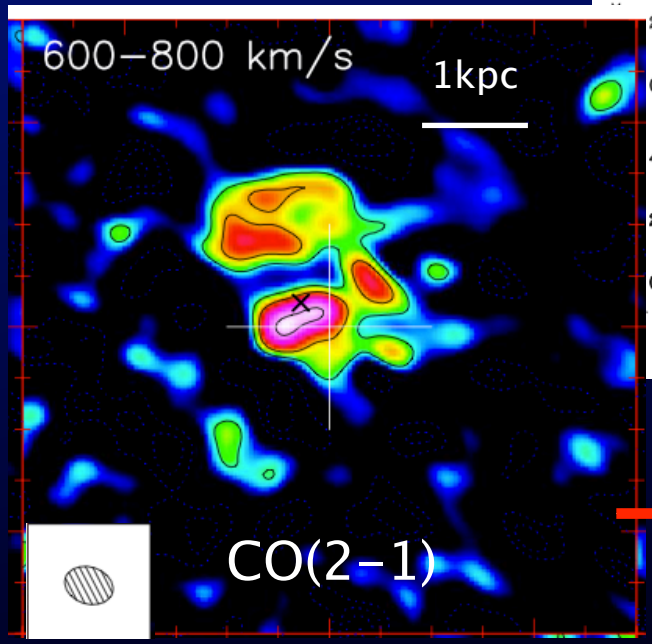




Aalto et al 2012

high-density tracers
HCN, HCO+, HNC

Lots of dense molecular gas in the outflow



Feruglio +2015

Extended on kpc scales

$P_K \sim 0.05\ L_{AGN}$

Momentum rate ~ $20\ L_{AGN}/c$

Molecular Outflows: ULIRGs

IRAS17208-0014

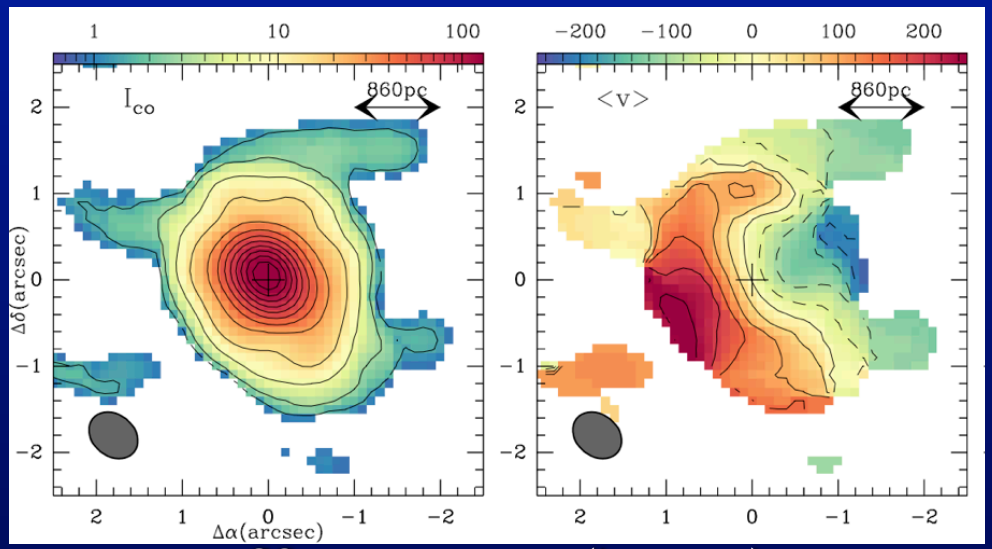
García-Burillo+2015, A&A submitted

-0.5”(400pc)-mapping of molecular disk with IRAM in CO(2-1) line

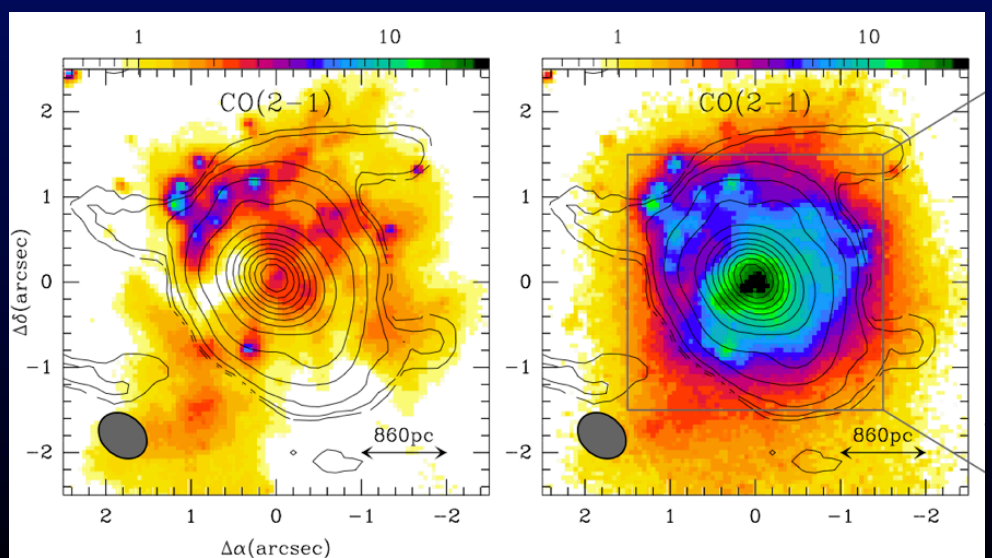
-Compact r=2 kpc-molecular disk of $M(H_2)$~6 10^9 M_{sun} fully resolved

-Molecular gas fuels SB episode (SFR=240 M_{sun}/year)

-Dominant rotating pattern distorted by strong non-circ. motions



CO moment maps (Ico, <v>)

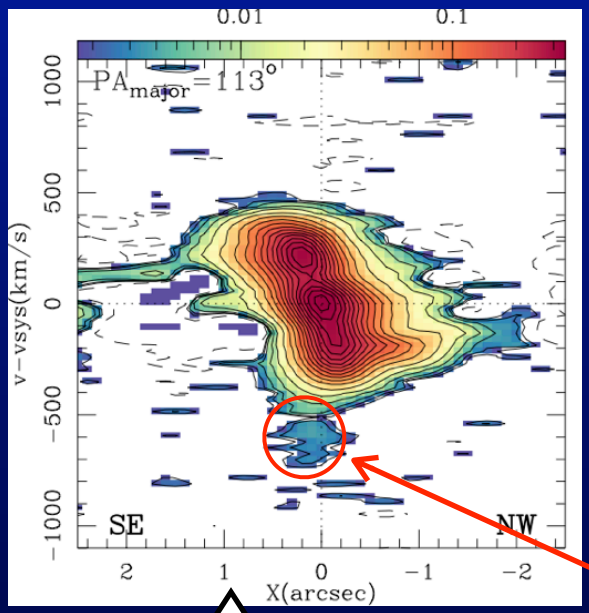


Ico (contours) on HST (optical(left), NIR(right)) images

Molecular Outflows: ULIRGs

IRAS17208-0014

García-Burillo+2015, A&A submitted



major axis pv-plot

-Emission at very high blue vels.: *v=[-500, -1000]km/s* clearly outside virial range-> CO ouflow much more extreme than revealed by Herschel data *(Sturm+11):*

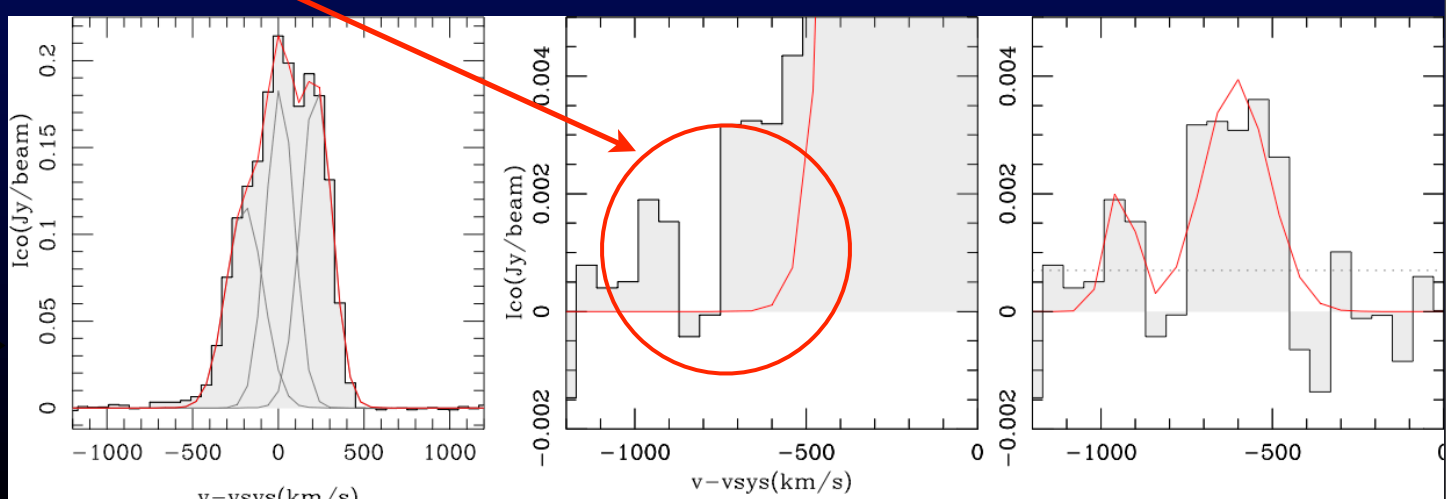
$v_{outflow}(CO) \sim 2 \times v_{outflow}(OH)$

-Molecular mass load rate:

v_{out}~600 km/s, R_{out}~200pc, M_{out}~5 x$10^7 M_{sun}$:

dM/dt ~330 M_{sun}/yr ~ (1-2) x SFR !

CO(2−1) spectrum at outflow peak



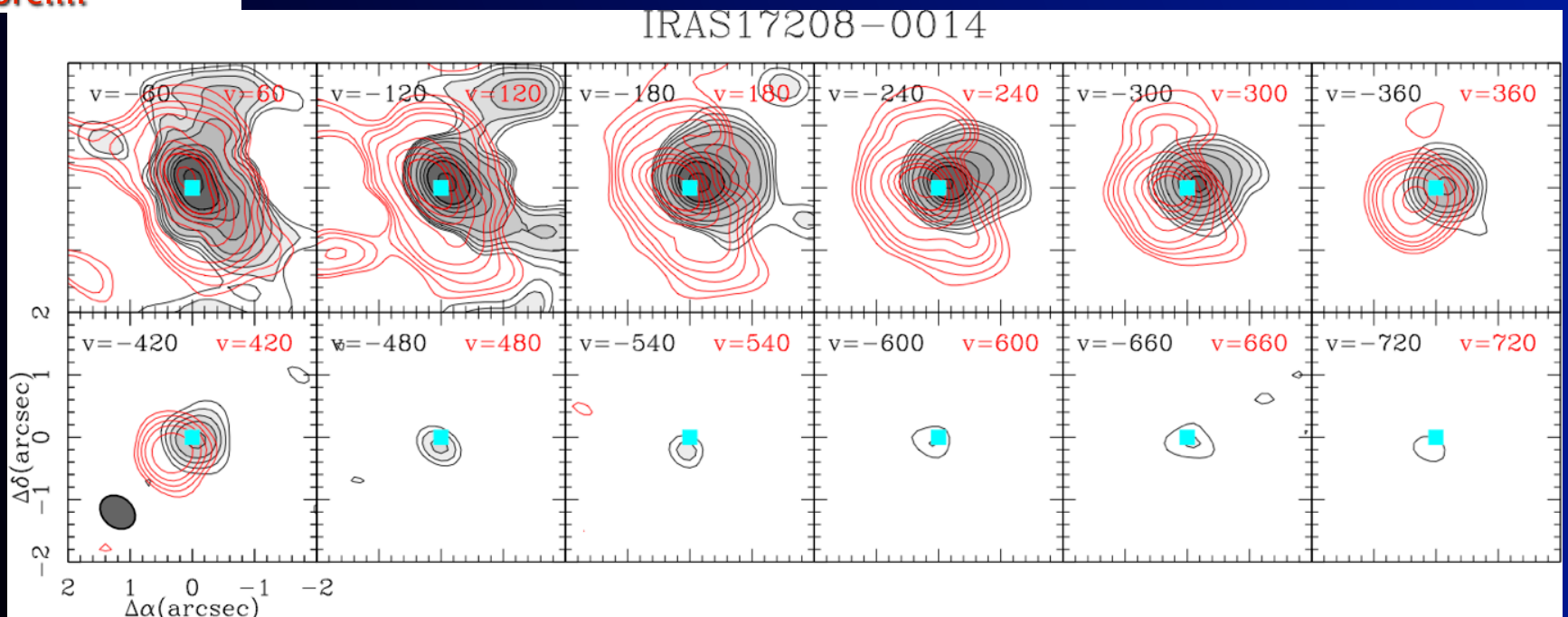
Molecular Outflows: ULIRGs

IRAS17208-0014

García-Burillo+2015, A&A submitted

-Subtraction of rotation shows PA of CO disk flips over (changes by 180º) already at v-v_{sys}=300 km/s--->dynamical decoupling of a non-coplanar outflow

before....



Molecular Outflows: ULIRGs

IRAS17208-0014

García-Burillo+2015, A&A submitted

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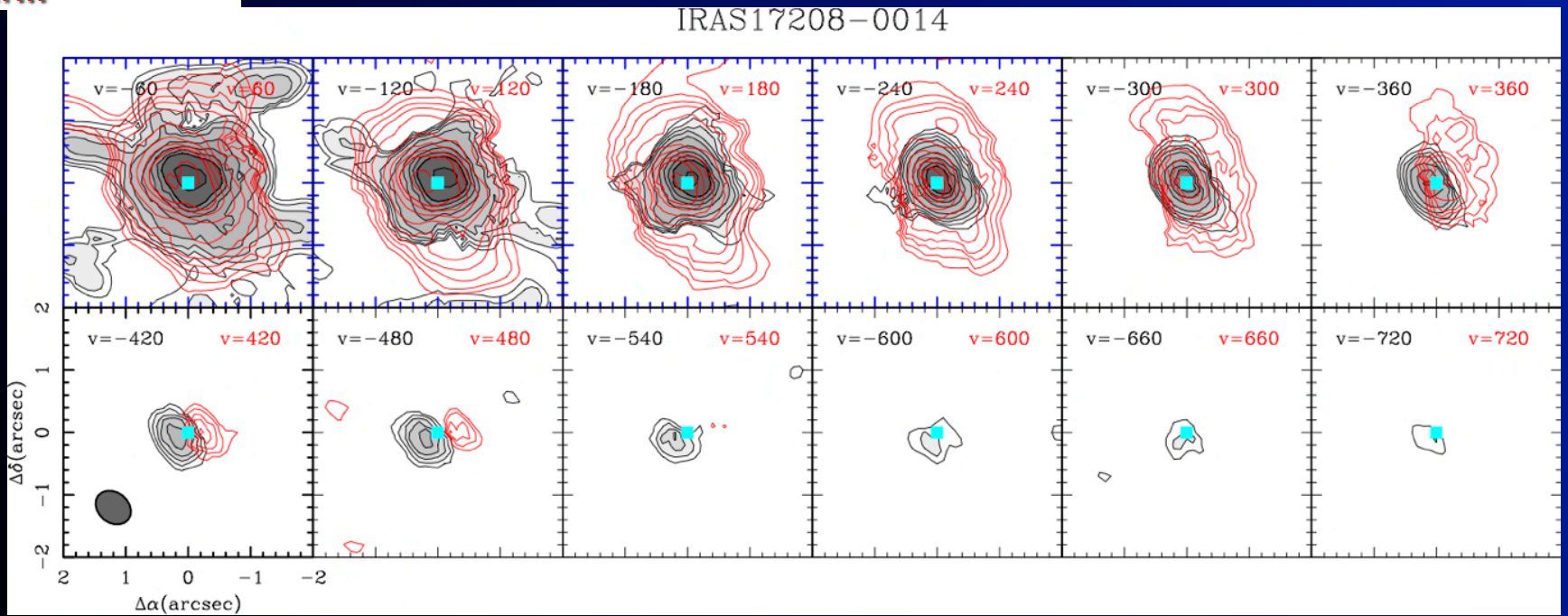

- *dM/dt ~ 1200 M_{sun}/yr ~ 3-5 x SFR*
- *Outflow NOT along minor axis*

...needs an obscured AGN?

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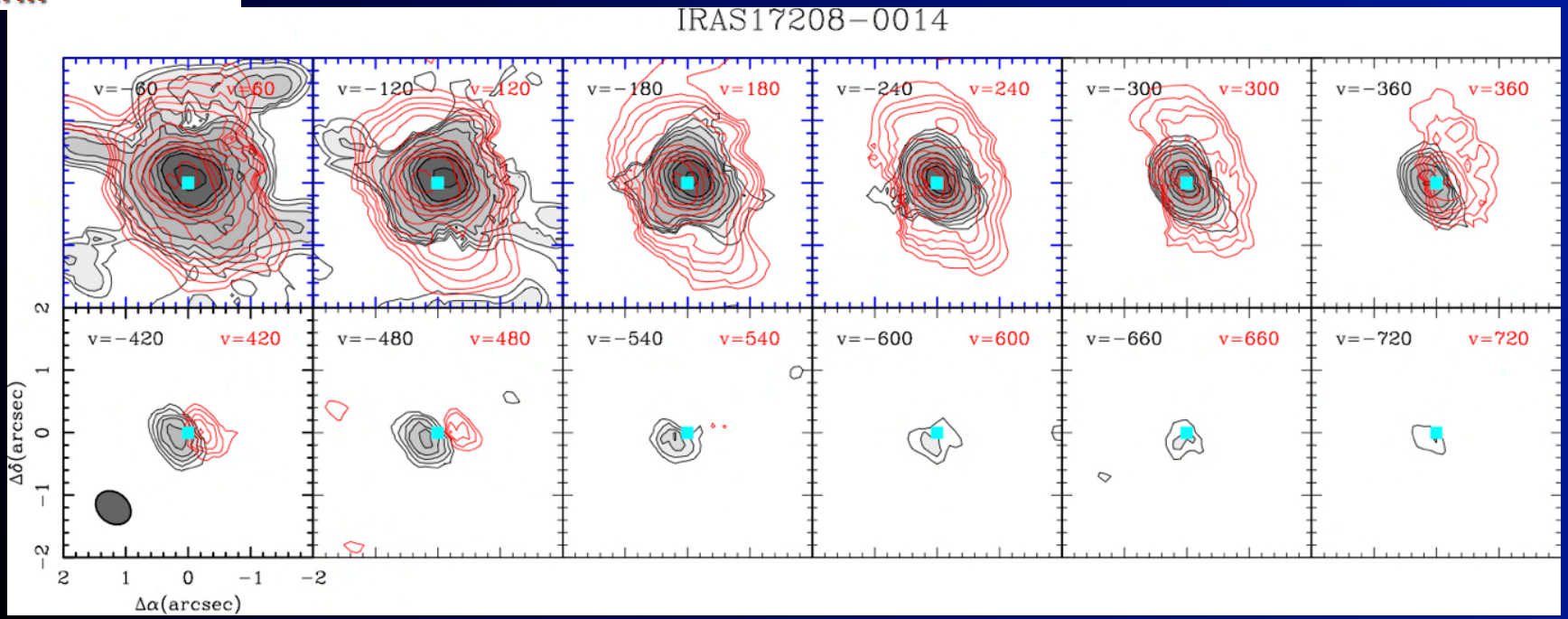

- *dM/dt ~ 1200 M_{sun}/yr ~ 5-7 x SFR*
- *Outflow NOT along minor axis*

...needs an obscured AGN?

→ **Spatial resolution key to unveiling outflows**

Molecular Outflows: ULIRGs

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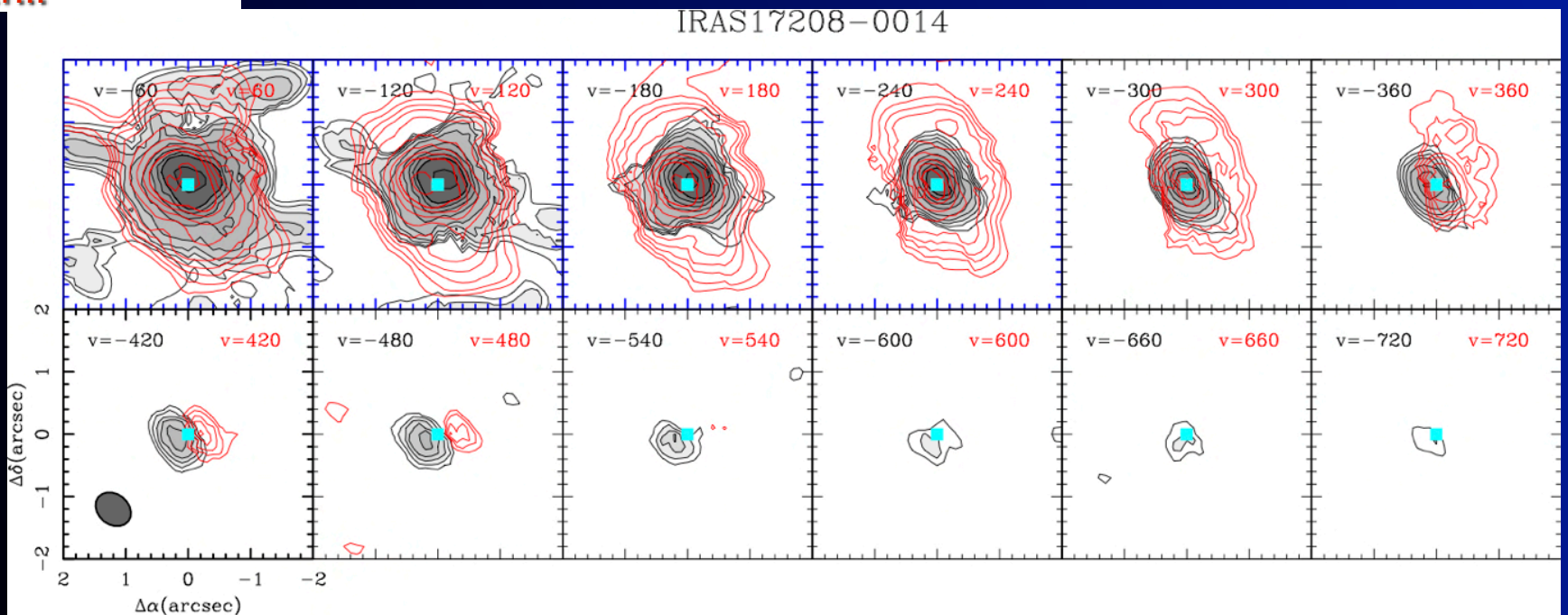

- *dM/dt ~ 1200 M_{sun}/yr ~ 3-5 x SFR*
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...needs an obscured AGN?

Comparison with
H_2 line VLT map of Emonts et al
HCN 4-3 ALMA map of Aalto et al

Conclusions - II: OUTFLOWS

- Mounting evidence of molecular winds detected in starbursts, local AGNs, RGs, and (U)LIRGs. Statistics to be improved.
- Energetically relevant, especially in mergers/extreme SBs and AGNs
  dM/dt up to 1000 M_{sun}/yr, dp/dt ~ (1-30) L_{bol}/c, L_{mech} up to 10^{11}erg/s
- Molecular outflows in local Seyferts relevant to self-regulate AGN fueling
- Preponderant role of AGN versus SF feedback action at higher L_{AGN}
- Measured velocities show most of molecular gas does not escape from disk to IGM...(fountain?)

Things to Do...

- Go high-resolution and 3D in emission lines: key to interpreting observed velocity fields. Detailed modelling to subtract rotation and non-circular motions NOT-related to outflow
- Go multi-phase: molecular phase is likely the most relevant, but picture from other phases much needed
- Go multi-line/multi-species: conversion factors from L(mol)--->M_{gas} still largely unconstrained and so is mass/energy budget

ALMA and NOEMA high-resolution + sensitivity surveys!!

Synergies with JWST, VLT, ELT, SKA

NIR/MIR 3D spectroscopy: JWST

NIRSpec: IFU (1–5μm)

-H_2 ro-vibrational line @2.1μm :

hot (T_k=1000-3000 K) molecular gas at ~ 0.1" up to z=1.3

-Paα, Brγ, FeII @ 3-5 μm up to z=1.5-2; also Hα up to z=3-5 in 3-4hrs

ionized gas at ~ 0.1"

MIRI: IFU (5–28μm)

-All the above lines but at higher z>2

-H_2 rotational lines at z=0:

warm (T_k=a few 100 K) molecular gas at ~ 0.2"-0.4"

-NeII, III at z=0 etc

ionized gas at ~ 0.2"-0.4"

→ inflows/outflows in H_2 + ionized gas with resolutions ~ ALMA

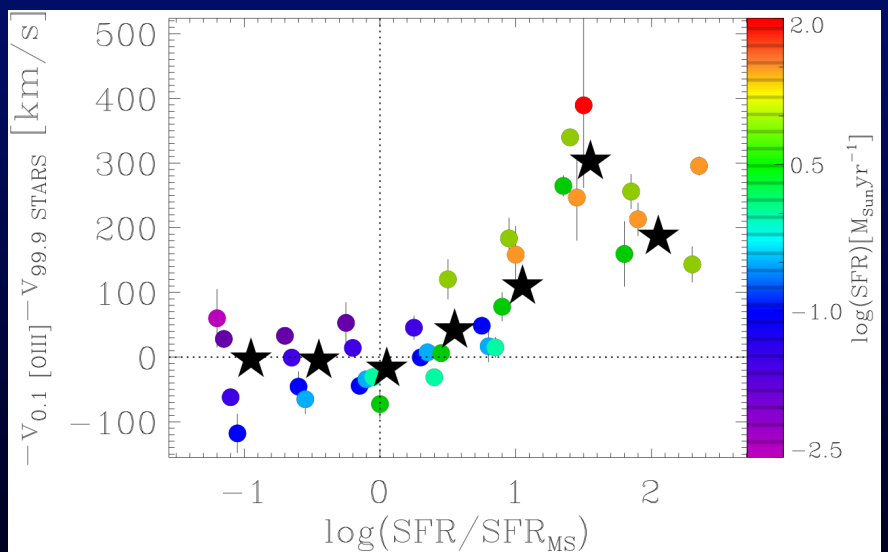
OPTICAL SPECTROSCOPY: SDSS4, VLT...

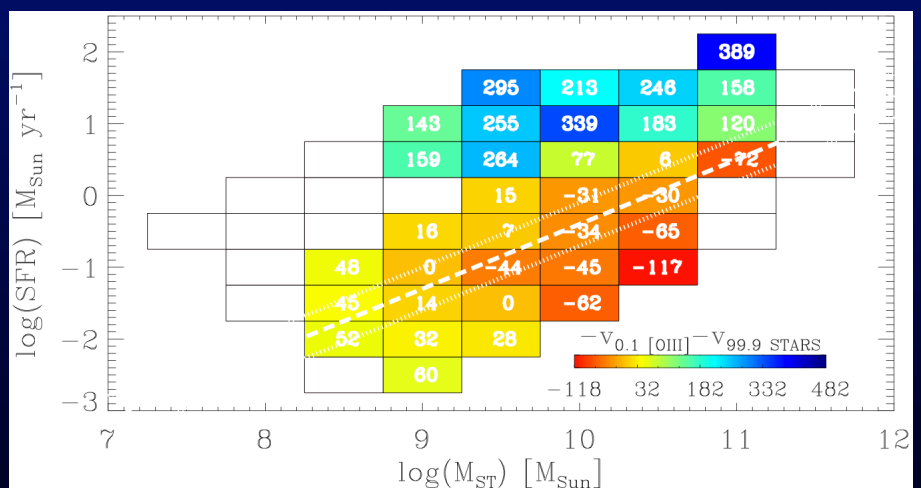
Cicone, Maiolino +2015

160,000 SDSS galaxies sorted into 50 bins in the M_*- SFR parameter space

Sharp increase of (ionized) gas outflows at SFR > SFR_{MS}

Outflows quench star formation and lower the SFR + bringing galaxy back on MS





➡ Next steps:

- 3D on large samples of galaxies: SDSS4-MANGA, MUSE at VLT...
- Investigate the ionized and atomic (NaID-line) outflows

HI 3D spectroscopy: SKA

HI absorption science with SKA1 possible observing parameters

Science goal	*SKA1*	*Redshift range*	*Receiver band*	*Spatial res.*	*Sky area*	*Spectral-line rms noise*	*Optical depth* τ	*Detections*
1. Inventory of HI in distant galaxies	Survey or Mid	to z=3	Band 1	~1 arcsec	1,000 deg^2	<0.1 mJy	<0.01 *(10 mJy source)*	~5000 assoc.; several hundred interven.
2. (i) Cold outflows (assoc.), ***(ii) Evolution of HI in galaxies (interv.)***	Survey or Mid	to z=3	Band 1	~1 arcsec	10,000 deg^2	<0.1 mJy	0.001 to 0.005 *(20-100 mJy source)*	A few hundred outflows; Several thousand intervening absorbers to z=3
3. HI at very high redshift	Low	3 < z < 8+	220 MHz band	~5 arcsec	>1,000 deg^2	<0.5 mJy	<0.05 *(10 mJy source)*	Unknown, *new discovery space!*

search at best resolution => then reprocessing/ follow up