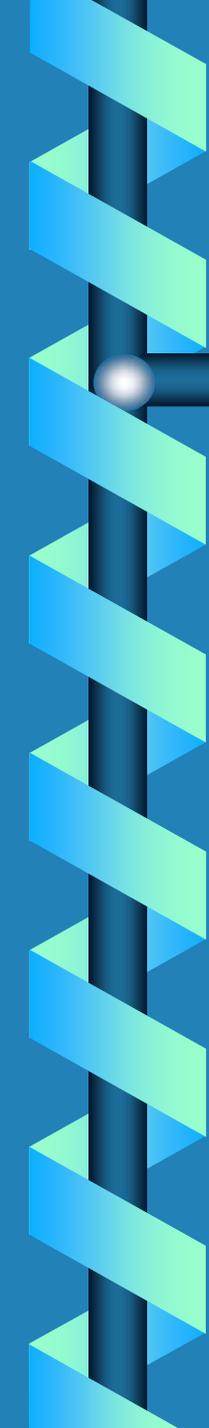




An Assessment of Faster-Than-Light Spacetimes: Make or Break Issues (paper AIAA-2006-4908)

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A Tale of Two FTL Spacetimes in General Relativity

- Traversable Wormholes (rich diversity)
- Warp Drives (rich diversity)
- All other FTL spacetime claims (in GR) are spurious
- There are wormhole/warp drive spacetimes in alternative gravity theories & D-Brane/quantum gravity theories

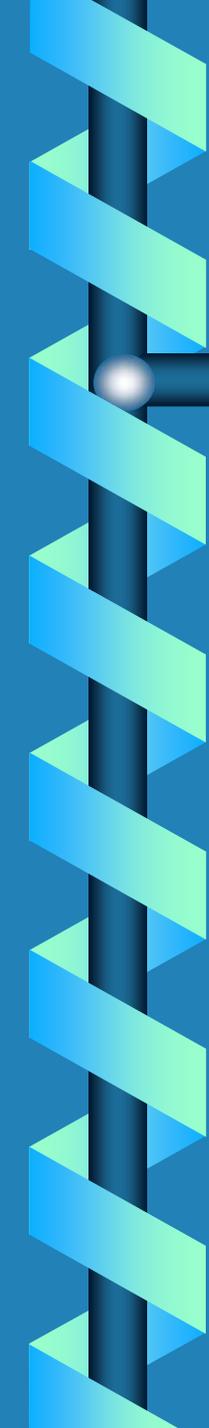
Violations of the Energy Conditions

- Hawking-Ellis "Classical Energy Conditions" must be violated to make FTL spacetimes in GR
- Energy conditions
 - Weak Energy Condition (WEC): $\rho_E \geq 0, \rho_E + p_i \geq 0$
 - Null Energy Condition (NEC): $\rho_E + p_i \geq 0$
 - Dominant (DEC) & Strong (SEC) Energy Conditions are less important
- All energy condition hypotheses have been experimentally tested in the laboratory & experimentally shown to be false - 25 years before their formulation
 - further investigation showed that violations of energy conditions are widespread for ALL forms of classical & quantum matter
- There is no such thing as "reasonable matter"

Engineering FTL Spacetimes Requires Energy Condition Violating "Exotic" Matter

- So...it's OK to violate the energy conditions...it's not a crime against nature
- Energy densities/fluxes and/or pressures of material required to create FTL spacetimes must be "exotic" (or "negative")
- "Negative" in the sense that material must have:
energy density \leq pressures
or rather
energy density < 0
(i.e., lower energy than surrounding vacuum)

→ "negative" is just a misnomer



Examples of Energy Condition Violating “Stuff” Found in Nature (or in the Lab)

- Static radially-dependent electric or magnetic fields
- Squeezed quantum states of the electromagnetic field & other squeezed quantum fields
- Gravitationally squeezed vacuum electromagnetic zero-point fluctuations
- Casimir Effect in flat or curved spaces
- Cosmological Inflation
- Cosmological Particle Production
- The Conformal Anomaly
- Gravitational Vacuum Polarization

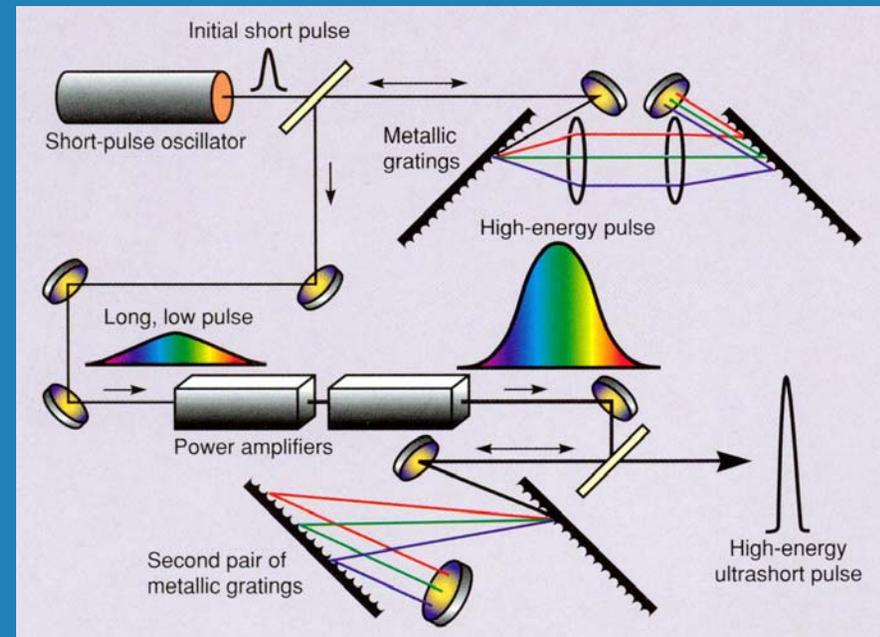
Other Examples of Energy Condition Violating "Stuff"

- Other quantum fields/states/effects
 - In general, the local energy density in quantum field theory can be negative due to quantum coherence effects
- Other examples studied: Dirac Field States
 - the superposition of two single particle electron states and the superposition of two multi-electron-positron states
 - in the former (latter), the energy densities can be negative when two single (multi-) particle states have the same number of electrons (electrons and positrons) or when one state has one more electron (electron-positron pair) than the other
- To be subject of future study

Lab Examples: Radial Electric or Magnetic Fields

Generate *radial* E- or B-field using Ultrahigh-Intensity Lasers (LLNL, UNR, UT):

- power intensity $\approx 10^{15} - 10^{26} \text{ W/cm}^2$ (10^{30} W/cm^2 using SLAC),
peak power pulse $\leq 10^3 \text{ fs}$
- B-fields: *several* $\times 10^6 \text{ T}$,
 $\rho_{\text{mag}} \sim \text{several} \times 10^{19} \text{ J/m}^3$
- E-fields: $10^{14} - 10^{18} \text{ V/m}$,
 $\rho_{\text{elec}} \approx 10^{16} - 10^{28} \text{ J/m}^3$
- Possible to generate km – AU sized wormholes in the lab: need static E,B



Lab Examples: (Electromagnetic) Casimir Effect

- Construct (spherically symmetric) wormhole using Casimir Effect: two closely spaced, concentric, thin electrically charged hollow spherical plates the size of Earth's orbit ($\sim 10^8$ km) to create negative Casimir energy

$$d = \left(\frac{\pi^3}{30}\right)^{1/4} \left(r_{wh} \sqrt{\frac{\hbar G}{c^3}}\right)^{1/2}$$
$$= \left(4.05 \times 10^{-18}\right) \sqrt{r_{wh}} \quad (\text{meters})$$

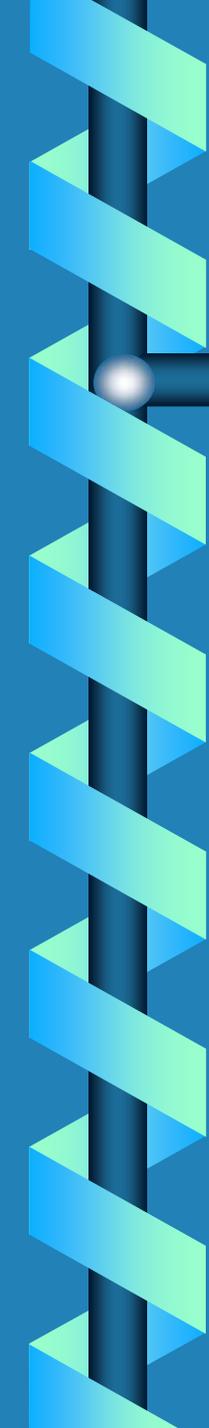
d = cavity plate separation
 r_{wh} = wormhole throat radius

Morris, Thorne & Yurtsever (1988)

- $r_{wh} = 1$ km: $d = 1.28 \times 10^{-16}$ m (\ll nuclear diameter), $\rho_{EC} = -4.83 \times 10^{36}$ J/m³
- $r_{wh} = 1$ AU: $d = 1.57 \times 10^{-12}$ m ($<$ electron's Compton λ), $\rho_{EC} = -2.16 \times 10^{20}$ J/m³
- Miniscule d unrealistic because Casimir Effect switches over into non-retarded field behavior ($\sim d^{-3}$) of van der Waals forces when $d < 15$ nm where plates are no longer perfectly conducting

Lab Examples: Squeezed Vacuum

- Squeezed vacuum state consists of a traveling electromagnetic wave that oscillates back and forth between negative and positive energy density, but has positive time-averaged energy density
- Squeezed Electromagnetic Vacuum:
 - moving some quantum-fluctuations of EM field out of $\cos\omega(t - z/c)$ part of the field and into $\sin\omega(t - z/c)$ part
 - one can “squeeze” variance of one observable provided variance in conjugate observable is stretched
 - observable that gets squeezed will have its fluctuations reduced below the vacuum ZPF
- Since the vacuum is defined to have vanishing energy density, any region with less energy density than the vacuum actually has a negative (renormalized) expectation value for the energy density

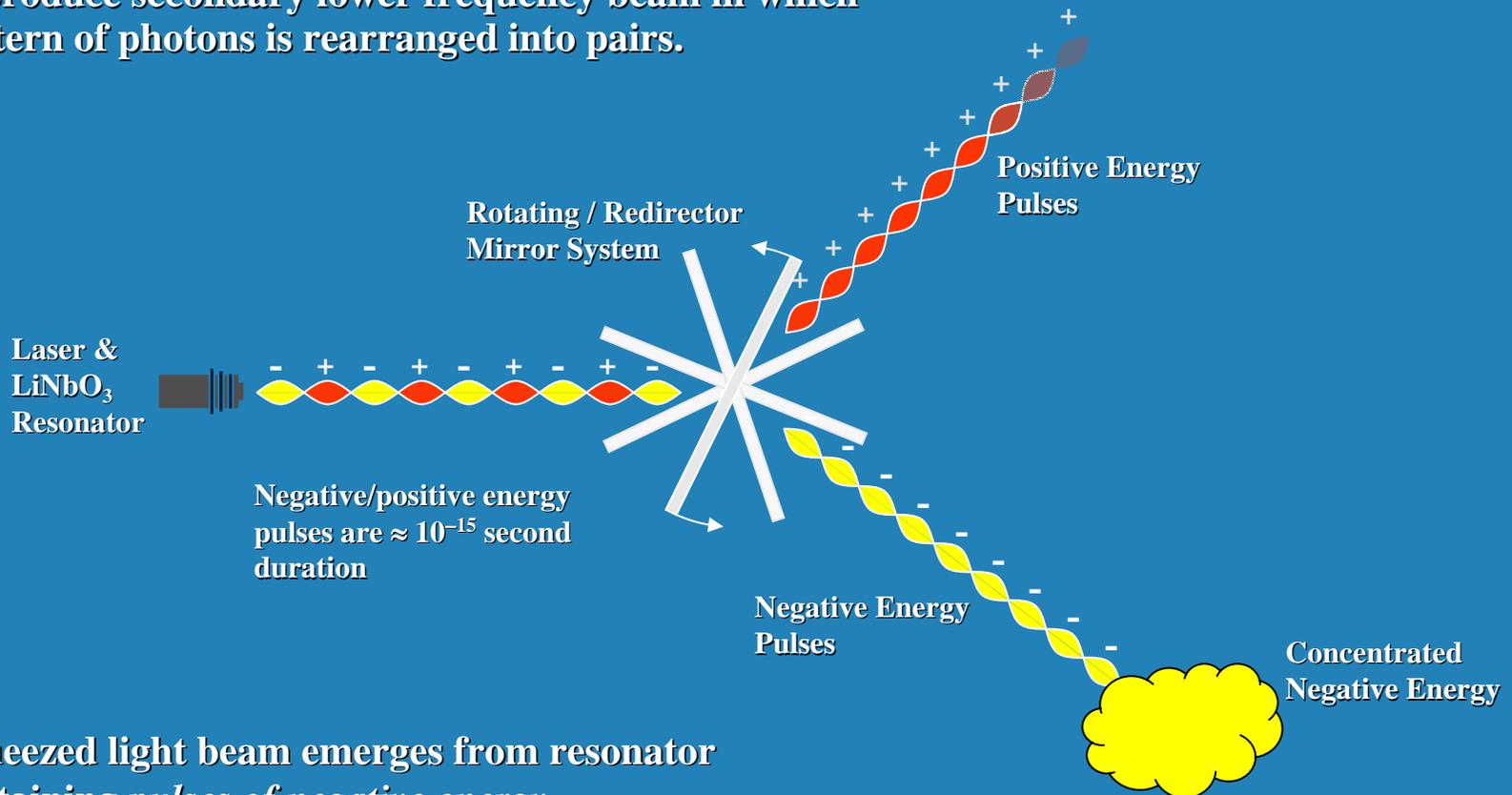


Experimental Squeezed Vacuum Source

- Ries, Brezger, Lvovsky (2003), "Experimental Vacuum Squeezing in Rubidium Vapor via Self-Rotation," *Phys. Rev. A*, 68, 025801
- "...we demonstrate a simple, scalable squeezed vacuum source which consists in essence of a continuous-wave (cw) diode laser and an atomic rubidium vapor cell."

Device Concept: Quantum Optical "Squeezing" of Light Effect

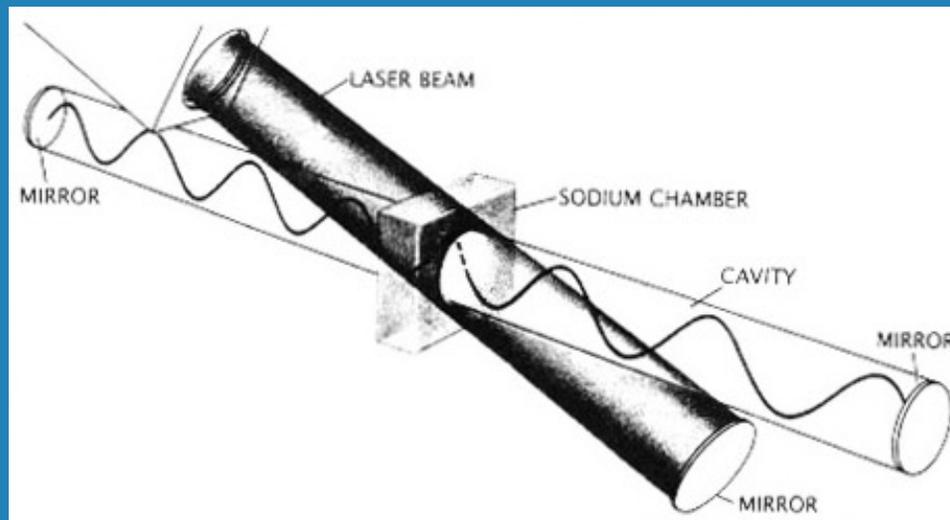
Laser beam is passed thru LiNbO₃ resonator, which acts to produce secondary lower frequency beam in which pattern of photons is rearranged into pairs.



Squeezed light beam emerges from resonator containing pulses of negative energy interspersed with pulses of positive energy.

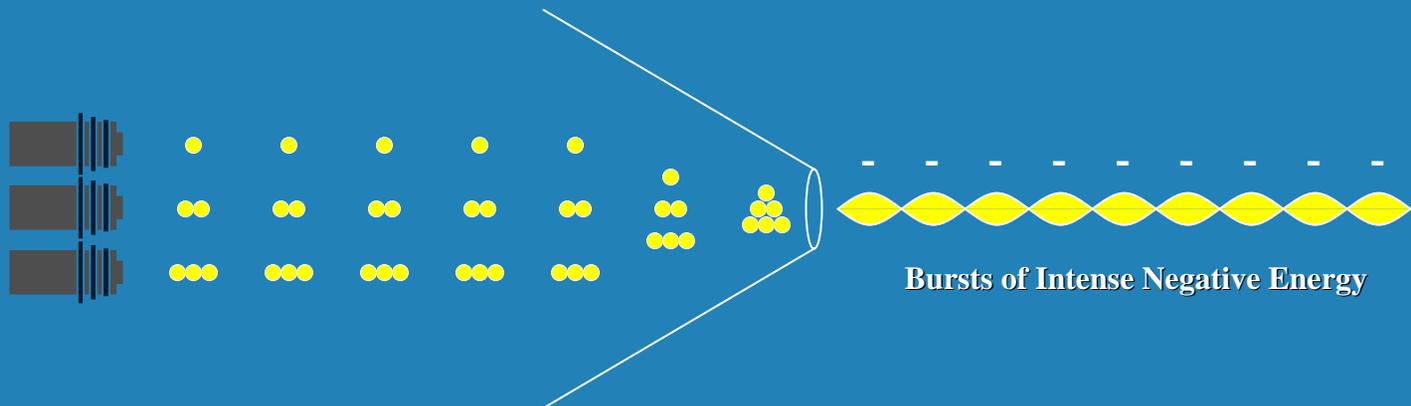
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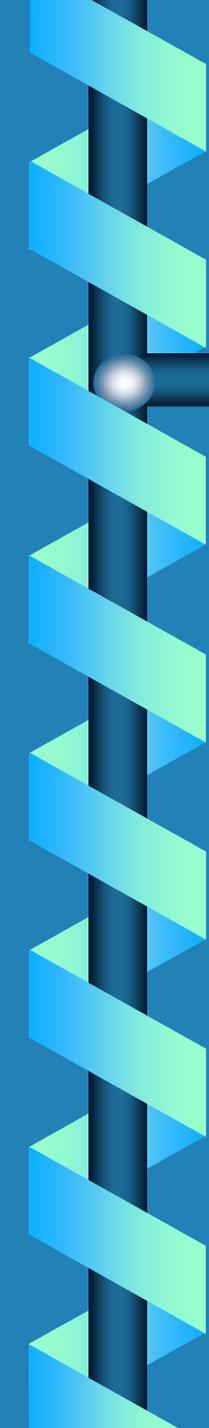
- Or a chamber of sodium gas is placed within squeezing cavity, and laser beam is directed thru gas:
 - beam is reflected back on itself by a mirror to form standing wave within sodium chamber
 - this wave causes rapid variations in optical properties of the sodium thus causing rapid variations in the squeezed light so that we can induce rapid reflections of pulses by careful design



Device Concept: Quantum Optical "Squeezing" of Light Effect

- Another way to squeeze light would be to manufacture extremely reliable light pulses containing precisely one, two, three, etc. photons apiece and combine them together to create squeezed states to order.
→ Superimposing many such states could theoretically produce bursts of intense negative energy.



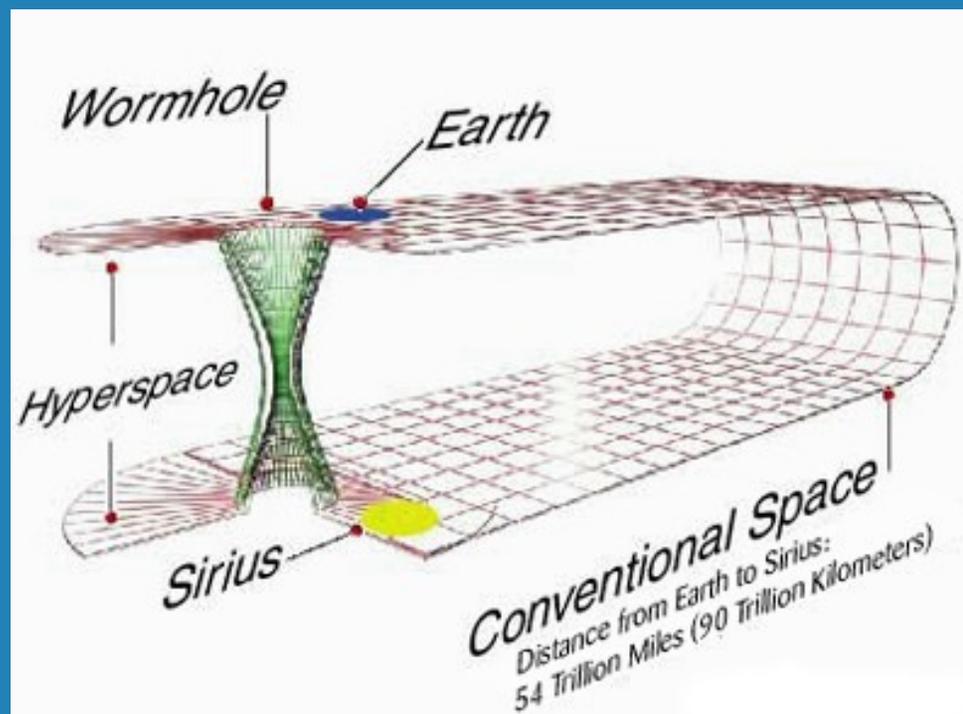


Single Photon Source in the Lab

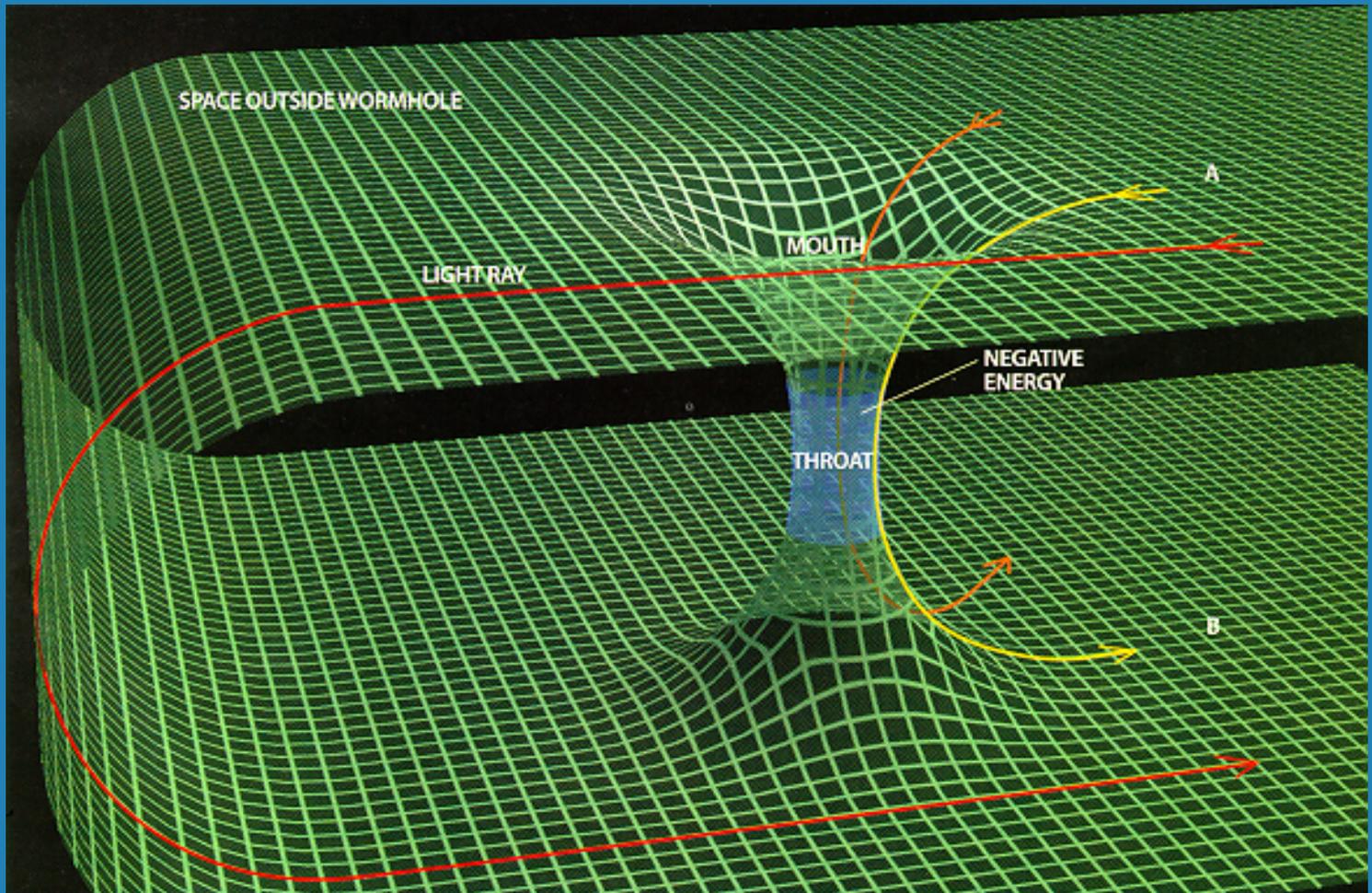
- Rabeau, J. R., et al. (2004), "Fabrication of single nickel-nitrogen defects in diamond by chemical vapor deposition," arxiv.org/cond-mat/0411245
- Rabeau, J. R., et al. (2004), "Diamond chemical vapor deposition on optical fibers for fluorescence waveguiding," arxiv.org/cond-mat/0411249
- used a microwave oven to fuse a tiny diamond, just $1/1000^{\text{th}}$ of a millimeter in length, onto an optical fiber, to create a single photon beam of light

Traversable Wormholes

- Hyperspace tunnels thru spacetime, which can:
 - ✦ connect remote regions within our universe
 - ✦ connect different universes
 - ✦ connect different space dimensions (for higher dimensional wormholes)
 - ✦ connect different chronological periods within the same space region (time machine!)
- This FTL spacetime violates the NEC



Negative Energy Engineering for Traversable Wormholes



Engineering Wormholes: How Much Negative Mass-Energy is Required?

Negative Mass Required to Create Wormhole of Given Size

Wormhole throat radius, r_{throat} (meters)	Required mass, M_{wh}
1000	$-709.9 M_J$
100	$-71 M_J$
10	$-7.1 M_J$
1	$-0.71 M_J$
0.1	$-22.6 M_{\oplus}$
.01	$-2.3 M_{\oplus}$

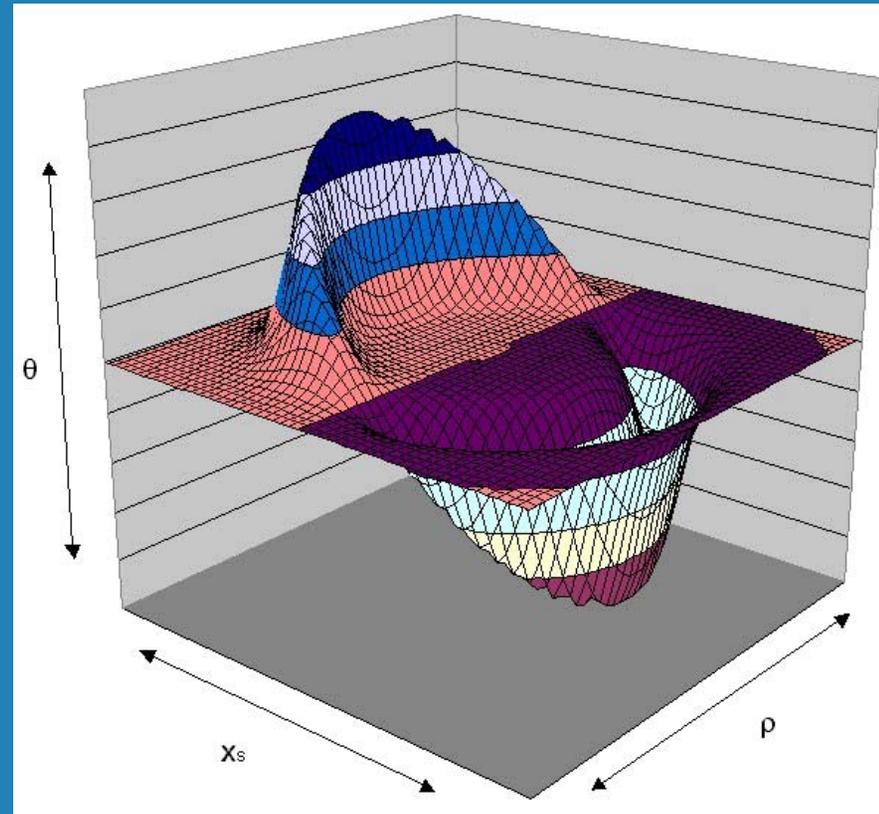
$M_J = 1.90 \times 10^{27}$ kg, mass of Jupiter

$M_{\oplus} = 5.98 \times 10^{24}$ kg, mass of Earth

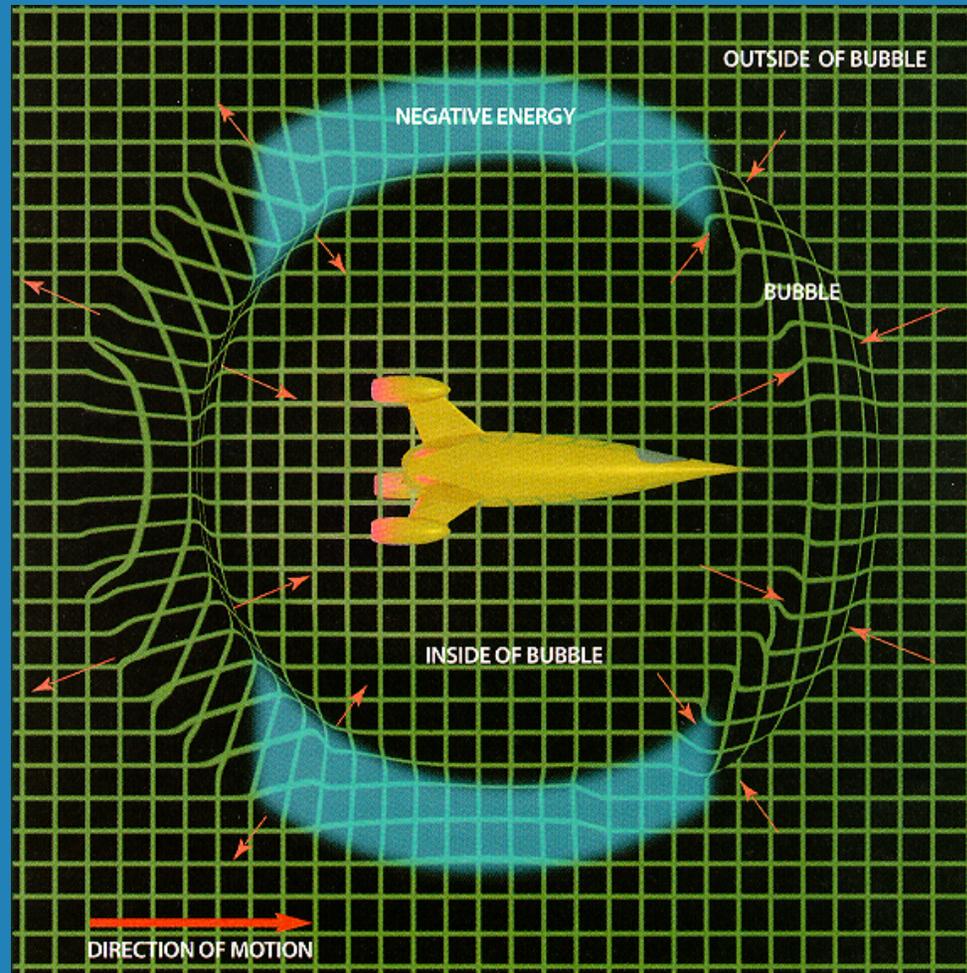
$$M_{wh} = -\frac{r_{throat} c^2}{G} = -(0.71 M_J) \frac{r_{throat}}{1 \text{ meter}}$$

Warp Drives

- Alcubierre plus several incarnations developed:
- ✦ Provides for simultaneous expansion of space behind a spacecraft & corresponding contraction of space in front of spacecraft
- ✦ World lines inside warp field region are spacelike as viewed by outside observers – gives FTL motion effect
- ✦ Spacecraft's moving frame never travels outside its local comoving light cone, thus does not violate Special Relativity
- This FTL spacetime violates the WEC & NEC



Negative Energy Engineering for Warp Drives



Net Total Negative Energy Required for Warp Bubble

$$E_{warp} = -\frac{v_{warp}^2 c^4 R^2 \sigma}{G}$$

(in Joules)

v_{warp} = dimensionless warp speed

R = radius of warp bubble

$\sigma \propto 1/\Delta$ (inverse warp bubble wall thickness)

Note: (positive) mass-energy of Sun is 1.79×10^{47} Joules

(Assume: $R = 50$ m, $\sigma = 10^3$ m⁻¹)

Warp Factor, v_{warp}	Required E_{warp} (Joules)
10^{-5} (= 3 km/sec)	-3.03×10^{40}
10^{-4} (= 30 km/sec)	-3.03×10^{42}
0.01 (= 3,000 km/sec)	-3.03×10^{46}
0.5 (= 150,000 km/sec)	-7.59×10^{49}
1 (= speed of light)	-3.03×10^{50}
2 (= 600,000 km/sec)	-1.21×10^{51}
10 (= 3.0×10^6 km/sec)	-3.03×10^{52}
100 (= 3.0×10^7 km/sec)	-3.03×10^{54}

c = speed of light (3×10^5 km/sec)

Quantum Inequalities Conjecture

- Model dependent time integrals of energy density along geodesics – for massless test particles
 - relates energy density of a free quantum field & time during which energy density is observed
- Energy Condition Violating “Stuff” all violate the QI
- Visser (1997): Observational data indicates that large amounts of “exotic” matter is required to exist in universe to account for observed cosmological evolution parameters & halo star age
- QI have not been verified by lab experiments or observational data
- Assumptions, efficacy of derivations for various cases have been called into question by numerous investigators
- Krasnikov (2005) constructed explicit counterexample for simple, generalized FTL spacetimes showing relevant QI do not hold
- Therefore, we will ignore the QI conjecture

Superior Quantifier for Energy Condition Violations & Negative Energy

- Spatial volume (definite) integrals:
 - Measures both WEC & NEC violations
 - Amount of WEC/NEC violation is defined as extent to which integrals become negative
 - Value of integrals provides info about total amount of WEC/NEC violating matter must be used to build any FTL spacetime
- Integrals can be adjusted to become vanishingly small by appropriate choice of parameters
- Examples can be constructed whereby violations can be made arbitrarily small – but not vanish entirely

$$\int \rho_E dV; \quad \int (\rho_E + p_i) dV$$

ρ_E = energy density

p_i = pressures

$dV = 4\pi r^2 dr$ or $(g_{\text{metric}})^{1/2} dr d\theta d\phi$

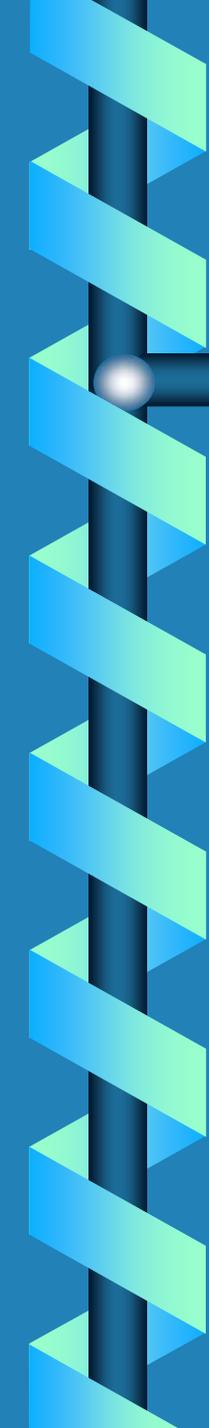
Case 1: Traversable Wormholes – A New Requirement on Negative Energy

- *ALL* Traversable Wormhole spacetimes now only require arbitrarily small quantities of negative mass-energy (Visser, Kar and Dadhich, 2003):

$$\rho_E = 0$$

$$\oint p_r dV \rightarrow 0 \quad (\text{radial pressure volume integral})$$

NOTE: Nonlinearity of Einstein field equations dictates that the total mass-energy of the wormhole system ≈ 0



Additional Constraints on Traversable Wormholes

- Detailed energy analysis & nonlinearity of Einstein field eqns. impacts coupling of finite spacecraft mass w/ each side of a wormhole's throat (or the mouth on each side of the throat)
- Specialized mass conservation law for combined system of spacecraft & wormhole:
 - finite mass spacecraft traversing a wormhole alters the (equivalent) mass of the wormhole mouths they pass through
- Entrance mouth absorbing spacecraft gains (equiv.) mass while exit mouth emitting it loses (equiv.) mass
- Suggests, but does not prove, the possibility of fundamental limit on total mass that can traverse a wormhole
- For sufficiently large net transfer of mass the final (equiv.) mass of exit mouth becomes negative
- Beneficial result because NEC violations are required to hold wormhole throat open

Case 2: Warp Drives

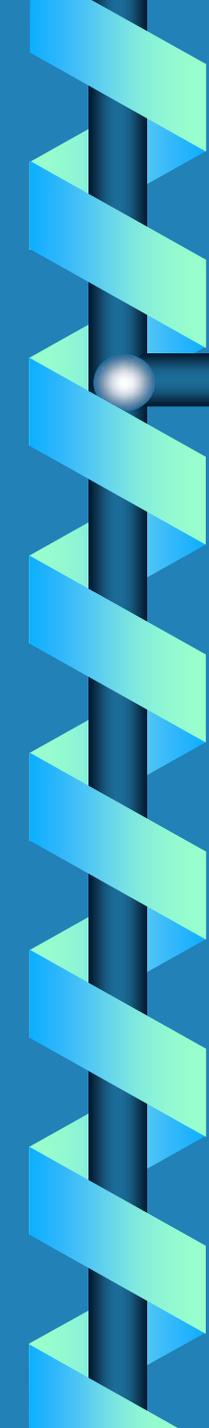
- Alcubierre & other warp drive incarnations are flawed: only consider spaceship as massless test particle moving on geodesic, not coupled to warp bubble
- Correct approach: finite mass spaceship coupled to warp bubble
 - net total energy stored in warp field < total mass-energy of spaceship
 - intrinsic nonlinearity of Einstein field equations
 - gives powerful constraint on warp speed
 - can only achieve absurdly low sub-light speeds for any reasonable engineering parameters

$$v_{warp} \leq \left[\left(7.41 \times 10^{-28} \right) \left(\frac{M_{ship} \Delta}{R^2} \right) \right]^{1/2}$$

M_{ship} = mass of spaceship

R = radius of warp bubble

Δ = warp bubble wall thickness



Observing Negative Energy: Optical Method

- Produces unique signature corresponding to lensing, chromaticity and intensity effects in micro- and macro-lensing events on galactic, extragalactic, cosmological scales
- Effects provide specific signature allowing for discrimination between ordinary and negative energy lenses via spectral analysis of astronomical lensing events
- Real background sources in lensing events can have non-uniform brightness distributions on their surfaces and a dependency of their emission with the observing frequency
 - these complications result in chromaticity effects, i.e. in spectral changes induced by differential lensing during the event
- Must be developed for lab-scale experiments

Observing Negative Energy: Non-Optical Method

- Response of switched particle detectors to static negative energy densities/fluxes:
 - based on free (massless) scalar field in flat 4-dimensional Minkowski spacetime
 - standard monopole detector switched on/off to concentrate measurements on periods of isolated negative energy density/flux
 - includes switching factor, 5 switching functions evaluated
- Result: Negative energy has effect of enhancing deexcitation (induce cooling) of a detector
- Cannot draw firm conclusion because modeling is only 1st order in perturbation theory:
 - not possible to predict if enhanced cooling is due to small violation of energy conservation expected in any process in which a general quantum state collapses to an energy eigenstate
 - or if it is a systematic reduction in the energy of detector

Conclusion

- Two forms of FTL spacetimes identified by Einstein's GR: traversable wormholes & warp drives
 - require introduction of negative energy densities/fluxes to implement
- Detailed energy analysis shows that all warp drives are not technologically practical to implement
 - high total negative energy → absurdly low sub-light speeds
- Detailed energy analysis shows that traversable wormholes appear to be the most practical to implement
 - arbitrarily small amounts of negative energy required
- We already make small amounts of negative energy in the lab
 - don't know if we can access larger amounts for extended periods of time over extended spatial distributions
- Proposals for optical observation of negative energy in outer space
 - further work is needed to downscale astronomical techniques for use at the lab scale
- Need to firm up our understanding of how non-optical lab detectors will respond to negative energy in situ