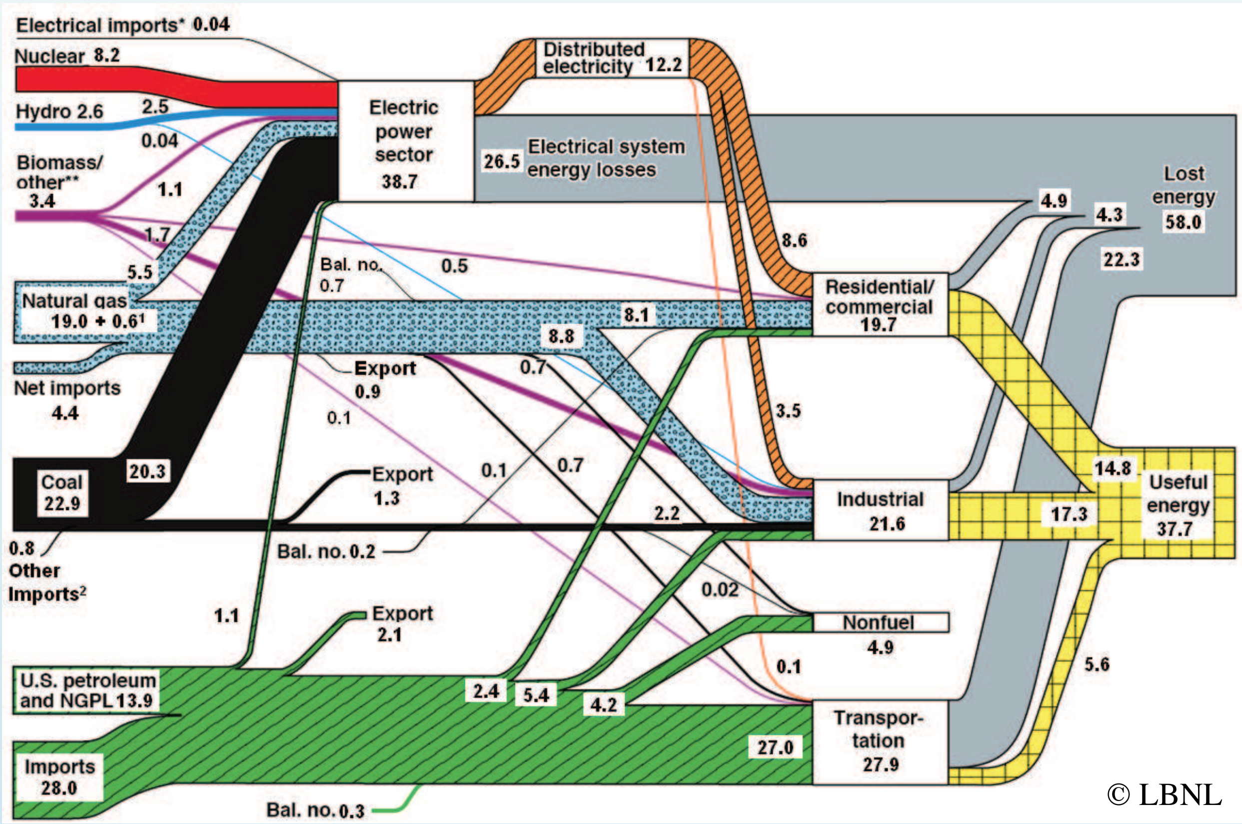
Teaching
"The Physics of Energy"
at MIT

Robert Jaffe

Washington Taylor



Supported in part by

- The MIT Energy Initiative
- The MIT Physics Department

Experience of developing and teaching a one semester course on "Physics of Energy"

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- Solid, relatively intense physics course

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- Universally accessible "capstone" course in modern, relevant science

  Based on universal science core prerequisites. Convey a unified picture of modern physics in the context of a single important application framework.

- Physics (of energy and the environment) for poets
  - Berkeley: Physics for Future Presidents (Richard Muller)
  - U. Virginia: Energy on this World and Elsewhere (Gordon Cates)
  - Princeton: Future Physics (Paul Steinhart)
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- Specialized topical courses (MIT examples)
  - Advanced Thermal Fluids Engineering
  - Fundamentals of Photovoltaics
  - Internal Combustion Engines
  - Fundamentals of Advanced Energy Conversion
  - Power Electronics
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- Science, policy and economics of energy (MIT examples)
  - Sustainable Energy (Elizabeth Drake, Michael Golay, Jeff Tester, and others)
  - Applications of Technology in Energy and the Environment (John Deutch, Richard Lester)

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- Unified view of energy landscape through the lens of physics
  - Intermediate level --- available to all with core science background
  - Essential tools for quantitative analysis

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Motivation, Goals I

- Energy, including sources, uses, storage, conversion, and transport, will perhaps be the most significant place where physics impacts society in the coming century.
- We recognize that energy issues involve more than science: technology, policy, economics, and ethics, among others. However, clear understanding of underlying science is essential.
- MIT graduates (and equivalents at other colleges and universities) will become policy makers, corporate leaders as well as scientists and engineers.
  - Scientists and engineers need and seek foundational background before sub-specialization.
  - Economists, policy makers, and corporate leaders need independent familiarity with fundamental principles such as the 1st and 2nd laws of thermodynamics and basic physics underlying nuclear power, solar energy, etc., to survive in a complex (dis-) information environment.

Motivation, Goals II

- Provide students both with a clear understanding of the physics concepts underlying energy options, and

  Convey a unified picture of modern physics in the concept of a single important application framework.

- At MIT we have a rather unique opportunity to carry out this experiment because all MIT students must take year of calculus and physics as freshmen, plus a term of chemistry.

  Similar to science core for physical scientists and engineers at many schools. But unusual for social and biological scientists.

Comments

- "How can I contribute?"
- <u>Not a survey course</u>
- Challenging in both depth and breadth

Strategy/history/status

- Developed 2006 --- 2008. Debuted Fall 2008 with about 35 students.
- Excellent reviews from students. Lessons to us!
- Now incorporated as foundational course in MIT's new Energy Minor.
- See http://physicsofenergy.mit.edu/ for more information. Notes, *etc.*, to appear this year.

The Big Picture

- Uses (~ 9 lectures)
- Sources (~ 20 lectures)
- Systems and synthesis (~8 lectures)

Review science core

Novel: stat. mech, quantum, fluid dynamics

Complex systems

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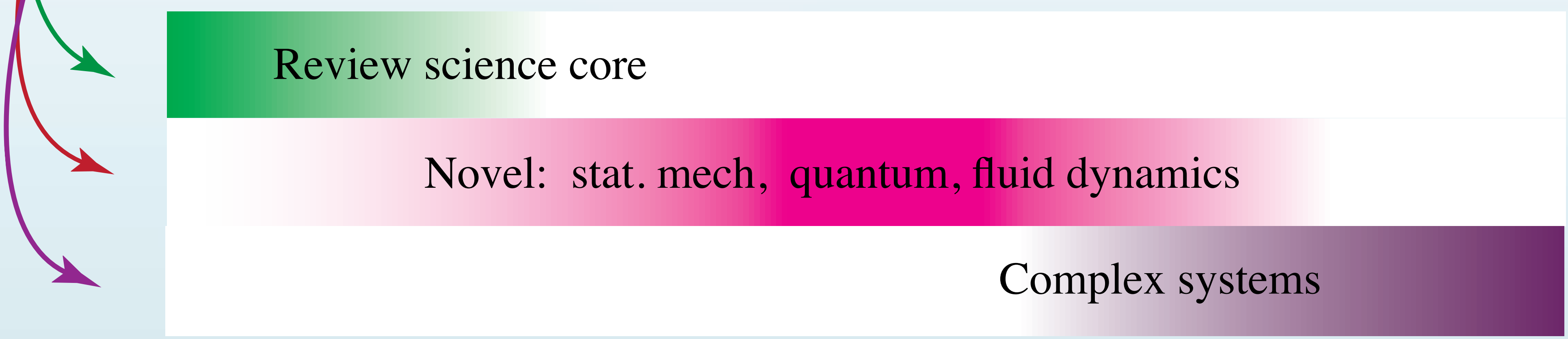

37 lectures

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END USES

CORE REVIEW

1. Introduction
2. Units and scales of energy use
3. Mechanical energy and transport
4. Heat Energy
5. Electromagnetic energy
6. Quantum mechanics I
7. Chemical and biological energy
8. Entropy and temperature
9. Heat engines
10. Internal combustion engines
11 - 12. Thermodynamics of energy conversion
13. Quantum Mechanics II

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NOVEL INTERMEDIATE PHYSICS

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SOURCES

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14. A tour of the microworld

15-19. The physics of nuclear energy

20. Energy flow through the universe

21-25. The physics of solar energy

26. Biological sources and fossil fuels

27-29. The physics of wind energy

30. Hydro and geothermal energy

31. Tidal, wave, and ocean power

32. Nuclear radiation, fuel cycles, waste and proliferation

33-35. The physics of climate change

36. Energy storage

37. Conservation

38. Summary and conclusions

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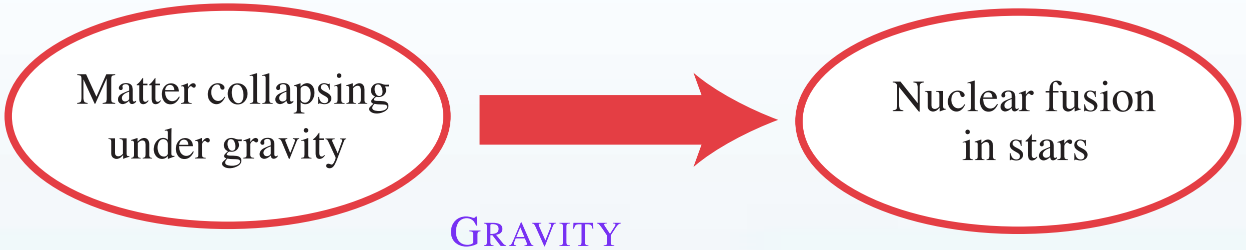
Nuclear fusion in stars



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STRONG INTERACTIONS
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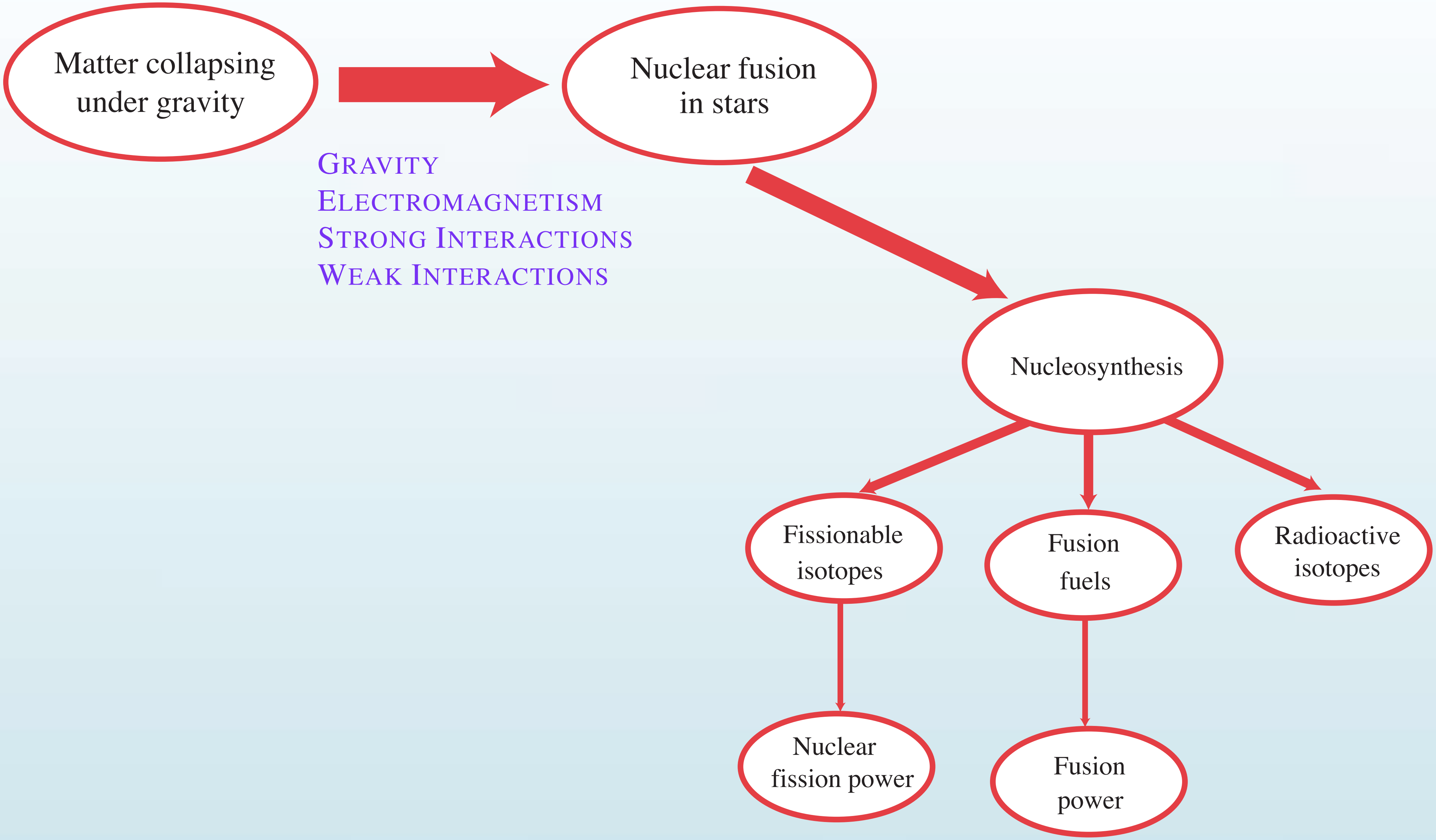
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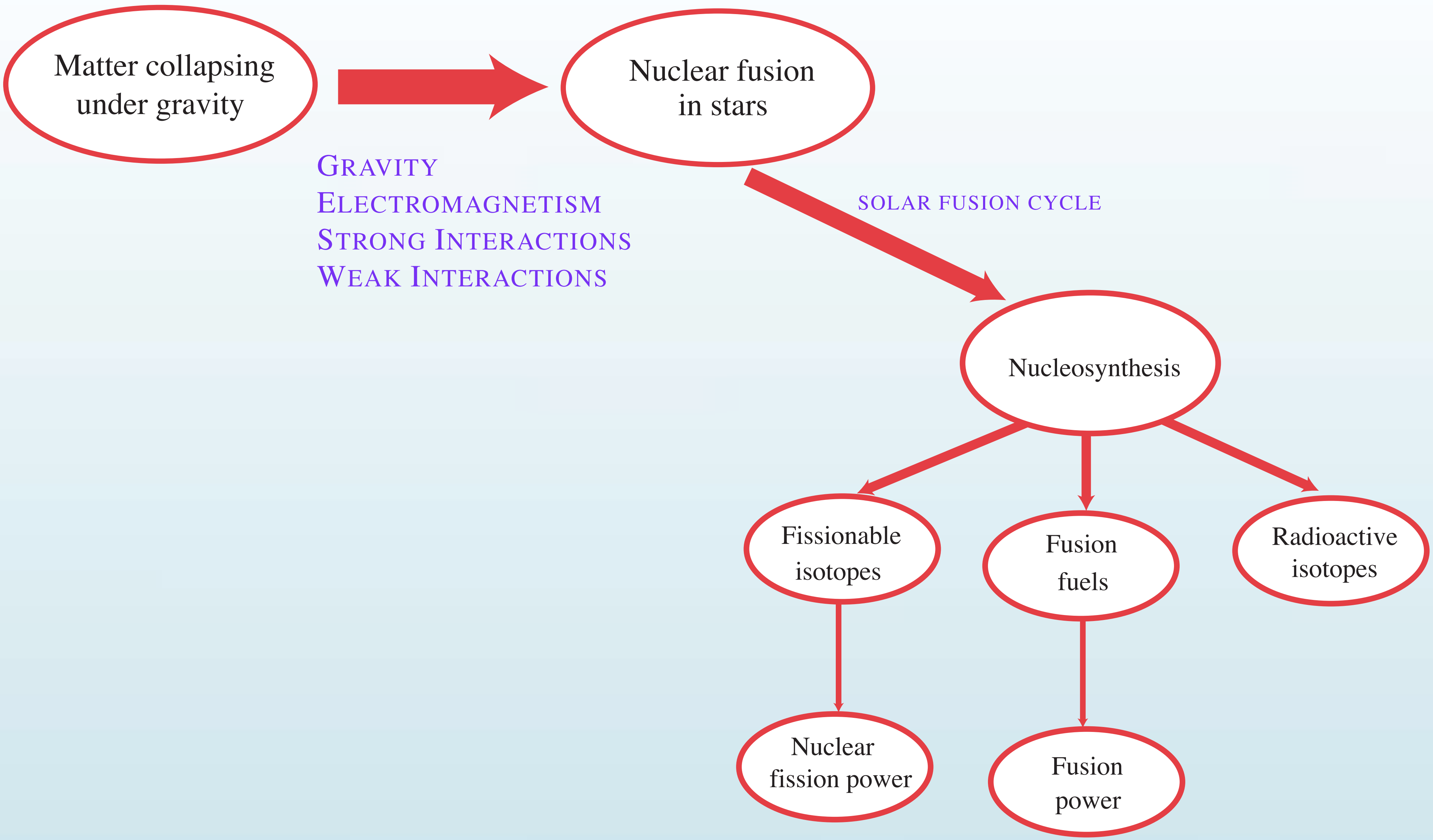

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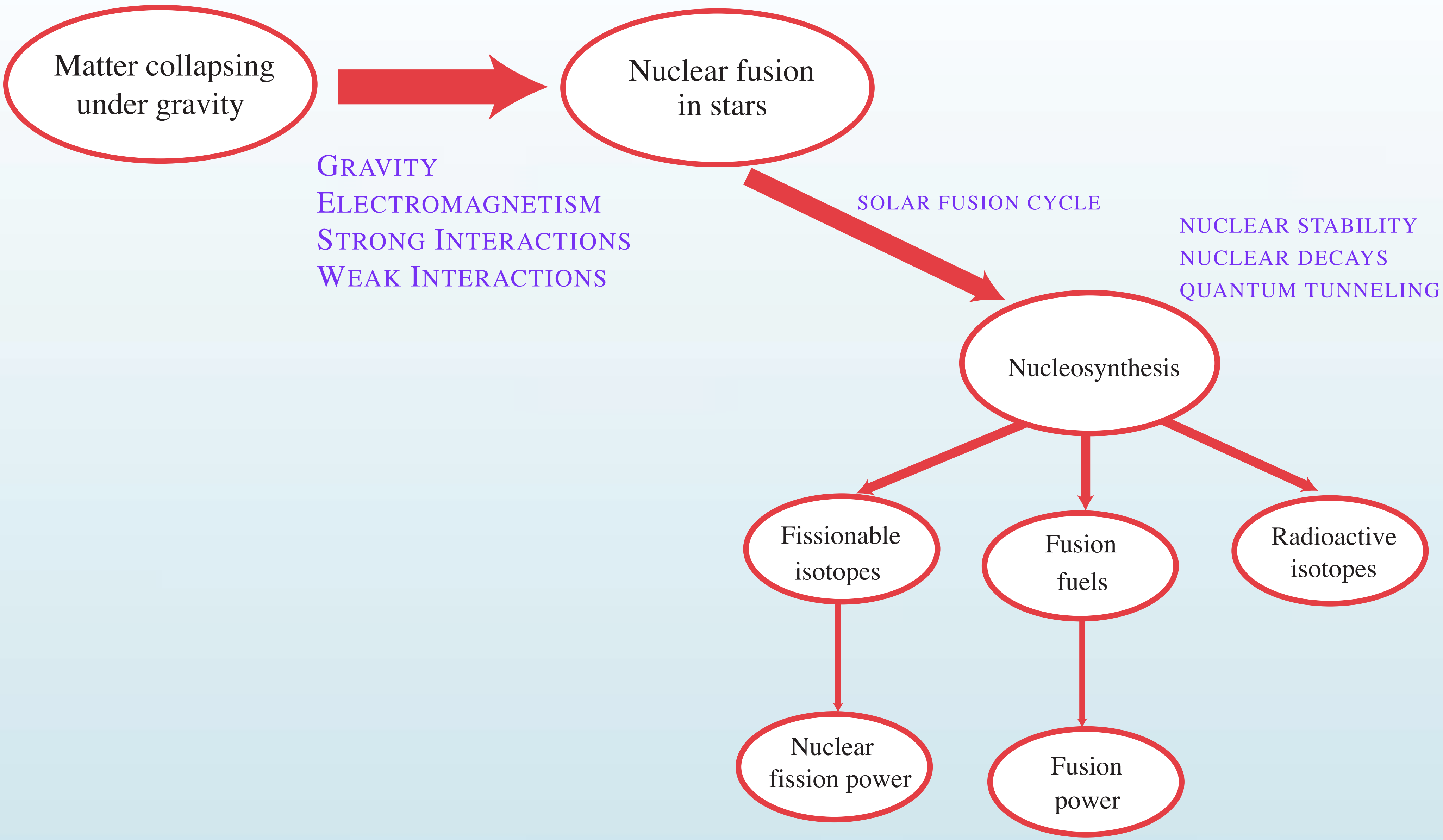
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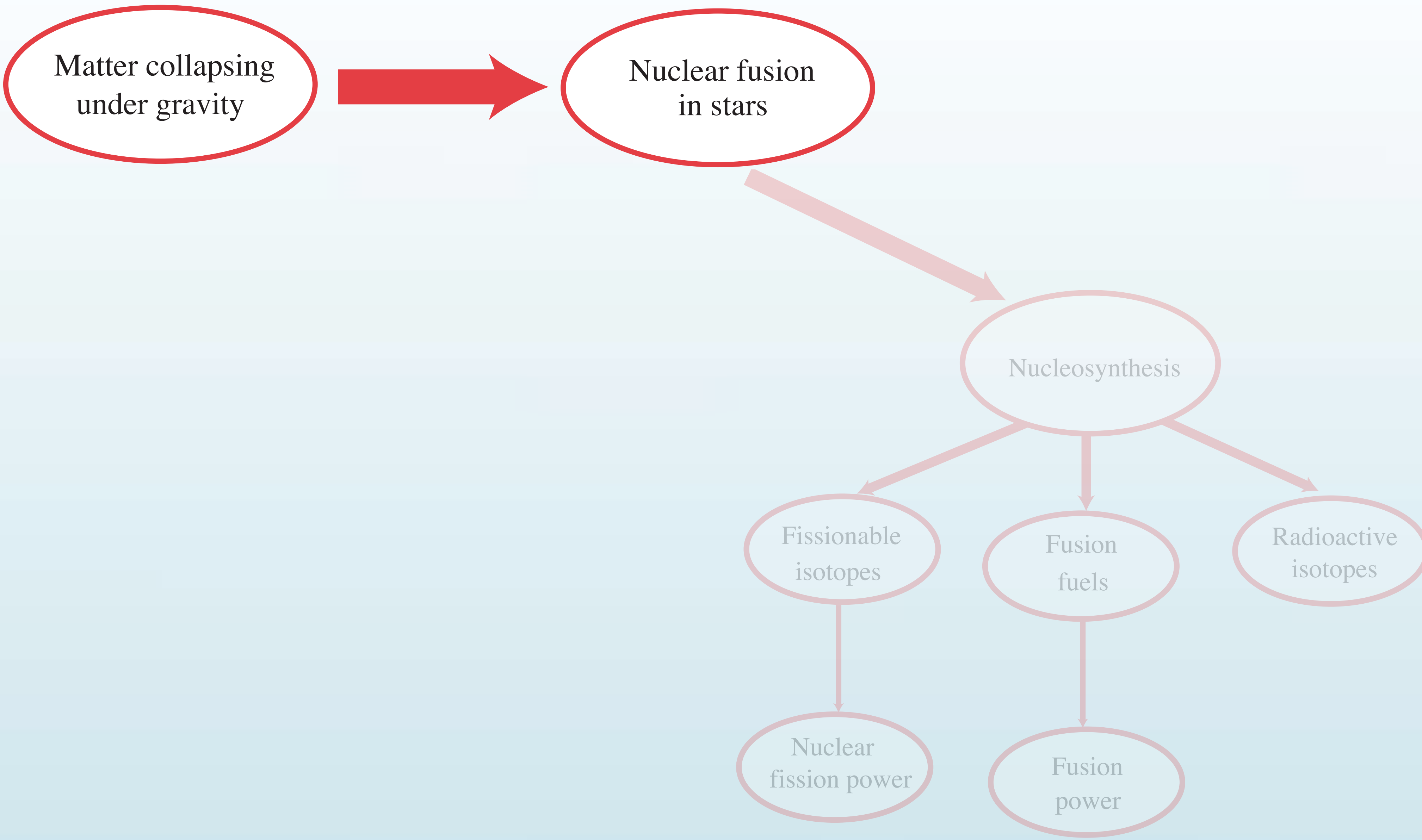
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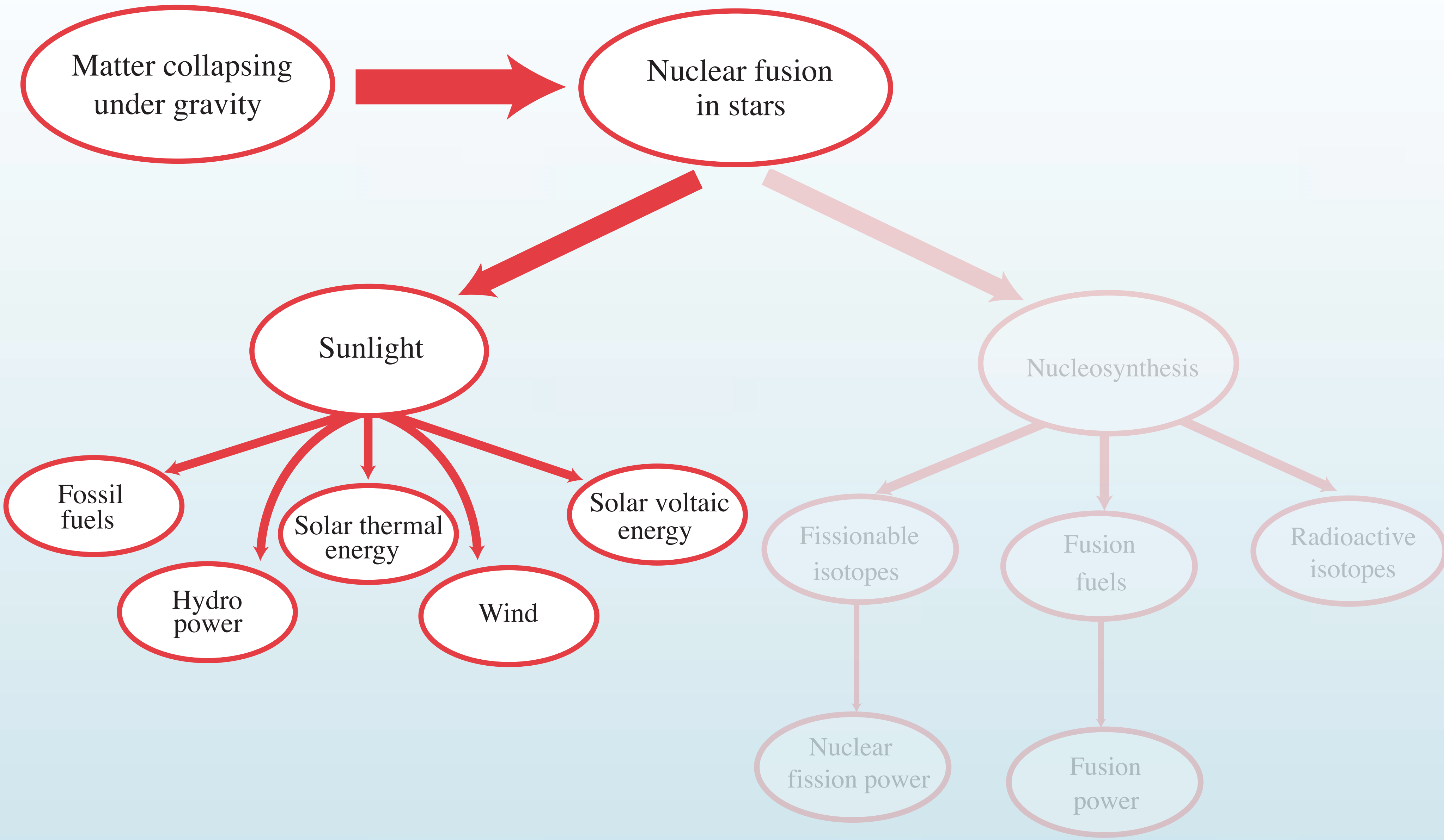

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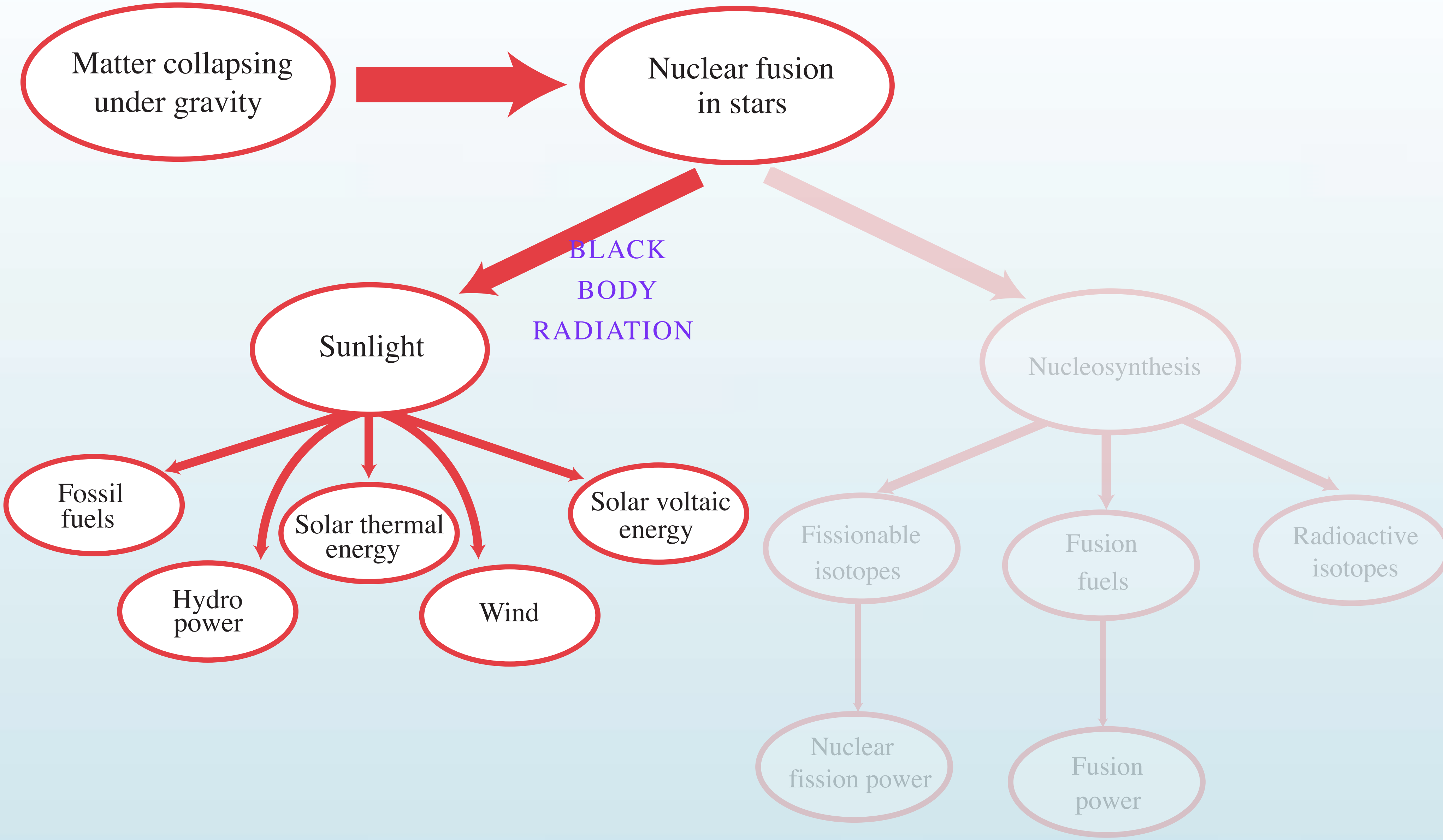

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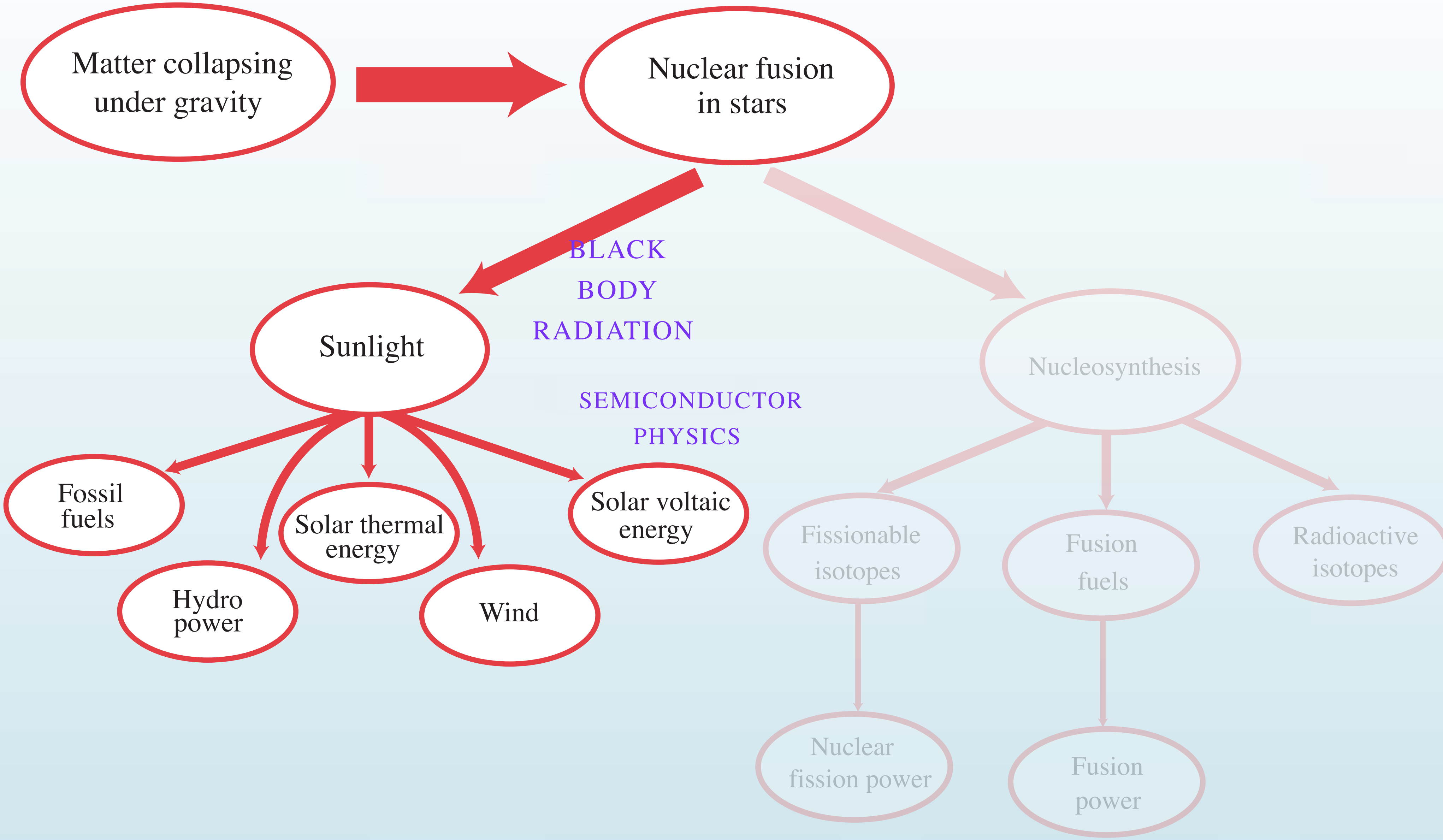
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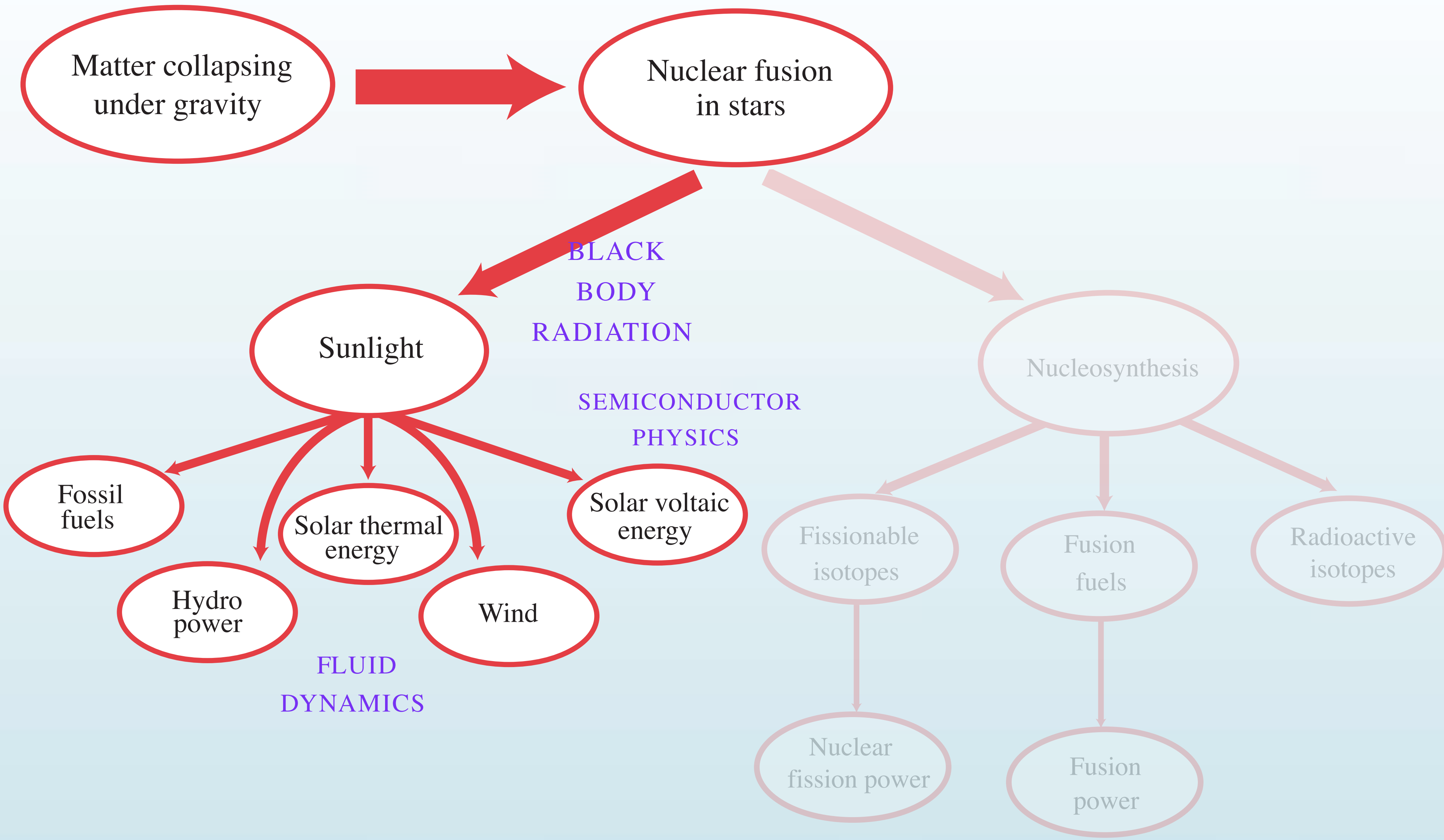
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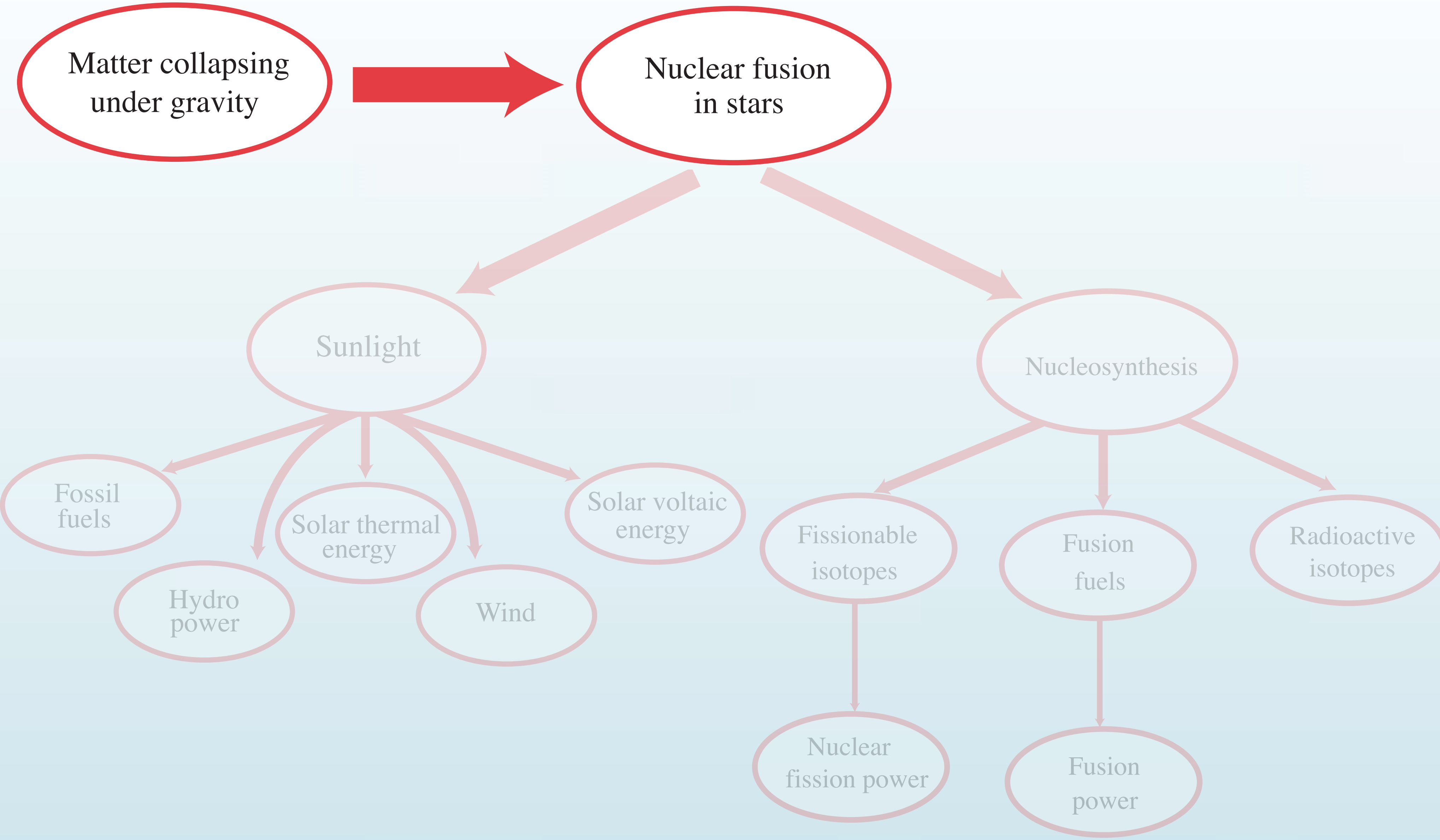

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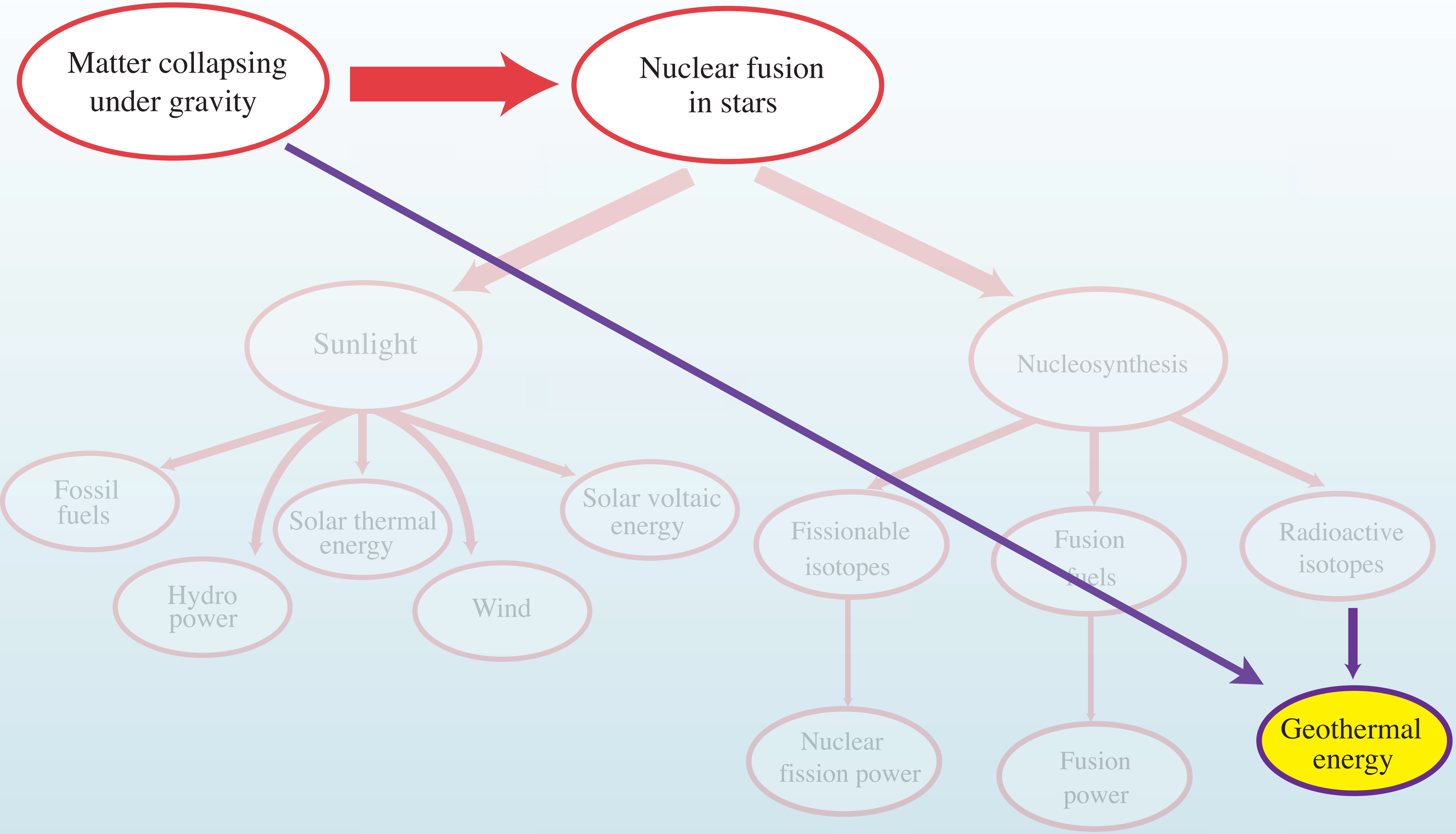
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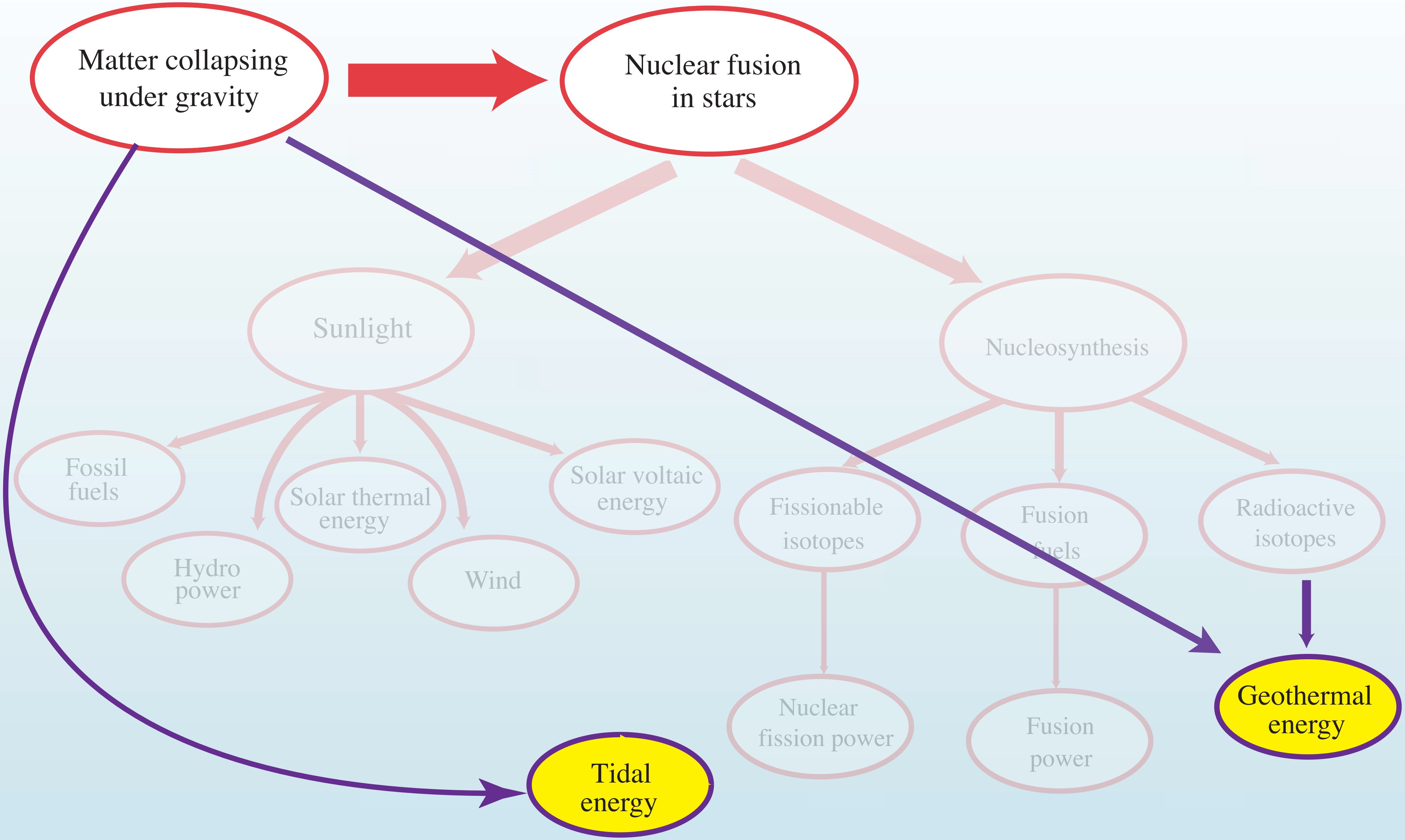
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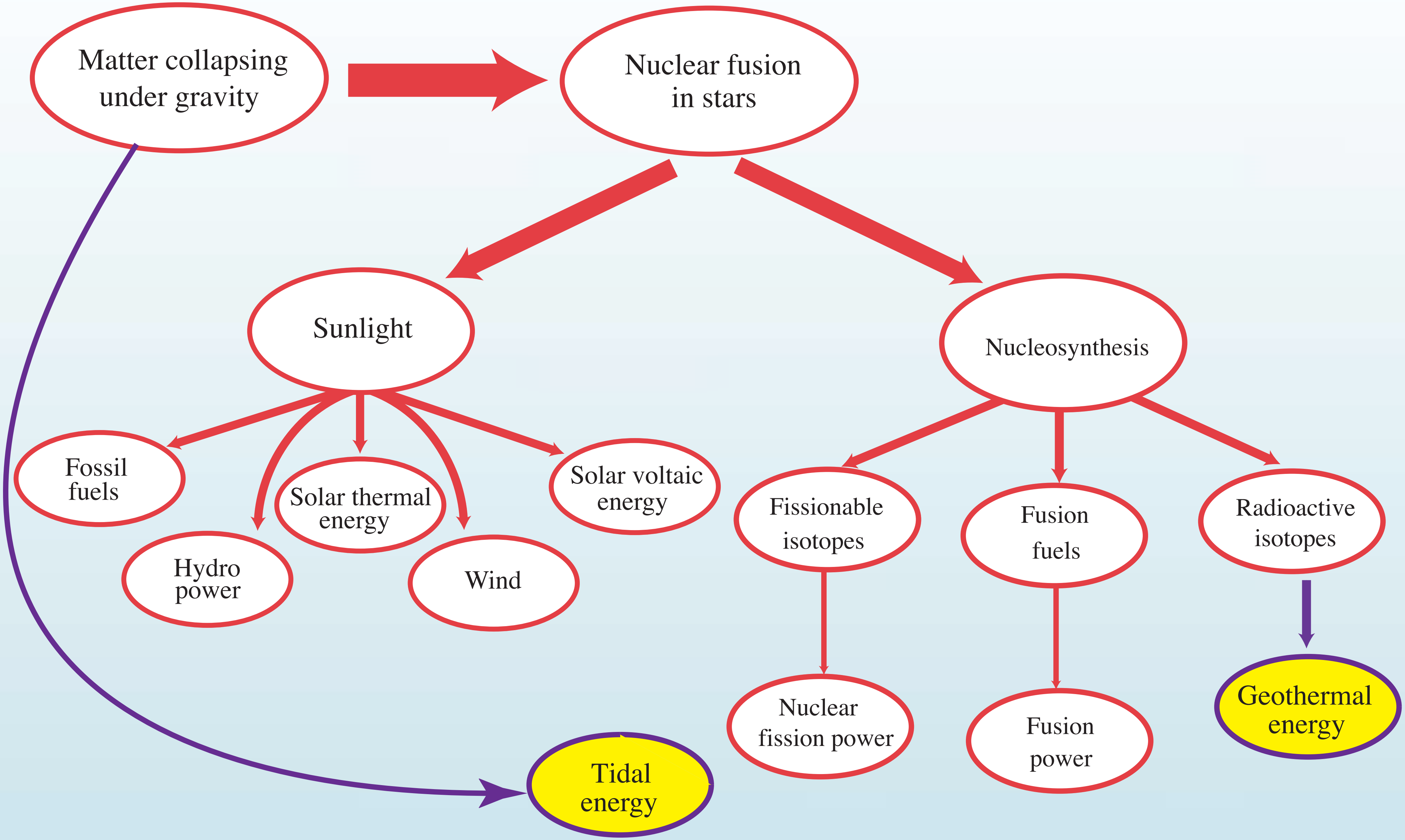


R. L. Jaffe, APS April meeting Denver, 2009

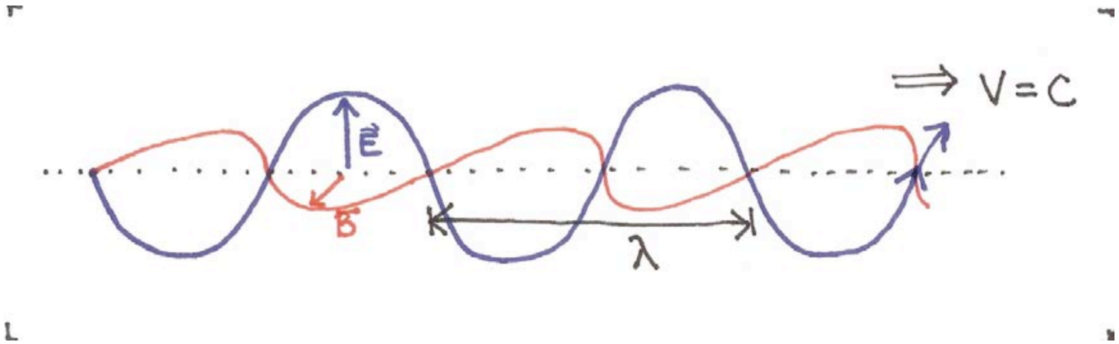
CTP center for theoretical physics

Overview of thread: Nuclear Energy

- Lecture 15: Nuclear forces, energy scales, and structure
  - Fundamental forces in the universe ("Tour of the microworld" #14)
  - Quantum states, binding energies ("Quantum I" #6)
  - Semi-empirical mass formula and applications
- Lecture 16: Nuclear binding energy systematics, reactions, and decay
  - Systematics of nuclear stability
  - Nuclear decays by weak and strong interactions, tunneling ("Quantum II" #13, "Geothermal Energy" #30)
- Lecture 17: Basic mechanisms of nuclear fusion and fission
  - Theory of fusion (Gamow theory) ("Solar energy" #21-25)
  - Fusion energy
  - Theory of fission: Prompt, spontaneous, induced ("Quantum II" #13)
- Lecture 18: Nuclear fission reactor physics, design and fuel cycles
  - Neutron cycle in a fission reaction,
  - Principles of a fission reactor ("Nuclear Hazards" #32)
- Lecture 19: Nuclear reactor power, safety, and operation
  - Neutron flux, fuel, and power in a model reactor
  - Factors affecting safety and operation ("Nuclear Hazards" #32)
- Lecture 32: Radioactivity and nuclear hazards
  - Types of radioactivity, dosage, units ("Tour of the microworld" #14)
  - Environmental sources of radioactivity ("Geothermal Energy" #30)
  - Nuclear fuel, fuel cycles, nuclear waste recycling and sequestration

Spectrum of solar radiation

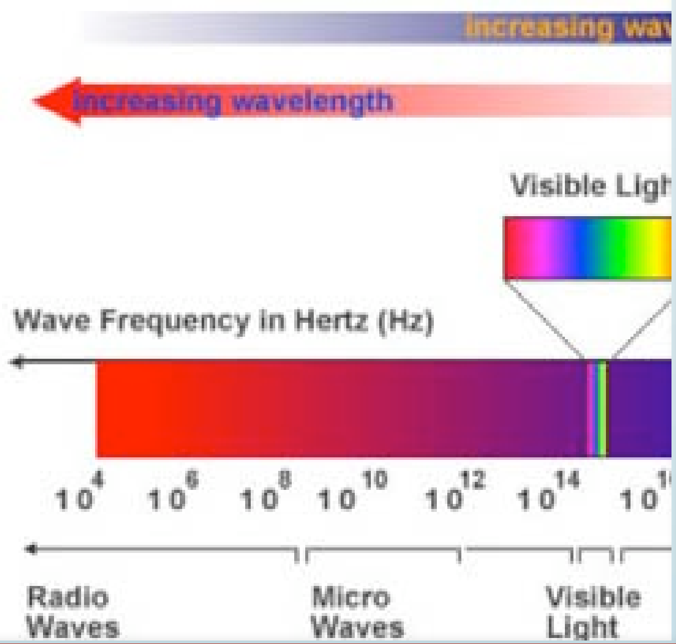
Recall: light comes in different wavelengths λ / frequencie



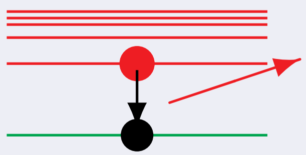
$\nu = c/\lambda = $ # oscillatio

Light comes in quanta

$E = h\nu = \hbar\omega \quad (h = 2\pi\hbar)$



Example: 3p → 2s in hydrogen



$$E_3 - E_2 \cong (\epsilon_0/4 - \epsilon_0/9)$$
$$\cong 1.89 \text{ eV}$$

$E_n = -\epsilon_0/n^2$

$\epsilon_0 = 13.6eV$

$$\nu \cong 4.57 \times 10^{14} \text{ Hz}$$

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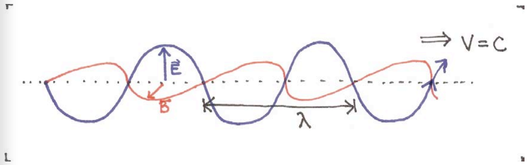

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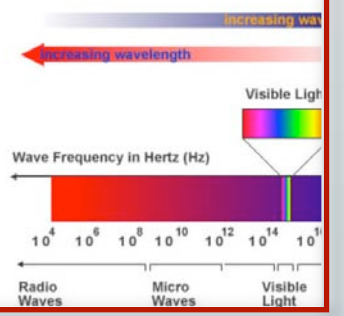

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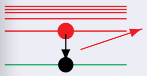

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The Weibull distribution:

- Simple, normalized probability distribution

  Depends on two parameters,

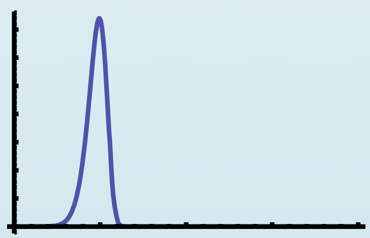
  ⋆ Scale parameter, λ

  ⋆ Shape parameter, k

$$f(v,k,\lambda) = \frac{k}{\lambda}\left(\frac{v}{\lambda}\right)^{k-1}$$
$$= \frac{d}{dv}\left(-e^{-(x}\right.$$

Why?

1. λ sets the scale $f(v,k,\lambda) = f(v/\lambda, k)$
2. k sets the shape
   - $k \to \infty$



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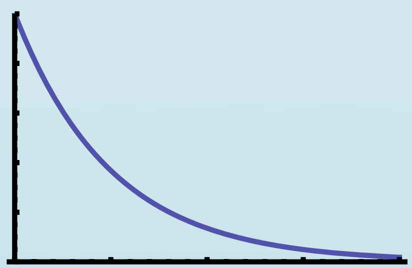

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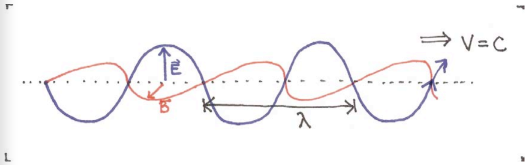

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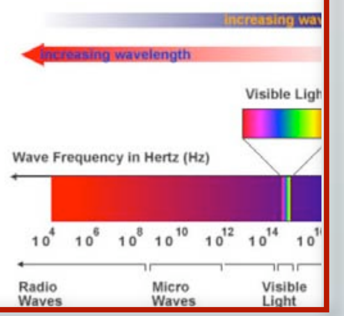

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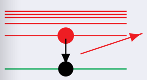

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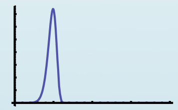

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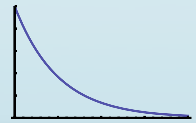


Spectrum of solar radiation

The Weibull distribution:

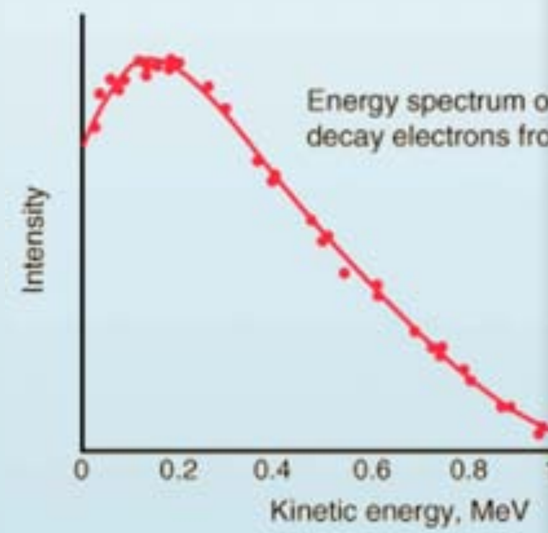
Why the Weak Interactions matter!

- They allow quarks to change flavor:

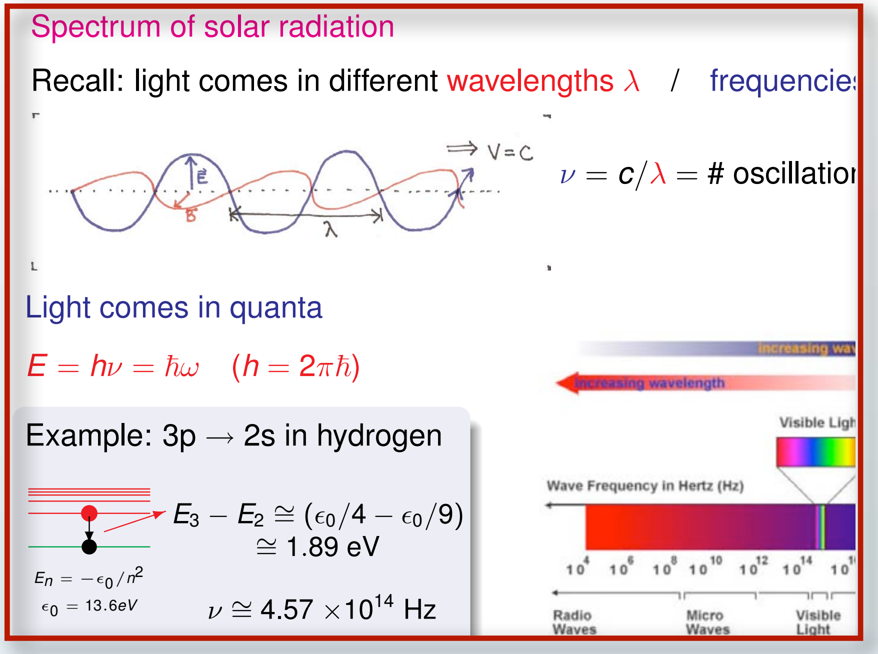
$$
\begin{aligned}
d &\rightarrow u + e + \bar{\nu}_e \\
&\Downarrow \\
(udd) &\rightarrow (uud) + e + \bar{\nu}_e \\
&\Downarrow \\
n &\rightarrow p + e + \bar{\nu}_e \\
&\Downarrow \\
{}^{40}\mathrm{K} &\rightarrow {}^{40}\mathrm{Ca} + e + \bar{\nu}_e
\end{aligned}
$$

- Conserves baryon number: 1/3
- Conserves electric charge: −1/
- Conserves electron number 0 —
- But does not conserve quark fla

β-decay



$${}^{210}\mathrm{Bi} \rightarrow {}^{210}\mathrm{Po} + e$$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V=C
λ
ν = c/λ = # oscillation
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increasing wavelength
Visible Ligh
Wave Frequency in Hertz (Hz)
Radio Waves
Micro Waves
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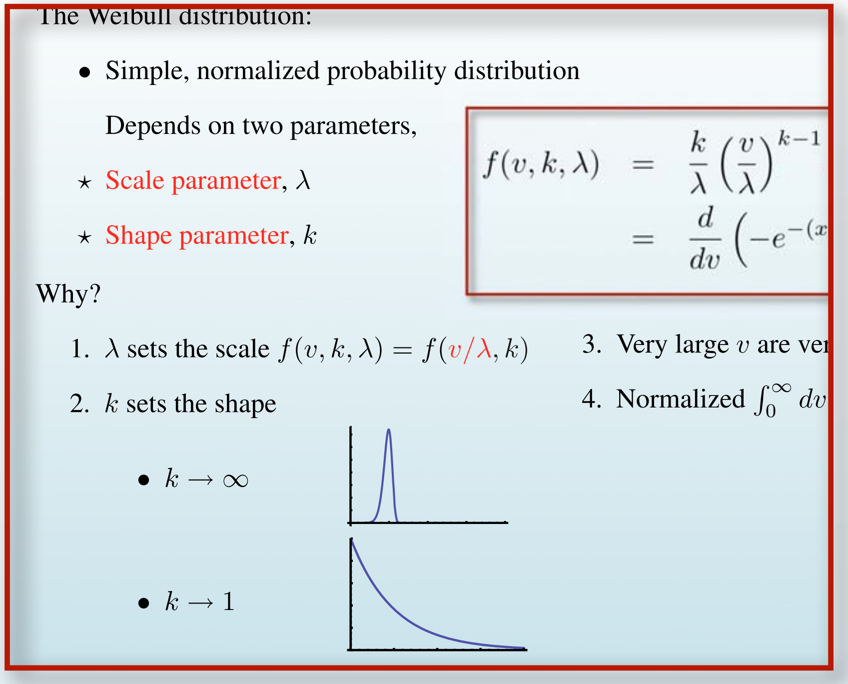
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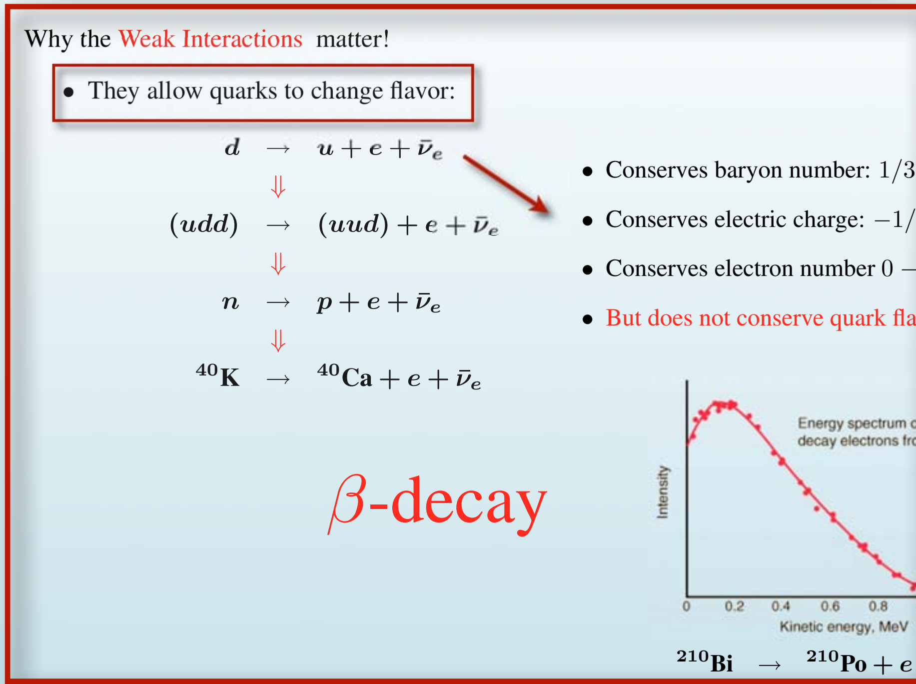
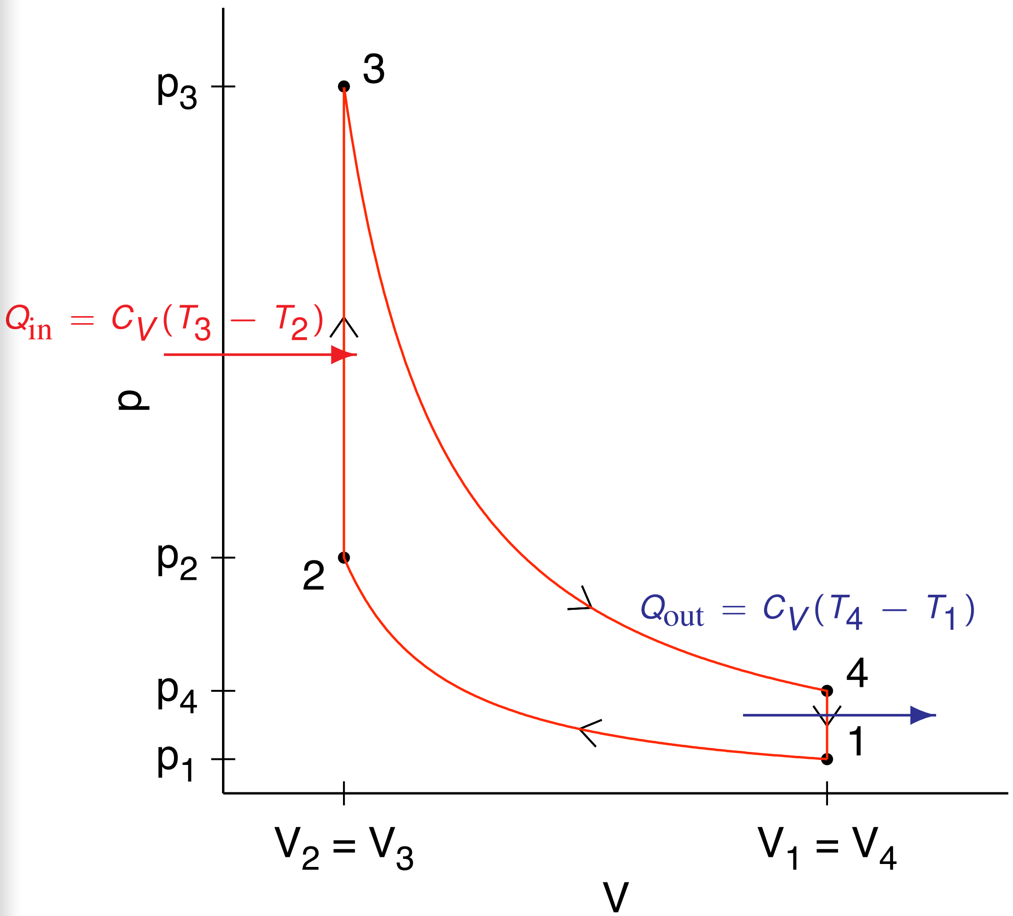
k → ∞
k → 1


Why the Weak Interactions matter!
They allow quarks to change flavor:
d → u + e + ν̄e
(udd) → (uud) + e + ν̄e
n → p + e + ν̄e
⁴⁰K → ⁴⁰Ca + e + ν̄e
Conserves baryon number: 1/3
Conserves electric charge: −1/
Conserves electron number 0 −
But does not conserve quark fla
β-decay
Energy spectrum o
decay electrons fr
Intensity
Kinetic energy, MeV
²¹⁰Bi → ²¹⁰Po + e

“Air standard” Otto cycle analysis



- Approximate by air a
- $Q_{\rm in}$ from combustion

$$\eta = \frac{Q_{\rm in} - Q_{\rm out}}{Q_{\rm in}} = 1 - \frac{T_4}{T_3}$$

$$p_1 V_1^\gamma = p_2 V_2^\gamma \Rightarrow T_1 V_1^{\gamma-1}$$

$$\Rightarrow T_2 = T_1 r^{\gamma-1} \quad (r =$$

and similarly $T_3 = T_4 r^{\gamma}$

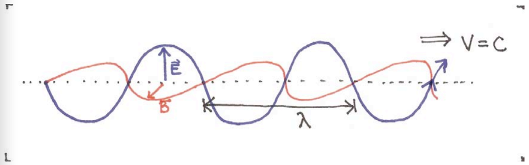
So

$$\eta = 1 - \frac{1}{r^{\gamma-1}} =$$

Critical feature: Compr

Spectrum of solar radiation

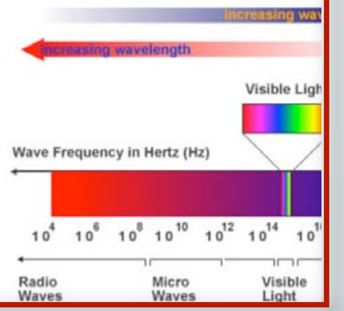
Recall: light comes in different wavelengths λ / frequencie



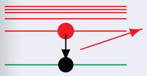
$\nu = c/\lambda =$ # oscillatio

Light comes in quanta

$E = h\nu = \hbar\omega \quad (h = 2\pi\hbar)$



Example: 3p → 2s in hydrogen



$E_3 - E_2 \cong (\epsilon_0/4 - \epsilon_0/9)$
$\cong 1.89$ eV

$E_n = -\epsilon_0/n^2$
$\epsilon_0 = 13.6eV$

$\nu \cong 4.57 \times 10^{14}$ Hz

The Weibull distribution:

- Simple, normalized probability distribution

Depends on two parameters,

⋆ Scale parameter, λ

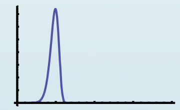
⋆ Shape parameter, k

$$f(v,k,\lambda) = \frac{k}{\lambda}\left(\frac{v}{\lambda}\right)^{k-1}$$
$$= \frac{d}{dv}\left(-e^{-(x}\right.$$

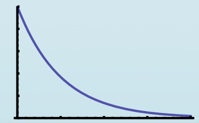
Why?

1. λ sets the scale $f(v,k,\lambda) = f(v/\lambda, k)$
2. k sets the shape
3. Very large v are ve
4. Normalized $\int_0^\infty dv$

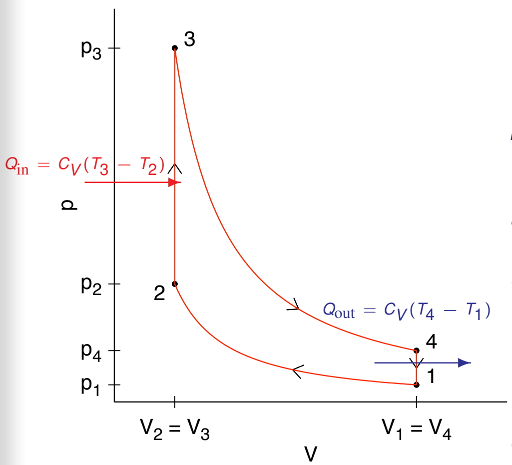
- $k \to \infty$



- $k \to 1$



"Air standard" Otto cycle analysis



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Critical feature: Compr

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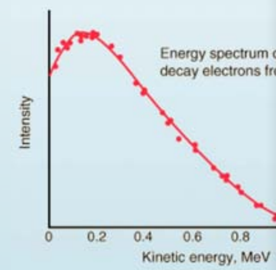
- They allow quarks to change flavor:

$d \to u + e + \bar{\nu}_e$
$\Downarrow$
$(udd) \to (uud) + e + \bar{\nu}_e$
$\Downarrow$
$n \to p + e + \bar{\nu}_e$
$\Downarrow$
$^{40}\mathbf{K} \to {}^{40}\mathbf{Ca} + e + \bar{\nu}_e$

- Conserves baryon number: 1/3
- Conserves electric charge: −1/
- Conserves electron number 0 −
- But does not conserve quark fla

β-decay



$^{210}\mathbf{Bi} \to {}^{210}\mathbf{Po} + e$

R. L. Jaffe, APS April meeting Denver, 2009

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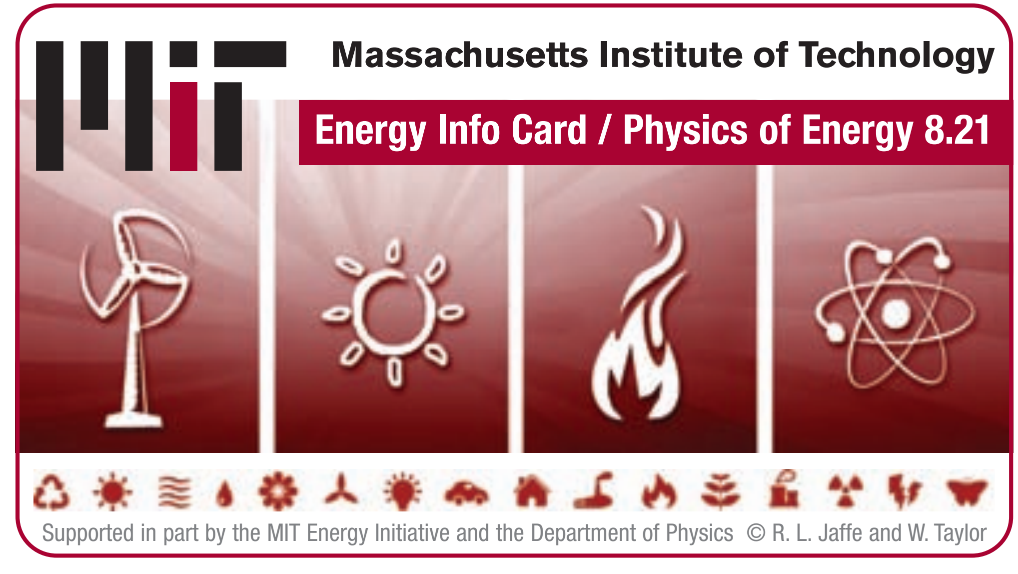
An “Energy Card”



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  - Fundamental constants
  - Energy data
  - Qualitative feel for energy magnitudes
- Following in a great (retro) tradition
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  - Aim to update and republish yearly

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Card / Physics of Energy 8.21

the Department of Physics © R. L. Jaffe and W. Taylor

Units of Energy and Power

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1 eV per molecule	≅	96.49 kJ mol^{-1}
1 erg	≡	10^{-7} J
1 foot pound	≅	1.356 J
1 $calorie_{IT^*}$ (cal_{IT})	≡	4.1868 J
1 $calorie_{th^*}$ (cal_{th})	≡	4.184 J
1 BTU_{IT^*}	≅	1.055 kJ
1 $kilocalorie_{IT^*}$ (kcal) or $Calorie_{IT^*}$ (Cal)	≡	4.1868 kJ
1 kilowatt-hour (kWh)	≡	3.6 MJ
1 cubic meter natural gas	~	36 MJ
1 therm (U.S.)	≅	105.5 MJ
1 tonne TNT (tTNT)	≡	4.184 GJ
1 barrel of oil equivalent	≡	5.8×10^{6} BTU ≅ 6.118 GJ
1 ton of coal equivalent	≡	7 $Gcal_{IT}$ ≡ 29.3076 GJ
1 ton of oil equivalent	≡	10 $Gcal_{IT}$ ≡ 41.868 GJ
1 quad	≡	10^{15} BTU ≅ 1.055 EJ
1 terawatt-year (TWy)	≡	31.56 EJ
1 watt (W)	≡	1 joule/sec
1 foot pound per second	≅	1.356 W
1 horsepower (electric)	≡	746 W
1 ton of air conditioning	≅	3.517 kW

≡ ↔ definition *th ≡ thermochemical
≅ ↔ four significant figures *IT ≡ International Table
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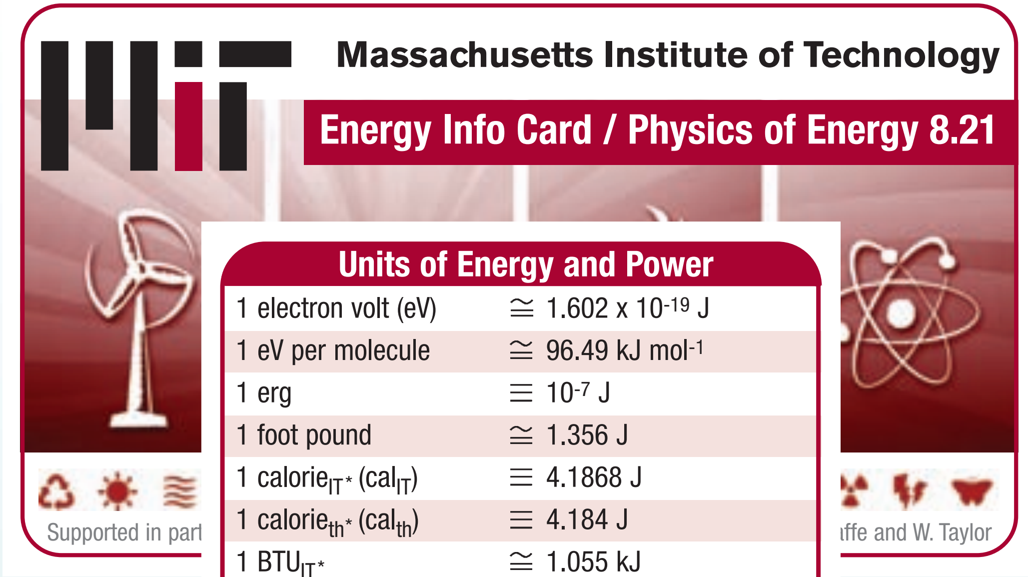

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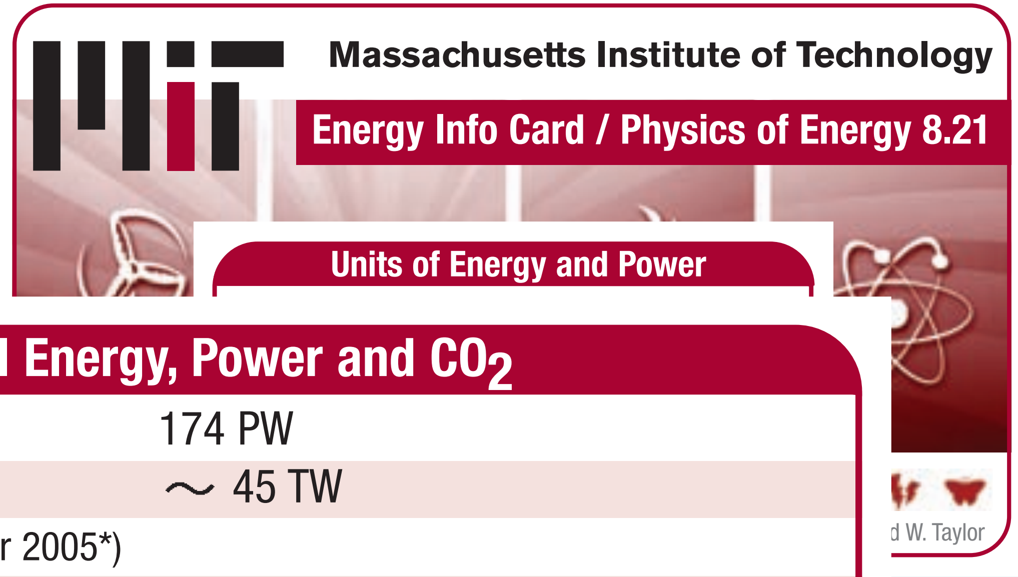

Global and National Energy, Power and CO_2	
Solar power incident on earth	174 PW
Total earth geothermal power output	∼ 45 TW
World / U. S. / Europe / China / Africa (year 2005*)	
Total energy consumption	**488** / 106 / 91 / 71 / 15 EJ
Electricity consumption	**57** / 14 / 12 / 8 / 2 EJ
Petroleum consumption	**187** / 56 / 36 / 15 / 7 EJ
Nuclear electric power	**9.5** / 2.8 / 3.4 / 0.2 / 0.0 EJ
Wind, solar, geothermal, wood, & waste electric power	**1.33** / 0.36 / 0.58 / 0.01 / 0.01 EJ
Energy related CO_2	**28.2** / 5.96 / 4.67 / 5.32 / 1.04 x 10^9 t
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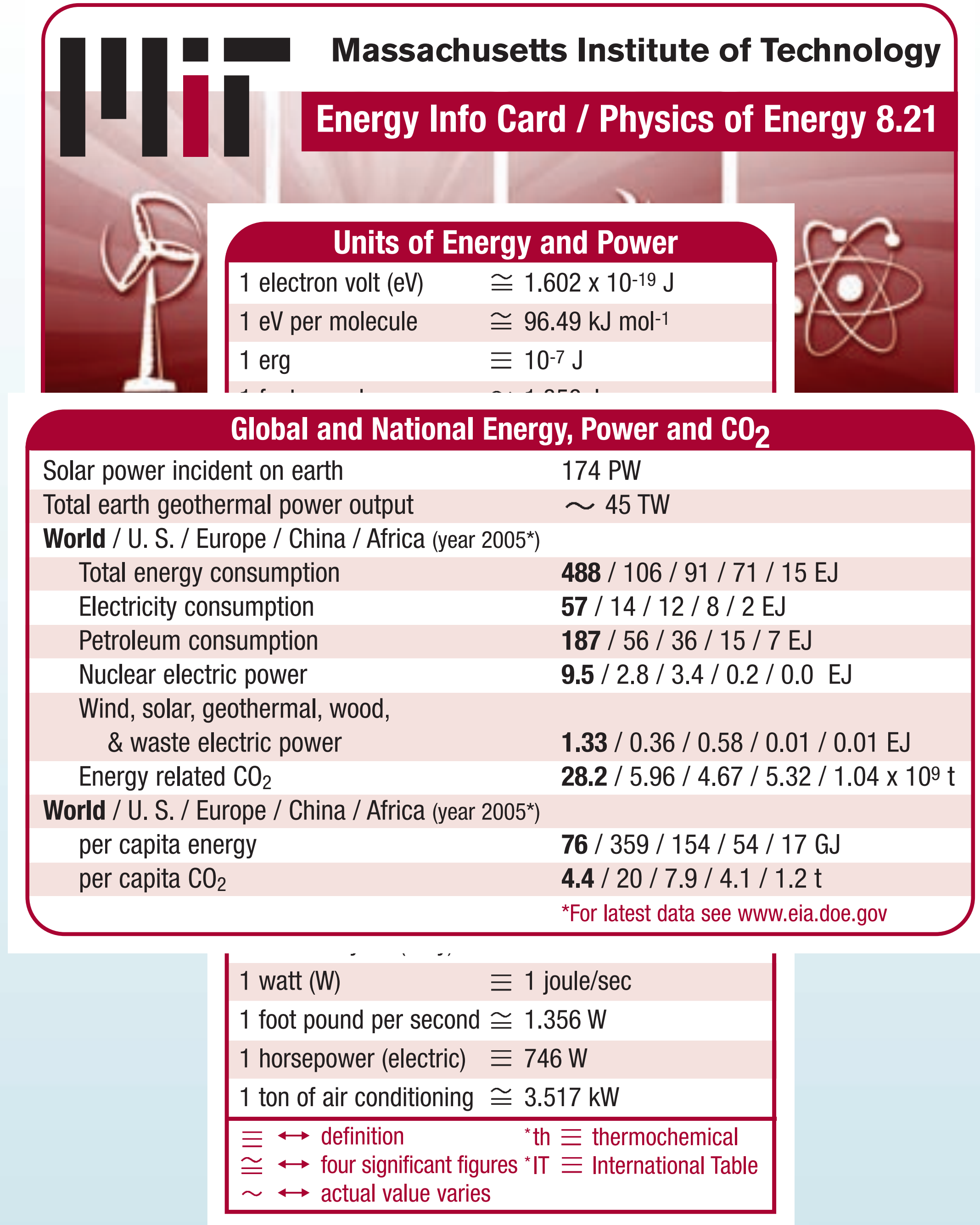

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Units of Energy and Power

Energy Orders of Magnitude

Energy Uses		Energy Examples	
1 J	Picking up a newspaper from the ground	1 J	Produced by a human being at rest in 1/100 s
1×10^{3} J	Talking on a cell phone for 10 minutes	1×10^{3} J	Produced by a match
3×10^{6} J	Eight hours hard manual labor	1×10^{6} J	In a Snickers bar
1×10^{9} J	Avg American daily consumption	1×10^{9} J	In an average lightning bolt
2×10^{12} J	Daily electricity use at MIT	1×10^{12} J	Lift the Apollo lunar module to the moon
7×10^{15} J	Daily U. S. imported gasoline	1×10^{15} J	Released by average hurricane in 2 seconds
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J

EJ

0.01 EJ

1.04×10^{9} t

J

oe.gov

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R. L. Jaffe, APS April meeting Denver, 2009

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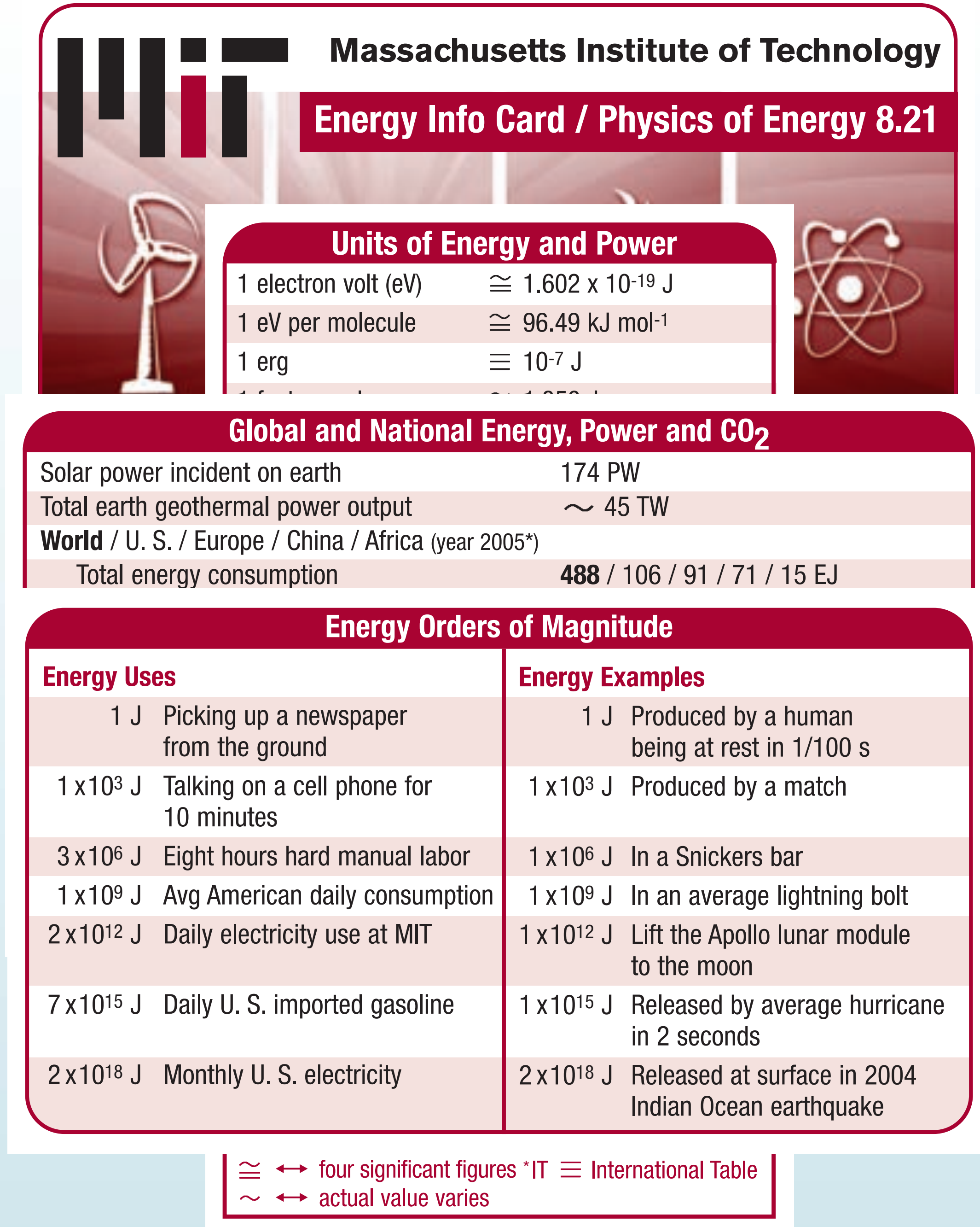

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Units of Energy and Power

1 electron volt (eV) ~ 1.602 x 10^{-19} J

Fundamental Constants and Useful Physical Quantities II

Mean radius of earth's orbit (1 A.U.)	1.495 978 706 60(20) x 10^{11} m
Earth mean equatorial radius	6.378 1366(1) x 10^{6} m
Mass of the earth	5.972 3(9) x 10^{24} kg
Average solar constant above atmosphere	1 366 W m^{-2}
Standard gravitational acceleration	9.806 65 m s^{-2} (exact)
Molar volume at STP	22.413 996(39) x 10^{-3} m^3 mol^{-1}
Gas constant ($R \equiv N_A k$)	8.314 472(15) J mol^{-1} K^{-1}
Water – latent heat of melting	334 kJ kg^{-1}
Water – latent heat of vaporization	2.26 MJ kg^{-1}
Specific heat capacity of water(15°C)/air(STP)	4.186 kJ $kg^{-1}K^{-1}$ / 1.0035 kJ $kg^{-1}K^{-1}$
Mass density of water(15°C)/air(STP)	999.1 kg m^{-3} / 1.275 kg m^{-3}
Molar heat of combustion (net calorific value) Hydrogen/Methane/Iso-octane/Graphite/Ethanol	242 / 800 / 5050 / 394 / 1330 kJ mol^{-1}
Half-life of ^{235}U / ^{238}U	7.0 x 10^{8} / 4.5 x 10^{9} yr
Half-life of ^{239}Pu / ^{232}Th	2.4 x 10^{4} / 1.4 x 10^{10} yr
Average annual environmental radiation exposure	3 x 10^{-3} Sv yr^{-1}

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Supported in part by the MIT Energy Initiative and the Department of Physics © R. L. Jaffe and W. Taylor

Energy and Power Quantities

Solar power output	384 YW
Rest energy of 1 kilogram	90 PJ
Energy to refine 1 barrel of oil	1.2 GJ
Estimated energy to produce 1 tonne of	
raw steel / aluminum / cement / glass	21.3 / 64.9 / 5.1 / 5.3 GJ
synthetic nitrogen / phosphate / potash fertilizer	78.2 / 17.5 / 13.8 GJ
Approximate energy content of one gallon of	
diesel / gasoline / ethanol / LNG	140 / 130 / 84 / 78 MJ
Energy content of one cord dried hardwood	26 GJ
Energy from complete fission of 1 kg ^{235}U	77 TJ

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Online Resources

MIT 8.21 Website	**physicsofenergy.mit.edu**
MIT Energy Club	web.mit.edu/mit_energy
MIT Energy Initiative	web.mit.edu/mitei
World Energy Council	www.worldenergy.org
International Energy Agency	www.iea.org
U. S. Department of Energy	www.energy.gov
U. S. Energy Information Administration	www.eia.doe.gov
National Renewable Energy Laboratory	www.nrel.gov
U. S. DOE Energy Efficiency and Renewable Energy	www.eere.energy.gov
Online Conversion	www.digitaldutch.com/unitconverter
National Institute of Standards and Technology (NIST)	physics.nist.gov/cuu/Units
NIST Guide to SI Units	physics.nist.gov/Pubs/SP811
Reaction Thermochemistry	webbook.nist.gov

Fundamental Constants and Useful Physical Quantities I

π	3.141 592 653 ...
e	2.718 281 828 ...
Planck's constant (reduced) ($\hbar = h/2\pi$)	1.054 571 628(53) x 10^{-34} J s
Speed of light (c)	2.997 924 58 x 10^{-8} m s^{-1} (exact)
Newton's constant (G_N)	6.674 28(67) x 10^{-11} m^3 $kg^{-1}s^{-2}$
Vacuum permeability (μ_0)	4π x 10^{-7} N A^{-2} (exact)
Vacuum permittivity (ε_0)	$(\mu_0 c^2)^{-1}$ = 8.854 187 817... x 10^{-12} F m^{-1}
Avogadro constant (N_A)	6.022 141 79(30) x 10^{23} mol^{-1}
Boltzmann constant (k)	1.380 650 4(24) x 10^{-23} J K^{-1}
Stefan-Boltzmann constant (σ)	5.670 400 (40) x 10^{-8} W m^{-2} K^{-4}
Electron charge (e)	1.602 176 487(40) x 10^{-19} C
Electron mass (m_e)	9.109 382 15(45) x 10^{-31} kg
Proton mass (m_p)	1.672 621 637(83) x 10^{-27} kg
Atomic mass unit or Dalton (u)	1.660 538 782(83) x 10^{-27} kg
Rydberg energy	13.605 691 93(34) eV

Fundamental Constants and Useful Physical Quantities II

Mean radius of earth's orbit (1 A.U.)	1.495 978 706 60(20) x 10^{11} m
Earth mean equatorial radius	6.378 1366(1) x 10^6 m
Mass of the earth	5.972 3(9) x 10^{24} kg
Average solar constant above atmosphere	1 366 W m^{-2}
Standard gravitational acceleration	9.806 65 m s^{-2} (exact)
Molar volume at STP	22.413 996(39) x 10^{-3} m^3 mol^{-1}
Gas constant ($R \equiv N_A k$)	8.314 472(15) J mol^{-1} K^{-1}
Water – latent heat of melting	334 kJ kg^{-1}
Water – latent heat of vaporization	2.26 MJ kg^{-1}
Specific heat capacity of water(15ºC)/air(STP)	4.186 kJ $kg^{-1}K^{-1}$ / 1.0035 kJ $kg^{-1}K^{-1}$
Mass density of water(15ºC)/air(STP)	999.1 kg m^{-3} / 1.275 kg m^{-3}
Molar heat of combustion (net calorific value)	
Hydrogen/Methane/Iso-octane/Graphite/Ethanol	242 / 800 / 5050 / 394 / 1330 kJ mol^{-1}
Half-life of ^{235}U / ^{238}U	7.0 x 10^8 / 4.5 x 10^9 yr
Half-life of ^{239}Pu / ^{232}Th	2.4 x 10^4 / 1.4 x 10^{10} yr
Average annual environmental radiation exposure	3 x 10^{-3} Sv yr^{-1}

SI Units

Mass	kilogram	kg	
Length	meter	m	
Time	second	s	
Force	newton	N	kg m s^{-2}
Energy	joule	J	kg m^2 s^{-2}
Power	watt	W	J s^{-1}
Pressure	pascal	Pa	N m^{-2}
Charge	coulomb	C	A s
Current	ampere	A	
EM Potential	volt	V	J C^{-1}
Resistance	ohm	Ω	V A^{-1}
Capacitance	farad	F	C V^{-1}
Inductance	henry	H	V s A^{-1}
Magnetic Field	tesla	T	V s m^{-2}
Amount	gram-mole	mol	
Temperature	kelvin	K	
Activity	becquerel	Bq	s^{-1}
Absorbed Dose	gray	Gy	J kg^{-1}
Dose Equivalent	sievert	Sv	J kg^{-1}

Prefixes

yocto (y)	10^{-24}	kilo (k)	10^3
zepto (z)	10^{-21}	mega (M)	10^6
atto (a)	10^{-18}	giga (G)	10^9
femto (f)	10^{-15}	tera (T)	10^{12}
pico (p)	10^{-12}	peta (P)	10^{15}
nano (n)	10^{-9}	exa (E)	10^{18}
micro (μ)	10^{-6}	zetta (Z)	10^{21}
milli (m)	10^{-3}	yotta (Y)	10^{24}

Handy Conversion Factors
(to four significant figures)

Units	Colloquial	SI
Mass	1 metric tonne (t)	1000 kg (exact)
	1 ounce (avoirdupois)	0.02835 kg
	1 pound (avoirdupois)	0.4536 kg
	1 ton (U.S.)	907.2 kg
Length	1 foot	0.3048 m (exact)
	1 mile	1,609 m
Time	1 year	3.156 x 10^7 s
Force	1 pound	4.448 N
Area	1 acre	4,047 m^2
	1 hectare	10,000 m^2 (exact)
Volume	1 liter (L)	0.001 m^3 (exact)
	1 fluid ounce (U.S)	0.02957 L
	1 liquid gallon (U.S.)	3.785 L
	1 liquid gallon (Imperial)	4.546 L
	1 oil barrel	159.0 L
	1 cord	3.625 m^3
Speed	1 mile per hour	0.4470 m s^{-1}
	1 knot	0.5144 m s^{-1}
Pressure	1 atmosphere	101,325 Pa (exact)
Temperature	ºCelsius (ºC)	K - 273.15 (exact)
	ºFahrenheit (ºF)	32 + 1.8ºC (exact)
Magnetic Field	1 gauss	0.0001 T (exact)
Radiation	1 rad	0.01 Gy (exact)
	1 rem	0.01 Sv (exact)

Units of Energy and Power

1 electron volt (eV)	≅ 1.602 x 10^{-19} J
1 eV per molecule	≅ 96.49 kJ mol^{-1}
1 erg	≡ 10^{-7} J
1 foot pound	≅ 1.356 J
1 calorie$_{IT*}$ (cal$_{IT}$)	≡ 4.1868 J
1 calorie$_{th*}$ (cal$_{th}$)	≡ 4.184 J
1 BTU$_{IT*}$	≅ 1.055 kJ
1 kilocalorie$_{IT*}$ (kcal) or Calorie$_{IT*}$ (Cal)	≡ 4.1868 kJ
1 kilowatt-hour (kWh)	≡ 3.6 MJ
1 cubic meter natural gas	~ 36 MJ
1 therm (U.S.)	≅ 105.5 MJ
1 tonne TNT (tTNT)	≡ 4.184 GJ
1 barrel of oil equivalent	≡ 5.8x10^6 BTU ≅ 6.118 GJ
1 ton of coal equivalent	≡ 7 Gcal$_{IT}$ ≡ 29.3076 GJ
1 ton of oil equivalent	≡ 10 Gcal$_{IT}$ ≡ 41.868 GJ
1 quad	≡ 10^{15} BTU ≅ 1.055 EJ
1 terawatt-year (TWy)	≡ 31.56 EJ
1 watt (W)	≡ 1 joule/sec
1 foot pound per second	≅ 1.356 W
1 horsepower (electric)	≡ 746 W
1 ton of air conditioning	≅ 3.517 kW

≡ ↔ definition; ≅ ↔ four significant figures; ~ ↔ actual value varies; *th ≡ thermochemical; *IT ≡ International Table

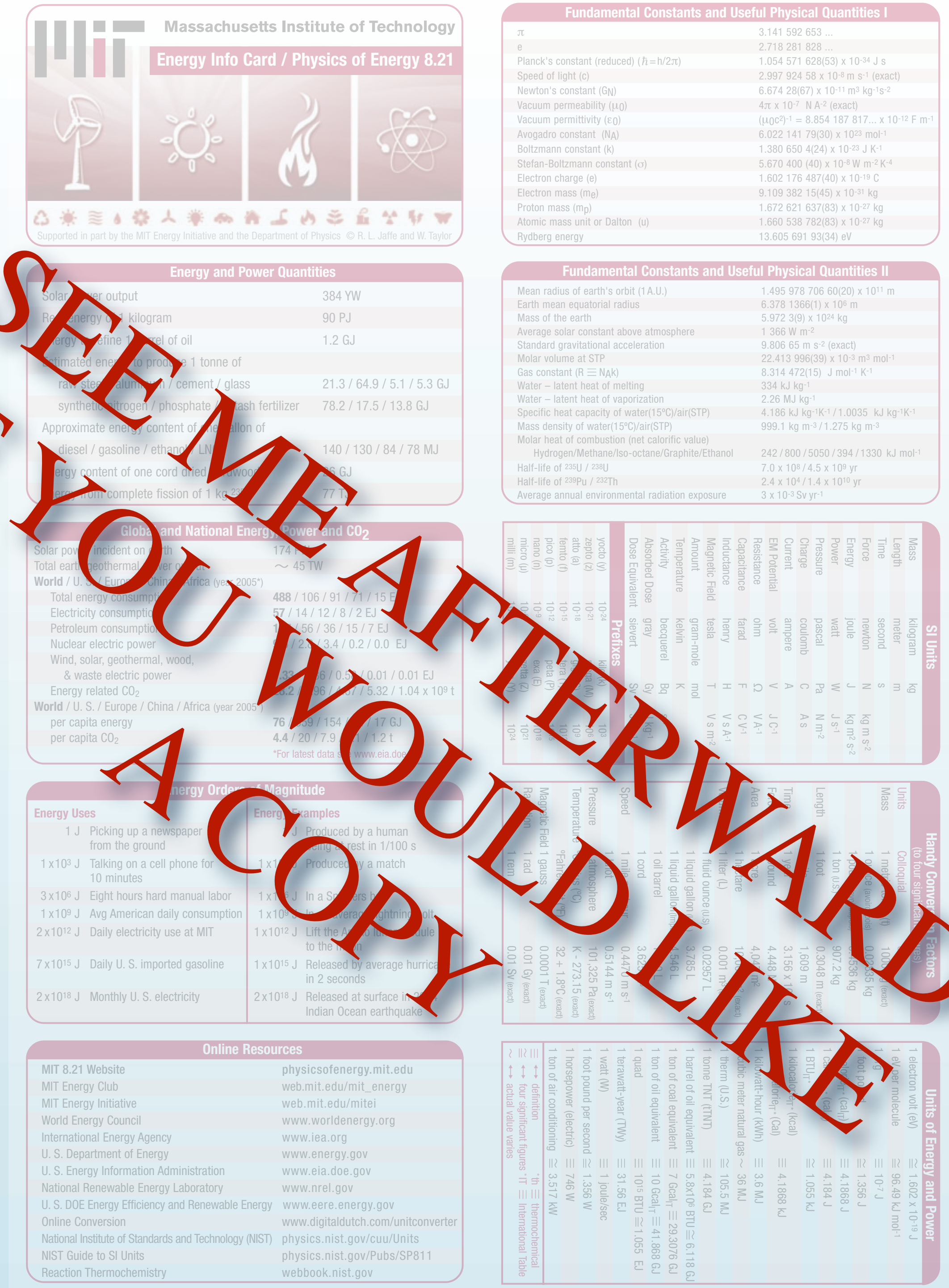
CTP center for theoretical physics

R. L. Jaffe, APS April meeting Denver, 2009

Thursday, May 7, 2009

An “Energy Card”

- We realized that students need easy access to
  - Multitude of conversion factors
  - Fundamental constants
  - Energy data
  - Qualitative feel for energy magnitudes
- Following in a great (retro) tradition
  - Decided on a “wallet card”
  - Aim to update and republish yearly



center for theoretical physics

MIT "Energy Minor"

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MITei MIT Energy Initiative

Starting Point for Undergraduate Framework

MIT students typically are firmly grounded in science and technology fundamentals through exposure to:

- General Institute Requirements
- Knowledge gained in their major area of study

MIT students would benefit from additional grounding in:

- E1 - Specific energy science foundations
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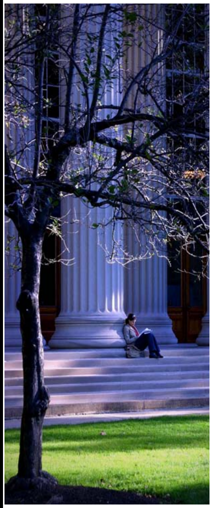

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FRESHMAN SOPHOMORE JUNIOR SENIOR

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- E0 - Freshman seminars/courses focused on energy
- Infusion of energy examples into GIRs

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- E3 – Energy Technology/Engineering in Context – application of laws and principles to specific energy context.

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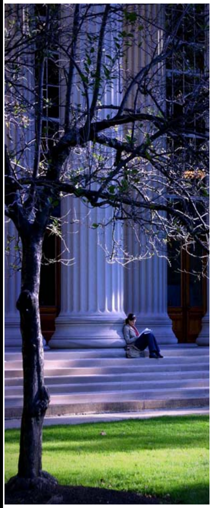

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- http://physicsofenergy.mit.edu