Neutrino Quantum Kinetics in Compact Objects

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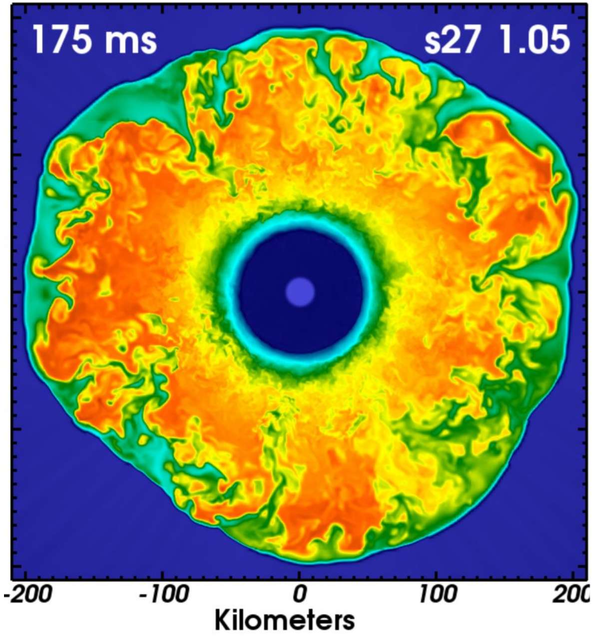
Gail McLaughlin
James Kneller
Alexey Vlasenko

Outline

1. Neutrino flavor oscillations in supernova engines
2. **IsotropicSQA**: open-source neutrino quantum kinetics
3. Order-of-magnitude decoherence rates.

Neutrinos in Core-Collapse Supernovae

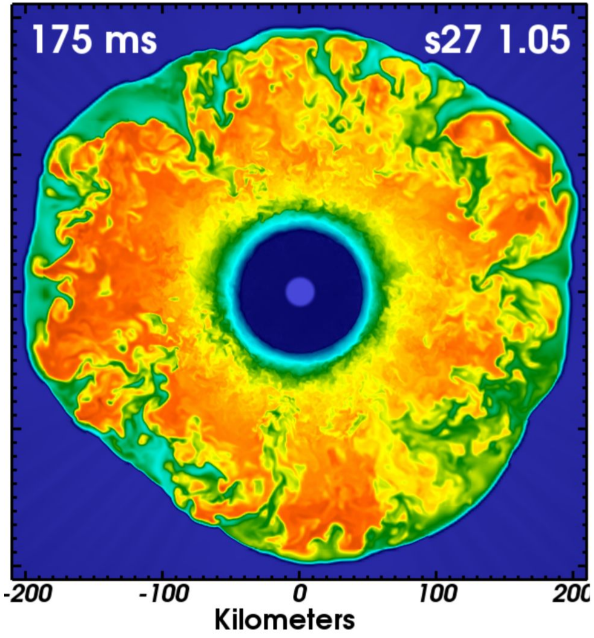


(Couch & O'Connor 2013)

Current Uncertainties

- Progenitor
- Equation of State
- Numerics
  - Resolution
  - Neutrino Transport Method
- Neutrinos
  - Microphysics
  - Flavor oscillations

Neutrinos in Core-Collapse Supernovae



(Couch & O'Connor 2013)

(e.g., Bethe 1985)

Neutrinos drive explosion through **heating**, my drive neutron star **kick**, and may be observed soon.

(e.g., Kusenko 2009)

- Delicate balance determines explodability
- Neutrinos **interact** and **oscillate**

(Historically, never at the same time)

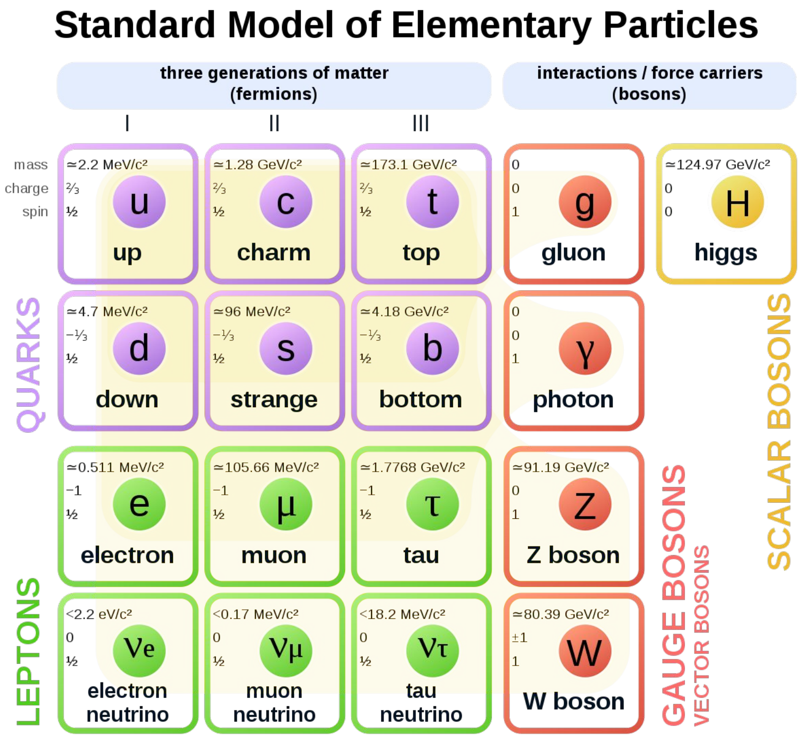
Neutrino Oscillations in Supernova *Engines*

1968 - 2001

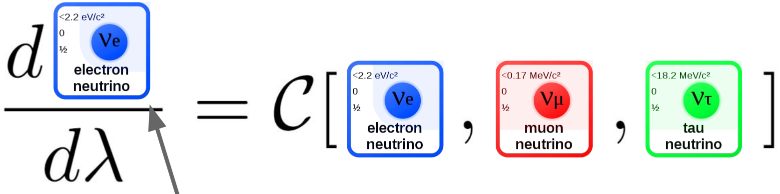
Oscillations Proposed and Discovered

Excessively simplified: Pontecorvo (1968), Ahmad+ (2001)

Neutrino Radiation Transport



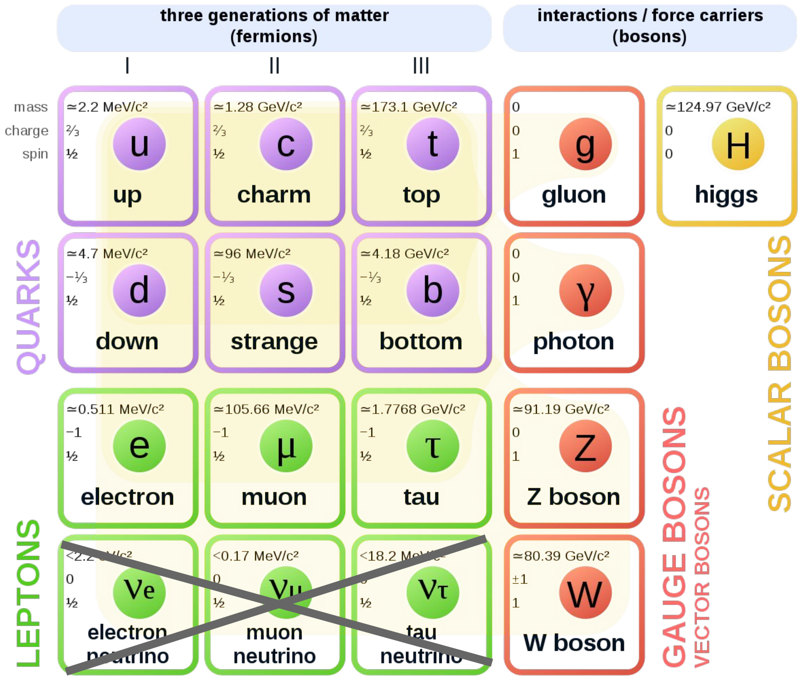
Treat each flavor separately:



$$f_{(\nu_e)}(\mathbf{x}, \mathbf{p}, t)$$

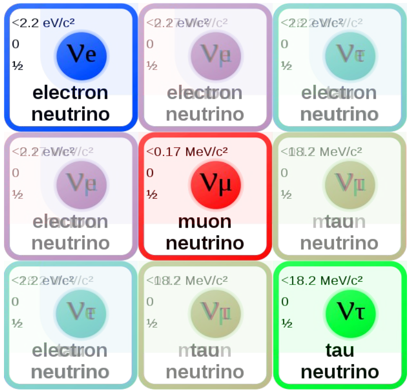
Neutrino Quantum Kinetics

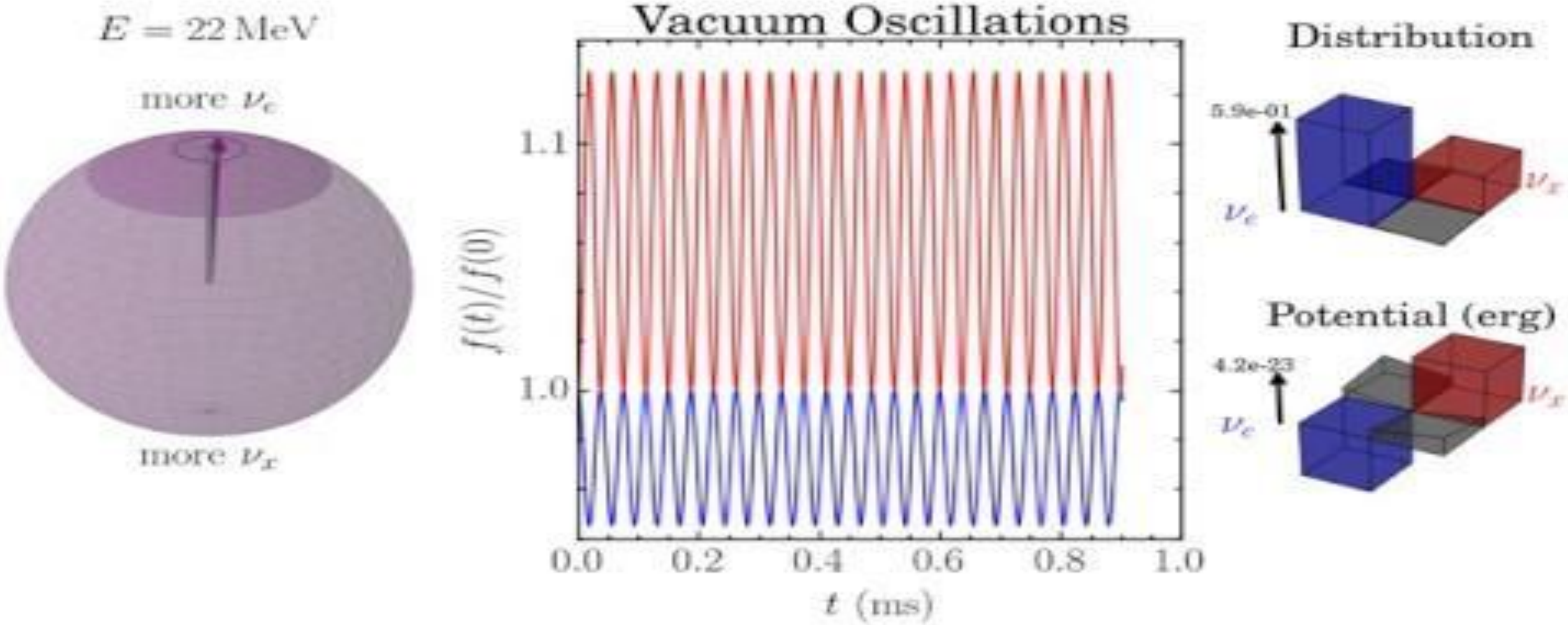
Standard Model of Elementary Particles



But the neutrino flavors are mixed!

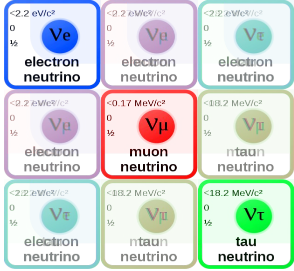
(Pontecorvo 1968, Wolfenstein1978, Mikheev & Smirnov 1985)





$E = 22\,\mathrm{MeV}$
more ν_e
more ν_x
Vacuum Oscillations
$f(t)/f(0)$
1.1
1.0
0.0
0.2
0.4
0.6
0.8
1.0
t (ms)
Distribution
5.9e-01
ν_e
ν_x
Potential (erg)
4.2e-23
ν_e
ν_x

Flavor Oscillations in Supernova *Engines*



1968 - 2001

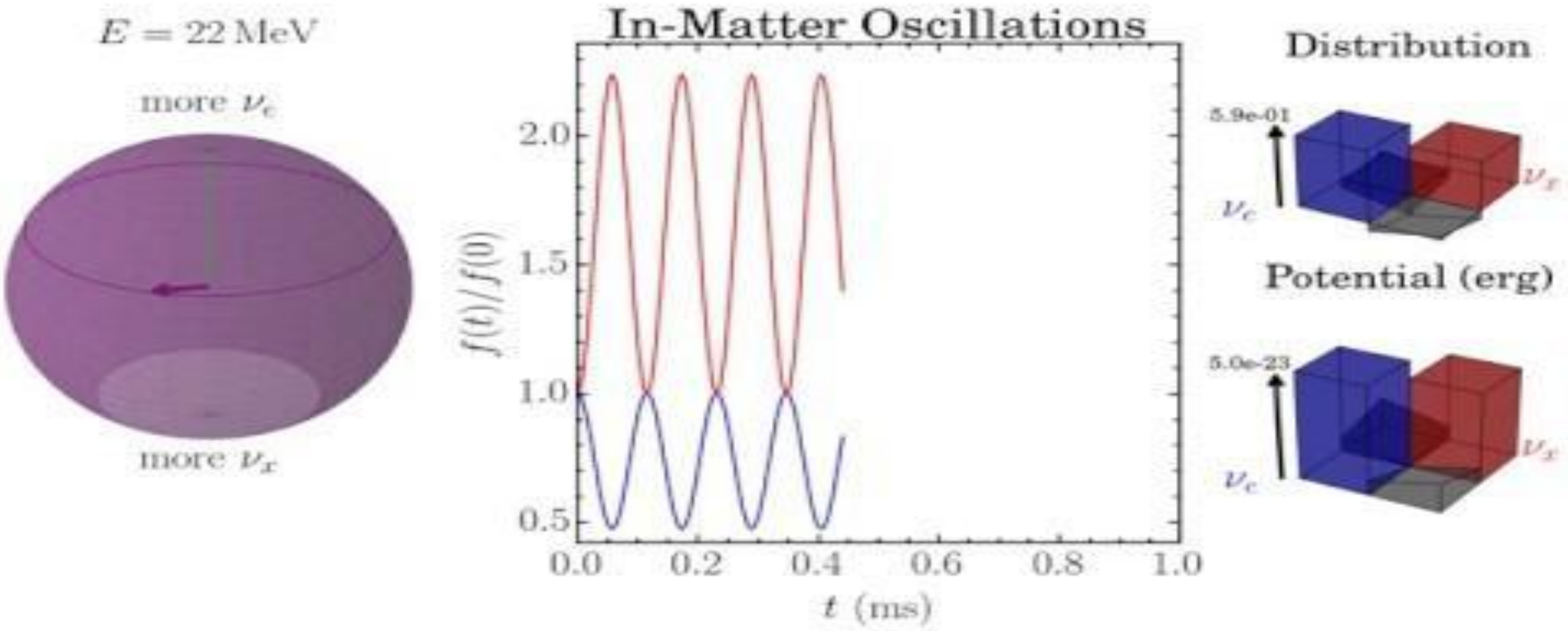
Oscillations Proposed and Discovered

Excessively simplified: Pontecorvo (1968), Ahmad+ (2001)

1978 - 2008

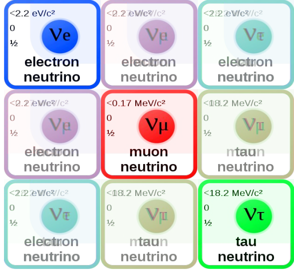
NO OSCILLATIONS: In-medium Effects

E.g., Wolfenstein (1978), Mkiheyev & Smirnov (1985), Fuller+ (1992), Quian+ (1993), Fogli+ (2007), Esteban-Pretel+ (2008)



$E = 22\,\mathrm{MeV}$
more ν_e
more ν_x
In-Matter Oscillations
$f(t)/f(0)$
2.0
1.5
1.0
0.5
0.0
0.2
0.4
0.6
0.8
1.0
t (ms)
Distribution
5.9e-01
ν_e
ν_x
Potential (erg)
5.0e-23
ν_e
ν_x

Flavor Oscillations in Supernova *Engines*



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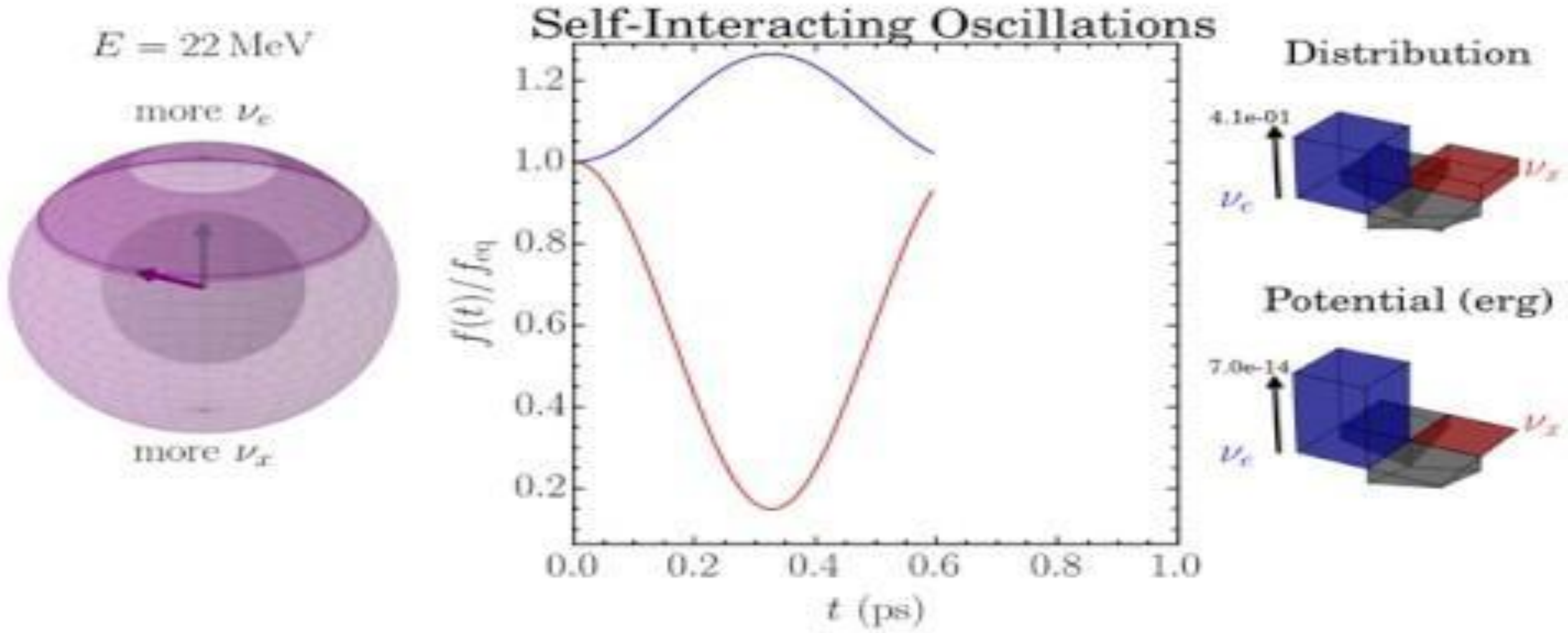
1987 - 2006

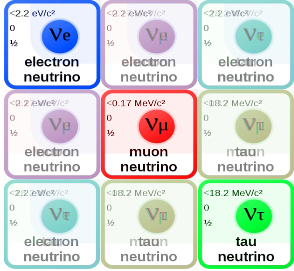
OSCILLATIONS: Neutrino-Neutrino Interactions

E.g., Fuller+ (1987,1988), Noetzold & Raffelt (1988), Pantaleone (1992,1998), Pastor+ (2002), Duan+ (2006)



$E = 22\,\mathrm{MeV}$
more ν_e
more ν_x
Self-Interacting Oscillations
1.2
1.0
0.8
0.6
0.4
0.2
$f(t)/f_{eq}$
0.0
0.2
0.4
0.6
0.8
1.0
t (ps)
Distribution
4.1e-01
ν_e
ν_x
Potential (erg)
7.0e-14
ν_e
ν_x

Flavor Oscillations in Supernova *Engines*



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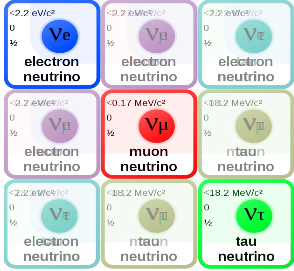
2011 - 2012

NO OSCILLATIONS: Direction-Dependent Calculations

E.g., Duan+ (2010), Dasgupta+ (2011), Chakrabotry+ (2011)

Flavor Oscillations in Supernova *Engines*



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2011 - 2012

NO OSCILLATIONS: Direction-Dependent Calculations

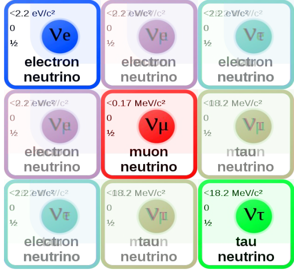
E.g., Duan+ (2010), Dasgupta+ (2011), Chakrabotry+ (2011)

2005 - present

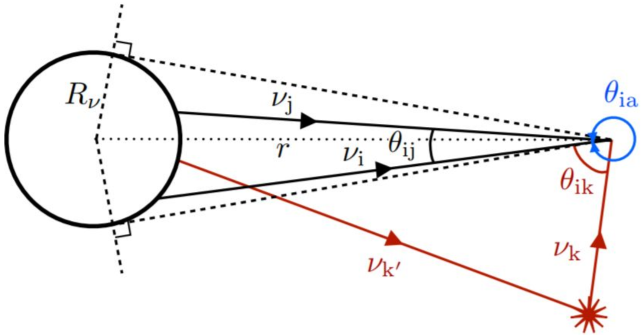
OSCILLATIONS: Direction-Dependent Calculations → New FAST Instability

E.g., Sawyer (2005), Sawyer (2015), Capozzi+(2015), Chakrabotry+ (2016), Tamborra+ (2017), Abbar + Volpe (2019), Yi+ (2019), Capozzi+ (2019), Abbar+(2019), Azari+ (2019), Walk+(2019) AND OTHERS

Neutrinos never cease to surprise us!



Neutrino Halo Effect

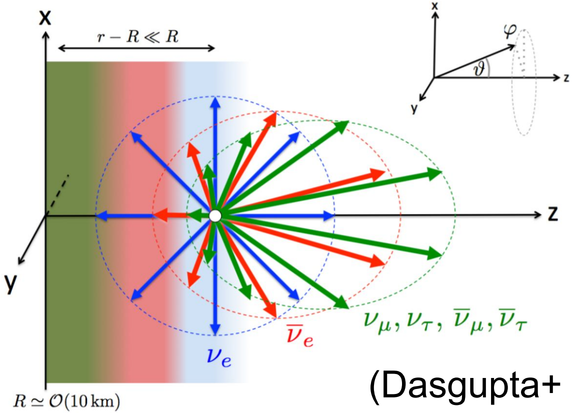


(Cherry+ 2012, 1203.1607)

Small number of reflected neutrinos can change neutrino flavors.

(Also, Cirigiliano+ 2018, 1807.07070)

Fast Oscillations

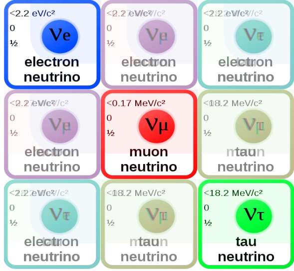


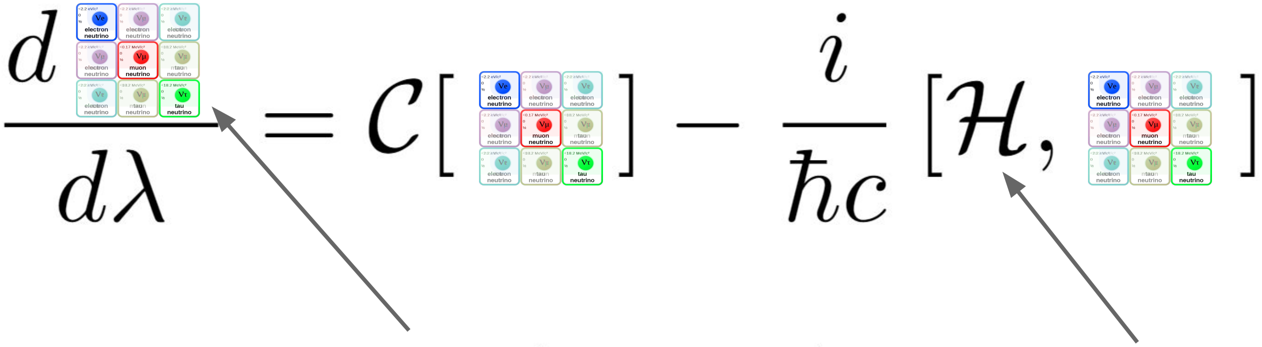
(Dasgupta+ 2017)

Neutrino/anti-neutrino angular dependence cause instabilities

(orig. Sawyer 2005, also Izaguirre+ 2016, Capozzi+ 2017, Dasgupta+ 2018, et al)

Neutrino Quantum Kinetics





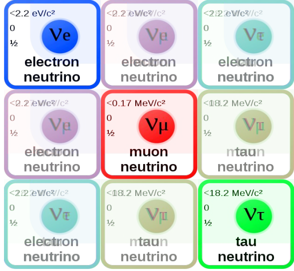
Cardall 2008
Vlasenko et al. 2014
Blaschke+Cirigliano 2016

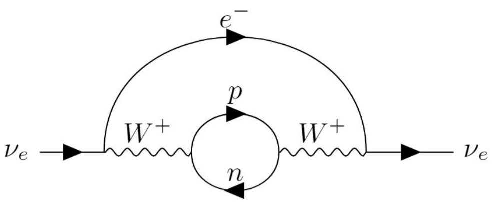
$$f_{ab}(\mathbf{x}, \mathbf{p}, t)$$

Different flavors experience different potentials.

Well, that’s not too bad, right?

Absorption and Emission



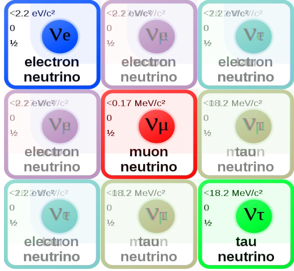


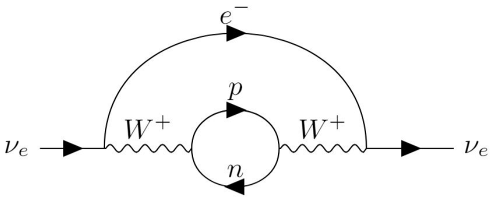
1) Read neutrino structure from diagram

$$C^+ \sim \begin{bmatrix} (1-f_{ee}) & -f_{e\mu}/2 & -f_{e\tau}/2 \\ -f_{\mu e}/2 & 0 & 0 \\ -f_{\tau e}/2 & 0 & 0 \end{bmatrix}$$

$$C^- \sim \begin{bmatrix} f_{ee} & f_{e\mu}/2 & f_{e\tau}/2 \\ f_{\mu e}/2 & 0 & 0 \\ f_{\tau e}/2 & 0 & 0 \end{bmatrix}.$$

Absorption and Emission





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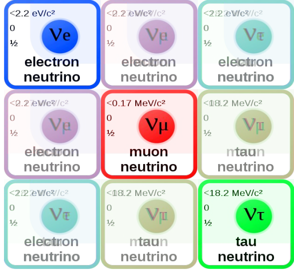
$$C^- \sim \begin{bmatrix} f_{ee} & f_{e\mu}/2 & f_{e\tau}/2 \\ f_{\mu e}/2 & 0 & 0 \\ f_{\tau e}/2 & 0 & 0 \end{bmatrix} .$$

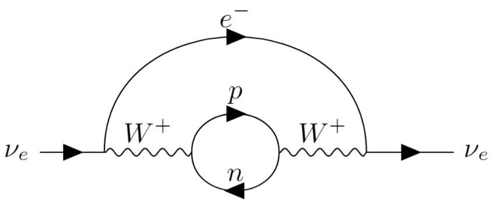
2) Require diagonals are the same as **known rates**

$$C^+_{ee} = j_{(\nu_e)}(1 - f_{ee})$$

$$C^-_{ee} = \kappa_{(\nu_e)} f_{ee} \, ,$$

Collision Rates → QKE Terms





QKE terms
from straightforward combinations of
ordinary terms

1) Read neutrino structure from diagram

$$C^+ \sim \begin{bmatrix} (1 - f_{ee}) & -f_{e\mu}/2 & -f_{e\tau}/2 \\ -f_{\mu e}/2 & 0 & 0 \\ -f_{\tau e}/2 & 0 & 0 \end{bmatrix}$$

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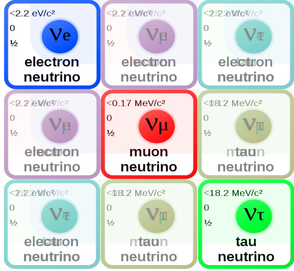
2) Require diagonals are the same as **known rates**

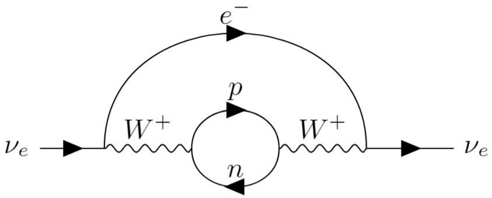
$$C^+_{ee} = j_{(\nu_e)}(1 - f_{ee})$$
$$C^-_{ee} = \kappa_{(\nu_e)} f_{ee} \,,$$

3) Profit.

$$C_{ab} = j_{(\nu_a)}\delta_{ab} - (\langle j \rangle_{ab} + \langle \kappa \rangle_{ab}) f_{ab}$$

Collision Rates → QKE Terms





QKE terms
from straightforward combinations of **ordinary terms**

We also include:
- Electron scattering/annhilation
- Neutrino scattering/annihilation
- Nucleon Scattering
- Effective bremsstrahlung

1) Read neutrino structure from diagram

$$C^+ \sim \begin{bmatrix} (1-f_{ee}) & -f_{e\mu}/2 & -f_{e\tau}/2 \\ -f_{\mu e}/2 & 0 & 0 \\ -f_{\tau e}/2 & 0 & 0 \end{bmatrix}$$

$$C^- \sim \begin{bmatrix} f_{ee} & f_{e\mu}/2 & f_{e\tau}/2 \\ f_{\mu e}/2 & 0 & 0 \\ f_{\tau e}/2 & 0 & 0 \end{bmatrix} .$$

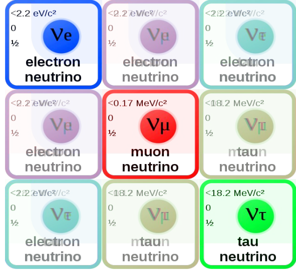
2) Require diagonals are the same as **known rates**

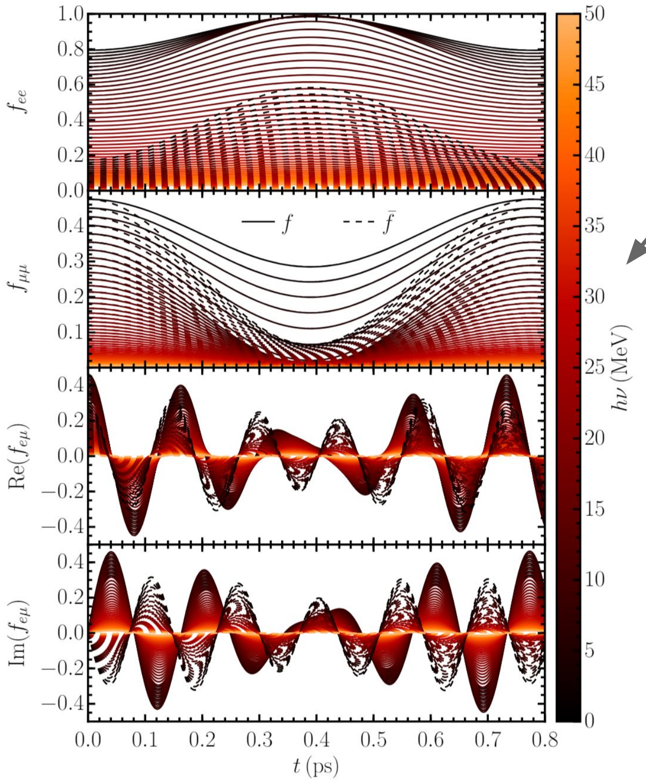
$$C^+_{ee} = j_{(\nu_e)}(1-f_{ee})$$
$$C^-_{ee} = \kappa_{(\nu_e)} f_{ee} \, ,$$

3) Profit.

$$C_{ab} = j_{(\nu_a)}\delta_{ab} - (\langle j \rangle_{ab} + \langle \kappa \rangle_{ab}) f_{ab}$$

Interactions + Oscillations

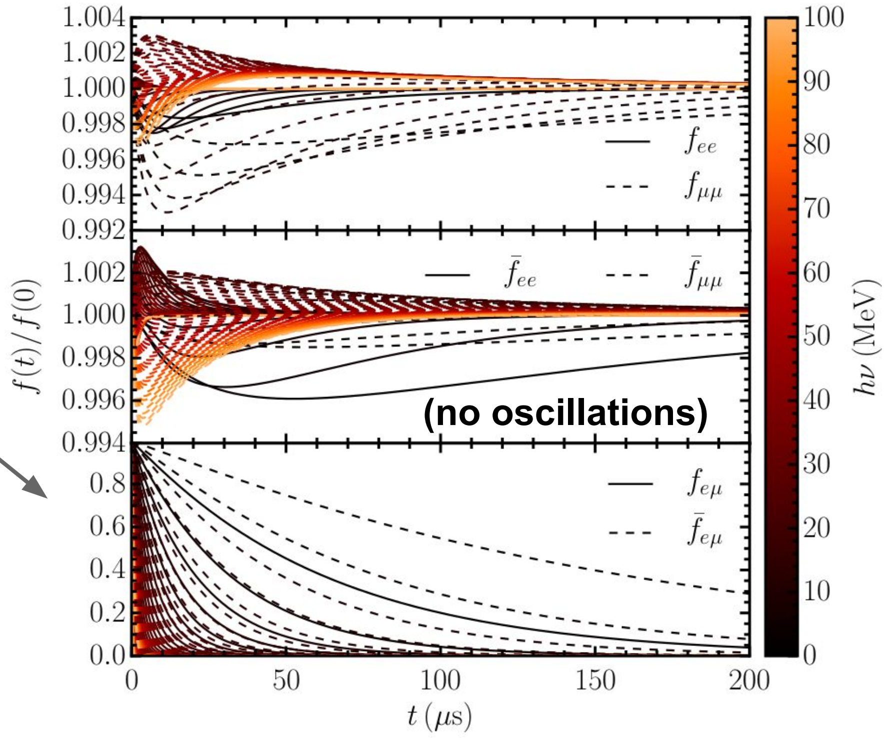




Oscillations are on extremely short timescales

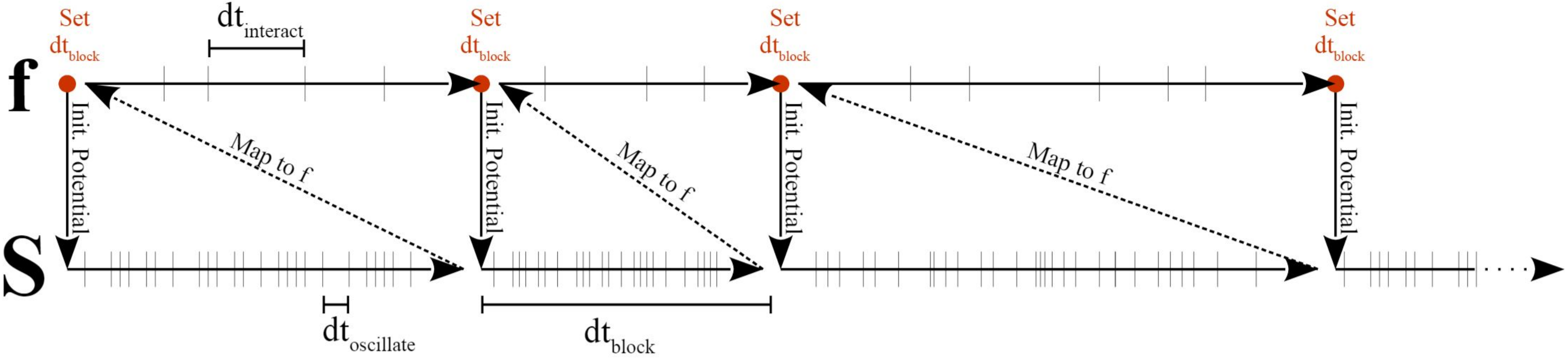
Interactions take 10^7 times longer!

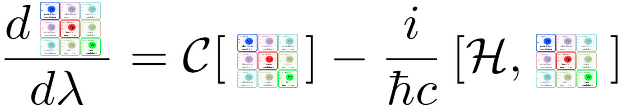
Not possible to evolve directly.



IsotropicSQA

github.com/srichers/IsotropicSQA



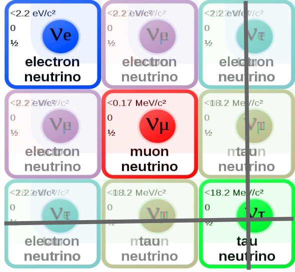


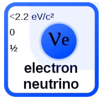
1) Evolve **oscillations only** for some “block” time
2) Evolve **interactions only** for same amount of “block” time
3) Check the impact of the interactions and adjust “block” time

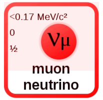
Details:

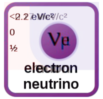
- Must randomize block time to accurately sample distribution
- Must evolve oscillations with high accuracy (many many timesteps)

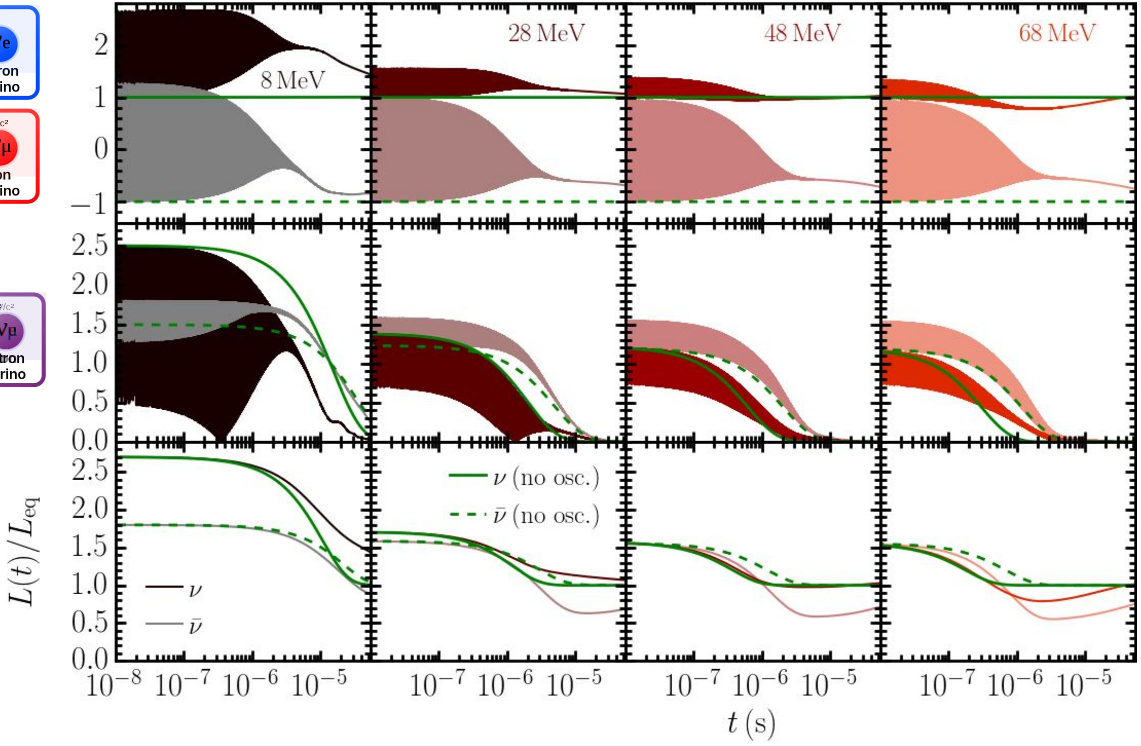
Everything Together









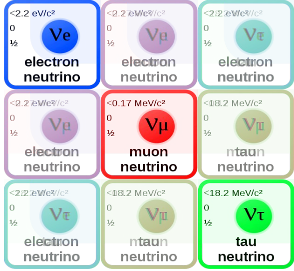


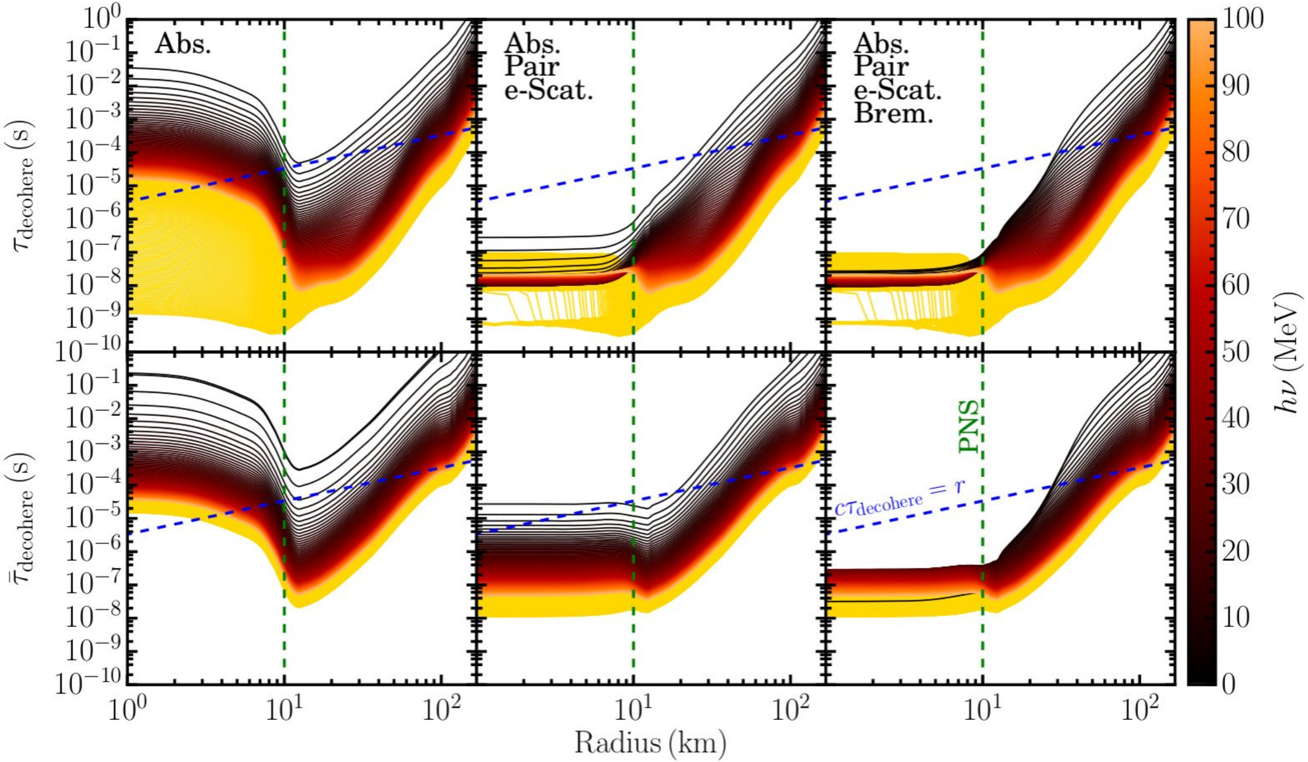
Decoherence with/without oscillations is **similar**

Separate timescales:

1) Damping oscillations
2) Relaxing to equilibrium

Many collision processes are important!





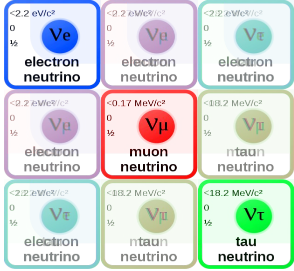
Core:

- Absorption/Emission
- Pair Processes
- Scattering
- Bremsstrahlung
- Neutrino-Neutrino

Heating Region:

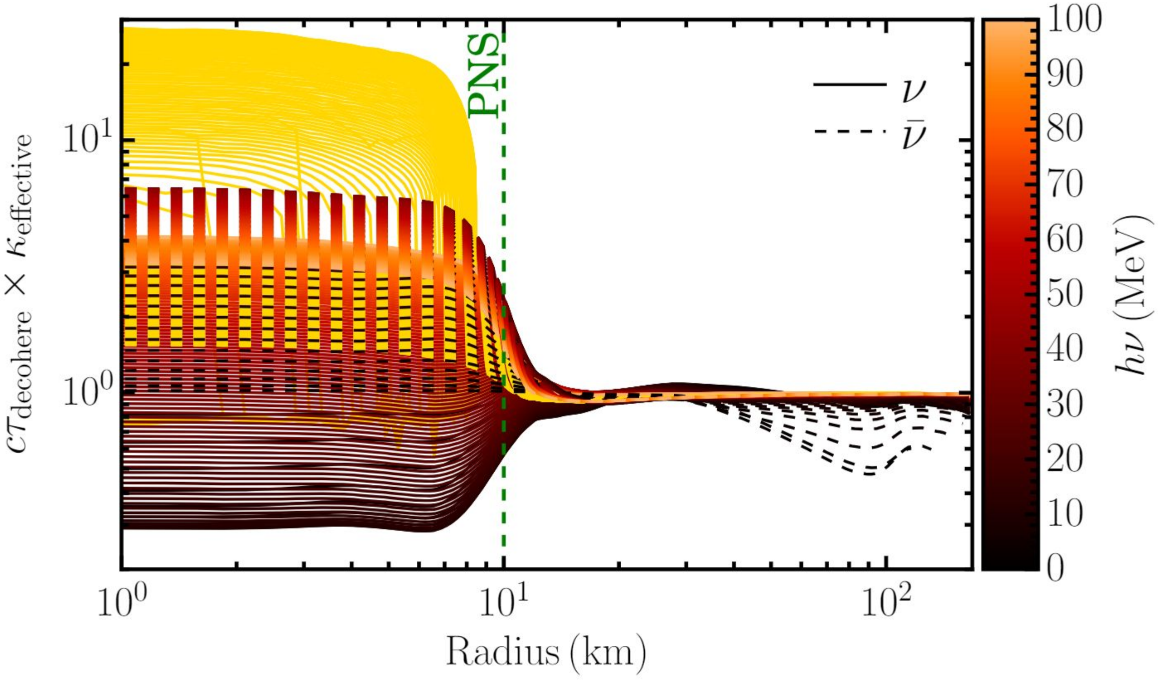
- Absorption/Emission

Simple “effective opacity”

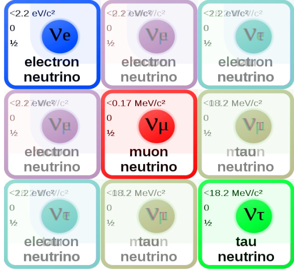


$$\kappa_{\text{effective}} := \kappa_{\text{abs},e\mu} + \frac{1}{2}\widetilde{\kappa}_{\text{scat},e\mu}$$

More effective than **mean free path** or **absorption opacity**



Conclusions



Existing neutrino interaction rates can be extended to **full QKE source terms!**

Effective opacity approximately predicts decoherence rates.

Many collision processes are significant.

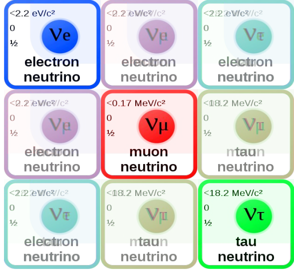
IsotropicSQA simulates **full isotropic QKEs** in supernova conditions.

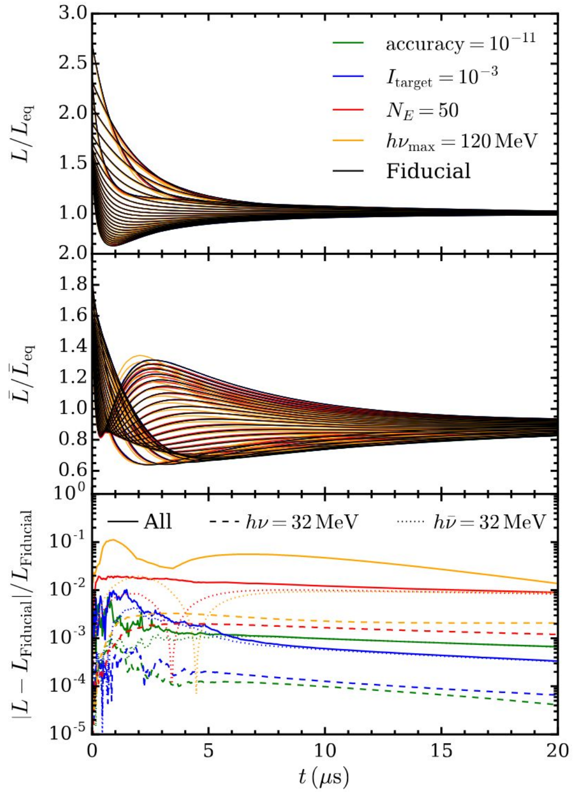
Isotropic**SQA**

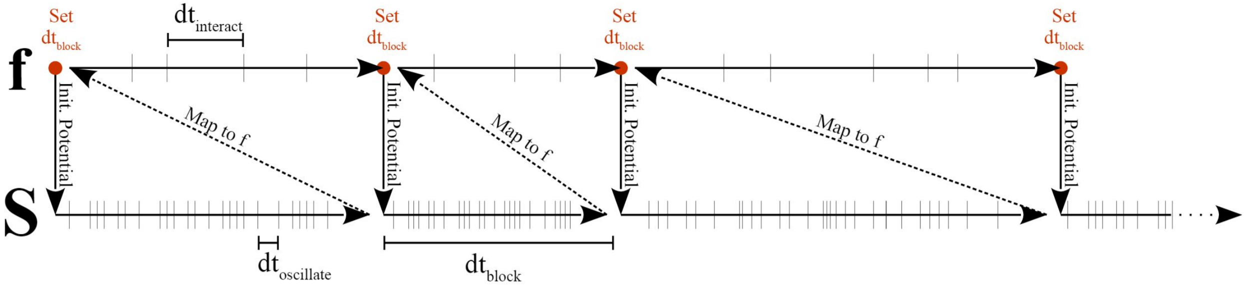
github.com/srichers/IsotropicSQA

Huge potential for improvement!

Numerical Challenges

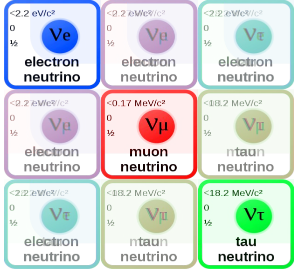


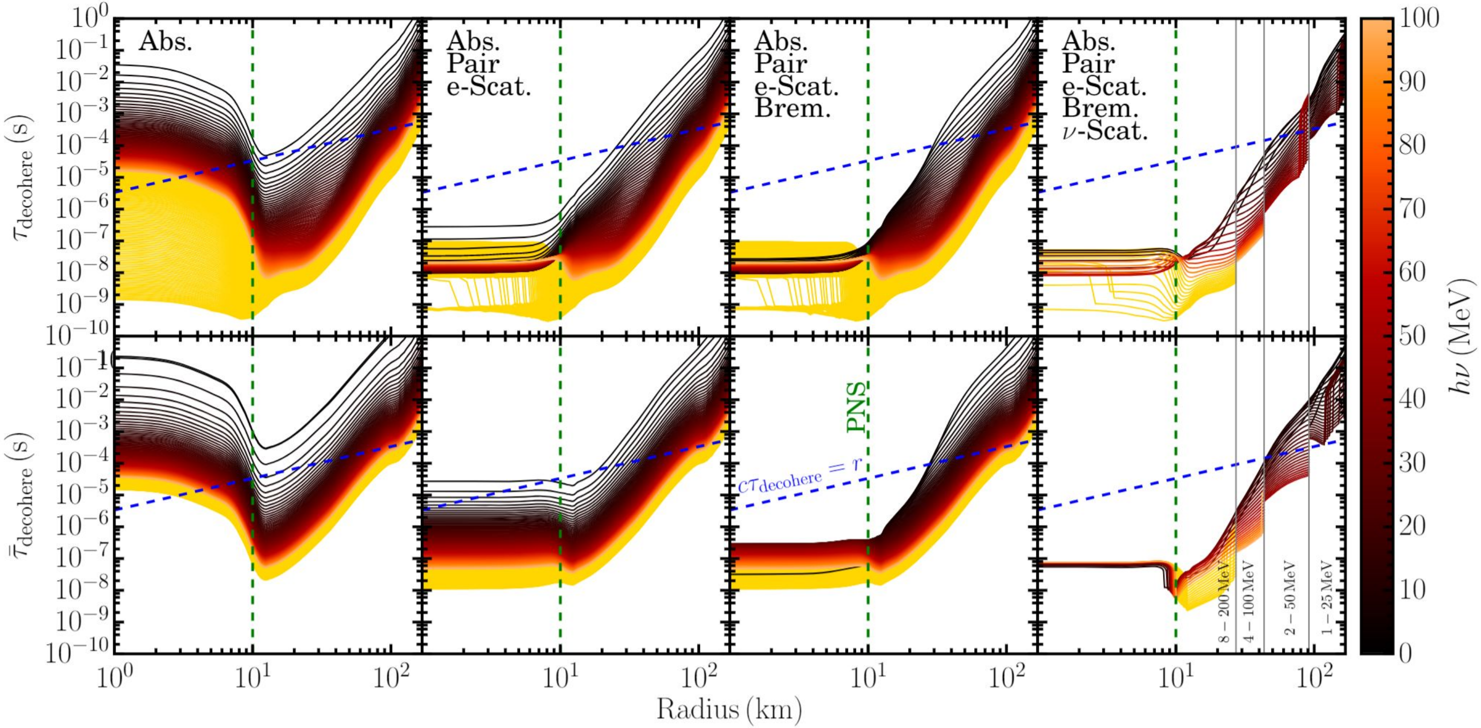




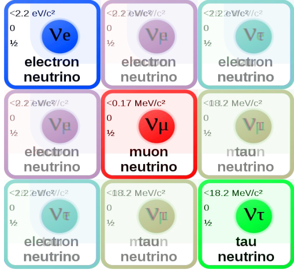
- Few evolution variables are **difficult to parallelize**
- **Conversion between S and f** induces error
- **Neutrino-neutrino interactions** scale with N_E^4 and require evenly-spaced energy grid
- Sensitive to size of the energy domain

Many collision processes are important!



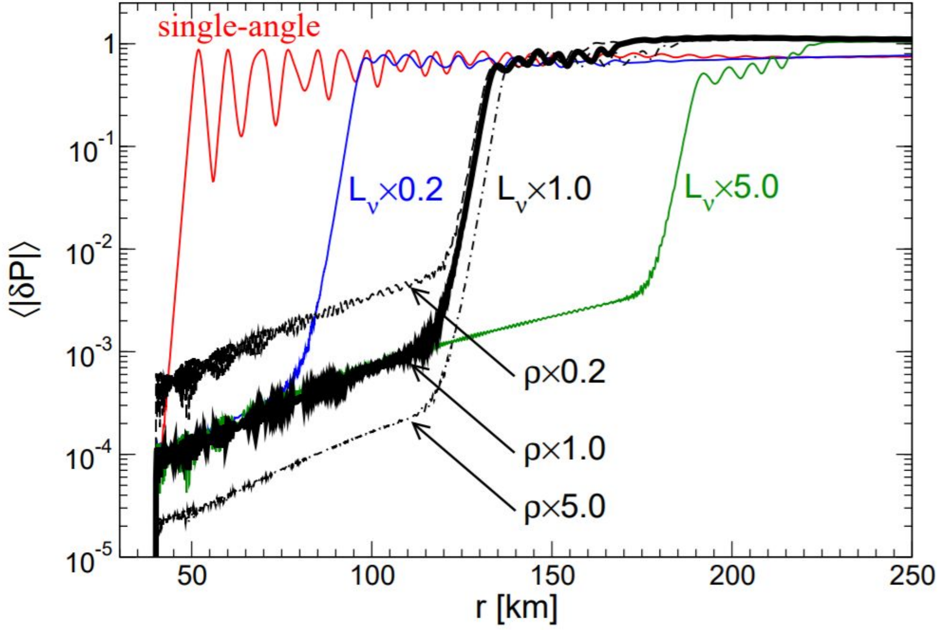


We don’t need to care, right?



1) Huge matter potential (Wolfenstein 1979)

2) **Multi-angle effects** suppress oscillations
(Chakraborty+ 2011, Duan+ 2011, Dasgupta+ 2012)



(Duan+ 2011)