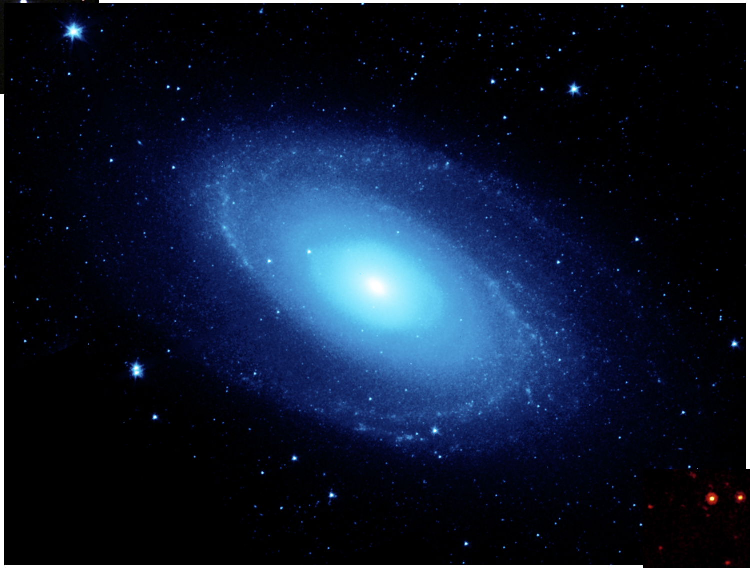
Spiral arms at low frequencies

Andrew Fletcher
Newcastle University

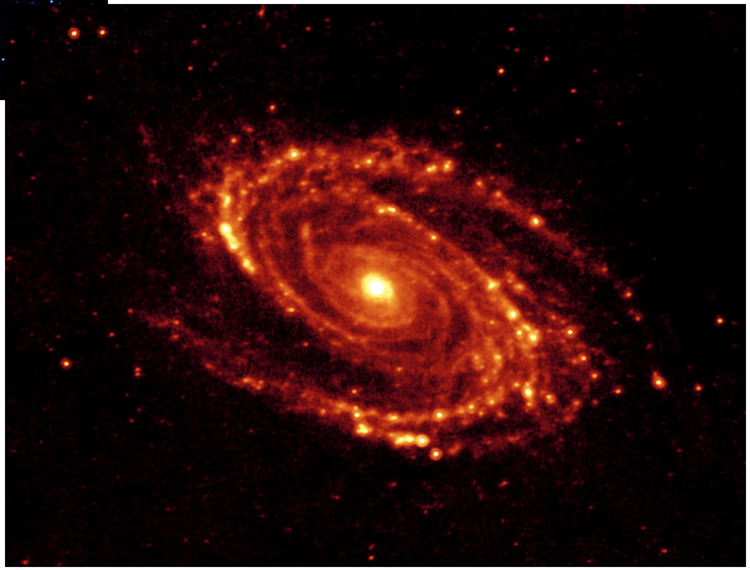
Massive galaxies:
2/3 spiral,
1/3 elliptical

M81

visible



3.6 μm, stars



24 μm, dust

Outline

- How are they formed?
- What are the predicted arm properties?
- How to identify the formation mechanism?
- What about (low-frequency) radio observations?

How are spiral arms formed?

There is no consensus! [Dobbs & Baba, PASA, 2014]

Possibilities include:

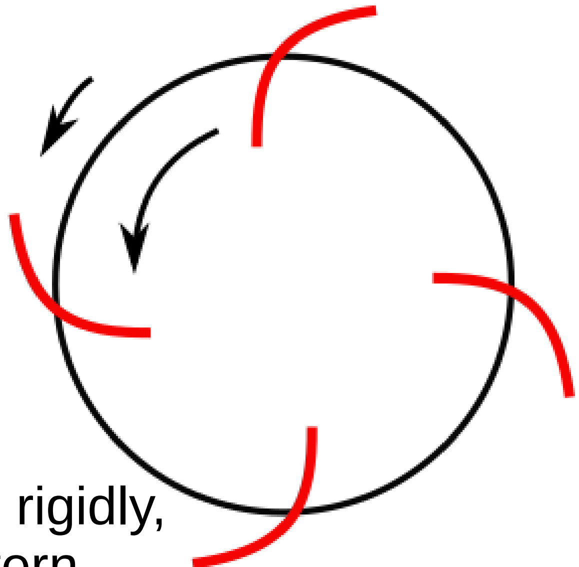
- density wave theory, [Lin & Shu, 1964, + many variants]
- transient “dynamic” spirals, [N-body simulations]
- bar-driven, [N-body simulations + stellar orbit theory]
- tidal interactions. [N-body simulations]

Spiral arm behaviour?

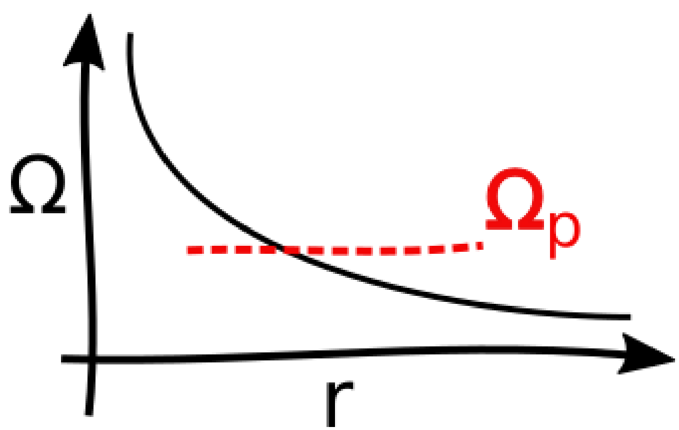
- Density wave:
  - quasi-stationary arms (**rotate rigidly**, Ω_p = constant),
  - Ω_p is pattern (angular) speed
- Dynamic:
  - short-lived segments form and break up
  - material arms (rotate with disc, $\Omega_p = \Omega(r)$, **co-rotation** everywhere)
- Bar-driven:
  - arms rotate: with bar or independently or some other way.
- Tidal arms:
  - quasi-stationary or material or kinematic (aligned elliptical orbits, $\Omega_p = \Omega(r) - \kappa(r)/2$, for 2-arms)

Pattern speeds

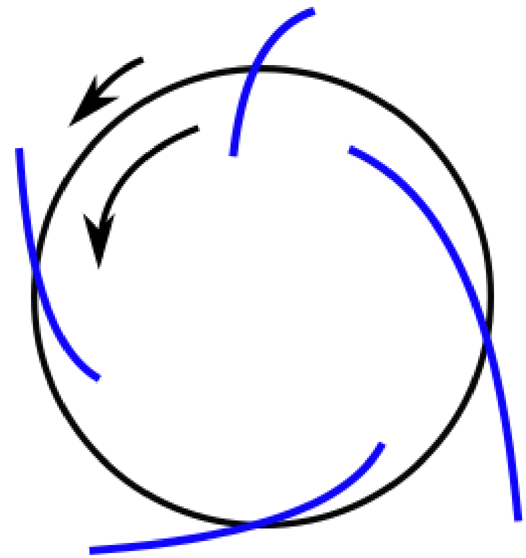
density wave



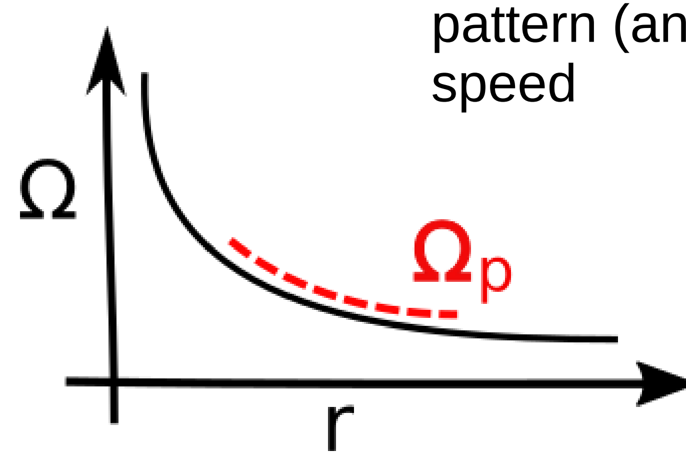
spiral rotates rigidly, constant pattern (angular) speed



material arm



spiral rotates with disc, variable pattern (angular) speed



How to identify mechanism?

- Do the arms move w.r.t. the disc?
  - fixed Ω_p or $\Omega_p(r)$
- How to find pattern speed:
  - spiral shock location, either side of co-rotation
  - offsets of e.g. CO and Hα
  - stellar age sequence w.r.t. spiral arm
  - velocity field
  - conservation of mass through arm (Tremaine-Weinberg method)
- Correlations:
  - pitch angle and shear
  - bar strength and spiral strength / contrast

THE ASTROPHYSICAL JOURNAL, 735:101 (11pp), 2011 July 10 doi:10.1088/0004-637X/735

OBSERVATIONAL EVIDENCE AGAINST LONG-LIVED SPIRAL ARMS IN GALAXIES

K. FOYLE[1,2], H.-W. RIX[1], C. L. DOBBS[3,4], A. K. LEROY[5,6], AND F. WALTER[1]
[1] Max-Planck-Institute für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany; foylek@physics.mcmaster.ca
[2] Department of Physics & Astronomy, McMaster University, Hamilton, Ontario L8S 4M1, Canada
[3] Max-Planck-Institut für extraterrestrische Physik, Giessenbachstraße, D-85748 Garching, Germany
[4] Universitats-Sternwarte München, Scheinerstraße 1, D-81679 München, Germany
[5] National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903, USA
Received 2011 January 13; accepted 2011 April 18; published 2011 June 22

ABSTRACT

We test whether the spiral patterns apparent in many large disk galaxies should be thought of as dynamical features that are stationary in a corotating frame for $\gtrsim t_{\rm dyn}$, as implied by the density wave approach for explaining spiral arms. If such spiral arms have enhanced star formation (SF), observational tracers for different stages of the SF sequence should show a spatial ordering, from upstream to downstream in the corotating frame: dense H I, CO, tracing molecular hydrogen gas, 24 μm emission tracing enshrouded SF, and UV emission tracing unobscured young stars. We argue that such a spatial ordering should be reflected in the angular cross-correlation (CC, in polar coordinates) using all azimuthal positions among pairs of these tracers; the peak of the CC should be offset from zero, in different directions inside and outside the corotation radius. Recent spiral SF simulations by Dobbs & Pringle show explicitly that for the case of a stationary spiral arm potential such angular offsets between gas and young stars of differing ages should be observable as cross-correlation offsets. We calculate the angular cross-correlations for different observational SF sequence tracers in 12 nearby spiral galaxies, drawing on a data set with high-quality maps of the neutral gas (H I, THINGS) and molecular gas (CO, HERACLES), along with 24 μm emission (*Spitzer*, SINGS); we include FUV images (*GALEX*) and 3.6 μm emission (*Spitzer*, IRAC) for some galaxies, tracing aging stars and longer timescales. In none of the resulting tracer cross-correlations for this sample do we find systematic angular offsets, which would be expected for a stationary dynamical spiral pattern of well-defined pattern speed. This result indicates that spiral density waves in their simplest form are not an important aspect of explaining spirals in large disk galaxies.

THE ASTROPHYSICAL JOURNAL, 763:94 (11pp), 2013 February 1 doi:10.1088/0004-637X/7

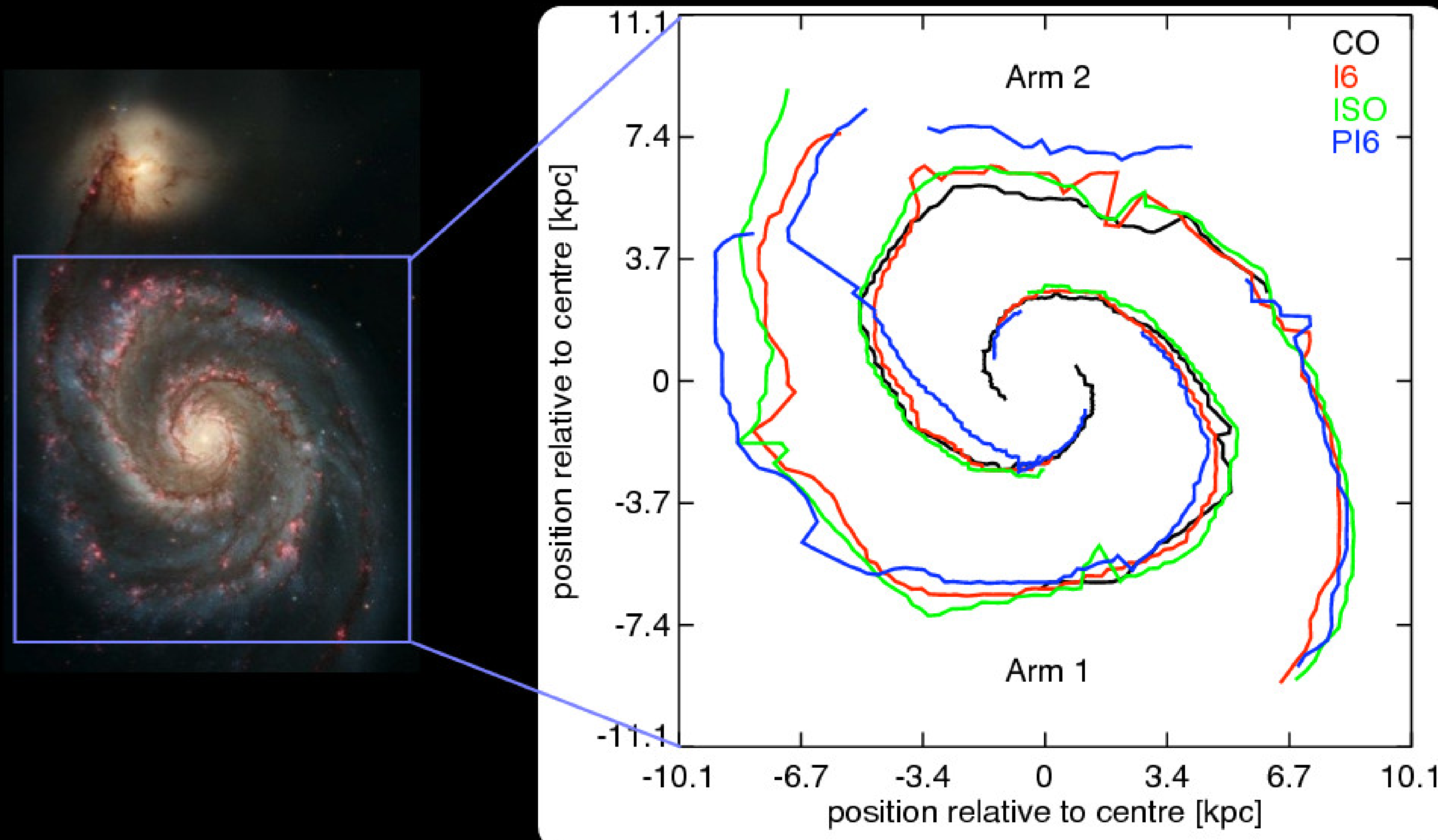
GEOMETRIC OFFSETS ACROSS SPIRAL ARMS IN M51: NATURE OF GAS AND STAR FORMATION TRACERS

MELISSA LOUIE[1], JIN KODA[1], AND FUMI EGUSA[2]
[1] Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA; melissa.louie@stonybrook.edu
[2] Department of Space Astronomy and Astrophysics, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Japan
Received 2012 February 27; accepted 2012 November 30; published 2013 January 14

ABSTRACT

We report measurements of geometric offsets between gas spiral arms and associated star-forming regions in the grand-design spiral galaxy M51. These offsets are a suggested measure of the star formation timescale after the compression of gas at spiral arm entry. A surprising discrepancy, by an order of magnitude, has been reported in recent offset measurements in nearby spiral galaxies. Measurements using CO and Hα emission find large and ordered offsets in M51. On the contrary, small or non-ordered offsets have been found using the H I 21 cm and 24 μm emissions, possible evidence against gas flow through spiral arms, and thus against the conventional density-wave theory with a stationary spiral pattern. The goal of this paper is to understand the cause of this discrepancy. We investigate potential causes by repeating those previous measurements using equivalent data, methods, and parameters. We find offsets consistent with the previous measurements and conclude that the difference of gas tracers, i.e., H I versus CO, is the primary cause. The H I emission is contaminated significantly by the gas photodissociated by recently formed stars and does not necessarily trace the compressed gas, the precursor of star formation. The H I gas and star-forming regions coincide spatially and tend to show small offsets. We find mostly positive offsets with substantial scatter between CO and Hα, suggesting that gas flow through spiral arms (i.e., density wave) though the spiral pattern may not necessarily be stationary.

M51: position of arm ridges



Patrikeev et al. 2006

Spiral structure in nearby galaxies – I. Sample, data analysis and overview of results

S. Kendall,* R. C. Kennicutt and C. Clarke

modes. There is no evidence that bars preferentially trigger the spirals, but they do appear to stir up non-axisymmetric structure in the disc. In contrast, there is evidence that strong/close tidal interactions with companion galaxies are associated with strong two-armed spiral structure in the IR, though there are a number of galaxies with relatively weak IR spiral structure that do not possess such companions.

The Astronomical Journal, 137:4487–4516, 2009 May
doi:10.1088/0004-6256/137/5/448

DO BARS DRIVE SPIRAL DENSITY WAVES?

maybe

Ronald J. Buta[1], Johan H. Knapen[2], Bruce G. Elmegreen[3], Heikki Salo[4], Eija Laurikainen[4], Debra Meloy Elmegreen[5], Ivânio Puerari[6], and David L. Block[7]
[1] Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA; rbuta@bama.ua.edu
[2] Instituto de Astrofísica de Canarias, E-38200 La Laguna, Spain; jhk@iac.es
[3] IBM Research Division, T.J. Watson Research Center, 1101 Kitchawan Road, Yorktown Heights, NY 10598, USA; bge@watson.ibm.com
[4] Division of Astronomy, Department of Physical Sciences, University of Oulu, Oulu FIN-90014, Finland; hsalo@sun3.oulu.fi, eija@sun3.oulu.fi
[5] Vassar College, Department of Physics & Astronomy, Box 745, Poughkeepsie, NY 12604, USA; elmegreen@vassar.edu
[6] Instituto Nacional de Astrofísica, Optica y Electrónica, Tonantzintla, PUE 72840, Mexico; puerari@inaoep.mx
[7] Anglo American Cosmic Dust Laboratory, School of Computational & Applied Mathematics, University of the Witwatersrand, P.O. Box 60 Wits, 2050, South Africa; David.Block@wits.ac.za
Received 2008 October 22; accepted 2009 February 28; published 2009 April 7

We present deep near-infrared
of a selected sample of near
sample covers a range of Hub
the spirals correlate with thos
has been predicted by theoret
at high redshift. Analysis of
where effects of extinction a
few excessively strong bars.
is relatively weak. We find t
the presence of a very strong
pattern speed, but that this m

The Astrophysical Journal Letters, 715:L56–L61, 2010 May 20
doi:10.1088/2041-8205/71

yes, in a statistical sense

BARS DO DRIVE SPIRAL DENSITY WAVES

H. Salo[1], E. Laurikainen[1,2], R. Buta[3], and J. H. Knapen[4,5]
[1] Department of Physics/Astronomy Division, University of Oulu, FI-90014, Finland
[2] Finnish Centre for Astronomy with ESO (FINCA), University of Turku, Väisäläntie 20, FI-21500 Piikkiö, Finland
[3] Department of Physics and Astronomy, University of Alabama, Box 870324, Tuscaloosa, AL 35487, USA
[4] Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain
[5] Departamento de Astrofísica, Universidad de La Laguna, E-38205 La Laguna, Tenerife, Spain
Received 2010 February 3; accepted 2010 April 20; published 2010 May 3

ABSTRACT

Recently, Buta et al. examined the question "Do Bars Drive Spiral Density Waves?", an idea supported by theoretical studies and also from a preliminary observational analysis. They estimated maximum bar strengths Q_b, maximum spiral strengths Q_s, and maximum $m = 2$ arm contrasts A_{2s} for 23 galaxies with deep Anglo-Australian Telescope (AAT) K_s-band images. These were combined with previously published Q_b and Q_s values for 147 galaxies from the Ohio State University Bright Spiral Galaxy Survey (OSUBSGS) sample and with the 12 galaxies from Block et al. Weak correlation between Q_b and Q_s was confirmed for the combined sample, whereas the AAT subset alone showed no significant correlations between Q_b and Q_s, nor between Q_b and A_{2s}. A similar negative result was obtained in Durbala et al. for 46 galaxies. Based on these studies, the answer to the above question remains uncertain. Here we use a novel approach, and show that although the correlation between the *maximum* bar and spiral parameters is weak, these parameters do correlate when compared *locally*. For the OSUBSGS sample, a statistically significant correlation is found between the local spiral amplitude, and the forcing due to the bar's potential at the same distance, out to ≈1.6 bar radii (the typical bar perturbation is then of the order of a few percent). Also for the sample of 23 AAT galaxies of Buta et al., we find a significant correlation between local parameters out to ≈1.4 bar radii. Our new results confirm that, at least in a statistical sense, bars do indeed drive spiral density waves.

What about low-frequency radio?

- massive stars: sources of cosmic ray electrons
- massive stars: concentrated in spiral arms
- pattern speed of spiral arm distinguishes different formation mechanisms
- does the azimuthal profile of synchrotron emission look different if sources move?

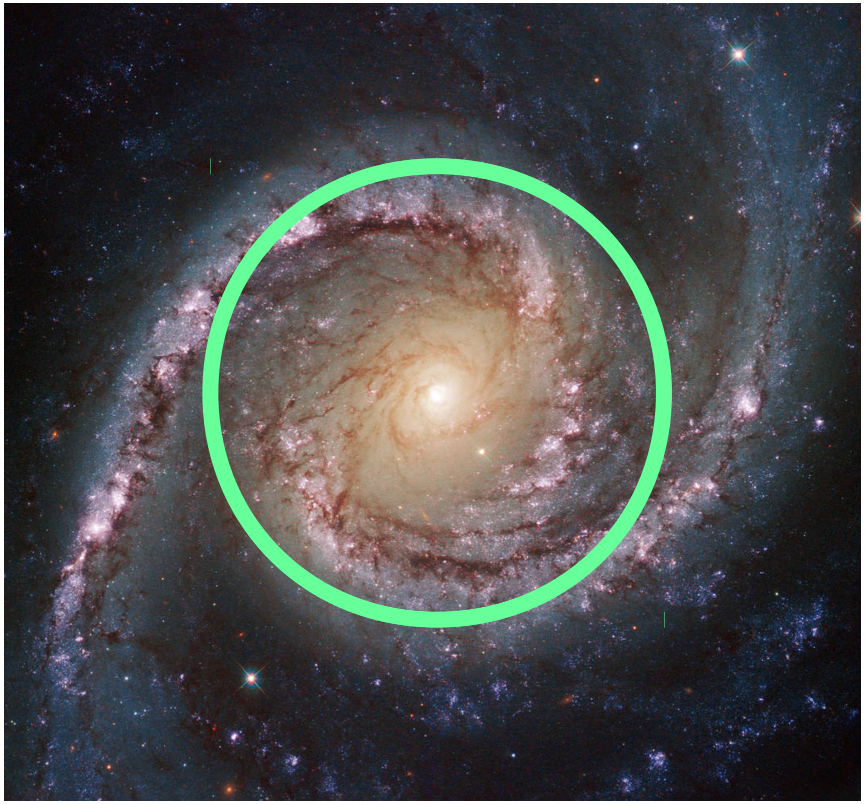
Diffusion energy-loss equation

$$\frac{\partial N}{\partial t} = D\nabla^2 N + \frac{\partial}{\partial E}[\beta E^2 N] + Q - \frac{N}{\tau_{\mathrm{esc}}}$$

diffusion energy loss source escape

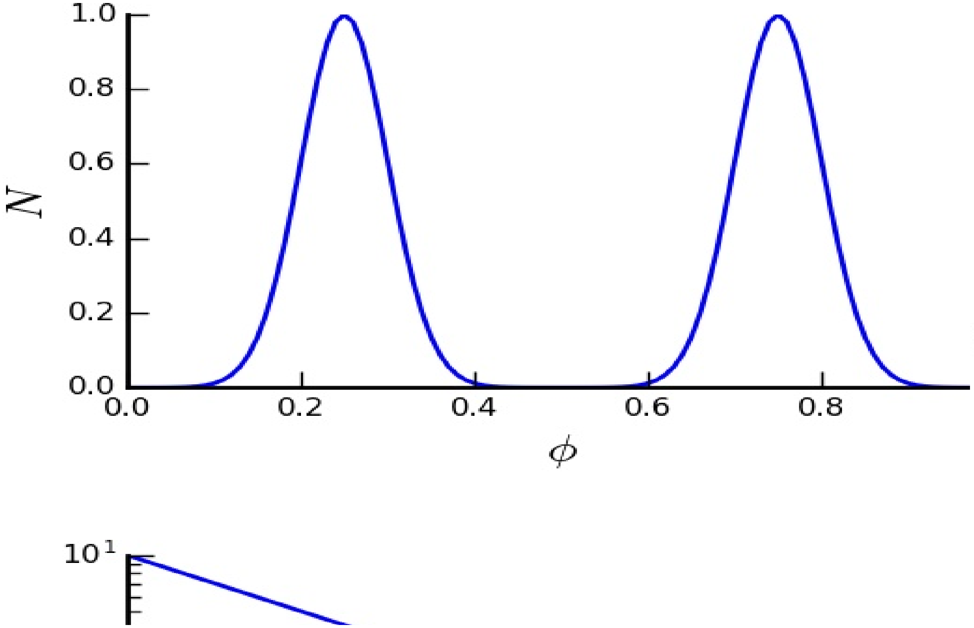
$$N(x, E, t) \quad Q(x, E, t)$$

solve around a ring in azimuth

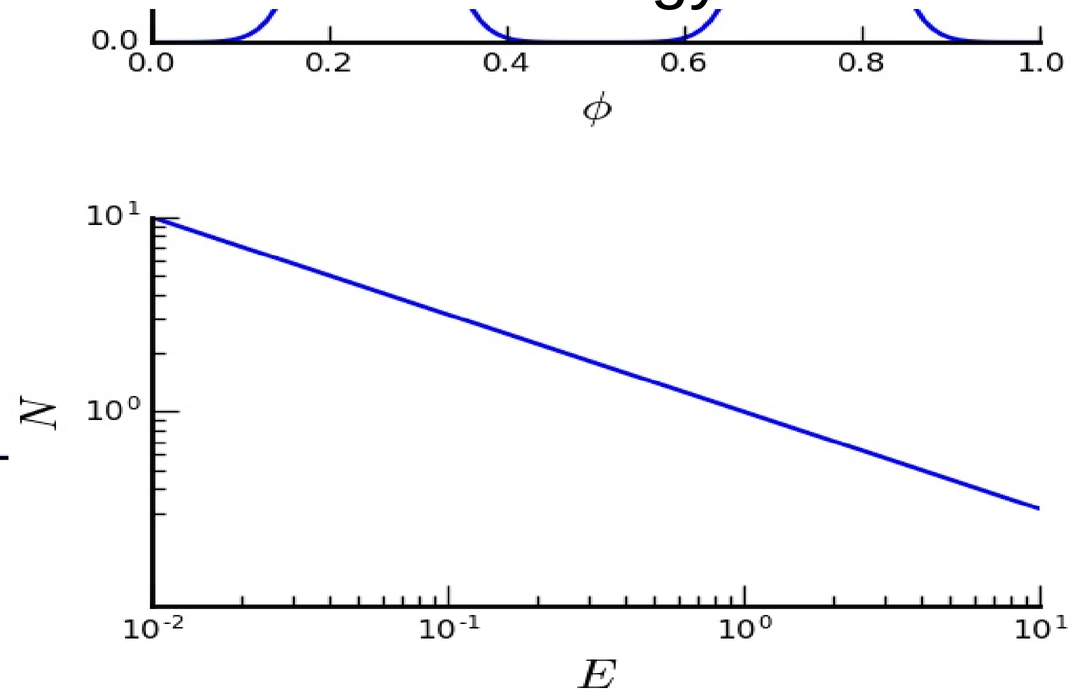


Cosmic ray sources

spatial distribution

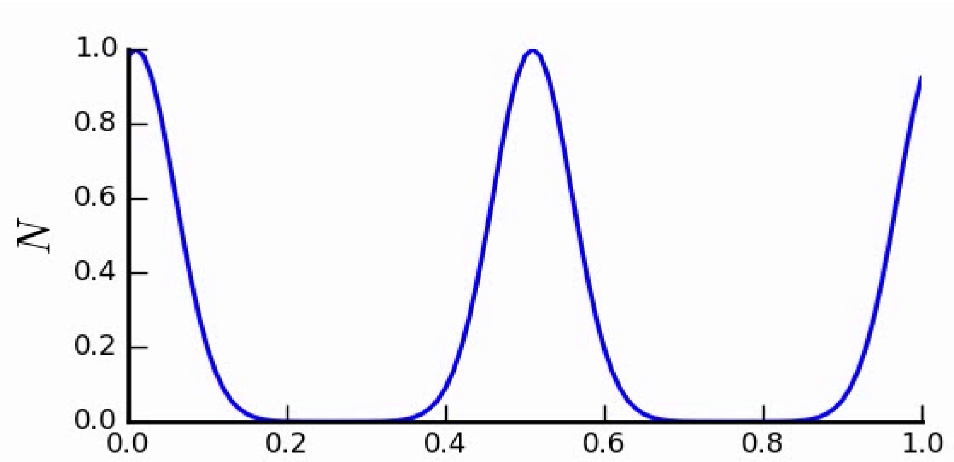


energy

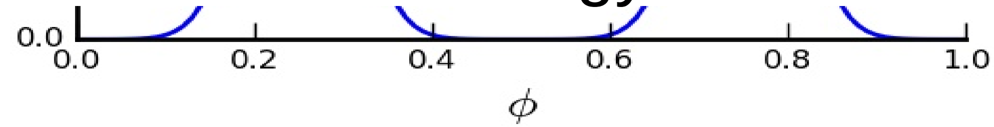


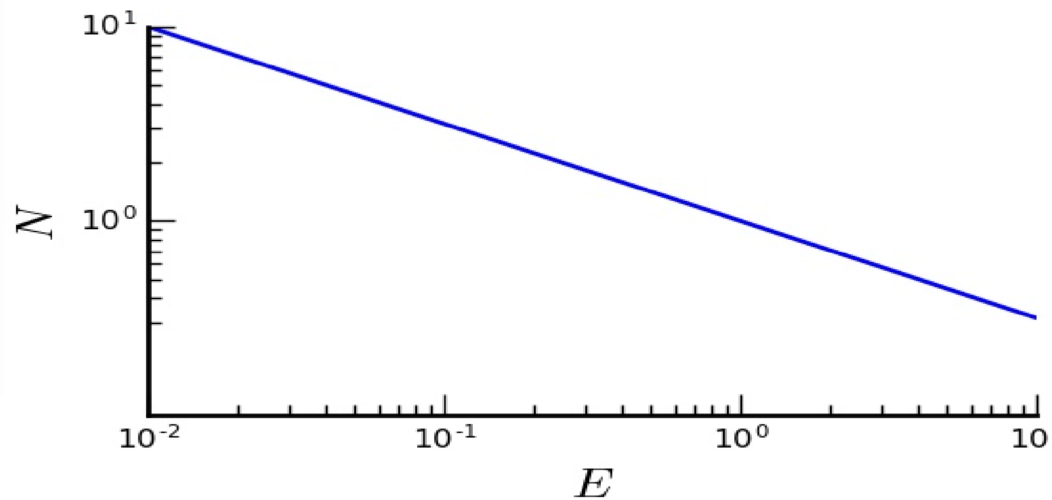
Cosmic ray sources

spatial distribution



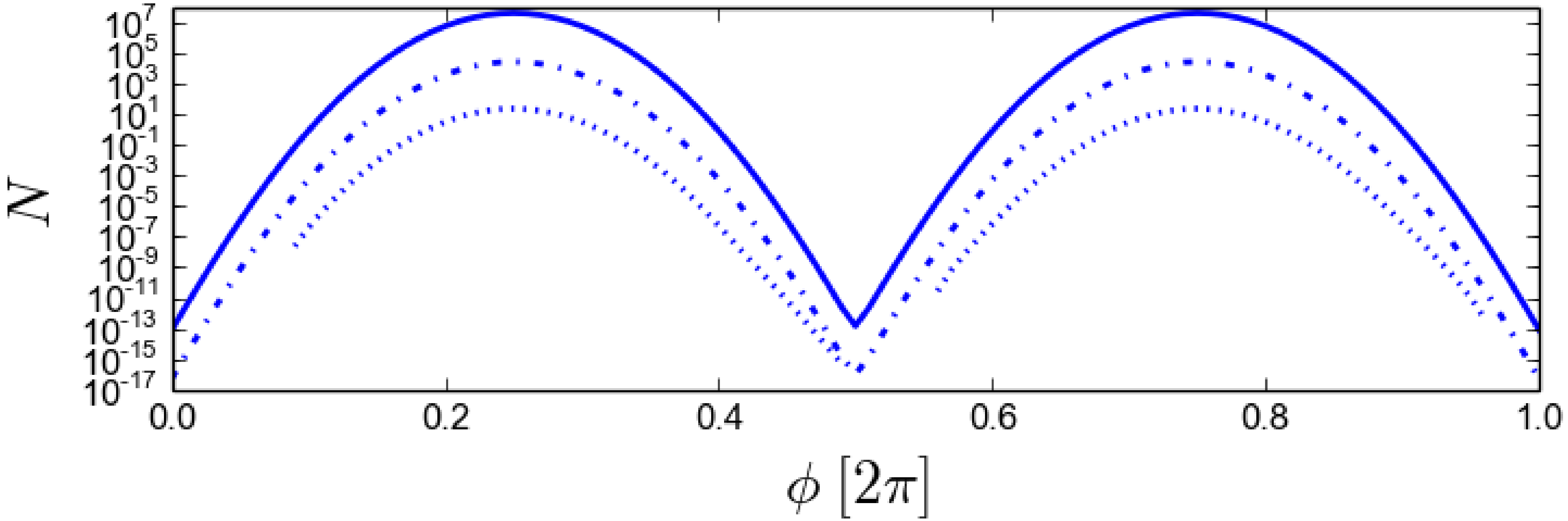
energy





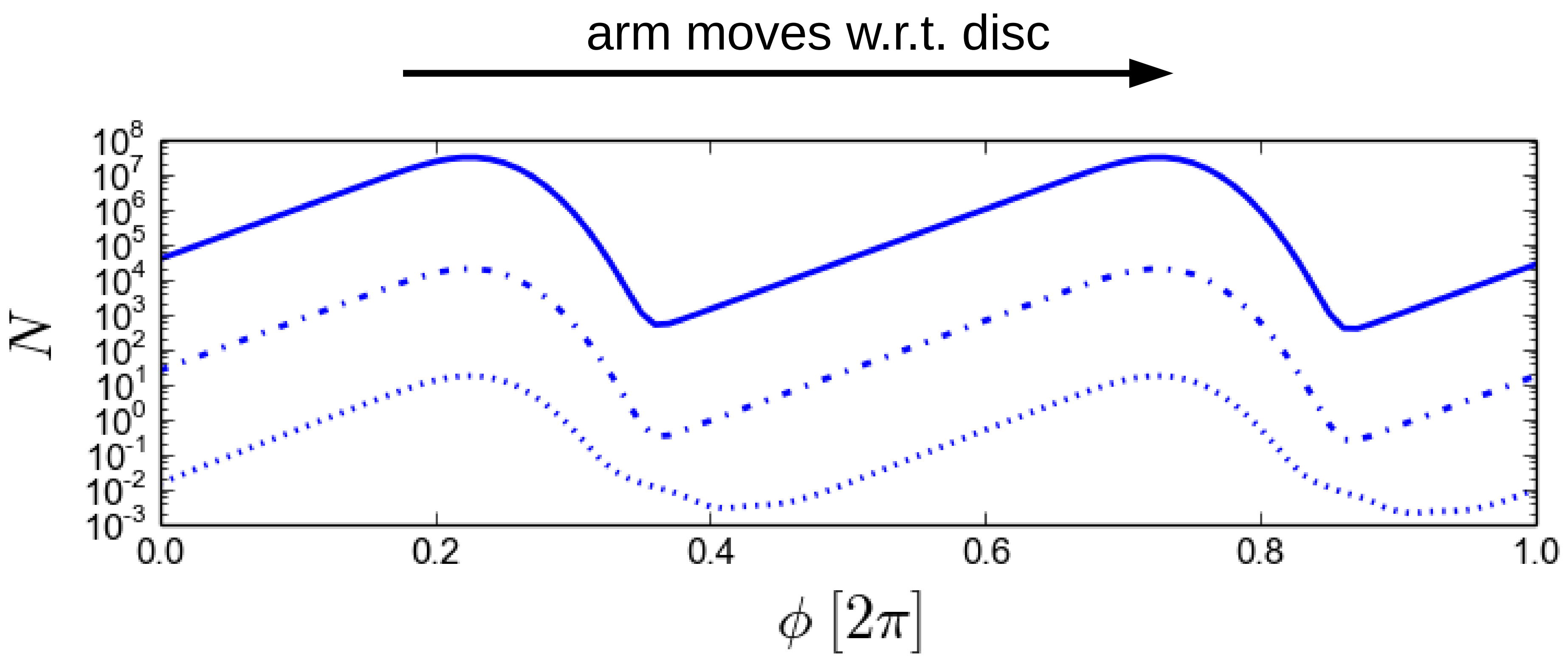
NB. This is a movie. The
source location moves.

Sample result: no pattern speed



material arm
or
density wave at co-rotation radius

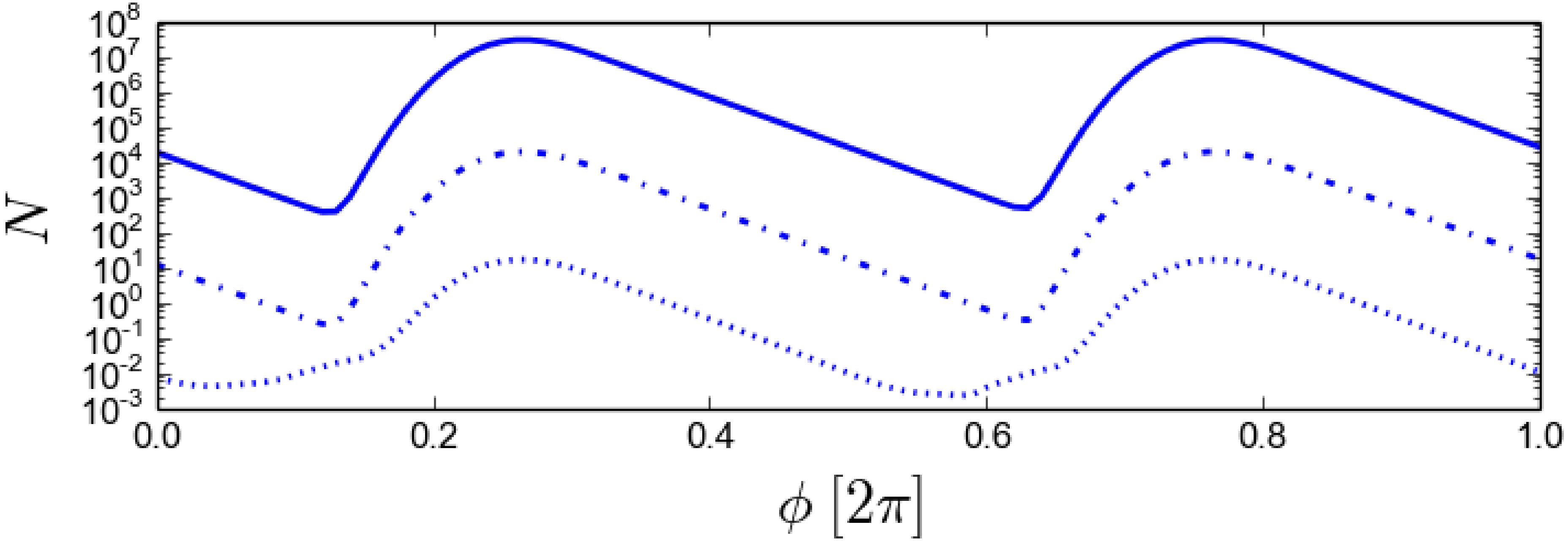
Sample result: one rotation of arms



density wave one side of co-rotation radius

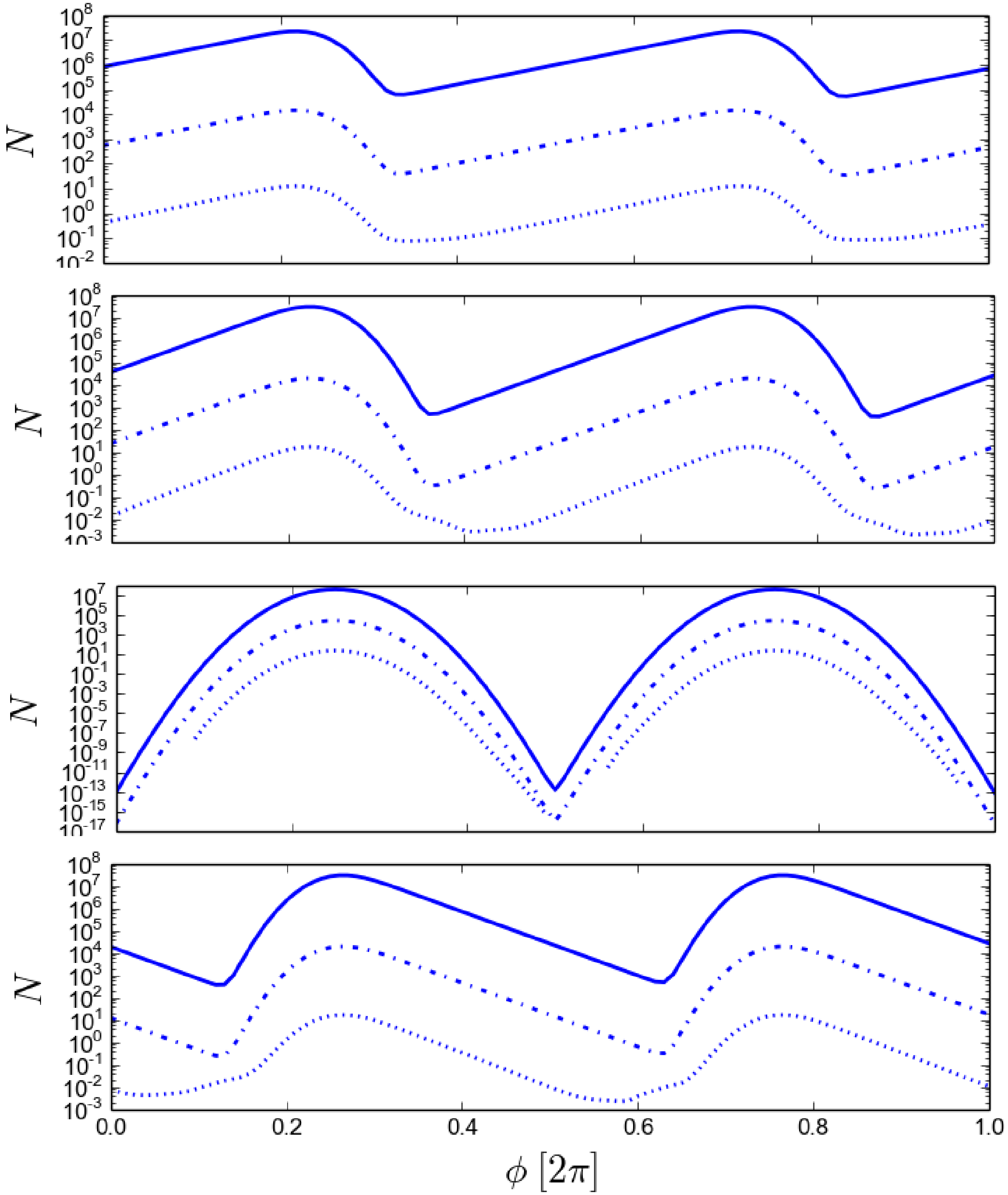
Sample result: one rotation of arms

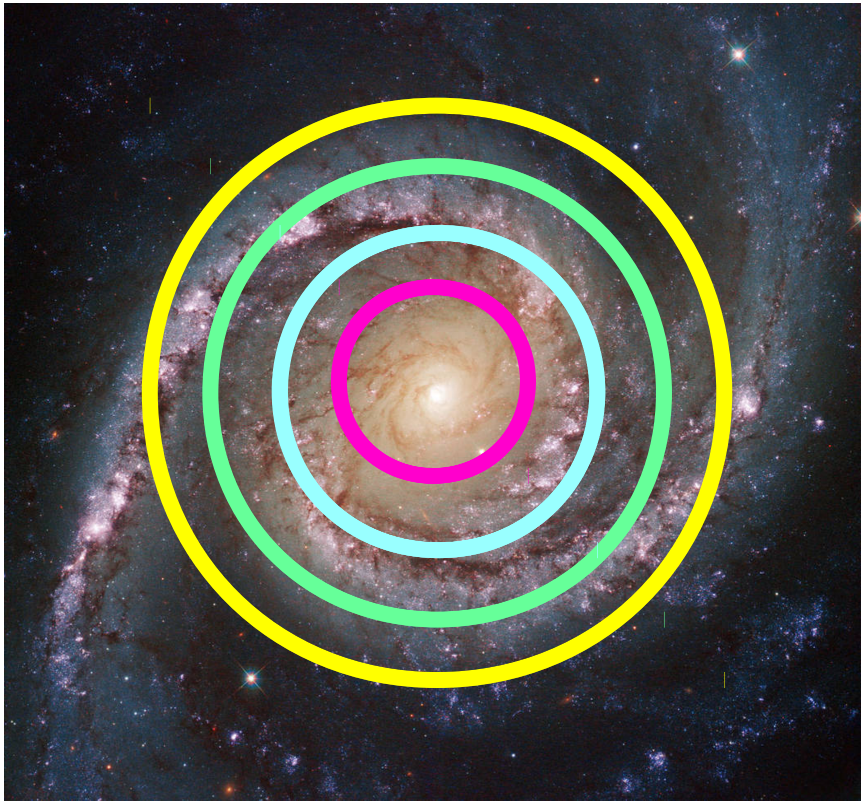
arm moves w.r.t. disc



density wave other side of co-rotation radius

Sample results





Pattern speed of spiral arm
(e.g. due to density wave)
=>
motion of cosmic ray sources
=>
asymmetry of synchrotron intensity

No pattern speed of arm
(e.g. material arm)
=>
symmetry of synchrotron intensity