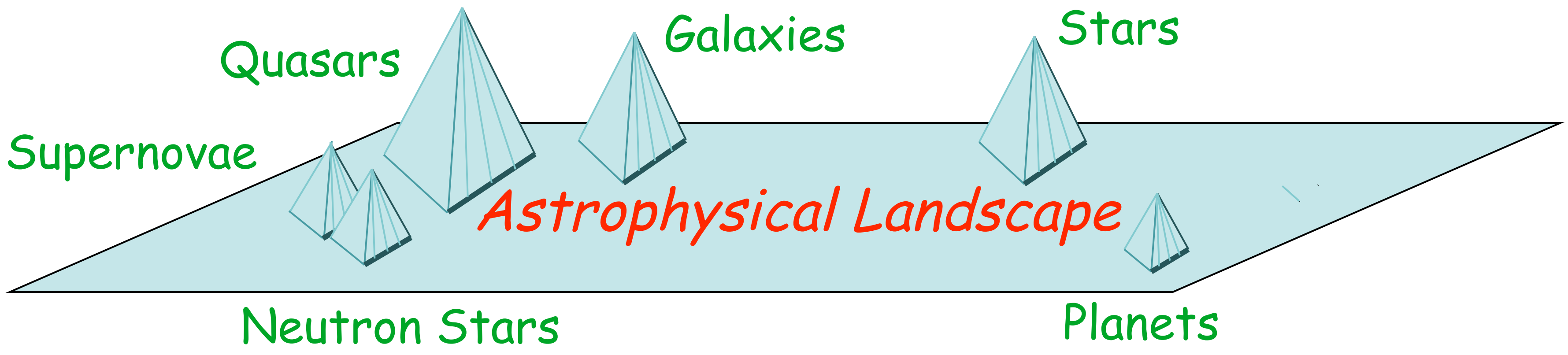
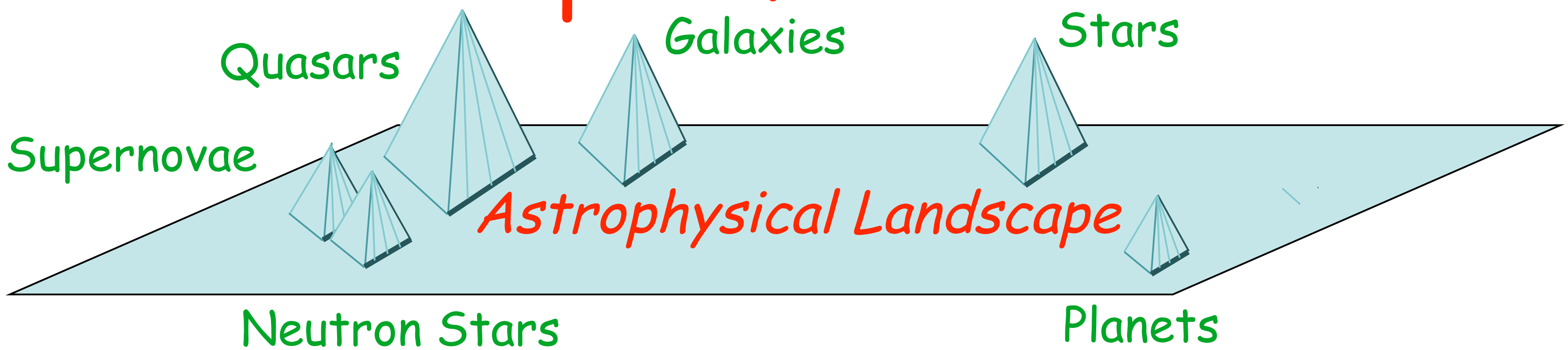
The Growth of Astrophysical Understanding:

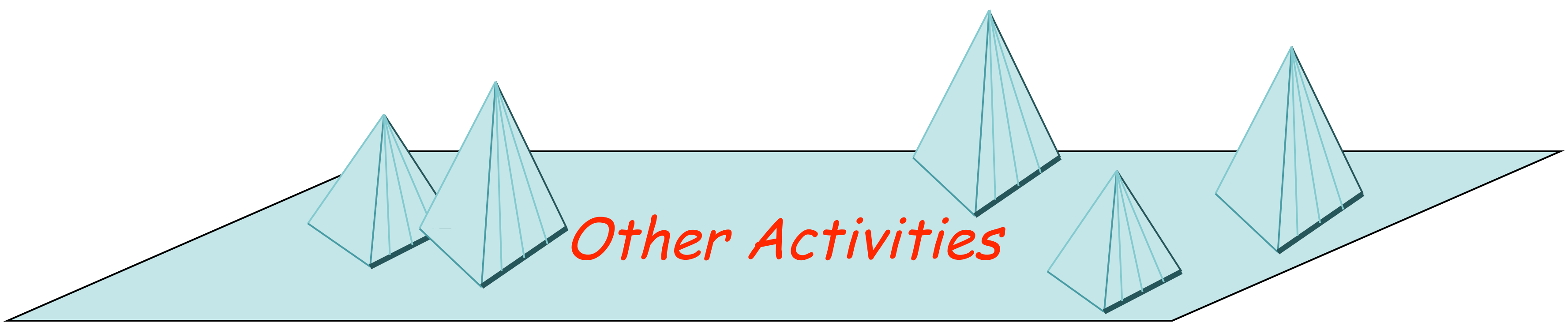
A Societal Endeavor

The Astrophysical Landscape



The Astrophysical Landscape and the Landscape of other Activities





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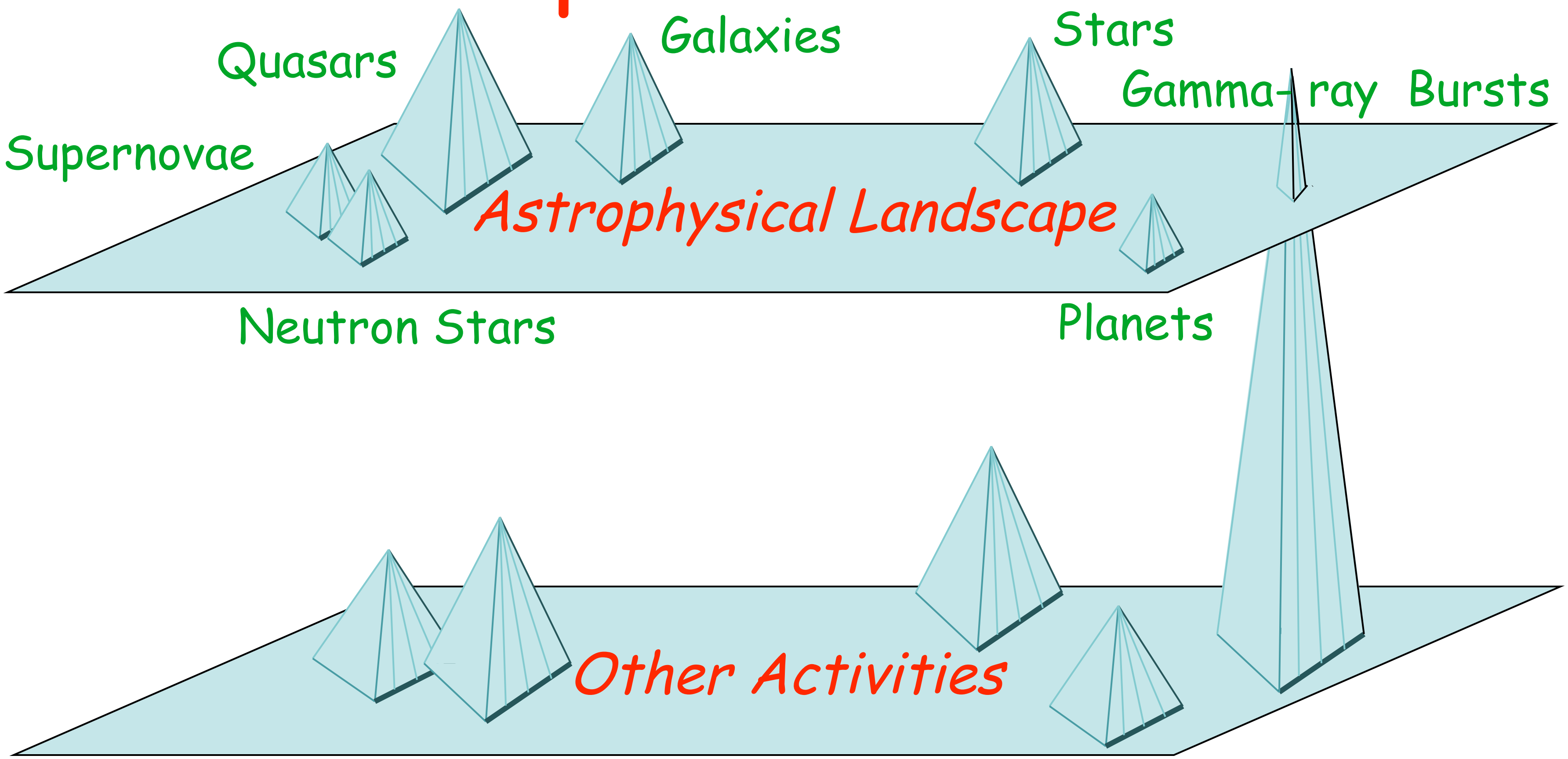
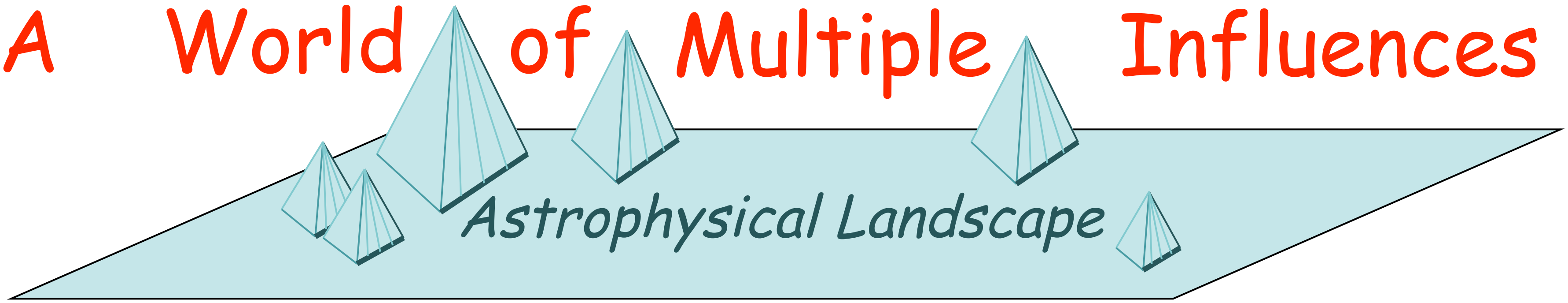


A World of Multiple Influences



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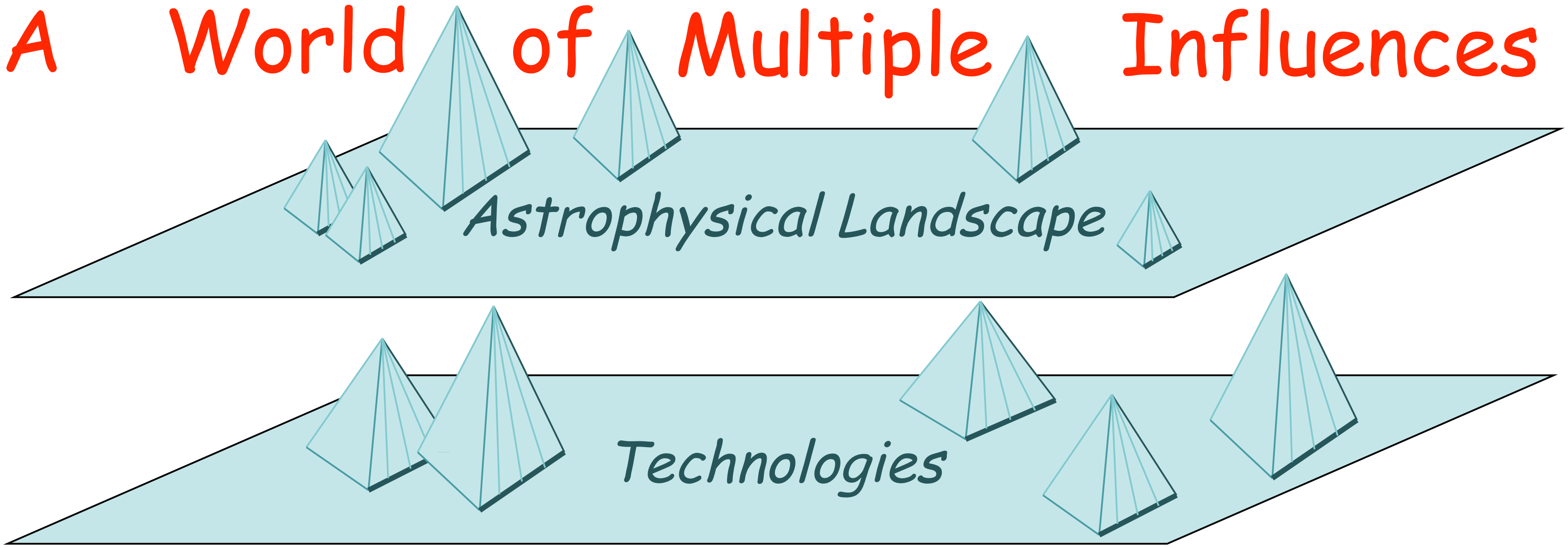

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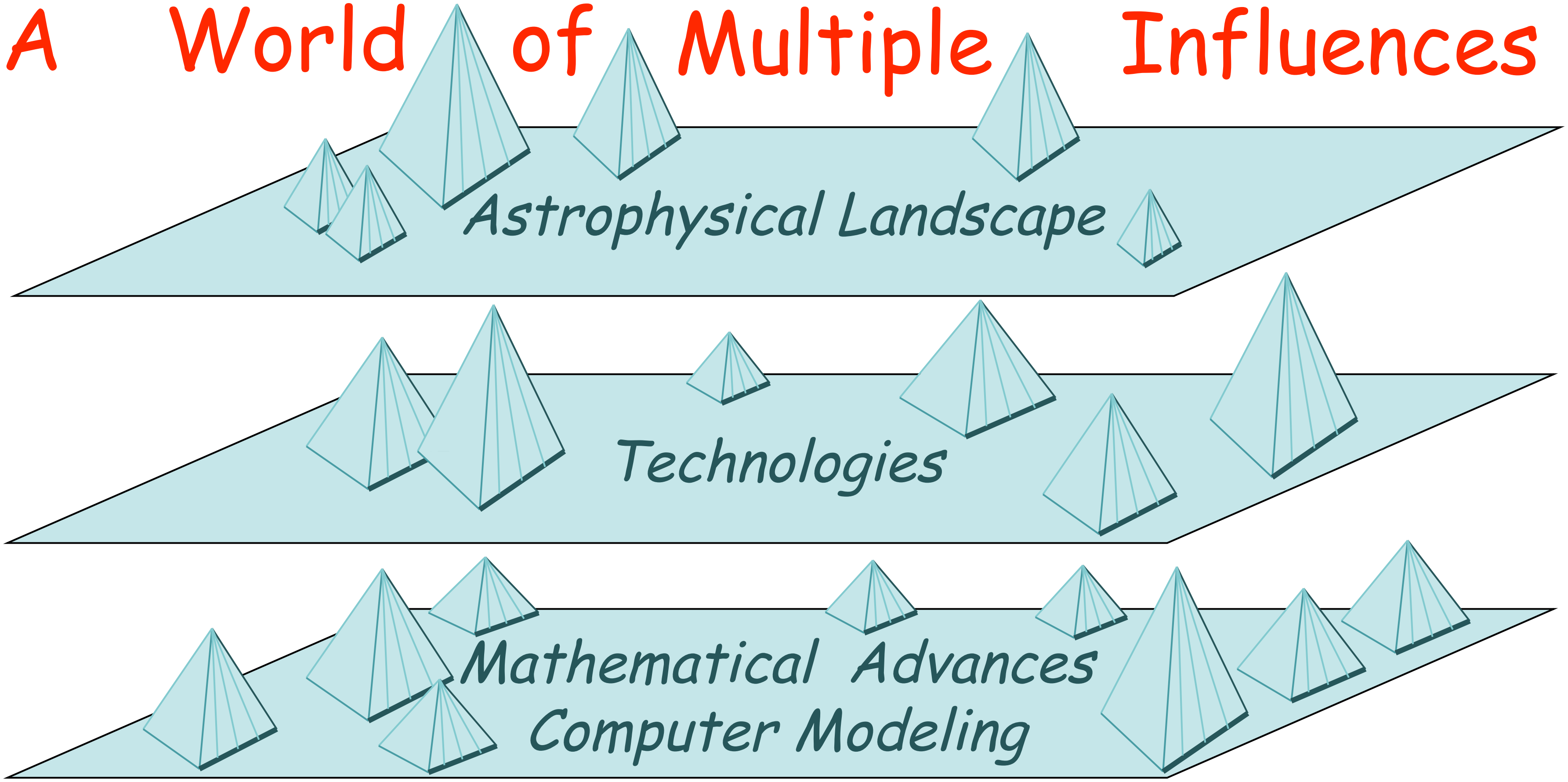

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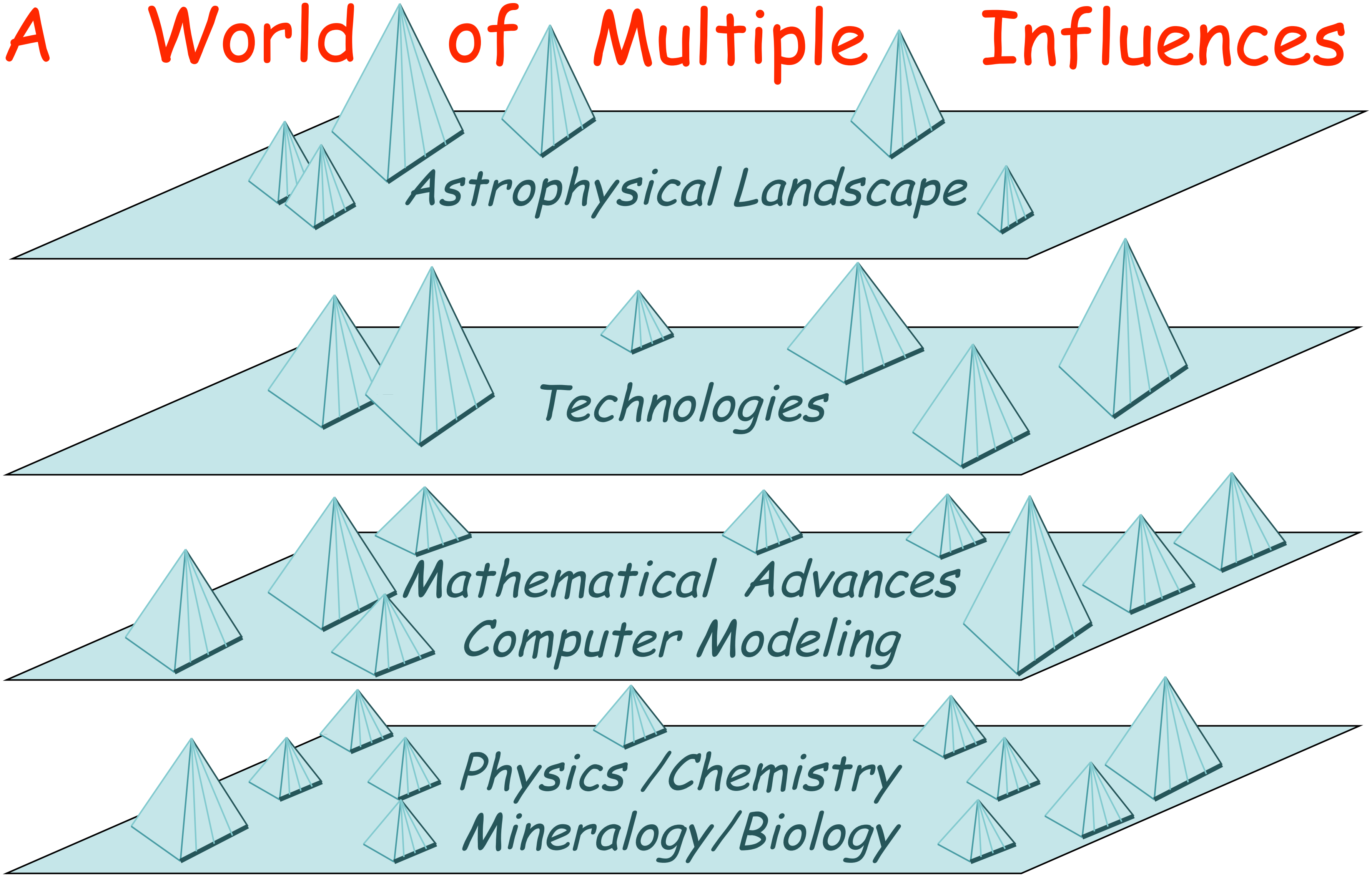
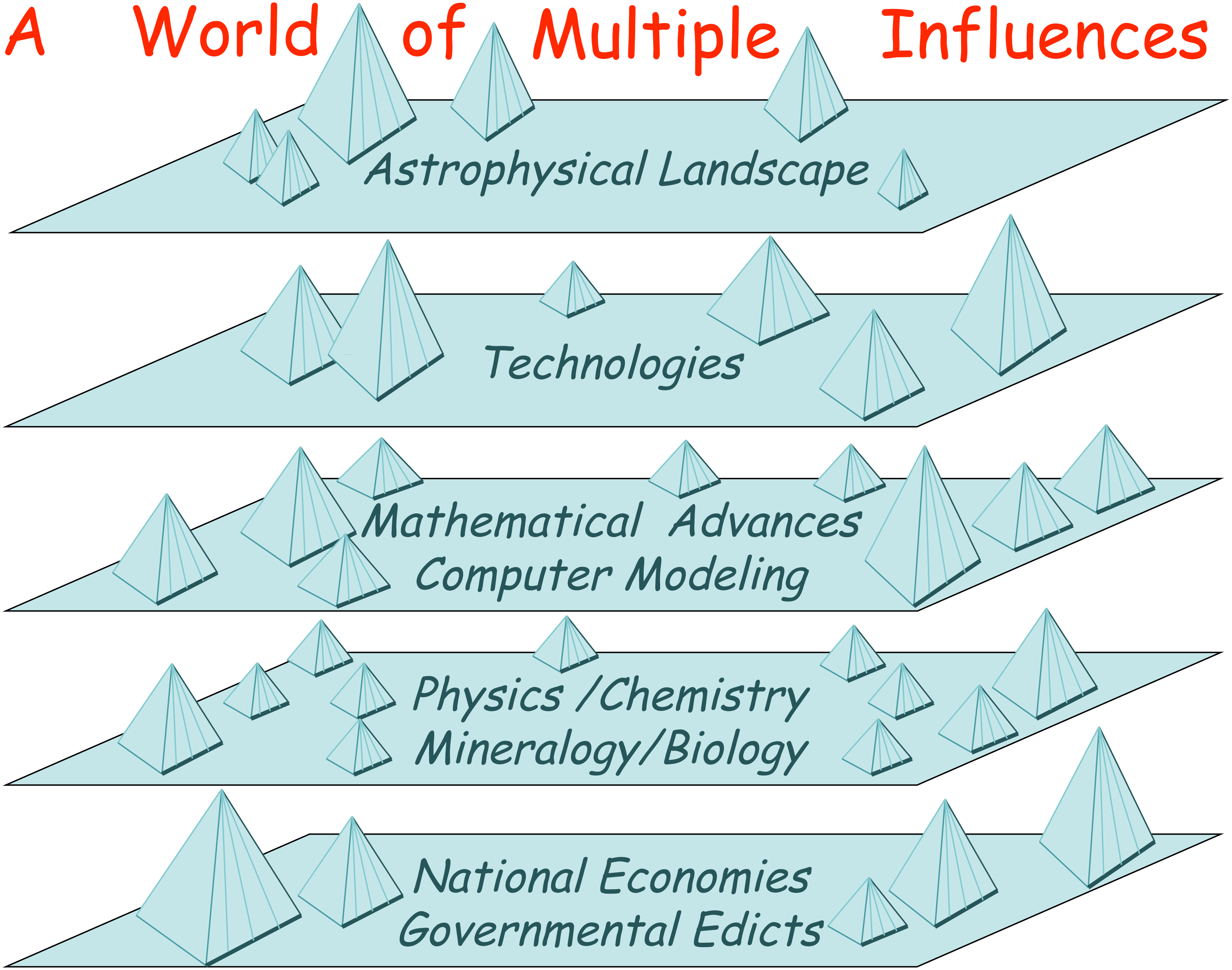
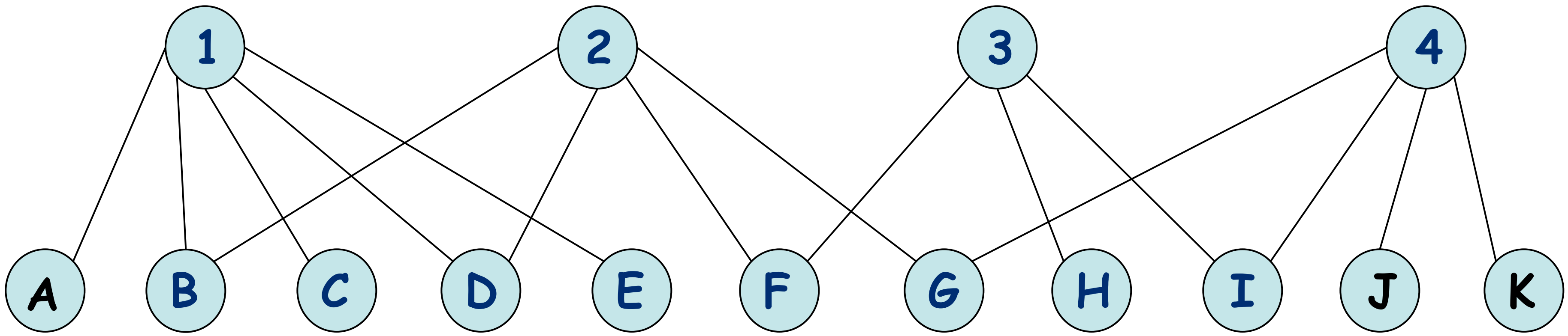


A World of Multiple Influences

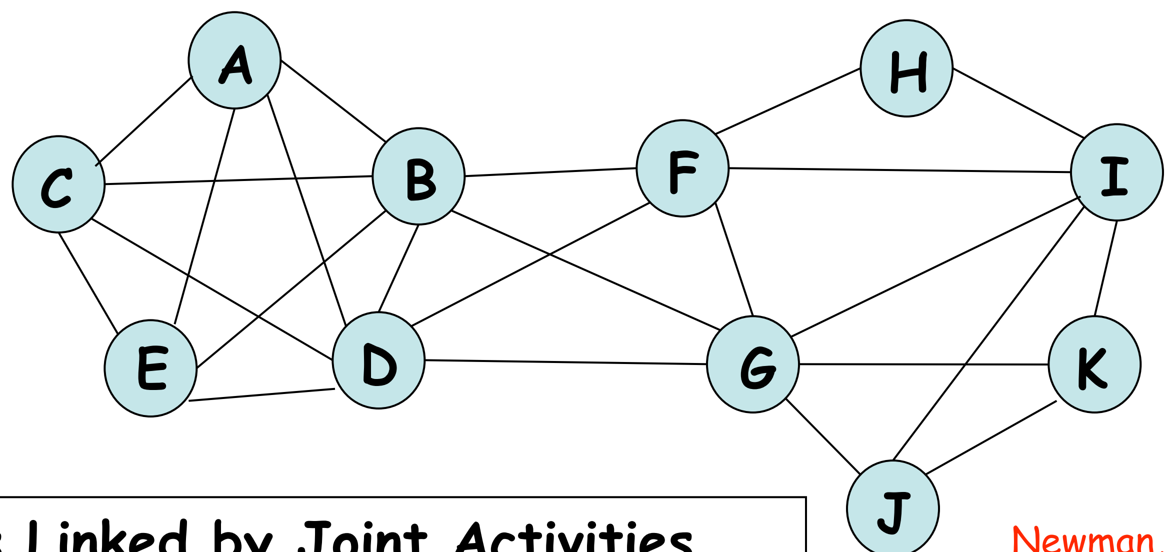


Scientists Linked through Joint Activities

Specific Activities



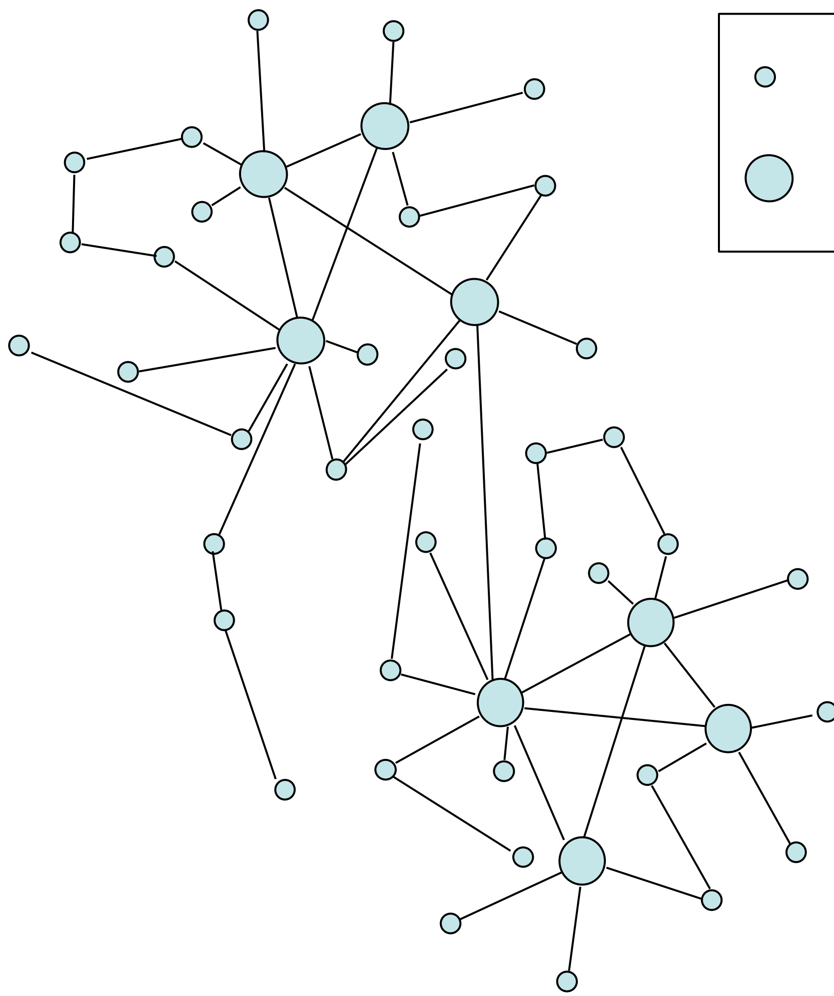
Scientists Collaborating on Joint Activities



Scientists Linked by Joint Activities

Newman, Strogatz & Watts, Phys. Rev. E 64, 026118, 2001

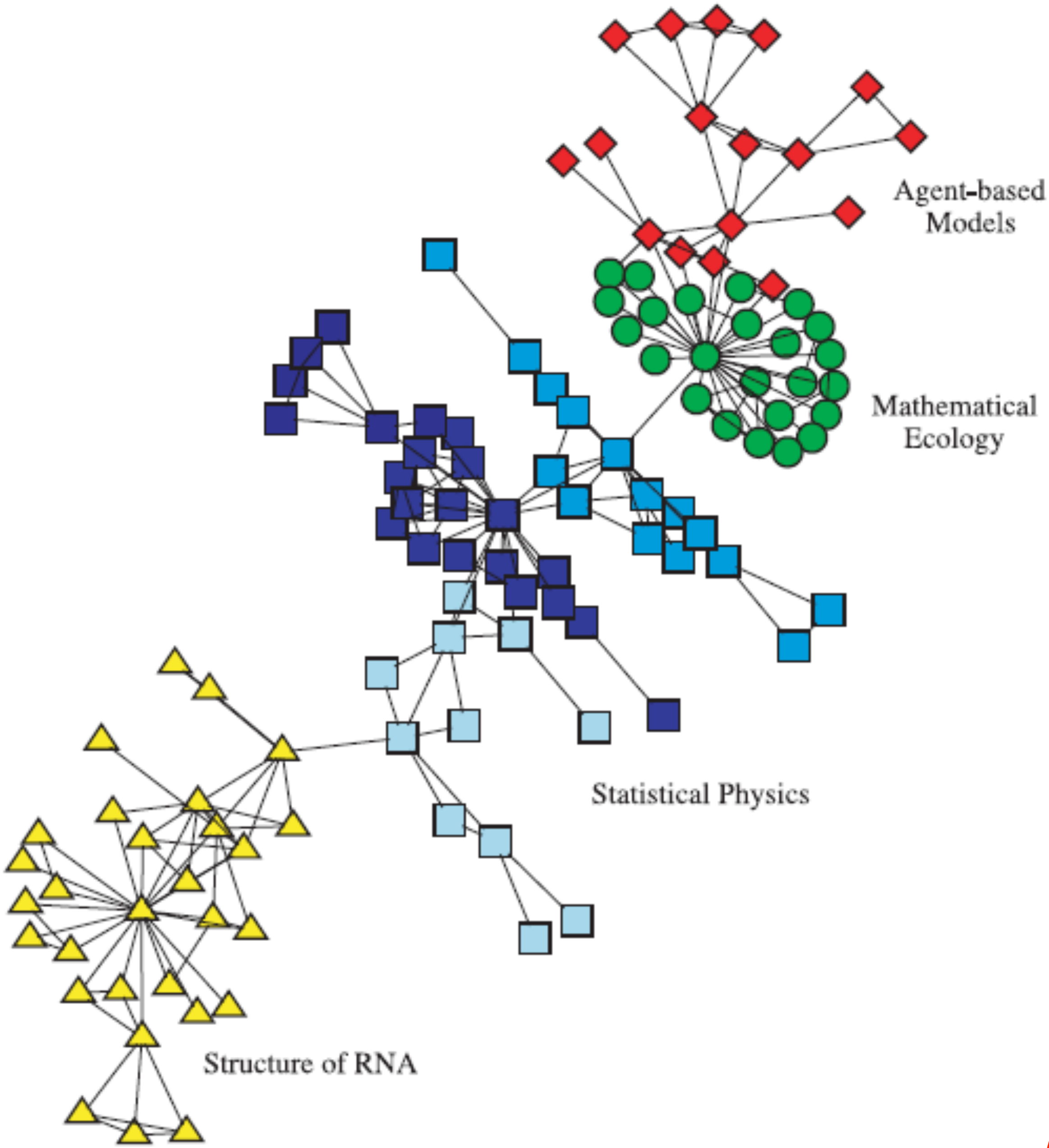
Astronomers Constituting the Nodes of a Network Linked through Collaborations



- Nodes linked with 1 or 2 others
- Nodes linked with ≥ 5 others

Note that this network has two populated areas joined by only one link, suggesting that these astronomers have little in common and work in different sub-disciplines

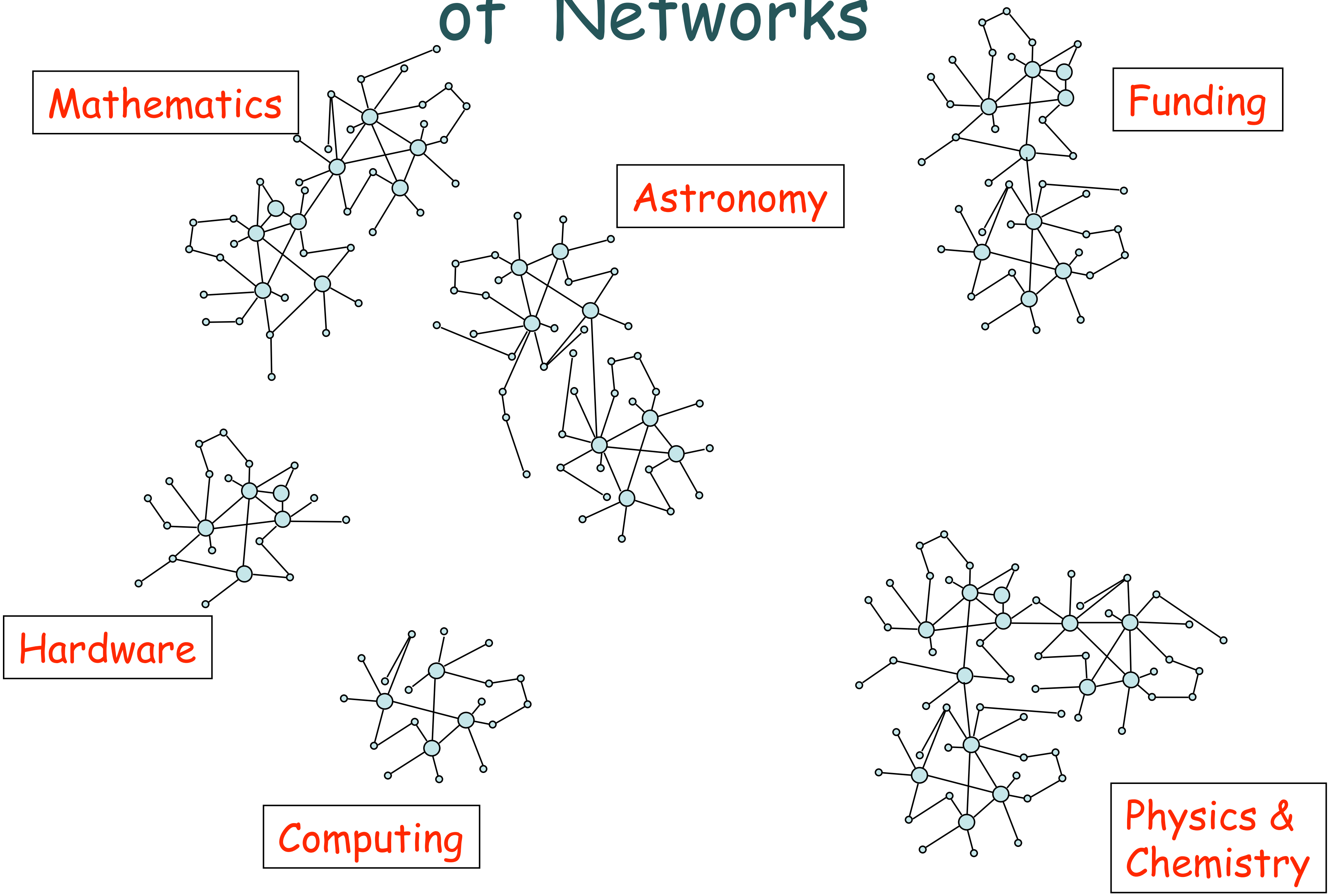
An Example of Research Networks



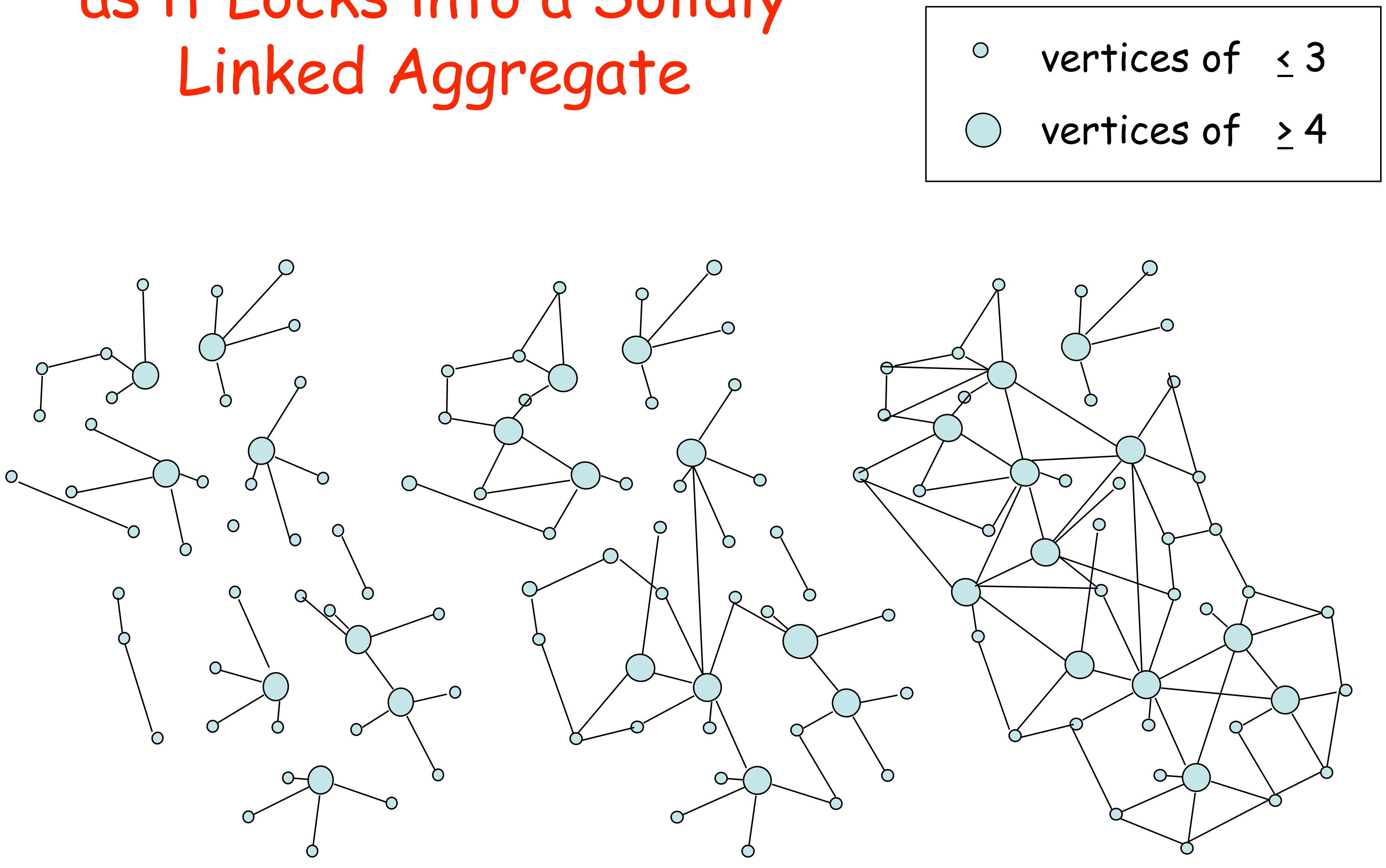
A co-authorship network at a private research organization. The ties across diverse disciplines are sparse compared to those within any research area but the influence of these few cross linkages can be seminal.

M. E. J. Newman, PNAS 101, 5200, 2004

Astronomy is Merely Part of a Larger Set of Networks



Phase Transition of a Network as it Locks into a Solidly Linked Aggregate



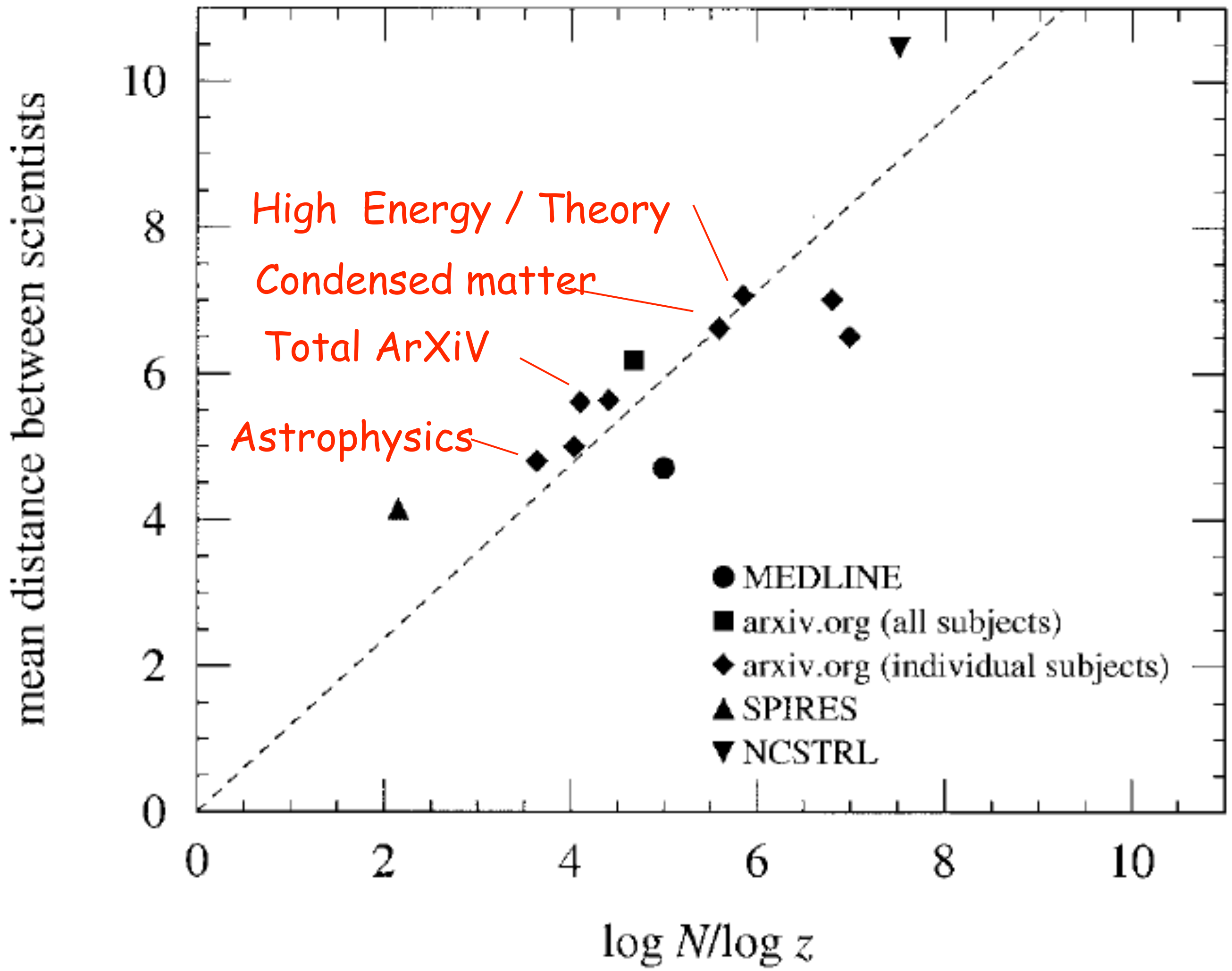
Statistics of Publications Networks

Derived from the astro-ph archives for 1995-199

Total number of papers	22,029	papers
Total number of authors	16,706	authors
Mean number of papers per author	4.8	papers
Mean number of authors per paper	3.35	authors
Mean number of collaborators per author	15.1	authors

Size of the giant component	14,849	authors
Second largest component	19	authors
Mean separation between authors	4.66	steps
Maximum separation between authors	14	steps

M. E. J. Newman, PNAS, 98, 404 (2001)



Average distance between pairs of scientists in the various communities plotted against the average distance on a random graph of the same size and average coordination number. The dotted line is the best fit to the data that also passes through the origin. N is the number of scientists with a mean number z of collaborators.

M. E. J. Newman, PNAS 98, 404 (2001)

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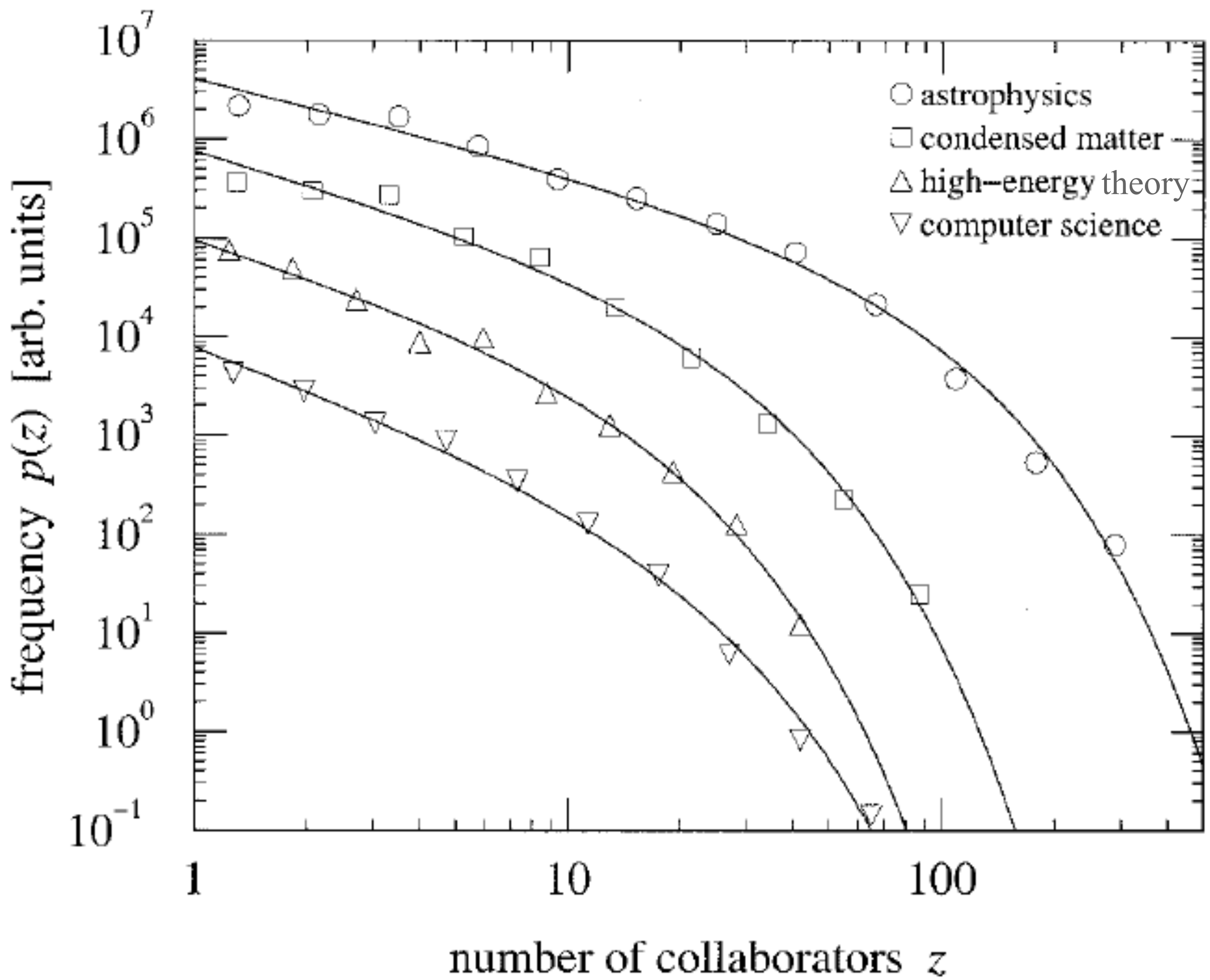
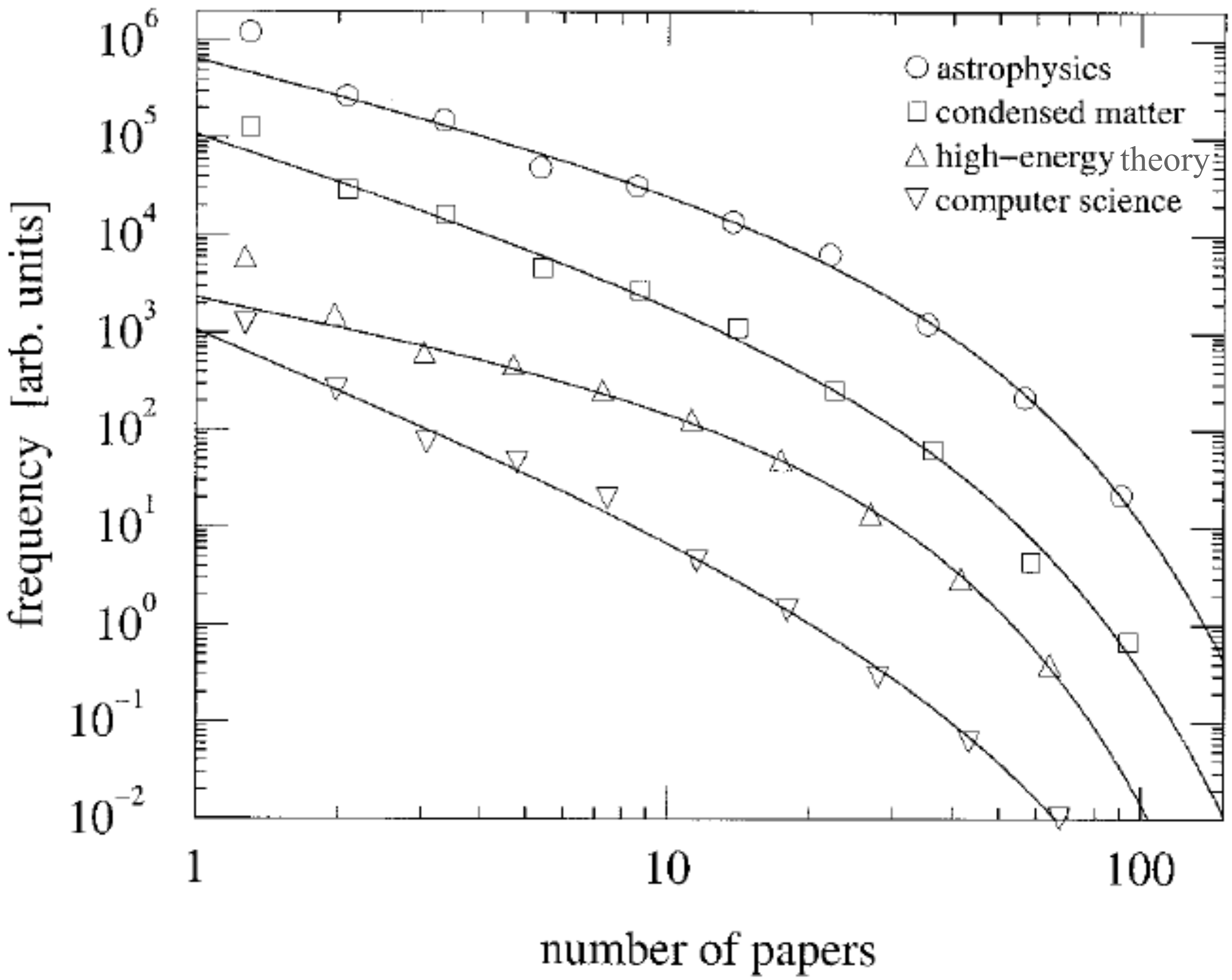


Histogram of the number of collaborators of scientists on papers listed in four Los Alamos / Cornell ArXiV data bases, during the 5 years, 1995-99. Solid lines are least squares fits, shifted vertically for clarity

M. E. J. Newman, PNAS 98, 404 (2001)



Histogram of the number of papers written by scientists in the four Los Alamos / Cornell ArXiV data bases during the 5 years, 1995-99. Solid lines are least-square fits shifted vertically for clarity.

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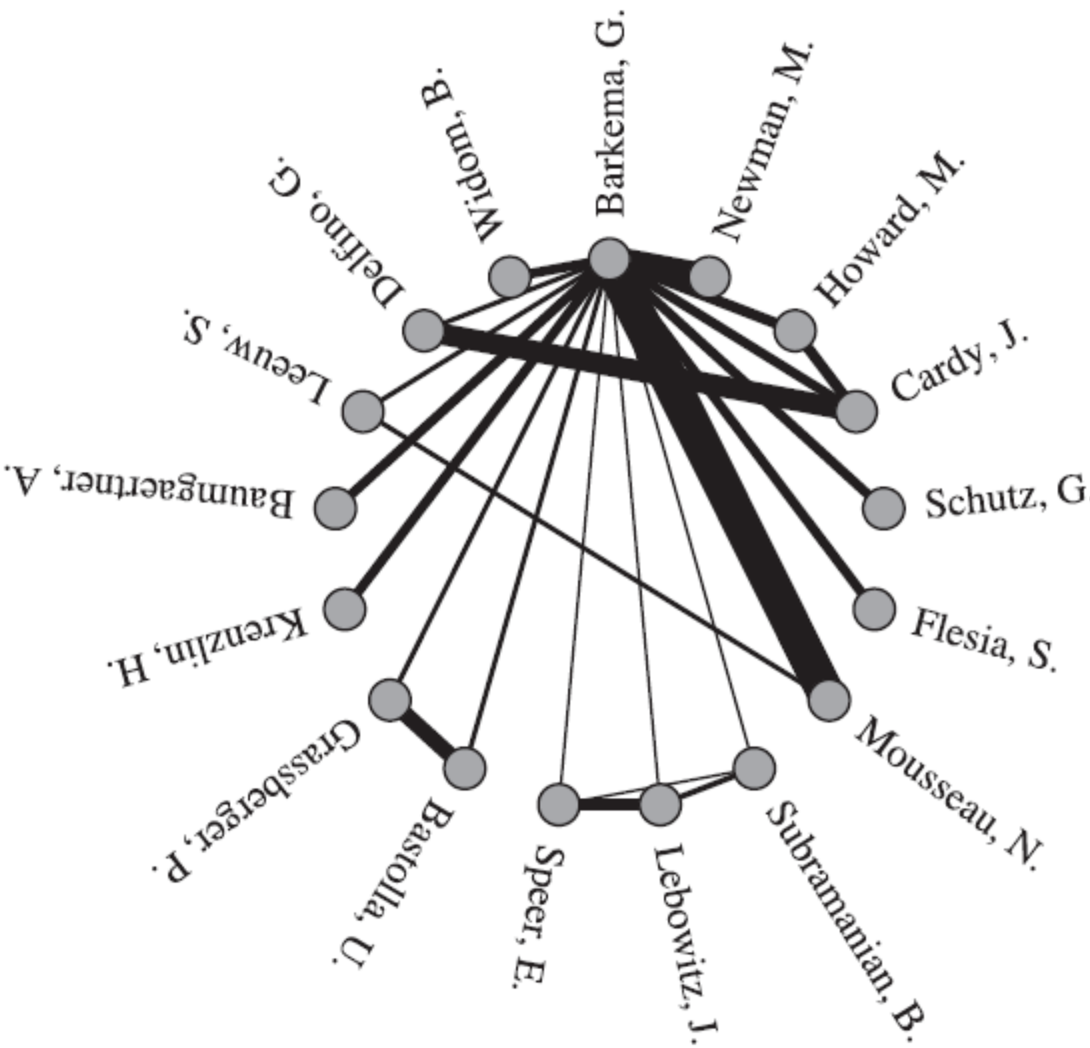
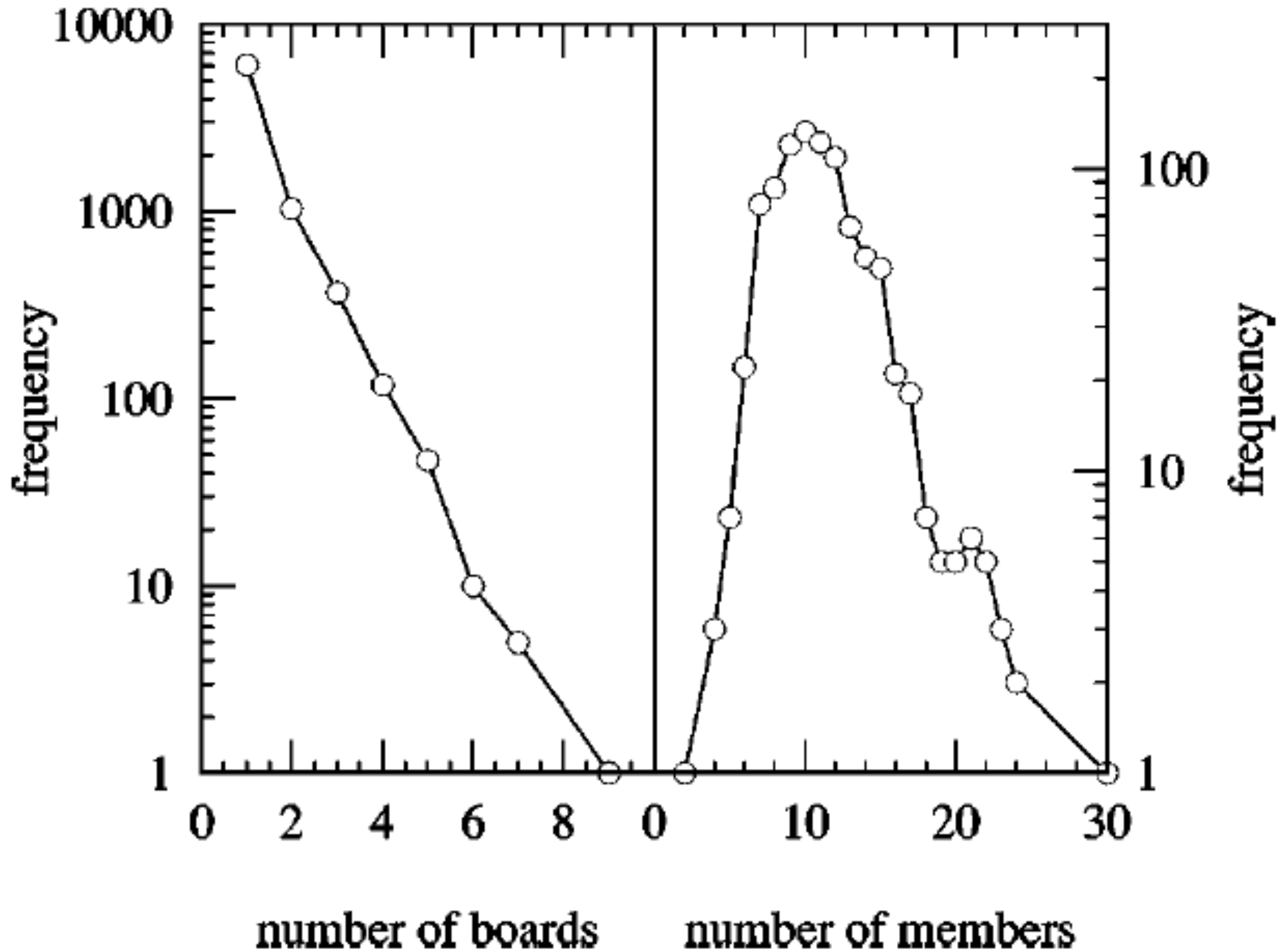
Collaboration Strength



Collaboration on a scientific paper signifies two authors are well acquainted only if few authors participate on a paper. Two scientists collaborating often and with few co-authors are likely to know and influence each other most strongly. Collaboration strength is proportional to the number of co-authored papers each weighted in inverse proportion to the number of co-authors.

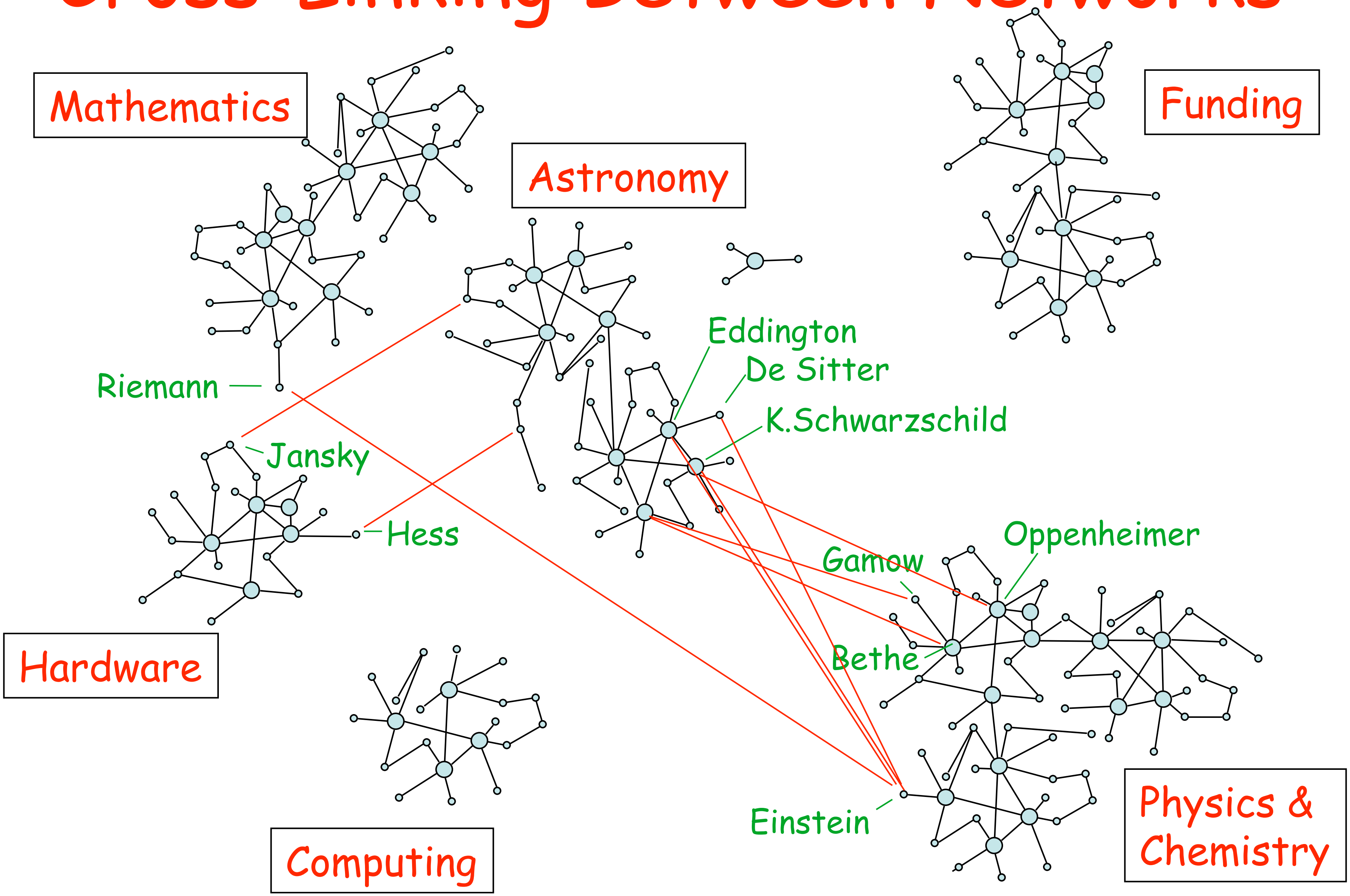
M. E. J. Newman, PNAS 101, 5200, 2004



Frequency distribution for the boards of directors of Fortune 1000 companies. Left panel: the numbers of boards on which each director sits. Right panel: the number of directors on each board. (These statistics seem to roughly hold for committees and boards on which astronomers sit.)

M. E. J. Newman, S. H. Strogatz & D. J. Watts, Phys. Rev. E, 64, 026118 (2001)

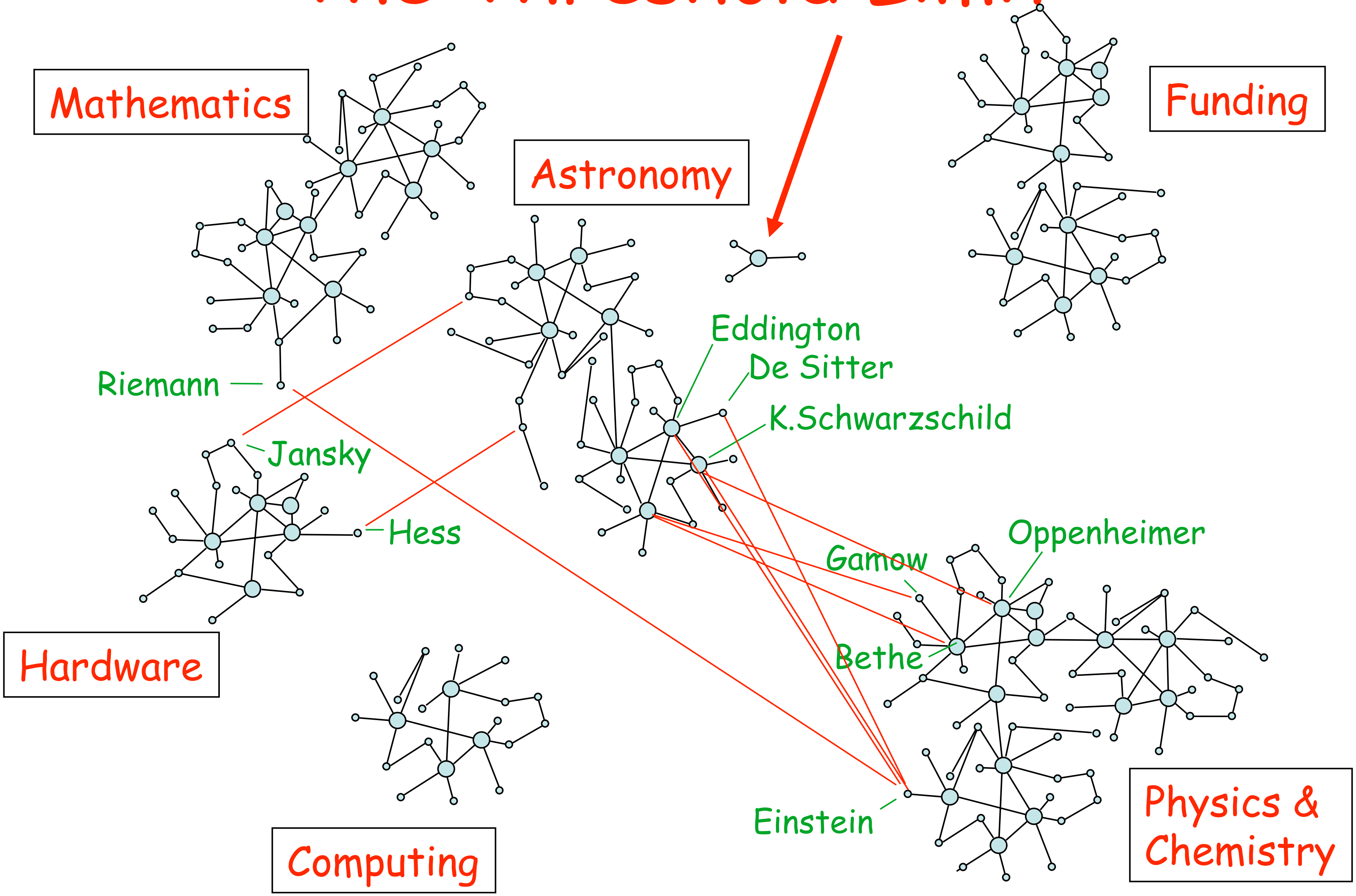
Cross-Linking Between Networks



Limits to the Growth of the Astrophysical Community

- The anthropologist Roland Fletcher has described three limits that determine the growth of human settlements:
Interference between occupants of the settlements [I],
Ease of communication between settlement members [C], and
A threshold density [T] below which settlements do not grow.
- In astrophysics we appear to have similar limits:
Limit [I] will be reached through the mutual interference of scientists spending all of their time on competing proposals.
Limit [C] will be reached when so many new papers are published each day that nobody can digest the information.
Limit [T] means that if you are working in an area where nobody else is interested, your efforts will not flourish.
- Although the astrophysics community can adapt to growth, growth, in turn, affects what the community may achieve.

The Threshold Limit



Coping with these Limits

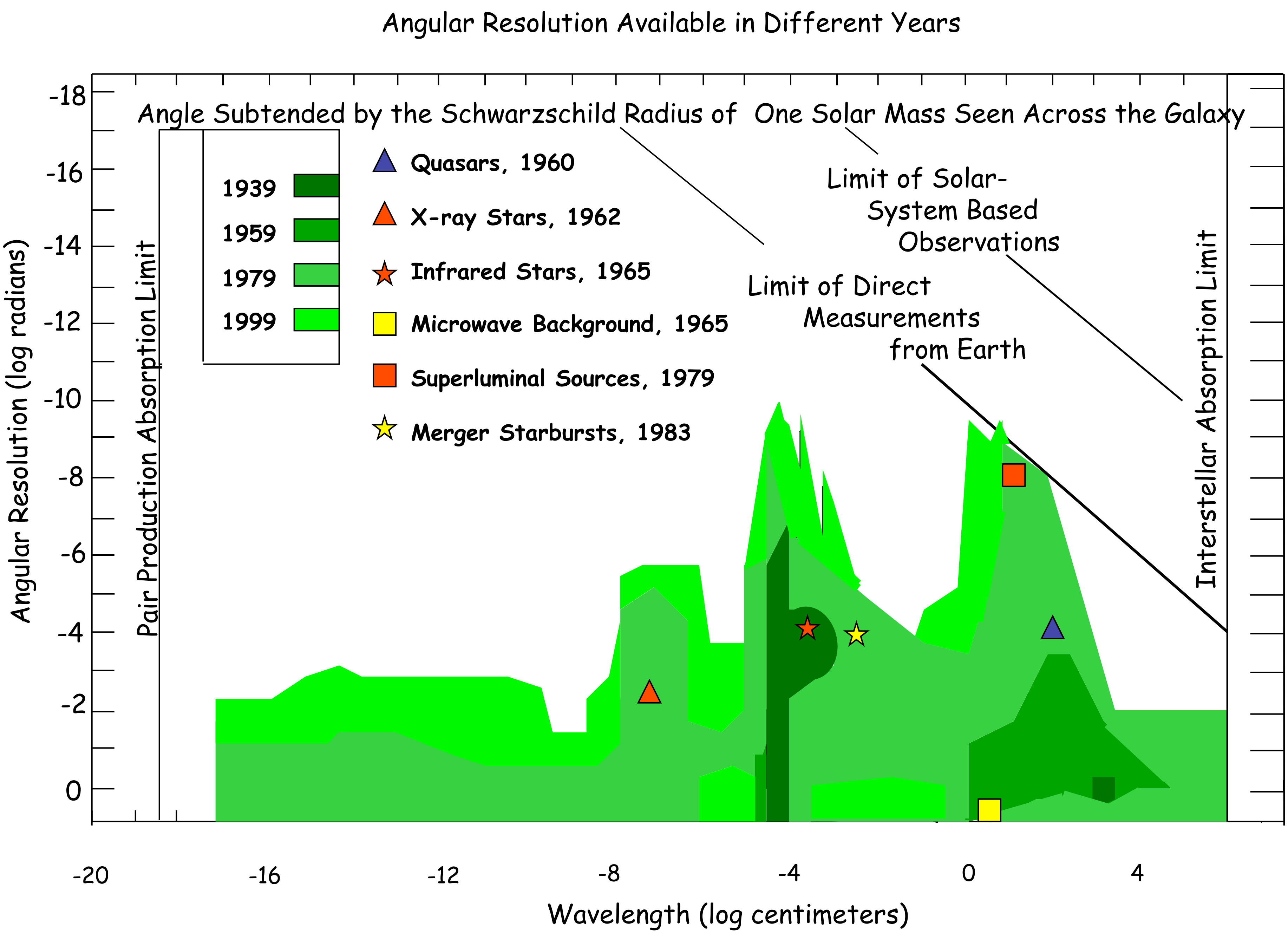
Interference Limit: To avoid excessive competition, astronomers are joining forces and submitting proposals with increasing numbers of co-investigators. Articles are written by larger numbers of authors, tending to dilute responsibility for critical examination. We may have to learn to handle this.

Communication Limit: The internet has permitted faster communication. Search engines have facilitated identification of correlations within and between massive data bases.

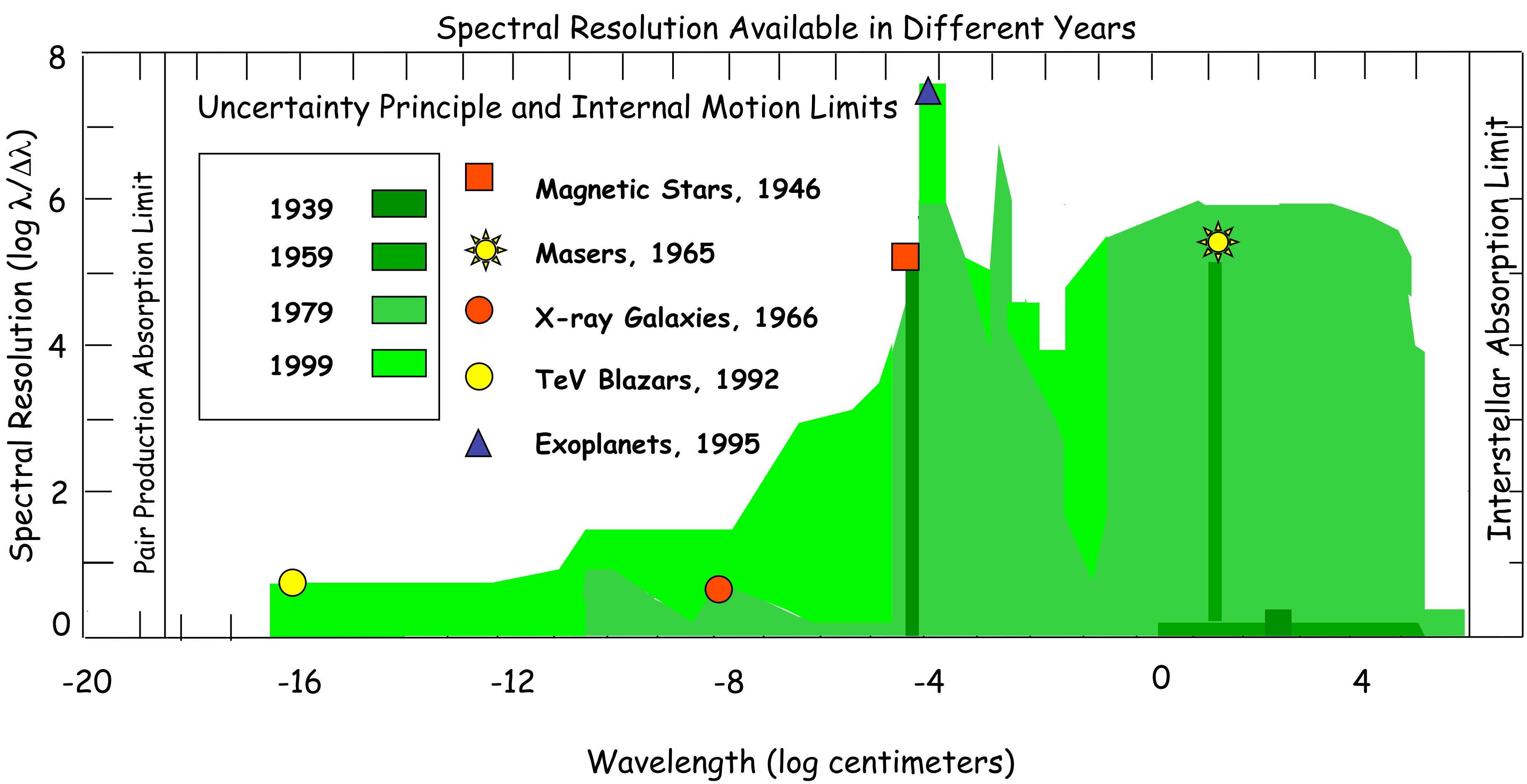
But escalating volumes of information will not be assimilated unless we find improved ways of presenting information.

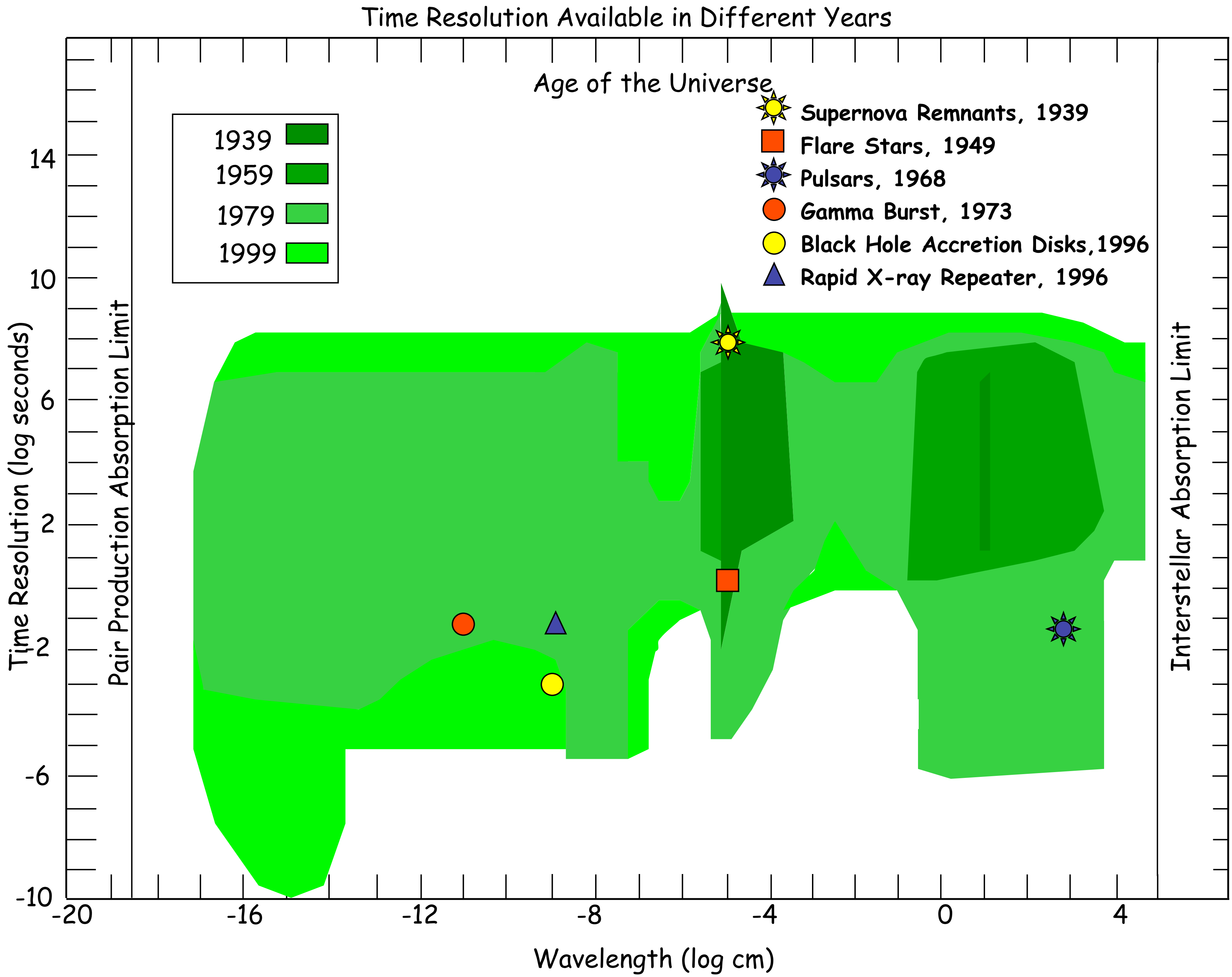
Lacking these, a glut of information may lead to increased specialization which, though lowering the pressure to assimilate information, will thwart establishing an overview.

These limits should be taken seriously given that we may only just be starting our quest for astrophysical understanding.

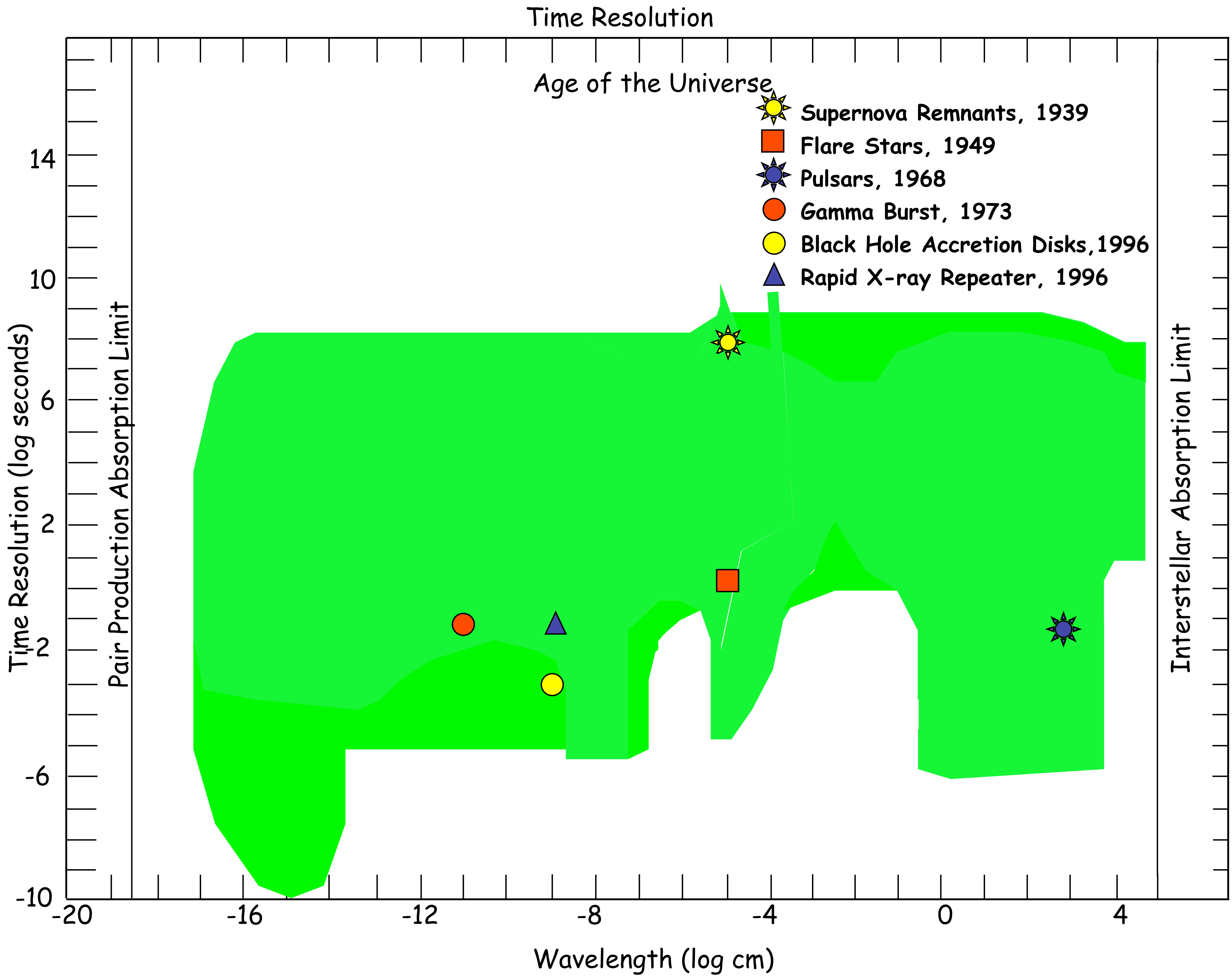


Angular Resolution Available in Different Years
Angle Subtended by the Schwarzschild Radius of One Solar Mass Seen Across the Galaxy
1939
1959
1979
1999
Quasars, 1960
X-ray Stars, 1962
Infrared Stars, 1965
Microwave Background, 1965
Superluminal Sources, 1979
Merger Starbursts, 1983
Limit of Solar-System Based Observations
Limit of Direct Measurements from Earth
Pair Production Absorption Limit
Interstellar Absorption Limit
Angular Resolution (log radians)
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
-20
-16
-12
-8
-4
0
4
Wavelength (log centimeters)


Spectral Resolution Available in Different Years
Uncertainty Principle and Internal Motion Limits
1939
1959
1979
1999
Magnetic Stars, 1946
Masers, 1965
X-ray Galaxies, 1966
TeV Blazars, 1992
Exoplanets, 1995
Pair Production Absorption Limit
Interstellar Absorption Limit
Spectral Resolution (log λ/Δλ)
Wavelength (log centimeters)
8
6
4
2
0
-20
-16
-12
-8
-4
0
4



Time Resolution Available in Different Years
Age of the Universe
1939
1959
1979
1999
Supernova Remnants, 1939
Flare Stars, 1949
Pulsars, 1968
Gamma Burst, 1973
Black Hole Accretion Disks,1996
Rapid X-ray Repeater, 1996
Pair Production Absorption Limit
Interstellar Absorption Limit
Time Resolution (log seconds)
14
10
6
2
-2
-6
-10
-20
-16
-12
-8
-4
0
4
Wavelength (log cm)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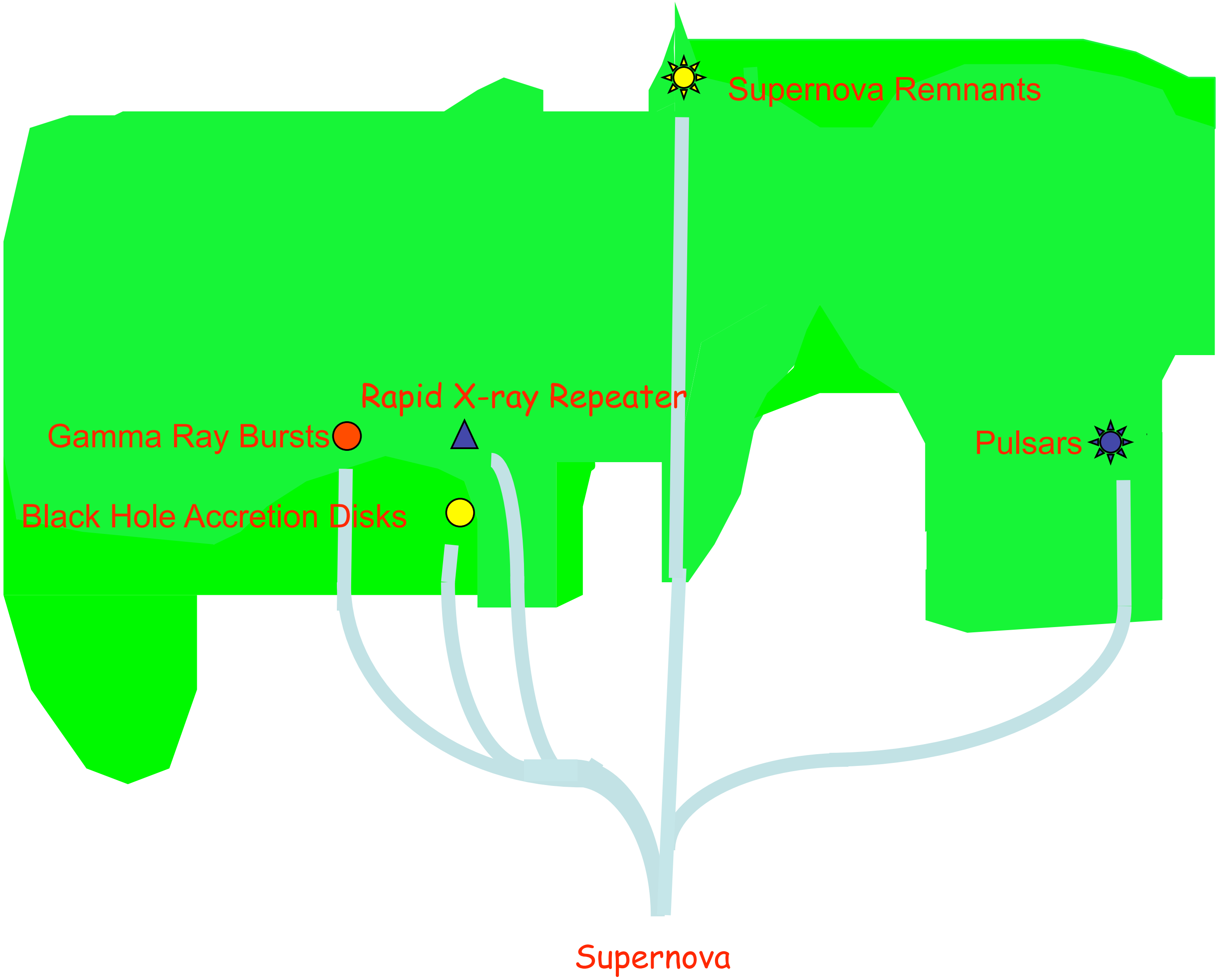
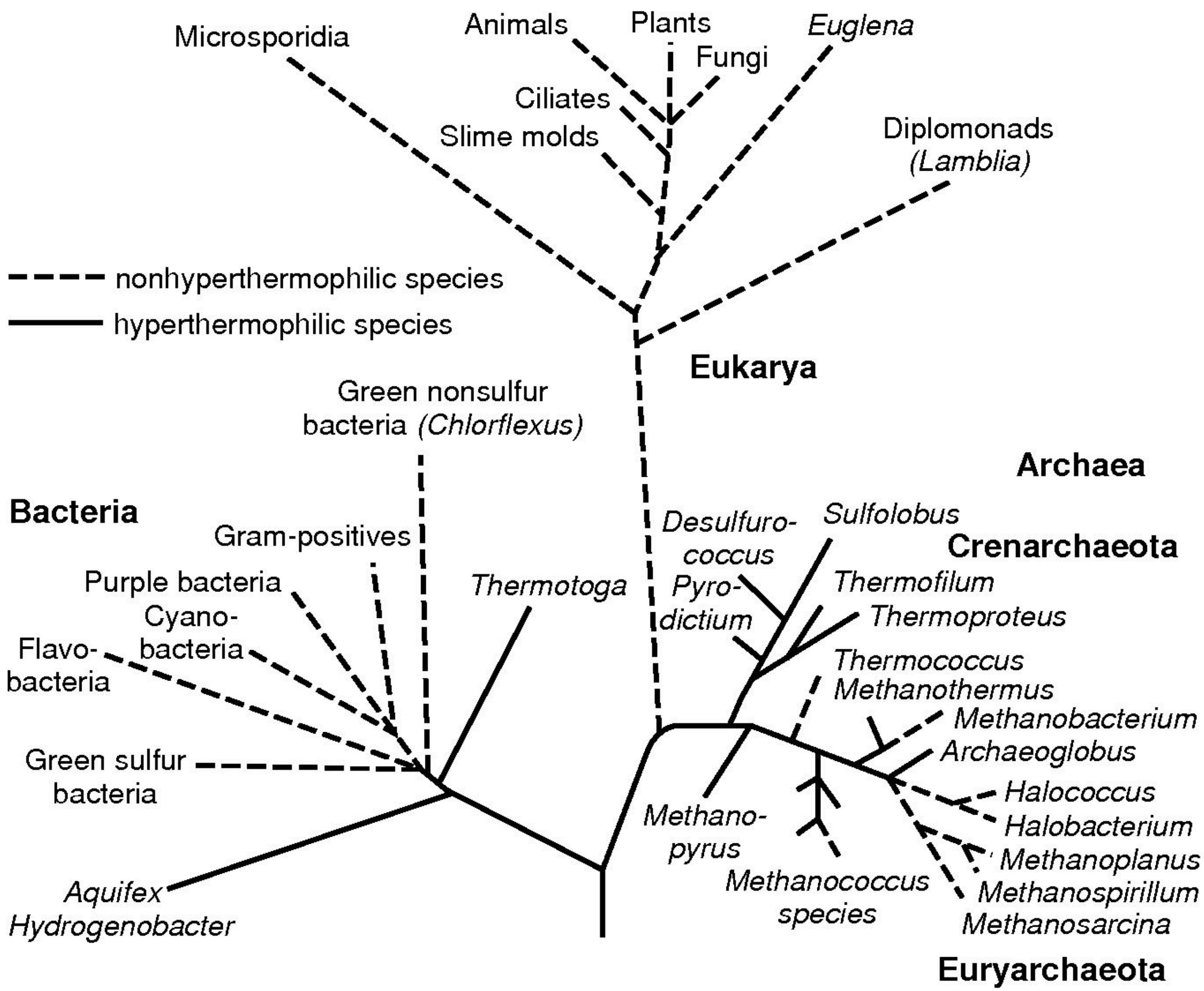
Time Resolution (log seconds)
Pair Production Absorption Limit
Interstellar Absorption Limit
14
10
6
2
-2
-6
-10
-20
-16
-12
-8
-4
0
4
Wavelength (log cm)



Supernova Remnants
Rapid X-ray Repeater
Gamma Ray Bursts
Pulsars
Black Hole Accretion Disks
Supernova

The Tree of Life
Demonstrating Biological Evolution



20th Century Contributors to Major Advances in Understanding

Albert Einstein	1916	General Relativity
Karl Schwarzschild	1916	Black Holes
Albert Einstein	1917	General Relativistic Cosmology
Alexander Friedman	1925	Expanding Universes
S. Chandrasekhar	1931	Quantum Statistics/White Dwarfs
Lev Landau	1932	Neutron stars
Hans Bethe	1939	Nuclear physics/Stellar Energy
Robert Oppenheimer	1939	Stellar Black Holes
George Gamow	1945	Adiabatic, hot early Universe
E.M. Lifshitz	1946	Cosmological Fluctuations
Ralph Alpher/Robert Herman	1948	Primordial Background Radiation
Enrico Fermi	1949	Origin of Cosmic rays
Alpher/Herman/Follin/Hayashi	1953	Primordial Nucleosynthesis
Burbidge^2/Fowler/Hoyle	1957	Stellar Nucleosynthesis
Martin Rees	1967	Superluminal Sources
Harrison/Zeldovich	1970/2	Primordial Fluctuations
Alan Guth/ Andrei Linde	1981/3	Inflationary Universe
Wolfenstein/Mikheyev/Smirnov	1978/86	Neutrino Oscillations and the Sun
Bohdan Paczynski	1998	Gamma-Ray Bursts as Hypernovae

* A somewhat random selection of significant theoretical advances

How Much do we Currently Understand?

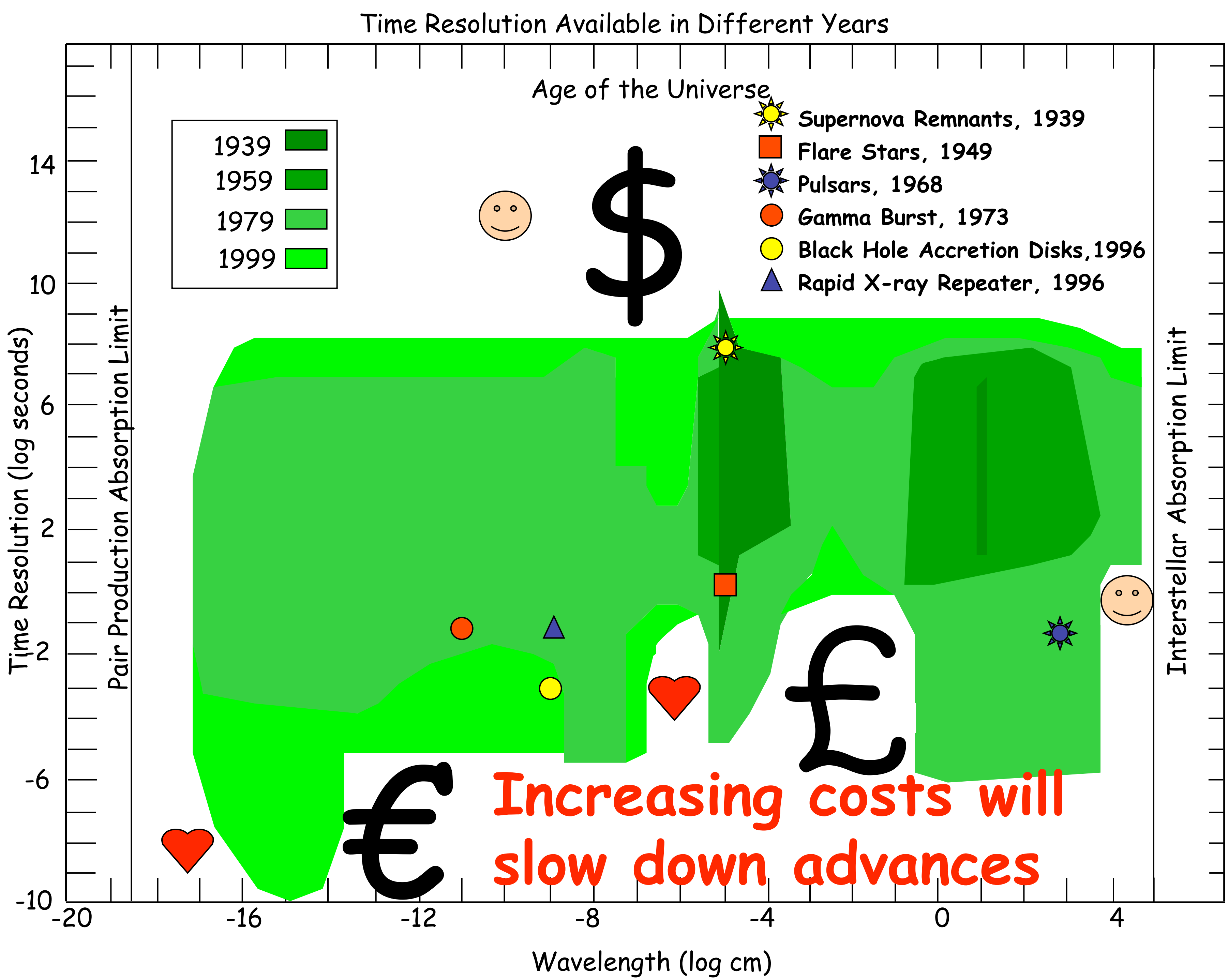
The Cosmic Energy Budget is an Indicator

Baryonic (Ordinary) Matter: $\Omega_B = 4\%$

Dark Matter: $\Omega_{DM} = 23\%$

Dark Energy / Quintessence $\Omega_\lambda = 73\%$

Since virtually all we know about the Universe is based on observations of baryonic matter it is hard to claim that we currently understand more than ~4% of what is going on.



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Pair Production Absorption Limit
Interstellar Absorption Limit
Time Resolution (log seconds)
Wavelength (log cm)
14
10
6
2
-2
-6
-10
-20
-16
-12
-8
-4
0
4
$
£
€
Increasing costs will slow down advances