The Origin of Time, Structure and Beauty

Julian Barbour, Oxford

Finnish Society for Natural Philosophy, Helsinki, May 2016

JB, Tim Koslowski, and Flavio Mercati,"Identification of a gravitational arrow of time", Phys. Rev. Lett. **113**, 181101 (2014)

"Entropy and the typicality of universes", arXiv: 1507.06498v2.

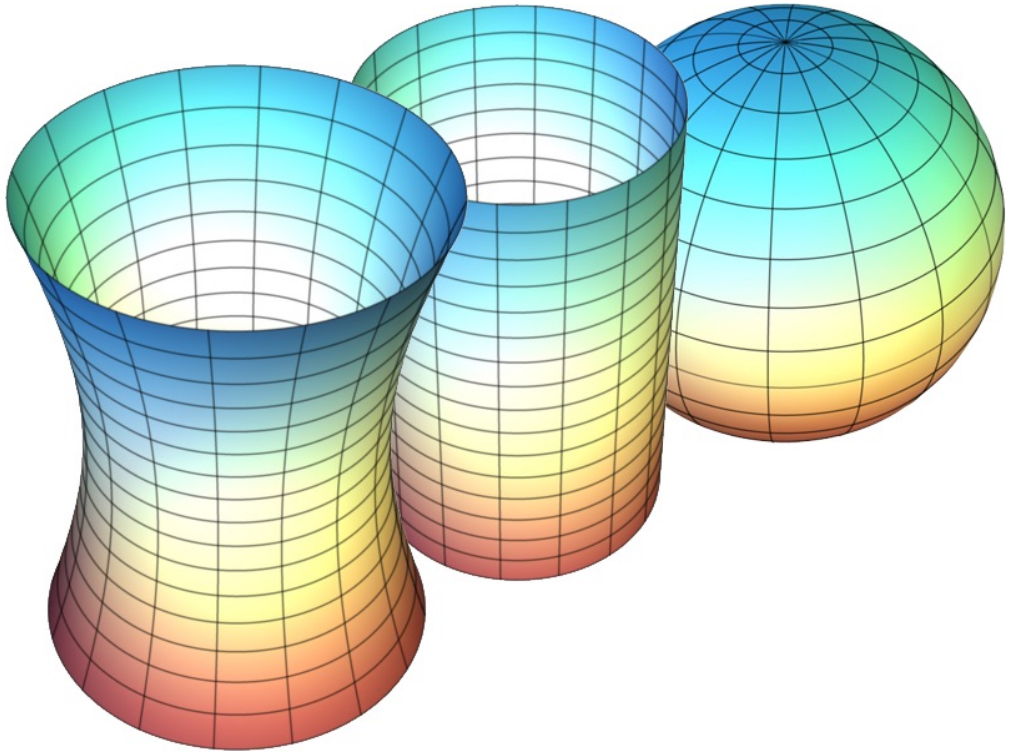
See also video link at platonia.com to talk by JB given at ETH Zurich, September 11, 2015

Diagrams by Flavio Mercati

The Conjecture

Timeless Laws of Geometry and Dynamics are
the Origin of Time, Structure and Beauty

First Timeless Law: Geometry



Galileo:

"He that attempts natural philosophy without geometry is lost."

Second Timeless Law: Dynamics

Hamilton's equations:

$$\frac{\mathrm{d}\mathbf{q}}{\mathrm{d}t} = +\frac{\partial \mathcal{H}}{\partial \mathbf{p}}, \qquad \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = -\frac{\partial \mathcal{H}}{\partial \mathbf{q}}$$

$$\mathcal{H} = \mathcal{H}(\mathbf{q}, \mathbf{p}, t)$$

Goethe's Faust:
"War est ein Gott, der diese Zeichen schrieb?"

"Was it a god who wrote these signs?"

An Outstanding Problem

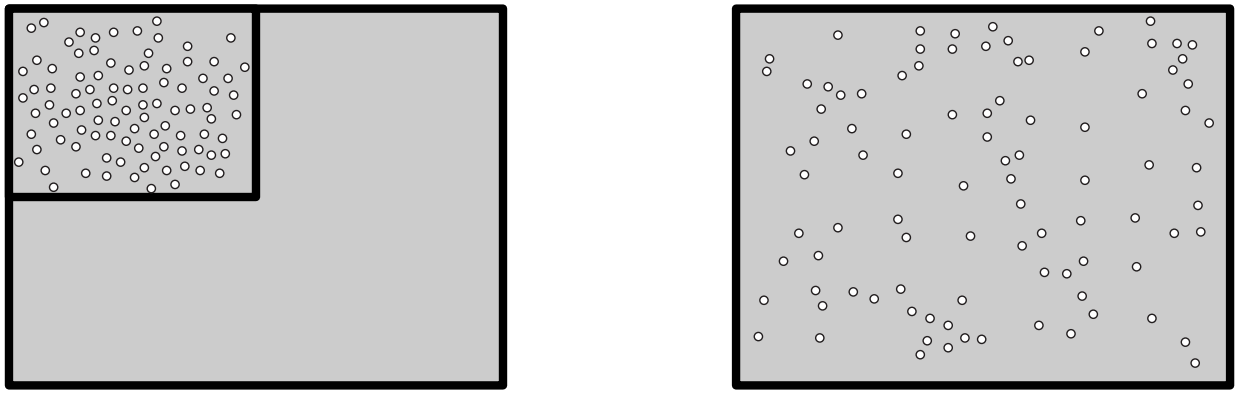
All known laws of nature are time symmetric

Whence comes the **arrow of time?**

Why Are the Past and Future so Different?

Entropy and the Second Law of Thermodynamics

Discovered by Rudolf Clausius (1850)



Order is transformed into disorder

Clausius: “The entropy of the Universe tends to a maximum”

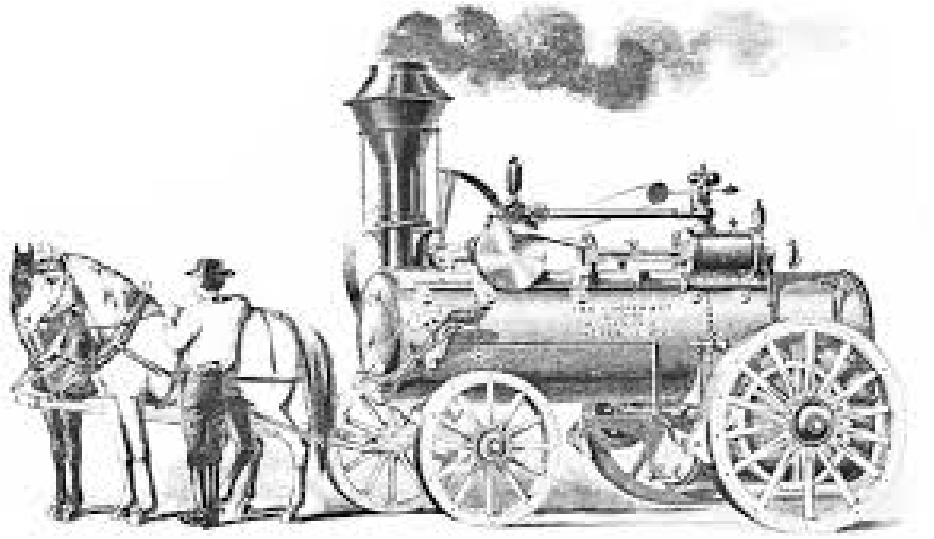
Ludwig Boltzmann 1844–1906

And time that gave doth now his gift confound.

The Inexorable Second Law

Arthur Eddington: “The law that entropy always increases, holds, I think, the supreme position among the laws of Nature . . . if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation.”

Sadi Carnot and Steam Engines



Reflections on the Motive Power of Heat 1824

Carnot showed how to maximize steam-engine efficiency:

$\epsilon = (T_1 - T_2)/T_1$, where T_1, T_2 are the absolute temperatures

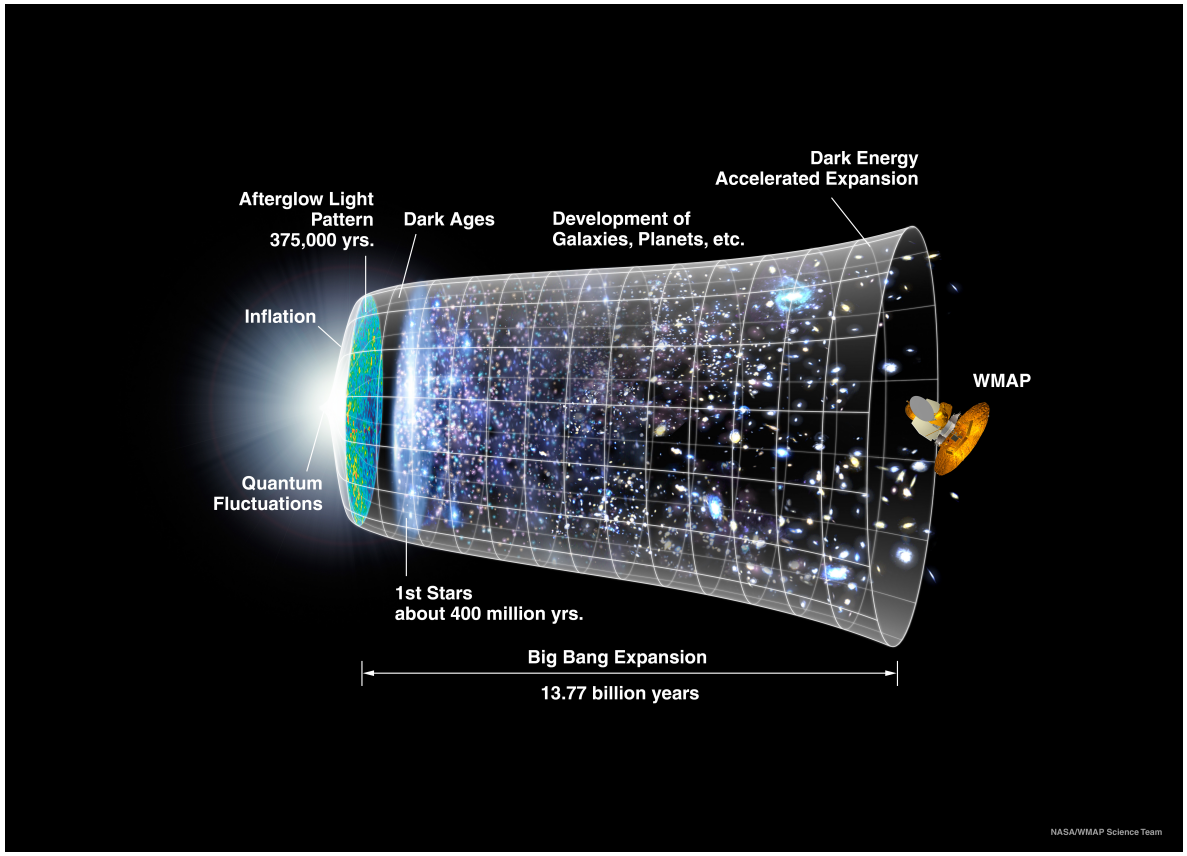
Water Waves

Disorder

$\rightarrow$

Outgoing Waves

Emergence of our Universe from the Big Bang



Growth of Order and Information

Key Insight

Carnot studied the behaviour of steam in a cylinder

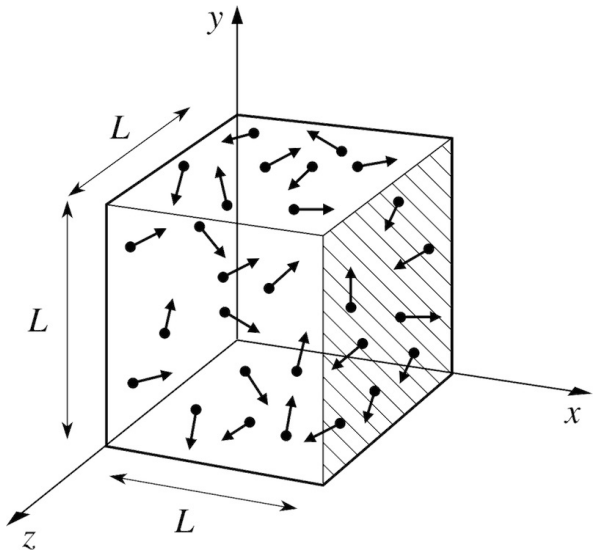
Conventional thermodynamic systems
are **confined**

The Universe is **unconfined**

Theoreticians have been conceptually conservative.
We need to conceptualize differently

Meaning and Significance of Confined

Ideal gas in a box



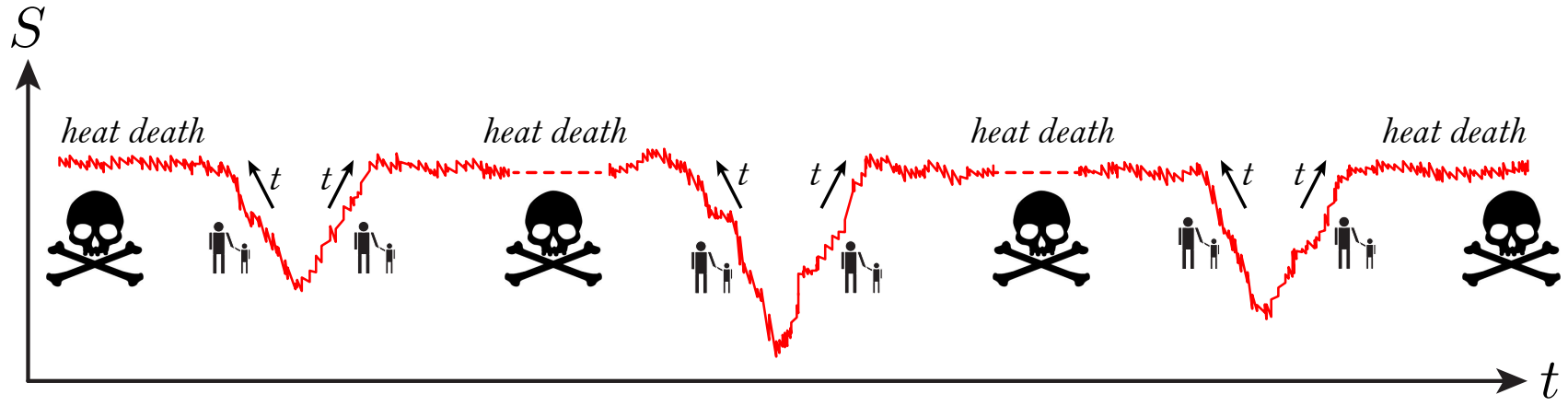
Controlled heat flow. Measurement of P, V, T in equilibrium. Clausius' definition of entropy increment:

$$\mathrm{d}S = \frac{\mathrm{d}Q}{T} + \frac{P\mathrm{d}V}{T}$$

T is the absolute temperature

Consequences of Confining Box

Expansion 'thwarted' $\Rightarrow$ time-symmetric Poincaré recurrrence



Boltzmann: "The universe is, and rests forever, in thermal equilibrium." Only near deep entropy dips "are worlds where visible motion and life exist . . . the direction of time towards the more improbable state [will be experienced as] the past."

Key insight: Time has no pre-existing direction

Each dip has one-past–two-futures

Explaining the Arrows

Boltzmann and Some Today: There was a huge fluctuation from thermal equilibrium in the direction we call the past

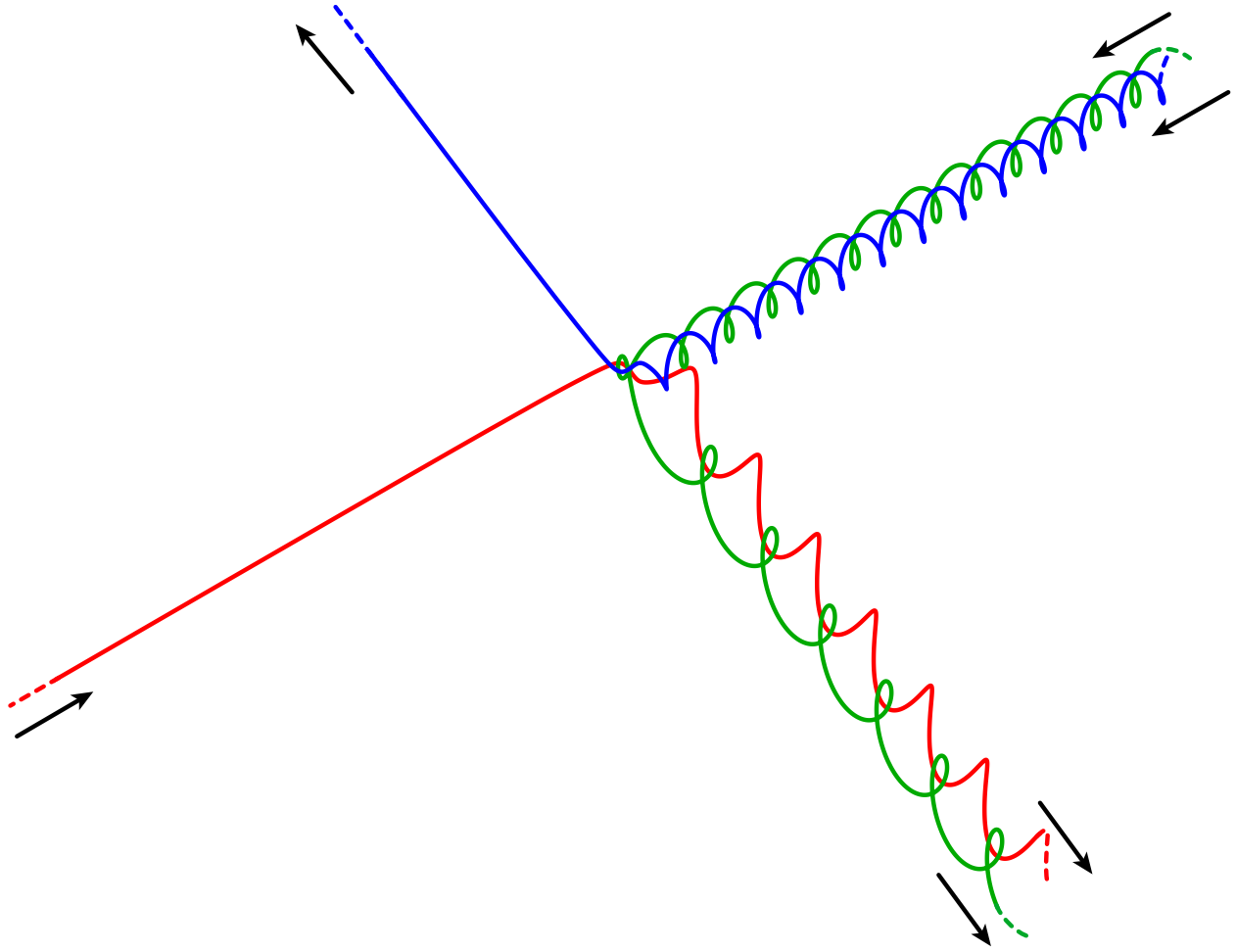
The Majority Today: The Universe began in the Big Bang with an extremely low entropy

The Past Hypothesis: The arrows of time are not due to the law but to some very special condition in our past

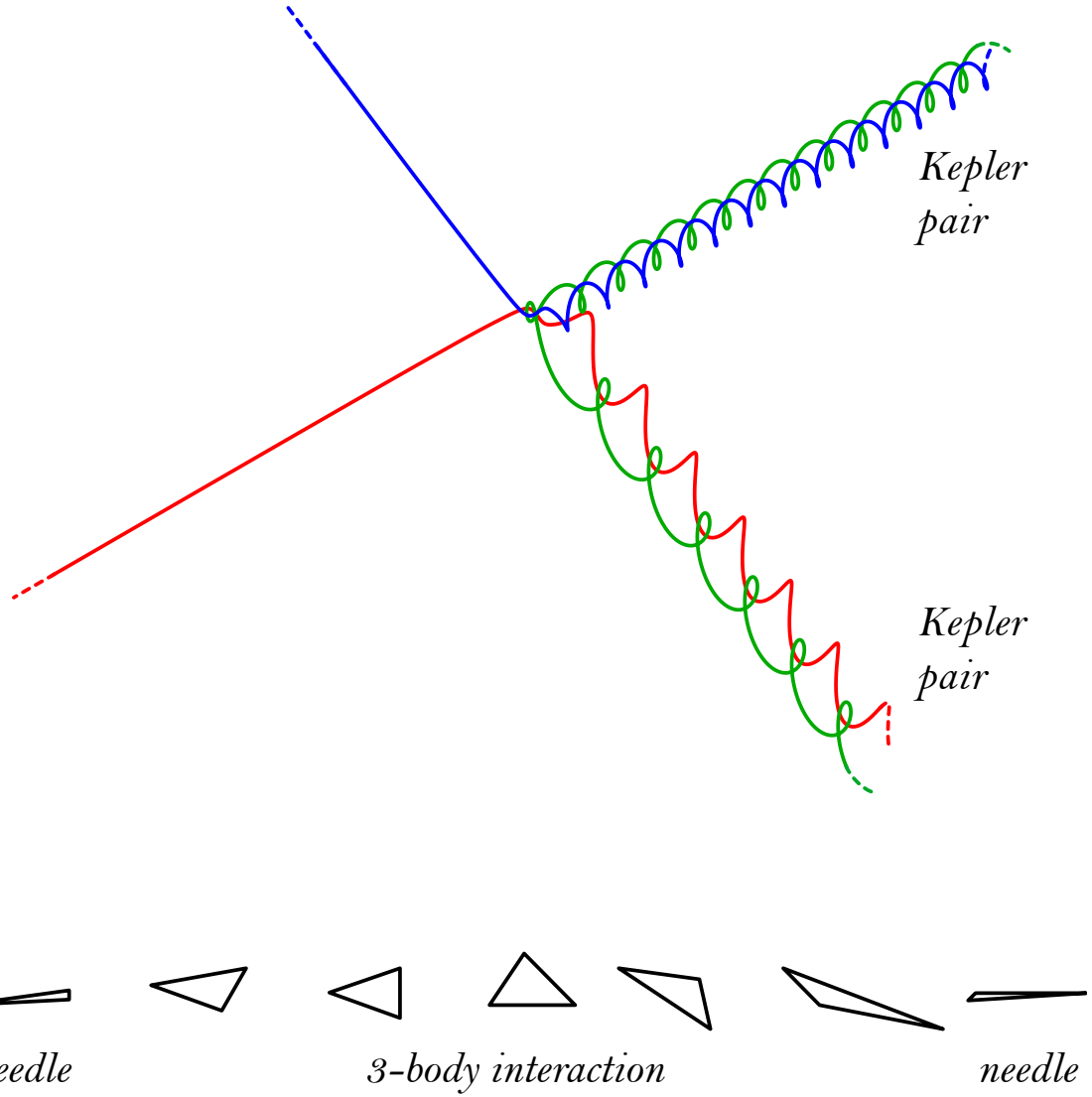
Not an explanation. An admission of defeat

Modern science fails to explain the most profound aspect of our existence

Relational Three-Body Motions



One-Past–Two-Futures



The Lagrange–Jacobi Relation

Centre-of-mass moment of inertia $I_{\text{cm}} = \sum_{a=1}^{a=N} m_a \, \mathbf{r}_a^{\text{cm}} \cdot \mathbf{r}_a^{\text{cm}}$

If V homogeneous, $\boxed{V(\alpha \mathbf{r}_a) = \alpha^k V(\mathbf{r}_a)}$, then $\boxed{\frac{1}{2}\ddot{I}_{\text{cm}} = E_{\text{cm}} - 2(k+2)V}$

If $\boxed{E_{\text{cm}} \geq 0}$, then because $\boxed{V_{\text{New}} < 0}$ and $\boxed{k = -1}$ we have $\boxed{\ddot{I}_{\text{cm}} > 0}$

I_{cm} is U-shaped upwards, the dilatational momentum $D == \frac{1}{2}\dot{I}_{\text{cm}}$
is monotonic and vanishes once at the **Janus point**,
the minimum of the root-mean-square length

$$\ell_{\text{rms}} := \sqrt{\sum_{a<b} \frac{m_a m_b \, r_{ab}^2}{m_{\text{tot}}^2}} = \sqrt{I_{\text{cm}}/m_{\text{tot}}}$$

Janus-Point Systems

Every solution divides at unique **Janus point J**

Evolution **time-asymmetric** either side of **J**

Arrows of time point away from **J** in each half

Water Waves

$\rightarrow$

Disorder

Outgoing Waves

Einstein (1909): Incoming waves very improbable, but

$\leftarrow$

$\rightarrow$

Outgoing Waves

Disorder

Outgoing Waves

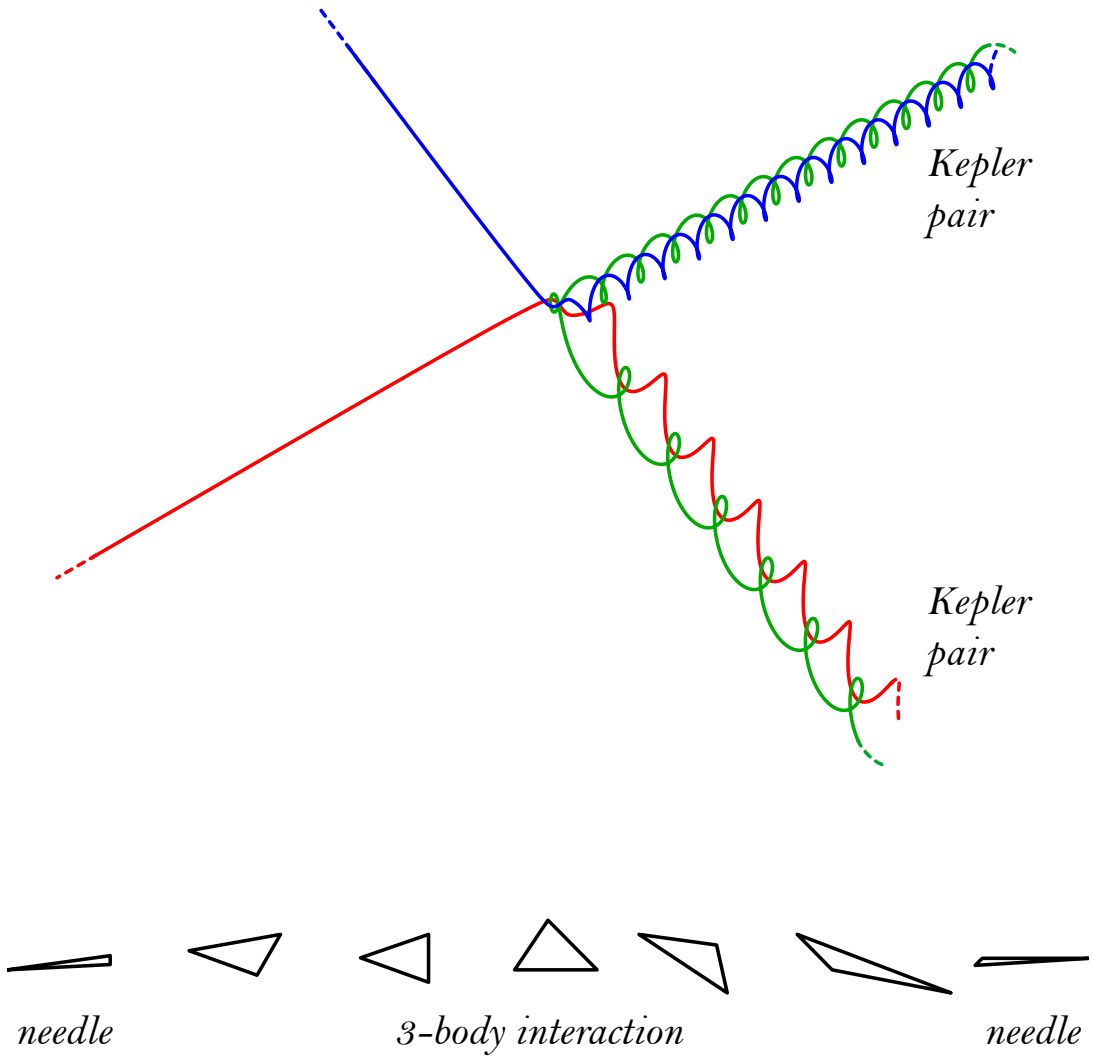
‘Seeing’ the Universe Expand

‘Expansion of universe’ is shorthand for evolution of ratios:

$$\frac{\text{Galactic Diameters}}{\text{Inter-Galactic Separations}} \to 0$$

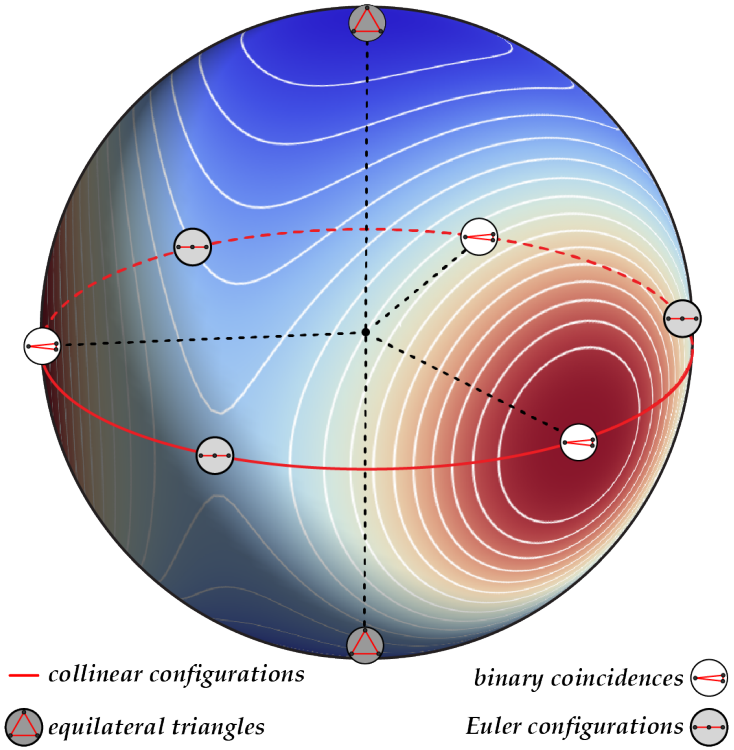
Dimensionless ratios alone have physical meaning

Shapes Are All We Need



Shape Space S

The space of the Universe's possible shapes



3-Body Shape Space

S: the space of triangle shapes

Shape Sphere for equal masses

Colour coding to be explained

A Scale-Invariant Measure of Clustering

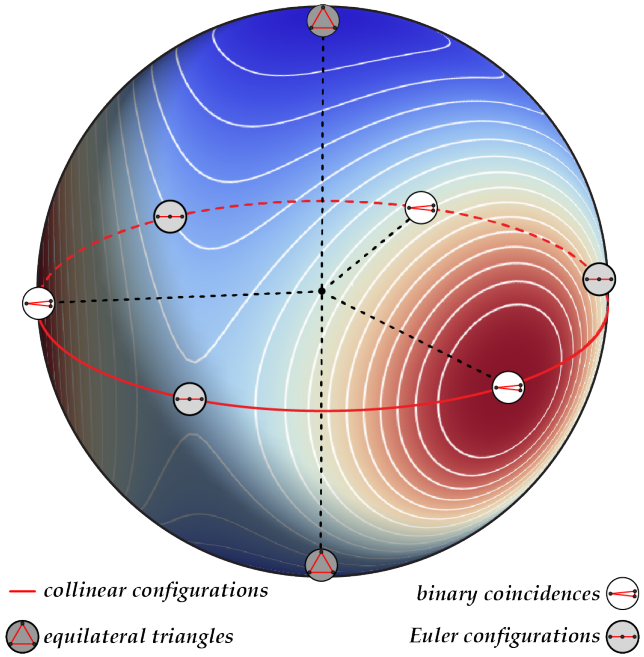
Ratio of **root-mean-square length** $\ell_{\rm rms}$
and **mean harmonic length** $\ell_{\rm mhl}$

$$\ell_{\rm rms} := \sqrt{\sum_{a<b} \frac{m_a m_b\, r_{ab}^2}{m_{\rm tot}^2}} = \sqrt{I_{\rm cm}/m_{\rm tot}}$$

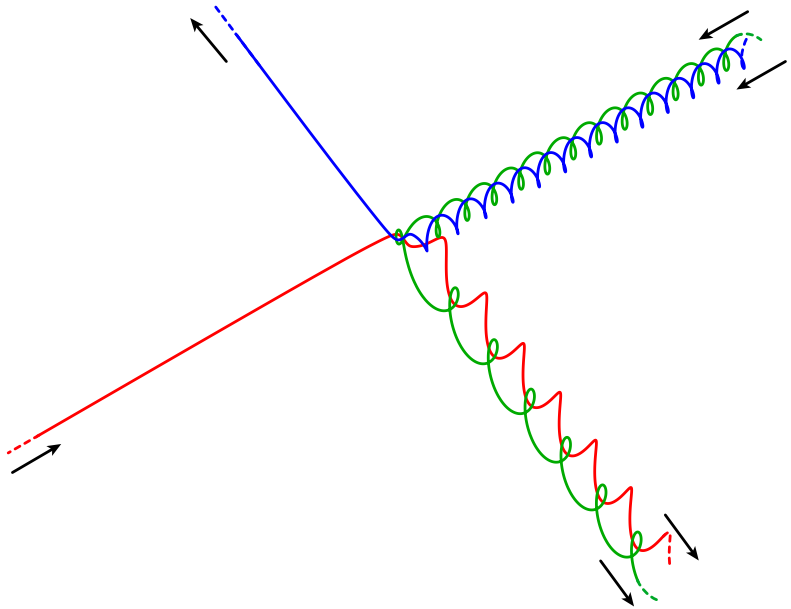
$$\ell_{\rm mhl}^{-1} = \frac{1}{m_{\rm tot}^2} \sum_{a<b} \frac{m_a m_b}{r_{ab}} = -\frac{1}{m_{\rm tot}^2} V_{\rm New}$$

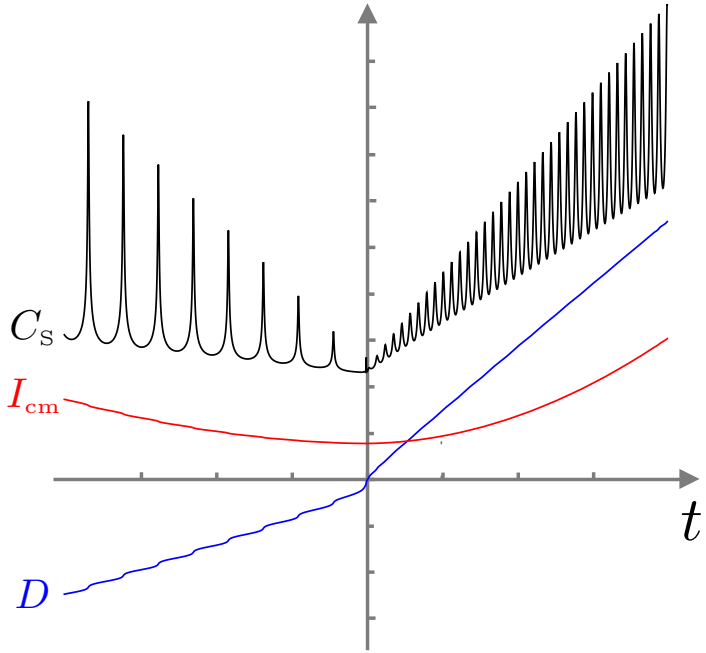
Shape Complexity: $\mathrm{C}_{\rm Shape} = \ell_{\rm rms}/\ell_{\rm mhl}$

A sensitive measure of clustering



Janus Point 'Seen' in Complexity

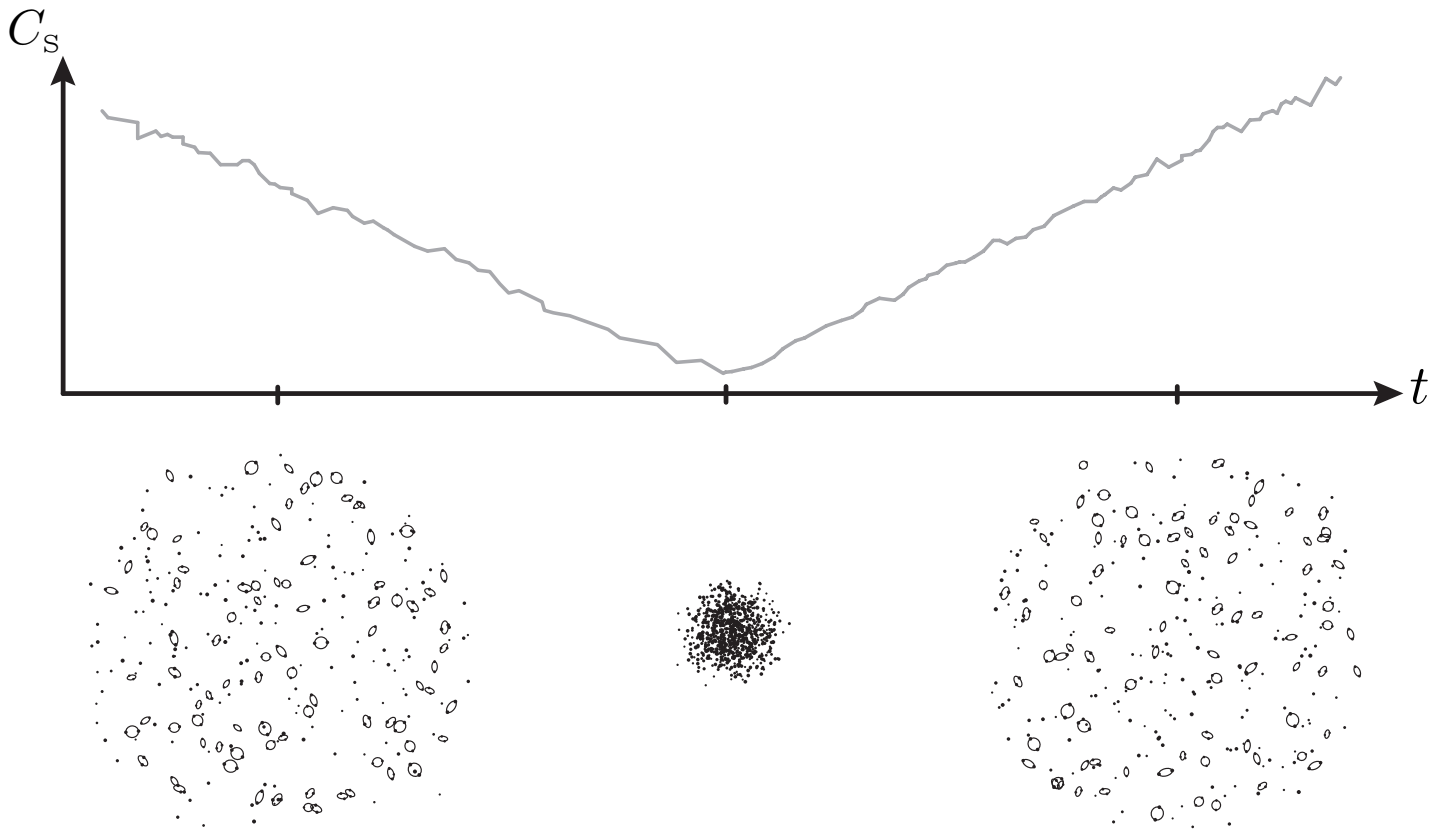




Blue singleton left, red singleton right

Orbital elements stabilize (records)

1000-Body Simulation



Simulation Above, 'Artistic Impression' Below

Liouville's Theorem and Shape Dynamics

Hamilton's equations

$$\frac{\mathrm{d}\mathbf{q}}{\mathrm{d}t} = +\frac{\partial \mathcal{H}}{\partial \mathbf{p}}, \qquad \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = -\frac{\partial \mathcal{H}}{\partial \mathbf{q}}$$

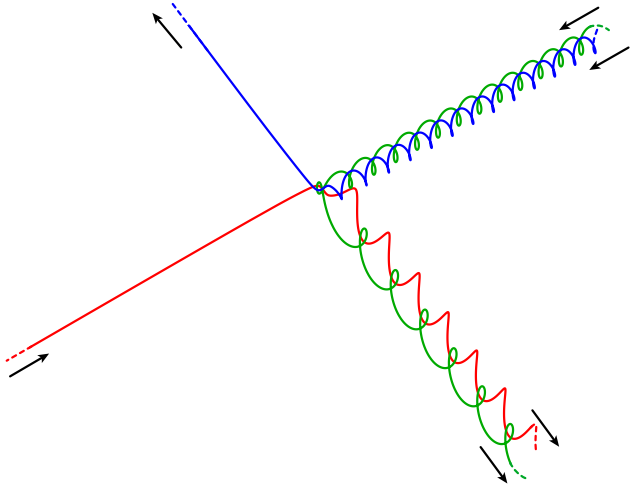
conserve phase-space volume

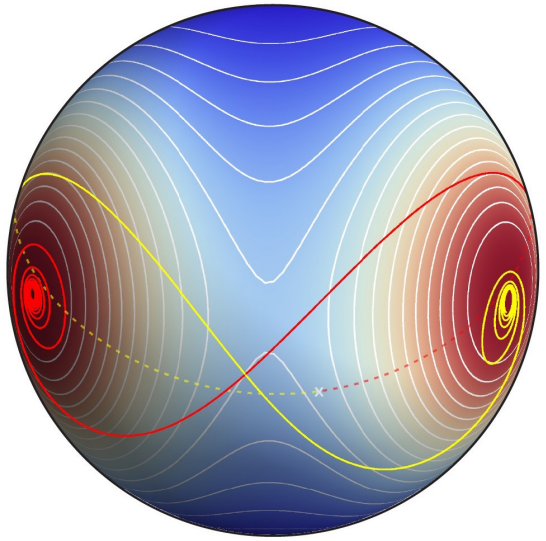
If scale part grows, shape part must decrease $\Rightarrow$

Attractors on Shape Space

Attractors and the Shape Potential

$$C_{\mathsf{Shape}} = -m_{\mathsf{tot}}^{-5/2}\sqrt{I_{\mathsf{cm}}}\,V_{\mathsf{New}} = -V_{\mathsf{Shape}}$$



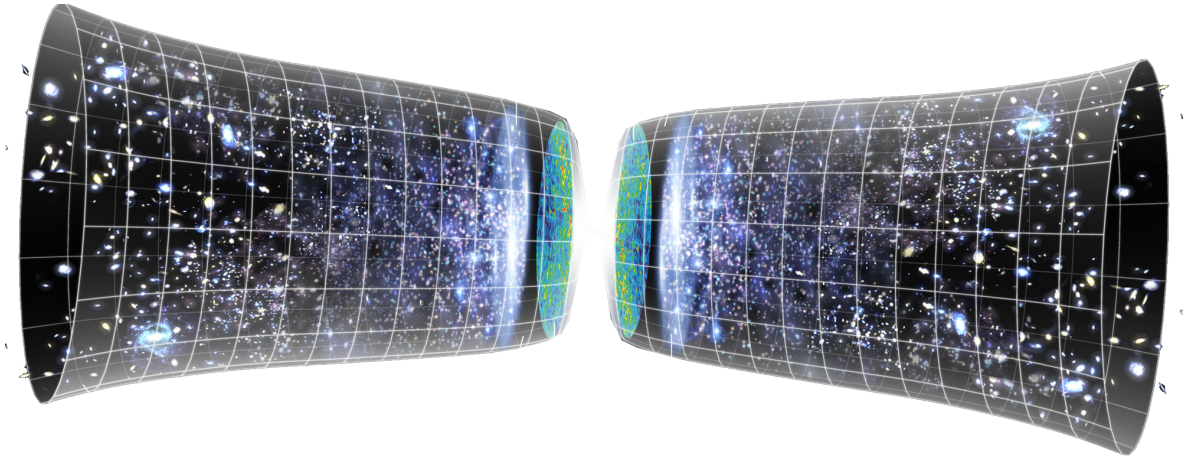


Is the Universe Confined or Unconfined?

Confined: Arrows of time rare

Unconfined: Arrows of time everywhere

What Is the Big Bang?

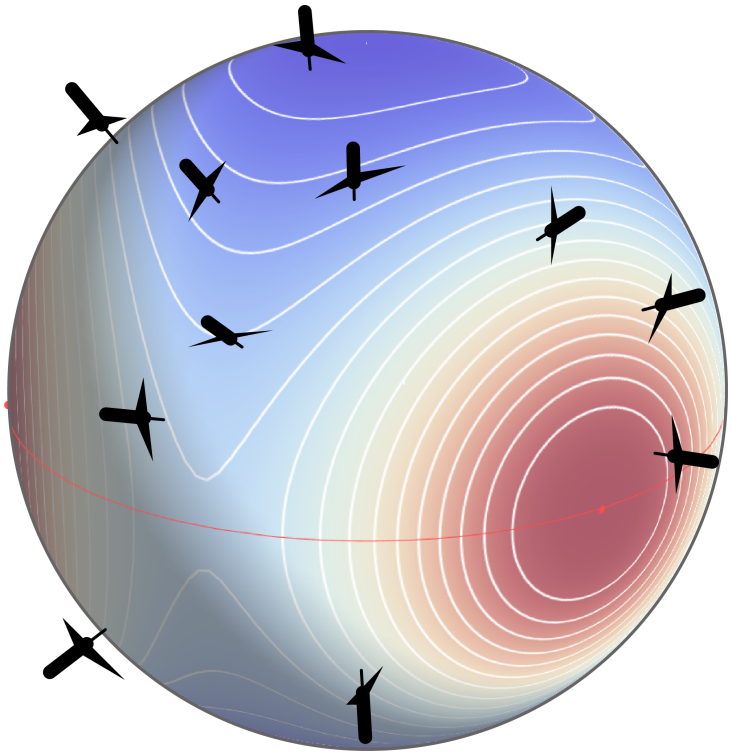


Volume goes to zero but shape changes smoothly

Is Our Universe Typical?

For known law of the universe, what will typical solutions be like?

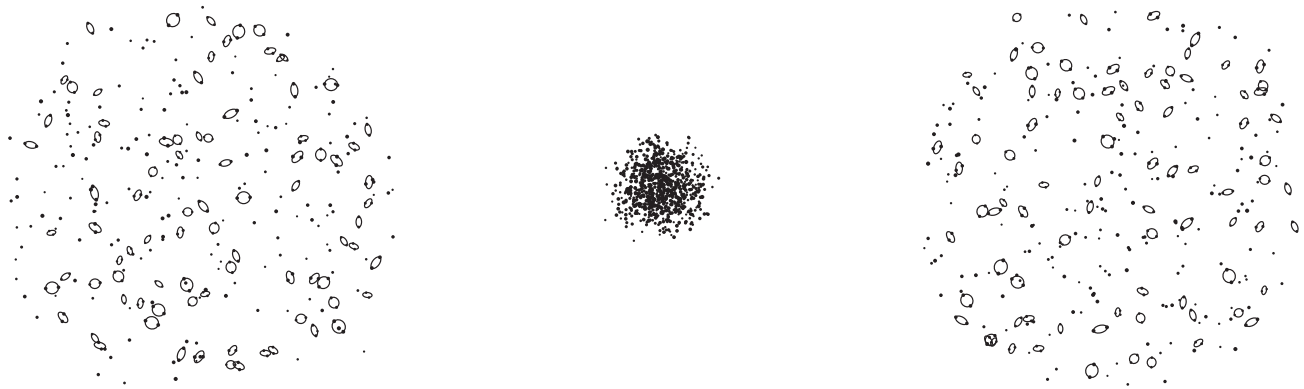
Laplace's Principle of Indifference: if N outcomes possible but nothing else known, give equal probability to each.



Let a blindfolded Creator throw darts at shape space. Few darts hit high-complexity shapes. Universe should be very uniform at its Janus point.

Origin of the Second Law

The entropy-like quantity for the Universe **decreases**



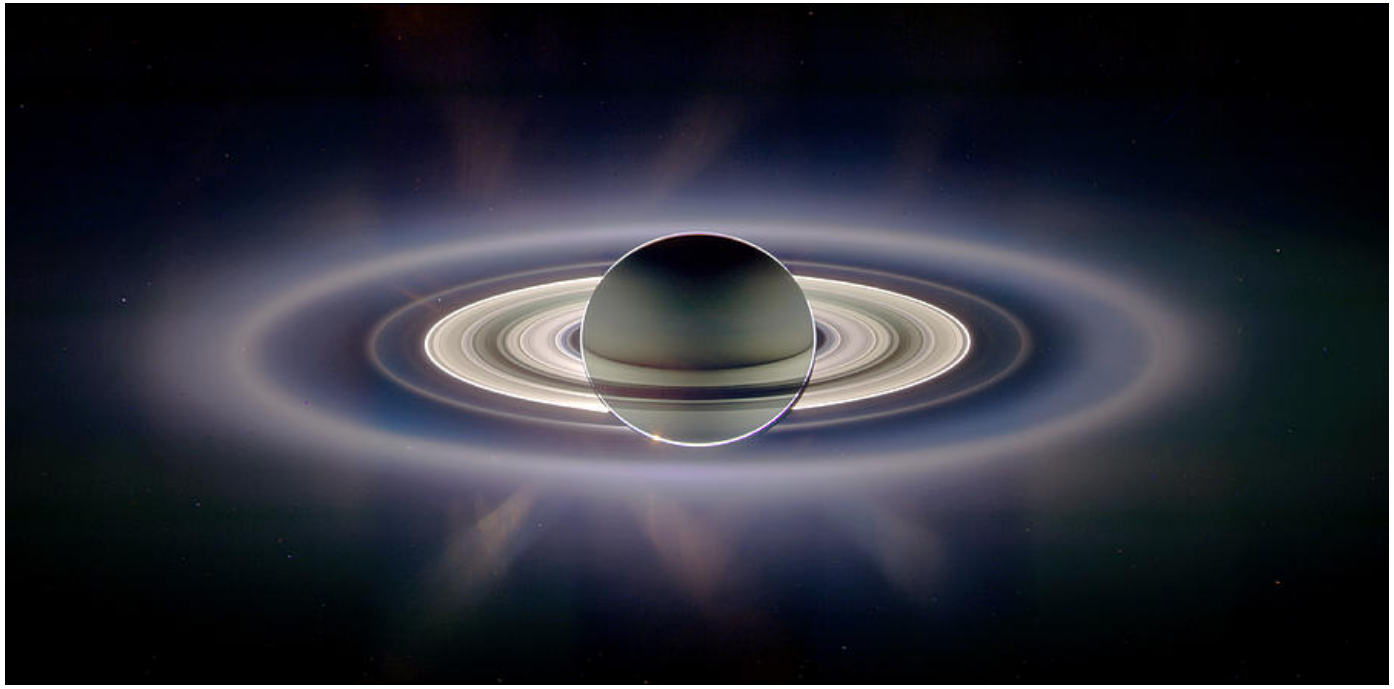
Second Law discovered for isolated subsystems of the Universe

Gravity & Quantum Mechanics $\Rightarrow$ Self-Confinement $\Rightarrow$ Second Law

Law of the Universe creates conditions for all steam engines

Man discovers entropy by maximizing their efficiency

Structure and Beauty Created by Law through Time



The Future of the Universe: Life or Death?

Shakespeare's Sonnet 60

Like as the waves make towards the pebbled shore,
So do our minutes hasten to their end;
Each changing place with that which goes before,
In sequent toil all forwards do contend.

Nativity, once in the main of light,
Crawls to maturity, wherewith being crown'd,
Crooked eclipses 'gainst his glory fight,
And Time, that gave, doth now his gift confound.

Time doth transfix the flourish set on youth,
And delves the parallels in beauty's brow,
Feeds on the rarities of nature's truth,
And nothing stands but for his scythe to mow.

And yet to times in hope my verse shall stand,
Praising thy worth, despite his cruel hand.

Hope in Infinity?

Leibniz: “We live in the best of all possible worlds”

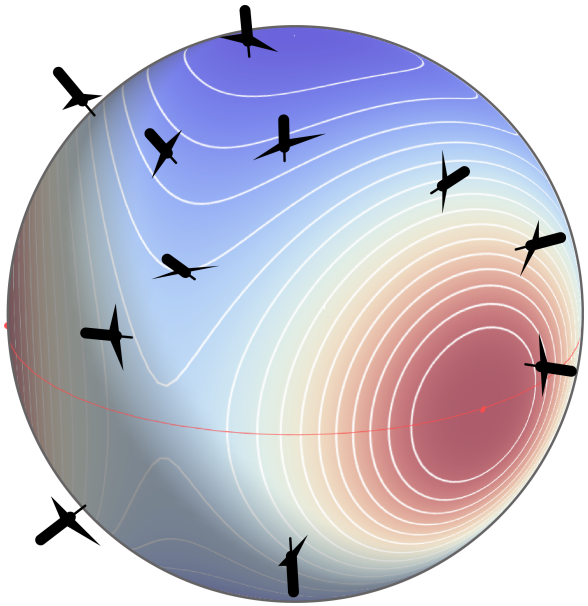
Monadology (1714), Sec. 58. “This is the means of obtaining as much variety as possible, but with the greatest order possible; that is to say, it is the means of obtaining as much perfection as possible.”

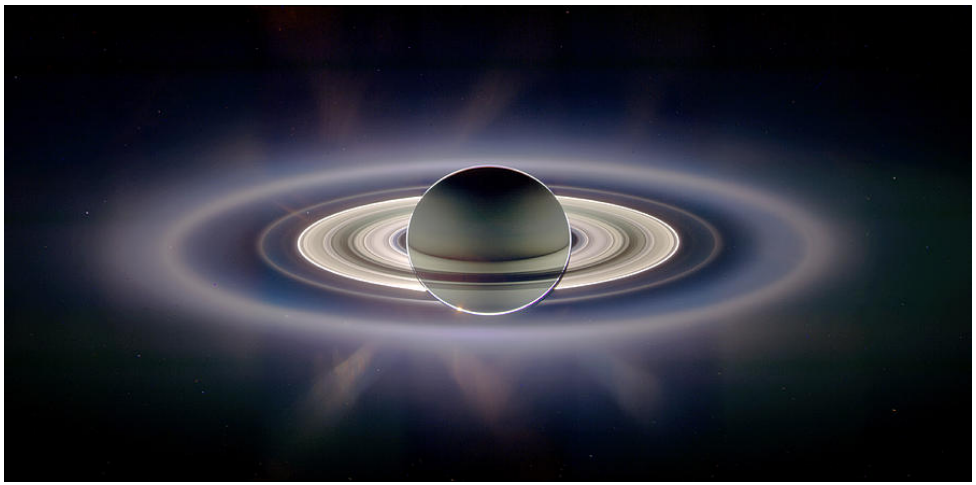
Two possibilities: Eternally perfect or striving to perfection

Real numbers can encode an infinite amount of information

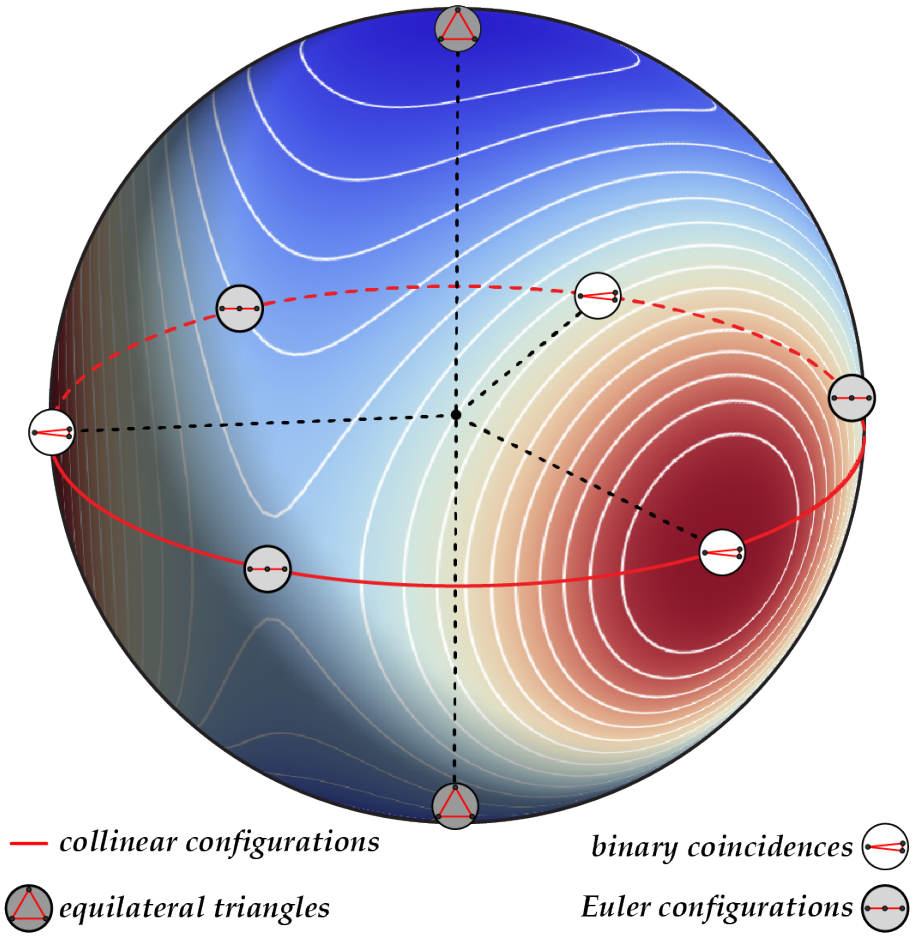
Is infinite Janus-point information unfolded in time?

Is Ever Finer Structure Revealed?





Evolution of Quantum Probability Mist



Mist concentrates on ever smaller regions of interesting structure.

Time is the ever-finer illumination of eternity

Bottom's Dream

When my cue comes, call me, and I will answer. My next is Most fair Pyramus. Heigh-ho! Peter Quince? Flute the bellows-mender? Snout the tinker? Starveling? Gods my life, stol'n hence, and left me asleep?

I have had a most rare vision. I have had a dream – past the wit of man to say what dream it was. Man is but an ass if he go about to expound this dream. Methought I was – there is no man can tell what. Methought I was, and methought I had – but man is but a patched fool if he will offer to say what methought I had. The eye of man hath not heard, the ear of man hath not seen, mans hand is not able to taste, his tongue to conceive, nor his heart to report what my dream was. I will get Peter Quince to write a ballad of this dream. It shall be called "Bottoms Dream" because it hath no bottom. And I will sing it in the latter end of a play before the duke. Peradventure, to make it the more gracious, I shall sing it at her death.