Stellar feedback

~~ALMA~~ Perspective

NOVICE !

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30 years on winds… (Armus+, Steidel+, Scoville+)

Some quotes from ARAA article on Galactic Winds (Veilleux+)

- *The dynamical timescales yield mass outflow rates ranging from ~< 0.1 M☉ yr−1 to ~> 10 M☉ yr−1, with a trend for the rate to increase with increasing SFR.*
- *Assuming that these estimates of neutral gas masses are correct, the ratios of Mdot to the global SFRs span η ≡ Mdot /SFR ≈ 0.01−10, consistent with those found by Martin (1999) for the warm ionized medium of ten galaxies*
- *Rupke et al. (2005b) find that ~ 5−10% of the neutral material in starburst-driven winds will escape. This may only be a lower limit: much of the gas above **v**esc may have already mixed with the IGM and would be invisible in Na I D absorption.*
- *Entrained Dust: dynamical times yield dust outflow rates of ~ 1 M☉ yr−**1***
- *New mm-wave arrays (e.g., CARMA, and especially ALMA) will map the molecular gas in a large sample of nearby galaxies with excellent resolution (< 1′ ′). Sub-mm and mid-IR data from the ground (e.g., SMA, JCMT, CSO) and from space (e.g., SST and Herschel) will constrain the amount and location of dust in the winds.*

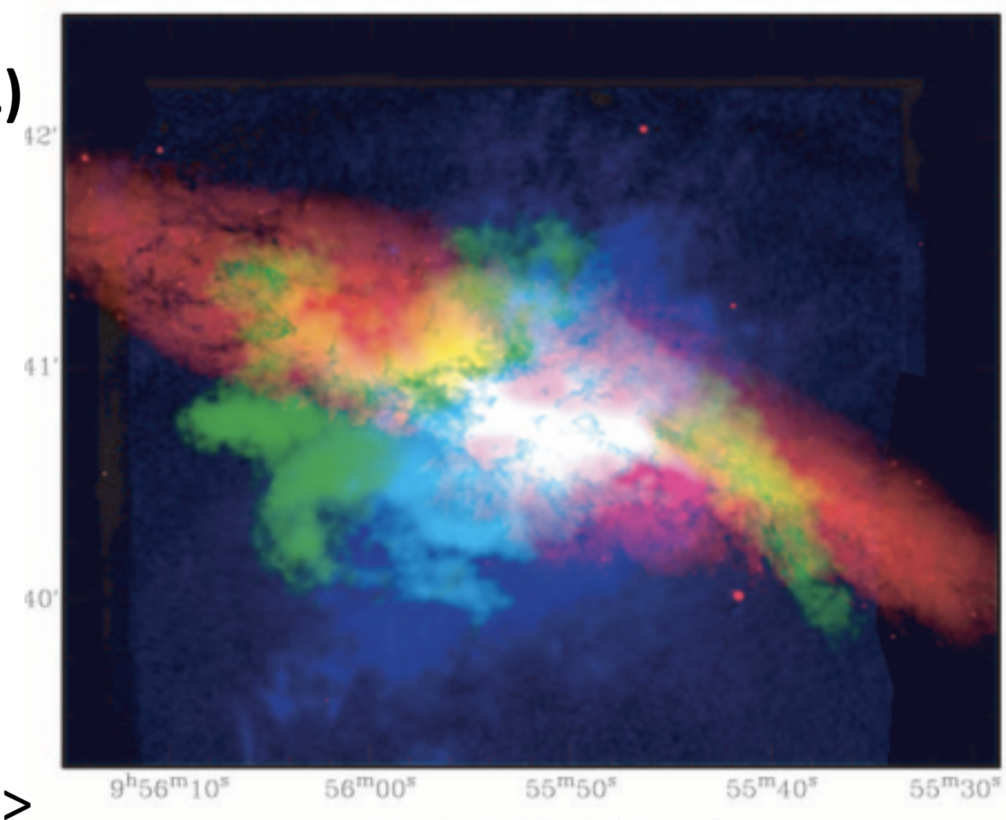
What about Molecular Gas?

M82 (Walter, Weiss Scoville+ 02)

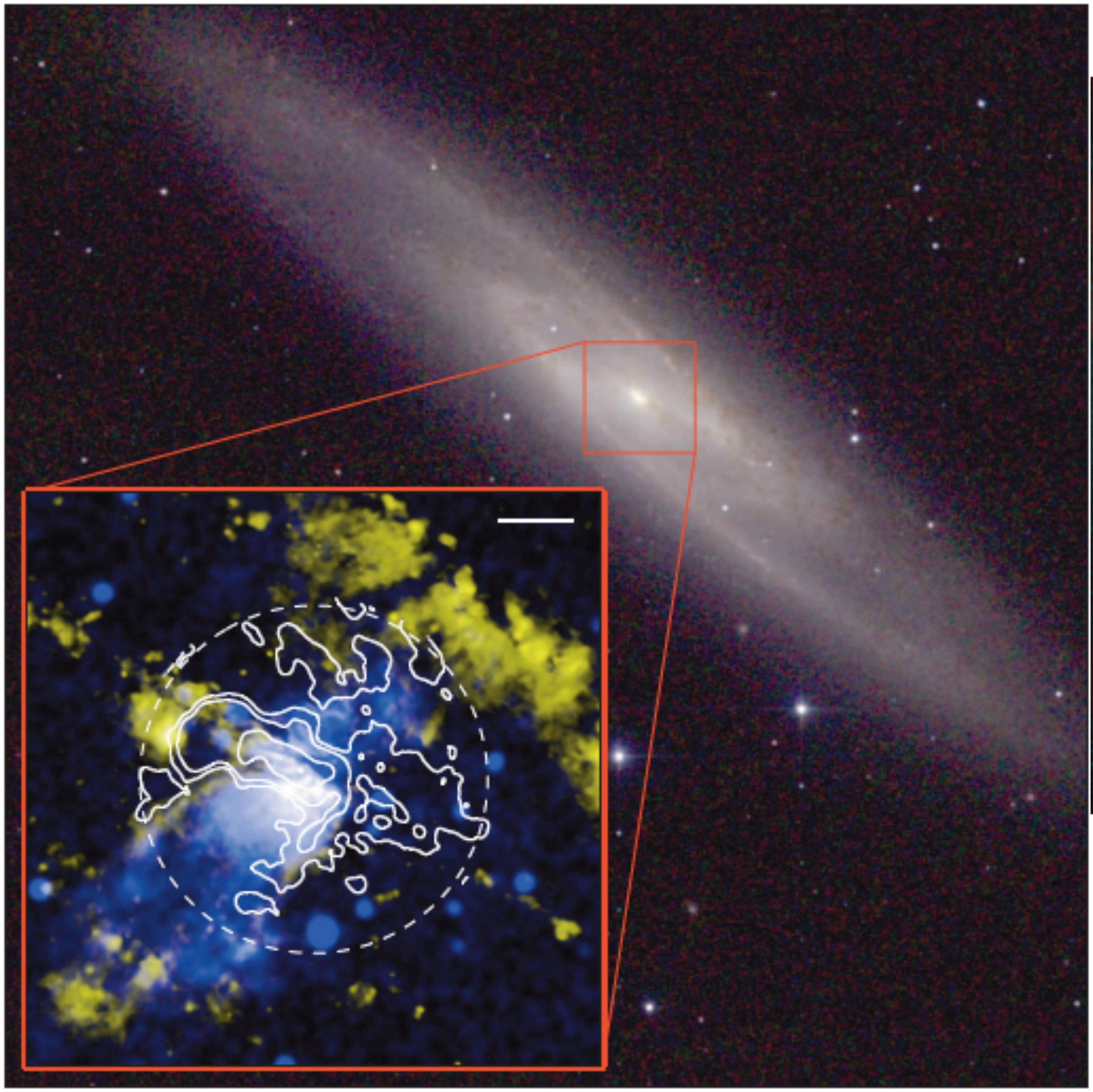
- Outflow velocities of 100 km/s
- 3.3 x 10^8 solar masses of H2 in outflow (X = 0.5)
- Few percent of total gas mass lost to IGM

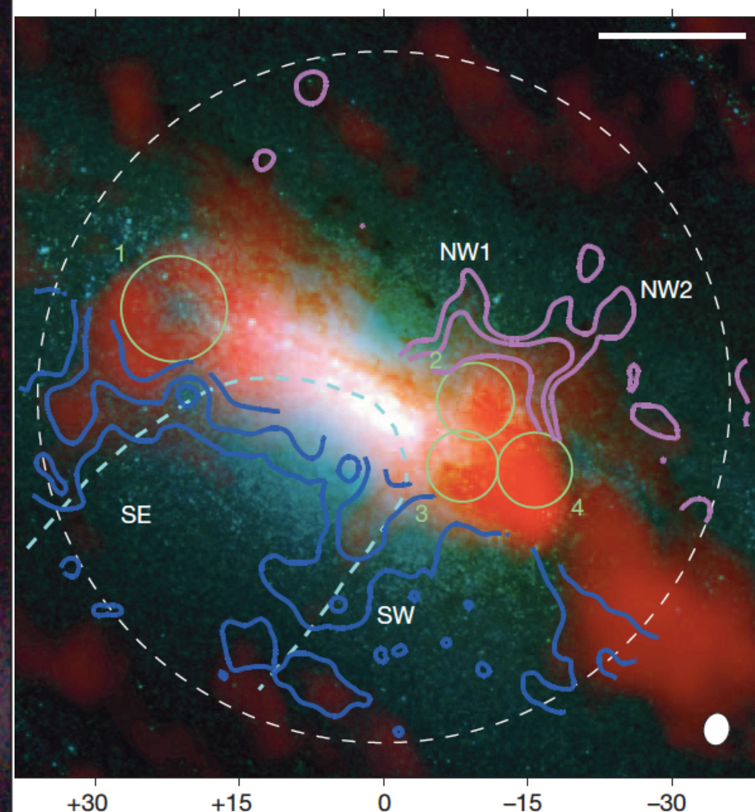
- Estimate 10 Myr to build up molecular outflow (mass + vel -> energy, SNe rate → lifetime of outflow)

- *No measurement of outflow rate*



"Suppression of star formation in the galaxy NGC 253 by a starburst-driven molecular wind" – Bolatto et al. (& Leroy)





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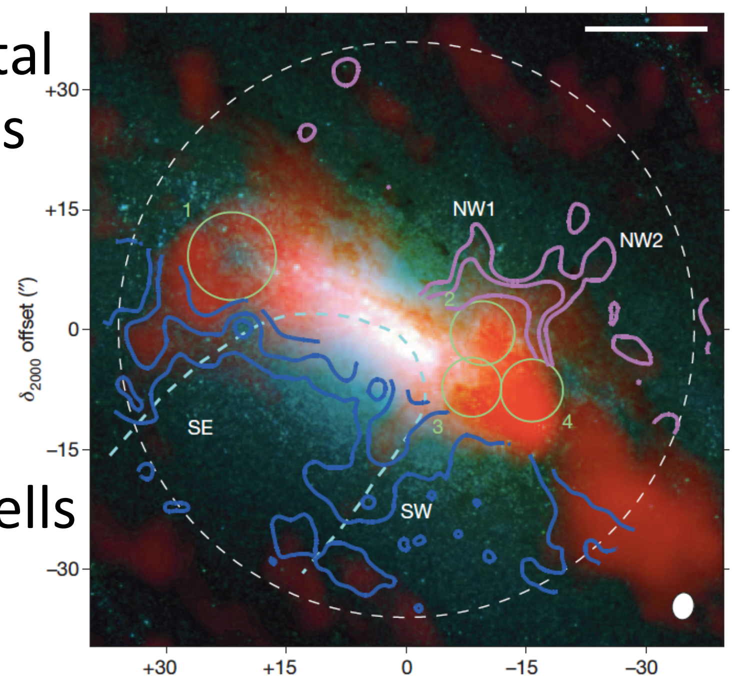
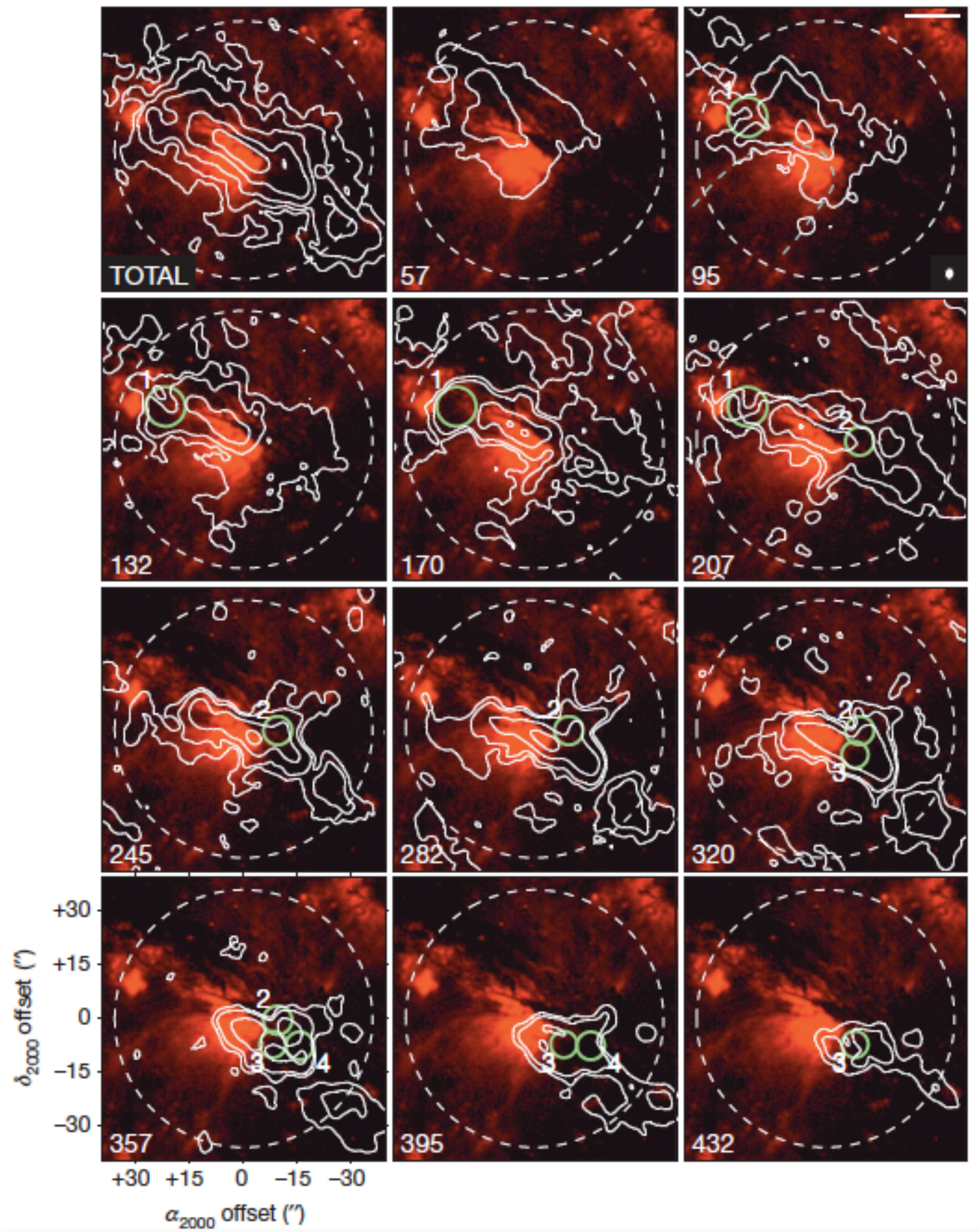
“ Most of the expelled mass (that is, the total mass flowing out from the nuclear region) is likely to be in atomic and molecular phases that are cooler than the ionized phases.” – how is this obvious?



- Molecular gas entrained in expanding shells
- Need resolution ~ 100pc or better
- NGC 253 – ionized wind from the central 200pc – moving at a few hundred km/s
- Extent of wind ~ 10 kpc (Hα, X-ray and UV)

- Molecular streamers in CO are seen
- “Perfectly” aligned with Halpha edges



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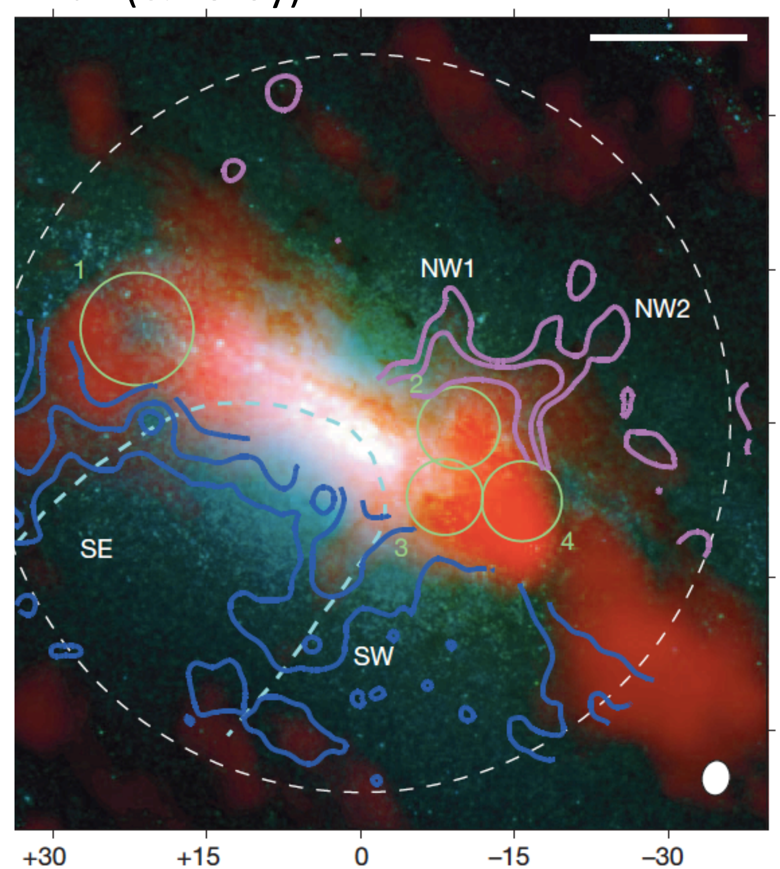

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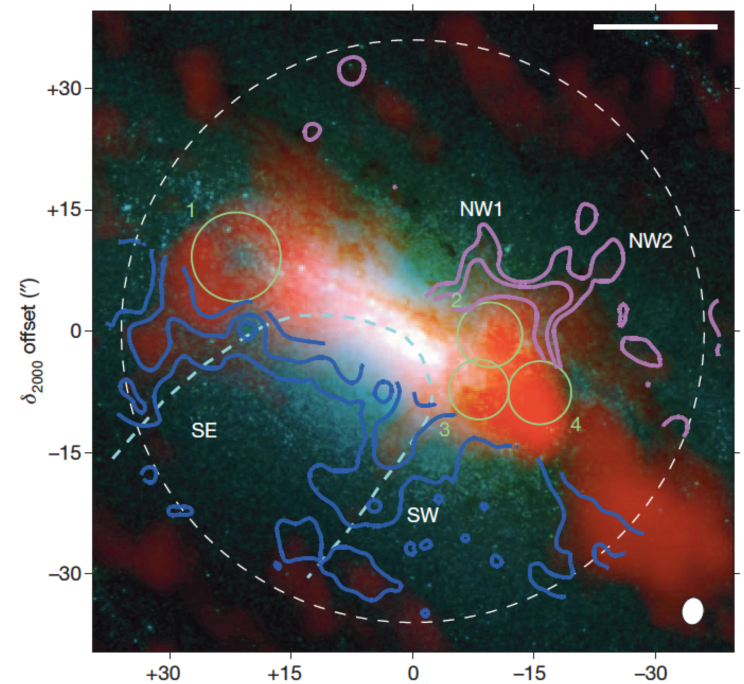
- Molecular streamers in CO are seen
- “Perfectly” aligned with Halpha edges

- No NE component seen – why not?

- Extraplanar CO can be traced to expanding super bubbles
- Shell radii ~ 60–90 pc,
- Expansion velocities of 23–42kms
- Characteristic dynamical ages of 1.4–4Myr
- Molecular masses of 0.3 -1 x 10^7 $M_\odot$



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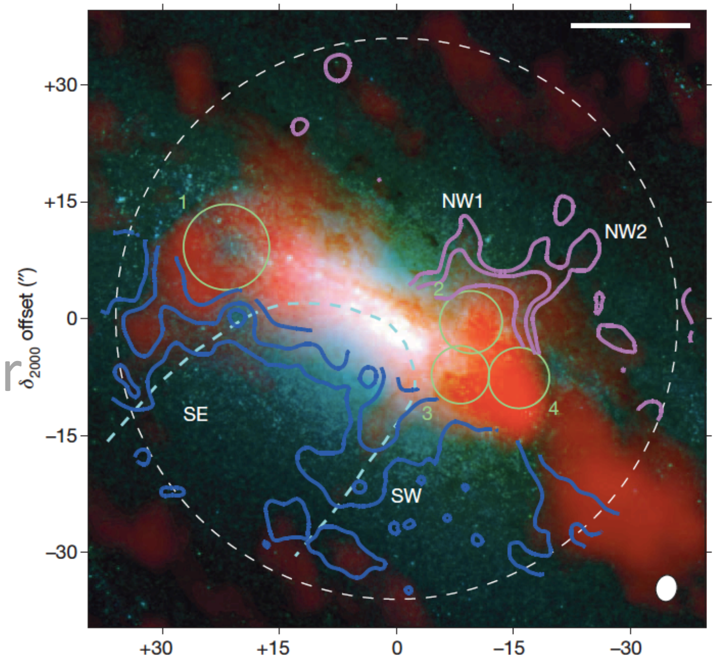

- Momentum: 8.5 – 40 x 10^7 $M_\odot$ km /s
- Energy: 2 -20 x 10^{52} ergs
  - Stellar wind + supernovae
  - 10^5 $M_\odot$ cluster provides 10^{39} erg / s? (McCray & Kafatos)
- Assume age of cluster – if 3 Myr – total energy from 10^5 cluster is 10^{39} * 3e7 * 3.2e7 ~ 10^{54} ergs

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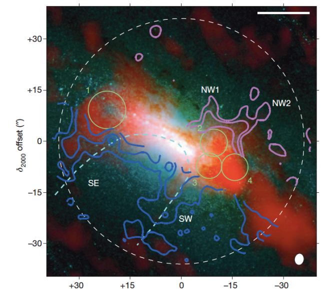

- Flux in CO measured as (K km/s pc^2)
- Multiply by α (solar mass / (K km/s pc^2)
- Assume an α **<u>10x</u>** lower than Galactic
- Total mass ~ 6.6 x 10^6 $M_\odot$

- Measure filament length - then divide by vel → age of 0.3 – 1 Myr
- Outflow rate = Total mass / Age ~ 9 $M_\odot$ / yr

Lots of hand wringing about this simple back of the envelope calculation – arguing this is the minimum of the outflow rate

- SFR ~ 3 solar masses per year..
- *Bottom line*
  - *Outflow rate comparable to SFR*
  - *SF will be quenched by this outflow*
  - *Molecular gas likely to be "re-used" when it rains back d*

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Other outflow examples in mm/submm

1. CO (1-0) and (3-2) in SDSS J135646.10+102609.0 - Sun+ ApJ, 2014, 790, 160
   - Very high velocities ~ 500 km/s
   - AGN driven wind, claim an outflow of 350 $M_{\odot}$ / yr!

2. CO outflows – broad line width around AGN (Combes, Garcia-Burillo + NUGA team)
   - Large outflows ~ 10-100 solar mass/yr **> SFR**

3. 10^{10} solar mass flows in BCGs – Russel, McNamara (couple of papers)
   - Broad line width – claim is 200 solar masses / outflow or inflow! ?

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ALMA strengths

- Various molecular species + warm and cold gas
- Velocities / velocity dispersion / velocity gradients
- Collimation
- Chemistry of outflows

- Observational considerations:
  - UV-coverage – coverage on variety of spatial scales
  - High angular and velocity resolution

What can we measure?

- The line of sight velocity → rotation curve, kinematics, velocity dispersion
- Molecular and atomic lines
  - Need to convert observed flux to a mass (not trivial even for CO (1-0))
  - Jy km/ s → M(H2) assumes that the molecular gas is a optically “thin” medium of optically thick clouds
  - High velocity flows undoubtedly change the conversion factor !
  - Moreover if we use higher J- lines – unclear how to translate that to a molecular mass
  - Need to model to disentagle systemic velocity / flows

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Does it make sense? / Talking Points

- Is there a conspiracy of outflow rates always ~ > SFR?
- Does it <u>really</u> imply quenching ??
- How much outflow / feedback we need to solve galaxy evolution at large and small scales?
- Should we also worry about inflow / (re-) accretion
- Where shall we make the observations? How many galaxies?
  - What about feedback in the MW?

- **What can we really derive robustly?**

If we can get all the phases, mass and velocities in the outflow – then we would have a good handle on the energetics → can determine how much is from stellar winds, SNe, etc.

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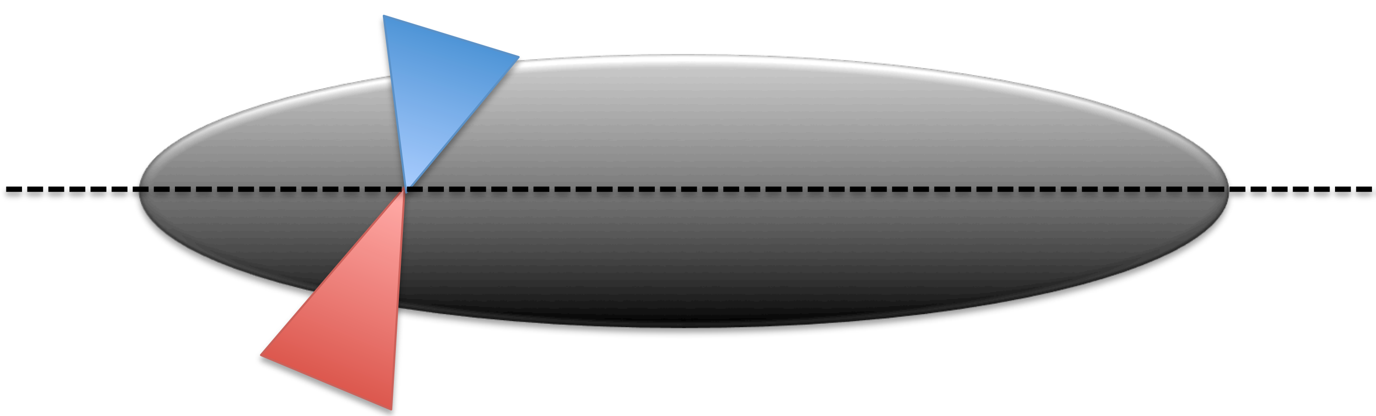
- Basic goal: Measure the mass outflow rate
- dM / dt = dM * velocity * distance?
- What is mass loading?
  - Simply because I see a velocity width in CO – I have no idea really how much mass is moving at that velocity
- Mechanical energy = Mv^2 -- again need to sort out “M”

Sketching an outflow



- CO outflows